Novel methods to study sea ice deformation, linear kinematic features and coherent dynamic elements from imaging remote sensing data

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Review

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Summary

This manuscript presents an analysis of sea ice deformation derived primarily from analysis of sequential synthetic aperture radar (SAR) images acquired north of Svalbard during the N-ICE2015 expedition. The novelness comes from the identification, naming, and quantitative characterization of coherent dynamic elements (CDEs). These features exist as regions of uniform ice motion between linear kinematic features (LKFs), which I believe were first described by Kwok in 2001. Ice motion is tracked through a combination of feature tracking and pattern matching to create a grid of regular spaced nodes, which are triangulated for the calculation of deformation. LKFs emerge as linear clusters of triangles that experience high degrees of shear, divergence, or both. CDEs occupy the regions between LKFs and the manuscript uses a number of different shape-related metrics to chart their evolution over the course of three separate storm events.

The manuscript also presents a scaling analysis of strain rate by combining the SAR-derived deformation measurements with those made using the ship radar and a network of GPS-tracked buoys. This allows power laws for strain rate and total deformation to be evaluated for length scales ranging from hundreds of meters to tens of kilometers.

Overall, I enjoyed reviewing this manuscript. I believe the CDEs that the author defines represent a useful concept for framing our thinking about the concept of ice floes and how stress and strain are organized within the ice pack. I have no significant concerns, but I feel the analysis of CDE shape statistics could be usefully improved and some more attention could be given to the structure and standardization of the text and figures to aid readability. I have tried to provide constructive suggestions with each of my comments below and I do not believe any of my concerns should be difficult to address.

Major Comments

1 Methods section would benefit from restructuring

I feel that readability of the methods sections could be improved with some restructuring of the text. Specifically, I would encourage the author to adopt a more chronological approach with description of the different steps involved in deriving the various results. For example, I find it highly non-intuitive that the text in section 3 goes into significant detail regarding the derivation of deformation components from triangulated ice motion data before the method for determining ice motion has been described in section 3.1.

On line 87, the text states "*information from individual images was processed into displacements, drift, and deformation*" and I think this would be a more appropriate order in which to describe the methodology to the reader (i.e., displacement and drift before deformation). However, at the same time, I also recommend reviewing the manuscript for consistent use of these terms. In particular, I cannot determine the difference between "drift" and "displacement" and the terms appear to be used

interchangeably later in the text, which makes it a little confusing to list them separately here. I recommend choosing one term and using it consistently.

2 More detail needed regarding definition of damage parcels

I think I understand how the damage parcels are defined, but I had to read section 3.3 multiple times to do so. For me, it would help to explicitly clarify the relationship between the location and distribution of damage parcels and the nodes of the triangulated grid. I'm a visual thinker and I believe many other readers are too, so I would encourage the use of an additional figure to help crystalize this important concept.

3 Clearer definitions of spatial scales

On line 144, the text equates a value of "$\lambda \gg 679\ m$" with "*scales approximately 10 km*" (sic). I feel more explanation is needed here to explain how "scale" is defined here and how it is quantitatively related to the value of λ.

4 Definition and use of CDE shape parameters could be improved

I have a number of comments about the definitions and explanations of the CDE shape parameters used in this manuscript. These are detailed in the sub-comments below, but in short, I recommend that the author considers alternative, potentially more suitable statistics and define them in more detail in the text. In particular, I encourage the use of a figure to help explain some of the details.

4a Shape diameters and radii

The bulleted text in section 3.4 makes a number of references to the diameter or radius of CDEs, but does not provide the reader with the specific details necessary to understand how these terms are applied to highly non-circular shapes like those of many CDEs. From context, I expect the "*max and min diameter*" used in the definition of roundness (line 236) is measured using either caliper distances or the dimensions of an enclosing rectangle, though in either case these are not strictly diameters since they do not necessarily pass through the center of the shape. Similarly, the "*mean diameter*" used in the definition of fragmentation (line 233) is not sufficiently defined. It could be the average of the minimum and maximum diameters, though a more common definition is the diameter of a circle with equal area to the shape in question. There are also other definitions of diameter and radius that would require explicitly defining the center of the CDE.

4b Fragmentation parameter

I had difficulty understanding how the definition of this parameter on lines 233-236 could be related to fragmentation of CDEs until I looked ahead to Figure 9 (hence why I recommend using an additional figure at this point in the manuscript). As defined, it is a measure of the complexity or non-circularity of the CDE perimeter, which does not necessarily have anything to do with fragmentation. An alternative statistic that might be more sensitive to how far the perimeter penetrates into the interior of the CDEs is the convexity, which can be defined as:

$$concavity = \frac{convex\ hull\ perimeter}{CDE\ perimeter}$$

This will take a value of 1 if the shape is convex or less than one if the perimeter has concavities. One advantage of this metric is that there is no underlying reliance on the properties of a circle. Also, there is a possible variant of this approach whereby the perimeters of all LKFs within convex hull (or just their skeletonized lengths) are also included with the CDE perimeter in the denominator. This would take account of all the unconnected LKFs that are currently encapsulated within CDEs without contributing to the fragmentation statistic.

4c Roundness parameter

As defined, this parameter could just as well be called “squareness” (a square would give the same value as a circle), but the parameter is really a measure of aspect ratio or elongation. A more suitable measure of roundness or circularity could be the ratio:

$$circularity = \frac{4\pi \cdot CDE\ area}{(convex\ hull\ perimeter)^2}$$

By using the convex hull perimeter (instead of the CDE perimeter), this metric is sensitive to overall elongation and angularity of the shape while being insensitive to the properties that are indicative of fragmentation.

4d Distance between LKFs

The distance between LKFs is defined as “*min and max CDE radius*” (line 239), but I suspect this should read “diameter” instead of radius. Please also see comment 4a above regarding detailed definitions of such dimensions.

5 Figure sub-panels

This is a minor comment, but applies it applies to every multi-panel figure. I encourage the author to label each sub-panel with a letter and use this an identifier in the text instead of relative descriptors like “left” and “right”. I understand this is partly stylistic, but I feel it removes any ambiguity when cross-referencing sub-panels both in the caption and in the main text (e.g., lines 341 and 346). It may also be required by the journal.

Minor comments

Line 144: I think there's an "*of*" missing before "*approximately*".

Line 153: I recommend adding letters to identify each panel (see comment 5 above). Although the references to “left”, “right”, etc in the caption are technically accurate, I find it would be helpful to explicitly identify that each instance references more than one panel in the figure.

Line 162: Replace “*of*” with “*by*”

Lines 167 & 168: I assume the author intended to remove these question marks before submission. Do they signify missing citations?

Line 170: What is “*DLDL*”? Is this simply a typo for DL?

Lines 170-171: I feel a little more explanation of Bouillon and Rampal's smoothing technique is necessary here. I do not think it should be necessary to be familiar with a cited work to understand the text in which the citation is made. Also, in this case, the text refers to a "kernel size of 3 triangles", whereas Bouillon and Rampal define the size of their kernel in terms of the number of vertices.

Figure 4: In its current form I do not feel this figure gives the reader much more information than is already provided in the text. Elsewhere, I recommend the inclusion of additional figures (see comments 2 and 4 above), so if space is an issue this figure could possibly be omitted. However, if the authors choose to keep the figure, then I feel some explanation should be given for the different colors used for boxes and arrows.

Line 209: Insert "*each*" between "*in*" and "*pair*"

Line 213: There are some unnecessary parentheses in this citation

Lines 214-215: See comment 1. Are displacements and sea ice drift the same thing?

Line 223: Replace "*nods*" with "*nodes*"

Line 233: If the author chooses to keep their definition of fragmentation (see comment 4b above) then I would replace "circumference" on line 233 with "perimeter", since the term circumference is only defined for a circle. Also, according to the definition given, a perfect circle would have a fragmentation value of 2π, not 0.

Figure 5: Similar to my comment for Figure 4, I do not feel figure 5 adds much value to the text. Instead, I think I would find it more useful to see a graphical representation of how nodes associated with LKFs and CDEs are enclosed in convex hulls (see comment 4 above).

Figure 6: The axis labels are quite difficult to read and the neither the caption nor the legend explain the meaning of the different colors. Also, I recommend using the same units and limits for the x-axes of all three plots.

Line 248: I think "*similar*" may be a more suitable word than "*resembling*"

Line 249: Replace "ad" with "and"

Lines 252-253: The text "*This increased α and β for ship radar to 24.61 and -0.7, respectively*" is confusing to me. The value of α is greater than that reported earlier in the paragraph for the full suite of data, but value of β represents a decrease. Some rewording may be necessary here.

Lines 256-265: This paragraph appears to be a duplicate of the preceding paragraph.

Line 266: Replace "amount" with "number", since this refers to a countable quantity.

Lines 267-268: This could be re-written as *"... increased α from 4.79 to 14.63 and β from -0.14 to -0.59*" to both improve clarity of the text and remove the need to use "respectively". This practice could be adopted in other place in the text too.

Line 277: Specify units after "*100*" (presumably meters).

Line 278: I'm not sure what "*boarding*" means in this context. Is this a typo? I would recommend using either "opening" or "widening" instead.

Figure 8: I think I would understand and appreciate this figure more fully if I was confident I understood how the damage parcels were defined and located. Please refer to my comment 2 above.

Line 325: I assume this question mark was not intended to be included in the text, like those on lines 167 and 168.

Line 326: I do not think Murzda et al's paper supports the assertion that "*large fractures ... healed slowly*". First, Murzda et al report crack healing on timescales of "tens to hundreds of seconds", which I would characterize as quite rapid in this context. Second, I'm not convinced their lab-based observations can easily be scaled up to that of the "large fractures" described in this study. Murzda et al explicitly note this at the end of section 1 of their paper.

Line 335: The "*continuous curve with increased parcel density*" is a pretty subtle feature. I recommend labelling it on this figure with some form of annotation.

Figure 9: The significance of the gray regions in the time series plots is not explained in the caption. From indirect cues in the main text, I assume they indicate the occurrences of storms. In addition to explaining their meaning in the caption, I also encourage the author consider

naming and labelling each storm uniquely (e.g., “mid-January storm”, etc, or more simply Storm 1, ...). This would allow easy and clear cross-referencing in the main text. I also encourage labeling each sub-panel with a letter, as per comment 5 above.

References cited in this review that are not cited in the manuscript

Kwok, R. (2001), Deformation of the Arctic Ocean Sea Ice Cover between November 1996 and April 1997: A Qualitative Survey, paper presented at IUTAM Symposium on Scaling Laws in Ice Mechanics and Ice Dynamics, Springer Netherlands, Dordrecht.