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THE IMPACT OF AFRICAN DUST ON THE NORTHERN ADRIATIC

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ABSTRACT

Atmospheric input has a significant impact on the marine environment. African dust originating in the arid and semiarid regions of northwestern Africa is the major source of natural atmospheric particles over to Mediterranean. Therefore, the current understanding of the role and effects of dust inputs to the Mediterranean has been reviewed and possible influence of these eolian dust deposits to the northern Adriatic highlighted.

Key words: African (Saharan) dust, Mediterranean, northern Adriatic, atmospheric input

IMPATTO DELLA POLVERE AFRICANA SUL NORD ADRIATICO

SINTESI

L'input atmosferico ha un impatto importante sull'ambiente marino. La fonte maggiore di particelle atmosferiche naturali che raggiungono il Mediterraneo è la polvere africana che ha origine nelle regioni aride e semiaride dell'Africa nord-occidentale. L'articolo pertanto presenta un resoconto delle conoscenze attuali sul ruolo e sugli effetti degli input di polvere nel Mediterraneo, nonché mette in risalto la possibile influenza dei depositi di tale polvere eolica sul Nord Adriatico.

Parole chiave: polvere africana (Sahariana), Mediterraneo, Nord Adriatico, input atmosferico

INTRODUCTION

Atmosphere is an important route for transport of aeolian particles, natural and pollutant, to the coastal and open seas. Atmospheric aerosols and rainwaters consist of inorganic and organic anthropogenic and biogenic compounds related to several emissions (Guerzoni *et al.*, 1999a). These substances include mineral dust, plant residues, heavy metals, nitrogen species from combustion processes an fertilisers, pesticides, and wide range of synthetic organic compounds from industrial and domestic sources. Recently, there has been much interest in atmospheric inputs, especially Saharan dust, and their impact on marine biogeochemistry (Martin *et al.*, 1989; Jickells, 1999; Guerzoni *et al.*, 1999a), oceanic sedimentation and sediment (Loÿe-Pilot *et al.*, 1986; Molinaroli, 1996, Węgrzynek *et al.*, 1997), soils (Herrmann *et al.*, 1996), and climate (Andreae, 1996; Tegen *et al.*, 1996).

The aim of the present paper is to review recent studies about the characteristics of the African dust inputs to seawater, especially to the Mediterranean, and to highlight the possible effects of dust transport to the northern Adriatic.

GENERAL OVERVIEW

A number of dust sources exists in arid regions of Africa (North Africa, Sahara, Sahel) which are active all year, especially during the summer when they feed strong pulses of dust across the Mediterranean to Europe and the Middle East and across the Atlantic to Caribbean, Central and North America (Prospero, 1996). African dust is frequently deposited also in the Alps and the Balkans (Vukmirović *et al.*, 1999) and sometimes reaches Scotland and Scandinavia (Tomadin *et al.*, 1996; Hjelmroos, 1996). The impact of African dust could be indicated also from the composition of ice in glaciers (De Angelis & Gaudichet, 1991). Inputs of desert aerosol are often described as events of "red snow" and "red rain" (Prodi & Fea, 1979; Bücher *et al.*, 1983) or "yellow rain" (Vukmirović *et al.*, 1999). Instead of "African", the generic term "Saharan" is frequently used that mainly relates to the northwestern part of Africa. However, Africa is not the only source. Western and central China is a source of yellow dust, which can scatter across Japan and the Pacific Ocean, but fine particles can also travel as far as North America and even the Antarctic Circle. In the present text, however, the desert dust related to Africa will be discussed.

The dust episodes bring mainly inorganic particles dominated by quartz, calcite and clay and minor fraction of organic material, even such as exotic pollen (Hjelmroos, 1996). Additionally, "pulses" of Saharan dust seasonally carry large amounts of metals of natural origin (Guerzoni *et al.*, 1999b).

These aerosols are mainly produced by aeolian erosion occurring in arid or semiarid areas. The emission strength is highly sensitive to changes of some climatic parameters such as wind velocity and precipitation (Marticorena & Bergametti, 1995). During long range transport, aerosols are modified by a variety of physicochemical processes (Jickells, 1999) and once the dissolved and particulate atmospheric inputs reach the ocean they become subject to variety of biogeochemical processes. The amount of particles precipitated and the size and composition of the particles vary depending on transport distance, wind and place of origin of the material (Molinaroli & De Falco, 1995). The majority of dust emissions is sporadic, spatially heterogeneous and large scale-variable, therefore the assessment of their impacts is difficult and remote sensing is essential tool for its study. Atmospheric dust can be readily observed by satellite (Meteosat, Sea-viewing Wide field-of-view Senzor *i.e.* SeaWIFS, TOMS satellite imagery, OSEI, AVHRR...), so several studies of atmospheric transport and deposition of dust are based on satellite images (Dulac *et al.*, 1996; Moulin *et al.*, 1997a, 1997c, 1998). Furthermore, many model simulations of Saharan dust episode have been made (Marticorena & Bergametti, 1995, 1996; Marticorena *et al.*, 1997; Chiapello *et al.*, 1997; Giorgi, 1996; Schulz *et al.*, 1998). Surface observations and modelling data are available On line (AERONET, NRL Surface, NRL Model).

MAIN TOPICS IN STUDIES OF THE IMPACTS OF AFRICAN DUST

Dust science is on the rise (in the last two decades), so several environmental effects of long-range transport and input of African dust have been proposed by different studies.

Atmospheric aerosols are of climatic importance due to their optical properties to absorb and scatter solar radiation depending on their chemical composition (Li *et al.*, 1996; Tegen *et al.*, 1996). The indirect effect on climate is linked to the formation of cloud condensation nuclei (CNN) and consequently to the number of cloud droplets, which enhance short-wave albedo of clouds (Houghton *et al.*, 1995). Consequently, clouds become microphysically unstable which leads to effective rain production (Levin & Ganor, 1996). The connection between dust and increasing snow signal (http://www.rnw.nl/science/html/sahara010219.html) has also been reported. Additionally, some scientist theorize that increasing amounts of aeolian dust could keep the temperature down by decreasing the amount of sunlight (http://news.nationalgeographic.com/news/2000/07/0710_dust.html).

Dust events influence also the pH of rainfall (Loÿe-Pilot *et al.*, 1986) and because the particles are chemically alkaline some scientists suggest their importance in neutralising acid rain (http://news.nationalgeographic.com/news/2000/07/0710_dust.html).

Some studies suggest that Saharan dust may play an important role in determining the frequency and intensity of hurricanes formed in the eastern Atlantic ocean (http://www.thirdworld.org/role.html).

Atmospheric supply of African dust material to the ocean seems to play a central role in trace matter chemistry of seawater (Remoudaki *et al.*, 1991; Guerzoni *et al.*, 1997, 1999a; Jickells, 1999).

Several studies indicate a strong correlation between dust inputs and different biological response. Recently, there is increased interest in the deposition of mineral dust to the oceans because of aerosol iron (Carder *et al.*, 1991; Zhu *et al.*, 1997), which is believed to be an important limiting nutrient for phytoplankton growth. The role of iron delivered by Saharan dust and ecology of harmful algal blooms (red tides) has been studied and reported by Lenes *et al.* (2001). There is also evidence that dust provides essential nutrients for Amazonian rain forests (Swap *et al.*, 1992). Moreover, the demise of coral reefs in the Caribbean basin was also linked to African dust and it is also hypotesized that African dust may also contribute to the global rise in respiratory infections (http://newscientist.com/ns/19990703/newstora10.html).

DUST OVER THE MEDITERRANEAN

Sources and chemical characterization of African dust

Atmospheric input is especially important in shelf seas and semi-enclosed seas such as the Mediterranean (Martin *et al.*, 1989) and as several millions of tons of particulate matter are transported from north Africa to the Mediterranean countries the study of dust transport and impacts in the Mediterranean is receiving increasing attention. The Mediterranean Sea borders on its northern shore to the highly industrialised regions, which act as a continuous source of anthropogenic *i.e.* urban-rich material to the atmosphere, and on its southern and eastern shores to arid and desert regions, including the Sahara and the Middle Eastern deserts (Molinaroli & De Falco, 1995). The most productive African dust sources have been selected and defined by different authors (D'Almeida, 1986; Avila *et al.*, 1996). Saharan dust originating from north Africa is the major source of natural atmospheric particles over the Mediterranean (Molinaroli & Ibba, 1995), and Libyan desert has been indicated as a major source of dust over the eastern Mediterranean (Moulin *et al.*, 1998). These areas are acting as sources of crustal material, which is transported largely in the form of non-continuous, dust "pulses" (Chester *et al.*, 1997). The anthropogenic and desert materials are chemically very different, in particular with respect to their trace metal content (Guieu & Thomas, 1996). Typical crustal elements are Al, Si, K, Ca, Ti, Fe, Mn, Rb, Co, Ba, and elements such as S, Zn, Pb, Cu, Cd and Br are mainly associated with anthropogenic activity (Bonelli *et al.*, 1996; Frau *et al.*, 1996). These inputs significantly influence the mineralogical and chemical composition of Mediterranean aerosol (Molinaroli *et al.*, 1999). The detailed estimates of atmospheric inputs to the Mediterranean were reviewed by Guerzoni *et al.* (1999a).

In the material collected over the Mediterranean basin, a wide types of crust-derived minerals such as clay minerals, quartz, feldspars, micas, calcite, dolomite and hematite have been identified (Molinaroli, 1996). Despite different chemistry in all cases, quartz, calcite and clays are the major components and among them clay minerals could be used as "source tracer" (Tomadin *et al.*, 1996; Molinaroli, 1996). Palygroskite is characteristic dust mineral of the north-west African origin in the Western Mediterranean samples (Molinaroli & Ibba, 1995; Molinaroli, 1996) and in the Eastern Mediterranean was more frequently detected smectite (Molinaroli, 1996). Kaolinite, common in desert weathering regimes, is more abundant in dust originating from eastern compared to the western Sahara and the highest concentrations have been observed off the Egyptian coast (Guerzoni *et al.*, 1999a). Moreover, the comparison of the illite/kaolinite ratio in the African dust and sediment of the Mediterranean could be used for indication of the contribution of dust (from different sources) deposition (Guerzoni *et al.*, 1999a). Similar, titanium was also proposed to be a good tracer-element for dust events and also the Ti/Ca, Ti/Fe and Al/Si concentration ratios (Bonelli *et al.*, 1996). Backward trajectories have shown (Chiapello *et al.*, 1997) that the calcium amount and Si/Al ratio of the transported dust differs according to the source regions (Sahel, north/west Sahara, south/central Sahara), in relation to their respective soil compositions.

Transport and deposition to the Mediterranean

Major dust storms are highly episodic and the direction of transport is also seasonal. The dust event is associated with appropriate conditions to mobilise and transport it to high altitude to allow long-range transport and it is climatically controlled (Schutz *et al.*, 1990). Routes of Saharan dust were studied for the western and central Mediterranean (Ganor & Mamane, 1982; Molinaroli & Ibba, 1995; Bonelli *et al.*, 1996) and also for the Eastern Mediterranean (Prodi & Fea, 1979) by several authors. Annual cycle of dust transport in Mediterranean atmosphere, deduced from climatological results, begins in spring over the eastern basin, has a maximum in summer over the western and central basins, and strongly decreases during autumn and winter (Moulin *et al.*, 1998). Spring and early summer constitute the favourable period for the sharav cyclones that move eastward along the north African coast cross the Mediterranean towards the north between Tunisia and

Egypt. In summer, the Saharan depression is combined with the semipermanent ridge over Libya and the associated dust transport occurs over the western and central Mediterranean (Moulin *et al.*, 1997c). The Scirocco wind may transport desert-derived dust from north Africa across the Mediterranean to Sicily, Sardinia, and the Italian Peninsula where, on termination of winds by passage of cold fronts, the dust burden is deposited in the so called "red rains" (Molinaroli & Ibba, 1995). These events are frequently observed also in the northern Adriatic and its hinterland.

Global estimates of dust deposition to the Mediterranean Sea range from ~25 to ~100 Tg yr^{-1} (Prospero, 1996). The deposition of dust occurs whether as dry (*i.e.* not involving an atmospheric aqueous phase) or wet deposition (precipitation scavenging). Both depositions are quite frequent over the Mediterranean (Molinaroli, 1996). In general, the wet deposition controls the flux of Saharan dust to the Mediterranean Sea and can sometimes occur only with a few raindrops (Loÿe-Pilot & Martin, 1996). However, the dry deposition can also be important (Guerzoni *et al.*, 1997). The wind-blown dust transported to the Eastern Mediterranean is mainly deposited by dry deposition, while in the Western Mediterranean wet deposition is dominant (Molinaroli, 1996).

Recent work and main results

Mediterranean Dust Data Base (MDDB) has been designed as the final product of the European MEDUSE (Mediterranean DUSt Experiment) Project. It started off on March 1, 1996 (and ended on April 30, 1998), its overall objective being to develop and to implement a prototype system for routine monitoring and prediction of atmospheric transport of desert dust in the Mediterranean region. An overview of remote sensing studies of African dust in the Mediterranean region was presented

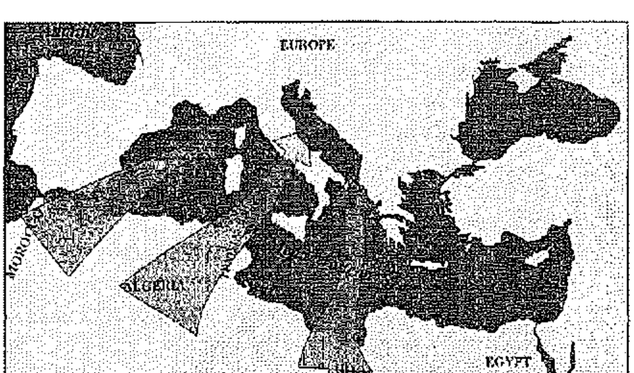

Fig. 1: Shematic trajectories of African dust input in western Mediterranean and Adriatic Sea.
Sl. 1: Shematski prikaz vnosa afriškega peska v Jadransko morje in zahodni del Sredozemskega morja.

by Dulac *et al.* (1997). Moreover, in 2001 the Mediterranean Israeli Dust Experiment (MEIDEX) was launched, its main objective being to investigate desert aerosol physical properties, transportation, and its effect on the energy balance and chemistry of the ambient atmosphere with possible applications to weather prediction and climate simulation (http://www.tau.ac.il/geophysics/MEIDEX/home.htm).

The most complete review of the impact of desert dust to the Mediterranean was presented by Guerzoni & Chester (1996) who had collected a number of papers given at the ADAM (The impact of African Dust Across the Mediterranean) conference held in Oristano, Sardinia, from 4-7 October 1995. However, most of the published studies on the atmospheric input of biogenic and anthropogenic compounds into the Mediterranean seawater were conducted in its western part (Bergametti *et al.*, 1989; Remoudaki *et al.*, 1991; Bergametti *et al.*, 1992; Carratalà *et al.*, 1996; Molinaroli *et al.*, 1999) and some studies were performed in the Eastern Mediterranean region (Levin & Ganor, 1996; Ganor & Foner, 1996; Mihalopoulos *et al.*, 1997; Herut *et al.*, 1999).

Dust inputs have a significant impact on the mineralogical composition of Mediterranean aerosol and on composition of the deep-sea sediments (Molinaroli, 1996). It was shown that the sources, the mineralogical composition, the trajectories of desert dusts as well as the sedimentation rate and the sedimentological properties of deep-sea sediments in the Western and Eastern Mediterranean are different (Molinaroli, 1996). There is strong evidence that atmospheric transport of trace elements related to African dust play a significant role on the geochemistry of the Mediterranean marine environment. Martin *et al.* (1989) reported that the atmospheric input of red dust is of the same order of magnitude as the annual downstream flow of rivers discharging to the Western Mediterranean and the atmospheric flux of Cu, Pb, and Cd exceeds river input by one to two orders of magnitude. The importance of mineral dust in influencing atmospheric and seawater (the distribution in the Mediterranean sea) concentrations of Mn (Remoudaki *et al.*, 1991; Guieu *et al.*, 1994), Fe (Bergametti *et al.*, 1989; Dulac *et al.*, 1996), Al (Dulac *et al.*, 1989; Guieu & Thomas, 1996), Cu (Remoudaki *et al.*, 1991; Chester *et al.*, 1996), Ti (Bonelli *et al.*, 1996), Pb, Zn (Chester *et al.*, 1996), Cd (Vukmirović *et al.*, 1999) and Zn, As *etc.* (Güllü *et al.*, 1996) have been also studied.

The major control on solubility of metals (Prospero *et al.*, 1987; Spokes *et al.*, 1994; Guerzoni *et al.*, 1999a) is thought to be the pH, governed by a balance between the acidic and neutralizing species present in precipitation. Rain waters coupled with air masses which had crossed Western Europe and had scavenged black particulate "urban-dominated" material from the air give rise to acidic rains. On the other hand, rain waters associated with air masses which had crossed North African sources, and which had scavenged red "crust-dominated" Saharan dust result in neutral to basic rains as a result of dissolution of calcium carbonate from the desert-derived aerosols (Chester *et al.*, 1997). Regarding the impact of dust on the rain acidity which effects rainwater chemistry, such as trace metal solubility and their further sea fluxes, several studies have been carried out in the Mediterranean (Loÿe-Pilot *et al.*, 1986; Loÿe-Pilot & Morelli, 1988; Chester *et al.*, 1996, 1997; Frau *et al.*, 1996, 1997; Carratalà *et al.*, 1996). Besides the trace metals, the strong SO_4^{2-} enrichment is widely observed in long-range transported Saharan dust. Deep ice core analyses (Wagenbach *et al.*, 1996) suggested that desert dust could pick up, transport and remove atmospheric sulphur and also contribute to natural SO_4^{2-} flux. That could be partly attributed to desert-derived gypsum (Loÿe-Pilot & Morelli, 1988). Dust usually also contains higher phosphorus concentration but solubility of inorganic phosphorus in seawater is lower. However, such dust events may still contribute to high amounts of phosphorus to the surface waters (Herut *et al.*, 1999) and in a highly stratified layer this source of phosphorus concentration would be more significant (Guerzoni *et al.*, 1999a). Bergametti *et al.* (1992) reported that in summer the atmospheric source of phosphorus concentration is dominant in the western Mediterranean, and that this input may account for new production. After the wet deposition of dust several blooms have been observed in the Mediterranean and in enclosed basins like the Black Sea (Saydam & Yilmaz, 1998; Saydam & Polat, 1999). Something similar, *i.e.* that such Saharan dust fallout may explain some summer algal blooms, was proposed by Dulac *et al.* (1996). Nevertheless, despite several observations of a biological response after dust storm, the causal relationship is not yet explained (Guerzoni *et al.*, 1999a). Saydam (1996) presented the most studied theory, known as Cemiliana hypothesis. He suggests that wet dust intrusion of iron supplied in marine environment from desert regions that has been photochemically reduced within cloud droplets to bioavailable Fe(II) oxidation stage resulted in phytoplankton bloom (Saydam, 1996; Saydam *et al.*, 1998). Hence, the relationship between atmospheric supply of iron to the sea surface and biological response was subject of various studies (Faust, 1994; Dulac *et al.*, 1996; Johnson *et al.*, 1997; Boyle, 1997).

IMPACT ON THE NORTHERN ADRIATIC

Atmospheric inputs of trace elements and potential pollutants have already been studied in the Adriatic (Guerzoni *et al.*, 1999a) and dust mineral signature in sediments in the Adriatic has also been reported (Molinaroli, 1996). On the contrary to the other part of the Mediterranean, only few studies on African dust have been made in the northern Adriatic. This is a shallow (mean depth 30 m), semi-enclosed marine basin characterized by limited water mass circulation and significantly higher productivity compared to the oligotrophic areas of the Mediterranean Sea (Pettine *et al.*, 1999). During the summer, when the current system is occasionally modified, the northern Adriatic becomes relatively isolated (closed circulation system prevails) from the remaining parts of the Adriatic Sea (Orlić, 1987). There is an important freshwater inflow, and because of its shallowness the northern Adriatic is subject to highly variable atmospheric forcing. According to the satellite data, Saharan dust reaches the northern Adriatic across the western Mediterranean (mainly over the Sardinia, Corsica and northern Italy or across the Sardinia and Sicily over middle of Italy) and across the Strait of Otranto along the entire Adriatic Sea (Figs. 1 & 2). Most of the desert dust transport over Adriatic seems to occur in early spring and summer. Previous studies indicate that the atmospheric contribution for total phosphorus and orthosilicate was relatively minor in the northern Adriatic (Deggobis & Gilmartin, 1990), but a more detailed study of the atmospheric particle matter input has not been carried out in this area. In their recent study, Giani *et al.* (2001) reported the importance of the downward flux of particulate organic matter in the shallow northern Adriatic basin for the sink and recycling of nutrients and oxygen consumption at the bottom. African dust probably plays a similar role in biogeochemical cycling (in water column and sediment) and in sedimentation of the particulate matter in the water column of northern Adriatic. The effect of such seasonal dust fallout, which bring nutrients (N, P, Ca, Si) and microelements such as Fe, is expected to be very important for the shallow northern Adriatic. The response of aquatic systems to additions of nutrients is generally an increase of algal biomass, which affects the species composition of phytoplankton assemblages (Conley *et al.*, 1993; Mozetič *et al.*, 1998). Although Saharan dust events exhibited lower inorganic phosphorus solubility in seawater, these episodes may still contribute high load phosphorous concentration to the surface waters according to their relatively high deposition raates and high total inorganic phosphorous concentrations (Herut *et al.*, 1999). In P-limited waters of the northern Adriatic (Chiaudani & Vighi, 1982; Maestrini *et al.*, 1997), particular dust event may cause an imbalance of N:P and trigger off a development of algal blooms. Moreover, the deposition of Saharan dust may alleviate iron limitation, which could be determinant for algal blooms, including harmful ones. Mineral dust particles may be also involved in scavenging and aggregation processes of organic matter or they can serve as substratum for plankton organisms.

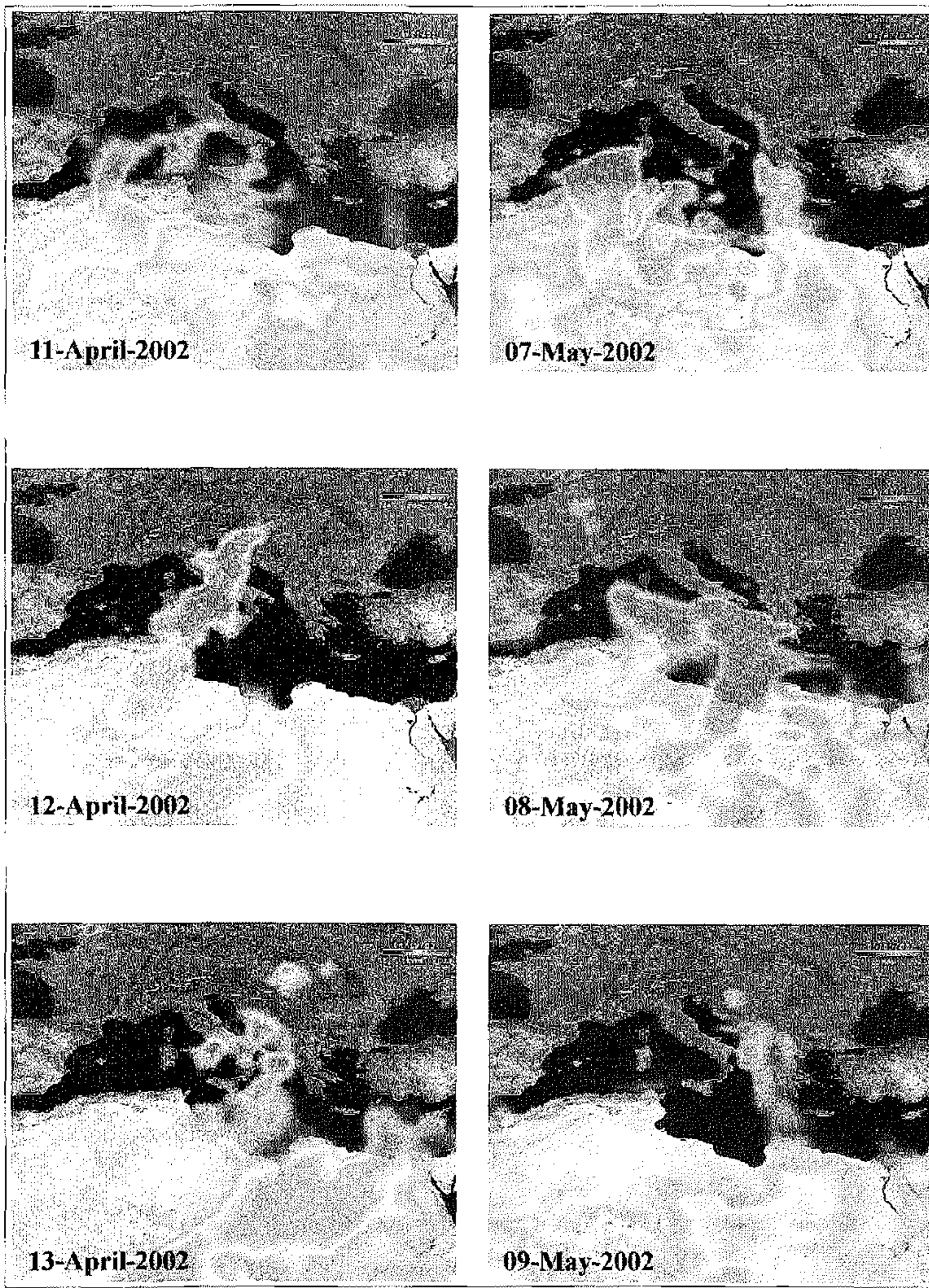

Fig. 2: Images from NASA's satellite based Total Ozone Mapping Spectrometer (TOMS) showing an African dust event over the Mediterranean and Adriatic Sea in April and May of 2002 (Photo courtesy Laboratory for Atmospheres TOMS Project, NASA Goddard Space Flight Center).

Sl. 2: Satelitski posnetki (Total Ozone Mapping Spectrometer - TOMS) vnosa afriškega peska v Sredozemsko in Jadransko morje v mesecu aprilu in maju 2002 (z dovoljenjem: Laboratory for Atmospheres TOMS Project, NASA Goddard Space Flight Center).

CONCLUSIONS

Bearing in mind, a) that atmospheric inputs of metals and nutrients to the Mediterranean appear to be of a similar magnitude to fluvial inputs and that atmospheric supply of several trace elements (total and dissolved input of these elements) and potential pollutants are very important for the Mediterranean and northern Adriatic (Guerzoni *et al.*, 1999a), b) that Saharan dust (containing minerals, nutrients, trace elements and pollutants) frequently reaches the northernmost part of the Mediterranean, c) the complexity of Adriatic (Cushman-Roisin *et al.*, 2000), and d) the lack of monitoring of African dust transport to the northern Adriatic, the future work is needed to provide basic information and estimation of atmospheric inputs.

In order to get more insight into the role of Saharan outbreaks in the northern Adriatic, a multidisciplinary research should be planned for the future in this area. Information such as dust transport (meteorology, mass trajectories), deposition and chemistry of supplied material are needed for better understanding of the impact and magnitude of dust inputs in biogeochemical cycles in the entire Adriatic, as well as in its sub basins (northern Adriatic, Gulf of Trieste).

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VPLIV VNOSA AFRIŠKEGA PESKA V SEVERNI JADRAN

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POVZETEK

Vnos snovi (naravnega in antropogenega izvora) preko atmosfere ima pomemben vpliv na morsko okolje. Glavni vir naravnih atmosferskih delcev, vnešenih v Mediteransko morje, je afriški pesek, pogosto imenovan "saharski", z izvorom v aridnih in semiaridnih območjih severozahodne Afrike. Prispevek podaja pregled dosedanjih raziskav vnosa afriškega peska v Mediteran in izpostavlja morebitno vlogo tovrstnih vnosov za severni Jadran.

Ključne besede: saharski (afriški) pesek, Mediteran, severni Jadran, atmosferski vnos

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