Second Response, Manuscript: egusphere-2024-382

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1 General Comments

Thank you for the positive feedback on the revised manuscript. One remaining major concern brought up was the need for further quantification of the kinematic influence of NPV-jet interactions. We have addressed this concern in two key ways. First, we follow the reviewer's and editor's advice to provide a more quantitative approximation of NPV's influence on the jet stream. Second, we hope to have better motivated the importance of some of the qualitative results regarding NPV-jet interactions mechanisms, which we stress are important results in their own right.

Here are the key changes made that we hope provide additional insight on the kinematic impact of NPV on the jet stream.

1. More intuitive relative vorticity inversion to estimate the added impact of NPV on the jet stream. We discuss the approach in more detail in response to the major comment from the reviewer. We hope that this approach is now a satisfying (or at least a reasonable estimate) for how much NPV contributes to the large-scale flow.

2. While there is certainly a desire to quantify these interactions, we stress that there are limitations to how much appropriate quantification we can do with reanalysis. The goal of the study has always leaned towards a more qualitative and exploratory evaluation of NPV-jet interactions through a composite framework. Specifically, highlighting some of the key circulation patterns and mechanisms we observe during NPV-jet interactions. We have added a schematic to the end of the results section to remind the reader of the dry dynamics mechanisms identified during NPV-jet interactions found in this study (and emphasize the fact that NPV-jet interactions appear to be a dry dynamics interaction).

3. Other minor personal changes have been added (slight rewrite of the discussion and conclusion to better emphasize the mechanistic results of NPV-jet interactions). These changes can be best seen in: L721-730 and L766-774. This also includes minor grammatical changes in some parts of the manuscript. We have also added relative vorticity contours to the composites to make it clear that regions of NPV are regions where anticyclonic vorticity is much stronger than background flow. This serves as additional evidence for the uniquely strong vorticity circulation associated with NPV compared to relative vorticity associated with larger-scale, benign negative PV anomalies. This property should also be more clear in the case-studies following a slight adjustment of the colorbar to show the contrast between anticyclonic vorticity within NPV and surrounding ridge.

2 Response to Reviewer 1

2.1 Major Comments

Comment 1: My main concern follows similar lines to RC2 major comment 2, namely that some of the signals attributed to NPVs in this work would be present even if the PV value did not go below zero (i.e. it was small, but not a NPV feature). RC2 focussed on Fig 6 (and their concern has been at least partially addressed by including a discussion of the 100-300km cases in Fig 7), but in my view the same concern holds for the relative vorticity inversion of Fig 8 (new numbering). Specifically, you invert (if i've understood correctly) the part of the relative vorticity field that lies within the NPV contour and then claim (L517) that 'the anticyclonic vorticity associated with NPV appeared to contribute to approximately 50% of the total non-divergent wind field'. I fear this may mislead readers. There is always negative relative vorticity on the southern side of the jet (by definition of vorticity) so claiming it is all 'associated with the NPV' is not a fair assessment. Indeed, one could argue that the NPV feature should only be associated to that part of the (absolute) vorticity field that is negative, and I suspect inverting this (much smaller) anomaly would produce a much smaller estimate of the impact on the wind field. I note that you do include a caveat along these lines towards the end of the discussion section (L675) but feel the conclusions drawn in section 3.3.1 need adjusting to reflect this important caveat, or even better, the alternative inversion calculation presented as well for comparison. I suspect similar is also true for the inferences drawn from the WAF calcuations in sections 3.3.2 and 3.3.3, but am less familiar with that diagnostic to know for sure. Please reread those sections with this concern in mind and adjust the language used as appropriate.

Response: We appreciate the comprehensive comment. As mentioned in the general comment, quantifying the dynamical relevance of NPV on the jet stream is complicated through ERA5 alone without additional high-resolution data and/or more complex methodological tools. The study intends to focus on more qualitative insight into the dynamical importance of NPV features on the large-scale flow, specifically through a climatology and by identifying mechanisms through which NPV interacts with the jet stream (i.e., highlighting the importance of dry dynamics interactions) with some complementary quantitative insight. Following the comments made, we do have an idea to improve our quantitative insight into how NPV influences the jet stream through relative vorticity inversion.

First, we agree with the reviewer, the 50% approximation is simplistic and does not do a good job at teasing out the added impact of relative vorticity associated with NPV on the jet stream. Personally, the section left a lot to be desired. As a response, L529-539 (Now L539-549) has been rewritten following a more quantitative evaluation of the NPV feature and its influence on the jet.

The reviewer suggests inverting the inertial unstable part of the NPV. This has been tested previously. Because synoptic-scale NPV is near-zero PVU (and just slightly inertial unstable), the inertially unstable part of the anticyclonic relative vorticity only contributes about 1 m/s to the total wind field (Fig. 1). However, this is not a fair attribution of the influence that NPV has on the large-scale flow either. This is because NPV has already been identified as having a much stronger anticyclonic vorticity compared to the background vorticity associated with the broader ridge within which it is embedded. Put another way, the inertially unstable part of the NPV feature is only a small component of the anticyclonic vorticity field associated with NPV.

It is better to identify the anticyclonic vorticity associated with NPV by subtracting the background flow from the total anticyclonic vorticity within the NPV feature, since the NPV feature ultimately represents a relative vorticity anomaly with respect to the background flow. This logic also follows from Harvey et al., (2020). Assume we have a pre-existing large-scale flow (i.e., a base-state ridge with no diabatic heating occurring). When heating occurs, PV is reduced in the upper-troposphere and perhaps we may get the generation of an NPV feature. A fair attribution would thus be found by taking the difference between the vorticity associated with the NPV feature and the base-state environment at the earlier time. This method follows a similar attempt to estimate the wind field associated with smaller-scale NPV features in Oertel et al., (2020). Our new method to estimate the circulation associated with NPV relative to the base-state is now outlined in the Methods section (Line 276-286).

We also provide an illustrative example of how this method is applied for synoptic-scale NPV features in the appendix section to help the reader more easily interpret our methodological approach. We stress that this method is only able to provide a rough estimate of the circulation associated with NPV. However, we hopefully provide a far more interesting way to quantify NPV that extends from previous literature compared to our previous version.

As for the WAF calculations, following the introduction of the new schematic at the end of the results section (New Figure 11), we want to emphasize that the WAF analysis is meant to primarily highlight the mechanistic aspects of NPV-jet interactions and not necessarily provide a detailed quantitative estimate of how much NPV contributes to the total WAF equation. We mainly want to show that NPV-jet interactions can be described using dry-dynamics and that they enhance wave activity via: Vorticity dipole interaction and due to strengthening the ageostrophic flux of geopotential by the shear accompanying the anticyclonic vorticity. We feel that the mechanistic insight is sufficient and we do not want it to get lost amid further quantification. We have however revised the conclusion section to better highlight these findings.

Further quantification will be more suitable for high spatial and temporal resolution case-study approaches, which may enable the application of more sophisticated methods (such as trajectory based analysis and outputting physics tendencies) to better quantify how heating influences circulation associated with NPV in future studies.

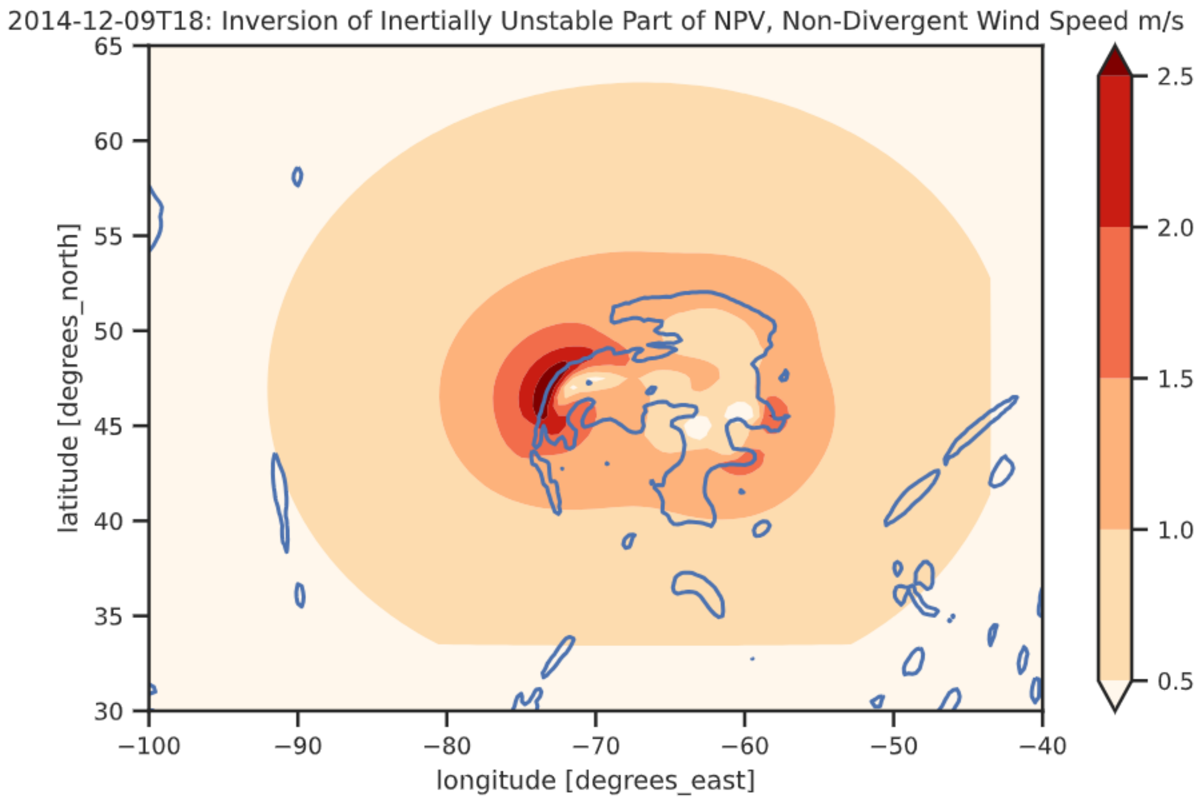

Figure 1: Inverting just the anticyclonic vorticity that is greater than coriolis parameter in the NPV feature of interest for the 2014-12-09T18 case. The boundary for the relative vorticity inversion is the NPV feature itself at 250 hPa.

2.2 Minor Comments

Comment - L24: As written, the third sentence of the Introduction overplays the role of diabatic processes relative to dry dynamics. Suggest a minor change to something like 'These eddies, which can include a strong contribution from cloud diabatic heating processes, act to perturb the jet stream's large-scale circulation away from its base state.

> **Response:** Thank-you, we have made the suggested change.

Comment - Line 102: Does the irrotational wind cause the outflow air to move just polewards, or in all directions?

> **Response:** The irrotational wind will advect the outflow radially outwards in all directions. However, we will generally see the preferential acceleration of outflow towards the jet due to the lower inertial stability on the equatorward side of the jet, which favors venting outflow poleward into the jet rather than in other directions.
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> But for the purpose of perturbing the jet stream (and since the irrotational outflow is established on the equatorward side of the jet stream), we just wanted to imply that the 'important' component of the advection occurs polewards. We have refined the sentence to make this more clear: "The irrotational wind field established by large-scale cloud systems make an important contribution to the poleward advection of the outflow and subsequent wind speed enhancements along the jet stream".

Comment - L72: How can the anticyclonic relative vorticity associated with NPV be an order of magnitude larger than the PV anomaly, when they have different units? Please clarify.

> **Response:** The wording has been edited to make more sense: "When NPV features are within large-scale negative PV anomalies like ridges, the anticyclonic relative vorticity from the NPV has been observed to be an order of magnitude greater than the vorticity from the surrounding large-scale negative PV

anomaly". The point we tried to make is that the anticyclonic vorticity associated with NPV has larger magnitude than anticyclonic vorticity associated with a benign large-scale negative PV anomaly.

Comment - L140: Could you explain what you mean by a 10 point Gaussian smoother? What is the half width of the smoothing kernel?

> **Response:** Smoothing is done with the Python package called MetPy. The Guassian smoother is a moving-average low-pass filter. The moving average is computed over 10 grid-points, hence the '10-point' smoother. We choose not to eidt anything in the manuscript since the exact details of the smoothing approach do not necessarily effect the reproducibility of the study, nor is it an important part of the methods.

Comment - L241: What is the streamfunction anomaly computed relative to? The seasonal mean streamfunction?

> **Response:** Correct, it is computed from the seasonal mean. We have added an additional sentence: "Note that the anomaly is computed from the seasonal climatological mean". (Now L243).

Comment - L265: Please describe the relative vorticity inversion calculation in more detail. What domain is the calculation performed over? If it's not a global inversion, what boundary conditions are applied?

> **Response:** We have added additional detail regarding the domain of the calculation, boundary conditions and that the inversion is computed regionally to the methods section of the paper. A more detailed summary of the inversion process is also summarized herein:
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> The inversion of vorticity is based on partitioning the full horizontal flow into a non-divergent flow component attributed to the vorticity in a spatially confined domain, an irrotational component attributed to its divergence, and the effect of the larger-scale environmental flow outside of the domain. Using a Green's function approach facilitates to attribute a horizontal flow field to the vorticity within a limited domain. Since our paper focuses on NPV features associated with a vigorous relative vorticity signature, we exclusively focus on the inversion to obtain non-divergent winds.
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> For readers that need more detail on the approach, we note that we provide a reference to Oertel and Schemm (2021), who have a paper dedicated to deriving the relative vorticity inversion.

3 Response to Reviewer 2

3.1 Minor Comments

The authors have made substantial improvements to the manuscript, particularly in the introduction. They have also spent considerable time addressing most of my comments, which I greatly appreciate. I would say that the advection in Fig. 6k still looks to have the wrong sign to me(!), since grad(PV) will be normal to the PV=2 contour. Maybe it is confusion over whether advection is -v.grad(PV) or +v.grad(PV)? The authors could also change "latitude and longitude" to "longitude and latitude" on line 242, to be consistent with the ordering of x and y.

> **Response:** Thank-you for your comment! First, we have changed "latitude and longitude" to "longitude and latitude" in line 242.
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> Regarding the PV advection plots, we have cross-checked to ensure that the PV advection sign is correct. However, we assume that there might be a slight artefact due to the centered composting approach where the wind vectors appear to be pointing from low to high values of PV for panels j and k, which may give the impression that the sign of PV advection should be the opposite as implied by the reviewer. However, we have cross-checked that the PV advection signal is correct. We suspect that the orientation of the vectors may contributing to some of the confusion, but this is likely that each centered composite may have notable variations in the tilt of the ridge, which may influence the direction of the wind vectors. Overall, we think no changes are needed as we make appropriate references to other studies following the previous round of revisions to validate the PV advection results.

4 References:

Harvey, B., Methven, J., Sanchez, C. and Schäfler, A., 2020. Diabatic generation of negative potential vorticity and its impact on the North Atlantic jet stream. Quarterly Journal of the Royal Meteorological Society, 146(728), pp.1477-1497.

Oertel, A., Boettcher, M., Joos, H., Sprenger, M. and Wernli, H., 2020. Potential vorticity structure of embedded convection in a warm conveyor belt and its relevance for large-scale dynamics. Weather and Climate Dynamics, 1(1), pp.127-153.

Oertel, A. and Schemm, S., 2021. Quantifying the circulation induced by convective clouds in kilometer-scale simulations. Quarterly Journal of the Royal Meteorological Society, 147(736), pp.1752-1766.