On the characteristics of sea ice divergence/convergence in the Southern Beaufort Sea

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Abstract

An understanding of spatial gradients in sea ice motion, or deformation, is essential to understanding ocean-sea-ice-atmosphere interactions and realistic representations of sea ice in models used for the purposes of prediction. This is particularly important for the southern Beaufort Sea, where significant offshore hydrocarbon resource development increases the risk of oil and other contaminants dispersing into the marginal ice zone. In this study, sea ice deformation is examined through evaluation of ice beacon (buoy) triplets from September to November, 2009 in the southern Beaufort Sea (SBS), initially identified according to distance from the coastline on deployment. Results from this analysis illustrate differences in the evolution of ice beacon triplets at the periphery and interior of the ice pack in the SBS. The time rate of change in triplet area highlights two intervals of enhanced divergence and convergence in fall, 2009. Investigation of sea ice and atmospheric conditions during these intervals shows that until mid-September, all triplets respond to northerly flow, while during the second interval of enhanced divergence/convergence in October only one triplet responds to persistent northeasterly flow due to its proximity to the ice edge, in contrast to triplets located at the interior of the pack. Differences in sea ice deformation and dispersion near the pack ice edge and interior are further demonstrated in the behavior of triplets B and C in late October/ early November. The results from this analysis highlight differences in dispersion and deformation characteristics based on triplet proximity to the ice edge, with implications for modeling studies pertaining to sea ice dynamics and dispersion.

1. Introduction

Sea ice motion in the Beaufort Sea is characterized by large-scale anticyclonic circulation known as the Beaufort Gyre, with reversals to cyclonic circulation during summer months and more recently throughout the annual cycle (Preller and Posey, 1978; LeDrew et al., 1978; Proshutinsky and Johnson, 1997; Proshutinsky et al., 2002; Lukovich and Barber, 2006). In the Beaufort Sea ice deformation, or spatial gradients in sea ice motion, is characterized by the formation of ridges and leads in response to atmospheric forcing and coastline geometry (Overland et al., 1995; Hutchings et al., 2011) due to compression against the multi-year ice (MYI) zone and North American continent (Hutchings et al., 2005).

Previous studies have used Lagrangian dispersion statistics and ice beacon trajectories to quantify sea ice drift and deformation in the Arctic (Colony and Thorndike, 1984, 1985; Rampal, 2008, 2009a,b). Single-particle (absolute) statistics provide a signature of large-scale circulation and capture linear time-dependence in fluctuating velocity variance characteristic of turbulent diffusion theory (Taylor, 1921; Rampal et al., 2009). Departures in ice fluctuating velocity statistics from turbulent diffusion are attributed to intermittency associated with sea ice deformation and internal ice stress (Rampal et al., 2009). A two-particle (relative) statistical analysis monitors sea ice deformation, and through evaluation of buoy pair separations as a proxy of strain-rate (divergence, convergence, and strain) components combined, demonstrates heterogeneity and intermittency in the sea ice deformation field associated with space/time coupling inherent in fracturing of the sea ice cover as described by sea ice mechanics (Rampal et al., 2008; Weiss, 2013). Rampal et al. (2008) noted that a triplet or multiple-particle analysis is necessary to illustrate the deformation and small-scale kinematic features of sea ice. Three -particle statistics enable a distinction between the individual strain-rate tensor components of divergence, convergence, and shear. More specifically, sea ice divergence depicts open water formation and accompanying processes such as new ice growth, brine rejection to the ocean, and heat and moisture exchange. Ice convergence depicts ridge and keel formation thus contributing to ice thickening (Stern and Lindsay, 2009; Kwok and Cunningham, 2012), with implications for ice hazard detection, oil spill and contaminant transport and shipping route assessments within an increasingly industrialized Arctic.

While sea ice deformation provides insight into both the amount of open water interspersed amongst ice, and sea ice thickness due to deformation and ridging (Kwok and Sulsky, 2010; Weiss and Marsan, 2004), statistical analysis and scaling laws for sea ice deformation provide a signature of ice mechanics and dispersion (Girard, 2009; Weiss, 2013). Recent modeling studies demonstrate the inability of current ice-ocean models to capture heterogeneity and intermittency in sea ice deformation, underscoring the need for improved understanding of ice mechanics in models (Girard et al., 2009). This has resulted in the development of an alternative observational and modeling framework that incorporates anisotropic features of internal ice stress (Hutchings et al., 2011; Girard et al., 2011). Documented also in recent studies is spatial scaling dependent on season and region, with comparatively high deformation rates and increasingly negative exponents during summer, at the periphery of the ice pack, or in first year ice (FYI) associated with loss of connectivity and coherence in the ice cover (Stern and Lindsay, 2009; Weiss, 2013). An assessment of ice beacon triplets as a measure of sea ice deformation based on distance from the continental coastline and pack ice edge, as in the present study, will contribute to an understanding of such scaling properties, and in particular dispersion near the pack ice edge periphery and interior, essential to sea ice mechanical modeling.

Previous studies have highlighted the role of forcing (namely wind stress) and coastline geometry in establishing lead patterns/fractures in the ice cover captured by sea ice deformation (Pritchard, 1988; Overland et al., 1995; Hutchings et al., 2005, 2011). Overland et al. (1995) demonstrated that in the Beaufort Sea for spatial scales exceeding 100 km the sea ice cover moves as an aggregate. For scales between 1 km and 100 km the ice cover moves as an aggregate or discrete entity based on whether an elliptic (homogeneous) or hyperbolic (discrete) regime is established relative to the coastline, providing a characterization of ice-coast interactions. More specifically, an elliptic regime is characterized by diffusive behavior and spatial homogeneity in the ice pack, in contrast to a hyperbolic regime that is characterized by propagation of discontinuities and directionality in the ice pack (Overland et al., 1995). Furthermore, for spatial scales on the order of 1 km the ice cover is characterized by floe, or ice-ice, interactions. An assessment of the relation between stress and sea ice deformation as part of the Surface Heat Budget of the Arctic Ocean (SHEBA) campaign in the western Beaufort Sea during the 1997/1998 winter demonstrated correspondence between sea ice stress measurements and regional-scale (10 – 100 km) deformation activity governed both by coastal geometry and wind direction and magnitude (Richter-Menge et al., 2002a), and highlighted the need for both stress and deformation measurements in modeling sea ice dynamics.

Overland et al. (1995) also demonstrate correspondence in atmospheric forcing and sea ice deformation in the Beaufort Sea over timescales exceeding 3 days, citing persistent winds as a contributor to a fractured ice cover due to compressional waves with comparable phase to the speed of atmospheric systems (5 – 10 m/s) associated with internal ice stress. An assessment of the April 1991 and 1992 Arctic Leads Experiment in the Beaufort Sea further demonstrated that for strong northerly and westerly winds lead orientation is influenced by coastal geometry and sea ice moves as a discrete entity, whereas for easterly winds the ice cover moves as an aggregate within a consolidated sea ice regime. Recent studies of observed ice conditions in the SBS note that during the 2009 *Amundsen* cruise, a storm over open water north of the Chukchi Sea generated long-period swells on September 6th, 2009 that penetrated 350 km into the pack ice of the Beaufort Sea resulting in the fracture of 2 – 3 km floes into 50 – 100 m floes (Prinsenberg et al., 2010; Asplin et al., 2012). It was further shown that the swell did not extend eastward beyond 134.5 °W, as determined from aerial surveys and thickness measurements on September 9th following the swell event. In the present study we examine the correspondence between changes in sea ice deformation and surface wind speed and direction relative to the ice edge in the Beaufort Sea between September and November, 2009.

Recent studies of sea ice motion in the marginal ice zone (MIZ) in the southern Beaufort Sea (SBS) analyzed ice beacon trajectories during the fall/winter of 2007/2008 as part of the International Polar Year Circumpolar Flaw Lead study based on absolute, or single-particle dispersion statistics to provide a regional account of sea ice dynamics (Lukovich et al., 2011). Results from this investigation highlighted the existence of two scaling law regimes, namely in the zonal direction characteristic of westward advection and in the meridional direction characteristic of a hyperbolic (strain-dominated) regime and quasigeostrophic turbulence (Lukovich et al., 2011). Coherent ice drift features associated with mesoscale ice dynamics, namely loop and meander reversal events in the SBS were also investigated through analysis of relative (two-particle) Lagrangian dispersion statistics (Lukovich et al., 2014). In the present study we examine smaller-scale features and deformation characteristics of sea ice motion in the SBS based on a three-particle analysis that monitors evolution in a triangular array of ice beacons during the fall of 2009. In particular, a triplet analysis is used to provide insight into sea ice convergence and divergence at the pack ice edge and interior that is essential to an accurate representation of sea ice dynamics in modeling studies and to our understanding of the role of sea ice dynamics in ocean-sea-ice-atmosphere interactions. In consideration of these objectives, we therefore examine the following research questions:

1. What is the evolution in area of ice beacon triplets during the fall of 2009? (Sea ice convergence and divergence)
2. Is sea ice deformation in fall 2009 governed by ice and/or atmospheric forcing? How is this evolution influenced by triplet proximity to the pack ice edge? (Sea ice and atmospheric forcing)

Background

1.1 Triplet analysis and applications

Early studies of oceanic circulation have used multiple particles to monitor small-scale deformation and mixing as opposed to larger-scale stirring mechanisms inherent in single-particle statistical analyses. The change in the area of a triangular configuration or triplet of drifters monitors the change in flow divergence, and can be expressed as

$$\frac{1}{A}\frac{dA}{dt} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y},$$

where A denotes the triangle area, and u and v depict the zonal and meridional components of ocean circulation (Molinari and Kirwan, 1975; LaCasce, 2008). Negative values correspond to convergence. Additional gradients in sea ice motion or deformation characteristics such as vorticity, shearing and stretching can also be computed from changes in the triplet area through rotation of the velocity vectors (Saucier, 1955). As one reviewer has noted, studies of sea ice deformation and morphology in the context of velocity derivatives suggests a minimum of six measurements to accurately resolve average derivatives and reduce estimation error (Thorndike, 1986). In the present study evolution in fractional rate of change in triplet areas rather than strain components is investigated to measure sea ice deformation. In non-divergent flow the triplet area is conserved so that expansion in one direction is accompanied by contraction in another direction and the triangle becomes an elongated filament (Prinsenberg et al., 1998). Non-conservation in area may be attributed to either divergent surface flow or, as has been demonstrated in previous drifter studies, random perturbations superimposed on the mean flow (LaCasce and Ohlmann, 2003; LaCasce, 2008). Changes in the aspect ratio, defined as the longest leg or base divided by the height, also illustrate changes in the triplet shape. Increasing values indicate elongation and filamentation of the triangular configuration, while decreasing values indicate an approach to an equilateral configuration.

Early applications of a Lagrangian triplet analysis include the investigation of surface drifters in the western Caribbean (Molinari and Kirwan, 1975) and in the Gulf of Mexico (LaCasce and Ohlmann, 2003). Both studies depict a monotonic increase in triplet area characteristic of displacements in response to wind forcing rather than divergent surface flow, the latter of which would be captured by both positive and negative divergence resulting in decreases in the triplet area (LaCasce and Ohlmann, 2003). It was further shown that a decrease in the aspect ratio in the Gulf of Mexico resembled a transition from non-local dispersion associated with elongation of the triangles to local mixing associated with a return to an equilateral configuration characteristic of turbulent dispersion (LaCasce and Ohlmann, 2003), suggesting that even if material boundaries are not resolved by the triplet area, and fluid is mixed into and out of the triangular configuration, both the divergence and aspect ratio values can be used to provide insight into the nature of dispersion within the enclosed area. Subsurface observations based on sulfur hexafluoride tracer release experiments in the northeast Atlantic also demonstrated filamentation of the tracer due to non-local stirring and subsequent mixing at smaller scales (Ledwell et al., 1988).

Ice beacon triplet arrays have been used in previous studies to monitor sea ice deformation off the Canadian east coast and in Antarctica (Prinsenberg et al., 1997; Heil et al., 2002; 2008; 2009; 2011). Studies of correspondence between ice stress, convergence and atmospheric forcing off the southern coast of Labrador in March, 1996 showed little change in convergence within an already compact ice cover, in addition to an increase in stress with winds and decrease in stress with temperature as the icepack loses its ability to transmit pressure (Prinsenberg et al., 1997). These results are consistent with studies of derived ice motion fields using synthetic aperture radar data showing sea ice deformation and production 1.5 times higher in the seasonal than in the perennial ice zone throughout the Arctic in late fall and winter due to differences in ice strength and thickness (Kwok, 2006). Hutchings et al. (2011) through analysis of a nested beacon configuration and array with spatial scales ranging from 10 km to 140 km as part of the March 2007 Sea Ice Experiment: Dynamic Nature of the Arctic (SEDNA) campaign in the western Beaufort Sea demonstrated coherence between 140 km and 20km divergence arrays for time periods of up to 16 days in March and over shorter (sub-synoptic) timescales following May.

Studies of the evolution in triangular configurations within a 24-beacon array in the western Weddell Sea in fall, 2004 during the Ice Station POLarstern (ISPOL) experiment indicated that changes in atmospheric circulation and winds govern sea ice deformation on weekly timescales in this region (Heil et al., 2008). More recent observational studies during the austral spring of 2007 as part of the Sea Ice Physics and Ecosystem eXperiment (SIPEX) illustrated a decrease in the influence of synoptic atmospheric forcing of sea ice drift off East Antarctica relative to earlier studies despite an anomalous increase in cyclonic intensity, and an increase in semi-diurnal motion variance. Significant divergence in the region evidenced in triplet area increases ranging from 230% in the eastern to 267% in the western portion of the region was also observed (Heil et al., 2011).

2. Methods

Sea ice drift data were obtained from an array of ten ice beacons and one ice mass balance buoy launched from the CCGS *Amundsen* in the marginal ice zone of the southern Beaufort Sea in September, 2009 (Figure 1 and Table I). From this array, four triangular configurations were selected, hereinafter referred to as triplets A to D, to monitor divergence and convergence of sea ice with initial inter-beacon distances of approximately 11, 11, 11.5, and 7 km for the shortest leg, and 15, 37, 11.5, and 12.5 km for the longest leg, respectively. Triplets A to D were deployed on MYI and labeled according to their proximity to the continental coastline: triplet A was located closest to the coastline, while triplet D was located furthest from the coastline. Position coordinates were available for all beacons in: triplet A until October 6th; triplet B until November 4th; triplet C until November 25th, and triplet D until November 3rd, yielding time intervals with durations of 28, 56, 77, and 59 days, respectively (Table II). The temporal resolution of the beacon data is two hours and daily averages were calculated for the analysis and time series. Since the anticipated lifetime of the beacon batteries is at least one year, the beacon longevity may be attributed either to alternative mechanical failure or ice deformation and ridging.

It should be noted that triplets are initially identified relative to the fixed reference of the coastline. However their evolution and in particular sea ice divergence and convergence are investigated relative to the dynamic frame of the pack ice edge to investigate differences in dispersion at the pack ice edge and interior.

Triplet areas were computed from recorded beacon latitude/longitude coordinates using Matlab® routines and the numerically stabilized Heron's formula $A = \sqrt{s(s-a)(s-b)(s-c)}$, where a, b, and c denote the length of the sides for each triplet, and $s = \frac{1}{2}(a+b+c)$. As reported in Lukovich et al. (2011), positional accuracy of the ice beacons ranged from $\delta x = 2.5$ to 5 m based on circular and spherical error probability associated with the GPS module, while temporal accuracy was on the order of nanoseconds and thus negligible. Position accuracy for the ice mass balance buoys was less than 3m according to Garmin GPS16X-HVS product Standard GPS accuracy. Error propagation analysis for the triangle area and triplet evolution according to Heron's formula yields initial error estimates on the order of $\delta_A = \frac{\delta x}{\sqrt{8}A}\sqrt{(b^2+c^2-a^2)^2a^2+(a^2+c^2-b^2)^2b^2+(a^2+b^2-c^2)^2c^2} \sim 0.05$, 0.12, 0.04, and 0.04 km^2 for triplets A to D, respectively. Ice and atmospheric conditions are investigated according to the spatial and temporal evolution in ice beacon triplet centroids. Ice drift velocities for each triplet centroid further highlight acceleration/deceleration in the triplet during fall, 2009.

A diagnostic known as the local meander coefficient, which is defined as the ratio of the total trajectory length to its net displacement over a given interval of time, has been used in the aforementioned studies of ice beacon triplets launched in Antarctica to monitor deviations of the beacons from their mean drift (Heil et al., 2008, 2011; Massom, 1992). Values of one indicate linear drift characteristic of the mean, whereas values significantly greater than one indicate erratic drift. High meander coefficients (> 8) for the ISPOL experiment in the Weddell Sea in the austral summer of 2004 were attributed to significant anticyclonic circulation associated with tidal forcing over shallow water (< 700 m). This is in contrast to low meander coefficients (~ 4) for ice drift over deeper water (> 900 m) less susceptible to tidal forcing (Heil et al., 2008). Even lower meander coefficient values (~1.1 – 1.8) for the SIPEX experiment off East Antarctica in the austral spring of 2007 were attributed to the dominant role of atmospheric forcing, namely persistent winds, relative to tidal forcing in this region (Heil et al., 2011). In the present study the meander coefficient is computed for the time interval during which all triplets are defined, from September 9th to October 6th, 2009, since its value depends both on deployment dates and duration of the trajectories that define the beacon triplets.

Sea ice extent and type are examined using Environment Canada Canadian Ice Service (CIS) weekly ice charts, in addition to 12.5 km resolution Advanced Microwave Scanning Radiometer – EOS (AMSR-E) daily sea ice concentration data. Daily and weekly maps illustrate spatial variability of sea ice concentrations in the SBS, while also enabling an assessment of ice conditions in the vicinity of the triplet centroids during their evolution from September to November, 2009.

Atmospheric forcing of sea ice was monitored through investigation of North American Regional Reanalysis (NARR) wind data (Mesinger et al., 2006). Atmospheric contributions to changes in sea ice deformation were investigated using daily averages of 10m zonal and meridional winds computed from 3-hourly NARR data for the SBS to generate time series of NARR winds highlighting the existence of on-shore and off-shore winds that would contribute to changes in the sea ice deformation in fall, 2009.

3. Results and Discussion

3.1 Sea ice convergence and divergence

A map of trajectories for all beacons launched in fall/winter of 2009 and 2010 illustrates the large-scale circulation pattern associated with the anticyclonic circulation in the southern segment of the Beaufort Gyre (Figure 1). Noteworthy is the existence of small-scale variability on the order of tens of kilometers superimposed on the larger-scale westward advection, captured by meander coefficients computed for each beacon duration (Table 1). Values of ~1.7 are found for beacons 9, 10, and 11 that comprise triplet D. This is in contrast to values of ~1.3 for beacons at lower latitudes, indicating more erratic ice drift at higher latitudes in the SBS in the fall of 2009. It should however be noted that these values (< 2) are smaller than those encountered in the Weddell Sea (~ 8) during the ISPOL experiment, as noted by Heil et al. (2008). Examination of ice beacon triplets also shows that they follow the same general path with increased elongation closer to the coastline until November, 2009 (Figure 1a), suggesting large-scale coherence in the pack upon which are superimposed smaller-scale features in response to forcing based on proximity to the ice edge associated with the tongue of MYI evident in the SBS at the time of deployment (Fig. 1b), as is discussed further in Section 3.2.

From the array of beacons released to the west of Banks Island in September, 2009, four triplets were initially identified according to their proximity to the coastline and fixed frame of reference (Figs, 1 and 2). Maps of triplets and their centroids highlight spatial differences in triplet evolution (Fig. 2), while time series capture temporal evolution in triplet configurations (Fig. 3). The initial configuration of triplet A is confined to the eastern Beaufort Sea (Fig. 2), and subsequently experiences horizontal deformation and elongation near 140°W on 19 September 2009 captured by a decline in area (Fig. 3). Triplet A then returns to pre-existing area values until early October. Triplet B initially demonstrates intervals of a zonally elongated configuration while advected westward (Fig. 2), captured by decreases in area on 15 and 17 September near 137 and 140 °W, and on 15 and 22 October near 147 and 150 °W, following which the triplet area increases (Fig. 3). Triplet B also exhibits increased temporal variability relative to other triplets.

At higher latitudes triplet C exhibits a decrease in area on 17 September associated with meridional alignment of the beacons near 73°N and 137°W (Fig. 2). Triplet C areas then return to initial values until 3 November near 155°W when two beacons within the triangular configuration are interchanged and the area begins to substantially increase (Fig. 3). Located further north than triplet C, triplet D maintains its initial configuration, with intervals when the beacons align within the meandering trajectory over spatial scales on the order of tens of kilometers in the eastern Beaufort Sea. Noteworthy are regions where the triplet D becomes “trapped” or stalled, namely near 74.5°N, 136°W, 73.5°N, 140°W, and 73.5°N, 145°W on 15 September, 7 and 15 October 2009, respectively. Triplet D exhibits a decline to vanishing area values near 15 – 16 September as the beacons align within a trapping regime near 74.5°N and 136°W (Fig. 2), followed by a gradual increase in area that approaches the initial state until early November (Fig. 3). Results from investigation of the spatial and temporal evolution in triplet area show that all triplets respond to a single forcing event in September, with differences between triplet behaviour providing a signature of regional variability. In October only triplet B exhibits the largest changes in area.

Temporal evolution in triangle shape is measured through analysis of the base, height, and aspect (base-to-height) ratio for each triplet (Fig. 4). Base values decrease with increasing latitude, highlighting elongation closest to the coastline (Fig. 4a). A gradual increase in base values is initially observed for triplets A to D until 14 September, followed by equilibration in all triplet values, with an increase near 24 October for triplet B and near 3 November for triplet C. Base values provide an interpretation of two-particle displacements or relative separation between a pair of particles. Constant slopes from 19 September to 14 October indicate coherence in triplet beacon trajectories over length scales of 20 km, 30 km, and ~70 km for triplets D, C, and B, respectively, while enhanced values following 24 October for triplet B and 3 November for triplet C indicate a change in ice drift characteristics and transition to an alternative dynamical regime. Height values capture triplet area behavior shown in Fig. 3, with vanishing values from 14 to 16 September evident in triplets B, C, and D, and from 15 to 22 October for triplet B, culminating in an increase in triplet B height values following October 24th (Fig. 4a). The absence of coherence indicative of small-scale (~ 6 km) variability is evident in differences in height values for triplets A and B, which share two of the three beacons comprising these triplets.

Time series for the aspect (base-to-height) ratio further highlight spatiotemporal differences in triplet evolution and shape (Fig. 4b). As is noted in the Introduction, decreasing values in, or negative slopes for plots of, the aspect ratios as a function of time indicate an approach to a more equilateral configuration where the triangle base and height are of comparable magnitude (aspect ratio ~ 1). Increasing values or positive slopes indicate elongated triangles characteristic of filamentation. Triplets A and C demonstrate positive slopes indicating a tendency for filamentation in the early and later stages of development. By contrast, negative slopes for triplet B approaching early November depict an evolution to a more equilateral configuration shown in Fig. 2. Local maxima in the aspect ratio with values exceeding in some instances 100 for triplet B in September and October indicate intervals of zonal alignment and shear. A local maximum in the aspect ratio for triplet D near 15 September corresponds to beacon alignment within the trapping regime located near 74.5°N and 136°W (Figs. 2 and 3). Triplets B, C, and D thus show enhanced aspect ratio values characteristic of shear following mid-September. Triplet B shows enhanced aspect ratios in October, while surviving triplets C and D show sustained yet decreasing shear with increasing distance from the coastline.

As previously noted, LaCasce and Ohlmann (2003) demonstrated in the study of oceanic drifter triplets an exponential increase in the triangle base and accompanying increase in height, and attributed this to the superposition of a diffusive or random-walk regime upon exponential stretching characteristic of shear. A similar increase in both triangle base and height in triplet B in early November in the present analysis suggest that ice deformation measured by triplet B captures analogous behavior; namely small-scale variability superimposed on exponential stretching, westward advection, and shear associated with anticyclonic circulation of the Beaufort Gyre evident in the elongation of triplet C in November. As is also noted in the Introduction, LaCasce and Ohlmann (2003) and LaCasce (2008) further showed that an elongated triplet configuration provides a signature of non-local forcing due to large-scale shear, as with anticyclonic circulation of the Beaufort Gyre, whereas evolution to a more equilateral configuration provides a signature of local forcing and mixing as at the periphery of the Beaufort Gyre in the SBS. A decrease in aspect ratios for triplet B in November in the present study thus indicates a transition to mixing, while an increase in triplet C aspect ratios in November highlights increasingly strain-dominated dispersion.

Centroid velocities for each triplet illustrate intervals of acceleration/deceleration that accompany spatiotemporal changes in triangular area, while also providing insight into spatial coherence of beacon triplets. Non-local behavior is captured by similar ice drift for all beacon centroids, while local differences in ice drift are captured by differences in ice drift speed and orientation (Fig. 5). Comparison of centroid velocities highlights intervals when sea ice in the SBS is governed non-local mechanisms, in which case it moves as a consolidated aggregate, or local mechanisms when it moves as a fractured ice cover governed by local interactions. All triplets show comparable ice velocities until late September, with a decrease in ice drift and deceleration that accompanies a reduction in triangle area near 15, 17, 19, and 21 September (Figs. 3 and 5). Comparable centroid drift velocities are similarly observed for triplets B, C, and to a lesser extent D until October 24th, following which increased ice drift is observed for triplet B relative to other triplets, reflecting its sudden increase in area and evolution to a more equilateral configuration.

Sea ice convergence and divergence are measured through analysis of the time (daily) rate of change in triplet area (Fig. 6 and Table 3). Intervals of divergence and convergence are observed from 10 to 24 September for triplets A to D, and from 8 to 26 October for triplet B. Triplet A diverges prior to 14 September 2009 near 72.5°N, 137.5°W as evidenced in an increase in triangle area and expansion in all three vertices (Fig. 2), followed by weak convergence and divergence associated with the elongation of the triplet and decrease in triplet area on 19 September. Amplified behavior is observed for triplets B, C, and D, with increasing divergence/convergence duration with increasing latitude. Enhanced convergence is observed for triplets B, C, and D on 15, 16, and 14 September, while divergence is observed on 16, 17-18, and 17 September, respectively. Dissimilarity in divergence/convergence for triplets A and B despite their close proximity implies loss of coherence/fracturing in the ice cover on spatial scales on the order of ~5 km in the vicinity of 72.5°N and 136.8°W.

During the second interval (8 to 26 October) triplet B exhibits enhanced divergence (Fig. 6) on 8 October and 15 October near 145°W and 147°W when beacon trajectories intersect, resulting in a near-alignment of the triplet array (Fig. 2) and vanishing area (Fig. 3). Strong divergence is observed on 21 October for triplet B associated with the filamentary structure near 151° W, prior to sustained divergence due to a significant increase in triplet area and evolution to a more equilateral configuration westward of 155°W in November (Fig. 2). By contrast, triplet C is characterized by divergence and convergence near 74°N, 158°W and 160°W on 13 and 15 November, respectively, in a manner consistent with the observed increase in the base-to-height ratio (Figs. 2 and 4).

Results from this analysis demonstrate that triplets A and C evolve to an elongated configuration and triplet B to a more equilateral configuration in the later stages of development. Triplet D, located furthest from the coastline, is characterized by beacon triplet alignment within trapping regimes. It is further shown that triplet area evolution is depicted by decreasing coherence with increasing latitude evident in triangle base length scales of 70 km, 30 km, and ~20 km for triplets B, C, and D respectively from mid-September to October. Intervals of enhanced divergent/convergent activity are observed for all triplets in September and for triplet B in October. Differences in triplets B and C near 155°W in November depict differences in dispersion. In the next section we examine sea ice and atmospheric conditions during these intervals of enhanced divergence and convergence.

3.2 Sea ice and atmospheric forcing

Weekly CIS ice charts from 7 September 2009 to 9 November 2009 (AMSR-E sea ice data from September 9th to November 14th, 2009) provide a reference of changes in ice conditions in the region encompassed by the beacon array (Fig. 7a). Noteworthy for the 7 September 2009 weekly ice chart is the tongue of multiyear ice (MYI) of 9/10 total ice concentration with floe sizes provided by the CIS ice chart egg code on the order of 2 to 10 km, within which most ice beacons for this study were launched, surrounded by lower ice concentration regions. A reduction in sea ice extent is observed until approximately 14 September, following which an ice cover consisting of old, thick first-year and grey ice with total ice concentrations exceeding 9/10 associated with evolution in the tongue of MYI is established in the SBS. New ice begins to form along the west coast of Banks Island on 5 October. A poleward retreat in the pack ice is observed on 12 October 2009. New ice begins to form along the northern coast of the Northwest Territories near Tuktoyaktuk on 19 October, while ice growth connecting the marginal ice zone to the west coast of Banks Island and pack ice (Fig. 7a) indicates the onset of ice-coast interactions in this region. The 26 October ice chart shows that a band of first year ice connects the shelf to the pack ice between 135°W and 150°W (depicted by ellipse in Fig.

7a) enabling the onset of ice-coast interactions with meridional motion of the pack ice. By 2 November a contiguous ice cover is formed with a band of new, thin (< 10cm) ice at 69°N between 140°W and 155°W, also evident in the 9 November ice chart, that would enable increased mobility in ice-ice/ice-coast interactions due to a weaker ice cover.

Maps of weekly AMSR-E sea ice concentrations (SICs) and evolution in triplet centroid positions for each week showing the position of each triplet relative to the ice edge also demonstrate that the triplet A centroid is located closest to the southern ice edge for the 14 – 21 September week during which weak divergence/convergence relative to other triplets is observed (Figs. 6 and 7b). Weak divergence/convergence relative to other triplets is also observed for triplet D from 4 – 12 September when it is located closest to the northwestern ice edge. By contrast, the triplet B centroid is located closest to the southernmost ice edge for the 14 – 21 October week when strong divergence is observed, and to both the southern- and westernmost ice edge for the 30 October - 9 November week when weaker divergence is observed as the triplet evolves to a more equilateral configuration.

We examine sea ice and atmospheric contributions to sea ice deformation in the context of the two intervals during which triplets exhibit strong divergence and convergence, namely from 10 to 24 September, and from 9 to 26 October (Fig. 6). In this and subsequent sections, and following the terminology for coherent oceanic and ice drift features, loop reversals refer to the spiraling motion of a triplet beacon, in contrast to meander reversals whereby advection exceeds rotational motion (Griffa et al, 2008; Dong et al., 2011; Lukovich et al., 2014). Loop and meander reversals are used qualitatively in this analysis to examine spatial coherence in triplet paths indicating intervals when the ice cover moves as a consolidated aggregate.

During the first interval from 10 to 24 September loop reversals are observed throughout the array, evident in triplet A, B, C, and D centroid paths on 14 September (Fig. 9), providing an indication of coherence in the ice cover. Progressively smaller anticyclonic loops with increasing distance from the southern ice edge and differences in the sense of the loops highlight regional spatial variability. More specifically, triplet A, situated at the southernmost edge of the MYI tongue within a lower (~70%) ice concentration regime (Figs. 8a and 9) diverges on 11 September at the onset of a loop reversal event, and during southeasterly (on-ice) wind conditions (Fig. 10). Triplet A then converges on 20 September during a northerly (off-ice) wind regime, and is characterized by horizontal alignment at the periphery of the ice edge and Beaufort Gyre in the vicinity of 90-100% SIC (Figs. 8a and 9). Triplet B converges on 15 September due to horizontal alignment at the southern ice edge following the loop reversal (Fig. 9), and on 20 September due to horizontal alignment and intersection of beacon paths within 90-100% SIC (Figs. 8b and 9) during strong (~ 4 – 6 m/s) northerly wind conditions (Fig. 10). Triplet C, characterized by 90-100% SIC (Fig. 8c) converges on September 16th due to meridional alignment following a comparatively small loop reversal experienced by one of the triplet beacons (Fig. 9) during southerly (off-ice for northernmost triplets) wind conditions (Fig. 10), following which the beacons travel as a coherent entity and the triplet area equilibrates until early November (Fig. 3).

At higher latitudes, and closer to the northwestern ice edge, triplet D converges on 14 September during the loop reversal experienced by all three beacons (Fig. 9), with NW to SE alignment within a 90-100% SIC regime during northwesterly (on-ice) wind conditions following which, as for triplet C, beacons evolve as a coherent entity. Triplet D located in the vicinity of 74°N and 135°W also exhibits a local rotation in this timeframe (Figs. 2 and 9) with triplet height values on the order of 100m (Fig. 4a), in keeping with the 50-100 m peak in floe size distribution encountered to the west of 134.5°W due to the non-locally generated long-wave swell event documented by Prinsenberg et al. (2010) and Asplin et al. (2012). Results from analysis of the first interval highlight the existence of loop reversals in response to initial southerly and subsequent persistent northerly winds for all triplets, general coherence within the pack in September 2009, upon which is superimposed smaller-scale variability due to local ice conditions and based on proximity to the southern and northwestern MYI ice edge, before the formation of a contiguous ice cover between the pack ice and coast in late October.

During the second interval of divergent/convergent activity from 8 to 26 October triplet B, consisting of surviving beacons located closest to the southern ice edge, diverges on 9 October and exhibits a northward drift prior to convergence and collapse of beacons near 147°W within 90-100% SIC (Figs, 8b and 9) during northeasterly (off-ice) wind conditions (Fig. 10). Convergence of triplet B on 11 October coincides with the appearance of a lower ice concentration regime (Fig. 8b) near 145°W during southeasterly (on-ice) wind conditions, while divergence occurs within 90 – 100% SIC on 15 October during northeasterly (off-ice) wind conditions (Figs. 9 and 10). Furthermore, triplet B diverges on 21 October within 90-100% SIC at the onset of enhanced variability in sea ice concentrations (Fig. 8b), with NW to SE alignment near 150°W (Fig. 9) due to the intersection of beacon paths during strong (~ 6 m/s) and persistent northeasterly (off-ice) wind conditions (Fig. 10).

Differences in sea ice deformation and dispersion near the pack ice edge and interior are demonstrated in the behavior of triplets B and C in late October/ early November. Divergence for triplet B following 23 October reflects an increase in area (Fig. 3) depicting evolution to a more equilateral configuration near 155°W (Fig. 2) as beacons approach the western edge of the ice pack uninhibited by adjacent coastlines (Fig. 7b) during northeasterly wind conditions (Fig. 10). By contrast, comparatively weak divergence for triplet C following 3 November reflects an increase in area (Fig. 3) depicting its evolution to an elongated configuration near 155°W (Fig. 2) due to its location further from the southern and western ice edges (Fig. 7b) where shear effects dominate. These results are consistent with the aforementioned observed decrease in aspect ratios for triplet B in November (Fig. 4b) highlighting a transition to mixing near the western ice edge that remains uninhibited by ice-coast interactions following the development of a contiguous ice cover in late October in response to northeasterly winds. By contrast, an increase in triplet C aspect ratios in November highlights increasingly strain-dominated dispersion further from the ice edge and closer to the pack interior. Differences in sea ice divergence and convergence for triplets B and C in the later stages of evolution near 155°W (Fig. 6) also indicate that beacons located closest to the western ice edge in triplet B are subject to smaller-scale forcing and cross-shear transport, whereas beacons located further from the ice edge are subject to westward advection and shear associated with large-scale circulation of the Beaufort Gyre.

Enhanced variability near the ice edge is also evident in the early stages of evolution in triplets D and A, located near the northwestern and southwestern ice edge respectively of the MYI ice tongue in early September. More specifically, triplet D beacons initially travel perpendicular to the ice edge until the onset of strong northerly winds in mid-September, captured in constant base, height, and aspect ratio values until 12 September (Figs. 7b, 3 and 4). Triplet A exhibits an increase in the base and height values, with a more rapid increase in the former, indicating the aforementioned superposition of stretching and diffusive behavior characteristic of cross-shear transport witnessed in the late stages of evolution for triplet B. A more gradual increase in the aspect ratio values (Fig. 4) relative to other beacons further suggests a transition from cross-shear to along-shear transport for triplet A with increasing distance from the southwestern ice edge.

Results from this analysis suggest that intervals of enhanced divergence/convergence for all triplets early in the season in September provide a signature of loop reversals and small-scale variability in response to persistent northerly winds, while intervals of enhanced divergence/convergence for triplet B later in the season provide a signature of significant dynamic variability and intersection of the beacon paths in response to persistent northeasterly winds due to a fractured and highly mobile ice cover near the southern and western ice edge. Spatial variability in triplet D located near the northern ice edge in early- to mid-September (Figs. 7b and 8d e) captured by comparatively high meander coefficients (Table 1), coherence over shorter length scales at higher latitudes from mid-September to mid-October (Fig. 4a), in addition to variability in divergence/convergence of triplet B located near the southern ice edge until late October and western ice edge until early November (Figs. 7b and 8b) further highlights differences in dispersion characteristics between the periphery and interior of the ice pack.

Overland et al. (1995) demonstrated that over length scales ranging from ice floe interactions at 1 km to 100 km a hyperbolic (discontinuous) ice regime is established in response to northerly and westerly winds due to ice-coast interactions. By contrast, an elliptic (diffusive) regime is established in response to easterly winds and when the pack ice is not contiguous with the coast. In the present analysis, triplets B, C, and D all show enhanced aspect ratios and intervals of divergence/convergence characteristic of shear in response to northerly winds following mid-September as triplets B and C travel parallel to the southern ice edge and triplet D travels parallel to the northwestern ice edge defined by the tongue of MYI, in a manner consistent with the hyperbolic regime described by Overland et al. (1995). Similarly in October, triplet B shows enhanced shear, and triplets C and D decreasing shear with increasing distance from the southern ice edge during predominantly northeasterly wind conditions and prior to the development of a contiguous ice cover between the pack ice and coast. However, triplet B evolves to a more equilateral configuration characteristic of cross-shear transport and mixing at the western ice edge in November in response to northeasterly winds, whereas triplet C, located further from the ice edge, continues to experience along-shear transport.

Similarly, beacons comprising triplets A and D located near the northwestern and southwestern edge of the MYI tongue travel perpendicular to the ice edge in the early stages of evolution, highlighting differences in dispersion at the pack ice edge and interior.

Richter-Menge et al. (2002a) also documented contributions from coastal geometry and wind direction to deformation activity in the southern Beaufort Sea, noting propagation of leads away from the shore with consolidation of the seasonal and perennial ice zone, and found coherence in sea ice drift and deformation over spatial scales of 200 km. Furthermore, Stern and Lindsay (2009) found reduced deformation within the MYI regime – as was found in the present study for triplets C and D during intermediate stages of evolution within the pack interior – in addition to 'localization' describing the strengthening of deformation at the smallest scales in support of a fracture as opposed to continuum description of ice deformation. Results from the present analysis confirm these findings and further illustrate, through evaluation of beacon triplets and small-scale deformation, spatial variability in dispersion at the pack ice edge and interior, with enhanced cross-shear transport in response to off-ice wind conditions. In addition, weak divergence/convergence implies an approach to a more equilateral configuration. Strong divergent/convergent activity suggests strong shear associated with along-shear transport.

These results are also consistent with those found in Lukovich et al. (2011), whereby zonal dispersion is characterized by the ballistic regime associated with anticyclonic circulation and westward advection at the southern segment of the Beaufort Gyre; and the hyperbolic (strain-dominated) regime associated with northward and southward displacements in the meridional direction. In the present study, differences in the latter stages of evolution in triplets B and C document similar behavior in terms of westward advection further from the ice edge and increased diffusive behavior associated with cross-shear transport at the western pack ice edge not contiguous with the coast.

It is also interesting to note that ice beacon trajectories track the memory of the ice edge and act as a prelude to the fracturing of the ice cover and polynya openings (Fig. 9), in a manner consistent with the observation that directionality and history govern regional ice dynamics (Coon et al., 1992; Overland et al., 1995). Beacon trajectories associated with triplets B and D in October and November follow both the southern and northern ice edges at the periphery of the MYI tongue in the SBS established/evident in mid-September (Fig. 9a). Furthermore, loop reversal events associated with increased divergent/convergent activity in triplets B and C in mid-September provide a signature of lower ice concentration regimes that emerge in mid-October (Fig. 9). Correspondence between beacon trajectories, triplet evolution and upcoming and antecedent ice conditions at the pack ice edge highlight the nature of spatiotemporal coupling in sea ice drift and dispersion in fall, with implications for forecasting and prediction.

Conclusions

In this study we investigate sea ice divergence and convergence in the southern Beaufort Sea from September to November 2009 based on an assessment of ice beacon triplets initially delineated according to their distance from the coastline, with triplet A centroids located closest to the continental coastline, and triplet D located furthest from the coastline. Results from this analysis highlight differences in dispersion at the periphery and interior of the ice pack. Investigation of sea ice divergence and convergence shows enhanced elongation closer to the coastline, evident in decreasing triplet base values with increasing latitude. Triplets also exhibit spatiotemporal differences in their evolution. Triplets A and C evolve to an elongated configuration characteristic of a filament, whereas triplet B evolves to a more equilateral configuration westward of 155°W following 23 October 23rd 2009. Triplet D is confined to the eastern segment of the Beaufort Sea until November 2009. It is further shown that triplet area evolution is depicted by decreasing coherence with increasing latitude, evident in triplet base length scales of ~70 km, 30 km, and 20 km for triplets B, C, and D respectively from mid-September to October.

The time rate of change in triplet area highlights two intervals of enhanced divergence and convergence in fall, 2009: one interval from 10 to 24 September for triplets A to D, and a second interval from 9 to 26 October for triplet B. Investigation of sea ice and atmospheric conditions during these intervals of enhanced divergence/convergence show that until mid-September, all triplets respond to northerly flow. Loop reversals observed throughout the array provide an indication of coherence in the ice cover. Progressively smaller anticyclonic loops at higher latitudes and differences in the sense of the loops highlight spatial variability associated with local ice conditions and proximity to the southern and western MYI ice edge, prior to the formation of a contiguous ice cover between the pack ice and coast in late October. During the second interval of divergent/convergent activity from 9 to 26 October, enhanced divergence/convergence is observed for triplet B at the southern ice edge. Differences in triplets B and C near 155°W in November illustrate differences in dispersion at the periphery and interior of the ice pack based on proximity to the western ice edge in the SBS. Triplet B evolves to a more equilateral configuration captured in decreasing aspect ratios indicative of mixing near the western ice edge in response to northeasterly winds, unimpeded by adjacent coastlines, whereas triplet C evolves to an elongated configuration captured by increasing aspect ratio values indicative of strain-dominated dispersion further from the ice edge and closer to the pack interior.

Results from this investigation are in keeping with earlier studies documenting hyperbolic (discontinuous) ice regimes in the SBS in response to northerly and westerly, and elliptic (diffusive) ice regimes in response to easterly winds characteristic of free drift conditions. Highlighted also is spatial variability in dispersion characteristics within the ice pack based on proximity to the ice edge. Following mid-September triplets B, C, and D show enhanced aspect ratios and intervals of divergence/convergence representative of shear in response to northerly winds as triplets B and C travel parallel to the southern MYI edge and triplet D travels parallel the northwestern MYI edge in a manner consistent with the hyperbolic regime. Similarly, in October, triplet B exhibits enhanced shear closest to the ice edge, and triplets C and D reduced shear in response to predominantly northeasterly winds, prior to the development of a contiguous ice cover between the ice pack and continental coast. However, in late October/early November, triplet B experiences cross-shear transport and mixing characteristic of an elliptic regime in response to northeasterly winds at the western edge of the ice pack, in contrast to triplet C which continues, further from the ice edge, to experience along-shear transport characteristic of the hyperbolic regime.

The use of ice beacon triplets provides an approach that complements spatial scaling analyses through an assessment of sea ice deformation at the pack ice edge and interior. In demonstrating a strong sea ice deformation response to persistent northerly winds throughout the ice pack in September 2009, and to persistent northeasterly winds at the periphery of the ice pack in November 2009, the results from this analysis underline the importance of atmospheric forcing and proximity to the ice edge as the pack ice becomes contiguous with the continental coastline during fall. Correspondence between beacon trajectories, triplet evolution and upcoming and antecedent ice conditions at the pack ice edge further highlight the nature of spatiotemporal coupling in sea ice drift and dispersion in fall, with implications for forecasting and prediction. An understanding of differences in dispersion and deformation at the ice edge and interior will be of increasing importance with continued loss in MYI, decline in summertime sea ice extent, sea ice edge retreat and, as is illustrated in the present ice beacon triplets analysis, the establishment of a sea ice regime characteristic of the marginal ice zone and increased mixing at the pack ice edge. Of interest for future modeling work and field campaigns is an assessment of sea ice deformation impacts on ocean-sea-ice-atmosphere dynamic interactions and turbulent exchange between the ocean and the atmosphere under varying ice and atmospheric conditions, which would contribute to improved representation of sea ice dispersion in modeling studies used for the purposes of prediction.

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Figure captions

Figure 1a. Map of study area and winter 2009/10 beacon trajectories superimposed on AMSR-E sea ice concentrations for September 9th, 2009 and depicting the marginal ice zone on deployment.

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Figure 1b. Map of study area and winter 2009/10 beacon trajectories. Blue, red, black and magenta indicate triplets A, B, C, and D, respectively, with triplet A located nearest to the coastline, and triplet D located furthest from the coastline. Triangles depict triplets on deployment on September 9th and, traveling westward, on September 15th, October 1st, 15th, and November 1st, respectively, and illustrate elongation of triplets located closest to the coastline.

Figure 2. Ice beacon trajectories for (from bottom panel) triplets A, B, C, and D. (Note the difference in scale.) Right-hand panel in second row from bottom depicts the initial evolution in triplet B.

Figure 3. Semilog plot of triangular area by date for ice beacon triplets A to D.

Figure 4. Semilog plot of the triangle a) height and base, and the b) aspect (base-to-height) ratio as a function of date for triplets A to D.

Figure 5. Centroid ice drift velocity (in m/s) as a function of date for triplets A (bottom) to D (top).

Figure 6. Evolution in sea ice divergence and convergence for triplets A to D from a) September 9, 2009 to November 12, 2009 and b) September 9, 2009 to October 4, 2009.

Figure 7a) Canadian Ice Service (CIS) weekly ice charts from September 7, 2009 to November 9, 2009. Ellipses depict the consolidation of marginal ice to the coast and perennial ice pack on October 19th and 26th. Triangles depict the approximate location of triplet centroids during intervals of enhanced divergence/convergence.

Figure 7b) Maps of weekly AMSR-E sea ice concentrations in addition to weekly evolution in triplet centroids showing proximity of triplets to the ice edge from September 4th, 2009 to November 14th, 2009. Note that triplet B centroids are depicted by white markers to distinguish beacon paths from 100% ice concentrations.

Figure 8. Evolution in mean (black solid line), minimum and maximum (red dashed line, left axis) sea ice concentrations, and divergence (red solid line, right-axis) within a ~25 km triplet centroid radius for triplets A to D.

Figure 9. Ice beacon triplet trajectories superimposed on selected daily maps of SIC during intervals of enhanced divergence/convergence (September 14th and 22nd, and

October 15th and 20th, 2009). Note that the trajectory colour for triplet B is red in September and blue-grey in October to distinguish beacon paths from 100% sea ice concentrations.

Figure 10. Daily local NARR wind vectors for the area surrounding the triplet centroids from September to November, 2009.

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