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West African Monsoon influence on the summer Euro-Atlantic circulation

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[1] The West African Monsoon (WAM) influence on the interannual variability of the summer atmospheric circulation over North Atlantic and Europe is investigated over the period 1971–2000. A set of sensitivity experiments performed through the Arpege-Climat Atmospheric General Circulation Model is analyzed, using the so-called "grid-point nudging" technique, where the simulated atmospheric fields in the WAM region are relaxed towards the ERA40 reanalysis. Observations confirm that a sizable part of the Euro-Atlantic circulation variability is related to the WAM, with anomalies of reinforced convection in the Sudan-Sahel region associated with positive North Atlantic Oscillation (NAO) phases and subsidence over eastern Mediterranean. The nudged simulations highlights the role of the WAM in driving the mid-latitude circulation. A strong monsoon is related to high-pressure anomalies over the Azores and positive NAO phases. **Citation:** Gaetani, M., B. Pohl, H. Douville, and B. Fontaine (2011), West African Monsoon influence on the summer Euro-Atlantic circulation, *Geophys. Res. Lett.*, *38*, L09705, doi:10.1029/2011GL047150.

1. Introduction

[2] The European climate is influenced by both mid-latitude and tropical climate systems. The North Atlantic Oscillation (NAO) is widely considered the most important mid-latitude source of temperature and precipitation variability over western Europe in winter, through changes induced in the North Atlantic storm track activity. A related index is defined as the leading Principal Component of the 500hPa geopotential height (Z500 hereafter) anomalies in the Atlantic sector, showing centers of action near the Azores islands and Iceland [*Hurrell et al.*, 2003]. While the NAO is mainly active in wintertime, it is also identified during summer. It is characterized by a more northern location and smaller spatial scale than its winter counterpart, with the high pressure centered west of the British islands and the low pressure pole over Greenland. Although it has a smaller amplitude than its wintertime counterpart, the summer NAO exerts a sizable influence on northern European rainfall and temperature, being of key importance in generating summer climate extremes in northwestern Europe [*Folland et al.*, 2009].

[3] The main tropical climate system affecting the European climate is the summer Asian monsoon. *Rodwell and Hoskins* [2001], investigating the role of the monsoons in maintaining the summer subtropical circulation, demonstrated that the diabatic heating in the Asian monsoon region can induce a Rossby wave pattern to the west. They found that the interaction between the Rossby waves and the mid-latitude westerlies produces an adiabatic descent over the Mediterranean and the subtropical Atlantic. Moreover, they specified that an African heating source induces little changes in the descent produced by the Asian monsoon. However, interactions between the summer Euro-Atlantic circulation and the convective activity of the West African Monsoon (WAM) and in the tropical Atlantic have been reported by several authors. *Fontaine et al.* [2010] related the recovery of monsoonal precipitation and Intertropical Convergence Zone (ITCZ) convection over northern Africa over the last 25 years to increased subsidence over southern Europe. *Black et al.* [2004] suggested possible teleconnections of the recent strong heat-wave event in 2003 in Europe to remote signals: the intensification of the Azores high, the northward shift of the West African ITCZ and a Rossby wave from tropical America. Moreover, *Cassou et al.* [2005] found that the excitation of the "blocking" and "Atlantic low" weather regimes over North Atlantic during summer extreme events over France are significantly favored by wetter-than-average conditions in both the Caribbean basin and the Sahel. These results have been recently substantiated by *Douville et al.* [2011] through a numerical study, finding a tropical control on the boreal summer mid-latitude stationary waves.

[4] Motivated by these recent results, we aim here to investigate the role of the WAM on the interannual variability of the atmospheric circulation over North Atlantic and Europe. We hypothesize that, though not prominent compared to the Asian monsoon, the WAM may have a significant impact on the descent over subtropical Atlantic and western Europe, with consequences on the regional circulation and climate.

2. Data and Methodology

[5] The investigation of the dynamical features of the interaction between the WAM and the circulation over the Euro-Atlantic sector is carried out through a set of sensitivity experiments performed using the Arpege-Climat Version 4.6 [*Déqué et al.*, 1994] Atmospheric General Circulation Model. We use the so-called "grid-point nudging" technique [*Bielli et al.*, 2010], where given prognostic variables are relaxed inside the WAM region towards the 6-hourly European Centre for Medium-Range Weather Forecasts Reanalysis (ERA40) [*Uppala et al.*, 2005]. The model relaxation leads to a correction of the regional biases and a more realistic description of the climate variability within the nudged domain. Arpege-Climat is run in linear T63 truncation, with

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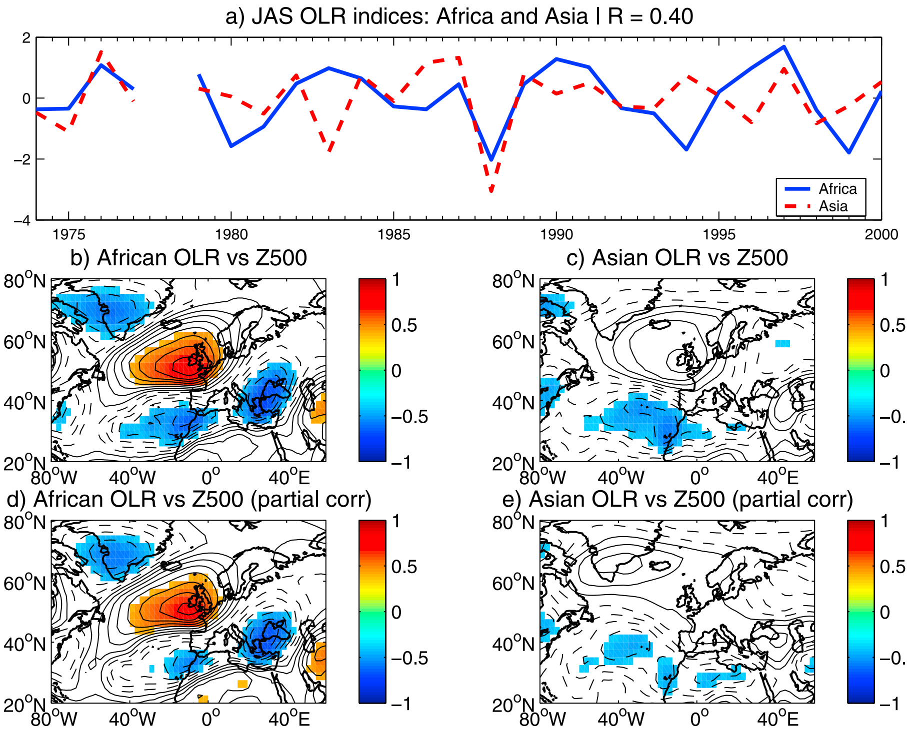

Figure 1. (a) Sahelian (20°W–40°E, 10°–20°N) and Indian (70°–90°E, 5°–25°N) convection indices in JAS. The correlation value between the two indexes is labeled on the figure. (b) Correlation between JAS Z500 and Sahelian convection. Contour interval is 0.1, solid (dashed) contours indicate positive (negative) values, color shadings are the correlation values 95% significant. (c) As Figure 1b but for Indian convection. (d, e) As Figures 1b and 1c but after removal of the covariance associated with the Indian and Sahelian index, respectively.

a reduced 128 × 64 Gaussian grid and 31 vertical levels. A semi-implicit, semi-Lagrangian, two-time level discretization scheme is used in the dynamical core. The physical package includes a mass flux convective scheme with a Kuo-type closure. The nudged variables are the zonal and meridional wind components, temperature, specific humidity and sea-level pressure and the nudging is applied on each time step ($t_{step} = 30$ minutes). The nudging consists in adding a $-\lambda(y\text{-}y_{ref})$ term in the model prognostic equations, where y is the model state vector, y_{ref} the reference field towards which the model is relaxed, and $\lambda = t_{step}/e_{time}$ is the strength of the relaxation, with e_{time} the e-folding relaxation time. The strength of the relaxation, λ, is varied according to the variable (5-hour e-folding time, i.e., $\lambda = 0.1$, for the wind components, and 12-hour e-folding time, i.e., $\lambda = 0.04$, for the other variables) and the vertical level (weaker at the 3 lowest and 5 highest levels) to let the model adjust to the nudging. The control experiment CtIV is a 30-year (1971–2000) free (i.e., not nudged) integration forced by observed (including the interannual variability) ERA40 SST fields, after a 2-year spin-up. All SST fields are monthly and are interpolated at the daily timescale through a quadratic conservative interpolation scheme. The nudged experiments are conducted relaxing the model over a tropical African-Atlantic domain (34°W–43°E, 5°S–21°N: Af experiments), prescribing interannually varying or climatological SST. The domain is centered on the boreal summer ITCZ and is surrounded by a buffer zone of about 900 km wide in which the nudging vanishes progressively to ensure a smooth transition between the nudged and free atmosphere. In the Northern Hemisphere, the southward boundary of the free atmosphere is therefore at 30°N. All nudged experiments consist of ensembles of 30 boreal summer simulations initialized on May 15th from each of the CtIV individual year. After a 15-day spin-up, outputs are archived for the period June–September (JJAS). The nudged interannual integrations are noted AfIVIV or AfIVCl when driven by interannually varying or climatological SST, respectively.

[6] The model outputs are compared with observed atmospheric variables from ERA40 and Outgoing Longwave Radiation (OLR) from National Oceanic Atmospheric Administration (NOAA) [*Liebmann and Smith*, 1996]. OLR is used as a proxy for the deep moist convection associated to the monsoonal circulation, because the cloud cover generated by the convective process reduces the thermal radiation reaching the top of the atmosphere; therefore intense (weak) convection is related to low (high) OLR values. NOAA data are provided from June 1974, but data from March to December 1978 are missing due to satellite failure.

[7] The WAM/Euro-Atlantic interactions are analyzed in July–August–September (JAS) when the monsoon is fully developed inland. The connection between the WAM variability and the Euro-Atlantic circulation is here explored at the interannual timescale. Any decadal trend has been removed applying a high-pass Butterworth filter with a 8-year cut-off, and the data have been standardized at each grid-point, in order to correctly compare the variability of different variables.

3. Observed Interannual Variability

[8] The individual contribution of the WAM and the Asian monsoon to the circulation variability over the Euro-Atlantic

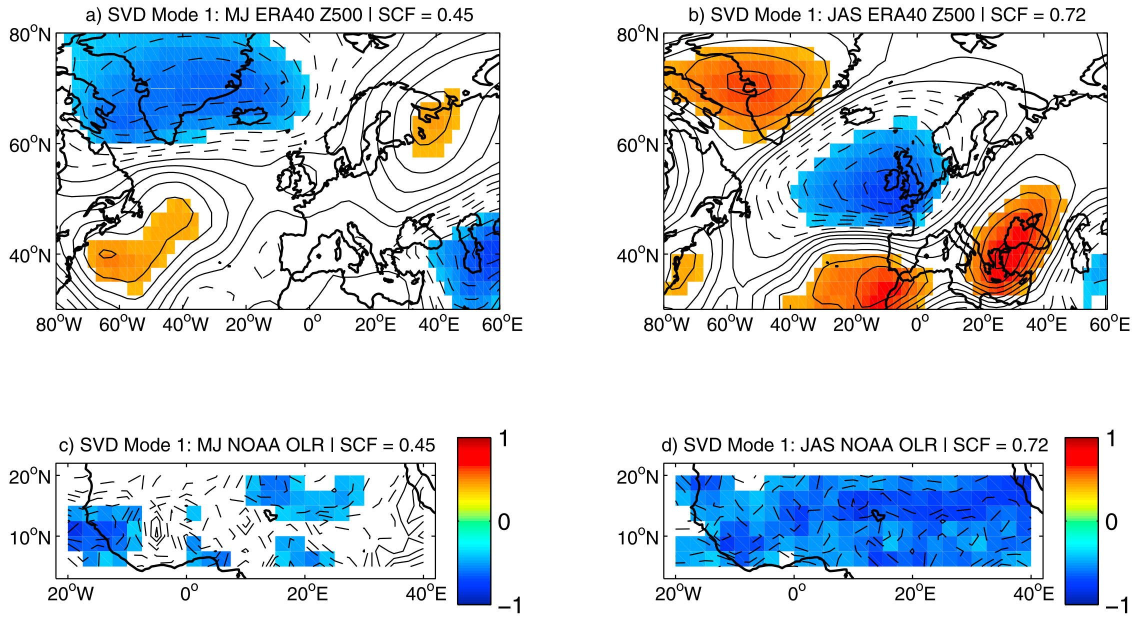

Figure 2. SVD analysis applied to OLR in northern tropical Africa and Z500 in the Euro-Atlantic sector, first mode displayed through heterogeneous correlation maps: (a, c) in May–June and (b, d) in June–August–September. Contour interval is 0.1, solid (dashed) contours indicate positive (negative) values, color shadings are the correlation values 95% significant.

sector is evaluated through the correlation between Z500 and regional convection indices over the Sahel and the Indian subcontinent, computed averaging OLR in the domains (20°W–40°E, 10°–20°N) and (70°–90°E, 5°–25°N), respectively (Figure 1a). High pressure is observed over subtropical North Atlantic when the Asian monsoon is strong (Figure 1c), while a coherent anomaly pattern over North Atlantic and Europe is related to the WAM variability, with a positive NAO-like pattern and subsidence in the eastern Europe associated with strong convection (Figure 1b). Because the Asian monsoon and the WAM tend to show in phase variability, with a 95% significant positive correlation ($r = 0.40$; Figure 1a), a partial correlation approach is used to have a more robust estimation of the specific contribution of the individual monsoons. The correlation patterns associated with the WAM (Figure 1d) and the Asian monsoon (Figure 1e) are almost unchanged, though slightly weakened, when the influence of the Asian monsoon and the WAM are removed, respectively. This result suggests a sizable relationship between the WAM and the North Atlantic circulation, which does not involve the Asian monsoon. In the remainder, focus is thus given on the WAM.

[9] The observed interannual WAM/Euro-Atlantic interaction has been studied focusing on the modes of covariance of the monsoonal convection and extra-tropical circulation through a Singular Value Decomposition (SVD) of OLR (20°W–40°E, 5°–20°N) and Z500 (80°W–60°E, 30°–80°N) fields (Figure 2). The southern border of the Z500 field is fixed at 30°N for consistency with the analysis of nudged simulations, in order to exclude the nudged domain. The field connection increases from May–June to JAS in terms of explained Squared Covariance Fraction (SCF = 0.45 to 0.72), with strong (weak) convection in the Sudan-Sahel related to high (low) pressure over eastern Mediterranean and positive (negative) NAO-like pattern. Hence, it is when the monsoonal circulation is clearly developed over West Africa that the stronger covariance is found between tropical and extra-tropical latitudes. In JAS, the results obtained by the SVD (Figure 2b) are also remarkably consistent with those obtained using simple linear correlations (Figures 1b and 1d), hereby suggesting that they are not method dependent.

[10] The Sahelian convection interannual variability is now compared to a NAO index defined as the difference between the Z500 in JAS averaged in a 10° squared domain centered over Azores (26°W, 38°N) and Iceland (22°W, 64°N), respectively [*Hurrell et al.*, 2003]. The correlation between Sahelian OLR and the NAO is negative and 90% significant (Table 1), indicating that a strong (weak) monsoon is related to positive (negative) NAO. Computing the correlation between the Sahelian convection and the individual components of the NAO index, namely the Azores and Iceland indices, the coefficient is negative and 90% significant when the Azores pole is considered, while the Iceland pole shows no significant correlation (Table 1). This suggests that the NAO is primarily associated with the WAM through the Z500 variability in the subtropical North Atlantic.

4. Nudged Simulations

[11] In this section we investigate the capability of the Arpege-Climat model in simulating such covariance between

Table 1. Correlation Between the Sahelian Convection Index (20°W–40°E, 10°N–20°N) and the NAO, Azores and Iceland Indices, Averaged in JAS in the Period 1971–2000[a]

	NAO	Azores	Iceland
ERA40	−0.36*	−0.36*	0.26
CtIV	−0.24	0.04	0.45**
AfIVIV	−0.50**	−0.41**	0.43**
AfIVCl	−0.53**	−0.58**	0.40**

[a] * 90% significant, ** 95% significant.

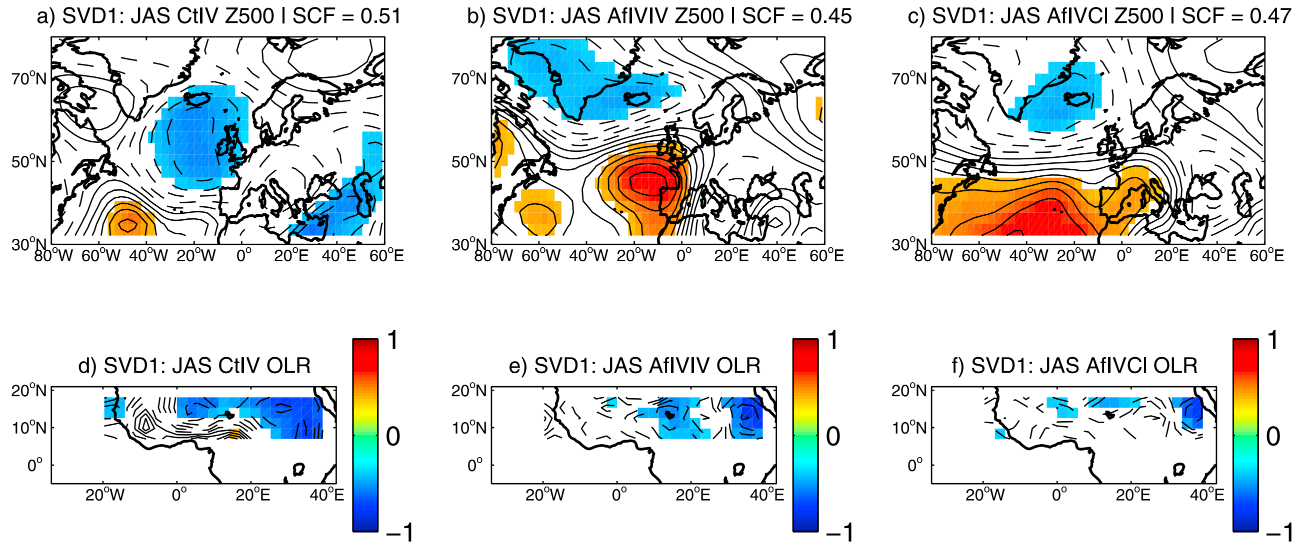

Figure 3. SVD analysis applied to OLR in northern tropical Africa and Z500 in the Euro-Atlantic sector, 1st mode displayed through heterogeneous correlation maps: (a, d) CtIV, (b, e) AfIVIV and (c, f) AfIVCl experiment. Figures 3d–3f fit the nudging domain. Contour interval is 0.1, solid (dashed) contours indicate positive (negative) values, color shadings are the correlation values 95% significant.

Sahelian convection and the North Atlantic circulation, in both its free and nudged configurations. SVD is applied to simulated OLR (20°W–40°E, 5°–20°N) and Z500 (80°W–60°E, 30°–80°N) in JAS (Figure 3). In Arpege-Climat (both in control and nudged simulations) the covariance explained by the first mode is around 0.50, underestimating the observed covariance pattern. When compared to observations (Figures 2b and 2d), CtIV describes well the connection between Sahel and North Atlantic, while the covariance is only partially described over subtropical North Atlantic and completely lost over Europe (Figures 3a and 3d). An improvement of the covariance description is observed in AfIVIV experiment, particularly over the subtropical belt, where the significance increases. The NAO-like dipole is repositioned in a more realistic configuration along the meridional direction, although the centers of actions are shifted too north compared to the observations, and its intensity and extension are better reproduced. Yet, the correlation over eastern Europe are not significant (Figures 3b and 3e). Results are generally unchanged (though slightly weakened) when the nudged simulation is driven by the climatological SST (AfIVCl; Figures 3c and 3f), demonstrating that the contribution of the SST forcing for explaining the covariance between the two regions is weak. In all cases however, the stronger covariance is found with convection over the eastern parts of the Sudanese-Sahelian belt (Figures 3d–3f), instead of the whole belt in the observations (Figure 2d). This could be due to the systematic dry (wet) biases of the model over West (East) Africa [*Pohl and Douville*, 2010]. Even in nudged experiments, Sahel remains slightly too dry over West Africa, in spite of the relaxation of the prognostic variables (not shown).

[12] The capability of Arpege-Climat in describing the interannual variability of the NAO and its individual components (Azores and Iceland indices) is next evaluated. The simulated correlation between the Sahelian OLR index and the NAO, Azores and Iceland indices is investigated and compared to the observations (Table 1). The simulated correlation is 95% significant when the nudged experiments are considered, both for the NAO and the Azores and Iceland components. In CtIV the correlation is significant only for the Iceland component. This could be due to a spatial bias of the Z500 pattern over the subtropical North Atlantic in the control experiment (Figures 3a and 3d), which is partly corrected in the nudged experiments. The above results suggest that, at the interannual time-scale, the WAM can modulate the NAO (strong monsoon related to positive NAO index), controlling the variability of the subtropical North Atlantic (strong monsoon related to high pressure).

[13] A possible mechanism underlying the WAM/North Atlantic relationship is hypothesized: changes in the monsoonal convection have a direct impact in the meridional overturning circulation over Africa and Atlantic, intensifying the Hadley cell, resulting in enhanced subsidence in the subtropics. The hypothesis is verified computing the correlation between the Sahelian OLR index and the streamfunction in the vertical plane averaged over the eastern Atlantic (40°–10°W). In ERA40, the Sahelian convection is positively correlated to the intensification of the northern Hadley cell, with significant values around 20° and 35°, consistent with increased subsidence over the Azores (not shown). In Arpege-Climat, the intensification of the Hadley cell is reproduced, though the correlations are weaker and significant only around 35°N, with consequent weak subsidence over the Azores (not shown). This could be due to the systematic dry biases of the model over West Africa [*Pohl and Douville*, 2010] and consequently over eastern Atlantic.

5. Conclusions

[14] In this work, the WAM modulation of the summer circulation variability in the Euro-Atlantic sector is studied, at the interannual time-scale, using both observational data (ERA40) and numerical experiments (nudged simulations performed using the Arpege-Climat model). Observations

confirm that a significant part of the interannual variability of the Euro-Atlantic circulation is related to the WAM. Specific relationships have been emphasized with the NAO index, the subtropical Atlantic and the Mediterranean. In JAS, reinforced convection in the Sahelian region is associated with positive NAO phases and subsidence over eastern Mediterranean. Though some observational and numerical studies already pointed out the reverse influence [*Vizy and Cook*, 2009; *Chauvin et al.*, 2010; *Gaetani et al.*, 2010], the role of the WAM in driving the mid-latitude circulation is confirmed in the model simulations: an improvement in the description of the mid-latitude interannual variability is observed when the Arpege-Climat model is nudged towards ERA40, compared to the control simulation. A strong effect is observed in the subtropical North Atlantic, with a strong monsoon related to high-pressure anomalies over the Azores and to positive NAO phases. The atmospheric nudging is effective in replacing the NAO centers of action in a more realistic configuration.

[15] We hypothesize that changes in the monsoonal convection have a direct impact in the meridional overturning circulation over Africa and Atlantic, intensifying the northern Hadley cell. The hypothesis is verified in ERA40, the Sahelian convection being positively correlated to the intensification of the meridional overturning circulation and to increased subsidence over the Azores. In Arpege-Climat, the intensification of the Hadley cell is reproduced, but the subsidence over the Azores is underestimated. Therefore, the possibility of an alternative or additive dynamical linkage (a westward propagating Rossby wave pattern in *Rodwell and Hoskins*' [2001] scheme) should be taken into account and investigated in future analysis.

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