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## Tropical Atlantic moisture availability and precipitation over West Africa: Application to DEMETER hindcasts

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[1] From rainfall analysis over West Africa (rotated empirical orthogonal functions, Varimax criterion), significant leading modes are identified: i.e., along the Gulf of Guinea, the Senegal/west Mali area, and the central Sahel. Using the moisture convergence/divergence (MCD) parameter derived from ERA-40, three leading empirical orthogonal function modes are extracted. They are respectively linked to the Intertropical Convergence Zone position, the equatorial Atlantic upper-ocean thermal conditions (center and west), and significantly correlated with identified rainfall modes. Linkages between temporal variability of the above modes and that of the tropical Atlantic upper-ocean thermal are highlighted. A new statistico-dynamical probabilistic model for West African rainfall prediction is thus built using MCD as predictors diagnosed from the DEMETER hindcasts. The model takes advantage of both identified statistical linkages, and conditional probabilities between precipitation occurrence and MCD values. It is found that new probabilistic scores for precipitation predictions, are significantly improved when compared to those which were obtained directly from DEMETER precipitation forecasts. **Citation:** Rogel, P., Y. M. Tourre, V. Benoit, and L. Jarlan (2006), Tropical Atlantic moisture availability and precipitation over West Africa: Application to DEMETER hindcasts, *Geophys. Res. Lett.*, 33, L21711, doi:10.1029/2006GL027178.

### 1. Introduction

[2] Several diagnostic studies have been conducted to understand the physical mechanisms involved with seasonal rainfall and sustained deep convection over West Africa [e.g., *Fontaine and Janicot*, 1996; *Message et al.*, 2004]. A large interannual variability of the system has been also identified [e.g., *Tourre et al.*, 1999].

[3] In order to better evaluate specific dynamics of the summer monsoon, seasonal forecasts from the DEMETER European and multi-model project (<http://www.ecmwf.int/research/demeter>) [*Palmer et al.*, 2004] have been used in this study for the 1980–2001 period. Simulations and output are from seven coupled models. Each individual research center involved, i.e., CERFACS (Centre

Européen de Recherche et de Formation Avancée en Calcul Scientifique), ECMWF (European Center for Medium-Range Weather Forecasts), INGV (Istituto Nazionale de Geophysica e Vulcanologia), LOCEAN (Laboratoire d’Océanographie et du Climat: Expérimentation et Approches Numériques) also former LODYC (Laboratoire d’Océanographie Dynamique et de Climatologie), Météo-France (with the Centre National de Recherches Météorologiques, or CNRM), UKMO (United Kingdom Met. Office), and MPI (Max-Planck Institut für Meteorologie), produced nine (9) 6-month-ahead forecasts initialized from ERA-40 [*Uppala et al.*, 2005]. As such, ‘63 (9 × 7) members’ or forecasts are used, each one being based upon different initial conditions associated with the respective coupled model. Each forecast is made from initial conditions starting the first of February, May, August, and November.

[4] Statistical analyses of output from the above allowed at first to assess forecasting skills by taking into account sea surface temperature (SST) from the surrounding ocean. Then predictors were to be identified for specific spatio-temporal precipitation regimes over West Africa. The position of the Intertropical Convergence Zone (ITCZ) and the moisture convergence/divergence (or MCD, hereafter) were thus computed. From statistical relationships between actual precipitation, output using MCD predictors/parameters and probabilistic scores, new and better forecasts were issued by using a statistico-dynamical probabilistic model, following *Garric et al.* [2002].

### 2. Data and Method

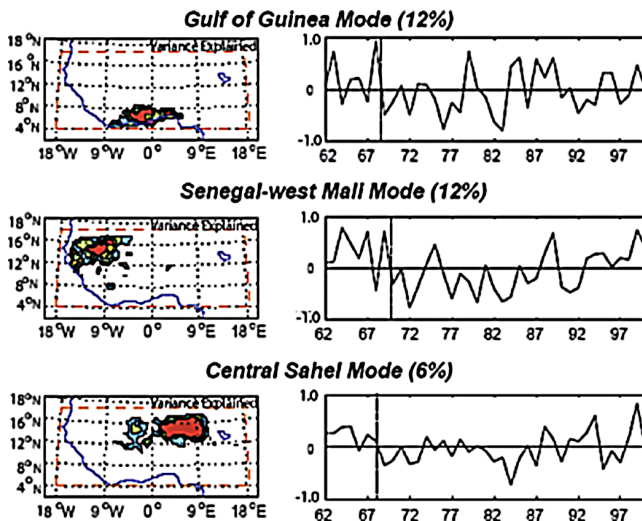
[5] Three unique data sets are used here: two are considered as “observation” and one as “hindcast”. The first observational dataset is for precipitation obtained at the Climate Research Unit of University of East Anglia (hereinafter referred to as CRU) [*Mitchell and Jones*, 2005]. It globally maps historical monthly precipitation data on a 0.5 degree grid-point system, starting in 1901. In this study, a subset from 1962 onward, for the West African domain (i.e., 20.25°W–20.25°E and 4.75°N and 20.25°N) and averaged from June to September (the summer monsoon), is used. The second observational dataset is from the ERA-40 atmospheric re-analysis database [*Uppala et al.*, 2005]. It includes winds and humidity at 850 hPa, from which MCD has been derived (see later in section 8). Data from 1962 onward, which includes the intense Sahelian drought of the early 70’s, is also used for the computation of statistical relationship, for the Atlantic Ocean and between 10°S and 20°N. Nevertheless only hindcasts which started in May and for the seven DEMETER coupled models, have been used (1980–2001 period). Thus the largest ensembles possible were made available for the experiment. The third dataset (or hindcast)

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**Figure 1.** Three leading rotated EOFs modes for precipitation over the West African window (dashed red rectangle). (top) Mode 1, the Gulf of Guinea mode (12% of total variance); (middle) mode 2, the Senegal/west Mali mode (12% of total variance); (bottom) mode 3, the central Sahel mode (6% of total variance). (left) Explained variance for each mode starts at the 60% threshold in light blue (with 10% increment). (right) Normalized amplitude functions (or principal components) for each mode. The vertical line indicates the starting period for rainfall deficit over West Africa.

is from the DEMETER project [Palmer *et al.*, 2004]. Only hindcasts which started in May and for the seven DEMETER coupled models, have been used (1980–2001 period). Thus, for each individual summer, a total of 63 “datasets” have been used to derive variables and parameters similar to that obtained in parallel from CRU and ERA-40.

[6] A rotated empirical orthogonal functions (REOFs) analysis (using Varimax criterion, after Richman [1986]) is performed for observed precipitation. Prior to the analysis, detrended data is normalized. The first ten ranked EOFs modes ( $\sim 80\%$  of total variance) are kept for the rotation.

[7] When Relative Operating Characteristics (or ROC, after Mason and Graham [1999]) curves are used to estimate probabilistic predictability of the ITCZ location, (using terciles from the seven coupled models), it is found that all scores are not better than the climatological probabilistic prediction. Thus ITCZ location was not a valid predictor to use in a statistical model for at least three reasons: persistence in monthly correlations (particularly true during springtime), a too-coarse wind-component resolution from models, and a significant ‘climatic drift’ in all seven coupled models over the tropical Atlantic region [Lazar *et al.*, 2005].

[8] The remedy was then to find a better integrated model predictor/parameter, and valid for both ERA-40 and DEMETER. It has to be associated with rainfall amount and more representative of larger scales events. This is accomplished by computing the MCD values using data from ERA-40, over the Atlantic Ocean and at the 850 hPa level. For each month, the quantity  $\text{div}(qV)$  is obtained first, where  $q$  is the specific humidity and  $V$  is the

horizontal wind, both taken at 850 hPa. This level represents quite well the moisture advection (and convergence/divergence) during the summer monsoon, which feeds the amount of condensation and deep convection processes over West Africa. Then averages for the summer monsoon period are computed. An EOF analysis is performed for the MCD field, and the first four modes which are well separated (i.e., non-degenerated) were kept for further statistics and correlation with precipitation.

### 3. Results

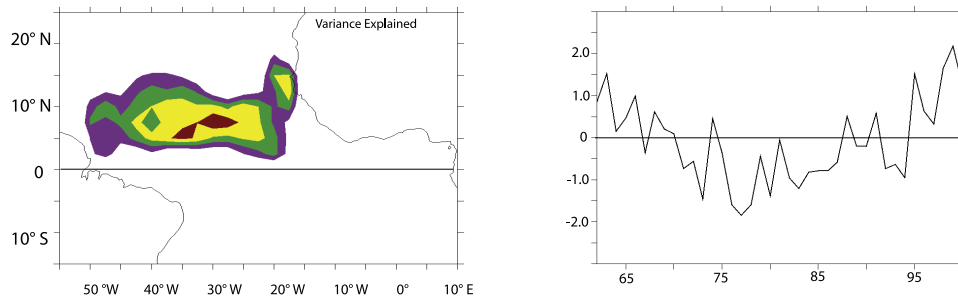
[9] In order to build a probabilistic model for precipitation, a detailed spatio-temporal distribution of precipitation regimes over West Africa, is necessary. By applying the REOFs technique to the precipitation dataset, the ranked first three modes are displayed in Figure 1. The first mode which represents 12% of the variance (after rotation) covers neighboring regions along the West African Gulf of Guinea coastline. It is therefore linked to summer monsoon rainfall associated with thick layered clouds of nimbostratus type [Nicholson, 1979]. Interannual and low-frequency precipitation variability can be seen from the modulating amplitude functions. Positive correlation of  $\sim 0.5$  between the amplitude function of this first mode and SST time-series from the Gulf of Guinea and along the equator (not shown) indicates of a possible direct relationship between precipitation amount there and the thermal state of the equatorial Atlantic upper-ocean (see section 10). The second mode which represents also 12% of the variance (after rotation) is found over Senegal/west Mali area. It is directly under the influence of the position of Azores anticyclone, the intensity of the deflected tradewinds from the eastern Atlantic, and the subsequent position of the ITCZ over the same region. This mode also belongs to the westmost section of the so-called Sahelian belt. Indeed, the low-frequency Sahelian drought from the late 60s until the late 80s is seen in its amplitude function. The third mode which represents 6% of the variance (after rotation), is over the central Sahel and in the middle of the Sahelian belt. The low-frequency drought period identified with the second mode, is also present and occurs when the Atlantic multi-decadal oscillation (or AMO after Kerr [2000]) was weaker and displayed a negative phase [Enfield *et al.*, 2001]. Precipitation in the region cover by the third mode is mainly due to easterly waves and convective clouds from squall-lines activity [Aspliden *et al.*, 1976]. It has been found that during the drought period mentioned above the center of the Azores anticyclone was displaced south-eastward [Tourre *et al.*,

**Table 1.** Correlations Between the Four Moisture Convergence/Divergence Modes and the Three Precipitation Rotated Modes<sup>a</sup>

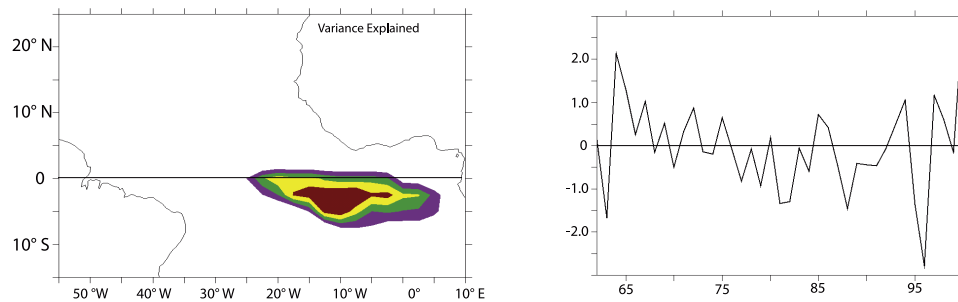
MCD	RR		
	PC3	PC2	PC1
PC1	<b>0.62</b>	-0.14	-0.28
PC2	-0.01	<b>0.40</b>	-0.01
PC3	0.12	0.14	<b>0.32</b>
PC4	-0.04	0.03	-0.06

<sup>a</sup>MDC, moisture convergence/divergence, and RR, precipitation rotated modes. Bold values are significant at the 95% level.

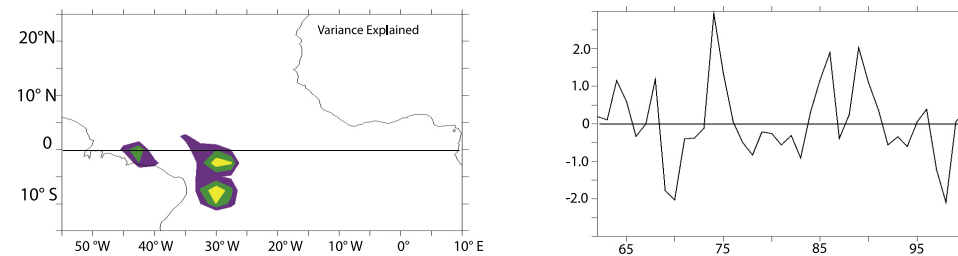
**MCD Mode 1 (17 % total Variance)**



**MCD Mode 2 (12 % total Variance)**



**MCD Mode 3 (9 % total Variance)**



**Figure 2.** Three leading EOFs modes for MCD over the tropical Atlantic Ocean: (top) mode 1 (17% of total variance); (middle) mode 2 (12% of total variance); (bottom) mode 3 (9% of total variance). (left) Explained variance for each mode starts at the 30% threshold, in purple (with 10% increment). (right) Normalized amplitude functions (or principal components) for each mode.

2006]. The precipitation regimes associated with the last two modes are thus directly linked with the seasonal and interannual latitudinal position of the ITCZ over the eastern Atlantic and West Africa. Unfortunately the detailed position of the ITCZ and its variability are not well enough described by the seven coupled models.

[10] In order to better evaluate statistics between MCD and precipitation modes an EOF analysis is performed for the MCD field, using the correlation matrix. The first four modes are well separated (i.e., non-degenerated) so no rotation was necessary. Correlation between the four MCD leading modes and rotated rainfall PCs are displayed in Table 1. It is clear that only the three leading modes for both parameters: i.e., precipitation and MCD, are significantly correlated. The explained variances and amplitude functions for the first three MCD modes are displayed in

**Table 2.** Anomaly Correlation Coefficient and Dimensionless Root Mean Square Error Scores<sup>a</sup>

	ACC			RMSE		
	PC1	PC2	PC3	PC1	PC2	PC3
Persistence	0.00	0.26	0.24	1.06	1.15	0.90
ECMWF	0.11	0.46	0.74	1.03	1.05	0.90
CERFACS	0.29	0.30	0.47	0.98	1.18	0.84
CNRM	0.35	0.29	0.40	0.96	1.19	0.85
INGV	0.34	0.26	0.63	0.98	1.24	0.73
LODYC	0.22	0.43	0.64	1.00	1.08	0.71
MPI	0.18	0.06	0.23	1.04	1.40	0.91
UKMO	0.27	-0.08	0.47	1.03	1.31	0.82
Multimodel	0.34	0.32	0.71	0.97	1.13	0.73

<sup>a</sup>ACC, anomaly correlation coefficient; RMSE, root mean square error. Seven DEMETER models ensemble means, the multi-model ensemble mean, and persistence.

**Table 3.** Examples of Conditional Probabilities for the First Two Precipitation and MCD Modes<sup>a</sup>

	B1	B2
A1	16%	80%
A2	84%	20%

<sup>a</sup>A is for rainfall ‘events’ and B is for so-called MCD ‘events.’

Figure 2. It is found that the first mode of MCD is located over the northern tropical Atlantic Ocean between 4°N and 12°N (Figure 2, top). By exploring the dynamical links with summer rainfall it is found that precipitation over the Sahel (PC3) is directly affected by the position of the ITCZ in the north tropical Atlantic, or the MCD over the same region (maximum explained variance of 50% for the MCD mode 1, and significant correlation of 0.62 in Table 1), a result somewhat expected. Indeed, it is also found that a highly significant correlation of 0.7 exists between MCD and meridional component of the tradewinds (not shown). The second MCD mode (Figure 2, middle) is significantly correlated with rainfall PC2 (0.40 in Table 1), and maximum explained variance of ~50% are found slightly south of the equator. Moreover, the MCD second mode is highly correlated with SST over the same area (~0.55), thus highlighting the relationship between moisture availability through the south-easterly tradewinds, and thermal state of the equatorial Atlantic Ocean. For the third MCD mode, the maximum explained variance of ~40% is found in the western equatorial Atlantic (Figure 2, bottom) with an anti-correlation (~-0.5) with SST anomalies there. The dynamical relationship must then be through the intensity of the northern hemisphere summer north-easterly flow and location of ITCZ there (sometimes found south of the equator). Since statistical and dynamical links seem well established between the first three MCD and precipitation modes a predicting statistico-dynamical multi-model is proposed for precipitation forecast based upon MCD modes used as predictors.

[11] From specific humidity forecasts and horizontal winds from DEMETER, MCD values are computed from June until September, averaged and then projected against the EOF modes obtained from ERA-40. No centering *per-se* had to be applied. Forecast ensembles are thus constructed for each principal component. For each model and the multi-model, and for the first three modes, correlation between anomalies (ACC) and Root Mean Square Error

(RMSE) are computed and displayed in Table 2. The use of persistence from May is also given for comparison. From the multi-model output, all correlations with PCs are larger than 0.3, with a value of  $r = 0.71$  highly significant with PC3. The RMSE are in general less than standard deviations (1.03, 1.19, and 0.93, respectively). From the above and the fact that models perform better than persistence, a statistico-dynamical model is presented hereafter.

[12] The model proposed here is to predict if each precipitation regime within the identified key rainfall regions (i.e., where maximum explained variances are found and displayed in Figure 1), is below or above climatology. It is meant to define objectively the probability of having rainfall amount below or above the median, for each region. Conditional probability technique is then used as follows (see Table 3). A1 is an event for the first precipitation mode with value larger than the median value for the same mode, A2 is the residual. The probability to have an event Ai is called  $p(A_i)$ . The same applies for the MCD or B events. Thus the conditional probability for one event Ai to occur after a Bj event is:  $p(A_i/B_j)$ . In Table 3 we see that conditional probabilities for A2/B1 and A1/B2 are high since an ACC of -0.62 was found between the first two components.

[13] Thus from:

$$p(A_i) = \sum_j p(A_i/B_j) \cdot p(B_j)$$

one can compute for each individual year the probability of having a rainy season below or above normal. The same approach applies for the second and third modes. The next step is a way of measuring and evaluating scores obtained from the proposed model.

[14] When ROC curves (for the seven models and the multi-model), and for negative anomalies only are computed as an example, the number of ‘good’ predictions is always larger than that of false alarms (not shown). While the usefulness of the multi-model is again demonstrated it was also found, for unexplained reasons, that the worse predictions were obtained when using the second modes.

[15] In Table 4, ROCs for each model and positive anomalies from the main modes are displayed. To the left are the values obtained by the statistical model presented here, compared to the DEMETER simulations (to the right). It is clear that results from the multi-model and the new

**Table 4.** Compared ROCs for Events “Negative Phase of the ith Mode of Precipitation” From the Two Prediction Systems<sup>a</sup>

	New Forecasts			DEMETER Forecasts		
	PC1	PC2	PC3	PC1	PC2	PC3
ECMWF	0.66	0.58	0.82	0.45	0.62	0.55
CERFACS	0.67	0.67	0.54	0.76	0.32	0.38
CNRM	0.76	0.56	0.69	0.46	0.47	0.52
INGV	0.75	0.69	0.73	0.56	0.77	0.71
LODYC	0.80	0.61	0.80	0.54	0.43	0.49
MPI	0.77	0.49	0.72	0.58	0.33	0.60
UKMO	0.75	0.66	0.64	0.59	0.49	0.77
Multi-model	0.85	0.64	0.82	0.67	0.46	0.70

<sup>a</sup>The improved new prediction systems are those using MCD as predictors and the ‘classic’ DEMETER forecasts by using straight precipitation output. ‘False alarm and hit’ rates are computed using probabilistic forecasts of an event based on 9 (for each individual models) and 63 (multi-model) members for each forecast.

prediction method, are far superior to rainfall prediction obtained directly from DEMETER. Additional computation was made using cross-validation by eliminating individual years appropriately, and for the full period. Then conditional probabilities were re-evaluated. When yearly forecasts are projected against the precipitation and MCD modes, results are somewhat similar, particularly for the multi-model: 0.79, 0.65, and 0.80, respectively and for each PC.

#### 4. Discussion and Conclusion

[16] It was found first that, even if the leading precipitation modes are well identified by using the rotated EOFs technique, and if their temporal variability was linked with ITCZ location and thermal state of the Atlantic Ocean, the ITCZ location is not well enough represented and defined by DEMETER models, for adequate use. The second result is that direct prediction of precipitation from DEMETER and over West Africa, was not significantly better than forecast using climatology, even when surface conditions during the onset of the summer monsoon are well simulated. Indeed, smaller-scale phenomena including evaporation, and condensation processes linked to processes such as deep convection are not well enough represented in the models.

[17] From the dynamical relationships between the MCD and precipitation during the monsoon season, a contemporaneous statistical-dynamical model has been proposed. The latter integrated larger-scale parameter which might be more suitable in terms of rainfall prediction. It is found that this proposed probabilistic model improved considerably prediction scores when compared to those obtained directly from DEMETER.

[18] Even if specific amount of rainfall could not be evaluated at this stage, valuable information in terms of ranking the intensity of rainfall during the summer monsoon (when compared to climatology), is obtained. It is believed that such statistical model and results can be proven useful as additional information for Early Warning Systems within the African Monsoon Multidisciplinary Analysis (AMMA) project, and decision and policy makers involved with water resources management, food security and public health sectors, among others.

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