2.3. Saharan dust inputs to the Northeast Atlantic

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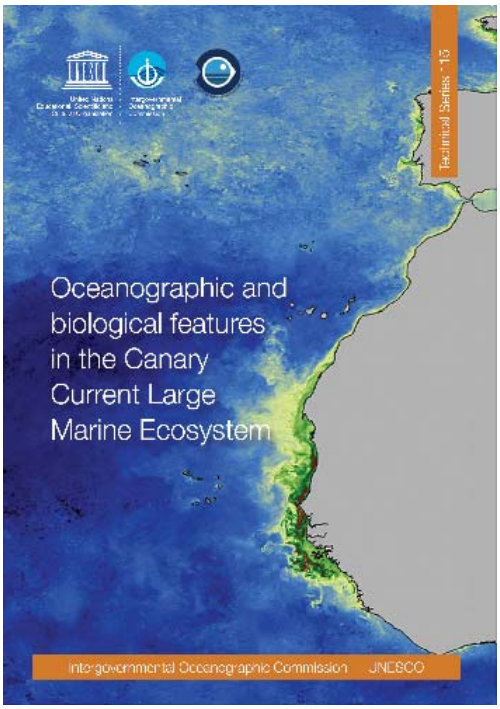

The report *Oceanographic and biological features in the Canary Current Large Marine Ecosystem* and its separate parts are available on-line at: http://www.unesco.org/new/en/ioc/ts115.

The bibliography of the entire publication is listed in alphabetical order on pages 351-379. The bibliography cited in this particular article was extracted from the full bibliography and is listed in alphabetical order at the end of this offprint, in unnumbered pages.

ABSTRACT
Mineral aerosol inputs to the Canary Current Large Marine Ecosystem (CCLME) are among the highest in the world, due to its proximity to the Sahara and Sahel deserts in Africa. North Africa accounts for approximately 55% of global dust emissions. An annual average deposition resulting from different models for the Northeast Atlantic ranges between 140 Tg yr^{-1} and 276 Tg yr^{-1}. Aerosol deposition is an important source of essential and limiting nutrients and trace metals (Fe, Co, Mn, Cu and Al) to the ocean, which may stimulate the autotrophic components (nitrogen fixation and diatoms). The impact of dust inputs on oceanic carbon uptake and climate is dependent on total dust deposition fluxes as well as the bioavailability of nutrients and metals in the dust. However, dust deposition measurements are very scarce in the CCLME region and there are very few sets of long-term measurements of aerosol concentrations, although such data is invaluable in quantifying atmospheric inputs to this important region. Moreover, these measurements are critical for constraining climate and biogeochemical models in the CCLME region, especially because the land use and the climate change could be increasing dust emissions from the African sources.

Keywords: Mineral aerosols · Dust deposition · Atmospheric transport · Dust variability · Biogeochemistry · Canary Current Large Marine Ecosystem · Northwest Africa

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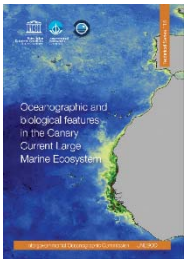

SAHARAN DUST INPUTS TO THE NORTHEAST ATLANTIC

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2.3.1. INTRODUCTION

African dust inputs have important effects on the climate, marine biogeochemistry and human health. Atmospheric deposition is estimated to provide 450 Tg yr^{-1} of dust to the oceans (Jickells et al., 2005). Almost half of this estimated global dust input is provided by the arid regions of the Sahara and Sahel deserts resulting in a westward flow of material over the North Atlantic Ocean (Schütz et al., 1981; d'Almeida, 1986; Harrison et al., 2001). Mineral aerosols play an important role in the climate on account of their direct effect on the radiation budget and indirect relationship with cloud microphysical properties (Arimoto, 2001; Forster et al., 2007). Atmospheric dust deposition is an important source of essential and limiting nutrients and metals to the ocean (Measures et al., 1986; Duce et al., 1991; Baker et al., 2003; Mills et al., 2004; Jickells et al., 2005) affecting the oceanic carbon uptake, phytoplankton growth and productivity. Recent reports also suggest that dust inputs may promote nitrogen fixation (Mills et al., 2004; Duarte et al., 2006; Moore et al., 2009), by providing iron and other trace metals.

Intense African dust intrusion episodes have both social and economic repercussions on the areas that are subject to them, particularly affecting agriculture, air traffic with the reduced visibility (Criado and Dorta, 2003; Griffin and Kellogg, 2004), and human health, since the inhalation of dust can aggravate respiratory diseases or contribute to triggering epidemics (Julià-Serdà et al., 2005; Thomson et al., 2006)

Atmospheric deposition of mineral dust supplies nutrients such as iron and other trace metals to the oceans. However, there are only a few limited datasets of direct measurements of dry and wet deposition flux in oceanic regions obtained during cruises (Duarte et al., 2006; Baker et al., 2013) or from collection sites located on islands (e.g. López-García et al., 2013). In addition, sediment trap studies show contradictory results concerning the impact of the dust on biogenic particles flux. Dust can act as ballast to enhance downward sediment rates (Francois et al., 2002). Moreover, the results from sediment traps could be influenced by mesoscale processes and lateral transport (relevant in the Eastern Boundary Upwelling System) variable in time, which makes it difficult to interpret the observations in the sediment traps. Lithogenic flux studies using sediment trap material have been carried out in the Canary Current Large Marine Ecosystem (CCLME) region (e.g. Neuer et al., 2004; Ratmeyer et al., 1999) in an attempt to link the atmospheric dust input with mineral composition and biogeochemical processes in the water column. The mineral assemblage of aerosol dust and deep-sea sediments reveals different source origins (e.g. Caquineau et al., 1998). Brust and Waniek (2010) have observed that the minerals (quartz, smectite, illite and palygorskite) present in the flux of lithogenic particles in sediment traps refer to a mixture of sources in the North African regions, predominantly northwestern African areas (Mauritania, Western Sahara and Morocco), showing seasonal and interannual variations. Quartz, feldspar, smectite, kaolinite, illite and palygorskite (silicates); calcite, Mg-calcite and dolomite (carbonates); magnetite, hematite and pirolusite (oxides); halite and gypsum (evaporites) are some of the minerals observed in the lithogenic material (e.g. Goudie and Middleton, 2001; Menéndez et al., 2007; Kandler et al., 2007, 2011; Engelbrecht et al., 2014). The mineral dust component in Cape Verde and the Canary Islands is dominated by silicates, kaolinite being

the dominant clay mineral in the aerosol from Cape Verde in comparison with the higher illite concentrations found in the Canary Islands (Kandler et al., 2007, 2011).

2.3.2. DATA SOURCES AND METHODS

The first long-term dust observations were made in the North Atlantic in 1965 in Barbados and in 1972 in Miami (Prospero et al., 1995; Prospero, 1999). In the Canary Islands, two observation sites have carried out dust measurements since 1987 at Izaña (Tenerife) (Prospero and Lamb, 2003) and since 1996 at Pico de la Gorra (Gran Canaria) (Torres-Padrón et al., 2002). The first long-term dust measurements in Cape Verde were carried out between 1991 and 1994 (Chiapello et al., 1995, 1997). In general, there are almost no direct measurements of dust deposition flux in the ocean (i.e. using automatic deposition collectors), apart from data collected during cruises (e.g. Duarte et al., 2006 in the subtropical Northeast Atlantic region) and at island sampling sites (Gelado-Caballero et al., 2005; Menéndez et al., 2007; López-García et al., 2013, in Gran Canaria). However, it is also possible to calculate dry deposition fluxes indirectly from atmospheric aerosol concentrations and estimated particle deposition velocities (Baker et al., 2010).

Aerosol remote sensing data has also been a valuable tool for locating the major dust sources and determining the variability of aerosol distribution and transport pathways (Herman et al., 1997; Prospero et al., 2002; Mahowald et al., 2003; Torres et al., 2002; Ginoux et al., 2012). Satellite data is used to detect sources, including small-scale structures (“hot spots”) that could substantially contribute to global dust emissions (Koren et al., 2006; Schepanski et al., 2007). Sources associated with small-scale features such as "hydrologic" (ephemeral and inland water bodies) and "anthropogenic" sources associated with some form of land use (agriculture) are still uncertain. The estimates of dust optical depth using the Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue algorithm have improved the detection of such dust sources. In addition, land-based remote sensing networks such as AERONET provide valuable information about Saharan dust outbreaks in the Northeast Atlantic region (NEA) region (Kaufman et al., 2005; Basart et al., 2009).

2.3.3. DUST OBSERVATIONS AND CLIMATOLOGY

2.3.3.1. Dust sources and emission

Mineral aerosols or desert dust are mainly soil particles suspended in the atmosphere by strong winds. Mineral aerosol production requires dry, non-vegetated and easily erodible soils (e.g. review by Mahowald et al., 2005). The major dust sources on a global scale are located in the arid regions of the Northern Hemisphere, extending from North Africa, the Middle East and Central and East Asia to China, grouped together as the “Dust belt" (Prospero and Lamb, 2003). The Sahara desert is considered by far the most active dust source in the world, although its contribution is confined to the Northern Hemisphere (Engelstaedter et al., 2006). Most of these dust sources are topographic depressions associated with deep alluvial deposits formed by intermittent flooding through the Pleistocene and Holocene (Prospero et al., 2002). Although many aspects of the global dust cycle are well known, the proportion in which different sources account for emissions is still uncertain on account of to the poor quantification of small-scale features (Table 2.3.1). Human interaction, especially attributable to intensive agriculture and deforestation, may account for 10%-50% of the total dust input. There is a wide range of estimates of the anthropogenic contribution to global dust emission: less than 10% (Tegen et al., 2004), 25% (Ginoux et al., 2012) or 50%

(Mahowald and Luo, 2003). For this reason, it would be necessary to establish the variations in anthropogenic dust sources because they are strongly dependent on climate variability.

Table 2.3.1. Estimates of mean annual dust emission for North Africa. The data compilation is based on the works of Goudie and Middleton (2001), Zender et al. (2004), Mahowald et al. (2005, 2010) and Huneeus et al. (2011) *The estimate is based on the sum of emissions from the individual source regions.

Reference	**Estimates for North Africa (Tg yr^{-1})**
Jaenicke (1979)	260
Schutz et al. (1981)	260
D'Almeida (1986)	630-710
Marticorena and Bergamatti (1995)	586-665
Prospero (1996)	170
Swap et al. (1992)	130-460
Callot et al. (2000)	760
Ozer (2001)	1600
Luo et al. (2003)	1114*
Ginoux et al. (2004)	1430
Miller et al. (2004)	479-589
Kaufman et al. (2005)	240 ± 80
Mahowald et al. (2010)	1367
Huneeus et al. (2011)	800

According to the most recent work of Ginoux et al. (2012), North Africa accounts for 55% of global dust emissions with only 8% being anthropogenic, mostly from the Sahel. This is a larger source of dust of an anthropogenic nature than previously estimated (e.g. Prospero et al., 2002).There is a clear separation between the natural dust sources in the Sahara and the anthropogenic dust in the southern Sahel.

The natural dust sources in North Africa include the major depressions (Bodélé and Qattara); large basins with sand seas (Erg of Bilma, Erg el Djouf, Grand Erg, and Libyan Desert); ephemeral lakes (Sebkhet te-n-Dgâmcha, Chott el Djerid, and Chott Melrhir); lakes in the Tiris Zemmour region; and the Nile River Basin. All of them are considered mainly natural sources. There are additional origins associated with ephemeral lakes: Chott el Hodna and Chott ech Chergui in the Atlas Mountains. Other smaller anthropogenic sources can be identified in coastal Morocco and Western Sahara, Tunisia, Libya and Egypt. The Western and Central Sahara and, to a lesser extent, the Sahel, are the sources of mineral dust transported to the Canary and Cape Verde Islands.

2.3.3.2. Transport

The aerosols generated on the African continent are transported across the Atlantic over long distances, even reaching areas of the Caribbean, Central America and South America, especially in the summer months (Figure 2.3.1). This fact was already described in Darwin's writings aboard the *Beagle* expedition (Darwin, 1846). The transport mechanisms of African dust are well understood (Prospero, 1999; Goudie and Middleton, 2001). There are large seasonal and spatial variations in mineral dust concentration over the Atlantic Ocean, greatly affected by the seasonal latitudinal shift of the Intertropical Convergence Zone (ITCZ).

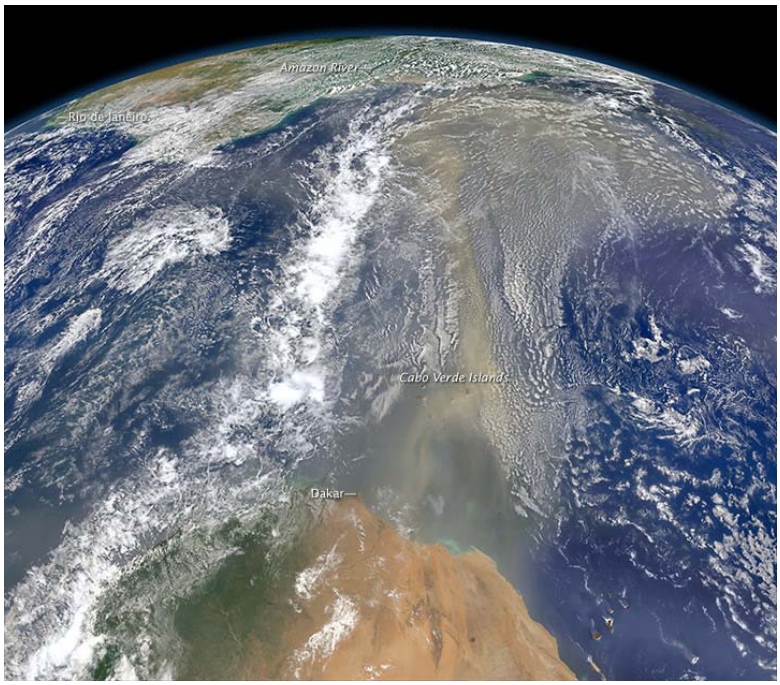

Figure 2.3.1. Dust heading west towards South America and the Gulf of Mexico on 25 June 2014. Visible Infrared Imaging Radiometer Suite (VIIRS) on Suomi NPP. NASA images by Norman Kuring, NASA's Ocean Color web.

During the summer, the ITCZ shifts northwards over the north-western part of the African continent (from approximately 5°N in winter to 19°N in summer), creating a thermal low over the surface of the African continent. This causes the North African high-pressure system to be located at higher altitude and consequently dust transport occurs high in the atmosphere within the so-called Saharan Air Layer (SAL). Dust transport is controlled by the African easterly jet and occurs between a height of 3 km and 6 km when the mineral dust layer is lifted above the Trade Wind Inversion layer (TWI) (Chiapello et al., 1995; Schepanski et al., 2009). The TWI restricts the vertical movements of mix between the Marine Boundary Layer (MBL) and the troposphere.

The MBL is limited by the base of the thermal inversion layer at altitudes that range between 500 m above sea level (a.s.l.) near the Azores High and 2000 m a.s.l. in the trade wind region close to the tropics. In subtropical regions, the upper limit of the marine boundary layer is usually bounded by the trade wind inversion layer. The TWI marks the boundary between the relatively cool and wet layer (MBL) and the relatively warm and dry layer located on the bottom of the free troposphere (Torres et al., 2001).

During winter, the ITCZ is located in its most southerly position and dust transport is controlled by high pressure systems located over the northern African continent. Mineral dust spreads over the NEA at relatively low altitudes, below 2 km height, and is injected mainly within the MBL (Kaufman et al., 2005; Díaz et al., 2006).

In the Canary Islands, the location of the TWI follows a seasonal pattern, occurring in summer between 770 m a.s.l. and 1380 m a.s.l. with an average thickness of about 560 m, while in winter the layer is found at higher altitude (1360 m a.s.l. to 1850 m a.s.l.) and with a reduced average thickness of about 360 m (Torres et al., 2001).

2.3.4. DISCUSSION

2.3.4.1. Dust distribution: spatial and temporal variability

In the NEA region, a strong seasonal variation of mineral aerosol concentration has been observed from the results of long-term sampling in the Canary and Cape Verde Islands. Similar mean atmospheric dust concentrations were measured at the island observation sites of Cape Verde (47.1 ± 55.5 μg m^{-3}) and the Canary Islands (45 ± 82 μg m^{-3}) in the CCLME. The highest mineral dust concentrations are registered during winter and early spring in the Canary Islands and during the late autumn and winter in Cape Verde (Gelado-Caballero et al., 2012; Fomba et al., 2014). This variability is mainly related to the influence of African air mass inflow in the lower atmospheric layer. The highest dust concentrations found in Cape Verde during the winter are strongly influenced by the Harmattan, a characteristic wind transporting Saharan dust at lower heights to the Atlantic Ocean. As a consequence of the seasonal pattern of dust transport, differences are found in the aerosol chemical composition between days with and those without dust events.

Long-term satellite data show a seasonal pattern similar to the *in situ* dust measurements. A mean seasonal pattern of emission and transport over the subtropical North Atlantic has been described by Ben-Ami et al. (2012), consisting of two strong dust seasons and one season with low dust loadings. During the first dust season (November-March), episodic dust events are originated in the Bodélé Depression and dust is transported southward and over West Africa and the Atlantic at ≈5°N. In the second dust season (May-September), the frequency of dust events is more uniform and emissions also have important contributions from the Bodélé Depression and Western Sahara (Figure 2.3.2). The dust plume advances northward to reach about 20°N. The third season with apparent low dust loadings (October-December) is not defined in the same manner according to the different satellite products. As has been mentioned before, island observations have clearly established dust transport towards Cape Verde during the late autumn and winter.

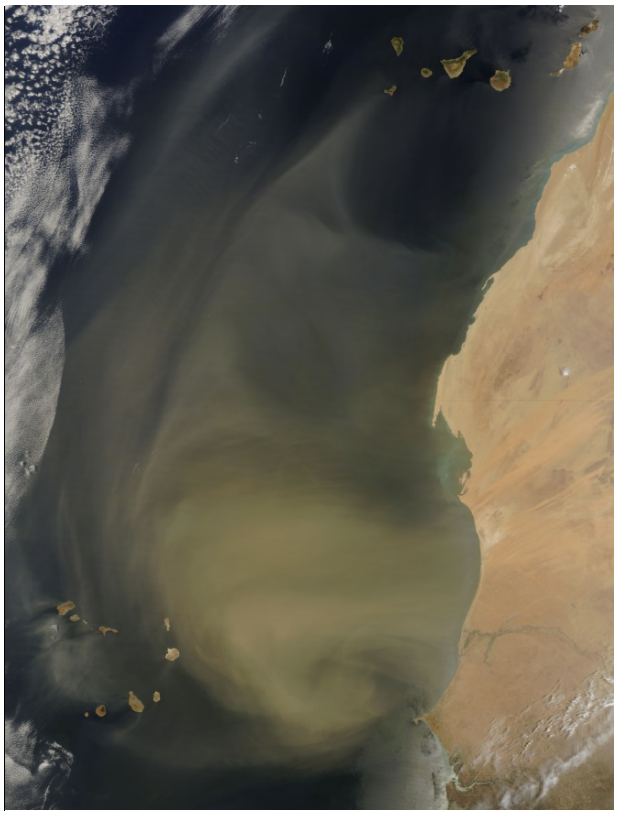

Figure 2.3.2. Dust plumes blew off the west coast of Africa on 9 May 2007. Moderate Resolution Imaging Spectroradiometer (MODIS) image from the Terra satellite (courtesy of Jeff Schmaltz, NASA Earth Observatory, using data from MODIS Land Rapid Response System, NASA Goddar Space Flight Center).

Dust deposition measurements are very scarce in the CCLME region. In the dust sources (i.e. Niger, Mali and Senegal) the dust deposition fluxes are very high, with values of the order of 100 g m^{-2} yr^{-1} (see Bergametti and Forêt, 2014). The deposition flux decreases with the distance from the dust sources. A long-term series of total deposition measurements carried out in Gran Canaria using surrogate surfaces has shown a dust deposition flux of 17 g m^{-2} yr^{-1} (Gelado-Caballero et al., 2012). Dry deposition dominated the particle flux, with wet deposition fluxes of around 10% of the total deposition flux. This deposition flux is consistent with estimates of an annual average deposition resulting from different models for the North Atlantic Basin which range between 140 Tg yr^{-1} and 254 Tg yr^{-1} (Table 2.3.2) (see Engelstaedter et al., 2006). Niedermeier et al. (2014) have estimated the deposition flux in Cape Verde applying five different methods, using meteorological and physical measurements, remote sensing and regional dust transport simulations, resulting in values ten times lower than those measured in the Canary Islands.

Table 2.3.2. Estimates of mean annual dust deposition to the global oceans (GO), North Atlantic Ocean (NAO). Duce et al. (1991) use a scavenging ratio (SR) of 1000 except for NAO (SR=200) whereas Prospero (1996) using the same model applied a SR of 200 globally. *Estimates are based on the sum of the individual ocean basins.

	Deposition (Tg yr^{-1})	
Reference	**GO**	**NAO**
Duce et al. (1991)	910	220
Prospero (1996)	358	220
Ginoux et al. (2001)	478*	184
Zender et al. (2003)	314	178
Luo et al. (2003)	428*	230
Ginoux et al. (2004)	505*	161
Tegen et al. (2004)	422	259
Kaufman et al. (2005)		140 ± 40
Jickells et al. (2005)	134*	202
Mahowald et al. (2010)	477*	276

2.3.4.2. Biogeochemical impacts of dust: nutrients supply

Because of the short residence time and a non-homogeneous spatial and temporal distribution of the dust sources, aerosols are distributed heterogeneously in the troposphere, with a maximum concentration near sources. More than 80% of the total mass of minerals contained in the mineral aerosols collected in Gran Canaria correspond to particles larger than 2.5 microns and contain aluminosilicates, feldspar, quartz, calcite and Fe-rich minerals such as hematite (López-García, 2012). Silicates such as illite, smectite, chloritoid, albite and plagioclase (Kandler et al., 2011) are dominant, accounting for about 60%-70% of the total mass of African mineral aerosols, while feldspars account for approximately 10%, which is a similar composition to that described for aerosols collected in Niger(Chou et al., 2008) and Morocco (Kandler et al., 2009). Calcite and iron-rich minerals are present in higher proportion in the mineral aerosol samples originating in North Africa than in the samples from the Sahel.

During transport, mineral aerosols undergo chemical and physical changes, especially due to cloud processes (i.e. condensation and evaporation), which may result in a substantial increase of dust solubility

and/or significant and relatively fast scavenging by rainfall (typically, in the span of one week). In addition, pH plays an important role in the control of solubility. Iron solubility kinetics for oxides and other minerals are very sensitive to pH variations (low pH increases the solubility). Probably the large variations in pH are related to the cloud processes (condensation and evaporation) around the dust particles. Dust particles can act as cloud condensation nuclei (CCN) and this interaction of dust particles with cloud water, or cloud processing, provides the main mechanism for uptake of acid gases in the atmosphere (Seinfeld and Pandis, 2006). Clouds can form and evaporate repeatedly (from 5 up to 10 times), before the dust is deposited on the ocean surface, and as the pH of the cloud changes in each of these condensation/evaporation processes, the dust particle can be substantially affected.

African mineral dust is relatively depleted in soluble P relative to other nutrients (soluble Fe and N) with respect to phytoplankton requirements for these elements. Measured soluble nutrient concentrations in the dust samples collected in the Canary Islands produced values of between 0.4-2.9 nmol m^{-3} phosphate and 21-64 nmol m^{-3} nitrate + nitrite, resulting in mean N:P, Fe:P and Fe:N ratios of 59, 1.4 and 0.03, respectively (Gelado-Caballero et al., 2012). In all samples the N:P, Fe:P and Fe:N ratios were significantly higher than the Redfield values. The relatively low abundance of P in atmospheric inputs appears to be related to the observed P limitation in the NE Subtropical Atlantic Ocean (Baker et al., 2003; Duarte et al., 2006).

Baker et al. (2013) have estimated total atmospheric input of Fe for the North Atlantic region using aerosol and rainwater samples collected during large-scale research cruises over two periods, April-June (AMJ) and September-November (SON). Soluble and Total Fe estimates were 0.032 and 0.76 Gmol (in AMJ) and 0.027 and 0.92 Gmol (in SON), respectively. The values are reasonably consistent with the results produced by Mahowald et al. (2009) from modelled mineral dust deposition and results from a regional dust transport model (Heinold et al., 2011) in the North Atlantic.

Ohde and Siegel (2010) have studied the biological response to coastal upwelling and dust deposition in the area off Northwest Africa around the Cape Verde Islands. Only six events of 57 strong storms were clearly related to an increase of chlorophyll-a caused by Saharan dust input and not by coastal upwelling processes, with a very small contribution (5%) to the variability of surface chlorophyll-a anomalies.

Increased rates of either primary or export production in response to fertilization by mineral dust input have not been clearly established in the eastern subtropical North Atlantic (Neuer et al., 2004). It has been suggested that iron delivered in dust is important to stimulate N_2 fixation which consequently raises N:P ratios above Redfield levels, making P the limiting nutrient for diazotrophs in the NEA region (Sohm et al., 2011). Although some studies have reported correlations between dissolved Fe concentrations and *Trichodesmium* abundance (Moore et al., 2009; Fernández et al., 2010), Agawin et al. (2013) did not find any correlation with N_2 fixation rates or with the abundance of *Trichodesmium* in the CCLME. Marañon et al. (2010) have suggested that the predominant type of metabolic response to enhanced dust fluxes depends on the ecosystem's degree of oligotrophy. Rubin et al. (2011) have reported that *Trichodesmium* colonies are able to trap dust particles and solubilize them to take advantage of the nutrients they might contain. The absence of a response in the N_2 fixation rates to dust inputs might be explained by the predominance of free trichomes over colonies in non stratified waters suggested by Benavides et al. (2011, 2013). As long as they are in this form, free trichomes would not be able to solubilize the particles and take advantage of the Fe contained in the dust.

2.3.4.3. Dust models

Regional or global dust models are used to obtain estimates of dust emissions, transport and deposition fluxes (reviews e.g. Tegen 2003; Mahowald et al., 2005). In the last few decades, aerosol modelling has improved their capacities (see for example Nickovic et al., 2001; Ginoux et al., 2004; Huneeus et al., 2011). Nevertheless, this modelling contains substantial uncertainties which may be related to the characteristics of the datasets used: ground-based and satellite remote sensing. Huneeus et al. (2011), comparing the results of 15 global models for the year 2000, found that dust deposition estimates present very large disparities among models, especially in their emissions. These dust models agreed within a factor of ten. This study emphasized the need for satellite observations to better characterize dust loads over source areas.

Using high-resolution data from MODIS Deep Blue in combination with other datasets including land use, Ginoux et al. (2012) have estimated that the anthropogenic dust sources account for 25% of global dust emissions. The study of these anthropogenic sources is essential, as it is estimated that the dust load may have doubled during the 20th century as a consequence of anthropogenic activities (Mahowald et al., 2010).

Despite the fact that the information provided by remote sensing is currently essential for understanding the dust cycle, given the sporadic and highly variable nature of dust inputs, long-term datasets are crucial in order to gain a further understanding of the composition and properties of African mineral dust as well as to constrain models of dust transport and deposition in the region. Accordingly, the sets of long-term measurements of aerosol concentrations over the NEA margin in Cape Verde and the Canary Islands, although discontinued, have established the daily, seasonal and interannual variations of dust concentration and the chemical characterization of aerosols over the NEA region (e.g. Patey, 2010; Gelado-Caballero et al., 2012).

There is a strong seasonal variation in aerosol components in the CCLME but mineral dust is mostly Saharan dust. According to regional dust models (e.g. Schepanski et al., 2009), the Sahara produces a larger amount of dust during summer, but the dust is transported at higher altitudes of up to 10 km within the SAL. In winter the dust is transported along the northeast trade winds at far lower altitudes. This transport pattern is consistent with the seasonal variability observed from *in situ* dust measurements in the region, with high atmospheric particle concentrations during winter. Air masses originating in the Sahel only represent around 10% of the dust events days in the Canary Islands and are observed mainly in the summer.

2.3.5. CONCLUSIONS AND RECOMMENDATIONS

There is a compelling need for long-term measurements to validate the models in the region and to identify the processes affecting dust emissions and transport and in order to understand the composition and properties of African mineral dust. Dust deposition is rarely measured directly and there are only a few sites located in the NE Subtropical Atlantic Ocean where long-term dust observations are carried out. More observations of nutrient deposition variability are needed for a better understanding of the ocean biogeochemistry and to be able to evaluate quantitatively the impact of dust on ocean productivity (Figure 2.3.3).

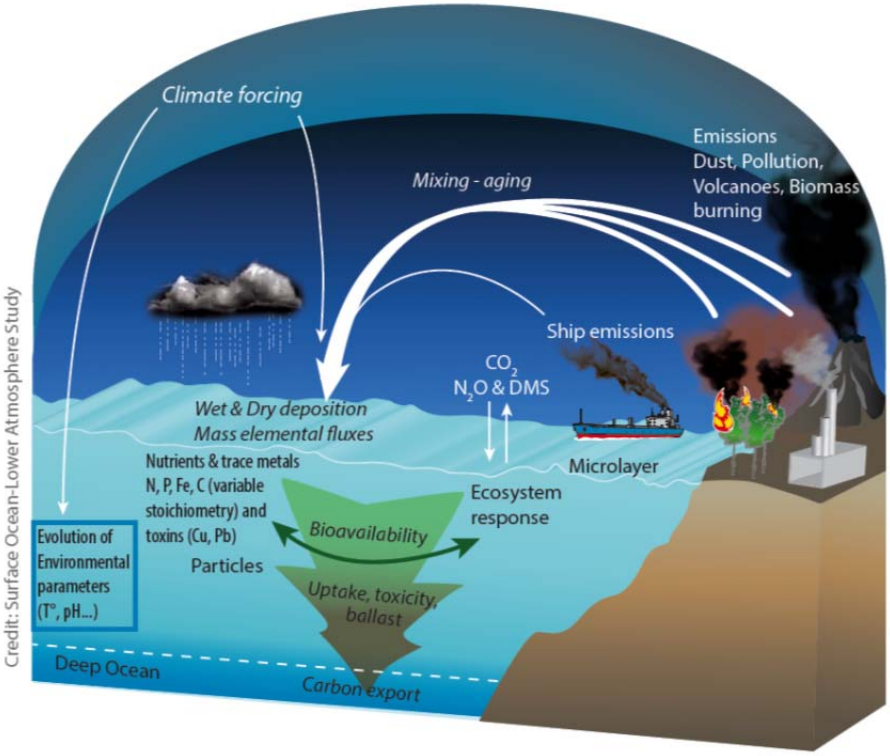

Figure 2.3.3. Conceptual diagram illustrating the main issues, processes and species relating to the SOLAS atmospheric nutrients strategy (Law et al., 2013).

Aerosol deposition is an important supply of macronutrients and trace metals (Fe, Co, Mn, Cu and Al) to the NE Subtropical Atlantic Ocean, which may stimulate the autotrophic components (nitrogen fixation and diatoms). A major effort is required to understand what fraction of these nutrients is bioavailable and what the different responses of phytoplankton communities are to the dust input. This is especially important to improve the estimates of dust impact on ocean biogeochemistry on a global and regional scale.

Human activities may be increasing atmospheric dust in the region as a consequence of land use and climate change. Change in dust deposition is likely to be strongly driven by the changes in precipitation, which alter soil particle structure. According to the projected precipitation, climate change may increase dust emission from dust sources. However, the projections for regions such as sub-Saharan Africa, which are known to be highly active sources today, are uncertain. In addition, an ever-growing demand for water resources for croplands, urban use and grazing may produce an increase of anthropogenic emissions associated with ephemeral water bodies. Dust models need to be improved to reduce uncertainties in dust source distribution and changes therein in response to human activities.

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