## Using regional wind fields to improve general circulation model forecasts of July–September Sahel rainfall

Ousmane Ndiaye,<sup>1,2</sup>\* Lisa Goddard<sup>1</sup> and M. Neil Ward<sup>1</sup>

<sup>1</sup> The International Research Institute for Climate and Society, The Earth Institute at Columbia University, Palisades, New York, USA <sup>2</sup> Department of Earth and Environmental Sciences, Columbia University, New York, NY, USA

**ABSTRACT:** This study develops and applies a model output statistics (MOS) approach for correcting poor general circulation model (GCM) seasonal rainfall predictions over the Sahel region of West Africa. It illustrates a methodology for approaching the MOS prediction of regional rainfall, drawing on knowledge of the regional circulation system.

The ECHAM4.5 GCM has very little skill in predicting July–September Sahel rainfall. However, the GCM is much more capable of reproducing the regional wind circulation at 925 hPa, especially over the tropical Atlantic. This is capitalized upon using a MOS approach that applies empirical orthogonal functions (EOFs) of the model's regional (tropical Atlantic and West Africa) 925 hPa wind as predictors in a regression with observed Sahel rainfall as the predictand. Over 1968–2002, the MOS system requires only the first wind EOF and improves the correlation skill of July–September Sahel rainfall from 0.07 (raw GCM) to 0.57. The MOS system is applied to GCM experiments using persisted sea-surface temperature (SST) anomalies from the months of June, May and April respectively, to estimate the potential of the system to make forecasts with lead times between 0 and 2 months ahead of the July–September season. Almost identical skill is achieved from the June SST, but May and April SSTs show a substantial decline in skill. This is mainly associated with a tendency in tropical Pacific SST anomalies from May to June, highlighting development of El Niño (La Niña) in Sahel dry (wet) years, though statistically significant tendencies are also found in the tropical Atlantic and Indian Oceans. The MOS approach is robust in simulation experiments over the 1950–2002 period, when one additional EOF in the MOS system is found to best capture the tropical Atlantic influence. For increasing forecast lead time, targeted prediction of SST from April to June is motivated by these findings. Copyright © 2008 Royal Meteorological Society

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### 1. Introduction

The Sahel region of West Africa has a short rainy season from June to September followed by a long dry season. The rainy season itself is marked by strong interannual variability embedded in low-frequency multidecadal variability (Nicholson and Grist, 2001). A forecast of the rainy season is crucial for the population in the Sahel. A good seasonal forecast can help them better prepare using limited economic resources. This has created in the scientific community an interest in understanding and predicting the Sahel rainfall variability.

Many studies have related Sahel rainfall variability to different components of the near-surface ocean and atmospheric boundary layer. The most investigated part is the near-global sea-surface temperature (SST) through its coupling with the atmosphere. The key SST regions identified include the tropical Atlantic (Lamb, 1978a; Hastenrath, 1990; Ward, 1998), the Pacific Ocean El Niño/southern oscillation (ENSO) region (e.g. Janicot et al., 1996; Ward, 1998) and an inter-hemispheric gradient of SST in the Atlantic, with components of the gradient present in the Indian and Pacific Oceans leading to its interpretation as a near-global inter-hemispheric contrast (Folland et al., 1986; Ward et al., 1993; Rowell et al., 1995). Some mechanisms relating the dynamics of Sahel rainfall and SST variability in different basins have been proposed. Over the tropical Atlantic, anomalous warm SST over the tropical south Atlantic basin corresponds to an inter-tropical convergence zone (ITCZ) anomalously south with excess rainfall south of 10°N in West Africa at the expense of rainfall in the Sahel (Lamb, 1978a,b). With regard to the tropical Pacific, the teleconnection between Sahel rainfall and the ENSO is now well established (Folland et al., 1991; Ward, 1998; Janicot et al., 2001). Tropical Pacific warm events (El Niño) are related to reduced rainfall in the Sahel, and cold events (La Niña) are associated with above normal rainfall in Sahel. One proposed mechanism is that warming over the tropical Pacific becomes associated with deep convection and upper-level divergence over the Indian Ocean with a descending branch over the Sahel (Shinoda and Kawamura, 1994; Giannini et al., 2003; Trzaska and

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<sup>\*</sup>Correspondence to: Ousmane Ndiaye, 133 Monell Building, Palisades, NY 10964-8000, USA. E-mail: ousmane@iri.columbia.edu

Janicot, 2003). It is likely that other mechanisms also contribute to the teleconnection between the African sector and the tropical Pacific as well.

These various teleconnection processes, in individual years, combine in different ways with different intensities to shape the climate over the Sahel. In addition, on the inter-annual timescale, there also appears to be substantial variability internal to the regional climate system and not related to remote teleconnection processes. General Circulation Models (GCMs) can help then to understand the various processes and interactions (e.g. Palmer, 1986), and to evaluate the fraction of variability attributable to teleconnections with SST, therefore estimating the potential for seasonal prediction (such as in Rowell *et al.*, 1995).

It is, however, the case that most GCMs fail to skillfully simulate the inter-annual variability of Sahel rainfall when driven with the observed SST. The first objective of this study is to develop and apply a methodology to approach seasonal prediction in this situation when there is strong evidence that in the real climate system, the SSTs do influence rainfall variability. A model output statistics (MOS) approach is taken (e.g. Feddersen et al., 1999; Landman and Goddard, 2005; Friederichs and Paeth, 2006), using large-scale fields from the GCM that do contain the relevant teleconnection information from the SST. Some of the previous MOS studies have taken a systematic approach and sought to correct GCM precipitation fields in global or continental domains for all seasons. Indeed, this was done by Friederichs and Paeth (2006) for the continent of Africa as a whole, establishing the viability of the MOS approach and baselines for the increases in skill that are achievable through such approaches. In this paper, we will now focus on a particular regional circulation system, and address the problem from the point of view of a forecaster seeking to develop the most robust and reliable system for a particular targeted predictand. This leads into discussion of the known linkages between global climate and the region's circulation and precipitation, and how they are best captured in a MOS forecast system. In this case, the GCM's low-level wind fields across the tropical Atlantic and West Africa turn out to contain the SST-forced predictive information for Sahel rainfall. Such a prediction system is expected to compliment empirical systems that use SST predictors (e.g. Folland et al., 1991). For example, the GCM can integrate the SST information in a more complete non-linear way than can empirical systems.

The choice of wind field for the MOS predictors is guided by the knowledge that in West Africa, the low-level wind is one of the major features of the rainfall dynamics. It is through the low-level wind that moisture is carried from the ocean in the monsoon flow to constitute precipitable water over land. Camberlin *et al.* (2001) relate SST variations to changes in East–West wind circulation patterns which impact rainfall through the monsoon flow. El Niño events tend to enhance lowlevel northeasterlies and to reduce the monsoon flow, which, coupled to a weakened upper easterly structure, favours dry conditions over West Africa. Thus, a MOS prediction system is constructed (Section 3) that uses a dynamically plausible field from the GCM as the predictor for the target Sahel seasonal rainfall.

A second objective of this study is to investigate the sensitivity of the MOS prediction system to lead time and sub-period for the Sahel rainfall forecast. One of the key issues related to forecasting the rainfall over the Sahel is the loss of skill with increasing lead time of just a few months, associated with developments in prerainy season ocean boundary conditions (see Ward et al., 1993). This study, therefore, investigates the loss of skill, and the associated patterns of SST evolution that lead to the loss of skill in the GCM predictions at lead times of up to 3 months (Section 4). A further key issue in Sahel prediction has been the representation and character of predictability through the contrasting wet and dry epochs. Using the GCM simulation experiments driven with observed SST over the longer period 1950–2002, the stability of the MOS through the wet and dry epochs is also investigated (Section 5).

## 2. Data

## 2.1. Rainfall data

The rainfall data are taken from the Global Historical Climatology Network (GHCN), version 2 beta, which is a compilation of global daily data from the World Meteorological Organization (WMO) network. A set of 156 stations within the Sahel domain has been considered. Sahel is defined here as the region bounded by  $18^{\circ}W-30^{\circ}E$  and  $12^{\circ}N-20^{\circ}N$ . We will compute first a monthly rainfall index by averaging existing station data in each year over the domain. From the July, August and September monthly indices we will calculate the mean July, August and September seasonal index over the 1950–2002 period.

#### 2.2. Reanalysis data

Wind data were extracted from archives of the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis project (Kalnay *et al.*, 1996). This data-set consists of a dynamical model interpolation of global meteorological observed variables at  $2.5 \times 2.5$  grid resolution from 1950 to 2002. Monthly mean data are averaged over the July-September (JAS) season. The fields of interest are the winds at 925 and 200 hPa.

### 2.3. GCM experiments

The atmospheric GCM used in this study is the ECHAM4.5, for which ensemble simulations of 24 members and retrospective forecasts of 12 members have been produced at the International Research Institute for climate and society (IRI). The ensemble mean is used in this study. Simulation ensemble mean results with 12 members were also analysed, and no difference of substance

was found compared to the results with the 24 members that are shown in the analyses in this paper. ECHAM4.5 is a spectral model at T42 resolution (approximately 2.8° horizontal resolution) with 18 levels in the vertical. More details of the model can be found in Roeckner et al. (1996). Two sets of ensemble runs are used in this study as in Goddard and Mason (2002). 'Simulation' runs were generated by forcing the ECHAM4.5 with observed simultaneous monthly mean SSTs. 'Persisted' runs refer here to forecasts by the GCM using SST anomaly (SSTA) persistence to generate the SST fields to drive the GCM. The SST persistence is designed as follows: for each month the SSTA is added to each of the following 5 months' SST climatology, which are then used to force the atmospheric GCM. The simulation runs are available from 1950 to the present. The persisted runs available to this study cover the period 1968-2002.

# 3. Model performance 1968–2002 with observed SST: direct GCM output and a MOS system

## 3.1. Model climatology

First, it was checked that the ECHAM4.5 simulates a reasonable climatological pattern of the rainfall and low-level winds over the Sahel and surrounding region (not shown). Indeed, the main structures of the wind circulation are all well simulated by the model. The monsoon flow is particularly well reproduced by the model. The strength of the southeasterly flow over the tropical South Atlantic and near the Brazilian coast is correctly simulated. The upper-level wind circulation at 200 hPa is also generally well captured. The ECHAM4.5 GCM reproduces the mean state of the climate. We will now examine how the model simulates the year-to-year climate variation over the Sahel.

## 3.2. GCM simulation skill

The skill of the GCM in simulating year-to-year seasonal variations is first evaluated for each grid-box by calculating the correlation between ECHAM4.5 simulations and the observations. The GCM does not simulate the inter-annual rainfall variations accurately over the Sahel during 1968-2002. On a grid-box-by-grid-box basis, the average correlation skill over the Sahel is 0.04 (map not shown). On the other hand, the year-to-year variation of the wind is well captured over much of the Atlantic basin and, with somewhat weaker skill, extends into West Africa. At 925 hPa, the model captures the wind variability over the tropical North Atlantic and over the South Atlantic basins, especially near the east coast of Brazil. At 200 hPa, the skill is also high, especially for the zonal (U) component, particularly around 10°N near the axis of the Tropical Easterly Jet (TEJ), whose variability is an important component related to Sahel rainfall (Fontaine and Janicot, 1992).

The use of indices, such as the West African Monsoon Index (WAMI), facilitates the examination of regional variability, removing the stringent requirement of accurately reproducing the local variability. The dynamical monsoon index, WAMI, is defined here as the shear between the low-level monsoon wind modulus at 925 hPa and the zonal wind component at 200 hPa, each averaged from 20°W to 20°E and from 3°N to 13°N as defined by Moron et al. (2004) and Garric et al. (2002). Figure 1 shows the WAMI during JAS as simulated by the GCM and observed in the NCEP reanalysis. The pearson correlation between the two indices is r = 0.53 over the 1968-2002 period. This indicates a reasonable agreement between the reanalysis and the GCM prediction of the WAMI based on observed SST. The step change in the reanalysis data prior to 1968 in Figure 1 is beyond the scope of this paper, but may at least in part be related to a change in the mix of observations entering the reanalysis.

A Sahel rainfall index was calculated by averaging station data during the JAS season over a box bounded by  $18^{\circ}W-30^{\circ}E$  and  $12^{\circ}N-20^{\circ}N$ . Figure 2 shows the time series of the observed index and the index calculated from GCM rainfall. On the multi-decadal timescale, though the GCM has the correct sign, it is unable to capture the magnitude of the difference between the wet period (1950–1970) and the more recent dry period. Interannual variability in the GCM is also too weak, and the year-to-year fluctuations show no agreement with observations. For the recent period dominated by interannual variability (1968–2002) the correlation is 0.07. The GCM is, therefore, able to better simulate variability in wind across both the tropical Atlantic and West Africa, than it is in the Sahel rainfall.

## 3.3. Using MOS to correct GCM Sahel rainfall

The model simulates the 925 hPa wind over the tropical Atlantic particularly well. Given the importance of regional wind variability for rainfall variability over the Sahel (Fontaine and Janicot, 1992; Fontaine *et al.*, 1995; Camberlin *et al.*, 2001), we hypothesize that a statistical transformation of the wind can be used to forecast the Sahel rainfall. A correlation empirical orthogonal function (EOF) analysis technique is applied, which regularly retrieves coherent spatial patterns through time. The EOF analysis is very widely used in climate data analysis (Lorenz, 1956; Bretherton *et al.*, 1992), and has been widely applied in empirical and MOS approaches to seasonal prediction (e.g. Ward *et al.*, 1993; Feddersen *et al.*, 1999).

For the MOS, the approach taken is to make a regression, or multiple regression, between the MOS predictors and the target predictand, the Sahel rainfall index. The candidate MOS predictors are the leading EOFs of the region's low-level wind field. Selection of which EOFs to include in the model needs careful consideration. The MOS systems in this and subsequent sections use cross-validation in which all information on the year being forecast (plus the year before and after) is withheld from model estimation. In other words, the



Figure 1. West Africa Monsoon Index (WAMI) in July–September (JAS) from NCEP reanalysis (solid line) and GCM simulation (dashed line), units are in m/s.



Figure 2. Sahel rainfall indices for the JAS season: observed (solid line) and simulated by the GCM (dashed line).

Table I. Skill of predicting Sahel rainfall 1968–2002, using a GCM MOS with zonal wind at 925 mb over the window 40°S–30°N latitude, 65°W–10°E longitude.

EOF number	1	2	3	4	5	6	7	8	9	10
%var	34	19	12	7	5	4	3	2	2	2
CV skill	0.57	0.52	0.57	0.59	0.58	0.55	0.55	0.56	0.55	0.48
R(EOFvSahel)	-0.63	-0.02	0.13	-0.28	-0.03	-0.11	-0.01	0.15	-0.13	-0.09

EOFs are incrementally added to the prediction system. The row headings are defined as follows: %var indicates the % of wind-field variance explained by each EOF, CV skill is the cross-validated correlation skill of the multiple regression model in predicting Sahel rainfall, R(EOFvSahel) is the individual correlation between each EOF and Sahel rainfall

window length for the cross-validation is 3 years. While a step-wise procedure has been applied to assist in predictor selection, the choice in this study is also made based on physical interpretation of the predictors in relation to known influences on the Sahel rainfall. However, results turn out to be very clear-cut and not sensitive across reasonable criteria for inclusion.

Table I provides a summary of model features and performance, as the number of EOFs in the model is incrementally increased from 1 to 10. The EOF1 of the 925 hPa zonal GCM wind across the tropical Atlantic and surrounding region (Figure 3) is found to contain essentially all the predictive information for the Sahel rainfall. The time series of the first EOF of the zonal wind is very similar to that of the first EOF of the meridional wind (correlation of 0.94 over 1968–2002), and no additional skill is achieved through the use of the meridional in place of the zonal wind.

A small peak (cross-validation skill r = 0.59) is found with the addition of zonal wind EOF4 (Table I). No physical significance could be attached to EOF4, which

Table II. Correlation skill of predicting Sahel rainfall 1968–2002 using a GCM MOS with different variables over the window  $40^{\circ}\text{S}-30^{\circ}\text{N}$  latitude,  $65^{\circ}\text{W}-10^{\circ}\text{E}$  longitude.

	U	Precip	Omega	Humidity	
EOF1	0.57	0.32	0.37	0.10	
Best model	0.59 (4 EOFs)	0.37 (4 EOFs)	0.52 (3 EOFs)	0.35 (4 EOFs)	

The column headings are defined as follows: U is zonal wind at 925 mb, precip is the regional precipitation field, omega is the vertical motion at 850 mb, and humidity is at 850 mb level. The top row uses the first EOF as MOS. The second row shows the best cross-validated result after incrementally adding additional EOFs



Figure 3. Spatial pattern of the first EOF of the 925 hPa GCM zonal wind during JAS 1968–2002.

explains only 7% of the total variance in the wind field (Table I). Furthermore, a pattern like EOF4 was not found to add skill in longer-period analyses (1950–2002, Section 5). Even with cross-validation, the risk of choosing a model that contains spurious fitting in the historical period is still present, and in this case, it is proposed that there is no sufficiently strong case to include EOF4. Note that when a model is constructed using EOF4 alone, and cross-validated, its skill is just r = 0.06, clearly not statistically significant, and so inclusion of EOF4 is not considered justified based on these statistical grounds either.

Before settling on the model in Table I with EOF1 of zonal wind, other checks were made to confirm robustness of the result and that substantial skill was not being lost through choice of MOS domain and variable. First, the regional domain for the MOS predictor was perturbed in each direction by up to 20° latitude and 20° longitude. The first EOF continued to be the dominant skill source, with cross-validated skill ranging from r = 0.53 to r = 0.58. It is proposed to maintain the original choice of the domain for the MOS, considering the slight peaks of skill with other domains as reflecting

statistical noise in the results, and not likely to lead to increases in skill when the system is applied in realtime.

A further aspect to check is whether a more global domain for the MOS predictors would improve skill. This was not expected to be the case. While near-global SST patterns are considered to influence the Sahel rainfall, the transmission of the global SST influence is considered to primarily occur through the regional circulation system, both in the real climate system and in the GCM. Thus, with an appropriately selected domain to capture the regional system, any global SST influences should be captured by the regional MOS. This indeed appears to be the case in the problem studied here. For example, taking a global tropics ( $40^{\circ}N-40^{\circ}S$ ) domain for the U-wind, cross-validation skill with EOF1 was found to be r = 0.46, with a small peak (r = 0.47) when three EOFs are used.

Finally, the possibility that other model variables may perform better as MOS predictors has been explored. A commonly used variable in MOS systems is model precipitation itself, under the hypothesis that the model can better represent the large-scale regional precipitation patterns which can then form useful predictors for particular target precipitation predictands. Two other variables that can be closely related to tropical precipitation are vertical motion at 850 mb and low-level humidity at 850 mb. The skill achievable with each of these three variables has therefore been tested (Table II). All models are inferior to the use of the zonal wind. Humidity and precipitation are quite substantially less skillful (best model correlations are less than r = 0.40), suggesting the model has difficulty with these variables in this region at this time of year. A model with three EOFs of vertical motion achieves the best result of the new models (r = 0.52) but is still inferior to the model with EOF1 of zonal wind. A further consideration was whether an index such as WAMI could be used as a MOS predictor to improve upon skill. The GCM's simulated WAMI has a cross-validated skill of r = 0.36 with the observed Sahel rainfall index, substantially less than that achieved by the EOF1 of zonal wind. Furthermore, when the model's WAMI is added to the zonal wind EOF1 in a regression model, the cross-validated skill was found to be less than that with the model of EOF1 alone.

In summary, over the period 1968–2002, the MOS system with the regional low-level wind EOF1 is capable of substantially improving the rainfall skill of the GCM

simulation, increasing the anomaly correlation coefficient of the Sahel index from 0.07 to 0.57. This indicates that the GCM can simulate correctly the low-level winds associated with the rainfall but fails to directly simulate the rainfall. It indicates also that wind at 925 hPa can be used here to correct poor GCM rainfall skill. Given the role of SST in influencing winds, and the linkage of wind fields to the Sahel rainfall, it is reasonable to assume this approach may be successful with other GCMs that have difficulty in predicting Sahel rainfall.

## 4. Model forecast skill and sensitivity to SST developments

### 4.1. Performance with persisted SSTA

Here we will study the skill of rainfall forecasting using SST persistence at lead times of zero (June) to 2 months (April) before the main Sahel rainy season in JAS. The first EOF mode is also used for the runs with persisted SST. The total wind variance explained by EOF1 is 34,

31 and 27%, respectively, for the forecast experiments with June, May and April persisted SSTA, and the spatial pattern of the leading mode is similar to the result with simulated SST (Figure 3) in all cases (not shown).

Before reviewing the skill of the MOS rainfall forecast system, we will consider the skill of the model wind fields, since they form the basis of the MOS system. The skill is calculated between observation and model at each grid point. Figure 4 shows skill maps for the zonal wind component at 925 hPa. The skill maps for the different lead times are very consistent in space, generally just weakening with the longer lead: centres of skill are always located over the east coast of tropical Northern and Southern America, and over the Gulf of Guinea near the equator. The skill is very similar for both U and V components (the latter is not shown). Results for the simulation (Figure 4(d)) and with persisted June SSTA (Figure 4(c)) are very similar. However, the persisted May map (Figure 4(b)) shows a notable drop in skill overall, and especially in areas in the eastern tropical North Atlantic and West Africa. The map for the



Figure 4. Skill of the GCM's zonal wind at 925 hPa during JAS 1968–2002. GCM is driven with: (a) persisted April SSTA, (b) persisted May SSTA, (c) persisted June SSTA, and (d) the actual observed SST through the JAS season. Values shown are the correlation between GCM and reanalysis zonal wind at each grid location. Shading indicates correlations significant at 90% confidence level.

persisted April SSTA experiments (Figure 4(a)) shows a further decline in skill.

Figure 5 compares MOS Sahel rainfall skill for the GCM forced with different SST boundary conditions (JAS, June, May and April). The MOS-corrected rainfall always performs better than the raw GCM rainfall. Persisted June SSTA experiments have almost the same skill as those with the observed SST. In other words, the SST boundary condition in June is as good as that of JAS for building a prediction model for the Sahel region targeting the JAS season. However, this provides a very short lead time for the targeted rainy season, as observations of June SSTs are not available until early July. The skill deteriorates from 0.55 with June persisted SST to 0.33 and 0.30 with May and April persisted SST, respectively. From June to May, in terms of percent variance explained, the drop is from 32 to 12%, compared to no drop of substance between JAS and June SST. These results are qualitatively similar to those found in Ward et al. (1993) where there was also a very substantial drop in skill when using May as compared to June persisted SSTs. Though those results were based on a much smaller sample of years, it is noteworthy that the same pattern emerges here.

This loss of skill from June to May appears to be real and substantial, and is crucial for the potential uses of the climate forecasts for those who need more lead time to plan for their activities. The next section investigates the source of the loss of skill.

#### 4.2. Key SST developments between May and June

The set of years is identified where the MOS correction forecast using both observed and June SSTA made an accurate rainfall prediction, while the model using May SSTA failed. We hypothesize that these failures are not due to random internal atmospheric dynamics but rather are due to systematic and rapid changes in the ocean boundary forcing from May to June. The analyses below identify the structure of the SST change and the sensitivity of the GCM's global tropics circulation to those SST changes.

The years identified for the analysis are indicated in Figure 6. In the wet years 1969, 1970 and 1988, the

0.6 0.5 ■ MOS GCM 0.4 0.3 Correlation 0.2 0.1 0 -0.1 -0.2 JAS June May April SST boundary conditions

Figure 5. Sahel JAS rainfall skill (1968-2002) from direct GCM output (open bars) and from application of the MOS system using GCM low-level wind EOF1 (shaded bars).

June persisted MOS gets the right rainfall response, as does the simulation. The May persisted SST MOS, however, produces either a very weak or an opposite response (open arrows, Figure 6). Likewise, a set of dry years (1972, 1976, 1986, 1997 and 2002) is identified when the simulation and the June persisted SSTA MOS capture the dryness in the Sahel, but the May persisted SSTA MOS produces a much weaker or opposite response (Figure 6, black arrows). To see the systematic changes in SST during these years, the following composite is constructed:

$$SST' = [(JUN_{69} - MAY_{69}) + (JUN_{70} - MAY_{70}) + (JUN_{88} - MAY_{88})]/3 - [(JUN_{72} - MAY_{72}) + (JUN_{76} - MAY_{76}) + (JUN_{86} - MAY_{86}) + (JUN_{97} - MAY_{97}) + (JUN_{02} - MAY_{02})]/5 (1)$$

where JUN<sub>69</sub> is the SSTA field for June 1969, etc. The field of SST' is shown in Figure 7(a). It can be interpreted as the systematic pattern of SSTA change (tendency) from May to June, in years when the May forecast fails but the June forecast successfully forecasts wet. The field multiplied by -1 can be considered the systematic pattern of SSTA change (tendency) from May to June in years when the May forecast fails, but the June forecast successfully forecasts dry. The wet and dry years are combined in this way to increase sample size and allow a more robust estimate of statistical significance (Castello and Shelton, 2004).

A substantial SSTA tendency from May to June in these years is found in the central and eastern Equatorial Pacific. The tendency is substantial both in terms of magnitude and statistical significance. The suggestion is that the forecast failures are associated with rapid developments from May to June in the ENSO phenomenon, with La Niña developing in wet years and El Niño developing in dry years. In addition, statistically significant SSTA tendencies are found in the tropical Atlantic and northwestern Indian Ocean, with SSTA cooling (warming) in these locations in the Sahel wet (drv) years.

To assess the implications of the SSTA tendencies for global tropics atmospheric circulation, a similar composite approach to Equation (1) has been taken with the GCM experiments:

$$JAS \text{ circulation} = [(JUN_{69} - MAY_{69}) + (JUN_{70} - MAY_{70}) + (JUN_{88} - MAY_{88})]/3 - [(JUN_{72} - MAY_{72}) + (JUN_{76} - MAY_{76}) + (JUN_{86} - MAY_{86}) + (JUN_{97} - MAY_{97}) + (JUN_{02} - MAY_{02})]/5$$
(2)





Figure 6. Sahel JAS rainfall indices: observed (solid) compared to predictions using the MOS system applied to the GCM. Sets of GCM experiments are shown using observed SST (sim), persisted June SST anomalies (Jun) and persisted May SST anomalies (May). Units are in mm/month anomaly.



Figure 7. Composites showing (a) the systematic tendency of SSTA (units in °C) from May to June in those years of an accurate MOS Sahel forecast from June SST, but a failed forecast from May SST, and (b,c) the impact of the SSTA tendency on JAS GCM circulation fields, namely, 925 hPa wind (b) and 200 hPa wind (c), wind units in m/s. The years included in the composites and calculation procedure is given in Figure 6 and Equations (1) and (2). The sign is for the tendency in a wet Sahel year, and fields should be multiplied by -1 for the tendency in dry Sahel years. Shaded areas indicate statistical significance at the 90% level according to the Mann–Whitney U test.

where JUN<sub>69</sub> is now the JAS GCM circulation in the experiment driven with persisted June SST anomalies for 1969. These fields are shown for near-surface wind (Figure 7(b)) and 200 hPa wind (Figure 7(c)). They can be viewed as the response of the model to the change in boundary forcing from May to June in years when the forecast from the May SST fails, but the forecast from the June SST successfully forecasts wet conditions in the Sahel. Again, as with the SST, when the circulation fields are multiplied by -1, they show the counterpart for the dry years. It can be seen that the SST tendencies are sufficient to drive a substantial change in the GCM response over the central and eastern Equatorial Pacific (magnitude 2 m/s), with statistically significant changes in the 200 mb upper-level easterlies extending from the eastern Pacific into the tropical Atlantic. At the surface in the tropical Atlantic, there are also significant changes in circulation, with stronger southeasterlies south of the Equator, and with some strengthening of the monsoon circulation north of the equator. This pattern resembles the one used in the MOS, and is consistent with the better performance of the MOS using June SST compared to May SST. The suggestion then, is that the teleconnection from the tropical Pacific to the tropical Atlantic basin is better established in the forecasts from June SSTs.

It is also possible that the tendencies in SST in the tropical Atlantic and tropical Indian Ocean (Figure 7(a)) are also playing a role in the better establishment of the circulation anomalies in the tropical Atlantic. Further investigation of this will assist in evaluation of whether SSTs outside the tropical Pacific need to be forecast from May to June in order to improve Sahel forecasts, and if so, which aspects of the SSTs. From the results here, the situation in the Indian Ocean appears particularly problematic. The tendency for cooling of SST

in the northwestern Indian Ocean induces in the GCM a significant weakening of near-surface monsoon flow over the western Indian Ocean (Figure 7(b)). Rather than a clue to the SST field that needs to be forecast, this is more likely a clue to a more fundamental problem of driving the GCM with observed SST, since cooling of the SST in this location is often a response to strengthened Indian monsoon, not a primary driving agent for atmospheric anomalies. This problem of monsoon circulations driving SST changes, that if used to drive a GCM give the opposite response in monsoon circulation, has now been quite widely investigated (e.g. Wang *et al.*, 2004).

This section has identified that systematic SST changes are found in the tropical Pacific, Indian and Atlantic Oceans from May to June in years when the June Sahel forecast is successful and the May forecast fails. The response of the GCM to those SST changes shows the establishment of significant circulation anomalies extending from the tropical Pacific into the tropical Atlantic, consistent with the MOS system being able to better forecast Sahel rainfall anomalies. The importance of rapid SST changes from May to June is established to be very real for Sahel rainfall prediction, and frames an important research question for understanding and predicting SST tendencies at this time of the year.

## 5. Performance of the MOS through the wet and dry Sahel epochs

It is known that during the wetter period (approximately 1950–1969), Sahel rainfall shows a much stronger linkage with the tropical Atlantic SST (Figure 8(a)), whereas during the drier post-1970 period, the influence of ENSO has been stronger (Figure 8(b)) (and see e.g. Janicot



Figure 8. Correlation between the observed JAS Sahel rainfall index and SST during JAS, (a) 1950–1969, and (b)1970–2002. Shading indicates statistical significance at the 90% confidence level.

*et al.*, 1996; Ward, 1998). While forecast GCM experiments were available only for 1968–2002, the simulations with observed SST were available for 1950–2002, and allowed investigation of the performance of the MOS over the whole period and in the sub-periods 1950–1969 and 1970–2002.

First, the performance of the raw model output is reviewed (Table III, row 1). For the period 1970–2002, as previously discussed, the raw output has near-zero skill. In the period 1950-1969, the raw output turns out to have some modest skill (r = 0.36). One interpretation is that the model is better able to directly simulate the effects of the tropical Atlantic SST on the rainfall, as compared to the effects of the tropical Pacific, which dominate in the 1970-2002 period. Over the whole period, 1950–2002, the correlation skill is r = 0.55. At first sight this appears a reasonable performance, though as previously noted, the trend that is substantially contributing to the correlation is greatly underestimated (Figure 2). It will be shown below that applying the MOS methodology based on the regional low-level wind field is able to substantially improve the skill in all sub-periods.

As a preparation for interpretation of the MOS results, Figure 9 shows that the teleconnection between observed Sahel rainfall and the simulated GCM low-level wind shows some differences between the two epochs. In the latter period 1970-2002 (Figure 9(b)) the pattern resembles a basin-wide modulation of the trade wind – monsoon circulation, resembling closely the EOF1 pattern of model wind that was used in the MOS in Section 3 (Figure 3). In the early period (Figure 9(a)), some of the basin-wide modulation is again seen, but in addition, there is more strongly superimposed a smaller-scale structure with divergence from the equatorial Atlantic, and anomalous westerlies across the northern tropical Atlantic sector into the Sahel of Africa.

When the MOS is applied to the whole period, 1950–2002, two modes provide skill in specification of the Sahel rainfall. The first mode (Figure 10(a)) is similar to the one found previously (Figure 3). The other mode that adds further skill (Figure 10(b)) is centred through the Equatorial and northern tropical Atlantic and resembles a more localized modulation of the ITCZ and associated monsoon flow. It can be seen to contain aspects of the model teleconnection map for the early period (Figure 9(a)). The first mode contains most of the skill (r = 0.68), but addition of the other mode does notably raise the skill further (r = 0.78, Figure 11).

Table III. Sahel rainfall correlation skill for raw GCM rainfall and the MOS system, based on GCM experiments driven with observed SST.

	1970-2002	1950-1969	1950-2002
Raw GCM	0.03	0.36	0.55
MOS	0.57	0.74	0.78
MOS 1950-1969	_	0.57	-
MOS 1970-2002	0.52	-	-



Figure 9. Regression between the observed Sahel index and each component of the GCM wind at 925 hPa during JAS for (a) 1950–1969 and (b) 1970–2002. Highlighted are areas where the correlation with one of the wind components is significant at the 95% level.

These two modes, with slightly modified form, are recovered in the two sub-periods (not shown). The first mode in 1950–1969 (not shown) has weight shifted somewhat further north than the EOF1 of 1950–2002 (Figure 10(a)), but over the period 1950–1969, the two time series correlate at extremely high levels (r = 0.92), indicating they are essentially capturing the same variability. The period 1950–1969 does, however, show itself to be rather short for defining the patterns for a stable MOS. The correlation skill of the MOS fitted over these years is 0.57 (Table III, row 3). The skill over the 1950–1969 period rises to r = 0.74 using the output from the cross-validated MOS analysis on the whole period of 1950–2002 (Table III, row 2).

For the period 1970–2002, while the additional mode is indeed recovered in the analysis it turns out to not add to the skill of the MOS. This is interpreted as an expression of the weaker equatorial and south tropical Atlantic SST influence on Sahel rainfall in this period.



Figure 10. EOF patterns of the GCM's 925 hPa zonal wind (experiment driven with observed SST, 1950–2002). (a) EOF1 1950–2002 (34% of variance); (b) EOF3 1950–2002 (12% of variance).

Overall, these results show a strong robustness of the MOS over a period when the background Sahel rainfall was slowly evolving, along with a changing balance of relationships with SST across the different ocean basins. The absolute level of skill for the 1950–2002 period needs to be interpreted with caution, since over this period, a strong low-frequency component is present in the time series, compromising somewhat the effectiveness of the cross-validation testing of the prediction system. Nonetheless, the stability of the modes and the performance in the two sub-periods are very encouraging. The results build confidence in the application of the MOS system for real-time prediction.

#### 6. Discussion and conclusions

In this study, we have seen that the ECHAM4.5 GCM poorly simulates the inter-annual Sahel rainfall. The inability of a GCM to simulate rainfall in this particular region of West Africa has many possible sources. Rainfall in GCMs is a combination of large-scale circulation and local sub-grid scale convection. Sub-grid scale rainfall in GCMs is resolved by parameterization, which may not be optimized for conditions in all regions. In the Sahel, most of the rainfall is from convective motions related to the ITCZ. So a GCM can easily fail to capture most of the rainfall over the Sahel due to improper parameterization. Another important feature in the Sahel is vegetation changes. The Sahel region has one of the steepest spatial gradients of vegetation. In 10° of latitude, vegetation changes from Saharan desert in the north to a tropical forest in the south. Vegetation changes have an impact on the rainfall through land surface properties such as surface albedo, evapotranspiration and roughness (Charney, 1975; Hales et al., 2004). Wang and Eltahir (2000), using a coupled biosphere-atmosphere model which includes explicit representation of vegetation dynamics over Sahel, show that the vegetation dynamics impacts the Sahel rainfall variability. The GCM with approximately 250 km coarse spatial resolution and a relatively simple land surface scheme is unlikely to capture vegetation effects over the Sahel, which can further explain the GCM's poor skill in rainfall simulation.

In the example presented in this paper, rainfall was poorly simulated by a GCM, yet in the study region, there is evidence for a substantial role of SST in the real climate system. The approach proposed is to explore, and when possible, capitalize on the model's good performance in those circulation features of the region that are known to be linked to observed rainfall variability. Other studies (and Friederichs and Paeth (2006) specifically for Africa) have shown the potential for improvement of rainfall skill over Africa by using MOS-calibration. The approach here has been to focus on a particular region (the Sahel) and identify a MOS correction system that focuses on the regional circulation system for the Sahel rainfall. It can serve as an illustration of methodology for approaching the development of a MOS system for a specific target region. Insights to the scale of the regional circulation system connected to Sahel rainfall, and known aspects of the SST-circulation-rainfall relationships, are drawn upon to arrive at a system that is as robust as possible and carries good physical climate justification. The model low-level wind field across the tropical Atlantic and West Africa was found to have a good relationship with the observed seasonal rainfall total. Knowledge of the Sahel rainfall and associated regional circulation system suggested this as a good candidate for a MOS system. Subsequent testing with other domain choices and MOS variables confirmed the low-level regional wind field as a strong and robust choice for a MOS system.

The MOS approach has used a regression between the observed Sahel rainfall index and the EOFs of the



Figure 11. JAS Sahel rainfall time series: observed (solid) and predicted using the GCM MOS (dashed). GCM is driven with the observed SST.

GCM's zonal wind field. For the period 1968-2002, the leading EOF contains good predictive power for the Sahel rainfall. The improvement in skill over the GCM's raw rainfall output is quite dramatic. Using observed SST the GCM simulates poorly the rainfall with a correlation skill of 0.07 while the first EOF of the zonal wind can be used to recover a correlation skill of 0.57. The possibility of building a usable climate forecast system was examined by persisting the SST anomalies of June and May to force the GCM. It was shown that using June SSTA one can obtain by MOS a skill similar (r = 0.55) to that using observed SST (r = 0.57). When persisted May SSTA is used, the skill deteriorates substantially to r = 0.33, corresponding, in terms of percent variance explained, to a drop from 32 to 12%. The drop does not appear to be a statistical sampling issue, as integrations from April SSTA also show similar low levels of skill. These results also mirror in pattern those found in Ward et al. (1993). The drop in skill is likely to have substantial implications for usability of seasonal forecast information which motivates further study to understand better the source of the loss of skill and possibilities for maintaining a better lead time for the skillful forecasts.

The source of such skill change between June (0.55)and May (0.33) is shown to be related to rapidly evolving boundary conditions between May and June. During wet years, May SSTA persistence often failed to give a good forecast because the SSTA over the tropical eastern Pacific was found to be cooler in June compared to May. Inspection of the years when the forecast fails shows that these are often years in which cold-phase ENSO conditions were developing during boreal spring. Conversely in dry years, the eastern tropical Pacific SSTA of June is warmer than that of May, with warm-phase ENSO conditions developing. In such years, the GCM from June SST shows much better the teleconnection from the ENSO region to the tropical Atlantic/West Africa sector (Figure 7(b) and (c)). The drop of skill then appears to be related to the so-called spring predictability

barrier for ENSO developments, with rapid and difficultto-predict ENSO developments at this time of year. It also suggests that the good correlation between ENSO and Sahel rainfall (e.g. Janicot *et al.*, 1996) has a strong component that derives from ENSO events that rapidly develop during boreal spring, with key SST developments for Sahel rainfall occurring from April/May to June.

In addition to the changes in the tropical Pacific, changes of similar sign tended to be found from May to June across much of the tropical Indian and tropical Atlantic Oceans. Whether the changes in these other ocean basins have dynamical implications for Sahel rainfall prediction remains to be investigated. One possible approach would be a targeted set of GCM experiments that could be used to explore whether SST predictions other than those for the tropical Pacific are needed. It will also be important to explore whether SST prediction schemes can provide boundary conditions based on information in May that leads to more accurate predictions of the Sahel rainfall. Such analysis is underway with a set of statistically predicted SST fields. Targeted GCM experiments can also be developed to explore whether dynamical SST prediction systems capture the key evolution of SST anomalies from May to June for the enhancement of Sahel rainfall predictions.

One concern was the stability of the MOS system given the known evolution, over 1950 to the present, of background Sahel rainfall levels, as well as the evolution of the dominant SST influence on the interannual variability, being primarily from the tropical Pacific during the dry epoch, and tropical Atlantic during the wet epoch. Using simulations with observed SST, the MOS system was applied over the whole period, 1950–2002, and on sub-periods 1950–1969 (Sahel wet) and 1970–2002 (Sahel dry). The system performed consistently skillfully, building confidence for real-time application. In addition to the basic tropical Atlantic trade wind/West Africa monsoon modulation mode (EOF1), a further mode (EOF3) was found to add skill when the system is applied over 1950–2002. This mode is a more localized wind circulation in the equatorial and tropical North Atlantic.

It is unlikely that application of other statistical prediction methods will alter substantially the levels of skill achievable from the ensemble mean wind simulations (e.g. Feddersen et al., 1999). One avenue that can go beyond information contained in the ensemble mean is signal-to noise EOFs (Tippett and Giannini, 2006). The application of this method to rainfall fields from ECHAM4.5 over West Africa showed some improvement of rainfall skill over direct model output, though not to the levels reported here based on the GCM wind fields. However, application of signal-to-noise EOFs to the wind fields may provide some further increase in skill above that reported here. A further area being investigated is the applicability of the approach to other GCMs that have difficulty in predicting Sahel rainfall. This is being explored both for individual models and in terms of the benefit of combining multiple models.

The existing MOS scheme developed in this paper performs with substantial skill when using June SST, and with reduced skill using April and May SST. It is beyond the scope of this paper to investigate the relative merits of empirical SST predictor versus GCM prediction systems. It is widely held that both approaches can contain useful skill, and that the approaches can be complementary and lead to the provision of more reliable information. Indeed, results with empirical predictors suggest that they are somewhat less sensitive to SST tendencies during boreal Spring (e.g. Ward et al., 1993), representing a further area for research. Situations where useful additional information can emerge from a GCM scheme such as the one proposed here include when SST effects interact in non-linear ways and when the SST pattern is particularly unusual. Especially given the robustness of the system over the period 1950-2002, the MOS system developed here would seem to provide a valuable additional tool for short lead-time seasonal prediction of July-September Sahel rainfall.

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