Response to Reviewers | Hauser et al. (Manuscript ID WCD-2022-44)

“Towards a diagnostic framework unifying different perspectives on blocking dynamics: insight into a major blocking in the North Atlantic-European region”

We would like to thank both reviewers for their time and effort to review our manuscript. We are happy about the positive impression of the reviewers and pleased to be able to contribute to a better understanding of blocking with the contained methods in this study. We agree that the manuscript is a bit long in its current form, but as also mentioned by one of the reviewers, we are introducing several new methods here that need to be explained in detail.

In this final answer, we comment on the major points raised by both reviewers and how we aim to address these. This response will be followed later by a detailed response to all reviewer comments and a revised manuscript.

(1) Role of the beta effect in the quasi-barotropic PV tendency term

The quasi-barotropic tendency term (QB), as introduced in the introduction and defined in Eq. 4, combines the two terms v' dot grad q_0 and v_0 dot grad q’. The first corresponds to the beta effect. Our rationale is that both terms together correspond to textbook linear theory of Rossby waves (in the 2D barotropic model): The first term represents intrinsic wave propagation and the second term the advection of existing (wave) anomalies by the background flow. Intrinsic propagation contains both, phase and group propagation. Sticking to linear theory for the moment, the amplitude change of anomalies is associated with group propagation (e.g., Fig. 8 in Wirth et al. 2018; discussion in Teubler and Riemer 2016, 2021). This amplitude change is the net effect of a dipole of positive and negative tendencies. The dipole is mostly responsible for the phase propagation, i.e., a displacement of the anomaly. In our framework, for real-atmospheric anomalies, we diagnose this net effect in the quasi-Lagrangian perspective by integrating over a specified anomaly. What we thus see and discuss in Fig. 10 is what the reviewer is asking for: The amplitude change of the anomaly due to the “beta term”. The advection by the background flow (v_0 dot grad q’) does not contribute to amplitude change of the anomaly (Eq. 9). The poleward movement of trajectories that the reviewer observes in Fig. 13 can be either associated with a net amplification of the anomaly, or simply due to air masses moving poleward ahead of the trough of an existing wave that does not amplify. (A Rossby wave is not a Lagrangian structure; air masses move “through” the wave.)

While the quasi-Lagrangian perspective focuses (by design) on the amplitude change of an anomaly, the Eulerian perspective is different. Taking the “projection approach”, the question is: What processes contribute to the formation of a specified pattern? Amplification of anomalies in the “right place” contributes, but also the re-arrangement of existing anomalies. In this context, both contributions to linear Rossby wave dynamics may thus contribute. And it is in this context that the background flow dominates and we thus focus on this mechanism: The anticyclone (in particular) is “pushed into place” by the background flow (Fig. 7c). The intrinsic phase propagation is directed against the mean flow and thus tends to propagate the anomaly out of the region of the regime pattern (= a negative contribution by v' dot grad q_0, not discussed explicitly in the submitted version of the manuscript). In this framework it is difficult to disentangle phase and group propagation. Comparing Fig. 10, however, we may note that there is a period form 12-15 March during which the negative anomaly persistently amplifies due to group propagation as represented by the quasi-barotropic term.

It is clear from the reviewer’s comment, however, that our presentation of the tendency terms lacks some clarity. We aim to make modifications to the manuscript to help clarification and to address the reviewer’s comment.

(2) Choice of the manuscript title

We agree with the reviewer that the title of the manuscript (currently: “*Towards a diagnostic framework unifying different perspectives on blocking dynamics: insight into a major blocking in the North Atlantic-European region*”) needs revision. The reviewer raised the point that the three perspectives are not as attractive and ‘unify’ might not be the appropriate word. The reviewer suggested using the wording ‘holistic view’ and we will change the title in the revised version of the manuscript.

(3) Consideration of the cyclonic anomalies exclusively in the Eulerian view

One of the reviewers raised the question why the cyclonic part of the European Blocking regime life cycle is exclusively discussed from the Eulerian perspective. This is indeed a fundamental difference between the Eulerian perspective, and the quasi-Lagrangian and Lagrangian perspective. The motivation for the development of the quasi-Lagrangian and Lagrangian perspective is based on earlier work by Schwierz et al. (2004), Pfahl et al. (2015) and Steinfeld and Pfahl (2019) that investigated blocking dynamics by exclusively looking at the anticyclonic PV anomaly. We are aware that based on these 2 out of 3 perspectives in the manuscript, we can hardly say something about the cyclonic counterpart of the regime pattern. We briefly address this point from a Eulerian perspective (since the framework allows us to consider cyclonic anomalies separately) but do not go into much detail as the analysis of the cyclonic regime part is not the main focus in this study. We will therefore not extend the quasi-Lagrangian and Lagrangian perspective to cyclonic anomalies. In a revised version of this manuscript, we will discuss this limitation in the introduction and conclusion as suggested by the reviewer.

(4) The reason for looking at PV anomalies and the choice/limitations of the selected threshold

The choice for tracking PV *anomalies* and not absolute features of PV is justified here briefly. First, the quasi-Lagrangian perspective (that represents the key perspective in this study) was developed with inspiration by the Schwierz et al. (2004) blocking detection algorithm which in turn is predominantly anomaly-based in its application. To be consistent and to be able to connect it as an add-on to the well-known algorithm by Schwierz et al. (2004), we decided to track PV *anomalies*. Second, the anticyclonic anomaly associated with the blocked regime is an anomalous PV feature and is easier to detect in an anomaly field than in an absolute field. Third, identifying PV features on an absolute PV field would not eliminate the choice of a threshold. Fourth, we make use of the quantitative PV framework developed by Teubler and Riemer (2016) to look at the processes associated with the amplitude evolution of 'blocks'. And this PV framework is developed for PV anomalies so that we also have to consider PV anomalies in order to apply this framework.

We are aware that the choice of a threshold is often subjective and gives room for criticism. In this particular case study, we use a fixed threshold for detecting negative PV anomalies that is -0.8 PVU and therefore ≠ 0.0 PVU as a threshold of 0 is not feasible for blocked regimes. A threshold of -0.8 PVU does not cover the entire anomaly area, but it avoids looking at very large features that span half the northern hemisphere. We did several tests for the selection of thresholds that are also useful for a year-round investigation (see below) but these tests will be mentioned in a follow-up study about the systematic investigation of blocked regimes in the ERA5 period. Some of the co-authors tried to use the threshold of 0.0 PVU in a previous study (Schneidereit et al., 2017) but failed with this approach for a blocking anticyclone over Europe. PV anomalies within Rossby Wave Packets (RWPs) are much more organised than those during blocking which is why a threshold of 0.0 PVU works for RWPs. Again, we are aware that theoretically the threshold choice of -0.8 PVU will not close the budget 100%.

A suggestion from one of the reviewers was to choose the amplitude metric to be the spatial integral of q' + 0.8 PVU where q' seems to be the threshold that we selected as -0.8 PVU. As pointed out above, we definitely see the risk that with the suggested adjustment (threshold for the area to be integrated = q' + 0.8 PVU = 0.0 PVU) the area of the PV anomaly will drastically increase in some cases, several actual single anomalies are thrown together, and important signals cancel out as a consequence.

One reviewer raised the comment that by using a threshold this method still misses some information on the initial origin of anomalies. However, we avoid a criterion for the minimum size of a PV anomaly, so that we can detect the anomaly growing into a block much earlier compared to other studies. Furthermore, we are not primarily interested in where the PV anomaly originates, but rather the temporal evolution just before it is identified as a block. We currently work on a year-round climatological analysis of blocked weather regime dynamics based on the full ERA5 period (1979-2021) where we use a running threshold for the detection of negative PV anomalies (with a stronger/weaker threshold in winter/summer). Detailed information about the thresholds and justifications will be given in a follow-up manuscript.

In a revised version of this manuscript, we will make the choice of using PV anomalies instead of PV features clearer as well as the justification why (and very roughly how) we have set a threshold.

(5) Why the Eulerian view is important in the synopsis of all perspectives

An intriguing motivation for the projections and hence the eulerian perspective is that it directly quantifies the processes leading to the evolution of the weather regime index (up to constants). Additionally, the quasi-lagrangian perspective cannot take into account the role of adjacent positive PV anomalies, which are part of the weather regime and should not be neglected. On the other hand, only the quasi-lagrangian perspective can quantify the processes upstream to the weather regime. Hence, the multi-perspective analysis is important to understand the full regime evolution. In the revised manuscript, we will point out even more the importance of the synopsis of all three perspectives.

(6) Consideration of more blocking mechanisms

In this study, we consider some proposed blocking mechanisms mentioned in Woolings et al. (2018). One reviewer commented that discussion is missing about other mechanisms like the well-known eddy-straining mechanism (Shutts, 1983). However, the goal of our study is not to combine as many blocking mechanisms as possible (and especially not with this single case study), but to present our developed frameworks through which we can gain more insights into blocking dynamics when looking at them from a climatological perspective. It is a good idea to look at the mechanism of Shutts (1983) from a quasi-Lagrangian perspective, however, we do not see this in this manuscript as the manuscript is already long enough. We would not like to further extend the current manuscript but will consider this additional analysis from a climatological perspective in a future study.

(7) Blocking from the perspective of weather regimes

One reviewer raised the question why a weather regime perspective is used in this study and generally as a basis for the developed perspectives. First of all, looking at blocking from a weather regime perspective brings in a new angle to the classical considerations which are mostly limited to the anticyclonic anomaly. Especially with the Eulerian framework we can gain insights into the dynamics of the cyclonic part during a blocked weather regime life cycle and investigate the full pattern. Weather regimes have implications for extended-range weather forecasting and a better understanding of their dynamics can help to improve the forecasts on subseasonal-to-seasonal (S2S) time scales. In particular the unique year-round weather regime definition used in this study brings in many advantages, especially the objective definition of the life cycles and its life cycle stages (onset, maximum and decay). Thus, a wide variety of blocking theories can be considered and tested for different life cycle stages in subsequent studies in which the frameworks are applied climatologically.

Regarding the comment for the misleading signals over the U.S. East coast (Line 360): We are aware of the baroclinic PV tendency over the U.S. East coast associated with a negative PV anomaly that dominates the overall baroclinic PV tendency signal in the projections. We will check the sensitivity of the results in Figure 6a and 6c when we do not consider the negative PV anomaly patch over the U.S. East coast.

(8) Block stationarity dynamics

One of the reviewers has emphasised that the quasi-Lagrangian framework might be able to explain why the block becomes strong and large, but not why it is stationary. We will not discuss this aspect in this manuscript but refer to the study of Teubler et al. (2022, WCDD) who find that eddy fluxes help to keep the block stationary from a Eulerian perspective. This motivates us to address the importance of splitting and merging of smaller-scale eddies for the stationarity and maintenance of the block in a subsequent climatological study. However, this kind of analysis goes too far here and becomes more interesting when a variety of cases are considered. In the revised manuscript, we will include that direction in the conclusions section for future work.

(10) References/technical comments

We apologise for typos and will of course be happy to discuss the additional references suggested by the reviewers in our revised manuscript, as well as the minor and technical comments by both reviewers.

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