Response to comment by Anonymous Referee #3

Circumglobal Rossby wave patterns during boreal winter highlighted by wavenumber/phase speed spectral analysis

Authors: Jacopo Riboldi , Efi Rousi , Fabio D'Andrea , Gwendal Rivière , and François Lott

Recommendation: Accept with minor revision

This study systematically identifies two circumglobal Rossby wave packets (CRWPs) using diagnostic analyses with Reanalysis data. The CRWPs were identified with an EOF analysis in wavenumber/phase speed space applied to the daily spectral amplitude of the meridional wind. The authors diagnosed many interesting features of these wave packets, including spatial structure, blocking frequency, and most interestingly a possible driving mechanism via MJO phase 3 tropical convection (for CRWP1) and the generation within the extratropics for CRWP2.

The authors also found linkages to the MJO, meridional heat flux, and baroclinicity, connections of the CRWPs to the North Pacific and North Atlantic storm track regions at different time lags, and even to wave packet propagation from the North Atlantic, followed by anticyclonic wave breaking and then propagation across the Mediterranean to the Middle East. This manuscript was a pleasure to read, and I learned a lot.

I recommend accepting this manuscript with minor revisions and suggest that the authors consider all my comments below.

Thanks a lot for your positive and constructive comments and for the time spent reading the manuscript. A detailed answer to each point is enclosed below.

Minor Comments

1. Line 88. It would be helpful to state here that the seasons will be examined separately, even though it is stated later. **The paper focuses on boreal winter, as indicated in the title, but the spectral analysis has been actually done for each day of each season between March 1979 and November 2019. Days belonging to neighboring months (e.g., February 1979 and December 2019) were always considered in the 61d time window needed to perform the spectral analysis, so the computation of the spectra is seamless across the Reanalysis period. Seasons are portrayed separately for Fig. 1 only, to illustrate the climatology. We will specify this aspect for further clarity.**

2. Line 112. The spectra are averaged over a very broad range of latitudes. How do the spectra vary if separate averages are performed for more narrow latitudinal bands? In other words, what would the spectra look like if there were four separate latitudinal bands that are 10 degrees latitudes wide, e.g., 35-45N, 45-55N, etc? Stated slightly differently, how sensitive are the results shown in Fig. 1 to choices of different latitudinal bands. Note that I am only asking this about Fig. 1. I don't expect that the authors redo their entire analysis for

these four bands, since the results presented in this manuscript are very interesting with this average over more than 40 degrees latitude.

This question is interesting under several aspects, because the choice of the latitudinal band is a factor determining the type of harmonics that the spectral analysis is capable of resolving. This is visible in the $cos(\phi)$ dependence of the phase speed:

$$c_p = \omega \, a cos(\phi) \, /n$$

and means that the same angular frequency ω would correspond to a higher phase speed at low latitudes and a lower phase speed at high latitudes. This effect was already discussed by Randel and Held (1991) and leads to the exclusion of few wavenumber/phase speed harmonics from the spectrum. A Supplementary Text S2 has been added to the Supplementary material to explain why this is the case and explicit the resolved range of phase speed.

In order to highlight this effect, we show here the seasonal mean (DJF) of spectral power density computed for different latitudinal ranges (Fig. R3.1). The plot to the left of the panel (Fig. R3.1a) is obtained by averaging only the latitudes between 35°N and 55°N, the plot on the right (Fig. R3.1c) by averaging between 55°N and 75°N. For comparison, the plot in the middle (Fig. R3.1b) is the same as in Fig. 1a, obtained by averaging across the full latitudinal range (35°N-75°N).

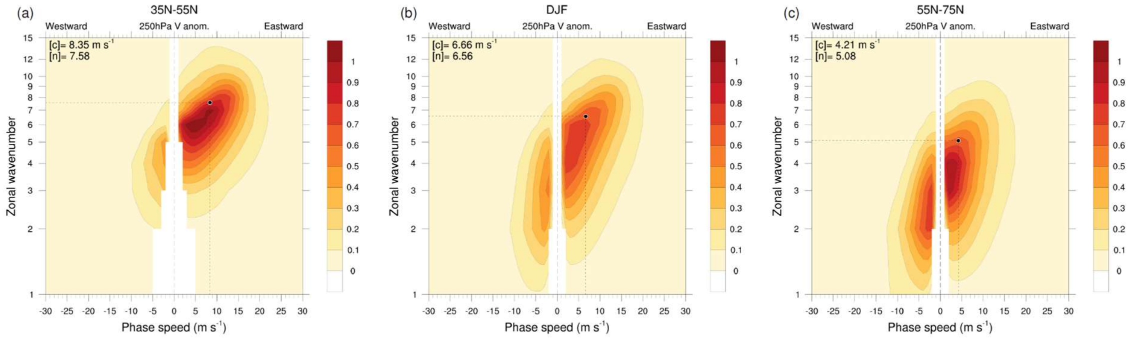

Fig. R3.1: DJF mean of wavenumber/phase speed spectra of meridional wind anomaly at 250hPa, obtained by averaging together periodograms computed across different latitude ranges: (a) 35°N-55°N, (b) 35°N-75°N, (c) 55°N-75°N. Units and notation as in Fig. 1 of the manuscript.

We can notice that low-latitude spectra do not resolve properly slow-moving waves for low wavenumbers, as indicated by the relatively large area of missing values around the $c_p = 0$ m/s line (as discussed in Supplementary Text S2). They also project over higher wavenumbers at low latitudes than at high latitudes: this is due to the horizontal scale of the anomalies (which is determined by physical processes like baroclinic instability) projecting on different zonal wavenumbers according to the latitude circle over which the spectral decomposition is performed. For instance, the latitude circle at ϕ_1= 36°N has a

length $L_1 = acos(36°) \approx$ 5000 km, while the length at ϕ_2= 72°N is $L_2 = acos(72°) \approx$ 2000 km: a ridge/trough couplet with a horizontal scale of 1000 km would then project on a wavenumber n=5 at ϕ_1 and on a zonal wavenumber n=2 at ϕ_2. These artifacts are an unavoidable limitation of performing spectral analysis over a latitude circle on a sphere: the averaging of the periodograms over the broad 35°N-75°N latitude range reduces their impact on the results. This beneficial effect can be noticed by looking at Fig. R3.2, which features a reasonable distribution of spectral power over the whole range of expected harmonics. We will highlight this effect in the text as an advantage of latitudinal integration, instead of the previously discussed "non-zonal propagation".

3. Line 113-114. It is not clear to me how this method gets around the issue of non-zonal propagation. To me, this just a limitation of the method. Since no method can address all questions, it is sufficient to simply acknowledge this limitation. Also, another advantage for not first averaging the meridional wind anomalies is that the meridional wind can sometimes be in the opposite direction at different latitudes for the same longitude, which would lead to the cancellation of the signal. Wave breaking and blocks are just two examples when this can happen. The authors may wish to mention this point. **Thanks for pointing it out, we will remove this reference to the non-zonal propagation. For the second comment, please see the next point.**

4. Line 117. I don't see how the vertical stacking, i.e., an equivalent barotropic vertical structure, is linked to the need for performing a latitudinal average. The authors may wish to explain this more carefully. **Thanks for pointing out this unclarity: we used the verb "stacked" inappropriately to indicate a meridional superposition of the anomalies, rather than a vertical superposition. This corresponds to what the reviewer was indicating in comment #3, as meridional wind anomalies can have opposite signs at the same longitude. We will employ the suggested formulation in the manuscript and substitute "stacking" with "meridional superposition".**

5. Line 121. I suggest that "precise" be replace by "state" or a similar word. **Thanks, replaced according to the suggestion.**

6. Line 136. It would be clearer to write "The circulation patterns associated with modes of spectral variability…". **Thanks, rephrased according to the suggestion.**

7. Figure 1. Westward phase speeds for all wavenumbers less than 8 is a little surprising to me, especially for the larger wavenumbers within this group. Since the Rossby wave dispersion relation depends on the background zonal-mean zonal wind and beta, or even better, the meridional potential vorticity gradient, are the westward phase speeds related to a small zonal-mean zonal wind within some latitudinal bands (see comment #2 above). Also, does the phase speed in the top left corner of each panel indicate the average phase speed. This isn't stated in the caption. **This is another interesting observation: we guess that these westward-propagating harmonics occur in correspondence of Rossby wave breaking, when troughs and ridges at the scale of a Rossby wave packet start to move from the east to the west following the nonlinear "bending" of the waveguide. Another**

possible explanation might involve the occurrence of atmospheric blocking, which often appears as a large-scale anticyclonic anomaly that is not part of a normal Rossby wave packet. In this case, the spectral analysis would project power over a broad range of wavenumbers (as the extreme case of a Fourier transform of Dirac's delta would project power on all wavenumbers). JR undertook a preliminary analysis to study the spectral signature (in terms of wavenumber/phase speed harmonics) of atmospheric blocking events and noticed that such events (defined with respect to the blocking index by Schwierz et al. 2004) feature anomalous spectral power for quasi-stationary and retrogressive harmonics (Fig. R3.2).

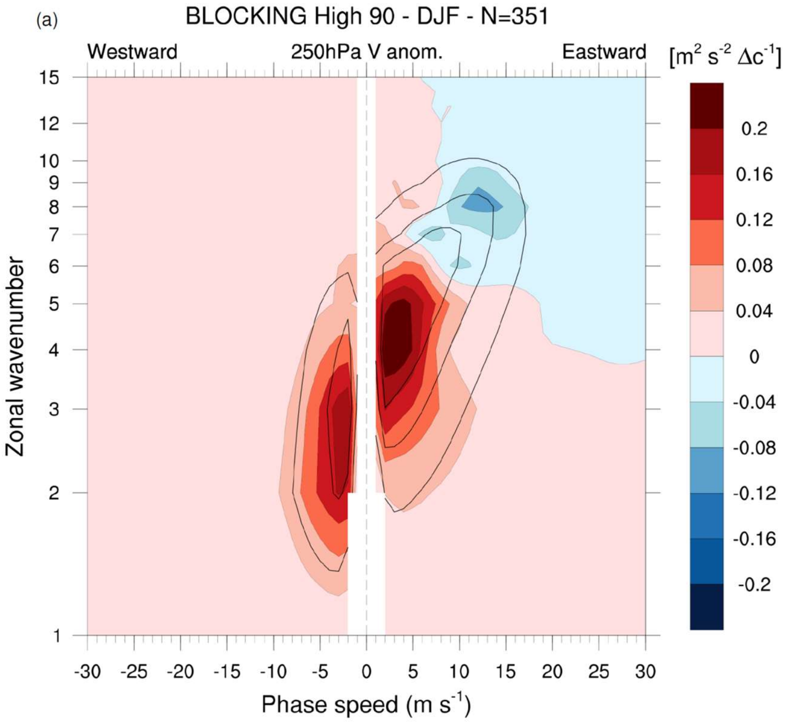

Fig. R3.2: Anomalous spectral density for N=351 days featuring the highest area (top 10%) covered by atmospheric blocking in the Northern Hemisphere (anomalies computed with respect to the seasonal cycle). This figure belongs to a poster that was discussed in the Blocking Workshop 2021: the poster is publicly available at the web page https://jriboldi.github.io/files/BW2021_Poster_Riboldietal.pdf or upon request to the corresponding author.

We will add a sentence to the manuscript to explicit this point: "We speculate that the power in those retrogressive harmonics is due to the occurrence of atmospheric blocking and Rossby wave breaking, phenomena that feature a disruption of the normal eastward propagation of upper-level troughs and ridges".

The [*c*] value indicates the value of phase speed (computed as in Riboldi et al. (2020) extrapolated from the climatological spectrum. Both [*c*] and [*n*] are obtained as weighted averages of phase speed and wavenumber with respect to the spectral power:

this will be made explicit in the caption by the new formulation "Both these quantities are obtained by weighting, respectively, the phase speed and the wavenumbers in the considered ranges with respect to the spectral power, and the respective values are reported in the top left corner of each plot."

8. Lines 153. "Propagation is misspelled. **Thanks, corrected.**

9. Line 155. "or" -> "of". **Thanks, corrected.**

10. Lines 190-191. The authors should provide greater justification for using the meridional component of the E-vector (Ey) as a proxy for wave breaking. After all, any horizontal tilt of eddies, no matter how small, will have a non-zero Ey. By looking at observational data, it is very easy to find many days with a fairly large Ey without wave breaking. On the other hand, when there is wave breaking, I would expect Ey to be quite large. It would be helpful for the authors to show some correspondence between large Ey and wave breaking. **Although we are aware that significant anomalies Ey do not necessarily imply wave breaking, we chose Ey for a few reasons: 1) it is easier to compute and based on fewer assumptions than an actual wave breaking diagnostic 2) it matches the employment of the zonal component of the E-vector (Ex) to highlight CRWPs 3) it is not a 0/1 field as the blocking, making it easier to build composites and test its significance. The usefulness of this quantity to highlight eddy/mean flow interaction was already shown by previous work (e.g., Schemm et al. 2018). To avoid misunderstandings with actual wave breaking, we will refer to "anomalous equatorward propagation of transient eddies". The second-last sentence of the abstract will be modified as follows "An anomalous equatorward propagation of Rossby waves from the Atlantic eddy-driven jet to the North African subtropical jet is observed for both CRWPs". Further references to anticyclonic wave breaking will be removed from the text.**

11. Line 226. Where is the reduced meridional gradient of geopotential that is being referred to? **We noticed in Fig.3 an increased meridional gradient of geopotential height, also reflected in the positive upper-level zonal wind anomalies at 250hPa. We will further explain the connection between the two in the text.**

12. Line 268. The process described with enhanced tropical convection and a negative vorticity anomaly matches that described by Sardeshmukh and Hoskins (1988, J. Atmos. Sci.) for the so-called Rossby wave source. It would be good to cite that paper. **We will add the reference to the suggested position, thanks for pointing it out: it indeed is the basis to describe the physical mechanism involved.**

13. Line 300. I assume that the authors are referring to Fig. 3d not Fig. 3e. **Yes, thanks a lot for spotting this typo and allowing us to correct it swiftly.**

14. Figure 7. Since a statistically significant MJO is found at positive lags, and CRWP2 shows anomalies in geopotential height at lower latitudes, it is possible that CRWP2 is exciting the MJO. This isn't surprising since many papers have shown results suggesting that

the MJO can be triggered by midlatitude disturbances. **Thanks for pointing this hypothesis out, we will add it to the text together with a few references to support it.**

Bibliography

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