Answer to Reviewer #1

1 General Comment

This manuscript presents a statistical analysis of blocking in part of the Northern Hemisphere with a focus on the North-Atlantic European region. Using a set of reanalysis data, the authors investigate blocking frequencies and their trends during the period 1990-2019. The study applies a novel method to assess blocking based on the detection of centers of vorticity; this method allows one to distinguish two different types of blocking and to consider the transitions between them.
The paper is a welcome contribution to the discussion, since blocking and related trends are important topics in our science, and in the end it would be desirable that the results will be published. By the use of their specific methodology, the authors are able to quantify a few novel aspects which would be hard to address using other methods. At the same time there is a number of issues which I think should be sorted out before the manuscript can be published.
We thank the reviewer for carefully reading our manuscript, and for the constructive comments. In the following we will respond to the comments and point out any changes we intend to make. The line numbers and figure references in the reviewer's comments refer to the original manuscript. The reviewer's comments are in black italic; our responses are in blue.

2 Major issues

Statistical significance

In several of the figures I was missing a quantification of the statistical uncertainty (e.g., Fig. 6, Fig. 9). In my eyes all results must be tested with regard to their statistical significance.

Thank you for this hint. We agree that all results need to come with an uncertainty estimate. Figure 6 and 9 were meant to give an overview of what can be seen directly from the data (counts and duration), no conclusion was meant to be based on these figures. However, in the revised version, we use Fig. 6 to demonstrate the sensitivity of our blocking identification process, see example below in Fig. 6. To this end, we point out, that we aim to detect the blocks in a Lagrangian sense. Therefore we need to ensure, that blocks identified in consecutive time steps represent the same system, more precisely that the high is the same as in the previous time step. To ensure this coherence, we introduced a minimum distance criterion between the locations of the high center in two consecutive time steps. This distance criterion was set to about 1000 km in our initial submission. In the revised paper, we will estimate the uncertainty of the method based on 10 additional identification procedures that just differ in this distance criterion. We will describe the method more detailed in the revision.

With respect to Figure 9, we now show uncertainties associated with estimating the occurrence probabilities of a binomial/multinomial process, Fig. 9

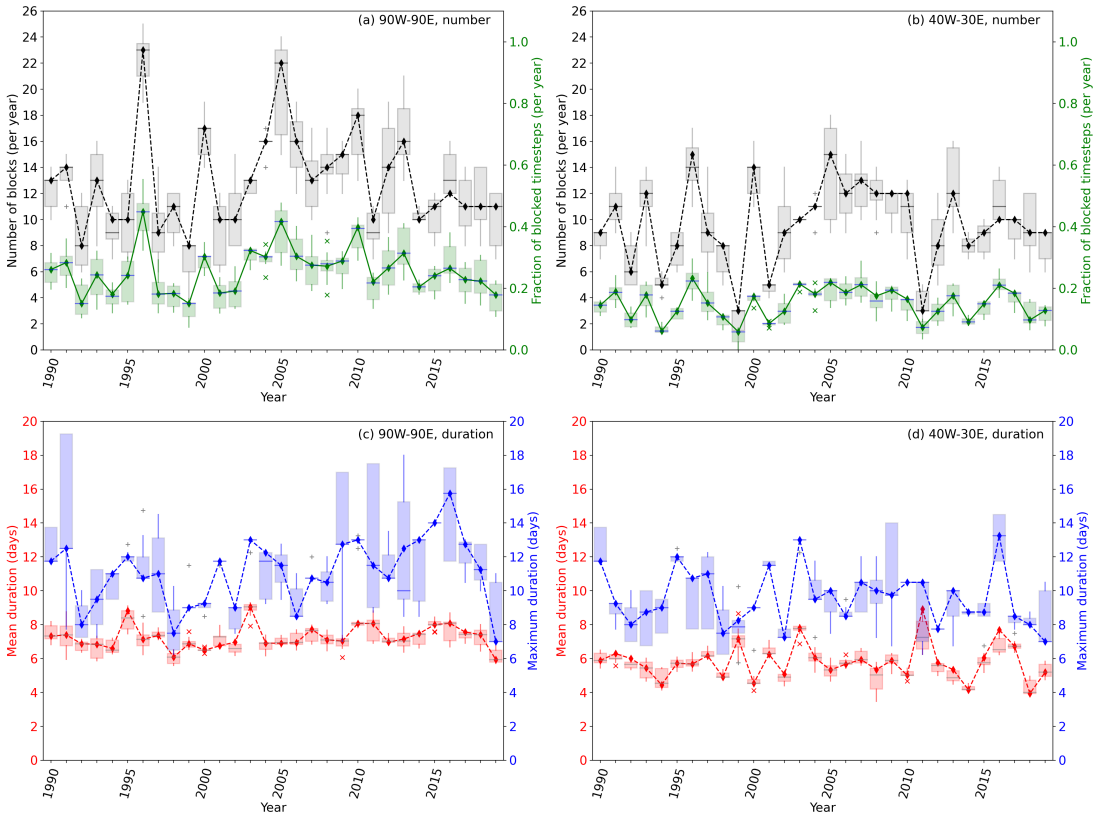
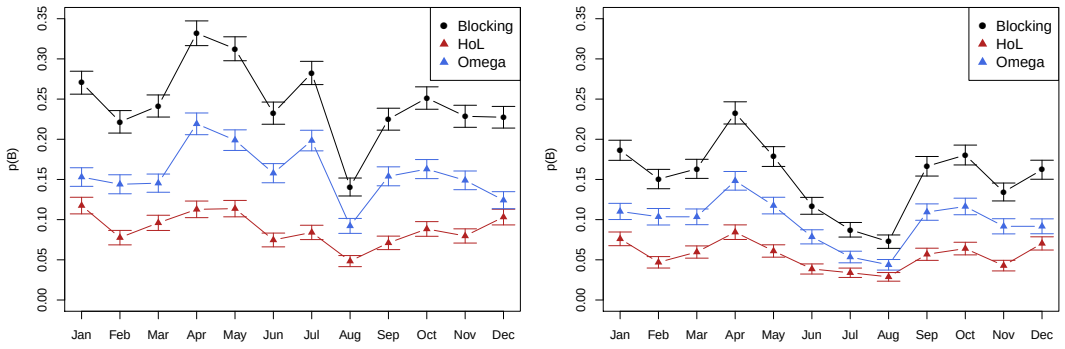


Figure 6: Sensitivity study of the blocking type detection method. Boxplots show the distribution of the annual number of blocking events and fraction of blocked time steps (top) for 10 different settings of the minimum distance criterion for the whole domain (90°W to 90°E) (left) and for Euro-Atlantic region (40° W to 30°E) (right). The lower two panels show the associated distribution of mean and maximum duration.



(a) 90° W to 90° E

(b) 40° W to 30° E

Figure 9: Blocking probability estimated for individual months for blocking in general, as well as separately for *High-over-Low* and *Omega*. (a) whole domain ($90° W$ to $90° E$) and (b) Euro-Atlantic subsection ($40° W$ to $30° E$). Whiskers shows 95% confidence intervals assuming Gaussian asymptotics for estimating binomial probabilities.

In some other plots the authors provide a range of statistical uncertainty, but I could not find out how this was determined and what assumptions were underlying this estimate. I think that the authors need to explicitly describe (in the methods section) how statistical uncertainty was determined.

Thanks for the hint! We estimate occurrence and transition probabilities using binomial and multinomial logistic regression realised in the framework of (vector) generalized linear models fitted with iteratively reweighted least squares Yee [2015] as mentioned in our section 3. Confidence intervals are derived based on the assumption of asymptotic normality of the likelihood-based estimator, i.e. $[\hat{\theta} \pm 1.96\,\sigma_{\hat{\theta}}]$. We state this now accordingly at the end of section 3.5.

In the main section (section 4) the authors discuss the results irrespective of whether they are significant or not. In several places they seem to draw firm conclusions from results which are (as the authors say themselves) not statistically significant. It think that this is not good scientific practice. Rather, only those results that are statistically significant can be considered as "results" and should be discussed and used (for instance) to test hypotheses etc. Marginal statistical significance occurs in the present case when breaking down the results to individual months or seasons in section 4 (e.g., Fig. 16). In particular, in the summary section the authors should only refer to those results which are statistically significant.

Thank you for this comment. Especially regarding the discussion, we now mainly consider significant results and if not, we marked that the results are not significant. We only show non-significant results, if they were our motivation for further studies (e.g. looking for seasonal dependence on blocks instead of years). We moved Fig. 13 and Fig. 14 with non-significant results into the supplementary material.

Better motivation

It would be desirable if the authors can provide a better or more explicit motivation for their work and, especially, for the specific method that they chose to use. What is the advantage of their method in comparison with the many other methods that have been used in the past? What specific questions can one address that previous authors were not able to address? Why are those questions important? One possible avenue for improvement into that direction would be to formulate an interesting hypothesis and test this hypothesis with the analysis.

Lacking a more explicit motivation, the reader is somewhat left in the limbo as to what one is supposed to learn. One can always invent a new method an apply that method to reanalysis data in order to produce "results". But without further comment it would not be clear to what extent these "new" results are important or relevant. To be sure, I believe that the authors are able to provide such an improved motivation. In fact, some material in this direction is scattered throughout the text. I just urge the authors to collect this information and illuminate it in a more explicit fashion.

These are very valid points. We now give a clearer motivation. The first central and innovative point in our analysis is the possibility to distinguish between High-over-Low and Omega blocking. Knowledge about trends in these two blocking types can have immediate impact on the trends of the associated weather phenomena such as heat waves, cold spells or extreme precipitation events. Although we do not study these impacts, our method and analysis clears the way for further studies regarding the associated or underlying processes. Therefore, we included in the discussion the following paragraph: *As a novel aspect we introduced a blocking type decision method, that identifies* High-over-Low *and* Omega *patterns for each blocked time step, separately. Blocked weather situations are usually analysed with respect to the persistent high pressure area, which might lead to droughts with devastating consequences. Additionally identifying the low pressure system allows for further studies on the impact of the steady low pressure systems such as heavy rainfall and floods. In this way, we could tackle the first question in the introduction, if we find a method to automatically distinguish between the different atmospheric blocking types,* High-over-Low *and* Omega *block.*

Second, we formulate appropriate statistical models to describe trends and tendencies of occurrence and transition probabilities. We assume binomial (blocking/no-blocking) and multinomial (HoL, Ω, no-blocking) processes and use vector generalized linear models with iteratively reweighted least-squares to estimate the associated probabilities and

trends together with their uncertainty.

The Markov-Chain as model for onset, decay (offset) and transitions between states are the third innovative point giving insight into the dynamics of blocking states. As last point, we consequently break down the analysis from annual over seasonal to monthly probabilities to demonstrate shifts in the seasonal cycle although overall annual probabilities do hardly change.

Moreover, we motivate our work with three main questions posed in the introduction and to be addressed in the discussion section:

1. Can we find a method to automatically distinguish between the two atmospheric blocking types High-over-Low and Omega blocks?

2. Do blocking occurrence probabilities undergo long-term changes? Do these changes depend on season or month?

3. Do onset, decay or transition probabilities from one blocking type to another undergo long-term changes? Do these changes depend on season or month?

What are the true results?

This issue is related to the previous one. In the discussion section (which is partly just a short version of section 4) the authors mention a few caveats and sensitivities, but the reader is not told whether and to what extent these have an impact on the results. In other words, which of the results are true results and which are only consequences of the specific method that was applied? For instance, transition probabilities depend on the temporal resolution of the underlying data, so the specific value of the probability cannot possibly be a "true result". Similarly, the discussion provides the statement that different methods yield different numbers. My question would be: which of the results survive a change in the method? More broadly speaking: what is this paper's unique contribution to the topic? The devil's advocate would argue: "Well, you are using a novel method to investigate a problem that has been studied often times before; your results differ to some extent from previous results and many of your results are statistically insignificant". I am sure the authors have a good reply to such a provocative statement.

Again, I think that there is a unique contribution to the topic from this paper, I only say that this must be worked out more clearly.

Thank you for this comment. You are right that the discussion has mainly been a short version of Section 4. We removed the summary in the first paragraph and reordered and rewrote the discussion. Thereby, we mainly discuss significant results and mention explicitly, whether a result is significant or not. As mentioned before, the main advantage of this study is the ability to automatically distinguish between the two blocking types *High-over-Low* and *Omega* block.

We further address your concerns by carrying out a sensitivity study on the method detecting and distinguishing the blocking types, see Fig. 6 above.

3 Minor issues

- *Quite a number of minor issues are added as comments to the pdf of the manuscript.*
  Thanks, we added the comments from the pdf-supplement below and answered them point-by-point.

- *Sections 5 and 6 are partly redundant. For instance, large parts of section 5 repeat what has been said in section 4. What's more important: the summary section should not simply be a shortened version of the results section; rather, the reader expects a summary (plus discussion) on a higher level of abstraction.*
  Thank you, we agree! For the revised manuscript we have already restructured the discussion and we will revise the conclusion, highlighting the main results and their possible explanations.

- *In some parts of the text the quality of the English could and should be improved. Please also note the supplement to this comment: https://wcd.copernicus.org/preprints/wcd-2020-62/wcd-2020-62-RC1-supplement.pdf*
  We will carefully reread the text and try to improve the English. We will answer your supplement comments, too, in the following.

Minor comments from the supplement

l. 14: not very idiomatic English ...
We rewrote the sentence: "A Markov model determines the probability of transitions between different states by taking into account the actual time step only while neglecting all previous ones."

l. 33: By the time this paper will be published, the years 2018 and 2019 will not be the past two years any longer.
Thank you for the hint, we have adjusted it accordingly.

l.45 ... but that's a very special form of "discretization". It may be misunderstood by some readers, because what comes to one mind in first place is that discretization means that the PDE is discretized by standard numerical methods ...which is probability not what you mean here.
Thanks for pointing this out! The point vortex formulation is based on a Langrange'ian view on a system of vortices. A vortex is represented completely by its location and

its circulation. The vorticity at these points goes to infinity, while the vorticity is zero elsewhere. Hence the term "discretized". We will clarify the statement in the text.

l.66 "Transitions between ..." This sentence does not connect well to the previous two sentences.
We tried to create a better connection to the sentence before.

l.76 .. but if the typical time scale of blocking formation etc. is much longer than 6h, then the novelty of this work (e.g. the 6 hourly time resolution) seems rather irrelevant...
The typical time scale of a long-lasting blocking event is about 5 to 7 days. However, we observe in our work, that within this time span, the blocks change between the High-over-Low and Omega blocking type. In our opinion it is very relevant to study these blocking type transitions as well as their trends since the weather associated with blocking can have a high impact. For example high precipitation events can occur that are typically associated with the lows of the blocking pattern. The location of the low(s) relative to the high determines the blocking type of course.

l.78 The science questions should be worth a little more elaboration, they are important but not very clear at this point
We have reconsidered and reformulated the scientific questions and tried to better integrate them into the introduction. We will then analyse our three main questions in detail in the discussion.

l.94 You are probably talking here about zero horizontal divergence, right? In this case this is NOT synonymous with "incompressible" flow, because the latter only implies zero 3D divergence.
Yes, your right. The point vortex model is a two-dimensional vortex model. Large-scale synoptic flows are quasi-two-dimensional and 2D flows are – due to mass continuity – equivalent to zero horizontal divergence. We will clarify this in the text!

l. 108 Do you mean "longitudinally-dependent"?
Yes, that is correct. The value of the central reference blocking latitude (CRBL) depends on the longitude. Thanks!

l. 114 unclear how this "shift" works in practice.
The variable *Delta*, which indicates the shift, is described in Richling et al. [2015] as a positive value [in deg_lat] for a possible latitudinal northward and southward shifting of the central reference blocking latitude (CRBL). A more detailed explanation can be found in Richling et al. [2015] in Section 2.1, where in equations (3) - (5) to calculate Φ_N, Φ_M and Φ_S *Delta* is applied. With the help of these latitudes, the geopotential height gradients on the northern (GHGN) and on the southern (GHGS) side of the CRBL can then be determined (Eq. (1) and (2) in Richling et al. [2015]) .

l. 128 resembles a box shape ...?
In a regular latitude-longitude projection or in a Mercator projection of the field, a high-over-low blocking can be approximated by a square (or a box), where the poleward side of the square surrounds the high and the equatorward side the low. We will rephrase the sentence to make it a bit clearer.

l. 134 v is the two-dimensional horizontal wind here, right? It would be good to say this explicitly.
Done.

l. 139 What does it mean to set a grid point to zero?
We will try to clarify this in the text. We now wrote in the revised manuscript: "On the other hand, all grid points with values of $W_k \leq 1$ will be set to zero to obtain a field of vortex patches. This field of vortex patches can then be multiplied with some field of interest, e.g. the vertical vorticty field. In this field, we search for the high that lies closest to the longest-blocked IBL."

l. 140 how exactly do you define "longest-blocked IBL"?
The IBL detection method gives a time- and longitudinally-dependent field $IBL = IBL(t, lon)$ of "1" and "0", where "1" stands for blocked and "0" for unblocked longitudes. A simply-connected "field" of "1" in this Hovmöller-like representation of the IBLs can then be studied regarding the duration each single IBL is blocked in a row. We count these time steps for each IBL. For example, if the IBL is blocked for 5 time steps in a row, it is labeled with a 5, etc. The IBL with the highest number is called the "longest-blocked IBL". We will clarify this in the text.

l. 141 Again, not clear how a dipole is enclosed by a box shape, neither how you maximize the trapezoid.
Thanks, we will add more text to clarify the procedure. However, the method is more detailed described in Hirt et al. [2018]. The main difference between Hirt et al. [2018] and the method used here is, that the decision which blocking type we have is done at every time step. Please take also a look at our example movie in the supplementary material, which shows nicely the transition between an *Omega* and a *High-over-Low* block.

l. 145 How did you determine the box?
The box surrounds the high. In a regular latitude-longitude block or a Mercator projection of the atmospheric fields, a *High-over-Low* can be approximated by a square that encases the poleward high and the equatorward low. We will add more meat to the text describing the method.

l. 146 What are "the circulations" of a pattern?
We will describe this in more detail in the text. In point vortex theory, each vortex has three important properties: its coordinates in the plane and its circulation $\Gamma = \int \zeta_d A$

with ζ: vertical vorticity and A: the vortex area. The circulation of a vortex can be interpreted as the global strength of the vortex and is a conserved quantity for 2D, inviscid flow. Each point vortex induces a circular velocity field around its location whose strength depends on its circulation and falls of with r^{-1} the distance r from the center. The motion of a point vortex is given by the sum of the velocities generated by all the other point vortices in the plane. Nummerically, the circulation can be determined for each grid point by multiplying the area associated with the grid point with the vertical vorticity at this grid point. The total circulation of a "real" vortex is then determined by summing up all grd points associated with the vortex. For example, for the high in our case, we sum up all grid point circulations that have a negative vertical vorticity value in the earlier described vortex patches field and that lie within the shape (trapezoid or box). We will add a clarifying picture to Figure 3. Moreover, for the principles of point vortex dynamics and its applications to atmospheric flows as well as details of the trapezoid method we refer to our previous works, e.g. Müller et al. [2015] and Hirt et al. [2018].

l. 155 Not clear how you arrived this criterion.
We will either try to add a clarifying picture to Figure 3 or add more text here.

Subcaption Figure 3: "The positive vorticity is calculated...." What is "the positive vorticity"?
We mean positive vertical vorticity, i.e. $\zeta > 0$. We will clarify this in the caption of the figure.

Subcaption Figure 3: The reader probably does not care what software you used to produce these plots.
Probably not. However, the journal usually wants to know if the there are any copyrights on the maps. That's why we added the software statement. We will ask the editor, if we can delete this information.

Figure 6: What is the level of statistical confidence of the data in these two plots?
For the two regions shown, we have only looked at the absolute numbers of blocking, mean and maximum durations in order to get a first impression of the identified blocking events with the help of our method and to recognise differences in the regions. Uncertainties can certainly be estimated for these numbers, but many steps are necessary in the method to obtain the blocking state. We will do some tests to estimate the uncertainty of the method.

l. 284 Are these (weak) increases statistically significant?
No, they are not. We decided to rewrite the results concerning Figure 6 and rather test for the uncertainty of the method explicitly.

Figure 7: How did you determine these confidence intervals?
We have added a short description in the method (Section 3.5) that explains in more

detail how we determined the confidence intervals for Fig. 7 and all subsequent figures.

l. 318 But not really statistically significant....
Yes, you are right. The small increase in the summer month (Fig. 8c) is not statistically significant, but the increase in Fig. 7b is significant for the summer.

l. 377 "offset" is very peculiar terminology in the present context, I would prefer "decay".
We can understand this argumentation, but will nevertheless stick with the term "offset". From a meteorological point of view, the use of the word "decay" describes the transformation from a blocked state to an unblocked state with the right words, as it is a process. In our work, we focus on the model view, in which there is only the state "on" or "off". Therefore we use the term "offset". However, when introducing the terms "onset" and "offset", we will add a sentence that addresses the underlying processes of the formation and the decay of a blocking.

l. 391 It seems that none of the trends in Figure 13 are statistically significant...
Yes, you are right. We have shown Fig.13 and Fig. 14 in our first draft to give an overview of all analysis and especially to visualize the results for the two transition matrices of Eq. 11 and Eq. 2. Now we decided to shift these two figures to the supplementary material and only show results for the 3x3 transition matrix.

l. 407 It seems somewhat problematic to discuss results that lack of statistical significance.
Thanks for pointing this out. We will try to only discuss statistically significant results. However, the matrix plots (Fig. 13 to 16 in the first manuscript) represent an entity. So we do not want to delete single subfigures. However, we decided to transfer the statistically insignificant figures (Fig. 13 and 14) to the supplementary material for the sake of completeness of the analysis.

l. 414 Again, if the result is not significant statistically, you should probably refrain from discussing it.
We will check everything in the results, discussion and conclusion sections and only focus on the statistically significant results.

Figure 14 Where is the color bar explaining the different colors?
Yes, we had forgotten the color bar in Fig. 14 and also in Fig. 16, which we have now added.

l. 424 investigations...are evaluated. [strange language]
The discussion section was completely rewritten. Hence, this sentence no longer exists in the revised script.

l. 430 Fine, you show the results, but some of these results are not statistically significant. I wonder what we learn from that.
We moved Fig. 13 and 14 to the supplementary material and will point out more clearly which the important and significant results are and what we can learn from them.

l. 432 Did you verify whether this increase is statistically significant?
No, we did not. It seems to be statistically insignificant and hence, we will remove this statement from the text. Thanks for pointing this out!

l. 443 Can you resolve this apparent contradiction between their results and your results?
One point is definitely that our methods are different. In our case, we search for a coherent blocking structure, that needs to have a minimum lifetime of 5 days (in the larger region) and should be composed of the same high (lows are allowed to change in time). Our initial IBL identification is moreover only a one-dimensional method. In Brunner et al. [2017] the identification of blocks is done with a two-dimensional blocking index. Blocks are long-lived (at least 5 days) and synoptically large ($\pm 7.5\circ$ longitudes). However, a blocking is counted whenever at least one of these blocked grid points is within the Euro-Atlantic region ($45°$–$72.5°N, 30°W$–$45°E$). In our case, at least half of the block, more precisely the circulation centroid, needs to be inside the Euro-Atlantic region (40W-30E). Summarized, there is no easy answer. We will do more tests and try to answer your question! Thanks a lot! This is also relevant for our discussion section.

l. 451 So to what extent do these caveats have an impact on your results?
We will try to do additional tests in the revised manuscript to estimate the impact!

l. 480 This number in itself does not make any interesting statement itself (because it depends on the temporal resolution of the underlying data)
Thanks, we added a time interval (6 hours) here.

l. 518 Where is the verb in this sentence?
We deleted this sentence.

l. 521 proportion of what?
Thanks. We rephrased the sentence: "While in July *Omega* blocks account for only about 25% of all observed blocks in 1990, we find on the one hand an increase in the number of blocks in general as well as a higher fraction of Omega blocks towards the end of the study period."

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Answer to Reviewer #2

Detring et al. present an analysis of long-term blocking changes over the past 30 years in the Northern Hemisphere. Using a novel method based on the kinematic vorticity number, the authors distinguish between long-term changes of Omega-blocks and High-over-low blocks. Though a general change of the blocking frequency over the 30 year period is not found, the authors identify pronounced changes when investigating trends on a monthly or seasonal basis. A key outcome is that Omega blocking is more likely to occur and to be more persistent than the High-over-Low blocking pattern.

To understand the changes/trends of blocking is an important topic in our science. Thus, the analysis is timely and the topic is likely to be of interest to the readership of WCD. However, there is a number of issues which need to be addressed before the manuscript can be published.

We thank the reviewer for carefully reading our manuscript, and for the constructive comments. In the following we will respond to the comments and point out any changes we intend to make. The line numbers and figure references in the reviewer's comments refer to the original manuscript. The reviewer's comments are in black italic; our responses are in blue.

Most important comments

1) *At many places trends/long-term changes are reported. However, most of the times, statements concerning the statistical significance of the results are missing. Further, the computation of the confidence intervals is not explained so that it remains unclear which of the results are "real" results. Investigating and commenting on the significance is particularly important since some of the results are likely to be based on small sample sizes. For example, it is reported that 13 (10) blocks occur per year in the large (small) domain. When breaking this down to a monthly basis the average number of blocks per month decreases to 1-2.*

   We estimate occurrence and transition probabilities using binomial and multinomial logistic regression realised in the framework of (vector) generalized linear models fitted with iteratively reweighted least squares [Yee, 2015]. Confidence intervals are derived based on the assumption of asymptotic normality, i.e. $[\hat{\theta} \pm 1.96\,\sigma_{\hat{\theta}}]$. We state this now accordingly at the end of section 3.5. Figure 6 shows the number of blocking events, an event last minimum 5 days, i.e. $5 \cdot 4 = 20$ time steps. In the following, we use the number of blocked time steps which is on average 24 time steps and thus the number of events is not as small as it appears from Fig. 6. In principle, a small number of events is not a problem for the binomial or multinomial model. However, the likelihood-based estimator can indeed be biased for small occurrence probabilities but here we are not in a critical range [cf. King and

Zeng, 2001]

2) *The trends inferred from the logistic regression approach are quite pronounced when considering individual months. For example, the logistic regression suggests that the probability of omega blocks during February has increased by a factor of three over the past 30 years. To better compare these results to the "observations" it would be beneficial if the actual numbers of blocked time steps were included in the corresponding figures. For example, vertical bars (in the same colours as the modeled probabilities) showing these numbers could be included in the panels of Fig. 8.*

You are right, there are few events that are used in the regression on a monthly basis. Nevertheless, due to our temporal resolution of 6 hours, each blocking consists of at least 20 time steps that are taken into account in the models (see also previous answer). It can be seen in Fig. 7 (initial manuscript) that an annual view shows no significant change in blocking (black line), but a split into seasons (coloured lines) does. To get an more detailed overview of the blocking probability for the individual months, we calculated the probability for every year for every month. This is shown as boxplots in Fig. 1 below for the whole domain. This figure shows that there are several month with only a few blocked time steps and others with quite a lot blocked time steps. This analysis is shown for blocking in general (upper panel) and *High-over-Low* and *Omega* blocks (lower panel). In addition the total number of blocked years for every individual month are shown as a line. We will include this Fig. 1 as well as the corresponding figure for the Euro-Atlantic sector ($40°W$–$30°E$ in the supplementary material.)

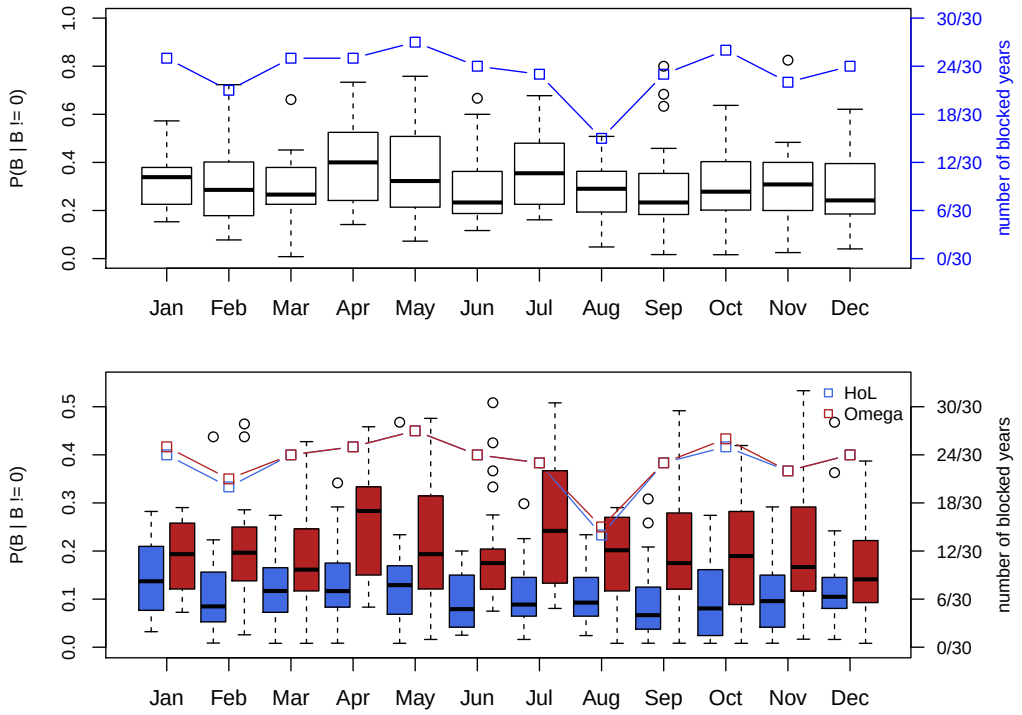

Figure 1: Boxplots for blocking probabilities estimated for individual months for blocking in general (upper panel), as well as separately for *High-over-Low* (blue) and *Omega* (red) (lower panel) for the Northern Hemisphere (90°W–90°E)). The probability is calculated for each year under the assumption that there is a corresponding blocking (*B, HoL, Omega*) in that year in the respective month ($P(B \mid B \neq 0)$). The absolute number of years in which a blocking occurred in the respective month is also given as the lines.

3) *A focus of the study is on observed blocking trends. However, references to related studies are missing in the introduction (Section 1). To put the results in context to previous studies, I strongly encourage the authors to provide information on observed trends found in other studies. To avoid an excessively long introduction, the discussion of weather regimes and Grosswetterlagen could be shortened considerably.*

Thank you very much for this very valid comment. We will rewrite the introduction to include literature on blocking trends. Moreover, we will try to shorten the paragraph on *Grosswetterlagen*, as suggested.

4) *The discussion in Section 5 is in large parts a repetition of Section 4. Many results are listed so that it is difficult for the reader to really identify the key outcomes of the study. In my view the discussion part would improve considerably if the authors formulated the key outcomes of the study more clearly and discussed their broader implications. For example, three key questions are raised in Section 1. Coming back to these questions in Section 5 would be one way to list the key results. Also, what are the broader implications of changing transition probabilities? Are some of these transitions particularly relevant for high impact weather or certain extremes? A further comment on Section 5 is that several caveats of the methodology are mentioned but it remains unclear whether and in which way these caveats affect the results. Though I generally advocate such critical discussions, clearer statements regarding the effect on the results are mandatory.*

Thank you for this hint! In order to emphasize the key outcomes, we have rewritten and reordered the discussion section. As suggested, we have revisited the three main questions we introduce in Section 1 for Section 5 and discuss them here. We slightly changed the three questions in the revised version to:

1. Can we find a method to automatically distinguish between the two atmospheric blocking types High-over-Low and Omega blocks?
2. Do blocking occurrence probabilities undergo long-term changes? Do these changes depend on season or month?
3. Do onset, decay or transition probabilities from one blocking type to another undergo long-term changes? Do these changes depend on season or month?

We will come back to these questions in the Discussion/Summary sections. This will hopefully highlight the main results more clearly. In addition, we now only discuss significant results. Furthermore, we will discuss the implications of the results as suggested. For example, the location of the low(s) relative to the high is relevant for high-impact weather such as high precipitation amounts. An observed trend in *High-over-Low* or *Omega* blocking therefore can have impact on the location of these precipitation events, too. Moreover, we will do additional tests to validate the significance of specific results, and to estimate the uncertainty of the methods, respectively.

Minor comments

Thanks for carefully reading and commenting on our paper! We will address every comment in the following.

- *Title: The title is very general. Please try to be more specific. For example, "Observed frequency and transition trends of Omega and High-over-low blocks" would be a more specific title which might help to increase the visibility of the article.*

Thank you for highlighting that our title was too general. We have followed your suggestion and agreed on the following new title: "Occurrence and transition probabilities of Omega and High-over-Low blocking"

- *l. 1: Consider to replace "very high" with "anomalously high". In some regions of the world "very high" may not mean "very high" in other regions of the world.*
  Done

- *l. 2: I'd suggest to use the wording "flanked by" instead of "in combination with".*
  Done

- *l. 6: here and elsewhere: Northern Hemisphere with capital letters.*
  Done

- *l. 8: "temporal development" is quite unspecific. Do you mean the long-term change/trend of blocking probabilities?*
  Yes, you are right. Temporal development is unspecific. We changed it to "long-term change".

- *l. 14: Initially and also later in the manuscript you talk about "weather patterns". Here, you introduce "weather regime". I suggest to use one of these terminologies consistently throughout the paper. In my opinion, "weather regime" is better suited than "weather pattern".*
  Thank you. It is indeed important to use a formulation consistently. However, our intention is to investigate the blocking as Langrange'ian system rather than a weather regime which would be a Eulerian view. The underlying theory behind the trapezoid method is, that a system of two to three interacting vortices form the block. We will follow the high in time and – depending on the location of the surrounding lows – decide if the vortex system represents a *High-over-Low* or an *Omega* block. This is why the term "weather regime" does not fit so well. "Weather pattern" seems to fit better. We will discuss the terminology in the manuscript, too, and will use it consistently.

- *l. 24: Consider to write "steady ridges" in italic font since this is a third type of blocking.*
  Done

- *l. 27: "can" instead of "could"*
  Done

- *l. 27: Please provide a reference showing that these transition can be "often" observed.*
  Thanks! We adapted the text and deleted the word "often". One aim of our paper is to analyse such transitions and our results show that transitions occur often. However, there are not many previous papers that already looked at the different types of blocking. A publication [Schielicke, 2017] showing a single case of transitions in summer 2010 is cited in the subsequent sentence.

- *l. 32: Please specify that this statement refers to central Europe (I guess).*
  Yes, we mainly meant central Europe. We changed the text accordingly. Thanks!

- *l. 36: The Deutscher Wetterdienst invalidated the record of 42.6°C recently (`https://www.dwd.de/DE/presse/pressemitteilungen/DE/2020/20201217_annulierung_lingen_news.html`)Please adapt the manuscript accordingly.*
  Thanks for pointing this out! The "annulling" of the record was published shortly before we submitted the paper and we were not aware of this fact. We adapted the text to the new records, that occurred on the same day at two stations in Germany and added the reference.

- *l. 46: Please remove brackets around (Helmholtz, 1858).*
  Done

- *l. 47: Missing full stop after circulation.*
  Done

  l. 47: Why do you introduce the terminology "positive circulation" and "negative circulation"? This terminology is not used at all in the manuscript.
  The terms "positive/negative circulation" are important for the blocking identification method (trapezoid method). However in this paper, we condensed the description of this method, since it was described already in detail in the publication of Hirt et al. [2018] Hence, you are right and we can delete the sentence in the introduction.

- *l. 83: Please use capital "S" when referring to a specific section (e.g., Section 2, Section 3, Section 3.2 etc).*
  Done

- *l. 93: Please explain why you decided to focus on the period 1990 to 2019. The NCEP-DOE Reanalysis are available for the period 1979-2020. Why did you decide to not include the 1980s period for your analysis? Since you are looking at*

long-term changes, 10 years of additional data may help to make your statements more robust.
It is a good point and you are right, a longer climatology would most probably give more robust results. We decided to use the data starting with the year 1990 since we based this work on the previous paper of Hirt et al. [2018] whose data basis also started in 1990. Unfortunately, an additional analysis would be too time-consuming at the moment, but we would like to apply the method to a longer and also to different data sets in the future.

- *l. 93: Better write "close to zero" instead of "very low". "Very low" could also mean "negative".*
  You are right, thanks!

- *l. 113: Better write "identify" or "capture" instead of "catch".*
  Done

- *l. 120-122: Please clarify this explanation. Does this mean you disregard one block if two blocks occur at the same time in different parts of the area? Or do you simply assign the two blocks to the same blocking type (HoL vs Omega)?*
  Yes, we disregard the second block if two blocking are identified at the same time in different parts of the region. We have adjusted the paragraph to better describe the procedure.

- *l. 140: Do you employ any criteria concerning the minimum size of the vortex patches?*
  No, even a single grid-point that has a kinematic vorticity number $W_k > 1$ counts as a vortex patch. Keep in mind, that each grid point is associated with an area of $2.5° \times 2.5°$ (latitude-longitude grid).

- *l. 142: I fully understand that you are not providing all details of Hirt et al. 2018. But could you at least mention the step size at which the size of the box increases? Is it 2.5° ?*
  Yes, in a first step, we identify the area associated with the high pressure systems. The box, that encloses the high, is then extended equatorwards by steps of 2.5° latitudes to obtain the box that minimizes the total circulation within the box. However, only negative circulation northwards the low centroid and positive circulation southwards the high centroid are taken into account for the calculation of the total circulation. This box shape represents the *High-over-Low* configuration. At the same time, we search for a minimum of total circulation within a trapezoidal shape, which represents an Omega configuration. Therefore, we enlarge the southern boundary of the original box symmetrically by steps of 2.5° longitudes

(on each side) up to a total length of the southern trapezoid boundary of 2.5 times the east-west-length of the box around the high center. The northern boundary remains fixed and only grid points whose centers lie within the trapezoidal shape are counted. Again, only certain areas of the trapezoid are attributed to the high (everything north of the mean latitude of the low centers), to the western low (everything below and west of the high centroid) and the eastern low (everything below and west of the high centroid).

- *l. 152: What exactly to you mean by "below the high center"? Do you mean south/equatorwards of the high center?*
  Yes, we meant south. Thanks. We adapted this in the text.

- *l. 158: Replace "where we" by "who".*
  Done

- *l. 160: What exactly do you mean by "large jumps"? Please be more specific and provide the threshold in km or degree longitude.*
  Thanks for pointing this out. We will add a sentence to the script. It means, that we split the blocking periods to smaller periods, if the position of the high centroid changes by either 10 degrees latitude ($\approx$ 1000 km in north-south direction) or 15 degrees longitude ($\approx$ 1000 km in west-east direction) in successive time steps, i.e. in a period of 6 hours. Although we allow for slow motions of the blocks, these "large jumps" rather indicate that a different high pressure system enters the configuration. In order to obtain configurations associated with the same high, we split such periods to two or more smaller periods. Of course this reduces the maximum duration of the blocking periods, but is also more consistent with following the block as a system of vortices (instead of a weather regime).

- *l. 157: How are the "circulation centroids" in Fig. 3b identified? This needs to be explained in the text.*
  Thanks! We will add a description of the circulation centroids identification to the text.

- *l. 165: The information on the life time is redundant and could be removed from the manuscript.*
  Do you mean from the whole manuscript or just in this sentence? Later in our analysis, we take a subset of the data for the Euro-Atlantic region. In this case, the system might stay for less than 5 days within the region. Otherwise, in an earlier step of the analysis, we split the IBL identified periods (which initially where $\geq$ 5 days) if the high centroid location jumps too largely from one time step to the

other. Hence, we think, it is worth pointing out at which steps of the analysis the 5 day criterion holds.

- *l. 168: Please use consistent terminology for the "Euro-Atlantic sector" (here you are using "European sector" elsewhere it is "Euro-Atlantic sector").*
  Thanks, we adjusted this and use only Euro-Atlantic sector/region.
- *l. 219: Better provide a reference to the work of Andrey Markov.*
  We will look for a suitable reference.
- *l. 248: Remove brackets around "e.g., Baclawski, 2008".*
  Done
- *l. 256: Do you mean "seasons" instead of "Seas"? Or did I miss the definition of this acronym?*
  Yes, you are right. We mean season and now we define this acronym "Seas", which is an operator in our equations, here.
- *l. 271: Are you really displaying a frequency in Fig. 5? Or is it rather the number of events in the 30-year period?*
  Yes, it is the number of events in the 30-year period. We adjusted the label accordingly.
- *l. 279: Please avoid descriptive information which can also be derived from the figure caption*
  Descriptive information about the regions were removed.
- *l. 293: Please insert "a" between "of" and "blocking".*
  Done
- *l. 300: I could not find the "straight-line estimates" in Section 4.1.2. My suggestion would be to include the straight line estimates in Fig. 6 (also for the benefit of the discussion in Section 4.1.2).*
  We added the straight line estimates for mean and maximum durations and made further tests on the uncertainties.
- *l. 300: Please see my comment on line 279.*
  Thanks, we try to avoid descriptive information that can also be derived from the figure captions.

- *l. 302: Insert "The" before "Average".*
  Done

- *l. Please be cautious concerning the terminology of "probability". Sometimes probability is used to describe a fraction (e.g., 301 p=0.24), here probability is used to describe a percentage. I'd suggest to be consistent regarding the terminology*
  We will reread the text carefully and use the term "fraction" in these cases.

- *l. 305: Please include references to the corresponding subfigures (Fig. 7a, b and so on).*
  We will add the references to the corresponding subfigures to the text.

- *l. 314: In Section 4.1.2 on average 10 9.8 blocks are found per year. When describing blocking probabilities on a monthly basis, did you not encounter any issues regarding the small sample size. Apologies if I missed this information.*
  Thanks for this comment. On the one hand, we look at blocked (vs. unblocked) time steps so a blocking could partly lie in two months. On the other hand, the absence of blocking in specific months is an important information with respect to blocking trends, too. Imagine that blocking occurs for the first 15 years of a time series regularly in one month and is for the last 15 years of the time series absent. From this follows, that there must be some process that leads to the absence over the last years. We added a figure (see Fig. 1) to the supplementary material, that additionally displays the total number of years accounting for the statistics in each month. From this figure you will get additional information about the number of blocked years for the different blocking types for the individual month. For every month and year the probability of blocking is calculated and displayed as boxplots. This information helps to better assess the underlying data.

- *l. 321: Use "For example" instead of "E.g." at the beginning of a sentence.*
  Done

- *l. 332: I'd suggest to write "...that September to March are characterized...". It is a bit odd to include "September" in the winter season.*
  Done

- *l. 335: Clarify that it is not the "Euro-Atlantic" region which peaks in April, but the blocking frequency which peaks in April.*
  Thanks! We rewrote the sentence accordingly.

- *l. 346: Please remove "the" before "both".*
  Done

- *l. 354: Please include "the" before "probability".*
  Done

- *l. 359: "a" instead of "an".*
  Done

- *l. 377: The terminology "offset" is a bit awkward. Please reconsider this terminology. The term "decay" is used more frequently to describe the transition from blocking to no blocking.*
  Thank you for this comment, which we also received from the first reviewer. As already written as a answer to the first review we can understand this argumentation, but will nevertheless stick with the term "offset". From a meteorological point of view, the use of the word "decay" describes the transformation from a blocked state to an unblocked state with the right words, as it is a process. In our work, we focus on the model view, in which there is only the state "on" or "off". Therefore we use the term "offset". However, when introducing the terms "onset" and "offset", we will add a sentence that addresses the underlying processes of the formation and the decay of a blocking.

- *l. 390: Why is the change in transition probabilities of particular interest? Are these associated with particular weather phenomena so that any long-term changes would have an immediate impact?*
  The trend analysis of transition probabilities can for example give insight if the transitions between the *High-over-Low* state and the *Omega* state has changed. Due to their different configurations, weather phenomena such as extreme precipitation events associated with the low(s) of these blocked states occur in different regions. So yes, you are right, that particular weather phenomena would have an immediate impact. We hope to encourage further studies on the reasons and underlying physical processes why different blocking types occur. Our method shows, that it is possible to differentiate between the different blocking types. Since the method does not change over the 30-year period. Changes in the blocking type probabilities, stems from the block climatology itself.

- *l. 394: What about the persistence? According to the bottom right figure, the persistence of blocking has decreased which would indicate shorter blocking durations. In Section 4.1.2 however, a slight increase in blocking duration is reported. Can you comment on this contradiction?*
  Thank you very much for pointing this out. Are you talking about Figure 13 (bottom right, initial manuscript) that describes the persistence of blocking? This indeed seems to be slightly decreasing. However, this result is not significant. The straight-line fits described in section 4.1.2 are also not significant. We will do more

tests and hope to answer your open question!

- *l. 394: Please label subfigures with a), b), c) etc. If subfigures are not discussed in the text (e.g., top left and bottom right in Fig. 13) this can be deleted from the manuscript.*
  Thanks, we will follow your advice! However, Figures 13-16 are the matrix representation of possible transitions (analogue to Eq. 11 and 12), hence, picking out single subfigures while deleting others gives an incomplete picture. Since Fig. 13 and 14 do not show any significant results, we have decided to include them in the appendix.

- *l. 396-400: Are these conclusions only valid for JJA or is it for all seasons? Please clarify in the manuscript.*
  In our revised manuscript, we added to each discussed result if it is significant or not. Moreover, we try to avoid the discussion of insignificant results.

- *l. 396: A legend is missing in Fig. 14. This makes it hard to follow the discussion.*
  Yes, you are right. We had forgotten the color bar/legend in Fig. 14 and also in Fig. 16, which we have now added. We have moved Fig. 14 to the appendix.

- *l. 404: The subfigures need to be labeled and referenced in the text. Otherwise, it is difficult to follow the discussion. Please consider to delete subfigures from the manuscript which are not discussed in the paper.*
  We have labeled the subfigures and added to every discussion the corresponding subfigure. Hopefully it is easier to follow our discussion, now. As already mentioned above the subfigures of Fig. 13-16 are arranged accordingly to the the transition matrices (analogue to Eq. 11 and 12) and deleting would give an incomplete picture.

- *l. 421-430: This paragraph basically only tells the reader what has been done and is thus a repetition of Section 4. Unless the authors have a strong argument on why this paragraph is important, I strongly recommend this paragraph from the manuscript.*
  Yes, you are right. We have deleted this paragraph from the discussion section.

- *l. 435: Where is it shown that the increase can be attributed to blocking events that occur over western Russia? Either show a Figure or reference other studies which support this interpretation.*
  Thank you very much for pointing this out! Because of your and the other reviewer's comments, we started to do additional tests to estimate the uncertainties of the method. We found that this increase is insignificant! Hence, we removed

this statement completely from the manuscript.

- *l. 442: Replace "E.g." with "For example".*
  Done

- *l. 443: Can you comment on the discrepancy between the study by Brunner et al. (2017) and this study? According to Fig. 8, the probability of blocking in February has increased by a factor of three (0.08 to 0.24). Do you have any explanation on why the conclusion in Brunner et al. (2017) is completely different?*
  One point is definitely that our methods are different. In our case, we search for a coherent blocking structure, that needs to have a minimum lifetime of 5 days (in the larger region) and should be composed of the same high (lows are allowed to change in time). Our initial IBL identification is moreover only a one-dimensional method. In Brunner et al. [2017] the identification of blocks is done with a two-dimensional blocking index. Blocks are long-lived (at least 5 days) and synoptically large ($\pm 7.5\circ$ longitudes). However, a blocking is counted whenever at least one of these blocked grid points is within the Euro-Atlantic region ($45°$–$72.5°N, 30°W$–$45°E$). In our case, at least half of the block, more precisely the circulation centroid, needs to be inside the Euro-Atlantic region (40W-30E). Summarized, there is no easy answer. We will do more tests and try to answer your question! Thanks a lot! This is also relevant for our discussion section.

- *l. 459: Can you be more specific about this statement? Does "deviations" mean that the trends reverse when using different parameters?*
  Thanks for your question! We will test if the trends remain stable! However, what we meant was a bit simpler: imagine, that the criterion for the minimum blocking duration is reduced to 4 days (instead of 5 days), then we would identify more blocked time steps. Otherwise, if we increase the minimum duration criterion to 6 days, we would detect less blocked time steps. We will try to be more specific here. Especially, we will try to discuss the impact to our results.

- *l. 498: In my opinion you could easily find out whether your results coincide with the results of Drouard and Wollings (2018). For example, you could display the occurrence frequency of High-over-Low and Omega blocks as a function of longitude. Though I do not expect such a figure in the manuscript, I would be very interested to see such an analysis to better put this study in context with previous studies.*
  This is very good idea. We plotted the total number of blocked time steps with respect to the blocking types and longitudes of occurrence in Fig. 2 below. Our method prefers more *Omega* blocks compared to *High-over-Low*s in general. This has two reasons: (i) on the one hand, it depends on the width of the box south of the center of the high, that is inspected regarding the mean vorticity within the middle Box 2 compared to the outer flanks Box 1 and 3 of the box (cf Fig. 3 in the original manuscript); (ii) on the other hand, the method searches for the

minimum total circulation within the trapezoidal and box shapes associated with the block. The *Omega* block has more freedoms to minimize the total circulation within the trapezoid. However, we observe that the fraction of *High-over-Low*s is highest between about $0° - 40°$E and between about 60°E−75°E. The fraction of *Omega* blocks is highest for longitudes west of −25°W and for a the region between about 40°E−60°E. This is indeed comparable to the results of Drouard and Wollings (2018) for their regions between $0° - 55°$. Their composites for the areas of Western-south central Europe (0–20°E, 40–50°N); Central Europe (20–40°E, 50–60°N) and Western Russia (35–55°E,45–55°N) indeed showed rather *High-over-Low* patterns for the first two regions and an *Omega* pattern for Western Russia. Note, that our analysis in Fig. 2 is based on the whole year, while Drouard and Woollings [2018] looked at the summer months June to August.

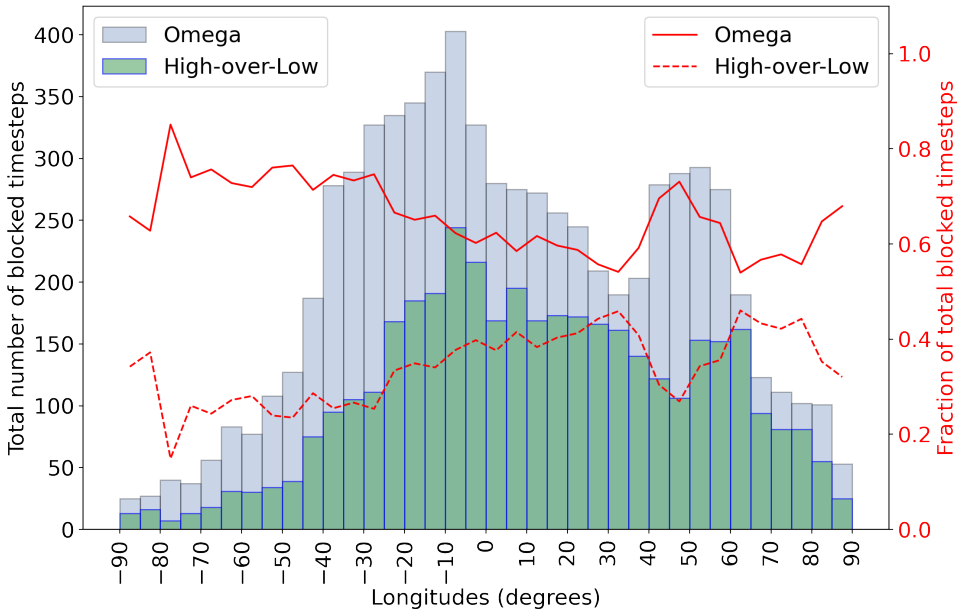

Figure 2: Number of total blocked timesteps for *Omega* and High-over-Low blocks (columns) and fraction of all blocked time steps associated with each blocking type (red lines). Note that this analysis is based on the whole year.

- *l. 510-516: How do these results relate to previous studies? Are these in line with previous results or do they contradict earlier studies?*
  We will rewrite the conclusion, highlighting how comparable our results are to previous studies.

- *l. 518: A verb is missing in this sentence.*
  We deleted this sentence.

- *l. 521: This sentence needs clarification. As it stands now "an increase in overall probability for blocking" and "a higher proportion towards the end of the study" somewhat mean the same thing. I guess you want to say that the number of all blocks increases and that the fraction of* Omega *blocks increases, too.*
  Yes, you are right. We adapted the sentence accordingly: "While in July the proportion of *Omega* blocks is only about 25% of all observed blocks in 1990, we find an increase in the number of blocks in general as well as a higher fraction of *Omega* blocks towards the end of the study period."

- *l. 525: Replace "this" with "these".*
  Done

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