Response to reviewers comments for the AMT article “The pilatus unmanned aircraft system for lower atmospheric research” by de Boer et al. The original reviewers’ comments are in *italics*, and author responses are included in red text.

***Reviewer 1:***

**General Comments:**

The manuscript describes the new unmanned research aircraft Pilatus, which is able to provide measurements of mean thermodynamic quantities, aerosol properties and radiation. The main goal in that study is to demonstrate the aircraft and the different on-board instrumentation, as well as show results from ground and flight tests. This aircraft can be a helpful contribution to improve the understanding of the aerosol properties and their radiative impact. The paper presents a novel system, combining measurements of radiation and aerosol observations on one airborne platform. Relevant scientific questions are listed, regarding these airborne measurements in the lower atmosphere. However they do not investigate these questions extensively here. The introduction of the aircraft is well presented and outlined, however at some points too many details are given. The scientific payload section can be shortened, while more information on the data processing and correction should be added. The technical description is overloaded with too many details and information in some parts (e.g. on the data-acquisition), which makes the section hard to follow and is not suitable for this journal. On the other hand a better description of the aerosol payload is necessary. Parts of details are missing, like the description of the Particle counter, comparison with another ground station or the aerosol inlet system. The inlet system has an important influence on the sampling efficiency and should be discussed in more detail. Further, the particle counter is only referred by one reference (Gao et. al 2015), however this paper is only submitted at this point, hence further information about the particle counter is not accessible to the reader at the moment. In general, data from more test flights would be helpful in order to derive substantial conclusions about the systems’ capability. However, due to the airspace restriction and limited test flights this was not possible. Nevertheless, the first results are promising, that the platform is suitable for atmospheric research. Based on my remarks I would recommend the paper to publication subject to major revisions.

We very much appreciate the constructive criticism provided by this reviewer. We believe that their feedback has led to a substantially-improved paper.

**Specific Comments:**

*Title: Why is pilatus not written in capital letter ?*

This has to do with the typesetting used by AMT/Copernicus. It was capitalized in our LaTeX-produced pdf. We will ensure that it is capitalized in the next version.

*Abstract: l.20: In the manuscript no comparison between airborne system and ground- based instrumentation is presented.*

It is unclear whether this is in response to the statement that we compare with surface-based radiation (line 18) or in response to the statement that previous comparisons have been completed between the aerosol size distributions from POPS and larger surface-based instrumentation (lines 20-22). If the latter, then it is true that these comparisons are not shown in this manuscript (but are shown in the Gao et al. article that is referenced). If the former, then these comparisons are shown as part of this manuscript (figures 6 and 7).

*Introduction:*

*p. 11989 l. 6: Please also refer to Platis et. al , 2015*

The list provided was not meant to be comprehensive, but rather provide a couple of examples. However, we have added the suggested reference to please the reviewer.

*p. 11990 l. 18: Other UAS campaign for aerosol investigation: Altstädter et. al. 2015, Platis et. al 2015.*

Again, the listing of articles on UAS-based aerosol research was not meant to be comprehensive, but we have added the requested references.

*Section 2:*

*General: Some parts of this section can be shorten. I think sometimes there are too many details given, which are not necessary for a reader in that study. E.g.: -p. 11992 l. 13 ff : Turning RotMax 50cc , Microsoft-Windows based, Multistar high capacity Lipo... -Description of the data-acquisition system: p. 11997 l. 20-29: Description is overloaded with too many detailed information about data processing.*

Thank you for pointing this out. We have reworked these sections to remove many additional (and likely unnecessary) details.

*Section 2.1:*

*p. 11991 l. 17 -19: This part is a repetition of the last section of the Introduction.*

We agree and have removed these sentences from the text.

*p. 11992 l. 6: How much payload is the Pilatus able to carry? Why is it substantially heavier than the ALADINA payload. What measurements targets are different? ALADINA measures also aerosol concentrations and thermodynamics.*

The Pilatus can carry up to 5.5 kg of payload. I'm not sure that I understand the question about payload weight… The Pilatus is carrying a broadband radiometric suite to measure net broadband short- or longwave radiation at the height of the aircraft. This is one difference from ALADINA. Secondly, the POPS instrument carried by the Pilatus is not only providing aerosol concentration (as is the case for the particle counters on the ALADINA), but also an aerosol size distribution.

*p. 11993 l. 9f: Skip the sentence: Because no fuel is carried... There is no need to explain that, as well as that the landing weight equals take-off weight.*

This sentence has been removed.

*Section 2.2:*

*General: This section is hard to follow due to its length (6 pages). Please divide this section into smaller subsection for each payload.*

We have reconfigured the section as suggested, and have added additional (sub)subsections for different portions of the section.

*p. 11993 l. 12 – 16. You should skip this paragraph or put it into the introduction*

We appreciate the suggestion, but feel that this paragraph is appropriate here, because it provides justification on why we are carrying the instruments that we are. Since this section describes these instruments, it seems to most naturally fit here. Should the editors agree that it does not belong here, we would reconsider moving this text around.

*p. 11993 l. 4: The down looking sensor is close to the ground surface. Have you experienced any problems when taking off on a dirty/mud runway due to dirt on the dome of the pyranometer?*

To date, all flights have been completed from a concrete runway, and we have not experienced any issues with dirt collection on the dome. This is certainly a consideration that we will need to keep in mind during more remote operations.

*p. 11995 l. 6: What is meant by 50-channel GPS? Is that important to know? Does the INS include a Kalman-Filter or is this done in post-processing?*

50-channel refers to the number of satellites tracked. However, we have removed this, since we believe it to be unnecessary for the average reader and have therefore removed this bit of information. The VectorNav INS does include a Kalman filter which couples position and velocity measurements from the GPS and inertial measurements form the other sensors to provide high accuracy attitude information when the sensor is undergoing dynamic motion.

*p. 11995 l. 10-13: That sentence is not clear to me. What do you mean for correcting for aircraft attitude. Why do you have to correct the aircraft attitude with radiation data? Why does the shading pattern block half of the sky view? I am not a radiation expert, but may be you can make that point more clear to me.*

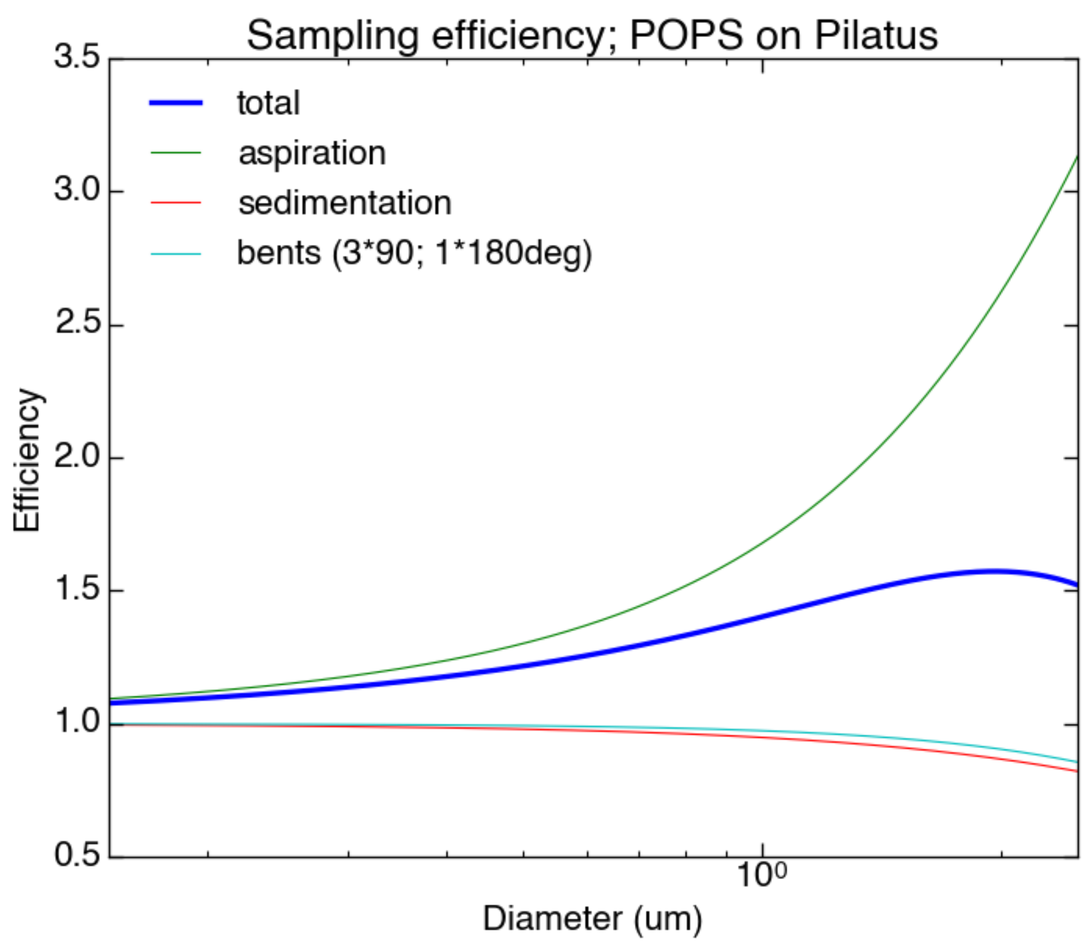
Shortwave radiation measurements are very sensitive to how the sensor is oriented toward the sun (as stated at the beginning of the paragraph). A sensor that is completely perpendicular to the sun will have a higher reading to one that is offset from perpendicular. Therefore, you can introduce variability in the shortwave radiation measurement simply by changing the attitude of the sensor. Since the platform attitude is constantly changing, this needs to be corrected for to get a measurement that is representative of “level” relative to the Earth’s surface. The shading pattern on the SPN-1 allows for simultaneous measurements of the direct and diffuse part of the solar radiation signal, since the pattern ensures that one of the SPN-1 sensor heads is always fully shaded, while at least one other is fully exposed to direct sunlight. This diffuse/direct separation is required in order to correct for attitude as described above. Ultimately, readers seeking more information on this process should go through the Long et al. article that is referenced.

*p. 11996 l. 6: What is the flow rate of air measured by the OPC? Please describe how many particle size channels the OPC has.*

The flow rate of POPS is 3cc/s. POPS does not have size bins. It sizes particles on the individuallevel. Binning was done after flight with an arbitrary number of 100 bins. Text has been added to convey these points to the reader.

*p. 11996 l. 7: How is the tubing constructed? What about the aerosol inlet system (isokenetic, isoaxial?) and sampling efficiency during cruising flight? (You can refer to (Baron and Willeke, 2001))*

We use mainly stainless steal and some smaller section of conductive silicone tubing. The tubing has an inner diameter of 1/16 inch (0.0015875 mm), with an overall length of 65 inches (1.65 m). The inlet has the following bends (approximately): three at 90 degrees, and one at 180 degrees. We use an isoaxial configuration, but it is not isokinetic. As far as the sampling efficiency goes, the figure below shows estimates based on Baron and Willeke. This discussion and figure have been included in the manuscript.




*In general a more detailed presentation of the aerosol particle counter is missing. The particle counter is only referred by one reference (Gao et. al 2015), however this paper is only submitted,* *hence further information about the particle counter is not accessible to the reader at the moment.*

This article has since been published and the reference has been updated. We have added some limited additional details on POPS, but assume that the reader will access the published Gao et al. article for more detailed information.

*Section 3:*

*p. 11998 l. 20-27: Please shorten. I think it is enough if you mention the maximum flight altitude is limited to 122m due to airspace restrictions.*

We disagree that this is the case. Because the regulatory environment requires flights under the COA process, we believe that it is important that we clearly state that we followed that process (and the limitations this imposes) within the body of the manuscript. We did remove one sentence on COAs being the available authorization option, however.

*p. 11999 l.6: May be readers , who haven't worked with INS, get confused with the term "offset characterization".*

We have added some text to hopefully clarify what is meant by offset characterization.

*p. 11999 l.8 : May be you should explain the term "level flight leg". Readers, who haven't worked with flight data, might not know what it means. (Same with non-level flight, non-level configuration).*

We have added the following text: "with nearly "level" (limited pitch and roll) flight" to hopefully clarify what is meant by "level flight leg".

*p. 11999 l.11-25: Does the Kalman-Filter work differently, when using the INS on a car platform compared the more dynamical airborne platform? Did you change the setup of the INS then?*

The VectorNav modifies its filter settings and operation for static versus dynamic conditions. When the sensor is not moving the heading information is not observable from the GPS and the system reverts to using the magnetometer in an Attitude Heading Reference System (AHRS) mode. When the system is moving and the GPS solution is reliable, the filter combines the GPS information with the accelerometers and gyros, but ignores the magnetometer. This is all handled autonomously by the sensor without user intervention. The GPS also aids in the correction of pitch and roll estimates due to induced accelerations due to dynamic motion. Overall, the sensor is more accurate in dynamic environments due to the GPS aided nature of the system.

We did not change the setup for the car versus aircraft platform. Both are dynamic enough to include the GPS aided information. The car environment does not likely require the system to correct for induced accelerations (though it could), but the sensor likely is correcting for induced accelerations while on the aircraft. That said, the most of the useful science was collected in steady level flight, which for all intensive purposes isn't much different than placing the sensors on a car driving in a straight line on a flat road.

*Fig.2: Figures b) and c) are hard to read because they are too small.*

The figure axes were updated and the figure was revised based on comments by the other reviewer.

*Fig.3: Is it possible to include the theoretical value of the shortwave radiation for that location and time as a comparison to the measured value?*
Yes, this theoretical clear-sky value has been included in the figure.

*Section 4:*
*Fig. 4: May be it would be more convenient to plot the potential temperature instead of the absolute temperature for indication of the mixed layer.*
We have plotted potential temperature, as suggested, and updated the text to reflect these changes.

*Fig. 5. The closed circle can hardly be distinguished from the thick line.*
We have increased the size of the circles.

*Fig. 6 and p. 12002 21 – p.12003 l. 4: It would be interesting to see a plot of roll angle compared to the down-welling shortwave signal, in order to see if both signals correlate or not. I did not understand if the periodic variations in the signal is only due to surface and cloud features or also due to the aircraft motion itself. (You refer to that also in the summary. There it is more clear to me.)*
The total tilt angle and the downwelling shortwave signal are already plotted together in figure 8. There is a clear correlation between the two, with high tilt angles showing increased downwelling shortwave, and negative tilt angles showing lower downwelling shortwave. The periodic variations in the signal in figure 6 are due to both cloud cover as well as the aircraft motion. We have updated the text to include the line: "The limited flight area, in combination with the relatively slow response time of the CGR-4 (18 s at 95 % response, 6 s at 63 % response), results in a periodic oscillation of the signal in both the down- and upwelling longwave radiation measured during these flights. "

*Fig. 7: Figure is hard to read. I suggest splitting the figure into 3 sub-figures for Down, Net and Up.*
We believe that splitting the figure up is unnecessary and would cause additional confusion. We have decreased the thickness of the lines representing the NREL data, which should make the figure somewhat easier to read. The bottom line is that shortwave radiation data on a partly cloudy day can be very variable and messy to plot.

*p.12003 l. 7-10. The authors state that the radiation measurements "agree reasonably" with a nearby reference station. More details on this comparison should be provided. The errors resulting from the aircraft movement in combination with possible cloud coverage and terrain features are the key point in assessing the feasibility of the presented approach. More comparisons with reliable radiation measurements should be provided to substantiate the claim of reasonable agreement.*

It is true that we could do a more thorough evaluation of the radiation measurements. However, it is important to note that the reason the radiation payload is as heavy as it is is because we are flying high-quality, research-grade broadband radiometers. In fact, the sensors that we are flying are the same instrument that we would compare to if we were to perform additional comparisons with "reliable radiation measurements" as suggested. Therefore, the instruments themselves do not necessarily need to be tested further. There is of course the question of the impact of aircraft movement and the limits associated with correcting for this. Of course, we do not have radiation instrumentation set up at our local airfield where we are allowed to operate the aircraft, and can not fly over areas where such sensors are available making a more direct comparison challenging. There will be opportunities to do such comparisons when the aircraft flies at the Oliktok Point facility in Barrow later this year, and we plan to do so. For the time being, the point that we were trying to make is that the measurements provided by the aircraft are in the same range as those collected at the surface from a nearby (12 km distance) site using reliable instrumentation.

*p.12003 l.15-24. This paragraph sounds more like methods and should be place in Section 3.*
We reworded this section and believe it is now appropriate for the flight results section.

*Summary:*
*p.12006 l. 20-p.12007 l.23: This paragraph sounds more like a very detailed outlook than like a summary. In general, I think that this outlook is far too detailed and is very speculative. For example, the sentence "Similarly, continued advancement in battery technology will allow the current aircraft to extend its mission time over the coming years" is purely speculative. The LiPo batteries used in this work are the current state of the art and have been so for some years now. Additionally, the authors want to deploy the aircraft in the arctic, where the low air temperature will limit the performance of the batteries.*
We do not believe that it is necessarily a bad thing to have some outlook with the summary section. We have retitled that section to "summary and outlook". Beyond the statement about battery technology, there is very little speculation in these paragraphs, and we are therefore a bit confused by the reviewer's criticism. Undoubtedly, people will want to know why this plane was built in the first place, and this section sheds light onto this. We have removed the statement about battery technology (although we do firmly believe that batteries will continue to advance to extend flight duration…).

*Technical Corrections:*
*p. 11989 l. 2:. has has... remove one has*
The extra "has" has been removed.

*p. 12001 l. 13: change to boundary-layer temperatures*
Done…
*p. 11992 l. 22: ...and sold by ICARE... I think this information is not really necessary for the readers.*
This has been removed from the text.

*References:*

*Altstädter, B., Platis, A., Wehner, B., Scholtz, A., Wildmann, N., Hermann, M., Käthner, R., Baars, H., Bange, J., and Lampert, A.: ALADINA – an unmanned research aircraft for observing vertical and horizontal distributions of ultrafine particles within the atmospheric boundary layer, Atmos. Meas. Tech., 8, 1627–1639, doi:10.5194/amt-8-1627-2015, 2015. 11992*

*Gao, R.-S., Telg, H., McLaughlin, R., Ciciora, S., Watts, L., Richardson, M., Schwarz, J., Per- ring, A., Thornberry, T., Rollins, A., Markovic, M., Bates, T., Johnson, J., and Fahey, D.: A light-weight, high-sensitivity particle spectrometer for PM 2.5 aerosol measurements, Atmos. Science. Technol., submitted, 2015. 11996, 12005*

*Platis, A.; Altstädter, B.; Wehner, B.; Wildmann, N.; Lampert, A.; Hermann, M.; Birmili, W. & Bange, J. An Observational Case Study on the Influence of Atmospheric Boundary-Layer Dynamics on New Particle Formation Boundary-Layer Meteorology, Springer Netherlands, 2015, 1-26*

These references are now included in the manuscript…

***Reviewer 2:***

**General Comments:**

The manuscript describes a new remotely piloted aircraft system (Pilatus) developed by the University of Colorado. It is an electrically powered fixed wing airframe with a wingspan of 3.2 m and a maximum take-off weight of 25 kg. The described system has been developed with a focus on atmospheric radiation (longwave and shortwave) and aerosols, but is also able to provide measurement of the mean thermodynamic parameters temperature, pressure and humidity, while wind measurements are obviously absent. The paper presents sensors and system development in great detail before shortly presenting the results of a few car-based (IMU) test measurements and a few hours of test flights during one day. The motivation for the development and scientific questions to be addressed in the future are mentioned, but of course not worked on within this limited data set from the test flights. In my opinion this paper shows a clear progress in the use of unmanned systems toward radiation and aerosol measurements, with a particular potential for applications in polar regions with limited infrastructure and harsh environmental conditions, although it will be interesting to see how it really will work out in low temperatures. My main criticism for the manuscript is the inconsistency (e.g. label size and style; line thickness) in the presented figures and the poor quality of several of them that make it difficult to follow the argumentation and conclusions of the authors. I will give detailed comments on this at the end of my specific comments. Overall I suggest this paper for publication after revisions.

Another general question to raise (that might also be shortly included somewhere in the manuscript) is if it is worth to deal with all the angular correction hassle for the radiation measurements by using a fixed wing aircraft while it seems to be much easier to use a rotary wing airframe, potentially in combination with a gimbal system for that purpose.

We very much appreciate the reviewer's comments and believe that they will result in a greatly improved manuscript. We agree that we should edit the figures to result in a better presentation and have done so in our revision. In regard to the question about using a fixed-wing platform vs.

a rotary wing platform, there are a couple of reasons why the fixed-wing platform is beneficial. First, this platform can cover a much greater area spatially, as it moves at ~50 knots vs. substantially lower speeds for multirotor systems. Secondly, there are very few multirotors that are large enough to provide the capacity necessary to carry the instrumentation as outlined here. For example, the SPN-1 payload consists of 3-4 kg of instrumentation in addition to the batteries required. This amount of weight, particularly if a gimbal system is also included, would really put a dent in multirotor endurance and it is unlikely that such a system would be able to cover the altitude ranges that the current platform can, since the benefit of wing lift would be lost in the return to Earth. Overall, we don't believe that this information needs to be included in the manuscript, but would be open to additional input from the editorial staff if they felt it would strongly enhance the paper.

**Specific comments:**

*p.11993, line 26: "sensor response time of approximately 0.4 s" for which temperature is this response time valid; in my experience the response time of temperature sensors has also a temperature dependency, although usually not as distinct as for the humidity*

This is a good point – the response time of the temperature sensor is likely impacted by the ambient temperature. Since this has not been fully characterized, we have removed the references to response times in the paper. We have completed some chamber-based response time testing for other UAS sensors, but not for this Vaisala sensor specifically, and therefore decided to remove the response time information.

*p.12000, line 24 and figure 4: are the profiles consequently taken from either ascending or descending profiles and in which average vertical velocity of the aircraft, or is it a mixture or a completely different flight pattern? would be important to know for the interpretation of the data and their variability*

It is fair to say that the flight pattern was not set up specifically for profiling. The profiles presented are distributions across all altitude ranges covered incorporating both the ascending and descending portions of flight. There was substantially more time spent around the top of the profile than between the surface and 100 m. Particularly the lowest 30-40 meters should be treated carefully as these were in the initial take off and final approach portions of the flight and therefore only include a very limited amount of sampling time. This is somewhat evident by the increased variability in the RH estimates from the lowest 40 m of flight. The text has been updated to provide some additional details on what the profiles represent.

*p. 12003: how is tilt defined; as deviation from the vertical and therefore a combination of the pitch and roll angles of the aircraft? Obviously only the shortwave radiation data are tilt corrected, as there is no IMU flown together with the pyrgeometers? Do you have an estimate which level of uncertainty that can add to your longwave radiation measurements? this issue should be mentioned/discussed*

Tilt is defined from zenith, regardless of direction, so it does indeed involve a combination of both pitch and roll. And yes, it is correct that there is no "tilt correction" for the pyrgeometers. The tilt correction is to account primarily for the direct component of the total shortwave measurement, with the assumption that the diffuse is largely unaffected for "modest" tilt,

which in our case is defined as 10 degrees of tilt or less. The longwave by definition is an emission regime, not a transmissivity and scattering regime as for the shortwave. Therefore, there is no "direct component" to the longwave to which to apply the tilt correction. So given our 10 degrees of tilt limit, the longwave is largely unaffected by this "modest tilt" as is the case for the diffuse component of the shortwave.
We do not have an estimate of uncertainty for the longwave beyond what is provided by the manufacturer of the instrumentation (Kipp and Zonen), who provide a window heating offset estimate of <4 W/m2, and small (<1%) dependence on temperature and non-linearity of the system.

*p. 12004, line 8: ". . ..by the time of the second flight"; in figure 10 it is flight 4?*
Yes, sorry – this was confusing. There were two SPN-1 flights, but these were flights 1 and flights 4 overall. We have gone through the text to update references to match the actual flight number, rather than using "first, second, etc.".

*p. 12004, line 26: replace "from the first and the second flight" by "from the first to the second flight"*
This has been corrected.

*p. 12005, description of figure 10: have all flights along the race track pattern shown been made in the same direction (clockwise/counterclockwise) or was there a switch in between different flights*
All flights were completed in the same direction (counterclockwise). This has been added to the first paragraph in this section.

*comments on figures:*
*figure 2: labels in b) and c) by far too small; I also see plot b) as very little informative, a terrain profile or the values of the local slope along the track would fit much better. I think you should even combine that with panel c), by plotting everything against the x-axis that should be the along-track distance*
The figure was updated as requested.

*figure 3: I would like to see a zoom-in on one of the tracks to see a bit more of the detail structure in the measurements. This could be done as inset or as separate panel side by side*
An inset has been added, as requested.

*figure 5: the closed circle for the mean cannot be distinguished from the interquartile range; please modify*
We have increased the size of the circles.

*figures 6 and 7: labels (and potentially also line thickness) too massive*
The labels have been resized to size 10, regular weight font. Additionally, the line thicknesses have been reduced.

*figure9: too small to follow the relevant information; maybe better to have two panels on top of each other?; labels can also be shrinked a bit*

The labels have been resized to size 10, regular weight font. Additionally, the lines have been decreased to 1 pt weight. We kept them side-by-side, as the y-axis is shared between the two figures, whereas the x-axis is not.

*figure 10: too big labels, too small figures*

The labels have been resized to size 10, regular weight font, and the figures have been adjusted to fill the remainder of the space. Additionally, we moved the colorbar to the bottom to increase the size of the figures.