Air-borne dust fluxes to a deep water sediment trap in the Sargasso Sea

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Abstract. The record of atmospheric dust deposition as recorded by a deep sea sediment trap in the Sargasso Sea is presented. The record is shown to be consistent with the limited available data on directly measured atmospheric dust loadings. The seasonality of the sediment trap dust flux is different from that of the atmospheric deposition as a result of seasonal biological cycles in the surface water. On the longer term the sediment trap dust flux undergoes quite large variations in the annual average flux from 3.6 to 9.4 mg m⁻² d⁻¹. These variations are shown to reflect changes in atmospheric transport efficiency from source regions in North Africa rather than changes in the strength of the dust source in that region. The changes in the dust inputs to this area of the Sargasso Sea appear not to have changed the flux of carbon reaching the deep water, and the implications of this are discussed.

1. Introduction

Sinking particles have been collected almost continuously since 1978 in sediment traps deployed 3200 m below the surface in the Sargasso Sea [e.g., Deuser et al., 1995]. This is the longest such record and has revealed important information on many aspects of deep ocean flux, notably the correlation between carbon and elemental fluxes including biogenic particles such as clay and their relation to the primary productivity of overlying waters [Deuser et al., 1983]. These relationships imply that sinking large organic particles, such as faecal pellets and marine snow, dominate and control the sinking particle flux of biogenic and abiotic material, resulting in rapid vertical transport and a close relationship between surface water processes and deep sea fluxes [Deuser, 1986]. The long term data set also reveals seasonal and interannual variations in fluxes and the composition of sinking material which can be related to changes in surface water processes and climatic variables, both at this site [Deuser, 1986; Jickells et al., 1990, Deuser et al., 1995] and on a wider scale [Jickells et al., 1996].

Here we consider the long term variability of aluminosilicate clay material captured by the sediment trap, material which is derived predominantly from wind borne mineral aerosol particles henceforth termed "dust" [Deuser et al., 1983]. Assuming lateral advection effects at this site to be modest [Jickells et al., 1987], an assumption evaluated in more detail later on, the dust flux measured in the sediment traps should be related to the atmospheric deposition of dust to the overlying surface waters of the Sargasso Sea. Dust concentrations over the North Atlantic vary considerably, reflecting atmospheric transport patterns from the major source regions in North Africa [Prospero, 1996; Moulin et al., 1997], and this pattern is also seen in average sediment trap dust fluxes at various sites in the North Atlantic [Jickells et al., 1996]. Dust content in deep sea sediments is usually interpreted in terms of atmospheric dust deposition and used to infer paleoaridity [Goudie, 1983; Goudie and Middleton, 1992; Rea, 1994], though the nature of this connection is rarely tested explicitly, and recent studies have emphasized the spatial and temporal variability of dust inputs [Murray et al., 1995].

Atmospheric dust levels are themselves important in climate control, both via albedo effects [Tegen and Fung, 1994; Tegen et al., 1996; Li et al., 1996] and possibly via the effects of atmospheric dust on marine primary productivity directly via iron limitation of photosynthetic carbon fixation [Martin et al., 1994; Kumar et al., 1995; Tortell et al., 1996; Coale et al., 1996] or indirectly via effects on nitrogen fixation rates [Michaels et al., 1996] or the sulphur cycle [Zhang et al., 1992]. Here we show that the dust flux recorded by the sediment trap varies considerably over the period considered (1978-1992) and investigate the factors controlling this variability, considering particularly the atmospheric dust record measured on Bermuda.

There is a long history of atmospheric trace element studies on Bermuda [Duce et al., 1976; Church et al., 1984; Arimoto et al., 1992, 1995; Ellis et al., 1993]. Continuous aerosol measurements made at a coastal site on the west end of Bermuda [Arimoto et al., 1995] show a pronounced seasonal cycle in dust (Al) transport with a maximum during the summer and a minimum during the winter. The summer dust events are associated with air mass trajectories that pass over the tropical North Atlantic Ocean [Arimoto et al., 1995] and Africa. These trajectories are consistent with the strong atmospheric circulation around the Bermuda-Azores High Pressure center, a common feature during the summer over the North Atlantic Ocean. Bermuda is affected by some dust events associated with transport from North America, usually in the spring and fall;
however, the dust concentrations associated with these events are much lower than the African dust events. When aerosol samples are grouped according to air mass trajectory [Arimoto et al., 1995], the mean Al concentration associated with trajectories from the east (1.26 mg m⁻³) is about 10 times greater than that for trajectories from North America (0.12 mg m⁻³). The Al concentrations obtained by Arimoto et al. [1995] during the summer months of 1989-1990 (geometric mean, 0.13 mg m⁻³ Al) agree with those previously obtained by Luce et al. [1976] on Bermuda during the summers of 1973 and 1974 (geometric mean, 0.14 mg m⁻³), suggesting dust transport to this region of the western North Atlantic Ocean is a fairly consistent phenomenon, although as we show later there are inter-annual variations in the dust transport to this area.

2. Methods

Full details of the sediment trap sampling program are presented elsewhere [Deuser, 1986; Deuser et al., 1995] as are the analytical methods used [Deuser et al., 1995, and references therein]. These analytical procedures are used to measure total mass, organic matter (equal to 2.3 times organic carbon), calcium carbonate, and opal. The aluminosilicate concentration is derived by difference:

\[
\text{total mass} - (\text{organic matter} + \text{calcium carbonate} + \text{opal}) = \text{aluminosilicate dust}
\]

The errors associated with the analyses of the individual components are CaCO₃ ± 3%, Opal ± 5%, and organic matter ± 10%. Thus the analytical uncertainty associated with this method of estimating dust fluxes to the sediment trap we estimate at ≤12%, though there may also be systematic errors associated with the assumption that these four components dominate the flux. The results of earlier studies [Deuser et al., 1981], which included direct measurements of Al fluxes to derive clay content in the trap material (assuming clay to be the dominant source of Al), suggest that such systematic errors are unlikely. An extended version of these data is presented in Figure 1, demonstrating that the dust fluxes estimated by difference and by direct Al measurement are closely correlated over the whole range of measurements with the best fit line passing through the origin within statistical error. We therefore conclude that the dust flux derived by differences does, indeed, represent aluminosilicate dust.

Atmospheric dust deposition fluxes to the surface waters of the Sargasso Sea have been discussed previously [Jickells et al., 1994] and are based on direct measurements of Al concentrations in rainfall and aerosols on Bermuda extrapolated over the surrounding Sargasso Sea. These aluminum concentrations are converted to dust fluxes by assuming an Al content of clays of 8% [Taylor and McLennan, 1985], a value essentially identical to that in Figure 1 (8.6 ± 1.4%).

3. Results

The average composition of <37 mm material collected by the sediment trap over the period 1981-1991 is 57% CaCO₃, 11% organic matter, 13% opal, and 20% dust. The coarser fraction collected by the sediment trap is overwhelmingly CaCO₃ and contains negligible amounts of dust. Large dust particles have been reported in the remote marine atmosphere [Betzer et al., 1988], but these are rare and do not contribute significantly to the overall flux. The average dust flux over the entire sampling period is 5.15 mg m⁻² d⁻¹, though this varies significantly over time (Figure 2).

3.1 Seasonal Variation

Atmospheric dust fluxes to this area peak in summer with 80% of the dust deposition on Bermuda occurring in the period July to September [Jickells et al., 1994]. This seasonal input drives a seasonal maximum in particulate aluminium [Jickells et al., 1990] and lithogenic silica [Brewinski and Nelson, 1995] concentrations in nearby surface ocean waters in summer. The flux of dust to the sediment trap, on average, shows little seasonality (Figure 3a) in contrast to the strong seasonality seen for biogenic components (e.g., Figure 3b), for which there is a marked maximum in spring associated with increased nutrient supply to surface waters in late winter and a resultant increase in primary production [Deuser et al., 1983]. The different seasonality of the dust and biogenic fluxes to the sediment trap result in seasonal variations in the composition of sinking material, for example, the ratio of dust to biogenic calcium carbonate [Jickells et al., 1990].

The net result of the different seasonality in the supply of atmospheric dust to surface waters and the rate of particle removal from surface waters is a rather constant dust flux to the sediment trap through the year. Thus on a subannual timescale the timing of deposition of atmospheric dust to the surface waters of the Sargasso Sea and the flux of dust into the deep sea are decoupled, because of biological mediation of the transport process from surface to deep waters. Short-term variations (less
than 1 year) in atmospheric dust deposition will thus not be recorded in the sediment trap. Such decoupling has been observed in other ocean areas [Buit-Meurant et al., 1989]. However, given an average lifetime of a dust particle in surface waters of the order of 100 days [Deuser et al., 1983], it is possible to compare atmospheric dust deposition fluxes to trap fluxes on a timescale of a year or so.

3.2 Comparison of Atmospheric Deposition Fluxes to Sediment Trap Fluxes

For the period July 1988 to June 1991 we have an essentially continuous record of aerosol Al [Arimoto et al., 1992, 1995] and rainwater Al concentrations measured on Bermuda which we convert to dust fluxes by assuming the dust is 8% Al. These rainwater measurements have been upgraded to include a more total digestion of particulate material in the samples, and thus the flux estimate here is higher than previous estimates of wet deposition [Jickells et al., 1994] at 0.8 mg m\(^{-2}\) d\(^{-1}\) (Veron, A. et al., unpublished data, 1996). In the case of aerosol measurements the analysis is for total Al since the determinations are based on instrumental neutron activation. To convert aerosol concentrations to dry deposition requires the use of dry deposition velocities which are very uncertain [Sievering, 1984]. Here we have used the recommendation of Duco et al. [1991] that dry deposition velocities for mineral dust lie in the range 0.3-3 cm s\(^{-1}\), yielding a dust dry deposition estimate of 1.2-11.6 mg m\(^{-2}\) d\(^{-1}\). This yields a total (wet plus dry) dust flux to Bermuda (and we assume to the neighboring Sargasso Sea) of 2-12.4 mg m\(^{-2}\) d\(^{-1}\) which can be compared to a dust flux measured by the sediment trap of 4.7 mg m\(^{-2}\) d\(^{-1}\).

The following is given: (1) Both records are quasi continuous, and occasional mechanical failures mean a few samples are missing (and results for these periods have been interpolated). (2) There are different mechanisms by which the dust fluxes are derived (aerosol Al measurements for atmospheric fluxes with assumed dry deposition velocities; rainwater Al concentrations for atmospheric wet dust fluxes; by mass difference for trap fluxes). (3) Bermuda deposition estimates are extrapolated over the adjacent Sargasso Sea; the agreement in fluxes is reasonable but does highlight the critical uncertainty in dry deposition velocities. A deposition velocity of 1 cm s\(^{-1}\) (the middle of the range) would give a total atmospheric dust deposition flux which almost exactly balances the sediment trap flux.

3.3 Interannual Variations

The deep sea sediment trap dust fluxes reported here show significant long-term changes (Figure 2). The average annual (calendar year) fluxes range from 3.6 to 9.4 mg m\(^{-2}\) d\(^{-1}\) (note in Figure 2 averages are for July to June years rather than calendar years for reasons discussed later). Despite the interannual variations there is still a significant correlation between dust and organic matter fluxes (R=0.51 and N=59, significant at 99.9% confidence level for the full measurement period) as noted previously [Deuser et al., 1983]. The correlation persists despite the interannual variations because the main variations particularly in organic carbon are seasonal rather than interannual, and hence
Figure 3. Annual cycle 1978-1991 of (a) dust flux at 3200 m and (b) organic carbon flux to the sediment trap. Cycles are 2 month moving averages computed as described by Deuser (1986). Note anomalous samples May 1981 and August 1982 are excluded [see Deuser et al., 1995].

these dominate the correlation. In the long-term record there are two periods of anomalously high fluxes (April/May 1981 and June/August 1992) for dust and other components which have been discussed elsewhere [Deuser et al., 1995]. Elimination of these high-flux periods from the record improves the smoothness of the seasonal cycle (Figure 3) but does not alter the interannual variability greatly. Thus 1981-1984 was a period of relatively high dust fluxes to the sediment traps (we consider July to June annual fluxes for reasons discussed below, and the mean for the 1980-1984 period of 6.10 ± 0.74 mg m⁻² d⁻¹ is statistically different, based on a T test, from the mean for the period 1984-1991, 4.67 ± 1.09 mg m⁻² d⁻¹, at the 95% confidence level). Biogenic fluxes do not show a similar period of high flux at this time, indeed the organic matter flux shows no consistent trend over the 14 year record. The organic carbon flux for the 1980-1984 period of 1.92 ± 0.43 mg m⁻² d⁻¹ is indistinguishable from the organic carbon flux for the 1984-1991 period of 1.98 ± 0.19 mg m⁻² d⁻¹. There is a long-term trend in the Opal/CaCO₃ ratio [Deuser et al., 1995]. However, this long-term biogenic trend is essentially unidirectional over the 1978-1991 period and hence quite different from the dust flux record. This implies that changes in the annual average dust flux (i.e., Figure 2) are not related to changes in biological cycling in the overlying water column and hence are more likely to reflect changes in the supply of dust to the area.

We therefore suggest that the variations in dust flux to the sediment trap may reflect changes in atmospheric dust deposition in the area. Such a change could occur as a result of increases in total atmospheric dust loading and/or changes in the efficiency of dust transport or deposition to this area. We do not have long-term local records of atmospheric dust loadings for the 1981-1991 period and so cannot directly test the hypothesis, but we can investigate this indirectly.

Dust transport to the Bermuda area is seasonal, and highest fluxes occur during summer as a result of strengthening of the Bermuda Azores High Pressure allowing more efficient transport from the desert regions of North Africa. This is clearly seen in both the 1988-1991 aerosol measurement [Jickells et al., 1994; Arimoto et al., 1995] and in satellite-measured aerosol optical depth (Article by K.B. Husar and L.L. Stowe is available on the
World Wide Web at http://capita.wustl.edu/CAPITA/CapitaReports/TropAerosol/trop2.html (Husker et al., Satellite sensing of tropospheric aerosols over the oceans with NOAA AVHRR, submitted to Journal of Geophysical Research, 1997). There is clear evidence that dust sources in North Africa have varied markedly over recent years in response to drought conditions in the mid-1980s [e.g., Prospero and Nees, 1986; Prospero, 1996] and to large-scale changes in atmospheric circulation pattern [Moulton et al., 1997] as shown by aerosol records from Barbados, a site directly downwind of the Sahara dust plume (Figure 3). The pattern at Miami is similar to that at Barbados [Prospero, 1996]. However, detailed examination of the Barbados atmospheric dust records with the sediment trap record suggests that variations in Saharan dust production alone cannot explain the long-term changes seen in the sediment trap record. Thus the Barbados aerosol dust record implies high dust production throughout the period 1983 to 1987, while dust fluxes to the sediment trap were at a maximum from 1981 to 1984. This implies that the efficiency of atmospheric transport, in addition to variations in source strength, must play a part in explaining the long-term deep sea sediment trap dust record seen.

The efficiency of atmospheric dust transport to this region depends on the pressure gradients over the Sargasso Sea and specifically the tendency for this gradient to draw the Saharan dust plume northward. This tendency is maximal in summer as the Azores High Pressure system intensifies, consistent with maximum aerosol concentrations in summer at Bermuda (see earlier). Subsequent discussion consequently focuses on the July, August, and September period. Since dry deposition appears to dominate the total deposition, we have also ignored rainfall frequency here. Consideration of the rainfall record for Bermuda suggests it shows little systematic seasonality and little change in annual amount over time from a mean for 1960-1989 of 122 mm.

In order to assess changes in the efficiency of dust transport to the Sargasso Sea from North Africa, we have calculated air parcel back trajectories for the period of maximum transport (July to September) for Bermuda from 1978 to 1992. Five day air parcel back trajectories were calculated 4 times a day for arrival at Bermuda at 950, 850, 700, and 500 hPa using the three dimensional Atmospheric Environment Service Long Range Transport of Air Pollution model [Voldner et al., 1981; Strohs and Bottenheim, 1995]. The trajectories for the period July to September of each year were divided into four groups (Figure 5): (1) those arriving from Europe, (2) those arriving from North America, (3) those arriving from the south, southwest, and east, that is, the sector from which Saharan dust will arrive and...
Figure 4. Atmospheric aerosol monthly mean dust concentration measured at Barbados.

Figure 5. The 950 hPa air parcel back trajectories arriving at Bermuda in July to September of 1980 and 1987. The sectors used for trajectory classification are also illustrated.
subsequently be referred to as the African sector, and (4) those unclassified, that is, trajectories which spent less than 70\% of the 5 days in any one sector.

At the lower altitudes of most relevance for dust transport and deposition over the Sargasso Sea (950 and 850 hPa) transport from the African sector dominates (Figure 6), consistent with other studies [Whelpdale and Moody, 1990] for this summer period. However, it is notable that over the 5 day period considered for the trajectories, most do not go back as far as North Africa. At progressively higher altitudes the westerly flow becomes more important. Here we focus on 850 hPa since this is closest to the altitude of most dust transport [Prospero, 1996].

Consideration of the interannual variation in the frequency (Figure 6) reveals considerable changes over the time period 1978 to 1992. Trajectories from the African sector occurred more than 80\% of the time in 1981 compared to less than 50\% of the time in 1987. The pattern of interannual variability is generally similar at 950 and 850 hPa, and the interannual changes appear to be part of a relatively steady longer-term trend with declining frequencies of trajectories from the south and east throughout the period 1981 to 1987. The causes of these long-term cycles reflect changes in the atmospheric pressure field, particularly the summertime position and intensity of the Azores High Pressure System, possibly related to larger-scale fluctuations such as El Niño Southern Oscillation (ENSO) and North Atlantic Oscillation. These will be considered in a separate publication.

To evaluate the importance of these changes in the frequency of transport from the African sector, we compare Figures 2 and

![Figure 6. Frequency of trajectories at 850 hPa arriving at Bermuda in the period July to September 1978 to 1992 from the various sectors in Figure 5. Note there are four trajectories each day. Note also 1984 includes 11 days of missing data; values for this period have been scaled up pro rata.](image-url)
atmospheric circulation to deep sea sediment fluxes appears to be close, as a result of the efficient biologically mediated transport of the dust particles from surface to deep waters, though with a time lag resulting from biogeochemical processing of the dust in the overlying water column. We have considered pressure anomalies over the North Atlantic for the period considered here with respect to the 1951-1980 mean. This comparison suggests that it is the 1984-1992 period that is relatively anomalous compared to the 30 year average and that the high frequency of African sector trajectories in the 1981-1983 period is the climatologically normal situation.

Importantly, it is also notable that these large-scale changes in dust fluxes have not resulted in comparable changes in organic carbon fluxes to deep water at the site. This may imply that the increased dust (and iron) inputs have not significantly affected new production rates in surface water either directly via iron fertilization or indirectly via an effect on nitrogen fixation [Michaels et al., 1996]. Alternatively, any such effects may be overwhelmed by changes in remineralization rates in the water below the euphotic zone but above the sediment trap. Recently, Gruber and Sarmiento [1997] demonstrated that the Sargasso Sea is an important area of nitrogen fixation in the oceans, possibly as a result of high iron inputs. Michaels et al. [1996] have suggested that changes in dust deposition over time to the Sargasso Sea associated with the Sahel drought may have significantly altered nitrogen fixation and even primary productivity. The conclusions of these two studies appear quite different. Michaels et al. [1996] suggest an increase in nitrogen fixation in the Sargasso Sea as a result of increasing dust inputs, and our results suggest no resultant increase in carbon export flux. However, these two conclusions may not, in fact, be contradictory.

In a recent study of the biogeochemistry of the subtropical North Pacific, another area of relatively high atmospheric dust input, Karl et al. [1997] report evidence from a number of disparate approaches pointing to a marked increase in nitrogen fixation rates during ENSO periods. They speculate that this may reflect changes in atmospheric iron supply. Furthermore, they suggest that the increase in the importance of nitrogen fixation as a nitrogen source may alter the mechanism of nutrient (and carbon) export, from a predominantly particulate-matter export to one where dissolved-matter (specifically dissolved organic nitrogen (DON) in their case) export processes may become more important. In the North Pacific case this increase in the importance of DON export may reflect increased nitrogen fixation directly or the resultant change from apparently nitrogen to phosphorus limitation on primary productivity. If increased dust inputs do, indeed, generally stimulate nitrogen fixation and hence primary production in such a way as to favor DON export rather than sinking particulate matter, then the increase in nitrogen fixation in the Sargasso Sea suggested by Michaels et al. [1996] would not necessarily result in an increase in particulate carbon export to the deep sediment trap considered here.

These results suggest a complex interaction of a range of nutrients including N, P, and Fe in the oceans regulating the export of carbon to the deep ocean. The unraveling of these interactions will require both intensive studies and long-term programs which couple atmospheric and oceanic components.
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