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A unifying view of climate change in the Sahel linking intra-seasonal, interannual and longer time scales

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Abstract

We propose a re-interpretation of the oceanic influence on the climate of the African Sahel that is consistent across observations, 20th century simulations and 21st century projections, and that resolves the uncertainty in projections of precipitation change in this region: continued warming of the global tropical oceans increases the threshold for convection, potentially drying tropical land, but this 'upped ante' can be met if sufficient moisture is supplied in monsoon flow. In this framework, the reversal to warming of the subtropical North Atlantic, which is now out-pacing warming of the global tropical oceans, provides that moisture, and explains the partial recovery in precipitation since persistent drought in the 1970s and 1980s. We find this recovery to result from increases in daily rainfall intensity, rather than in frequency, most evidently so in Senegal, the westernmost among the three Sahelian countries analyzed. Continuation of these observed trends is consistent with projections for an overall wetter Sahel, but more variable precipitation on all time scales, from intra-seasonal to multi-decadal.

Keywords: regional climate change, precipitation projections, Sahel, drought, character of precipitation, daily precipitation, frequency of precipitation, intensity of precipitation, Senegal, Burkina Faso, Niger

1. Introduction

The Sahel, the semi-arid southern edge of the Sahara desert, has long focused the attention of climate scientists and development practitioners. Only 30 years ago in the grip of multi-decadal drought [1] and recurrent food insecurity [2], it is now rebounding by building resilient ecosystems and livelihoods [3–5]. However, persistent poverty and insufficient investment in agricultural development recurrently raise concerns about the impact of drought [6], while disagreement in projections of regional precipitation change [7–9], a situation common throughout the tropics [10, 11], limits the practical use of climate information in charting development on adaptation time scales.

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Table 1. Interannual correlations of indices of Sahel rainfall ([1, 35, 40, 42]; data from [51] is averaged over 10°–20°N, 20°W–40°E) and various SST indices averaged over May–October, including the one proposed here—the difference between the subtropical North Atlantic and the global tropical oceans. NAtl–SAtl is the difference between tropical North (5°–25°N, 75°–15°W) and tropical South Atlantic (20°S–5°N, 45°W–15°E). Eq. Ind. O. is the average over the equatorial Indian Ocean (15°S–15°N, 50°–90°E). Niño3 is the average over the central and eastern equatorial Pacific (5°S–5°N, 150°–90°W).

Sahel index	Period	NAtl minus global tropics	NAtl–SAtl	Eq. Ind. O.	Niño3
Nicholson [1]	1901–95	0.52	0.46	−0.49	−0.23
Ali and Lebel [35]	1950–2006	0.71	0.47	−0.52	−0.32
Giannini *et al* [40]	1930–2000	0.68	0.45	−0.60	−0.44
Lamb [42]	1941–2004	0.70	0.48	−0.51	−0.31
CRU TS2p1 [51]	1950–95	0.70	0.50	−0.61	−0.33

Previous investigations of projections of regional rainfall change in the Sahel took stock of the disagreement in direction, attempting to discern between ‘good’ and ‘bad’ models on the basis of their representation of climatological features [7] and to explain such disagreement either on the basis of disagreement in sea surface temperature (SST) projections [12], or on the basis of the dominance of local, land-driven versus remote, ocean-driven processes [13]. Confined to the evaluation of model simulations, these studies ended in an impasse. We resolve this impasse, and validate our ‘re-interpretation’ of the role of the oceans in global coupled model simulations with an analysis of observations. We proceed in three steps: (i) we identify an SST-based metric that explains the disagreement in model projections of future rainfall change, (ii) in light of this metric, we revisit the historical relationship between oceanic influence and continental precipitation response that forms the basis for seasonal-to-interannual prediction, simplifying it in line with theories of precipitation change in a warming world, and (iii) we seek dynamical validation of the processes linking oceanic influence and regional rainfall response in the character of precipitation in historical records of daily rainfall in Senegal, Burkina Faso and Niger.

2. Making sense of 21st century projections of tropical precipitation

The metric that we propose to resolve the disagreement among models in projections of Sahel precipitation change is the difference in temperature between the subtropical North Atlantic and the global tropical oceans. This relative metric of SST change is consistent with reasoning used to provide an alternative interpretation of trends in Atlantic hurricane activity [14]. While only marginally different from previously employed indices in the seasonal-to-interannual prediction problem—indices which reflect current understanding of the separate influences of the world’s oceans and will be discussed in greater depth in section 3 (related to that, also see table 1)—only this metric explains model disagreement in projections of future change. We posit that this is so, because it captures the essence of the processes involved: as the global tropical oceans warm, the temperature threshold for deep convection rises [15–17]. Continued (transient) warming alone can cause tropical land to dry, as in the development stages of an El Niño event [18, 19], or in projections of a delayed onset of monsoons [20, 21]. However, the higher convection threshold can be met if sufficient moisture is supplied. While plausible to conceive that the entire tropical Atlantic contributes climatological moisture to the West African monsoon [22, 23], here we pinpoint the subtropical North Atlantic as the source of the variability in moisture supply that makes or breaks deep convection at the Sahelian margin [24–26]. In figure 1, the scatter of CMIP3 [27] and CMIP5 [28] models aligns along a slope relating changes in Sahel rainfall, averaged between 10° and 20°N, 20°W and 40°E, to the difference between local and global surface temperature, respectively represented by the North Atlantic averaged between 10° and 40°N, 75° and 15°W, and the global tropics averaged between 20°S and 20°N. No other index of Atlantic temperature, whether tropical North Atlantic (10°–25°N, 75°–15°W), tropical South Atlantic (20°S–10°N, 75°W–15°E), tropical Atlantic (20°S–20°N, 75°W–15°E) or the difference between tropical North and South Atlantic, investigated in [12], performs comparably to our subtropical North Atlantic index. In figure 1, past change is in green and blue dots in the lower left quadrant, most coherent in CMIP3 [9]: whether due to natural [29] or anthropogenic [30–32] causes, late 20th century drought is consistent with the North Atlantic not keeping pace with warming of the global tropical oceans. The insufficiently moist near-surface westerly flow starved the continent of the humidity needed to trigger vertical instability [33]. Future change is in yellow and red dots mostly in the upper right quadrant, signifying that a future wetter outcome is possible if warming of the North Atlantic continues to exceed that of the global tropics. Past and future are no longer inconsistent. The multi-model ensemble behavior is evident—the correlation between rainfall over land and the temperature difference over the oceans is 0.33 in CMIP3, and 0.52 in CMIP5 (see figure 2 for individual model behavior). The lower correlation in CMIP3 is entirely due to the two ‘outlier’ models projecting a dry future, the yellow and red dots in the upper, left corner. When they are removed the correlation value rises to 0.66. In [34], these same two models develop a Saharan heat low farther to the east than in observations or other models, and a consequent low-level circulation over West Africa that disables the westerly inflow of moisture from the North Atlantic. Therefore, despite warming of the North Atlantic Ocean that exceeds global tropical warming, these two models are unable to converge anomalous moisture to simulate a wetter Sahel.

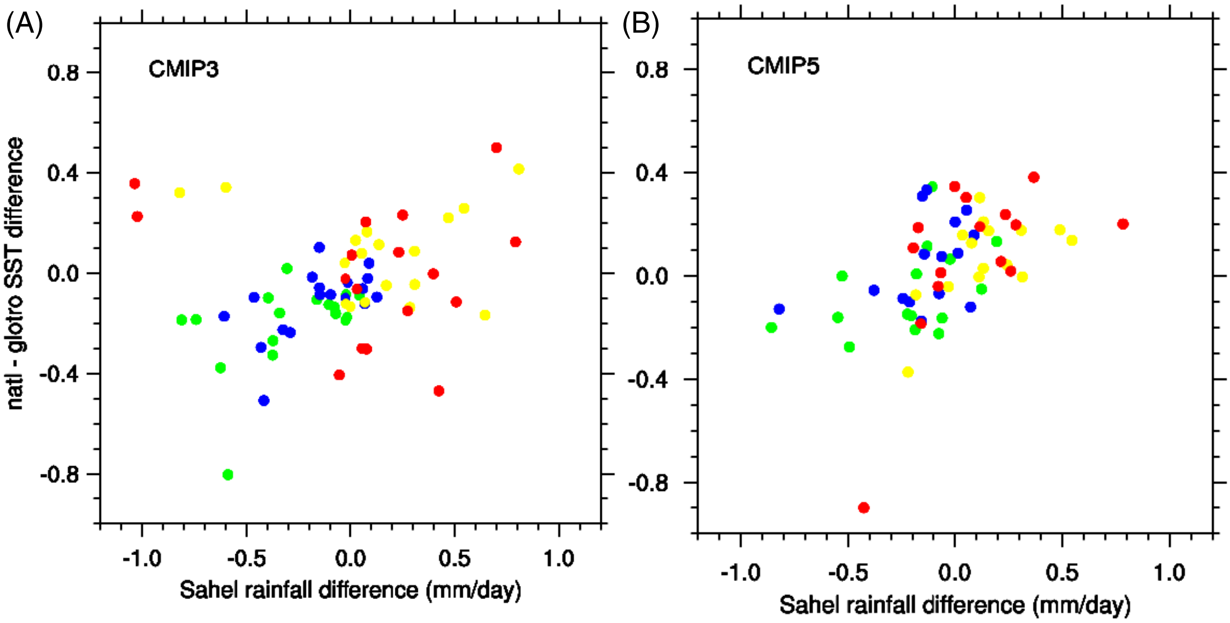

Figure 1. Simulated change in Sahel rainfall in (A) CMIP3 and (B) CMIP5 models against the change in (surface air) temperature difference between the subtropical North Atlantic and the global tropical oceans. All averages are taken July–September. Green dots identify the change between the end of the 20th century (CMIP3/20c3m, CMIP5/historical) and the 'pre-Industrial' control, blue dots the change between end and beginning of the 20th century, yellow dots the change between the middle of the 21st century (CMIP3/A1B scenario, CMIP5/RCP4.5) and the end of the 20th century, and red dots the change between end of the 21st and 20th centuries—we averaged 100 years of pre-Industrial control, and up to 3 ensemble members of the 20th and 21st century simulations when available. There are 17 models in the CMIP3 scatter, 15 in the CMIP5 scatter.

3. Oceanic influence in regional variability and change

The difference in temperature between the subtropical North Atlantic and the global tropics synthesizes separate measures of Atlantic and Indo-Pacific influence with roots in the extensive literature on the 20th century evolution of the climate of the Sahel, which was characterized by an abrupt shift from the anomalously wet decades of the 1950s and 1960s to persistently dry conditions in the 1970s and 1980s [1, 35]. The north-south gradient in Atlantic SST has long been held responsible for variations in the latitudinal location of the Inter-Tropical Convergence Zone and its continental extension into West Africa [36]. The cooling of the North Atlantic relative to the South Atlantic that characterized the end of the 20th century contributed to the drying of the Sahel. Such drying was unprecedented in the instrumental record, though perhaps not on millennial time scales [37], in magnitude, duration and spatial extent [38], because a cooler North Atlantic coincided with the emergence of oceanic warming, whether of the southern compared to the northern oceans [39], or of the equatorial Indian Ocean as a proxy for tropic-wide warming [40] (figure 3).

Our new metric compares favorably with indices computed using [41] to represent oceanic influence on Sahel rainfall [1, 35, 40, 42] on interannual time scales, in table 1. The performance of our metric supports a re-interpretation of oceanic influence on the climate of the Sahel, one in which we seek to make sense of processes at intra-seasonal, interannual and multi-decadal time scales. The two ingredients are tropical mean sea surface temperature, which reflects the top of the atmosphere energy constraint imposed by greenhouse gas warming through deep convection [15, 33], and is responsible for setting vertical stability globally from the top down, and local sea surface temperature, which can modulate stability from the surface up, through the effect that changes in evaporation and atmospheric moisture content have on local moisture supply. In figure 4 we explore the relative roles of North Atlantic, on the y axis, and global tropical SSTs, on the x axis, as proxies for local/moisture and global/temperature conditions, respectively, at interannual to multi-decadal time scales. If our hypothesis were valid, i.e., that it is the warming of the North Atlantic relative to the global tropical oceans that holds the key to Sahel precipitation, then we would expect wet anomalies to dominate when the North Atlantic is warmer than the global tropics, i.e., for points above the $y = x$ diagonal line. Conversely, we would expect dry anomalies to dominate points below the same $y = x$ diagonal line. Indeed, precipitation anomalies become more coherent in sign as one moves perpendicularly away from the diagonal $y = x$ line. Dry years, in open circles, are the norm sufficiently below such line, towards the lower right corner. Wet years, in filled circles, are the norm sufficiently above such line, towards the upper left corner.

4. Oceanic influence from sub-seasonal to multi-decadal time scales

We seek further evidence in support of our dynamical argument using daily data from 31 stations in Senegal, made

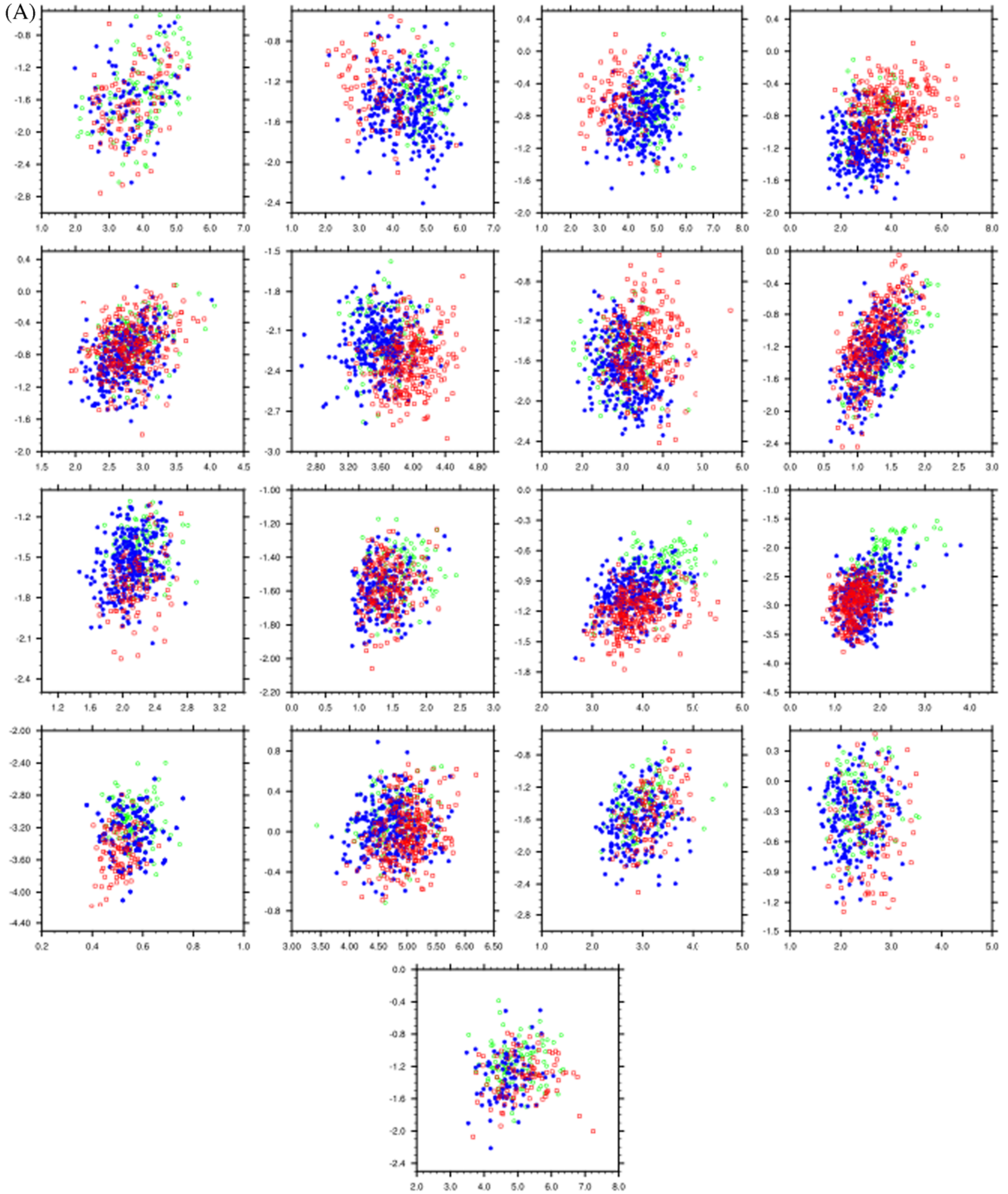

Figure 2. Individual model scatter of Sahel precipitation, in mm/day on the *x*-axis, against the difference in surface air temperature between the subtropical North Atlantic and the global tropics, in °C on the *y*-axis, in the (A) CMIP3 and (B) CMIP5 simulations: green indicates data points from the pre-Industrial control, blue from the 20th century (20c3m in CMIP3, historical in CMIP5), and red from the 21st century (A1B in CMIP3, RCP4.5 in CMIP5) simulations. Individual model correlation values, computed on the ensemble of simulations, range between −0.16 and 0.61 in CMIP3 and between −0.17 and 0.55 in CMIP5.

available by the *Institut Sénégalais de la Recherche Agricole* (ISRA) and the *Agence Nationale de l'Avion Civile et de la Météorologie* (ANACIM), 51 stations in Burkina Faso, made available by the *International Crops Research Institute for the Semi-Arid Tropics* (ICRISAT), in Bamako, Mali, and 12 stations in Niger, made available by the Direction Nationale

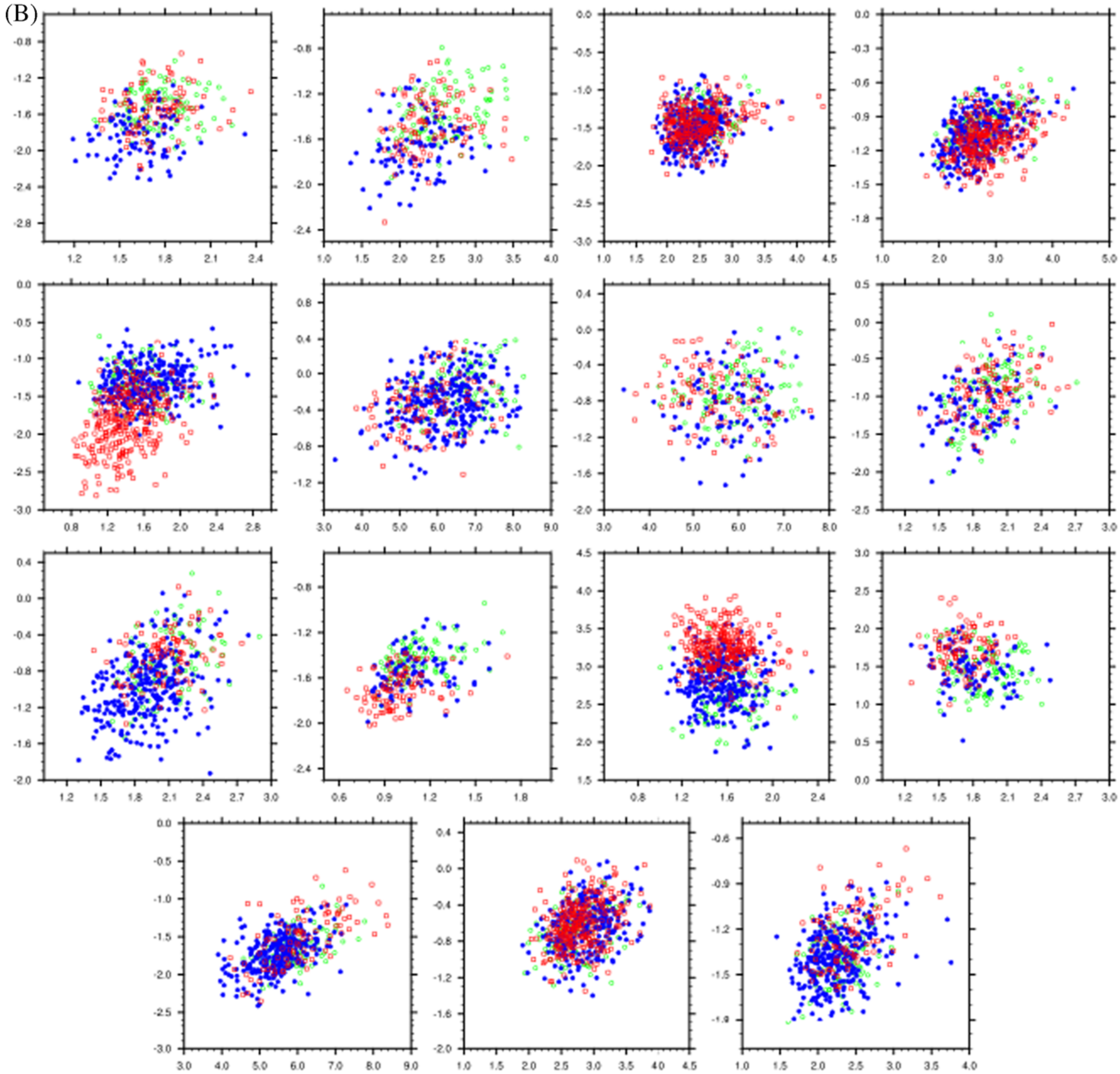

Figure 2. (Continued.)

Table 2. Correlations of number of rainy days, and median intensity, by country, with indices of SST variability.

Country	Period	SST index	Frequency of rainy days	Median intensity
Burkina Faso (51 stations)	1941–2008	Global tropical	−0.30[a]	−0.06
		NAtl minus global tropical	0.31[a]	0.34[b]
Niger (12 stations)	1960–2000	Global tropical	−0.25	−0.12
		NAtl minus global tropical	0.45[b]	0.27
Senegal (31 stations)	1950–2010	Global tropical	−0.49[b]	0.00
		NAtl minus global tropical	0.70[b]	0.39[b]

[a] Denotes statistical significance at 95% level.

[b] Denotes statistical significance at 99% level.

de la Météorologie, in Niamey, Niger (table 2). At each station and for any given year, we exclude missing values from the computation of frequency of rainy days and median rainfall intensity during rainy days. Frequency is computed as the ratio of number of days with rainfall greater than 1 mm to the total number of days in which an observation was reported. Median daily intensity is computed over rainy days only, i.e., it is the median value for days with rainfall greater than 1 mm. We standardize each station's time series over the years of record, and average over all stations to obtain one single normalized

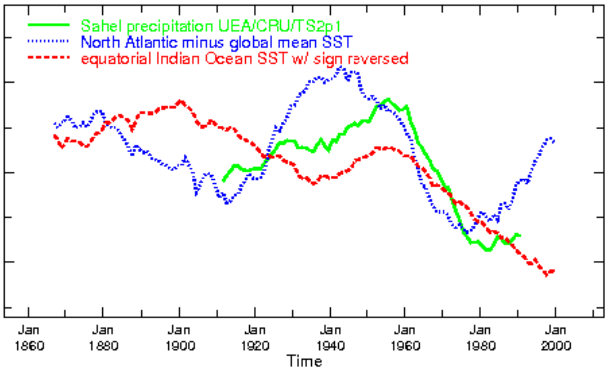

Figure 3. 21 yr running averages of Sahel rainfall (10°–20°N, 20°W–40°E) in solid green, North Atlantic (0°–60°N, 60°W–0°E) minus global mean (60°S–60°N) SST, in dotted blue, and equatorial Indian Ocean SST (15°S–15°N, 50°–90°E) with sign reversed, in dashed red. Precipitation is from UEA/CRU/TS2p1 [51], SST from Kaplan/Extended [52, 53].

time series [43] for frequency of rainy days, and for median intensity, for each country.

If warming increases vertical stability, we expect it may manifest in a delay in the onset of the rainy season [20, 44], an increase in the frequency of long dry spells [45], or more generally a reduction in frequency of rainy days. If, on the other hand, the moisture supplied from a warmer ocean can overcome this upped ante, or increased threshold for convection, then more intense rainfall becomes possible, reflected in the potential for a higher median intensity [46]. In figure 5 we plot rainy day frequency and median intensity for Senegal against the same scatter of SST indices used in figure 4, i.e. subtropical North Atlantic SST on the y axis, global tropical SST on the x axis. These plots broadly reflect the same asymmetry discussed in the case of figure 4, that perpendicular to the diagonal $y = x$ line, with increased frequencies or intensities above it, consistent with above average seasonal rainfall, and reduced below it, consistent with below average rainfall. In addition, we note a complementary asymmetry, along the same $y = x$ line. This asymmetry is most apparent when North Atlantic temperatures are higher than the global tropical mean, i.e. when we find ourselves above the $y = x$ line, in a situation when North Atlantic moisture supply meets the threshold set by the global tropical oceans. The larger positive anomalies in rainy day frequency occur towards the lower left corner, i.e. at lower temperature anomalies, when the relatively low thresholds for deep convection set by the global tropical oceans can be met more frequently by convergence of North Atlantic moisture. Conversely, the larger positive anomalies in median intensity occur towards the upper right corner, i.e. at higher temperature anomalies, when warmer global tropical oceans make it possible to attain higher intensities.

5. Conclusion: from past drought to partial recovery and beyond

The drought years between 1968 and 1984 were dominated by negative values in frequency of rainy days [47, 48], and in median intensity (figure 6). Conversely, recent years have been marked by the relative predominance of values in frequency of rainy days typical of drought years, but combined with significant variation in median intensity, including large positive values coincident with positive anomalies in global tropical and North Atlantic SST. Therefore, the character of precipitation during the recent recovery appears to have had a distinctly different flavor if compared to the wet period around the middle of the 20th century: fewer rainy days, as during persistent drought, made up for in the seasonal totals by an increase in median intensity of daily rainfall.

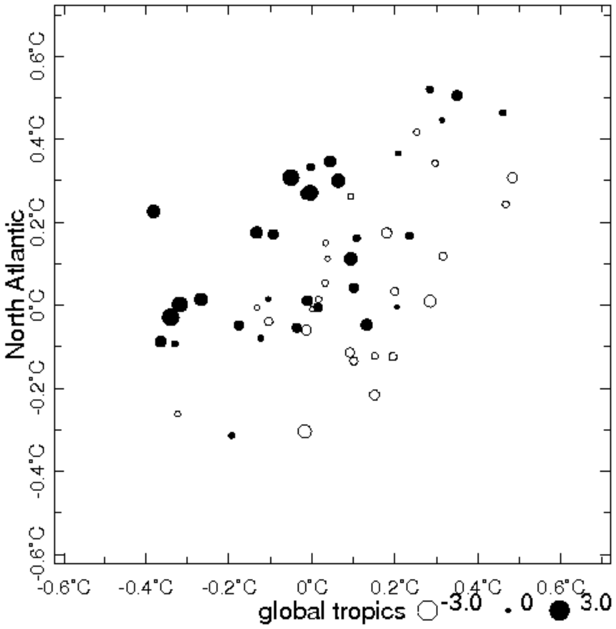

Figure 4. The Ali and Lebel (2009) index of standardized Sahelian precipitation [35] against May–October SST indices averaged over the subtropical North Atlantic (y-axis) and the global tropics (x-axis): open circles represent negative anomalies of the rainfall index, filled circles positive anomalies, and the size of the circle is a measure of amplitude of the anomaly, in units of standard deviation. SST anomalies, in °C, are computed with respect to the 1961–90 climatology.

Despite the scatter around the origin in the panels in figure 1, which could reflect variations among models in how they balance local/land and remote/oceanic influence of greenhouse gas-induced warming [13], the multi-model ensembles of CMIP3 and CMIP5 projections that point towards the possibility of a wetter future for the Sahel are consistent with the current trend towards a recovery of the rains. We can begin to root these projections in the understanding of the influence of the oceans on the climate of this region that has matured over the past quarter century. Therefore, the more plausible, near-term scenario is that the Sahel will continue to stay wet if North Atlantic warming continues to out-pace the global tropical oceans. If the Sahel were to get wetter through a more marked increase in intensity rather than in frequency of precipitation, as discussed here, sound adaptation would have to contend with increased

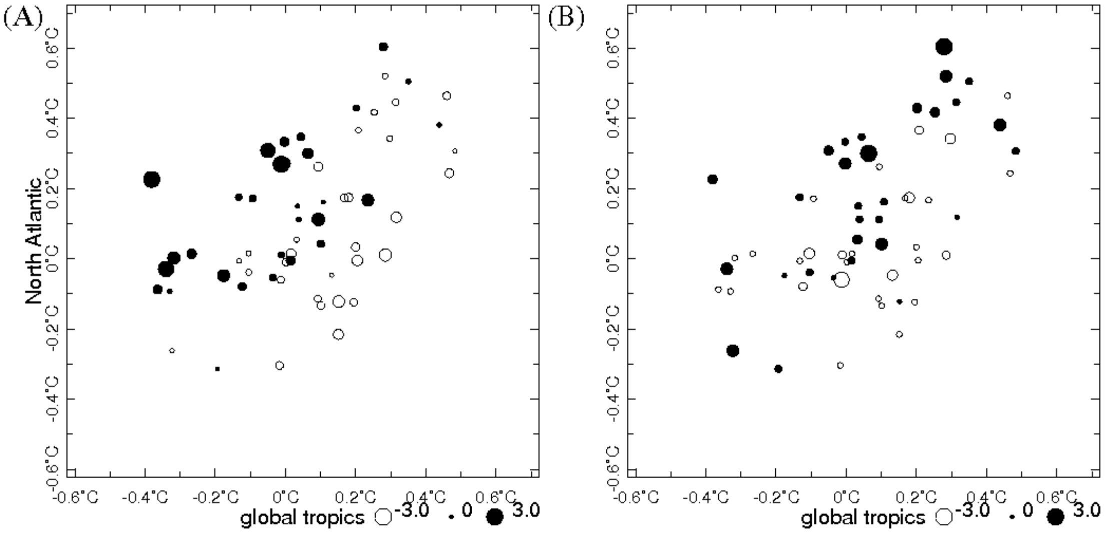

Figure 5. Standardized anomalies in (A) frequency of rainy days and (B) median intensity of rainy days in Senegal over 1950–2010 against the same scatter of SST anomalies in the subtropical North Atlantic, on the y-axis, and in the global tropics, on the x-axis, used in figure 4. Open circles represent negative anomalies, filled circles positive anomalies. The size of the circle is a measure of amplitude of the anomaly, in units of standard deviations.

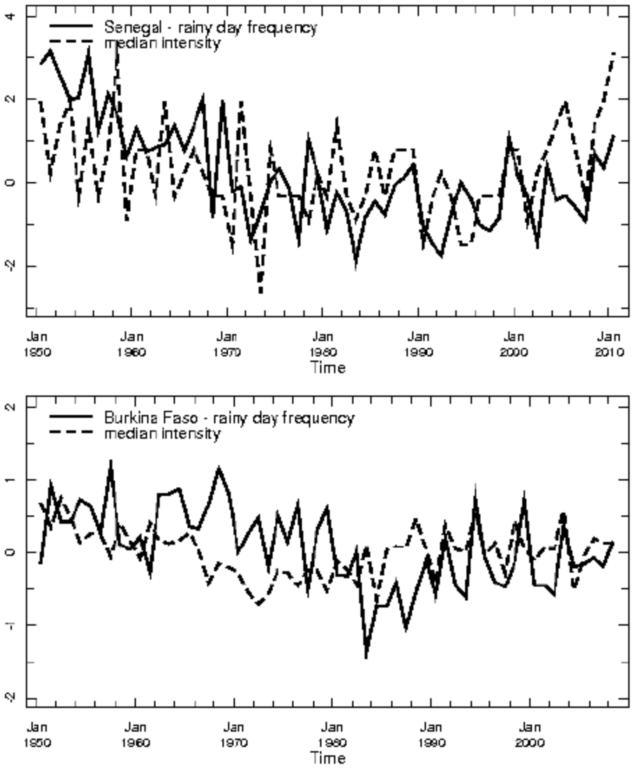

Figure 6. Time series of standardized frequency of rainy days (solid line) and median intensity (dashed line) in Senegal and Burkina Faso over the common period 1950–2008.

variability on all time scales, as already recognized on the ground [49, 50].

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The authors declare to have no potential conflict of interest.

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