Predictability of Seasonal Sahel Rainfall Using GCMs and Lead-Time Improvements Through the Use of a Coupled Model

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ABSTRACT

The ability of several atmosphere-only and coupled ocean-atmosphere general circulation models (AGCMs and CGCMs, respectively) is explored for the prediction of seasonal July–September (JAS) Sahel rainfall. The AGCMs driven with observed sea surface temperature (SST) over the period 1968–2001 confirm the poor ability of such models to represent interannual Sahel rainfall variability. However, using a model output statistics (MOS) approach with the predicted low-level wind field over the tropical Atlantic and western part of West Africa yields good Sahel rainfall skill for all models. Skill is mostly captured in the leading empirical orthogonal function (EOF1), representing large-scale fluctuation in the regional circulation system over the tropical Atlantic. This finding has operational significance for the utility of AGCMs for short lead-time prediction based on persistence of June SST information; however, studies have shown that for longer lead-time forecasts, there is substantial loss of skill, relative to that achieved using the observed JAS SST.

The potential of CGCMs is therefore explored for extending the lead time of Sahel rainfall predictions. Some of the models studied, when initialized using April information, show potential to at least match the levels of skill achievable from assuming persistence of April SST. One model [NCEP Climate Forecasting System (CFS)] was found to be particularly promising. Diagnosis of the hindcasts available for the CFS (from lead times up to six months for 1981–2008) suggests that, especially by applying the same MOS approach, skill is achieved through capturing interannual variations in Sahel rainfall (primarily related to El Niño-Southern Oscillation in the period of study), as well as the upward trend in Sahel rainfall that is observed over 1981– 2008, which has been accompanied by a relative warming in the North Atlantic compared to the South Atlantic. At lead times up to six months (initialized forecasts in December), skill levels are maintained with the correlation between predicted and observed Sahel rainfall at approximately r = 0.6. While such skill levels at these long lead times are notably higher than previously achieved, further experiments, such as over the same period and with comparable AGCMs, are required for definitive attribution of the advance to the use of a coupled ocean-atmosphere modeling approach. Nonetheless, the detrended skill achieved here by the January–March initializations (r = 0.33) must require an approach that captures the evolution of the key ocean-atmosphere anomalies from boreal winter to boreal summer, and approaches that draw on persistence in ocean conditions have not previously been successful.

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1. Introduction

The climatology of the Sahel region is dominated by dry conditions for most of the year, with a single peak in rainfall during boreal summer. It is well established that there is a strong relationship between this July–September (JAS) seasonal Sahel rainfall and near-global patterns of sea surface temperature (SST; Lamb 1978a,b; Folland et al. 1986; Wolter 1989; Hastenrath 1990; Rowell et al. 1995; Fontaine and Janicot 1996; Ward 1998; Thiaw et al. 1999; Giannini et al. 2003). This now constitutes the basis of operational short lead-time seasonal forecasting over West Africa (e.g., ACMAD 1998).

However, many atmospheric general circulation models (AGCMs) when forced with the observed SST continue to have difficulty in simulating the observed variations of seasonal rainfall over the Sahel. This was noted in many early simulations (Sud and Lau 1996) and is generally noted to still be the case today (e.g., Lau et al. 2006; Scaife et al. 2009). This is despite the early realization that SST in all ocean basins could potentially impact Sahel rainfall in an AGCM (Palmer 1986).

The approach taken in Ndiaye et al. (2009), to address the problem with AGCM simulations of Sahel rainfall, was to focus on indices of the regional circulation system predicted by the AGCM (ECHAM4.5) and to use the indices in a model output statistics (MOS) to predict Sahel rainfall. The ECHAM4.5 AGCM is typical in its poor level of skill for Sahel rainfall; however, using the low-level wind field over the tropical Atlantic and western part of West Africa, a level of skill in predicting Sahel rainfall is achieved that is comparable with the small number of AGCMs that have been able to successfully represent the impact of SST directly on Sahel rainfall (e.g., Giannini et al. 2003). The use of the tropical Atlantic wind fields in this way is consistent with diagnostics studies (e.g., Lamb 1978a,b; Hastenrath 1990; Janicot 1992) that have shown how, in the observed climate, the tropical Atlantic wind field is strongly tied to Sahel rainfall variations.

For seasonal prediction with an AGCM, the model must be driven with a predicted field of SST. A simple approach is to assume persistence of SST anomalies when generating SST boundary conditions for AGCM forecast runs. For AGCM forecasts of Sahel rainfall, the published literature contains no clear systematic improvements on this approach. Applying the persistence approach, although June SST showed good skill in Ndiaye et al. (2009), prediction skill from May and April SST was substantially reduced, even after applying the MOS system.

A complicating factor for seasonal prediction of Sahel rainfall is the strong presence of multidecadal variability as well as strong interannual variations of rainfall (Nicholson 1980). The post-1970 period is recognized as being, on average, relatively dry compared to the 1950-70 period, with some amelioration of conditions having occurred in recent years. The SST patterns associated with the multidecadal and interannual Sahel rainfall fluctuations have substantial differences (Ward 1998). On the interannual time scale, variations in the tropical Atlantic, and variations throughout the tropics associated with El Niño-Southern Oscillation (ENSO), tend to be dominant. On the multidecadal time scale, large-scale contrasts of warming/cooling in the North Atlantic compared to the South Atlantic and Indian Ocean have been found to accompany low-frequency (time scale greater than about 10 yr) Sahel rainfall fluctuations throughout the twentieth century (Folland et al. 1991; Giannini et al. 2003; Zhang and Delworth 2006; Knight et al. 2006). There has emerged contrasting properties of seasonal prediction skill associated with the two time scales. Skill in terms of correlation between predicted and observed rainfall is generally less if there is less low-frequency variance in the analysis period. For example, achievable skill is less for the post-1970 period, as compared to the post-1950 period. Furthermore, to date, there is very limited lead time for forecasts of the interannual timescale seasonal rainfall variations, for which skill has been largely confined to very short lead times (zero to onemonth lead). This is found in statistical seasonal forecast schemes that use SST (Ward 1998) and in AGCMs driven with persisted SST (Ndiaye et al. 2009).

The period of AGCM forecasts available to the scientific community for study is, for practical reasons, mostly concentrated in the post-1970 period. This period is known to be one in which Sahel rainfall has shown a strong correlation with tropical Pacific SSTs related to ENSO (Semazzi et al. 1988; Janicot et al. 1996, 2001; Ndiaye et al. 2009). Indeed, the abrupt skill drop between May and June was found in Ndiaye et al. (2009) to be primarily related to the SST evolution over the eastern equatorial Pacific (Niño-3 region), although significant changes in the tropical Atlantic and tropical Indian Ocean were also noted. This drop of skill limits the utility of the seasonal climate forecast. The short lead time of the forecast is a constraint on the timely dissemination of climate information to potential users to better plan their climate-related activities (such as farming, water management, and malaria disease control). The longer the lead time, the better it is for the users in this region of the world where resources are very limited and need to be managed with care.

The objectives of the current study build on the above findings in two primary ways. First, we aim to generalize the MOS approach using the tropical Atlantic circulation, noting the single-model result with the ECHAM4.5 AGCM found in Ndiaye et al. (2009), and exploring its applicability generally across AGCMs. If a positive result can be achieved, this builds confidence in the use of AGCMs for Sahel rainfall prediction. A positive result may also guide analyses for improvements in the representation of Sahel precipitation itself in AGCMs. Second, the study considers the ability of coupled oceanatmosphere general circulation models (CGCMs) for increasing the lead time of skillful Sahel rainfall predictions. In the CGCMs, analysis is made of both model precipitation and the potential for using the predicted regional circulation system as a MOS predictor for the rainfall. For the most promising coupled model, diagnosis of the teleconnections, from the tropical Pacific and in the Atlantic, is undertaken to reinforce conclusions about the ability of the model to project forward the coupled system and anticipate the key tropical Atlantic wind fields for specifying Sahel rainfall. Furthermore, since the period of model hindcasts covers 1981-2008, the study considers the extent to which the model skill is derived from an ability to track the recent recovery in Sahel rains (low-frequency component of rainfall), as well as the ability to capture the interannual variations in rainfall such as associated with ENSO. Since the CGCMs studied do not have directly comparable AGCM prediction experiments, interpretation on the source of any improvements in skill require an element of diagnostic interpretation. For example, it can be argued that advances in skill achieved by a CGCM may be attributable solely to the atmospheric component of the model or to the exact period of analysis. Therefore, diagnostics on the ability to represent evolution of coupled oceanatmosphere phenomena previously not represented in AGCM prediction experiments and assessment of the characteristics of trend and interannual components separately all add to the insights that can be gained from the experiments analyzed here.

We first describe the data and methods used (section 2). The robustness of the MOS approach for Sahel seasonal rainfall prediction is explored in section 3, evaluating the performance of eight AGCMs driven with observed SST. In section 4, the predictability of Sahel rainfall from April–May initial conditions is explored in coupled CGCMs. In section 5, the most promising coupled model [the Climate Forecasting System (CFS)] is evaluated for longer-lead predictions, with initializations at incrementally increasing lead times up to 6 months ahead of the Sahel rainfall season (initializations in December). The ability of the seasonal forecasts from the CFS to capture the interannual (detrended) variations in Sahel rainfall is also presented in section 5. Section 6 focuses on the recent observed upward trend



FIG. 1. Standardized July–September Sahel rainfall indices from GHCN stations network (circle) and the index constructed by Lamb (diamond). (right) The number of stations used in the GHCN index (thin line) is indicated on the *Y* axis.

(1981–2008) in Sahel rainfall and the extent to which this rainfall trend and related ocean–atmosphere variations are present in the CFS seasonal predictions. Conclusions are presented in section 7.

2. Data and methods

a. Rainfall data

Rainfall data are taken from the Global Historical Climatology Network (GHCN). A set of 131 stations within the domain bounded by 18°W-30°E and 12°-20°N is used to construct a Sahel rainfall index. The index for July-September is calculated by averaging the standardized seasonal rainfall anomaly at each station (hereafter referred to as the GHCN series). Particularly since the number of stations available to construct this index decreases in recent years (Fig. 1), results are compared with a widely used July-September Sahel index (hereafter referred to as the Lamb index, as described in Bell and Lamb (2006); with updated series to 2008 provided through P. J. Lamb 2008, personal communication). The series are shown in Fig. 1 for the years 1968–2008, which is the maximum period over which AGCM runs are analyzed here. The two time series are very well correlated over 1968–2001 (r = 0.96), and discrepancies are mostly confined to 2005-08, with only 2006 having a discrepancy of substance. The correlation over the whole period is r = 0.88. The GHCN time series is used as the primary target predictand, but results are cross checked with the Lamb index and tests undertaken to check for sensitivity to the inclusion of the less certain last few years. Overall, the two series are broadly consistent, including in terms of interannual variability and in terms of the modest recovery of rains since the peak of the

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TABLE 1. The AGCM simulations that are analyzed.

	ECHAM4.5	GFDL	COLA	ECPC	ECHAM5	ECHAM5	NSIPP	Coupled climate model (CCM3.6)
Provider of the runs	IRI	NASA	COLA	SCRIPPS	IRI	IRI	NASA	NCAR
Ensemble members	24	10	10	12	16	24	9	24
Spatial resolution	$T42 \sim 2.81^\circ$	$2.5^{\circ} \times 2^{\circ}$	$T63 \sim 1.875^\circ$	$2.5^{\circ} imes 2.5^{\circ}$	$T85 \sim 1.41^\circ$	T42 2.81°	$2.5^{\circ} \times 2^{\circ}$	$T42\sim 2.8^\circ$

extended drought in the early 1980s (Nicholson 2005; Giannini et al. 2008). Most analyses are confined to the use of these observed Sahel rainfall indices. However, for the global precipitation composite in section 6, data are taken from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997).

b. SST and atmospheric observations

SST data are taken from the National Oceanic and Atmospheric Administration (NOAA)/Climate Diagnostics Center (CDC) dataset (Smith and Reynolds 2003), while the National Centers for Environmental Prediction (NCEP)– National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al. 1996) are used to construct observed atmospheric teleconnection maps for comparison with the GCMs teleconnection structures.

c. Atmospheric and coupled GCMs simulations

Multiyear simulations are analyzed from eight different AGCMs (1968–2001) and eight different CGCMs (the CFS is for 1981–2008, the other seven all end in 2001, with various start years, mostly before 1975). The characteristics of the eight different AGCMs are summarized in Table 1. All these AGCMs were forced with observed July–September SST.

The Development of a European Multimodel Ensemble System for Seasonal-to-Interannual Prediction (DEMETER) project provides seasonal hindcasts using seven global coupled ocean–atmosphere models with different atmospheric and oceanic components (Palmer et al. 2004). The set of integrations that allow evaluation of July–September Sahel rainfall forecasts is initialized around 1 May each year, forecasting the period from May to October during each year. Thus, only one lead time on the JAS Sahel rainfall season can be investigated. Details of the models are documented in Palmer et al. (2004).

A set of coupled model seasonal hindcasts is also analyzed from the NCEP CFS (Saha et al. 2006). The atmospheric component is the NCEP–Global Forecast System (GFS) model (Moorthi et al. 2001) with T62 spatial resolution, and the ocean component is the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model version 3 (MOM3; Pacanowski and Griffies 1998) with a zonal resolution of 1 degree and a meridional resolution that varies from ¹/₃ degree near the equator to 1 degree near the poles. The runs cover 28 yr from 1981 to 2008, and each integration corresponds to a 9 months lead-time forecast. For each month, the CFS run is initialized at 0000 UTC in 3 different periods of 5 consecutive days each separated by 10 days. Monthly data are created by averaging the 15 daily initializations during each month. (The initializations termed month n, while predominantly drawing on ocean and atmosphere information from month n, actually also draw on some information from the first 3 days of month n + 1, details in CFS documentation available online at http://cfs.ncep.noaa.gov/menu/doc/.) Results on the model's ability to represent ENSO have been documented (Wu et al. 2009). Analysis here represents a test of the ability to represent information that is related to Sahel rainfall in the July–September season. The model's climatology in the Sahel has been studied (Thiaw and Mo 2005), noting a dry bias in the model's rainfall that is corrected here using standardized units throughout, and more substantially, by employing the MOS approach with the tropical Atlantic winds. A MOS approach offered some promise for CFS forecasts of Sahel rainfall at very short (1-month) lead time (Mo and Thiaw 2002), so results here extend those findings to the longer lead times.

d. MOS approach

Seasonal forecasts are generated by applying a MOS to AGCM output (Feddersen et al. 1999; Landman and Goddard 2005; Friederichs and Paeth 2006). In Ndiaye et al. (2009), it was shown that the tropical Atlantic lowlevel wind was the best approach using the ECHAM4.5 simulations, compared to using a range of different domains and variables. Given that the low-level tropical Atlantic wind is known to be strongly tied to monsoonal circulation and rainfall in the Sahel, the choice of this approach was also validated based on physical climate insight. Also, it was shown that over the period from 1970, use of just the first empirical orthogonal function (EOF1) over this domain provided a model that captured most of the prediction signal. The statistical model used in the MOS is least squares regression, with the EOF time series of the GCM output forming the predictor, and the Sahel rainfall index forming the predictand. The GCM output is always the predicted JAS

wind field, and no time filtering is applied (i.e., there is no distinguishing of interannual and multidecadal time scales). As a first step, a similar approach is taken here with the larger sample of models. The first EOF of the GCM's JAS zonal wind is used to capture the climate variability over the tropical Atlantic (including the western part of West Africa) bounded by 30°N-40°S and 60°W–10°E (the same domain as in Ndiaye et al. 2009). Partly driven by the available archived field, analyses used either 925 (all AGCMs) or 850 hPa (all CGCMs). For runs where both fields were available, skill was found to be insensitive to the choice of these two levels. A cross-validation approach is applied by leaving 3 yr out, the year to be forecasted plus the year before and after. In addition to considering the skill using just one EOF, the optimum number of EOFs (up to a maximum of five) is also explored. The choice of exploring up to five EOFs was based on inspection of scree plots and noting the cumulative percent variance explained typically approached about 70% for five EOFs.

3. Robustness of regional circulation as a MOS predictor for Sahel rainfall

Up to now, it has been recognized that most AGCMs, when driven with observed SSTs, are poor in their ability to predict Sahel seasonal rainfall. If the MOS approach in Ndiaye et al. (2009) proved robust across many models, it could represent an advance of considerable practical significance. First, it would indicate that the key information from SSTs was being captured by most models, at least in the regional circulation system. In other words, the poor performance of models could be expected to be improved through addressing the better translation of the tropical Atlantic wind field anomalies into the deeper monsoon anomalies and associated precipitation over West Africa. Second, even without further model improvement, it would imply most models could be used now in real time to extract relevant information on Sahel rainfall, at least at short lead time, by applying the same MOS approach.

We apply the MOS strategy to the multiyear simulations of the eight AGCMs available to this study. The analyses use the same period (1968–2001) as in Ndiaye et al. (2009). Figure 2 summarizes the skill of the MOS (open bar) compared to the skill of AGCM rainfall (filled bar). The AGCM precipitation has very low skill in six of the eight AGCMs. In contrast, the MOS skill is quite consistent throughout all the AGCMs, with correlation skill scores generally in the approximate range of r = 0.4 to r = 0.55.

In Fig. 2, the skill shown in the lower open bar is that using EOF1 alone, with the exception of the results for



FIG. 2. Sahel rainfall skill during 1968–2001 from various AGCMs forced with observed SST. Skill is shown for AGCM rainfall (shaded bars) and after applying a MOS to the 925-hPa tropical Atlantic wind field (open bars). The first open bar indicates the skill when the MOS predictor is the best single EOF, usually the leading EOF (see Fig. 3). If a combination of up to 5 EOFs improves the skill further, the additional skill is indicated by the additional (thin line) open bar, and the number of EOFs yielding the best skill is indicated by the digit on the top of the open bar.

the GFDL and ECPC models. For these models, a lowerorder EOF contains the leading signal for predicting Sahel rainfall (EOF2 for ECPC and EOF3 for GFDL). Figure 3 shows the spatial pattern of the leading explanatory EOF in each of the models (EOF2 for ECPC, EOF3 for GFDL and EOF1 for all other models). The similarity of the large-scale spatial pattern is clear, with zonal wind anomalies of one sign in the tropical and subtropical South Atlantic and a (somewhat more varying) pattern of opposite sign in the tropical North Atlantic and into West Africa. A change of sign is common around the tip of northeast Brazil on the west side of the Atlantic. The EOF is capturing large-scale and coherent fluctuations in the intertropical convergence zone (ITCZ), the West African monsoon, and their complex interactions with the Northern and Southern Hemisphere Hadley circulations in the Atlantic sector. It is interesting that ECPC and NSIPP, the only two models that have any success of substance with their direct model-output rainfall, have particularly similar patterns over West Africa and especially Sahel latitudes. Most other models vary considerably in their low-level wind weights over West Africa, likely reflecting their difficulty in translating the large-scale circulation over the tropical Atlantic into model rainfall over the Sahel. The time series of each of the EOFs in Fig. 3 is shown in Fig. 4, strongly reinforcing the idea that the ability to represent the interannual variation of



FIG. 3. The 925-hPa zonal wind EOF that provides the best MOS predictor of Sahel rainfall in each of 8 AGCMs. The percentage of variance and correlation with observed Sahel rainfall index are in brackets.

the tropical Atlantic wind field associated with Sahel rainfall variations is a robust feature across models, even if the spatial expression varies somewhat over and close to West Africa.

In Ndiaye et al. (2009), the use of one EOF could not be substantially improved upon by adding further EOFs to the MOS when applied over the period of 1968–2001. Figure 2 shows that this result is largely reproduced here. For the models where EOF1 was not successful (GFDL, ECPC) a leading explanatory EOF does emerge at lower order (EOF2 for ECPC, EOF3 for GFDL). However, it is also clear that the prediction signal has become split across more than one EOF, such that more substantial improvements in skill are obtained for multiple EOF models (0.37–0.51 for GFDL, 0.28–0.45 for ECPC). Nonetheless, with the multiple EOFs applied in this way for the ECPC and GFGL models, the MOS approach using tropical Atlantic winds is able to recover skill comparable to the other models.

Overall, the use of tropical Atlantic wind fields permits recovery of skill levels at or approaching the best ones found for specifying Sahel rainfall from SST over this approximate post-1970 period, suggesting that AGCMs are generally able to capture a substantial part of the interannual variability of the tropical Atlantic wind fields that are tied to Sahel rainfall variability. In most cases, this can be achieved through the use of a single EOF, and



FIG. 4. Time series of each of the EOFs shown in Fig. 3 (colored lines), along with GHCN Sahel rainfall index (black line). Numbers in brackets indicate the correlation skill with Sahel rainfall.

in all cases, a single EOF captures a significant fraction of the predictable Sahel variance. This encourages use of this approach in operational seasonal forecast settings and testing of the approach in the study of coupled model simulations in the following sections.

4. Predictability from April-May initial conditions

Previous predictability studies of Sahel rainfall have used prerainfall season SSTs in empirical prediction models (e.g., Folland et al. 1991; Ward 1998; Thiaw et al. 1999), or AGCMs driven with forecast SST anomalies, often applying the persistence assumption (Goddard and Mason 2002). Especially when focusing on the interannual variability of rainfall, a very substantial loss of skill has generally been found when using SST information in April and May, as compared to using SST information in June. This result was isolated using empirical approaches in Ward (1998) and was found in early AGCM studies (Ward et al. 1993). The result was also found in Ndiaye et al. (2009) when using the MOS system applied to the ECHAM4.5 AGCM forced with persisted SST. The MOS correlation skill was found to be 0.55 with June SST, 0.33 with May SST, and 0.30 with April SST.

It is therefore of interest to evaluate the ability of coupled ocean–atmosphere models to predict Sahel rainfall, considering both model rainfall and using the MOS system discussed in the previous section, to see if skill can be gained at a longer lead time. Furthermore, if skill is achieved, to assess if the improvements appear attributable to ocean–atmosphere developments that were previously not captured in prediction systems.

First, we focus on the results from the CFS, from which the most comprehensive set of hindcasts is available to this study, initialized at monthly resolved lead times and available for the years 1981–2008. The skill of the model precipitation predictions and the MOS system predictions are shown in Fig. 5. For now we focus on the right side of the panel, showing the skill of simulations that are termed as initialized in April, May, and June.

First, for the CGCM precipitation (shaded bars, Fig. 5), it is noted that runs initialized in June, May, and April all display substantial skill. Furthermore, the skill does not decay but rather is maintained as the lead time increases. The most likely interpretation of the slight dip in skill in May, compared to June and April initializations, is considered due to sampling error rather than a repeatable phenomenon.

Applying the MOS system (open bars in Fig. 5) does not substantially alter the skill levels, but rather, skill is generally at approximately the same level as achieved with the model rainfall. However, these MOS results do



FIG. 5. As in Fig. 2, but for the CFS CGCM (with 850-hPa wind), showing skill at increasing lead times from June initialization (zero lead on the JAS Sahel rainfall season) up to December initialization (6-month lead).

demonstrate that use of the low-level wind (mostly EOF1) is again effective for Sahel prediction, here, in a coupled forecast system. Furthermore, as diagnosed subsequently in sections 5 and 6, the skill of the MOS system and the model rainfall is found to contain somewhat different aspects of the rainfall variability. The spatial pattern of the EOF1 of the low-level wind from the CFS runs initialized in June, May, and April is shown in Fig. 6b, confirming a similar large-scale spatial pattern compared to the ones in Fig. 3. Again, consistency is greatest south of the equator, with more model-specific features emerging north of the equator, especially over West Africa itself.

The forecast skill shown in Fig. 5 is reproduced when the Lamb Sahel rainfall index is used as the target predictand. For example, for the April, May, and June initializations, the average MOS EOF1 skill using GHCN is 0.51, whereas using the Lamb index, the average correlation skill is 0.56. The CFS appears to contain skill that is comparable to that achieved with observed SST, and appears to have broken through the problem of losing skill substantially when forecasts are made using April information as compared to June information.

The DEMETER CGCMs were all initialized around 1 May, so their Sahel rainfall skill can be compared with that achieved by systems using April information, and specifically here, the April initialized runs of the CFS. The model rainfall and the MOS predicted rainfall from low-level EOF1 were analyzed in the same way as reported above for the CFS. For all DEMETER experiments, 2001 is the last forecast year. MOS predicted rainfall (Fig. 7a) and CGCMs' rainfall (Fig. 7b) are plotted for all available years in 1968–2001 for the



FIG. 6. As in Fig. 3, but for the CFS CGCM (with 850-hPa wind), pooling together forecasts for JAS that were initialized in (a) January, February, and March and (b) April, May, and June.

DEMETER models and for the April initialized CFS. Figure 7 also indicates the years available for each model and the correlation skill for each model. Most models (five of seven) show very low levels of skill in their Sahel rainfall predictions (r < 0.20), with five of seven showing small increases in skill when the MOS is applied but with levels of correlation skill still generally below r = 0.3. There are two models [the European Centre for Medium-Range Weather Forecasts (ECMWF), r = 0.42; and Max Planck Institute (MPI), r = 0.49] that emerge from the set as most promising in their Sahel rainfall predictions. These skill levels are only comparable or slightly higher than that generally achieved using persistence approaches. The results do support the assertion that coupled models are becoming important contributors to the Sahel rainfall prediction problem. However, since some predictive information is known to be present in April SST (e.g., Ward et al. 1993; Ward 1998), it is difficult to draw the conclusion that the skill levels represent a clear advance that is attributable to the CGCM approach. Two aspects motivate a more detailed analysis of the CFS experiments. First, the CFS skill levels make a jump that more clearly separates them from the other models. Second, due to the start times available for hindcasts, only the skill of models from initialization around 1 May can be considered for the DEMETER runs; whereas for the CFS, a much larger set of hindcasts is available, permitting skill levels to be established and diagnosed more robustly across varying lead times.

The level of skill achieved with the CFS is consistent with the model being able to capture the evolution of the coupled ocean–atmosphere system through the period April–June (AMJ) and arrive at a correct representation of the atmospheric teleconnection response in the tropical Atlantic wind field and indeed the model output Sahel precipitation itself. An ability to represent such developments provides strong support for the CGCM being able to access sources of skill that are not achievable with AGCMs, at least when the AGCMs use SST persistence. The following diagnostic analysis is therefore designed to assess if the CFS results are rooted in the key coupled ocean–atmosphere developments for Sahel rainfall.

In Ndiaye et al. (2009), when the persistence approach led to Sahel forecast failures in the period 1968–2001, the key SST evolution from April to June was shown to be associated with developments in the central and eastern equatorial Pacific. To diagnose the ability of the CFS to capture such evolution of SST and develop the key teleconnection structures in the tropical Atlantic, the following approach is taken. We first calculate the observed teleconnection between JAS Niño-3 and the pattern of JAS SSTs (Fig. 8a) and JAS near-surface (the 1000-hPa level) winds (Fig. 8b). These represent the teleconnection structures that need to be in place in the coupled model forecasts, especially the linkages from the tropical Pacific to the tropical Atlantic. First, we address the SST aspects and then address the wind aspects.

First, to highlight the failure of the persistence approach for this climate forecast problem, we correlate



FIG. 7. Time series of observed Sahel rainfall along with predicted Sahel rainfall from the seven DEMETER CGCMs (initialized 1 May) and the CFS CGCM (initialized in April). (a) After applying MOS (same procedure as in Fig. 5) with the best single EOF and (b) CGCM rainfall. Numbers in brackets indicate the correlation skill with Sahel rainfall and the forecast years included in the analysis.

the JAS Niño-3 index to each SST grid box from April to June (Fig. 9). While the June map (Fig. 9a) contains much of the JAS teleconnection structure achieved with JAS Niño-3 (Fig. 8a), the maps for May and April are dramatically weaker in the central and eastern tropical Pacific. The SST correlation over the Niño-3 region is strong in June (r = 0.8, Fig. 9a), weakens in May (Fig. 9b) and drops drastically to about r = 0.4, and is only significant over a much smaller area during April (Fig. 9c).

Figure 8a shows the known teleconnection between El Niño (La Niña) and warmth (cool conditions) in the tropical North Atlantic (Enfield and Mayer 1997; Lau and Nath 2001). The panel with April SST (Fig. 9c) contains a much weaker signal for this tropical North Atlantic teleconnection, which indicates that the warmth is usually not already in place in the North Atlantic in April, in those years that have strong El Niño presence in JAS (and vice-versa, cool conditions are not in place in those years when La Niña is present in JAS). Figure 8a



FIG. 8. Observed JAS Niño-3 index correlation 1981–2008 with (a) observed JAS SST and (b) reanalysis JAS 1000-hPa u and v wind. A vector is formed using the u correlation (zonal component of the vector) and the v correlation (meridional component of the vector). Correlations significant at the 95% level are shaded (for the wind map, shading is applied if either the u or the v is significant).

also shows the teleconnection between El Niño (La Niña) and warmth (cool conditions) in the northwestern Indian Ocean. Again, Fig. 9c shows that in April, the warmth is not present in the northwestern Indian Ocean, in those years when July–September sees the presence of El Niño (and vice-versa, cool conditions are not in place in those years when La Niña is present in JAS). So these Indian and North Atlantic Ocean teleconnection features can be considered as ones that develop during boreal spring



FIG. 9. Observed JAS Niño-3 index correlation 1981–2008 with (a) observed June SST, (b) observed May SST, and (c) observed April SST. Correlations significant at the 95% level are shaded.

along with Niño-3 development. The tropical North Atlantic development implies that during an El Niño, the North Atlantic actually warms. In terms of local SST forcing on Sahel rainfall, this is consistent with a wetter Sahel. The warming can therefore be considered a negative feedback on the large-scale forcing, which generates atmospheric teleconnection structures from the Pacific to the Atlantic that favor drier conditions in the Sahel (Janicot et al. 1996). This was noted in the coupled mode connecting ENSO to Sahel rainfall in Ward (1998) and may be one of the reasons why AGCMs have difficulty with representing the impacts of ENSO directly on the rainfall because they need to correctly balance these processes in the tropical Pacific and Atlantic domains.

A further aspect of Fig. 8a is the negative correlation with tropical South Atlantic SST. This is not a widely reported phenomenon in the literature, and when noted, has been not as easily interpreted in terms of physical mechanism (Enfield and Mayer 1997). Its presence here may be amplified through chance sampling in this period. Further uncertainty is cast by the fact that the teleconnection shows as strongest in Fig. 9b, which suggests tropical South Atlantic SSTs in May are a precursor of ENSO development into July–September. Given the difficulties in interpretation, less emphasis is placed on this SST teleconnection structure, though it could be worthy of future investigation.

Next, we consider the extent to which CFS forecasts contain teleconnection structures with the observed JAS Niño-3. If we were to correlate CFS predicted fields with the CFS JAS Niño-3, we would obtain the internal model teleconnection structures. These could be realistic but the model might have no predictive capability, developing ENSOs and associated teleconnection patterns in the wrong years. By using the observed JAS Niño-3 as the base index for teleconnection maps, the model must both develop ENSOs in the correct years, and with the correct teleconnection structure, in order for the model teleconnection fields to be comparable with the observed ones in Fig. 8. Therefore, the observed JAS Niño-3 is correlated with the predicted JAS SST field that is generated by each of the initialization times. First, for the tropical Pacific, it is clear that runs initialized in June (Fig. 10a), May (Fig. 10b), and April (Fig. 10c) all successfully represent the evolution of tropical Pacific SST to match the observed Niño-3 in JAS and its teleconnection across the Pacific basin. The performance represents a substantial improvement upon persistence, as evidenced by comparing Fig. 9c (April persistence used to predict JAS SST) with Fig. 10c (April initialized model prediction of JAS SST).

The CFS also reproduces aspects of the SST development in the western Indian Ocean and tropical



FIG. 10. Observed JAS Niño-3 index correlation (1981–2008) with CFS JAS SST predictions. (a) CFS is initialized in June, (b) initialized in May, and (c) initialized in April. Correlations significant at the 95% level are shaded.

Atlantic Oceans. The aspects in the North Atlantic and western Indian Ocean are actually least clear in the June initialized results (Fig. 10a), suggesting the longer lead may allow the CGCM to better develop the teleconnections between a developing El Niño (La Niña) in the tropical Pacific and warming (cooling) in the North Atlantic and the western Indian Ocean (Figs. 10b,c). There is also a tendency for the negative correlation to be present in the South Atlantic, such that Figs. 10b and 10c have all the basic elements in the tropical Atlantic and western Indian Ocean that are found in the observed teleconnection structure (Fig. 8a).

These results reveal a good ability to represent the evolution of SST teleconnections associated with ENSO, during the buildup to the Sahel rainfall season. A good ability to represent many key aspects of the corresponding sequence of low-level atmospheric circulation teleconnections is also seen in Fig. 11. For example, Fig. 11c shows that CFS runs initialized in April produce JAS Pacific wind fields that correlate strongly and consistently with the observed Niño-3 JAS index. The levels of teleconnection representation are as strong for the April initializations (Fig. 11c) as they are for the May (Fig. 11b) and June (Fig. 11a) initializations. The pattern is comparable to that achieved between the observed Niño-3 and the observed JAS reanalysis winds (Fig. 8b).

In support of the good skill in predicting Sahel rainfall (Fig. 5), JAS teleconnection structures in the tropical



FIG. 11. As in Fig. 10, but for CFS 1000-hPa wind predictions. A vector is formed using the u correlation (zonal component of the vector) and the v correlation (meridional component of the vector). Shading is applied if either the u or the v correlation is significant at the 95% level.

Atlantic are also reproduced in the model runs initialized in April, May, and June. In other words, the runs initialized during boreal spring produce forecast JAS tropical Atlantic wind fields that correlate with the observed JAS Niño-3 in ways that are largely consistent with the observed teleconnection structures. For the nearsurface zonal wind, opposite sign correlations are found in the tropical North and tropical South Atlantic, with the tip of northeast Brazil being the latitude of the change of sign in most maps (Fig. 11). The results in Figs. 10 and 11 are interpreted as strong evidence that the results of the good skill in Sahel prediction are indeed connected to very large-scale Pacific and Atlantic developments that are being successfully simulated by the CFS. It lends considerable support to the hypothesis that the CFS is able to forecast the key developments from April for the predictable part of the Sahel rainfall variance that is related to ENSO.

In summary, the CFS forecasts initialized in April project tropical Atlantic wind conditions for JAS that correlate strongly with the observed JAS Sahel rainfall index. A major part of this is achieved through developments in the tropical Pacific and tropical Atlantic that are consistent with the observed climate system teleconnections across the Pacific–Atlantic sector. This suggests the coupled model is able to skillfully project forward the coupled system over this challenging period in the Pacific–Atlantic sector. Indeed, there is no substantial change in Sahel rainfall prediction skill when lead time increases from zero months (June initialization) to two months (April initialization). This motivates investigation of the additional CFS runs that are available out to a lead time of six months (December initialization).

5. Further analysis of the CFS predictability and comparisons at up to 6-month lead time

The skill of the model precipitation and MOS system are plotted in Fig. 5 for all runs for which a forecast for JAS is available from the CFS. The longest lead time available corresponds to approximately 6 months before the JAS rainfall season, being initialized in December and available from 5 January. Figure 5 shows that generally, for initialization before April, the model precipitation skill falls quite substantially compared to the shorter lead-time forecasts. However, for the MOS on the regional circulation, skill levels are maintained remarkably stable just using EOF1, even up to the 5-month lead time (January initialization). The leading EOF spatial pattern is very stable for these initializations and similar to that found for the shorter lead-time initializations (cf. Fig. 6a and Fig. 6b). For December initialization, the skill drops to r = 0.35 when using just EOF1 in the MOS system. However, comparable skill levels are recovered using the leading five EOFS (r = 0.58).

To confirm that these long-lead forecast skill improvements are reflected in large-scale model fields, the analyses with observed JAS Niño-3 are repeated using the predicted JAS SST (Fig. 12) and circulation (Fig. 13) for each of the initialization months. For example, Fig. 12b shows that even for forecasts initialized in February, predicted JAS SST in the central and eastern tropical Pacific correlates over a wide area at over 0.5 with the observed JAS Niño-3, and since these are correlation values at individual model gridboxes, the information for the largescale atmosphere that is contained in the overall field of SST in the coupled model may be substantially higher. In addition, predicted SST in the tropical North Atlantic and western Indian Ocean continues to correlate positively with the observed JAS Niño-3, indicating representation of these teleconnection structures at long lead time.

The predicted JAS near-surface winds from December initialization (Fig. 13d) still show a strong and widespread teleconnection structure with the observed JAS Niño-3 SST. However, the pattern is weakening and especially so to the north of the equator (cf. Figs. 13d and 13a). This is true in both the Pacific and in the tropical Atlantic and may reflect the greater difficulty in recovering the MOS skill for Sahel rainfall using December initializations.



FIG. 12. As in Fig. 10, but for CFS (a) initialized in March, (b) initialized in February, (c) initialized in January, and (d) initialized in December.

However, for initializations from at least January onward (Figs. 13a–c), the teleconnection structure response of the CFS supports the assertion that the model runs contain useful information at long lead for Sahel rainfall. Even from December initialization, information is still present that allows skilful MOS predictions, even if the information is in a somewhat different form, with less of the relevant information found in fields north of the equator.

Another aspect of Figs. 10 and 12 is that they pose the question of whether the predicted SST fields may serve as more effective MOS predictors than the tropical Atlantic wind fields. Such a possibility was not an option in Ndiaye et al. (2009), where different variables in an atmosphere-only model were explored for making MOS predictions of Sahel rainfall. A detailed investigation is beyond the scope of this paper, but a check was made on whether there were any obvious gains to be achieved from substituting SST for wind in the MOS system. One of the challenges in trying to use the SST as a MOS predictor is that SST information is likely entering the tropical Atlantic wind field and West African monsoon from multiple geographic sources, even though a primary source



FIG. 13. As in Fig. 11, but for CFS (a) initialized in March, (b) initialized in February, (c) initialized in January, and (d) initialized in December.

in the 1981-2008 period appears to be from the tropical Pacific. The advantage of using the wind field in the tropical Atlantic is that it effectively integrates the relevant SST information from around the globe and provides a distinct geographic domain over which to construct the MOS predictors. Various SST domains were tried for SST MOS predictors. None of the domains improved upon the skill achieved by the low-level tropical Atlantic wind field. One of the best SST options was to take the global belt spanning 40°N-40°S. For this experiment, the average correlation skill score for SST for January-March (JFM) initializations was 0.49, compared to 0.54 for the tropical Atlantic wind field. For AMJ initializations results were very similar (0.49 versus 0.52). The main conclusion is that the low-level wind field remains a robust integrator of relevant forecast information in this coupled model setting. With a coupled model, the variable SST is a candidate for use in a MOS, but it does not here usurp the tropical Atlantic low-level wind field's position as the favored variable on which to perform MOS.

The skill levels in Fig. 5 from January to June initializations do change modestly from month to month. A



FIG. 14. Observed (thick solid line) and CFS predicted Sahel rainfall indices. (a) Predictions are from the MOS correction applied to January–March initialized forecasts (dashed line) and April–June initialized forecasts (dotted line), (b) the CFS rainfall, expressed in standardized units, from initializations in January– March (dashed line) and April–June (dotted line).

substantial part of that is considered to be due to sample size. To partly confirm that hypothesis, and also to provide a year-by-year summary of the forecast system, forecasts have been averaged together across initializations in January–March and across initializations in April–June. The model precipitation and MOS results (using EOF1) are shown as time-series plots in Fig. 14. The general consistency of the MOS forecasts for the shorter and longer lead time can now be seen (Fig. 14a). The skill is comparable for the pooled January–March (r = 0.57) initialized forecasts and the pooled April–June (r = 0.54) initialized forecasts.

Inspection of Fig. 14 gives the impression that the MOS contains substantial skill on the interannual time scales (Fig. 14a), whereas much of the correlation skill achieved by the model precipitation from the CFS is derived from the upward trend in both the observation and the CFS rainfall predictions (Fig. 14b). This is indeed confirmed in Table 2, which compares the correlation skill for the series in Fig. 14 before and after detrending. After detrending, the MOS skill is maintained at substantial levels (r = 0.39, 0.33 for initializations in AMJ and JFM, significant at 95% and 90%,

TABLE 2. CFS forecast skill (correlation) 1981–2008 for July– September Sahel rainfall, from AMJ and JFM initializations. Results are shown for CFS precipitation and for the MOS system using low-level wind EOF1 (Fig. 6). Results are also shown when time series are detrended over the 1981–2008 period.

	JFM	AMJ
Model precipitation predictions	0.24	0.57
Model precipitation predictions after detrending	-0.22	0.31
MOS EOF1 predictions	0.57	0.54
MOS EOF1 predictions after detrending	0.33	0.39

respectively, with a confident full degree of freedom assumption since the series are detrended). For the model precipitation predictions, after detrending there is no skill for JFM initialized forecasts (r = -0.22), while skill drops substantially from r = 0.57 to r = 0.31 when predictions from the AMJ initializations are detrended.

The levels of skill achieved by the MOS on the detrended series are slightly higher than the magnitude of the correlation between the observed JAS Niño-3 and Sahel rainfall for the period (r = -0.36, after series are detrended). For comparison, using Niño-3 as a predictor for Sahel rainfall in this period loses skill very rapidly as lead time increases, in a manner consistent with that described in Ward (1998). The Niño-3 monthly correlations with JAS Sahel rainfall for the 1981-2008 period are (all series detrended) r = -0.34 (June), r = -0.28(May), r = -0.26 (April), r = -0.17 (March), r = -0.08(February), and r = -0.01 (January). These results reinforce the idea that SST persistence provides some interannual skill in predicting Sahel rainfall based on ENSO at short lead times. The results also reinforce the idea that persistence performs very poorly at longer lead times. This highlights the progress of achieving, even after detrending, levels of skill of 0.33 (January-March initialization) and 0.39 (April-June initialization) with the CFS MOS system.

6. The trend component of Sahel rainfall 1981–2008 in observations and CFS seasonal predictions

It is well known that Sahel rainfall has a strong lowfrequency component of variance (Nicholson 1980), which has been expressed in recent decades in an extended relatively dry period through the 1970s and 1980s, with a widely documented modest recovery after the 1980s (Nicholson 2005, Herrmann et al. 2005). In terms of the shift of rainfall from the 1950s to the 1980s, the recent upward trend is often considered relatively modest. However, it is clearly present visually for the 1981–2008 period for which the CFS forecasts are available (e.g., Fig. 1, Fig. 14), and it is confirmed to be a statistically significant trend, measured in terms of linear regression TABLE 3. Composite difference of July–September values, 1994–2008 minus 1981–93. Results are for observed and CFS-predicted precipitation and SST indices. Predictions are initialized in JFM and AMJ. Precipitation results (in standardized units, for the Sahel region) are shown for observed, CFS predictions, and predictions using the MOS on the low-level wind (Fig. 6). The SST index is AtlN-S (defined in text), and units are degrees Celsius. Statistical significance is estimated using a t test.

		Precipitation					SST		
		CG	СМ	MOS prediction		North – South Atlantic			
	Obs	CFS JFM	CFS AMJ	CFS JFM	CFS AMJ	Obs	CFS JFM	CFS AMJ	
Diff.	1.24	1.17	1.03	0.90	0.54	0.32	0.33	0.29	
p value	0.000	0.000	0.000	0.009	0.008	0.000	0.000	0.000	

or composite difference. It is therefore considered a real physical aspect of the climate system, likely to have expression in large-scale ocean-atmosphere fields, and it is of interest to consider how the CFS forecast system has performed in this context. Following analysis and inspection of the Sahel rainfall series, the period has been divided into the relatively dry early set of years (1981–93) and the more recent wetter years (1994–2008), for the purpose of constructing composite differences. Table 3 summarizes such differences for the observed Sahel series, the MOS predictions using EOF1, and the CFS rainfall predictions, providing quantification and statistical significance for the trends in these quantities. In the observations, the difference is 1.24 standardized units, which is significant at the 99% level using a t test. This trend is well captured in the CFS rainfall in both JFM and AMJ initializations. Both show a strong trend, slightly larger for the JFM initializations, with a difference of 1.17 and 1.03 standardized units, respectively, with both significant at the 99% level (Table 3).

The composite analysis also confirms a positive trend in the MOS predictions using EOF1, though the trend is weaker, with a difference between the two periods of 0.90 and 0.54 standardized units, respectively, for JFM and AMJ initializations. The implication is that CFS wind EOF1 does contain an upward trend but of a magnitude that leads to a somewhat underestimated upward trend in Sahel rainfall when the MOS prediction system is applied. Skill statistics are very sensitive to trend (i.e., capturing a trend in a set of forecasts can substantially increase a skill score), and the slightly stronger trend in the JFM initialized forecasts (Table 3) likely explains why the JFM MOS predictions do not contain the expected skill reduction relative to the shorter lead-time AMJ predictions (Table 2). When the series are detrended over 1981–2008, the JFM initialized predictions do become less skillful than the AMJ initialized predictions (r = 0.33 compared to r = 0.39, Table 2).

Further insight on the trends is gained from composite difference JAS fields for the low-level wind, precipitation, and SST for observations (Fig. 15; and for the JFM initialized forecasts, Fig. 16-the composite for AMJ initialized forecasts has similar structure). In the observed SST composite difference (Fig. 15a), the first impression is of a general warming signal, as would be expected given the known global warming through the period (Solomon et al. 2007). However, the warming is far from spatially uniform, and in general, the warming in the North Atlantic is substantially greater than that in the South Atlantic. The role of such an arrangement of relative temperature gradient (including the Indian Ocean with the South Atlantic) has been previously proposed in explaining low-frequency Sahel rainfall fluctuations through the twentieth century (Folland et al. 1991; Rowell et al. 1995; Hoerling et al. 2006), and an index is used in many empirical Sahel seasonal prediction systems to represent this effect (ACMAD 1998). The North Atlantic part of the interhemispheric SST contrast has been recognized to project strongly on the Atlantic multidecadal oscillation (AMO, Enfield et al. 2001), which itself has been directly associated with low-frequency Sahel rainfall variations (e.g., Zhang and Delworth 2006; Knight et al. 2006). The implication from Fig. 15a is that a distinct North Atlantic versus South Atlantic temperature difference has been evolving through the 1981-2008 period, with a strong contribution from the AMO (e.g., Ting et al. 2009) and with a sign that would support the increase in Sahel rainfall precipitation. Consistent changes are found in the tropical Atlantic wind field (Fig. 15c), changes that resemble the leading wind EOF discussed earlier in models, with large-scale fluctuation in the North and South Atlantic trade wind systems.

Figure 16 reveals the extent to which the CFS forecasts contain the above low-frequency climate fluctuations over 1981–2008. First, for the SST composite, the CFS (Fig. 16a) is generally cooler than observed (Fig. 15a) in the recent period. However, since the north–south gradient of SST is hypothesized to be a key factor for Sahel rainfall, it is important to assess the extent to which the CFS forecasts are capturing this aspect. The composite maps show that the North Atlantic forecasts for JAS clearly tend to be warmer than the South Atlantic



FIG. 15. Composite difference 1994–2008 minus 1981–93 for observed JAS fields. (a) SST (°C), (b) rainfall (CMAP dataset, mm day⁻¹), and (c) reanalysis 1000-hPa wind (m s⁻¹). For the SST and rainfall fields, hashing is applied if the difference is significant at the 95% level using a *t* test. For the wind field, shading is applied if either the *u* or the *v* difference is significant at the 95% level.

(Fig. 16a). The precipitation (Fig. 16b) over West Africa and across the tropical Atlantic is also modified in a manner that is broadly consistent with observations (Fig. 15b), with enhanced precipitation across the Sahel and northern side of the ITCZ across the tropical Atlantic, with a partial compensation in areas to the south (the partial compensation on the south side is more pronounced in the model than in observations). Key for interpreting the MOS rainfall results, the tropical Atlantic low-level wind field (Fig. 16c) is found to have a pattern that has resemblance to the EOF1 modes used in the MOS system, with anomalous easterlies south of the equator and, more noticeably, anomalous westerlies north of the equator; although the wind expression is somewhat weak, especially south of the equator. Thus, these results are consistent with the EOF1 of the CFS



FIG. 16. As in Fig. 15, but for CFS predictions of JAS fields. Fields shown are the average of predictions initialized in January– March.

wind containing a positive trend over the period, but more weakly than observed, leading to the weaker trends in the MOS rainfall prediction than observed.

A further aspect of the CFS SST composite (Fig. 16a) is that it reveals an apparent tendency to predict cool conditions in the central and eastern equatorial Pacific during the more recent period. Though it appears the cooling is more pronounced in the CFS forecasts than it is in the observations, a tendency to forecast La Niña is not the dominant feature of the composite trend in the forecasts. Inspection of the predicted and observed Niño-3 time series (not shown) shows that there is not a dramatic bias toward forecasting La Niña development and associated cold conditions in the latter period. Furthermore, if a dominant aspect of the composite difference for the CFS were a tendency for La Niña in the recent period, then from the teleconnection structures of the CFS ENSO in Figs. 10 and 12, warmer conditions in the South Atlantic and cooler conditions



FIG. 17. Time series of JAS AtlN-S SST. Observed (thick line) predicted by the CFS from initializations in January–March (dashed line, r = 0.64 with observed) and initializations in April–June (dotted line, r = 0.78 with observed).

in the North Atlantic would be expected in Fig. 16a. Therefore, in the Atlantic sector, the trends appear to represent features that are not a direct response to a trend in the CFS toward cooler conditions in the eastern tropical Pacific.

To further investigate the observed and model Atlantic SST variations over 1981-2008, an index of north minus south SST over the Atlantic basin (AtlN-S) has been calculated (Fig. 17). The index is calculated for the Atlantic domain 30°S–60°N and is calculated as (60°– 10°N) minus (10°N–30°S). The dividing line for the difference is taken at 10°N given the general results in the literature that show this to be the approximate latitude at which the zero line of the north-south contrast usually emerges in July-September teleconnection analyses with Sahel rainfall (Folland et al. 1986; Rowell et al. 1995) and represents a measure that contrasts SST approximately to the north and south of the latitude of the ITCZ at this time of year. As expected from the composite maps (Figs. 15 and 16), the observed and modelpredicted time series of AtlN-S show significant upward trends (Table 3). The observed JAS index has a positive correlation with observed Sahel rainfall over this period (r = 0.54), consistent with the relationship between such indices and Sahel rainfall throughout the twentieth century (Folland et al. 1986, 1991). The CFS JAS Sahel rainfall is strongly related to the model's AtlN-S (r = 0.55for AMJ initializations, r = 0.65 for JFM initializations), supporting the relationship to be an integral feature of the model's regional climate system, as also suggested in the composite maps (Fig. 16).

Furthermore, it is clear from Fig. 17 that the CFS is quite effective at containing the AtlN-S information in its JAS SST predictions, from both JFM initialization times (r = 0.64) and AMJ initialization times (r = 0.78).

Persistence in the observed AtlN-S index is quite high (r = 0.53 for JFM to JAS, r = 0.72 for AMJ to JAS), so the above skill for the CFS represents a modest improvement on persistence. However, even modest improvement is noteworthy; it suggests that the CFS skillfully maintains, over its multimonth forecast, the approximate initialized AtlN-S anomaly value, and in addition, introduces some modest skillful developments.

The interpretation is that CFS seasonal forecasts successfully track many of the observed trends in the climate of the study region and the Atlantic Ocean. This is achieved because the CFS contains and skillfully projects forward in its seasonal forecasts, variations of AtlN-S, low-level tropical Atlantic winds, and Sahel rainfall. The low-level tropical Atlantic winds yield a modest underestimation of the MOS-predicted Sahel rainfall. The reason for this underestimation is beyond the scope of the current paper and requires further investigation. While adding AtlN-S as a predictor in the MOS system might be suggested from the above analysis to yield a better trend in the MOS system, results to this point do not indicate that such an approach leads to any major immediate improvement.

7. Conclusions

This paper has addressed two main aspects of Sahel rainfall prediction. First, results have shown that, when driven with observed SST, AGCMs usually do contain information about the observed interannual Sahel rainfall variability, through their predictions of the low-level tropical Atlantic-West Africa wind field. Previous results have found most AGCMs unable to directly represent the Sahel's rainfall variability. Therefore, this new result is considered to have significant implications about the utility of AGCMs for prediction of Sahel rainfall in the context of seasonal time scales, and potentially other time scales (decadal, climate change), whenever there may be more confidence in model projections of tropical Atlantic wind fields as compared to Sahel rainfall. For seasonal predictions, lead time beyond a month has previously been a problem even for the best models that represent Sahel rainfall.

Therefore, the second main aspect presented here has been the study of coupled models and the potential to improve the lead time for skillful seasonal forecasts of Sahel rainfall. Results have identified the potential for coupled models to break through the lead-time barrier, with skill superior to that previously reported using empirical or AGCM approaches. Drawing on integrations with the CFS, skill levels only slightly less than those achieved by the best approaches using observed SST have been achieved at lead times of up to six months, utilizing information in the tropical Atlantic–West Africa predicted wind field.

The CFS skill on the interannual time scale is dependent on applying the MOS approach, and the key information is captured effectively in the first EOF of the low-level tropical Atlantic winds. The information in the tropical Atlantic wind field is confirmed to be part of large-scale developments in the coupled model involving recognizable teleconnection structures from the tropical Pacific to the tropical Atlantic in the SST and low-level wind fields. Documenting these large-scale teleconnection structures in the model reinforces confidence that the results illustrate the potential of coupled models to represent the evolution of the climate system through this period of the annual cycle, and specifically, to represent key aspects that are relevant for anticipating Sahel rainfall anomalies.

The period of study with the CFS forecasts (1981–2008) also contains a significant upward trend in Sahel rainfall, continuing the low-frequency component of the region's climate that has been well documented through the twentieth century. The CFS forecasts contain the upward trend, both in model rainfall and the MOS (at reduced magnitude), and the trend is diagnosed to a warming in the SST of the North Atlantic (relative to the South Atlantic), in both observed and model predicted fields.

While the levels of Sahel rainfall skill achieved through the CFS at lead times up to 6 months are greater than found in previous studies, care is required in attributing and interpreting the skill. AGCMs driven with observed SSTs have successfully tracked decadal variations in Sahel rainfall (e.g., Zeng et al. 1999; Giannini et al. 2003; Scaife et al. 2009) and the relevant decadal SSTs are known to persist from early in the year to boreal summer (Folland et al. 1991; Ward 1998). Therefore, over periods when Sahel rainfall exhibits strong decadal fluctuations, it is possible that AGCMs driven with persisted SSTs may be able to achieve substantial seasonal forecast skill simply by tracking the decadal rainfall variations. Such experiments conducted with the atmospheric component of the CFS over the period 1981–2008 would allow clearer attribution of skill gains to the application of a coupled model approach. Ideally, assessments would be over a longer period to allow assessment of model forecast systems over the 1950–present period, taking in a better sample of lowfrequency and high-frequency Sahel rainfall fluctuations. In particular, the AGCM experiments driven with observed SST reported here (1968-2001) cover a period that contains a relatively small fraction of variance in the low frequency, and therefore provides little insight into the ability of AGCMs to track decadal variations. In contrast, the period of CFS forecasts (1981–2008) does contain a substantial low-frequency component (the upward trend), permitting the discussion of the extent to which the CFS forecasts are both capturing the interannual variations and tracking the lower frequency trend.

The long lead skill achieved by the CFS after detrending is scientifically encouraging but requires careful perspective in practice. The diagnostic analysis of the coupled ocean–atmosphere fields strongly suggests that the skill achieved represents an advance that can be attributed to the ability to project forward the coupled system by a CGCM. Previous studies have not found skillful detrended signals in the SST at such long lead times for Sahel rainfall. However, the level of skill (r = 0.33 for JFM initializations) is still modest in practical terms such that users should consider such a system as providing a modest ability to capture the year-to-year swings in rainfall, embedded in a more reliable ability to track the lowerfrequency variation.

This study (AGCMs and CGCMs) has focused on post-1967, the period for which most model simulations are available, allowing coherent pictures to be drawn by studying models over comparable years. On the interannual time scale, this period permits a close assessment of skill associated with ENSO but does not allow a good assessment of the ability to capture the tropical Atlantic mode of SST variability that was particularly important for interannual variability in Sahel rainfall during the wetter regimes of 1950-70 and earlier in the century (Ward 1998; Janicot et al. 2001). The issue emerged in the study of Ndiaye et al. (2009), where for MOS correction focused on AGCM predictions for 1950-70 or including the full period 1950-2000, a second model wind mode emerged as a MOS predictor that specified rainfall variability specifically associated with tropical Atlantic SST. Consideration of this aspect is beyond the scope of the current paper, but presents itself as an important question for future study. It is particularly important to address, given the results of Vizy and Cook (2001), showing that coarse-resolution GCMs can be expected to have particular difficulty with resolving the impact of the tropical Atlantic SSTs that give rise to enhanced (reduced) rainfall in the Sahel with compensating reduced (enhanced) rainfall over the Guinea Coast region.

A further aspect that is not strongly present in the 1981–2008 period, but has been shown to be a strong forcing agent on low-frequency Sahel rainfall fluctuations, is low-frequency change in the Indian Ocean SST (Folland et al. 1986; Giannini et al. 2003). For the purpose of diagnosis here, an index of Atlantic north–south contrast has been used. It was found that adding Indian Ocean SST into the index did not contribute to explanatory power in the period 1981–2008, although it is known that including the Indian Ocean is important for indices that explain the low-frequency rainfall fluctuations through the whole twentieth century. Indeed, in the presence of continued global warming, it has been noted that there is potential for trends in all ocean basins to play a significant role (e.g., Lu and Delworth 2005; Biasutti and Giannini 2006) in driving anomalies in regional circulation such as in the tropical Atlantic–West African monsoon. The robustness of GCMs in general, and a MOS system such as proposed here, requires careful monitoring in the presence of such trends.

An important area for further study remains the development of systems to operationally downscale forecasts into information at smaller scales within the Sahel and also to develop other predictands like water satisfaction indices or frequency of rainy events greater than a certain threshold. Such scales of information, and such variables, can be more suited to many user needs and can be expected, in general, to be more effectively translated into action.

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