Response to Reviewer #1

We thank the reviewer for helpful comments. Our responses to the reviewer's specific comments are listed below. The reviewer's concerns are in bold italicized font and our responses are in regular font. The page numbers and line numbers given in our responses below are in reference to the revised version of the manuscript.

Radiative forcing from stratospheric aerosols is a major driver of climate variability. Building robust and consensual observational records of stratospheric aerosol observations is thus critical to understand past climate changes and to predicting future climate. For the satellite era, this task is made particularly challenging by the fact that different periods are covered by different instruments with different measurement technique, so that producing an homogeneous and consistent continuous record is difficult. To address this challenges, the Global Space-based Stratospheric Aerosol Climatology (GloSSAC) dataset v1.0 was produced (Thomason et al., ESSD 2018) and has since become the reference dataset of stratospheric aerosol observations. In particular, it has been used as input to historical experiments of Phase 6 of the Climate Model Intercomparison Project. This manuscript presents the latest version v2.0 of the GloSSAC dataset which follows the original version v1.0 and its update v1.1. Many improvements have been done since version v1.0 and in particular: i) the dataset is now extended to year 2018; ii) an error in the processing of data from the CLAES instrument has been corrected; iii) the processing of data from the OSIRIS and CALIPSO instrument has been improved, in particular thanks to data from SAGE III having become recently available and overlapping with the OSIRIS/CALIPSO observations. Given these major improvements and the importance of the GloSSAC dataset, this manuscript will be an extremely valuable contribution and I recommend its publication following minor revisions. The manuscript describes and justifies in great details the updates to GloSSAC, and generally reads well. There are a few places where I think the figures or text could be improved (cf minor comments below). My main comment is that even though technical changes since v1.0 are well described, the paper lacks figure(s) and discussion extensively comparing v2.0 to v1.1 and v1.0 (cf specific comment below), which seems important given this paper provides an update to an existing dataset. I think this would represent an important improvement to the paper, and that it wouldn?t require much work from the authors which is why I recommend minor revisions.

Specific comments

1) If I?m not mistaken Figure 15 is the only figure showing the final differences between two versions of the GloSSAC (v2.0 and v1.1) and only do so for the 2002-2016 period. I don?t think GloSSAC updates have been documented in a peer-reviewed literature since GloSSAC 1.0 release (Thomason et al. 2018)? It thus seems very

important to show the differences between all three versions (1.0, 1.1 and 2.0) and for the full period in common (1979-2016). From my own analyzes of GloSSAC version it seems that each version is different in the post-Pinatubo period, which is one of the period with the most research on stratospheric aerosol forcing. I thus really think that figure 15 should be extended to include all versions/the full common period. In addition to showing contour plot of SAOD as a function of latitude and time, I also think it would be very valuable to compare global mean SAOD time series between the three versions as this is the canonical metric for stratospheric aerosol impact on climate. Section 5 of the manuscript should then be extended to discuss these differences in greater details. Getting an idea of SAOD differences among GloSSAC versions will likely be a major expectation of GloSSAC users from this paper, so I strongly encourage the authors to address this comment.

Figure 15 is now extended to the entire record of GloSSAC and now shows AOD plots of v 1.1 and v 2.0. We also included another figure (Figure 16) that show v 1.0 and v 2.0 and their differences. Additional plots include a global SAOD plot (Figure 18) with labels of volcanic eruptions on Figures, and we discuss these changes in section 5.0.

2) In line with comment 1 above, I think that the abstract should end with a few sentences summarizing the main changes between versions in terms of SAOD. The abstract is very focused on the technical changes in GloSSAC 2.0 which is of course appropriate for an ESSD paper, but it is currently hard for a scientist with little expertise in remote sensing to get a sense of the impacts of these changes on the GloSSAC product from the current abstract.

Thanks for this suggestion. While we appreciate the reviewer for this suggestion, due to the word limit constraints for the abstract, we are not able to include this into the abstract. We now address this in the conclusion section of the paper (lines 3:8, page 17).

3) This comment is very much a suggestion. Figure 1 is an excellent introduction figure to the manuscript. I was wondering if it could be complemented (or if you could add a new figure) showing a timeline of some of the main features/limitations/challeng in the GloSSAC record, such as what type of instrument is used (e.g. solar occultation or other), the resolution/frequency of measurements (e.g. global daily coverage with OSIRIS/CALIOP vs global monthly coverage with SAGE instruments), assumptions required (e.g. periods in which an assumption on size distribution is required), etc... Such a figure would enable people with limited expertise in remote sensing to understand in one glance some of the main features of the GloSSAC dataset before using it, which I believe would be very valuable.

We have added a paragraph (line 25:30, page 2 and line 1:5, page 3) about the main features, limitations and challenges. The new paragraph now reads as:

”Figure 1 depicts the measurements that are currently used for constructing GloSSAC data. While Thomason et al. (2018) discusses about the measurements that have been used in GloSSAC v 1.0 dataset in detail, some of the main features of entire GloSSAC v2.0 dataset including various space based measurements, their limitations and some challenges are worth mentioning here. We divide the entire dataset into three periods based on the measurements used. The first period being the pre-SAGE II period (January 1979- September 1984), followed by SAGE II period (October 1984 - August 2005) , post-SAGE II period (September 2005- May 2017), and SAGE III/ISS period (June 2017-present). Pre-SAGE II period data mostly consists of data from solar occultation measurements such as SAM II , SAGE and some surface based Lidar measurements (Thomason et al., 2018). For SAGE II period, the measurements are dominated by solar occultation measurements that provide multi-wavelength measurements for size information. For the post-SAGE II era, we are limited to single wavelength measurements from OSIRIS and/or CALIPSO. While OSIRIS and CALIPSO continue to make daily global measurements with a less direct measurement of aerosol extinction coefficient that requires further assumption of particle size, additional direct measurements of aerosol extinction coefficient from SAGE III/ISS are now available that provides a roughly monthly coverage of multi-wavelength measurements since June 2017. ”

page 1 line 1: I stumble a bit on the first sentence of the abstract. In addition to being a bit cumbersome, it introduces what a stratospheric aerosol dataset should do, but the second sentence does not follow on the dataset so it?s confusing.

We rewrote the sentence to have the continuity.

page 1 line 7: I don?t think Zanchettin et al. (2016) is the adequate reference for CMIP6 unless you are talking specifically about VolMIP.

Replaced with Eyring et al. (2016).

Page 2 line 4-5: ”can impact climate on scales from the subtle [...] to the more profound [...]”: I find this wording vague and confusing: are you talking about the timescales of the impacts? Their magnitude?

We changed it to ”can impact climate on magnitudes from ....

I would be more specific and clear about the difference in these modelling approaches, e.g. ”Some of these modelling studies directly use observations of stratospheric aerosol optical properties as input, whereas other use observations of SO2 as input and interactively simulate stratospheric aerosol life cycle”

We specifically state that in the following paragraph (lines 10-15, page 2).

page 2, line 6-14: You focus on GCMs study as a motivation but I feel like you could

include other examples that have used the GloSSAC dataset to make important contributions. In a purely observational study, Stocker et al (2019, https://agupubs.onlinelibrary quantify the temperature footprint of 21st century eruptions using GloSSAC which in turns enable to better quantify temperature trends related to anthropogenic forcing. Aubry et al. (2020, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019JD03130 used GloSSAC to calibrate a box model of volcanic forcing. Such box model is the typical tool used to derive SAOD/forcing time series from ice-core records so that?s an important application of dataset like GloSSAC. These are just suggestions and application to GCM study is of course a major motivation, but I think it?s nice to highlight that applications of the GloSSAC dataset go beyond that.

Thanks for the suggestion. We now added a sentence on Stocker et al., 2019 (line 15, page 2).

page 2, line 14: I am not too sure where to put this comment, but it feels like the paper under review by Rieger and co-authors (https://gmd.copernicus.org/preprints/gmd-2019-381/) is very relevant to your paper and should be mentioned if its publication status allows it. Maybe instead of in the introduction it would fit better in your discussion of an extended figure 15 (cf specific comments) showing the differences in SAOD between v1.0, v1.1 and v2.0 for 1979-2016.

We have added this reference in SAOD discussion section.

page 2, line 15: it?s a bit confusing as you say "mostly unchanged" followed by "significant improvements" and "major version change". These statements sound contradicting and you may want to reformulate.

The data sources are unchanged. However the usage of the data (with some updated versions) and the analysis approach resulted in significant improvements. We have revised the sentence now and it reads as:

"While data sources are mostly unchanged from earlier versions, there are significant improvements in the use of OSIRIS and CALIPSO data with inclusion of SAGE III/ISS data for the first time."

page 3, line 13-33: this feels like a very detailed and technical discussion of the changes you made for an introduction. I feel like this content should be in section 2 instead?

We have now moved those lines to section 2.

page 4, line 7: there and hereafter, I suggest you provide date in parenthesis when you refer to XXX instrument period. It will be very helpful for readers not perfectly familiar with the period spanned by different instrument.

Done.

page 4, lines 10-18: if I?m not mistaken no figure illustrate these results? The Pinatubo period is of course of utmost interest to climate modelers so it feels like there should be a figure accompanying this paragraph? (although if you extend Figure 15 according to my suggestions that would illustrate this paragraph well)

We now discuss this in section 5.0.

page 5, line 14-16: this is an important comment. Again it would be nice to specify dates in parenthesis for user who are not familiar with SAGE missions dates. I know that the reader could just look at Figure 1 but it would facilitate the reading if you also provide such dates directly.

Done.

General comment on section 2: I enjoyed this section and although I don?t have the expertise to understand all details, you clearly highlight the differences in methods/ limitation/challenges of different periods of the GloSSAC record. A figure with a timeline showing this features would be a very neat addition (see specific comment 3 for a more detailed suggestion)

We have now added a paragraph in the beginning of section 2 and discuss Figure 1 and the instruments used in detail.

page 6 line 7: maybe you could give an idea of the uncertainty on the 50 sr value?

This number comes from OPC and lidar measurements study Jäger and Deshler (2002, 2003) that is based on specific size distributions. It could also be tested theoretically using Mie theory with an assumption of size distributions. Again, please note that lidar ratio strongly depends on size distribution. So, specifically using a constant number for extinction-to-backscatter ratio has limitations. For this study, we however used a pseudo-extinction to backscatter ratios (defined as "Scale Factor" in the manuscript) and its related uncertainties in Figure 9. Using a value of 53 sr seems reasonable between 30S and 30N from 18 km and above based on Figure 9a and the relative standard deviation based on our method is mostly within ± 20% (Figure 9b).

Also, Vernier et al. (2011) reported the variability in lidar ratios across various latitude bands, showing lidar ratios vary with latitude and altitude.

page 6, lines 25-34: Is this cloud-clearing method more challenging to apply when there is a very large volcanic eruption (e.g. Pinatubo like or larger)? I?m just wondering whether the IQR would be larger following a large eruption.

There are limitations on this method as well, especially when we use this in the vicinity of tropopause with large eruptions. It is particularly challenging to differentiate between clouds and aerosols near tropopause during and following volcanic eruptions. We are currently working on developing a cloud screening algorithm for SAGE III/ISS in particular which could be incorporated in a future version of GloSSAC.

Page 8 line 4-5: does the Raikoke 2019 eruption provide a good test for this hypothesis?

The technique we use in here has limitations when it comes to periods of volcanic activity particularly due to change in size distributions and for the period 2005-2017, we are limited to using single wavelength measurement that lacks information about aerosol sizes. Yes, multiwavelengths measurements have been available from SAGE III/ISS since June 2017, which help us understand better as to how aerosol size changes during and following a volcanic eruption. For the Raikoke eruption, a detailed study using SAGE III/ISS measurements is in progress.

Page 9 line 2-3: why do you say "though probably not at 756nm"? Doesn?t figure 5b show a strong high bias in the lower stratosphere and low bias in the tropical midstratosphere?

We are aware of a low bias at 521 nm channel of SAGE III/ISS. We, however do not observe any such changes in other aerosol measurement wavelengths such as 756 nm. In addition, for Figure 5a, there is an additional complexity that the OSIRIS 525 nm extinction coefficient is computed from a constant Angstrom exponent of 2.33 while 750 nm extinction coefficient is the primary reported wavelength for OSIRIS and Figure 5b is a straightforward comparison with SAGE III/ISS. Therefore, comparing the differences between Figure 5a and 5b is not a direct one.

Page 9 line 14: I can?t find the definition of lambda

Lambda represents wavelength. The sentence now reads as : "$(\frac{\lambda_{525}}{\lambda_{750}})$ represents ratio of wavelengths at 525 and 750 nm."

section 3-4: these sections were generally clear and provide a good overview of differences between instruments and data processing/conforming procedures employed by the authors.

Thanks.

page 13 line 33: So I guess the tropopause height is a climatology as in Thomason et al. (2018)? I think it would be useful to remind here the period used to derive this climatology, as well as the reanalysis used (MERRA if I remember correctly). Additionally, the tropopause height is quite variable at highlatitude and is increasing in the tropics as a consequence of anthropogenic forcing. Given these two points, I am wondering why you are using a climatology instead

of the reanalysis data directly? Differences would likely be small but it would be a bit more rigorous approach? As an example figure S1 in Aubry et al (2020, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019JD031303) show GloSSAC SAOD at v1.0 and v1.1 using the MERRA climatology and the NCEP-NCAR reanalysis for tropopause height with some interesting differences. I haven?t analyzed these differences further, but the SAOD I get are smaller for the 21st century which could be in part due to tropopause height increase?

The tropopause climatology is derived from MERRA for the SAGE II lifetime as stated in Thomason et al. (2018) paper. We continue to use that in here as well. Yes, we do agree that the tropopause is variable with latitude and time of the year and using a climatology may not be an accurate representation. We will definitely keep this suggestion in mind and make use of a variable tropopause in a future version of GloSSAC.

Section 5: please see my specific comment 1, but I really believe that this section would be more complete if you: -show differences between all 3 versions of GloSSAC -show differences for the full time period shared between the 3 version (1979-2016) -show global mean SAOD time series in addition to SAOD contour plot -extend text in section 5 to include discussion of the above

We have now revised this section to include the entire record of SAOD.

page 14 lines 22-23: it feels like you could add a few references to support this statement? There have been multiple modelling studies showing that post- 2005 SAOD enhancement can be largely explained by SO2 emissions from explosive volcanic eruptions as well as wildfire for some of the recent years. See e.g. Schmidt et al. (2018, https://doi.org/10.1029/2018JD028776), Peterson et al. (2018, https://www.nature.com/a 018-0039-3) or Aubry et al. (2020, https://agupubs.onlinelibrary.wiley.com/doi/full/10.102

Done. The sentence now reads as:

”As with v1.0, we cannot exclude the possibility that on-going volcanic activity plays a dominate role in the apparent enhancement after 2005. This possibility is bolstered by noting that optical depths shown in Figures 15b and 15e approach those observed in 2004, 2013, early 2014 during a lull in a decade of repeated minor volcanic stratospheric enhancements. We also note that several recent modeling studies (e.g. Schmidt et al., 2018; Aubry et al., 2020) using sulfur dioxide emissions in aerosol-climate models, have reported an enhancement in SAOD for the post-2005 time period.”

page 16 line 9: avoid repetition of ”inferred 1020nm extinction” twice in the same sentence. Otherwise, I think this is a nice paragraph to close the conclusion section!

Done.

Section 6: the conclusions are ok but overall I feel like you could be a bit more succinct on some of the technical details, and that you should add a few sentence commenting on major differences in SAOD in GloSSAC 2.0 compared to 1.0/1.1. This really seems critical as the aim of the paper is to present the newest version of the GloSSAC dataset, so in general it really feels like you should do more to compare SAOD in the different versions. This would likely be the most expected results from this paper for users of the GloSSAC product.

We now briefly discuss changes in SAOD occurred in version 2.0 compared to previous versions.

Table 1 caption: replace "since 2002" by "over 2002-2018" as this table doesn?t include 2019/2020 eruptions (e.g. Raikoke and Ulawun in 2019, Taal in 2020)

We have now revised the table to include all events since 1979.

Figure 7: I like this figure a lot. Maybe you could have a SI table specifying the dates of "after"/"before" (or add these dates in the caption directly)

We have added dates to each event in the figure. There is another paper in review in ACP (https://doi.org/10.5194/acp-2020-480) that discusses this method in detail.

Figures 10/12/17: given the differences between datasets are relatively small, I?m wondering if you should not use lines instead of markers? The marker sometime overlaps a lot making it harder to distinguish any systematic difference.

Done. Replaced makers with lines.

Figures 13-16: on most of these figures, the density of contour labels is too high and prevent the reader to see clearly the data on the figure (this is made worse by the white rectangles in which each label is inserted). Consider removing the labels altogether or at least reducing their density/removing white rectangles.

Done. Removed labels and contours from all these plots and a new color scale has been used.

Figure 16: it looks like this figure has been stretched horizontally?

This has been fixed. It was in fact related to the adjustment of the figure size that was made in the latex version.

References

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Response to Reviewer #2

We thank the reviewer for helpful comments. Our responses to the reviewer's specific comments are listed below. The reviewer's concerns are in bold italicized font and our responses are in regular font. The page numbers and line numbers given in our responses below are in reference to the revised version of the manuscript.

General Comments The paper presents the new version of the GLoSSAC aerosol climatology (version 2), and details all changes brought with respect to the former version 1.1, for wich changes are also briefly described with respect to version 1.0. Prominent changes are the availability of a new version for OSIRIS (version 7.0) with an improved quality, and th release of a standard CALIOP extinction product. Beyonf an improvement of the overall quality, this brings new possibilities to refine the derivation of some GLoSSAC products (e.g. through the use of variable extinction-to-backscatter ratio). Overall, the paper is clear, well written and well structured, in particular the introduction and conclusions. In many places, citation of the first GloSSAC paper (Thomason et al., 2018) is required. I suggest to specify the section to which the citation refers in this paper, in order to ease the reading. A recurrent assuymption is that the SAGE instrument SAGE II and SAGE III/ISS are golden standards, and the key benchmark by which all other data sets have to conform. A very good reason for this is that SAGE instruments are using solar occultation, a technique requiring few assumptions for the data retrieval. SAGE II also has an excellent reputation and was a very long-duration mission. However, doing so ignores the possibility that SAGE II ageing affects the quality of the measurements at the end of the SAGE II, although the use made of SAGE II to calibrate OSIRIS and CALIOP is of critical importance for GLoSSAC. It should be reminded that SAGE II is about 18-years old when OSIRIS and CALIPSO are launched. On the other hand, SAGE III/ISS is recent, and one could miss the broader view on the real quality of this data set. This point of view should also be discussed or at least mentioned, with reference to validation papers giving more insight into the quality of the dataset during the critical period overlapping with the OSIRIS and CALIPSO missions. Overall, the paradigm is that everything is fine tuned to match the two SAGE datasets (and OSIRIS where these datasets are unavailable), but sometimes at all costs, without too much consideration for the consistency or physical significance of the methodology (e.g. different Angstrom exponents used for OSIRIS and CALIOP conversion purposes, ?We do not assume that the derived Angstrom coefficient has any physical meaning it is simply a mean to push OSIRIS toward SAGE II?, L. 22-24, p.9). The fact that instruments (SAGE, OSIRIS, CALIOP) are based on totally different measuring techniques that might have an impact in some altitude or latitude range is hardly considered or discussed, although this might provide an insight into main differences between the data sets. The way CALIOP backscatter coefficient is conformed to GLoSSAC extinction coefficient is also not fully convincing.

Automatically considering a hierarchy of values (?SAGE II is the best instrument?, ?SAGE II/ISS is equal to SAGE II?, ?OSIRIS in the best one after SAGE?) without questioning the physics, the evolving atmospheric state, or any consideration related to aging instruments, has the consequence that SAGE II?s spectre is still hovering on the quantification of the extinction coefficient in the stratosphere as it is about 14 years after SAGE II?s death. This should be questioned or, at the least, discussed.

Specific comments

L. 18-20, p.3: This sentense sound odd. What do the authors mean by ?data (: : :) are made to match or conform with SAGE II?? Do they refer to the transformation of the other source data sets in extinction coefficient profiles at 525 nm/1020 nm at the SAGE II vertical grid? This should be clarified.

Here, for example, we use data from OSIRIS and CALIOP other than SAGE. And, their primary quantity of measurement is different (OSIRIS reports extinction coefficient (after retrieval) at its primary wavelength of 750 nm whereas CALIOP's primary measurement is backscatter coefficient). To match or conform to SAGE II means converting these into SAGE II primary measurements of aerosol extinction at 525 and 1020 nm, either using an Angstrom exponent (for OSIRIS) or using a lidar ratio (for CALIPSO). We included information about primary measurements of OSIRIS and CALIOP as examples in the text (Line 2, page 4).

L. 20-22, p.3: A reference to the first GLoSSAC paper, Thomason et al. (2018) is necessary here to make clear what the authors mean.

Thomason et al. (2018) reference is now included in the text whenever it is needed.

L. 23-27, p.3: Same remark for this discussion: a reference to Thomason et al. (2018) is needed.

Done. (line 18, page 4)

L. 30-32, p.3: Aren?t these differences due to fundamental differences in measurement principles and in such a case, wouldn?t it be a useful way to explore differences and possibly reconcile both techniques?

There are fundamental differences in measurement principles. However, the difference that we see, for example in the conversion of backscatter coefficient to extinction clearly shows some anomalous extinction to backscatter ratios when CALIPSO backscatter coefficient is compared against OSIRIS and/or SAGE extinctions, indicating these differences are due to measurement/conformance deficiencies. These anomalous extinction to backscatter ratios are consistently seen in the entire record of comparison. In addition, we note the differences between OSIRIS and SAGE II/III extinctions and their possible causes were reported earlier (Bourassa et al., 2012; Rieger et al., 2015; Kremser et al., 2016).

L. 33-34, p. 3: What are these changes included in interim version 1.1? Please refer to Section 2.1 where it is described or possibly provide some reference.

The changes made to v 1.1 was mostly to correct how CLAES data is used in the lower stratosphere for the period between July 1991 and April 1993.

We have added a sentence that reads as ”The changes made to interim version 1.1 is described below in Section 2.1.” (Line 26, page 4)

L. 34-35, p.3: If this data set is key, it should at least be cited!

We added a reference in here. The sentence now reads as :

”Within v2.0, a key data set (McCormick et al., 1979) used in the SAGE/SAGE II gap period (1982-1984) has been updated.” (line 27, page 4)

L. 12-13, p.4: This has definitely to be developed and described carefully. Which ground-based lidar product was used, at which location, and which assumptions were used to match them with remote sensing data? Combination of lidar measurements and extinction measurements are not straightforward. Which lidar ratio was used, and how were the data combined?

A detailed description about this is given in section 2.2 (p 8-10) of Thomason et al. (2018) and in section 4.2 of SPARC (2006). The lidar ratios were used from Jäger and Deshler (2002, 2003). We added the reference now and the sentence now reads as:

”CLAES data becomes available in October 1991 but is used in combination with a ground-based lidar product to estimate the aerosol levels from July to September 1991 and is used standalone for a decreasing span of altitude and latitude until the end of its mission in April 1993 (Thomason et al., 2018; SPARC, 2006).”

L. 14-16, p.4: Again, how was this combination (here: CLAES-HALOE with SAGE II) implemented? If only a few points are considered, the possible impact of biases may be high? These aspcts should be carefully discussed.

Please note that this is described in detail in section 2.2 of Thomason et al. (2018). Actual coincidences, by usual standards is pretty low, so we are using some binned comparisons but it still ends up averaging hundreds of data points. The uncertainty in the fits is a part of the error budget for these parameters. In addition, figures 6,7, and 8 of Thomason et al. (2018) show how the combinations were used.

L. 18-19, p.4: ?A few defects missed in v1.0?: which kind of defects and what were the consequences of these defects? Is there any publication or technical report where

these modifications could be found?

While it did not make much difference between the two approaches, we decided that the more conservative use of CLAES and HALOE data preserved the sampling pattern of SAGE II that appears in the entire SAGE II part of the record (1984-2005). Unfortunately, we do not have any publication on this. There is a product quality summary document available from ASDC for v 1.1 and 2.0.

L. 21, p.4: How did this outlier removal occur? Smooth curves may be esthetically more satisfactory, but at risk of leaving out minor events of interest, and possibly of importance for the climate modelling applications the authors want to serve. Also, outlier removal may imply the use of poorly controlled data manipulation and of changes in values very dificult to trace. How did the authors deal with this difficulty? See also comment on L.8, p.7.

We do not think it adversely affects the data by applying an outlier filter as we note that the filtering has only very minimal impact on 452, 525 and 1020 nm extinction coefficients but it impacts 386 nm extinction by reducing noise- a channel with increased noise (Thomason et al., 2008) and should be used cautiously due to the noise in the data which we note in the manuscript and in the previous version (Thomason et al., 2018).

L. 24-26, p.4: This sentence is useful for readers not familiar with the SAGE II dataset. Please provide a citation where this issue is discussed.

We added a couple of references here and the sentence now reads as:

”Users should continue to use caution using the SAGE II 386 nm aerosol extinction coefficient data as a low bias is evident in this data in the lower and upper stratosphere and at all altitudes as aerosol extinction coefficient magnitudes approach background levels (Thomason et al., 2008, 2018). ”

L. 26-29, p.4: In Thomason et al. (2018), (at least) two kinds of interpolation mechanisms are used for gap filling. One is a linear intepolation in time (but not in latitude and altitude), and another one is the use of an empirical relationship between the 1020 nm and 525 nm extinction coefficient values defined from a statistical analysis of pairs of (1020 nm, 525 nm) extinction coefficient values retrieved from SAGE II observations (Fig. 8 of this paper). Which one is meant here by the authors?

We used the empirical relationship between 1020 and 525 nm extinction coefficient values.

L. 30, p.4: The concept of equivalent latitude is unclear for a possible ?new reader?. Please provide a reference.

We have now added reference and the sentence now reads as:

”In addition, with the apparent success of filling the high latitudes using the equivalent latitude/latitude mechanism developed based on Manney et al. (2007) for v1.0 (Thomason et al., 2008), we have reduced the role of simple linear interpolation at high latitudes and allow the new equivalent latitude/latitude mechanism fill more of the missing data at high latitudes."

L. 31, p.4: ?The new filling mechanism? is unclear. Do the authors mean: ?the filling mechanism by use of equivalent latitude?? (or ?new more elaborate mechanism? that might be distinguished from ?simple mechanism?). Also, ?the simple intepolation?: do the authors mean ?a linear interpolation? (with respect to time?)?

We have revised the sentence now and it reads as:

"In addition, with the apparent success of filling the high latitudes using the equivalent latitude/latitude mechanism developed based on Manney et al. (2007) for v1.0 (Thomason et al., 2008), we have reduced the role of simple linear interpolation at high latitudes and allow the new equivalent latitude/latitude mechanism fill more of the missing data at high latitudes."

A detailed description as to how the interpolation is done is given in Thomason et al. (2018).

L. 33, p.4: Please be specific to ease the reading: ?the simple (linear?) interpolation process??

We are not sure what the reviewer is referring to ? If it is line 31, we now changed to "linear" interpolation.

L. 1, p.5: It might be useful to specify that these quantities reflect the natural variability and the instrumental error, respectively. In Thomason et al. (2018), an increased value of zonal standard deviation is described when averaging by latitude is used, especially at the boundary of the polar vortex. Is it observed accordingly here that the more extensive use of the equivalent latitude results in a decreased zonal standard deviation?

The use of equivalent latitude reduces the zonal standard deviation in areas where strong zonal gradients occur. The standard deviations we report are always a combination of measurement noise and natural zonal variability.

L. 1-2, p.5: Again, this sentence requires a citation.

We are not sure about the citation of Line 1-2. If it is about CLAES and HALOE data sets, we have now included references to those data sets. The sentence now reads as : "The CLAES (Massie et al., 1996) and HALOE (Thomason, 2012) data sets now include zonal standard deviation and median reported measurement uncertainty following the approach used for SAGE II data. The conversion of CLAES and HALOE data follow the methodology described in Thomason et al. (2018)."

L. 3-5, p.5: This sentence is particularly unclear. Please rephrase, and specify

sections or figures in Thomason et al. (2018) that may ease the understanding of the method.

The conversion of CLAES and HALOE data is described in detail in Thomason et al. (2018). We, think that including the same method here will be a repetition.

Title 2.1 and l. 6-16, p. 5: I suggest to keep the structure and similar titles as in Thomason et al. (2018) by splitting this section is a 2.1 ?The SAGE II period? and ?The pre-SAGE II period?. This should ease the reading, and a possible combined reading of both paper in parallel (and e.g. the comparison of methods used, such as interpolatin methods).

Done. We now use two subsections under Section 2.1.

L. 10, p.5: ?the results?: Do the authors mean ?the values extended along isentropic surfaces between Nov. 1981 and Oct. 1984??

Yes. The sentence now reads as:

"While the revised file was nominally created in same way as the existing data file, the values extended along the isentropic surfaces can be significantly smaller at times than those used in v1.0 particularly in the Southern Hemisphere during the Spring."

L. 5-7, p.6: I guess the two ?potential sources of bias? are basically a single one. Please rephrase. This source of bias is not ?potential?, but real and potentially quite significant. In Thomason et al. (2018) the lidar ration was equal to 50. Why this change, and what are the effects of this change?

The sentence now reads as: "Finally, the conversion from backscatter coefficient to extinction coefficient presents a source of bias; as this process depends on details of an unknown aerosol composition and size distribution (Kar et al., 2019) that is a another potential source of bias."

While the method described in Thomason et al. (2018) is dependent on a median value that is obtained from a relationship between CALIOP backscatter coefficient and OSIRIS extinction, the lidar ratio of 53 is from Kar et al. (2019). We do not think that it makes much of a difference between using 50 and 53 in the lidar ratios. Also, the method used in Thomason et al. (2018) for the CALIOP data is different compared to Kar et al. (2019) method. We also see significant difference in the backscatter coefficient data between these two versions in the lower stratosphere and also at higher latitudes. Therefore, comparing these two data set based on lidar ratio difference may not be a direct comparison.

L. 22-23 p.6: Please provide some explanation or a reference for the PSC identification.

Different methods have been used for detecting PSCs in different data sets. For SAGE measurements, we use a threshold temperature of 200 K, meaning if the temperature is below 200 K between tropopause and 25 km, then those measurements are eliminated as PSCs. For OSIRIS data, additional constraints are used in addition to temperature based PSC detection (Rieger et al., 2019). For CALIPSO, a method employed by Pitts et al. (2009) is used which is also a temperature based approach.

L. 19, p.6: ?found in the lower stratosphere?: at all latitudes?

Occurrences of clouds have often reported in the Upper Troposphere Lower Stratosphere (UTLS) region in the tropics (± 20^0) and midlatitudes (± $40\text{-}60^0$) in addition to the PSC's in the polar latitudes.

L. 5-7, p.7: See comment on L. 21 p.4.

Again, we do not think it adversely affects the data by applying an outlier filter. And, as mentioned in the paper, we are not using the conservative IQR method which appears to remove some of the enhanced aerosol extinction data. We also ensured that we are not removing any peak data points that occurs due to any volcanic/fire events in the data as it is evident from the time series plots (Figure 10, 12 and 17) that show "before" and "after" conformance of OSIRIS data. These plots clearly show peaks associated with any volcanic/fire events. Again, we are using only a very minimal outlier removal as it can be seen from Figure 1.

L. 8, p.7: Being resigned to accept this fact is harmful because it is known that the accumulation of medium eruptions plays an important role in the correct assessment of the aerosol radiative forcing [Vernier et al., Geophys. Res. Letter, doi:10.1029/2011GL047563, 2011; Bingen et al., Remote Sensing Env., doi: 10.1016/j.rse.2 2017], a key issue CMIP6 is intended to address.

We are not sure what the reviewer is referring to. If the reviewer is concerned about the depiction of volcanic events in the GloSSAC data, it is clear from the time series plot (Figures 10, 12, and 17) that almost all volcanic events can be identified with the peak in the data and the cloud filtering method has a minimal impact on them.

L. 13-15, p.7: ?the extreme outlier was effective at identifying outliers in the aerosol distribution?: The formulation is confusing, please revise. ?outliers in the aerosol distribution?: do the authors mean ?outlying data possibly related to medium volcanic/ pyrocumulonimbus events??)

The sentence now reads as:

"We found that the conservative outlier appeared to remove many enhanced aerosol measurements particularly when stratosphere is perturbed due to volcanic/pyrocumulus events, whereas the extreme outlier was effective at identifying outliers in the density distribution. Therefore we use the extreme outlier to clear cloud-affected observations from the data set.”

L. 7, p.8: Using a constant Angstrom exponent implies the assumption that the particle size distribution is constant. This is potentially a rough assumption impacting the accuracy of the values of the extinction coefficient at 525 nm used in GLoSSAC.

This method has been employed in previous studies (e.g. Bourassa et al., 2012; Rieger et al., 2015). And, the conversion factor and the difference between OSIRIS and SAGE II measurements were noted in (Rieger et al., 2015) which led to a scaling of extinction based on OSIRIS to SAGEII extinction ratio (Rieger et al., 2015). As described in the following sections of the paper, we are using a climatological Angstrom exponent and currently we do not have any other way to address this issue. May be a possible transient Angstrom exponent can be implemented in a future version.

L. 11, p.8: What is a ?strong aerosol measurement wavelength??

What we mean by strongest aerosol wavelengths is with least uncertainty and increased accuracy in measurements. For SAGE II and SAGE III/ISS, there are two strongest wavelengths channel in common which are 525 and 1020 nm. We revise the sentence now as:

” Since the SAGE III/ISS instruments operates in a manner similar to SAGE II, the expectation is that there would be minimal bias between these instruments at least at the strongest aerosol measurement wavelengths of 525 and 1020 nm.”

L. 18, p.8: What do the authors mean by ?a rather benign October 2004?.

The sentence is now revised as:

”In figures 4a and 4b, it is apparent that for much of the stratosphere the difference between SAGE II and OSIRIS is less than 10% particularly in Figure 4a for a rather benign (less affected by volcanic/fire events) October 2004.”

L. 19 and 32, p.8: These estimates are particularly optimistic. Following the color bars, the differences often exceed 50% in both cases.

The sentence now reads as:

”However, it is also clear that OSIRIS extinction is consistently higher than SAGE II in the lower stratosphere with percentage difference exceeding 50% near the tropopause. Another departure is shown in Figure 4b for March 2005 that shows similar features as October 2004. However, in the tropical low and middle stratosphere there is a difference of about 50% in an enhanced aerosol layer associated with the eruption of Manan in January 2005.”

L. 1-3, p.9: The assumptions made for the conversion of OSIRIS extinction coefficient from 750 nm to 525 nm seems an obvious cause of deficiency, which is confirmed by the result of the revision of the conversion factor as illustrated in

Figure 5c (and the end of Section 2.4). See comment on L. 7, p.8..

We agree that using a constant Angstrom exponent may not work well during volcanic events and we state that in the manuscript as one of the caveats. Again, this method has been employed in previous studies (e.g. Bourassa et al., 2012; Rieger et al., 2015). And, the conversion factor and the difference between OSIRIS and SAGE II measurements were noted in Rieger et al. (2015) which led to a scaling of extinction based on OSIRIS to SAGEII extinction ratio (Rieger et al., 2015). As described in the following sections of the manuscript, we are using a climatological Angstrom exponent and at this point we do not have any other way to address this issue. May be, a possible transient Angstrom exponent could be implemented in a future version.

L. 17-20, p.9: Did the authors compare the results obtained only with SAGE II, and only with SAGE III? This seems important to assess possible differences, either between the two SAGE instruments, or between both periods.

Since the SAGE III/ISS instruments operates in a manner similar to SAGE II and SAGE III meteor, the expectation is that there would be minimal bias between these instruments at least at 525 and 1020 nm. Some previous studies have compared/validated SAGE II with SAGE III meteor (Thomason et al., 2010; Damadeo et al., 2013). While the differences between SAGE II and SAGE III meteor aerosol extinction coefficient are relatively smaller, previous studies (Thomason et al., 2010; Damadeo et al., 2013) reported a small bias between SAGE II (v 7.0) and SAGE III (v 4.0) meteor that are within ± 10% for measurement wavelengths at 525 and 1020 nm for the altitudes between 7 and 25 km.

L. 22-24, p.9: This statement is particularly strange! The Angstrom exponent does have a physical meaning, since it reflects the size properties of the aerosol population. Pursuing as sole purpose the replication of one data set at all costs (even one supposed to be good, although its comparison with the real truth is impossible ? this should always be kept in mind!) and getting rid of any concern about the correct quantification of known underlying effects at this aim, looks problematic to me.

We have revised text and replaced Angstrom exponent with "Pseudo Angstrom exponent". Please note that we are conforming the data based on OSIRIS and SAGE II/III extinction comparisons as is described in the manuscript. The pseudo angstrom exponent we use here is merely a scaling factor that conforms OSIRIS data to SAGE II/SAGEIII. We do agree that size changes during volcanic events do matter and we currently do not have a way to address this issue. However, we are working on developing a method as to how various volcanic eruptions affect the particle sizes (Thomason et al., 2020), which might help us understand better about the process. We plan to implement a possible correction on size dependence particularly following a volcanic/fire event in a future version of GloSSAC.

L. 24-25, p.9: ?Angstrom exponent values?.

Yes. It is now corrected.

Caption Figure 4, 5, and 8: The quantity provide should be precisely mentioned, e.g.: ?OSIRIS and SAGE II extinction coefficient at 525 nm?. In caption of Figure 5, ?for at? is not correct and ?for? should be removed. In caption of Figure 8, ?Altitude versus Latitude of percent difference.? is meaningless. Difference in what? The authors should also clearly mention the period covered by this plot.

Done.

L. 27, p.9: I suggest to stick to the naming ?Angstrom exponent?. Please check the whole document.

Done. We now checked for consistency and only ”Angstrom exponent” is used throughout the document.

L. 32, p.9: After using an Angstrom exponent of 2.33 to convert OSIRIS extinction coefficient from 750 nm to 525 nm (cf. L. 7, p. 8), another value of the same Angstrom exponent, 1.50, is used to convert the CALIOP extinction coefficient from 532 nm to 525 nm. Why such a difference? This incoherence should be discussed or justified.

The Angstrom exponent of 1.5 is typically used for CALIOP conversion of aerosol extinction (Vernier et al., 2011). We, however, changed that to 2.33 to be consistent with the values used in the manuscript. We have updated Figure 8a, b that use Angstrom exponent to convert CALIOP extinction.This method is just for the comparison purpose (between this version and the conformed version of CALIOP extinction). And, we note that this conversion does not matter as far as the GloSSAC data is concerned as we are not using extinction computed by this method in GloSSAC. We instead use the conformed aerosol extinction that have been computed using scale factor (Figure 9) as described in the manuscript.

L. 7-8, p.10: Smaller eruptions also occurred during the SAGE II mission (1984-2005). Is there any similar observations by SAGE II that might support such tendency? This might help depicting if such effect is real, or is the reflect of some limitation either of the OSIRIS instrument, or of the OSIRIS retrieval.

Yes. There is another paper in ACP which is in review (https://doi.org/10.5194/acp-2020-480) that discusses how various volcanic eruptions impact aerosol sizes that occurred during SAGE II mission and also in the current SAGE III/ISS mission.

L. 25, p.10: ?roughly consistent with values for sulfuric aerosol in the stratosphere?: The extinction-to-backscatter ratio shows much variability in the stratosphere (See

for example Vernier et al., Geophys. Res. Lett., 38, L12807, doi:10.1029/2011GL047563, 2011), and the size characteristics also play a role in the variability of this parameter. Hence, I think that this statement is not very relevant.

We revised the sentence and it reads as:

”This value, 53 sr, is roughly consistent with the extinction-to-backscatter ratio used within CALIOP data processing (50 sr).”

L. 29, p.10: ?As a result?? This sentence is the transition between considerations about version 1.0, and work around version 2. This should be made clear by an adequate introduction. Furthermore, at this stage, it would ease the reading to remind that the CALIOP extinction coefficient product by Kar et al. (2019) is the one used in GLoSSAC, as mentioned in L. 3-4, p.3.

Not sure what the reviewer’s comment is. We have already cited Kar et al. (2019) in here where we mention standard stratospheric aerosol product.

L. 31-32, p.10: Why are the authors using now another value of the Angstrom exponent (1.50) for the conversion CALIOP, while a value of 2.33 was used before for OSIRIS extinction conversion? This is quite confusing and increase the level of incoherence between the data sets.

The Angstrom exponent of 1.5 is typically used for CALIOP conversion of aerosol extinction (Vernier et al., 2011). We, however, changed that to 2.33 to be consistent with the values used in the manuscript. We have updated Figure 8a, b that use Angstrom exponent to convert CALIOP extinction.This method is just for the comparison purpose (between this version and the conformed version of CALIOP extinction). And, we note that this conversion does not matter as far as the GloSSAC data is concerned as we are not using extinction computed by this method in GloSSAC. We instead use the conformed aerosol extinction that have been computed using scale factor (Figure 9) as described in the paper.

L. 7-10, p.11: I don?t understand what the authors intend here. In 3, p.10, it is explained that the CALIOP extinction used in GLoSSAC is the CALIOP extinction product (Kar et al., 2019) at 532 nm, converted to 525 nm based on an Angstrom exponent of 1.50. Why do they use now the CALIOP 532 nm backscatter converted using an empirical scaling factor, with some kind of warning that this scaling factor will also reflect ?any kind of biases?? This is extremely confusing.

We compared the standard CALIOP extinction product (after using angstrom exponent of 2.33 to convert from 532 nm to 525 nm) with conformed OSIRIS and SAGE III/ISS data. We however, consistently see an enhanced aerosol extinction in the lower stratosphere and also at higher latitudes (poleward of 40 N/S), indicating that the CALIOP data is biased high. We, therefore thought it is appropriate not to use standard CALIOP extinction, but use CALIOP backscatter and the scale factor (based on OSIRIS 525 nm extinction and CALIOP 532 backscatter) to convert backscatter coefficient to extinction. This scale factor is like a pseudo lidar ratio which has altitude-latitude dependence. We note that Kar et al. (2019) has also pointed out increased extinction levels in the lower stratosphere and higher latitudes in the standard CALIOP data and also computed a lidar ratio (Figure 13 of Kar et al. (2019)) that are retrieved using SAGE III/ISS extinction and CALIOP backscatter measurements which also shows that lidar ratios are variable.

L. 13-27, p.11: I don?t really understand what the authors are doing here. The CALIOP backscatter is the primary quantity measured by CALIOP. What is the interest of rederiving the primary measured quantity from the CALIOP extinction (derived with a simplified assumption of a constant lidar ratio equal to 50), using an empirical scaling factor taking into account all possible problems (?aerosol-related effects and bias between the two data sets?), based on modified (?bias-corrected?) OSIRIS extinctions at another wavelength with some rough approximation about the atmospheric transmission (mentioned as ?clearly not correct? by the authors themselves) , and a simplified formula to account for the scattering ratio and molecular backscatter. And from the conclusion that ?it does not matter a great deal whether we use the standard CALIOP stratospheric backscatter product or the alternative alternative?, the authors choose using this hazardous construction of alternative backscatter product! This is extremely strange and confusing, and if the aim is ? again ? to ?match? at all costs CALIOP with OSIRIS, the methodology used is, at the least, questionable.

We initially thought of using the standard particulate backscatter product. We later realized that the particulate backscatter in the Level 3 data file is retrieved using a lidar ratio 50 Sr. So, if we use the retrieved particulate backscatter for computing scale factor (SF) which is based OSIRIS extinction to CALIPSO backscatter ratio, we are in fact using a SF (which is similar to a lidar ratio) on a product that was already retrieved using a constant lidar ratio of 50. We, therefore used an alternate method that does not use any fixed value for lidar ratio. Please note that a similar method has been used earlier for retrieving backscatter measurements (Vernier et al., 2009). Below is a formulation that we used to derive particulate backscatter as described in the current version of the manuscript. We start with the scattering ratio which is defined as the ratio of total backscatter coefficient to molecular backscatter coefficient. We then assume the transmission of atmosphere ($T_{[\lambda,p]}(z)^2$) is close to 1 as shown in the second step of the formulation. The particulate backscatter ($\beta_{[\lambda,p]}(z)$) is then derived using scattering ratio and molecular backscatter.

$$\text{Scattering Ratio} \equiv SR \equiv \frac{\text{Total Attenuated Backscatter}}{\text{Molecular Attenuated Backscatter}} \tag{1}$$

$$SR = \frac{\left(\beta_{\lambda,m}(z) + \beta_{\lambda,p}(z)\right) T^2_{\lambda,m}(z) T^2_{\lambda,oz}(z) \cancelto{1}{T^2_{\lambda,p}}(z)}{\beta_{\lambda,m}(z) T^2_{\lambda,m}(z) T^2_{\lambda,oz}(z)} \tag{2}$$

$$SR = \frac{\beta_{\lambda,m}(z) + \beta_{\lambda,p}(z)}{\beta_{\lambda,m}(z)} \tag{3}$$

$$SR = 1 + \frac{\beta_{\lambda,p}(z)}{\beta_{\lambda,m}(z)} \tag{4}$$

$$SR \cdot \beta_{\lambda,m}(z) = \beta_{\lambda,p}(z) + \beta_{\lambda,m}(z) \tag{5}$$

$$\beta_{\lambda,p}(z) = (SR \cdot \beta_{\lambda,m}(z)) - \beta_{\lambda,m}(z) \tag{6}$$

, where $\beta_{[\lambda,m]}(z)$, $\beta_{[\lambda,p]}(z)$, $T_{[\lambda,oz]}(z)^2$, and $T_{[\lambda,p]}(z)^2$ are molecular backscatter, particulate backscatter , ozone and particulate transmittance respectively.

We have computed a percent difference between the standard retrieved backscatter coefficient and the backscatter coefficient computed using the alternate method (inferred backscatter). As shown below in Figure 1a, the percent difference computed between retrieved and inferred backscatter for March 2007. At altitudes above 18 km, the percent difference is below ±10%, while the percent difference increases to about ±30% near below 15 km. While there is increased difference below 18 km, it does not really matter much as we scale those differences away in the conformance process by using OSIRIS extinction to CALIOP backscatter, defined as scale factor (SF) in the manuscript. We then computed the ratio of 525 nm OSIRIS extinction to 532 nm CALIOP backscatter coefficient using both the retrieved and the inferred CALIOP backscatter. Figure 1b,c show the ratio of OSIRIS extinction to retrieved and inferred CALIOP backscatter coefficient respectively for March 2007. There are differences between the two methods particularly below 18 km, where they match with the increased percent difference shown in Figure 1a. While the SF computed using retrieved CALIOP backscatter shows values below 30 sr below 18 km (Figure 1b), the SF using inferred CALIOP backscatter shows a higher SF which is around 40 sr (Figure 1c). Generally, below 18 km the retrieved backscatter coefficient is larger than inferred backscatter coefficient. However, these differences are scaled away in the conformance process where we use OSIRIS extinction to CALIOP backscatter ratios (SF) as they are evident from Figure 1. We, therefore believe that our alternate method to infer backscatter coefficient is not a hazardous construction of backscatter.

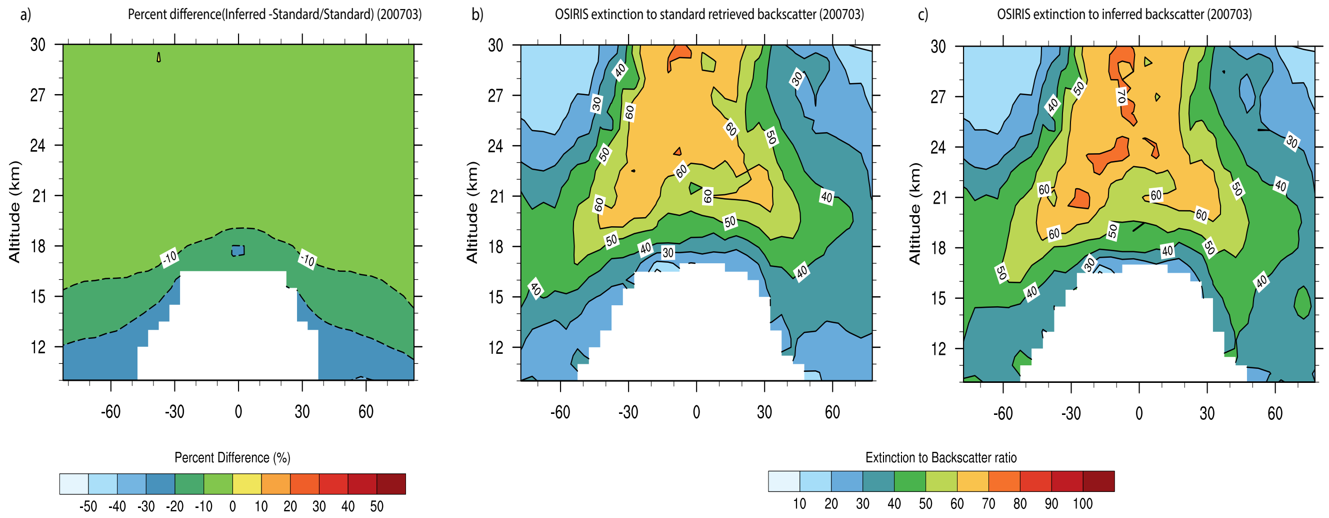

Figure 1: Percent difference and extinction to backscatter ratios for 200703. (a) percent difference between standard retrieved and inferred CALIOP backscatter coefficient computed as (Inferred-Standard/Standard)*100, (b) 525 nm OSIRIS extinction to retrieved 532 nm CALIOP backscatter and (c) 525 nm OSIRIS extinction to inferred 532 nm CALIOP backscatter.

Additionally, as pointed out by reviewer 3, Kar et al. (2019) reported large differences (> ±50%) with SAGE III/ISS below 20 km, which could be due to the presence of clouds. These differences are consistent with OSIRIS data as well. This was the reason we decided to use the conformance process based on the extinction to backscatter ratio as shown in Figure 9 of the manuscript, also shown in Figure 1 above.

L. 29-30, p.11: The SF values varying between 25 and 65 might reflect the objective to get rid of the fixed 50-value of the lidar ration used by Kar et al. (2019) to better match local aerosol features. If this indeed is the case, the authors should completely revise this discussion to make it clear, and they should justify why they expect improvement with respect to Kar et al. (2019), see previous comment.

Our response to the previous comment in detail, answers this comments as well.

Figure 5: It is very strange to mix both SAGE II and SAGE II/ISS overlap periods as if these two SAGE sensors were one single data set or mission. SAGE II and SAGE III/ISS are two different instruments measuring different situations in very different conditions. Assimilating the SAGE II and SAGE III/ISS to one single perfect data set looks excessive, and at least, results for both data sets should also be shown (or quantified in some way) to justify that just mixing both is appropriate.

Since the SAGE III/ISS instruments operates in a manner similar to SAGE II and SAGE III meteor, the expectation is that there would be minimal bias between these instruments at least at 525 and 1020 nm. Some previous studies have compared/validated SAGE II with SAGE III meteor (Thomason et al., 2010; Damadeo et al., 2013). While the differences between SAGE II and SAGE III meteor aerosol extinction coefficient are relatively smaller, previous studies (Thomason et al., 2010; Damadeo et al., 2013) reported a small bias between SAGE II (v 7.0) and SAGE III (v 4.0) meteor that are within ± 10% for measurement wavelengths at 525 and 1020 nm for the altitudes between 7 and 25 km. We are not sure if any quantification can be done with SAGE III/ISS and SAGE II as they differ in measurement time period. The best we can do is to compare these measurements with OSIRIS that have overlap measurements with these two instruments, which we have done in the manuscript. We do not think assimilating SAGE III/ISS and SAGE II will create any bias in the monthly climatology of pseudo angstrom exponent, followed by the conformance of the data.

L. 1-4, p.12: The methodology used here is expected to provide more variations of the extinction-to-backscatter ratio than the fixed one assumed by Kar et al. (2019). However, the question is to know it the whole construction with a succession of more or less coarse assumptions used here provide a better estimate of this parameter. See also comment on L. 29-30, p.11

Please see a detailed response to an earlier comment L 13-27, p. 11.

Additionally, as pointed out by reviewer 3, Kar et al. (2019) reported large differences (> ±50%) with SAGE III/ISS below 20 km, which could be due to the presence of clouds in CALIOP data. These differences are consistent with OSIRIS data as well. We also note the pattern of the lidar ratio based on SAGE III/ISS extinction and CALIOP backscatter (Figure 13 of Kar et al. (2019)) is more or less consistent with our SF in Figure 9a.

L. 20, p.13: Is the linear interpolation implemented only in the time dimension? What about the possible use of equivalent latitudes? This should be specified.

When no data is available, grids are filled using linear interpolation in time.

The sentence is now revised and it reads as:

”It should also be noted that, in some cases (particularly for February 2016 and October 2018) when no CALIOP data is available, we linearly interpolate CALIOP data in time between January (September) and March (November) of 2016 (2018) to fill in the missing monthly data following methods used in interpolating SAGE II data.”

Figure 15: The choice of dynamic range for the color scale of pannels 15(a), (b), (d), and (e) is particularly poor. Same for Figure 16. Differences mentioned in L. 2-3, p.14 are hardly visible, and the ?substantially smaller enhancement? in 2005 in version 2.0 with respect to version 1.1, is just invisible in both cases to me.

Done.

L. 4-11, p.14: Could several latitudinal dependence and hemispheric dependences possibly be explained by differences in data coverage and/or in intrumental techniques? This possibility has not been discussed.

Some differences may be the result of the different performances of the instruments and that those differences may well be of latitude dependence (e.g. like the scattering angle effect for limb scatter instruments).

L. 22-27, p.14: I think, indeed, that in view of all efforts made to force some data sets to fit in as much as possible some other one, any discussion about trends Is absolutely premature.

Please note that the conformance was done based on studying each data set carefully. Many previous studies have reported the difference between SAGE and OSIRIS measurements (e.g. Bourassa et al., 2012; Rieger et al., 2015) in the first place and for CALIOP, with the standard stratospheric aerosol product we clearly see an enhancement in the lower stratospheric/higher latitude data which is also pointed out by Kar et al. (2019). So, the conformance process was based on studying each data set carefully. While the conformance process applied here merely force the data toward SAGE II/ III-ISS based on intercomparison of individual data sets, we do not believe any signatures of volcanic/fire aerosol is compromised as they are evident in the entire record. Additionally, these signatures are evident from figures 10, 12, 15, 16, 17 and 18.

L. 24, p.2: incorrect sentence: ?whose accuracy? should be removed.

Done.

L. 25, p.2: ?Which this change?? (Or another change?)

The sentence is revised and now reads as:

”With these changes, the retrieved extinction coefficient at 750 nm is in better agreement with observations by SAGE II and SAGE III/ISS than the version used in GloSSAC v1.0 (v5.07).”

L. 3, p.5: missing period (?.?).

Done.

L. 16-17, p.4: odd sentence.

We are not sure what the author is referring to. The sentence seem to be correct.

P. 25, p.6: New sentence starting with ?However, ? ?

Revised the sentence and now reads as:

”While the OSIRIS version 7.0 aerosol data product is similarly cloud screened (Rieger et al., 2019),we, however found some additional clearing was beneficial to the analysis.”

L. 3, p.5: ?its?.

We do not see any ”its” in this line though.

L. 20, p.7: incorrect sentence: ?can transition?.

The sentence is now revised and reads as: ”Cloud identification is complicated by mixed fields of view where observations transition between mostly cloudy extinctions and extinction ratios and those more typical of purely aerosol.”

L. 24, p.7: incorrect reference: should be ?Thomason and Vernier (2013)?.

Done. The sentence now reads as: ”Various techniques to parse these mixed measurements have been developed and GloSSAC makes use of the technique developed by Thomason and Vernier (2013). ”

L. 16, p.9: ?Extinction?.

The sentence is now revised and reads as:

”where, $k_{525[t,m,i,j]}$, and $k_{750[t,m,i,j]}$ are extinctions at 525 nm and 750 nm respectively, $\eta_{[m,i,j]}$ is the pseudo Angstrom exponent while the indices $[t, m, i, j]$represent year, month, latitude, and altitude respectively. $(\frac{\lambda_{525}}{\lambda_{750}})$ represents ratio of wavelengths at 525 and 750 nm. All data are gridded to 5 degree latitude and 0.5 km altitude resolution. ”

Caption Figure 9: The authors should be more explicit: ?(b) Relative standard deviation of the extinction-to-backscatter ratio shown in (a)?. ?deviation of (a) in percent? is unclear.

Done. It now reads as

”(b) Relative standard deviation of (a) is computed at each grid point with respect to the median value in percent”

L. 30, p. 12: ?We use? with capital letter.

Done.

L. 31-32, p.12, L. 18, p.15, and caption Figure 11: ?SAGE II and SAGE III/ISS?.

Revised as ”between OSIRIS and SAGE II/SAGE III-ISS”.

L. 19-21, p.19: Rieger et al. (2019) is published, and the reference should be adapted.
Done.

References

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Response to Reviewer #3

We thank the reviewer for helpful comments. Our responses to the reviewer's specific comments are listed below. The reviewer's concerns are in bold italicized font and our responses are in regular font. The page numbers and line numbers given in our responses below are in reference to the revised version of the manuscript.

General comments: The paper describe the development of the stratospheric aerosol data set GloSSAC V2.0 and changes made since the last release of V1.1. The methodology of the data set construction and rational is clearly described. The paper is well written, and the results are presented and discussed with sufficent details. I recommend for publication subject to the following changes.

Major comment: I find the authors choice of conforming rather than excluding data that exhibit very large biases (> 50 %) somewhat concerning. Mainly because some of these data may be affected by clouds. Kar et al. (2019) reported large differences with SAGE III/ISS below 20 km, which can be explained in part by subvisible cirrus cloud scattering artifacts that may appear to within several kilometers above the tropopause. In addition, the authors failed to explain the advantage of using the newly released CALIOP standard products instead of version 4.0 Level 1 data used in GloSSAC V1.0. Do they believe that their approach produces better product than what was used in V1.0 and V1.1?

When we have started our efforts to incorporate CALIOP data in to GloSSAC v 2.0 by using version 4.0, level 1 data as it was used in GloSSAC 1.0 and 1.1, the official CALIPSO stratospheric aerosol product was released. The release of CALIPSO standard stratospheric aerosol product was followed by a paper that was published (Kar et al., 2019). After the release of the official CALIOP stratospheric aerosol product, it was appropriate for us to use the standard stratospheric product from CALIPSO team instead of using version 4.0 level 1.0 data. To some extent we had no choice but to use the CALIPSO data as it is a priority for the data set to be gap free. The old technique used a fixed extinction to backscatter ratio that created what we believe have biases in the lower stratosphere. The new approach seems to minimize this issue. We do agree with the reviewer that there is large bias in CALIOP data, sometime exceeding 50% when compared to other data products. This was the reason we decided to use the conformance process based on the extinction to backscatter ratio as shown in Figure 9. As you can see from Figure 9a that the extinction to backscatter ratio decreases to even less than 30 sr as noted in the manuscript. By using these values, we believe the bias in the lower stratosphere has been reduced to a greater extent although not completely bias free. We also note that CALIOP data is used only when other extinction measurements (OSIRIS or SAGE III/ISS) are not available which occurs mostly at higher latitudes. Attached is a figure that shows the percent difference between the standard CALIOP product and the bias corrected CALIOP extinction (after conformance process) for 201711. It is evident from this figure that the conformance process help reduce the bias in the data particularly in the lower stratosphere where the percent difference (STANDARD-CORRECTED/CORRECTED)*100) exceeds 80% indicating the conformed CALIOP extinctions values have been reduced significantly. We do agree that this will not completely remove the bias in the lower stratosphere but it clearly helped reduce the bias in the lower stratosphere in particular.

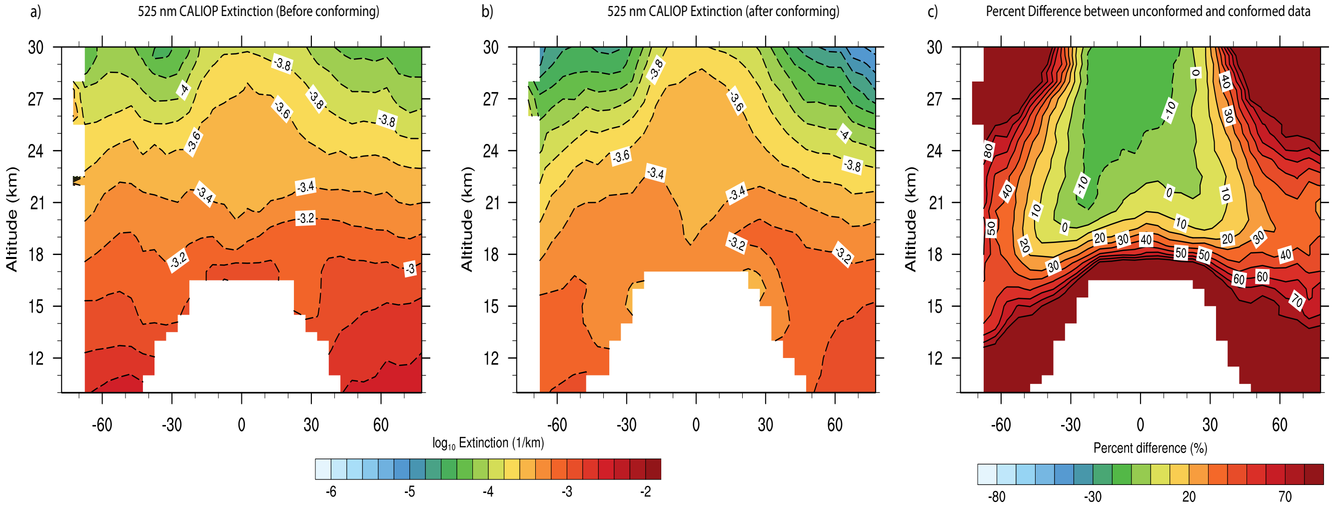

Figure 1: CALIOP extinction coefficient and percent difference for 201711. (a) Standard CALIOP extinction coefficient (CS) at 525 from the standard CALIOP data product, (b) CALIOP data after conformance (CC), following method described in manuscript, and (c) Percent difference computed as (CS-CC/CC)*100. The standard CALIOP extinction is available at 532 nm and is converted to 525 nm using a constant Angstrom exponent of 2.33 in (a).

General comments:

Table 1: Some of the volcanic eruptions listed in table 1 did not reach the stratosphere and thus are not relevant to this dataset. The table should be modified to include only volcanic eruption that are evident in GloSSAC dataset.

We have now revised Table 1 to extend the record back to 1979 as one of the reviewers suggested to include the entire record of GloSSAC. We also label these in Figure 15, 16 , and 18.

Figure 1: the figure is identical to figure 1 published earlier by (Thomason et al., 2018), which shows SAGE III/ISS as a future instrument. I suggest either updating the figure or simply just cite the figure in (Thomason et al., 2018).

We have revised this figure and made necessary changes so that the figure now shows SAGE III/ISS as current instrument.

Page 3, first paragraph: The authors need to add a brief statement justifying the change and summarizing the differences between the new CALIOP products and the

one used in V1.1.

We have added a brief statement toward the end of the paragraph and it now reads: " While we use the standard CALIPSO stratospheric aerosol product, enhanced levels of aerosol extinction in the lower stratosphere are consistently noted in the entire dataset after comparing against OSIRIS and SAGE III/ISS. We, therefore decided to use a conformance process which is described below that helps reduce the bias in the lower stratosphere and also at higher latitudes."

Page 8 L6: ?OSIRIS extinction is also routinely produced at 525 nm, : : :? should be replaced by ?OSIRIS extinction can be produced at 525 nm, : : :? or something like that. The original text implies that it is part of the official V7.0 release.

The sentence is revised and now reads as " In addition to 750 nm, OSIRIS extinction can be calculated at 525 nm...."

Page 8 L10: ?Since the SAGE III/ISS instruments operates in a manner virtually identical to SAGE II? ?virtually identical? should be replaced by ?similar? since the two instruments have different designs and age. Toward the end of its life, SAGE II was an aging instrument that operated on reduced duty cycle as compared to the newly refurbished SAGE III/ISS instrument.

The sentence now reads as "Since the SAGE III/ISS instruments operates in a manner similar to SAGE II, the expectation is that there would be minimal bias between these instruments at least at the strongest aerosol measurement wavelengths at 525 and 1020 nm."

Page 8, L15: ?SAGE II and SAGE III/ISS are relatively unbiased with each other? this not accurate since both (Thomason et al., 2010) and (Damadeo et al., 2013) reported 10 % bias between SAGE II and SAGE III Meteor, which is supposed to be identical to SAGE III/ISS. The differences between SAGE II and III should be acknowledged and discussed in this section.

We now add another footnote about the bias between SAGE II and SAGE III meteor which now reads as "While the differences between SAGE II and SAGE III meteor aerosol extinction coefficient are relatively smaller, some previous studies (Thomason et al., 2010; Damadeo et al., 2013) reported a small bias between SAGE II (v 7.0) and SAGE III (v 4.0) meteor that are within ± 10% for measurement wavelengths of 525 and 1020 nm for the altitudes between 7 and 25 km."

Page 8, footnote 1: ?While the OSIRIS instrument performance has remained unchanged over time,? This not exactly accurate. According to Bourassa et al. (2018) and Rieger et al. (2019), OSIRIS had a small drift that resulted in a pointing error and a correction was applied to V7.0. Please modify the text accordingly.

Yes. We changed the footnote to "While the OSIRIS instrument performance has relatively remained unchanged over time, the scattering angle has slowly drifted, and the fraction of ascending/descending node measurements has changed. These factors may affect overall data quality."

Page 9, L23: I suggest changing ?Angstrom exponent? (where appropriate) to something like ?pseudo Angstrom exponent? to eliminate any confusion regarding its physical meaning.

Done.

Figure 7: Can you add the year to the volcanic eruption label?

Done.

Section 3.1: The paragraph describing the choice between using the standard CALIOP stratospheric backscatter or the alternative product is confusing and difficult to follow, especially when the authors conclude that ?it ultimately does not matter a great deal whether we use the standard CALIOP stratospheric backscatter product or the alternative product described above?. If that is the case, why not use the standard product and eliminate the confusion? Also, the CALIPSO section in supplementary materials implies that the standard products were used.

Sorry about the confusion. We initially thought of using the standard particulate backscatter product. We later realized that the particulate backscatter in the Level 3 data file is retrieved using a lidar ratio 50 Sr. So, if we use the retrieved particulate backscatter for computing scale factor (SF) which is based OSIRIS extinction to CALIPSO backscatter ratio, we are in fact using a SF (which is similar to a lidar ratio) on a product that was already retrieved using a constant lidar ratio of 50. We, therefore used an alternate method that does not use any fixed value for lidar ratio.

We have computed a percent difference between the standard retrieved backscatter coefficient and the backscatter coefficient computed using the alternate method (inferred backscatter). The Figure 2a below, shows the percent difference computed between retrieved and inferred backscatter for March 2007. At altitudes above 18 km, the percent difference is below ±10%, while the percent difference increases to about ±30% near below 15 km. While there is increased difference below 18 km, it does not really matter much as we scale those differences away in the conformance process by using OSIRIS extinction to CALIOP backscatter, defined as scale factor (SF) in the manuscript. We then computed the ratio of 525 nm OSIRIS extinction to 532 nm CALIOP backscatter coefficient using both the retrieved and the inferred CALIOP backscatter. Figure 2b,c show the ratio of OSIRIS extinction to retrieved and inferred CALIOP backscatter coefficient respectively for March 2007. There are differences between the two methods particularly below 18 km, where they match with the increased percent difference shown in Figure 2a. While the SF computed using retrieved CALIOP backscatter shows values below 30 sr below 18 km (Figure 2b), the SF using inferred CALIOP backscatter shows a higher SF which is around 40 sr (Figure 2c). Generally, below 18 km the retrieved backscatter coefficient is larger than inferred backscatter coefficient. However, these differences are scaled away in the conformance process where we use OSIRIS extinction to CALIOP backscatter ratios (SF) as they are evident from Figure 2b,c.

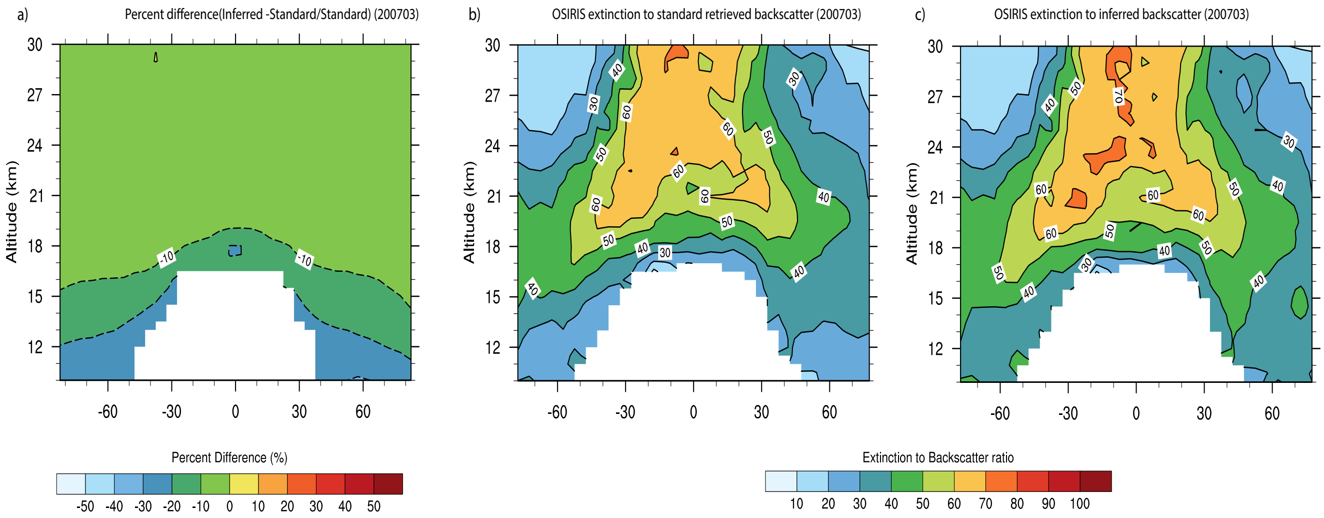

Figure 2: Percent difference and extinction to backscatter ratios for 200703. (a) percent difference between standard retrieved and inferred CALIOP backscatter coefficient computed as (Inferred-Standard/Standard)*100, (b) 525 nm OSIRIS extinction to retrieved 532 nm CALIOP backscatter and (c) 525 nm OSIRIS extinction to inferred 532 nm CALIOP backscatter.

Page 11, L29-30: ?except at higher altitude at polar latitudes where it is possible that the impact of the polar vortex plays a role in producing SFs less than 10 sr? I find it difficult to believe that the effect of PSC can cause this small ratio at altitudes between 25 ? 30 km, and the statement is pure speculation. Unless the authors can show that this low ratio takes place during the winter season and low temperature, which are ideal for PSCs formation, I suggest deleting it.

We have now revised the sentence.

Page 12, L11: The authors claim that the difference between CALIOP and SAGE III/ISS is now below 20 %, when in fact figure 8d clearly shows the differences are mostly 30 and 40 %. Please revise the text accordingly.

It is now revised and reads as :”Similarly, the difference between the scaled CALIOP stratospheric extinction and SAGE III/ISS is now mostly below 30% except near the tropical lower stratosphere and polar high altitudes, whereas the the difference between standard CALIOP stratospheric extinction coefficient and SAGE III/ISS is also often more than 50%.”

Figure 10 and 12: Can you change the y-axis to linear scale instead of log. The log

scale makes it difficult to see the differences between different measurements.

We tried changing it to linear scale but looked crowded. But, we changed ”markers” to ”lines” which we hope is now clearer in the revised figure.

Figure 6 and 11: Can you modify the color scale to -1 to 5.

Done.

Page 13 second paragraph: The authors use angstrom exponents to infer 1020 nm, similar to the method used to derive 520 nm. Can they comment on any potential use the two wavelengths in climate models, which will most likely use it to infer particle size information?

This has already been mentioned in the summary section (last point) that reads :

”While the inferred 1020 nm extinction in GloSSAC v2.0 for the post-SAGEII era (2005-2018) is improved compared to v1.0, there are limitations with the inferred 1020 nm extinction. We note that deducing size information using 525 10 and 1020 nm extinction ratio for the period between August 2005 and June 2017 may still be an issue with single wavelength measurement from either OSIRIS or CALIOP, particularly during and following a volcanic event, despite some improvement in the inferred 1020 nm extinction. While this is clearly a limitation, we are not able to address changes in extinction ratio for volcanic events in v2.0 where the data set is based on only one wavelength. As a result, it is likely that GloSSAC extinction for small volcanic events during the OSIRIS/CALIOP period will be biased high 15 to an unknown extent. Further study into this period may result in changes in a future version of GloSSAC. Since June 2017, multi-wavelength extinction coefficient data became available from SAGE III/ISS, giving us an opportunity to compare/validate OSIRIS/CALIOP data particularly during and following such events.”

Figure 13, 14 and 15: Can you modify the color scale to properly show the volcanic enhancements. Also, can you remove the labels as they are distracting and interfere with the figure.

We have now modified the color scale which we hope now show any volcanic enhancements. We have removed the labels too.

Section 5: It?s difficult to follow the arguments regarding figure 15 because of the color scale, which doesn?t show the author?s argument. Please modify the color scale accordingly.

Done.

Figure 16: Again, can you adjust the color scale to show the smaller volcanic eruptions? In addition, remove the labels and add a symbol or a label denoting the

location and time of each volcano.

Done. This figure has been moved and used in Figure 15 instead, as this figure now shows SAOD for the entire GloSSAC record. We have now used labels for volcanic eruptions at the respective latitude and time of the year.

Figure 17: Can you comment on the lack of seasonality in CALIOP data in the southern and northern hemisphere compared to other data set?

Unfortunately, we are not able to comment on this now as the CALIOP data set does not have it for reasons we cannot account for.

Section 6 Conclusions and future work: There is no mention of any addition of new data sets when figure 1 implies that SCIAMACHY and OMPS will be added in the future.

We have added a sentence toward the end of the manuscript that reads as:

”There are additional datasets that are available for stratospheric aerosol extinction coefficients. We plan to evaluate and use these datasets, including SCanning Imaging Absorption spectrometer for Atmospheric CartograpHY (SCIAMACHY) and Ozone Mapping Profiler Suite (OMPS).”

Supplementary materials, Figure 1: The figure needs further explanation, what year, SAGE II or III/ISS? The text implies both datasets without explaining the methodology to combine it. What wavelength? 750 nm converted to 525? How?

While our intent to use this figure was to show relative percent difference with respect to the monthly climatology of angstrom exponent, we realize that it may not be a statistically correct approach as there are not enough data points in each grid for computing standard deviation. We, therefore removed this figure from supplementary.

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Thomason, L. W., Moore, J. R., Pitts, M. C., Zawodny, J. M., and Chiou, E. W.: An evaluation of the SAGE III version 4 aerosol extinction coefficient and water vapor data products, Atmospheric Chemistry and Physics, 10, 2159–2173, https://doi.org/10.5194/acp-10-2159-2010, URL `https://www.atmos-chem-phys.net/10/2159/2010/`, 2010.

A Global Space-based Stratospheric Aerosol Climatology (Version 2.0): 1979-2018

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Abstract. A robust stratospheric aerosol climate data record enables the depiction of the radiative forcing of this highly variable component of climate. ~~Since~~ In addition to the radiative forcing, stratospheric aerosol also plays a key role in the chemical processes leading to ozone depletion~~, stratosphere~~ . Therfore, stratospheric aerosol is one of the crucial parameters in understanding climate change in the past and potential changes in the future. As a part of Stratospheric-tropospheric Processes and their Role in Climate (SPARC) Stratospheric Sulfur and its Role in Climate (SSiRC) activity, the Global Space-based Stratospheric Aerosol Climatology (GloSSAC) was created (Thomason et al., 2018) to support the World Climate Research Programme (WCRP)'s Coupled Model Intercomparison Project Phase 6 (CMIP6) ~~(Zanchettin et al., 2016)~~(Eyring et al., 2016) . This data set is a follow-on to one created as a part of Stratosphere-Troposphere Process and their Role in Climate Project's Assessment of Stratospheric Aerosol Properties (ASAP) activity(SPARC, 2006) and a data created for Chemistry-Climate Model Initiative (CCMI) in 2012 (Eyring and Lamarque, 2012). Herein, we discuss changes to the original release version including those as a part of v1.1 that was released in September 2018 that primarily corrects an error in the conversion of Cryogenic Limb Array Etalon Spectrometer (CLAES) data to Stratospheric Aerosol and Gas Experiment (SAGE) II wavelengths, and the new release, v2.0. Version 2.0 is focused on improving the post-SAGE II era (after 2005) with the goal to mitigate elevated aerosol extinction in the lower stratosphere at mid and high latitudes noted in v1.0 as noted in Thomason et al. (2018). Changes include the use of version 7.0 of Optical Spectrograph and InfraRed Imaging System(OSIRIS), the recently released Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) Lidar Level 3 Stratospheric Aerosol profile monthly product, and the new addition of SAGE III/ISS. Here, we use an observed relationship between OSIRIS extinction at 750 nm and SAGEII/ SAGE III/ISS extinction at 525 nm to derive Altitude-Latitude based monthly climatology of Angstrom exponent to compute OSIRIS extinction at 525 nm, resulting in a better agreement between OSIRIS and SAGE measurements. We employ a similar approach to convert OSIRIS 750 nm extinction to 1020 nm extinction for the post-SAGEII period. Additionally, we incorporate the recently released standard CALIPSO stratospheric aerosol profile monthly product into GloSSAC with an improved conversion technique of 532 nm backscatter coefficient to extinction using an observed relationship between OSIRIS 525 nm extinction and CALIPSO 532 nm backscatter. SAGE III/ISS data is also incorporated in GloSSAC to extend

the climatology to the present and to test the approach used to correct OSIRIS/CALIPSO data. The GloSSAC v2.0 netcdf file is accessible at https://doi.org/10.5067/glossac-l3-v2.0 (Thomason, 2020).

1 Introduction

Stratospheric aerosols play a key role in determining the chemical (e.g. Hofmann and Solomon, 1989; Fahey et al., 1993; Solomon et al., 1996) and radiative (e.g. Minnis et al., 1993; Ridley et al., 2014) balance of the atmosphere. Variations in the stratospheric aerosol levels due to volcanic activity can impact climate on ~~scales from the subtle~~ the magnitudes from subtle surface temperatures changes (e.g. Solomon et al., 2011) to the more profound ~~(e.g. Hansen et al., 1992; Robock and Mao, 1995; Robock, 2~~ surface cooling (e.g. Hansen et al., 1992; Robock and Mao, 1995; Robock, 2000) and associated precipitation changes (e.g. Haywood et al
.

The impact of volcanic eruptions is often studied using Global Climate Models (GCM). Some of these modeling studies (e.g. Stenchikov et al., 2006; Berdahl and Robock, 2013; Fyfe et al., 2013) rely on observational data to represent stratospheric aerosols while others (e.g. Aquila et al., 2013; Mills et al., 2016; Timmreck et al., 2018) interactively model stratospheric aerosol variations. A robust stratospheric aerosol climatology can play a key role to the success of both approaches to ~~modelling~~ modeling the effects of stratospheric aerosol either as a direct input to GCMs or as an observational data set with which to verify the performance of an interactive aerosol scheme (e.g. Aquila et al., 2013; Mills et al., 2016). GloSSAC dataset has also been used in an observational study (Stocker et al., 2019) to quantify the temperature footprint of 21st century eruptions that enables to better quantify temperature trends related to anthropogenic forcing. As a part of SPARC's SSiRC activity, GloSSAC was created (Thomason et al., 2018) to support, among other endeavors, the WCRP's CMIP6 project ~~(Zanchettin et al., 2016)~~ (Eyring et al., 2016; Zanchettin et al., 2016). This data set spans from 1979 to 2016 and is a follow-on to one created as a part of SPARC's Assessement of Stratospheric Aerosol Properties (ASAP) activity (SPARC, 2006). Herein, we report on the development of GloSSAC version 2.0 data that extends the data set through 2018. While ~~analysis approach and~~ data sources are mostly unchanged from earlier versions, there are significant improvements in the use of OSIRIS and CALIPSO data ~~and~~ with inclusion of SAGE III/ISS data ~~is included~~ for the first time. As a result, a major version change is warranted and users should use this version even for periods prior to the end of v1.1 (December 2016).

~~We summarize the usage of space and ground-based data sets in Figure 1. Some changes are not immediately obvious from~~

2 The construction of version 2.0

Figure 1 depicts the measurements that are currently used for constructing GloSSAC data. While Thomason et al. (2018) discusses about the measurements that have been used in GloSSAC v 1.0 dataset in detail, some of the main features of entire GloSSAC v2.0 dataset including various space based measurements, their limitations and some challenges are worth mentioning here. We divide the entire dataset into three periods based on the measurements used. The first period being the pre-SAGE II period (January 1979- September 1984), followed by SAGE II period (October 1984 - August 2005) , post-SAGE

II period (September 2005- May 2017), and SAGE III/ISS period (June 2017-present). Pre-SAGE II period data mostly consists of data from solar occultation measurements such as SAM II , SAGE and some surface based Lidar measurements (Thomason et al., 2018). For SAGE II period, the measurements are dominated by solar occultation measurements that provide multi-wavelength measurements for size information. For the ~~figure. For instance, we now~~ post-SAGE II era, we are limited to single wavelength measurements from OSIRIS and/or CALIPSO. While OSIRIS and CALIPSO continue to make daily global measurements with a less direct measurement of aerosol extinction coefficient that requires further assumption of particle size, additional direct measurements of aerosol extinction coefficient from SAGE III/ISS are now available that provides a roughly monthly coverage of multi-wavelength measurements since June 2017.

We now use OSIRIS version 7.0 rather than the previous release version 5.07. OSIRIS (2001 to present) remains a key component of the GloSSAC data as it is the only data set that spans both the SAGE II period (1984-2005) and the start of the SAGE III/ISS mission in 2017. In version 5.07, aerosol extinction at 750 nm was retrieved at approximately 2 km resolution using a multiplicative relaxation technique (Bourassa et al., 2012). OSIRIS version 7.0 data ~~(Rieger et al., 2019)~~ (Rieger et al., 2019) uses a multiwavelength retrieval ~~whose accuracy~~ that improves the accuracy of the extinction product by reducing sensitivity to the unknown particle size distribution in the inversion. With ~~the~~ these changes, the retrieved extinction coefficient at 750 nm is in better agreement with observations by SAGE II and SAGE III/ISS than the version used in GloSSAC v1.0 (v5.07). A detailed description of the retrieval process and comparisons to SAGE II and SAGE III/ISS are available in ~~Rieger et al. (2019)~~Rieger et al. (2019). It should be noted that while the OSIRIS mission continues, data for 2018 is not available at the time the data record was developed and thus not included in the GloSSAC data set.

We continue to make use of CALIPSO's Cloud-Aerosol Lidar with orthogonal Polarization (CALIOP) aerosol backscatter coefficient measurements. The CALIPSO mission (Winker et al., 2009) has been providing cloud and aerosol profiles since 2006. CALIOP data was used in GloSSAC v1.0 during the post-SAGE II era, critically in regions and time periods where OSIRIS data are not available. For GloSSAC v1.0, we used CALIOP version 4.0 level 1 aerosol data product at 532 nm and identified and removed observations that suggested the presence of cloud using the depolarization measurement. The remaining data was compiled into the spatial temporal resolution used in GloSSAC (monthly, 5 deg latitude bins, and 0.5 km altitude bins). Since the release of GloSSAC v1.0, the CALIPSO team has released a standard stratospheric aerosol extinction and backscatter products (Kar et al., 2019) in a spatial/temporal resolution compatible with GloSSAC. This data product is now used rather than the level 1 data. While we use the standard CALIPSO stratospheric aerosol product, enhanced levels of aerosol extinction in the lower stratosphere are consistently noted in the entire dataset after comparing against OSIRIS and SAGE III/ISS. We, therefore decided to use a conformance process which is described below that helps reduce the bias in the lower stratosphere and also at higher latitudes.

New to GloSSAC, we now use version 5.1 data from the latest series of Stratospheric Aerosol and Gas Experiment on International space station (SAGE III/ISS) satellite. Like SAGE II, SAGE III/ISS uses the solar occultation technique (McCormick et al., 1979) to make near global measurements of stratospheric aerosol, ozone, water vapor, and nitrogen dioxide with a vertical resolution of 1 km on a roughly monthly time scale. Aerosol extinction coefficient at 9 wavelengths are provided including at the GloSSAC standard wavelengths near 525 and 1020 nm. SAGE III/ISS data are available from June 2017 and we incorporate the data into GloSSAC from that time forward as the primary data set similar to the way in which SAGE and SAGE II are used earlier in the data record.

For individual instruments, we have expanded the practice of including data in the original parameter and wavelength as possible (e.g. OSIRIS extinction at 750 nm, and CALIOP backscatter coefficient) in the GloSSAC spatial temporal resolution and now include most data sets as components of the GloSSAC data set. The point of origin of each individual dataset is clearly denoted for all data points in the now 40-year record at the primary 525 and 1020 nm wavelengths. As with v1.0, we recommend using original, unconformed, and uninterpolated data for comparison purposes. Conformance follows the basic paradigm of v1.0 but has changed in some instances to reflect better understanding of instrumental differences (Thomason et al., 2018). SAGE II version 7.0 continues to act as the standard throughout the data set. As a result, similar to GloSSAC v1.0, data from other platforms and sometimes made of different aerosol properties and/or at different wavelengths are made, on average, to match or 'conform' with SAGE II at 525 and 1020 nm. This is mostly done using simple linear scaling factors rather than retain offsets that may be created by switching from one data source to another. For instance in v1.0, the conversion factor used for 532 nm backscatter coefficient to 525 aerosol extinction coefficient (53 sr) was selected to minimize the overall difference between SAGE II and CALIOP backscatter data (Thomason et al., 2018). An exception to this process was higher than expected extinction in the lower stratosphere in mid and high latitudes during the CALIOP/OSIRIS era based on observations at similar overall aerosol levels during the SAGE II period. Both GloSSAC v1.0 and v1.1 retained these offsets in extinction as, at the time, it was not clear if the difference was due to real geophysical variability possibly driven by volcanic activity or due to deficiencies in conversion process or in the source data itself. A goal of this release was to understand and, as necessary, mitigate this discrepancy (Thomason et al., 2018). While the changes in the both CALIOP and OSIRIS source data sets have reduced the apparent anomaly in extinction inferred for this period, both data sets, adjusted using the conformance approaches used in v1.0, continue to suggest higher levels of aerosol extinction coefficient in the lower stratosphere than observations by SAGE II would suggest . At the same time, very similar discrepancies were noted between OSIRIS and CALIOP data and SAGE III/ISS observations some 12 years later. Given these facts, we are now confident that these differences are due to measurement/conformance deficiencies and we have developed new techniques to bring these data sets into greater conformity with SAGE II; they are discussed below.

Additional changes to this GloSSAC version relative to the v1.0 as described in Thomason et al (2018) include all changes made in the interim version 1.1. The changes made to interim version 1.1 is described below in Section 2.1. Within v2.0, a key data set (McCormick et al., 1979) used in the SAGE/SAGE II gap period (1982-1984) has been updated. We have expanded the GloSSAC v2.0 netCDF to include stratospheric aerosol optical depth at the primary reporting wavelengths of 525 and 1020 nm and we now retain the native measurements for all instrument data sets (e.g., CALIOP backscatter coefficient at 532 nm) as well as values after conversion to 525 and/or 1020 nm. We also now include reported measurement uncertainty and zonal variability where available at both the native measurement form and at the GloSSAC extinction wavelengths. The updated file resides at NASA's Atmospheric Sciences Data Center and has a unique DOI:10.5067/GLOSSAC-L3-V2.0 .

3 ~~The construction of version 2.0~~

2.1 Changes prior to the end SAGE II period

2.1.1 Updates to the SAGE II Era (October 1984-August 2005)

Since the release of GloSSAC v1.0, an interim version was released that corrected a coding error in the initial implementation of the conversion of CLAES infrared aerosol extinction coefficient data to the SAGE II and primary GloSSAC reporting wavelength at 1020 nm. The primary impact was a substantial exaggeration, sometimes exceeding a factor of 2, in the peak aerosol extinction associated with the Pinatubo eruption in the tropics in the several months following the eruption in June 1991. CLAES data becomes available in October 1991 but is used in combination with a ground-based lidar product to estimate the aerosol levels from July to September 1991 and is used standalone for a decreasing span of altitude and latitude until the end of its mission in April ~~1993.~~ 1993 (Thomason et al., 2018; SPARC, 2006). The use of CLAES (Massie et al., 1996) and Halogen Occultation Experiment (HALOE) (Thomason, 2012) data in GloSSAC version 1.1 was also decreased by only employing it to fill latitude/temporal bins in which SAGE II data existed but did not extend as low as the tropopause. This significantly reduced the impact of both CLAES and HALOE in the data set but made spatial and temporal sampling in this period more consistent the sampling throughout SAGE II mission. These changes are continued into v2.0. Some additional quality control (QC) was performed that caught a few defects missed in v1.0.

Compared to the important change requiring the release of version 1.1, only relatively minor additional changes to the SAGE II and pre-SAGE II portions of the data set are included in v2.0. The changes to the SAGE II era within GloSSAC include improved outlier filtering for the SAGE II aerosol extinction coefficient data. In this case, we eliminate as outliers, any data in a GloSSAC bin that exceeds 3.5 median absolute deviations from the median value of all observations within a GloSSAC bin. This filtering has a minimal impact on the results for 452, 525 and 1020 nm but substantially reduces noise in the data at 386 nm, and reduced the need for manual QC repairs of that data set. Users should continue to use caution using the SAGE II 386 nm aerosol extinction coefficient data as a low bias is evident in this data in the lower and upper stratosphere and at all altitudes as aerosol extinction coefficient magnitudes approach background levels (Thomason et al., 2008, 2018). Where aerosol extinction is only available at 1020 nm, the extinction coefficient data sets at 452 and 386 nm are now filled using the same mechanism to fill missing data at 525 nm so that all four wavelength arrays are complete above the tropopause throughout the SAGE II era, as is described in Thomason et al. (2018).

In addition, with the apparent success of filling the high latitudes using the equivalent latitude/latitude mechanism developed based on Manney et al. (2007) for v1.0 (Thomason et al., 2008), we have reduced the role of simple linear interpolation at high latitudes and allow the new ~~filling~~ equivalent latitude/latitude mechanism fill more of the missing data at high latitudes. While the overall changes with this approach are small, it did reduce the need for manual QC of the data set as the interpolation process was apparently responsible for creating some of that faulty data. The CLAES ~~and HALOE~~ (Massie et al., 1996) and HALOE (Thomason, 2012) data sets now include zonal standard deviation and median reported measurement uncertainty following the approach used for SAGE II data. The conversion of CLAES and HALOE data follow the methodology described in Thomason et al. (2018). In addition, we now compute the standard deviation of the extinction conversion as a function of the CLAES/HALOE extinction and use this as uncertainty in the conformed 525 and 1020 nm data products as this source of uncertainty is significantly larger than the reported measurement uncertainties.

2.1.2 Updates to the pre-SAGE II Era (January 1979- September 1984)

A component contributing to pre-SAGE II era in previous GloSSAC versions has been completely revised. In v1.0, SAM II 1000 nm aerosol extinction profile data on potential temperature surfaces was used for input in middle and high latitudes between the end of the SAGE I period in November 1981 and the start of the SAGE II data set in October 1984. It was originally created for use in the ASAP data set (SPARC, 2006) and the original code has been lost. While the revised file was nominally created in same way as the existing data file, the ~~results~~ values extended along the isentropic surfaces can be significantly smaller at times than those used in v1.0 particularly in the Southern Hemisphere during the Spring. The cause for this difference is not clear but may be partly due to changes in the potential temperature fields used in the original construction (from NCEP) compared to the new version (from MERRA 2). This data is used at high latitudes in the northern hemisphere (above 60N) but is a key component in the southern hemisphere south of 30S. Generally, the lack of mid-latitude data in the Southern Hemisphere is a significant limiting factor to the quality of the GloSSAC depiction of stratospheric aerosol during the gap between the end of the SAGE I mission and the start of the SAGE II mission.

2.2 Updates to the Post-SAGE II space-based Era for v2.0

Data from a large number of space-based instruments are available for stratospheric aerosol from 1979 through 2018 (see Figure 1). As with v1.0, GloSSAC uses as few instruments as necessary to complete the climatology. We make this decision to limit the impact of differences between instruments due to measurement techniques and wavelength range as well as an assessment of the general quality of the instrument's data set. Before September 2005, the data set is dominated by solar occultation instruments with the end of SAGE II mission effectively marking the end of the solar occultation era (Thomason et al., 2018). After the end of the SAGE II mission in August 2005, GloSSAC data are exclusively dependent on observations by OSIRIS and CALIOP until mid-2017 and this dependence is not simply a change in instrument but also represents a fundamental change in the measurements provided by these instruments. A positive factor is that these instruments provide near global daily coverage compared to the roughly monthly rate from a solar occultation instrument such as SAGE II. These instruments measure aerosol using techniques that are less direct than those by solar occultation and whose accuracy is dependent to some extent on aerosol properties that are not directly observed. OSIRIS observations at 750 nm, for instance, are dependent on estimates of the aerosol scattering phase function which relates to the aerosol size distribution and composition. This relationship plays a role in converting the measured radiance to aerosol extinction coefficient and can cause a bias in the product, even though the v7 algorithm attempts to reduce this dependence. OSIRIS stratospheric aerosol measurements can also be sensitive to the presence of cloud and thus requires caution in using OSIRIS observations near the tropopause, particularly in the tropics. CALIOP uses lidar to measure stratospheric aerosol backscatter coefficient at 532 nm. While this instrument provides by far the greatest density of measurements the precision of individual measurements in the stratosphere is poor and substantial averaging is required to provide GloSSAC compatible profiles with a precision comparable to those provided by either OSIRIS or a SAGE instrument. The accuracy of CALIOP data is strongly dependent on a normalization process that assumes that a region of the stratosphere (>37 km) is aerosol free; an assumption that is never correct and subjects CALIOP to potential bias in it's backscatter coefficient measurements. Finally, the conversion from backscatter coefficient to extinction coefficient presents ~~another potential ~~a source of bias; as this process depends on details of an unknown aerosol composition and size distribution (Kar et al., 2019) that is a another potential source of bias. For the CALIOP stratospheric aerosol product, an aerosol extinction-to-backscatter ratio of 50 sr (Kar et al., 2019) has been used — a value that is typically used for background stratospheric aerosol (Jäger and Deshler, 2002, 2003; Illingworth et al., 2015; Kremser et al., 2016).

A new data set included in GloSSAC v2.0 is SAGE III/ISS. This instrument, whose mission began in June 2017, is an updated version of the SAGE III/Meteor 3M instrument and works in a manner substantially the same as SAGE II. Within GloSSAC, SAGE III/ISS plays a crucial role in understanding the apparent enhanced lower stratospheric aerosol throughout the OSIRIS/CALIOP period by comparing results from the on-going overlap period. Given the potential issues in the usage of OSIRIS and CALIOP in GloSSAC and the new information provided by the new SAGE III mission, we have completely revised the analysis process for these instruments for v2.0. This process is described below.

2.2.1 Cloud Clearing Method

Stratospheric aerosol measurements by CALIOP, OSIRIS, SAGE II, and SAGE III/ISS can be affected by the presence of cloud in the lower stratosphere/near tropopause. However, for the purposes of GloSSAC, clouds are considered an interfering species and measurements that are inferred to be influenced by the presence of clouds are identified and eliminated from further use in the data set. Generally, clouds are found in the lower stratosphere (as inferred from the MERRA tropopause) and downward and in the wintertime polar vortex as polar stratospheric clouds (PSCs). The efficacy of PSC identification is variable from instrument to instrument (including SAGE II): ice PSCs are identified effectively in all source data sets but the efficacy of saturated ternary solution (STS) and nitric acid trihydrate (NAT) PSC identification is a mixed with at least some likely to be identified as aerosol and retained in the analysis. CALIOP stratospheric aerosol product is cloud-cleared and no additional cloud processing is necessary. ~~The ~~While the OSIRIS version 7.0 aerosol data product is similarly cloud screened ~~(Rieger et al., 2019) however,we~~(Rieger et al., 2019),we, however found some additional clearing was beneficial to the analysis. Cloud identification process for OSIRIS is a single wavelength process and based on the straightforward observation that the presence of some cloud among mostly aerosol observations skews the distribution of aerosol extinction coefficient toward larger values (Thomason and Vernier, 2013). Assuming that such positive outliers contain cloud, we have devised a simple statistical approach to cloud identification based on Interquartile Range (IQR). This technique is based on median statistics rather than mean as the extinction coefficient distribution at altitudes from the lower stratosphere into the troposphere may be skewed by the presence of cloud. Measurements that include the presence of cloud may have extinction up to several orders of magnitude larger than local aerosol extinction coefficient that, in turn, have large impacts on standard statistical quantities like standard deviation. In the presence of unknown but potentially large outliers, IQR is a more conservative measure of the spread of a distribution than standard deviation (Iglewicz and Hoaglin, 1993).

In our implementation, we use yearly data at each altitude (0.5 km) and latitude (5 degree) bin to determine an extinction coefficient probability density function. We used lower quartile (Q1) and upper quartile (Q3) of the underlying distribution to find IQR, which is defined as Q3-Q1, a good measure of the spread in the data relative to median. Here, an extreme outlier is defined as Q3+(3.5*IQR) and a more conservative outlier (Q3+(1.5*IQR)) are used for comparison (Iglewicz and Hoaglin, 1993). A complicating factor is the presence of several small volcanic events during the OSIRIS lifetime and a major pyrocumulus event (August 2017). It is possible that an aggressive outlier process could misidentify measurements of fresh material from either phenomena as cloud events leading to their erroneous exclusion from the data set. Of course, the very nature of GloSSAC is not conducive to a meaningful depiction of the early evolution of recent volcanic events (Thomason et al., 2018). Figure 2 shows the probability density function of aerosol extinction at 750 nm for two cases in 2011 at 18 km with the threshold used (dashed vertical line) for the outlier detection, whereas Figure 3 demonstrates vertical profile of threshold values with mean and median of the distribution. Figure 3 clearly shows the difference between mean and the median profile as the mean profile has higher extinction values in the lower stratosphere due to skewness in the mean statistics. We found that the conservative outlier appeared to remove many enhanced aerosol measurements particularly when stratosphere is perturbed due to volcanic/pyrocumulus events, whereas the extreme outlier was effective at identifying outliers in the ~~aerosol~~ density distribution. Therefore we use the extreme outlier to clear cloud-affected observations from the data set.

For SAGE II cloud clearing, we use the ratio of aerosol extinction at two wavelengths (525 and 1020 nm) as a stand in for aerosol size as well as the magnitude aerosol extinction coefficient. In this space, away from major volcanic events like Pinatubo, clouds manifest a large extinction with 525 to 1020 nm aerosol extinction ratio near 1. Typical stratospheric aerosol manifests smaller extinction magnitudes and with extinction ratios between 2 and 4. Cloud identification is complicated by mixed fields of view where observations ~~can~~ transition between mostly cloudy extinctions and extinction ratios and those more typical of purely aerosol. As a result, the distribution of extinction and extinction ratio shows a continuum between clearly cloud and clearly aerosol observations that makes distinguishing purely aerosol measurements from those affected by cloud ambiguous. Various techniques to parse these mixed measurements have been developed and GloSSAC makes use of the technique developed by ~~Thomason et al. (2013).~~ Thomason and Vernier (2013). A similar technique for SAGE III/ISS is in development but not currently available. For this version of GloSSAC, we note 1) no large volcanic aerosol event have occurred during the SAGE III/ISS mission prior to the end of 2018 and 2) the overall aerosol loading of the stratosphere in this period is low. As a result we can eliminate most observations containing cloud by eliminating all observations where the extinction ratio is less than 2 below 24 km. Given the timing of observations, SAGE III/ISS through 2018 had not observed any polar stratospheric clouds. Not surprisingly, this approach misses some mixed cloud-aerosol observations but these are effectively identified using the IQR-based cloud detection algorithm used with OSIRIS.

2.3 Comparison of OSIRIS with SAGE II and SAGE III/ISS measurements

Within the GloSSAC paradigm, it is important to not simply observe the agreement between OSIRIS and SAGE II but also mitigate these differences as effectively as possible. We compare SAGE II and OSIRIS once the data have been incorporated into GloSSAC measurement grid: zonally averaged monthly level 3 product at 5 degree latitude and 0.5 km altitude resolution.

OSIRIS version 7.0 standard aerosol product is reported at a wavelength of 750 nm. During the overlap period (2002-2005), we can directly compare these measurements and develop a technique to close observed mutual biases. This technique can then be applied to the entire OSIRIS data record with the assumption that the basic nature of the bias is consistent throughout the period. This is an assumption that may be challenged by a number of small volcanic eruptions occurring during this period which likely change the nature of the aerosol size distribution but for which little means to assess and mitigate are currently available. In addition to 750 nm, OSIRIS extinction ~~is also routinely produced~~ can be calculated at 525 nm, a SAGE II measurement wavelength, using a constant Angstrom ~~coefficient~~ exponent of 2.33 to convert from 750 nm to 525 nm (Rieger et al., 2015). The one critical exception to this occurs after mid-2017 when the SAGE III/ISS mission begins. SAGE III/ISS makes extinction coefficient measurements at 521 and 756 nm that are near both wavelengths at which OSIRIS reports extinction coefficient. Since the SAGE III/ISS instruments operates in a manner ~~virtually identical~~ similar to SAGE II, the expectation is that there would be minimal bias between these instruments at least at the strongest aerosol measurement wavelengths of 525 and 1020 nm.

A minimal conformance test is that the comparison between SAGE II and OSIRIS in the first overlap period should be very similar to the comparison between SAGE III/ISS during the second overlap period. We expect that the observed correspondence between OSIRIS, SAGE II and SAGE III/ISS will show this consistency only if 1) the performance of OSIRIS does not change with time [1], 2) SAGE II and SAGE III/ISS are relatively unbiased with each other [2], and 3) the state of the stratosphere has not changed to the point where it has had a deleterious impact on OSIRIS aerosol retrievals. In figures 4a and 4b, it is apparent that for much of the stratosphere the difference between SAGE II and OSIRIS is less than 10% particularly in Figure 4a for a rather benign (less affected by volcanic/fire events) October 2004. However, it is also clear that OSIRIS extinction is consistently higher than SAGE II in the lower stratosphere with percentage difference exceeding ~~30~~50% near the tropopause. Another departure is shown in Figure 4b for March 2005 that shows similar features as October 2004. However, in the tropical low and middle stratosphere there is a difference of about ~~30~~50% in an enhanced aerosol layer associated with the eruption of Manan in January 2005. Manam is typical of small eruptions observed by SAGE II and later by SAGE III in which a substantial increase in aerosol extinction coefficient occurs with an increased in 525-to-1020 nm aerosol extinction ratio. This suggests that extinction is dominated by smaller particles in the volcanic layer than prior to the eruption and is much different than the large extinction/large particle size associated with larger eruptions such as the June 1991 eruption of Pinatubo. Similar small volcano effects are noted in the SAGE II data associated with Ruang in 2002 and by SAGE III/ISS Ambae in July 2018. Figure 5 shows a measurement comparison between June 2017 OSIRIS at 525 nm and SAGE III/ISS at 521 nm (a) and between OSIRIS at 750 nm and SAGE III/ISS at 756 nm (b). Since OSIRIS data is only available through the end of 2017 at this time, relatively little comparative data is currently available. Comparisons between OSIRIS and SAGE III/ISS are complicated in the overlap period by the pyrocumulus fire event in August 2017 which was inhomogeneously distributed in the northern

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[1] While the OSIRIS instrument performance has relatively remained unchanged over time, the scattering angle has slowly ~~changed~~drifted, and the fraction of ascending/descending node measurements has changed. These factors may affect overall data quality.

[2] While the differences between SAGE II and SAGE III meteor aerosol extinction coefficient are relatively smaller, some previous studies (Thomason et al., 2010; Damadeo et al., 2013) reported a small bias between SAGE II (v 6.2) and SAGE III (v 4.0) meteor that are within ± 10% for measurement wavelengths of 525 and 1020 nm for the altitudes between 7 and 25 km.

hemisphere throughout the second half of 2017. OSIRIS extinction at 750 nm is in reasonable agreement with SAGE III/ISS (b) except in the lower stratosphere and in tropical latitudes where the difference can exceed 20% in a pattern similar to that seen between SAGE II and OSIRIS (Figure 5a). However, the differences between OSIRIS at 525 nm and SAGE III/ISS at 521 nm, shown in Figure 5a, are significantly larger than those seen in Figure 4a that suggests either deficiencies in the conversion process of OSIRIS measurements from 750 nm to 525 nm or that SAGE III/ISS 521 nm data is low-biased in the lower and mid stratosphere at 521 nm though probably not at 756 nm. In general, comparisons of OSIRIS suggest general agreement with both SAGE datasets except in the lower stratosphere where it appears that OSIRIS is biased high relative to the SAGE II and III/ISS measurements. The need for long-term consistency among data sets effectively requires that OSIRIS be brought into conformance (bias reduced as much as possible) with SAGE II measurements.

2.4 OSIRIS extinction coefficient conformance process

Ultimately, the need to reduce the observed differences between SAGE II and OSIRIS are most relevant during the period between the end of the SAGE II mission and the start of the SAGE III/ISS mission. We have developed a mechanism for this in which we have derived a monthly mean Angstrom ~~coefficient~~ exponent (hereafter "pseudo Angstrom exponent") for the overlap period using SAGE II and SAGE III/ISS 525 nm aerosol extinction with OSIRIS data at 750 nm effectively creating a 4-year climatology of ~~Angstrom coefficient~~ pseudo Angstrom exponent based on measured values. Within GloSSAC, the Angstrom model for aerosol extinction wavelength dependence for 525 and 750 nm is given by

$$k_{525[t,m,i,j]} = k_{750[t,m,i,j]}\left(\frac{\lambda_{525}}{\lambda_{750}}\right)^{\eta_{[m,i,j]}}$$

where, $k_{525[t,m,i,j]}$, and $k_{750[t,m,i,j]}$ are extinctions at 525 nm and 750 nm respectively, $\eta_{[m,i,j]}$ is the ~~angstrom~~ pseudo Angstrom exponent while the indices $[t,m,i,j]$represent year, month, latitude, and altitude respectively. ~~Extnetion~~ $(\frac{\lambda_{525}}{\lambda_{750}})$ represents ratio of wavelengths at 525 ~~nm~~ and 750 nm. All data are gridded to 5 degree latitude and 0.5 km altitude resolution. A monthly median climatology of pseudo Angstrom exponent is then computed and smoothed using a 3X3 median boxcar filter in altitude and latitude. Linear interpolation is used to fill in missing values in the monthly grid. Figure 6 shows altitude versus latitude plots of monthly climatology of pseudo Angstrom exponent and shows a modest annual cycle particularly in the tropical lower stratosphere. While the standard OSIRIS 525 nm aerosol extinction product uses a fixed Angstrom ~~coefficient~~ exponent of 2.33, we compute values between 1 and 3 for much of the stratosphere and occasionally are less than 0 in the lower tropical stratosphere. We do not assume that the derived value for ~~Angstrom coefficient~~ pseudo Angstrom exponent has any physical meaning as it accounts for not just the actual behavior of aerosol but also for potential deficiencies in both data sets and it is simply a means to push OSIRIS extinction measurements toward those produced by SAGE II. Using this climatology of ~~Angstrom~~ pseudo Angstrom exponent values, we can convert any month of OSIRIS data to 525 nm. For example, using the monthly-based pseudo Angstrom exponent for October 2004, the agreement between modified OSIRIS and SAGE II are almost entirely below 10% (Figure 4c). To some extent this is the expected result though it generally suggests that the ~~Angstrom coefficient~~ pseudo Angstrom exponent is reasonably stable throughout the overlap period. However for the March 2005 analysis, OSIRIS predictions for 525 nm remain substantially greater than those measured by SAGE II in the region containing material from the recent Manam eruption (Figure 4d). This suggests that the changes in the observed Angstrom ~~coefficient and climatological~~ exponent and climatological pseudo Angstrom value remain significantly different during this small volcanic event. This is not an issue for GloSSAC for this eruption as SAGE II data is used in this period. However during the period between SAGE II and SAGE III/ISS there are a number of similar small volcanic events that could easily have a similar behavior. Figure 7 demonstrates how a variety of small to very large eruptions manifest themselves in the SAGE II/III-ISS data record. It shows the 1020-nm extinction coefficient and 525 to 1020-nm aerosol coefficient ratio at the peak extinction following 5 eruptions (Pinatubo, Nyamuragira/Nevado del Ruiz, Ruang, Manam, Ambae) connected to values that occurred at the same altitude/latitude just prior to the eruption. The Pinatubo eruption, that dominates much of the SAGE II record is by far the largest event and is the only one where the apparent aerosol size increases with the event (decreased aerosol extinction ratio). Most events in this plot show that aerosol 'size' is apparently smaller after a volcanic event than before the event occurred. Sometimes this is fairly subtle (Nyamuragira/Nevado del Ruiz) but sometimes can be very pronounced (Ruang). There is a tendency for smaller eruptions to produce larger extinction ratio but this is not, for this limited sample, sufficiently well behaved to be considered predictive. The conformance process, as it is currently implemented would produce horizontal lines in Figure 7 showing no change in ratio from before an event to afterwards. While this is clearly a shortcoming, we are not able at this time to account for changes in extinction ratio for volcanic events in GloSSAC v2.0 where the data set is based on only one wavelength (either OSIRIS or CALIOP). As a result, it is likely that GloSSAC extinction for small volcanic events during the OSIRIS/CALIOP period will be biased high to an unknown extent. Further study into this period may result in changes in a future version of GloSSAC. The overall conformability of OSIRIS, SAGE II and SAGE III/ISS is ultimately tested by the comparison in Figure 5c which shows the comparison of revised OSIRIS 525 nm aerosol extinction coefficient data, as computed using the SAGE II-based pseudo Angstrom exponent, and SAGE III/ISS measured 521 nm aerosol extinction coefficient. In this comparison, we see that differences that were generally larger than 20% and often in excess of 50% are now reduced to mostly less than 10% except at high northern latitudes at higher altitudes. While these differences are larger than those found with SAGE II and OSIRIS, the new conformance process clearly is a better step forward in combining these data sets into a uniform data set.

3 Comparison of CALIOP with OSIRIS and SAGE III/ISS measurements

In GloSSAC v1.0, CALIOP and OSIRIS were used as equal partners in which extinction values from each instrument were used where the other was not available and averaged where both existed. Unfortunately, there is no direct overlap between CALIOP and SAGE II mission lifetimes (missing by about 8 months) so that direct comparisons of these data sets is not possible. In v1.0, CALIOP 532 nm backscatter coefficient was converted to 525 nm extinction using the mean ratio of OSIRIS 525 nm extinction to CALIOP backscatter coefficient in the GloSSAC data set. This value, 53 sr, is roughly consistent with the extinction-to-backscatter ratio used within CALIOP data processing (50 sr)~~and roughly consistent with values for sulfuric aerosol in the stratosphere~~. In v1.0, CALIOP converted 525 nm aerosol extinction is roughly consistent with OSIRIS; particularly in producing more aerosol extinction in the lower stratosphere than would be expected based on similar, but in this case not contemporaneous, SAGE II values. As a result, we compare the recently released standard CALIOP extinction coefficient product (Kar et al., 2019) with conformed OSIRIS and SAGE III/ISS data. All three data sets are used at the GloSSAC spatial/temporal resolution. Since CALIOP stratospheric aerosol extinction is reported at 532 nm, a constant Angstrom exponent of ~~1.50~~ 2.33 is used here for the conversion of particulate extinction from 532 to 525 nm (an adjustment of 2%). Figure 8a and 8b show relative difference plots between OSIRIS/ SAGE III/ISS and CALIOP for November 2017. Equatorward of 30 degrees and above roughly 18 km, the differences between the CALIOP extinction product and OSIRIS and SAGE III/ISS are generally between ± 20%. However, the CALIOP standard extinction coefficient product is much larger (>50%) in the lower stratosphere globally as well as in the entire stratosphere poleward of 40S and 40 N. While some of these differences may be attributable to the wildfire-driven pyrocumulonimbus (PyroCb) events (e.g. Peterson et al., 2018), similar discrepancies persist even when the stratosphere is unperturbed by any volcanic/PyroCb events.

3.1 Conforming CALIOP backscatter coefficient to GloSSAC extinction coefficient

Due to the discrepancy between OSIRIS/SAGE III and CALIOP, we conform CALIOP data using an empirical scaling factor (SF) which is defined as the ratio of bias corrected OSIRIS extinction at 525 nm and CALIOP backscatter coefficient at 532 nm. It is analogous to an extinction-to-backscatter coefficient except that it also attempts to account for bias between OSIRIS and CALIOP and thus the SF should not be viewed as reflecting only underlying aerosol properties. We compute the SF using monthly OSIRIS 525 nm extinction and CALIOP 532 nm particulate backscatter coefficients. The particulate backscatter and extinction products in the standard CALIOP level 3 stratospheric data are retrieved using a lidar ratio of 50 str (Kar et al., 2019). As we are effectively revising this factor, we do not use products derived using it but rather rederive the backscatter coefficient using the attenuated scattering ratio that is also reported as a part of this product. In this approach, we also assume that the transmission of the atmosphere is close to 1 throughout the stratosphere which allows us to neglect the attenuation term in the equation of total attenuated backscatter. With this approximation, the particulate backscatter coefficient is computed using simplified formula (SR*MBKS)-MBKS, where SR is the scattering ratio and MBKS is the molecular backscatter and is also provided in the CALIOP stratospheric aerosol product. Since the assumption that the transmission of stratosphere is close to 1 is clearly not correct, it is not surprising that the recomputed backscatter coefficient is somewhat less than with the level 3 retrieved particulate backscatter. We find in general that the difference increases with decreasing altitude and is about 10% difference at 18 km and close to 30% at 10 km and that the relative differences exhibit low variance at any given altitude/latitude/time bin. Since, in order to conform the CALIOP data to the conformed OSIRIS data at 525 nm, we are forced to use SFs that are empirical and account for several effects including both aerosol-related effects and bias between the two data sets, it ultimately does not matter a great deal whether we use the standard CALIOP stratospheric backscatter product or the alternative product described above. For GloSSAC v2.0, we choose to use the alternative backscatter product but users should keep in mind that this choice merely adjusts the size and perhaps the physical meaning of the SF and not the outcome of the 525-nm extinction coefficient estimation. As the CALIOP stratospheric product evolves, we will reconsider the approach in future releases of GloSSAC. Figure 9a shows annual median of OSIRIS 525-nm extinction to CALIOP 532-nm backscatter ratio as a function of altitude and latitude. Here, the magnitude of the SF varies from between 25 and 65 sr except at higher altitude at polar latitudes where ~~it is possible that the impact of the polar vortex plays a role in producing SFs~~ SFs are less than 10 sr. Figure 9b shows the standard deviation for this depiction and we find that the overall behavior of the SF is reasonably consistent throughout the entire period. To implement this conversion process, we use monthly median values of the SF for the entire overlap period for OSIRIS and CALIOP (06/06 to 12/17) and apply the conversion factors to the entire CALIOP data set at a simple multiplication factor dependent on only latitude and altitude. While it is tempting to infer that CALIOP data processing for this product is using the wrong extinction-to-backscatter ratio, it is important to recall that it seems apparent that CALIOP stratospheric extinction values are biased high compared to OSIRIS conformed data and SAGE III/ISS comparisons by consistent margins in the lower stratosphere and high latitudes where the largest departures of the SF from a value of 50 str occur. It is worthwhile to note here that Kar et al. (2019) also computed stratospheric aerosol 532 nm lidar ratio using extinction coefficients from SAGE III/ISS and backscatter measurements from CALIOP for the period June 2017 through August 2018. We note the pattern of their lidar ratio (Figure 13 of Kar et al. (2019)) is more or less consistent with our SF in Figure 9a.

Figures 8 includes the percent difference plots between the empirically scaled CALIOP 525 nm extinction and OSIRIS (c) and SAGE III/ISS (d) for November 2017. It is clear that while the differences are not eliminated, the difference between CALIOP and OSIRIS (Figure 8c) is now mostly within ± 20%, compared to the standard CALIOP extinction shown in Figure 8a where the difference between standard CALIOP stratospheric extinction coefficient and OSIRIS was often more than 50%. Similarly, the difference between the scaled CALIOP stratospheric extinction and SAGE III/ISS is now mostly below ~~20%~~ 30% except near the tropical lower stratosphere and polar high altitudes, whereas the the difference between standard CALIOP stratospheric extinction coefficient and SAGE III/ISS is also often more than 50%. Figure 10 shows monthly time series of SAGE II, OSIRIS, bias corrected OSIRIS, CALIOP, bias corrected CALIOP, and SAGE III/ISS extinction for altitudes and latitudes where conformance has been an issue between the data sets. The time series plots show: 1) the OSIRIS and CALIOP extinction coefficient at 525 nm before conformance are substantially higher than those provided by SAGE II/SAGE III/ISS and 2) these differences are substantially reduced after the conformance process. There are still some clear observations where significant differences among the products exist. Most can be associated with episodic enhancements by a number of small volcanic eruptions (see Table 1) and a major pyrocumulous event in August 2017. Part of these differences may be due to spatial inhomogeneity of the distribution of aerosol in the first several months following eruptions. However, as previously discussed, the conformance processes applied to OSIRIS and CALIOP cannot adequately account for fresh aerosol from these events. Nonetheless, given the status of OSIRIS/CALIOP/SAGE conformance in GloSSAC v1.0, the process used in the new version represents an imperfect step forward.

4 Constructing 1020 nm Extinction Record in the post-SAGE II period

For GloSSAC v1.0 (Thomason et al., 2018), extinction measurements at 525 and 1020 nm were included in the stratospheric aerosol record. The post-SAGE II record was focused on producing a uniform extinction coefficient record at 525 nm and aerosol extinction coefficient at 1020 nm was inferred using an empirical relationship between 525 to 1020 nm extinction ratio and 525 nm extinction derived from SAGE II data. However, this process was not fully successful and a noteworthy bias between the SAGE II and post-SAGE II period at 1020 nm was observed in v1.0 (Thomason et al., 2018) leading to recommendations to avoid using 1020 data in the v1.0 data set in the post SAGE II part of the record. For GloSSAC v2.0. ~~we~~ We use a different strategy focused on using monthly pseudo Angstrom exponents computed using measurements between OSIRIS and SAGE II/SAGE ~~III/ISS~~ III-ISS that is functionally identical to the method used in section 4.2 to infer extinction at 525 nm from OSIRIS. We produce a monthly average of pseudo Angstrom exponent using SAGE II/SAGE III/ISS 1020 nm and OSIRIS 750 nm extinction coefficient (Figure 11). Generally, we'd expect to derive a similar pseudo Angstrom exponents for the 750 to 1020 nm conversion as used in the case of inferring OSIRIS 525 nm extinction from SAGE II 525 nm extinction coefficient. However we find, particularly in the lower stratosphere, significantly larger exponents for the 750-to-525 nm extinction conversion than for the 750-to-1020 nm conversion. For instance, in the lower tropical stratosphere, we find values for the former as large as 0 whereas as comparable values for the latter are less than -3.

We use these monthly pseudo Angstrom exponents to infer an OSIRIS extinction coefficient product at 1020 nm for the post-SAGE II period. Again, we do not propose these exponents as having only information regarding aerosol optical properties as they also account for systematic differences between aerosol data products. These empirical parameters are simply what are required to bring OSIRIS aerosol extinction data into conformance with SAGE II/III data and fulfill the goals of GloSSAC v2.0. In order to infer 1020-nm extinction coefficient from CALIOP 532 nm backscatter data, we follow the same procedure as we employed to infer CALIOP 525 nm extinction in section 5.1. Figure 9c shows annual median of OSIRIS extinction at 1020 nm to CALIOP 532 nm backscatter ratio. Despite whatever shortcomings these values may have relative to reflecting aerosol properties, we use these ratios to compute CALIOP extinction at 1020 nm.

Figure 12 shows the monthly time series for SAGE II, SAGE III/ISS and conformed OSIRIS and CALIOP data at some lower stratospheric levels. We find that OSIRIS 1020 nm extinction is in reasonable agreement with SAGE II and SAGE III/ISS 1020 nm extinction coefficient with an overall agreement between OSIRIS and SAGE II/SAGE ~~III/ISS~~ III-ISS of ±20%. It should be noted that there are still some significant outliers between SAGE products and the converted OSIRIS values almost always associated with significant increases in the stratospheric aerosol burden such as those following Manam volcanic eruption in January 2005 where apparent changes in aerosol size may be playing an out sized role. Figure 12 further shows that CALIOP 1020 nm extinction fits in reasonably well with OSIRIS, and SAGE III/ISS, suggesting that the inferred 1020 nm extinction is fairly robust. It should also be noted that, in some cases (particularly for February 2016 and October 2018) when no CALIOP data is available, we linearly interpolate CALIOP data in time between January (September) and March (November) of 2016 (2018) to fill in the missing monthly data following methods used in interpolating SAGE II data. In GloSSAC version 2.0, the data between August 2005 (after SAGE II mission ends) and June 2006 (CALIOP mission starts), the only data set available is OSIRIS and there are cases when missing data in OSIRIS needs to be filled. In such cases, we either use the closest month data or a linear interpolation when there is more than two consecutive months of data available at each grid point, while assuring the consistency and continuity in the merged data. SAGE III/ISS data is incorporated into the extinction record from June 2017 and we prioritize SAGE III/ISS data over OSIRIS and CALIOP whenever SAGE III/ISS data is available. Figure 13 and 14 show extinction from bias corrected 525 and 1020 nm respectively for OSIRIS, CALIOP, SAGE III/ISS and merged extinction at 47.5 N latitude. Overall, the continuity in the data is maintained after merging different datasets. Uncertainties related to each variable are also included in the final data product (see supplementary information on how uncertainties are estimated).

5 Stratospheric aerosol optical depth

A formal stratospheric aerosol optical depth (SAOD) at 525 and 1020 nm is included in GloSSAC v2.0. We compute SAOD by integrating aerosol extinction at respective wavelengths from the monthly-average tropopause in the data set to 40 km following the method described in Thomason et al. (2018). Figure 15 shows latitude versus monthly time series of SAOD from GloSSAC v1.1 , this version (v2.0) and the difference between v2.0 and v1.1 for the entire 40 year record that depicts major and minor volcanic eruptions. Figure 15a shows a consistent 525 nm optical depth enhancement at mid and high latitudes across the transition between SAGE II and OSIRIS in August 2005 which is a reflection of the lower stratospheric discrepancy observed in previous versions. Thomason et al. (2018) suggested that this could be related to the January 2005 eruption of Manam but also recognized that it may be an instrumental artifact. We show SAOD from the merged GloSSAC v2.0 data in Figure 15b where updated versions of OSIRIS and CALIOP data have been conformed to SAGE II (CALIOP indirectly so) and we now include data from SAGE III/ISS. The relative difference between GloSSAC 2.0 and GloSSAC 1.1 is shown in Figure 15c. It is evident from Figure 15c that smallest difference between version 2.0 and v1.1 occurs in the Southern Hemisphere, while in Northern Hemispheric higher latitudes the difference is between 10 and ~~30~~40%. Compared to the optical depths shown in Figures 15a and 15b, it is clear that while some enhancement after 2005 remains it is substantially smaller than in v1.1. For the period between 1979 and 2005, the differences between version 1.1 and 2.0 are seen during and following El Chichón (1982) and Pinatubo (1991) eruptions. The increase in percent difference in 1991 is mostly driven by a change in version 2.0 to not interpolate from May to July in SAGE II data.

At 1020 nm, the SAOD was noted as a deficiency in v1.0 as the conformance process did not produce satisfactory results for this period. In Figure 15d, it is clear that a much larger discontinuity across the instrument transition in 2005 at 1020 nm than at 525 nm. In Figure 15e, we observe that evidence for a discontinuity across the instrument change in 2005 is significantly reduced and, in fact, it is not clear that one exists at all. The differences in the two versions is shown in Figure 15f where we find that the optical depth for this period is reduced by as much as 50% at high latitudes.

Figure 16 shows ~~the entire 40 year record of SAOD for 525 and 1020 nm that depicts major volcanic eruptions such as El Chichón in 1982 and Mount Pinatubo in 1991. Figure~~ a similar plot but for version 1.0 and 2.0. The significant differences between version 1.0 and 2.0 remain somewhat similar to differences between v 1.1 and 2.0 shown in Figure 15. Figure 17 shows monthly time series of GloSSAC v2.0 SAOD at 525 nm for three different latitude bands for the entire 40 year record. Signatures of major volcanic eruptions (e.g. El Chichón in 1982 and Mount Pinatubo in 1991) and several other minor volcanic eruptions as listed in Table 1 in the post-SAGEII era are clearly evident in Figure 17. Figure 17 also shows how individual measurements of OSIRIS, CALIOP and SAGE III/ISS contribute toward the post-SAGE II aerosol record of GloSSAC v2.0. Additionally, a global SAOD time series for the entire record is shown in Figure 18. The percent difference of global SAOD of earlier versions with respect to v 2.0 is shown in Figure 18 (b) and (d). The largest percent difference in SAOD occurs in

June 1991 in both 525 and 1020 nm percent difference plot (b,d), which is due to a change in version 2.0 of GloSSAC to not to interpolate from May to July in SAGE II extinction coefficient data that are related to the usage of CLAES data. The difference in SAOD in the post-SAGE II period (after 2005) is due to the changes in version 2.0 that has improved over the older versions. This difference is mostly due to a reduction of SAOD at higher latitudes as they are evident from Figure 15 (c,f). For 1020, the difference between older versions and version 2.0 is much larger because of the reduction in discontinuity across instruments due to the conformance process used in version 2.0. We also note that in Figure18d, the SAOD has significantly reduced (as much as 50% or more) for 1020 nm as they are evident from Figure 15f as well. These differences may have implications on climate modeling as one of the recent modeling studies (Rieger et al., 2020) shows that the difference between v3.0 and v4.0 of CMIP6 stratospheric aerosol data that are derived from v 1.0 and v1.1 of GloSSAC causes a reduction in instantaneous top-of-the atmosphere radiative forcing following Pinatubo eruption.

As with v1.0, we cannot exclude the possibility that on-going volcanic activity plays a dominate role in the apparent enhancement after 2005. This possibility is bolstered by noting that optical depths shown in Figures 15b and 15e approach those observed in 2004, 2013, early 2014 during a lull in a decade of repeated minor volcanic stratospheric enhancements. We also note that several recent modeling studies (e.g. Schmidt et al., 2018; Aubry et al., 2020) using sulfur dioxide emissions in aerosol-climate models, have reported an enhancement in SAOD for the post-2005 time period. Nevertheless, we cannot exclude that some bias across the transition between SAGE II and the OSIRIS/CALIOP period continues to exist. It is possible that with further overlap between SAGE III/ISS and OSIRIS and CALIOP that a better understanding of instrumental differences will permit a more robust conformance process for future versions of GloSSAC.

6 Conclusions and Future Plans

Here we present v2.0 of GloSSAC that extends from 1979 through 2018 with the addition of new SAGE III/ISS data toward the end of the record and with some changes to the data used in the post-SAGE II era. We now use OSIRIS version 7.0 data ~~(Rieger et al., 2019)~~ (Rieger et al., 2019) instead of version 5.07, which was used in GloSSAC v1.0. The OSIRIS version 7.0 data is improved in terms of data quality in the lower stratosphere. However, the bias in the lower stratosphere is not entirely resolved as higher percent differences still exist between OSIRIS and SAGE II/SAGE III/ISS. Here, we use a conformance process to reduce the observed differences between OSIRIS and SAGE II/SAGE III/ISS, which is based on monthly pseudo Angstrom exponent computed using 750 nm OSIRIS extinction and 525 nm SAGE II/SAGE III/ISS extinction coefficients. A similar approach is implemented for inferring 1020 nm extinction coefficient. We continue to make use of CALIOP data in this version as well with some changes. At the time of development of GloSSAC v1.0, there was no standard stratospheric aerosol product available from CALIOP and therefore used its version 4.0 level 1 aerosol backscatter coefficient product at 532 nm and identified and removed observations that suggested the presence of cloud using the depolarization measurement (Vernier et al., 2009; Thomason et al., 2018). The cloud-cleared backscatter coefficients were then compiled into the spatial temporal resolution used in GloSSAC (monthly, 5 deg latitude bins, and 0.5 km altitude bins). Now that the CALIPSO standard stratospheric aerosol product (Kar et al., 2019) is available, we use the standard stratospheric aerosol product. However, we note that standard

CALIOP aerosol extinction coefficient computed at 525 nm tend to overestimate aerosol extinction in the lower stratosphere globally as well as in the entire stratosphere poleward of 40S and 40N. We, therefore use a SF based on conformed OSIRIS extinction coefficient and CALIOP estimated backscatter to conform the CALIOP data. The conformed CALIOP extinction coefficient is in reasonable agreement with OSIRIS and SAGE III/ISS with some exceptions. These changes resulted in an improved version 2.0 data. Some important changes in version 2.0 include, change in the usage of CALES data during Pinatubo time period that resulted in a reduction of extinction coefficient following Pinatubo, and improved extinction coefficients in the post-SAGE II era data. These changes in version 2.0 reflect in 525 nm SAOD data as about 80% reduction of SAOD occurs in June 1991 when compared against previous versions due to changes in the usage of CLAES data, whereas in the post-SAGE II period we note no significant change in SAOD at 525 nm. However, for 1020 nm extinction we note a significant improvement in the post-SAGEII era that results in significant reduction (as much as 50% or more) of SAOD in version 2.0 due to the new conformance process based on monthly angstrom exponent, where we observe that evidence for a discontinuity across the instrument change in 2005 is significantly reduced. Overall, the quality and robustness of the stratospheric aerosol product have improved for GloSSAC v2.0 with some issues that still persist in the data set which we mention below:

- Despite using a monthly based measured pseudo Angstrom exponent in converting OSIRIS extinction from its native wavelength of 750 nm to 525 nm, we note that this method has its own limitations during periods when the stratosphere is perturbed due to volcanoes/PyroCb events. OSIRIS 525 nm extinction coefficient is somewhat biased high in such events where we have SAGE II/SAGE III/ISS data to compare. Although, the monthly based pseudo Angstrom exponent correction significantly improves the comparison between OSIRIS and SAGE II extinction at 525 nm, we note somewhat large percent differences (>20%) between OSIRIS and SAGE II following Manam eruption (Figure 4d). Similar instances are also noted when both data are available and more so in the tropical latitudes between 20S and 20N. We, unfortunately do not have SAGE II measurements after August 2005 to validate OSIRIS data. However, toward the end of the record we use SAGE III/ISS to validate OSIRIS and CALIOP. For this time period, the agreement between SAGEIII-ISS and OSIRIS/CALIOP extinction coefficient is mostly within ±20%, but degrades somewhat during and following Canadian PyroCb events in 2017. Coincident OSIRIS and SAGE III/ISS measurements during this time period are studied in Bourassa et al. (2019).

- Since we use CALIOP stratospheric aerosol data to fill in missing OSIRIS data for the time period from June 2006 onward, issues pertaining to CALIOP data should also be mentioned. The standard CALIOP stratospheric aerosol product provides backscatter coefficient as it needs to be converted to extinction coefficient at the wavelength of interest for the GloSSAC usage. The standard CALIOP product also provides extinction at 532 nm. However, we note that CALIOP standard extinction product is biased high when compared against SAGE III/ISS and OSIRIS (Figure 8a,b). We, therefore compute particulate backscatter from scattering ratio and molecular backscatter coefficient and further infer extinction coefficient using Altitude-Latitude based scale factor (SF) which is derived from conformed OSIRIS extinction coefficient and estimated CALIOP backscatter coefficient. With this bias correction, bias between OSIRIS and corrected CALIOP extinction has now been reduced. However, it should also be noted that any bias in OSIRIS data will be reflected in CALIOP inferred extinction as we use OSIRIS extinction in the conversion process. While it gives us confidence in both bias corrected OSIRIS and CALIOP extinction in comparison with SAGE III/ISS that the differences between these data sets are mostly within ±20%, the representation of aerosol extinction coefficient particularly during small volcanic eruptions that occurred during OSIRIS/CALIOP period (2006-2017) is still a challenge with single wavelength measurements (either OSIRIS or CALIOP). We also note that the bias in the lower stratosphere is not entirely resolved as differences still exist between OSIRIS/CALIOP and SAGE measurements.

- While the inferred 1020 nm extinction in GloSSAC v2.0 for the post-SAGEII era (2005-2018) is improved compared to v1.0, there are limitations with the 1020 nm extinction. We note that deducing size information using 525 and 1020 nm extinction ratio for the period between August 2005 and June 2017 may still be an issue with single wavelength measurement from either OSIRIS or CALIOP, particularly during and following a volcanic event, despite some improvement in the inferred 1020 nm extinction. While this is clearly a limitation, we are not able to address changes in extinction ratio for volcanic events in v2.0 where the data set is based on only one wavelength. As a result, it is likely that GloSSAC extinction for small volcanic events during the OSIRIS/CALIOP period will be biased high to an unknown extent. Further study into this period may result in changes in a future version of GloSSAC. Since June 2017, multi-wavelength extinction coefficient data became available from SAGE III/ISS, giving us an opportunity to compare/validate OSIRIS/CALIOP data particularly during and following such events.

There are additional datasets that are available for stratospheric aerosol extinction coefficients. We plan to evaluate and use these datasets, including SCanning Imaging Absorption spectrometer for Atmospheric CartograpHY (SCIAMACHY) and Ozone Mapping Profiler Suite (OMPS).

7 Data File Contents and Accessibility

The contents of the GloSSAC v2.0 netCDF file is similar to that for v1.0. Some additional data records include gridded SAGE III/ISS data at 9 wavelengths and the original unconformed data for CLAES, HALOE, OSIRIS, CALIOP. All space-based data sets include the median reported uncertainty and the zonal standard deviation for each instrument product and for its conformed version in each altitude/latitude/time bin in which data is available. Version 2.0 also includes SAOD at 525 and 1020 nm. The contents of the GloSSAC v2.0 netCDF file are listed in Table A2 with variable name and description. Table A3 lists the data flag values associated with the dataset.

The GloSSAC v2.0 netcdf file is available from NASA Atmospheric Data Center (https://asdc.larc.nasa.gov/data/GloSSAC/GloSSAC_V2.0.nc) and referenced using its DOI: https://doi.org/10.5067/glossac-l3-v2.0 (Thomason, 2020).

8 Data availability

The GloSSAC v2.0 netcdf file is available from NASA Atmospheric Data Center (https://asdc.larc.nasa.gov/data/GloSSAC/GloSSAC_V2.0.nc) and referenced using its DOI: https://doi.org/10.5067/glossac-l3-v2.0 (Thomason, 2020).

Author contributions. MK and LT conceived the idea and methodology used in this paper. MK carried out the analysis, while NE helped with version 1.1 of the data (data prior to 2001). LR and AB provided us with version 7.0 of OSIRIS data, participated in the scientific discussion in regard to OSIRIS data in particular. LM provided help with the equivalent latitude that was used in filling data for SAGEII era. MK wrote the manuscript, while all authors reviewed the manuscript and provided with advice on the manuscript and figures.

Competing interests. The authors declare that they have no conflict of interest.

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Table 1. List of significant volcanic eruptions~~since 2002 with VEI ≥3~~/wild fire events that occurred during the entire record of GloSSAC

Volcano Name	**Eruption Date**	**Latitude**
~~Ruang~~ St. Helens (He)	27 Mar 1980	46N
El Chichón (El)	4 Apr 1982	17N
Nevado del Ruiz (Ne)	14 Nov 1985	5S
Kelut (Ke)	10 Feb 1990	8S
Pinatubo (Pi)	15 Jun 1991	15N
Cerro Hudson (Ce)	12 Aug 1991	46S
Rabaul (Ra)	19 Sept 1994	4S
Ulawun (Ul)	29 Sept 2000	5S
Shiveluch (Sh)	22 May 2001	56N
Ruang (Rn)	25 Sept 2002	2N
Reventador (Rv)	03 Nov 2002	0N
Manam (Mn)	27 Jan 2005	4S
Soufriere Hills (Sh)	20 May 2006	16N
Tavurvur (Tv)	07 Oct 2006	4S
Chaiten (Ch)	02 May 2008	42S
Okmok (Ok)	12 Jul 2008	55N
Kasatochi (Ka)	07 Aug 2008	55N
Fire/Victoria (Vi)	07 Feb 2009	37S
Sarychev (Sv)	12 Jun 2009	48N
Nabro (Nb)	13 Jun 2011	13N
Kelut (Ke)	13 Feb 2014	8S
Calbuco (Cb)	22 April 2015	41S
~~Fuego~~ Canadian Wildfires (Cw)	~~03 Jun~~ August 2017	51N
Ambae	27 July 2018	~~14N~~ 15S

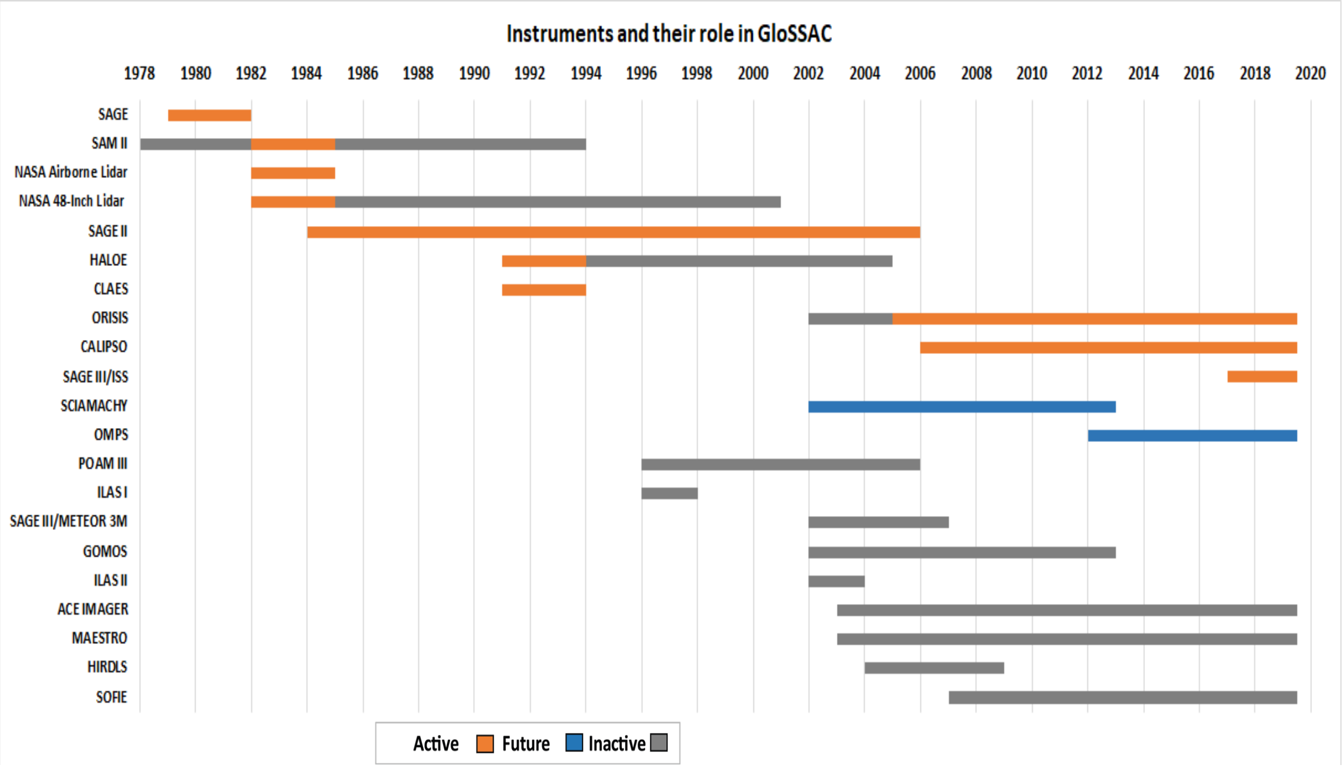


Figure 1. Space-based measurements of stratospheric aerosol extinction coefficient data used in GloSSAC.

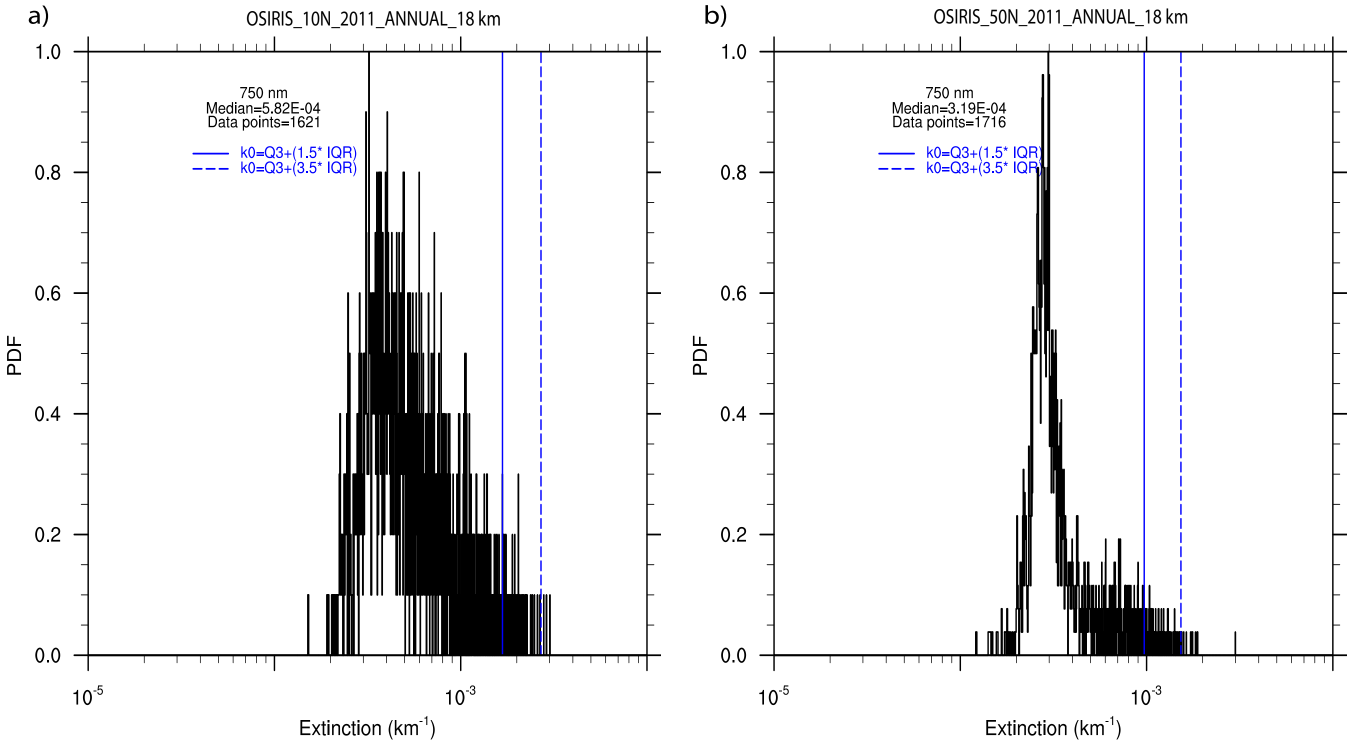


Figure 2. Probability density function (PDF) of aerosol extinction at 750 nm. PDF is shown as number of events normalized to the maximum value. The solid blue vertical line represents upper outlier in the data while dashed blue vertical line represents extreme outlier.

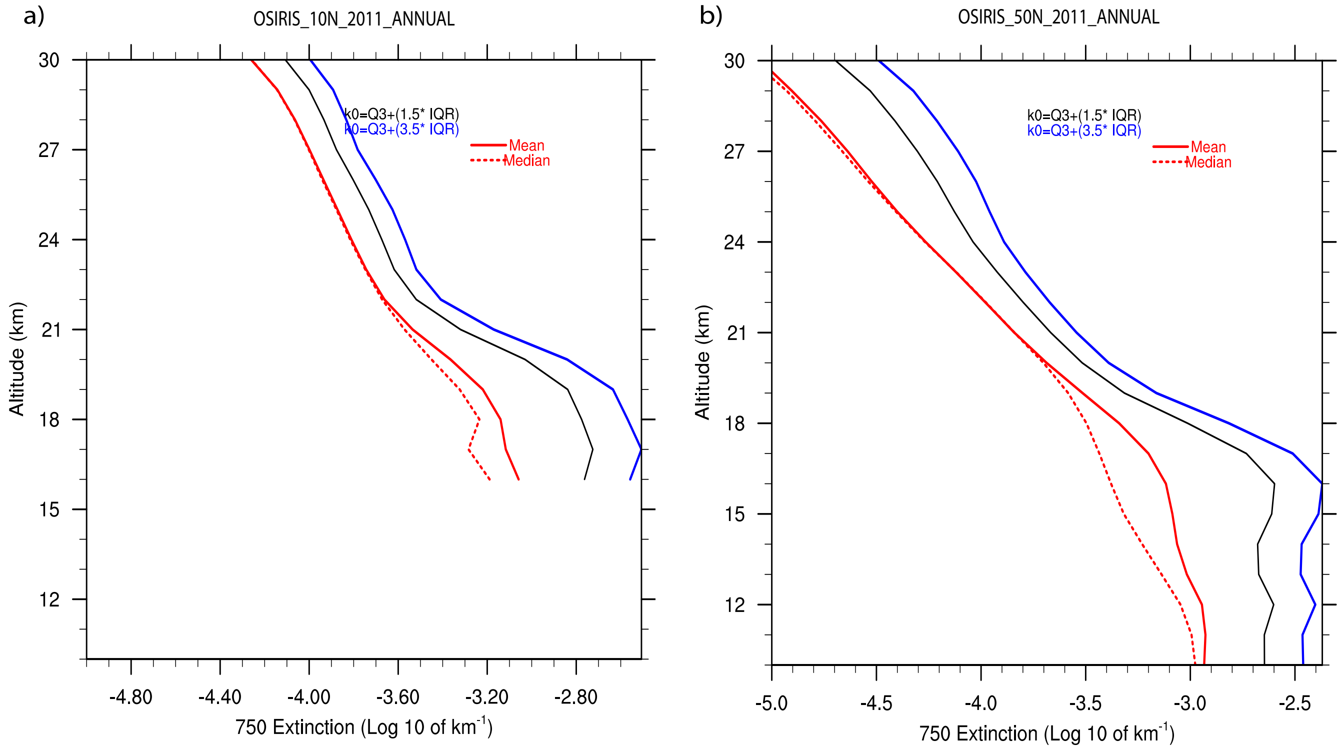


Figure 3. Vertical profiles of OSIRIS version 7.0 level 2 extinction coefficient at 750 nm for the separation of aerosol from enhanced aerosol/cloud values along with mean and median of extinction before cloud clearing for (a) 10N for 2011, and (b) same as in (a) but for 50 N.

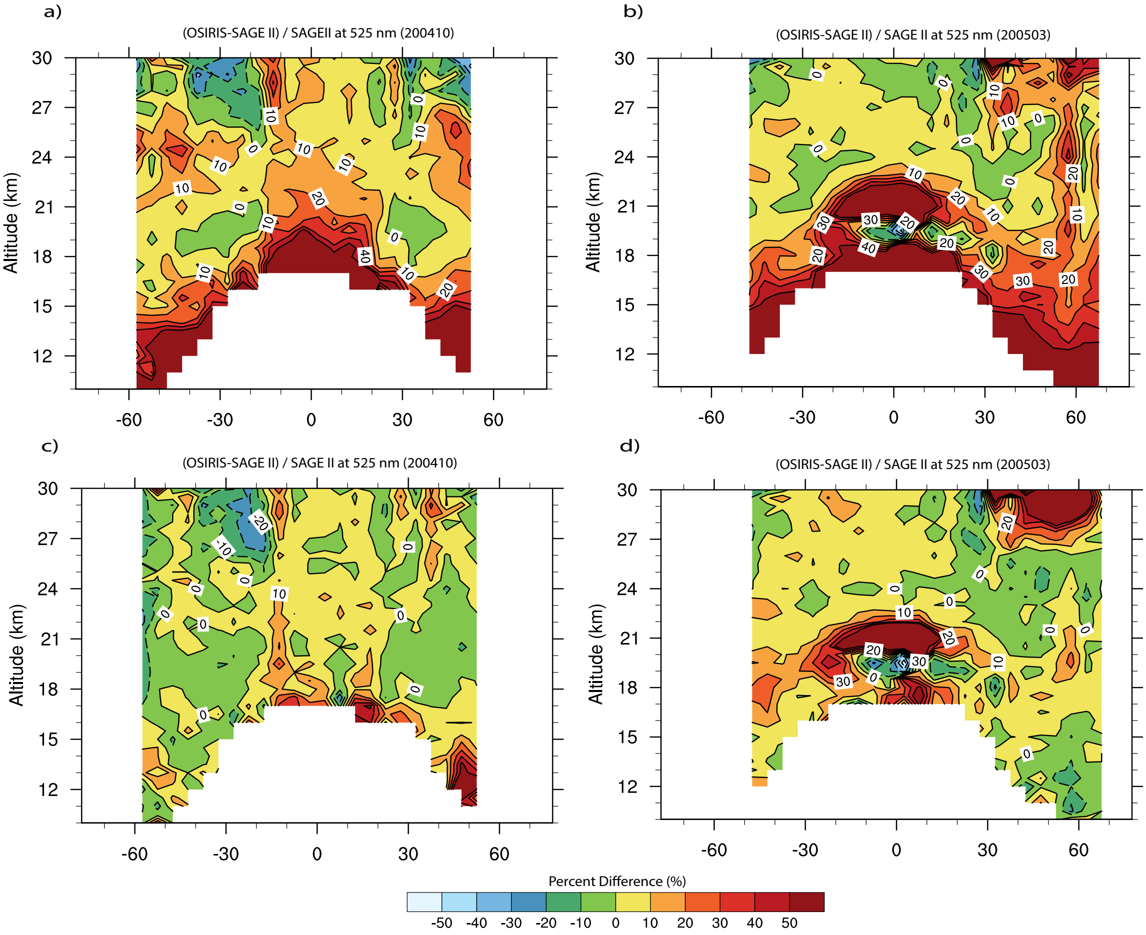


Figure 4. Altitude versus latitude of percent difference between OSIRIS and SAGEII extinction coefficient at 525 nm. (a) and (b) show the percent difference plots for 200410 and 200503 respectively for which OSIRIS ~~data~~ extinction coefficient at 525 nm is computed using a constant Angstrom exponent of 2.33. (c) and (d) are same as in (a) and (b) but after implementing a monthly based Angstrom exponent to compute OSIRIS extinction at 525 nm.

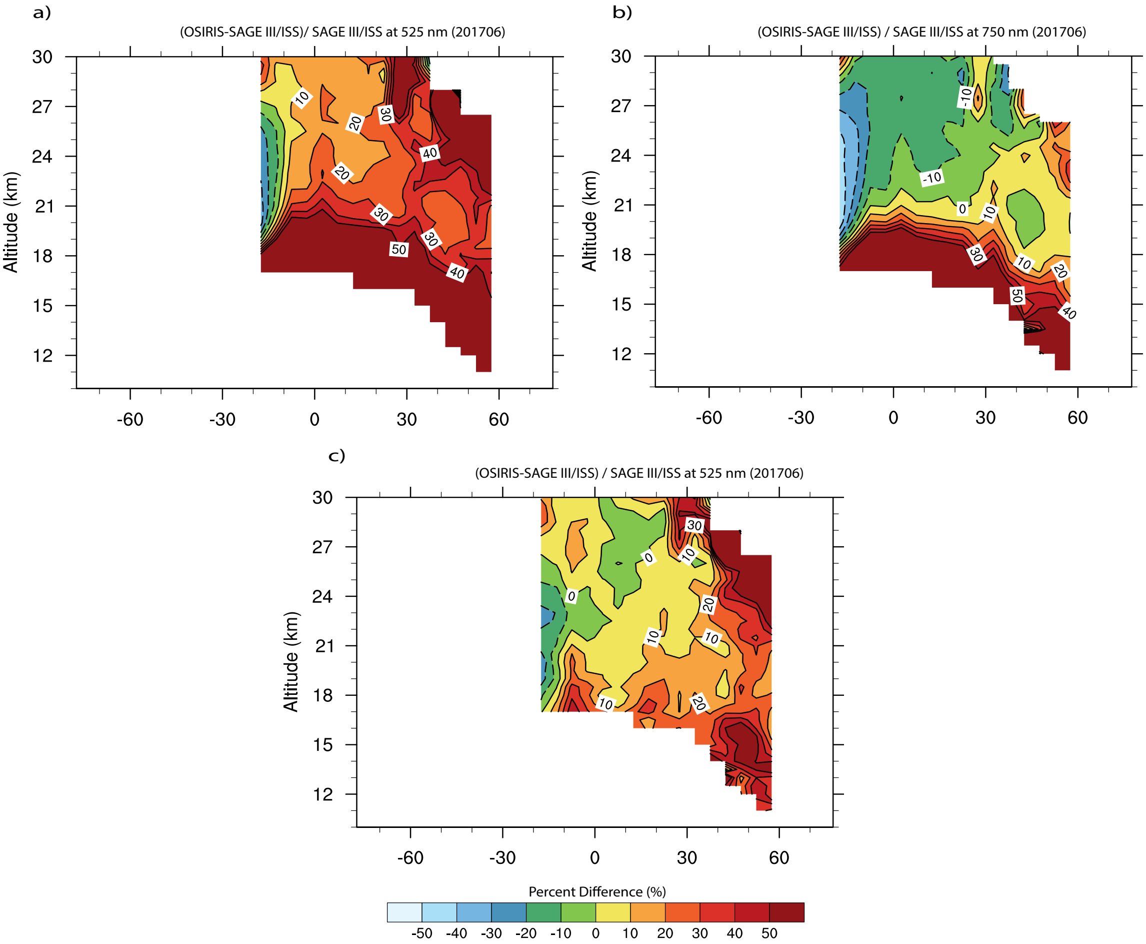


Figure 5. Altitude versus latitude of percent difference between OSIRIS and SAGE III/ISS ~~for~~ extinction coefficient (a) at 525 nm for 201706, and (b) at 750 nm for 201706. OSIRIS extinction coefficient used in (a) is computed using a constant Angstrom exponent of 2.33~~where as~~, whereas in (c) a monthly based pseudo Angstrom exponent is used to compute OSIRIS extinction at 525 nm.

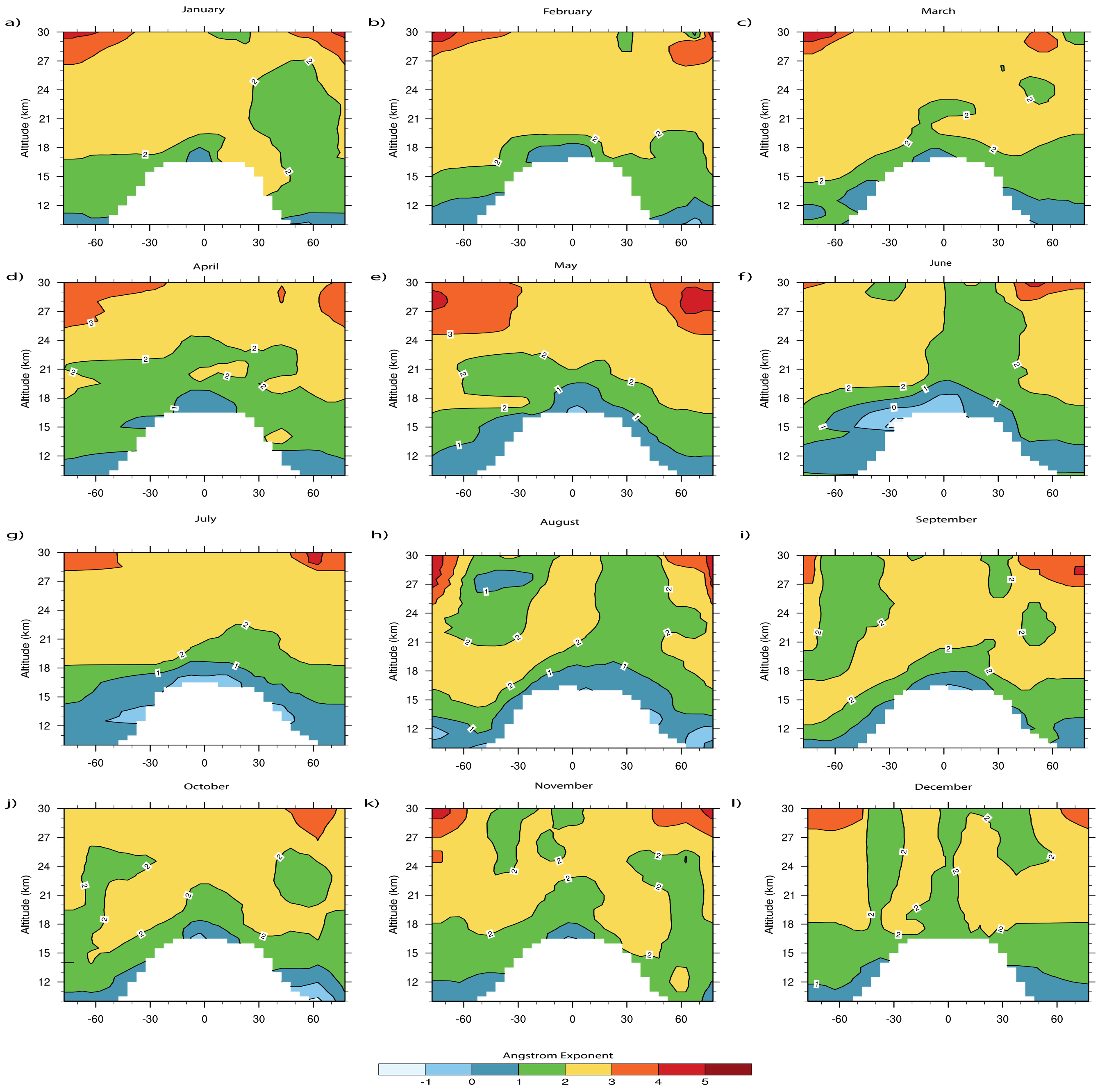


Figure 6. Altitude versus Latitude of pseudo Angstrom exponent monthly climatology derived using OSIRIS 750 nm extinction and SAGEII/ SAGE III/ISS 525 nm extinction. A 3X3 median smoothing is used to remove any outliers and then linearly interpolated to fill in any missing data.

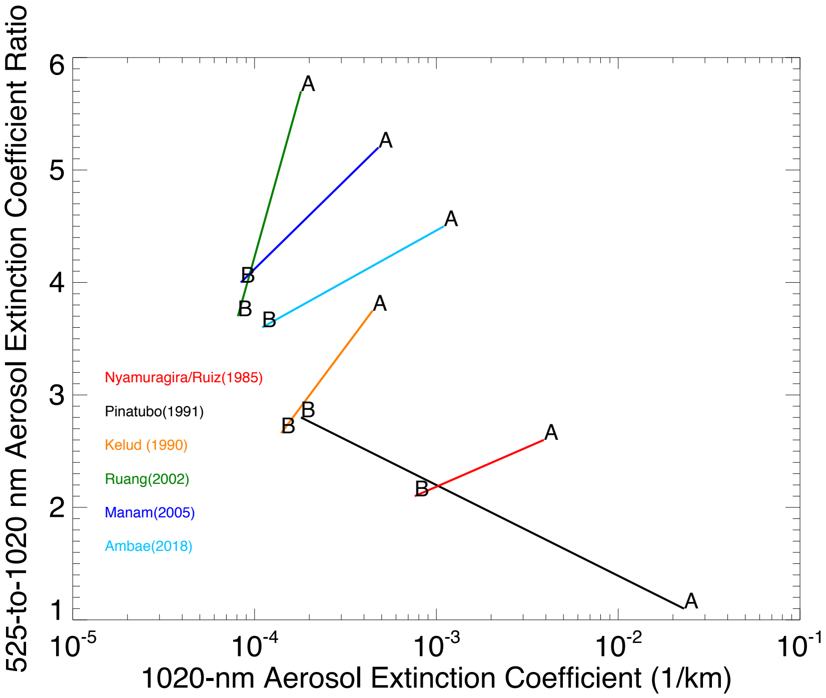


Figure 7. 525 to 1020 nm extinction ratio versus 1020 nm extinction ratio for several volcanic eruptions since 1990. The change in aerosol extinction coefficient and extinction ratio for each volcanic event is denoted denoted by two points "B" and "A" which represents change in extinction coefficient and extinction ratio "Before" and "After" eruption.

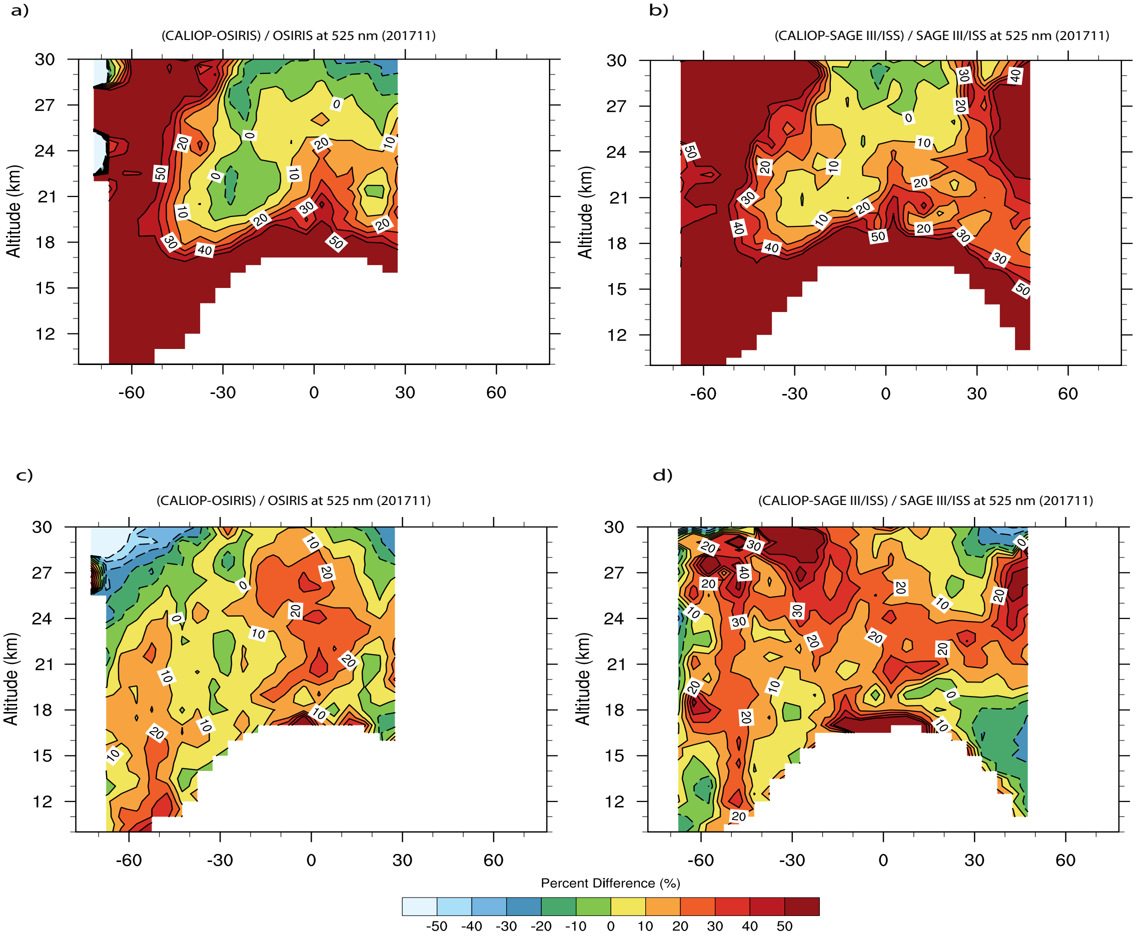


Figure 8. Altitude versus ~~Latitude~~ latitude of percent difference between CALIOP, OSIRIS and SAGE III/ISS extinction coefficients. Percent difference computed (a) between CALIOP and bias corrected OSIRIS extinction coefficient at 525 nm for 201711, and (b) between CALIOP and SAGE III/ISS extinction coefficient at 525 nm for 201711. (c) and (d) are same as in (a) and (b) but CALIOP ~~data~~ extinction is bias corrected.

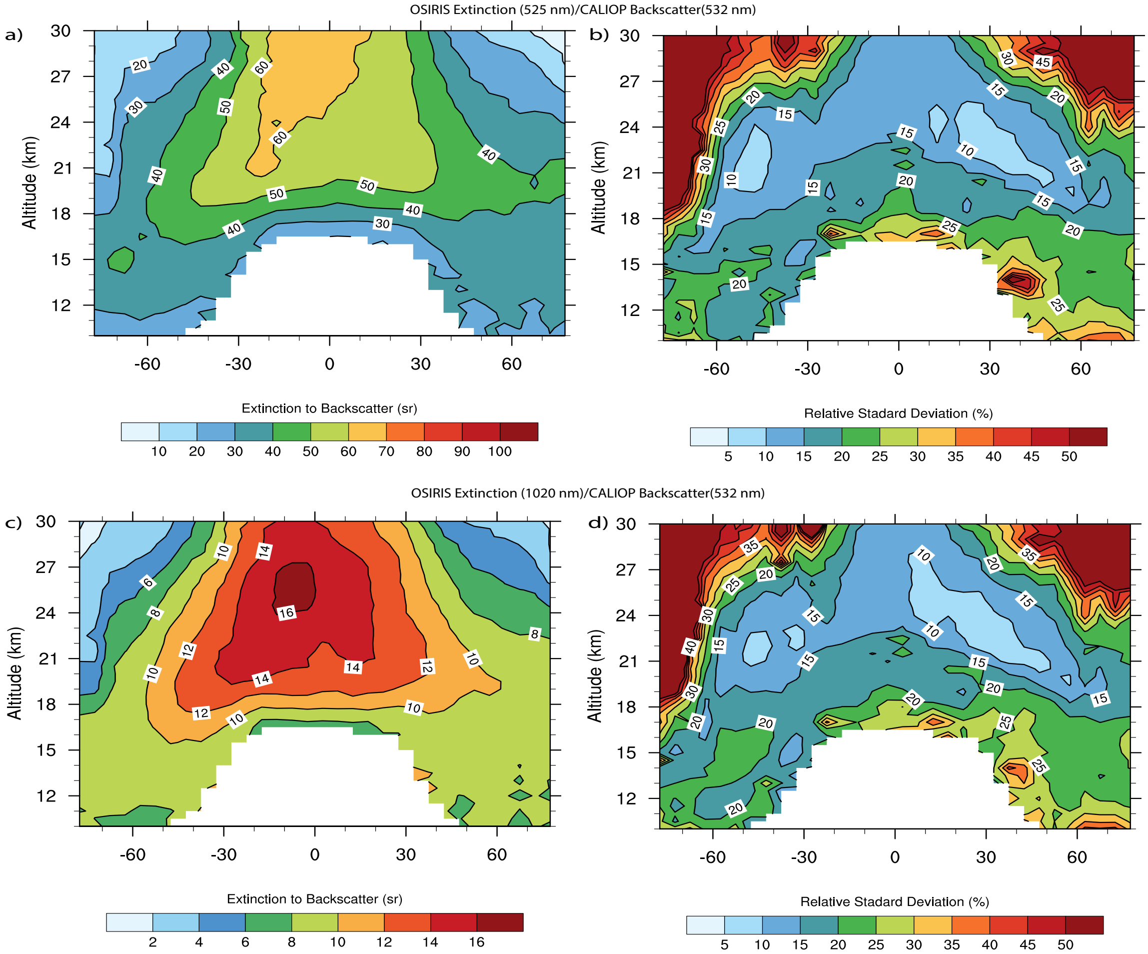
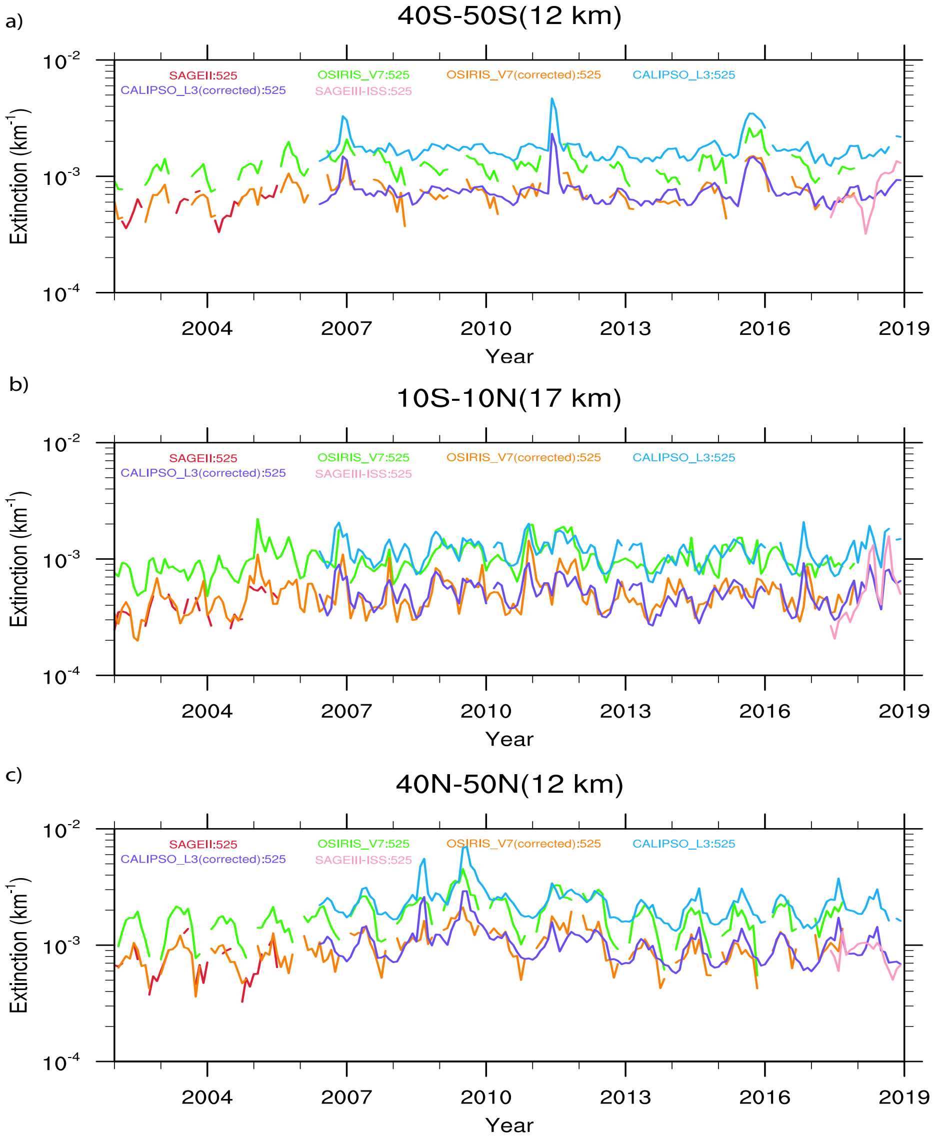


Figure 9. Altitude-Latitude dependence of median annual ~~525 nm~~ OSIRIS extinction to 532 nm backscatter ratio (OSIRIS/CALIOP) for the overlap period (2006-2017). (a) OSIRIS 525 nm extinction to CALIOP 532 backscatter ratio (SF), (b) Relative standard deviation of (a) is computed at each grid point with respect to the median value in percent. (c) and (d) are same as in (a) and (b) but using OSIRIS 1020 nm extinction.


a) 40S-50S(12 km)

b) 10S-10N(17 km)

c) 40N-50N(12 km)

Figure 10. Zonally averaged monthly time series plots of extinction coefficient at 525 nm for different latitude bands and altitudes.

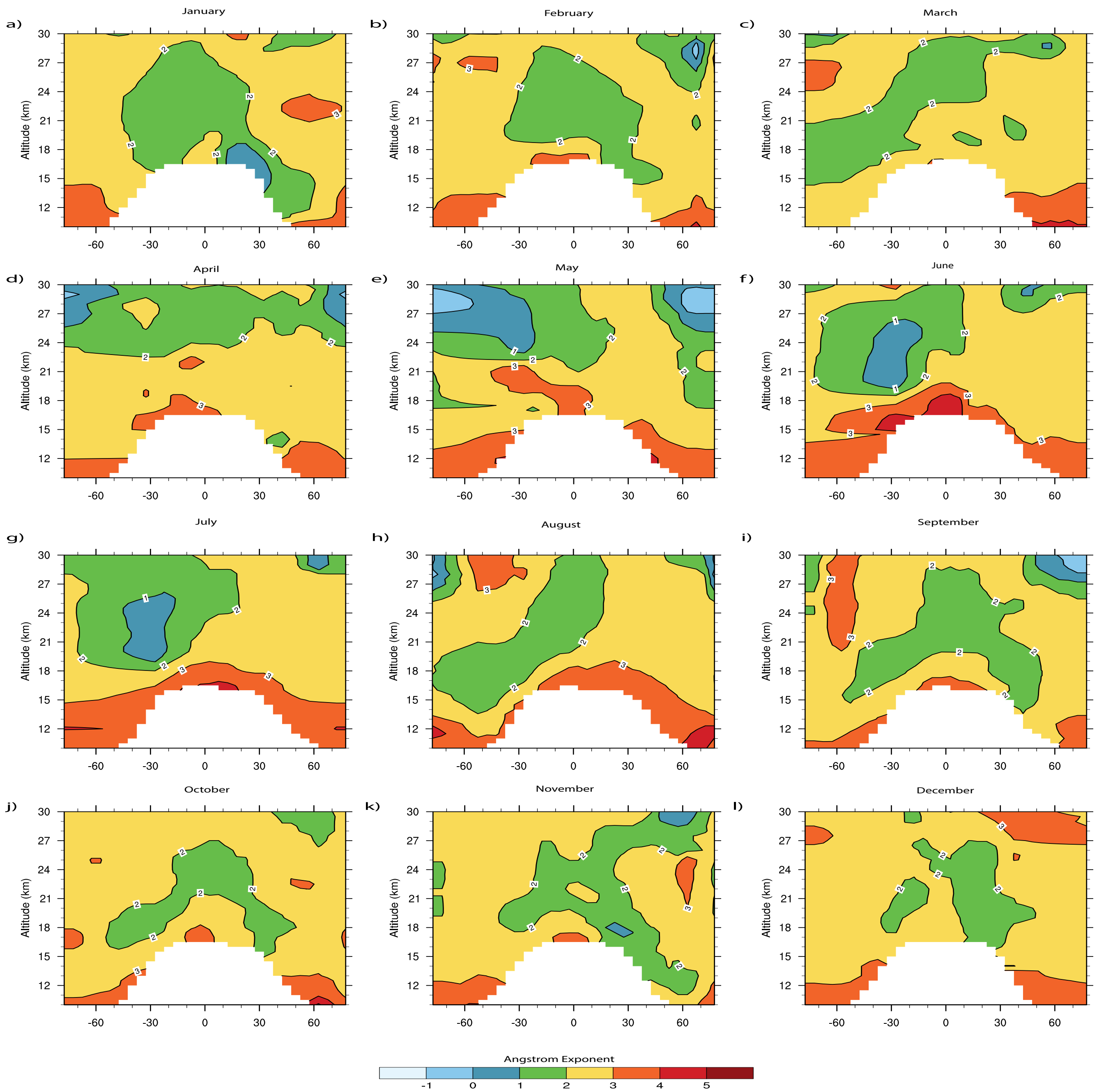


Figure 11. Altitude versus Latitude of pseudo Angstrom exponent monthly climatology derived using OSIRIS 750 nm extinction and SAGE II/SAGE ~~III/ISS~~ III-ISS 1020 nm extinction. A 3X3 median smoothing is used to remove any outliers and then linearly interpolated to fill in any missing data.

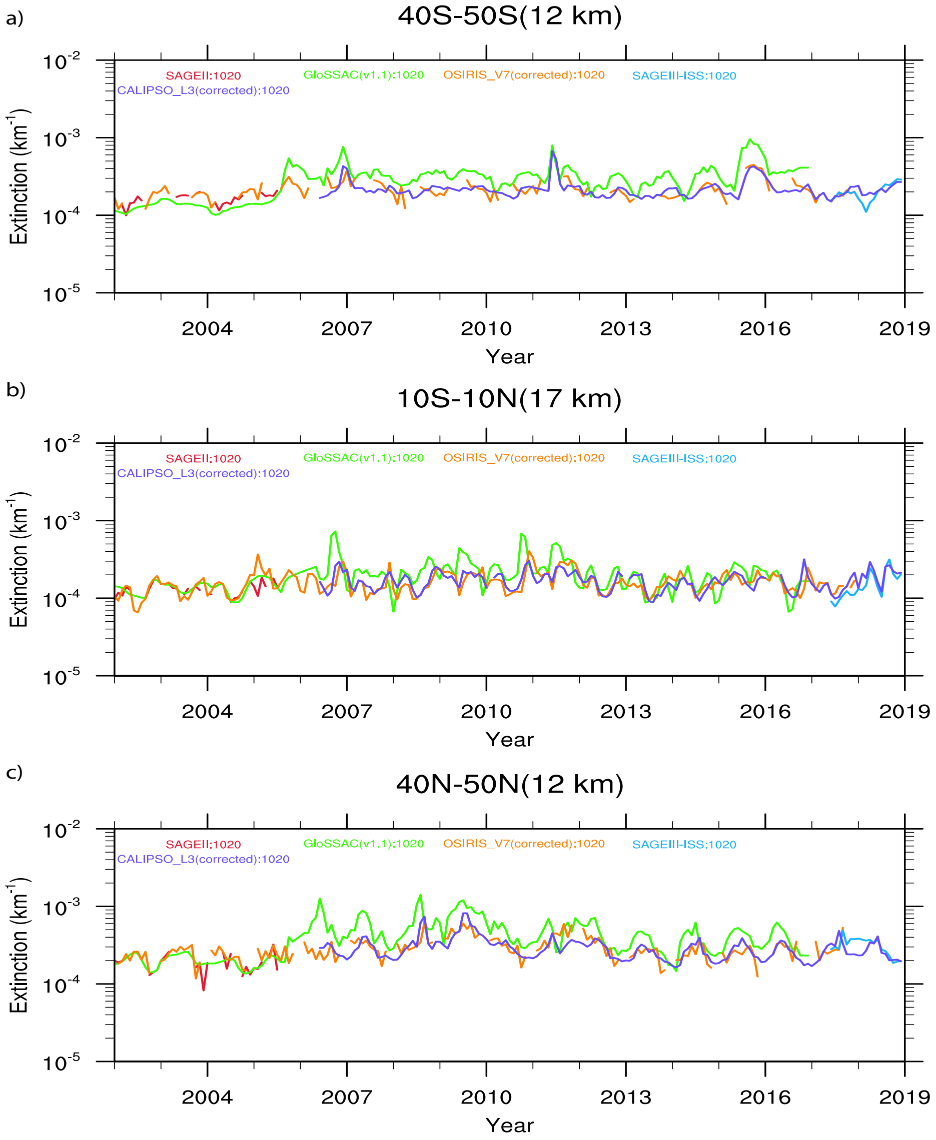


Figure 12. Zonally averaged monthly time series plots of extinction coefficient at 1020 nm for different latitude bands and altitudes.

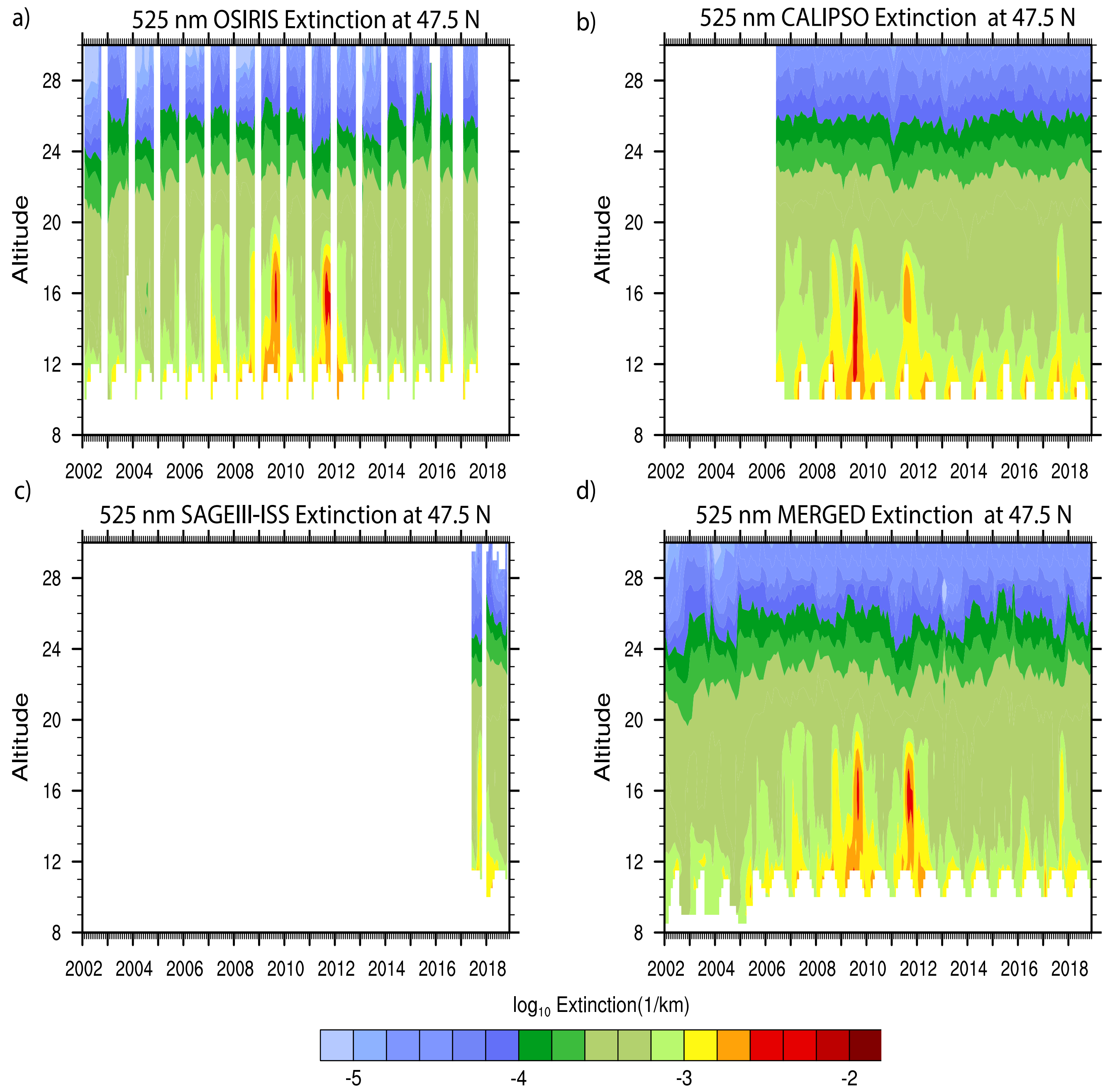


Figure 13. Altitude versus monthly time series of ~~Extinction~~ 525 nm extinction coefficient at 47.5 N latitude~~for 525 nm for~~ . (a) bias corrected OSIRIS extinction coefficient , (b) bias corrected CALIOP extinction coefficient (c) cloud cleared SAGE III/ISS extinction coefficient and (d) final merged 525 nm GloSSAC v2.0 ~~data product~~extinction coefficient.

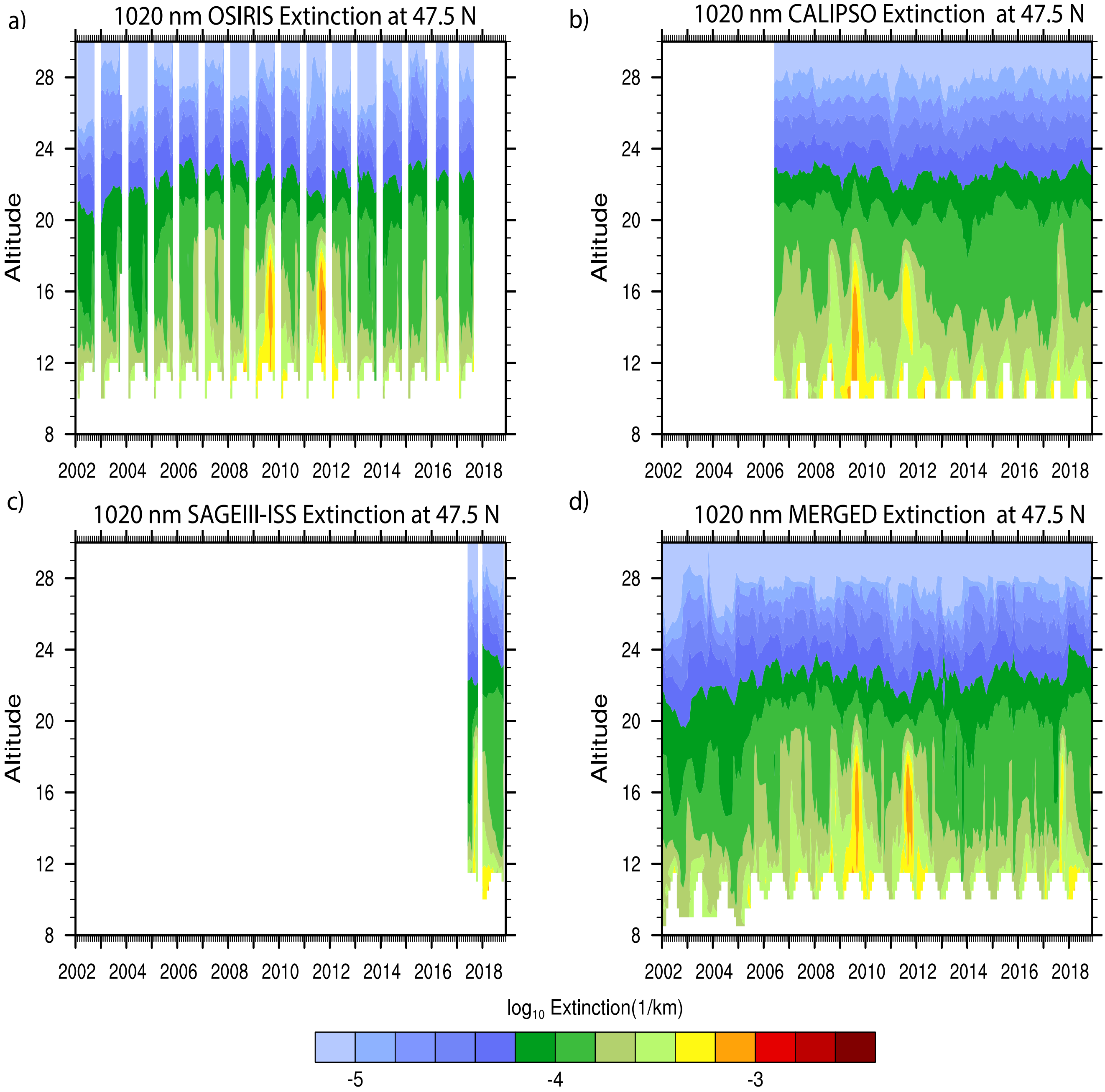


Figure 14. Altitude versus monthly time series of ~~Extinction~~ 1020 nm extinction coefficient at 47.5 N latitude~~for 1020 nm for~~ . (a) bias corrected OSIRIS extinction coefficient , (b) bias corrected CALIOP extinction coefficient (c) cloud cleared SAGE III/ISS extinction coefficient and (d) final merged 1020 nm GloSSAC v2.0 ~~data product~~extinction coefficient.

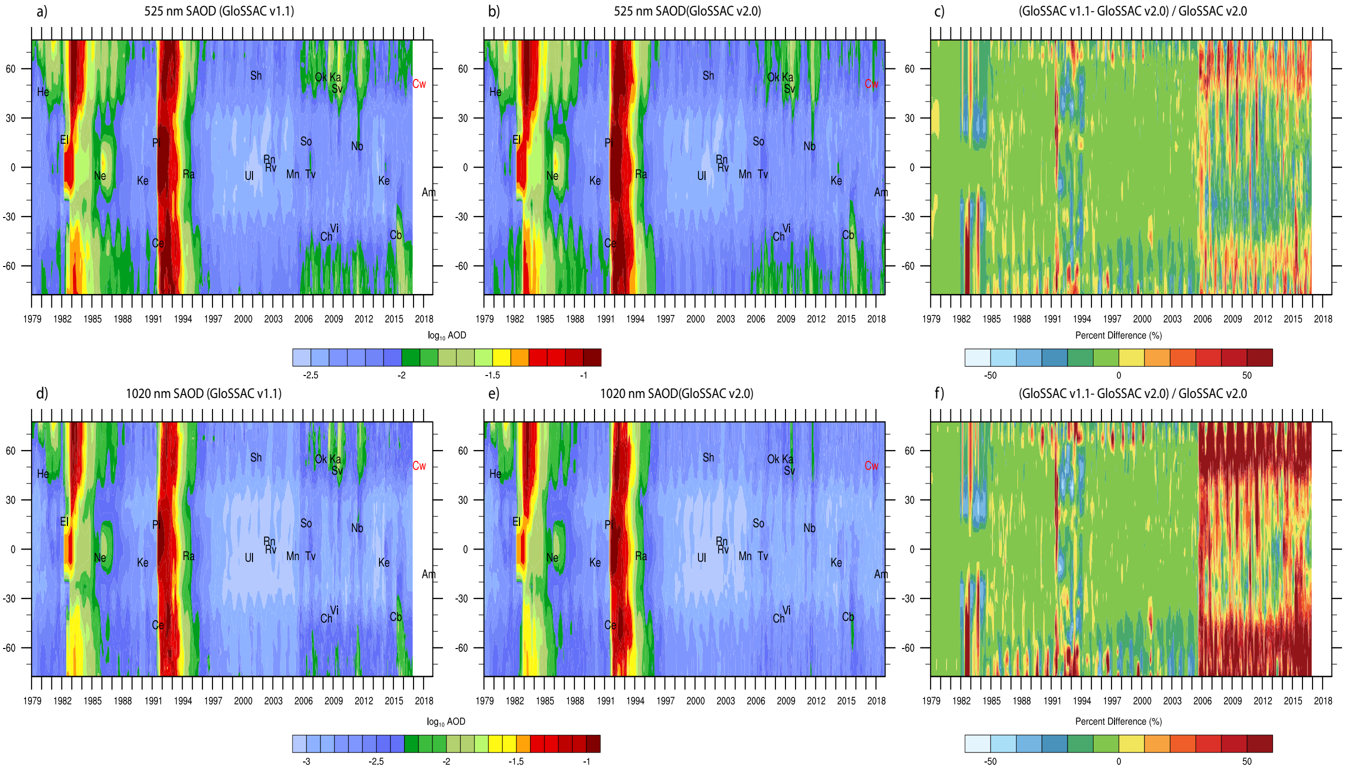


Figure 15. Latitude versus monthly time series of SAOD at 525 and 1020 nm: (a) using GloSSAC v1.0 , (b) using merged OSIRIS bias corrected version 7.0, bias corrected CALIOP, and SAGE III/ISS data (GloSSAC 2.0) and (c) percent difference between a and b. (d), (e), and (f) are same as (a), (b), and (c) but for 1020 nm extinction. For 525 nm extinction, OSIRIS data is bias corrected using monthly pseudo Angstrom exponents shown in Figure 5, while CALIOP 525 nm extinction is inferred using OSIRIS 525 nm extinction to CALIOP 532 nm backscatter ratio. For 1020 nm, OSIRIS data is bias corrected using monthly pseudo Angstrom exponents shown in Figure 11, while CALIOP 1020 nm extinction is inferred using OSIRIS 1020 nm extinction to CALIOP 532 nm backscatter ratio.

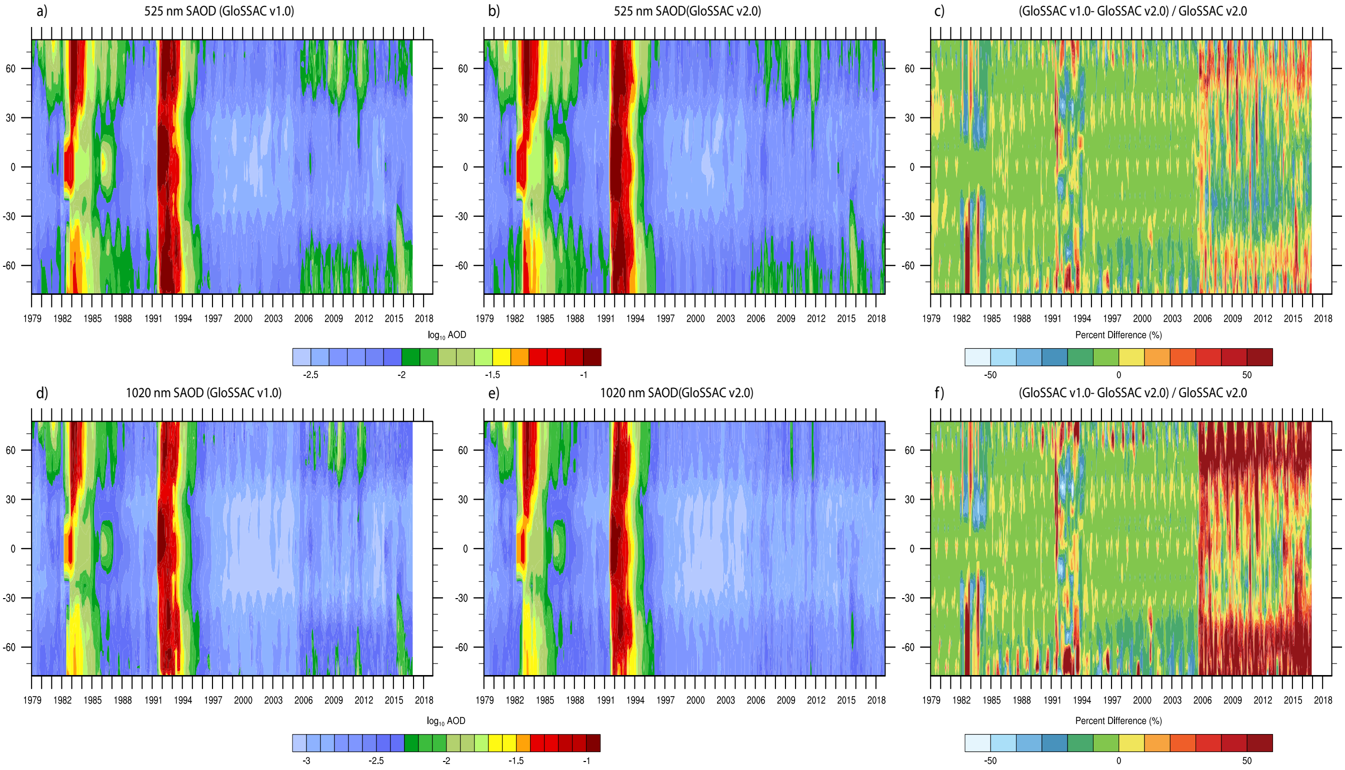


Figure 16. ~~Latitude versus monthly time series of SAOD at 525 and 1020 nm.~~Same as in Figure 15 but for GloSSAC v 1.1 is replaced by GloSSAC v 1.0

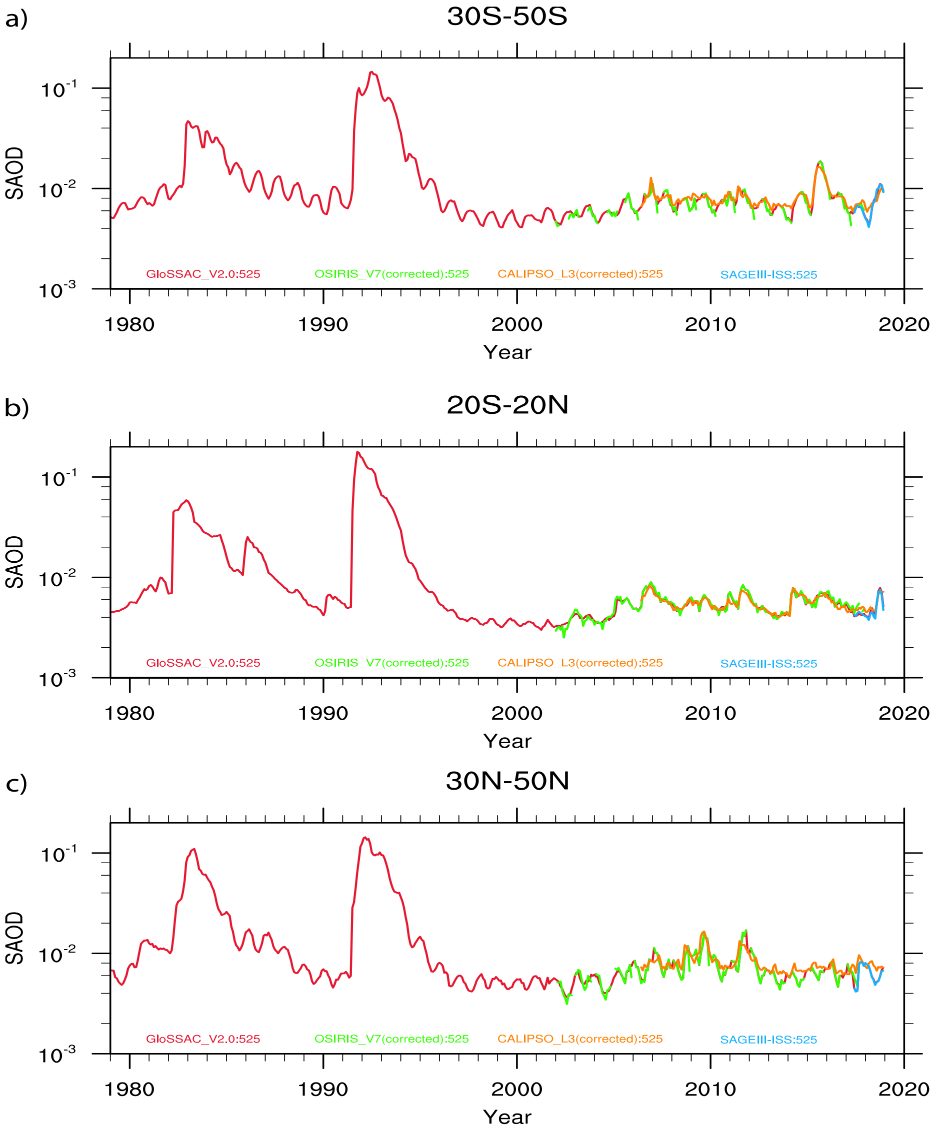


Figure 17. Zonally averaged monthly stratospheric aerosol optical depth at 525 nm for (a) 30S-50S , (b) 20S-20N , and (c) 30N-50N .

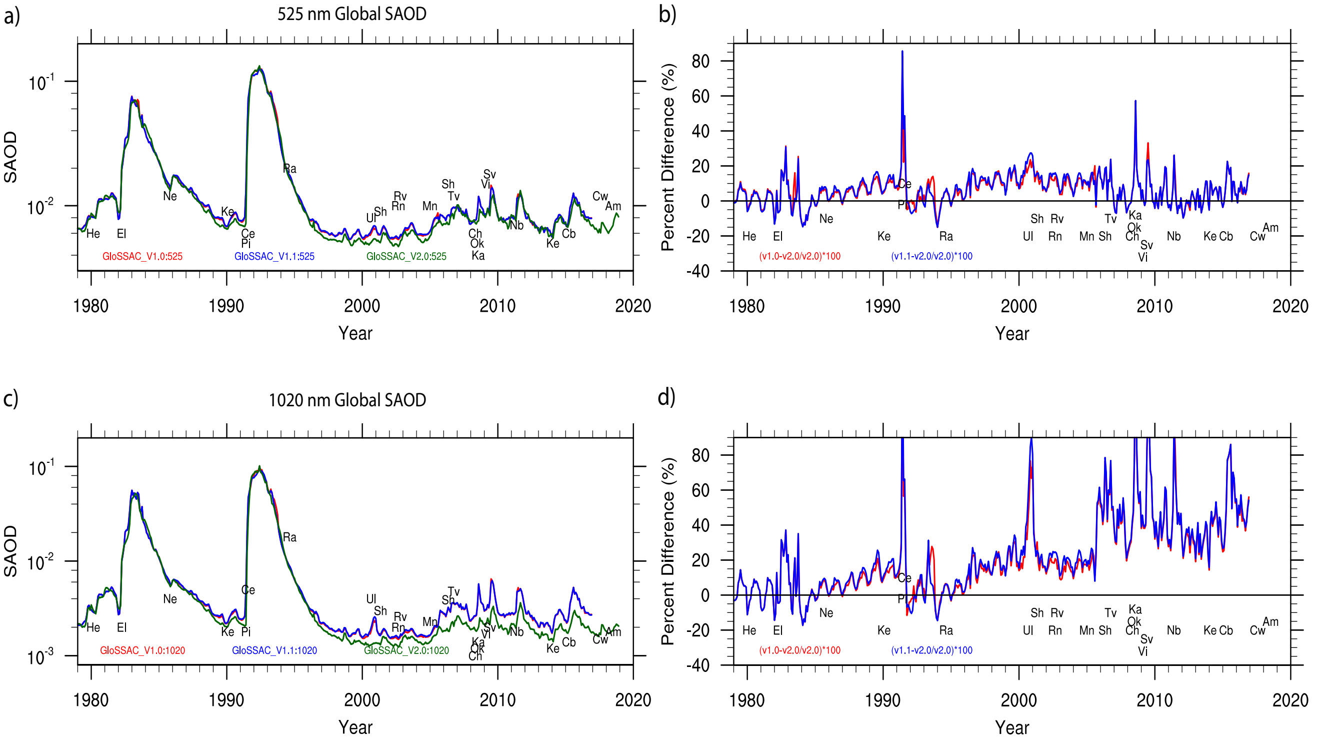


Figure 18. Global stratospheric aerosol optical depth at 525 (a) and 1020 nm (c). Percent difference between versions for 525 and 1020 nm extinction are shown in (b) and (c) respectively. Percent difference are computed with respect to v 2.0 as (v1.0 (v1.1)-v2.0/v2.0)*100.

Table A1. Acronyms

ASAP	Assessment of Stratospheric Aerosol Properties
CALIOP	Cloud-Aerosol Lidar with orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CCM	Chemistry-Climate Model
CCMI	Chemistry-Climate Model Intercomparison
CLAES	Cryogenic Limb Array Etalon Spectrometer
CMIP	Climate Model Intercomparison Project
CMIP6	Coupled Model Intercomparison Project version 6
GCM	Global Climate Model
GloSSAC	Global Space-based Stratospheric Aerosol Climatology
HALOE	Halogen Occultation Experiment
ISS	International Space Station
NASA	National Aeronautics and Space Administration
NAT	Nitric Acid Trihydrate
OSIRIS	Optical Spectrograph and InfraRed Imager System
PSC	Polar Stratospheric Cloud
SAGE	Stratospheric Aerosol and Gas Experiment
SF	Scale Factor
SPARC	Stratospheric-tropospheric Processes and their Role in Climate
STS	Saturated Ternary Solution
SSiRC	Stratospheric Sulfur and its Role in Climate
VEI	Volcanic Eruption Index
WCRP	World Climate Research Programme

Table A2. List of Variables in the netcdf file

Variable Name	**Description**
Caliop_Backscatter_Coefficient_532	Estimated CALIOP backscatter coefficient at 532 nm regridded to GloSSAC grid
Caliop_Extinction_Coefficient_532	Standard CALIOP extinction at 532 nm from CALIOP Level 3 file regridded to GloSSAC grid
Caliop_Aerosol_Extinction_Coefficient	Conformed CALIOP aerosol extinction coefficient at 525 and 1020 estimated using Scale Factor
Caliop_Aerosol_Extinction_Coefficient_Flag	CALIOP Aerosol Extinction Coefficient Flag
Caliop_Scale_Factor_Median	Annual median Scale Factor of CALIOP data estimated at 525 and 1020 nm
Caliop_Scale_Factor_Standard_Deviation	Standard Deviation of Scale Factor of CALIOP data estimated at 525 and 1020 nm
CLAES_Extinction_Coefficient	CLAES extinction coefficient interpolated to SAGE altitude resolution at 7.80 μ m
CLAES_Extinction_Coefficient_Standard_Deviation	Standard Deviation of CLAES extinction coefficient at 7.80 μ m
Glossac_Aerosol_Extinction_Coefficient	GloSSAC Aerosol Extinction Coefficient at GloSSAC wavelengths
Glossac_Aerosol_Extinction_Coefficient_Flag	Merged Aerosol Extinction Coefficient Flag
Glossac_Aerosol_Optical_Depth	Aerosol Opitcal Depth at GloSSAC wavelengths
Glossac_Aerosol_Extinction_Coefficient_Median	Zonal Median of Merged Aerosol Extinction Coefficient at GloSSAC wavelengths
Glossac_Aerosol_Extinction_Coefficient_Std	Standard Deviation of Merged Aerosol Extinction Coefficient at GloSSAC wavelengths
HALOE_Extinction_Coefficient	HALOE extinction coefficient interpolated to SAGE altitude resolution at 3.40 μ m
HALOE_Extinction_Coefficient_Standard_Deviation	Standard Deviation of HALOE extinction coefficient at 3.40 μ m
High_Altitude_Climatology	Monthly Climatology for the high altitude stratosphere
Osiris_Extinction_Coefficient_750	Zonally averaged 750 nm extinction coefficient interpolated to SAGE altitude resolution
Osiris_Median_Extinction_Coefficient_750	Zonal median 750 nm extinction coefficient interpolated to SAGE altitude resolution
Osiris_Standard_Deviation_Extinction_Coefficient_750	Zonal standard deviation of 750 nm extinction coefficient interpolated to SAGE altitude resolution
Osiris_Aerosol_Extinction_Coefficient	Conformed Osiris Aerosol Extinction coefficient at 525 and 1020 nm
Osiris_Aerosol_Extinction_Coefficient_Flag	OSIRIS Aerosol Extinction Coefficient Flag
Osiris_Aerosol_Extinction_Coefficient_Standard_Deviation	Estimated standard deviation of conformed aerosol extinction coefficient at 525 and 1020 nm
Sageiii_ISS_Aerosol_Extinction_Coefficient	Zonal mean SAGE III/ISS Aerosol Extinction coefficient at nine wavelengths
Sageiii_ISS_Aerosol_Extinction_Coefficient_Median	Zonal median of SAGE III/ISS Aerosol Extinction Coefficient at nine wavelengths
Sageiii_ISS_Aerosol_Extinction_Coefficient_Standard_Deviation	Zonal Standard Deviation of SAGE III/ISS Aerosol Extinction Coefficient at nine wavelengths
Sageiii_ISS_Cloud_Cleared_Aerosol_Extinction_Coefficient	SAGE III/ISS Cloud Cleared Aerosol Extinction coefficient at nine wavelengths
Sageiii_ISS_Cloud_Cleared_Aerosol_Extinction_Coefficient_Median	Zonal median of SAGE III/ISS Cloud Cleared Aerosol Extinction Coefficient at nine wavelengths
Sageiii_ISS_Cloud_Cleared_Aerosol_Extinction_Coefficient_Standard_Deviation	Zonal Standard Deviation of SAGE III/ISS Cloud Cleared Extinction Coefficient at nine wavelengths
Sageiii_ISS_Cloud_Cleared_Aerosol_Extinction_Coefficient_Flag	SAGE III/ISS cloud cleared aerosol extinction coefficient flags
Stratospheric_Background	Clean period monthly climatology

Table A3. GloSSAC data flag values and description

Flag Value	Source
1	SAGE II
2	CLAES empirically scaled to 1020 nm
3	HALOE empirically scaled to 1020 nm
4	Equivalent latitude reconstruction
5	ASAP-based tropical lidar fill data for the Pinatubo period, it is used in part in the June 1991 to September 1991 period
6	Pinatubo June fix where data from May 1991 is used where no SAGE II observations occur rather than interpolating between very clean May 1991 and very volcanic July 1991
7	525 estimates from valid 1020 nm data
8	CALIOP backscatter coefficient converted to 525 nm extinction coefficient based on Scale Factor (SF)
9	OSIRIS bias corrected extinction coefficient based on monthly Angstrom exponent
10	CALIOP backscatter coefficient converted to 1020 nm extinction based on Scale Factor (SF)
11/12	Linearly interpolated from points within 2 months. No additional interpolation involving altitude or latitude is included
14	SAM II/SAGE data from January 1979 through December 1981
15	Replicated (same value) downward in Lidar period (1982–1984); mostly only below 10 km and at higher latitudes
16	1000 nm SAM II extinction and extinction inferred from airborne and ground-based lidar (January 1982 and October 1984)
20	High-altitude climatology; average of data between 1984 and 1990 and between 1995 and 2005
21	Quality controlled data, values removed and interpolated across.
22	Some individual holes in otherwise continuous data patched using adjacent grid spots
24	Estimated 525 nm data where 1020 nm data exists during the Pinatubo period
27	Linearly interpolated bias corrected OSIRIS extinction coefficient at 525 and 1020 nm
28	Linearly interpolated bias corrected CALIOP extinction coefficient at 525 and 1020 nm
29	SAGE III/ISS extinction coefficient
30	Linearly interpolated SAGE III/ISS extinction coefficient