Reply to M. Tesche

We would like to thank M. Tesche for his comments. We have done our best to address each of the points as detailed below. The main points that need addressed are given in bold with the response in italics. Some additional points that were mentioned are appended at the end.

Main Comments:

Use of the term sea spray aerosol as a synonym for marine aerosol.

We have modified the manuscript to say marine aerosol where sea spray was used.

Results of direct measurements of the lidar ratio of marine aerosol are marginalized in the manuscript and not properly addressed in the discussion of the findings.

We have modified our introduction to the following:

"To date, experimental techniques for measuring the lidar ratio directly include the use of High Spectral Resolution Lidar (HSRL, Eloranta, 2005; Hair et al., 2008) and Raman Lidar (RL, Ansmann et al., 1990). These instruments are capable of measuring aerosol backscatter and extinction parameters independently and therefore do not require the lidar ratio to be prescribed (e.g., Shipley et al., 1983; Grund and Eloranta, 1991; Piironen and Eloranta, 1994; Müller et al., 2007; Amiridis et al., 2009; Tesche et al., 2009a,b; Burton et al., 2012). A suite of directly measured marine lidar ratios reports values on average, 29±5 (Cattrall et al., 2005). Other techniques like the inversion of AERONET sun photometer data (Holben et al., 1998) along with Mie theory can also provide the lidar ratio (the supplementary Table S1 summarizes available methods to retrieve and values of the lidar ratio for marine regions with a more complete list of experimentally determined lidar ratios found in Cattrall et al., 2005, and references therein)."

We have also briefly discussed how our results compare to measured ones in section 3.2:

"Analysis of data indicates that a mean lidar ratio of 26 sr is the most probable value that occurs for the majority of CALIOP retrievals over the oceans. This value compares well with those reported in the literature. Müller et al. (2007) found a marine aerosol lidar ratio of 23±3 and 23±5 sr using RL and Burton et al. (2012; 2013) reported a range from 15-27 sr using HSRL. Bréon (2013) used a different space-based retrieval and saw S_p for marine aerosol is typically on the order of 25 sr. Table S1 reports some additional values of marine aerosol S_p measured by other techniques."

A critical discussion of the AOD derived with SODA is missing. This makes it impossible to assess the reliability of subsequently deduced parameters, and thus, the scientific quality of this paper.

We feel that the data presented by the collection of papers from Josset et al. (2008; 2010a,b; 2011; 2013) serves as the main basis for the reliability of the SODA product. The SODA product's error sources and uncertainties have been carefully evaluated (Josset et al. 2008, 2010a, 2010b, 2011, 2012, 2013) and SODA output h   as been successfully compared with MODIS, HSRL and POLDER. Additionally, because of its reliability and ease of use, SODA operational output is now a freely distributed science product used by many investigators.

It is true, that the low concentration of marine aerosol poses a challenge for satellite based retrievals of the AOD; however, we have gone to extensive lengths to only analyze those layers with high signal to noise ratios and adequate backscatter. The results of the retrieved lidar ratios agree well with literature values. Furthermore, the lidar ratios are a function of both the AOD and the integrated attenuated backscatter (IAB). Low AOD retrievals will have low IAB and not pass the threshold requirements on the relative error of IAB (see manuscript section 2.4, paragraph 3). In other words, AOD scales with IAB and so our lidar ratios are mostly a product of high AOD and high IAB over marine regions.

Despite all this in the modified manuscript we now include comparison of collocated HSRL and SODA AOD data (during a CALIPSO underpass). The text now reads:

"To further assess the reliability of SODA marine aerosol product we also compared collocated HSRL and SODA AOD data. Figure 6a shows results from three CALIPSO (and therefore SODA) underflights validated against HSRL. According to Fig. 6 for AODs < 0.3 (comprising the majority of marine aerosol retrievals), SODA compares reasonably well to HSRL ($R^2 = 0.82$). Additionally, Fig. 6b illustrates that the relative uncertainty in the SODA retrieved S_p is less than 50% for AODs > 0.05. The bulk of AODs measured by CALIPSO exceed this value under the quality control criteria discussed in Sec. 2.4. Errors were estimated based on Eq. 12 in Josset et al. (2011) and are representative of an upper bound due to the usage of the absolute value. Therefore, for AODs > 0.03, we expect lidar ratio retrieval uncertainties below 50%."

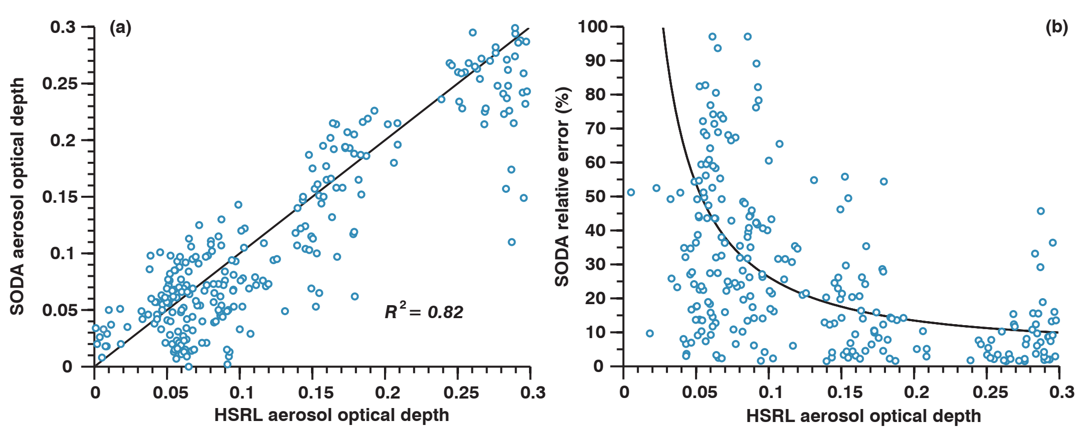

Fig. 6 *(a) A scatter plot of SODA AOD relative to AOD measured by HSRL at 532 nm. The dashed black line illustrates the 1:1 line. (b) Relative uncertainty in the SODA column lidar ratio as a function of HSRL AOD with the black line showing the least squares exponential fit as in Eq. 15 Josset et al. (2012).*

SODA comparison with maritime aerosol network (MAN) data for our time period within 60 km radius results in 13 matched data points, which are too few for a useful comparison.

There is not enough convincing evidence for a wind-speed dependence of the lidar ratio of marine aerosol.

We observed weak wind speed dependence and believe, as discussed in the paper, many factors other than the wind speed may play a role in determining the lidar ratio. However, we agree with the reviewer that "wind-speed dependence is a major issue for the sea spray community" and feel that including the dependence in the supplement and discussing it briefly in the text is appropriate. Examining potential dependence of the lidar ratio on the wind speed was also requested by one of the anonymous reviewers. We explicitly discuss the low number of retrievals at the tails of the wind speed and mention the range for which we feel the parameterization to be most valid.

The text has been modified as follows: "Previous studies reported small decrease in marine aerosol lidar ratio with the increase in wind speed (Sayer et al., 2012). In general, wind speed alone is expected to be a poor predictor of marine aerosol lidar ratio, as aerosol volume size distribution and optical properties are likely to be influenced by a number of other parameters including relative humidity and marine boundary layer depth. Nevertheless, as wind speed dependednce of marine aerosol S_p is of considerable interest for the remote sensing community we have developed a parameterization of the lidar ratio with wind speed and include as a part of the supplementary information (see Fig. S2). Parameterization is based on a full range of wind speed values from 0 - 25 ms^{-1}, but given the low number of retrievals at very low (< 4 ms^{-1}) and very high (> 15 ms^{-1}) wind speeds, along with the large range of lidar ratios retrieved at low wind speeds (roughly ± 17 sr), we recognize the need for further constraints in these regions. Overall, given the number of retrievals and confidence bounds, we believe our parameterizationcan can be a useful tool for predicting marine aerosol S_p ($\lambda = 532\ nm$) at wind speeds between 8 and 15 ms^{-1} with an error of ± 2 sr."

Additional Comments:

The authors should state somewhere that CALIOP AOD is not considered as a reliable operational output. A comprehensive overview of CALIOP-derived AOD can be found in Winker et al. (2013). In my opinion, CALIOP AOD can only be used for cloud-free profiles for which a surface signal is detected. This information is provided in the 5-km aerosol profile product. I assume that using CALIOP

observations according to the availability of SODA AOD intrinsically accounts for cloud-free conditions and for a surface signal being detected. Is that correct? It is worthwhile mentioning that somewhere in the Section 2.4 (Data selection method). The presence of clouds above the marine aerosol layer would increase the value of the total integrated backscatter coefficient.

As described in the paper SODA output only for cloud-free atmospheric column was retained when the surface signal was detected and was intrinsically the strongest signal in the profile. SODA does provide cloud optical depth. We use the vertical feature mask from CALIPSO to make sure we only analyze columns with 1 layer and that layer is classified as marine aerosol. We modified the text to avoid any further confusion:

"Therefore, when determining the lidar ratio of marine aerosol using Eq. 4, the algorithm only retains the data in which clean marine is the only type of aerosol present in the entire cloud-free atmospheric column."

In Section 2.4, the text from page 221, line 8 to page 222, line 14 basically describes the same procedure as the one from page 222, line 15 to page 223, line 11. I suggest to harmonize and shorten this section.

We have modified section 2.4 to the following:

"As different aerosol sub-types have different lidar ratios, application of Eq. 4 to episodes when aerosols other than sea spray are present in the atmospheric column may lead to erroneous results for the calculated $\overline{S_p}$. We developed a strict scene selection algorithm to minimise the contamination of AOD and therefore $\overline{S_p}$ by aerosol types other than marine (e.g., anthropogenic pollution, biomass burning, and dust),. The algorithm first uses the feature classification flags in the CALIOP aerosol layer product. We start with clean marine aerosol that is identified based on surface type (as determined by the location of the satellite) and either total integrated attenuated backscatter $\gamma' > 0.01$ $km^{-1}sr^{-1}$ or total integrated attenuated backscatter $\gamma' < 0.01$ $km^{-1}sr^{-1}$ and volume depolarization ratio $\delta' < 0.05$ (Omar et al., 2009). As multiple types of aerosols can be found within retrieved vertical profiles (e.g., dust above sea spray), aerosol feature types that have been identified as marine in a given atmospheric column are not enough to carry out the analysis. Therefore, when determining the lidar ratio of marine aerosol using Eq. 4, the algorithm only retains the data in which clean marine is the only type of aerosol present in the entire cloud-free atmospheric column. To further reduce the uncertainty, we constrain the analysis to single layer profiles and remove profiles in which marine aerosol layers are vertically stacked within an atmospheric column. Therefore, the vertically integrated particulate attenuated backscatter $\overline{\Gamma_p}$ is replaced by Γ_p. Similarly, the column lidar ratio $\overline{S_p}$ is reduced to S_p in the remainder of the text. Note also that all quantities discussed are particulate quantities and therefore, molecular scattering is removed using gridded molecular and ozone number density profile data from the Goddard Earth Observing System Model, version 5 (GEOS-5) analysis product available from the NASA Global Modeling and Assimilation Office (GMAO) (Winker et

al., 2009). Operationally, particulate scattering is determined to be where the ratio of the CALIOP 532 nm scattering profile normalised by the GEOS-5 molecular scattering profile is greater than one $\left(\frac{\beta'_{532}}{\beta_m} > 1\right)$. *Errors associated with* $\overline{\Gamma_p}$ *are discussed in Sec. 4.*

All data is for nighttime and is binned into 2º × 5º latitude and longitude, respectively, grid cells. Collocated wind speed is taken from the Advanced Microwave Scanning Radiometer - Earth (AMSR-E) observing system. To identify distinct features associated with the variability in marine aerosol lidar ratio over different parts of the oceans, the selected data is examined in relation with other variables such as season, spatial location and wind speed.

Some additional measures were taken to target layers with a high signal-to-noise ratio and grid cells with a significant number of observations. These measures included (i) ensuring the relative error in Γ_p *due to random noise in molecular backscatter was* $<$ *50%, (ii) the collocated SODA 5 km layer was composed of at least 70% shot-to-shot data and (iii) the total number of retrievals per 2º × 5º grid cell ranked above the first quartile of the grid cell frequency distribution. Such strict quality controls considerably increase the reliability of the analysis despite reducing the total number of data points. It should be noted that a large number (over 260,000) of data points remained for robust statistics after all the quality control and quality assurance tests. A caveat, despite such rigorous quality control criteria, remains when interpreting data near coastlines as the CALIOP scene classification algorithm may mistakenly identify mixtures of continental pollution and marine as clean marine aerosol (Burton et al., 2013; Oo and Holz, 2011; Schuster et al., 2012) causing an overestimation in the lidar ratio inferred from Eq. 4. Further discussion of error analysis is given in Sec. 4 below."*

Given that the conclusions of the paper still hold after the authors check for the issues raised above, I suggest going for a more daring title like: Spaceborne observations of the lidar ratio of marine aerosols.

We have revised the title as suggested.

Response to Anonymous Reviewer # 2

We would like to thank Reviewer #2 for his/her comments. We have done our best to address each of the points as detailed below.

pg3 ln11 - replace 'although' with 'however'

Replaced.

Please revise:
Other techniques like the inversion of AERONET radiometer data (Holben et al., 1998) along with Mie theory can also provide the lidar ratio (the supplementary Table S1 summarizes available methods to retrieve the lidar ratio). A more complete list can be found elsewhere (Cattrall et al., 2005; Smirnov et al., 2001).
to:
Other techniques like the inversion of AERONET radiometer data (Holben et al., 1998) along with Mie theory can also provide the lidar ratio. The supplementary Table S1 summarizes available methods to retrieve the lidar ratio and a more complete list can be found elsewhere (Cattrall et al., 2005; Smirnov et al., 2001).

Changed. The text now reads: "Other techniques like the inversion of AERONET sun photometer data (Holben et al., 1998) along with Mie theory can also provide the lidar ratio. The supplementary Table S1 summarizes available retrieval methods and values of the experimentally determined lidar ratios over the marine regions."

pg7 ln22 - symbol error and the sentence is confusing, repeating integrated attenuatted backscatter with different criteria. Please revise.

The sentence now reads:

"We start with clean marine aerosol that is identified based on surface type (as determined by the location of the satellite) and then retain only the data with total integrated attenuated backscatter $\gamma' < 0.01$ *$km^{-1}sr^{-1}$ and volume depolarization ratio* $\delta' < 0.05$ *(Omar et al., 2009)."*

pg11 ln 31 - replace 'easy' with 'simple'

Replaced.

pg13 ln24 & 29 symbol error

All symbol errors are fixed in the modified manuscript.

pg14 ln7 - Josset et al. (2008, 2010) show good agreement of the AOD with MODIS at tropical latitudes and for optical depths ranging from clean to polluted. It would be better to characterize the agreement for the conditions and locations that you are considering. It is recommended that the statistics be included for a more relevant subset of the data in Josset et al. (2010) if possible, otherwise the constraints of the evaluation should be stated explicitly.

We agree with the reviewer. The modified manuscript we now include comparison of collocated HSRL and SODA AOD data (during a CALIPSO underpass). The text now reads:

"To further assess the reliability of SODA marine aerosol product we also compared collocated HSRL and SODA AOD data. Figure 6a shows results from three CALIPSO (and therefore SODA) underflights validated against HSRL. According to Fig. 6 for AODs < 0.3 (comprising the majority of marine aerosol retrievals), SODA compares reasonably well to HSRL (R^2 = 0.82). Additionally, Fig. 6b illustrates that the relative uncertainty in the SODA retrieved S_p is less than 50% for AODs > 0.03. The bulk of AODs measured by CALIPSO exceed this value under the quality control criteria discussed in Sec. 2.4. Errors were estimated based on Eq. 12 in Josset et al. (2011) and are representative of an upper bound due to the usage of the absolute value. Therefore, for AODs > 0.05, we expect lidar ratio retrieval uncertainties below 50%."

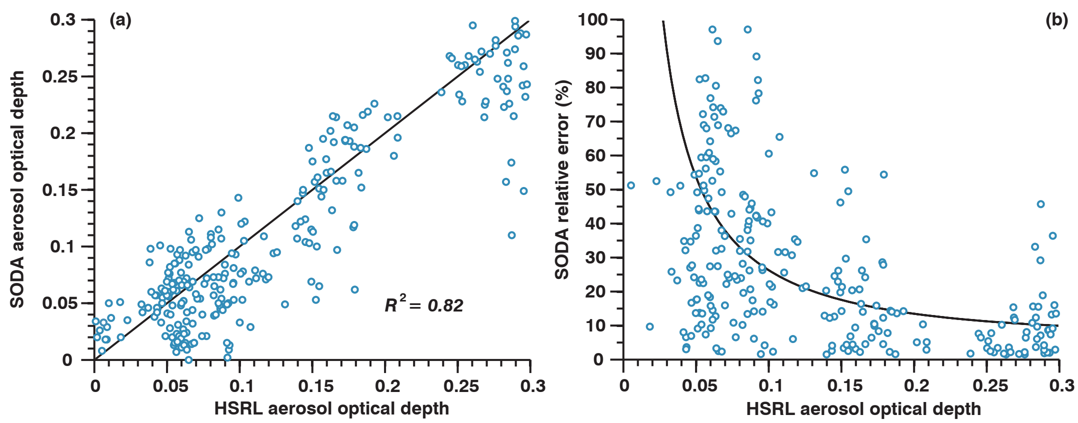

Fig. 6 *(a) A scatter plot of SODA AOD relative to AOD measured by HSRL at 532 nm. The dashed black line illustrates the 1:1 line. (b) Relative uncertainty in the SODA column lidar ratio as a function of HSRL AOD with the black line showing the least squares exponential fit as in Eq. 15 Josset et al. (2012).*

SODA comparison with maritime aerosol network (MAN) data for our time period within 60 km radius results in 13 matched data points, which are too few for a useful comparison.

+/- symbol errors in table S1

Symbol is fixed in the modified manuscript.

Please revise this sentence (in Table S1) to better define 'aerosol return':

Text in Table S1 has been revised. The text now reads:

"The HSRL technique relies on the difference in spectral distribution of backscattered signal from molecules and particulates. Discrimination between aerosol/cloud and molecular returns in the receiver is accomplished by splitting the returned signal into two optical channels: the molecular backscatter channel, which is equipped with an extremely narrowband iodine vapor absorption filter to eliminate the aerosol returns and pass the wings of the molecular spectrum, and the total backscatter channel, which passes all frequencies of the returned signal. After appropriate internal calibration of the sensitivities of the two channels, the signals are used to derive profiles of extinction, backscatter coefficient, and extinction-to-backscatter ratio, Sp."