Reply to reviewer 1

We would like to thank the reviewer for their time, especially since this is a long paper, and useful & considerate comments. Their comments are repeated below in italic, followed by our answers.

My only truly general remark would be that the work got chopped up into too many (3) papers, leading to some repetition but also requiring the reader to have at hand the other papers, and actually making parts of the previous papers, less than a year old, somewhat obsolete.

These papers bring out different aspects of sampling issues, for a variety of observing systems and observables. While there is a thematic overlap, we feel the overlap is small content-wise:

- S16a concerns spatial sampling, in a model evaluation context. It uses regional model data and assumes highly localised observations. It really is a study of sampling errors for continuously measuring (in-situ) ground-sites or incidental flight campaigns. It shows that different observations can lead to very different sampling errors. It includes a lot of sensitivity studies for different strategies in comparing a global model to the observations.
- S16b concerns temporal sampling, in a model evaluation context. It used global model data and real remotely sensed observations. It compared sampling errors to actual model errors and showed them to be of similar magnitude. It also showed that models compared better with real observations after temporal collocation. It showed that the sampling error for visual remote sensing data would depend on longitude when using daily model data.
- The current study concerns spatio-temporal sampling in a general sense. It uses regional model data and a separate model for (idealised) observational spatio-temporal sampling. It allows the study of sampling issues in satellite L3 data (not possible with S16a or S16b) and provides realistic estimates for representation errors after temporal collocation (again not possible with S16a or S16b).

The paragraph describing S16a and S16b (p 2 line 20-28, in the introduction) has been rewritten to clarify this.

Specific concerns/suggestions

The title needs to be more specific clarifying that this paper is about aerosols. The scope of the results presented here does not warrant the current title.

The reviewer is correct in suggesting that the magnitude of representation errors may be very different for observations that we have not considered. Our literature study suggests that compared to aerosol observations, representation errors in e.g. ozone, solar surface radiation or water vapour column are relatively small (we are not saying they are insignificant!). Although we only consider aerosol measurements, it should be noted these are very diverse in nature and often the result of very different processes (see also S16a). Consequently, we believe that our paper holds interest for other fields: 1) it provides a paradigm for studying these errors (we have not encountered the combined issue of spatio-temporal sampling in the literature before); 2) it shows how representation errors depend on sampling strategies and averaging procedures. We find it hard to believe that this will be fundamentally different for other observables.

The nature of ACP and the content of the abstract make the limitations in our paper quite clear, but a title should also be used to advertise a particular topic. We suggest to keep the title as it is.

Even though this paper is about aerosols the introduction could/should touch more broadly upon the literature that exists in other atmospheric domains also outside the assimilation context.

We were not aware of the work on representation in ozone measurements. The Nappo report can no longer be found in the BAMS archive (presumably this is a summary only), and our university library staff could not obtain a copy of the full report. While we have not been able to obtain the Nappo et al. report, the other papers mentioned by the reviewer will be referenced.

We also suggest Lin et al. 2015 GRL "Revisiting the evidence of increasing springtime ozone mixing ratios in the free troposphere over Western North America" and Boersma et al. 2016 GMD "Representativeness errors in comparing chemistry transport and chemistry climate models with satellite UV-Vis tropospheric column retrievals" to add to the paragraph describing representation studies in climate variables, surface radiation, SST and water vapour measurements.

Even though some references are provided in the introduction to empirical estimates of aerosol spatio-temporal variability and some caveats are given in the conclusions, it would be good to have a paragraph providing some quantitative information on the known/expected variability within a model pixel, i.e. variability at scales smaller than 10km and 1hour. This is in particular relevant to assess the completeness of the error estimates for in situ measurements.

Unfortunately, we don't know of any beyond what we already mention (e.g. Anderson et al 2003). Since most atmospheric variables show a power law distribution when performing a Fourier analysis in space and time (see also Fig 3, S16b), we suggest that variability below 10 km and 1 hour will typically be smaller than that above 10 km and 1 hour. Undoubtedly exceptions will exist.

Technical comments

Section 2.1,1st sentence seems redundant (basically saying that the simulated fields are those that were simulated)

The sentence reads: "The simulated fields examined in this paper are, for obvious reasons, all observables". It is a slightly trivial sentence but simulated fields are not necessarily observable.

Section 2, more general: are the hourly data hourly averages or hourly snapshots?

They are snapshots, except for the precipitation which are accumulated fields. This will be added to Sect 2.

Page 5,line 10 (about the observational sampling): in reality, the observations don't occur exactly on the x,y,t of the model. Does that matter, and if not, why not?

This is an unavoidable simplification. If the high-resolution runs were at 100 m instead of 10 km, we would be able to position in-situ observations even more accurately compared to the larger area. However, given the large size of the represented area (210 by 210 km2), we expect an error of at most 10 km in the location of an observation to be negligible in impact. See also our answer to the reviewer's third specific suggestion and the expected variation at 10km scales.

Page 5, line 14: temporal collocation can of course also be used when comparing different measurement (e.g. in situ versus satellite, so not only in observation-model comparisons), so the scope of these results is wider than is portrayed in the paper.

Indeed. This is why we tried to avoid mention of model evaluation in the current paper. (Note that the previous paper was titled: "Will a perfect model agree with perfect observations? The impact of spatial sampling"). The representation issue is also (or even doubly) important when comparing different observational datasets.

Section3, more general: why only look at temporal collocation and not spatial collocation? Clouds could also be dealt with using spatial masks instead of temporal collocation. For orography, a spatial mask would be the only solution.

Possibly we misunderstand the question but if that were possible, wouldn't representation errors (after collocation) be zero by definition? We have assumed that the represented area has a fixed size & shape, either because it represents a model gridbox or because of operational considerations (it is possible to identify regions where the field values strongly correlate with the observations, e.g. Piersanti et al. APR 2015. But those regions will vary from day to day and location to location, making this approach unpractical). Note that even the influence of orography is not clear cut, as usually wind-flows combine with orography to cause the representation issues.

Page 7, section 3.4, 1st sentence: Fig. 6 is the first box-whisker plot, not Fig.7

Corrected.

Page 8, section 4, 1st sentence: Maybe add "only" to the beginning of the sentence: "Only the EMEP..."

Agreed.

Section 4 (and subsequent, more general): why this particular choice of 210x210km2? Most current gridded data sets, whether from satellite or model, have better resolution than that.

It shows our interest in model evaluation (most state-of-the-art global aerosol models still run at fairly low resolutions). A typical T63 grid translates into a 210 by 210 km2 box at the equator. Note that we have included analysis of representation errors for smaller areas (and see also S16b for more detail on this), in particular 110 by 110 km2 (1 by 1 degree at the equator).

Page 8, line 9: explain why day-light AOT is lower than average AOT, if known.

Average day-light AOT is only slightly smaller than night-time AOT (few %) for unknown reasons. However, average clear-sky AOT is decidedly smaller than cloudy AOT (mostly due to increased humidity in the cloudy column). Day-light is mentioned in because it is one of two conditions for valid observations. We have replaced 'clear-sky day-light AOT' with 'observable AOT' and added an explanation.

Page 8, line 21: how come? Please explain briefly.

We assume the reviewer would like to know why EMEP shows smaller representation errors than WRF-Chem. We discuss this in S16a in some detail. Briefly, it is impossible to say why without a separate study into why EMEP and WRF-Chem differ in the first place. We noted that magnitudes and spatial patterns agreed nicely, giving us confidence in the use of these models.

Section 5: again, why 210x210?

See before.

Page 8, line 29-30: is it known why cloudy AOT is larger than clear-sky AOT for these regions?

Please see explanation before (the question regarding page 8, line 9).

Page 9, line 12. Although you make it explicit later in the paper (in section 5.3), I think it would be good to state earlier on that the strong effect of temporal sampling/the huge gains with temporal collocation, are all about clouds.

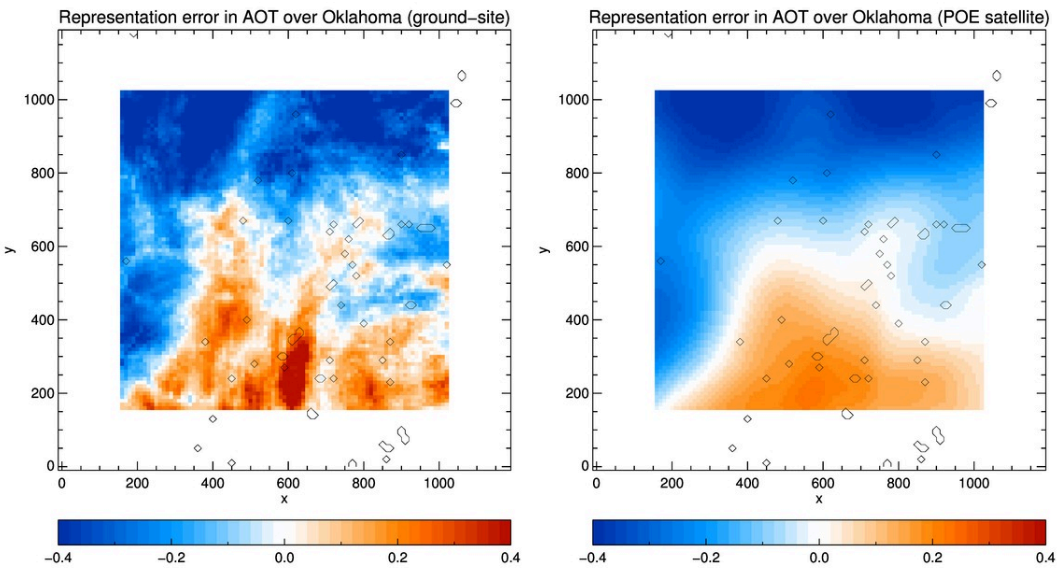
This is true for ground-sites, polar orbiting satellites with short repeat cycles or geo-stationary satellites. But for polar-orbiting satellites with long repeat cycles (e.g. LIDAR), the operational cycle (revisit time) is far more important.

Page 9, line 14: satellites -> satellite

Corrected.

Page 9, line 19: you point out the similar errors between a ground-site and a satellite sounder with a repeat cycle of 1 day. That may be true for the average size of the errors, but the spatio-temporal pattern of those errors should be vastly different, no? The paper contains lots of box-whisker plots summarizing the statistical properties of the representation errors. It would perhaps be nice to see some more maps (like Figs 3 and 4) to be able to judge the spatial patterns of the representation errors. This is to be seen as just a suggestion: if the authors don't see *value in that, they can perhaps just include a statement to explain why no further maps are shown.*

The spatial pattern of those representation errors is somewhat different but not too much. One of our conclusions is that monthly data like L3 suffers mostly from temporal sampling issues (no observations at night time or cloudy skies). This will be fairly similar for a ground-site and a satellite. We show results for Oklahoma below:



We suggest to add one of these figures to the paper, because they show that although overall statistics (box-whisker plots) seem unbiased, strong bias may exist in separate parts of the region.

Page 9, line 32: due to -> obtained after temporal

Agreed.

Page 12, line 16: please explain somewhere what N10 is.

This is now explained in Sect. 2.1: "N10 and N50, number densities for particles with diameters exceeding 10 resp. 50 nm"

Page 14, line 4-5 (Section 9.2). You state: "The number of observations used in constructing monthly averages cannot be used to control representation errors". I don't understand where this conclusion comes from (which probably indicates I misunderstood something earlier on). I can hardly believe this to be correct: surely a monthly average based on a measurement every day of the month will lead to a better estimate of the monthly mean than an average based on just 1 measurement?

While we agree with the reviewer's point point, we wanted to study representation errors in the context of realistically achievable number of observations. The reviewer's example is fairly abstract as both cases seldom occur.

The relevant figure is Fig. 8 that shows monthly representation errors for ground-sites as a function of *required* temporal coverage. *Actual* temporal coverage (or the number of observations) will always be higher and is shown by the black dotted line (right axis). The brown line (left axis) represents representation errors when data are *not* collocated (which is what our statement was about). Note that an increased number of observations *may* reduce representation errors, as is shown for Japan. However, for Oklahoma (and most other regions) this error hardly changes with the number of observations. A combination of strong temporal variation throughout the day, and different spatial sampling of the ground-site and represented area prevents an increasing number of observations to reduce representation errors.

Strictly speaking our statement should have read "Using a minimum required number of observations cannot be relied upon to control representation errors." The text will be changed.