nature climate change

LETTERS

PUBLISHED ONLINE: 27 JUNE 2016 | DOI: 10.1038/NCLIMATE3065

Anthropogenic Mediterranean warming essential driver for present and future Sahel rainfall

Jong-yeon Park[1,2*†], Jürgen Bader[1,3] and Daniela Matei[1]

The long-lasting Sahel drought in the 1970s and 1980s caused enormous human and socio-economic losses[1], driving extensive research on its causes[2–8]. Although changes in global and regional sea surface temperatures (SSTs) are thought to be dominant drivers of the severe Sahel drying trend[9–12], the mechanisms for the recent recovery trend are not fully clear yet, but are often assumed to be akin to the previous SST–Sahel drought linkage[13–15]. Here we show, by analysing observational and multi-model data and conducting SST-sensitivity experiments with two state-of-the-art atmospheric models, that the SST key area causing the recent Sahel rainfall recovery is the Mediterranean Sea. Anthropogenic warming of this region has driven the shift from the tropical Atlantic and Indo-Pacific oceans, which historically were the main driver of Sahel drought. The wetting impact of Mediterranean Sea warming can become more dominant in a future warming climate and is key to understanding the uncertainty in future Sahel rainfall projections.

The summer rainfall over the semiarid African Sahel is known for its pronounced multi-decadal variability over the past century[2]. In particular, the persistent Sahel drought in the 1980s is the strongest inter-decadal climate signal among all recent observational records in global monsoon regions[16]. Intensive studies on the outstanding drying trend have shown that oceanic forcing is the dominant driver of the observed low-frequency variability of Sahel rainfall[3,9–12], with land surface feedbacks only amplifying the SST-driven rainfall anomalies[7]. The underlying SST changes associated with the historical Sahel drought include anomalies mainly in the Atlantic[17,18] and Indo-Pacific[4,9], with the Mediterranean SST anomalies acknowledged to partly contribute to the drought period[10]. An interhemispheric asymmetry of global SST anomalies that may include some of the aforementioned regional SST anomalies has been also recognized as an important component of the Sahel rainfall change by meridionally shifting the tropical rainbelt[2,19]. Additional forcing from aerosols and greenhouse gases may contribute to the rainfall change by the direct radiative impact on local land surface processes and the indirect impact via changes in global SSTs[8].

In contrast to the extensive research on the severe Sahel drying trend during 1950–1990, the cause of the recent wetting trend since the 1990s has not been fully elucidated. Rather, the same mechanism causing the Sahel drought is often assumed to hold for the recent wetting trend. Given the time-varying SST–Sahel rainfall relationship[13] and the recently occurring climate shifts in global oceans[20,21], however, a different mechanism may be responsible for the recent Sahel wetting. In particular, tropical convection, which can excite atmospheric waves and link remote SST forcing to Sahel rainfall responses, is sensitively dependent on the mean state of the atmospheric boundary layer[22]. In this regard, the previously known pathway of SST impact might be modified by the increased tropical mean SST observed in recent years. Therefore, we will examine the detailed mechanisms of Sahel rainfall changes in a warming climate by focusing on the recent Sahel wetting.

Since the 1970s, summer Sahel rainfall shows a marked contrast with drying conditions until the mid-1980s and wet conditions afterward (Fig. 1a). The composite difference of SST between wet and dry years exhibits an interhemispheric contrast of SST anomalies, including a positive north–south SST gradient across the tropical Atlantic and cooling in the Indian Ocean and eastern Pacific. This SST pattern is robust even when using the precipitation and SST data from different observational products and generally consistent with the SST difference between wet years in the 1950/60s and dry years in the 1970/80s[2] (Supplementary Fig. 5). Thus, it might be tempting to conclude that the same mechanism governing the past Sahel rainfall change holds for the recent period of Sahel wetting. However, the magnitudes of SST anomalies in the tropics, a key area for understanding Sahel rainfall variations until the mid-1980s, are still quite different in the past and recent periods. Moreover, even the same magnitude of SST anomalies may trigger different atmospheric teleconnections of SST impact due to the recent tropical warming trend, suggesting the necessity of careful examination of the recent SST–Sahel relationship.

The role of the recent SST changes in forcing the Sahel wetting is investigated by performing a series of SST-sensitivity experiments with an atmospheric general circulation model (AGCM). The model used here is ECHAM6, the latest version of the atmospheric component of the Max Planck Institute Earth System Model. ECHAM6 shows a good performance in capturing the observed characteristics of West African monsoon rainfall (Supplementary Figs 1 and 2).

The modelled rainfall response to the global SST anomalies in Fig. 1b shows a significant increase in Sahel rainfall (Fig. 1c and Supplementary Fig. 6a). This suggests that the recent Sahel wetting can be explained by SST changes, which may support the previously known wetting effect of the positive north–south tropical Atlantic gradient and Indo-Pacific cooling. However, further experiments forced by the composite SST anomalies restricted to the tropics and extratropics show that the recent Sahel rainfall increase mostly results from the Northern Hemisphere (NH) extratropical SST anomalies, not from the tropical SST patterns. In fact, the tropical SST anomalies turn out to have a significant drying impact on the Sahel. This result differs from earlier studies in that forcing from the tropical oceans, such as the tropical Atlantic, Indian and Pacific

[1]Max Planck Institute for Meteorology, Hamburg 20146, Germany. [2]Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, New Jersey 08540, USA. [3]Uni Climate, Uni Research & the Bjerknes Centre for Climate Research, Bergen 5007, Norway. [†]Present address: Program in Atmospheric and Oceanic Sciences, Princeton University, 201 Forrestal Road, Princeton, New Jersey 08540, USA. *e-mail: jongyeon@princeton.edu

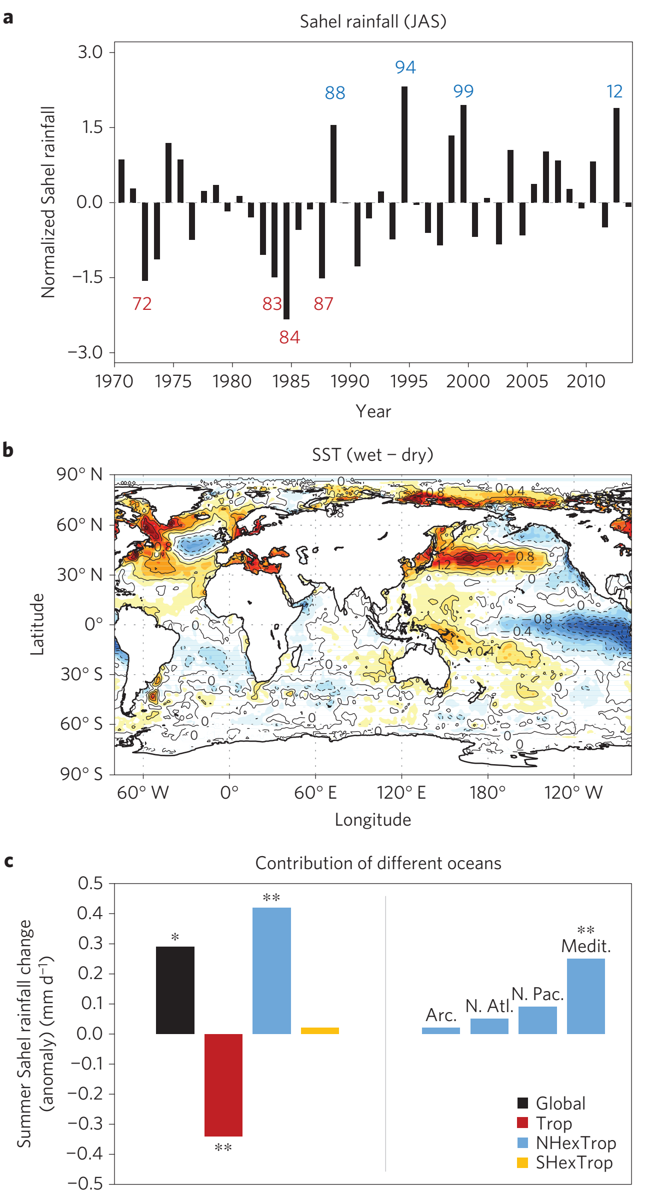

Figure 1 | Contributions of different ocean basins to the recent Sahel wetting. a, Time series of observed summer (July–September, JAS) mean rainfall anomalies over the Sahel (10° W–30° E; 10°–20° N) during the period 1970–2013. The wet and dry years are identified by rainfall anomalies exceeding ±1.5 s.d., and are highlighted blue and red respectively. **b**, Composite mean difference of observed summer SSTs between the wet and dry years in the Sahel region (unit, °C). **c**, Simulated summer Sahel rainfall responses from ECHAM6 forced by global (black), tropical (red, 30° S–30° N), NH extratropical (blue, 30°–75° N), and Southern Hemisphere extratropical (orange, 30°–75° S) SST anomalies in **b**. The NH extratropical impact is subdivided into four different NH extratropical ocean basins, Arctic (Arc., 0°–360° E, 65°–90° N), North Atlantic (N. Atl., 100° W–0°, 30°–65° N), North Pacific (N. Pac., 60° E–100° W, 30°–65° N), and the Mediterranean Sea (Medit., 0°–50° E, 30°–50° N). The significant rainfall responses are marked by a single asterisk (*) indicating $P < 0.10$ and by double asterisks (**) indicating $P < 0.05$ significance level.

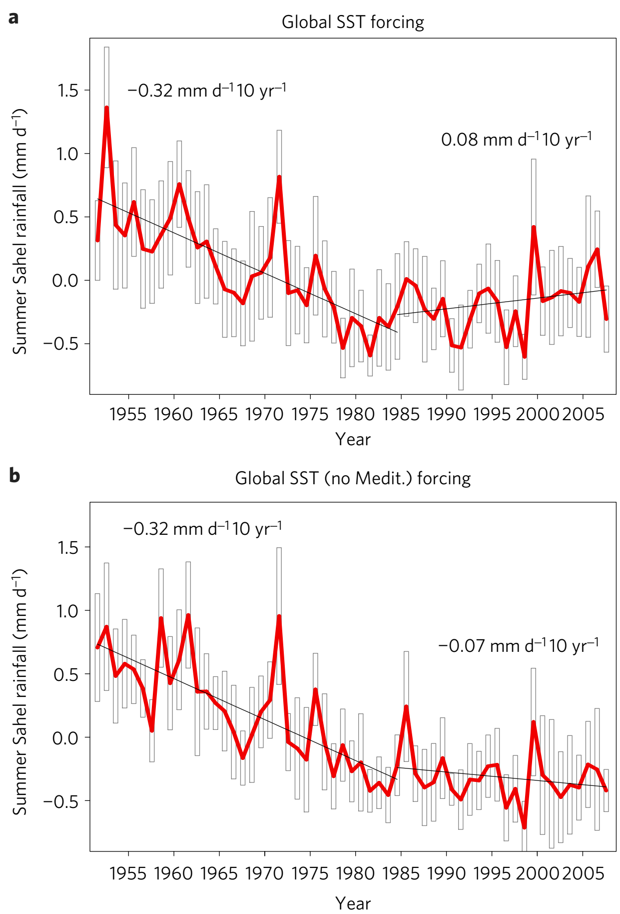

Figure 2 | Dominant role of the Mediterranean Sea in the recent recovery of Sahel rainfall. a, Time series of summer Sahel rainfall simulated by ECHAM6. The model is forced by historical AMIP2 SST forcing (1951–2007) with fixed greenhouse gas concentrations (CO_2, 348 ppm; CH_4, 1,620 ppb; N_2O, 312 ppb). The red line is the ensemble mean of ten simulations and the bars show ±1 s.d. of the ensemble spread. Linear-regression lines in the earlier (1951–1984) and later periods (1984–2007) are shown with black lines. **b**, As in **a**, except over the Mediterranean Sea, where an interannually non-varying climatological SST forcing is imposed. The trends for the later period (1984–2007) are significantly different between the two experiments at $P < 0.01$ level.

oceans, may not always be dominant in driving historical Sahel rainfall variations[11].

Such inconsistency in the past and recent relationships between tropical SST and Sahel rainfall is caused by a different atmospheric teleconnection under a warming tropical climate. In the past Sahel wet period, anomalous cooling in the Indian Ocean and eastern Pacific reduced the vertical stability of the tropical atmosphere by decreasing moist static energy at upper levels, providing a favourable condition for large-scale convection over tropical continents, and consequently leading to an increase in Sahel rainfall[4,9]. In the recent Sahel wet period, however, the western Pacific warm pool region may play a dominant role in controlling tropical atmospheric stability. The tropical atmospheric response to the grand La Nina-like pattern change (warming in the western Pacific and cooling in the eastern Pacific) shows that the stabilizing impact, or equivalently drying impact, of western Pacific warming dominates the wetting impact of SST changes in other tropical ocean basins (Supplementary Fig. 7). This modified tropical SST–Sahel teleconnection is presumably due to a stronger sensitivity of tropical deep convection to western Pacific SST anomalies, which is caused by a marked observed warming over the western Pacific warm pool[21].

The wetting impact of the NH extratropical SST changes, the key for the recent Sahel rainfall increase, is further analysed. To understand the detailed extratropical SST–Sahel rainfall

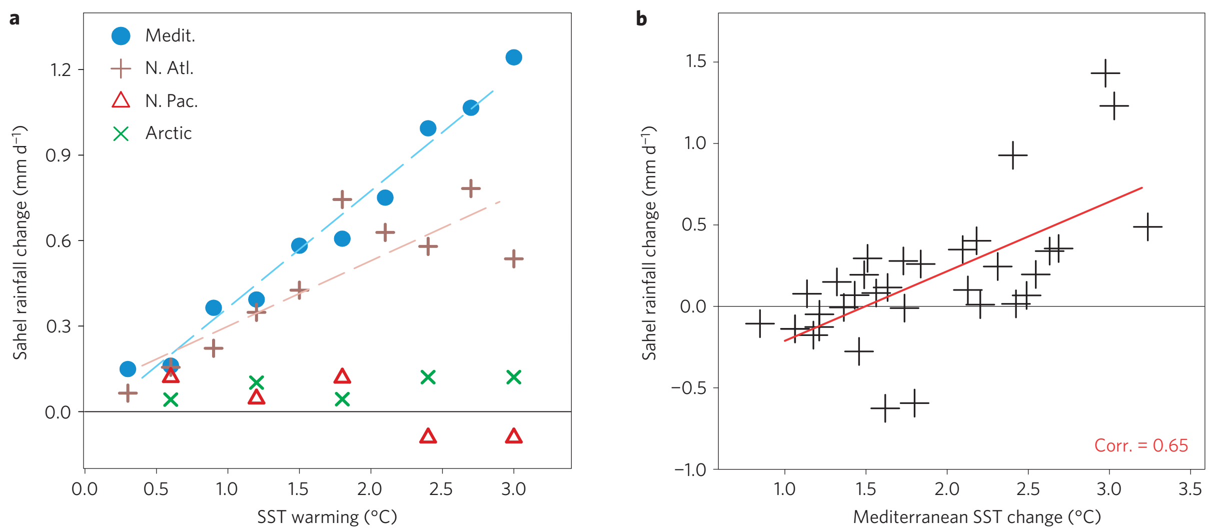

Figure 3 | Increasing impact of the Mediterranean Sea in a warming climate. a, Sahel rainfall responses to different magnitudes of uniform warming in the individual NH extratropical ocean basins. **b**, Scatter plot of future Sahel rainfall changes against future Mediterranean SST changes across the 34 CMIP5 models. The future change is defined as the mean difference between the periods 2010–2099 and 1910–1999. Each mark represents an individual CMIP5 model. The fitted linear-regression line is shown as a red line. The indicated correlation coefficient (Corr.) between future changes in Mediterranean SST and in Sahel rainfall is significant at $P < 0.01$ level.

relationship that has been strengthened in recent decades, the NH extratropical forcing used in the AGCM experiment is further separated into four different ocean basins, Arctic, North Atlantic, North Pacific, and Mediterranean Sea. The rainfall responses show that the Mediterranean warming is the most dominant contributor to the recent Sahel wetting (Fig. 1c). Forcing from other NH extratropical ocean basins, however, contributes only a minor portion to the Sahel wetting despite their larger area. Also, decadal changes in the SST forcing defined by the mean difference between the earlier dry period (1970–1985) and later wet period (1994–2013) show the dominant role of the Mediterranean Sea in forcing the recent recovery of Sahel rainfall (Supplementary Fig. 8).

A set of two experiments, in which the model is driven by historical global SSTs with and without historical variations in Mediterranean SSTs, clearly supports the dominant role of Mediterranean warming in the recent Sahel rainfall recovery (see Fig. 2a,b). Without information on the recent Mediterranean warming, which is most likely attributed to increasing anthropogenic greenhouse gases (Supplementary Fig. 9), the model simulates the persistent drying condition over the Sahel. An interesting finding is that, compared with SST impact, the direct radiative impact of greenhouse gases (not via SSTs) contributes negligibly to the historical Sahel rainfall variations (see Figure 2a and Supplementary Fig. 10). This gives more credit to the mainstream view that historical SST forcing is dominant in driving the Sahel rainfall evolution[2,5,9–12], rather than to the view that the direct radiative impact of greenhouse gases plays a dominant role in a warming climate[23]. One reason why in one certain model the direct impact of greenhouse gases predominates over the indirect impact via SST could be their underperformance in simulating the historical SST–Sahel rainfall relationship, thereby muting the SST impact (Supplementary Fig. 11). Our results are confirmed by the same experiments using another state-of-the-art AGCM (Supplementary Figs 3 and 4). Although this finding still relies on the results from two models, the increasing role of the Mediterranean Sea is also confirmed by the observational evidence that shows a substantially increased correlation between the Sahel rainfall and Mediterranean SST over the recent period (Supplementary Fig. 12).

How will the Sahel rainfall change in the future if the warming in the extratropics continues as projected by most climate models? To understand the first-order response of Sahel rainfall to future extratropical warming, additional SST-sensitivity experiments are performed by applying various magnitudes of uniform warming in different extratropical ocean basins. The Mediterranean impact on Sahel rainfall turns out to be the dominant factor, with a strong Sahel rainfall response proportionally increased with the magnitude of SST warming (Fig. 3a). The North Atlantic warming generally shows a weaker impact on Sahel rainfall compared with the Mediterranean warming, with a linearly increasing rainfall response to weak SST warming but a steady response to strong SST warming. The other ocean basins, Arctic and North Pacific, however, do not exhibit such a distinct Sahel rainfall response to different magnitudes of SST warming. The dominant impact of Mediterranean Sea warming suggests that its wetting impact may become more important as global warming progresses, particularly when future extratropical warming is greater than tropical warming.

A key issue in West African monsoon research is a large uncertainty in future Sahel rainfall projections[6,13]. Different climate models disagree even on the sign of the future Sahel rainfall trend. A multi-model analysis reveals that variation in the magnitude of future Mediterranean warming is closely correlated with diverse future Sahel rainfall projections across the climate models (Fig. 3b). In particular, the relationship becomes more obvious when considering the relative Mediterranean Sea warming compared with tropical SST warming in that the wetting impact of Mediterranean warming potentially competes with the drying impact of overall tropical warming in the future (Supplementary Fig. 13). Such a successful explanation of the future Sahel rainfall uncertainty implies that the disparate Mediterranean Sea warming simulated by current climate models is a crucial source of the future uncertainty despite other possible factors influencing future Sahel rainfall (for example, intermodal variations in land surface processes, future SST anomalies, and model sensitivity to SST forcing). This result is consistent with a recent work that suggests future NH differential warming as a key to understanding the discrepancy in the future Sahel rainfall[24], but further providing a unifying view of present and future Sahel rainfall changes as a consequence of anthropogenic Mediterranean Sea warming.

As a further check on the role of the Mediterranean Sea in the future, we quantify the relative contribution of different ocean

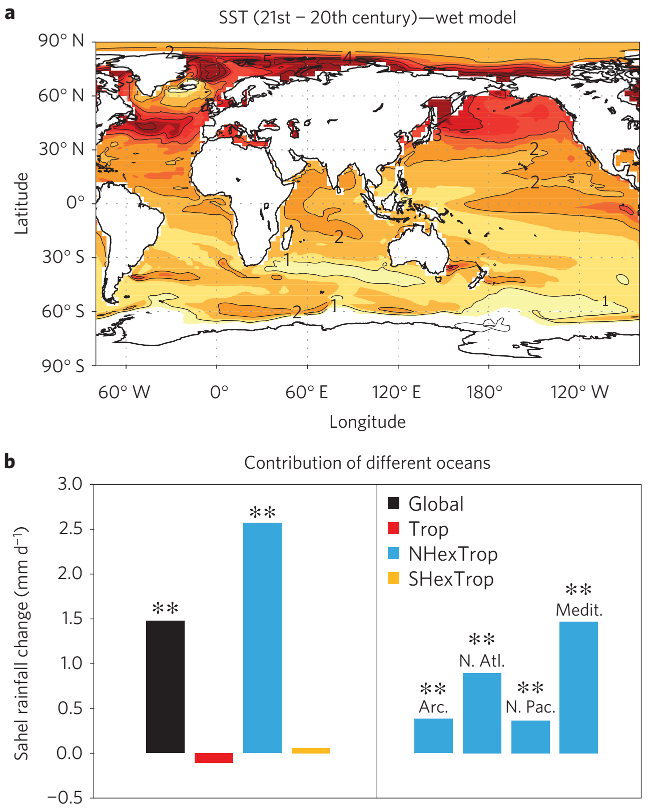

Figure 4 | Contributions of different ocean basins to a strong future Sahel wetting. a, Summer mean SST difference between the twenty-first and twentieth century simulated by MIROC-ESM that projects a strong future Sahel wetting (unit, °C). **b**, Similar experiments as shown in Fig. 1c but with ECHAM6 forced by the future SST warming from **a**. The significant rainfall responses are marked by double asterisks (**) indicating $P < 0.05$ significance level.

basins to future Sahel rainfall changes by choosing a climate model that projects a strong Sahel wetting. A similar AGCM experiment forced by the projected future SST warming from the selected climate model, MIROC-ESM, shows that the strong future Sahel wetting mostly comes from the extratropical warming, particularly with a dominant impact from Mediterranean Sea warming (Fig. 4). The wetting impact of North Atlantic warming contributes the second most despite its larger magnitude of warming compared with the Mediterranean warming. Warming in the Arctic and North Pacific oceans contributes only a little to the future Sahel wetting.

The mechanism of the Sahel rainfall increase by Mediterranean Sea warming is consistent with previous works[10,25,26], showing that the moist air by enhanced evaporation over the Mediterranean Sea advects southward into the Sahel, and then leads to the enhanced low-level moisture convergence and increased rainfall (Supplementary Fig. 14). This initial rainfall increase is then amplified by a moisture influx from the tropical Atlantic. A moisture budget analysis also demonstrates that the Sahel rainfall increase is dominated by the meridional moisture advection and convergence in early monsoon season and then followed by the dynamic reinforcement of monsoon flow in late monsoon season (Supplementary Fig. 15). The enhanced monsoon flow is associated with the surface warming of the Sahara and the accompanying increase in the strength of the Saharan Heat Low (Supplementary Fig. 14), which is consistent with recent studies suggesting a relationship between Saharan desert warming and Sahel wetting in a warming climate[27,28].

One great concern for West African societies is to understand whether the recent increase in Sahel rainfall will be sustained or not. Our findings establish the Mediterranean Sea as a crucial factor determining present and future Sahel rainfall trends. Looking ahead into the long-term future, greenhouse gases will continue to rise and this rise is likely to increase Mediterranean SST, which can provide a favourable condition of persistent Sahel wetting. Therefore, a careful investigation of how the Mediterranean Sea responds to anthropogenic climate change is a critical issue in improving the reliability of future Sahel rainfall projections.

Methods

Methods and any associated references are available in the online version of the paper.

Received 29 October 2015; accepted 26 May 2016;
published online 27 June 2016

References

1. Kandji, S. T., Verchot, L. & Mackensen, J. *Climate Change and Variability in the Sahel Region: Impacts and Adaptation Strategies in the Agricultural Sector* (United Nations Environmental Programme and World Agroforestry Centre, 2006).
2. Folland, C. K., Palmer, T. N. & Parker, D. E. Sahel rainfall and worldwide sea temperatures, 1901–85. *Nature* **320,** 602–607 (1986).
3. Hoerling, M., Hurrell, J., Eischeid, J. & Phillips, A. Detection and attribution of twentieth-century northern and southern African rainfall change. *J. Clim.* **19,** 3989–4008 (2006).
4. Janicot, S., Moron, V. & Fontaine, B. Sahel droughts and ENSO dynamics. *Geophys. Res. Lett.* **23,** 515–518 (1996).
5. Martin, E. R. & Thorncroft, C. D. The impact of the AMO on the West African monsoon annual cycle. *Q. J. R. Meteorol. Soc.* **140,** 31–46 (2014).
6. Cook, K. H. & Vizy, E. K. Coupled model simulations of the west African monsoon system: twentieth- and twenty-first-century simulations. *J. Clim.* **19,** 3681–3703 (2006).
7. Zeng, N., Neelin, J. D., Lau, K. M. & Tucker, C. J. Enhancement of interdecadal climate variability in the Sahel by vegetation interaction. *Science* **286,** 1537–1540 (1999).
8. Rotstayn, L. D. & Lohmann, U. Tropical rainfall trends and the indirect aerosol effect. *J. Clim.* **15,** 2103–2116 (2002).
9. Bader, J. & Latif, M. The impact of decadal-scale Indian Ocean sea surface temperature anomalies on Sahelian rainfall and the North Atlantic Oscillation. *Geophys. Res. Lett.* **30,** 2169 (2003).
10. Rowell, D. P. The impact of Mediterranean SSTs on the Sahelian rainfall season. *J. Clim.* **16,** 849–862 (2003).
11. Lu, J. & Delworth, T. L. Oceanic forcing of the late 20th century Sahel drought. *Geophys. Res. Lett.* **32,** L22706 (2005).
12. Giannini, A., Saravanan, R. & Chang, P. Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science* **302,** 1027–1030 (2003).
13. Biasutti, M., Held, I. M., Sobel, A. H. & Giannini, A. SST forcings and Sahel rainfall variability in simulations of the twentieth and twenty-first centuries. *J. Clim.* **21,** 3471–3486 (2008).
14. Li, H., Wang, H. & Yin, Y. Interdecadal variation of the West African summer monsoon during 1979–2010 and associated variability. *Clim. Dynam.* **39,** 2883–2894 (2012).
15. Mohino, E., Janicot, S. & Bader, J. Sahel rainfall and decadal to multi-decadal sea surface temperature variability. *Clim. Dynam.* **37,** 419–440 (2011).
16. Trenberth, K. *et al*. *Climate Change 2007: The Physical Science Basis* (IPCC, Cambridge Univ. Press, 2007).
17. Sutton, R. T. & Hodson, D. L. R. Climate response to basin-scale warming and cooling of the North Atlantic Ocean. *J. Clim.* **20,** 891–907 (2007).
18. Vizy, E. K. & Cook, K. H. Mechanisms by which Gulf of Guinea and eastern North Atlantic sea surface temperature anomalies can influence African rainfall. *J. Clim.* **14,** 795–821 (2001).
19. Chiang, J. C. H. & Friedman, A. R. Extratropical cooling, interhemispheric thermal gradients, and tropical climate change. *Annu. Rev. Earth Planet. Sci.* **40,** 383–412 (2012).
20. Hakkinen, S. & Rhines, P. B. Decline of subpolar North Atlantic circulation during the 1990s. *Science* **304,** 555–559 (2004).
21. Park, J.-Y., Yeh, S.-W. & Kug, J.-S. Revisited relationship between tropical and North Pacific sea surface temperature variations. *Geophys. Res. Lett.* **39,** L02703 (2012).
22. Zhang, C. D. Large-scale variability of atmospheric deep convection in relation to sea-surface temperature in the tropics. *J. Clim.* **6,** 1898–1913 (1993).
23. Dong, B. & Sutton, R. Dominant role of greenhouse-gas forcing in the recovery of Sahel rainfall. *Nature Clim. Change* **5,** 757–760 (2015).

24. Park, J.-Y., Bader, J. & Matei, D. Northern-hemispheric differential warming is the key to understanding the discrepancies in the projected Sahel rainfall. *Nature Commun.* **5,** 1–8 (2014).
25. Fontaine, B. *et al*. Impacts of warm and cold situations in the Mediterranean basins on the West African monsoon: observed connection patterns (1979–2006) and climate simulations. *Clim. Dynam.* **35,** 95–114 (2010).
26. Gaetani, M., Fontaine, B., Roucou, P. & Baldi, M. Influence of the Mediterranean Sea on the West African monsoon: intraseasonal variability in numerical simulations. *J. Geophys. Res.* **115,** D24115 (2010).
27. Cook, K. H. & Vizy, E. K. Detection and analysis of an amplified warming of the Sahara Desert. *J. Clim.* **28,** 6560–6580 (2015).
28. Lavaysse, C. Saharan desert warming. *Nature Clim. Change* **5,** 807–808 (2015).

Acknowledgements
We acknowledge the modelling groups and the World Climate Research Programme's Working Group on Coupled Modelling for their roles in making available the CMIP5 multi-model data set, and the German Climate Computing Center (DKRZ) for providing the computer hardware for our model experiments. This work was supported by the BMBF projects, RACE (FKZ:03F0729D) and MiKlip (FKZ: 01LP1158A), and was carried out in the frame of the internal MPI-M project 'Tropical VIBES'.

Author contributions
J.-y.P., J.B. and D.M. contributed to developing the research. J.-y.P. performed the analysis and SST-sensitivity experiments. All authors discussed the results and wrote the paper.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.-y.P.

Competing financial interests
The authors declare no competing financial interests.

Methods

The primary precipitation and sea surface temperature (SST) data used in this study are obtained from the Global Precipitation Climatology Center[29] operated by the German National Meteorological Service, and the extended reconstructed SST version 3 (ref. 30) provided by the National Oceanic and Atmospheric Administration (NOAA) National Climate Data Center. The precipitation from the Climatic Research Unit and Global Precipitation Climatology Project data sets, and the SST from the NOAA Optimum Interpolation SST and Hadley Centre data sets are also used to check the robustness of our results. The wet and dry years for the composite analysis are defined on the basis of 1.5 s.d. of the July–September mean Sahel rainfall anomalies during 1970–2013.

The multi-model data set shown in Fig. 3b is obtained from the Coupled Model Intercomparison Project (CMIP5) archive. A total of 34 CMIP5 models, which provide SST and precipitation outputs during 1860–2100, are used in this study. The future scenario chosen is representative concentration pathway 4.5, a medium radiative forcing scenario.

The AGCM model used for the SST-sensitivity experiments is ECHAM6, developed at the Max Planck Institute for Meteorology. The model has a T63 horizontal resolution (1.875° × 1.875°) and a high vertical resolution with 47 levels. The ECHAM models are known to simulate the African monsoon with reasonable accuracy and have been extensively used for West African monsoon studies[9,15]. The precipitation response shown in Fig. 1c is the Sahel rainfall difference between two AGCM experiments, one forced by the composite (wet minus dry years) SST anomalies in Fig. 1a superposed on the monthly climatological SSTs used in the Atmospheric Model Intercomparison Project (AMIP2), and the other one by the AMIP2 climatological SSTs during 1979–2008 (repeated annual cycle). Similarly, the Sahel rainfall response shown in Fig. 3a is the mean difference between the perturbed run forced by various magnitudes of uniform warming in an individual ocean basin and the control run forced by the AMIP2 climatological SSTs. The SST boundary forcing for the AGCM experiments shown in Fig. 4b is obtained from MIROC-ESM in CMIP5. ECHAM6 is forced by two climatological SSTs averaged over the last 30 years of the twentieth (1970–1999) and twenty-first century (2070–2099) from MIROC-ESM. In the case of isolating the impact of a certain area, the perturbed SST boundary forcing is prescribed only over the individual ocean basin. For all of the SST-sensitivity experiments, other boundary conditions (for example, greenhouse gases and solar radiation) are identical for the perturbed and control runs. A total of 20 ensemble runs initiated from different states are conducted, and only the summer (July–September) mean is shown in this study. A statistical test is applied to model responses on the basis of two-tailed Student's *t*-test.

References

29. Schneider, U. *et al*. GPCC's new land surface precipitation climatology based on quality-controlled *in situ* data and its role in quantifying the global water cycle. *Theor. Appl. Climatol.* **115,** 15–40 (2014).
30. Smith, T. M., Reynolds, R. W., Peterson, T. C. & Lawrimore, J. Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006). *J. Clim.* **21,** 2283–2296 (2008).