ACP-2019-136 – Reply to Referee #2

Jörg Burdanowitz, Stefan A. Buehler, Stephan Bakan and Christian Klepp

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E-mail address: joerg.burdanowitz@uni-hamburg.de

In the following answer we proceed as follows. Text from Referee #2 is shown in *italic*, our answer in **bold** and changes in the manuscript are highlighted in blue.

This paper uses high-temporal resolution precipitation and SST observations over the ocean to describe the relationship between SSTs and precipitation. Overall the paper is scientifically sound with only minor clarifications needed. It is well organized, but needs corrected for several grammar or English mistakes. The content is useful to ACP readers because the observational work may help the community understand how precipitation could possibly change under global warming. Also, from a mechanistic perspective it is important to know how precipitation changes with SSTs. Below are specific minor comments.

First of all, we would like to thank Referee #2 for taking the time to review our draft and making suggestions to improve it. We appreciate the critical points raised by the referee and hope to be able to resolve these issues.

Specific minor comments:

1) Can the authors comment on the consequences of ignoring the warm-layer effect? Since the results of the paper are highly dependent on correctly getting SST, it would be useful to know how important the warm-layer affect is. Perhaps there are other papers that have assessed the warm-layer affect that the authors can cite.

Unlike the cool-skin effect, the warm-layer effect on the SST is

not considered explicitly in OceanRAIN because most ships lack providing continuous measurements of the surface radiation budget. Instead, OceanRAIN contains a warm-layer flag (WLF) that indicates the quality of the derived SST product. According to this WLF [Klepp et al., 2018], only less than 9% of all raining cases might be affected by a warm layer (wind speeds <6 m/s and global radiation >50 W/m or wind speeds <2 m/s). We added this information to the manuscript as follows: "However, according to the OceanRAIN warm-layer flag (Klepp et al., 2018), less than 9 % of all cases with precipitation could be affected by a warm layer.**". To illustrate this a bit better, please have a look at the relative distribution of the absolute wind speed in OceanRAIN (Fig. 1). The maximum occurrence is reached well above 6 m/s. Nevertheless, in some regions with constantly low wind speeds and strong global radiation, strong warm layers can develop. Assuming a wind speed of about 2 m/s, [Fairall et al., 1996] found warm-layer temperature differences of 1 to 2 K between morning and afternoon peak SST. Considering these values (about 2 K) and their occurrence (about 9% of time) for our calculated precipitation scaling results in precipitation rates underestimated by less than 2% per SST bin for the 99th percentile. For OceanRAIN this lies below the uncertainty introduced by limited sampling. More evidence on how the warm-layer effect influences the precipitation scaling could be gained through a case study which, however, goes beyond the scope of this study.**

2) Were other omega ranges explored besides those shown in Fig. 5 and 6? It wasn't clear how the ranges shown were chosen. Perhaps the authors could elaborate on the choice of omega ranges.

Yes, we tested different omega ranges. The ones shown in Fig. 5 and 6 we chose as a compromise of a decent sample size per bin (N) and an omega sufficiently different from 0. This means, when moving towards "extremely" low omega values the P-scaling increases but the sample size no longer suffices to be able to calculate the P percentiles for all or at least most of the SST bins. To circumvent this issue, we also tried to increase the bin size but this did not lead to satisfying improvements. Furthermore, the "extremely" low omega values are a bit misleading because they are valid for grid sizes of about 30 km for about an hour. However, these strong vertical movements are usually strongly limited

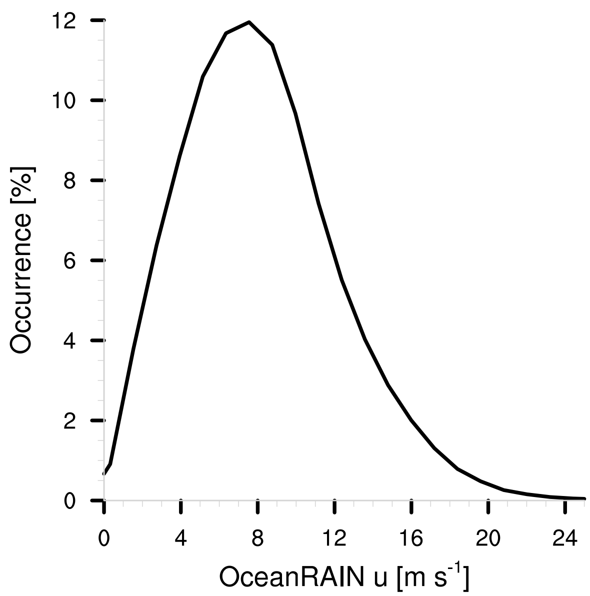

Figure 1: Relative occurrence of absolute wind speed u from all OceanRAIN cases (P $\geq$ 0).

in time and space, which makes it very challenging to match them with point measurements on moving ships. Having the above mentioned points in mind, we believe that the chosen thresholds are a good compromise to consider sample size and point-to-area differences while getting a sufficiently large signal from negative omega values (i.e. rising motion). To reflect this in the manuscript, we added the following sentence: "This range represents a good compromise between a clear signal of rising motion and a sufficiently large size of remaining OceanRAIN samples.**".**

3) The local minimum in precipitation scaling at 26 °C is mentioned in the abstract and summary section, but is not discussed in the results section of the text until section 3.4 where it is abstractly referred to (i.e., not explicitly referred to as a minimum at 26 °C, rather referred to as a drop-off in precipitation scaling at high temperatures). I think this minimum at 26 °C refers to the dip seen in Fig. 2b, but could the authors clarify what that dip refers to and discuss it in sections 3.2 or 3.3.

First of all, we thank the referee for pointing to an insufficiently

explained conclusion. However, the "drop-off" mentioned in Section 3.4 refers exclusively to the precipitation scaling over land that usually increases until a certain temperature and then drops off due to decreasing precipitation event duration with temperature (e.g., [Haerter et al., 2010], [Utsumi et al., 2011]). To test whether this holds true over ocean, we consider the precipitation event duration t_E from OceanRAIN. In contrast to land-based data, t_E does not decrease with temperature. Accordingly, this supports our observation (Fig. 2a and 2b) that does not show a "drop-off" in the precipitation scaling as over land. However, we agree that the local minimum at 26 °C in ERA5 (Fig. 2b) is apparent. To mention this earlier in the manuscript we added a sentence when Fig. 2 is first mentioned and slightly modified the subsequent sentence as follows. "Precipitation in ERA5 reveals a local minimum at about 26 °C, which we will discuss later. Altogether ERA5 shows a much lower P-scaling compared to OceanRAIN with values of [...]**". Although we are not entirely sure what explicitly causes this local minimum, we would like to make some reasonable assumptions. First, the SST is not the only trigger for precipitation. To some extent, regions play a role in which precipitation is positively or not at all correlated with SST (i.e. precipitation increases or remains constant with decreasing SST). This can be seen in Fig. A1b (appendix) that shows a less pronounced minimum at 26 °C including these regions compared to Fig. A1a, which does not include these regions. Second, conditions of negative omega values (i.e. rising motion) are not favorable for the precipitation minimum at about 26 °C. Therefore, we would argue that the minimum might be caused by atmospheric conditions under which precipitation formation is suppressed, commonly observed over relatively low SST regions in the subtropics (bluish areas in Fig. 3a). However, more detailed investigations of the omega profile over the whole atmospheric column could shed more light on this issue. We incorporated these thoughts into Section 3.3, which reads now as follows: "**Constraining ω_{500} to rising motion strongly reduces the local minimum at about 26 °C in Fig. 2b (see Fig. 6a). From this and areas of weak or positive correlation between SST and precipitation (Fig. 3 and Fig. A1), we suppose that atmospheric conditions of weak ω_{500} contribute to the local minimum at 26 °C in ERA5. It might therefore seem natural that suppressed dynamical drivers of precipitation, predominantly in the subtropics, could generate this local minimum in precipitation intensity. Proving this assumption, however, goes beyond the scope of this work.**". Finally, we would like to emphasize that it remains unclear whether this precipitation minimum points at a deficiency in ERA5 or represents a feature that is not visible in OceanRAIN due to the limited and inhomogeneous sampling. We added the following sentence to the conclusions and modified the subsequent sentence. "**However, it remains open whether this minimum reveals a deficiency in ERA5 – e.g. by suppressing precipitation formation too strongly in the subtropics – or whether this minimum has not yet become visible in OceanRAIN due to limited sampling. The data sampling density plays a crucial role in precipitation-sparse regions that would need the longest sampling to be well represented.**".**

4) On page 13, the sentence beginning with "Accordingly, constraining to lower omega 500..." needs clarified. Constraining the lower limit in the omega 500 ranges?
We agree that the sentence was not clear enough and thank the referee for bringing this to our attention. We meant that a shift of the omega range towards lower values has hardly any influence on the P-scaling of the higher percentiles. Only the P-scaling of the lower percentiles increases. The sentence now reads: "Accordingly, the shift of the range of ω_{500} toward lower values (rising motion) tends to equalize the P-scaling at different P percentiles. This mainly results from an increase in P-scaling at lower percentiles, while the P-scaling remains approximately constant for high percentiles.**".**

5) On page 15, in the summary/conclusions section the sentence beginning with "Unlike over land due to moisture..." needs clarified. I don't know what the authors mean by "we find no decreasing precipitation rates over temperature ranges of more than 8 K" What figure does this refer to? I'm not sure where this conclusion comes from or what it means.
We thank the referee for drawing our attention to this unclear sentence. The first part of the sentence "Unlike over land due to moisture limitations" refers to previous studies over land that found a clear drop-off of the P-scaling at a certain temperature, typically above 20 °C. According to e.g., [Hardwick Jones et al., 2010], this drop-off is caused by the lack of available moisture needed to fuel precipitation formation. However, lack of moisture over the ocean is not to be expected. [Drobinski et al., 2016] explain the drop-off (they call it "hook shape") by the lifted level of condensation coin-

ciding with higher surface temperatures in a dry environment. We added these thoughts to the manuscript as a possible explanation: "In contrast to studies over land, we find no "hook shape" (Drobinski et al., 2016) or clear drop-off (Hardwick Jones et al., 2010) of precipitation over the ocean towards high SSTs. Drobinski et al. (2016) explain the "hook shape" by the lifted level of condensation under higher surface temperatures in a dry environment. **With the threshold of 8 K in** "[...] we find no decreasing precipitation rates over temperature ranges of more than 8 K (Fig. 2) "**, we meant to emphasize that we also find decreasing precipitation with increasing SST but only over very limited SST ranges. The dip in the ERA5 precipitation is discussed separately. We adapted the text so that it more clearly reflects the precipitation curve at high SSTs for OceanRAIN. (mainly Fig. 2)** "Instead, despite the variability in OceanRAIN, we find a continuous increase in OceanRAIN precipitation with increasing SST, including the highest SSTs."

Technical comments:

1) P-scaling needs defined a precipitation-scaling (P-scaling)

We note that we missed to properly introduce the variable P for precipitation rate in the text. P appears first in Table 1. Therefore, we introduce P in the first sentence of the subsection "Methods" (see comment 3). The P-scaling is properly introduced in the following sentence: "Second, for each of the percentiles, we calculate the slope using two linear regression methods in order to derive the precipitation scaling (P-scaling).**".**

2) English needs cleaned up. One example is on page 2, 2nd paragraph that starts with "As a reason.." "As a reason" is an awkward phrase. Also, saying "Then, first, we investigate" is awkward. Just say "First, we.." Another example is page 12 where the authors say "Its influence..." "Its" is an ambiguous pronoun that needs clarified

We thank the reviewer for the suggestions to improve the English. On page 2 we replaced "As a reason" with "As a consequence**". We omitted "Then" and replaced "Its influence" by "**The influence of these weakly correlated areas on the whole ERA5 dataset is shown in Appendix A1.**".**

3) The authors say the "standard way to calculate the sensitivity of precipitation to a change in SST..." Are there references backing up this standard method?

We added the reference of [Lenderink and van Meijgaard, 2008] that are one of the first who used SST binning to estimate the precipitation scaling. The text now reads "A standard way to calculate the sensitivity of precipitation to a change in SST is to divide the precipitation rate (P) into SST bins (e.g., Lenderink and van Meijgaard, 2008). For each of the 1 °C bins, percentiles of precipitation rate can be calculated.**".**

4) The grey lines in Figs. 2, 5, and 6 are very hard to see

We kindly acknowledge the comment of the referee. We are aware that the lines are a bit pale but the idea is that they guide the eye of the reader. In panels a,b,e and f they refer to the 7%/K P-scaling while they "extend" the y-axis ticks in panels c and d. We did not make them black or bold to not distract too much from the actual content of the panels. Overall, the grey lines are not necessary to understand the Figure.

5) On Fig. 2c maybe the authors could add a line indicating the 1000 min threshold. The authors say on page 8 that there are several bins with less than 1000 min, but it only looks like the last bin is less than 1000.

Originally, we had highlighted the same line of N=100 in 2c and 2d as in Fig. 5c and 5d (see your comment 6). However, we decided to only show 100 as the minimum on the y-axis. We do not want to show an orange line for N=1000 (inconsistent with Fig. 5c,d). Nevertheless, we corrected the mistake in the text, spotted by the referee. We replaced "1000" by "10,000**". Please note that this is not a specific threshold that we chose but more of a marker for orientation to spot bins of lower robustness in panel c.**

6) Fig. 5, what does the yellow line in c and d represent?

The orange line in Fig. 5c and 5e marks the threshold of 100 samples/minutes of data under which no 99th percentile can be calculated. It was meant as a kind of orientation mark for the reader to note where the results are less robust. We added the following sentence to the caption of Fig. 5: "Orange line in (**c**) and (**d**) marks the lowest N for which P_{99} can be calculated.**".**

References

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