3.4 Spring Interannual Variability of the Saharan Dust Transport in the Mediterranean.

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1. Introduction

Natural mineral aerosol (dust) plays an important role in forcing climate variability by affecting the atmospheric radiation balance through the modification of the optical thickness [*Tegen et al.*, 1997; *Haywood and Boucher*, 2000]. Moreover, dust can indirectly influence the climate through changes in the clouds development and properties [*Wurzler et al.*, 2000; *Mahowald and Kiehl*, 2003]. On the other hand, a complex climate-dust feedback has been pointed out, because the dust amount in the atmosphere is influenced by climate variability and changes in the extent of dust sources, naturally or anthropogenically induced [*Tegen et al.*, 1996; *Harrison et al.*, 2001].

The Mediterranean region is particularly affected by dust transport because its geographical position just north of the Sahara desert, the world largest dust source [*Washington et al.*, 2003]. The Saharan dust transport over the Mediterranean is prominent between March and September, with maxima in spring in the Eastern Mediterranean (EM) and in summer in the Western Mediterranean (WM) [*Moulin et al.*, 1998]. The mobilization of dust over North Africa and the intrusion into the Mediterranean region are related to specific synoptic conditions favorable to the extraction from the surface, the lifting above the boundary layer and the advection northwards: specifically, the spring transport is associated with the transit of the Sharav cyclones over North Africa, while the summer transport is associated with the coupling between the Balearic low and the Saharan high [*Moulin et al.*, 1998]. A relationship between the Mediterranean dust load and the North Atlantic Oscillation (NAO) has been found at the interannual time-scale, and a recent positive trend in the dust transport from the Sahara has been highlighted [*Moulin et al.*, 1997; *Dayan et al.*, 2008; *Antoine and Nobileau*, 2006]. The Saharan dust has a sizable impact on the air quality in the Mediterranean region, because its contribution to the ozone and particulate matter concentration [*Bonasoni et al.*, 2004; *Pederzoli et al.*, 2010]. Concerning the effects in catalyzing or suppressing precipitation, the dust role is still debated [*Levin et al.*, 1996; *Rosenfeld et al.*, 2001].

While the NAO role in the interannual modulation of the Saharan dust transport into the Mediterranean has been already highlighted [*Moulin et al.*, 1997; *Dayan et al.*, 2008], the contribution of the regional atmospheric circulation has been less studied. Therefore the aim of this work is to investigate the relationship between the circulation variability in the Mediterranean region and the Saharan dust transport. The spring (March to May, MAM) interannual variability in the period 1979-2005 is analyzed, with a specific emphasis given to the atmospheric variability driven by the Mediterranean Sea Surface Temperature (SST) anomalies.

2. Data and Methodology

The Mediterranean region is defined within the domain (10°W-40°E, 25°N-50°N). The dust load is estimated using the Aerosol Index (AI) measured by the NASA Total Ozone Mapping Spectrometer (TOMS) [*Torres et al.*, 2002], available form November 1978 to April 1993 (Nimbus-7 spacecraft) and from August 1996 to December 2005 (Earth Probe spacecraft). Owing to the data coverage, the MAM analysis is restricted to 1979-1992 and 1997-2005.

The atmospheric circulation is described through the wind field and the geopotential height at 700 hPa (W700 and Z700, respectively) extracted from the NCEP-DOE Reanalysis 2 dataset (R-2) [*Kanamitsu et al.*, 2002], and the SST is extracted from the NOAA Extended Reconstructed SST V3 dataset [*Smith et al.*, 2008]. The Saharan dust is observed over the Mediterranean up to 6-7 km altitude [*Alpert et al.*, 2004], therefore the 700 hPa pressure level (around 3 km altitude) is chosen to represent the bulk of the transport over the boundary layer. The dust extraction and lifting are related to the transit of low pressure systems accompanied by intense winds close to the surface, and the occurrence of these conditions is evaluated over North Africa and Middle East (20°W-50°E, 20°N-40°N) computing the stormtrack [*Harnik and Chang*, 2003] and the Potential Dust Uplift (PDU) over land [*Wiegand et al.*, 2011] using the R-2 meridional wind at 300 hPa and wind speed at 10 m, respectively. In the PDU computation, the 8 m/s wind speed threshold for the emission of desert dust [*Chomette et al.*, 1999] is set to 6 m/s, in order to take into account a possible R-2 underestimation of the wind speed over the North Africa seashore, similar to that reported by *Koren and Kaufaman* [2004] for NCEP Reanalysis (8-30%).

The atmospheric circulation variability is studied in a wide domain enclosing Europe, North Africa and Middle East (20°W-50°E, 20°N-55°N), through a Principal Component Analysis (PCA) [*von Storch and Zwiers*, 1999] of Z700, while the relationship between the SST and the atmospheric circulation is studied through a Maximum Covariance Analysis (MCA) [*von Storch and Zwiers*, 1999] of Z700 and Mediterranean SST. Then, the expansion coefficients (ECs) associated with the modes explaining the highest variance and covariance are linearly correlated to the variables associated with the dust extraction, lifting and transport. The statistical analysis is applied after the subtraction of any linear trend, in order to focus on the interannual variability.

3. Results

The main modes of the MAM atmospheric circulation variability are displayed in Fig. 1. The 1st PC, explaining 33% of the total variance, shows positive Z700 anomalies over western Europe and negative anomalies over Egypt and Middle East (Fig. 1a); while the 2nd PC (20% explained variance) shows a wide negative Z700 anomaly centered over Italy (Fig. 1b). The interannual modulation of the circulation anomaly patterns is described by the ECs time-series displayed in Fig. 1cd.

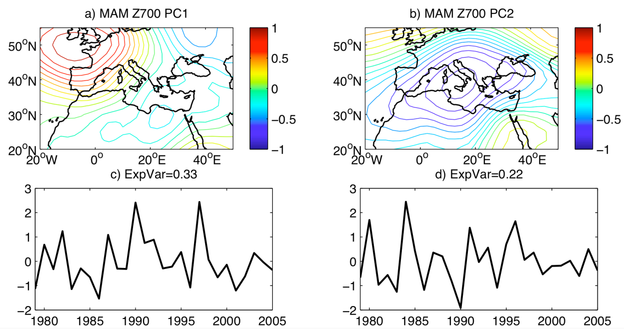

Figure 1
1979-2005 PCA applied to the Euro-African Z700, 1st (left panels) and 2nd (right panels) mode displayed through homogeneous correlation maps of the anomaly patterns (a,b) and associated ECs time-series (c,d).

The 1st PC anomaly pattern is positively correlated to a northeasterly W700 flow in the WM and negatively correlated to the AI in the central Mediterranean (Fig. 2a). It follows that negative (positive) AI anomalies in the central Mediterranean are associated with an anticyclonic (a cyclonic) anomaly over western Europe, favoring a northeasterly (southwesterly) flow crossing the WM. The storm activity shows significant correlations over the sea in the central-WM (Fig. 2c), and the PDU is significantly correlated over Turkey, while correlations over North Africa are not significant (Fig. 2e), indicating a weak link between the AI anomalies and potential dust sources in the Sahara desert.

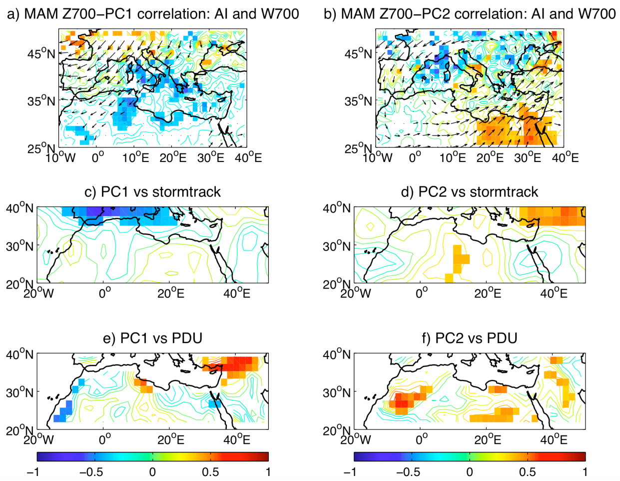

Figure 2
Linear correlations for the PCA ECs time-series, 1st mode (left panels) and 2nd mode (right panels): AI and W700 (a,b), stormtrack (c,d) and PDU (e,f); shadings and arrows are values 90% significant.

The 2nd PC anomaly pattern is positively correlated to a cyclonic circulation enclosing the entire Mediterranean region, with northeasterly and southwesterly W700 flows in the WM and EM, respectively, accompanied by negative AI correlations west of Italy and positive AI correlations over Egypt (Fig. 2b). The stormtrack shows positive correlations over Turkey and in the Libyan desert (Fig. 2d), the latter connected to positive PDU correlations (Fig. 2f), suggesting a possible dust extraction and lifting process in the Libyan desert and an eastward transport on the W700 anomalous flow towards Egypt.

The regional atmospheric circulation influence on the dust transport is further specified selecting that part of the variability related to the Mediterranean SST, through a SST-Z700 MCA. The 1st covariance mode, explaining 69% of the Squared Covariance Fraction (SCF), shows in the central-EM an extended negative Z700 anomaly (Fig. 3a) associated with cold SST anomalies (Fig. 3c). The 2nd mode (24% explained covariance) shows a Z700 anomaly dipole in the northwest-southeast direction, with low pressure over France and high pressure over Egypt (Fig. 3b), related to a SST anomaly dipole in the west-east direction, with warm anomalies in the EM and cold anomalies in the WM (Fig. 3d). The interannual evolution of the covariance patterns is related to the ECs time-series displayed in Fig. 3ef. In both the 1st and the 2nd mode the anomaly patterns are time-correlated over the 99% significance level (r = 0.72 and r = 0.76, respectively).

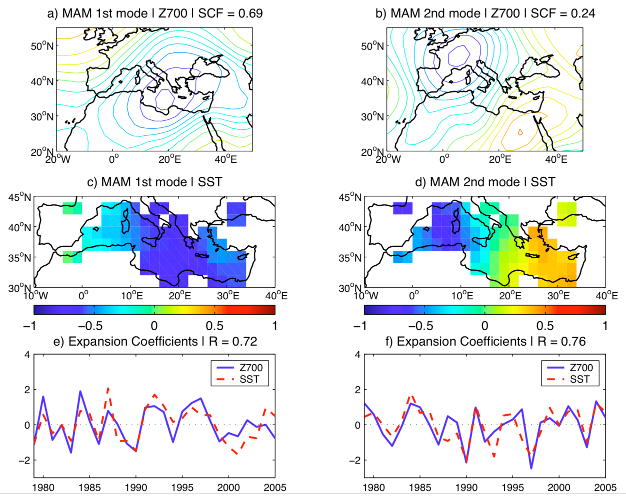

Figure 3
1979-2005 MCA applied to Mediterranean SST and Euro-African Z700, 1st (left panels) and 2nd (right panels) covariance mode displayed through heterogeneous correlation maps of the Z700 (a,b) and SST (c,d) anomaly patterns and associated ECs time-series (e,f).

Correlating the ECs time-series associated with the Z700 1st covariance mode to the AI and W700 fields, negative AI correlations over Italy, Balkans and Greece and positive correlations over Egypt are observed, accompanied by a cyclonic circulation centered over the central Mediterranean (Fig. 4a). The Z700 covariance pattern is positively correlated to the storm activity over Turkey and locally in the Libyan desert (Fig. 4c), and to the PDU in the eastern Sahara around 20°N (Fig. 4e), indicating possible dust extraction and lifting processes in the Libyan desert connected to the aerosol anomalies over Egypt through the westerly branch of the cyclonic anomaly.

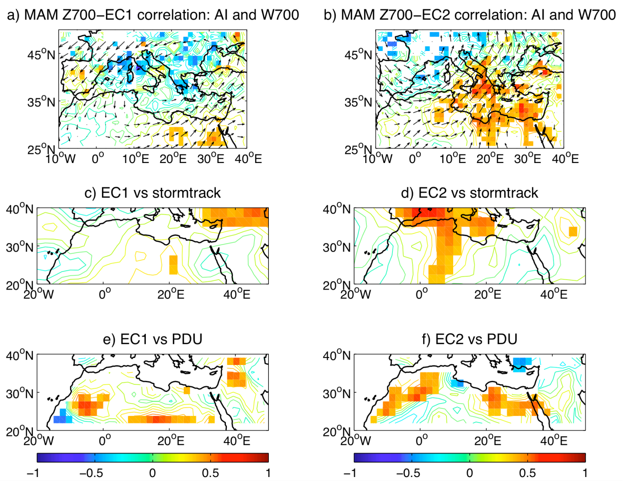

Figure 4
Linear correlations for the Z700-associated MCA ECs time-series, 1st mode (left panels) and 2nd mode (right panels): AI and W700 (a,b), stormtrack (c,d) and PDU (e,f); shadings and arrows are values 90% significant.

Considering the ECs associated with the Z700 2nd covariance mode, positive AI correlations are well organized in the central-EM, accompanied by southwesterly and southerly W700 flows originating over North Africa and crossing the Mediterranean (Fig. 4b). The Z700 covariance pattern is positively correlated to the stormtrack over western North Africa and central-WM (Fig. 4d), and close to the surface the PDU shows positive correlations over Algeria and Egypt (Fig. 4f). It results that positive AI anomalies in the central and EM can be explained as dust transported by the cross-Mediterranean flows from sources in Algeria and Egypt, where the dust mobilization can be associated with the enhanced cyclonic activity over western North Africa and central Mediterranean.

Comparing the PCA and MCA anomaly patterns, the similarity between the 1st and 2nd PCs and, respectively, the 2nd and 1st covariance modes are quite evident (Fig. 1 and 3), as well as the similarity between the correlation maps (Fig. 2 and 4). The more robust results obtained using the SST-Z700 MCA suggest a prominent role of the SST in modulating the dust transport into the Mediterranean. Specifically, the SST gradient in the zonal direction (Fig. 3d) is effective in displacing the Z700 and W700 anomalies in a configuration highly favorable to Saharan dust extraction and intrusion in the central-EM, with a cyclonic anomaly over the WM, a westerly flow over Morocco and Algeria and a high pressure anomaly over Egypt (Fig. 3 and 4, right panels). This configuration is consistent with that reported by *Moulin et al.* [1998] for the spring and early summer dust transport in the central-EM. This result is confirmed if the total SST variability is taken into account, as well. A detrended and standardized EM-AI is computed averaging the AI in the EM (15°E-35°E, 30°N-40°N), and a Mediterranean SST gradient index is defined as the SST detrended and standardized difference between the EM (15°E-35°E, 30°N-45°N) and WM (5°W-15°E, 30°N-45°N), then the correlation is computed, resulting positive and 90% significant (r = 0.37).

4. Conclusions

In this work the influence of the regional atmospheric circulation on the spring Saharan dust transport in the Mediterranean is investigated, focusing on the interannual variability in the period 1979-2005. Results show significant correlations between the AI variability in the central-EM and the stand-alone atmospheric variability in the Mediterranean region, although the association between aerosol anomalies and potential dust sources in North Africa is weak. On the contrary, a robust relationship between AI anomalies and Saharan dust transport is found when the atmospheric variability driven by the Mediterranean SST is considered. Specifically, positive aerosol load anomalies over Egypt are associated with a cyclonic circulation enclosing the entire Mediterranean, driven by cold SST anomalies, and positive aerosol load anomalies extend into the central-EM when the atmospheric circulation shows cyclonic anomalies in the WM and anticyclonic anomalies in the EM, driven by a positive EM-WM SST gradient.

The SST gradient contributes to the Mediterranean dust transport displacing the atmospheric circulation anomalies in a configuration highly favorable to the Saharan dust extraction and transport northwards. The mechanism explaining the central-EM aerosol load anomalies as dust transport can be depicted as follows: (1) the positive SST gradient enhances the storm activity over western North Africa and the penetration into central Mediterranean, favoring dust extraction in Algeria and Egypt; (2) the cross-Mediterranean flow, resulting from the circulation anomalies, transports the desert dust from the North Africa sources towards the central-EM.

This climatological picture is favorable to and consistent with the synoptic mechanism suggested by several authors for the dust origin and transport in the central-EM I spring, consisting in westerly depressions entering North Africa and mobilizing dust from Morocco to Libya [*Dayan et al.*, 1991; *Moulin et al.*, 1998]. In addition, the highlighted sizable role of the Mediterranean SST gradient in the modulation of the circulation and dust transport has a potential impact on the predictability of the spring seasonal dust load in the EM.

Acknowledgments

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NCEP R-2 and NOAA ERSST V3 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web-site at http://www.esrl.noaa.gov/psd/.

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