# Dust deposition pulses to the eastern subtropical North Atlantic gyre: Does ocean's biogeochemistry respond?

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[1] Enhancement of primary and export production following dust deposition pulses is well established for High Nutrient Low Chlorophyll regions, but the effect of atmospheric dust on the biogeochemistry of oligotrophic gyre regions remains unclear. Here we report atmospheric dust concentrations measured on Gran Canaria, Canary Islands, concomitantly with upper water biogeochemistry at the oligotrophic time series station ESTOC (European Station for Time series in the Ocean, Canary Islands) during a 2-year period from winter 1997 to 1999. ESTOC is located in the eastern subtropical Atlantic gyre about 100 km north of Gran Canaria and 500 km west of the Sahara, and receives aeolian dust episodically mainly in winter and summer. We found a close correlation of the magnitude of atmospheric dust concentration in winter with the magnitude of downward particle flux at ESTOC, mainly due to a relative increase in lithogenic matter and carbonate sedimentation. Higher aerosol concentration was not accompanied by higher primary or export production, however, indicating that phytoplankton production remained unaffected by atmospheric nitrogen supply on a seasonal or yearly timescale. However, by estimating bioavailable iron input and the need of the phytoplankton population, we found that the highly episodic dust pulses might exert a feast and famine effect on the phytoplankton. Despite the high lithogenic matter input, carbonate, mainly stemming from coccolithophorids, exceeded in importance the role of lithogenic matter as ballasting agent of sinking organic matter. *INDEX TERMS:* 4801 Oceanography: Biological and Chemical: Aerosols (0305); 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615); 4863 Oceanography: Biological and Chemical: Sedimentation; *KEYWORDS:* atmospheric dust deposition, particle flux, subtropical North Atlantic gyre, ESTOC, iron

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## 1. Introduction

[2] The Sahara desert is the main supplier of dust to the subtropical North Atlantic and Mediterranean with an estimated annual deposition of $220 \times 10^{12}$ g yr$^{-1}$ [*Duce and Tindale*, 1991] The dust plume can be traced year-round by satellite, and its maximum shifts from around 5°N in winter to around 20°N in summer, driven by the shift of the Intertropical Convergence Zone [*Moulin et al.*, 1997]. The Canary Islands region (28°N–29°N) is located on the northern margin of the main dust cloud and thus receives episodic pulses with peaks reaching the area mainly in winter and in summer/fall [*Pérez-Marrero et al.*, 2002; *Torres-Padrón et al.*, 2002]. The latter authors determined dust concentrations during 1997 and 1998 on the mountaintop of Gran Canaria Island (1980 m) and found considerable seasonal and interannual variability with concentration pulses exceeding 1000 μg m$^{-3}$. These pulses were brought about by Saharan dust storms that lasted a few days up to 1 week. The total yearly input of dust was estimated from 1 to $2.4 \times 10^6$ tons in the Canary Islands region (an $800 \times 100$ km$^2$ box ranging from 24°N to 30°N and 300 to 400 km offshore [*Ratmeyer et al.*, 1999a]), corresponding to about 1% of the total mass of dust advected westward from the Sahara [*Torres-Padrón et al.*, 2002; *Schütz*, 1980].

[3] The dust input in 1998 was considered unusual in that it delivered 30 g m$^{-2}$ yr$^{-1}$, the largest input since 1985 and a factor of 2.5 higher than the yearly input of 1997 [*Torres-Padrón*, 2000]. *Dong et al.* [2000] showed that the 1997–1999 ENSO cycle imposed strikingly different weather

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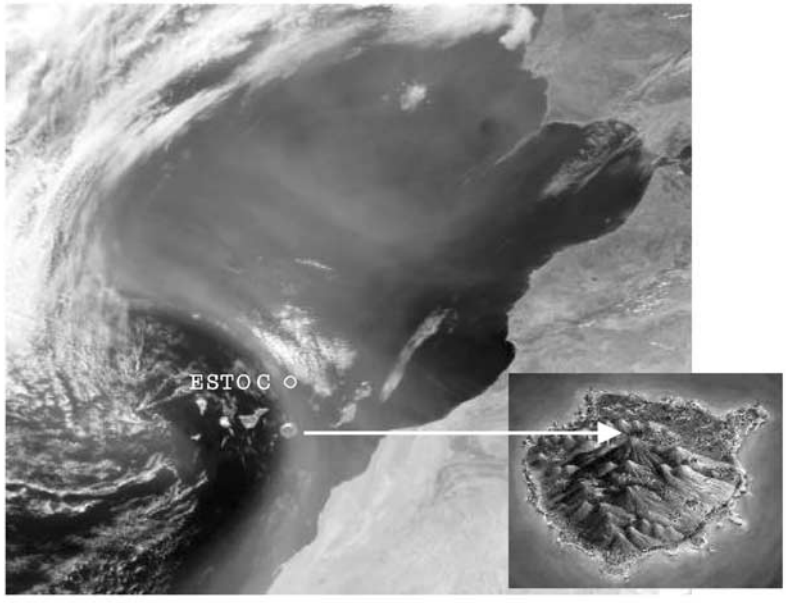


**Figure 1.** Location of time series station ESTOC 100 km north of Gran Canaria off northwest Africa and the "Pico de la Gorra" on Gran Canaria (insert) where the dust concentration measurements were carried out (1980 m above see surface). SeaWiFS image (courtesy NASA/Goddard) shows a large dust cloud advecting from the Sahara on 6 March 1998. See color version of this figure at back of this issue.

conditions over the North Atlantic. This large-scale climate fluctuation might influence the location and extent of the high-pressure system over the Sahara and southern Mediterranean that channels easterly, dust-laden winds from areas in the north-central regions of the Sahara [*Pérez-Marrero et al.*, 2002].

[4] The impact of atmospheric dust input on ocean biogeochemistry is thought to be twofold; it can provide nutrients for phytoplankton growth (both macronutrients and trace metals [e.g., *Jickells*, 1999; *Gao et al.*, 2003]), and it can accelerate or induce carbon sedimentation by adsorption, ballasting, and possibly aggregation of marine particles such as detritus or fecal pellets [*Ittekott*, 1993; *Hamm*, 2002; *Armstrong et al.*, 2002]. The close association of lithogenic matter and organic carbon in sinking particulates has commonly been observed [*Jickells et al.*, 1998; *Fischer and Wefer*, 1996; *Neuer et al.*, 1997; 2002a; *Ratmeyer et al.*, 1999a; *Fischer et al.*, 2004], and a general temporal coupling of atmospheric fluxes with particle sedimentation has been found in the Mediterranean [*Migon et al.*, 2002] and off Cape Blanc (northwest Africa [*Ratmeyer et al.*, 1999b; *Bory and Newton*, 2000; *Bory et al.*, 2002]). However, only in a few instances was the data resolution or availability appropriate to unequivocally show a clear response between dust input and upper water biogeochemistry [e.g., *Buat-Ménard et al.*, 1989; *Lenes et al.*, 2001; *Bishop et al.*, 2002]. In this study we investigate if pulsed dust inputs affect the biogeochemistry in the eastern subtropical North Atlantic gyre, by comparing a high-resolution, biannual data set of atmospheric dust concentration recorded on Gran Canaria, off the northwest coast of Africa, with concomitant surface water and particle flux data at the North Atlantic time series station ESTOC.

## 2. Methods

### 2.1. Dust Concentration

[5] Aerosol concentration was determined daily during 1997 and 1998 with five high-volume capture systems mounted on the "Pico de la Gorra," the highest mountain on Gran Canaria, Canary Islands (27°55′N, 16°25′W, 1980 m elevation, Figure 1). The material was collected on GF/A glass fiber filters (see *Torres-Padrón et al.* [2002] for details of the analysis). The island top was chosen as a collection site to avoid any anthropogenic contamination stemming from the island itself. Comparisons with satellite imagery in the region showed that atmospheric optical thickness at ESTOC covaried with the dust concentration measurements at the island top of Gran Canaria (R. Davenport et al., manuscript in preparation, 2004).

### 2.2. Water Column Measurements

[6] Particle flux was determined using AQUATEC 20-cup time series traps close to the ESTOC station (29°11′N, 15°27′W, water depth 3600 m) about 100 km north of Gran Canaria (Figure 1). For the time period overlapping with the dust measurements in the air, we show particle flux determined with the shallow traps of

**Table 1.** Mooring Data for Particle Traps Used for This Study

| | CI 7 | CI 8 | CI 10[a] |
|---|---|---|---|
| Collection period | 23 Dec. 1996 to 27 Sept. 1997 | 5 Oct. 1997 to 16 March 1998 | 3 Oct. 1998 to 23 Jan. 1999 |
| Collection interval, days | 14 | 9.5 | 19,[b] 9.5 |
| Trap depth, m | 500 | 330 | 640 |

[a]Corresponding depth of previous deployment CI9 is missing due to trap malfunction.
[b]First three cups.

three moorings (denomination CI7, 8 and 10 [*Neuer et al.*, 2002a]; see Table 1). Analysis of particulate matter is given in detail elsewhere [*Neuer et al.*, 2002a; *Fischer and Wefer*, 1991]; briefly, lithogenic matter was determined as the difference of total particle weight and opal (determined by automated wet leaching method [*Müller and Schneider*, 1993]), carbonate (determined as the difference of total carbon and acidified samples adjusted for molar equivalents), and organic matter (2 times particulate organic carbon).

[7] Hydrography and chlorophyll *a* were determined monthly or bimonthly at ESTOC (29°10′N, 15°30′W) with standard methods as described by *Neuer et al.* [2002a, 2002b]. Mixed layer depth was chosen as the depth where water column density $\sigma_t$ exceeded the surface value by 0.125 and standing stock of nitrate was determined by

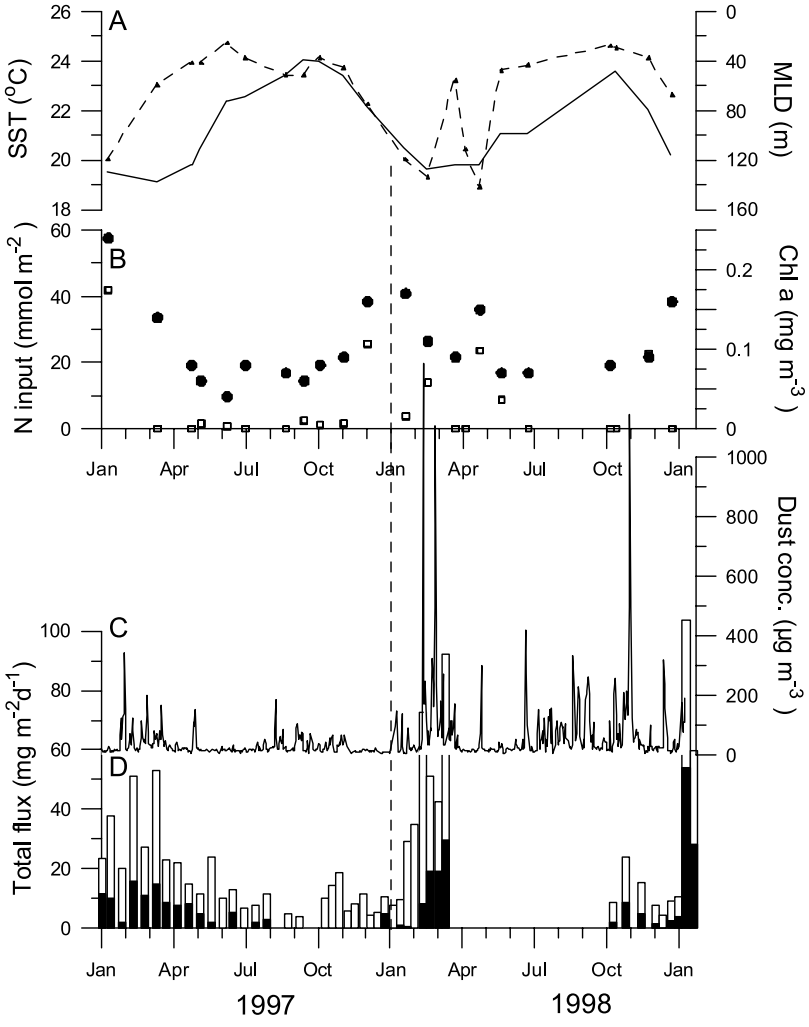


**Figure 2.** (a) Surface temperature (solid line) and mixed layer depth (dashed line); (b) nitrate input into mixed layer (open squares) and chlorophyll concentration (10 m, solid circles); (c) dust concentration in the air; and (d) total and lithogenic (solid bars) particle flux. All data were determined concomitantly; Figures 2a and 2b data are from monthly sampling at ESTOC; Figure 2c data are from high-volume capture systems located on Gran Canaria, and Figure 2d data are from particle traps moored at ESTOC.

integration of measurable nitrate (measured by applying standard colorimetric techniques) in the mixed layer [*Neuer et al.*, 2002b]. For primary production, a bio-optical model was applied to surface chlorophyll and surface temperature determined on the monthly sampling cruises, assuming 50% cloud cover [*Davenport et al.*, 2002].

## 3. Results

### 3.1. Aerosol Concentration and Particle Flux

[8] Particle flux at ESTOC was distinctly seasonal with flux peaks following the phytoplankton (chlorophyll) maximum in the winters of 1997–1999 (Figures 2b and 2d). Phytoplankton maxima coincided with the convective winter mixing that reached to about 150 m, coincident with a cooling of the SST (Figure 2a). Winter mixing typically results in an input of new nitrogen into the mixed layer; this was measurable during both winters at ESTOC (Figure 2b). Monthly hydrography for January 1999 is not available until 31 January 1999; thus we cannot resolve the hydrographical situation preceding the particle peak beginning of January 1999. However, both station data (S. Neuer et al., manuscript in preparation, 2004) and SeaWiFS data of the winter of 1999 [*Davenport et al.*, 2002] show that chlorophyll *a* concentration in the surface did not reach values higher than 0.18 mg $m^{-3}$ before the large observed particle flux peak occurred between 4 and 13 January.

[9] As shown previously by *Torres-Padrón et al.* [2002], atmospheric dust concentration peaks episodically in the Canary Islands region and highest dust concentrations are most prevalent in winter and summer/fall. The interannual variability between the two years is considerable, with dust concentration peaks in 1998 exceeding those of 1997 by more than a factor of 3. Also notable is the high dust concentration that was measured during the end of October/beginning of November 1998, which was accompanied by high precipitation (R. Davenport et al., manuscript in preparation, 2004). Dust measurements are available until 7 January 1999; owing to intense precipitation, the high volume samplers could not measure a large dust input on 8 January 1999. Analyses of filtered snow and rain samples collected on 8 January 1999, after the Saharan input, revealed dust fluxes of 160 mg $m^{-2}$ $d^{-1}$ which, converted to atmospheric concentration (by assuming a settling rate of 1.4 cm $s^{-1}$ [*Torres-Padrón et al.*, 2002]) was included as final data point in the dust data series shown in Figure 2c. The atmospheric dust measurements had to be terminated shortly after the weather-induced hiatus, due to construction at the site.

### 3.2. Particle Composition

[10] Lithogenic matter flux was largest in absolute values as well as relative contribution during the winter particle flux maxima, and higher during the winter of 1998 than during the preceding year. Lithogenic matter sedimentation reached values of 10–15 mg $m^{-2}$ $d^{-1}$ (30% of total, winter 1997) and 20–30 mg $m^{-2}$ $d^{-1}$ (38–45% of total, winter 1998). The maximum of lithogenic matter flux during the observation period was 54 mg $m^{-2}$ $d^{-1}$ in January 1999, constituting 52% of total particle flux (Figure 2d).

[11] Overall average lithogenic matter sedimentation was 10 mg $m^{-2}$ $d^{-1}$, which is about 1.5 times higher than lithogenic matter fluxes found at approximately the same latitude but 300–500 nautical miles farther west in the subtropical North Atlantic gyre [*Jickells et al.*, 1996], and twice the average of about 5 mg $m^{-2}$ $d^{-1}$ found by *Jickells et al.* [1998] in the Sargasso Sea. In contrast, the lithogenic fluxes at ESTOC are about 5 times lower than average values found farther south at a mesotrophic station off Mauritania, below the main Saharan dust cloud [*Bory and Newton*, 2000].

[12] Carbonate sedimentation, mainly derived from coccolithophorids [*Abrantes et al.*, 2002], was the other major constituent of the sinking particulate matter (Figure 3). Its flux maxima reached highest values of 27 mg $m^{-2}$ $d^{-1}$ (50% of total; February and March 1997), 51 mg $m^{-2}$ $d^{-1}$ (70% of total, March 1998) and 39 mg $m^{-2}$ $d^{-1}$ (38% of total, January 1999).

[13] The contribution of opal, indicative of the sedimentation of diatoms, was much smaller than that of lithogenic matter and carbonate, and fluctuated markedly (Figure 3). With a contribution of usually less than 1 mg $m^{-2}$ $d^{-1}$, there were some peaks around or slightly above 2.5 mg $m^{-2}$ $d^{-1}$ (early March 1997, corresponding to 5.5% of total particle flux) and 1.6 mg $m^{-2}$ $d^{-1}$ (February and March 1998, around 2% of total particles), and in January 1999, 2.4 mg $m^{-2}$ $d^{-1}$ contributing 2.3% to total particles.

[14] The results of the biogenic components are in agreement with data on the total phytoplankton community. *Abrantes et al.* [2002] showed a dominance of coccolithophorids in the nanophytoplankton and microphytoplankton community during all seasons, ranging from 64% (July 1998) in summer to 93% in winter (January 1997), and diatoms varying between 2% in January 1997 and a maximum of 28% in April 1997.

## 4. Discussion

### 4.1. Association of Particle Flux and Atmospheric Dust Concentration

[15] In general, two different patterns can be observed when comparing particle flux at ESTOC with aerosol concentration. First, there is a concomitant seasonal variability, with highest fluxes in the water column coinciding with the timing of largest dust concentration in the air. Secondly, within the 2-year observation period, we observed an interannual variability, with the large dust peaks during 1998 coinciding with the higher particle flux during the same period.

[16] Overlapping seasonality and interannual variability per se does not imply a causal relationship. Only if a biogeochemical response can be identified directly following a pulsed aeolic input could a causal link be inferred [e.g., *Bishop et al.*, 2002]. The monthly water column data at ESTOC do not offer sufficient resolution, but the highly resolved atmospheric dust concentrations as well as the concomitant particle flux measurements afford such a comparison within the timescales of a trap collection interval. To investigate if there was a pattern between particle fluxes and atmospheric dust, we integrated aerosol concentration over

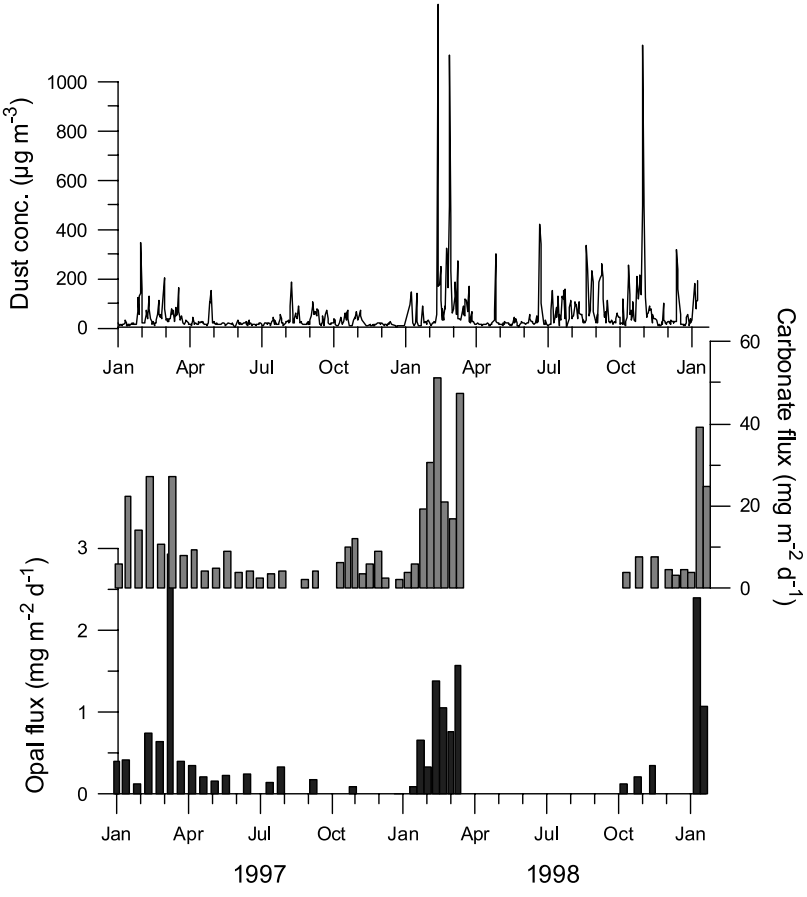


**Figure 3.** (bottom) Opal and (middle) carbonate fluxes at ESTOC from January 1997 until January 1999. (top) Atmospheric dust concentration during the same time period.

the same time interval as particle fluxes. We found that in winter and spring of 1997, particle flux peaks followed dust deposition peaks by one trap collection interval (Figure 4). This delay was also observed in winter of 1998 (with one exception). In fall of 1997 and 1998, peaks overlapped with no lag. In summer 1997 and in one instance in December 1998, the atmospheric concentration peaks were not associated with any particle flux peaks. Assuming that the observed peak associations are not coincidental, we will investigate two hypotheses that might explain the observed coupling: first, the potential fertilization effect of Saharan dust, and second, the potential aggregation/ballasting effect of lithogenic matter.

### 4.2. Potential Fertilization Effect of Saharan Dust

[17] Potential nutrient input of atmospheric aerosols is a function of provenance, distance from the source at time of deposition, and aerosol modification by atmospheric chemistry. Aerosol concentrations and bioavailability has been investigated chiefly for iron, the biologically most important element associated with dust [cf. *Jickells*, 1995, 1999], especially with respect to the limiting effect on nitrate drawdown in open ocean High Nutrient-Low Chlorophyll (HNLC) regions [e.g., *Martin et al.*, 1994] as well as in coastal waters such as the central California upwelling region [*Hutchins and Bruland*, 1998; *Firme et al.*, 2003]. In the Gulf of Alaska, a typical HNLC region, *Bishop et al.* [2002] could link an Asian dust storm to a subsequent increase in water column POC, observed robotically. The proximity of ESTOC to the Sahara and the complete depletion of nitrate in surface waters do not point to iron limitation of phytoplankton production. Also, in the absence of notable nitrogen fixation at ESTOC [*Neuer et al.*, 2002b], we do not expect a preferential stimulation of nitrogen fixers by dust-derived iron as has been observed for example on the West Florida Shelf [*Lenes et al.*, 2001]. However, given the very episodic nature of dust deposition to the ESTOC area, it is necessary to compare the rates of aeolic iron deposition and average need of the phytoplankton community to evaluate if there could occur a supply shortage. In Table 2 we compare seasonal deposition of dust and total and soluble iron (using data from the literature regarding iron content and range of solubility) with the range of assimilated iron derived from integrated primary production and a range of molar Fe:C values. The highest deposition periods occurred in winter and summer (1997) and in winter and fall (1998), integrated deposition in winter 1998 was more than twice that in 1997, and, in fall 1998, more than 6 times the value of the same period in 1997. The yearly range of total Fe deposition of 0.4 and 1 g $m^{-2}$ $yr^{-1}$

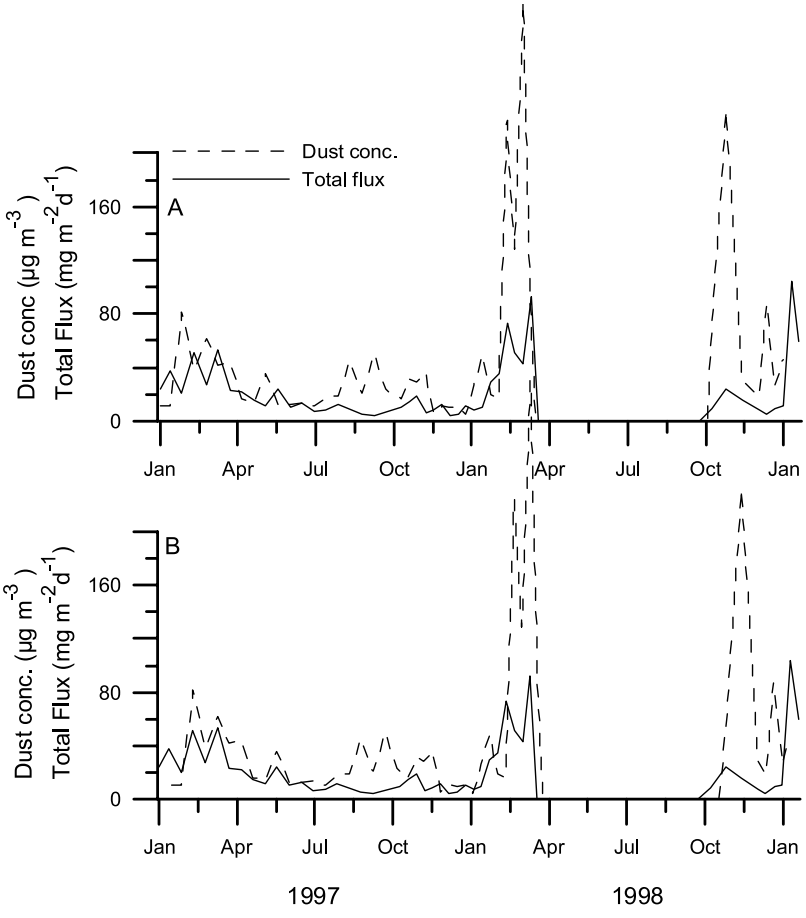


**Figure 4.** (a) Daily dust concentration averaged over duration of trap collection interval and total particle flux at ESTOC (values plotted at mid-interval). (b) Same as Figure 4a, but average dust concentration was plotted with a delay of one collection interval.

(corresponding to 6.8 to 18.4 mmol Fe $m^{-2}yr^{-1}$) was in the range of estimates shown by *Duce and Tindale* [1991] of 0.1 to 1 g $m^{-2}$ $yr^{-1}$ for the area, but the atmospheric iron deposition was more than 10–35 times the mean value used by *Fung et al.* [2000] for total iron deposition in the northern subtropical Atlantic (about 0.5 mmol Fe $m^{-2}$ $yr^{-1}$). This discrepancy shows that there is a need to distinguish between the eastern, more dust influenced, and western, less "dusty" subtropical Atlantic when calculating basin wide estimates of iron supply.

[18] The iron demand of the phytoplankton is determined by the cell Fe:C ratio which is quite variable (varies with species, cell size, light adaptation, preferred nitrogen source, and growth rate), and is a function of the ambient concentration of chelated iron [*Sunda and Huntsman*, 1995, 1997]. We used a mean Fe:C ratio of 10 μmol Fe per mol C which was used by *Coale et al.* [1996] for the equatorial Pacific iron fertilization experiment, and a range of 4 to 20 μmol Fe per mol C which was determined by *Sunda and Huntsman* [1997] for a variety of species, growth rates, and light intensities. Comparing the range of seasonal iron demand based on the measured primary production at ESTOC with the range of soluble (and thus bioavailable) iron [*Fung et al.*, 2000], it becomes clear that the fraction of supplied to assimilated iron varies considerably (Table 2). In seasons of low iron deposition (such as in spring and fall 1997) and high cellular demand for iron, the iron need of the phytoplankton community may not be covered by atmospheric iron. Using the mean $Fe/C_{cell}$ ratio of 10 μmol Fe per mol C and assuming a 1% solubility, the phytoplankton community in spring and fall 1997 would have to satisfy about 60–70% of its iron demand by regenerated or external sources. It is interesting to note that during the winter and spring 1997, particle flux peaks had the most consistent lag phase with dust deposition (Figure 4), pointing to a possible biological response. In contrast, the soluble iron supply was abundant during all seasons (but spring) in 1998, and far exceeded the iron need of the primary producers. This comparison points to the importance of seasonal and interannual differences in iron supply to the eastern subtropical gyre, and the concomitant feast and famine situation to which the phytoplankton is exposed, despite of the overall abundance of dust deposition.

[19] Input of organic or inorganic nitrogen species into the upper ocean by dust is not well documented but may be important, considering the large dust flux emanating from the Sahara into the nitrogen-depleted subtropical North Atlantic gyre. *Eglinton et al.* [2002] determined a mean

**Table 2.** Seasonal Aeolian Dust and Iron Deposition and Total Fe Assimilation by the Phytoplankton

| Season[a] | Deposition | | | Primary Production, mol C $m^{-2}$ | Iron Assimilated,[e] μmol Fe $m^{-2}$ | Fraction of Supplied/ Assimilated Iron[f] |
|---|---|---|---|---|---|---|
| | Dust,[b] g $m^{-2}$ | Fe,[c] mg $m^{-2}$ | $Fe_{sol}$,[d] μmol $m^{-2}$ | | | |
| | | | *1997* | | | |
| Winter | 4.7 | 163.7 | 29.3–293 | 3.1 | 30.9, 12.4–70.9 | 0.9 |
| Spring | 1.7 | 58.6 | 10.5–105 | 2.8 | 28.4, 11.3–44.5 | 0.4 |
| Summer | 3.0 | 105.5 | 18.9–189 | 2.8 | 27.6, 11.0–30.9 | 0.7 |
| Fall | 1.4 | 50.4 | 9.0–90 | 2.6 | 25.8, 10.3–56.8 | 0.3 |
| **Sum, $yr^{-1}$** | **11** | **378** | **68–677** | **11** | **113, 45–203** | **0.6** |
| | | | *1998* | | | |
| Winter | 10.4 | 364.27 | 65.2–652 | 3.0 | 29.9, 12.0–35.5 | 2.2 |
| Spring | 2.9 | 99.91 | 17.9–179 | 3.3 | 33.4, 13.4–43.4 | 0.5 |
| Summer | 7.5 | 263.77 | 47.2–472 | 2.9 | 28.8, 11.5–59.0 | 1.6 |
| Fall | 8.6 | 301.60 | 54.0–540 | 2.4 | 24.4, 9.8–53.6 | 2.2 |
| **Sum, $yr^{-1}$** | **29** | **1030** | **184–1844** | **12** | **116, 47–191** | **1.6** |

[a]Seasons: Winter, 1 January to 31 March; Spring, 1 April to 30 June; Summer, 1 July to 30 September; Fall, 1 October to 31 December.
[b]Dry deposition velocity: 1.4 cm $s^{-1}$ [*Torres-Padrón et al.*, 2002].
[c]Fe-content of 3.5% WT [*Duce*, 1986].
[d]Soluble iron, assuming a solubility index range of 1–10% [*Fung et al.*, 2000].
[e]Fe:C-ratio 10 μmol/mol, range 4–22 μmol/mol [*Sunda and Huntsman*, 1995, 1997].
[f]For Fe:C-ratio 10 μmol/mol and 1% solubility index.

value of total organic carbon (TOC) on a buoy dustfall sample off northwest Africa (about 18°N, 600 km off the coast, collected between October 1992 and June 1993) of 1%, and a $C_{org}/N_{tot}$ value of 11.45. These values are in good agreement with those determined by *Lavik* [2001]; samples collected on ship-borne filters during a north-south transect of RV *Meteor* along the northwest African coast between February and March 1998 of 0.7 wt% TOC and a mean C/N of 18 (value for a dust sample collected at 30°N latitude). Considering the range of dust deposition of 11 and 29 g $m^{-2}$ $yr^{-1}$ with a total nitrogen content of 0.05%, the maximal N-input by dust would range between 0.4 and 1 mM N $m^{-2}$ $yr^{-1}$, a range that is confirmed by preliminary short-term (≤6 hours) $NO_3$ + $NO_2$ dissolution experiments of a dust sample suspended in seawater. In addition, for the Canary Islands we estimate a wet deposition of about 0.7 mmol $m^{-2}$ $yr^{-1}$ from a total of 140 L $m^{-2}$ $yr^{-1}$of rain [*Torres-Padrón et al.*, 2002] and a fixed nitrogen concentration of 5 μmol N $L^{-1}$ (G. Lavik, personal communication, 2003). Thus, compared to a new production of approximately 30 mmol N $m^{-2}$ $yr^{-1}$ at ESTOC [*Neuer et al.*, 2002b], dust-derived nitrogen deposition (wet and dry) amounts to 4–6% of the new nitrogen need in the Canary Islands region on an annual basis. The small overall importance of new nitrogen input at this location is furthermore supported by the similarity of water column chlorophyll or primary production (Figure 2, Table 3) in winter periods 1997 and 1998, despite the more than twofold enhanced dust input in winter 1998. In fact, organic carbon sedimentation normalized to 150 m was almost identical for the two winter periods (Table 3).

[20] In contrast to winter periods, which receive nitrate by convective overturn, the aeolic inputs might be of higher importance during summer and fall, when mixed layer depth is shallow (Figure 2a). Pulsed supplies such as the one in fall 1998 (30 October 1998, 1383 mg $m^{-2}$ $d^{-1}$ for 1.4 cm $s^{-1}$ settling velocity) would supply around 50 μmol N $m^{-2}$ $d^{-1}$, which is in fact close to a value determined by *Baker et al.* [2003] off northwest Africa at 30°N in October 2001 (approximately 30 μmol N $m^{-2}$ $d^{-1}$). New production during this time period corresponds to about 500 μmol N (determined from average daily organic carbon export and a C:N ratio of 6, and normalized to 150 m depth); thus about 10% of the new nitrogen need would be supplied by dry nitrogen deposition. It is possible that the peak coincidence observed in October 1998 was influenced by this enhancement of new production.

[21] Considering future scenarios of enhanced anthropogenic pollution and nitrogen loading of the dust at these latitudes [e.g., *Watson*, 1997], especially for winds with North African or southern European provenance [cf. *Baker et al.*, 2003], the aeolic fertilization effect might become more important in coming decades. Significant fertilization of phytoplankton production was observed off Great Britain [*Spokes et al.*, 2000] with winds stemming from northern Europe.

### 4.3. Potential Ballasting Effect of Lithogenic Matter

[22] Because of the small grain size of Saharan dust arriving in the Canary Islands region (0.6–5 μm [*Torres-*

**Table 3.** Comparison of Primary Production, Aeolian Dust Deposition, and Particle Sedimentation Integrated for Winter (January–March) of 1997 and 1998 (g $m^{-2}$)

| | 1997 | 1998 |
|---|---|---|
| Aeolian dust deposition[a] | 4.7 | 10.4 |
| Primary production | 37 | 36 |
| Trap fluxes | | |
| Corg[b] | 0.73 | 0.76 |
| Lithogenic matter | 0.94 | 1.4 |
| Carbonate | 1.6 | 2.3 |
| Opal | 0.08 | 0.07 |

[a]Assuming deposition velocity of 1.4 cm $s^{-1}$ [*Torres-Padrón et al.*, 2002].
[b]Organic carbon sedimentation, normalized to 150 m [*Martin et al.*, 1987] (open ocean composite).

*Padrón et al.*, 2002]), lithogenic matter will only sink when packaged in larger particles such as aggregates or fecal pellets. Fecal pellets were previously identified as important vehicles of particle sedimentation at ESTOC [*Fischer et al.*, 1996] and are known to efficiently transport lithogenic matter to deeper depths [e.g., *Buat-Ménard et al.*, 1989]. However, considering the importance of carbonate as a constituent of sinking particles in our study, this mineral is likely equally important as a ballasting agent [cf., *Klaas and Archer*, 2002]. To elucidate the importance of carbonate and lithogenic matter as ballast of POC sedimentation, we integrated and compared organic and mineral particle flux for both winter periods in 1997 and 1998, during which aeolic dust deposition was markedly different (Table 3). During the winter period of 1998, dust deposition was higher by a factor of 2.5 compared to 1997 (for a deposition velocity of 1.4 cm $s^{-1}$ [*Torres-Padrón et al.*, 2002]), but lithogenic matter sedimentation was only higher by a factor of 1.5 (Table 3). During peak lithogenic sedimentation fluxes in the winters of 1997 and 1998, maximum weight ratios of terrigenous matter to organic carbon (Lith/Corg) was in the range of 6–7; the highest ratio observed occurred in January 1999 with 12.9 (trap CI10; see also Figure 3).

[23] In contrast, carbonate sedimentation was higher by a factor of 1.7 and 1.6 than lithogenic matter sedimentation in winter of 1997 and 1998 (Table 3). Maximum carbonate to organic carbon weight ratios during peak flux events in both winters ranged from 7 to 9, and thus were usually greater than the Lith/Corg ratio. Considering the similar density of carbonate and quartz, it is apparent that despite the high lithogenic matter loading of the sinking particulate matter, carbonate is the dominant ballast mineral for organic carbon sedimentation in this region [cf. *Fischer et al.*, in press]. It is curious that the carbonate loading of sinking organic matter is highest during times when lithogenic matter flux is also at its peak. The fact that the higher aeolic matter deposition in winter 1998 also caused a higher carbonate sedimentation, by a factor of 1.4 (see also Figure 3), similar to the enhancement of lithogenic matter (despite almost identical organic carbon export) might indicate a higher biological susceptibility of coccolithophorids to dust-induced fertilization compared to other phytoplankton.

### 4.4. Role of Fecal Pellets

[24] The importance of fecal pellets in particle sedimentation stresses the role of higher trophic levels in the timing of particle flux peaks and sedimentation of ballast minerals. Despite a lack of data on the seasonality of zooplankton in the area, most likely their abundance will be higher during or immediately following the wintertime phytoplankton maximum or maxima. The close association of fecal pellet flux following dust deposition has been observed in the Mediterranean [*Buat-Ménard et al.*, 1989], and has been invoked by *Bory and Newton* [2000] for the tropical eastern North Atlantic. Zooplankton abundance and fecal pellet production will respond to increases in primary production, even buffering fluctuations of ambient phytoplankton biomass [cf. *Donaghay et al.*, 1991]. This trophic response, which acts on timescales of 1–2 weeks [*Buat-Ménard et al.*, 1989] might explain the close association of particle flux with atmospheric dust concentration found in winter (Figure 4), when organic matter in the water column is high and the zooplankton population can readily respond to increases in primary production. The unusually large and early sedimentation pulse of January 1999, containing the highest lithogenic matter sedimentation found during the observation period, might have been caused by fecal material that settled suspended lithogenic particles remnant of the dust storms that had occurred during preceding weeks.

### 4.5. Discrepancy of Atmospheric Input and Lithogenic Matter Sedimentation

[25] Only about 13% (1998) to 20% (1997) of atmospheric dust input was collected by the shallow sediment traps when comparing the integrated fluxes of winter 1997 and 1998 (Table 3). This discrepancy might be partly offset by possible undertrapping of shallow particle traps (but see *Neuer et al.* [2002a]) and/or an overestimation in the deposition velocity used to calculate dust deposition. Considering a potential error due to an overestimation of deposition velocity (e.g., 1 cm $s^{-1}$ instead of 1.4 cm $s^{-1}$) or undertrapping (e.g., 25%), the ratio of lithogenic matter to atmospheric dust deposition would in this case increase to 36% (1997) and 24% (1998). Thus a large fraction of the terrestrial matter is not removed by particle sedimentation, remains in the water column, and likely is advected southward in the Canary current. The waters to the north experience less dust input as they are farther removed from the main Saharan dust cloud [e.g., *Duce and Tindale*, 1991], so the southward advection of the surface water masses would cause a net export of suspended dust from the area. Interestingly, *Bory et al.* [2002] find that farther south off Mauretania (~20°N) trap fluxes were a factor of 2–3 times larger than mean atmospheric dust input. The authors explain this by advective input of dust-laden water from the east, closer to the source regions of aeolic Saharan dust. Thus, whether an area acts as a source or sink of advected dust is a function of the suspended dust load of the water advected into a region relative to the dust input at the site itself and the removal efficiency of the local biological community (i.e., strength of the biological pump).

## 5. Concluding Remarks

[26] ESTOC is an important reference station for studies relating atmospheric dust deposition with particle sedimentation in the eastern subtropical Atlantic as it lies immediately downwind of the Sahara. In contrast to other locations farther south in the main dust plume, ESTOC receives dust mainly episodically in winter and summer. The present data set included 2 years that differed in dust deposition and allowed us to investigate if episodic dust pulses had an effect on the local oceanic biogeochemistry. We found that in addition to the general seasonal coincidence of dust input and particle flux maxima in winter/spring, there was an association of dust deposition and flux maxima in both winter periods on shorter timescales. From calculations of nutrient input and plankton community needs, we conclude that on a yearly scale, nitrogen fertilization by the dust is

small, especially during wintertime when deep convection supports new production. We found, however, that nitrate deposition by the dust might be significant during the strongly stratified late summer-fall period when aeolic deposition is high. Because of the episodic nature of dust deposition, stimulation of the phytoplankton in winter by iron input is possible and might explain some of the temporal coupling of particle flux and maxima of atmospheric dust. This hypothesis needs to be tested with data on the bioavailability of iron and the actual iron need of the phytoplankton population during each season. The comparison of carbonate and lithogenic matter as ballasting agents shows that because of the dominance of calcite in the sinking particles, the importance of lithogenic matter as ballasting agent is secondary in the eastern subtropical North Atlantic gyre. Thus we show preliminary evidence that there is a biogeochemical response to dust deposition, if only by some nutrient stress relief. Obviously, more temporally resolved data are needed, such as continuous recordings of upper water column nutrient and plankton concentrations and remotely operated high-resolution particle traps.

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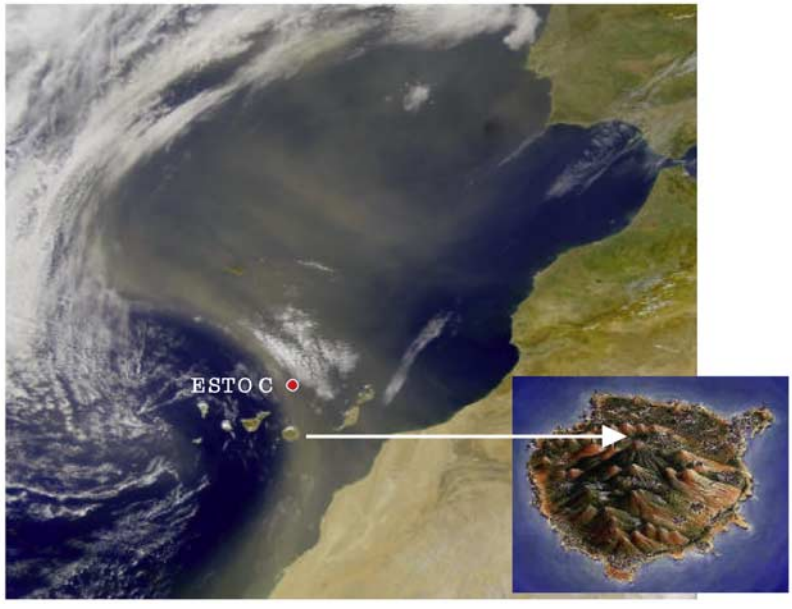


**Figure 1.** Location of time series station ESTOC 100 km north of Gran Canaria off northwest Africa and the "Pico de la Gorra" on Gran Canaria (insert) where the dust concentration measurements were carried out (1980 m above see surface). SeaWiFS image (courtesy NASA/Goddard) shows a large dust cloud advecting from the Sahara on 6 March 1998.