

Dear Dr. Perdigão,

thank you for taking the time to handle our manuscript! Please find below our responses to the comments by referee #1.

When considering the reviewer comments, we realized that the title of our manuscript may have been somewhat misleading: As it was submitted, the title might give the impression that the paper describes how Sahel rainfall *will* respond to future global warming. That is not the case, and we apologize for any misunderstanding this may have caused. We suggest amending the title as follows:

“Non-linear intensification of Sahel rainfall as a **possible** dynamic response to future warming”

This should make it clear that we do not provide a definite outlook on the future of Sahel rainfall, but rather demonstrate the *possibility* of a strong, non-linear intensification in state-of-the-art climate models. This is the idea with which we had written the paper, as also reflected in the abstract; we hope this may already resolve a number of issues, as we will detail now.

In response to the referee’s comments under a):

- 1) Since the manuscript does not yet include an overview of the spatial patterns of rainfall change in all models, we suggest adding a set of figures as Supplementary Material. These figures show the patterns of rainfall change for all 30 models (see attachment). This would allow the reader to better assess the Wet7 models in the context of the other models, thereby complementing Figure 1.

Apart from this, we would like to point out that the focus of the paper is not to prove that a non-linear intensification is going to happen in the future, nor to make any kind of statistical statement such as: “Most models show...” or even “X out of Y models show...”. The aim of the paper is to point out a possibility of future monsoon dynamics and to suggest a mechanism for that possibility.

To this end, it is not our goal to define an objective method for model selection. Our goal is to show that there are a significant number of models that exhibit a non-linear intensification of Sahel rainfall; and that these models are not simply outliers with particularly poor performance. The selection of the Wet7 models for further analysis has been based on a combination of different aspects: The magnitude of change in Sahel rainfall over the 21<sup>st</sup> century, and the location and spatial pattern of the rainfall changes. These aspects are difficult to combine into a single, objective measure, and we see no particular merit in doing so. Instead, we try to be as transparent as possible about our methods and the models that we selected, so that the reader can follow our line of analysis and, if need be, repeat the analysis with a different set of models. The supplementary figures mentioned above should help in this regard. We believe that any rule of selection would lead to a loss of information because we would have to either leave models out that show the phenomena or find a complicated selection rule that would be quite artificial.

We further note that the rainfall change shown in Figure 1 refers to the average over a common region (0-30°E, 10–20°N) for all 30 models. While the referee rightly points out that CanESM2 and NorESM1-M are “drier” than some other models in Figure 1, we nonetheless selected

CanESM2 because it exhibits a strong rainfall increase further east, as visible in Figure 4. Similarly, we selected NorESM1-M because, although somewhat weak in magnitude, its pattern of rainfall change is similar to that of the other Wet7 models, in the sense that it shows an increase particularly in the north-central Sahel region that is rather dry today. Nonetheless, one might argue to exclude NorESM1-M from the Wet7, or to include an eighth model; there is no obvious dividing line, but rather a gradient between the models as to how pronounced they show the effect that we want to demonstrate here. We note that we do not apply any statistics across models; each model is analyzed on its own, so if a model were to be removed from or added to the Wet7 subset, the results for the other models would remain unchanged.

We have rephrased the section on model selection as follows, including reference to the new Supplementary Figures (see also the revised manuscript, attached):

**“Three models (MIROC-ESM-CHEM, MIROC-ESM, BNU-ESM) project an increase of over 100% in average summer (July–September) rainfall across the central and eastern Sahel by the end of the 21st century (Fig. 1). Some other models (notably FGOALS-g2, MIROC5, CanESM2, NorESM1-M) project slightly smaller rainfall increases but with similar patterns as the three wettest models: a pronounced rainfall increase north and east of the present core monsoon region (Fig. 2; notice that while CanESM2 has only a moderate wetting trend over the central Sahel region analyzed in Fig. 1, it shows a strong rainfall increase in the eastern Sahel). This is in contrast to the majority of models which do not show a marked rainfall increase outside the present-day monsoon region (Supplementary Figures). We select the above-mentioned seven models—hereafter referred to as the “Wet7” subset—for further investigation, in order to elucidate possible mechanisms behind the strong rainfall increase in presently dry regions.”**

Note the reordering of the main Figures: previous Fig. 4 is now Fig. 2.

- 2) We would argue in a similar way with regard to the domain selection: There is no obviously “correct” way of selecting the spatial domains; instead, we show the locations of the domains we chose in relation to both the relative and the absolute rainfall change, so that the reader can see what is captured by these particular domains. In fact, we have already harmonized the locations and sizes of the terrestrial domains to some extent; the existing differences across models are due to differences in model resolution and to differences in the actual spatial patterns in which the rainfall changes occur (for example, we have chosen a more eastern domain for CanESM2). Our experience with different choices for these domains confirm the referee’s notion that “small differences in size/position should not produce large differences” in the results.
- 3) We believe this might be a misunderstanding caused by ambiguous language in our final paragraph. We do not mean to say that the non-linearity is more or less pronounced in the SST or GMT domain. Rather, we refer to the observation in Figure 7 that “the marked increase in Sahel rainfall begins at remarkably similar levels of SST change across the Wet7 models: Mostly

at around, or just below 1°C of SST warming”. In the GMT domain, the temperature at which the marked rainfall increase begins is less similar across the models, for the reasons that we mention.

We have amended the text as follows, and hope to be clearer now:

“Given the different regional distribution of the warming signal in different models and the fact that GMT and SST do not necessarily co-vary on an annual time scale, there is not as clear an association of the rainfall change with GMT change as with SST change: **The GMT level at which Sahel rainfall begins to increase strongly is somewhat different across the models.** However, it may be noted that in many of the models the “Paris range” of 1.5–2.0°C of global warming (UNFCC 2015) presents an approximate dividing line between the historical Sahel climate regime and a substantially wetter future climate.”

- 4) It would indeed be desirable to understand better the specific reasons for why a model does or does not exhibit a strong non-linear Sahel rainfall increase. However, we are afraid this is beyond the scope of the present paper. We hope that the paper may prompt other researchers – in particular those who are more familiar with individual models, e.g. the model developers – to investigate these processes in more detail, perhaps using designated model experiments.

b) The referee is absolutely right that our study focuses “on the mechanisms underlying the projections of a “wet” model subset”. As mentioned above, we suggest changing the title in order to not create a false impression of the scope of the study. We have also added the following text in the Conclusions section:

“The mechanism we suggest here would act on top of these two mechanisms, and help explain the abruptness of the Sahel rainfall response to global warming **seen in some models.**”

**“We have found a strong, non-linear Sahel rainfall increase only in a minority of the CMIP5 models, and we do not mean to imply that these particular model simulations are more realistic than others.”**

#### Minor comments:

Page 2, line 18: “pronounced rainfall increase north and west”, I see the rainfall increase north and east actually.

The referee is right, we have corrected this mistake.

Figure 1: I don’t see the discussion on the ability in modelling of drought crucial for the paper, which basically focuses on trends rather than multidecadal oscillations. Moreover, the discussion on the ability to reproduce multidecadal oscillations is rather concise and does not add much to the discussion. Even the ability of the Wet7 subset in simulating the big drought is questionable. Indeed, though Wet7 are

above the average, FGOALS-g2 simulates almost no drought, and CanESM2, BNU-ESM and NorESM1-M are just slightly dry. I suggest to remove this figure, because not crucial for the model selection.

We agree that the drought is not the focus of our paper. However, we believe that Figure 1 provides useful context for the entire model ensemble, and the relatively good performance of the Wet7 for the drought magnitude underlines the fact that these models are worth studying for this particular region, and are not some outliers which should not be trusted at all. We don't mean to suggest that the Wet7 are the "best" models. As stated in the manuscript, the analysis of the drought magnitude merely "may serve as an additional motivation to further study the future projections by these models, which we do in the following. We point out, however, that there is much variation among the Wet7 models themselves in terms of past and projected rainfall changes".

Figure 2: The MIROC5 ability in simulating the multidecadal variability is quite good in the second half of the century, and less good in the first half. Moreover, the assessment is only qualitative, not supported by any metric. Similarly to the comment above, I suggest to remove this argument to support the model selection.

Along the same lines as above, we would prefer to keep this part of the argument, because it contributes to elucidating the performance of the Wet7 models in the context of the full model ensemble. We would also not remove Figure 2 because it provides an overview of the model ensemble's future rainfall projections and thereby provides the reader with important contextual information. Previous reviewers also found this figure useful. We have rephrased the discussion of model selection, as mentioned above, and hope that it will become clear now that model selection is not based on the drought performance.

Figures 4-6: Statistical significance of the differences should be assessed.

We believe that showing both absolute and relative rainfall differences gives an idea about the significance of the differences compared to the overall magnitude, and is indeed more meaningful than some statistical measure of significance.

Figures 7, 8, 9 and 11: XY axes should share the same range, for better comparison.

Because the focus here is on the shape of the rainfall change over temperature over time, rather than on a comparison of the magnitude of change across models, we would prefer to keep the axes ranges as is, in order to provide good readability also for the lower-magnitude changes.

Conclusions: The inclusion of the Mediterranean role in the discussion is helpful for understanding the main idea of the study in a broader context. I think that this could be emphasised in the conclusions.

Thanks for this suggestion, which we have taken up in the revised text:

**“Our analysis also provides further evidence for the role of the Mediterranean Sea as a contributor to enhanced Sahelian moisture availability, which then further amplifies inflow from the North Atlantic through latent heating over the Sahel.”**

The referee also raises some questions referring to Figures S2, S3, and S4. We believe he is referring to an older manuscript version here, which was accompanied by a Supplement. In the last revision, we moved the Supplementary figures into the main manuscript, and there is no Supplement now.

Jacob Schewe, for the authors

01 June 2017

# Non-linear intensification of Sahel rainfall as a possible dynamic response to future warming

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**Abstract.** Projections of the response of Sahel rainfall to future global warming diverge significantly. Meanwhile, paleoclimatic records suggest that Sahel rainfall is capable of abrupt transitions in response to gradual forcing. Here we present climate modeling evidence for the possibility of an abrupt intensification of Sahel rainfall under future climate change. Analyzing 30 coupled global climate model simulations, we identify seven models where central Sahel rainfall increases by 40% to 5 300% over the 21<sup>st</sup> century, owing to a northward expansion of the West African monsoon domain. Rainfall in these models is non-linearly related to sea surface temperature (SST) in the tropical Atlantic and Mediterranean moisture source regions, intensifying abruptly beyond a certain SST warming level. We argue that this behaviour is consistent with a self-amplifying dynamic-thermodynamical feedback, implying that the gradual increase in oceanic moisture availability under warming could trigger a sudden intensification of monsoon rainfall far inland of today's core monsoon region.

## 10 1 Introduction

The Sahel is a wide semi-arid belt spanning the African continent south of the Sahara desert, and is home to a large population strongly reliant on agriculture (Sissoko et al., 2010). Its climate has been characterized by devastating droughts, such as in the 1970s and 80s (Folland et al., 1986; Zeng, 2003), alternating with episodes of abundant rainfall such as in the 1930s and 50s, and even destructive rain and flood events such as in 2007 (Tschakert et al., 2010; Tarhule, 2005). The 1970s/80s drought, 15 which resulted in persistent food shortage and widespread famine (Nicholson, 2013), has been attributed to anthropogenic reflective aerosols as well as variations in Atlantic sea surface temperature (SST), which may have been partly human-induced and partly due to natural variability (Giannini et al., 2003; Biasutti and Giannini, 2006). Rainfall has partially recovered more recently (Lebel et al., 2009), a trend that has been attributed both to the direct radiative effect of anthropogenic greenhouse gases (Dong and Sutton, 2015) and to SST warming, especially in the Mediterranean (Park et al., 2016).

20 While coupled climate models generally capture the temporal pattern of the 1970s/80s drought (Biasutti and Giannini, 2006), most simulations from the recent Coupled Model Intercomparison Project phase 5 (CMIP5) underestimate its magnitude Biasutti (2013). At the same time, projections of future rainfall changes diverge substantially across the models (Power et al., 2012). The CMIP5 multi-model mean was shown to exhibit only a slight increase in overall Sahel rainfall (Fontaine et al., 2011; Biasutti, 2013), with a wetting trend over the central and eastern Sahel and drying over the westernmost part, under the

highest Representative Concentration Pathway (van Vuuren et al., 2011), RCP8.5. Individually, some of the models project a much stronger rainfall increase, while others even project an overall decrease.

This uncertainty in future projections raises questions about potential mechanisms of change that may be present in some models but not others, and that may be responsible for the large differences between models. In particular, paleoclimatic records suggest that Sahel rainfall is capable of abrupt transitions in response to gradual forcing (DeMenocal et al., 2000; McGee et al., 2013); and theoretical studies have demonstrated that such a non-linear response can in principle arise from internal monsoon dynamics (Levermann et al., 2009; Seshadri, 2016). In this study, we examine Sahel rainfall in state-of-the-art climate model simulations and show that in those models that exhibit the strongest rainfall increase, this increase is non-linearly related to the SST warming in the tropical North Atlantic and Mediterranean moisture source regions. We argue that this behaviour is consistent with the theory and paleoclimatic evidence mentioned above. Considering that this non-linear rainfall response may be more pronounced in some models than in others may contribute to understanding the differences between the models' future projections.

## 2 Methods and Results

We investigated Sahel rainfall in 30 Coupled Model Intercomparison Project phase 5 (CMIP5) global climate models under RCP8.5 (see Appendix A). Three models (MIROC-ESM-CHEM, MIROC-ESM, BNU-ESM) project an increase of over 100% in average summer (July–September) rainfall across the central and eastern Sahel by the end of the 21<sup>st</sup> century (Fig. 1). Some other models (notably FGOALS-g2, MIROC5, CanESM2, NorESM1-M) project slightly smaller rainfall increases but with similar patterns as the three wettest models: a pronounced rainfall increase north and east of the present core monsoon region (Fig. 2; notice that while CanESM2 has only a moderate wetting trend over the central Sahel region analyzed in Fig. 1, it shows a strong rainfall increase in the eastern Sahel). This is in contrast to the majority of models which do not show a marked rainfall increase outside the present-day monsoon region (Supplementary Figures). We select the above-mentioned seven models—hereafter referred to as the “Wet7” subset—for further investigation, in order to elucidate possible mechanisms behind the strong rainfall increase in presently dry regions. We note that the Wet7 can largely account for the positive rainfall trend that has been found in the CMIP5 ensemble as a whole (cf. Roehrig et al., 2013; Park et al., 2015): The Wet7 multi-model mean shows a doubling of average summer rainfall by 2100 (Fig. 3). In contrast, the mean over the 23 other models exhibits only a weak wetting trend of less than 20%; trends in the individual models are small and some models even show a drying trend.

Although we focus here on the future projections, we also note that the Wet7 models perform better than average in reproducing the magnitude of the 1970–1989 drought period, the three MIROC models especially being very close to observed values (orange lines in Fig. 1, and inset in Fig. 3). This observation is consistent with a more comprehensive analysis of the CMIP5 models for the historical period (Biasutti, 2013), which found that past multi-decadal variability is underestimated by all except a few models, one MIROC model among them. It may serve as an additional motivation to further study the future projections by these models, which we do in the following. We point out, however, that there is much variation among the Wet7 models themselves in terms of past and projected rainfall changes, and the dynamical features discussed below may be more

or less developed in different models. We use the wettest model, MIROC-ESM-CHEM, to illustrate our discussion, and show the other six models as evidence that our findings are not exclusive to just one model.

The seasonal distribution of the rainfall change in the Wet7 shows a clear monsoonal shape, despite considerable spread in its magnitude (Fig. 3). Generally, the rainfall increase occurs over a broad region between 10 and 20°N, i.e., extending into today's Sahara desert (Fig. 4). Conversely, rainfall decreases somewhat in the more humid regions around the Gulf of Guinea and the West coast. This pattern corresponds to an inland shift compared to the present-day rainfall regime. At the same time, the near-surface, southwesterly winds intensify in the northern and eastern parts of the Sahel, near the positive rainfall anomaly, while they do not change much near the coast (Fig. 5). This suggests that the rainfall increase is not simply a consequence of thermodynamic changes (higher water-holding capacity of warmer air), but goes together with a shift in West African monsoon circulation dynamics.

Sahel rainfall has been linked to Atlantic as well as Mediterranean SSTs via evaporation rate and moisture supply (e.g. Giannini et al., 2003; Rowell, 2003). In order to examine temporal patterns of rainfall and SST change more closely, we average each model's summer rainfall over a rectangular subregion of the Sahel (solid boxes in Fig. 4 and 5). The subregions are chosen to encompass an area where the rainfall increase is substantial in both absolute (Fig. 4) and relative terms (Fig. 5), and to be similar in size and location across the different models' grids (except for CanESM2 where the rainfall increase is located further east than in the other models). Thus, the subregions are generally located northward of the present-day core monsoon regions, which also see rainfall increases but less pronounced in relative terms. Similarly, we identify for each model one region in the tropical North Atlantic ocean and one in the Mediterranean Sea (dashed boxes in Fig. 4) as the main sources of additional moisture influx into the Sahel, based on the lower-troposphere moisture flux changes (arrows in Fig. 4).

Moisture influx from both sources into North Africa is projected to increase in the Wet7 models (Fig. 2). However, moisture flux from the Atlantic into the Sahel subregion increases more strongly than from the Mediterranean by the end of the 21<sup>st</sup> century (Fig. 2 and 6). Moreover, only the Atlantic branch is accompanied by an increase in near-surface wind speed (Fig. 5). Thus, while the increased moisture import from the Mediterranean appears to be due to higher SST and evaporation alone, increased wind speed further amplifies moisture import from the Atlantic; a mechanism already proposed by Rowell (2003).

Sahel rainfall generally increases as the surface of the oceanic moisture source regions warms (Fig. 7 and 8). But this relation is not linear. Rainfall shows little response to SST changes within a range of approx. 1°C around the present-day value; but when SST increases beyond this point, rainfall shifts abruptly to a stronger level, where it then keeps increasing as SST rises further. Given the convex shape of the temperature forcing over time, the abruptness of the rainfall response is expected to be less apparent in the time domain; nonetheless, rainfall appears relatively stable over the historical period, before it begins increasing strongly in the 21<sup>st</sup> century (Fig. 9).

Numerous paleoclimatic reconstructions reveal abrupt shifts in monsoon systems in Asia (Gupta et al., 2003; Wang et al., 2008) and Africa (DeMenocal et al., 2000; McGee et al., 2013; Weldeab et al., 2007) before and throughout the Holocene. In those cases, external forcing through changes in solar insolation was much more gradual than that associated with modern anthropogenic climate change. A physical mechanism has been proposed to explain such abrupt shifts in large-scale monsoon rainfall in response to gradual forcing (Levermann et al., 2009, 2016): While the summer monsoon circulation is initiated

by differential warming of land and ocean in spring, it is latent heat release from precipitation that maintains the land–sea atmospheric temperature contrast throughout the summer and thus drives the monsoon winds into the continental interior. The monsoon winds in turn supply the moisture necessary to maintain precipitation. Summer monsoon rainfall is thus powered by a positive feedback between moisture inflow and atmospheric heating. This positive moisture–advection feedback gives rise to a threshold behaviour with respect to external quantities that govern the energy budget of the monsoon; in particular, in this simplified theory, there is a minimum atmospheric humidity in the oceanic moisture source region below which such a monsoon circulation cannot be maintained (Schewe et al., 2012).

This framework has been used to explain abrupt variations in monsoon strength documented in Asian speleothem (Schewe et al., 2012) and pollen records (Herzschuh et al., 2014), but has not yet been applied to modern monsoon systems. We suggest that it is also useful for understanding the projected Sahel rainfall changes in the Wet7 models. Today, the West African monsoon is most active between the Gulf of Guinea coast and the southern edge of the Sahel (Nicholson, 2013). Rainfall declines towards the continental interior, and while central and eastern Sahel rainfall still exhibits a clear seasonality, it is relatively weak and erratic (compared to e.g. the Indian monsoon with its intense rainfall throughout much of the subcontinent). An increase in evaporation due to ocean warming in the tropical North Atlantic and the Mediterranean increases moisture availability. Once atmospheric humidity exceeds the monsoon threshold even in the more continental parts of the Sahel, the moisture–advection feedback can amplify the monsoon response by enhancing the westerly monsoon winds and thus the moisture influx from the North Atlantic. These inland regions thereby become increasingly connected with the oceanic moisture source, and benefit from further increases in oceanic evaporation.

This framework can explain the observed shape of the rainfall response in both the time and SST domains (Fig. 10): The functional form of the rainfall–SST relationship found in the Wet7 models (most prominently in MIROC–ESM–CHEM) resembles the concave form and threshold behaviour that arises from the above theory; given the convex form of mean SST forcing under global warming, the resulting pattern of rainfall over time is one where rainfall is relatively stable and low up to a certain point and then starts rising quasi–linearly.

### 3 Discussion and Conclusions

This explanation of an abrupt intensification of inland monsoon rainfall in the Sahel region is consistent with studies suggesting a substantially wetter Sahel, and Sahara, region in past climates compared to today (DeMenocal et al., 2000; Gasse, 2000). It is also consistent with theories linking rainfall changes in the Sahel to a combination of a local (through radiative forcing changes) and a remote (through tropical SST impacts on atmospheric stability) forcing mechanism (Giannini, 2010; Giannini et al., 2013; Seth et al., 2010). In a warming world, the remote mechanism would increase atmospheric stability especially in places with oceanic influence, and make it harder for convection to set in. Acting in the other direction, the local mechanism would directly warm the surface and decrease vertical stability over land. The mechanism we suggest here would act on top of these two mechanisms, and help explain the abruptness of the Sahel rainfall response to global warming **seen in some models**. It would particularly affect the more continental parts of the region. We note that part of the increased moisture influx is through

westerly winds near 10°N, a flow called the West African Westerly Jet (Pu and Cook, 2010, 2012). While its intraseasonal dynamics are somewhat distinct from the more southerly monsoon flow across the Gulf of Guinea, on a seasonal timescale both are driven by the pressure—and thus, temperature—gradient between the eastern Atlantic and the Sahel, and would be subject to the dynamical feedback mechanism described above. Our analysis also provides further evidence for the role of the

5 Mediterranean Sea as a contributor to enhanced Sahelian moisture availability, which then further amplifies inflow from the North Atlantic through latent heating over the Sahel.

We have found a strong, non-linear Sahel rainfall increase only in a minority of the CMIP5 models, and we do not mean to imply that these particular model simulations are more realistic than others. Consideration of the mechanism demonstrated here may, however, help to make sense of the diversity of model projections, and eventually establish a more consistent un-

10 derstanding of the Sahel's future climate in a warming world. We also note that the marked increase in Sahel rainfall begins at remarkably similar levels of SST change across the Wet7 models: Mostly at around, or just below 1°C of SST warming (Fig. 7).

In order to put these regional climatic changes in the context of global anthropogenic warming, we also show the projected Sahel rainfall changes over global mean temperature (GMT) change (Fig. 11). Given the different regional distribution of the warming signal in different models and the fact that GMT and SST do not necessarily co-vary on an annual time scale, there is

15 not as clear an association of the rainfall change with GMT change as with SST change: The GMT level at which Sahel rainfall

begins to increase strongly is somewhat different across the models. However, it may be noted that in many of the models the “Paris range” of 1.5–2.0°C of global warming (UNFCCC, 2015) presents an approximate dividing line between the historical Sahel climate regime and a substantially wetter future climate.

## Appendix A: Models and data

20 We analyzed simulations from the BNU-ESM, CanESM2, FGOALS-g2, MIROC-ESM-CHEM, MIROC5, MIROC-ESM, NorESM1-M (Wet7 subset), ACCESS1-0, ACCESS1-3, CESM1-BGC, CESM1-CAM5, CMCC-CM, CMCC-CMS, CMCC-CESM, CNRM-CM5, EC-EARTH, FIO-ESM, GFDL-CM3, GFDL-ESM2M, GFDL-ESM2G, GISS-E2-H, GISS-E2-R, HadGEM2-ES, HadGEM2-CC, Inmcm4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MRI-CGCM3, and MPI-ESM-MR global climate models, driven by historical forcing and the RCP8.5 greenhouse gas concentration scenario (Taylor et al., 2012; Meinshausen et al., 2011). Simulation data was obtained from the CMIP5 archive at <http://cmip-pcmdi.llnl.gov/cmip5/>. Where several realizations of the same model simulation were available, we used the r1i1p1 configuration, since this one was available from all models. Near-surface wind data was not available for FGOALS-g2, therefore we show 850mb wind. CRU TS3.1 monthly precipitation data was obtained from <http://badc.nerc.ac.uk>.

30 *Author contributions.* J. Schewe and A. Levermann designed the research. J. Schewe carried out the analysis and wrote the paper, with contributions from A. Levermann.

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

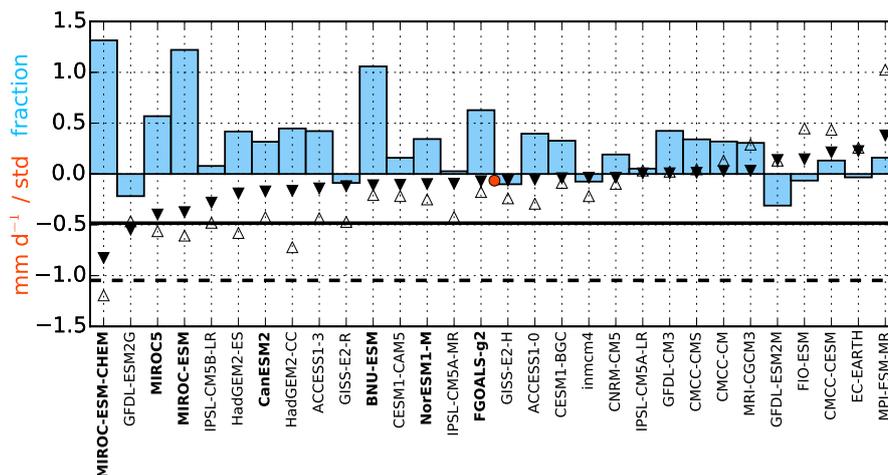
*Acknowledgements.* We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output. J.S. received funding through the Leibniz society's EXPACT project (SAW-2013-PIK-5).

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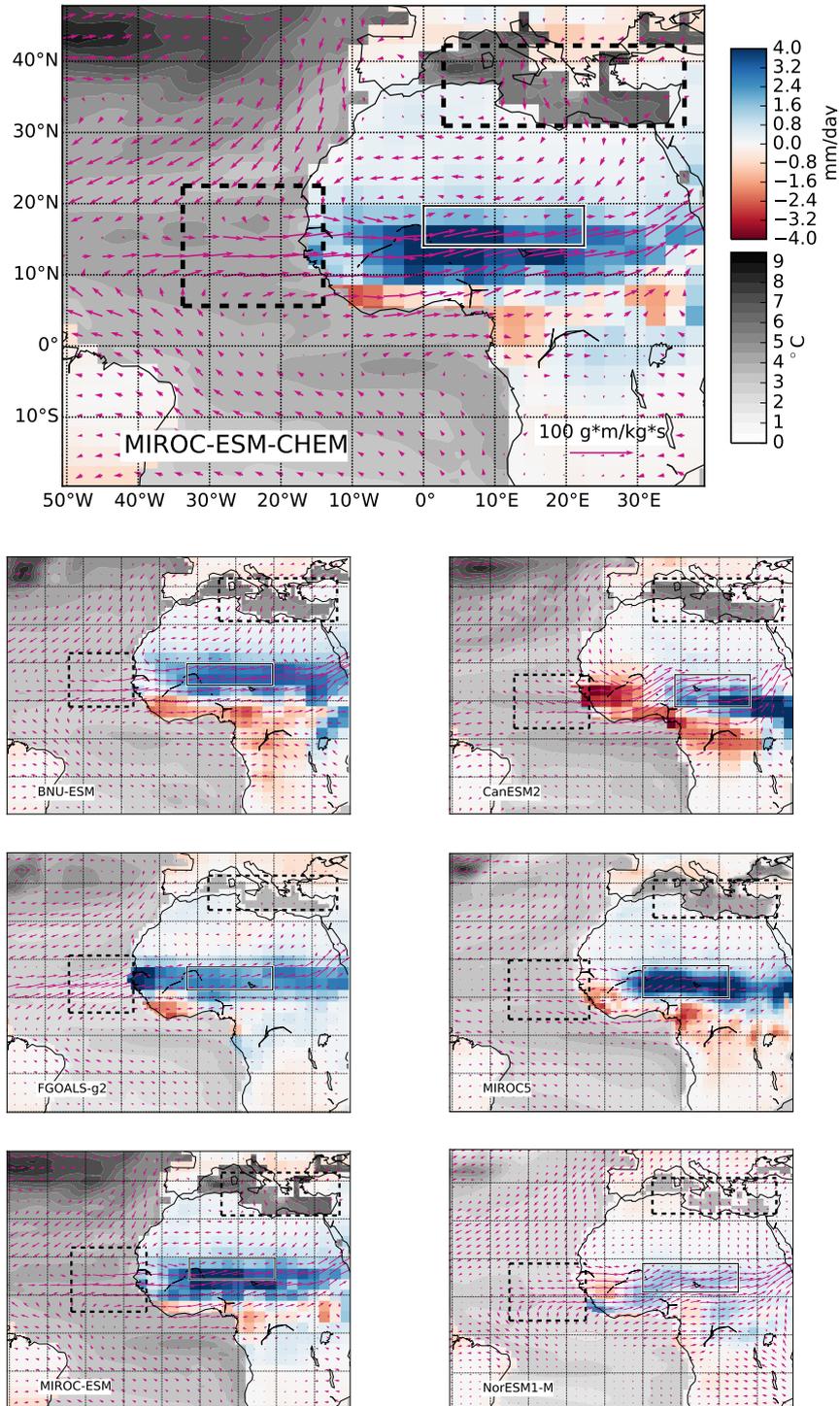
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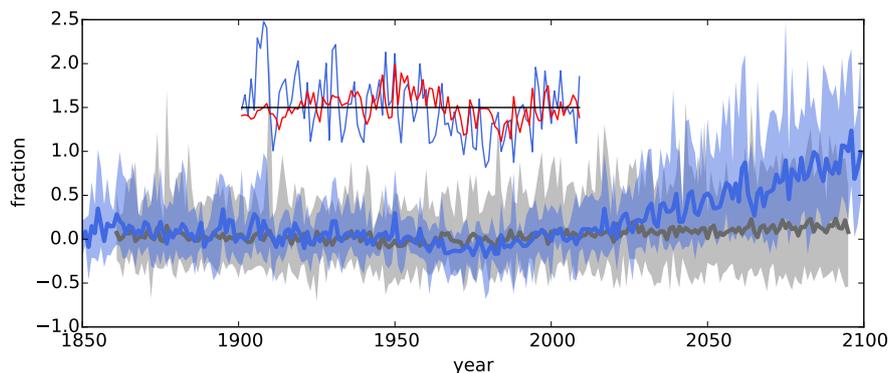
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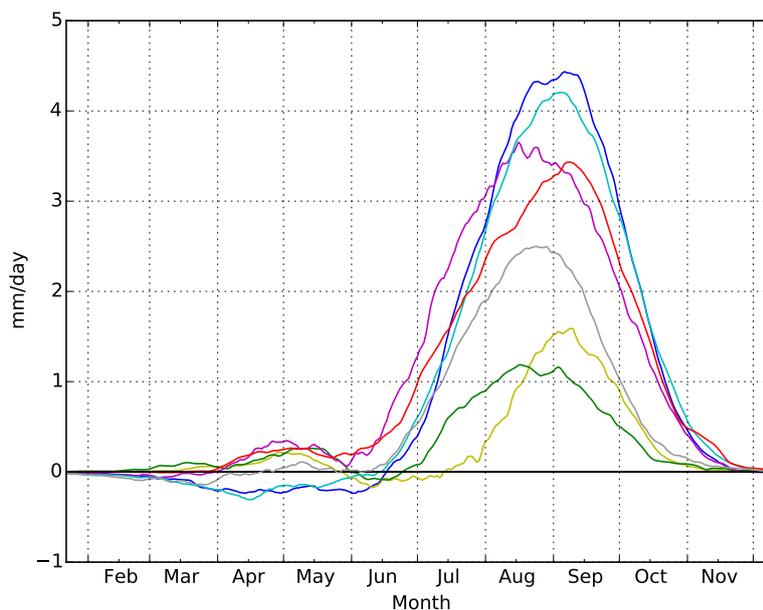
**Figure 1.** Past and future Sahel summer rainfall in CMIP5 coupled climate models. Blue bars show the change in central and eastern Sahel average summer rainfall (0–30°E, 10–20°N, July–September) by the end of the century (2071–2095) under RCP8.5 compared to the 1901–1999 average fraction of that average. The seven models investigated in detail in this paper (Wet7 subset) are marked in bold. Filled triangles show the difference (drought minus non-drought) between the 1970–1989 drought period and the rest of the observational period (“non-drought”, 1901–1969 and 1990–2009), in mm/day. Open triangles show the same difference divided by the standard deviation of the non-drought period, in units of standard deviations. The solid and dashed horizontal lines show the respective observed values (CRU TS3.1, Harris et al. (2014)). The orange circle indicates the median deviation from the observed drought–non-drought difference across the model ensemble; i.e. models shown to the left of this point are closer than average to the observed value.



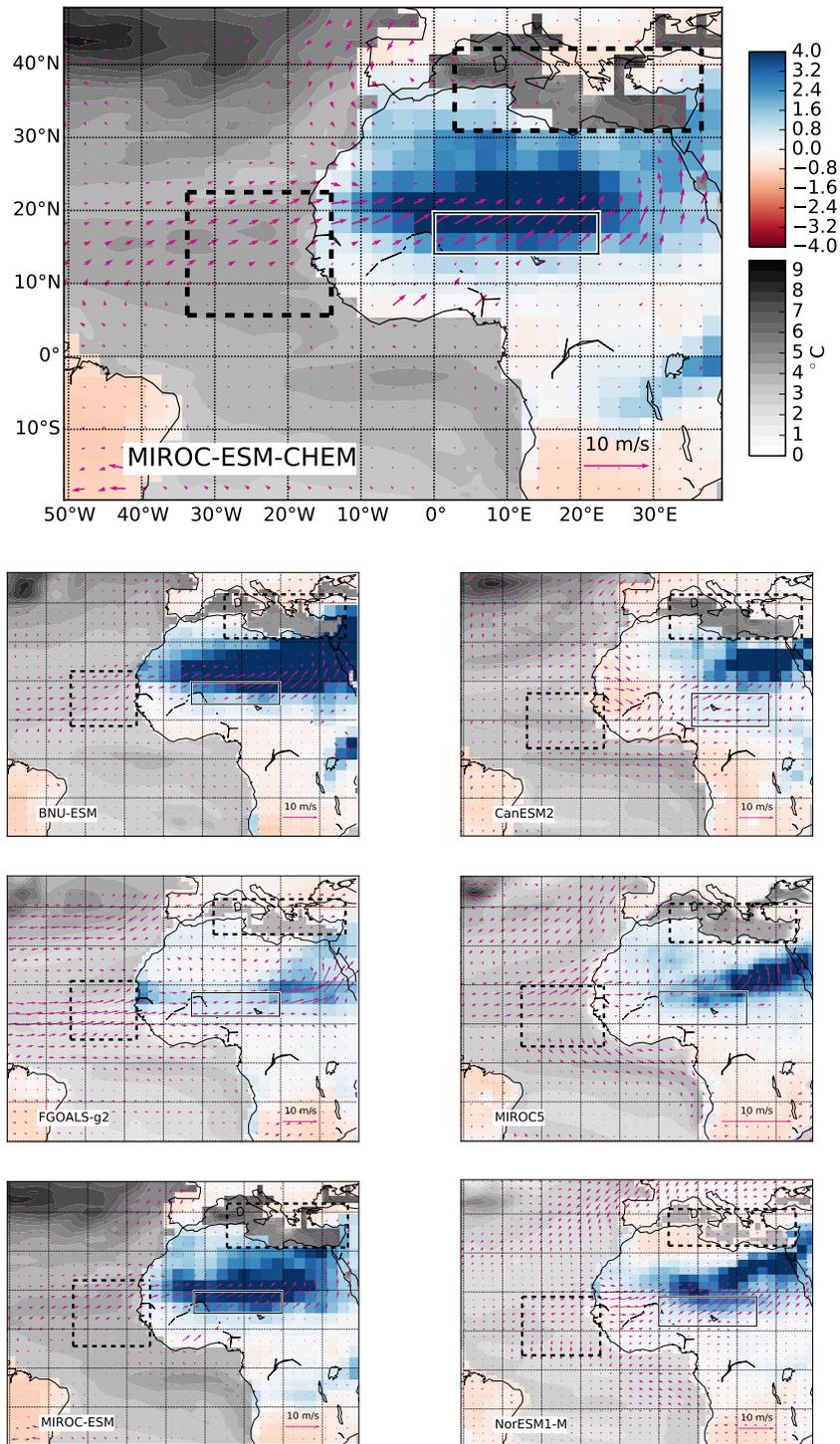
**Figure 2.** Simulated changes in Sahel summer climate under RCP8.5 in the Wet7 models. For each model the differences in July–September rainfall (colours), sea surface temperature (SST, greyscale; contour spacing is 0.5K), and moisture flux integrated vertically over the three bottom–most pressure levels (1000, 925, and 850 mb; arrows) are shown between the 20<sup>th</sup> century (1900–1999) and the end of the 21<sup>st</sup> century (2070–2099). Solid (dashed) boxes show the regions over which rainfall (SST) differences are averaged for Fig. 7 and the following figures. The color scale, vector scale, and coordinate labels of the top panel apply to all panels.



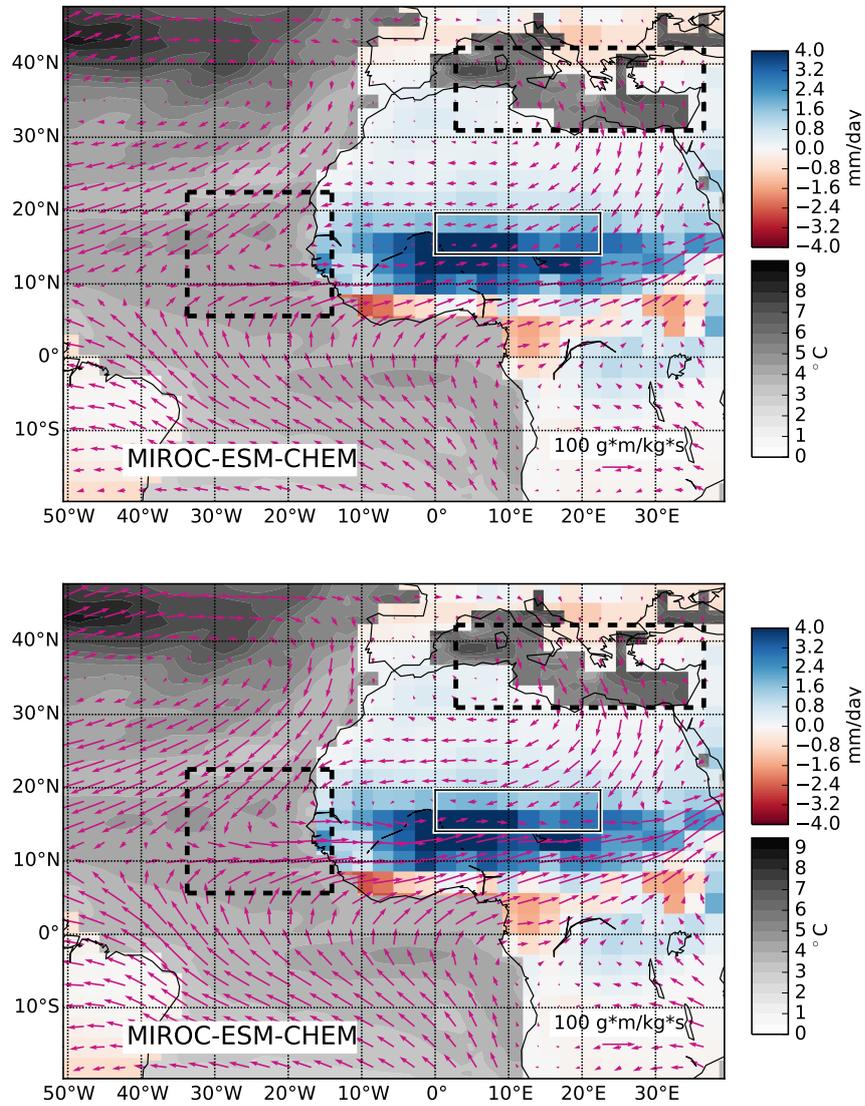
**Figure 3.** Sahel summer rainfall in two model subsets and in observations. Shading shows the envelopes (minimum and maximum among models) of Sahel summer rainfall ( $0\text{--}30^\circ\text{E}$ ,  $10\text{--}20^\circ\text{N}$ , July–September) in the Wet7 subset (blue) and in 23 other CMIP5 models (grey) under historical forcing and the RCP8.5 greenhouse gas concentration scenario. Shown is the deviation from the 1900–1999 average, as fraction of that average. The thick lines indicate the averages of each set of models. Data between 1850–1860 and between 2095–2100 was unavailable for some of the models, therefore the grey line and shading only extend from 1860–2095. The inset shows the CRU TS3.1 observational data set covering 1901–2009 (red) and the corresponding portion of the MIROC–ESM–CHEM simulation (blue), in the same units as the other data but offset by 1.5 in the vertical for clarity.



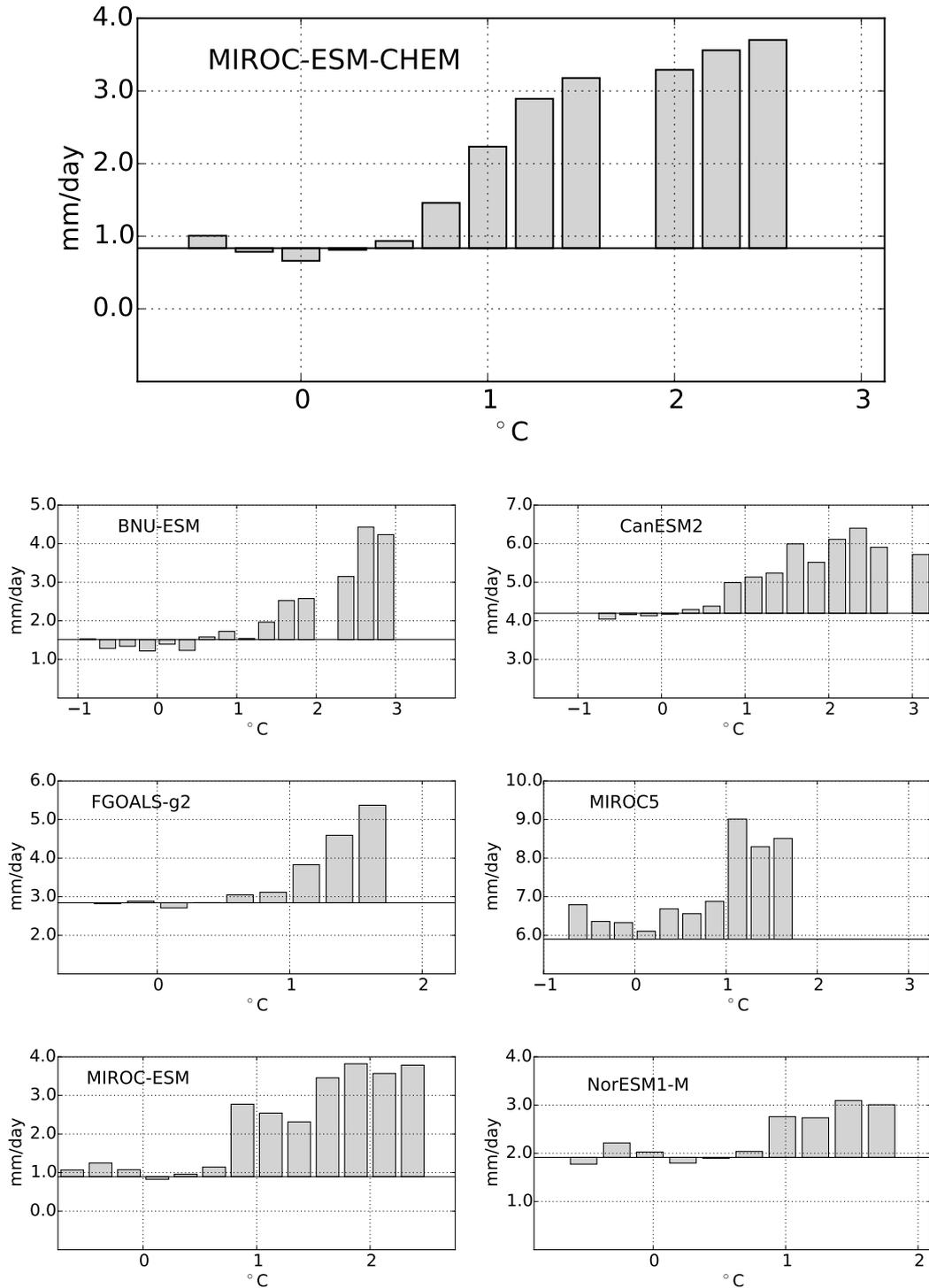
**Figure 4.** Change (future minus past) in average Sahel ( $0\text{--}30^\circ\text{E}$ ,  $10\text{--}20^\circ\text{N}$ ) daily precipitation between the end of the 20<sup>th</sup> century (1970–1999) and the end of the 21<sup>st</sup> century (2070–2099), in the Wet7 models. All timeseries filtered with a 6–week running mean.



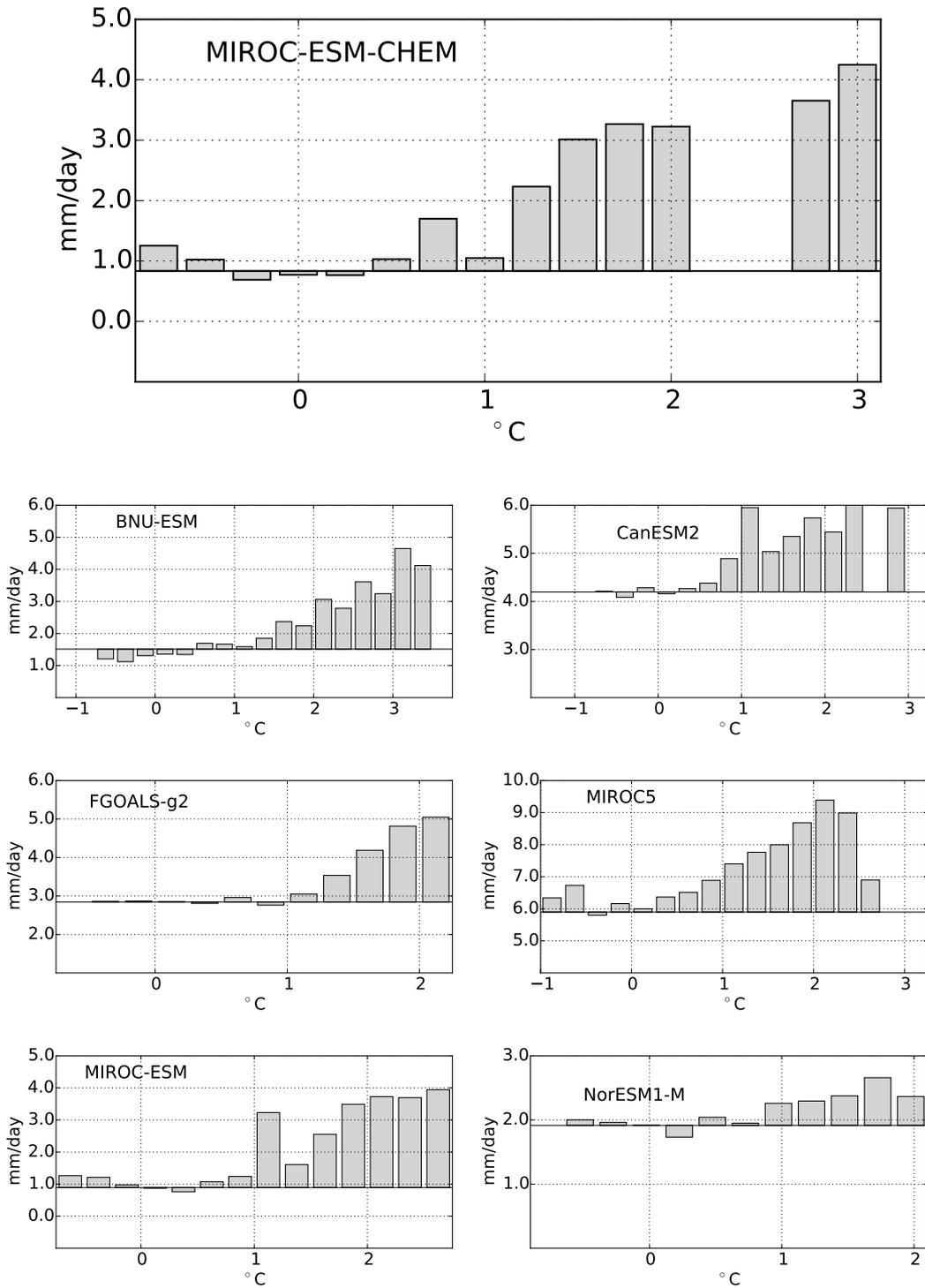
**Figure 5.** As Fig. 2, but colours show relative (rather than absolute) rainfall differences, in multiples of the reference value; and arrows show changes in near-surface winds (850mb winds for FGOALS-g2, where near-surface wind speed was not available).



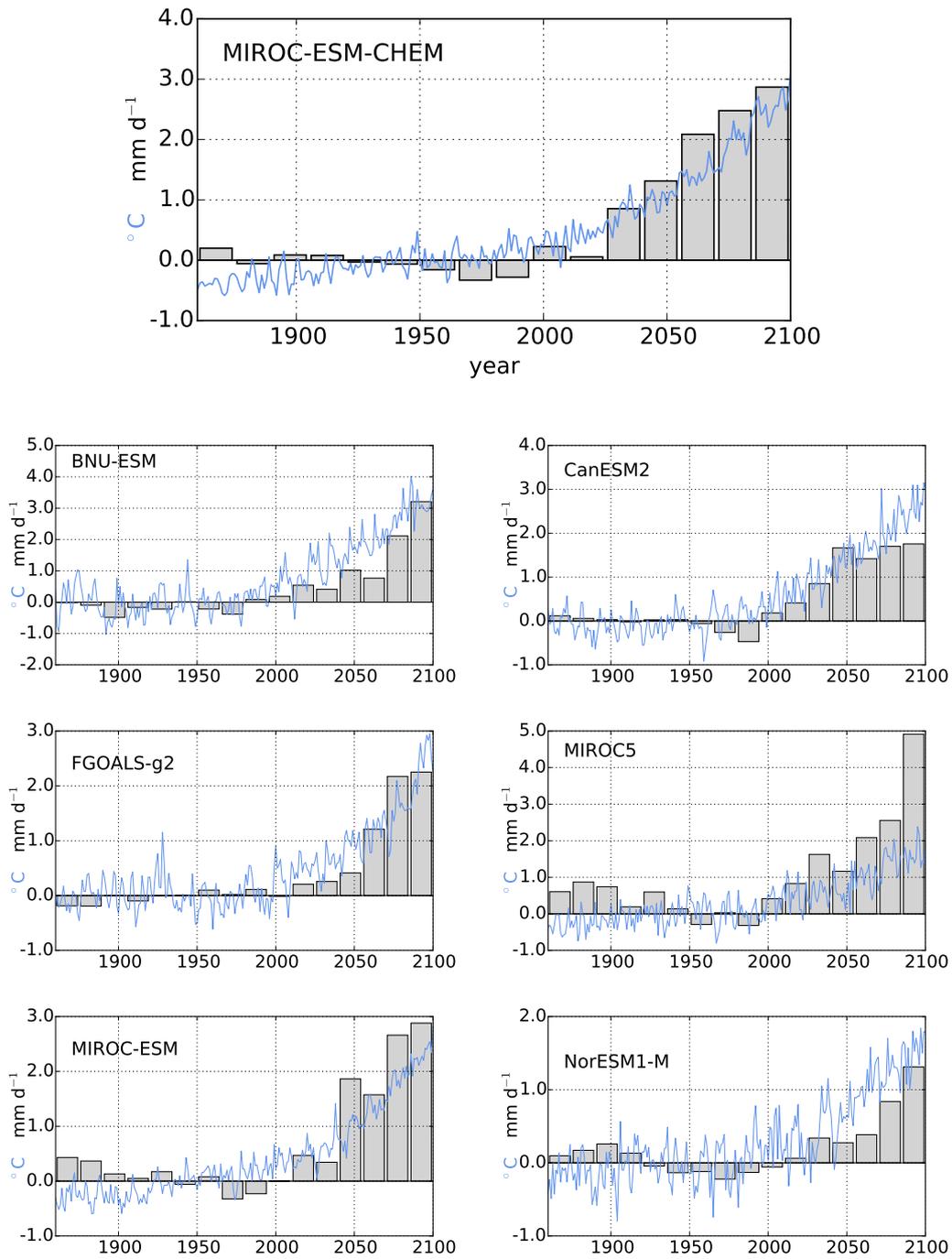
**Figure 6.** As top panel in Fig. 2 but showing absolute moisture flux in the 20<sup>th</sup> century (1900–1999, top) and the end of the 21<sup>st</sup> century (2070–2099, bottom).



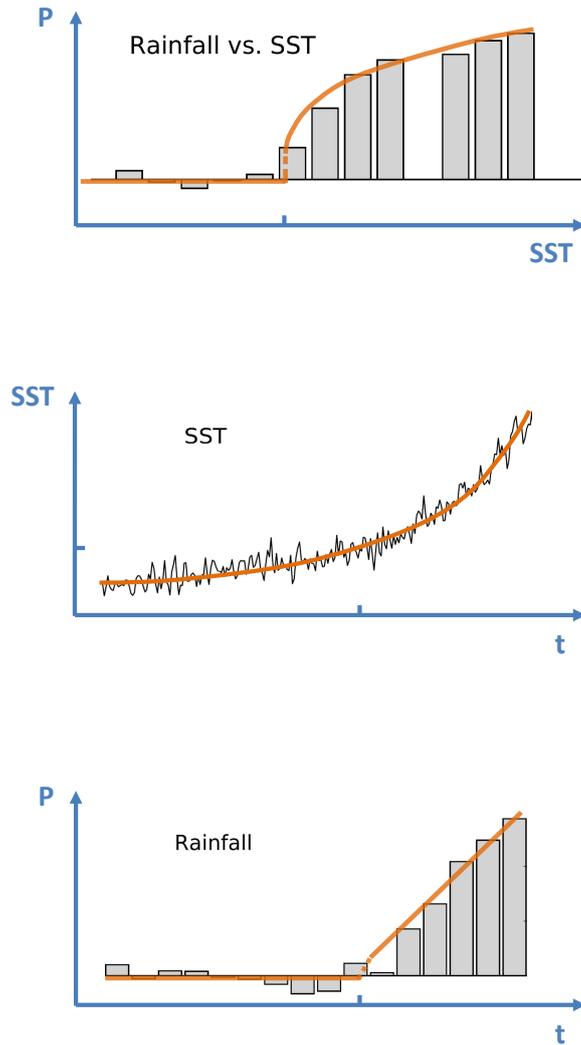
**Figure 7.** Median Sahel July–September rainfall for different intervals of tropical North Atlantic SST change (interval width 0.25°C), including all data between 1850 and 2100. Bars illustrate the deviation from the 1900–1999 rainfall average (horizontal black line), and SST change is also relative to the 1900–1999 average. Bars are only shown if at least 5 years fall into the respective temperature interval. Rainfall and SST are averaged over the corresponding boxes shown in Fig. 2 and 5.



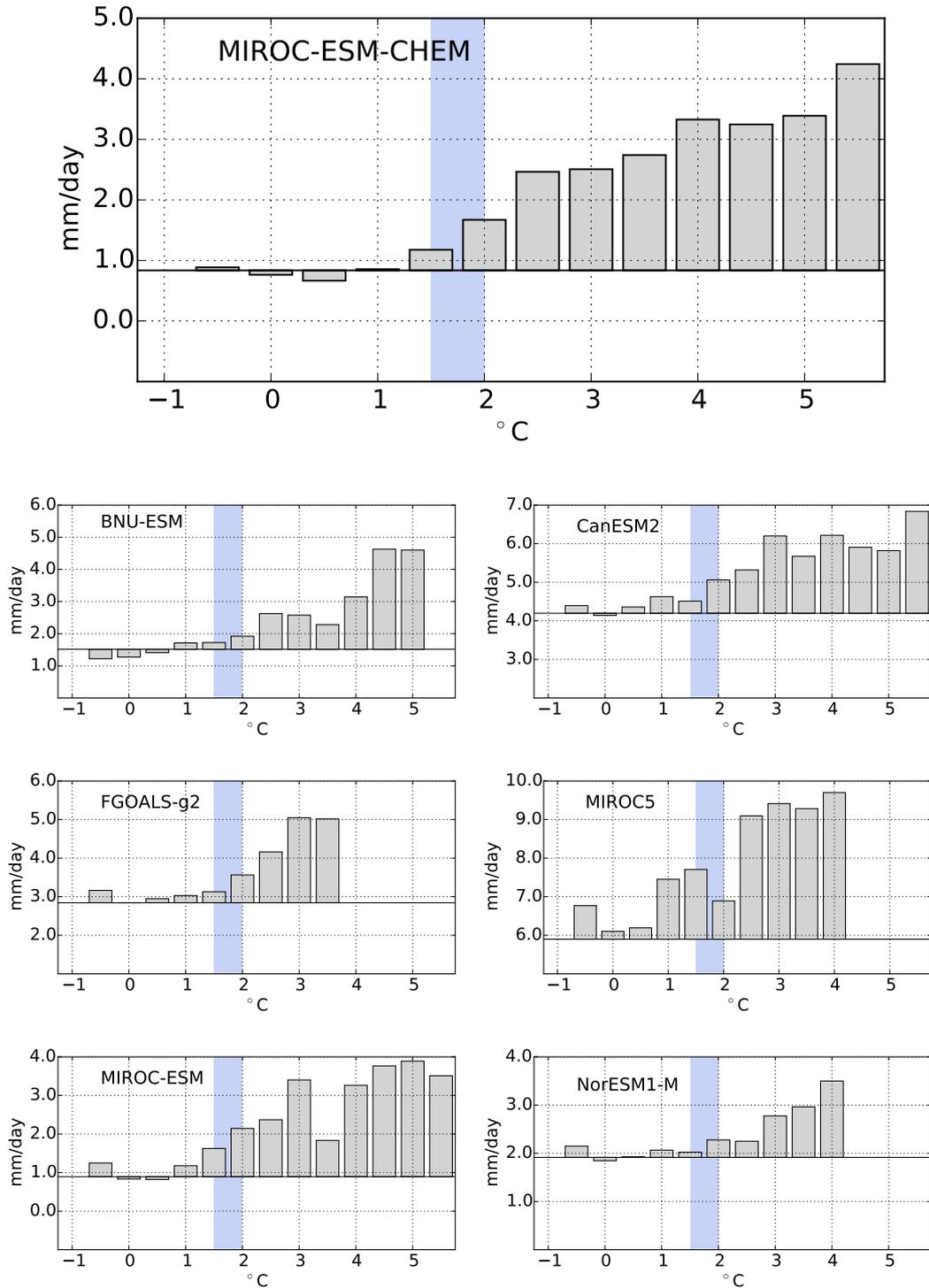
**Figure 8.** As Fig. 7 but for Mediterranean SST change.



**Figure 9.** Mean Sahel July–September rainfall in 15-year intervals. Bars illustrate the deviation from the 1900–1999 rainfall average (horizontal black line), in mm/day. Blue line shows yearly July–September tropical North Atlantic SST, in °C (same axis).



**Figure 10.** Comparison of model simulations with the concept of a monsoon threshold. Data are from the MIROC-ESM-CHEM simulation, and are identical to the data shown in the top panels of Fig. 7 and 9; they are shown here without labels to emphasize the functional form. Orange lines (with blue axes) show illustrative functional forms that qualitatively match those of the simulation data, and are consistent with analytical results from a minimal monsoon model (Schewe et al., 2012): The moisture–advection feedback implies that no continental monsoon exists below a certain threshold (blue tick mark) in the energy budget—here controlled by sea surface temperature (SST)—, whereas above the threshold, monsoon intensity is a concave function of SST (top). In combination with a convex SST evolution (middle), this behaviour can give rise to the observed rainfall evolution over time, where rainfall is relatively stable and low up to a certain point and then starts rising quasi-linearly.



**Figure 11.** As Fig. 7, but with global mean temperature (GMT) change on the horizontal axis, instead of SST change. The blue shading marks the “Paris range”, i.e. the global warming levels consistent with the United Nations’ 2015 Paris Agreement (UNFCC, 2015).