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Skill of Sahel rainfall variability in four atmospheric GCMs forced by prescribed SST

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[1] The inter-annual and long-term variability of July–September regional rainfall over the central and western Sahel (16°W–20°E; 11.25°–18.75°N) is evaluated using 21 runs from four atmospheric general circulation models (AGCMs) integrated from 1948. The skill is stronger at decadal time scales: each AGCM simulates quite successfully the rainfall decrease from the wet 1950–60s toward the dry 1970–90s although its amplitude is lower than observed. At inter-annual time scales, the skill is smaller and decreases over time between the 1950–70s and the recent dry period; all AGCMs have a close to zero skill around the 1980s. This is not linked to a reduced AGCM sensitivity to global SST but to their failure to reproduce the observed SST-rainfall teleconnection changes, in particular the weakening (strengthening) linear relationship with the equatorial and southern Atlantic (equatorial Pacific). *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology. **Citation:** Moron, V., N. Philippon, and B. Fontaine, Skill of Sahel rainfall variability in four atmospheric GCMs forced by prescribed SST, *Geophys. Res. Lett.*, 30(23), 2221, doi:10.1029/2003GL018006, 2003.

1. Introduction

[2] Long-term observed rainfall variations over Sahel exhibit significant changes from wet conditions in the 1950–60s to drier ones in the 1970–90s. These inter-decadal fluctuations represent one of the strongest climatic signals in the 20th century [AMMA, 2002]: the abnormally dry conditions have been associated with warmer than normal sea surface temperatures (SST) in the southern Atlantic, the southern and equatorial Pacific (El Niño conditions) and the Indian ocean, and colder than normal SSTs in the northern Atlantic and the northern Pacific [e.g., Folland *et al.*, 1986; Fontaine and Janicot, 1996; Rowell *et al.*, 1995; Ward, 1998]. These relationships depend strongly on the frequencies considered since teleconnections between Sahelian seasonal rainfall and SST at low frequency (LF) time scales differ from those at high-frequency (HF) [e.g., Ward, 1998]. Moreover, at HF time scales, relationships between Sahelian seasonal rainfall and

Tropical Pacific and southern and equatorial Atlantic are unstable [Janicot *et al.*, 1996, 2001].

[3] It is clear that many AGCMs forced by prescribed SST have difficulty in reproducing these teleconnections fluctuations, especially at HF time scales [Sperber and Palmer, 1996; Sud and Lau, 1996]. This is partly due to the fact that the range of physical processes and scales involved in rainfall cannot be fully resolved in any AGCM and must be parameterized; accurate simulation of rainfall represents a great challenge for AGCMs.

[4] The aim of this study is to investigate the skill (i.e., similarity between simulations and observations) and reproducibility (i.e., similarity amongst the runs) of a seasonal Sahelian rainfall index (SRI) in 4 AGCMs (ARPEGE, GISS, ECHAM 3 and ECHAM 4) forced by the same prescribed SSTs. These AGCMs capture the temporal variability of a regional monsoon wind index reasonably [Fontaine *et al.*, 1995]. An analysis of the variations of skill at HF time scales and of the teleconnections between SRI and some SST indices is also performed. This letter is divided into six sections: section 2 briefly describes the data and methods, sections 3, 4 and 5 present respectively the mean skill, its time evolution and the reproducibility, and the relationships with 4 SST indices. Section 6 provides concluding remarks.

2. Data and Methods

[5] The AGCMs used in this study have been already presented in Moron *et al.* [2001] for ECHAM 3 and 4, Cassou and Terray [2001] for ARPEGE and Hansen *et al.* [2002] for GISS and only a brief summary is given here (Table 1).

[6] The runs are forced with observed SST and ice coverage from the data set provided by the Hadley centre. All runs differ only by their initial conditions. The soil hydrology uses a “bucket scheme” (i.e., a single soil layer with constant moisture capacity) in ECHAM 3 and ECHAM 4 and a more physically-based approach to predict soil moisture for ARPEGE and GISS. The highest rainfall associated with the northernmost location of the Inter-Tropical Convergence Zone are located slightly too far north in these AGCMs, but this shift does not exceed 2° (not shown). There is also a weak dry bias, except for ARPEGE.

[7] SRI is defined as the standardized mean of the standardized anomalies inside the Sahelian box (16°W–20°E; 11.25°N–18.75°N), matching the usual definition of central and western Sahel [e.g., Rowell *et al.*, 1995; Fontaine and Janicot, 1996; Ward, 1998; Philippon and Fontaine, 1999]. Observations are taken from the Climatic Research Unit data set [Hulme, 1992]. For each AGCM, SRI is computed for each run and then averaged. The time series are filtered with a butterworth digital filter which divides the variance into HF and LF parts. The cut-off is at

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Table 1. Main Characteristics of the 4 AGCMs Used

AGCM	Horizontal resolution	Vertical resolution	Number of runs available	Period available
ECHAM 3	T21	19	5	1950–1994
ECHAM 4	T30	19	3	1961–1994
ARPEGE	T63	31	8	1948–1997
GISS	4° (lat) × 5° (lon)	12	5	1951–1998

8 years as in *Ward* [1998]. Considering other cut-off values (such as 10 years) does not change the final results. Linear correlations are tested with the “random-phase” test [*Janicot et al.*, 1996, 2001; *Ebisuzaki*, 1997]. For each pair of time series to be correlated, 1000 random time series having the same power spectrum as the original one but random phases are correlated and the linear correlations are ordered in ascending order. The upper 10% tail gives the one-tailed 10% level of significance with the alternative hypothesis that the correlation is positive. When running correlations are used, the procedure is the same, except that running correlations are computed on the random time series. Reproducibility is estimated with the method of *Rowell* [*Rowell et al.*, 1998]. The full variance of an ensemble of runs of a given AGCM is separated into an internal and an external (= “SST-forced”) part. This procedure is also used to estimate the similarity between the ensemble mean of each AGCM.

3. HF and LF AGCM Skills

[8] Table 2 displays correlations between observed and simulated SRI and Figure 1 presents the respective time series together with their LF and HF components. The observed SRI (Figure 1a) exhibits the classical behaviour already analysed by numerous authors [e.g., *Folland et al.*, 1986; *Ward*, 1998; *Philippon and Fontaine*, 1999] and characterized by an opposition between the anomalously wet 1950–60s and dry 1970–90s. AGCMs quite accurately reproduce the decreasing trend (Table 2, “R-LF”). Note also (Figure 1b) that the simulated LF component is consistent amongst the AGCMs until 1975–1977, but quite different afterwards; the AGCMs do not simulate accurately the two driest phases in 1972–73 and 1982–84. Regarding the HF variability (Table 2, “R-HF”), the simulations are clearly not consistent with the observations, particularly for ECHAM 3 and 4.

4. Time Evolution of HF Skill and Reproducibility

[9] Figure 2a displays the temporal evolution of HF skill estimated from running 20-year periods (running windows

Table 2. Correlation Coefficients Between Observed and Simulated SRI for Non-Filtered (2nd Column), LF (3rd Column) and HF (4th Column) Time Series

	Period	R (all)	R - LF	R - HF
ARPEGE 3	1948–1997	0.59***	0.73*	0.34**
ECHAM 4	1961–1994	0.10	0.47	-0.06
ECHAM 3	1950–1994	0.57***	0.75*	0.22
GISS 2000	1951–1998	0.41***	0.75***	0.29*

One, two and three stars indicate correlations significant at the 0.1, 0.05 and 0.01 one-sided levels respectively.

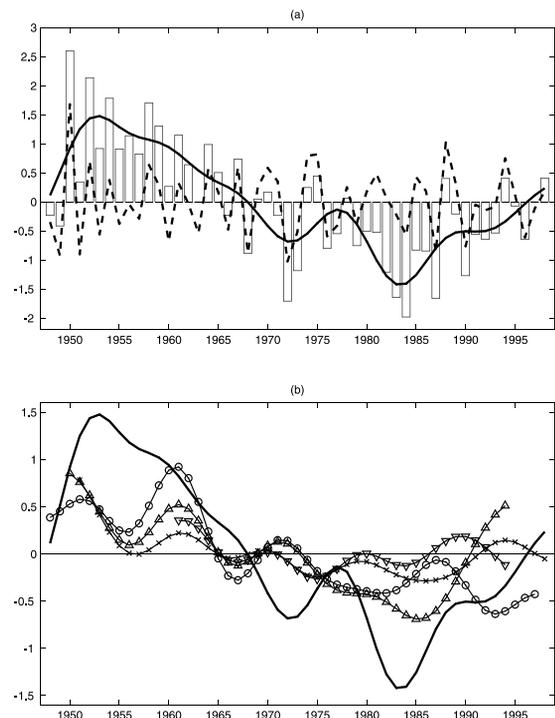


Figure 1. (a) Normalized observed SRI (bar) with its low-frequency (>8 years) and high frequency (<8 years) components superimposed as a full thick line and a dashed thick line respectively; (b) low-frequency (>8 years) of observed (thick line) and simulated (thin line + circle: ARPEGE; upper triangle: ECHAM 3; lower triangle: ECHAM 4; cross: GISS) SRI.

from 15 to 25 years have been tested and found to yield similar results). The time evolution of correlations between the observed and simulated SRI is quite consistent amongst the AGCMs, with the skill strongly decreasing during the dry period. This is particularly clear for ARPEGE (circles in Figure 2a) which shows the highest correlations: skill ranges from moderate to strong until 1968–87 ($r = 0.45$ – 0.60) but decreases toward zero afterwards. The correlations for ECHAM 4 (lower triangle in Figure 2a) are never significant at the one-sided 0.1 level. Thus, HF SRI variability is better simulated during the wet period than during the driest period around the 80s. This is consistent with results of the first AMIP experiment [*Sperber and Palmer*, 1996; *Sud and Lau*, 1996] and may be related, to first order, to a decrease of the SST-forced variance.

[10] The mean values of SST-forced variance range from 21.5% (ECHAM 3) to 30% (ARPEGE) indicating that at least 70% of the HF variability of SRI remains unpredictable from such AGCM integrations. This amount of internal variance limits the highest attainable skill [*Rowell et al.*, 1995; *Rowell*, 1998]. The temporal evolution of SST-forced variance is quite noisy amongst the AGCMs; additionally, no systematic decrease of this SST-forced variance is observed during the driest period (Figure 2b) except for GISS (values range from 35–45% until 1969–88 to 14–30% afterwards). The part of common variance (Figure 2b, thick lines) in the 4-members ensemble mean (or 3-members for 1951–1994) indicates the internal consistency between the AGCMs.

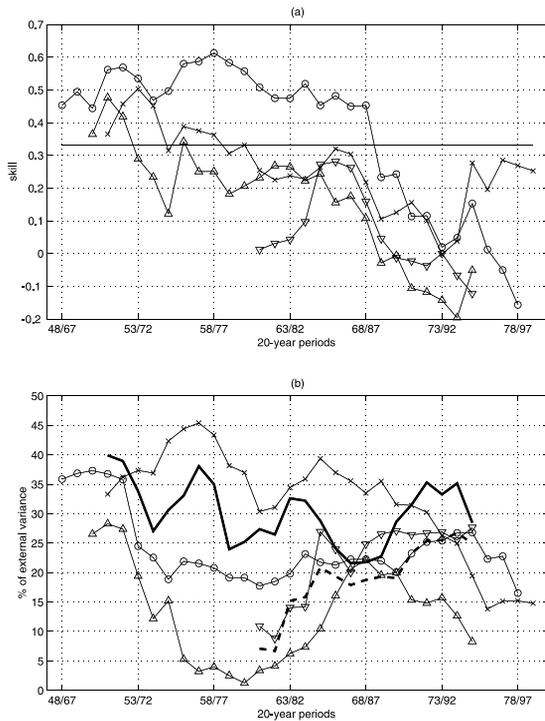


Figure 2. (a) Running correlations on 20-year overlapping periods between observed and simulated (thin line + circle: ARPEGE; upper triangle: ECHAM 3; lower triangle: ECHAM 4; cross: GISS) SRI. The straight line indicates the one-sided 0.1 level of significance; (b) SST-forced variance on 20-year overlapping periods for simulated (line + circle: 8 runs from ARPEGE; upper triangle: 5 runs from ECHAM 3; lower triangle: 3 runs from ECHAM 4; cross: 5 runs from GISS) SRI. The thick full (dashed) line is the common variance estimated from the mean score for GISS, ECHAM3 and ARPEGE (GISS, ECHAM3, ECHAM4 and ARPEGE).

Values range from 30% with 3 AGCMs (Figure 2b, thick full line) to 10%–25% with 4 AGCMs (Figure 2b, thick dashed line) but there is no decrease over time in contrast to skill. In other words, the observed skill decrease over the recent period seems unrelated to the decrease of SST-forced variance within a given ACGM ensemble or between AGCMs, but could be linked to (i) changes in the SST-SRI linear connections which are not (or only partly) reproduced by AGCMs, and/or (ii) an enhanced impact of land surface conditions on SRI variability during the dry period. The first point is further investigated in the next section.

5. SST-SRI Linear Relationships and Their Evolution

[11] The simulation of the SRI-SST teleconnections at HF timescales is studied with 4 SST subequatorial indices (NINO: 180°–270°E 5°N–5°S; EAT: 30°W–15°E; 10°S–5°N; IND 40°–60°E; 5°S–10°N; and WPAC 120°–160°E; 10°S–5°N). Correlation values (Table 3) indicate that AGCMs do not simulate accurately the linear relationship between SST and SRI at this timescales; ARPEGE is the most skillful with correlations that agree in sign with the

Table 3. Correlation Coefficients Between Observed and Simulated SRI and 4 SST Indices at High-Frequency Timescales

	OBS-HF	ARPEGE-HF	ECHAM4-HF	ECHAM3-HF	GISS-HF
NINO-HF	−0.5***	−0.25*	0.56***	−0.07	−0.08
EAT-HF	−0.38**	−0.14	−0.39*	−0.39*	−0.46***
IND-HF	−0.47***	−0.19	0.24	−0.07	0.04
WPAC-HF	0.23	0.13	−0.46**	−0.13	−0.03

One, two and three stars indicate correlations significant at the 0.1, 0.05 and 0.01 two-sided levels respectively.

observed ones but with absolute values that are strongly underestimated (Table 3). The other AGCMs reproduce well the relationship with the southern and equatorial Atlantic but not the observed relationship with the central and eastern equatorial Pacific and western Indian Ocean (Table 3). Notice also that ECHAM 4 is very sensitive to the western Pacific SST but produces anomalies of opposite sign.

[12] Figure 3 displays running correlations obtained between the HF SRI and four HF SST indices. The observed linear relationship with NINO is quite accurately simulated by GISS (Figure 3a, cross) and ARPEGE (Figure 3a, circle) during the 1950–70s. Afterwards, modelled correlations

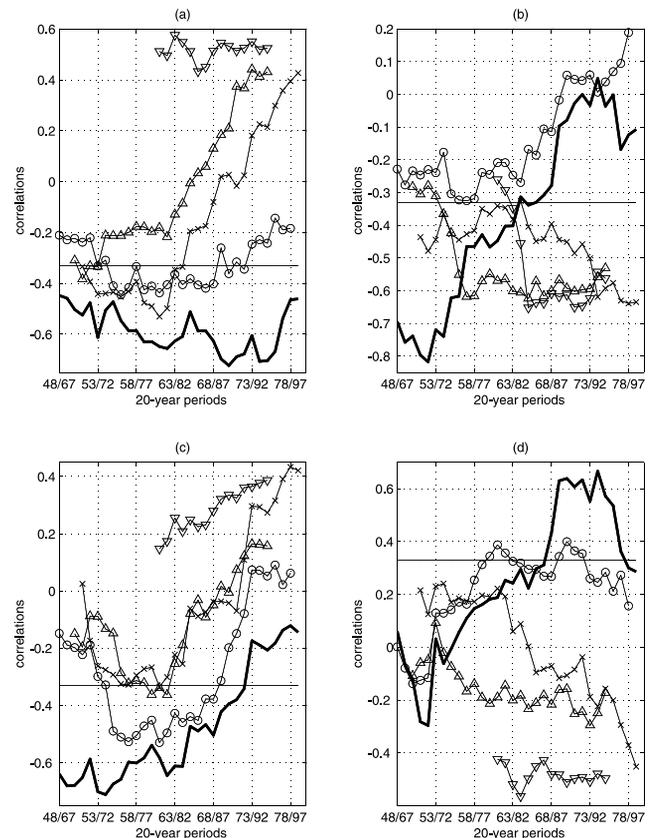


Figure 3. Running correlations on 20-year overlapping periods between HF observed (thick line) or simulated (thin line + circle: ARPEGE; upper triangle: ECHAM 3; lower triangle: ECHAM 4; cross: GISS) SRI and (a) HF-NINO; (b) HF-EAT; (c) HF-IND and (d) HF-WPAC (see text for SST index definitions). The straight line indicates the one-sided 0.1 level of significance (H1: correlation is negative for (a), (b) and (c) and positive for (d)).

weaken whereas they strengthen in observations (Figure 3a, thick full line). When the dry period begins, the correlation between the observed SRI and EAT (Figure 3b, thick full line) tends to zero during the 1970–90s. Such an evolution is only simulated by ARPEGE (Figure 3b, circle) since the other AGCMs produce an evolution of the opposite sense. Considering the other SST forcings, especially WPAC, the AGCMs, except ARPEGE, simulate negative correlations during the dry period when significant positive ones are observed (Figure 3d).

6. Concluding Remarks

[13] The main low frequency (LF) signal of SRI variability, that is a change from wet (during the 1950–60s) to dry (during the 1970–90s) conditions, is well reproduced by the four AGCMs studied in this paper (Figure 1). This provides indirect evidence that recent abnormally dry rainy seasons are mainly due to low-frequency changes in SST forcing at large scale. Other results (Figure 2 and Table 2) clearly show that the HF signal is simulated less accurately. This can be partly attributed to the intrinsic variability of the simulated atmospheres: the SST-forced variance at HF timescales never exceeds 30% for the whole period, which defines an upper limit of model skill [Rowell, 1998]. The skill at HF timescales is also strongly model-dependent. We recall here that the HF skill of the West-African monsoon index for the same AGCMs (not shown) ranges from 0.5 to 0.7 during the 1963–1994 period. We could then hypothesize that the dynamical link between the regional monsoon and the SRI is underestimated in these AGCMs. Even if it is impossible to clearly explain the difference in skill obtained with each AGCM, the best skill at HF timescales is reached by the AGCM (i.e., ARPEGE) having the highest resolution, the most sophisticated land surface scheme (with GISS), but also having the largest ensemble (Table 1). The low resolution certainly introduces a misrepresentation of the rain events. Nevertheless, even ARPEGE appears to be under-sensitive to ENSO events. The SRI skill at HF timescales is lower over the recent dry period (1972–1990) than before, without however any systematic decrease of the SST-forced variance or of the coherency between AGCMs. Simulations do not capture the recent observed strengthening (weakening) teleconnection with the Pacific (Atlantic) SSTs. The decrease in skill could also partly be related to an increase of the continental surface forcing which is not prescribed in these experiments [Zeng *et al.*, 1999; Zheng and Eltahir, 1998].

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