Response to referee #3.

We thank the anonymous referee for the constructive comments that helped to improve the paper. All further questions/comments are answered/annotated in the following, the manuscript is changed accordingly. (Referee comments are emphasized in *italics*.)

General:

Validation of the chemistry climate models CCMs) with respect to their abilities to represent the Asian summer monsoon (ASM), especially the Asian monsoon anticyclone (AMA) is an important task for the atmospheric community. The paper uses MIPAS and ERA-Interim data to validate such CCMs; the comprehensive analysis is clear and well presented. In the second part, the interannual variability of the ASM/AMA system is considered. However, there are some major points which need a more detailed discussion.

Major points:

1. Fig 3 and 4
Both figures show the results relative to the tropopause pressure that is certainly a good idea. You write that in order to account for differences among the CCMs in the location of AMA, the mean anomaly averaged over 30 degree was "centered where the 150 hPA eastward directed divergence free zonal wind maximizes". However, I would like to see such differences in the model representation and would recommend to use a much simple averaging over 120-160E. Maybe you can make two figures for this (you do something similar in Fig 8). Furthermore, the most important information shown in Fig 3/4 are for me temperature anomalies (rather than wind anomalies) which are extremely difficult to read. A compromise could be to show wind anomalies in the absolute range 120-160E and temperature anomalies by using the relative coordinate defined by the wind maximum (and only to mention in the text that such "shifted" wind patterns are very similar for ERA-Interim and the MMOD analysis) .

Including an additional Figure into the manuscript will further enlarge it. In view of the statement included in the second major point and also referring to anonymous referee 2, Fig. 3 and 4 are no longer contained in the manuscript but rather moved to the supplementary material, provided with the revision of the manuscript.
However, we followed the recommendation of the referee to present two kinds of sectional averages for the core region of the AMA with one highlighting the temperature anomalies (shaded) for a fixed range 60-120°E (Fig. S2) and one with the currently used method to create the sectional averages and highlighting the wind anomalies (shaded) (Fig. S1).
The motivation for the original Fig. 4 (now Fig. S3) is to show the different meridional velocities at the western and eastern edges of the AMA, therefore the shading should highlight these differences.

2. Fig 10 and the discrepancy with Randel et al 2015
This is a very interesting and important point. However, a simple explanation referring to "different approach" is not enough for me. You can certainly repeat the Randel's procedure by using ERA-Interim H2O (instead of MLS like in Randel et al.). If you get a similar picture ("more convection makes a dry anomaly") than is your statement ("different approach") correct. Otherwise, without such a test you have a "confusing result" if compared with the published work of Randel et al 2015.

We followed the advice of the anonymous referee and analysed the ERA-Interim data (water vapour, temperature, and horizontal wind components) and NOAA OLR data in the same way as it was done by Randel et al. (2015) (R15). We created wet and dry composites on the basis of daily data from May to September for years from 2005 – 2013, to be as much comparable to R15 as possible (Fig. 1). We did the same kind of analyses for daily data from July to August for years from 1979 – 2013 (Fig. 2), to be comparable with the regression analyses of the manuscript. As in R15 the ERA-Interim data were pre-processed with the multiple linear regression model (MLR), to create a time series of daily ERA-Interim data without trend, and QBO/ ENSO induced variability. When using the same time periods as R15, i.e. data from May to September for years from 2005 – 2013, we get similar OLR anomalies over the region 20-30°N/90-120°E, which was identified by R15 as the key convective region, showing reduced convective activity over this region for the wet composite and intensified convective activity for the

dry composite (s. Fig. 1, top). Also the structure of the temperature anomalies are similar to R15, although less pronounced for the wet anomalies (s. Fig. 1, second row).
When we repeat the analyses with data covering only July to August but using the years from 1979 – 2013 we can confirm the OLR anomalies shown in Figure 1 over the region 20-30°N/90-120°E and also the structure of the temperature anomalies, with the temperature anomalies of the wet composite now more pronounced. But for the adjacent region in the south, extending from the Indian subcontinent, the Bay of Bengal (BoB) to Vietnam, we get the opposite anomalies with more intense convective activity for the wet composite and reduced convective activity for the dry composite (s. Fig. 2, top). Based on the results of Figure 2 and based on the results of the MLR for the monsoon circulation index (MIDX) (see Figure 10 of the manuscript) we come to the conclusion that the wet anomalies are connected with a more intense Asian summer monsoon. From this comparison it seems that the differences to R15 can partly be explained by a different time period used in their study. It seems that the differences to R15 are partly due to a different representation of the ASM intensity. The conclusions drawn from the additional analyses are included in the revised manuscript. Two additional Figures are part of the supplementary material.

. . . Furthermore, the paper is in my opinion too long. I would recommend to publish two parts: (1) validation with MLS/ERA-Interim and (2) Iterannual variability. But, that is your decision.

Section 3 is now shortened, as Fig. 3 and 4 moved to the supplementary material. However, we don't want to separate the paper into two parts.

Minor points:

1. General
In almost all your figures you use a matrix of sub-panels. It would be easier to read such figures if you would denote every row and every column separately. E.g. Fig 5/6 θ = 360 370, 380 K for the rows and MIPAS/MMOD for the columns.

We followed the advice and organised the labelled Figures by rows and columns.

2. P1, abstract, L14-15
please mention "zonally asymmetric ENSO response versus zonally symmetric QBO modulation"

We have included a more detailed description of the QBO modulation in the abstract of the revised manuscript.

3. P1, L24
first "wave-driven" forcing, followed by heat transport from the tropics to the high latitudes and, finally slow ascent due to radiative heating - please reformulate

The intention was to characterize the vertical transport confined to tropical latitudes, rather than to describe the full picture of the meridional tracer transport in the middle atmosphere. The section is now rewritten to avoid any misunderstanding.

4. P 2, L 20-25
To discuss the importance of the Tibetan Plateau you should also mention the Boos and Kuang, Nature 2010 paper stating that for the formation of the Asian monsoon circulation pattern orography is the most important factor and the impact of sensible heat (Tibetan Plateau) is rather a second order effect

This alternative result of Boos and Kuang (2010) are now cited in the revised manuscript.

5. P3 L 10-13
Maybe you should discus it more carefully: the core of the anticyclone is rather in the extratropics than in the tropics. Furthermore, the anticyclone itself acts more as an isentropic blower. Inside of the anticyclone the the tropospheric pollution are

trapped and probably transported into the TTL (Randel et al., Science, 2010). Outside of the anticyclone a strong in-mixing of stratospheric signatures into the TTL happens (see related paper from Konopka et al and Ploeger et al)

This paragraph is now revised and extended by a short comment on in-mixing, as it was analysed by Konopka et al. (2009) and Ploeger et al. (2012).

6. P3 L14
...(QBO) or the "internal variability of the ASM iteslf".

This is now specified as proposed.

7. P4, L26
"aspects of the climatological state are compared with" - which aspects, please reformulate

This is now formulated more specifically.

8. P6, caption Fig 1
please use the abbreviation WIDX

The revised version of Figure 1 does not include the Walker circulation index (WIDX) any more.

9. P6, L5
"graduate" - I am not sure that this is a right word. Maybe "mask" or "suppress"

We reformulated the sentence.

10. P7, L5
Explain the vector k

Done.

11. P9 L2
Use the notation ψ for the divergence-free part of the flow. Same for χ (which were defined in the previous section).

Done.

12. P12 Fig 5
The enhanced signatures of H2O north of 30N seem to propagate eastward mainly by planetary waves as described by Ploeger et al. Maybe you would like to include some comments about this point

A short statement on this is now included in the manuscript and the reference to Ploeger et al. (2013) is given.

13. P14 Fig 7
There are much lower temperatures at 380 K for MMOD than for ERA. On the other side MMOD are moister compared with MIPAS. You should comment this point

There are different points used for the statistics of the H2O maximum and the temperature minimum in the region enclosed by the rectangle at 380 K. Whereas the lowest temperatures are located at the southern edge of the AMA the maximum in H2O within the rectangle is located on average at the north-eastern corner of the rectangle.

14. P14 L9
"O3 in the UTLS can better serve as a passive tracer..." - maybe you can make this point earlier, e.g. as you introduce O3 into your discussion

The sentence has moved to the beginning of the paragraph.

15. P15 Fig 8
After the major point 1 was included, Fig 8 would be easier to understand

The major point 1 is only included in the supplementary material, but we hope that the information given by the additional Figure can be helpful to understand the Figure still included.

16. P15 last sentence and P16 first sentence
This feature was discussed in literature as in-mixing, see Konopka et al 2009, 2010, Ploeger et al 2012. Maybe you would like to include these references into your discussion

The suggested references are now taken into account.

17. P17 caption of Fig 7 (and Fig 2)
You introduced the decomposition given by the eq (1) but you do not use the introduced notation. Please state it explicitly if you show ψ, χ, χ^* , etc.

Done.

18. P17 L13
For me MIDX is a more direct measure of the anticyclone rather than of the whole ASM system

Please see our response to point 21 below.

19. P18 Fig 10 and the discrepancy with Randel et al 2015 see major point 2

Please see our response to major point 2.

20. P19 Fig 11
I think, you use the ERA-Interim related results too strong as a benchmark for the following investigations. Whereas ERA-Interim temperatures and probably H2O are good enough for your study, ERA-Interim ozone around and below the tropical tropopause is probably not good enough for that (mainly because only O3 column is constrained by sat elite observations as described in Dragoni et al., 2011) . In the following you describe large differences in ozone between multimodel average of the CCMs and the ERA-Interim. I would recommend to exclude completely the ERA-Interim ozone.

Because ozone has a relatively long lifetime in the UTLS region it can be used as a complementary dynamical tracer. Due to a lack of a direct observational constraints we should not expect that ERA-Interim ozone matches absolute (in-situ observed) ozone values well, but interannual variability and thus regression patterns should generally be matched reasonably well. We have included a "health warning" in the manuscript.

21. P20 L7
"As MIDX is a direct measure of the strength in upwelling" - for me MIDX is a direct measure of the (divergence) of the

anticyclone, please re-formulate

The MIDX is created from the transient eddy part (i.e. after subtracting the zonal average) of the velocity potential (χ*'). The maxima in χ*', the individual values of the MIDX, are thus taken from a purely divergent field. We agree with the referee that the horizontal divergence is connected to the horizontal, purely rotational (divergence free) circulation, as the maximum of the horizontal divergence occurs where the streamlines of two reversed circulation cells diverge. On the western side of the respective maximum in χ*' the anticyclonic flow of the AMA is located, whereas on the eastern side cyclonic flow prevails. For continuity reasons the divergence has to be connected with upwelling, which can be seen as connected with convective uplift.
We have reformulated the sentence to emphasize the importance of the upper tropospheric divergence.

22. P20 L9
...or have increased H2O or less O3

23. P20 L10
...or decreased H2O or higher O3

This serves as a general introduction of the MIDX regression coefficients for positive or negative signs. When a variable increases with increasing MIDX, we get a positive regression coefficient and vice versa. The statements are not meant to describe the regression coefficients that should be expected in the monsoon anticyclone.

24. P21 L17
"The negative O3 caused...." - I do not understand your explanation. Negative O3 anomaly means a stronger tropospheric influence (more upwelling) that is in agreement with the positive H2O anomaly. Please clarify

Both, the negative O3 anomalies and the negative temperature anomalies are nearly co-located with each other and also with the anticyclonic anomalous circulation pattern. There is no contradiction to the positive H2O anomaly that extends over larger parts of the AMA (at 380 K as well as at 100 hPa). The positive H2O anomaly seems to be more related to the positive temperature anomaly at the southern edge of the AMA.
This is now also discussed in the revised manuscript.

25. P22 L15
"unexpected positive response" - see comments above to ERA-Interim ozone

We added a comment about the limitations of the ERA-Interim O3 data.

26. P25 L23
"many regions" - please list these regions

The regions are now explicitly listed.

27. P26 L17
...suggest transport of H2O through this region

H2O is now explicitly stated.

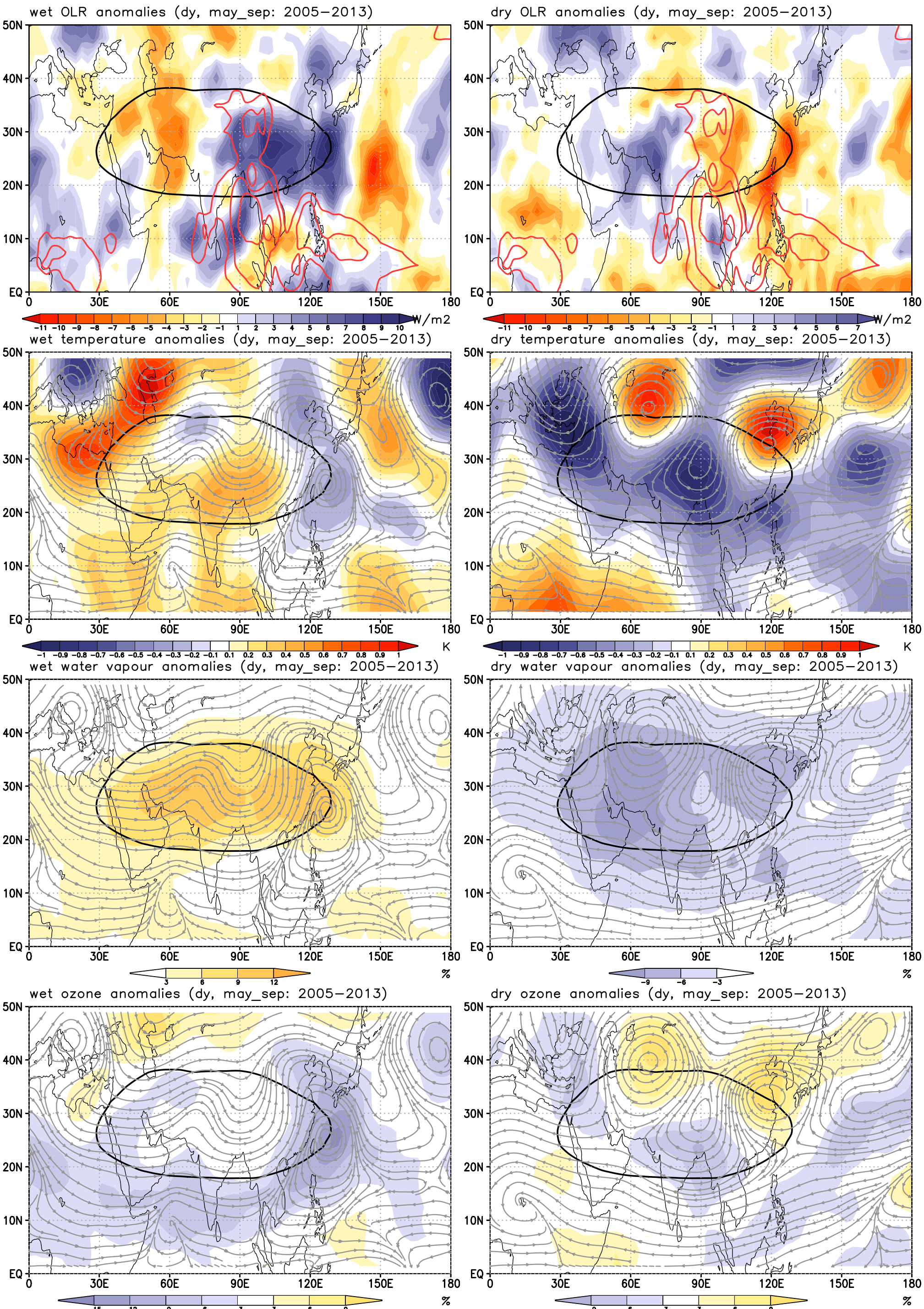

Figure 1. Composited anomalies for wet (left) and dry (right) 100 hPa ERA-Interim water vapor extrema from May to September over the Asian monsoon region (20–40°N, 40–140°E) analysed for years from 2005–2013, from top to bottom for NOAA OLR, ERA-Interim temperature, water vapour, and ozone without QBO and ENSO variability. Overlaid as streamlines in grey are the composited horizontal wind anomalies; the 16.750 m geopotential height contour is overlaid in black. Results for OLR are shown averaged 0–10 days prior to the stratospheric water vapour extrema; overlaid red contours indicate climatological OLR values ≤ 220 W m^{-2}. Adapted from Randel et al. (2015).

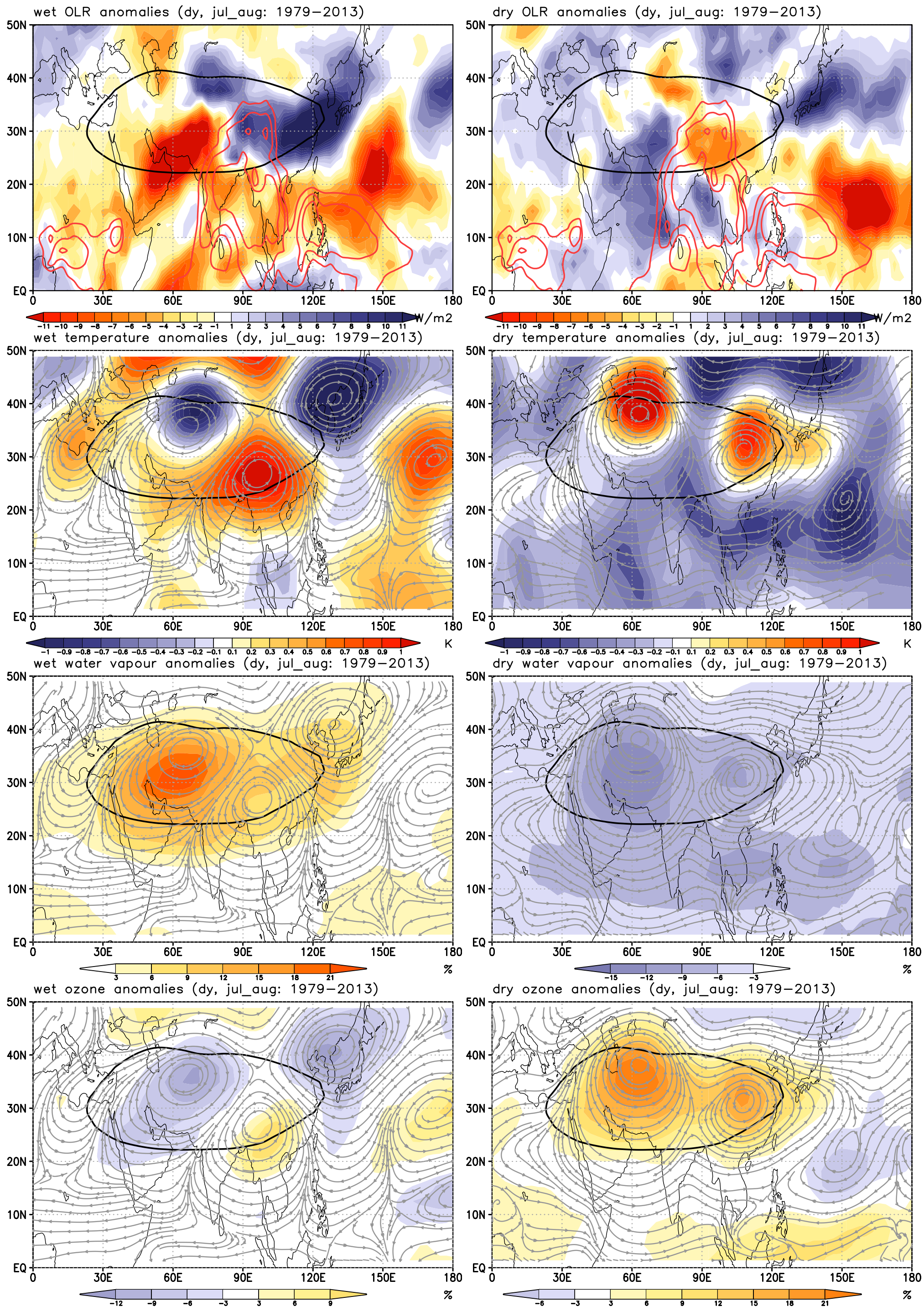

Figure 2. As Fig. 1 but using data from July to August for years from 1979–2013.

References

Boos, W. R. and Kuang, Z.: Dominant control of the South Asian monsoon by orographic insulation versus plateau heating, Nature, 463, 218–222, doi:10.1038/nature08707, http://dx.doi.org/10.1038/nature08707, 2010.

Konopka, P., Grooß, J.-U., Plöger, F., and Müller, R.: Annual cycle of horizontal in-mixing into the lower tropical stratosphere, J. Geophys. Res.: Atmos., 114, doi:10.1029/2009JD011955, http://dx.doi.org/10.1029/2009JD011955, d19111, 2009.

Ploeger, F., Konopka, P., Müller, R., Fueglistaler, S., Schmidt, T., Manners, J. C., Grooß, J.-U., Günther, G., Forster, P. M., and Riese, M.: Horizontal transport affecting trace gas seasonality in the Tropical Tropopause Layer (TTL), J. Geophys. Res.: Atmos., 117, doi:10.1029/2011JD017267, http://dx.doi.org/10.1029/2011JD017267, d09303, 2012.

Ploeger, F., Günther, G., Konopka, P., Fueglistaler, S., Müller, R., Hoppe, C., Kunz, A., Spang, R., Grooß, J.-U., and Riese, M.: Horizontal water vapor transport in the lower stratosphere from subtropics to high latitudes during boreal summer, J. Geophys. Res.: Atmos., 118, 8111–8127, doi:10.1002/jgrd.50636, http://dx.doi.org/10.1002/jgrd.50636, 2013.

Randel, W. J., Zhang, K., and Fu, R.: What controls stratospheric water vapor in the NH summer monsoon regions?, J. Geophys. Res.: Atmos., doi:10.1002/2015JD023622, 2015.