Changes in atmospheric aerosol loading retrieved from space based measurements during the past decade

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Dear Dr. A. M. Sayer,

We thank you for the constructive comments, which replies are listed on the supplement.

The text on page 26003 (middle of the page), pointing out the sampling issues associated with satellite aerosol optical depth retrievals, makes good points and it is worth articulating them. A few wording choices struck me as odd, however, such as describing these satellite instruments as 'experimental' when I'd consider them a proven technology (as imagers of this basic type have been flying for decades and being carried on with VIIRS; caveat being I'm not an engineer so maybe some subtlety escapes me). Perhaps the authors use the word 'experimental' as the sensors' primary purposes are mostly not aerosol remote sensing? If so, perhaps a reword to something like 'non-aerosol-focussed' would be better. The point about diurnal cycles is relevant and I thought I'd mention this recent paper, which provides an example of that (MODIS missing peak aerosol loading due to overpass times):

Kocha, C., P. Tulet, J.-P. Lafore, and C. Flamant (2013), The importance of the diurnal cycle of Aerosol Optical Depth in West Africa, Geophys. Res. Lett., 40, 785–790, doi:10.1002/grl.50143.

Another recent paper makes some points about diurnal cycles and the radiative effects of aerosol:

Arola, A., Eck, T. F., Huttunen, J., Lehtinen, K. E. J., Lindfors, A. V., Myhre, G., Smirnov, A., Tripathi, S. N., and Yu, H.: Influence of observed diurnal cycles of aerosol optical depth on aerosol direct radiative effect, Atmos. Chem. Phys., 13, 7895-7901, doi:10.5194/acp-13-7895-2013, 2013.

-> It will be rewritten and the references (Kocha et al., 2013; Arola et al., 2013) be additionally cited as your suggestion.

I don't know that the question of aerosol diurnal variability has been entirely solved. However, over the time range for morning and afternoon satellites, I was under the impression that in many cases it is not large. See e.g. this paper for more information:

Smirnov, A., B. N. Holben, T. F. Eck, I. Slutsker, B. Chatenet, and R. T. Pinker, Diurnal variability of aerosol optical depth observed at AERONET (Aerosol Robotic Network) sites, Geophys. Res. Lett., 29(23), 2115, doi:10.1029/2002GL016305, 2002.

Anyway, my point here is that there is a distinction between the aerosol diurnal cycle overall (which may be large in some cases, and is in at least some, as Kocha et al present), and the specific part of the diurnal cycle which is sampled by your specific satellite sensors (here about 10:30 am to 1:30 pm) and is likely to (in many cases) be small. With that in mind, I'd found it odd that authors mentioned the overpass time difference as the first (and by inference most important, although perhaps that's just my reading) sampling problem for trend/change detection. I'd have put things like calibration stability or cloud coverage first. On the topic of calibration stability, for SeaWiFS this was very good and we also checked temporal stability of AERONET validation at long-term sites as a sanity check in our previous study (Hsu et al, ACP, 2012; some references about SeaWiFS radiometric performance are given in there).

Also relevant are things like inconsistency of spectral bands and spatial resolution between different sensors, which mean that applying consistent retrieval algorithms to their measurements is difficult or impossible.

-> We agree with your comment that sensor calibration, retrieval accuracy, and cloud contamination are very important as discussed in many previous studies. However, we have found and emphasized in the manuscript that different and limited temporal sampling of polar-orbiting satellites is also a significant uncertainty factor in the trend estimates. As shown in Section 3, the temporal correlation coefficient between the resampled AERONET data (i.e. at 10:30 a.m.±30 min, 12:20 p.m.±30 min, and 01:30 p.m.±30 min.) and all available data ranges widely from 0.72 to 0.98. This is good chance of deriving different trends from the different/limited samplings.

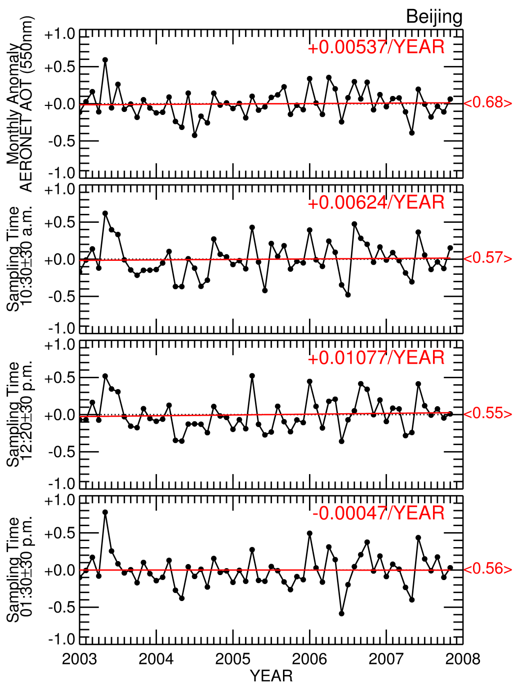

Fig. S1. Monthly anomaly of AERONET AOT (550nm) (i.e. all available data or sampled at 10:30 a.m.±30 min, 12:20 p.m.±30 min, and 01:30 p.m.±30 min.) and corresponding trend estimates at Beijing station.

Figure S1 shows a specific example of linear trends at the station Beijing derived using monthly AERONET AOTs (550 nm), which are calculated either by the sample data observed around the local equatorial crossing times (i.e.,

10:30±30 a.m. for Terra, 12:20±30 p.m. for OrbView-2, and 01:30±30 p.m. for Aqua) or averaged using all available observations. It shows clearly that the trend estimates from different samplings differ from each other.

Tab. S1. Trend estimates of AERONET AOT (550 nm) in different sampling times and corresponding relative differences.

AERONET Stations	Geolocations (lat.[°]/lon.[°]/alt.[m])	Research Periods	Linear Trends of AERONET AOT (550 nm) in Different Sampling Times [yr^{-1}] and (Relative Percentage Differences [%])			
			All Available	10:30±30 a.m.	12:20±30 p.m.	01:30±30 p.m.
Avignon	43.93/4.88/32	2001~2005	**+0.00120**	**+0.00344 (+186.7%)**	**+0.00599 (+399.2%)**	**+0.00334 (+178.3%)**
Banizoumbou	13.54/2.66/250	2002~2008	**+0.00538**	**+0.00857 (+59.3%)**	**+0.00196 (-63.6%)**	**+0.00700 (+30.1%)**
Beijing	39.98/116.38/92	2003~2007	**+0.00537**	**+0.00624 (+16.2%)**	**+0.01077 (+100.6%)**	**-0.00047 (-108.8%)**
Dakar	14.39/-16.96/0	2004~2008	**-0.00834**	**-0.00936 (+12.2%)**	**-0.00907 (+8.8%)**	**-0.01011 (+21.2%)**
GSFC	38.99/-76.84/87	1995~2008	**-0.00219**	**-0.00054 (-75.3%)**	**-0.00062 (-71.7%)**	**+0.00038 (-117.4%)**
Ispra	45.80/8.63/235	2001~2007	**-0.00496**	**+0.00101 (-120.4%)**	**+0.00279 (-156.3%)**	**+0.00019 (-103.8%)**
Mauna_Loa	19.54/-155.58/3397	1998~2009	**+0.00014**	**-0.00000 (-100.0%)**	**+0.00008 (-42.9%)**	**+0.00014 (+0.0%)**
MD_Science_ Center	39.28/-76.62/15	2000~2006	**-0.00225**	**-0.00463 (+105.8%)**	**-0.00043 (-80.9%)**	**-0.00033 (-85.8%)**
Mongu	-15.25/23.15/1107	2000~2004	**+0.00002**	**+0.00104 (+5100.0%)**	**-0.00292 (-14700.0%)**	**+0.00123 (+6050.0%)**
Ouagadougou	12.20/-1.40/290	2000~2004	**+0.02895**	**+0.01635 (-43.5%)**	**+0.01478 (-48.9%)**	**+0.02017 (-30.3%)**
SEDE_ BOKER	30.86/34.78/480	2003~2008	**+0.00143**	**+0.00161 (+12.6%)**	**+0.00116 (-18.9%)**	**+0.00165 (+15.4%)**
Sevilleta	34.35/-106.89/1477	1998~2002	**+0.00232**	**+0.00101 (-56.5%)**	**+0.00104 (-55.2%)**	**+0.00034 (-85.3%)**
Shirahama	33.69/135.36/10	2003~2009	**+0.00107**	**+0.00263 (+145.8%)**	**+0.00461 (+330.8%)**	**+0.00218 (+103.7%)**
Skukuza	-24.99/31.59/150	2000~2007	**-0.00463**	**-0.00022 (-95.2%)**	**-0.00438 (-5.4%)**	**-0.00468 (+1.1%)**
Solar_Village	24.91/46.40/764	2001~2007	**+0.01965**	**+0.01531 (-22.1%)**	**+0.01814 (-7.7%)**	**+0.01875 (-4.6%)**

In same manner, we have tested all available AERONET data, which length are longer than 5 years (see Yoon et al., 2012) and the relative differences in the trend estimates of different sampling are shown in Table S1. Except in the case of the station Mongu (because of an almost negligible trend of all available data), the relative differences between the trends of all available data and sample data are significantly large at all stations (i.e., Avignon, Beijing, GSFC, Ispra, MD_Science_Center, Shirahama, and Skukuza stations close to urban or industrial areas: -156% ~ +399.2%, Banizoumbou, Dakar, Ouagadougou, SEDE_BOKER, and Solar_Village stations near desert regions: -63.6% ~ +59.3%, Mauna_Loa in *free troposphere* and open ocean: -100% ~ +0%, and Sevilleta in rural region: -85.3% ~ -55.2%). Therefore, since there is no difference in retrieval accuracy, cloud-filtering method, and spatial resolution in this test, these relative differences are attributed only to the different and limited sampling times.

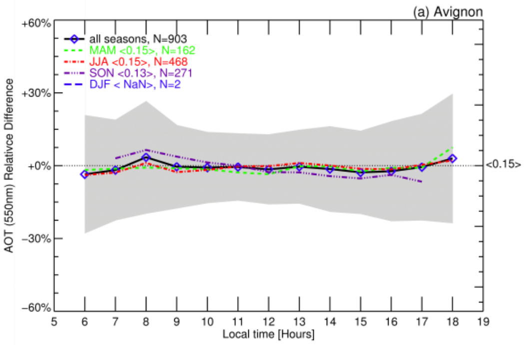

Fig. S2. Diurnal variation of AERONET AOT (550nm) for seasons at the station Avignon.

Furthermore, even though the diurnal variation is not large as the case of Avignon in Figure S2, the trend estimates using the different samplings can be significantly different (i.e. +178.3% ~ +399.2%) as shown in Table S1. This shows that it is limited to draw a reasonable conclusion from trend estimates based on different/limited samplings.

Certainly, as you pointed, the sensor calibration stability, retrieval accuracy, and cloud contamination are very important issues in the trend study. However, as demonstrated in our manuscript and above using the AERONET data, this

study have highlighted that the limited and different sampling is also a major uncertainty factor and should be considered in trend estimates. Therefore, in order to minimize the uncertainty caused by the limited and different sampling in this study, we have used optimally different satellite measurements (i.e. MODIS-Terra, MISR-Terra, SeaWiFS-OrbView-2, and MODIS-Aqua) representative for various sampling times (i.e., 10:30±30 a.m., 12:20±30 p.m., and 01:30±30 p.m.).

Going back to overpass time for a moment, the wide swath of MODIS/AVHRR/VIIRS means that the local time at opposite edges of the swath will be significantly different from the nominal equatorial crossing time at the centre of the swath. For trend analyses from these instruments, I suspect any diurnal variation across these would cancel out given sufficient sampling.

-> Even though MODIS swath is so large, 2330 km, the revisit cycle is about one to two days (MODIS Webpage, http://modis.gsfc.nasa.gov). Therefore, the limited sampling can be still a significant issue in the trend estimate.

Page 26005-26006: why do you cite an IOCCG report as a reference for the MODIS, MISR, and SeaWiFS instruments? These seem out of place and not really relevant as general introductions to these sensors. I also couldn't find the reference in the bibliography. I'd suggest just removing it as the textual descriptions and other cited references are sufficient.

-> We will add the missing reference in the bibliography.

For MODIS, it seems as though the authors are not using the Deep Blue dataset (see e.g. the hole over the Sahara in presented maps). I'd encourage them to use Deep Blue to fill some of the Dark Target gaps: the dataset is stored in the same files as the authors must already have, and it'd provide a useful backup to the other sensors. Our own SeaWiFS-based analysis (Hsu et al, ACP, 2012, which is cited but results not discussed) found some strong positive trends over the Arabian Peninsula, and it looks like the same is seen in this study with e.g. MISR. So by including MODIS

Deep Blue you'd have an additional check there. In Figure 3 the authors note that the Middle East lacks MODIS data but this is a problem which would be easily remedied via inclusion of Deep Blue data into that record. I would be happy to advise the authors regarding Deep Blue data use.

Perhaps the authors could even add the NASA SeaWiFS product to their own analysis (I'd be happy to provide assistance regarding data use) and show these things quantitatively side by side. de Meij et al (2012) also looked at emissions as possible reasons for aerosol trends, and again discussing their results would be relevant to the topic here.

-> We thank you for the constructive suggestion. As you know, the main goals of this study are to improve and to analyze the trend estimates of atmospheric aerosol by minimizing the uncertainty caused by the unrepresentative sampling. When started this study, we firstly and carefully selected the satellite-derived AOT products representative for the sampling times (i.e., 10:30±30 a.m. for Terra, 12:20±30 p.m. for OrbView-2, and 01:30±30 p.m. for Aqua). In particular, since MODIS and MISR are onboard the same space platform, Terra, we chose the MISR product for the trend estimates over desert regions in this study. In addition, because as shown in Table S1 the different/limited sampling causes a relatively small difference (-63.6% ~ +59.3%) in the trend estimate at AERONET stations (i.e. Banizoumbou, Dakar, Ouagadougou, SEDE_BOKER, and Solar_Village stations) near desert regions, we concluded that only MISR product is enough to estimate trend over desert regions. Of course, we are happy if we do further study including additional satellite-derived AOT products (e.g. MERIS AOT product, NASA SeaWiFS product, MODIS deep-blue product, and so on). For that, firstly it is necessary to evaluate the weighted trend model introduced in this study.

Page 26013: the authors state that SeaWiFS orbital time drift is one potential reason for weaker trends observed by SeaWiFS than AERONET. Based on the previous papers I linked to on diurnal variability, I doubt that's a significant cause.

-> As shown before in Figure S1 and Table S1, the different and limited sampling can lead to different trend estimates. Therefore, the SeaWiFS orbital

time shift can be a significant cause for the discrepancy between SeaWiFS and AERONET trends.

The regional results and discussion in the study are interesting. However many of these results were reported previously by Hsu et al (ACP, 2012) and de Meij et al (Atmos Env, 2012), which are cited parenthetically in the introduction to the study, but not discussed in the text. In fairness to the previous work, I would have liked to see the authors compare their estimates to the existing prior research on this subject, and discuss similarities/discrepancies. See, for example, Figure 9 of Hsu et al (2012) in comparison to Figure 8 of the present study. My eyeballing suggests that some of the results are quantitatively similar to those of Hsu et al (2012), which would be quite a nice achievement in my view (similar results with different algorithms).

In any case, this is a complicated topic, and no single study gives us the final word on aerosol trends, so I think it's important to present comparisons between these different analyses to figure out whether the different studies are reporting consistent results. If they are consistent, great (but we still have to be careful as many trend analyses are based on the same underling datasets so may not be truly independent analyses) and if they're not consistent, maybe we can figure out why. The lack of this comparative discussion of the trends is my main issue with the paper. It's important to place research in the proper context.

-> We will improve the trend analysis part in the manuscript by comparing with the results from the previous studies.

Reference

Yoon, J., von Hoyningen-Huene, W., Kokhanovsky, A. A., Vountas, M., and Burrows, J. P.: Trend analysis of aerosol optical thickness and Ångström exponent derived from the global AERONET spectral observations, Atmos. Meas. Tech., 5, 1271–1299, doi:10.5194/amt-5-1271-2012, 2012.