Authors' Response to Reviewer 2

General Comments. Review of manuscript egusphere-2025-2212: "Response of Northern Hemisphere Rossby wave breaking to changes in sea surface temperature and sea ice cover" by Tahvonen et al.

In this manuscript the authors assess the impact of changes in STTs and Sea Ice on RWB frequencies in the Northern Hemisphere using an appropriate experiment design to test these. Using this, the authors show that the SSTs have a more profound impact on the jet streams in the NH but the results are inconclusive in as far as the impacts of sea ice is concerned because the models do not seem to agree. The manuscript is succinct and it is well written. I have some comments that the authors should/could take into consideration before it is published.

Response: We thank the reviewer for their detailed comments that have helped to improve the quality of the manuscript. We have listed the comments made by the reviewer below and address each of them individually. Changes to the manuscript text are indicated in the boxes shaded gray.

Major comment:

Comment 1

The main concern that I have as a reviewer of this manuscript, as well written as it is and as impressive the model experiments as they are, is that it disagrees with established results with regards to the poleward migration of the jet and therefore the impact that this might have on RWB events. Whilst the DJF eastward shift in the jet is an interesting finding, is it realistic? Is it observed in the observations in the early 21st century? For instance, do we see this behaviour when we compare 1950 – 1969 vs 2000 – 2019 but weaker in strength.

Response:

The poleward migration of the Northern Hemisphere jet streams has only been projected with low confidence by the IPCC (IPCC, 2023), who also note substantial seasonal and longitudinal variation in the response of the jet streams to increased GHGs. Additionally, many studies focus on changes at lower levels, whereas we consider upper-level changes at 250 hPa. For corroboration of our results on zonal wind changes at 250 hPa, Fig. 1 shows zonal wind changes in DJF and JJA in both models used and in two scenarios, SSP585 and SST_{SSP585}, with styling replicated from Figs. 3-4 of Harvey et al. (2020) who examine multi-model means of 250 hPa zonal wind changes in CMIP models. Fig. 3f of Harvey et al. (2020) presents DJF zonal wind changes in the SSP2-4.5 scenario, and shows, along with a poleward shift, an eastward extension for the North Pacific jet stream. The Atlantic jet also accelerates over Europe. Qualitatively the features in Fig. 1a-b show a similar pattern, although the magnitudes of the changes are larger as Fig. 1 depicts the effects of more extreme SST and SIC changes. Similar conclusions can be drawn by comparing Fig. 4f from Harvey et al. (2020) and Fig. 1c-d for JJA.

A poleward shift in jet stream latitudes has most commonly been found in zonal averages of zonal wind (e.g. Yin, 2005; Yu et al., 2024). To demonstrate how our results compare with these studies, we have plotted zonally averaged zonal wind changes in our respective models during the boreal winter, as shown in Fig. 2. This figure replicates Fig. 4g of Yu et al. (2024), who examine the individual effects of SST changes on the Northern Hemispheric climate. Although the primary characteristic at 250 hPa is an overall acceleration, both Fig. 2a-b and Yu et al. (2024) show a poleward shift at lower levels, and deceleration near the poles and the tropics. Based on these two examples, we argue that our results are not in disagreement with previous results, but simply presented and discussed so that focus is on features other than those commonly discussed in previous research.

Lastly, we want to emphasise that our experiments do not attempt to capture the full atmospheric response to climate change, but to examine only the effects of SST and SIC changing according to an extreme warming scenario (SSP5-8.5). This goal is explicitly stated in e.g. the abstract and on lines 107-108 of the preprint. Therefore some differences between our results and full climate change studies are to be expected. However, we do see the necessity of addressing the zonal wind changes observed in our results in more detail. The introduction and discussion chapters of the manuscript have been edited accordingly. More changes related to how we discuss the jet streams in the manuscript can be found in the response to Comment 1 by Reviewer 3.

Introduction:

> Harvey et al. (2020) studied CMIP6 simulations and noted that in addition to a poleward shift, the Pacific and Atlantic upper level jet streams also exhibit significant eastward acceleration during the boreal winter. This could have an impact on RWB, which as stated tends to occur in the vicinity of jet exits.

Results:

> At a zonally averaged level (not shown), zonal wind in DJF does exhibit a poleward shift across pressure levels in the troposphere, which many previous studies have also found (e.g. Yin, 2005; Barnes and Polvani, 2013). However, as the response in both RWB and zonal wind is clearly zonally asymmetric in our results, we will consider the entire Northern Hemisphere without zonal averaging.

Discussion:

> However, in the Northern Hemisphere, the response of the jet streams to climate change has been found to be uncertain (IPCC, 2023) and to vary by basin and season without a uniform poleward shift (e.g. Simpson et al., 2014; Matsumura et al., 2019; Harvey et al., 2020). Our results similarly indicate that the response of RWB frequencies to changes in SST and SIC are basin-dependent and that a poleward shift of the jet streams, although visible at a zonally averaged level, does not appear to be the main cause of these changes.

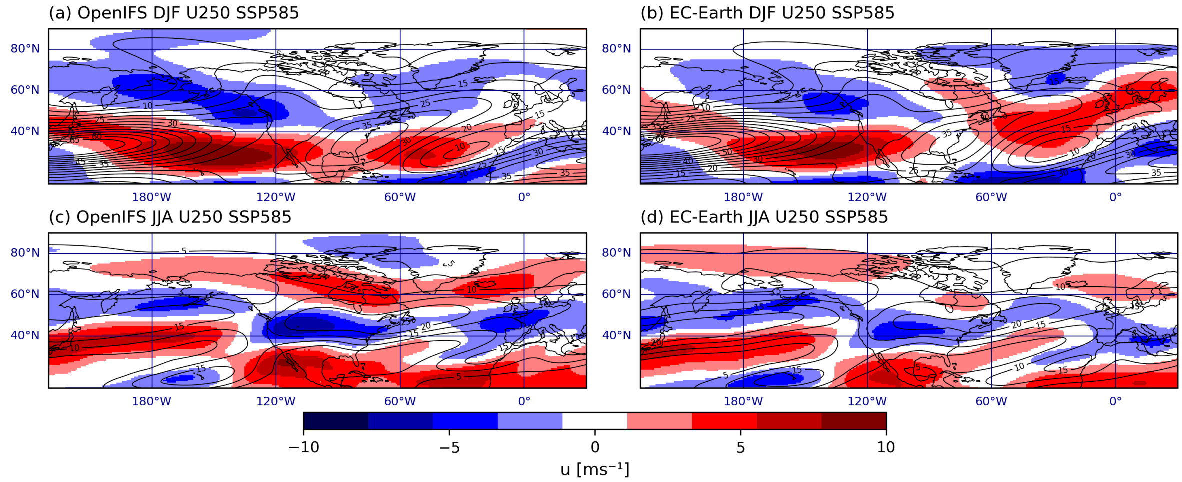

Figure 1: Changes in 250 hPa zonal wind in the SSP585 simulations, i.e. simulations using SSP5-8.5 SSTs and SIC. DJF changes in panels a-b with OpenIFS on the left and EC-Earth on the right. Panels c-d: JJA changes in the same order.

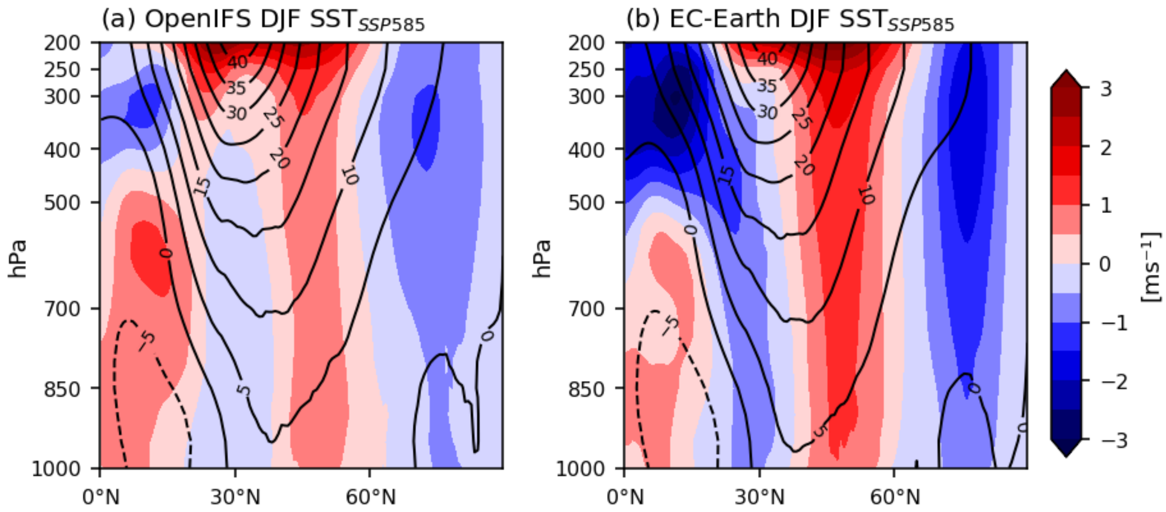

Figure 2: Zonally averaged vertical cross-sections of changes in zonal wind speeds between Baseline and SST$_{SSP585}$ (former subtracted from latter) in a) DJF in OpenIFS b) DJF in EC-Earth.

Minor comments

Comment 1

Lines 25 – 35: Whilst one understands that the study focuses on AWB and CWB types, but why was the equatorward/poleward RWB neglected in this discussion. As we well now know, Thorncroft et al (1993) identified LC1 and LC2 which are equatorward but Peters and Waugh (1996) then showed that these two have poleward counterparts. This should at least be acknowledged here. Also, there are several studies which have shown that these 4 types actually exist in “observations” (reanalyses products).

Response:

Thank you for bringing this to our attention. This is a very good point and an oversight on our part. This point and a reference to Peters and Waugh (1996) has been added to the introduction. The following text in the Introduction has been edited, with an added mention of barotropic shear as suggested in your following comment:

> These different orientations are very commonly used to categorise RWB into two types: cyclonic wave breaking (CWB) or anticyclonic wave breaking (AWB). Based on life cycle experiments (Thorncroft et al., 1993) and observations (Peters and Waugh, 1996) RWB is sometimes further divided into poleward and equatorward AWB and CWB depending on the direction the associated air masses are primarily advected in. Thorncroft et al. (1993) showed with idealised baroclinic lifecycle simulations that in AWB, anticyclonic shear causes a trough and a ridge to rotate around one another anticyclonically. They describe this occurring to a positively tilted trough that has been advected equatorward, while Peters and Waugh (1996) note that AWB can also occur due to a ridge being advected poleward: these result, respectively, in equatorward and poleward AWB. CWB requires the influence of cyclonic barotropic shear, and involves a trough and a ridge rotating around one

another cyclonically. Thorncroft et al. (1993) found equatorward CWB to occur to a negatively tilted trough propagating equatorward, while poleward CWB primarily involves the advection of a negatively tilted ridge poleward of the jet axis (Peters and Waugh, 1996).

Comment 2

Lines 40 to 45: The role of barotropic shear in influencing the morphology of RWB appears to be missing here.

Response:

We have added a mention of the effect of barotropic shear on the life cycles of cyclones as stated in Thorncroft et al. (1993).

CWB requires the influence of cyclonic barotropic shear, and involves a trough and a ridge rotating around one another cyclonically.

Comment 3

Lines 45 – 50: COLs can also be viewed from the traditional synoptic meteorology point view (in geopotential height fields) and some studies have shown that RWB events precede COL formation. Perhaps the point of view of the synoptic meteorologist should be considered here and the role of the jet streaks that arise as the waves break and the transverse ageostrophic circulations that materialise here leading to vertical ascent. This is important to raise because there are several studies that have created climatologies of COLs from the traditional point of view and papers such as Wernli and Sprenger (2007), Portmann et al (2020) that have done the same from a PV perspective yet how these two meteorological worlds link is not considered in the lit review in this paper.

Response:

Cut-off lows are mentioned on lines 45-50 as we are discussing phenomena related to RWB from a PV perspective. However we do not think that further discussion of cut-off low climatologies is beneficial since ample grounds for comparison between our results and previous literature on RWB climatologies already exists. Since research on cut-off lows in future climates is as of yet sparse, the role of cut-off lows in the discussion would also be very limited.

Comment 4

Lines 90: There are some studies in the SH that might be relevant here, even though they focus on the ozone depletion/recovery response during the summer season there (DJF) there.

Response:

In the case of changes to the Northern Hemisphere zonal circulation due to climate change, we think it is best to contain the discussion to studies made of the Northern

Hemisphere in order to not make the manuscript overly long.

Comment 5

Section 3.1: (I have some general comments for this section to help improve it)

- May I suggest presentation of the composites of AWB and CWB here to show that the categorisation method employed in this study actually work. These should include the isotachs please so that the climatologies in Fig 3 can then be better explained.
- I also strongly suggest that the authors consider presenting ERA-5 versions Figure 3, either as additional panels to that Figure or separately so that the models can be quantitatively compared with the "observations".
- In the caption of Figure 3, please change the order in which AWB and CWB are presented and specify the years for these simulations

Response:

We address the listed comments in the order they are given:

- We have conducted extensive visual inspection during the code development and testing process to confirm that the RWB categorisation method works as stated in the manuscript. The method is based on the detailed description given by Bowley et al. (2019) who further base their method on Barnes and Hartmann (2012). A similar approach has been independently developed by e.g. Strong and Magnusdottir (2008). The accuracy of our implementation of the method is further supported by the fact that many previous studies have found similar climatologies for AWB and CWB: see e.g. Bowley et al. (2019), Jing and Banerjee (2018), Abatzoglou and Magnusdottir (2006) and Strong and Magnusdottir (2008). Calculating composites of RWB would be interesting but it is unfortunately a very complex task, as the method detects RWB over a large range of sizes, with widths ranging from about 5 degrees longitude to over 40 degrees of longitude. To improve transparency we have added an example of CWB to Fig. 2 of the manuscript. For these individual instances of RWB, adding isotachs made Figure 2 rather messy and hence we concluded this was not useful, but we hope that this works as additional assurance of the reliability of the method.

- Thank you for the suggestion. The intent of this comment appears to be a wish to investigate how well our simulations agree with ERA5. For a comparison of flow conditions over the Atlantic, we can direct the reviewer to Figs. 1 and A2 of Köhler et al. (2025). We also wish to reiterate that the goal of the Baseline simulations is not to perfectly replicate past climate, but to demonstrate the state of an atmosphere forced with annually repeating present-day SSTs and SIC. As this acts to suppress interannual variation, perfect agreement with ERA5 is neither to be expected nor is it the goal of the Baseline simulation. Furthermore, downloading and processing ERA5 data to reproduce Fig. 3 would be an excessive amount of work for a figure that would at most end up as supplemental material for the aforementioned reasons. However our results are at least visually comparable with e.g. Bowley et al. (2019) who implement a very similar detection method to an atmospheric reanalysis. LaChat et al. (2024) also present in their Fig. 2 a climatology of RWB in DJF in the Northern Hemisphere based on ERA5.
- The order of AWB and CWB in the caption has been edited according to your suggestion. As for the years, we wish to emphasise that as average SST and SIC conditions are repeated each year, the years of the simulation are not analogous to any specific time in the past. Therefore we think that referencing years would only create confusion.

Comment 6

Lines 190 – 195; 210: I strongly suggest that the authors perhaps consider Peters and Waugh (2003) who looked at jet configurations in the SH to explain some of the morphologies of RWB events identified there. This might help to explain some of the location of the surf zones. For instance, in Fig 3f I see AWB events on the cyclonic barotropic shear side of the jet in the Pacific Ocean, which kind of goes against the grain, but if one considers the 10 m/s isotach once can see why that AWB centre is there. This seems to be easily explained by Peters and Waugh (2003), see their schematic in Figure 3.

Response:

Thank you for the suggestion. Peters and Waugh (2003) indeed explain some features of RWB surf zones very well and we have added this to the discussion.

In reference to Baseline DJF AWB over the Atlantic-Eurasian surf zone:

> Peters and Waugh (2003) note that a jet configuration where a polar jet is located closely upstream from a subtropical jet favours RWB: such a double jet configuration is climatologically apparent over the North Atlantic-Eurasian surf zone and therefore provides an explanation for the abundant AWB.

In reference to the zonal wind structure in Baseline JJA:

> In OpenIFS, the North Pacific AWB maximum is downstream from the maximum of the Asian jet; in EC-Earth, the 20 m s^{-1} contour extends over 60° further east than in OpenIFS and the AWB maximum is located south of it. Together with the subtropical jet between 180°E - 120°W, the Asian jet forms a double jet structure that strongly promotes AWB (Peters and Waugh, 2003) over the Central Pacific, as we also suggested to be the case over the Atlantic in DJF.

In reference to AWB and zonal wind changes in the SSP585 simulations in JJA:

An eastward shift in the location of the jet exit may be related to the increase in AWB frequencies over the Central Pacific, downstream from the new location of the jet exit. This could also be interpreted as an eastward shift of the double jet structure acting to support AWB, and the changes in AWB would then simply reflect this shift. However, as the decreases in AWB frequencies over the West Pacific and Asia are much larger than the increases over the Central and East Pacific, it is unlikely that this is the only cause for the changes. Over North America, the jet weakens by 3 m s^{-1} in OpenIFS and by 4 m s^{-1} in EC-Earth: the two shifts over East Pacific and North America are located near areas where AWB frequencies decrease and CWB frequencies increase over North America. Over western Europe, wind speeds decrease. In OpenIFS, zonal wind speed increases in Arctic areas and off the coast of West Africa, while the increases are smaller in EC-Earth. These changes to the relative strengths and positions of the eddy-driven and subtropical jet likely have implications leading to the increase in AWB frequencies over Europe and North Africa, particularly when a double jet is present (Peters and Waugh, 2003).

Comment 7

Lines 240-245: Can the authors provide some reflection on the jet that does not seem to be migrating poleward with increasing GHGs. This issue should also be attempted to be addressed in current climate in reanalysis.

Response:

Firstly, we must reiterate that GHGs are not increased in our experiments. Rather we change SST and SIC according to an extreme climate warming scenario while keeping e.g. GHGs as in the present climate. Similarly the Baseline simulation is not a reanalysis, as those simulations also use annually repeating SST and SIC and this should strongly act to suppress any interannual variation. This comment is closely connected to Comment 1, and the reply to this comment already involves some reflection on this matter. As stated in the response to Comment 1, we have added commentary on this to the introduction and discussion. However, we do not see additional reflection to be necessary here as these results are not completely unprecedented.

Comment 8

As discussion on the changes in the flow and its impacts during JJA shown in Figure 5 e – f is not provided in the manuscript or it is very thin and therefore needs to be given some attention.

Response:

Commentary on Fig. 5e-f is provided on lines 271-278 of the preprint, and this commentary has been extended as detailed in Comment 6. Additionally changes in the summer are discussed in the discussion on lines 359-363. JJA changes in zonal wind and RWB frequencies are difficult to connect over many areas, as other effects, particularly monsoon circulations, also effect RWB during this season.

Comment 9

Lines 325: The direction of eddy momentum fluxes should be explicit here (for in stance the fact that AWB is associated with poleward momentum fluxes)

Response:

Thank you for the suggestion. We have added a mention of the directions of momentum fluxes to line 322-323 as follows:

The poleward momentum flux associated with AWB causes the jet stream to shift poleward, while with CWB the momentum flux as well as the movement of the jet are equatorward.

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