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Atmospheric Chemistry and Physics Discussions



# *Interactive comment on* "A PV-based determination of the transport barrier in the Asian summer monsoon anticyclone" *by* F. Ploeger et al.

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**General comment:**

We thank the reviewer for her/his careful consideration of the manuscript and her/his well thought-out comments, which significantly helped to improve the paper. In the following, we address all comments and questions raised (Reviewer's comments in italics). Text changes in the manuscript are highlighted in red (except minor wording changes). Main changes, related to all Reviewers's comments, concern: (i) an extended discussion of the evolution of the PV-gradients and the related transport barrier over the season and potential relations to convective activity (including ozone, mean age, OLR and diabatic heating rates in the revised Fig. 12) in section 5, (ii) a criti-

cal discussion of the leakiness of the diagnosed barrier (discussion), (iii) an extended discussion of MLS observations and the comparison between model and MLS (discussion, including a new Fig. 14), and (iv) shifts of the old section 6 to the appendix, of the discussion of the layer where our criterion is applicable to section 4, and of the discussion of the anticyclone location probability to the new section 6.

**Major comments:**

1. *As previous studies have shown, Ertel's PV and long-lived tracer distributions are highly correlated in their spatial and temporal distributions inside the Asian monsoon anticyclone. I don't necessarily think the PV as a barrier but as a measure of confinement of the air masses within the anticyclone. This barrier is leaky and also has large variability, if it exits. The authors also have introduced three other variables to characterize the monsoon anticyclonic boundaries in section 2, which include, PV, circulation and stream function. With this in mind, the authors have to emphasize if it is possible to define a barrier over the monsoon region. Maybe there is no barrier? Why using PV gradients defining the transport barrier following Nash et al. (1996) over the monsoon region is applicable and what that means physically. Also, as the magnitude of PV is highly dependent on altitude, it will be useful to use MPV (modified PV) instead of PV and show how the results will change.*

We agree with the Reviewer's view that there is some transport across PV-contours and that the enhanced PV gradient in the monsoon region is better interpreted as a measure of confinement than as a rigid barrier to transport. We note and discuss this now more critically at several places in the manuscript (e.g., end of introduction, discussion). However, we keep the term "barrier" for the sake of having a clear terminology (and because of its frequent use in the existing literature).

As our analysis is carried out on surfaces of constant potential temperature using a modified PV by scaling with a $\theta$-dependent function, as used e.g. by Randel et al. (2006), would cause no change to PV-gradients and therefore to the fact whether a



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maximum gradient emerges or not (only the corresponding PV-value would change). To keep things as simple as possible we therefore don't introduce modified PV.

2. *The 380 K isentropic surface can well be representing the dynamic variability of the Asian monsoon anticyclone in the tropics and subtropics. However, as shown in the previous studies, the transport processes near the Asian monsoon region are occurring in the thick layer instead of on a surface. In fact, 360 K can be a better representative of the Asian monsoon anticyclone itself (where both the jet streams act as a boundary, see Fig. 1). Even though the transport barrier defined in this study is most distinguishable at 380 K surface, I think it is important to emphasize how the entire monsoon system has rather a layered structure and the method used in this study is subjective to the PV values itself. For example, based on Fig. 13 one can probably define transport barriers at 370 and 390 K as well based on smaller PV gradients over different equivalent latitudes.*

Indeed, maximum PV gradients can be found also at 370 and 390 K, as discussed in relation to Fig. 8 (already in the submitted version). This part has been moved to Sect. 4 in the revised version, to have its discussion at an earlier place in the paper. Moreover, we extended this paragraph to include now also a brief discussion about the layered structure of the monsoon system.

3. *Defining polar vortex edges, as in the previous studies, can be useful in knowing polar vortex breakdown dates and so on. Then how is the definition of transport barrier in the Asian monsoon anticyclone based on PV gradients useful? For example, can this diagnostics be used in quantifying vertical transport from the upper troposphere to stratosphere or size of the anticyclone? Are the characteristics of the transport barrier affected by the convective activities in the lower troposphere and the strength of vertical and horizontal circulations near the monsoon region? I think the importance (and usefulness) of defining anticyclonic transport barrier based on PV gradients has to be emphasized in a broader context in relation with dynamical and chemical variabilities of the monsoon anticyclone and convection.*



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For understanding the details and exact mechanisms of Asian monsoon transport into the lower stratosphere (e.g., of pollution) it is indeed important to know the degree of confinement inside the anticyclone. As shown in recent studies, the anticyclone is composed by air masses originating from different pathways, like upward transport inside the anticyclone core (Bergmann et al., 2013), or injection into the anticyclone edge by taifoons (Vogel et al., 2014). The mixing between these air masses and hence chemical reactions and lifetimes will depend on the degree of isolation of the core from the edge region. Furthermore, knowledge of the anticyclone core (inside the PV-barrier) offers a method to determine the anticyclone size and to tag air masses which are inside the anticyclone. This offers new opportunities for model studies as well as for the interpretation of measurements. A new paragraph in the discussion focuses on these issues.

Defining exact onset and breakdown dates of the anticyclone by using the determined PV-barrier seems problematic to us, because the anticyclone needs to be sufficiently strong for the PV-barrier criterion to hold. Hence, confinement of trace gases inside the anticyclonic circulation becomes evident from visual inspection of tracer maps already 1-2 weeks before the barrier can be determined. Likewise, when the anticyclonic circulation weakens tracer anomalies in the monsoon region remain a few weeks after the last date with a clear PV-gradient maximum. These issues are described and discussed now in Sect. 5.

For a more appropriate discussion of the relation between the transport barrier characteristics and convective variability, we now include timeseries of OLR and integrated diabatic heating rate (as proxies for convection) in Fig. 12. During end of July, the variability in the barrier and the related disagreement between PV- and CO-gradient maxima appear to follow strong convective activity with a lag of about a week, similar to the time lag between the anticyclone response and convection as found by Randel et al. (2006). Also during beginning of July and mid-end of August the increase in the barrier PV-value seems to follow strong convection. The significance of this observa-



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tion and the detailed mechanism involved need to be further studied. We discuss these issues now in Sect. 5 in relation to Fig. 12.

**Minor comments:**

P1, L59 – *is* → *and is*

We think this would change the meaning of the sentence and therefore we keep the old version. Please correct us if we are wrong!

P1, L60-67 – *It should be mentioned that why those simple methods are problematic or unsatisfactory and also how it affects the results of various diagnostics (related to major comment ♯ 1).*

The sentence has been slightly extended, and together with the extended discussion about the usefulness of determining the transport barrier (see reply to Issue 3) hopefully clarifies these issues.

P1, L68 – *What does 'physically motivated' mean?*

"Physically motivated" here should mean that the PV-gradient related transport barrier is based on conservation properties of the flow. The sentence has been reworded.

P2, L93 – *'We interpolated...'* → *What are the reasons for the horizontal interpolation and also what is the original grid of the ERA-interim data?*

The formulation in the submitted version was not correct - thanks for pointing this out! We used the ERA-Interim data on the $1^\circ \times 1^\circ$ horizontal grid as provided by the ECMWF and interpolated it only in the vertical.

P2, L57 – *in the monsoon* → *in the monsoon anticyclone*

Done.

P2, L150 – *At the end of this paragraph, a brief comment about CLaMS CO and ozone reproducing climatology and/or observations will be helpful.*



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The description of CO, ozone and mean age in the model has been extended, including appropriate references showing comparisons with observations in the UTLS.

P3, L176 → *model and simulations → model simulations and the satellite observations*

This formulation was indeed nonsense - Thanks for pointing this out! Sentence has been changed.

P3, L202 – *What are the boundaries of the Asian monsoon region here?*

This information was included in the caption of Fig. 3 (10°N-60°N and 10°W-160°E). We include it now also in the main text.

P3, L232 - *-10E → 10W?*

Changed!

P4, L320- 325 – *This is an interesting point. As the anticyclone itself won't disappear during this period, one can argue that this PV gradients-based method fails locating the transport barrier. Do the actual PV values and tracers maxima show clear boundary of the anticyclone during this period? Or the anticyclone is simply too weak to act as a transport barrier?*

Trace gas confinement inside the anticyclone (at 380K) can be seen already 1–2 weeks before the PV-gradient maximum clearly emerges, and remains also longer than the barrier may be determined. Our interpretation is that the anticyclonic circulation and the related confinement need to be sufficiently strong that the PV-gradient barrier criterion in the monsoon holds. This is more clearly discussed now in Sect. 5 and in the discussion (Sect. 7).

P5, L380-383 – *Is there any possible explanation to this feature?*

See our response to Major comment 3.

P5, L459 – *Also, there is a possibility that the monsoon anticyclone is not as isolated*



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*as the polar vortex or the jet stream.*

Indeed, we think this is the case! We significantly changed the whole discussion paragraph with the aim to clarify things.

P6, L548-550 – *More specific information about how this can be done?*

We included a new paragraph about the usefulness of the determined transport barrier in the discussion (see our reply to Major comment 3), and also briefly refer to this discussion here.

P7, L685 – *This citation year needs to be corrected from 2006 to 2007.*

Corrected!

P9, Fig. 2c – *The wind vectors are hard to see in this plot. Using slightly darker grey color should help. . P9, Fig. 4 – I have a feeling that the map projection underneath the PV contours is not correct. The secondary PV minimum on the left hand side should sit somewhere in the Middle East not over North America or Pacific (see Fig. 10 of Garny and Randel, 2013).*

Wind vectors in Fig. 2 are in darker grey now. Regarding Fig. 4 we cross-checked that the secondary PV minimum at 380 K on 6 July 2011 is indeed located above Northern America, and is related to Rossby-wave breaking occurring there on this particular day. Interestingly, at 360 K there is an additional PV minimum over the Middle East (as in Garny and Randel, 2013) also on this day, which is not detectable at 380 K.

P14, Fig.11b – *The crosses in this plot rather look like asterisks on top of filled circles, which make it harder to distinguish from the black diamonds. I would recommend using crosses or pluses in grey colors. Also related to this plot, I wonder why this method works the best in early July. If this method were going to be more practical, I would think it should work from the onset to the end of the summer monsoon.*

We changed the symbols in the figure (new Fig. 12) to improve the presentation quality.



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The discussion of the evolution of the PV-gradient maximum is now extended, including potential relations to convective activity (see reply to major comment 3).

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