Response to Referee 2 Comments (D. Watkins)

We would like to thank Dr. Watkins for evaluating our manuscript and for providing constructive feedback. In this document we will address the comments point by point.

We show referee comments in black text and our response in blue.
Changes in the manuscript are described in orange..

Review of "Patterns of wintertime Arctic sea ice leads and their relation to winds and ocean currents"

Overview

The authors compare a new high resolution wintertime sea ice lead data set against modeled ocean currents from FESOM and wind from CCLM and ERA5. The results show a compelling linkage between small-scale ocean currents associated with gradients in bathymetry and regions with enhanced lead frequency. The influence of winds is examined in terms of monthly averages of velocity and divergence. The manuscript demonstrates that the new lead dataset has broad potential for increasing our understanding of ice processes.

General comments

The role of small-scale ocean currents is often neglected in discussions of ice motion and deformation. This study makes a strong argument that ocean currents, particularly those forced by bathymetry, are important for setting up regions of stronger ice deformation, resulting in regions of higher lead frequency. The results are based on a new dataset as well as new runs of a modern ocean model with high spatial resolution. My main concerns are with the treatment of wind forcing and with the attribution of causality for ocean currents. In the following I will pose a few questions for the authors that I think need to be addressed before the manuscript is ready for publication.

We appreciate the reviewers' comments and are convinced that they will help to focus and tighten the scope of our hypotheses and conclusions. We agree that some points must be made more clearly and will address these in our revised version.

The revised version is restructured based on both reviewers' comments and suggestions. The Results chapter is now first showing the inter-annual and regional variabilities and focusing on trends, including individual months. Changes have been applied to all chapters with the overall to tighten the focus and specify the conclusions.

Can the lead fraction dataset distinguish between leads, polynyas, and regions of low sea ice concentration? If not, how does this affect the interpretation of regions marked as having high lead frequency? I question whether the high lead fractions shown in Baffin Bay, the Barents Sea, and the Greenland Ice Tongue are conflating leads with the typically low sea ice concentrations in those regions.

We appreciate your remark. Due to our retrieval method we define a lead as a significant positive surface temperature anomaly (see Reiser et al., 2020, https://doi.org/10.3390/rs12121957). As such, it includes low-sea concentration areas (that can during winter be considered as network of leads, except from the outer MIZ). Regions that were outside the sea-ice area during year when the ice edge was further north are not included as leads in the climatology.

How does variability in the location of the ice edge affect the reported lead fractions? From the example image in Figure 2a, I see that the highest lead frequencies are found in the marginal ice zone and along coasts. Looking at the red arrow in Figure 3a, I am concerned that the lead frequencies reported near Nova Zemlya represent different numbers of years, as there is often open water for a large fraction of that transect.

As mentioned above, if an area is south of the ice edge during any year, meaning that there is open water as given by an AMSR-E SIC of 0%, we consider this as outside of the sea ice area and the Lead Fraction is zero.

What role does wind direction have on the lead fraction near coasts? The manuscript states that there is no indication that wind impacts the location of the lead regions. The analysis focuses on monthly averaged values of divergence and wind speed and attempts to correlate wind values with lead fraction in each grid point. I think that the lack of connection between winds and lead fraction results from the analysis method.

We totally agree. We do not intend to say that "there is no indication that wind impacts the location of the lead regions" and will adjust our statements accordingly. Winds will definitely play a role in the opening and closing of flaw leads for example. We rather want to say that there is no obvious connection between mean patterns in wind fields and the observed mean location of leads. Looking at the temporal pan-Arctic scale we find monthly changes in the divergence of the wind field to be correlated with lead dynamics. That does not mean, however, that in individual regions and for certain periods and events, strong wind speeds and coastal geometry will definitely play a significant role in the opening and closing of leads, which is e.g., shown in the preprint of Jewell et al., 2023.
We want to make this point more clear in the revised version with the changes indicated below…
Changes are made in Section 4.1, see pdf_diff with changes highlighted.

The effects of winds on sea ice represents an integration of stresses upwind. The geometry of wind stress and coastlines is a critical component of preferential lead formation. In particular, coastal regions are strongly affected by changes in the wind direction even if the wind speed is constant. See for example Lewis and Hutchings 2019, Jewell and Hutchings 2022, and the preprint of Jewell et al. 2023 for analysis of sea ice lead formation in the Beaufort Sea. How does the choice of monthly averaged winds affect the interpretation? Using monthly averages removes effects of cyclones and most synoptic variability, which are especially important for ice dynamics. Model output is hourly, so this aspect of dynamics is captured partially–why not use higher temporal resolution for the reanalysis? It is possible that the high lead frequency seen along coastlines and near the boundaries of landfast ice corresponds with reversals in the direction of along-shore breezes as the ice is alternately pushed toward and away from the coast. This effect would not be seen in the monthly average wind speed. Consideration of the monthly standard deviation of wind velocity components or wind direction may be useful there.

We agree that many atmospheric datasets provide a lot more potential for an in-depth analysis of the regional forcing for lead opening/closing dynamics, while the results presented here are meant to present the new lead climatology and provide first explanations and hypotheses for why leads are found where we see them in this new data set and also point towards the open questions, which your question here is a part of.

Fig. R2_1 shows the mean wind speed, 90th percentile and standard deviation of C15 wind speed for 2002-2016, based on daily instead of monthly data. For the correlation with lead frequencies on the monthly time scale, using daily atmospheric data and the associated variations does not make a substantial difference. Higher spatial resolutions, in contrast, might well do so.

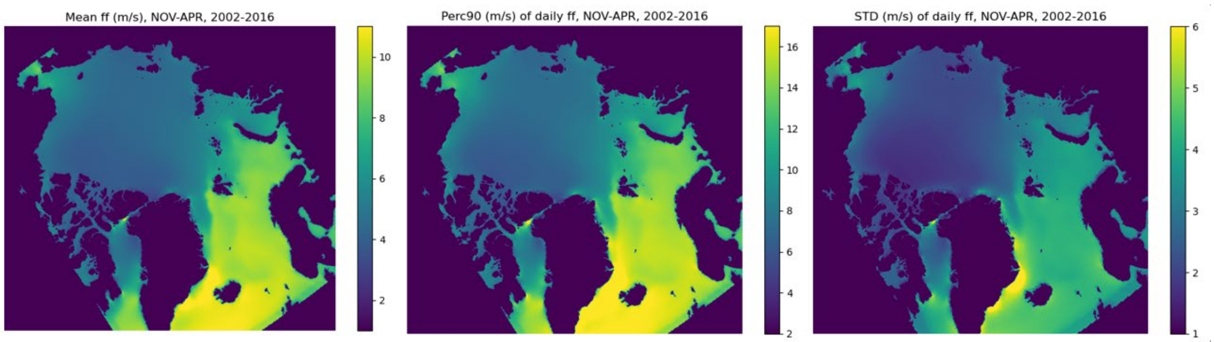

Figure R2_1: *Left: Mean C15 wind speed (ff, m/s) from daily data, middle: 90th percentile of daily ff, right: STD of daily ff, NOV-APR, 2002-2016.*

We will discuss this topic more thoroughly in the revised version and also add literature about patterns of extreme winds in the Arctic (*Gutjahr and Heinemann, A model-based comparison of extreme winds in the Arctic and around Greenland, 2018,* https://doi.org/10.1002/joc.5729). We will also add a new figure to the revised version (Figure 10), which underlines the effect of the ocean:

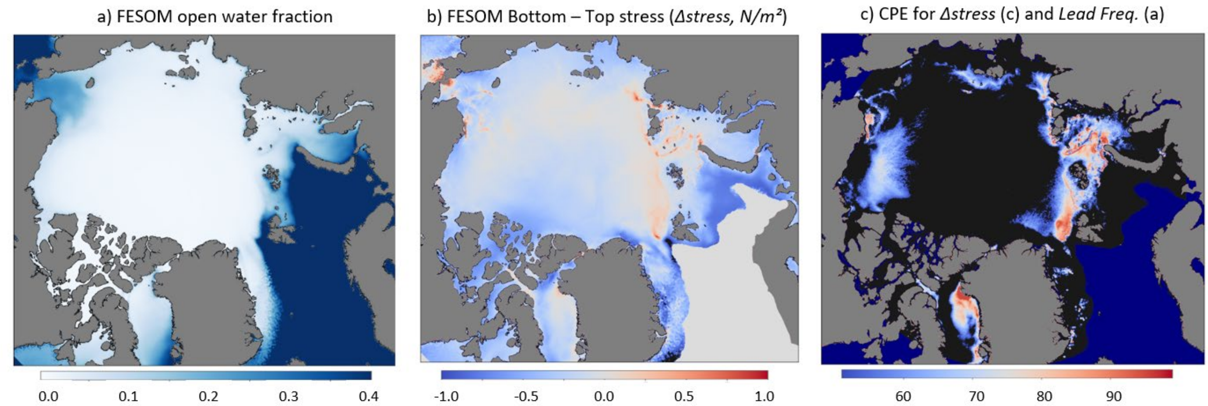

Figure R2_2: *a) FESOM mean open water fraction, b) FESOM sea-ice stress difference bottom - top, c) Coincident Percentile Exceedance (CPE) of the FESOM stress difference and mean lead frequency. FESOM data are for the period 2002-2016.*

See changes in section 4.1. There is also a new subection 3.1.6 (Winds vs. ocean forcing in the mean lead fields) that refers to the new figure (R2_2) and the role of ocean forcing vs. winds in shaping the mean lead patterns.

Can the authors rule out other possible causes for the co-location of high lead fraction and strong ocean currents? I agree with the authors that the cross sections showing enhanced currents implies that currents are a possible cause for enhanced lead formation. However, coastal interaction in combination with higher frequency wind variability (hours to weeks) may also result in higher lead frequency. I think the case could be strengthened by testing other candidate factors, and also by testing the hypothesis that high ocean currents lead to high lead fraction by looking at other regions where ocean currents are high. Are strong gradients in ocean currents always associated with increased lead frequency? If not, can the discrepancy be explained?

Thanks for this remark. It represents one of the open questions that we want to point out with our paper rather than trying to answer it with the given analysis. Answering this question in detail requires an in-depth analysis of regional specifications in current structures and potentially the influence of warm Atlantic water, which would definitely go beyond the scope of this paper. What we aim to conclude here is, however, that there is potentially a much stronger relationship in topographically steered ocean currents and lead dynamics than anticipated so far and that regional peculiarities and

detailed mechanistic processes should be accounted for in future studies. We also think that the main forcing for lead formation will be a mixture ocean currents, winds and coastal geometry with regionally differing individual contributions.
These two figures below show where high LFQ does not correspond with strong ocean currents and vice versa.
We have added these open questions to the discussions section in 4.3

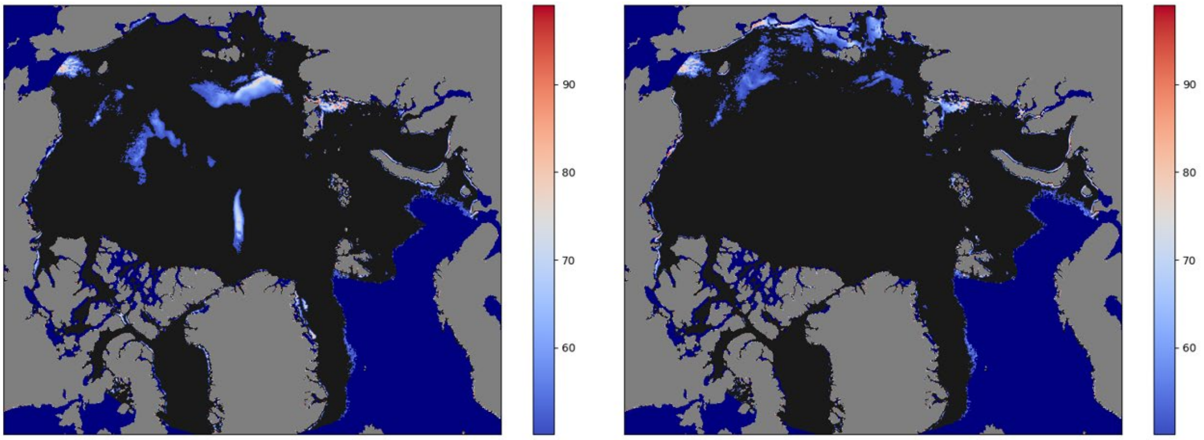

Figure R2_3: *Where do we have low lead freq. and strong currents? Regions, where mean LFQ is smaller then its 30th percentile and FESOM_vel (left) and FESOM_eke (right) exceed the percentile given by color.*

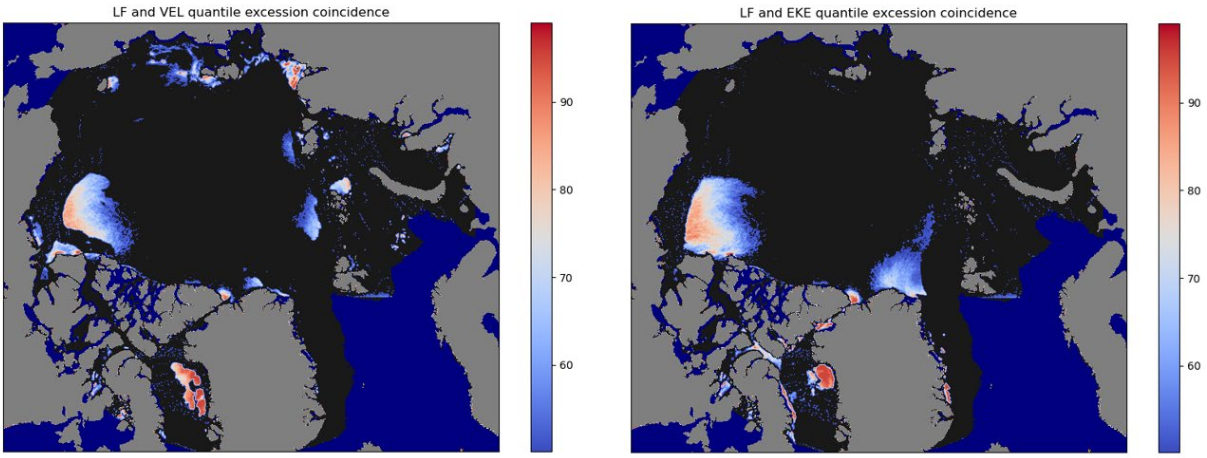

Figure R2_4: *Where do we have weak currents and high lead freq.? Regions, where mean FESOM_vel (left) and FESOM_eke (right) are lower than their 30th percentiles and mean LFQ exceeds the percentile given by color.*

Minor comments

49 Artefact → Artifact
Done.

95 Shear is a form of deformation, what specifically is meant here? Spreen et al. 2017 discuss total deformation is the divergence and shear added quadratically, which is a standard measurement. Perhaps the authors meant to write "Total deformation".
Changed to "total deformation"

Figure 6 – CPE is a useful tool for seeing where both lead frequency and ocean current metrics are anomalous. It would be useful to also see the regions where one quantity is anomalous and the other

is not, for example where there is enhanced lead frequency with no corresponding increase in current speeds or EKE. Are there places where a strong boundary current does not appear to affect the LFQ?

See figures R2_2 and R2_3, here in the response letter. These figures are not included in the manuscript but the discussion is extended picking up on your comment and the conclusion that can be drawn from these figures.

Figure 7 – Is it known why coast effects are so strong in C15, and why the coastal winds are so different between ERA5 and C15?

Differences in the wind between ERA5 and C15 result from a different horizontal resolution and the sea ice parameterization (see Heinemann et al. 2022, DOI: 10.1525/elementa.2022.00033). In coastal areas near Greenland and in areas with complex topography these effects can be large (see Heinemann and Zentek 2021, doi: 10.3390/atmos12121635; Kohnemann and Heinemann 2021, doi: 10.33265/polar.v40.3622).
We've added this note to the figure caption

Figure 11 – date index should be in dates for the time series, not in month numbers since some arbitrary start date, as done in Figure 8.
Changed.

245 I suggest replacing "increasing towards South" with "increase southward"
Done.

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