# ACP-2019-136 – Reply to Referee #1

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

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In the following answer we proceed as follows. Text from Referee #1 is shown in *italic*, our answer in **bold** and changes in the manuscript are highlighted in blue.

*Overall I felt the paper read well (barring a few issues noted below). The topic is timely and of great interest to a wide user/research community. Although there were a few minor issues, I believe that the paper is broadly acceptable as is.*
**We would like to express our gratitude to Referee #1 for taking the time to review our manuscript and, in particular, for putting so much time and effort in improving the language and the clarity. We really appreciate that. We reply to some of the comments in more detail while we accepted almost all the suggestions to improve the language in the text (marked with "Done."). New or updated sentences are given in blue inside quotation marks. Please also consider the marked-up version made with *latexdiff*.**

## Minor corrections/suggestions:

*P1, L6: replace 'to constrain' with 'the constraint of the'.*
**Done.**

*P1, L11: should there be 'decreasing' or 'increasing' before 'SST'?*
**We meant 'increasing' SST and added this in the text.**

*P1, L15: wording, perhaps 'Overall, high resolutions in observations and climate models...'*

**Done.**

*P1, L19/20: omit 'and rises'*
**Done.**

*P2, L6: insert 'there is' before 'medium' and omit 'is found'*
**Done.**

*P2, L7: replace 'On' with 'At' and 'scale' with 'scales'*
**Done.**

*P2, L32: omit first 'different'*
**Done.**

*P3, L1: replace 'Forth' with 'Fourth'*
**Done.**

*P3, L14: perhaps insert ':' after 'charge' and replace 'on' with 'at'*
**Done.**

*P3, L16: insert 'caused' after 'volume'*
**Done.**

*P3, L28: wording/clarification of date range of data – since currently it states 2010-2016, then back to 1950 to the present (which includes 2010-2016!).*
**We agree that the wording is a bit misleading here. What we meant is that the ERA5 data was first released in July 2017 only for 2010-2016. Few months later, they released the period 1979-2010 and 2016 to 3 months from present while 1950-1979 is planned for late 2019 (source: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). We modified the text as follows: "**Released in July 2017, the data provided hourly analyses and forecast fields at a spatial resolution of globally 31 km for the period of 2010 to 2016, which has been extended back to 1979 until three months to present (Hersbach and Dee, 2016)**".**

*P3, L30: should 'sst' and 'tp' be in parentheses?*
**Yes, we put them in parentheses.**

*P4, L2: remove ',' after 'SST is' (perhaps), replace 'by' with 'in' and 'steps' with 'increments'*
**Done.**

*P4, L4: replace 'from' with 'for' and omit 'well'*
**Done.**

*P4, L6: replace 'As' with 'Since'*
**Done.**

*P4, L7: insert 'also' after 'we'*
**Done.**

*P4, L8: omit 'as well'*
**Done.**

*P4, L14: first sentence is perhaps a little simplistic. Needs to be reworded ('according to' is an odd term) – perhaps 'Oceanic precipitation forms as a consequence of the global atmospheric circulation systems' – not quite, but better.*
**We modified the sentence as follows: "**Oceanic precipitation is driven by the global atmospheric circulation systems.**".**

*P4, L15: replace 'A sufficient' with 'Sufficient' – and again on line 17.*
**Done.**

*P4, L17: insert 'is possible' after 'sampling'.*
**Done.**

*P5: It would be useful to know the total number of observations – not just the raining ones. (this also relates to the 'sparse sampling' mentioned on P6 L11.*
**Thank you for that remark. The number is already mentioned in the caption of Tab. 1 but we agree that this can be overlooked easily. We added this number of observations to the main text that reads: "**The global-ocean operation of RVs used in OceanRAIN ($5.396 \cdot 10^6$ min in total; $0.473 \cdot 10^6$ min with precipitation) suggests sufficient spatial sampling is possible.**".**

*P6, L1: 'ice drift' or 'drifting ice'?*

**Thank you for the question. We meant drifting (sea) ice and changed the text accordingly.**

*P6, L9: replace 'Minimal' with 'Minimum'*
**Done.**

*P6, L10: perhaps replace 'spare sampling' with 'low occurrence'?*
**We would like to keep "sparse sampling" since "low occurrence" would imply that precipitation has a low occurrence while we mean the (low) data sampling density of OceanRAIN at some locations.**

*P6, L21: replace 'follows' with 'shows', 'to increase with' with 'of increasing'*
**Done.**

*P6, L22: replace 'grows' with 'increases'*
**Done.**

*P7: would be useful to have a larger gap between the upper and lower parts of the figures. Do the 'grey lines' noted in the caption only apply to (e) and (f)?*
**The gap between which panels do you mean? The space between a)/b) and c)/d) is small on purpose because upper and mid panels share the same x-axis labels (SST) and tickmarks. The 'grey lines' refer to both a)/b) and e)/f) but we see that it is not clear enough (e.g. panels c/d also have grey lines). Therefore, we moved the following sentence to the description of panels a/b and added the word "slope": "**Grey lines indicate 7% $K^{-1}$ slope**". In e)/f) the 7% $K^{-1}$ line is trivial.**

*P10, L8/9: mentioned here and elsewhere – the vertical velocities <100 hPa day$^{-1}$ – might be useful to provide a general (short) background on this at some stage.*
**We follow the referee's suggestion and add the following clarification:** "Negative $\omega_{500}$ values correspond to rising motion." **(P10, L8). In the following sentence we add the term** "absolute" **as we meant absolute vertical velocities $|\omega|$ which was unclear before. The sentence now reads** "Almost two thirds of the global-ocean ERA5 timesteps during July 2010, as an example, have absolute vertical velocities $|\omega_{500}|$ below 100 hPa day$^{-1}$ (Fig. 4a).**".**

*P11, L8: replace 'enough' with 'sufficient'*
**Done.**

*P12, L1: insert 'that are' before 'mainly'*
**Done.**

*P12, L6: remove 'that' after 'sample' and replace 'contains' with 'that contain', and replace 'rates' with 'values'.*
**Done.**

*P12, L10: replace 'about' with 'approximate'*
**Done.**

*P14: I was a little surprised by this figure and the precipitation timescales: surely at mid-latitudes the precipitation events would be relatively long given the size of the precipitation systems?*
**There are two aspects to be considered. First, the latitudinal precipitation distribution, as we imagine it, is mainly driven by precipitation accumulation while the precipitation event duration is driven by the precipitation occurrence and the way how precipitation is organized. In their Figure 3, [Klepp et al., 2018] show that in the inner tropics precipitation rates above 5 mm/h contribute by 76% to accumulation while precipitation rates below 0.5 mm/h contribute by 57% to the occurrence. This means, even in the inner tropics, light rain dominates the precipitation occurrence and thus, most of the precipitation events. In the mid-latitudes, they find similar values for the occurrence as in the inner tropics. However, we assume most precipitation events to be linked to frontal passages. In particular, cold fronts and post-frontal convection lead to rather small but intense, short-lasting showers. In our Figure 7b, the minimum in mean precipitation event duration is mainly driven by the minimum in the higher percentiles (99th and 99.9th), i.e. precipitation events that last longer than an hour. To clarify this in the text, we modified the text as follows: "**The shortest mean precipitation event duration occurs at 15 °C while the longest mean precipitation event duration occurs around 2 and above 28 °C. The mean is mainly driven by the highest percentiles (99th to 99.9th exceeding 2 h) that mainly cause the minimum at 15 °C but it is less pronounced for the 50th to 75th percentile where precipitation event duration remains about constant

(Fig. 7b)**". This relative minimum in precipitation event duration seems plausible to us but nevertheless we cannot rule out that this is a sampling artifact as the very long-lasting precipitation events occur the least. To reflect this in the text, we complemented the sentence "**Nevertheless, heterogeneous spatial sampling by the ships can lead to a biased picture (see Fig. 3 in [Burdanowitz et al., 2018]); e.g. the Eastern Atlantic has been more densely sampled compared to the Western Atlantic**" by "**which might have an effect on the occurrence of very long-lasting precipitation events**". Second, please note that a precipitation event here is defined as the number of consecutive minutes with precipitation whereas one minute of no-precipitation suffices to end an "event" and, perhaps, be followed by the next event thereafter. In other datasets with 10-min or even 60-min resolution, these gaps of few minutes without precipitation would vanish and events would seem to last longer than they actually do.**

*P15, L7: '2000 bin-1' – presumably '2000 samples per bin'?*

**Yes, we followed your suggestion and changed the text to "**2000 samples per bin**".**

*P16, L25: insert 'us' after 'allow'*

**Done.**

*P16, L34: replace 'resolution is' with 'resolutions are'*

**Done.**

## References

[Burdanowitz et al., 2018] Burdanowitz, J., Klepp, C., Bakan, S., and Buehler, S. A. (2018). Towards an along-track validation of hoaps precipitation using oceanrain optical disdrometer data over the atlantic ocean. *Quarterly Journal of the Royal Meteorological Society*, 144(S1):235–254.

[Klepp et al., 2018] Klepp, C., Michel, S., Protat, A., Burdanowitz, J., Albern, N., Kähnert, M., Dahl, A., Louf, V., Bakan, S., and Buehler, S. (2018). OceanRAIN, a new in-situ shipboard global ocean surface-reference dataset of all water cycle components. *Scientific Data*, (5):180122.

# ACP-2019-136 – Reply to Referee #2

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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**

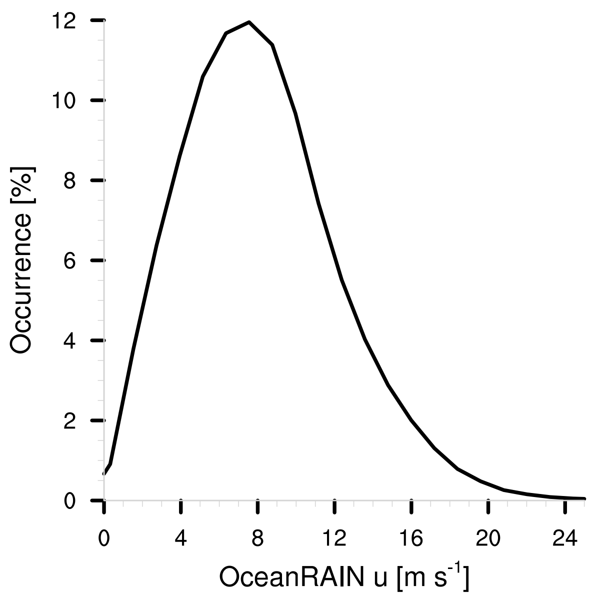


Figure 1: Relative occurrence of absolute wind speed $u$ from all OceanRAIN cases (P $\geq$ 0).

**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 $\omega_{500}$ 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 $\omega_{500}$ 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 $\omega_{500}$ 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

[Drobinski et al., 2016] Drobinski, P., Alonzo, B., Bastin, S., Silva, N. D., and Muller, C. (2016). Scaling of precipitation extremes with temperature in the french mediterranean region: What explains the hook shape? *Journal of Geophysical Research: Atmospheres*, 121(7):3100–3119.

[Fairall et al., 1996] Fairall, C. W., Bradley, E. F., Godfrey, J. S., Wick, G. A., Edson, J. B., and Young, G. S. (1996). Coolskin and warm-layer effects on sea surface temperature. *Journal of Geophysical Research: Oceans*, 101(C1):1295–1308.

[Haerter et al., 2010] Haerter, J. O., Berg, P., and Hagemann, S. (2010). Heavy rain intensity distributions on varying time scales and at different temperatures. *Journal of Geophysical Research: Atmospheres*, 115(D17):D17102.

[Hardwick Jones et al., 2010] Hardwick Jones, R., Westra, S., and Sharma, A. (2010). Observed relationships between extreme sub-daily precipitation, surface temperature, and relative humidity. *Geophysical Research Letters*, 37(22):L22805.

[Klepp et al., 2018] Klepp, C., Michel, S., Protat, A., Burdanowitz, J., Albern, N., Kähnert, M., Dahl, A., Louf, V., Bakan, S., and Buehler, S. (2018). OceanRAIN, a new in-situ shipboard global ocean surface-reference dataset of all water cycle components. *Scientific Data*, (5):180122.

[Lenderink and van Meijgaard, 2008] Lenderink, G. and van Meijgaard, E. (2008). Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nature Geoscience*, 1:511.

[Utsumi et al., 2011] Utsumi, N., Seto, S., Kanae, S., Maeda, E., and Oki, T. (2011). Does higher surface temperature intensify extreme precipitation? *Geophysical Research Letters*, 38.

# On the sensitivity of oceanic precipitation to sea surface temperature

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**Abstract.** Our study forms the oceanic counterpart to numerous observational studies over land considering the sensitivity of extreme precipitation to a change in air temperature. We explore the sensitivity of oceanic precipitation to changing sea surface temperature (SST) by exploiting two novel datasets at high resolution. First, we use the Ocean Rainfall And Ice-phase precipitation measurement Network (OceanRAIN) as an observational along-track shipboard dataset at 1-minute resolution. Second, we exploit the most recent European Re-Analysis version 5 (ERA5) at hourly resolution on 31 km grid. Matched with each other, ERA5 vertical velocity allows ~~to constrain~~ the constraint of the OceanRAIN precipitation. Despite the inhomogeneous sampling along ship tracks, OceanRAIN agrees with ERA5 on the average latitudinal distribution of precipitation with fairly good seasonal sampling. However, the 99th percentile of OceanRAIN precipitation follows a super-Clausius–Clapeyron scaling with SST that exceeds 8.5 % $K^{-1}$ while ERA5 precipitation scales with 4.5 % $K^{-1}$. The sensitivity decreases towards lower precipitation percentiles while OceanRAIN keeps an almost constant offset to ERA5 due to higher spatial resolution and temporal sampling. Unlike over land, we find no evidence for decreasing precipitation event duration with increasing SST. ERA5 precipitation reaches a local minimum at about 26 °C that vanishes when constraining vertical velocity to strongly rising motion and excluding areas of weak correlation between precipitation and vertical velocity. This indicates that instead of moisture limitations as over land, circulation dynamics rather limit precipitation formation over the ocean. For strongest rising motion, precipitation scaling converges to a constant value at all precipitation percentiles. Overall, high ~~resolution in observations as well as climate models is~~ resolutions in observations and climate models are key to understand and predict the sensitivity of oceanic precipitation extremes to a change in SST.



## 1 Introduction

The equilibrium water vapor pressure increases with temperature, as described by the Clausius-Clapeyron (CC) equation, ~~and rises~~ by about 7 % $K^{-1}$ (e.g., Trenberth et al., 2003; Held and Soden, 2006). The same CC-scaling of 7 % $K^{-1}$ atmospheric moisture increase has also been found in modeling studies (Stephens and Ellis, 2008; Allan et al., 2014) and observations (Wentz and Schabel, 2000; Simmons et al., 2010; O'Gorman et al., 2012). Willett et al. (2010) report a global change of

7.3 % $K^{-1}$ for global humidity observations from 1973-1999. As more atmospheric moisture can lead to stronger precipitation events, a similar scaling relation for precipitation is expected; however, the actual rate of change in precipitation with warming is still uncertain which is what this study addresses over the ocean.

Despite being studied for some years, the uncertainty in the rate of change for precipitation exceeds that of the atmospheric moisture content because radiative constraints rather than moisture availability limit precipitation. Estimates for the change in global mean precipitation range between 1-3 % $K^{-1}$ (Allen and Ingram, 2002; Arkin et al., 2010; Allan et al., 2014). Over the global land area, ~~medium confidence is found~~ there is medium confidence that precipitation increased during the second half of the 20th century while high confidence is found for the Northern-hemisphere mid-latitudes (IPCC, 2014a). ~~On regional scale~~ At regional scales and for sub-daily precipitation estimates, some studies find changes ~~to~~ strongly exceed 10 % $K^{-1}$ (Lenderink and van Meijgaard, 2008, 2010). How widespread such cases of super-CC scaling occur is under debate (Haerter and Berg, 2009; Lenderink et al., 2017). Hardwick Jones et al. (2010) find a positive scaling for sub-hourly precipitation rates over Australia between 20 and 26 °C while they find a negative scaling above 26 °C due to moisture limitations. Utsumi et al. (2011) reveal latitudinal differences of CC-scaling as well as marked differences between daily and sub-daily to sub-hourly precipitation rates. Accordingly, resolution plays a crucial role in the scaling of precipitation over land with surface temperature.

Unlike over land, it remains widely unknown how precipitation scales with sea surface temperature (SST) over the ocean, particularly at sub-daily resolution, though the ocean covers more than 70 % of the Earth's surface and receives 77 % of its precipitation (Schmitt, 2008). As a ~~reason~~consequence, no long-term records of precipitation exist over the ocean (IPCC, 2014b; Maggioni et al., 2016). The few existing shorter datasets are often limited by measurement quality, sparse data coverage and low temporal resolution.

Under the challenging oceanic conditions with high wind speeds of varying direction and sea state, optical disdrometers have been recommended as a reference in-situ instrument to measure precipitation (Taylor, 2000; Weller et al., 2008). Since 2010, the Ocean Rainfall And Ice-phase precipitation measurement Network (OceanRAIN; Klepp et al., 2018) provides high-quality in-situ oceanic precipitation data from optical disdrometers at 1-minute resolution. We use this dataset in combination with the most recent European Re-Analysis version 5 (ERA5) of the European Centre for Medium-Range Weather Forecasts (ECMWF) to investigate the sensitivity of oceanic precipitation to changing SSTs.

In addition to thermodynamic drivers such as SST, dynamic drivers as part of the general atmospheric circulation strongly control if and how much precipitation is formed in the atmospheric column. Emori and Brown (2005) find an overall increase of mean and extreme precipitation, mainly due to thermodynamic changes while dynamics tend to diminish precipitation, particularly in the subtropics. Changes in extreme precipitation are particularly important as they account for most of the accumulation. To shed light on observed changes in extreme precipitation with SST we constrain extreme precipitation from OceanRAIN by the circulation regime using vertical velocities from ERA5.

The manuscript starts introducing the data sets and the methods used. ~~Then, first,~~ First, we investigate the OceanRAIN sampling and how ~~different~~ precipitation intensities change with latitude. Second, we consider the change of different precipitation percentiles with respect to a change in SST. Third, we investigate the distribution of vertical velocity in ERA5 and use it to exclude regions of low correlation between precipitation and vertical velocity. We also compare OceanRAIN with ERA5 for the same vertical-velocity regime (lifting airmass). ~~Forth~~Fourth, we consider how the precipitation event duration changes with SST. The last chapter summarizes our findings and presents some concluding thoughts and next steps.

## 2 Data and methods

### 2.1 Data

#### OceanRAIN

The Ocean Rainfall And Ice-phase precipitation measurement Network (OceanRAIN; Klepp, 2015; Burdanowitz et al., 2016; Klepp et al., 2018) provides water- and energy-cycle related parameters from ~~Jun~~ June 2010 to ~~Apr~~ April 2017 over the global ocean, collected onboard eight research vessels (RVs). In OceanRAIN version 1.0 (OceanRAIN-W; Klepp et al., 2017), these RVs include the German RVs *Polarstern* (since Jun 2010), *Meteor* (since Mar 2014), *Maria S. Merian* (Oct 2012 to Jun 2014) and *Sonne* (Sep to Oct 2012) as well as its successor *Sonne II* (since Nov 2014). The Australian RV *Investigator* (Jan to Feb 2016) and the US-American RV *Roger Revelle* (Aug to Sep 2016) contributed temporarily to OceanRAIN. Klepp et al. (2018) describe the post-processing and quality-checking of the OceanRAIN data in detail. OceanRAIN is publicly available free of charge~~,~~ : more information can be accessed ~~on~~ at https://oceanrain.org/.

Precipitation as rain, snow or mixed-phase precipitation is derived from particle size distributions recorded by the optical disdrometer ODM470, manufactured by the German company Eigenbrodt GmbH & Co KG. In the ODM470, a photo diode receiver detects the signal reduction of a near-infrared diode within the cross-sectional area of the optical measuring volume caused by falling hydrometeors (Lempio et al., 2007). The ODM470 was specifically designed to measure precipitation over the ocean: its cylindrically shaped measuring volume and its wind vane attached on a pivotable axis ensure high-quality precipitation measurements even under rough oceanic conditions with strong and highly varying wind speed and sea state. In addition, the typical mounting height of 30 to 45 m reduces unwanted influences by wave water and sea spray.

The SST in OceanRAIN has been interpolated from the bulk water temperature that is measured in sea water inlets of the respective RV at 2 to 7 m depth. The interpolation uses the cool skin parametrization after Donlon et al. (2002). The warm-layer effect is currently neglected. 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.

#### ERA5

The European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis version 5 (ERA5) has been developed through the Copernicus Climate Change Service (C3S; C3S, 2017). The ERA5 data assimilation system uses the current Integrated Forecasting System (IFS) version 41r2. Released in July 2017, the data ~~provides~~ provided hourly analyses and forecast fields at a spatial resolution of globally 31 km for the period of 2010 to 2016, which has been extended back to ~~1950 and~~ 1979 until three months to present (Hersbach and Dee, 2016). We use the following parameters from ERA5: vertical velocity $(w)$ at the 500 hPa pressure level, and sea surface temperature $(sst)$ as well as total precipitation $(tp)$ at the surface level. The data has been downloaded via the ECMWF Web API from the ECMWF data archive (MARS).

### 2.2 Methods

A standard way to calculate the sensitivity of precipitation to a change in SST is ~~, first, to bin precipitation rates by 1°C steps of SST~~ 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. We consider the 25th, 50th, 75th, 90th and 99th percentile to mainly reflect the sensitivity of high precipitation rates ~~from~~ for which the 99th percentile ~~well~~ represents heavy precipitation (see Tab. 1 for all names). Second, for each of the percentiles, we calculate the slope using two linear regression methods in order to derive the precipitation scaling ($P$-scaling).

**Table 1.** Quantitative (mm h$^{-1}$) and qualitative intensities for each of five percentiles of OceanRAIN precipitation rate for $5.396 \cdot 10^6$ ($0.473 \cdot 10^6$ precipitating) minutes from June 2010–April 2017).

| Percentile | $P$ [mm h$^{-1}$] | Intensity |
|---|---:|---:|
| 25th, $P_{25}$ | 0.05 | weak |
| 50th, $P_{50}$ | 0.18 | light |
| 75th, $P_{75}$ | 0.80 | medium |
| 90th, $P_{90}$ | 2.64 | strong |
| 99th, $P_{99}$ | 14.74 | heavy |

~~As~~ Since the widely used linear regression method of ordinary least squares (OLS) has some major weaknesses when it comes to outliers and skewed distributions, we also use the Theil-Sen estimator (TSE; Theil, 1950; Sen, 1968) as a more robust method~~, as well~~. TSE is much less susceptible to outliers (Wilcox, 2001), which is particularly needed for the much smaller sample of OceanRAIN data compared to ERA5. In addition, we simulate the robustness of the fit by bootstrapping. By these means, we get a more complete picture of how susceptible precipitation is to a change in SST.

## 3 Results

### 3.1 Is the OceanRAIN sampling sufficient to study the precipitation scaling with SST?

Oceanic precipitation ~~forms according to~~ is driven by the global atmospheric circulation systems. The atmospheric circulation follows seasonal insolation changes. ~~A sufficient~~ Sufficient seasonal sampling of precipitation is therefore needed from all climate zones for our attempt to investigate the precipitation sensitivity to SST changes. The global-ocean operation of RVs used in OceanRAIN ~~suggests a~~ ($5.396 \cdot 10^6$ min in total; $0.473 \cdot 10^6$ min with precipitation) suggests sufficient spatial sampling is possible. Most oceanic regions are well sampled during all seasons (dark-blue boxes in Fig. 1a).

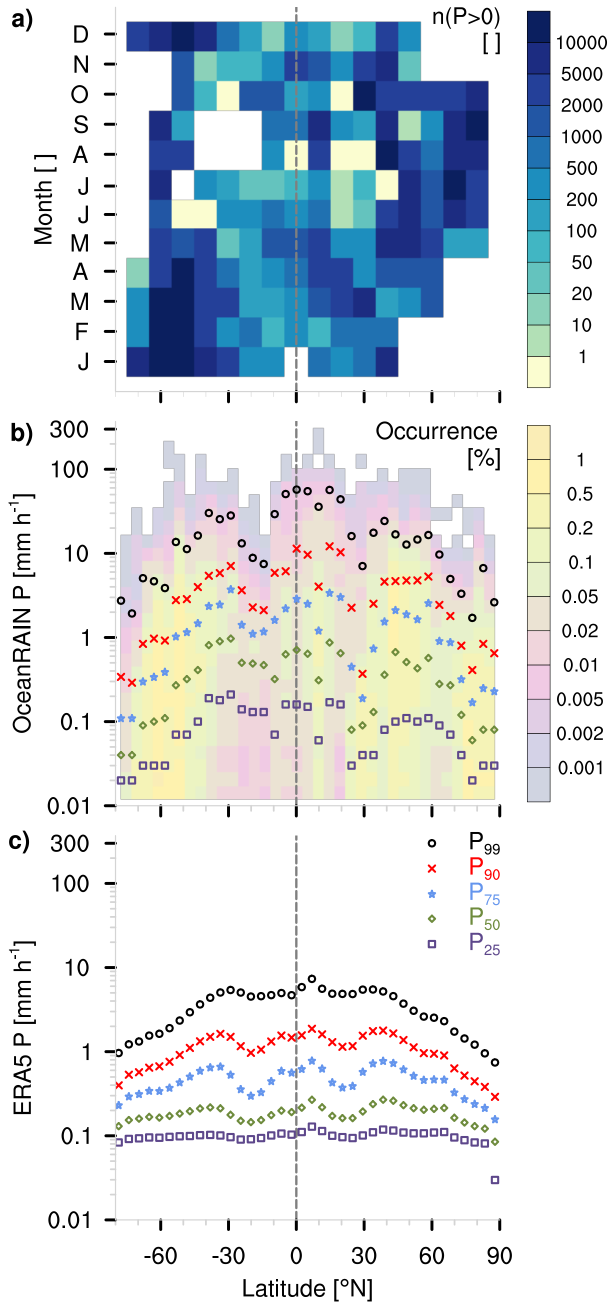


**Figure 1. (a)** 2D-histogram of OceanRAIN (Jun 2010–Apr 2017) precipitating minutes, $n(P>0)$, per month as a function of latitude. Zero values (yellow boxes) indicate no precipitation sampled while white boxes were not sampled at all. **(b)** Five percentiles of OceanRAIN precipitation (mm h$^{-1}$) as a function of 1° latitude bands with relative occurrence (%) shown in color. **(c)** as b) but for ERA5 (Jun 2010–Dec 2016).

Some measurement gaps exist during winter of the respective high-latitude regions towards both poles due to ~~ice drift~~ drifting ice and rough weather conditions. The Southern Oceans around 30° S are sparsely sampled during late boreal summer as well as the northern mid-latitude regions from 50 to 70° N during late boreal winter (light-blue boxes). In some subtropical regions, no precipitation was observed during times of OceanRAIN sampling (yellow boxes). Nevertheless, we find no pronounced gaps of seasonal sampling that would introduce seasonal biases with respect to latitude in OceanRAIN.

Without obvious seasonal biases, we expect OceanRAIN to reflect the mean latitudinal precipitation distribution according to the atmospheric circulation patterns. In particular for strong-to-heavy precipitation (see Tab. 1 for classification), the highest precipitation rates occur at or close to the equator while for weak-to-medium precipitation the highest precipitation rates also occur around 30° S (Fig. 1b). ~~Minimal~~ Minimum precipitation rates at all intensities are found at both poles and in the subtropics at about 30° N and 15° S, respectively. The exact positions of latitudinal precipitation minima and maxima vary with intensity, likely related to sparse sampling e.g. in the dry subtropics (purple colors in Fig. 1b). Nevertheless, the OceanRAIN time period of Jun 2010–Apr 2017 reflects the expected mean precipitation distribution with respect to latitude.

Comparing the latitudinal distribution of precipitation rates from OceanRAIN to that of ERA5 reveals overall good agreement on the main climatological patterns and some major differences (Fig. 1c). One of them—the much lower amplitude of precipitation rates from ERA5—can be explained by the lower spatial and temporal resolution of ERA5 compared to OceanRAIN. The reduced variability for heavy precipitation in ERA5 compared to medium intensities marks a second distinction between OceanRAIN and ERA5, likely related to recurrence times of extreme precipitation events that exceed the typical OceanRAIN sampling of about 1000 min of precipitation per box mainly in the subtropics (Fig. 1a). Building on these results, a further exploration of both data sets seems plausible to investigate the sensitivity of precipitation to SST changes.

### 3.2 How does precipitation change with SST?

Despite a pronounced variability, precipitation ~~follows~~ shows a clear trend ~~to increase with~~ of increasing SST at all five $P$ percentiles over the global ocean in OceanRAIN (Fig. 2a). The sensitivity of precipitation to SST ~~grows~~ increases for higher precipitation intensities. While weak precipitation increases by 4.5 % $\mathrm{K}^{-1}$ and light-to-medium precipitation increases by more than 6 % $\mathrm{K}^{-1}$, heavy precipitation increases by almost 9 % $\mathrm{K}^{-1}$ according to TSE (Sect. 2). Here, the less robust OLS method leads to significantly lower sensitivities of 2.5 (weak) to 6 % $\mathrm{K}^{-1}$ (heavy), considering the median of 100-times resampled data of randomly chosen 50 % of the binned intensities.

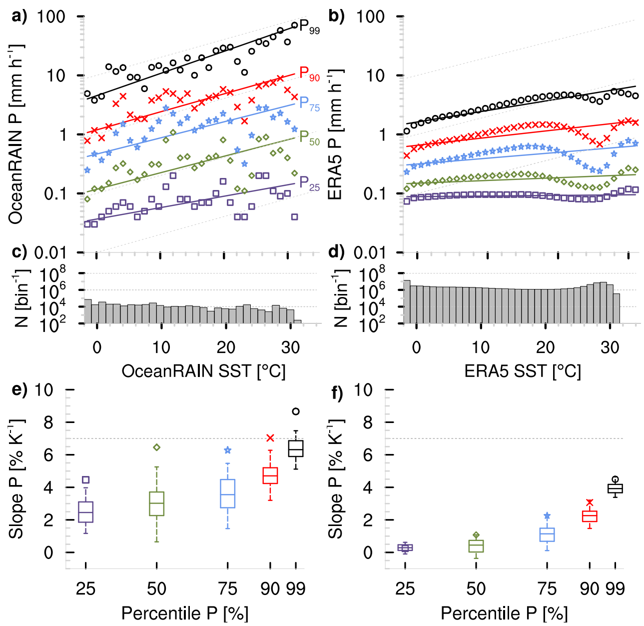


**Figure 2.** Five percentiles of **(a)** OceanRAIN (Jun 2010–Apr 2017) and **(b)** ERA5 (Jun 2010–Dec 2016) precipitation rate $P$ (mm h$^{-1}$) as a function of bin-wise SST (°C) shown with linear regressions from TSE calculation. Grey lines indicate 7 % K$^{-1}$ slope. **(c),(d)** Histograms illustrate number of cases $N$ (bin$^{-1}$) for all in a) and per month in (b). **(e),(f)** Slopes from TSE regressions (% K$^{-1}$) in (a),(b) are indicated by markers as a function of percentile. Boxes (5th–95th percentile) refer to OLS method as comparison using a 100-times resampling of the halved dataset.~~Grey lines indicate 7 % K$^{-1}$.~~

The interquartile spread of 1 to 2 % $\mathrm{K}^{-1}$ (50 % of the sensitivity) and data samples of much less than ~~1000~~10,000 min for some of the bins (Fig. 2c) indicate a high variability which is why we put more trust in the sensitivities calculated by the more robust TSE.

~~For~~ Precipitation in ERA5 ~~, we find~~ 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 about 0.3 to 3.1 % $\mathrm{K}^{-1}$ for weak-to-strong and of 4.5 % $\mathrm{K}^{-1}$ for heavy precipitation with TSE (Fig. 2b,f). As these numbers rely on global ocean coverage, even the average monthly data sampling density of $10^6$ ~~$\mathrm{bin}^{-1}$~~ per bin (Fig. 2d) strongly exceeds that of OceanRAIN, resulting in a smoother trend of the $P$-scaling and a lower interquartile spread of 0.4 to 0.8 % $\mathrm{K}^{-1}$. As a consequence, the TSE always lies within the uncertainty of the OLS method (5th–95th percentile). Nevertheless, the question arises whether only resolution differences cause the systematically lower $P$-scaling in ERA5 compared to OceanRAIN.

### 3.3 Can vertical velocity help to understand the precipitation scaling with SST?

To enhance our understanding of different $P$-scalings over the ocean, we consider vertical velocity at 500 hPa from ERA5 to select cases that favor precipitation formation. As an indicator, we use the temporal correlation $r(P,\omega_{500})$ at each grid point between hourly precipitation $P$ and hourly 500 hPa vertical velocity $\omega_{500}$ from ERA5. As in Emori and Brown (2005), we use $r(P,\omega_{500}) = -0.2$ as a threshold (note that we define positive vertical velocity as subsiding motion). The resulting areas of weak or even positive $r(P,\omega_{500})$ for a month (bluish colors in Fig. 3a) mainly comprise but are not limited

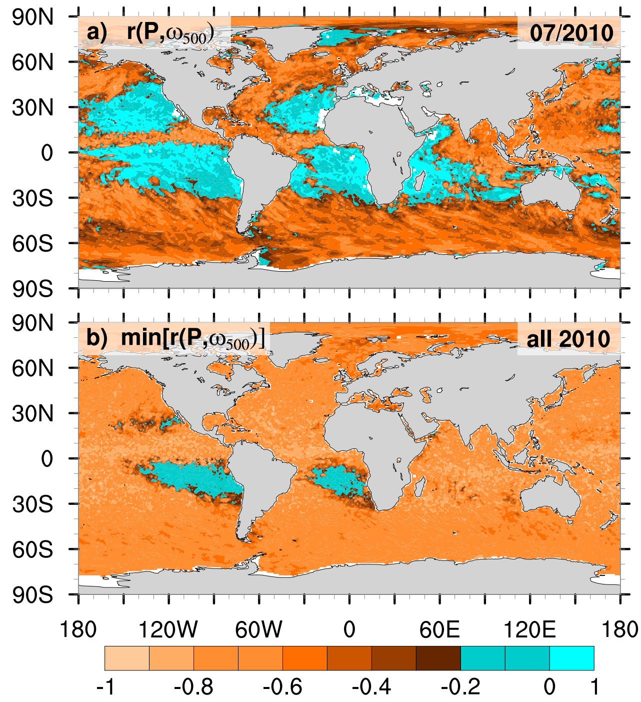


**Figure 3.** Maps of temporal correlation $r(P, \omega_{500})$ for each ERA5 gridbox for **a)** July 2010 and **b)** the ~~minimal~~ minimum monthly correlation for the year 2010. Blue colored areas are weakly or positively correlated and are excluded from further analysis ($r > -0.2$; Emori and Brown, 2005).

to areas of subsidence and relatively low SSTs and amount to 5 % of the global ocean precipitation (see Fig. A1 for influence on ERA5). Unlike earlier studies, note that we use hourly instead of daily (e.g. Emori and Brown, 2005) or monthly timesteps (e.g. Oueslati and Bellon, 2015) for correlation but correlations are calculated per month. The high seasonal variability of $r(P,\omega_{500})$ leaves only small areas with a constantly weak $r(P,\omega_{500})$ over a whole year (e.g., minimum for each month of 2010 in Fig. 3b). While the size of the areas varies slightly, the Southeast-Pacific and Southeast-Atlantic areas of constantly weak correlation stay the same for the years 2010-2016 while elsewhere $r(P,\omega_{500})$ remains mostly below -0.2 (not shown).

In order to use $\omega_{500}$ to constrain OceanRAIN precipitation, we match each minute of OceanRAIN precipitation with the closest hourly $\omega_{500}$ of ERA5. Negative $\omega_{500}$ values correspond to rising motion. Almost two thirds of the global-ocean ERA5 timesteps during July 2010, as an example, have ~~vertical velocities~~ absolute vertical velocities $|\omega_{500}|$ below 100 hPa day$^{-1}$ (Fig. 4a).

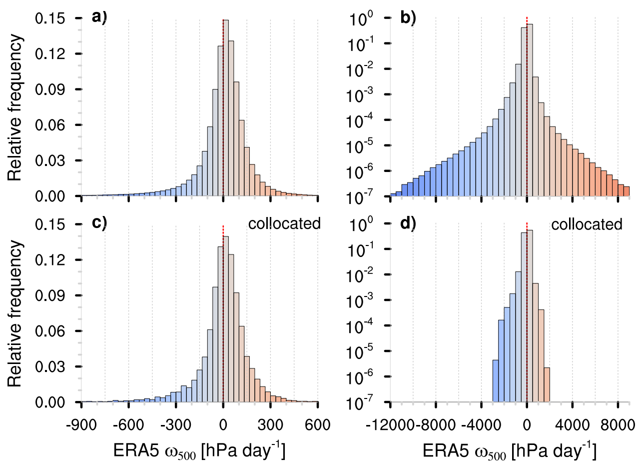


**Figure 4.** Histograms of relative frequency for $\omega_{500}$ (blue: rising; red: subsiding motion) of (a),(b) all ERA5 gridboxes and (c),(d) for OceanRAIN–ERA5 collocated ERA5 gridboxes with (a),(c) linear ordinate and (b),(d) logarithmic ordinate for strong motion.

The slightly left-skewed distribution of $\omega_{500}$ ($\gamma = -3.44$) has a 1st percentile of $-692$ hPa day$^{-1}$, a 99th percentile of 410 hPa day$^{-1}$, a mean of $-1.1$ hPa day$^{-1}$ and a median of 15.5 hPa day$^{-1}$ (Fig. 4b). When being matched to OceanRAIN, the $\omega_{500}$ distribution of ERA5 loses its extremes (1st percentile: $-602$ hPa day$^{-1}$, 99th percentile: 385 hPa day$^{-1}$; Fig. 4c and d with log y-axis) while the left-skewness slightly reduces ($\gamma = -2.03$). Nevertheless, the $\omega_{500}$ distribution of OceanRAIN–ERA5 matched timesteps is very similar to the overall ERA5 distribution of July 2010 (Fig. 4a and c).

The OceanRAIN–ERA5 matched timesteps enable a direct comparison between both datasets for the $P$-scaling. We define a range of $-1500 < \omega_{500} < -50$ hPa day$^{-1}$ that, first, selects upward motion that generally fosters precipitation to form and, second, that provides ~~enough~~ sufficient matches per SST-bin to allow ~~calculating~~ the highest percentiles to be calculated (Fig. 5c,d).

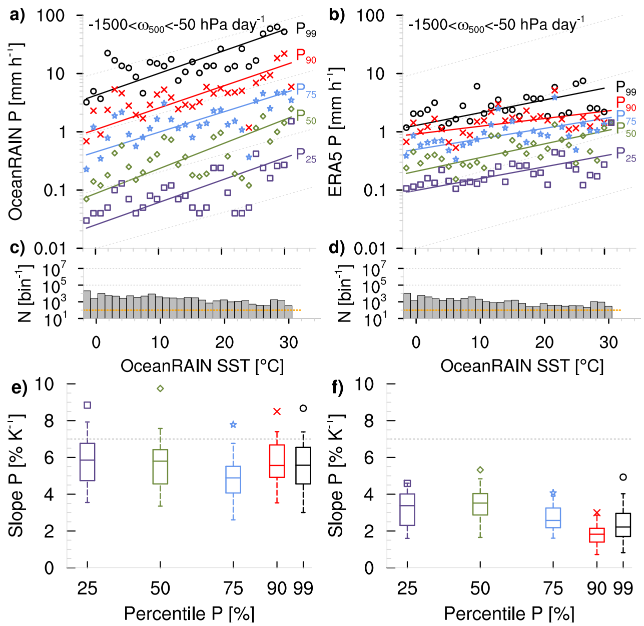


**Figure 5.** As Fig. 2 but for all OceanRAIN–ERA5 matched timesteps for **(a)**,**(c)**,**(e)** OceanRAIN and for **(b)**,**(d)**,**(f)** ERA5, both for rising motion ($-1500 < \omega_{500} < -50$ hPa day$^{-1}$) and excluding regions of $r(P, \omega_{500}) > -0.2$ from Fig. 3. Orange line in (**c**) and (**d**) marks the lowest N for which $P_{99}$ can be calculated.

This range represents a good compromise between a clear signal of rising motion and a sufficiently large size of remaining OceanRAIN samples. Third, we exclude grid boxes with a temporal correlation of $r(P,\omega_{500}) > -0.2$ per month, that are mainly associated with dry areas of subsidence (see Fig. 3). ~~Its influence~~ The influence of these weakly correlated areas on the whole ERA5 dataset is shown in Appendix A (see Fig. A1). Also note that we use OceanRAIN SSTs for both data sets as the usage of ERA5 SSTs would reduce the total number of usable timesteps (437,000 without $\omega_{500}$ constraint) by 6.6 % (not shown). The resulting sub-sample of matched timesteps for ERA5 (hourly) and OceanRAIN (every minute) comprises about 110,000 timesteps. The relatively low number of remaining timesteps limits the statistical robustness of the sample ~~that~~ for some of the 1°C SST-bins ~~contains~~ that contain less than 1,000 precipitation ~~rates~~ values (Fig. 5c,d). The data sparsity results in a quite scattered sensitivity distribution (Fig. 5a,b). Compared to the larger sample of OceanRAIN measurements and ERA5 data (see Fig. 2), first, particularly the weak-to-medium precipitation rates increase at a much higher rate with constrained $\omega_{500}$. Second, all OceanRAIN precipitation percentiles scale with 7.5 to 10 % K$^{-1}$ (ERA5: 3 to 5.5 % K$^{-1}$) according to TSE (Fig. 5e,f). This means an ~~about~~ approximate constant sensitivity of precipitation to a change in SST, for OceanRAIN even ~~as~~ at super-CC scaling, while the sensitivity difference remains between ERA5 and OceanRAIN.

To understand whether this about uniform sensitivity at all precipitation percentiles results from the $\omega_{500}$ constraint, from the data sparsity or is a feature of the matched sub-sample of data, we consider ERA5 with the same constraint of $-1500 < \omega_{500} < -50$ hPa day$^{-1}$ but globally for the full ERA5 period leading to more than 1000-times more data (monthly $N$ in Fig. 6c).

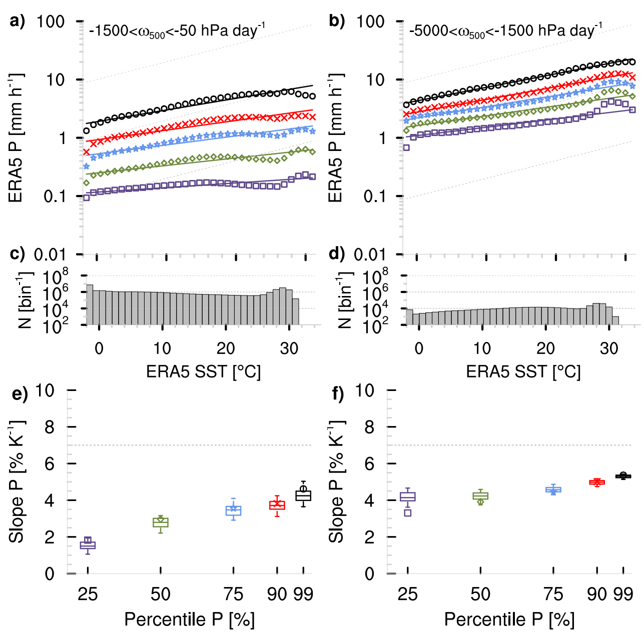


**Figure 6.** As Fig. 5 but for complete ERA5 period. Panels (a),(c),(e) are constrained by $-1500 < \omega_{500} < -50$ hPa day$^{-1}$ and (b),(d),(f) by $-5000 < \omega_{500} < -1500$ hPa day$^{-1}$.

Compared to OceanRAIN, the $P$-scaling smoothens for all precipitation percentiles (Fig. 6a) while the interquartile spread reduces (Fig. 6e). Compared to Fig. 5f, mainly the $P$-scaling of weak precipitation decreases below 2 % $K^{-1}$ for medium-to-heavy precipitation it remains between 3 and 5 % $K^{-1}$. Compared to Fig. 2e, the $P$-scaling increases more steeply for weak precipitation, reaches a plateau for medium-to-strong intensities before it increases again for heavy precipitation. Accordingly, the sensitivity in Fig. 5f points at the slightly increased sensitivities for low precipitation rates for the $\omega_{500}$ constraint while the picture is mainly blurred due to the small sample size.

Constraining $\omega_{500}$ 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 $\omega_{500}$ 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.

To further investigate the influence of a constraining $\omega_{500}$, we consider stronger rising motion between $-5000$ and $-1500$ hPa day$^{-1}$ (Fig. 6b). Compared to somewhat weaker rising motion in $\omega_{500}$, the weak precipitation rates increase by about an order of magnitude while heavy precipitation rates are higher by a factor of 2. The change in the $P$-scaling with SST smoothens while it tends towards a constant slope at all percentiles (Fig. 6f). This constant slope marks a linear increase and saturates for strongest rising motions at approximately 6 % $K^{-1}$ in ERA5 (not shown). Accordingly, ~~constraining lower~~ the shift of the range of $\omega_{500}$ toward lower values (rising motion) ~~tend to harmonize the slopes of different precipitation percentilesby mainly lifting the~~ tends to equalize the $P$-scaling at different $P$ percentiles. This mainly results from an increase in $P$-scaling at lower percentiles~~while high percentiles remain about constant~~, while the $P$-scaling remains approximately constant for high percentiles.

### 3.4 Does a change in precipitation event duration with SST affect the precipitation scaling?

Over land, previous studies state a decrease in precipitation event duration with increasing air temperature that explains the drop-off in precipitation scaling at high temperatures found for ~~sampling rates of 1 hour and above~~ hourly to daily sampling rates (Haerter et al., 2010; Utsumi et al., 2011). Haerter and Berg (2009) explain the decreasing event duration with a shift toward more convective precipitation events at high temperatures. To check whether this holds over the ocean we calculated the OceanRAIN precipitation event duration by counting uninterrupted periods of continuous precipitation at 1-minute sampling. The average precipitation event lasts between 6 and 11 min with an uncertainty of 1 to 2 min obtained from bootstrapping (Fig. 7a).

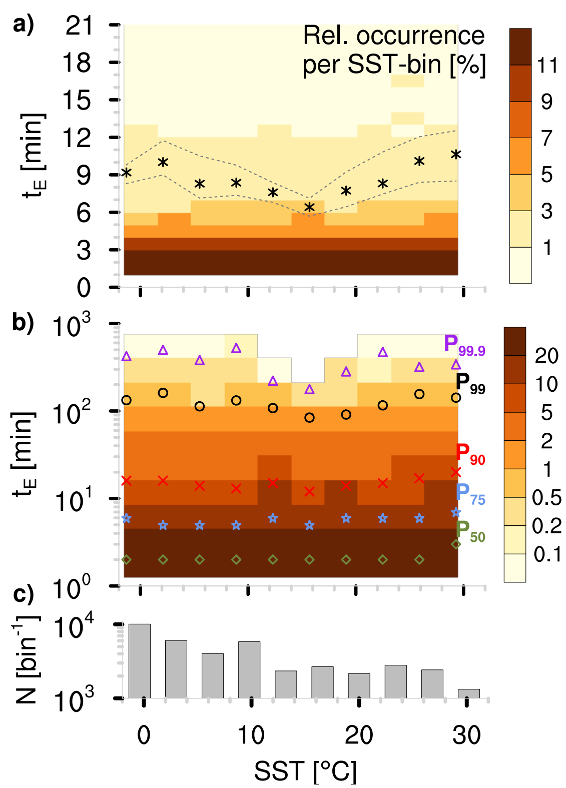


**Figure 7.** 2d-histogram as a function of precipitation event duration $t_E$ (min) and OceanRAIN SST (°C) for (a) linear and (b) logarithmic ordinate. Colors indicate relative occurrence (%) per SST-bin. Markers in (a) show mean per SST-bin surrounded by minimum and maximum from 100-times resampling as a measure of uncertainty. Markers in (b) show percentiles 50, 75, 90, 99 and 99.9 of $t_E$. Panel (c) shows the number $N$ of events per SST-bin.

The shortest ~~events occur~~ mean precipitation event duration occurs at 15°C while the longest ~~events occur~~ mean precipitation event duration occurs around 2 and above 28°C. ~~This holds true for~~ The mean is mainly driven by the highest percentiles (99th to 99.9th exceeding 2 h) that mainly ~~influence the mean~~ cause the minimum at 15°C but it is less pronounced for the 50th to 75th percentile where precipitation event duration remains about constant (Fig. 7b). Although the precipitation event duration tends to decrease between 2 and 16°C as over land (Haerter et al., 2010; Utsumi et al., 2011), we find no systematic decrease over the whole SST range.

The precipitation event duration as a function of temperature can be influenced by several factors. First, the heterogeneous sampling in OceanRAIN can influence the event duration. Exceeding 2000 ~~bin$^{-1}$~~samples per bin, the sampling density per SST-bin seems fairly good for most of the SST range; below 12°C it even exceeds 4000 samples per bin (Fig. 7c). Nevertheless, heterogeneous spatial sampling by the ships can lead to a biased picture (see Fig. 3 in Burdanowitz et al., 2018); e.g. the Eastern Atlantic has been more densely sampled compared to the Western Atlantic which might have an effect on the occurrence of very long-lasting precipitation events. Second, the ship movement relative to cloud movement can affect the retrieved event duration. However, this effect cancels out over almost 40,000 events sampled from OceanRAIN (not shown). Overall, influences by the heterogeneity of OceanRAIN on the precipitation event duration cannot be ruled out but seem rather limited according to our investigations.

## 4 Summary and concluding remarks

This study forms the oceanic counterpart to numerous observational studies over land that considered the sensitivity of extreme precipitation to a change in air temperature. Unlike earlier studies with mainly hourly to daily sampling calling for higher resolution (e.g., Panthou et al. 2014; Drobinski et al. 2016), we consider precipitation rate and SST at a very high sampling rate of 1 minute from OceanRAIN optical disdrometer measurements aboard global-ocean research vessels. In addition, hourly measurements of the new ERA5 reanalysis serve to compare and, additionally, constrain precipitation by large-scale vertical velocity.

OceanRAIN challenges the user with its non-uniform sampling and variable spatial resolution along ship tracks. However, at the same time, it offers a unique opportunity to study oceanic precipitation at high quality with global-ocean sampling at 1-minute temporal resolution. Additionally, we show that differences in seasonal and latitudinal sampling are small, which could otherwise affect the precipitation scaling (Schroeer and Kirchengast, 2018). Furthermore, the OceanRAIN average precipitation distribution with latitude looks similar to that in ERA5 with its homogeneous global-ocean coverage.

For OceanRAIN, the 99th percentile of 1-minute precipitation rates shows a super-CC scaling of almost 9 % K$^{-1}$ in line with studies over land (e.g., Bürger et al. 2014; Schroeer and Kirchengast 2018) while for ERA5, the 99th percentile of the hourly ERA5 precipitation rates increases by only 4.5 % K$^{-1}$ (linear regression using Theil-Sen estimator). The tendency of a stronger scaling with higher temporal sampling confirms findings by Utsumi et al. (2011) and Drobinski et al. (2016). This difference in CC-scaling ranges between 4 and 6 % K$^{-1}$ for the weak-to-strong precipitation rates between OceanRAIN and ERA5. For both data sets precipitation increases with SST at all percentiles considered. ~~Unlike over landdue to moisture limitations~~

~~(Hardwick Jones et al., 2010)~~In contrast to studies over land, we find no ~~decreasing precipitation rates over temperature ranges of more than 8 K but an increase again towards highest SSTsof about 30°C.~~ "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. Instead, despite the variability in OceanRAIN, we find a continuous increase in OceanRAIN precipitation with increasing SST, including the highest SSTs.

Nevertheless, the ERA5 precipitation rates reveal a local minimum at about 26°C. When excluding areas of weak temporal correlation of 500 hPa vertical velocity with precipitation rate, the local minimum in precipitation scaling becomes weaker. Despite the fact that the hourly vertical velocity might not necessarily be the best indicator for large-scale subsidence, the ~~dip~~ minimum vanishes when constraining precipitation to rising motion below $-1500$ hPa day$^{-1}$. From this, we infer that dynamical drivers such as subtropical large-scale subsidence inhibit precipitation formation and cause the local precipitation minimum at 26°C.

~~The fact that the local precipitation minimum is hardly~~ 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 ~~likely arises from the low~~ due to limited sampling.

The data sampling density ~~, specifically~~ plays a crucial role in precipitation-sparse regions that would need the longest sampling to be well represented. Generally, the non-uniform sampling by ships in OceanRAIN results in a more variable precipitation distribution with respect to SST. Therefore, we mainly rely on the Theil-Sen estimator (TSE) as linear regression method, which is less susceptible to outliers (Wilcox, 2001) instead of only trusting the widely known ordinary least squares (OLS) method.

Although we find a more steady precipitation scaling in OceanRAIN compared to ERA5 at high SSTs, there is no evidence that this is caused by a decreasing duration of precipitation events with temperature as indicated by studies over land (Haerter et al., 2010; Utsumi et al., 2011). Instead, we find a minimum average precipitation event duration in OceanRAIN of 7 min at about 15°C that rises beyond 10 min above 28°C. This temperature dependence remains the same for higher percentiles corresponding to longer events. As most of the precipitation events last only few minutes, this confirms our decision to use a high temporal sampling rate of 1 minute to exclude resolution artifacts from the precipitation scaling. At 1-minute resolution, we find no evidence of generally decreasing precipitation event duration with temperature.

For the OceanRAIN–ERA5 matched timesteps, we find a high uncertainty for the reduced data sample using vertical velocity in 500 hPa from ERA5 to constrain precipitation rates. The OceanRAIN precipitation scales with super-CC behavior at all precipitation percentiles (8 to 10 % K$^{-1}$) while ERA5 precipitation scales with 3 to 6 % K$^{-1}$, confirming the offset that we found between both unconstrained datasets. The offset in precipitation scaling is therefore likely attributable to the marked difference in spatial resolution that confronts the OceanRAIN along-track data with the areal ERA5 data of 31 km grid boxes. Furthermore, constraining precipitation towards strongly rising air-masses leads to a precipitation scaling that converges towards 6 % K$^{-1}$ for all precipitation rates in ERA5. For OceanRAIN, the too-small data sample for precipitation in lifting air-masses does not allow us to derive a number for the scaling but the offset to ERA5 and the scaling with the OceanRAIN–ERA5 matched data both suggest super-CC scaling for OceanRAIN.

Two aspects should be kept in mind when interpreting our results. First, the average precipitation scaling should not be directly translated into an increase of local precipitation per degree of warming, as locally dynamic processes can strongly alter the precipitation–SST relationship. Second, in light of the projected rising global mean temperature by anthropogenic climate change, large-scale circulation changes and other side effects in the Earth system could contribute or counteract the diagnosed precipitation sensitivity to a change in SST. Therefore, care needs to be taken when interpreting our results that are valid under the present climatic conditions.

Next steps would include more local analyses at 1-minute resolution once data sampling allows ~~to globally resolve the~~ highest precipitation intensities to be resolved globally. Furthermore, higher ~~resolution is~~ resolutions are needed in global climate models to project the hydrological sensitivity of extremes in a warming climate and its feedbacks.

*Data availability.* The OceanRAIN data is available through the Climate and Environmental Retrieval and Archive (CERA) of World Data Center for Climate (WDCC) via Klepp et al. (2017). The ERA5 data is available through the Climate Data Store (CDS) Application Program Interface (API) via the Copernicus Climate Change Service (C3S, 2017).

## Appendix A: How circulation dynamics impact the precipitation scaling in ERA5

To shed light on the influence of circulation dynamics on the $P$-scaling of ERA5, we consider the temporal correlation $r(P,\omega_{500})$. According to Emori and Brown (2005), we exclude all precipitation time steps with $r > -0.2$ diminishing the influence of precipitation from very shallow convection and large-scale subsidence. The resulting precipitation distribution with respect to SST reveals a less pronounced minimum at about 26°C (Fig. A1b). This leads to a slight increase of the $P$-scaling at all intensities (Fig. A1e-f). Accordingly, $\omega_{500}$ itself can better explain the ~~dip~~ minimum at 26°C compared to areas of low correlation between $\omega_{500}$ and $P$.

*Author contributions.* J.B. analyzed the data, made the figures and wrote the manuscript. S.B., C.K. and S.A.B. gave scientific advice and helped improving the manuscript.

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

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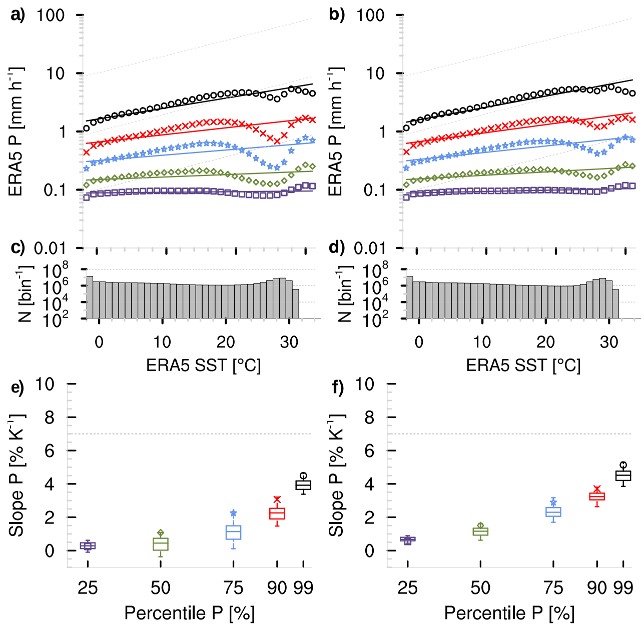


**Figure A1.** Left panel is same as right panel of Fig. 2. Right panel excludes regions of $r(P,\omega_{500}) > -0.2$ from Fig. 3 for complete ERA5 period.

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## References


Allan, R. P., Liu, C., Zahn, M., Lavers, D. A., Koukouvagias, E., and Bodas-Salcedo, A.: Physically Consistent Responses of the Global Atmospheric Hydrological Cycle in Models and Observations, Surveys in Geophysics, 35, 533–552, https://doi.org/10.1007/s10712-012-9213-z, 2014.

Allen, M. R. and Ingram, W. J.: Constraints on future changes in climate and the hydrologic cycle, Nature, 419, 224, https://doi.org/10.1038/nature01092, 2002.

Arkin, P. A., Smith, T. M., Sapiano, M. R. P., and Janowiak, J.: The observed sensitivity of the global hydrological cycle to changes in surface temperature, Environmental Research Letters, 5, 035 201, https://doi.org/10.1088/1748-9326/5/3/035201, 2010.

Burdanowitz, J., Klepp, C., and Bakan, S.: An automatic precipitation-phase distinction algorithm for optical disdrometer data over the global ocean, Atmospheric Measurement Techniques, 9, 1637–1652, https://doi.org/10.5194/amt-9-1637-2016, 2016.

Burdanowitz, J., Klepp, C., Bakan, S., and Buehler, S. A.: Towards an along-track validation of HOAPS precipitation using OceanRAIN optical disdrometer data over the Atlantic Ocean, Quarterly Journal of the Royal Meteorological Society, 144, 235–254, https://doi.org/10.1002/qj.3248, 2018.

Bürger, G., Heistermann, M., and Bronstert, A.: Towards Subdaily Rainfall Disaggregation via Clausius-Clapeyron, Journal of Hydrometeorology, 15, 140312141057 000, https://doi.org/10.1175/JHM-D-13-0161.1, 2014.

C3S: ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate, Copernicus Climate Change Service (C3S), https://cds.climate.copernicus.eu/cdsapp#!/home, 2017.

Donlon, C. J., Minnett, P. J., Gentemann, C., Nightingale, T. J., Barton, I. J., Ward, B., and Murray, M. J.: Toward Improved Validation of Satellite Sea Surface Skin Temperature Measurements for Climate Research, Journal of Climate, 15, 353–369, https://doi.org/10.1175/1520-0442(2002)015<0353:TIVOSS>2.0.CO;2, 2002.

Drobinski, P., Alonzo, B., Bastin, S., Silva, N. D., and Muller, C.: Scaling of precipitation extremes with temperature in the French Mediterranean region: What explains the hook shape?, Journal of Geophysical Research: Atmospheres, 121, 3100–3119, https://doi.org/10.1002/2015JD023497, 2016.

Emori, S. and Brown, S. J.: Dynamic and thermodynamic changes in mean and extreme precipitation under changed climate, Geophysical Research Letters, 32, L17 706, https://doi.org/10.1029/2005GL023272, 2005.

Haerter, J. O. and Berg, P.: Unexpected rise in extreme precipitation caused by a shift in rain type?, Nature Geoscience, 2, 372, https://doi.org/http://dx.doi.org/10.1038/ngeo523 10.1038/ngeo523, 2009.

Haerter, J. O., Berg, P., and Hagemann, S.: Heavy rain intensity distributions on varying time scales and at different temperatures, Journal of Geophysical Research: Atmospheres, 115, D17 102, https://doi.org/10.1029/2009JD013384, 2010.

Hardwick Jones, R., Westra, S., and Sharma, A.: Observed relationships between extreme sub-daily precipitation, surface temperature, and relative humidity, Geophysical Research Letters, 37, L22 805, https://doi.org/10.1029/2010GL045081, 2010.

Held, I. M. and Soden, B. J.: Robust responses of the hydrological cycle to global warming, Journal of Climate, 19, 5686–5699, https://doi.org/10.1175/jcli3990.1, 2006.

Hersbach, H. and Dee, D.: ERA5 reanalysis is in production, https://confluence.ecmwf.int/display/CKB/What+is+ERA5?preview=/58140637/58140636/16299-newsletter-no147-spring-2016_p7.pdf, 2016.

IPCC: Observations: Atmosphere and Surface, pp. 159–254, Cambridge University Press, https://doi.org/10.1017/CBO9781107415324.008, 2014a.

IPCC: Observations: Ocean Pages, pp. 255–316, Cambridge University Press, https://doi.org/10.1017/CBO9781107415324.010, 2014b.

Klepp, C.: The oceanic shipboard precipitation measurement network for surface validation – OceanRAIN, Atmos. Res., 163, 74–90, https://doi.org/10.1016/j.atmosres.2014.12.014, 2015.

Klepp, C., Michel, S., Protat, A., Burdanowitz, J., Albern, N., Louf, V., Bakan, S., Dahl, A., and Thiele, T.: Ocean Rainfall And Ice-phase precipitation measurement Network – OceanRAIN-W, https://doi.org/10.1594/wdcc/oceanrain-w, 2017.

Klepp, C., Michel, S., Protat, A., Burdanowitz, J., Albern, N., Kähnert, M., Dahl, A., Louf, V., Bakan, S., and Buehler, S.: OceanRAIN, a new in-situ shipboard global ocean surface-reference dataset of all water cycle components, Scientific Data, p. 180122, https://doi.org/10.1038/sdata.2018.122, 2018.

Lempio, G. E., Bumke, K., and Macke, A.: Measurement of solid precipitation with an optical disdrometer, Advances in Geosciences, 10, 91–97, https://doi.org/10.5194/adgeo-10-91-2007, 2007.

Lenderink, G. and van Meijgaard, E.: Increase in hourly precipitation extremes beyond expectations from temperature changes, Nature Geoscience, 1, 511, https://doi.org/10.1038/ngeo262, 2008.

Lenderink, G. and van Meijgaard, E.: Linking increases in hourly precipitation extremes to atmospheric temperature and moisture changes, Environmental Research Letters, 5, 025 208, https://doi.org/10.1088/1748-9326/5/2/025208, 2010.

Lenderink, G., Barbero, R., Loriaux, J. M., and Fowler, H. J.: Super-Clausius–Clapeyron Scaling of Extreme Hourly Convective Precipitation and Its Relation to Large-Scale Atmospheric Conditions, Journal of Climate, 30, 6037–6052, https://doi.org/10.1175/JCLI-D-16-0808.1, 2017.

Maggioni, V., Meyers, P. C., and Robinson, M. D.: A Review of Merged High-Resolution Satellite Precipitation Product Accuracy during the Tropical Rainfall Measuring Mission (TRMM) Era, J. Hydrometeor., 17, 1101–1117, https://doi.org/10.1175/JHM-D-15-0190.1, 2016.

O'Gorman, P. A., Allan, R. P., Byrne, M. P., and Previdi, M.: Energetic Constraints on Precipitation Under Climate Change, Surveys in Geophysics, 33, 585–608, https://doi.org/10.1007/s10712-011-9159-6, 2012.

Oueslati, B. and Bellon, G.: The double ITCZ bias in CMIP5 models: interaction between SST, large-scale circulation and precipitation, Climate Dynamics, 44, 585–607, https://doi.org/10.1007/s00382-015-2468-6, 2015.

Panthou, G., Mailhot, A., Laurence, E., and Talbot, G.: Relationship between Surface Temperature and Extreme Rainfalls: A Multi-Time-Scale and Event-Based Analysis, Journal of Hydrometeorology, 15, 1999–2011, https://doi.org/10.1175/JHM-D-14-0020.1, 2014.

Schmitt, R. W.: Salinity and the Global Water Cycle, Oceanography, 21, https://doi.org/10.5670/oceanog.2008.63, 2008.

Schroeer, K. and Kirchengast, G.: Sensitivity of extreme precipitation to temperature: the variability of scaling factors from a regional to local perspective, Climate Dynamics, 50, 3981–3994, https://doi.org/10.1007/s00382-017-3857-9, 2018.

Sen, P.: Estimates of the Regression Coefficient Based on Kendall's Tau, Journal of the American Statistical Association, 63, 1379–1389, https://doi.org/10.1080/01621459.1968.10480934, 1968.

Simmons, A. J., Willett, K. M., Jones, P. D., Thorne, P. W., and Dee, D. P.: Low-frequency variations in surface atmospheric humidity, temperature, and precipitation: Inferences from reanalyses and monthly gridded observational data sets, Journal of Geophysical Research-Atmospheres, 115, D01 110, https://doi.org/10.1029/2009jd012442, 2010.

Stephens, G. L. and Ellis, T. D.: Controls of Global-Mean Precipitation Increases in Global Warming GCM Experiments, Journal of Climate, 21, 6141–6155, https://doi.org/10.1175/2008JCLI2144.1, 2008.

Taylor, P.: Intercomparison and Validation of Ocean-Atmosphere Energy Flux Fields, in: Final report of the Joint WCRP/SCOR Working Group on Air-Sea Fluxes, p. 325, WCRP-112, WMO/TD-1036, 2000.

Theil, H.: A rank-invariant method of linear and polynomial regression analysis., Nederl. Akad. Wetensch., Proc., 53, 386–392, 1950.

Trenberth, K. E., Dai, A., Rasmussen, R. M., and Parsons, D. B.: The Changing Character of Precipitation, Bulletin of the American Meteorological Society, 84, 1205–1218, https://doi.org/10.1175/BAMS-84-9-1205, 2003.

Utsumi, N., Seto, S., Kanae, S., Maeda, E., and Oki, T.: Does higher surface temperature intensify extreme precipitation?, Geophysical Research Letters, 38, https://doi.org/10.1029/2011GL048426, 2011.

Weller, R. A., Bradley, E. F., Edson, J. B., Fairall, C. W., Brooks, I., Yelland, M. J., and Pascal, R. W.: Sensors for physical fluxes at the sea surface: energy, heat, water, salt, Ocean Sci., 4, 247–263, https://doi.org/10.5194/os-4-247-2008, 2008.

Wentz, F. J. and Schabel, M.: Precise climate monitoring using complementary satellite data sets, Nature, 403, 414, https://doi.org/10.1038/35000184 10.1038/35000184, 2000.

Wilcox, R. R.: Robust Regression, pp. 205–228, Springer New York, New York, NY, https://doi.org/10.1007/978-1-4757-3522-2_11, 2001.

Willett, K. M., Jones, P. D., Thorne, P. W., and Gillett, N. P.: A comparison of large scale changes in surface humidity over land in observations and CMIP3 general circulation models, Environmental Research Letters, 5, https://doi.org/10.1088/1748-9326/5/2/025210, 2010.