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The Cryosphere Discussions

Interactive comment on "Variability of sea ice deformation rates in the Arctic and their relationship with basin-scale wind forcing" *by* A. Herman and O. Glowacki

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We would like to thank all reviewers – Jennifer Hutchings, Florent Gimbert and the Anonymous Referee No. 1 – for their insightful and very valuable comments and suggestions that animated us to additional discussions on our results and helped to prepare the new and (we believe) improved version of the manuscript. Because all three commentaries contained closely related criticism, we decided to formulate a few general remarks on some selected issues raised in all (or at least two) reviews, followed by a detailed response to questions/comments of individual reviewers.

1 General comments

Much criticism has been directed toward the part of our manuscript devoted to the simple 'model' that was meant to provide a more 'theoretical' basis for the observed ice deformation–wind relationships. We agree that both the model and the discussion related to it were oversimplified and we accept all criticism directed towards that part of our paper. Our main intention was to show that — under certain assumptions — the mean sea-ice deformation within a certain spatial domain depends on the integral of the wind forcing over that domain, as these are exactly the two quantities analyzed in our study. We agree that the model didn't provide much new insight into the force balance of sea ice, and that presenting it in a 'numerical' form was an unnecessary complication.

Another aspect of our work that was – in one way or another – commented in all reviews, concerns the influence of (i) the scale of analysis and (ii) the spatial heterogeneity of ice deformation magnitudes in the Arctic on the resulting correlation coefficients. In view of the above criticism, we decided to add a new element to our study: an analysis of (i) the spatial distribution of extreme deformation events, and (ii) changes of the correlation coefficient C with changing size and location of the domain of analysis.

Our new results show that the occurrence probability of strong, localized deformation events is not uniform in space, but is significantly higher in some coastal regions, especially along the coast of Alaska, in the East Siberian Sea and close to the New Siberia Islands, as shown in the attached Fig. 1. Interestingly, there are no corresponding occurrence maxima along the coast of the Canadian Archipelago — presumably because of the larger thickness and strength of the (predominantly perennial) ice pack in that region. As shown in a number of studies (e.g., Steele et al. 1997, Kwok 2006), seasonal sea ice in the Beaufort and East Siberian Sea has lower thickness and concentration, and higher velocities than elsewhere, which makes it susceptible to coast-constrained deformation.

Considering the inhomogeneous spatial distribution of strong-deformation events, we repeated the correlation analysis separately for two subdomains of the study area — loosely termed the 'coastal' and the 'central' region (including the coastal zone of Canada). As Fig. 1 schematically illustrates, the subdomains were obtained by step-wise moving the upper-left corner of the original domain towards its center. At each step, the correlation C was calculated for the two regions separately, i.e., for $\bar{\tau}_a$ and $\tilde{m}_{q,L}$ estimated based on a subset of data from that region. The results for $L = \Delta x$ and two selected values of q are shown in Fig. 2. The values of C increase with the increasing width of the coastal region, especially within $\sim$400 km from the coast (circles in Fig. 2) – remarkably, the same distance was found by Thorndike and Colony 1982 as the boundary of the area within which the coasts influence the sea ice motion. However, within the central region, the values of C for $q = 1$ do not increase, but decrease with increasing distance of its edges from the coast. The rate of change of C with changing surface area is similar in the two domains, suggesting that the size of the area of study has more influence on C than the location of that area within the Arctic Basin (tests for subdomains with randomly selected positions and sizes – not shown – confirm this conclusion). For large q, i.e., moments representing strong, localized deformation, the values of C remain low and relatively constant independently of the scale of observation; for the mean deformation rates ($q = 1$), coherence with the wind forcing emerges with increasing spatial scale — thus, our results are in agreement with the recent results of Hutchings et al. (2011), who found that the spatial coherence displayed by sea ice deformation is low at sub-synoptic scales and increases with increasing scale of observation, and that (at least in late winter and early spring) the coherent behavior of deformation is controlled by the synoptic atmospheric forcing.

2 Reply to the comments of the Anonymous Referee No. 1

1. **The model.**
   Following your suggestion, we are planning to remove the entire model-related part from the revised manuscript, and to replace it with some remarks on the variance of ice deformation rates explained by the wind forcing and by the seasonal cycle in ice thickness and strength.

2. **Details of the cubic splines method.**
   We used the smoothing splines method in de Boor's formulation (de Boor, C., A Practical Guide to Splines, Springer, 2001), for $m = 2$ (cubic splines). The smoothing factor was very low and equaled $5 \cdot 10^{-5}$. Generally, our results were not sensitive to the choice of parameters, provided the smoothing factor was sufficiently low.

3. **Strong, localized deformation events.**
   We discussed those issues in the general discussion above.

4. **Minor comments.**
   Thank you for all comments and corrections. We will apply all of them in the revised manuscript.

3 Reply to the comments of Jennifer Hutchings

1. **Scale-dependent coherence between ice deformation and wind.**
   You write: "At small spatial scales, I find that deformation becomes less coherent with surrounding ice and wind." Our new results confirm this finding – see the general discussion above.

2. **The model** As already stated above, we accept all criticism directed toward our model; we plan to remove that part from our revised paper...

3. **Interpretation of the results in terms of explained variance.**
...and, following your suggestion, we intend to replace that part with a new one, in which we will summarize the contribution of the wind forcing and of the seasonal trend to the total variance of deformation. In the case of the mean deformation rates, the seasonal cycle represents approximately 50% of the variance, and the wind forcing represents again 50% of the remaining variance (of the detrended data). Our analysis does not permit to identify processes responsible for the remaining part of variability of the deformation rates.

4. **Influence of the coasts on the ice stress.**
As already mentioned above, we indeed do find exceptionally strong deformation in the coastal zone (Fig. 1). However, we also find that the correlation between the wind and the mean sea ice deformation decreases with decreasing domain size, roughly independently on the location (i.e., distance from the coasts) of that domain. If we analyze the central Arctic alone, the correlation coefficients are not higher, but lower than for the whole dataset – confirming your analysis from the Beaufort Sea (Hutchings et al. 2011).

5. **The state of knowledge of mechanisms of sea ice deformation.**
By saying that our knowledge is "far from satisfactory" we didn't mean to ignore or play down the achievements of researchers who contributed to this field. In our opinion, this statement simply underlines that a lot remains to be done, which seems uncontroversial to us...

4 Reply to the comments of Florent Gimbert

1. **New elements in our work compared to Thorndike and Colony (1982).**
There are a number of important differences between our approach and the one used by T&C. The major part of their analysis concerned *local* correlation between the wind forcing and the *velocity* of sea ice. One of their main assumption was that the gradient of internal stress can be excluded from the leading-order local momentum balance equation of sea ice in the central Arctic. If the sea ice deformation is concerned, they estimated deformation rates at the $\sim$500 km scale and analyzed them in relation with gradients of the wind. Importantly, they used the geostrophic wind as a measure of the forcing acting on the ice, which has some drawbacks , as it produces spurious seasonal cycle in the atmospheric forcing (in the case when the seasoanl cycle in the atmospheric stability is not accounted for – see e.g. Steele et al. 1997).
Our analysis concentrates on statistical properties (precisely: the moments of the probability distribution functions) of the total sea-ice deformation rates over a certain spatial domain, not on local deformation rates.

2. **Spatial scale of our analysis.**
Following your suggestion (as well as suggestions of other reviewers), we extended our analysis by repeating it for domains with different sizes and locations within the Arctic basins – see the general discussion above.

3. **Deviation from scaling seen in Fig.1c.**
Marsan et al. (2004) analyzed a single selected situation (6. Nov 1997). In the whole RGPS data set, there are maps which exhibit deviations from scaling and other that do not. As we say in our paper, the deviations are present if exceptionally strong, localized deformation rates occur somewhere in the study area.

4. **Further comments on Fig.1c.**
We will recompute the moments for more densely spaced Ls in the range of low values, so that the distribution of dots is more uniform – although we don't actually find that it brings any new insight (we don't expect the shape of the curves to change). We also don't find that adding a new figure zoomed onto low q values would provide any new information (we checked that).

5. **Analogous analysis for summer periods.**
The summer RGPS data contains much larger errors and, to the best of our knowledge, it has been very rarely used in scientific publications. We did not used the data in our analysis and could only speculate on the wind–ice deformation relationships during the summer periods.

6. **The bootstrap method.**
It is a standard method, in which the correlation coefficient (or other statistical measures) are calculated for a number of randomly selected sub-samples of the analyzed data, and then averaged. It is a standard, well documented method (see, e.g., "Matlab Recipes for Earth Scientists"), which aims at reducing the influence of outliers onto the obtained correlation coefficients.

7. **The influence of Δt on the results.**
The optimal time lag between the two datasets used in our study was chosen based on the obtained values of the correlation coefficients. The values of C were only slightly lower (by less than $\sim$0.05) for values of Δt between 1.5 and 3 days. The loss of correlation is smooth, not abrupt.

8. **The meaning of the "99% confidence level".**
It means that the probability that the observed correlations occur accidentally is < 1%.

9. **References to your recent works.**

We will clarify this in the revised manuscript. Thank you for pointing this out.

Interactive comment on The Cryosphere Discuss., 6, 3349, 2012.

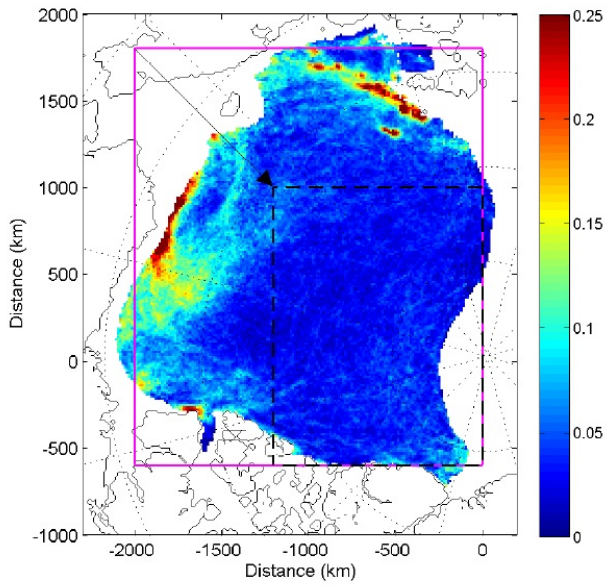

Fig. 1. Occurrence probability of extremely strong deformation events in the study area, defined as the largest 5% of all $\dot{\epsilon}_t$ values from each deformation map. The rectangular frames and the arrow illustrate the division of the study area into the 'central' and the 'coastal' region (within and outside of the dashed box, respectively), used to study the influence of the domain size and location on the values of C.

Fig. 1.

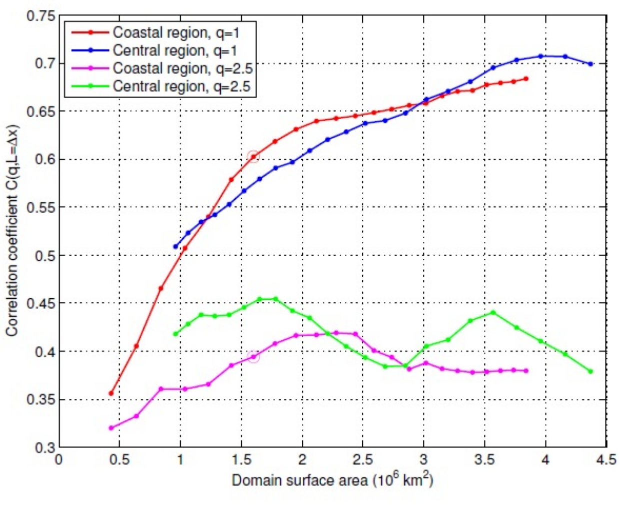

Fig. 2. Variability of $C(q, L = \Delta x)$ with changing size of the two analyzed sub-domains, the 'coastal' region and the 'central' region (Fig. 1), for $q = 1$ and $q = 2.5$. Data points corresponding to the width of the coastal region equal to 400 km are marked with circles.

Fig. 2.