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Spatiotemporal patterns of Saharan dust outbreaks in the Mediterranean Basin

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ABSTRACT

Saharan dust outbreaks transport appreciable amounts of mineral particles into the atmosphere of the Mediterranean Basin. Atmospheric particulates have significant impacts on numerous atmospheric, climatic and biogeochemical processes. The recognition of background drivers, spatial and temporal variations of the amount of Saharan dust particles in the Mediterranean can lead to a better understanding of possible past and future environmental effects of atmospheric dust in the region.

For this study the daily NASA Total Ozone Mapping Spectrometer's and Ozone Monitoring Instrument's aerosol data (1979–2012) were employed to estimate atmospheric dust amount. Daily geopotential height, wind vector and meridional flow data of the distinguished dust events were obtained from the NCEP/NCAR Reanalysis to compile mean synoptic composite maps. In order to identify the typical dust transportation routes and possible source areas, the backward trajectories were plotted using the NOAA HYSPLIT model.

The main period of the dust transportation is from March to end of August, when the thermal convective activity forces the injection of particles to higher atmospheric levels. However, seasonality patterns of the different Mediterranean sub-basins show quite large differences. In western sub-basins, the maxima of Saharan dust outbreaks is in summer, related southwest flow between a southward emanating trough and the northward migrating subtropical high-pressure centre. In the eastern basin, dust storms occur typically in spring, generated by the warm sector winds on foreside of eastward moving Mediterranean and Sharav cyclones. The seasonal distribution of dust events in the central sub-basins shows a bimodal characteristic with a spring and summer peak.

1. Introduction

Atmospheric mineral dust particles are standing in the focal point of recent climatic and various environmental investigations (Stout et al., 2009). Studies of the last two decades recognised and confirmed that mineral dust has significant impacts on numerous atmospheric, climatic and biogeochemical processes (Harrison et al., 2001; Kohfeld and Tegen, 2007; Maher et al., 2010; Pósfai and Buseck, 2010; Shao et al., 2011). Tropospheric dust particles absorb, scatter and reflect the incoming solar and outgoing terrestrial radiation and modify the albedo of the surface, thereby exerting a direct influence on the energy budget (Arimoto, 2001). By acting as effective cloud condensation nuclei, input of tiny mineral particles into the atmosphere has an effect on life-time of clouds, influencing the radiation balance via an indirect way (Andreae and Rosenfeld, 2008; Klein et al., 2010). However, both direct and indirect effects of atmospheric dust on overall radiation budget remain uncertain, since it depends on its mineralogical, granulometric and related optical properties, atmospheric life-time, concentration and vertical distribution, mostly determined by the chemical composition of source area(s) and by the meteorological background of dust transportation.

Annually, 1–3 billions of tons mineral dust is emitted into the atmosphere from arid-semiarid areas and the most important source regions are situated in Northern Africa; Saharan and Sahel sources are responsible for 50–70% of the global dust emission (Tegen et al., 1996; Mahowald et al., 1999, 2006; Ginoux et al., 2001; Miller et al., 2004). These are unevenly distributed distinct dust hot-spot areas with various seasonal distribution and magnitude of emission, and with different geomorphological

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characteristics (e.g. ephemeral, salt and dry lakes, ephemeral streams and wadis, seasonal marshes, alluvial fans) (Middleton and Goudie, 2001; Prospero et al., 2002; Washington et al., 2003; Goudie and Middleton, 2006; Varga, 2012). At these places the deflation leads to severe soil erosion, loss and coarsening, and also to crop and natural vegetation damage.

Saharan dust can often be observed over the Atlantic Ocean, Mediterranean and Red Sea, and also in the atmosphere of distant areas (e.g. North and South America, Northern Europe). Typically, four main off-coast dust transportation routes can be distinguished: (1) westward transport of the Saharan Air Layer over the North Atlantic (Prospero, 1970; Prospero, 1996; Swap et al., 1992); (2) southward to Gulf of Guinea by the Harmattan (McTainsh and Walker 1982); (3) northward to Europe associated with different synoptic meteorological situations (Barkan et al., 2005; Engelstaedter et al., 2006; Stuut et al., 2009; Barkan and Alpert, 2010; Israelevich et al., 2012; Varga et al., 2013); and (4) eastward to the Middle East (Alpert and Ziv 1989).

The atmosphere of the Mediterranean Basin is highly influenced by dust emission of the surrounding desert areas that release the overwhelming majority of the total Mediterranean aerosols (Moulin et al., 1998; Gkikas et al., 2013). Obviously, the several hundred thousand tons of Saharan dust transported northward influence numerous constituents of environmental systems around the Mediterranean Sea. The increased dust concentration during heavy dust outbreaks often exceed $PM_{2.5}$ and PM_{10} standards of the European Union in Spain (Rodríguez et al., 2001), in Italy (Matassoni et al., 2011) and in Greece (Gerasopoulos et al., 2006), raise the levels of particulate matter in (ambient) air, and hence is able to affect human's health (Griffin et al., 2001; Pey et al., 2013; Morman and Plumlee, 2013). Further, the alkaline dust particles neutralize atmospheric acidity and reduce the frequency of acid rains (Roda et al., 1993; Rogora et al., 2004 and Špoler Čanić et al., 2009).

Iron- and phosphorus-rich particles, acting as fertilising agents have major impact on marine ecosystems, and through biogeochemical interactions, they affect the primary phytoplankton production and the carbon cycle (Ridgwell, 2002; Maher et al., 2010). Moreover, dust deposited in marine areas could trigger algal blooms (Guerzoni et al., 1999).

Saharan dust addition plays crucial role in the unique Mediterranean terra rossa formation too, where the chemical compounds of soils (e.g. silt sized quartz in limestone or basalt derived soils) can only be explained by some external, aeolian dust accretion as it was identified in Portugal (Jahn et al., 1991), in Spain (Muhs et al., 2010), in Italy (Jackson et al., 1982), in Croatia (Durn et al., 1999), in Greece (MacLeod, 1980), in Turkey (Atalay, 1997) and in Israel (Yaalon and Ganor, 1973; Yaalon, 1997). Small pulses and near-continuous dust addition to soil could affect the whole texture, individual horizons and the fertility by dust-derived nutrients and clay minerals (Simonson, 1995).

Dust activity of Saharan sources has been much more dominant during Pleistocene glacial periods, as it is inferred by the widespread aeolian dust deposits (loess, desert loess, loess-like deposits and marine sediments) of the investigation area with relevant Saharan contribution (Tsoar and Pye, 1987; Cremaschi, 1990; Rózycki, 1991; Moreno et al., 2002; Hoogakker et al., 2004; Larrasoaña et al., 2008; Újvári et al., 2012).

For all the mentioned reasons, a better understanding of background drivers of Saharan dust emissions towards the Mediterranean Sea is thought to be a crucial issue. This study is aimed at providing information on the seasonality, synoptic meteorology, transport pathways and source areas of Saharan dust in the atmosphere of different sub-basins of the Mediterranean Sea. In fact, the identification of synoptic meteorological patterns favouring to dust transportation could help to (1) forecast possible severe future dust intrusions; (2) provide analogies for reconstruction of past dusty events; and (3) validate results of global circulation and paleocirculation models.

2. Methods

For the appropriate monitoring of Saharan dust events, we applied the long-term daily aerosol measurements of NASA's Total Ozone Mapping Spectrometer (TOMS Version8) and Ozone Monitoring Instrument (OMI – Daily Level 3 Gridded Products; OMTO3d) – source: ftp://ftp.toms.gsfc.nasa.gov). The TOMS Aerosol Index (AI) and OMI'S TOMS-like (AI) are measures of how much the wavelength dependence of backscattered ultraviolet radiation from an atmosphere containing aerosols differs from a pure molecular atmosphere, as it was defined by the NASA/GSFC Ozone Processing Team, and given as

$$AI = 100 \times \left(log_{10} \frac{I_{360_{meas}}}{I_{331_{meas}}} - log_{10} \frac{I_{360_{calc}}}{I_{331_{calc}}} \right), \tag{1}$$

where I_{360_meas} and I_{331_meas} are the measured 360 nm and 331 nm radiance, and I_{360_calc} and I_{331_calc} are the calculated 360 nm and 331 nm radiance for a Rayleigh atmosphere (Herman et al., 1997; Torres et al., 1998). Positive values of AI indicate absorbing aerosols (dust, smoke from biomass burning), while negative values represent sulphates or sea-salt particles. Since Saharan dust transport into the Mediterranean is generally associated with high aerosol optical depth (Gkikas et al., 2009), higher AI values can rather be explained by dust episodes than sparse biomass burning events. TOMS and OMI TOMS-like AI measurement series were used by several previous studies to identify dust events and source areas (e.g. Prospero et al., 2002; Washington et al., 2003; Gao and Washington, 2009; Varga, 2012).

The sensors have been measuring the atmosphere's absorbing aerosol content since November 1978 on board of different sun-synchronous satellites (1978–1993 Nimbus-7; 1996–2004 Earth Probe; 2005–2012 Aura). As it was showed by Li et al. (2009), that OMI AI is a consistent continuation of TOMS AI of Nimbus-7 and Earth Probe, and according to spatial (Deroubaix et al., 2013) and temporal (Sreekanth and Kulkarni, 2013) correlation analyses, and regression analyses with other aerosol products (Ahn et al., 2008), the different AI records can be merged into one aerosol time-series. A 0.75 scale factor was used in the case of Earth Probe data series, as it was recommended by Hsu et al. (1999). Due to satellite failure (1993–1996) and calibration drift (2001–2004 some measurement series are failed to provide reliable information); even so TOMS and OMI TOMS-like AI has the longest available global record of atmospheric dust emission (Kiss et al., 2007). For the calculations, the 9490 (26×365) daily data-matrices of 1979–1993 (Nimbus-7), 1996–2000 (Earth Probe) and 2005–2012 (Aura OMI) data periods were analysed with MathWorks' MATLAB software, while the average monthly maps were processed in Golden Software SURFER 8. Difference between the resolution of TOMS AI ($1° \times 1.25°$) and OMI AI ($1° \times 1°$) was handled by kriging interpolation (re-gridding) and by aggregating the gridded data into grid clusters.

The extended investigation area is located between 31°N–43.5°N and 9°W–35°E, sorted into 136 grid clusters for episode identification, time-series and seasonality analyses. Based on the seasonality patterns and geographical distributions, five main Mediterranean sub-basins were distinguished (Fig. 1).

We identified days of Saharan dust intrusions by using the standardised AI values ($AI_{st} = (AI - AI_{mean})/\sigma_{AI}$), where AI_{mean} is the yearly regional mean AI, σ_{AI} is the standard deviation and $AI_{st} > 1$ values represent a dusty atmosphere (Barkan et al., 2005). In order to define the synoptic meteorological patterns leading to