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Manuscript title: The regional distribution characteristics of aerosol optical depth over the Tibetan Plateau

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We would like to thank the editor and reviewer for their valuable comments and suggestions, which contribute to improve the quality of our paper. In the response, we first summarize major revisions, and then present the item-by-item response to the reviewer's comments.

Major revisions

1. According to suggestion of Anonymous Referee #1, we made more discussions about the uncertainties in characterization of aerosol type from CALIPSO. See Section 2 in the revised manuscript, please. We also deleted the redundant and improper sentences in our former manuscript, and modified the ambiguous expressions.

2. According to suggestion of Anonymous Referee #2, we made more discussions about the estimated uncertainties and cloud contamination on the MISR data. See Section 2 in the revised manuscript, please. We also made some discussions about aerosol intrusion in stratosphere. See Section 3.3 in the revised manuscript, please. The conclusions were rewritten in the revised manuscript. See Section 4 in the revised manuscript, please.

3. The possible factors influencing the transport of aerosols to the TP are better discussed, including the emission sources, high altitude terrain and atmospheric circulation. See Section 3.4 in the revised manuscript, please.

<u>Response to Anonymous Referee #1</u>

<u>Comment</u>

The article contains some interesting results regarding aerosol optical depth (AOD), aerosol type, and aerosol vertical distribution analysis over the Tibetan Plateau. It is an observational study using long term MISR AOD retrievals and CALIPSO aerosol type characterization over the TP. The paper is primarily descriptive, offering some limited insights into possible causes of aerosol distribution over the region. The authors use the ERA-Interim reanalysis to show seasonal meteorology (winds) in the area and to link the atmospheric circulation with AOD distribution over the TP. Generally, the study presents some useful, although rather limited science results.

<u>Response</u>

Thank you very much for positive evaluation. We appreciate the comments and suggestions, which are helpful to the quality of this manuscript.

General comments.

The authors do not elaborate on limitations of the satellite datasets, neither use ground-based observations to justify the representativeness of satellite retrievals in the region. In particular, the uncertainties in characterization of aerosol type from CALIPSO are not discussed in sufficient detail. The pure dust samples over the northern India appear excessive (Figure 3). One would expect higher concentration of anthropogenic pollution in this area. Furthermore, some analyses of smoke samples over the TP seem dubious, as they are not directly linked to the sources south from the TP.

<u>Response</u>

Thank you very much for your very good and detail suggestions and comments. We are very grateful that you point out the inadequacy in this study, which contribute to improve the quality of our paper. We searched the literatures, and made more discussions about the estimated uncertainties on the MISR data. Please see detail in

Section 2 Page 5 line 8-13. We also made more discussions about the uncertainties in characterization of aerosol type from CALIPSO. Please see detail in Page 6 line 27-29 and Page 7 line 1-15 in the revised manuscript.

We think the results of desert dust over the northern India are reliable. Previous validation studies showed the best agreements for the aerosol type of desert dust. Not only dust but also polluted dust samples are shown over the northern India. Polluted dust samples include anthropogenic pollution. The Thar Desert, known as the Great Indian Desert, is located in the northwestern part of the Indian subcontinent. Gautam et al. (2011) reported high dust loading during the pre-monsoon season based on Aerosol Robotic Network (AERONET) observations. Based on the Moderate Resolution Imaging Spectroradiometer (MODIS), AERONET and Total Ozone Mapping Spectroradiometer (TOMS) data, Jethva et al. (2005) indicated coarse-mode particles (dust) were dominant during April to June over Indo-Gangetic Basin, and the entire Indo-Gangetic basin was dominated by the fine-mode particles during the winter. Ramachandran and Cherian (2008) also revealed dust activity peaked over north and west India during March to May. Therefore, we think the result of dust is reliable.

We appreciate your careful reading and valuable comment. The previous expression is not appropriate. Smoke samples over the central TP are not directly linked to the sources from the northern India. We added the sentence 'Detected smoke samples are a bit higher in the central TP in summer, which may be due to local emission.' to be more accurate. Please see detail in Page 12 line 28-29 in the revised manuscript.

Please see the following reference:

- Gautam, R., Hsu, N. C., Tsay, S. C., Lau, K. M., Holben, B., Bell, S., Smirnov, A., Li, C., Hansell, R., Ji, Q., Payra, S., Aryal, D., Kayastha, R., and Kim, K. M.: Accumulation of aerosols over the Indo-Gangetic plains and southern slopes of the Himalayas: distribution, properties and radiative effects during the 2009 pre-monsoon season, Atmospheric Chemistry and Physics, 11, 12841-12863, 10.5194/acp-11-12841-2011, 2011.
- Jethva, H., Satheesh, S. K., and Srinivasan, J.: Seasonal variability of aerosols over the Indo-Gangetic basin, Journal of Geophysical Research: Atmospheres, 110, D21204, 10.1029/2005JD005938, 2005.

- Ramachandran, S., and Cherian, R.: Regional and seasonal variations in aerosol optical characteristics and their frequency distributions over India during 2001–2005, Journal of Geophysical Research: Atmospheres, 113, D08207, 10.1029/2007JD008560, 2008.

Specific comments

1. It would be beneficial to have the geographic regions mentioned in the text labeled on the topographic map in Fig. 7. A reader might not be very familiar with names such as Quaidam Basin, Tarim Basin, Hexi Corridor, the mentioned mountain ranges on the TP and the corridors in the Himalayas. As the impact of topography is extensively discussed in the study, proper labeling will improve readability.

Response

Thank you very much for your helpful suggestion and comment. We followed your suggestion and labeled these names in this Figure. We also made some descriptions 'The TP is surrounded by several deserts, including Taklimakan Desert in Tarim Basin, Gobi Desert and the deserts in Southwest Asia and Middle East. Indo-Gangetic Plains are located to south of the TP, with high aerosol loading (Gautam et al., 2011). Several mountains are located on the TP, including Himalayas Mountains, Gangdise Mountains, Nyainqentanglha Mountains, Tangula Mountains and Kunlun Mountains. The elevation differences of these mountains are at least 500m and usually 1000 m or even more compared with the surrounding areas.' in Page 2 line 20-26 in the revised manuscript. We moved this figure before other figures followed the suggestion of Referee 2. Please see Figure 1 in the revised manuscript.

We also added the following reference in the references list in the revised manuscript :

- Gautam, R., Hsu, N. C., Tsay, S. C., Lau, K. M., Holben, B., Bell, S., Smirnov, A., Li, C., Hansell, R., Ji, Q., Payra, S., Aryal, D., Kayastha, R., and Kim, K. M.: Accumulation of aerosols over the Indo-Gangetic plains and southern slopes of the Himalayas: distribution, properties and radiative effects during the 2009 pre-monsoon season, Atmospheric Chemistry and Physics, 11, 12841-12863, 10.5194/acp-11-12841-2011, 2011.

2. In the abstract, I find it confusing that the authors talk about a natural boundary that extends to an altitude of 6-8 km. The boundary discussed in the text is between the more polluted northern TP and the less polluted southern TP. I don't understand the need to mention the height of the boundary, which is a horizontal (latitudinal) phenomenon. The aerosol layer, according to the CALIPSO data, extends to about 6-8 km.

Response

Thank you very much for your comment. Higher dust occurrence in the northern TP and lower dust occurrence in the southern TP can be observed. This is actually a latitudinal phenomenon. Three-dimensional distributions of aerosols can be investigated based on CALIPSO data. In vertical distributions, more dust layers are detected over the northern TP, which can be seen from surface to a height of 6-8 km. Therefore, we mention the height of this dividing line. The expression of boundary may be confusing and not appropriate. We followed your suggestions and changed the previous sentences into 'A dividing line of higher dust occurrence in the northern TP and lower dust occurrence in the southern TP can be observed clearly at altitude of 6~8 km above sea level, especially in spring and summer.'. Please see in Page 2 line 6-8 in the revised manuscript.

3. (in abstract) "... it is possibly associated with the high altitude terrain in the same geographic location." How high is this mountain range in comparison to the surrounding terrain?

Response

Thank you very much for your valuable and helpful comment. We are grateful that you point out this issue which we have ignored before. From Figure 1 in the revised manuscript, we can know that most of Tangula Mountains are above 5500 m. The surrounding regions are about 500 m - 1000 m lower than the mountains. We made some descriptions about the mountain ranges on the TP and highlighted the elevation difference in the introduction. The sentences are 'Several mountains are located on the TP, including Himalayas Mountains, Gangdise Mountains, Nyainqentanglha

Mountains, Tangula Mountains and Kunlun Mountains. The elevation differences of these mountains are at least 500m and usually 1000 m or even more compared with the surrounding areas.' in Page 2 line 23-26 in the revised manuscript.

4. (in abstract) "The whole TP blocks the atmospheric aerosols ... on the TP also cause an obstruction to the transport of aerosols". This sentence is unclear and appears redundant.

Response

Thank you very much for your comment. We followed your suggestion and deleted this sentence in the revised manuscript.

5. (page 4, line 5-6) How is the special pattern consistent with the vertical distribution?

Response

Thank you very much for your comment. We mean that AOD is higher over the northern TP than the southern TP. Dust is the main aerosol type over the TP. In the vertical distribution, the dust occurrence is also higher over the northern part than the southern part of the TP. Therefore, the special pattern is consistent with the vertical distribution.

6. (p6, line 18) It should be ~15 instead of ~10 years.

Response

Thank you very much for your comment. We followed your suggestion and changed '~10 years' into '~15 years'. Please see in Page 7 line 28 in the revised manuscript.

7. (p6, line 25-26) What is the elevation difference of these mountain ranges with respect to their surrounding area?

Response

Thank you very much for your comment. We redrew the elevation figure with a new color to highlight the elevation difference. Tangula Mountains are located in the middle of the TP. From the topography of the TP, we can know the mountain ranges are usually higher than 5500 m. On the two sides of the mountain ranges, the elevations vary from 4000 m to 5000 m. The elevation differences of these mountain ranges with respect to their surrounding areas vary from 500 m to 1000 m or even more. We highlighted the elevation difference in the Introduction section. The sentences are ‘Several mountains are located on the TP, including Himalayas Mountains, Gangdise Mountains, Nyainqentanglha Mountains, Tangula Mountains and Kunlun Mountains. The elevation differences of these mountains are at least 500m and usually 1000 m or even more compared with the surrounding areas.’. Please see detail in Page 2 line 23-26 in the revised manuscript.

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8. (p7, line 10) Mentioning “high precipitation” is not justified. Precipitation does not obstruct AOD retrievals; clouds do.

<u>Response</u>

Thank you very much for your valuable comment and pointing out the unsuitable place. We followed your suggestion and changed this sentence into ‘Unfortunately, AOD over the southeast TP cannot always be determined in each season due to thick cloud.’. Please see detail in Page 8 line 22-23 in the revised manuscript.

9. (p7, 12-13) Repetition. This sentence repeats what was already said before.

<u>Response</u>

Thank you very much for your comment. We followed your suggestion and deleted this sentence in the revised manuscript.

10. (p7, 16-17) Tarim Basin and northern India do not have “extremely high” AOD values in each month. For example, Tarim Basin has small and medium AODs in fall and winter.

<u>Response</u>

Thank you very much for your valuable comment. We are grateful that you point out this issue. We deleted this sentence here, and discussed the influence of emission sources over the surrounding regions in Section 3.4. The sentences are ‘Much higher aerosol loads are observed over the surrounding regions of the TP. AOD peaks during spring and summer over Tarim Basin. “Strong anticyclonic wind anomaly at 500 hPa and enhanced easterly wind at 850 hPa” over the Tarim Basin during spring and summer are good for dust entrainment, vertical lofting, and horizontal transport (Ge et al., 2014). Indo-Gangetic basin, encompassing most of northern India peninsula, extends from Pakistan in the west to Bangladesh in the east. Indo-Gangetic basin is one of the most heavily populated regions of the world. There are a large quantity of emissions of biomass burning and fossil fuel over South Asia, where is adjacent to the TP (Ramanathan et al., 2005). AOD over the Indo-Gangetic basin can reach extremely high values throughout the year, peaking during spring and summer due to enhanced emission of natural aerosols (Dey and Di Girolamo, 2010). Furthermore, aerosols layers exist above the TP over the northern Indian peninsula and Tarim Basin during spring and summer. Dust and polluted dust layers exhibit a relatively greater thickness over the regions north of the TP than the regions south of the TP during spring and summer. The aerosol concentrations and the heights of aerosol layers over the surrounding regions have great influences on the transport of aerosols.’. Please see detail in Page 14 line 4-20 in the revised manuscript.

We also added the following references in the references list in the revised manuscript :

- Dey, S., and Di Girolamo, L.: A climatology of aerosol optical and microphysical properties over the Indian subcontinent from 9 years (2000–2008) of Multiangle Imaging Spectroradiometer (MISR) data, Journal of Geophysical Research, 115, 10.1029/2009jd013395, 2010.
- Ge, J. M., Huang, J. P., Xu, C. P., Qi, Y. L., and Liu, H. Y.: Characteristics of Taklimakan dust emission and distribution: A satellite and reanalysis field perspective, Journal of Geophysical Research: Atmospheres, 119, 2014JD022280, 10.1002/2014JD022280, 2014.
- Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J. T., Washington, W. M., Fu, Q., Sikka, D. R., and Wild, M.: Atmospheric brown

clouds: impacts on South Asian climate and hydrological cycle, Proceedings of the National Academy of Sciences of the United States of America, 102, 5326-5333, 10.1073/pnas.0500656102, 2005.

11. (p7, 17-18) Repetition.

<u>Response</u>

Thank you very much for your comment. We followed your suggestion and deleted this repetitive sentence in the revised manuscript.

12. (p7, 22) It should be fifteen years.

<u>Response</u>

Thank you very much for your comment. We followed your suggestion and changed 'ten years' into 'fifteen years'. Please see the sentence in Page 9 line 4 in the revised manuscript.

13. (p7, 22) Repetition.

<u>Response</u>

Thank you very much for your comment. We followed your suggestion and deleted this repetitive sentence in the revised manuscript.

14. (p7, 24-28, and p8, 1-4) This section could be shortened and better organized. Some sentences could be combined to offer a better flow.

<u>Response</u>

Thank you very much for your valuable comment. We followed your suggestion and organized these sentences. The revised sentences are 'The aerosol load is relatively high over the northern TP during April to June, while it is high over the southern TP during June to August. Single monthly peak occurs over both the northern and southern TP. The monthly peak is observed in May and July, respectively. Moreover, the monthly zonal peak of AOD in the northern TP is about 1.5 times that in the southern part. Previous studies showed similar results based on surface observations (Gobbi et al., 2010; Xu et al., 2014). The zonal means over the whole TP are even below 0.10 during November to January.’. Please see in Page 9 line 5-11 in the revised manuscript.

15. (p9, 14-18) Confusing analysis of the height of the boundary. See point 2 above.

<u>Response</u>

Thank you very much for your comment. We mean that obvious different dust occurrences were observed at the regions north and south of a line. This line seems to divide the dust occurrences on the whole TP. This phenomenon can be seen clearly from the surface to a height of 6~8 km in vertical distributions. The expression of boundary may be confusing and not appropriate. We changed the previous sentences into ‘The demarcation of dust occurrence between the northern and southern TP can be seen clearly from surface to a height of about 6~8 km during spring, while it becomes unapparent at high altitudes. Dust layer can only extend to the altitudes of 8~10 km over the TP during summer, and the demarcation appears to be obvious at an altitude of less than 7 km.’ in Page 11 line 7-11 in the revised manuscript.

16. (p9, 18-19) “Dust occurs much less frequently above the TP in autumn and winter,...” Repetition.

<u>Response</u>

Thank you very much for your comment. We followed your suggestion and deleted this repetitive sentence in the revised manuscript.

17. (p9, 22-23) Could you offer an explanation for that?

<u>Response</u>

Thank you very much for your comment. Dust usually occurs frequently to the north of the TP in each season, and dust occurs relatively frequently to the south of the TP in spring. More detected dust samples are shown over the northern TP than the southern TP. Dust aerosol layer need to be higher than the northern or southern edge of the TP, which is a requirement for aerosol transport to the TP. The altitude of the northern edge is much lower than the southern edge. The Himalayas Mountains located at the southern edge effectively block the transport of dust into the TP. The blocking effect may be weaker on the northern edge than the southern edge with lower altitude. Therefore, we make this inference. We followed your suggestion and made some more explanations 'Aerosol layer firstly needs to be present higher than the TP elevation, which is a requirement for aerosol transport to the TP. Apparently the southern edge is much higher than the northern edge of the TP. The transport of aerosols from north of the TP seems easier rather than south of the TP.' in the discussions in Page 14 line 28-29 and Page 15 line 1-2 in the revised manuscript.

18. (p10, 12-13) The scale is saturated, therefore it is impossible to see any differences in vertical distribution even if they existed.

Response

Thank you very much for your valuable comment. We appreciate that you find this sentence not accurate. We meant that the occurrences of polluted dust in column over the TP did not change obviously in each season. But some differences in vertical distribution of polluted dust actually exist. This sentence is not accurate. Therefore, we deleted this sentence in the revised manuscript. We would like to use the same color bar in all figures of vertical distribution. The color bar we used could highlight the differences of dust occurrences on the TP well, and then we did not change the color bar in this figure at last.

19. (p10, 17) Redundant.

Response

Thank you very much for your comment. We followed your suggestion and deleted this unnecessary sentence in the revised manuscript.

20. (p10, 22-23) This is too obvious.

Response

Thank you very much for your comment. We followed your suggestion and deleted this unnecessary sentence in the revised manuscript.

21. (p11, 1-12) In the smoke analysis, smoke appears to be disconnected from sources to the south and north of the TP. This is especially visible in summer. There is slightly higher sampling in the central TP, whereas you would expect higher smoke samplings closer to potential sources in the northern India. It suggests that local sources might be at play?

Response

Thank you very much for your valuable and helpful comment. We have ignored this issue before. Detected smoke samples are a bit higher in the central TP in summer. We added the sentence 'Detected smoke samples are a bit higher in the central TP in summer, which may be due to local emission.' to be more accurate in the revised manuscript. Please see Page 12 line 28-29 in the revised manuscript.

22. (p11, 13-24) Could you elaborate a bit about CALIPSO uncertainties in determining aerosol type? Maybe some of the features you analyze are merely instrument or algorithm artifacts? See the general comment.

Response

Thank you very much for your valuable and constructive comment. The comment and suggestion are quite helpful to the quality of this manuscript. We followed your suggestion and added more discussions in Section 2 about CALIPSO uncertainties in determining aerosol type. The sentences are 'The classification algorithms use the integrated attenuated backscatter measurements, the volume depolarization ratio measurements, surface type and layer altitude to determine aerosol type (Omar et al., 2009). The similarity of the optical properties between polluted continental and smoke aerosols makes the classification of these two aerosol types difficult (Omar et al., 2009). Mielonen et al. (2009) made comparisons of Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) level 2 aerosol types and those derived from Aerosol Robotic Network (AERONET) inversion data. The results revealed the greatest agreement for the dust type (91 %), moderate agreement for the polluted dust type (53 %), and poorer agreement for smoke (37 %) and for polluted and clean continental combined (22 %). Burton et al. (2013) made comparisons of aerosol types between CALIPSO and airborne High Spectral Resolution Lidar, which showed the best agreement for desert dust (80 %) and marine aerosols (62 %), moderate agreement for the polluted continental aerosols (53 %), but relatively poor agreement for polluted dust (35 %) and smoke (13 %). Although previous studies showed different results of quantitative validations, these researches indicated the classifications for dust aerosols were reliable. Moreover, it is necessary to state that the classifications of smoke aerosols presented here are subject to large uncertainty.' in Page 6 line 27-29 and 7 line 1-15 in the revised manuscript.

Several quality control flags are used to get level 3 data. The uncertainties are random, and CALIPSO uncertainties are same on the northern and southern TP. The classifications of dust aerosol are most reliable. The differences of vertical dust occurrences between the northern and southern TP do exist. We think that the misclassifications of aerosol types sometimes occur, but the uncertainties will not lead to the significant differences between the northern and southern TP. The classifications of smoke aerosols presented may be subject to large uncertainty. The vertical distributions are real, but not due to instrument or algorithm artifacts.

We also added the following references in the references list in the revised manuscript :

- Burton, S. P., Ferrare, R. A., Vaughan, M. A., Omar, A. H., Rogers, R. R., Hostetler, C. A., and Hair, J. W.: Aerosol classification from airborne HSRL and comparisons with the CALIPSO vertical feature mask, Atmos. Meas. Tech., 6, 1397-1412, 10.5194/amt-6-1397-2013, 2013.
- Mielonen, T., Arola, A., Komppula, M., Kukkonen, J., Koskinen, J., de Leeuw, G., and Lehtinen, K. E. J.: Comparison of CALIOP level 2 aerosol subtypes to aerosol types derived from AERONET inversion data, Geophysical Research Letters, 36, L18804, 10.1029/2009GL039609, 2009.
- Omar, A. H., Winker, D. M., Vaughan, M. A., Hu, Y., Trepte, C. R., Ferrare, R. A., Lee, K.-P., Hostetler, C. A., Kittaka, C., Rogers, R. R., Kuehn, R. E., and Liu, Z.: The CALIPSO Automated Aerosol Classification and Lidar Ratio Selection Algorithm, Journal of Atmospheric and Oceanic Technology, 26, 1994-2014, 10.1175/2009JTECHA1231.1, 2009.

23. (p11, 21) Unclear and redundant.

Response

Thank you very much for your comment. We deleted this sentence in the revised manuscript.

24. (p11, 26-27) "... aerosols hardly come from local contributions." Any proof? Citations?

Response

Thank you very much for your valuable and helpful comment. The previous expression is not rigorous. We followed your suggestion and added some references. We changed the previous sentences to 'The TP has quite pristine atmospheric conditions, that is to say, few aerosols come from local contributions. Zhang et al. (2015) showed local emissions contributed only a small percentage of BC in the Himalayas and Tibetan Plateau. There are no obvious sources of biomass burning on the TP (Mouillot and Field, 2005).'. Please see detail in Page 13 line 19-22 in the revised manuscript.

We also added the following references in the references list in the revised manuscript :

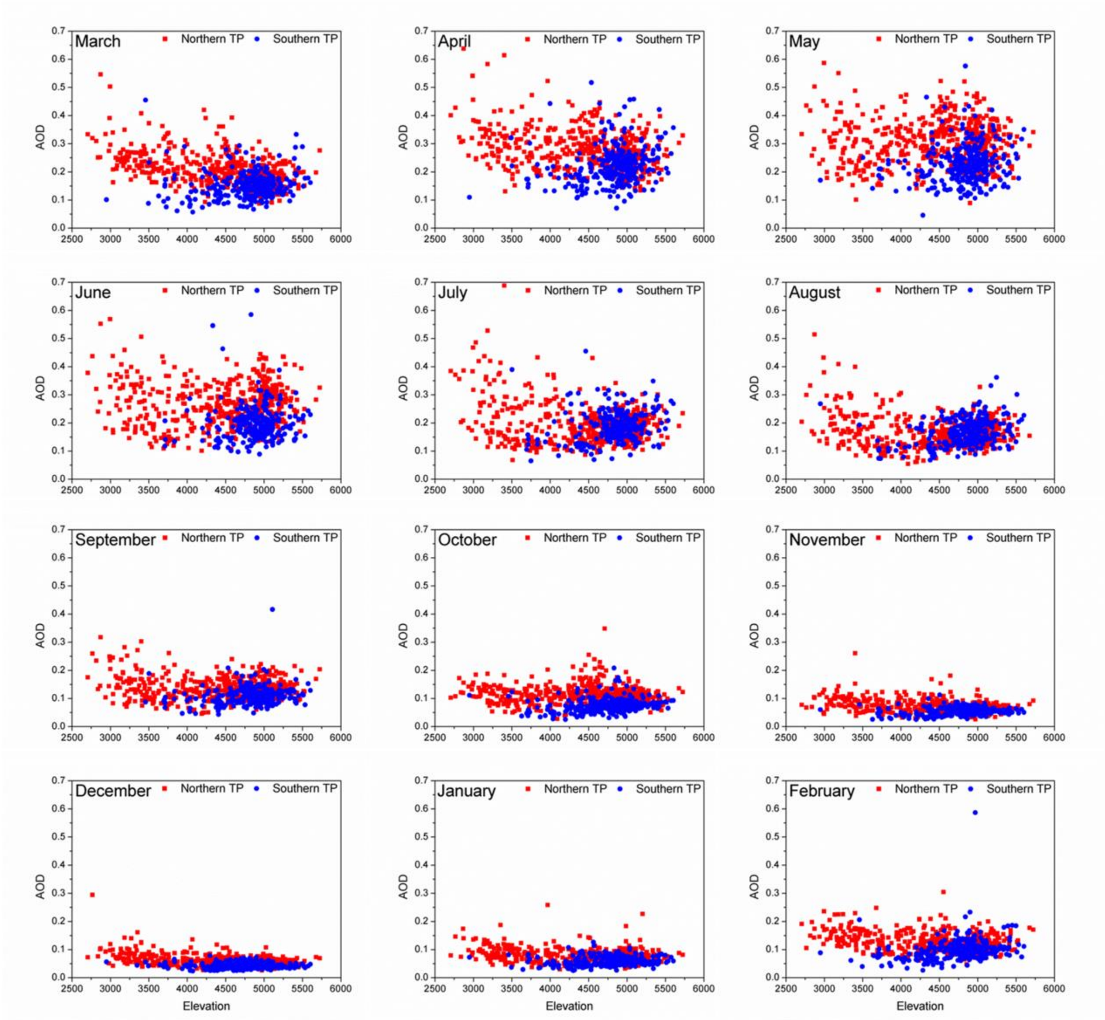
- Mouillot, F., and Field, C. B.: Fire history and the global carbon budget: a 1 °× 1 ° fire history reconstruction for the 20th century, Global Change Biology, 11, 398-420, 10.1111/j.1365-2486.2005.00920.x, 2005.
- Zhang, R., Wang, H., Qian, Y., Rasch, P. J., Easter, R. C., Ma, P. L., Singh, B., Huang, J., and Fu, Q.: Quantifying sources, transport, deposition, and radiative forcing of black carbon over the Himalayas and Tibetan Plateau, Atmos. Chem. Phys., 15, 6205-6223, 10.5194/acp-15-6205-2015, 2015.

25. (p12, 19) "This phenomenon may be related to the terrain of the TP." A plot of AOD vs. elevation would be highly in place here to support this statement and the analysis.

Response

Thank you very much for your suggestion and comment. TP is the most prominent and complex terrain feature on the Earth, and several mountains are located on the TP. Aerosols decrease during the transport process. The mountains possibly block the transport of aerosols. However, AOD is not completely inversely correlated with elevation. It not means that AOD must be higher at lower altitudes or lower at higher altitudes. AOD is also related with the distance between the study regions with emission sources. Atmospheric circulation fundamentally controls where the aerosols come from. We changed the previous sentence to 'The aerosol distributions are impacted by the mountain ranges on the TP.' in Page 14 line 24-25 in the revised manuscript.

We also made the plot of AOD vs. elevation in each month. The northern TP is defined as the region north of 33°N, and the southern TP is defined as the region south of 33°N. AOD decreases with elevation over the northern TP to some extent, while AOD does not decrease with elevation over the southern TP. Please see the following figure in detail.



26. (p12, 22-25) Repetition.

<u>Response</u>

Thank you very much for your comment. We followed your suggestion and deleted the repetitive sentences in the revised manuscript.

27. (p12, 27-28) "Aerosols are rarely transported onto the TP across other parts of the Himalayas Mountains." The data does not support this statement. It's speculation.

<u>Response</u>

Thank you very much for your suggestions and comment. This sentence is speculation. This statement is not scientific and appropriate. We deleted this sentence in the revised manuscript.

28. (p13, 1-3) Not very scientific statement. Speculation.

Response

Thank you very much for your suggestions and comment. We are grateful that you point out this inappropriate statement. Our data cannot support this statement well. We deleted this sentence in the revised manuscript.

29. (p13, 4-5) Repetition.

Response

Thank you very much for your comment. We followed your suggestion and deleted this repetitive sentence in the revised manuscript.

30. (p13, 5-8) A confusing analysis of the vertical extend of the horizontal boundary. See point 2.

Response

Thank you very much for your comment. The dust occurrences are clearly higher in the northern TP than the southern TP. This is actually a latitudinal phenomenon. Moreover, this dividing line can be observed from the surface to a height of 6~8 km in vertical distributions. Maybe the expression of boundary is ambiguous. We changed the sentence into 'The demarcation acts as a dividing line of higher dust occurrence in the northern TP and lower dust occurrence in the southern TP.'. Please see detail in Page 15 line 12-13 in the revised manuscript.

31. (p13, 12) "... and the extremely high mountains ..." Again, how much higher are these mountains than the surrounding terrain? Could you be specific?

Response

Thank you very much for your valuable comment. There are several mountains on the TP, including Himalayas Mountains, Gangdise Mountains, Nyainqentanglha Mountains, Tangula Mountains and Kunlun Mountains. The Himalayas Mountains are usually higher than 6000 m. The elevations of Gangdise Mountains vary from

5500 m to 6000 m, bordered by Nyainqentanglha Mountains on the east. The Nyainqentanglha Mountains are higher than 5000 m at least. The Tangula Mountains are usually higher than 5500 m. The Kunlun Mountains on the west are higher than 5500 m, the Kunlun Mountains in the middle are higher than 5000 m, and the Kunlun Mountains on the east are higher than 4500 m. These mountains are at least 500 m higher than the surrounding areas. The elevation differences of these mountains compared with the surrounding areas are usually 1000 m or even more. We added more descriptions 'Several mountains are located on the TP, including Himalayas Mountains, Gangdise Mountains, Nyainqentanglha Mountains, Tangula Mountains and Kunlun Mountains. The elevation differences of these mountains are at least 500m and usually 1000 m or even more compared with the surrounding areas.' in Page 2 line 23-26 in the Introduction section in the revised manuscript.

32. (p13, 28) Figure 8 does not support this statement. Airflow at 33-34 N is slightly northerly, with a substantial vertical component. Judging by the streamlines, the flows meet closer to ~30 N.

Response

Thank you very much for your valuable and helpful comment. We appreciate that you point out this mistake. I am very sorry that I made a mistake when I draw the wind fields in the former manuscript. I extracted the data wrongly when drawing this figure. Now I have corrected this error in the revised manuscript. Moreover, we added the horizontal wind fields at 500hPa to analyze the impact of atmospheric circulation better. Please see Figure 8 and Figure 9 in the revised manuscript. We changed the previous sentence to 'With the summer monsoon developing, the southwesterly winds at 500 hPa reach the northward maximum extent over the TP. Furthermore, the northern atmospheric circulation system and south Asian monsoonal system meet around 34~35 °N in the middle of the TP.' in Page 16 line 9-13 in the revised manuscript. We also made many revisions in the discussions in Section 3.4. Please see detail in Page 15 line 22-29, Page 16 line 1-29 and Page 17 line 1-15 in the revised manuscript.

33. (p13, 29) Repetition.

Response

Thank you very much for your comment. We followed your suggestion and deleted this repetitive sentence in the revised manuscript.

34. (p14, 3) Strong updrafts are also clearly shown over the TP.

Response

Thank you very much for your comment. We also mean that strong updrafts are shown over the main body of TP. Maybe our sentence seems ambiguous. We changed this sentence into 'Updrafts are also shown on the whole TP.' in Page 16 line 9 in the revised manuscript.

35. (p15, 9-10) "Aerosols are found to be more easily transported onto the TP across the northeastern edge..." I have an issue with the word "northeastern". The data shows that AODs are higher over the northern TP, suggesting advection from the north. Why then the northeastern direction is singled out as dominant? I don't think the data supports that.

Response

Thank you very much for your comment. The data actually shows that AODs are higher over the northern TP. We do not mean the advection is from northeastern direction. We mean here that 'northeastern' is northeastern edge around Qaidam Basin. The northeastern part of TP is with relatively lower altitudes. The conclusion section has been rewritten followed by the suggestion of Referee 2, and we do not mention this sentence in the conclusions in the revised manuscript. We followed your suggestion and changed similar expressions in the revised manuscript. We changed the former sentence 'Aerosols appear to be more easily transported over the main body of the TP across the northeastern edge rather than the southern edge. This is may be because the altitude is much lower at the northeastern edge than that of the Himalayas located along the southern edge of the TP.' into 'Aerosols appear to be more easily transported to the main body of the TP across the northern edge rather than the southern edge. This is may be partly because the altitude is lower at the northern edge than that of the Himalayas located along the southern edge of the TP.' in the revised manuscript. Please see in abstract in Page 1 line 24-25 and Page 2 line 1-2 in the revised manuscript.

36. (p15, 11-12) Confusing. The aerosol layer extends to 6-8 km, not the boundary.

Response

Thank you very much for your helpful suggestions and comment. Our previous expressions may be confusing. Here we mean that different dust occurrences are observed between the northern and southern TP during spring and summer. This demarcation acts as a dividing line. Dust occurrences over the regions north of this dividing line are clearly different from the regions south of this line. In addition, this demarcation can be observed from surface to an altitude of 6~8 km in vertical distributions. We changed the previous sentence to 'Higher dust occurrence in the northern TP and lower dust occurrence in the southern TP are observed during spring and summer. This dividing line is located around 33~35°N in the middle of the plateau. In addition, this demarcation extends from the surface to an altitude of 6~8 km.'. Please see in Page 18 line 20-23 in the revised manuscript.

37. (p15, 20) "... and aerosols can even spread to the region north of 33-34N" Redundant.

Response

Thank you very much for your comment. We followed your suggestion and deleted this sentence in the revised manuscript.

38. (p15, 27-29) This was not explored in the text.

Response

Thank you very much for your comment. We followed your suggestion and deleted this sentence in the revised manuscript.

Response to Anonymous Referee #2

Comment

The paper deals with the quantification of aerosol properties over the Tibetan plateau, using satellite measurements from MISR and CALIPSO. The authors report a climatology of the aerosol optical depth (AOD) at 558 nm from MISR and of the aerosol type, according to the CALIPSO classification. The MISR dataset used ranges from March 2000 to December 2014, while the CALIPSO data are from March 2007 to February 2015. The authors produced a series of climatological averages, providing height resolved transects with significant seasonal variations. The Qaidan basin results to have the highest aerosol AOD throughout the year.

Response

Thank you very much for positive evaluation. We appreciate the comments and suggestions, which are helpful to the quality of this manuscript.

Figure 7 should be moved before any other map, highlighting the regions mentioned in the text: the Qaidam basin, the Gobi and Taklamakan deserts, the Tarim basin. As mentioned, the authors find that the highest AOD is found over the Qaidam basin. As far as I know, this region is rather populated and many industries and caves are here located.

Response

Many thanks for your helpful suggestions and comments. We followed your suggestions and moved this figure before any other map. We redrew this figure to highlight the regions mentioned in the text. We also added some descriptions 'The TP is surrounded by several deserts, including Taklimakan Desert in Tarim Basin, Gobi Desert and the deserts in Southwest Asia and Middle East. Indo-Gangetic Plains are located to south of the TP, with high aerosol loading (Gautam et al., 2011). Several mountains are located on the TP, including Himalayas Mountains, Gangdise Mountains, Nyainqentanglha Mountains, Tangula Mountains and Kunlun Mountains. The elevation differences of these mountains are at least 500m and usually 1000 m or even more compared with the surrounding areas.' in the Introduction section in Page 2 line 20-26. Please see Figure 1 in the revised manuscript.

We appreciate that you show another possible reasons for high AOD over the Qaidam Basin. We followed your suggestions and added some discussions to be more accurate. The sentences are 'Frequent dust storms mainly lead to the high AOD (Zhang et al., 2003; Wang et al., 2004). Human activities, including such as fossil fuel combustion and industrial emissions over the Qaidam Basin, also contribute to the increasing aerosol concentrations to some extent (Streets et al., 2003; Zhang et al., 2009; Liu et al., 2015).' in Page 8 line 3-7 in the revised manuscript.

We also added the following references in the references list in the revised manuscript :

- Gautam, R., Hsu, N. C., Tsay, S. C., Lau, K. M., Holben, B., Bell, S., Smirnov, A., Li, C., Hansell, R., Ji, Q., Payra, S., Aryal, D., Kayastha, R., and Kim, K. M.: Accumulation of aerosols over the Indo-Gangetic plains and southern slopes of the Himalayas: distribution, properties and radiative effects during the 2009 pre-monsoon season, Atmospheric Chemistry and Physics, 11, 12841-12863, 10.5194/acp-11-12841-2011, 2011.
- Liu, Z., Guan, D., Wei, W., Davis, S. J., Ciais, P., Bai, J., Peng, S., Zhang, Q., Hubacek, K., Marland, G., Andres, R. J., Crawford-Brown, D., Lin, J., Zhao, H., Hong, C., Boden, T. A., Feng, K., Peters, G. P., Xi, F., Liu, J., Li, Y., Zhao, Y., Zeng, N., and He, K.: Reduced carbon emission estimates from fossil fuel combustion and cement production in China, Nature, 524, 335-338, 10.1038/nature14677.
- Streets, D. G., Bond, T. C., Carmichael, G. R., Fernandes, S. D., Fu, Q., He, D., Klimont, Z., Nelson, S. M., Tsai, N. Y., Wang, M. Q., Woo, J. H., and Yarber, K. F.: An inventory of gaseous and primary aerosol emissions in Asia in the year 2000, Journal of Geophysical Research: Atmospheres, 108, 8809, 10.1029/2002JD003093, 2003.
- Wang, X., Dong, Z., Zhang, J., and Liu, L.: Modern dust storms in China: an overview, Journal of Arid Environments, 58, 559-574, http://dx.doi.org/10.1016/j.jaridenv.2003.11.009, 2004.
- Zhang, Q., Streets, D. G., Carmichael, G. R., He, K. B., Huo, H., Kannari, A., Klimont, Z., Park, I. S., Reddy, S., Fu, J. S., Chen, D., Duan, L., Lei, Y., Wang, L.

T., and Yao, Z. L.: Asian emissions in 2006 for the NASA INTEX-B mission, Atmos. Chem. Phys., 9, 5131-5153, 10.5194/acp-9-5131-2009, 2009.

- Zhang, X. Y., Gong, S. L., Shen, Z. X., Mei, F. M., Xi, X. X., Liu, L. C., Zhou, Z. J., Wang, D., Wang, Y. Q., and Cheng, Y.: Characterization of soil dust aerosol in China and its transport and distribution during 2001 ACE-Asia: 1. Network observations, Journal of Geophysical Research: Atmospheres, 108, 4261, 10.1029/2002JD002632, 2003.

However, some important aspects are not faced in the discussion:

1. Which are the estimated uncertainties and errors on the MISR retrieval in such high altitude regions?

Response

Thank you very much for your valuable suggestions and comments. We followed your suggestion and made more discussions about the estimated uncertainties and errors on the MISR retrieval. Xia et al. (2008) made comparison of MISR AOD with ground-based hazemeter measurements made at Lhasa and Haibei station on the TP. The results revealed most collocated data points showed an excellent agreement. The correlation coefficient was 0.81 and 27 out of total 32 data points were within the expected MISR uncertainty (i.e., maximum of 0.05 or 20% of AOD). The mean bias was about 0.014 and the root mean square error (RMSE) was 0.035, respectively. Their results indicated MISR AOD accuracy over the TP is apparently better than MODIS AOD.

The added sentences are 'The accuracy of MISR AOD was much better than MODIS AOD over land (Abdou et al., 2005). Xia et al (2008) made comparisons of MISR AOD with ground-based hazemeter measurements made at Lhasa and Haibei station on the TP, which showed high correlation coefficient and low root mean square error.' in Page 5 line 8-12 in the revised manuscript.

We also added the following references in the references list in the revised manuscript :

- Abdou, W. A., Diner, D. J., Martonchik, J. V., Bruegge, C. J., Kahn, R. A., Gaitley, B. J., Crean, K. A., Remer, L. A., and Holben, B.: Comparison of coincident Multiangle Imaging Spectroradiometer and Moderate Resolution Imaging Spectroradiometer aerosol optical depths over land and ocean scenes containing Aerosol Robotic Network sites, Journal of Geophysical Research: Atmospheres, 110, D10S07, 10.1029/2004JD004693, 2005.

- Xia, X., Wang, P., Wang, Y., Li, Z., Xin, J., Liu, J., and Chen, H.: Aerosol optical depth over the Tibetan Plateau and its relation to aerosols over the Taklimakan Desert, Geophysical Research Letters, 35, 10.1029/2008gl034981, 2008.

2. How heavy is the possibility of cloud contamination on level 3 MISR data?

Response

Thank you very much for your valuable comments. We searched more literatures about the cloud contamination on MISR data. Cloud contamination actually exists in satellite aerosol products, including MISR data. Shi et al. (2014) made an evaluation of cloud contamination on the MISR Level 2 aerosol products using MODIS cloud mask products. The results showed thin cirrus cloud contamination introduced a possible ~0.01 high bias for the over-water MISR AOD retrievals, while this number increased to 0.015–0.02 over the mid- to high-latitude oceans and Southeast Asia. The Level 3 Aerosol product is a summary of the Level 2 Aerosol product.

We followed your suggestion and made more discussions about cloud contamination on MISR data in the revised manuscript. The sentences are 'One of the key issues for satellite aerosol products is cloud contamination, including MISR data (Kahn et al., 2010). Three cloud-mask products are used in the aerosol pre-processing. The MISR Standard Products include three separate MISR-derived cloud Masks: Radiometric Camera-by-camera Cloud Mask (RCCM) (Yang et al., 2007), Stereo-Derived Cloud Mask (SDCM) (Moroney et al., 2002) and Angular-Signature Cloud Mask (ASCM) (Di Girolamo and Wilson, 2003). Based on collocated MISR and Moderate Resolution Imaging Spectroradiometer (MODIS) data, Shi et al. (2014) suggested that cloud contamination existed in both over-water and over-land MISR AOD data, with heavier cloud contamination occurring over the high latitude southern hemispheric oceans.'. Please see detail in Page 4 line 26-28 and Page 5 line 1-7 in the revised manuscript.

We also added the following references in the references list in the revised manuscript :

- Di Girolamo, L., and Wilson, M. J.: A first look at band-differenced angular signatures for cloud detection from MISR, Geoscience and Remote Sensing, IEEE Transactions on, 41, 1730-1734, 10.1109/TGRS.2003.815659, 2003.
- Kahn, R. A., Gaitley, B. J., Garay, M. J., Diner, D. J., Eck, T. F., Smirnov, A., and Holben, B. N.: Multiangle Imaging SpectroRadiometer global aerosol product assessment by comparison with the Aerosol Robotic Network, Journal of Geophysical Research: Atmospheres, 115, D23209, 10.1029/2010jd014601, 2010.
- Moroney, C., Davies, R., and Muller, J. P.: Operational retrieval of cloud-top heights using MISR data, Geoscience and Remote Sensing, IEEE Transactions on, 40, 1532-1540, 10.1109/TGRS.2002.801150, 2002.
- Shi, Y., Zhang, J., Reid, J. S., Liu, B., and Hyer, E. J.: Critical evaluation of cloud contamination in the MISR aerosol products using MODIS cloud mask products, Atmos. Meas. Tech., 7, 1791-1801, 10.5194/amt-7-1791-2014, 2014.
- Yang, Y., Di Girolamo, L., and Mazzoni, D.: Selection of the automated thresholding algorithm for the Multi-angle Imaging SpectroRadiometer Radiometric Camera-by-Camera Cloud Mask over land, Remote Sensing of Environment, 107, 159-171, http://dx.doi.org/10.1016/j.rse.2006.05.020, 2007.

3. A rather trivial observation leads to the thought that the total AOD is anti-correlated with the ground elevation. This would indicate that, since the tropopause is almost constant even over high mountains, less atmosphere means less aerosol.

Response

Thank you very much for your comment. We have not considered this possible impact. To be more precise and scientific, we added some discussions 'Alternatively, uneven terrain may have a trivial impact on satellite aerosol observations in a different way. Since the tropopause is almost constant even over high mountains, less atmosphere leads to lower AOD.' in Page 15 line 19-21 in the revised manuscript.

4. Higher aerosol loads come from the most populated regions. These points should be better discussed and highlighted before the publication. An interesting topic that is just sketched is the possibility of aerosol intrusion in stratosphere, since spring observation often show aerosol layers up to 11-12 km ASL. I encourage the authors to better develop this part. Furthermore, the conclusions

look very shy and generic.

Response

Thank you very much for your valuable and constructive comments and suggestions. We appreciate your valuable advices to improve the quality of our manuscript. We did our best to discuss the transport of aerosols from the surrounding regions to the TP. Firstly, we added more discussions about aerosols over the most populated regions. The sentences are 'More smoke samples are detected over the Indo-Gangetic Plains rather than the areas north of the TP. The altitude of smoke aerosol layer is higher in summer than other seasons over Indo-Gangetic Basin. Although the heavy summer rains remove a large amount of soluble gases and aerosols, less soluble species can be lifted to the upper troposphere in deep convective clouds and then be transported away from Indo-Gangetic Plains by strong upper tropospheric winds.' in Page 12 line 15-20 in the revised manuscript. We also added the discussions of the influences of the emission sources on aerosol transport. The sentences are 'Much higher aerosol loads are observed over the surrounding regions of the TP. AOD peaks during spring and summer over Tarim Basin. "Strong anticyclonic wind anomaly at 500 hPa and enhanced easterly wind at 850 hPa" over the Tarim Basin during spring and summer are good for dust entrainment, vertical lofting, and horizontal transport (Ge et al., 2014). Indo-Gangetic basin, encompassing most of northern India peninsula, extends from Pakistan in the west to Bangladesh in the east. Indo-Gangetic basin is one of the most heavily populated regions of the world. There are a large quantity of emissions of biomass burning and fossil fuel over South Asia, where is adjacent to the TP (Ramanathan et al., 2005). AOD over the Indo-Gangetic basin can reach extremely high values throughout the year, peaking during spring and summer due to enhanced emission of natural aerosols (Dey and Di Girolamo, 2010). Furthermore, aerosols layers exist above the TP over the northern Indian peninsula and Tarim Basin during spring and summer. Dust and polluted dust layers exhibit a relatively greater thickness over the regions north of the TP than the regions south of the TP during spring and summer. The aerosol concentrations and the heights of aerosol layers over the surrounding regions have great influences on the transport of aerosols.' in Page 14 line 4-20 in the revised manuscript. We highlighted how the atmospheric circulations affected the aerosols transported from surrounding regions to the TP. I am very sorry that I made a mistake when I draw the wind fields in the former manuscript. I extracted the data wrongly when drawing Figure 8. Now I have corrected this error in the revised manuscript. Moreover, we added the horizontal wind fields at 500hPa to analyze the impact of atmospheric circulation better. Please see Figure 8 and Figure 9 in the revised manuscript. We also made many revisions in the discussions in Section 3.4. Please see detail in Section 3.4 in Page 15 line 22-29, Page 1-29 and Page 17 line 1-15 in the revised manuscript.

We are grateful for your great ideas about aerosol intrusion in stratosphere. We added more discussions 'Detected aerosol layer even reaches up to upper troposphere and lower stratosphere over the TP and the regions north of the TP. Frequent dust activities and little precipitation may be favorable for dust intrusion in stratosphere. Stratosphere-troposphere exchange is a hot topic, and aerosols intruding into stratosphere will lead to a negative radiative forcing (Solomon et al., 2011). Previous studies mainly focused on deep fast convective transport of polluted air from the atmospheric boundary layer into the upper troposphere and lower stratosphere during Asian summer monsoon season (Fu et al., 2006; Randel et al., 2010). The non-volcanic aerosol layer near the tropopause was detected vertically from 13 to 18 km based on CALIPSO observations during the Asian summer monsoon, and AOD here has increased three times since the late 1990s (Vernier, 2015). However, our results suggest the TP and the regions north of the TP may also act as alternative pathways for aerosols from troposphere to stratosphere during the spring period. The mechanisms of spring dust transport from the atmospheric boundary layer into the upper troposphere and lower stratosphere need further rigorous studies and discussions.' in Page 10 line 21-29 and Page 11 line 1-7 in the revised manuscript. In this study, aerosol layers are discussed below 12 km using CALIPSO level 3 data. We would like to focus on this issue when discussing the results at a higher altitude. This good idea provides the direction for our future study.

We followed your suggestion and did our best to rewrite the conclusion section. Please see detail in Page 18 line 1-29 and Page 19 line 1-9 in the revised manuscript.

We also added the following references in the references list in the revised manuscript :

- Dey, S., and Di Girolamo, L.: A climatology of aerosol optical and microphysical properties over the Indian subcontinent from 9 years (2000–2008) of Multiangle Imaging Spectroradiometer (MISR) data, Journal of Geophysical Research, 115, 10.1029/2009jd013395, 2010.
- Fu, R., Hu, Y., Wright, J. S., Jiang, J. H., Dickinson, R. E., Chen, M., Filipiak, M., Read, W. G., Waters, J. W., and Wu, D. L.: Short circuit of water vapor and polluted air to the global stratosphere by convective transport over the Tibetan Plateau, Proceedings of the National Academy of Sciences, 103, 5664-5669, 10.1073/pnas.0601584103, 2006.
- Ge, J. M., Huang, J. P., Xu, C. P., Qi, Y. L., and Liu, H. Y.: Characteristics of Taklimakan dust emission and distribution: A satellite and reanalysis field perspective, Journal of Geophysical Research: Atmospheres, 119, 2014JD022280, 10.1002/2014JD022280, 2014.
- Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J. T., Washington, W. M., Fu, Q., Sikka, D. R., and Wild, M.: Atmospheric brown clouds: impacts on South Asian climate and hydrological cycle, Proceedings of the National Academy of Sciences of the United States of America, 102, 5326-5333, 10.1073/pnas.0500656102, 2005.
- Randel, W. J., Park, M., Emmons, L., Kinnison, D., Bernath, P., Walker, K. A., Boone, C., and Pumphrey, H.: Asian Monsoon Transport of Pollution to the Stratosphere, Science, 328, 611-613, 10.1126/science.1182274, 2010.
- Solomon, S., Daniel, J. S., Neely, R. R., III, Vernier, J. P., Dutton, E. G., and Thomason, L. W.: The Persistently Variable "Background" Stratospheric Aerosol Layer and Global Climate Change, Science, 333, 866-870, 10.1126/science.1206027, 2011.
- Vernier, J. P., Fairlie, T. D., Natarajan, M., Wienhold, F. G., Bian, J., Martinsson, B. G., Crumeyrolle, S., Thomason, L. W., and Bedka, K. M.: Increase in upper tropospheric and lower stratospheric aerosol levels and its potential connection with Asian pollution, Journal of Geophysical Research: Atmospheres, 120, 2014JD022372, 10.1002/2014JD022372, 2015.