Answer to Review 2

General Comments

The authors analyse the projected changes in cyclone intensity, PV anomalies and wind speed for North Atlantic cyclones in an 10-member ensemble of CESM-LENS climate simulations for the historical period (1990-2000) and late XXI Century following the RCP8.5 scenario (2090-2100). With this aim, a composite analysis is performed to evaluate the characteristics of the (most) extreme cyclones and how these are affected in a warmer climate. The main novelty of this study is the use of piecewise PV inversion to evaluate the relative contributions of PV changes at different levels to changes in low level winds, which in my opinion is a very promising approach (also to evaluate other cyclone features). The manuscript is well written and fits well into the scope of the journal. Moreover, it surely includes interesting and publishable material. Still, some aspects should be strengthened before the paper can be accepted for publication. I largely see these comments as "minor". Please find detailed comments below. If needed, I would be willing to review the paper again upon resubmission.

Thank you for providing a review for our manuscript and for your positive and helpful feedback. We have prepared this document to answer to your comments. The line number and figure references in the reviewer's comments refer to the original manuscript. The reviewer's comments are in black, and our responses are in blue

Main Comments

a) The main shortcoming in the present study is the limited discussion with the available literature, particularly with the "conclusions" section. This may have been postponed for the "part 2 manuscript", but as it is the manuscript has a bit of an unfinished feeling. For example, it would be helpful to clearly stated in how far the present manuscript provided new insights compared to recent review papers (notably Catto et al. 2019, also co-authored by S.P.)

Moreover, some more detailed discussion about the caveats of the selected approach would be helpful. Some statements are made within the results chapters (e.g. lines 200-202; 418-424), but these should be properly stated and discussed in the conclusions. This should include a) single model approach b) single tracking method c) selection of vertical levels d) PPVI decomposition

We will describe the limitations of this study in more detail and add more discussion in comparison with the literature. The respective part of the conclusion section (lines 472-500) will be supplemented as follows (original text in blue, new parts in red):

At the end of the century, projected changes in cyclone frequencies are relatively small, with a general tendency towards slight decreases in many regions. Nevertheless, for the 10% most intense cyclones, an eastward displacement of the main oceanic storm track over the eastern North Atlantic is projected, associated with an increase in cyclone track density over northwestern Europe. These findings on cyclone frequency changes are generally consistent with previous studies using other climate models and cyclone tracking approaches (Pinto et al., 2009; Ulbrich et al., 2009; Zappa et al., 2013). Also, projected cyclone intensity changes, measured in terms of lower-tropospheric maximum relative vorticity or wind speed, are relatively small, again consistent with previous studies (Zappa et al., 2013; Catto et al., 2019).

In spite of such small overall intensity changes, our composite analysis indicates structural changes in the typical wind patterns associated with intense North Atlantic cyclones. In particular, an increase of wind velocities in the warm sector southeast of the cyclone center, potentially related to strengthening the low-level jet ahead of the cold front, and a southeastward broadening of the associated footprint of strong winds is projected. While some previous studies on future wind changes in cyclones have not detected such a robust change (Michaelis et al., 2017), consistent results regarding the broadening wind footprint have been obtained from idealized simulations (Sinclair et al., 2020) and a recent analysis of CMIP6 model projections (Priestley and Catto, 2021). Together with the eastward shift of storm tracks, this may lead to increased wind hazards in western Europe, which has also been seen in other model studies (Mölter et al., 2016).

In order to better understand the dynamical mechanisms behind these wind speed changes, a PV anomaly and inversion analysis have been conducted. PV inversion has been used previously to study future changes in cyclone propagation (Tamarin and Kaspi, 2017; Tamarin-Brodsky and Kaspi, 2017), but here it has been used for the first time for the investigation of future changes in the near-surface wind patterns associated with midlatitude cyclones. In agreement with many previous studies (Pfahl et al., 2015; Marciano et al., 2015; Michaelis et al., 2017; Zhang and Colle, 2018; Sinclair et al., 2020), we find an increase in lower-tropospheric PV near the cyclone center and fronts that is most likely due to increased latent heating in a warmer and thus more humid climate (Büeler and Pfahl, 2019). [...]

The analysis presented here has some limitations. It is based on a single climate model and thus does not take model uncertainty into account. Some confidence in the projection of the chosen CESM model is provided by the fact that the results on cyclone frequency changes and also the changes in near-surface wind patterns are consistent with other, multi-model studies (see again Ulbrich et al., 2009; Zappa et al., 2013; Priestley and Catto, 2021). On the other hand, by using several ensemble members, we have assessed the robustness of our findings with respect to natural climate variability (similar to, e.g., Yettella and Kay, 2017). Furthermore, our study uses a single cyclone tracking algorithm, which has been applied successfully before in many other studies on midlatitude cyclones (e.g., Pfahl et al., 2015, Sprenger et al, 2017) and gives results that are in the range of other tracking schemes (Neu et al., 2013). Arguments for the robustness of our findings with respect to this choice of the tracking scheme are, again, that similar results have been obtained with other tracking algorithms, also using the same climate model (Day et al., 2016), and that the dependence on the tracking scheme is generally weaker for intense (compared to weak) cyclones (Neu et al., 2013, Ulbrich et al., 2013). Our results have been presented on specific vertical levels, but are generally robust with respect to small shifts of these levels (see for instance Figs. 8 and 9). Finally, as discussed in section 4.4, the PV inversion results can be affected by errors due to imperfect knowledge of boundary conditions, non-linearities and numerical inaccuracies. Especially the separation between low-level PV anomalies and lower boundary θ-anomalies is affected, since the far impact of the low-level PV anomalies onto potential temperature below is not known. Nevertheless, we have shown that the associated residuum of the decomposition is relatively small and that the inversion method is able to reproduce the main features of the projected wind changes.

In summary, the PV analysis performed in this study provides insights into the role of altered upper-tropospheric dynamics and increased latent heat release in a warmer climate for future changes in near-surface wind fields around extratropical cyclones. The projected broadening of the wind footprint southeast of the cyclone center that can be explained by a combination of these processes may have important consequences for future changes in wind hazards. This study thus contributes to reducing the uncertainties associated with future changes in near-surface winds in cyclones (cf. Catto et al., 2019) through improved process understanding. In the second part of this study, Lagrangian air stream analyses will be used to complement and expand these dynamical insights.

b) The second main shortcoming is a limited quantification of uncertainty regarding the PPVI decomposition. While the uncertainty within the 10-member ensemble is shown in the previous sections and figures (e.g. line 343-344 regarding Fig. 7d), this is not the case for Figs 9-11. I wonder if this aspect could be enhanced (also in connection with lines 418-424).

The figures will be updated showing the agreement between ensemble members, as also shown below. The main characteristics (future response) described in the text are generally consistent for at least 80% of the ensemble members. A note on the relatively weak consistency of the low-level changes in the balanced flow (Fig. 10e) will be added to line 414:

Also, projected future changes in the balanced wind (Fig. 10e) reproduce changes in the full wind (Fig. 8b) fairly way, although they are less consistent between the different ensemble members.

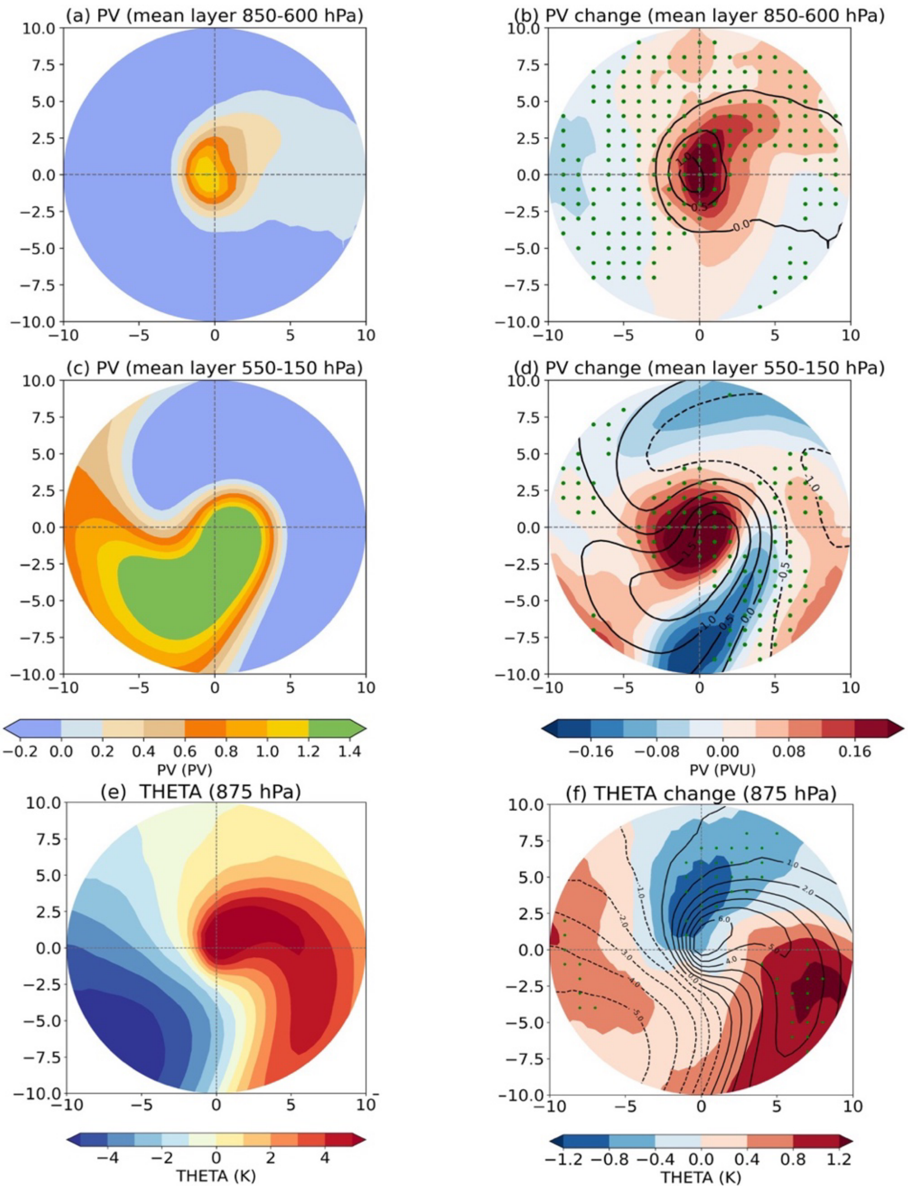


Figure 9. Present-day composites for extreme cyclones of PV averaged over a) the lower troposphere (850-600 hPa), c) the upper troposphere (550-150 hPa) and potential temperature at 875 hPa (lower boundary) for winter in the North Atlantic region. Future changes of the lower tropospheric PV, upper tropospheric PV and potential temperature are shown in b, d, and f respectively. The present-day mean of each field is overlaid as black contour lines in b, d and f. The composites are shown at the time of maximum intensity (time=0). Green dots denote regions of ensemble agreement on the sign of change.

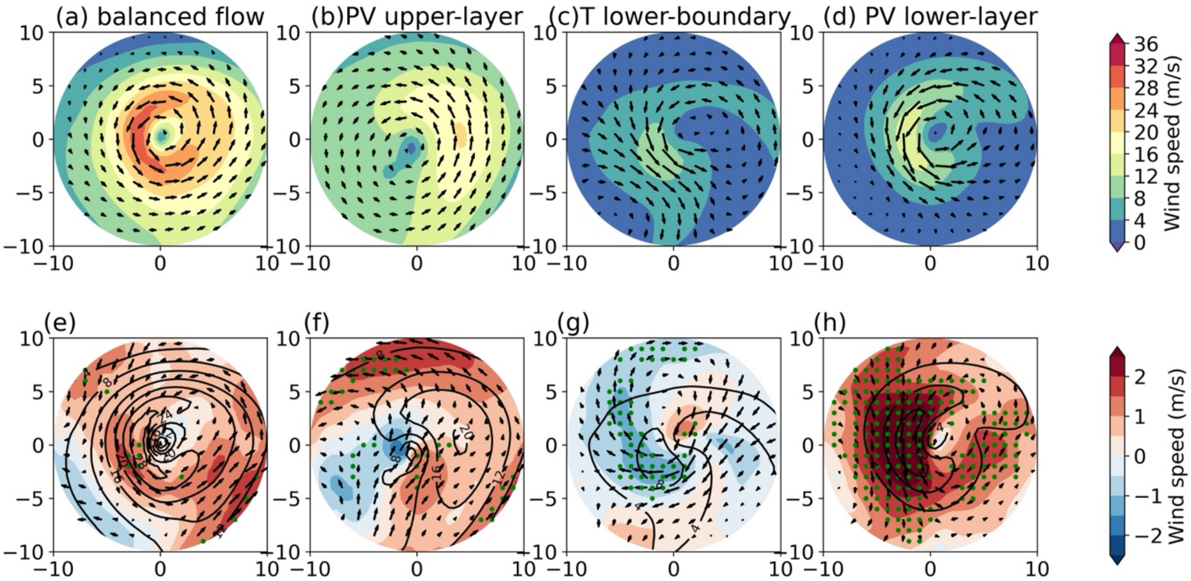


Figure 10. PPVI decomposition of the wind composites at 850 hPa in present-day climate (upper row) and their future change (lower row). The total balanced wind composite obtained from the full PV inversion is shown in figures a) and e). The other figures show the wind composites obtained from inverting (b, f) the upper-layer PV anomalies, (c, g) temperature anomalies at the lower boundary, and (d, h) the lower-layer PV anomalies. Green dots denote regions of ensemble agreement on the sign of change.

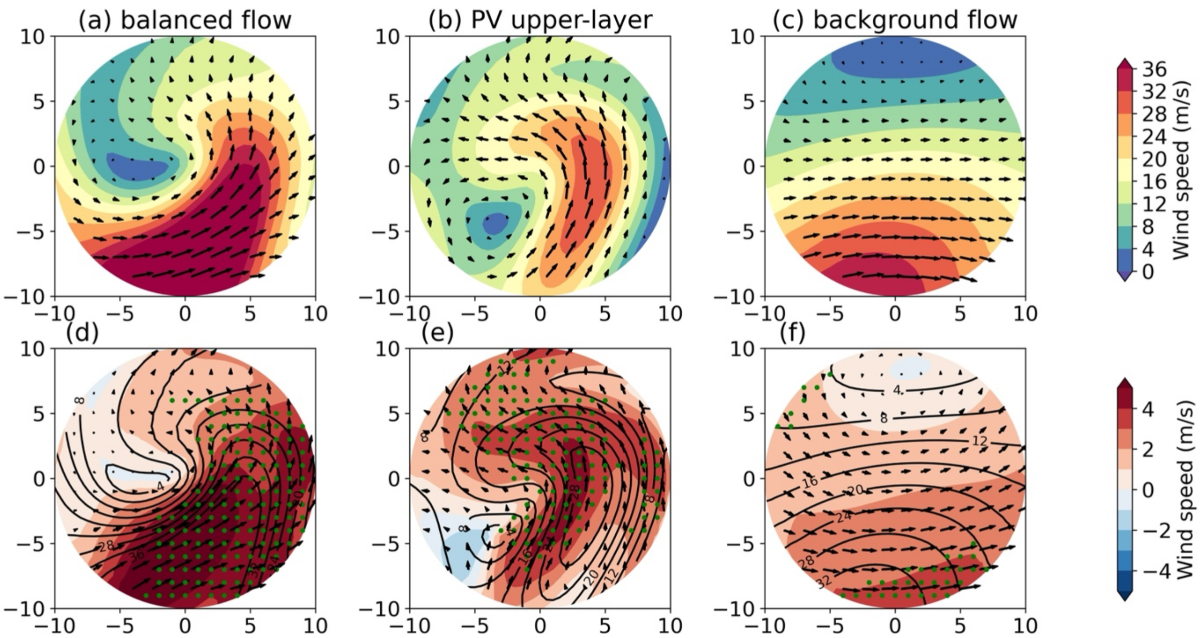


Figure 11. PPVI decomposition of the wind composites at 250 hPa in present-day climate (upper row) and their future change (lower row). The total balanced wind composite obtained from the full PV inversion is shown in figures a and d. The other

figures show the wind composites obtained from inverting (b, e) the upper-layer PV anomalies and (c, f) the background PV. Green dots denote regions of ensemble agreement on the sign of change.

Minor Comments

1) Lines 2-3: I would not say that "changes in cyclone strucuture and dynamics are unclear", but rather that "**SOME** changes in cyclone structure and dynamics are unclear", in the lines of the discussion presented in Catto et al. 2019. Please enhance.

Thanks for pointing this out, we will adapt the lines as follows:

[…] however, the involved changes in cyclone structure and dynamics are not entirely clear.

2) Line 23-24: Please add Klawa and Ulbrich (2003) as a reference, other also possible

We will add this reference.

3) Line 46: Please add the review paper Ulbrich et al. (2009) as a reference

We will add this reference.

4) Line 63-64: Please add Donat et al. (2010) as a reference, others also possible

We will add this reference.

5) Lines 116-118: I do not thing that using rotated or non-rotated composites would make a strong difference for the 10% stronger cyclones, but this could make a difference looking at the 1% strongest ones (which should follow a more northward tilted track) … wonder why rotation of the composites have provided less clear results …. It should be the other way around … did you also produce this S1 figure for the 1% strongest ones?

We did a test for the 1% strongest cyclone using ensemble member 1 (see Fig. C1 below). We observe similar behavior as for the intense cyclones (10 % strongest). The non-rotated composite (left panel) shows a stronger temperature gradient in the present-day and the future response shows a larger increase in the cold region than the warmer region. Accordingly, the use of the non-rotated composites is justified for extreme cyclones as well.

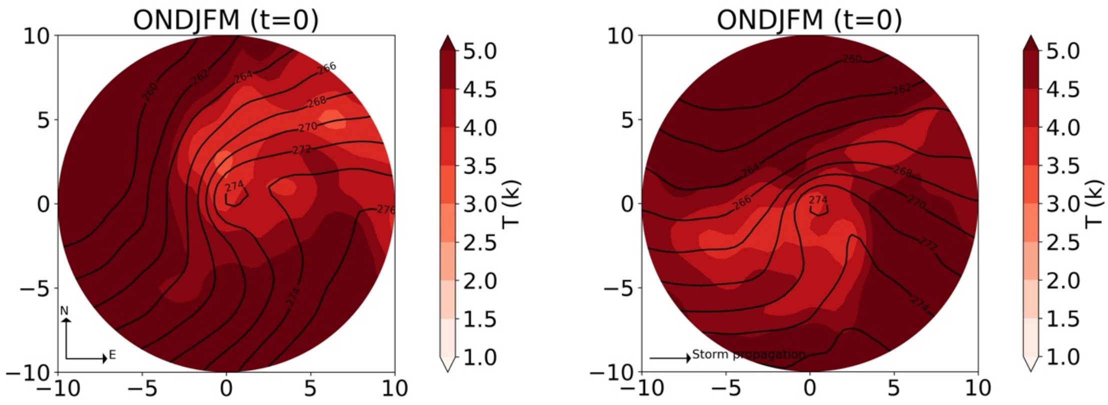


Figure C1. Cyclone temperature composites response for winter in the North Atlantic. a) Non-rotated and b) rotated in the direction of the storm's displacement. Present-day mean is overlaid as black contour lines and future response is shaded. The composites are shown at the time of maximum intensity (time=0). Extreme storms (1% strongest) are averaged for the ensemble member number 1 of the CESM-LENS dataset. Present-day: 36 storms and future climate: 31 storms.

6) Line 180: Please add Neu et al. (2013)

We will add this reference.

7) Line 200-202: Please add the information that Zappa et al (2013) was using the Hodges scheme, and add that the sensitivity of the climate change signal of cyclones to the choice of tracking method was analysed in detail in Ulbrich et al. (2013).

We will add a sentence (after line 202) to include this information as below:

Also note that Zappa et. al (2013) used the Hodges scheme for cyclone identification and tracking (Hodges, 1999). The sensitivity of the climate change signal of the cyclones to the choice of the tracking method was analyzed in detail by Ulbrich et al. (2013)

8) Lines 241-249: please compare the climate change also to other manuscripts than only Zappa et al. (2013). For example, Pinto et al (2009) found a similar spatial pattern – but slightly shifted southward (cf. Fig. 14) - when analysing the 10% strongest cyclones in a ensemble of ECHAM5 simulations.

We will add a sentence (after line 249) with the suggested reference as below:

Furthermore, the mean response found in the CESM model is also consistent with previous studies using single models (Leckebusch and Ulbrich, 2004; Pinto et al., 2009). For example, Pinto et al. (2009) analyzed the 10% strongest storms in the North

Atlantic during the extended winter (October-March) with the ECHAM5 model and found an increase in cyclone frequency over the British Isles and the North Sea, but with the maximum increase slightly shifted southward in comparison to our results.

9) Line 475: Please add the review article from Ulbrich et al. (2009) and others.

We will add this reference.

10) The colour scale in Fig 2a and 4a should be changed, as it is quite misleading.

We will modify the color scale as below:

Figure 2a:

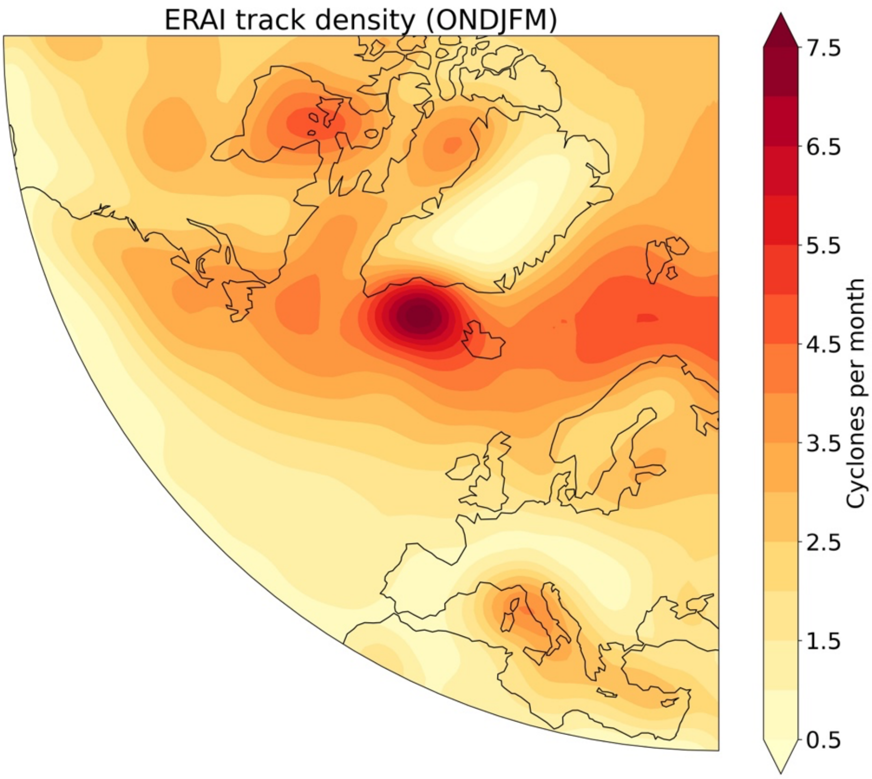
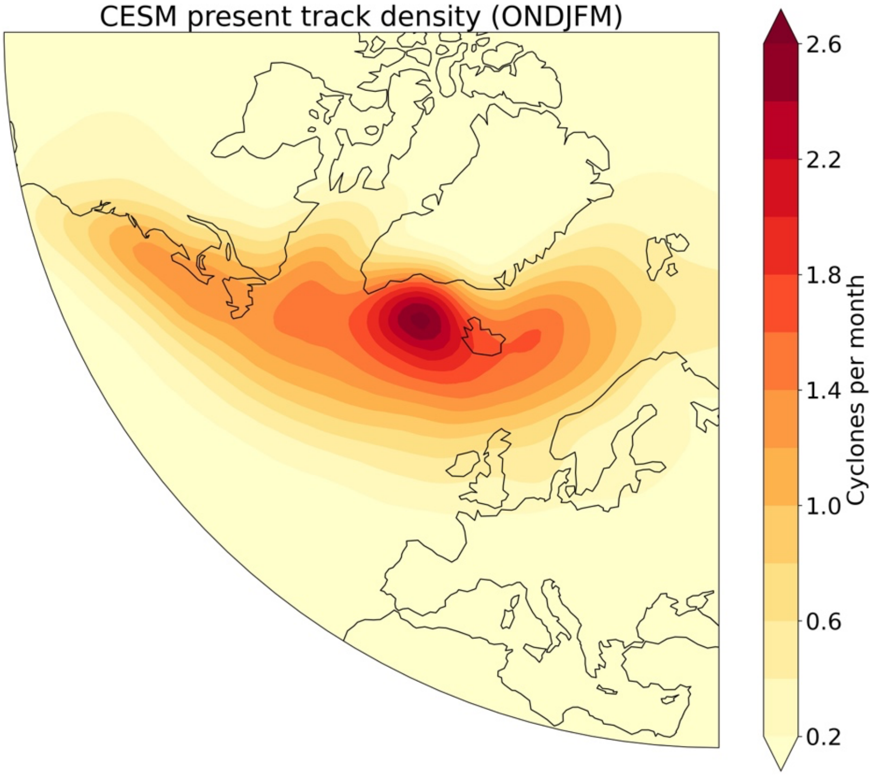


Figure 4a:


CESM present track density (ONDJFM)
2.6
2.2
1.8
1.4
1.0
0.6
0.2
Cyclones per month