In black: original response

In blue: changes in manuscript

To both referees:

Thank you to both referees for their constructive comments on the manuscript. A shared critique was the absence of literature regarding the topic of moving atmospheric blocks. The papers mentioned by both referees are of great help and will be used to strengthen the background of the present study and to place it in a better scientific context. Below, answers to specific comments made by the referees can be found.

Response Anonymous Referee #1:

1. Misunderstanding of the quasi-stationarity of blocking.

We will include more information on how we interpret quasi-stationarity. The three classifications named in the referee's comment are already included in our introduction (see l. 37), but we can expand on this more. In a lot of papers where the blocking index of Tibaldi and Molteni is used, a Eulerian framework is applied, which does not allow analysis of any dynamics in the blocking system. This is the view we wanted to challenge in this study, combined with an impact driven view for which it is more intuitive to look relative to the impact location.

- Definition of quasi-stationarity is better explained in 2.4

2. The description on "To our knowledge, no studies have considered the effect that the propagation velocity of atmospheric blockings has on our weather" is not correct. […] Please the authors read these previous papers

Thank you for providing these papers. We did not find these when we were looking for papers on the movement of atmospheric blocks. We will include them to improve the background and scientific context of the paper.

- Papers reverenced by the reviewer are added in the introduction

3. What is the difference between the author's results and previous results?

The most robust feature we see is that stronger westward retrogression is more often seen with blocks with a large blocking size. This is not in contradiction with Luo et al. who state: "When atmospheric blocking is stronger, it shows less eastward movement, larger zonal scale or blocking size and slower decay (Zhang and Luo 2020)". It is reassuring that these results are also found for the GCM ensemble studied here. Furthermore it is very interesting to read that the PV framework is able to explain the results, in terms of underlying properties, e.g. that a weak meridional PV gradient may support long-living 'blocking' features.

4. […] Thus, I do not think that the results based on the 2D Cell-tracking algorithm are correct.

In our approach a blocking 'object' is defined as an atmospheric feature meeting certain characteristics. These definitions are widely applied in literature to diagnose blocking. As such our blocking objects have a zonal velocity, defined as the propagation speed of the center of mass. This pragmatic approach is indeed quite different from a more fundamental wave-theoretical framework in which blocking is defined in terms of interaction of underlying atmospheric waves. In the revised version we will point out these different viewpoints such that no confusion can remain.

- More information in introduction

5. The unit about the zonal propagation velocity of atmospheric blocking. The zonal velocity of Rossby waves is expressed in the unit of "m/s". Thus, I suggest that in Tables 1-2 and Figs. 4, 9, the unit "km/day" should be changed into the unit:"m/s".

The referee suggests to adjust the units of km/day to m/s to align with previous studies. We originally chose to use the unit of km/day, as it gives a better indication of the total distance covered by the block during its lifetime. We do agree that it may be confusing with the more generally used m/s. We will decide on whether we will use both units together or solely use m/s from now on.

- We changed all units to m/s

6. There are different zonal movement speeds of atmospheric blockings in different region. The authors should calculate the zonal propagation velocity of atmospheric blocking by dividing the Northern Hemisphere into three (five) regions in winter (summer) according to Fig.2. Unfortunately, the authors did not discuss this issue.

We discussed the differences in zonal movements speeds in different regions in Figure 6, where we show the spatial distribution of blocks depending on their propagation speed. In this study, we aim to keep a global view on atmospheric blocks, while still showing regional differences by using figures like 2 and 6. We suggest to remake figure 4 based on different zonal regions on the northern hemisphere and comment on any differences we find in the supplements.

- We remade figure 4 for two sections of the world, but the results were not very different. We added them in the supplements (figure S11 and S12).

7. Line 183: The authors should clearly describe what do the 10th, 50th, and 90th percentiles mean.

The percentiles are calculated per blocking characteristic. They show the 90th, 50th, and 10th percentile of e.g. size per velocity interval, and similar so for the duration and intensity. We will add some information to the text to make this clearer.

- We described the percentiles more in section 3.2 and figure 4.

8. Please explain why the large blocking size tends to be westward-moving and why long-lived or large amplitude blocking tends to be eastward-moving in Fig. 4.

The westward movement is in line with Rossby wave propagation theory. The longer-lived and more intense blocks fall in the quasi-stationary range, with zonal velocities tending toward the east. We do not have an explanation for the last group of eastward-moving large amplitude blocks, as we are still trying to understand this phenomenon.

9. I do not think that the results in Fig. 6 are correct. I do not understand why summer eastward-moving atmospheric blocking events are more frequent in high-latitudes. In contrast, winter eastward-moving atmospheric blocking events are more frequent in the relatively low latitudes.

To start, the frequencies are normalised, so direct comparison in their absolute numbers is not possible using this figure. Our hypothesis for the difference between summer and winter is the absence of a mean jet during the summer, while this is present during winter, combined with the shifting minimum latitude of the high-pressure belt with the seasons. We can add a figure to the supplements showing the mean jet using Z500 mean geostrophic velocities. We can also add the total number of blocking events in the upper right corners of each subfigure of Figure 6.

- We added the description above in section 3.4

10. In the conclusion section, the authors should also strengthen some comparisons with the previous similar studies.

We will add the studies provided by the referee for comparison in the conclusions.

- We added the provided studies in the conclusion

Response Anonymous Referee #2:

<u>*Introduction:*</u> *The authors derive average velocities of the blocks of about 3.5 m/s (300 km/day) which is still much smaller than the typical synoptic scale wind speed of U=10 m/s. From the introduction, the reader gets the impression that the velocities of the block are much higher so that the quasistationarity assumption does not hold. Please clarify.*

In Table 1 we find that absolute zonal mean velocity is approximately 300 km/day or 3.5 m/s. The majority of the blocks have velocities around this value and are categorized as quasi-stationary. However, the 10% fastest moving blocks in both directions exceed the 10 m/s (>864 km/day) and therefore are classified as eastward- or westward moving blocks. We will add the absolute velocities where we now use percentiles to make this clearer, and check the introduction to see where these assumptions are not stated well enough. We think the title might contribute to the confusion, as it is maybe too generally stated.

- We added absolute velocities where first only percentiles were given and we changed the title. We also tried to nuance the explanation on quasi-stationarity.

<u>Section 2.1 and 2.2.:</u> *Out of curiosity from my side: What method do you use to regrid the data? Is smoothing applied, too? What is your motivation to use these two datasets?*

The motivation for the ECE3p5 and ERA5 datasets is that ERA5 is broadly accepted as the most suitable reanalysis dataset for the midlatitudes on the northern hemisphere, where its biases are limited. The ECE3p5 is the in-house variant of EC-Earth3 and corrected for its biases in the northern hemisphere. We assessed the ability of ECE3p5 to accurately represent atmospheric blockings. The data was regridded using bilinear interpolation with additional smoothing. We will add this to the methods.

- We added extra explanation to sections 2.1 and 2.2

<u>Section 2.3:</u> *Your method has a lot of thresholds at several places. How much are the results depending on these settings? Please check that you explain all variables. In the equations you sometimes use t as a coordinate and in other equations d, I assume that it is time in both cases. Why do you change the nomenclature?*

Using "t" and "d" was a typo, as both should be "t" for time. We tested the dependence on the minimum latitude. Results for this are shown in the Supplements. All other threshold follow from the studies cited in this section.

- We fixed the typos in section 2.3

<u>l. 113/eq. (7): *Please explain in more detail the meaning of BI? How can wie interpret the values of BI.*</u>

<u>*l.117: Relating to my former comment: What is the meaning of the different thresholds? Can you give idealized examples?*</u>

The phi underneath eq. 7 is a typo and should not be here. It has not been taken into account in our calculations. The definition of the blocking intensity follows from the paper of Wiedenmann et al. (2002). It is a diagnostic for the relative strength of large-scale flow regimes within blocking regions. The thresholds we used for weak and strong blocking events also come from the paper of Wiedenmann et al. (2002), who based the categorisation on which blocks were within and outside of one standard deviation of the 30-year mean intensity of their dataset. We will add some examples of blocks falling within the different categories.

- We tried to explain blocking intensity better in section 2.3

l. 119/fig. 2: *You speak of blocking intensities, but the figure shows frequencies. Please explain.*

This is a mistake, thank you for noticing. We made two versions of this figure: one with the intensities, and one with the frequency of blocked days, which were exchanged. It should be "Mean BI [-]" and we will change this for the next version.

- We fixed this mistake

Section 2.5: *How would your results change if you used maximum or minimum temperature instead of mean temperature?*

We expect using minimum and maximum temperatures would have the most impact in summer for the maximum temperature, as temperature differences between day and night are larger in summer compared to winter. In winter, the minimum temperatures are probably lower. We think this will result in similar patterns, but likely with larger temperature anomalies. We did prepare the minimum and maximum temperatures and could make additional figures for the supplements if needed.

Section 3.1: *How do you define the size of the blocking high? By summing up the grid points? How are winter and summer defined?*

The size of the blocks is defined by the sum of the gridpoints, converted to km^2. This is explained in l. 135-138 and eq. 8. Winter and summer are defined as December-January-February, and June-July-August respectively. This is explained in l.142-144.

Table 1: *I would recommend to additionally give the velocities in m/s since it then could be more easily compared to the standard assumption of U=10m/s on the synoptic scale.*

See answer on AR1, Q5.

- We changed all units to m/s

Section 3.2: *How do you define westward/eastward propagating and quasistationary systems. Please give a clear definition. I am very confused how many systems are in which category and if you define these by certain thresholds or by percentiles. If you use percentiles, please also add the according velocities per category.*

We defined the westward, eastward, and quasi-stationary blockings based on percentiles. We defined $v_x \leq P10$ to be westward moving and $v_x \geq P90$ to be eastward moving. Everything in between $P10 < v_x < P90$ we defined as quasi-stationary. This division was made separately per season. This is explained in section 3.4, but we will check if this needs to be replaced to earlier in the text. We will add the absolute velocities with the percentiles.

- We added the absolute velocities everywhere and added grey shaded areas to figures 4 and 7 to better indicate the different blocking systems.

Fig. 4: *Can you please add a contour to the frequency shading that represents the percentage of systems: for example does the second blue shading already contain 50% of all systems? If this is not possible at all, please add the probability density distribution or a histogramm of the velocities. I still wonder how many systems are slowly moving and how many systems are faster moving.*

Thank you for this suggestion. We will try to make this clearer in the figure.

- Instead of adding contours, we went with the solution of adding grey shading, as stated one comment above this one.

Fig. 5: *Some of the data is cut of in the left figure. The 15 day rolling mean is impossible to see, please use a different color, e.g. black, for these lines.*

We will adjust the figure for the cut-off data and change the colour of the 15-day rolling mean to black for better visibility.

- We fixed both the colours and the framing of the figure

l. 235: *Are these the values of the 15 day rolling mean?*

These are the mean values over all blocks and ensembles per day, and not their 15 day rolling mean. We will clarify this in the text.

- Added clarification

Fig. 8: *the 40 degree times 80 degree is latitude-longitude, correct? Can you please add composite geopotential height lines here. This could also give you some information on blocking type.*

Yes, the 40x80 is the latitude x longitude. This is a good idea to add the geopotential lines. We will try to add them to the figure.

- We added the z500 lines in figure 8

Table 2: *For the velocities there seem to be very long tails. I would recommend to either add more percentiles (5%,10%, 90%,95%) or add a figure showing the probability density function. See also my comment regarding Fig. 4.*

It is true that the tails are long. If we would add more percentiles to the table, we would also have to add more percentiles to Figure 8 to match. In this figure, you can see that the differences in effect on the temperature is not as large as the jump in velocities. Therefore, we do not think that adding more percentiles to the figure would be beneficial. To option of adding a histogram to Figure 4 is probably more intuitive.

- We changed the percentiles from 0-20-40-60-80-100% to 0-5-10-90-95-100% in figure 8 and added information to table 2.

l. 351: *over 2x*

We will remove the double “over”.

- We fixed this typo