

Interactive comment on “**On the characteristics of sea ice divergence/convergence in the Southern Beaufort Sea**” by J. V. Lukovich et al.

Anonymous Referee #1

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In September 2009, 11 buoys (beacons) were deployed on the sea ice of the southern Beaufort Sea. The authors group these beacons into 5 triangles (triplets, labeled A-E) and analyze the motion and area of each triplet during Sept-Oct-Nov 2009.

Thank you for your helpful and insightful comments and suggestions. Please find below responses to your questions.

First I would like to comment on the quality of the figures. I printed a hard-copy of the pdf, and most of the accompanying figures are too small to read the axis labels and/or too small to see what’s going on. This seems to be partly the fault of the journal and partly the fault of the creators of the figures. In my opinion, figures should be fully legible and intelligible when printed. I can read the main body of the text perfectly well in the hard-copy printout, but not the figures. The authors should use font sizes for the axis labels and legends that are the same size as the main text, and the journal should not shrink figures in order to squeeze multiple panels onto a single page if doing so C1582 makes the figures illegible.

The authors have made significant effort in the revised manuscript to improve the quality of the manuscript figures to ensure that they are legible.

I have three main comments about the paper.

1. The authors use the change in area of the triangles to measure divergence, as in equation (1): $(1/A)dA/dt = \text{divergence}$. This is theoretically valid, but in practice the use of only 3 points leads to large error estimates and extreme sensitivity. Thorndike (Kinematics of Sea Ice, Chapter 7 in The Geophysics of Sea Ice, NATO ASI Series, vol 146, 1986) finds that the ratio of estimation error variance to signal variance is about 0.7 when using 3 points to estimate divergence (see Fig 23b and the discussion at the top of page 536). Furthermore, a simple analysis of the area of a triangle, $A = (1/2)\text{base} \times \text{height}$, shows that for a constant base b and variable height h , $\text{divergence} = (1/A)dA/dt = (1/h)dh/dt$ so when h is small, the divergence is extremely sensitive to small changes in a single vertex of the triangle (the one that’s not part of the constant base). Figure 2 shows that in fact there are many highly elongated triangles in this data set. The problem is this: in estimating the divergence of a region using a discrete set of boundary points, the implicit assumption is that the points adequately resolve the material boundary of the region. In other words, as the shape evolves over time,

there should not be a flux of ice into or out of the region. But a region of sea ice defined by a highly elongated triangle will almost certainly violate this implicit assumption in a big way. The sides of the triangle will almost certainly not be material boundaries. If one could track (say) 10 points along one side of the triangle, one would often find that after one time step, the 10 points no longer fell along that side of the triangle. In other words, 3 points do not accurately resolve a large material element of sea ice, especially when that element is highly elongated. As Thorndike (1986) showed, 6 points provide much better accuracy. It's too bad the authors did not group the beacons into sets of 6. The bottom line is: I question the quality of the divergence measurements from this data set.

Sea ice deformation in Thorndike (1986) is described by large scale average strain rates $\frac{\partial u_i}{\partial x_j}$ used derive strain rate invariants including sea ice divergence and convergence (p. 521, Thorndike, 1986). A similar approach is incorporated in the study of sea ice deformation in East Antarctica (Heil et al., 2011). In the present study sea ice divergence and convergence are described by the fractional rate of change in the triplet area, computed using Heron's formula as described below. Reference to the review by Thorndike (1986) is included in the revised manuscript in the context of estimation error, the strain component and triplet area approach.

The numerically stabilized version of 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 $s = \frac{1}{2}(a+b+c)$, is used to compute the triangle area and is implemented in the present analysis in order to avoid the sensitivity that the present Reviewer notes to small changes in a single vertex resulting in small h and an elongated triangle. This is now emphasized in the Methods section of the revised manuscript.

Increasing area for triplet B during the late stages of evolution in the present study suggests that sea ice is mixed into and out of the triangular configuration. As is noted by LaCasce (2008), however, even if material boundaries are not resolved by the triangles, the aspect ratio can be used to provide insight into the nature of dispersion and mechanisms involved/responsible for such behavior. A continued increase in the aspect ratio following rapid elongation and collapse in area suggest sustained shear dispersion. In contrast, a decline in the aspect ratio indicative of an approach to a more equilateral configuration could provide a signature of an inverse cascade or transport of energy from small to large scales of motion. In the present study, an increase in and non-conservation of triplet B area in the later stages of evolution suggests that sea ice is mixed into and out of the triangular configuration near the pack ice edge. Elongation of triplet C at the southern periphery of the Beaufort Gyre provides a signature of shear associated

with anticyclonic circulation. Non-conservation of area and its implications for an assessment of dispersion are also addressed in the revised manuscript in response to this and similar concerns expressed by the present and third referee.

Furthermore, in light of comments provided by the present and third Reviewer regarding highly elongated triplets, analysis of triplet E has also been excluded in the revised manuscript in order to focus the discussion and study on sea ice divergence/convergence within the central pack, and in particular on differences in sea ice deformation near the pack ice edge and interior.

2. The "Results and discussion" section is mainly a detailed description of the figures. Page 4292 describes Figure 2. Pages 4293-4 describe Figures 3 and 4. Page 4295 C1583 describes Figure 5. And so on, through most of the section. It is frankly rather tedious.

The authors agree that detailed descriptions for each of the figures in the initial manuscript detract from the paper objectives, namely i) evolution in ice beacon triplet area in the fall of 2009 and ii) ice and atmospheric contributions to the observed behavior in sea ice convergence/divergence. Effort has been made in the revised manuscript to consolidate the descriptions in order to highlight differences in sea ice divergence/convergence near the pack ice edge and interior based on the position of the beacon triplet relative to the ice edge.

3. The actual main results seem to be that the ice behaves differently near the ice edge, near the coast, and in the interior of the pack; the wind affects the ice motion in different ways; and there are episodes of large divergence.

The authors emphasize in the revised manuscript differences in sea ice divergence and convergence at the pack ice edge and interior based on the position of the triplet relative to the ice edge, intervals of enhanced divergence/convergence in September, 2009 for all triplets and in October, 2009 for only triplet B, and the influence of winds on deformation associated with ice-ice and ice-coast interactions, in an attempt to better convey the main results that the present reviewer has noted.

Specific Comments

Page 4284, lines 10-11. What does it mean for "spatial scaling" to have "high values"?

This sentence has been revised to clarify its meaning, and now reads

'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).'

Thank you for pointing this out.

Page 4287, lines 23-24. "increase in triplet area characteristic of non-divergent flow". But if the area is increasing, doesn't that imply divergence? See equation (1).

Although area is conserved in non-divergent flow, an increase in area may be a result of surface divergence or random displacements induced by such influences as surface winds, as is noted by LaCasce and Ohlmann (2003). This is now stated in the revised manuscript in the following sentence:

'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).'

An increase in triplet area observed in studies by Molinari and Kirwan (1975) and LaCasce and Ohlmann (2003) is attributed to random displacements associated with wind forcing superimposed on the normal motion rather than surface divergence. Due to an absence of convergence that would cause the triplet areas to decrease, ruling out divergent flow, the authors attributed an increase in area to the superposition of random walks associated with wind forcing on the surface flow. This sentence has been clarified in the revised manuscript

'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).'

Page 4289, lines 9-10. Wow, E is an extremely elongated triangle, with shortest leg 11 km and longest leg 400 km!

The authors have removed Triplet E from the analysis in light of the present and third Reviewer's comments, and to focus the assessment on sea ice convergence and divergence near the pack ice edge and interior.

What is the temporal resolution of the beacon data? In other words, when you plot a time series like Figure 3, are you plotting one value per day? 10 values per day?

The temporal resolution of the beacon data is two hours, and daily averages are computed for the analysis and time series. This is now noted in the Methods section.

Page 4290, line 4. The formula for δA is not dimensionally correct, so an algebra error must have occurred somewhere. Since a, b, c have dimensions of length (L), the expression inside the square root has dimension L^6 and so the overall expression has dimension $L^3/L^2 = L$, not L^2 .

Thank you for pointing this out. The positional error δx was inadvertently excluded from the equation in the original version of the manuscript. This has been corrected. The error bars are now also included in Figure 3.

Page 4293, line 17. Not sure what is meant by "signature of regional small-scale constraints". See also page 4299 line 2.

This phrase was initially intended to address regional variability in triplet area evolution, and has been changed in the revised manuscript to "with differences providing a signature of regional variability" to reflect this. Similarly, the phrase "highlight spatial variability in the influence of small-scale constraints" has been changed to "highlight regional spatial variability".

Page 4294, line 14. In Fig 4b, I don't see much of a positive slope for triplet E.

As previously noted, analysis of triplet E has been excluded from the study.

Page 4297, line 21. There is no scale bar in Fig 7a so it's impossible to tell that the floe sizes are 2 to 10 km. Or does that information come from another source?

The floe sizes were obtained from the CIS ice charts and egg code, as is now noted in the revised manuscript.

Page 4298, line 9. Spell out what SIC stands for.

SIC has been expanded in the revised manuscript.

Page 4298, lines 24-25. The authors define "loop reversal events" as "the spiraling motion of a triplet beacon", and "meander reversal events" as "advection exceeds rotational motion". First, I don't understand how these "reversal events" are calculated, and second, why not use the beacon triplet positions to calculate the vorticity of the triangle, if the goal is to describe rotation?

Loop and meander reversal events are not calculated in the present study, but are instead identified as and refer to coherent features in the centroid paths. The phrases "loop reversal events" and "meander reversal events" have been changed to "loop and meander reversals" to highlight that these are features in the centroid trajectories used to identify coherence in sea ice deformation. The following statement has also been included in the revised manuscript to clarify reference to loop and meander reversals:

'Loop and meander reversals are used qualitatively in the present study to examine spatial coherence in triplet paths indicating intervals when the ice cover moves as an aggregate entity.'

Page 4298, lines 27-28. "loop reversal events are observed throughout the array ... (Fig 9)." I can't make out anything in Fig 9. Where should I see a loop reversal event?

Loop reversals are now identified in the panel showing sea ice concentrations and centroid paths on 14 September in Fig 9. Reference is also made to this panel in the revised manuscript.

Figure 4b. Wow, the aspect ratios of the triangles are sometimes 100 or more.

Large aspect ratios depict triplet elongation and filamentation. Specific reference is now made to the values associated with local maxima observed in triplets B, C, and D in the description of Figure 4.

Figure 6. The units on the Y-axis are given as 1/sec but this cannot be correct. Probably it should be 10^{-6} /sec.

Thank you for pointing this out. The divergence units have been corrected.

Figure 8 caption, "within a 0.21 degree ... radius" – does this mean 0.21 degrees of latitude? Can you give the radius in km instead?

This value refers to 0.21 degrees in the zonal and meridional directions, and is now expressed in terms of km, with a value of ~ 25 km.

Figure 9. I can't figure out what I'm supposed to be seeing.

Significant effort has been made to improve the quality of this figure, depict the evolution in triplets superimposed on sea ice concentrations, and highlight their shape relative to the ice edge. The text has also been modified to capture features illustrated in this figure.

Figure 10. The wind vectors appear to be plotted on top of one another. I cannot distinguish the wind for one triplet from the wind for another.

Figure 10 has been modified to illustrate differences in winds surrounding triplet centroids.

Technical Corrections

In the Abstract, after the first occurrence of the word "beacon" on line 7, insert "(buoy)" to clarify the meaning of beacon.

This has been included in the abstract. Thank you.

Page 4284, line 25. Insert "is" after "the ice cover".

This has been changed.

Page 4287, section heading "Triplet analysis and (oceanic and sea ice) applications". I suggest either removing the parentheses or removing the entire parenthetical phrase.

The parenthetical phrase has been removed.

Page 4288, line 27. Antarctic should be Antarctica.

This has been corrected.

Page 4289, line 4. "Sea ice drift data were determined from...". Probably better to say "were obtained from".

The word "determined" has been replaced with "obtained".

Page 4290, line 21. Put the word "forcing" immediately after the word "atmospheric".

The ordering in wording has been changed.

Page 4292, line 26. "the time rate of change of which monitors ice convergence". Better to say "measures ice convergence". People and gadgets can monitor things, but time rates of change do not monitor things.

This phrase has been removed in consolidation of descriptions for Figures 2 and 3 in the revised manuscript.

Page 4293, line 19. Same comment about monitored vs. measured. Page 4296, line 1. Same comment.

"Monitored" has been replaced with "measured" in both instances.

Page 4298, lines 25-26. I don't see Griffa et al (2008) or Lukovich et al (2014) in the References. Please check all references.

Both references are now included in the References in the revised manuscript.

Page 4300, line 3. Delete "in" after the word "highlight".

This has been changed.

Page 4311, Table 1. Correct the 3 typos in the caption.

These typos are corrected in the revised manuscript.

Page 4313, Table 3. In the column labeled "Intervals" I see the notation "09/10-09/24" and "10/09-10/26". Are these meant to be dates in the format MM/DD? The dates in the final column are in the format YY/MM/DD so "09/10" looks like it could be 2009 October or it could be September 10 with the year 2009 implied.

The dates are changed in the "Intervals" column to the YY/MM/DD format to ensure consistency with the format used in the final column of Table 3. Thank you for this suggestion.

Conclusion and Recommendation

This paper is basically a long description of the motions of 11 buoys in the southern Beaufort Sea in Sept-Oct-Nov 2009. There is nothing technically wrong with it, once a few minor details are corrected and the figure quality is improved.

I leave it to the editor to decide whether such a paper belongs in The Cryosphere.