Response to Anonymous Referee #2

We thank you for your careful reading of the manuscript. The comments and suggestions are valuable and very helpful for revising and improving our manuscript. We have made revisions according to your comments and suggestions, as described below.

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.

<u>Response</u>

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.