



## **Joint Meeting of GESAMP Working Group 38 and the WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS):**

*Workshop on Modelling and Observing the Impacts of  
Dust Transport/Deposition on Marine Productivity,  
Sliema, Malta, 7-9 March 2011*

### **Report**

#### **A. Introduction**

Since 2007 GESAMP Working Group 38 has been studying the atmospheric input of chemicals to the ocean. These efforts have focused specifically on:

- Assessing the need for the development of new model and measurement products for improving our understanding of the impacts of the atmospheric deposition of nitrogen species and dust (iron) to the ocean;
- Reviewing the present information on the atmospheric deposition of phosphorus species to both the marine and terrestrial environments, considering both natural and anthropogenic sources, and evaluate the impact of atmospheric phosphorus deposition on marine and terrestrial ecosystems. To consider whether such a review of any other substance would be useful.
- Cooperating with the WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) and with the WMO Precipitation Chemistry Data Synthesis and Community Project to evaluate the needs of the marine community and assist in clearly articulating them in the development of these WMO efforts.

The earlier work and meetings of Working Group 38 took place at two meetings. The first meeting was at the University of Arizona, Tucson, Arizona, USA from 10-14 December 2008. The second meeting was at IMO in London, England from 12-15 January 2010. In order to elaborate more specifically the role of minerals carried by dust that are involved in marine biological production, and to achieve more detailed and specific description of the atmospheric transport and deposition process of iron- and phosphorus-carried minerals, WMO proposed in 2010 that the above activities of Working Group 38 be extended and that it meet jointly with the WMO SDS-WAS, with the overall objectives to:

- Identify test-bed regions for future studies (Central Atlantic; North Pacific; Indian Ocean; others);
- Employ dust/iron/phosphorus models with resolutions as high as possible;
- Improve quantitative estimates of the geographical distribution of mineral fractions;
- Assess, through long-term (re-analyses) and case-studies, the oceanic input of minerals and the marine response provided by dust/Fe/P, utilizing ocean modeling, remote-sensing and in-situ observations; and
- Elucidate environmental and climatic consequences.

A third meeting of Working Group 38 to address these issues was held in Malta from 7-9 March 2011, gathering together the SDS-WAS and GESAMP scientific communities working on these issues. Attendees at this meeting are indicated in Appendix I. The three-day workshop focused on the three primary topics outlined below, and which are related to the objectives above. Individuals from GESAMP and SDS-WAS were asked to co-lead the discussions and report developments in each topic area. The goal was to provide advice as to how impacts of dust transport on marine productivity can most profitably be addressed in the future activities of WMO and GESAMP. The three topics discussed at the Malta meeting were:

- Topic 1 Improving the quantitative estimates of the geographical distribution of the transport and deposition of mineral matter and its content to the ocean.
- Topic 2 Long-term assessment of mineral dust/Fe/P input to the ocean: In-situ observations and marine response utilizing coupled atmospheric transport and ocean biogeochemical modeling and remote sensing
- Topic 3 Specifying test-bed regions for joint studies of the transport and deposition to the ocean of mineral matter utilizing SDS-WAS transport modeling

Three reports were developed in these areas, and they are presented below. In places there is some overlap in the discussion in these reports, but in order to make each report complete, we have let such overlaps remain.

## **B. Report on Topic 1**

### **Improving the quantitative estimates of the geographical distribution of the transport and deposition of mineral matter and its content to the ocean**

Co-Discussion Chairs: F. Dentener (GESAMP), M. Schulz (WMO SDS-WAS)  
Rapporteur: I. Tegen

#### **1. Introduction**

Emissions of mineral dust have impacts on the local and global environment, with implications for human health, visibility, and climate. One particular concern is the transport of mineral dust, containing macro- and micronutrients, to the ocean and the resulting influence on the biological productivity of the oceans. Dust deposition can be derived from measurements, but the dearth of

data usually prevents a complete assessment based on measurements alone. Therefore models are often used to calculate deposition fluxes of dust on larger scales. Reliable dust deposition calculations require sound knowledge on all processes involved: 1) dust emission 2) the composition of emitted dust 3) transport from the sources and 4) size dependent removal by wet deposition (precipitation), sedimentation and dry deposition.

Several global and regional deposition estimates have been published. They generally reveal large inter-model deviations and large disagreement with measurements. The verification of model performance is impeded by a lack of benchmark data. The measurements are often discontinuous, obtained at different time periods, and have a limited representativity for larger scales. They are often obtained close to dust sources and therefore do not cover regions further away from the sources. Especially in the Southern Hemisphere, where oceanic nutrient limitation may be strongest, there is a severe lack of deposition measurements. In addition there are a variety of measurement techniques that are not easy to compare, and there is severe lack of reliable direct dry deposition measurements.

In this report we evaluate the state-of-art knowledge and uncertainties regarding the deposition of dust on the ocean and its mineralogical composition provided by models and measurement datasets. Global climate models were recently intercompared by Huneus et al. (2011) using results from the AEROCOM model intercomparison. The deposition calculations from these global models are frequently used as input for biological productivity calculations. A model-measurement comparison (Huneus, 2011) shows that global models do reproduce the observed data over several orders of magnitude. However, the agreement with individual measurements is within a factor of three at best. To estimate the flux of mineral nutrients to the ocean, the mineralogical composition of dust deposited at the surface ocean must be known. Very few studies have been performed to assess mineralogical composition of dust over the ocean, and thus the associated uncertainties in the mineralogy are even larger than for dust alone.

Regional models have recently been used for dust forecasts, and some of the models are integrated in the newly established WMO SDS-WAS. These models include more detailed information on local dust source conditions and meteorological conditions, but are not necessarily optimized to provide reliable dust deposition calculations. This workshop report highlights possibilities for a more integrated approach to improve the dust deposition calculations to the ocean using the newest information available from regional and global models and measurements. It also identifies areas for further improvement and recommendations for science. In the following section we start discussing the availability of benchmark data, including their mineralogical composition. We then identify the necessary steps regarding model development, model experiments and diagnostics. We finish with an evaluation of the state-of-knowledge regarding climate and anthropogenic influences on deposition of dust-related nutrients.

## 2. Measurement Benchmark Dataset

- a) *What is the current state of the art of measurements needed to estimate dust-related nutrient deposition fluxes?*

Various deposition observational datasets provide important information on the magnitude and temporal variability of dust deposition. However, the scarcity and the limited representativity of

the data often preclude regional to global assessments of dust deposition. Therefore, observations are most essential to support the modeling of deposition fluxes of dust-related nutrients.

There are not too many stations performing measurements of mineral dust deposition over the oceans. The AEROCE network containing a number of remote stations in the Atlantic and the SEAREX network in the Pacific were closed more than a decade ago. Fortunately, in the last years a few new sophisticatedly equipped monitoring stations have been established, often under the umbrella of the GAW program (e.g., Malta and Izana). However, there is no systematic recent overview available of stations qualifying to monitor dust and dust deposition in the large monitoring networks (EBAS, EMEP, AENET). In addition, research programs in Africa and in Asia (e.g., AMMA, ACE-ASIA), ship measurements (e.g., A. Baker) have provided additional shorter-term information. Nevertheless, these data are not sufficient to provide a complete overview of deposition to the world's oceans.

In addition to dust deposition and dust surface concentration, spectral aerosol optical depths from ground based and satellite remote sensing are increasingly used to constrain models. However, these measurements are often associated with ambiguities due to a lack of understanding of the measurement errors, uncertainties regarding the vertical distribution of dust (for passive satellite sensors) and the degree of representation.

The quality of the experimental observations is often difficult to evaluate due to a lack of standardization of sampling and analytical methods, particularly concerning surface concentrations and deposition and particle solubility. Underestimates in dry deposition of dust can be made when dry deposition is inferred from size-segregated aerosol measurements that use a cut-off diameter. In this approach the few large particles (>20 $\mu$ m) that are the major contributors to the mass flux get neglected.

Furthermore, most of the time the datasets integrate also the contribution of sources other than dust. A careful evaluation of the data is therefore necessary to separate these additional contributions. For instance the quantitative comparison of model output with spectral optical depth data from passive remote sensing, which integrates all aerosol components, might be ambiguous far away from source regions due to mixing of dust with concurrent contributors such as sea salt, anthropogenic pollution and biomass burning. Ocean sediment trap mass fluxes could provide additional information on atmospheric dust deposition provided that the location is not strongly affected by coastal or upwelling sources of nutrients.

Iron (Fe) is one of the key-nutrients associated with mineral dust fertilizing the oceans. Measurement progress has been made towards linking the iron solubility to the dust mineralogy, particularly for African sources, and enhanced effort has focused on developing refined maps of the soil mineralogy. Sun photometers from the AERONET stations have also been used to derive the hematite content of dust. New field and laboratory data have been acquired pointing out the role of particle mixing and chemical processing during transport in increasing the solubility of iron-related dust.

b) *What do we need to improve the estimate of dust-related nutrient deposition fluxes?*

Long-term standardized observations are essential in order to constrain the temporal variability of dust-related nutrient deposition fluxes. Recommendations on this point are twofold:

- Existing stations in the northern hemisphere, some of which are historical (e.g., the Barbados station), should be maintained.
- New long-term observing programs should be promoted downwind from dust source areas in the Southern Hemisphere (South America, Australia, South Africa), where observations are very sparse and the ocean ecosystem is expected to be most sensitive to Fe inputs.

The pertinence of existing and new monitoring stations with respect to their location and their ability in representing dust-unperturbed or perturbed conditions should be properly assessed, and this is addressed by the report on Topic 3.

The estimate of dust deposition fluxes and the assimilation of observations by models will benefit from the definition of commonly agreed standards with respect to sampling fractions and analytical protocols. This will allow harmonization of coordinated measurements of benchmark parameters such as size-dependent nutrient solubility, aerosol concentration, and chemical/mineralogical composition, concurrent to bulk dry and wet deposition measurements. This effort can benefit from working groups active in this area (SOLAS, EU projects EUSAAR/ACTRIS). Aerosol collection on both PM<sub>2.5</sub> and TSP fractions should be pursued as much as possible. Comparison of inferred and direct dry deposition measurements should also allow improving the estimate of the size-dependent dry deposition velocity for use in models.

The prediction of aerosol mineralogy is based on soil properties. However, the mineralogy of transported dust may be very different from the parent soil. so-called fractionation or enrichment process should be urgently addressed to better understand the mineralogical composition. The size-segregated mineralogy and solubility should also be observed as a function of dust age in the atmosphere. be fully included into dust models, dedicated intensive field observations and laboratory-based studies are required in order to evaluate the soil/aerosol size and mineral fractionation at emission and the physico-chemical processing (mixing, heterogeneous reactions, etc.) controlling their evolution during transport.

Finally, existing data from various measurements need to be re-assessed, and their consistency and uncertainties better characterized. Global benchmark data are made available in various contexts, but a continuously updated overview of such datasets in regional and global modeling is highly recommended. New data from lidar networks and space-borne lidars, as well as satellite aerosol products from desert regions (MODIS Deep Blue and MSG-DSAF) but also from PM<sub>10</sub> networks near dust source regions, should be exploited in an open manner to provide high resolution information on dust rise events.

### 3. Model Development, Experiments, Diagnostics and Documentation

#### *a) Current status*

Several model simulations exist today that provide a temporal and spatial distribution of dust deposition to the ocean. A multi-model ensemble mean such as from AeroCom is generally assumed to represent a best guess for the global distribution. Higher time and space resolved dust deposition is available from regional models, such as those currently employed and further improved in the framework of the WMO-SDS (Asia, Africa), ICAP, and the United States.

Recently, more vigorous attempts have been made to evaluate the model deposition with actual deposition measurements (e.g., Huneus et al, 2011; Sugimoto et al., 2011; Uno et al., 2006). A problematic factor in the evaluation of the models is the often unknown error of the deposition data. These studies show that the global distribution of a wide range of deposition flux values is relatively well reproduced. However, dust deposition is captured within at best a factor of 3 at single stations. The largest discrepancies appear for sites remote from dust sources with very low dust deposition, which seem to be overestimated by most models. The very limited data coverage in the Southern Oceans is most critical, especially because large sensitivity to atmospheric dust and iron inputs has been suggested for these areas.

*b) What is needed?*

A general problem for dust modeling is the conditions in the source regions, which are not sufficiently well characterized. The influence of changing land management practices and variability of vegetation cover is recognized as an important factor driving dust emissions, but it is often not included in models. As mentioned earlier, mineralogical composition of soil and the fractionation of the dust emissions also need to be improved in the models. More sophisticated modeling of chemistry and aerosol coupling would be needed if it were ascertained that during atmospheric transport of mineral dust the solubility of iron, phosphorus and other micronutrients is controlled by photochemical and in-cloud processing of mineral aerosol.

More comparisons of models to observations of deposition are suggested to be crucial. High quality long-term measurements of surface concentration and wet deposition are needed. Model dry deposition is more problematic to validate mainly because of still existing measurement problems. The recent decrease in such measurements and the missing commitment of funding agencies to ensure the continuation of selected long-term monitoring is problematic with respect to a better understanding of the evolution of dust levels in general and dust and climate interactions in particular.

Models and measurements often are interpreted in different ways. A particular problem is the dust particle size spectrum, which is often not covered to the same extent by models and measurements. Coarse particle fractions require additional attention to understand dust near source regions, in particular since those particles may deliver a considerable fraction of the dust mass flux into the oceans. Validation of deposition in models is important to help the dust model development in general, because it provides a check of the dust cycle and dust budget away from emissions sources. SDS dust models will thus profit from such evaluation work with co-benefits for the prediction of atmospheric dust in chemical weather forecasting.

Common model experiments using harmonized emission flux assumptions should be considered, especially by the SDS community. Significant value would be added to align those with periods and locations where more data are available. Both WMO-SDS nodes have proposed a model intercomparison. It would be useful to open these intercomparisons to other groups. Periods suggested as common reanalysis are the year 2006 and the spring of 2007. Common analysis among nodes could be useful to identify problems and provide input to global model. Furthermore, cooperation of initiatives such as AeroCom and ICAP is recommended.

Assimilation of satellite-derived optical depth has been shown by several groups to lead to improved aerosol fields. For instance, the use of the ground-based lidar network data and CALIOP data with real-time distribution have shown recently its capability for improving model representation and forecast. In East Asia, there have been some efforts using the case study of the April 2007 dust event within the TEMM context (see the SOLA special issue). Horizontal and vertical transport pathways and subsequent ocean deposition of mineral dust and bio-available iron were also studied for two large dust outbreaks originating in the source regions of South America (Johnson et al., 2011). The associated model work is thus close to providing a more realistic dust reanalysis on global and regional scales. Because of the sensitivity of aerosol optical depth to primarily fine particles, additional validation is needed for the coarse dust aerosol fraction by surface in-situ concentration and deposition measurements. We note, however, that data assimilation, while improving our understanding of aerosol abundances, may not always lead to improvements in the estimated deposition rates.

Inter-annual and inter-decadal variability of regional dust sources is observed in many arid and semi-arid regions but not well understood. Such understanding would be needed to understand the long-term recent and future change in dust impact on ocean biogeochemistry. Possible research could involve the coordinated hindcast simulation of dust for periods where observations of dust in the atmosphere exist, such as the hindcast proposed in the framework of AeroCom for the period 1980-2008.

The requirements in terms of spatial and temporal coverage of dust deposition for a better understanding of the impact of dust on ocean biogeochemistry should be better defined. While daily deposition fields are needed for interpretation of short events, monthly global model results might be sufficient to study decadal and inter-annual trends in dust in the different parts of the global ocean. A further outstanding issue is what minimum model resolution is needed for assessment of the role of nutrient deposition in the oceans.

It was considered that the necessary documentation of model experiments (physics) is often incomplete and difficult to retrieve for those not directly involved in the experiments. The documentation of dust model simulations may be improved further by systematically making use of supplements in publications. This should be accompanied by making available model fields in the form of CF-compliant netCDF datasets via ftp sites or via common databases such as AeroCom, SDS, ICAP model intercomparisons. A publication should be accompanied by crucial model fields, such as monthly surface concentrations, emissions, dry and wet deposition fluxes, column loads and 3D mass mixing ratios of all individual dust tracers as well as dust aerosol optical depth.

#### 4. Climate and anthropogenic influences on deposition of dust-derived nutrients to the oceans

Dust is the largest single source determining the global aerosol burden. As a consequence, anthropogenically or climate induced changes in atmospheric dust will have a large impact on climate in general, and deposition of nutrients to the ocean in particular. Model simulations of the current impact of dust on the ocean carbon cycle are highly uncertain. A few recent studies

suggest that mineral dust input in the oceans suppresses CO<sub>2</sub> by 10-20 ppm, subject to large uncertainty. Changes in climate conditions and human influences on the environment can impact the delivery of nutrients to ocean surfaces by aeolian dust in different ways. Understanding those interactions are thus of importance for characterizing possible future changes in their oceanic impact.

The effect of climate on dust emission is complex. Climate directly affects wind erosivity by controlling windspeed, and more importantly, wind gustiness. Precipitation also impacts dust emission through delivery of wind-erodible and dust-sized particles. Years of high dust emission can follow years of especially high, or high intensity, precipitation that causes greater overland flow and sediment delivery to dust source regions. Climate also impacts vegetation, and large amounts of antecedent precipitation in drylands can sharply reduce wind erosion by the growth of plants in previously unvegetated areas. In addition, there are factors that control atmospheric dust, e.g., human activities that directly impact the erodibility and emissivity of the surface, and these are not yet well understood.

Dust emission occurs when the erosivity of the wind exceeds the erodibility of the soil in unvegetated bare gaps. Soil erodibility, characterized by the threshold wind speed for soils, is largely a function of the soil surface texture and the presence of biological or physical surface crusts. Dust emission efficiency, i.e., the amount of dust produced for a given amount of aeolian transport, also depends on the surface soil texture. Although human activities and climate have little impact on soil surface texture, they can have a major influence on the state of crusts that protect the soil from erosion and dust emission. Activities such as grazing, tillage, and vehicular movement destroy soil crusts and decrease the threshold wind speed. Activities that remove or reorganize vegetation, such as land clearing, deforestation, grass-to-shrub conversion, and overgrazing reduce the sheltering effect of vegetation and will also increase dust emission.

Nutrient delivery from dust deposition into the ocean depends on dust concentrations, nutrient concentration within the particles and solubility of the nutrients. Emissions of reactive gases and secondary aerosols from anthropogenic sources have increased since preindustrial times and are expected to have increased the solubility of micronutrients in dust particles, in particular downwind of industrialized regions (Solmon et al., 2009). This depends on atmospheric processing of the particles and will change with changes in the anthropogenic concentration of reactive gases (e.g., SO<sub>2</sub>, NO<sub>x</sub>, etc.) that can mobilize the nutrients iron and phosphorus. The relevant timescale to look at is preindustrial to present. The longest ongoing measurement of dust concentrations at the surface is at Barbados, where measurements exist since the late 1960s (Prospero and Lamb, 2003). Trends in 20<sup>th</sup> century dust from visibility reduction measurements at meteorological stations have been inferred as a surrogate indicator for dust emissions (Mahowald et al. 2007). Such long-term observations indicate that there has been a strong increase in dust emission and transport over the tropical Atlantic in the beginning of the 1970s at the onset of severe drought conditions in the Sahel region. Other regionally significant dust increases have occurred, e.g., in the Aral Sea region or during the dust bowl years in the southwestern US in the 1930s and 1950s, but not much dust from these events may have reached the ocean.

## 5. Recommendations

The view that emerges from this analysis is that dust emission is highly dependent on changes in the climate as well as changes in source functions as a result of anthropogenic activities. This means that current dust parameterizations that necessarily simplify the processes that lead to dust emission, particularly in global models may not work well under different climate regimes. As a result, parameterizations of desert dust emission may need to be made more process-specific before improved future predictions can be made. Furthermore, the impacts of human activities on vegetation and on soil crusts need to be included in models to understand the overall impact of humans on the dust cycle. At present, neither models nor observations of soil and vegetation disturbance by humans exist that can clearly guide our understanding of the impacts of humans on dust. Indeed, even the inclusion of so-called "natural" dynamic vegetation in global or regional climate models is in its infancy, and until these models can do a good job of predicting vegetation functional type, cover, and dynamics well, it will be very difficult to estimate the impact of climate on future dust emissions through its impact on the terrestrial biosphere.

Understanding what controls the interannual changes in dust on different timescales is a key factor for identifying the role of meteorology. What cannot be explained by climatology would indicate trends in anthropogenic sources and shifts in climate regimes. Particular focus should extend to understanding controls of dust sources and transport in the southern hemisphere, which are less well known than the major dust sources in the northern hemisphere.

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## **C. Report on Topic 2**

### **Long-term assessment of mineral dust/Fe/P input to the ocean: In-situ observations and marine response utilizing coupled atmospheric transport and ocean biogeochemical modeling and remote sensing**

Co-Discussion Chairs: Manmohan Sarin (GESAMP) and Slobodan Nickovic WMO SDS-WAS)  
(Natalie Mahowald in absentia, GESAMP)

Rapporteur: Luisa Ickes

#### **1. Introduction**

The large-scale atmospheric transport of mineral dust originating from source regions (primarily from northern African and Eastern Asian desert areas) and subsequent deposition to the open ocean is a dominant process for the input of iron and phosphorus and their impact on the marine biogeochemistry. However, the air-sea deposition of mineral dust is highly episodic and variable in space and time. Furthermore, there are a limited number of case studies addressing the issue

of direct impact (assessed through an increase in surface primary productivity) and/or the phase lag in the marine response to the atmospheric dust deposition. The results and inferences drawn from these case studies are often debatable and generally inconclusive. A detailed and specific description of the atmospheric transport and deposition processes of Fe- and P-carrying minerals to the open ocean requires systematic field measurements and satellite-based observations, together with the development of models. Such an approach would help to improve our understanding of regional and global scale impacts, as indicated in the report on Topic 1.

Regional and temporal scale studies are also essential to assess the physico-chemical properties of mineral dust and its potential role in the supply of atmospherically derived Fe and P, and to improve the quantitative estimates of their geographical deposition to the ocean surface. Mineral dust particles vary over a wide size range, from ~0.1 to ~100  $\mu\text{m}$  diameter. The coarser particles are primarily deposited near the source regions. However, long-range transport of fine particles (< 10  $\mu\text{m}$ ) is of utmost relevance and provides the most conducive surface area for heterogeneous phase chemistry. Preferential accumulation of nitrate on calcium-rich dust compared to sulfate accumulation on alumino-silicate rich dust particles has been reported (Sullivan et al., 2007). The occurrence of Fe primarily associated with the alumino-silicate mineral phase limits its solubility in seawater. Thus, the amount of water-soluble aerosol-Fe continues to remain a major source of uncertainty in assessing the impact of the atmospheric supply of Fe on marine biogeochemistry. Under present-day conditions of growing anthropogenic activities, the chemical processing of mineral dust particles during their long-range transport, mediated by acidic constituents (e.g.,  $\text{SO}_2$  and its oxidation products) and sunlight, is of growing importance for the enhanced solubility of aerosol Fe. Likewise, it is essential to evaluate the impact of atmospheric deposition of phosphorus species, from both natural and anthropogenic sources, on the marine ecosystem.

In this context, long-term field observations and the development of atmospheric transport models for specific case studies are of utmost relevance for documenting dust emissions from source regions and their ultimate deposition to the ocean surface. Although global models have frequently been used to capture large-scale features of dust transport, the development of regional models is required for better resolution of the temporal variability of the emission and transport of dust. The use of high-resolution soil mineralogical maps would also be useful for modeling dust production and aid in simulating 3D transport and transformation of different minerals as a result of atmospheric processing (including the process of Fe-solubility). The use of ocean thermodynamic and marine ecology models provides valuable information on marine primary production and nitrogen-fixation triggered by the atmospheric input of mineral dust and iron.

Satellite-based observations of chlorophyll-a and primary productivity in the surface ocean have been successfully used in specific case studies. However, establishing a significant relationship between atmospheric dust deposition and satellite-derived ocean productivity is necessary to understand and quantify the short-term variability in the marine response of surface primary productivity to dust deposition. Looking from a different perspective, it is also likely that the variability in the marine response to dust/Fe/P input is driven by large-scale ocean circulation. Atmospheric deposition of dust may drive primary productivity in most of the Fe-limited regions and/or it is driven by other micronutrients. Determining the mineral phases containing Fe and P,

their solubility and uptake by the primary producers are also key issues. One of the pertinent questions that must be answered is - what scale-length is important in studying the short and long-term marine responses? The size, shape and population of primary producers may be important in determining the impact of atmospheric Fe/P inputs.

## 2. Observation parameters

We suggest a set of relevant and important measurements that should be considered in specific case studies. These are required for a better assessment of the atmospheric deposition vis-à-vis the marine response as well as for model validation:

- Atmospheric and size-dependent aerosol parameters: Total suspended particulates (TSP), PM<sub>2.5</sub>, mineral dust and a suite of diagnostic tracers (Al, Ti, Si, K, PO<sub>4</sub>, SO<sub>4</sub>, NO<sub>3</sub>, NH<sub>4</sub>), heavy-metals (V, Pb, Cd, Ni), water-soluble fractions of Fe and P; wet- and dry-deposition fluxes of nutrient constituents (Fe as well as inorganic and organic P and N).
- Seawater parameters: Salinity, temperature, density, mixed layer depth, chlorophyll-a biomass, pCO<sub>2</sub>, POC, PON, DOC, CDOM, inorganic N and P, photosynthetically active radiation (PAR), DMS, N<sub>2</sub>O and other biogenic trace gases, taxonomic composition of different species (cyanobacteria vs micro-algae), primary productivity and nitrogen-fixation, as well as carbon-based models coupled with sediment trap data.

## 3. Major existing gaps and questions:

We have identified some major existing gaps and questions related to our present-day understanding of the atmospheric transport of mineral dust and some model limitations for observing the impacts of dust deposition on marine productivity. These include:

- What particle-sizes and mineralogy of atmospheric mineral dust need to be measured for case-study assessment and deposition of dust-derived Fe and P?
- What processes control Fe- and P-solubility in mineral dust and is wet vis-à-vis dry-deposition most important in air-sea deposition fluxes? The solubility of both Fe and P in the source regions of dust and during long-range transport (chemical processing) are major uncertainties. Is biomass-burning a significant source of soluble Fe and P in the area downwind of these source regions?
- How does the marine ecosystem respond to the atmospheric input of dust in Fe- and P-limited oceanic regions (in micro-nutrients rich or poor waters)?
- What is the selective response of oceanic biomass and different phytoplankton communities (procariota vs eucariota) to dust input? How does dust affect the upper trophic levels?
- What is the impact of dust deposition on carbon sequestration and on the global carbon cycle and climate?

## 4. Action and recommendations

We have compiled a list of publications that addresses both the atmospheric transport and deposition of Fe and P to the marine environment and the associated oceanic response. This

annotated publication list is presented in Appendix II. This list should be helpful in the development of subsequent case studies.

Prior to the meeting of WG 38 in Malta, the group addressing Topic 2 was asked to address the need for expanding the scope of case-studies in order to overcome the limited data set currently available with respect to spatial and temporal variability in the atmospheric deposition of mineral dust and the marine response on both short- and long-time scales. At the end of the Malta meeting we made the following recommendations:

- Identify new taxonomic and functional (nitrogen fixing and primary productivity) pico-planktonic and micro-planktonic groups to help understand surface ocean biogeochemical processes and model simulation in response to the atmospheric supply of Fe.
- Develop atmospheric chemistry-transport models that include a complex Fe dissolution scheme that will allow better assessment of Fe-solubility as a function of dust load, mineralogical composition, ambient atmospheric temperature and relative humidity, abundances of trace species (in particular acidic species) and cloud-processing. It is further essential to understand the marine response to the supply of soluble-Fe during atmospheric processing of mineral dust vis-à-vis “bio-available Fe produced by in-situ leaching of mineral dust by surface sea water.
- Utilize as much as possible deposition fluxes based on sediments trap measurements to provide additional evidence on the marine response to the air-sea deposition of mineral dust.
- Compile published evidence on the mineralogy of dust from source regions and promote *in-situ* observations of the size-resolved physical and mineralogical composition of soils. Although individual event-based studies provide critical information, long-term time-series observations away from dust source regions are most appropriate.
- Design and improve coupled models by incorporating complex atmospheric and marine biogeochemical processes.

#### **D. Report on Topic 3**

##### **Specifying test-bed regions for joint studies of the transport and deposition to the ocean of mineral matter**

Co-Discussion Chairs: Alex Baker (GESAMP) and Carlos Pérez Garcia-Pando (WMO SDS-WAS) (Joseph Prospero in absentia - GESAMP))

#### **1. Introduction**

As outlined in the reports on Topic 1 and Topic 2, there are several aspects of the transport and deposition of mineral dust to the ocean that are very poorly understood and require further study, both through observations and modeling. These include:

- Characterizing dust sources and transport pathways, especially those in the southern hemisphere;
- Quantifying changes in the solubility of dust components during transport through the atmosphere and identification of the factors responsible for those changes;
- Measurements and parameterisations of dry deposition fluxes of mineral dust and its chemical constituents; and
- Quantifying the impacts of dust deposition on marine primary production and nitrogen fixation.

In this report we briefly summarize the current state of knowledge for each of these aspects and recommend work that might be carried out to advance the science in each field.

## 2. Current Status

### *a) Dust sources and transport*

The successful modeling of dust processes and an improved understanding of the iron cycle requires a better understanding of the factors that contribute to the uncertainties of the dust cycle in the models. Because of inter-model differences in simulated dust emission and deposition fluxes, estimates of the impact of dust on ocean CO<sub>2</sub> uptake in HNLC (high nutrient-low chlorophyll) regions are highly uncertain. The recent AeroCom dust model evaluation and inter-comparison has shown that models tend to greatly (10x) over estimate deposition to large areas of the Pacific, the Southern Ocean, and Antarctica. And yet from the standpoint of ocean impacts of dust-Fe on the oceans, these regions are critically important because large areas are characterized as HNLC and, consequently, would be most responsive to dust-Fe inputs. Many models reproduce reasonably well the seasonal variability of the Earth's most prolific dust source, North Africa. This performance is attributable to the fact that there are many more studies of African dust transport to remote regions than there are for dust from other regions. Consequently models are well tuned to this source. This tuning results in large model biases when applied to other source regions. Because of this, source emissions from other arid regions (e.g. Asia) have to be tuned to other measures such as aerosol optical depth (AOD). Another important problem in models is that in general they miss the winter transport of Saharan dust to South America. Also models show strong divergences in the southern hemisphere.

Models are almost completely dependent on the data set generated by the various University of Miami sites that were set up in the late 1970s and which continued into the mid-late 1990s after which time only a few stations continued operations. Thus the models are working on data sets in which the oldest data are, for the most part, thirty years old and the youngest about 12-15 years old. The longest data set is from Barbados, which started in 1965 (with Parkin and Delany) and continues to this day, i.e. 45 years. The second longest set is from Miami, which started in 1974.

### *b) Solubility of dust components*

There are many reports of studies on iron solubility in atmospheric aerosols, but rather few on the solubility of other potentially biogeochemically active elements. For iron, there are a number of different processes that might influence the overall amount of iron released into seawater after aerosol/dust deposition. Some proposed processes operate in the source region, some during atmospheric transport, and some after deposition into the ocean. Different processes are likely to be significant in different environments, and there is no consensus on which processes dominate. Baker and Croot (2010) recently reviewed the status of research into aerosol iron solubility. They noted that progress in this field was hindered by the lack of standardized methods and suitable reference materials. Probably as a consequence of the rather poor status of observational studies, there is a similar diversity of approaches to the treatment of iron solubility in modeling studies. It is encouraging that recent modeling work recognizes these problems, in particular that it is unrealistic and inadequate to use a single, fixed value for the fraction of iron released into seawater from mineral dust.

#### *c) Dry deposition fluxes*

There are almost no direct measurements of dry deposition. Most estimates of dry deposition flux are based on concentrations measurements multiplied by a dry deposition velocity. Very often these dry deposition velocities are taken from the summary of Duce et al. (1991), but in general the users of this procedure do not seem to be aware of the very high level of uncertainty associated with those values, even though those authors pointed this out. Models use rather crude dry deposition schemes because there is a lack of data to evaluate more detailed schemes. Consequently, as shown in the recent AeroCom intercomparison, models yield a wide range of estimates of dry deposition fluxes and also of the ratios of wet-to-dry deposition.

#### *d) Impacts on marine biogeochemistry*

Most of the more compelling evidence for links between atmospheric mineral dust inputs and marine biogeochemistry comes from broad-scale observations. Examples include: observations that nitrogen fixing organisms (*Trichodesmium*) are much more abundant in the tropical North Atlantic (where there is a strong dust input) than in the tropical South Atlantic (where dust inputs are low); the fact that (iron-limited) HNLC waters are generally located in areas far removed from the major dust source regions; and in the southern hemisphere that the dust supply is linked to glacial and interglacial cycles and seems to be related to changes in atmospheric CO<sub>2</sub> concentrations. Smaller scale experiments (e.g., bottle incubations of phytoplankton and meso-scale ocean fertilization experiments) have also provided firm evidence that the components of mineral dust (particularly Fe and P) can have significant impacts on marine biogeochemistry in some ocean regions. However in on-deck incubation studies where dust additions were conducted alongside element addition experiments, the results have often resulted in rather different responses in chlorophyll concentrations and productivity changes from those obtained by addition of Fe, P or Fe and P.

Recent sediment trap studies show an increased flux of biogenic particles that is apparently a response of primary producers to fertilization by mineral dust inputs. Enhanced biogenic particle fluxes recorded in traps at times of elevated mineral dust trap loadings indicate significant enhancement of primary production, even when this production is undetected by satellite

chlorophyll-a retrievals. The lack of satellite detection of enhanced chlorophyll-a concentrations may in some cases be due to the presence of deep chlorophyll maxima at depths below those visible to satellite-borne instruments.

### 3. Recommendations and proposed future work

#### *a) Dust sources and transport - proposed sampling sites*

AeroCom Phase II will incorporate additional diagnostics that will allow more comprehensive assessments of models and lead to improvements in simulating the global dust cycle. The new model experiments will store detailed size distribution information, which will allow us to address issues such as the impact of the simulated size distribution in reproducing the dust deposition flux and surface concentration, which are crucial to understanding the iron cycle. However, we need additional observations mainly in the southern hemisphere to help constrain models. Ideally, model evaluation and improvement would benefit from combined measurements of dust surface concentration and column (sun-photometer and vertically resolved lidar) concentration together with rainfall (wet deposition). Below, we present our recommendations for sites that could serve as long term monitoring stations:

\* *North Atlantic*: Stations in the North Atlantic will play an important role by making measurements of aerosols and deposition which will serve as the critical test-bed data for the further development of dust transport models. Also they will generate the baseline data needed to track the response of North African dust sources, by far the largest in the world, as climate changes.

- **Barbados**: Studies on Barbados and Miami have shown large changes in dust transport over the past decades. As for the future, the 2007 IPCC report suggests that large areas of northern North Africa will become drier; but, critically, the models could not agree on the future direction of a large area of North Africa in the Sahara and the Sahel that is known to be a major source of present-day dust. In this context Barbados is a vitally important station to monitor this source and the transport to the Atlantic. Logistics are excellent and local technical support is available through scientific institutions on the island.
- **Bermuda, Miami and Izaña**: Although a lesser priority, these stations would provide data on the latitudinal distribution of dust transport. These data are important for assessing nutrient inputs to the central Atlantic. Bermuda will also serve to characterize the transport of dust and "industrial" iron to the central Atlantic; although very little soil dust emerges from North America, "industrial" iron could have a significant impact on ocean biogeochemistry because it is much more soluble than dust-Fe. Both Miami and Bermuda will also provide test data for models which all seem to have difficulties in resolving transport in the transition regions between major wind systems (i.e., in the Atlantic, between the trade winds and the westerlies). Local support is available through the University of Miami in Miami, on Bermuda by the Bermuda Institute of Ocean Sciences (BIOS) and at Izaña by the Izaña Atmospheric Research Centre.

- **French Guiana:** There is a great need for a station in French Guiana to characterize low-latitude dust transport. A study carried out 30 years ago in Cayenne by the University of Miami showed that in late winter and spring, the transport of African dust to South America was as great as that taking place in the summer months at Barbados. This transport is prominent in satellite products. It is notable that in the recent AeroCom model intercomparison, the models missed or greatly underestimated this transport. French Guiana has good infrastructure and can provide high-quality scientific support.
- **Iceland:** A station in Iceland would play an important role in characterizing the response of high-latitude deserts to climate change. Studies on Heimaey, Iceland, that began in 1991 with the University of Miami show that there is considerable dust activity on Iceland, much of it linked to periglacial deposits. These sources are expected to become more active with time as the glaciers retreat. A recent study in the Gulf of Alaska shows that outbreaks of glacial dust along the coast are an important source of iron over a large region of the eastern Gulf. Thus, glacial sources can be expected to become increasingly important as an iron source in the coming decades. In Iceland logistics and scientific support are excellent.

\* *South Atlantic:*

- **Falkland Islands:** The Falklands are ideally located to measure the activity of dust sources in southern South America, which is believed to have been a major dust source during glacial periods (as reflected by great increases in dust concentrations in Antarctic ice cores at those times). The University of Miami operated a station in the Falklands beginning in the 1980s. Because of logistics and infrastructure limitations the sampler was not well sited. Consequently samples were heavily impacted by local sources, primarily peat burning. However, the infrastructure should have improved since the mid-1990s when sampling was stopped there. The University of East Anglia has recently established a new site in the western Falklands with a clean air sector directly exposed to southern South America. No results are yet available from the site, but it is hoped that it will provide a much-needed record of dust concentrations in the region.

\* *North Pacific:*

- **Midway:** Midway is ideally situated to monitor the transport of dust from Asian sources; a station on this island should have a very high priority. Measurements made by the University of Miami starting in 1981 and ending in 2001 clearly show the strong spring cycle of Asian dust transport along with the transport of high concentrations of pollutants. The presence of both dust and pollutants in the same air mass could have a great affect on Fe solubility in contrast to African dust, which is usually associated with relatively low concentrations of pollutants. Also we might expect to measure high concentrations of "industrial" iron that is known to be highly soluble. In 2001 NASA established an AERONET site on Midway; these measurements clearly document the strong impact of the spring dust/pollution transport

on the yearly cycle of AOD. Midway is now wildlife refuges under the Dept of the Interior. Regular flights to the island have resumed recently. Consequently logistics and local technical support should be good.

- \* South Pacific: Australia is believed to be the major source of dust for the South Pacific and the Southern Ocean.
- **Norfolk and Chatham Islands**: These islands are ideally suited to monitor this source. Norfolk would capture dust transport out of Australia to the northeast and Chatham Island the transport to the Southeast. The University of Miami had operated long-term sites on these islands in the past. The logistics are quite good, as is local support for operations.
- \* Indian Ocean:
  - **The Maldive Islands**: As a follow-up on the INDOEX program and under the leadership of V. Ramanathan (Scripps/UCSD), a Climate Observatory was established at Hanimadhoo Island in the northern part of in the Republic of the Maldives. The site is strongly impacted by the annual monsoon cycle. With the Northeast Monsoon it receives great quantities of dust and pollution largely transported from the Indian subcontinent, the Middle East, and North Africa. During the Southwest Monsoon the air is extremely clean. This would be an ideal region to study the effects of pollution on dust Fe solubility and the seasonal variability of impact of dust on local water biogeochemistry.
  - \* The Southern Ocean: There are not many good options in this region. Logistics are difficult and there is very little dust.
  - **Cape Grim**: The Cape Grim Baseline Air Pollution Station, located in remote northwestern Tasmania, would be ideal from the standpoint of its location with respect to Australia and the presence of a highly capable staff. But for the study of dust there are concerns about strong upslope winds that could carry local dust to the site.
  - **Reunion Island**: Reunion is well located and there is good local support. But there is not much dust in this region and sampling could be exacerbated by local impacts.
  - **Marion Island and Prince Edward Island**: These would be excellent except for very bad logistics (which may have improved since the mid-90s). Because of its location in the "roaring forties", weather is frequently rainy and often severe; consequently the air is very clean.

b) *Solubility of dust components*

There are many issues we need to understand concerning the solubility of iron. For example, what transformations affect iron solubility in the atmosphere? Can we distinguish and quantify the relative importance of mineralogy, size and atmospheric chemical processing? What are the relative contributions of desert dust and combustion/anthropogenic aerosol to the soluble iron budget? Are there anthropogenic contributions to other key elements (e.g., contributions to the load of phosphorous observed in dust events due to the use and production of fertilizers have been observed over the Indian and North Atlantic Oceans)? In this regard, we suggest specific atmospheric experiments including detailed observations and modeling (including dust and atmospheric iron processing) downwind of the two main source regions (North Africa and East Asia).

For example downwind of North Africa, four sites (Izaña, Cape Verde, Barbados and Bermuda) could be used for a coordinated experiment. Ideally, measurements would include:

- Aerosol physics: size, number, surface area and mass distributions, altitude resolved aerosol properties (lidar measurements), aerosol optical depth (sun photometer) [All of the above sites currently house AERONET sun photometers, and three (Izaña, Barbados, Bermuda) also have lidar instruments].
- Size resolved aerosol chemistry and rainfall chemistry: Total iron (and Al, Mn, Ti, P, Ca, Si, Na, micronutrient and potentially toxic trace metals) and soluble iron (and Al, Mn, Ti, P, Ca, Si, Na, micronutrient and potentially toxic trace metals) – probably by more than one method, nitrate, sulfate, oxalate, other organic acids, black carbon, organic carbon, V, K<sup>+</sup>, ammonium, organic N, organic P.
- Mineralogy: Clays, iron oxides (hematite, goethite, amorphous iron oxides)
- Aerosol Mass Spectrometry: mixing state of dust, nitrate, sulfate
- Deposition fluxes: Wet deposition and direct measurements of bulk or dry flux

*c) Dry deposition fluxes*

There is an urgent need to improve estimates of dry deposition fluxes of mineral matter to the ocean, both in terms of observational and modeling work. This field does not appear to have advanced significantly in the last ~30 years, and the use of inadequate and highly uncertain parameterizations of dry deposition velocity is commonplace. The GESAMP/SDS-WAS group is unaware of any workers currently making progress in this field.

*d) Impacts on marine biogeochemistry*

Natural dust inputs may affect primary productivity and nitrogen fixation in certain ocean regions. Experiments designed to demonstrate the impact of such events on marine ecosystems pose some significant challenges. *In situ* experiments will be logistically difficult, requiring access to the study site by a relatively large number of researchers, potentially for many weeks at

a time. Thus a large research vessel and/or easy access to a well-equipped marine laboratory will be required.

The choice of study site will also be problematic. Areas which are frequently subject to dust inputs may already have sufficient supplies of dust-borne trace elements, and thus would not show a strong response to a given deposition event, whether natural or deliberately introduced. The response of areas with less frequent (and possibly weak) dust inputs may be dependent on seasonality in dust inputs and community composition. In some circumstances it may be desirable to study the first deposition of dust to waters after a prolonged absence of dust. Perhaps the most dramatic results might be expected from studying the deposition of dust to a region that very rarely receives dust. In practice such an experiment would be very difficult to plan and conduct for a natural dust event because we are not able to reliably predict individual dust outbreak events on relevant timescales, particularly with regard to the availability of research vessels. One potential solution to this problem would be to perform “deliberate dust release” experiments, of the type already conducted for meso-scale iron enrichment experiments in the remote ocean. Such experiments would also pose significant technical problems, but a preliminary scoping study carried out by the University of East Anglia indicated that none of these problems was insurmountable.

Experiments aimed at investigating the influence of dust on primary productivity would be conducted chiefly in HNLC areas (as have iron enrichment experiments), while studies of dust/nitrogen-fixation interactions would be carried out in tropical and sub-tropical waters. A summary of the atmospheric and marine measurements that might be made during such experiments is given in the table below. The marine measurements proposed recognize the central role of iron as a micronutrient in the oceans, but also highlights the need to study other dust components, particularly the other micronutrient trace elements (e.g. Zn, Co, Cu, Cd, Ni), whose behavior will become better known in the coming years as a result of the recently started international GEOTRACES Program.

#### **Atmospheric Measurements**

Wet deposition and direct measurements of bulk or dry flux, aerosol and rainfall composition (total and soluble trace elements, inorganic and organic N and P, atmospheric N isotopes\*

*\* indicates parameters of particular importance for nitrogen-fixation studies*

#### **Marine Measurements**

Dissolved Fe & Fe-binding ligands, nitrogen fixation rate\*, marine N isotopes\*, macronutrients, trace elements/micronutrients, photosynthetic efficiency, algal and bacterial productivity, carbon export, ocean physics

Any such experiments would benefit from longer-term monitoring of atmospheric dust inputs to the study region (perhaps from nearby island monitoring sites), remote sensing of dust and ocean parameters, integrated modeling support, and ocean surveys in the study region conducted using robotic ocean gliders.

Sediment traps attached to deep-sea moorings at different depth levels are a good tool to observe changes in particle flux (lithogenic and biogenic particles) continuously. Factors controlling the particle transport in the ocean such as displacements by currents and biological processes (e.g., aggregation, disaggregation), which also affect trap efficiency, must be taken into account. At

the least, the lithogenic flux in open ocean regions can be used as an estimate for aerosol deposition to the oceans. Long-term sediment trap study sites have been established at different oceanic sites, which are influenced by dust outbreaks (e.g. Kiel 276 at 33°N and 22°W, Tropical Eastern North Atlantic Time-Series Observatory at 17.59°N and 24.25°E, Bermuda Atlantic Time Series Study at 31.67°N and 64.17°W). Those study sites are often associated with atmospheric observatories. Ocean and atmospheric observatories together with satellite and modeled dust occurrence and deposition data will help to reveal and understand the biogeochemical response to dust input.

#### 4. References

Baker, A. R., and P. L. Croot (2010), Atmospheric and marine controls on aerosol iron solubility in seawater, Mar. Chem., **120**, 4-13.

Duce, R. A., et al. (1991), The atmospheric input of trace species to the world ocean, Global Biogeochem. Cycles, **5**, 193-259.

### **E. Potential importance of volcanic emissions on marine biogeochemical cycles and clouds**

Mitsuo Uematsu (GESAMP)

#### 1. Introduction

Large volcanic eruptions have been observed and their impacts have been reported on land and they have affected peoples' lives during the past several decades. Included are such eruptions as Mt. St. Helens (USA) in 1980, Pinatubo (The Philippines) in 1991, and Mt. Eyjafjallajökull (Iceland) in 2010. Volcanoes emit a number of gases (H<sub>2</sub>O, CO<sub>2</sub>, H<sub>2</sub>S, SO<sub>2</sub>, HCl, HF, H<sub>2</sub>, N<sub>2</sub>, Ar, CH<sub>4</sub>, CO, NH<sub>3</sub>) and ash particles that contain Si, Al, Fe, Ca, and P, both through sporadic explosions and continuous eruptions. It is well known that those gases and particles affect the composition of the atmosphere and, through this, global climate. However, there is very little knowledge of their impact on the marine environment, although many volcanic activities have been reported in oceanic regions. In this brief report three case studies addressing different marine-related processes are introduced, and the importance of sporadic volcanic emission on biogeochemical cycles and climate, especially over the Pacific Ocean, are discussed.

#### 2. Case 1: Supply of nitrogen compounds

The eruption of the Miyake-jima Volcano (34.08°N, 139.53°E) in the Izu Islands, Japan, 180 km south southwest of Tokyo, began on 8 July 2000. A substantial amount of NH<sub>3</sub> gas was found to be emitted from the Miyake-jima Volcano together with SO<sub>2</sub> gas, and geochemically significant quantities of aerosol particles composed of ammonium sulfate formed in that volcanic plume. Through the use of satellite images, the additional atmospheric deposition of ammonium sulfate to the ocean caused an increase of phytoplankton in the nutrient deficient region south of the Kuroshio Current. The emission of volcanic gases from Miyake-jima has likely been modifying

marine air quality as well as the open ocean ecosystem over parts of the western North Pacific for the past several years (Uematsu et al., 2004).

### 3. Case 2: Supply of Iron

The horizontal distribution of dissolved iron in surface waters of the North Pacific Ocean have been investigated along with basic biogeochemical parameters between 40-49°N and 160-175°E in the western subarctic North Pacific during the July-August 2008. A total of 101 surface samples (depth about 1 meter) were collected using a towed fish and Teflon pumping system. Analysis of these samples produced high-resolution maps of dissolved iron, macronutrients and chlorophyll-a in this region. Dissolved iron in the surface waters was variable, ranging from 0.01 nM to 0.18 nM. Phytoplankton blooms ( $\approx 2.2 \mu\text{g Chl a L}^{-1}$ ) were dominated by large centric diatoms, and they were observed in a low salinity (33.0-33.2) water mass at 41-42.5° N along 160° E. Dissolved iron in the low salinity water ranged from 0.01-0.16 nM, with minimum values found where the chlorophyll-a concentration was highest. Another small phytoplankton bloom dominated by *prymnesiophytes* was observed near the southern boundary of a high nutrient/low chlorophyll (HNLC) region around 44.7° N along 160° E, where dissolved iron was in the 0.03-0.05 nM range. Although most of the surface water samples collected from the high nitrate (8-17  $\mu\text{M}$ ) subarctic gyre region showed low phytoplankton standing stocks (0.4-1.0  $\mu\text{g Chl a L}^{-1}$ ), a sharp increase in chlorophyll a concentration up to 2.4  $\mu\text{g L}^{-1}$  was observed over the Emperor Seamount Chain (48.6-48.8° N; 168-170° E). This phytoplankton community was primarily composed of pennate diatoms, *prymnesiophytes* and *cryptophytes*. Relatively high salinity values of the surface water over the seamount indicate that uplift of the iron-rich subsurface water stimulated phytoplankton growth over the seamount. However, surface dissolved iron concentrations were consistently low at 0.03-0.05 nM over the seamount, probably due to rapid uptake of the supplied iron by the plankton assemblage. On the other hand, atmospheric deposition of volcanic ash from Karymsky volcano, Kamchatka, Russia, was detected at 48.8° N; 168° E during the cruise. The deposition occurred 4 days before the observation of high chlorophyll waters in the same region, and the surface chlorophyll-a concentration was  $\approx 0.7 \mu\text{g L}^{-1}$  before the deposition event. Bottle incubation experiments conducted during the cruise confirmed that phytoplankton could increase their chlorophyll a biomass from 0.4  $\mu\text{g L}^{-1}$  to  $>2 \mu\text{g L}^{-1}$  within 3 days if sufficient iron ( $\approx 2 \text{ nM}$ ) was added. These results suggest that iron released from volcanic ash could also play an important role in phytoplankton production in these HNLC waters (Takeda et al., 2010).

### 4. Case 3: Effect on marine clouds

Kilauea Volcano on Hawaii Island in the Hawaiian Islands experienced an active eruption from 19 March until the end of December 2008. The eruption released approximately  $1.8 \times 10^6$  tons of  $\text{SO}_2$ , which was oxidized to sulfate aerosol during transport to the northwest Pacific Ocean. The volcanic sulfate aerosol layer covered a large area ( $\sim 6.5 \times 10^6 \text{ km}^2$ ) of the lower troposphere over the North Pacific for several months. The sulfate aerosol affected the formation of cumulus water clouds by reducing the typical cloud droplet effective radius by  $\sim 25\%$  and increasing the

cloud fractional coverage over the ocean from 9.9% to 13.4% (over the region 170°E-160°W, 10°N-20°N). The affected cumulus clouds appeared whiter than normal and thus reflected more solar radiation. Consequently, satellite observations revealed an approximately 1% increase in albedo at the top of the atmosphere to the west of the Island of Hawaii (over the region 170°W-155°W, 18°N-20°N), which induced a  $\sim -5 \text{ W m}^{-2}$  change in the shortwave radiation budget. Modeled daily average incoming surface shortwave radiation for the same region was also diminished by  $\sim 5 \text{ W m}^{-2}$  and the sea surface cooled by  $\sim 0.1 \text{ K month}^{-1}$ . This large impact of the Kilauea eruption may also have affected the oceanic environment (Eguchi et al., 2011).

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## **F. Policy considerations**

Atmospheric mineral dust originates from very specific source areas and is then transported over long distances, influencing the climate and chemistry of the atmosphere on local, regional, and global scales. It has implications for human health, visibility, and climate. It also provides essential components for ocean fertility, primarily the micronutrient iron. Policy-makers must be aware of the importance of atmospheric mineral dust and its wide range of environmental impacts.

Continued support for research on mineral dust has multiple benefits ranging from improving short-term forecasting to improved understanding of the role of mineral dust in supplying nutrients to the world's oceans. Recently, supplying iron to iron-depleted regions was proposed as a form of *geo-engineering* to remove carbon dioxide from the atmosphere. While a discussion of the pros and cons of this approach is beyond the scope of this document, clearly an improved understanding of the role of mineral dust and related processes will inform a balanced decision-making.

Measurements on various times scales have suggested strong correlations of dust emissions, transport and deposition with climate change. Models have severe difficulties in reproducing these relationships, possibly due to anthropogenic activities unrelated to climate not being sufficiently included in these models. Therefore, despite reasonable performance under current conditions, the predictive capacity of models for future conditions is highly uncertain. Given the

importance of dust in the earth system, including deposition to the oceans, it is one of the primary uncertainties in future climate change conditions.

The increased supply of dissolved phosphorus from atmospheric anthropogenic sources (through large-scale use in fertilizers) may also have a significant impact on ocean surface biogeochemistry. Model simulation studies for future scenarios are highly uncertain due to the extreme variability on the regional scale. We emphasize the need for the development of chemistry-driven atmospheric transport models and measurement parameters for improving our understanding of the impacts of the atmospheric deposition of dust/Fe/P to the ocean.

The lack of high quality, harmonized deposition measurements available for model verification is a serious issue. It is recommended to use the existing WMO GAW sites for extended measurements pertaining to dust deposition and the related ocean biological and physical parameters. Additional atmospheric sampling sites, especially in the Southern Hemisphere, are necessary. Therefore continuing long-term observations remains of highest priority, both for improving models and monitoring future changes.

Finally, institutional support for assessment activities, intercomparisons, and appropriate identification and documentation of models and measurements, remains a high priority. This is necessary to ensure an improved understanding of the role of dust on longer time scales.

## Appendix I

### Attendees at the Malta Meeting

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## Appendix II

### List of Representative Papers that Address the Impact of Dust Deposition on Marine Biogeochemistry

**Abbreviations:**

AOD: aerosol optical depth

CCN: cloud condensation nuclei

DMS: Dimethyl sulfide

HNLC: high nitrate low chlorophyll

SIZ: sea-ice zone

SOA: South Atlantic Ocean/ SO: Southern Ocean

*Note: References of relevance for ocean response, although not directly demonstrating the ocean response, are given in italics.*

Authors	Title	Contents	Publication
O. Aumont L. Bopp M. Schulz	What does temporal variability in aeolian dust deposition contribute to sea-surface iron and chlorophyll distributions?	<ul style="list-style-type: none"> <li>- global model of ocean biogeochemistry forced with daily fields of dust deposition to investigate impact of variability of dust deposition (1996-2001)</li> <li>- dust deposition explains a large part of the temporal variability of surface iron in the tropical regions and in part of the subarctic Pacific</li> <li>- while dust deposition is dominated by daily events, its impact on surface iron is maximal on interannual timescales</li> <li>- largest fluctuations of surface iron produced by dust occur in oligotrophic regions where phytoplankton growth is not primarily controlled by iron availability → variability of surface chlorophyll induced by aerosol iron is predicted to be very small everywhere</li> </ul>	Geophysical Research Letters, Vol. 35, L07607; 2008 doi: 10.1029/2007GL031131
A.R. Baker P.L. Croot	Atmospheric and marine controls on aerosol iron solubility in seawater	<ul style="list-style-type: none"> <li>- fraction of atmospheric deposited iron plays a keyrole for the productivity in many open ocean regions</li> <li>- basic idea and interactions of solubility of iron in seawater is presented</li> <li>- experimental methods for the determination of iron solubility is discussed</li> </ul>	Marine Chemistry, Vol. 120, Issues 1-4, pp. 4-13; 2008 doi: 10.1016/j.marchem.2008.09.003

J.K.B. Bishop R.E. Davis J.T. Sherman	Robotic Observations of Dust Storm Enhancement of Carbon Biomass in the North Pacific	<ul style="list-style-type: none"> <li>- investigations with two autonomous robotic profiling floats (subarctic North Pacific, 10 April 2001, 8 months) → records of carbon biomass variability from surface to 1000 meters below surface</li> <li>- marine biological response to dust event (passage of Gobi desert dust cloud) → near doubling of biomass in the mixed layer over a 2-week period</li> <li>→ temporal evolution of particulate organic carbon enhancement and an increase in chlorophyll use efficiency ↔ natural iron fertilization by the dust</li> </ul>	Science, Vol. 298, no. 5594, pp. 817-821; 2002 doi: 10.1126/science.1074961
N. Cassar M.L. Bender B.A. Barnett S. Fan W.J. Moxim H. Levy II B. Tilbrook	The Southern Ocean Biological Response to Aeolian Iron Deposition	<ul style="list-style-type: none"> <li>- gross primary production and net community production (comparable to export production) are compared with model estimates of dissolved iron over large areas of the Southern Ocean → export production is proportional to modeled input of soluble iron in aerosols (fertilization due to addition of aerosol iron)</li> <li>- aerosol iron input particularly enhances gross primary production over the large area of the Southern Ocean downwind of dry continental areas → sequestration of carbon dioxide</li> <li>→ may have been a major cause of the reduction of atmospheric CO<sub>2</sub> during the ice ages</li> </ul>	Science, Vol. 317, no. 5841, pp. 1067-1070; 2007 doi: 10.1126/science.1144602
F. Chai M.-S. Jiang Y. Chao R.C. Dugdale F. Chavez R.T. Barber	Modeling responses of diatom productivity and biogenic silica export to iron enrichment in the equatorial Pacific Ocean	<ul style="list-style-type: none"> <li>- Diatoms contribute to the initial increase of the total phytoplankton biomass due to iron enhancement, but decrease sharply after 10 days because of mesozooplankton grazing (grazing pressure prevents significant phytoplankton biomass accumulation)</li> <li>- increasing mesozooplankton grazing rate, the diatom increase due to iron addition stays at minimum level, but small phytoplankton tend to increase</li> <li>- larger size of the iron patch tends to produce a broader extent and longer-lasting phytoplankton blooms</li> <li>- modeled depth-time distribution of sinking biogenic silica (BSi) indicates that it would take more than 30 days after iron injection to detect any significant BSi export out of the euphotic zone</li> </ul>	Global Biogeochemical Cycles, Vol. 21, GB3S90; 2007 doi: 10.1029/2006GB002804
S.C.Doney I. Lima R.A. Feely D.M. Glover K. Lindsay N. Mahowald J.K. Moore R. Wanninkhof	Mechanisms governing interannual variability in upper-ocean inorganic carbon system and air-sea CO <sub>2</sub> fluxes: Physical climate and atmospheric dust	<ul style="list-style-type: none"> <li>- presentation of a systematic global analysis of the magnitude and processes governing carbon system variability on subannual to decadal time-scales</li> <li>- mechanisms governing interannual variability in the upper-ocean carbon system and air-sea CO<sub>2</sub> flux differ with region (major regions: Southern Ocean, tropical Indo-Pacific, and Northern Hemisphere temperate and subpolar latitudes)</li> <li>- Ocean circulation is the dominant underlying factor driving biogeochemical variability over most of the ocean</li> <li>- Variations in atmospheric iron deposition downwind of dust source regions generate substantial variability in ocean export production and air-sea CO<sub>2</sub> flux in</li> </ul>	Deep-Sea Research II, 56, pp. 640-655; 2009 doi: 10.1016/j.dsr2.2008.12.006

		HNLC in the Southern Ocean, equatorial Pacific and subpolar North Pacific - reduced global dust deposition (beginning in the mid 1990s) generates increased air-sea CO <sub>2</sub> outgassing in the Southern Ocean	
D.J. Erickson III J.L. Hernandez P. Ginoux W.W. Gregg C. McClain J. Christian	Atmospheric iron delivery and surface ocean biological activity in the Southern Ocean and Patagonian region	- iron is a limiting nutrient for biologic activity in many parts of the world ocean - correlation analysis to clarify the spatial response of chlorophyll concentrations to iron flux in oceanic biogeochemistry → several regions between 40°S and 60°S show correlations from 0.6 to 0.95 (significant at the 0.05 level), particularly the Patagonian region - surface chlorophyll and iron flux follow similar patterns (chlorophyll may be displaced to different latitudes due to meridional ocean transport) - dust deposition of Fe may occur in one region and then ocean circulation moves the fertilized water mass away from the area of highest Fe flux → non-co-location of high CHL and high dust flux	Geophysical Research Letters, Vol. 30, no. 12, pp. 1609-1613; 2003 doi: 10.1029/2003GL017241
S. Fan W.J. Moxim H. Levy II	Aeolian input of bioavailable iron to the ocean	- soluble Fe fraction increases with transport time from the source region and with the corresponding decrease in dust concentration → small Fe solubility and large dust deposition near the sources → large Fe solubility corresponding to smaller dust deposition distant from source regions - anthropogenic emissions of SO <sub>2</sub> and NO should have caused a significant increase in hematite dissolution and soluble Fe input to the North Atlantic and North Pacific Oceans since the industrial revolution - re-mineralization of organic matter in the mixed layer does not lead to significant iron recycling	Geophysical Research Letters, Vol. 33, L07602; 2006 doi: 10.1029/2005GL024852
A.J. Gabric R.A. Cropp G.H. McTainsh B.M. Johnston H. Butler B. Tilbrook M. Keywood	Australian dust storms in 2002–2003 and their impact on Southern Ocean biogeochemistry	- 2002-2003 most active dust storm seasons in the last 40 years in Australia → large dust plumes advected over the adjacent SO → large scale natural dust fertilization in the Australian sector of the SO ↔ importance of dust derived nutrients in the marine carbon cycle of the SO - dust storm events that were advected south in late October, early November and January had a clear affect on AOD values in the 40°-45°S and 45°-50°S bands → strong coherence between the optical characteristics of the SO atmosphere and dust loading - satellite and field data on surface chlorophyll indicate a significant biological response (unusually strong south of 50°S), associated with a strong CO <sub>2</sub> drawdown	Global Biogeochemical Cycles, Vol. 24, GB2005; 2010 doi:10.1029/2009GB003541
A.J. Gabric J.M. Shephard J.M. Knight G. Jones A.J. Trevena	Correlations between the satellite-derived seasonal cycles of phytoplankton biomass and aerosol optical depth in the	- the production of DMS is related to atmospheric sulfate aerosols in the upper ocean (confirmed through shipboard measurements, global modelling) - correlation between surface chlorophyll (CHL) and AOD is analysed - mean CHL and AOD time series (1997-2004) are strongly coherent in the band between 50°S and 60°S (with absence in the SIZ south of 60°S)	Global Biogeochemical Cycles, Vol. 19, GB4018, pp. 10; 2005 doi: 10.1029/2005GB002546

	Southern Ocean: Evidence for the influence of sea ice	<ul style="list-style-type: none"> <li>- interannual variability in CHL occurs in the SIZ related to the variability in sea-ice production during the previous winter</li> <li>- clear latitudinal difference in the cross correlation between CHL and AOD, with the AOD peak preceding the CHL bloom by up to 6 weeks in the SIZ → substantial trace gas emissions (aerosol precursors) are being produced over the SIZ in spring (October–December) as sea ice melts</li> </ul>	
A.J. Gabric R. Simó R.A. Cropp A.C. Hirst J. Dachs	Modeling estimates of the global emission of dimethylsulfide under <b>enhanced greenhouse conditions</b>	<ul style="list-style-type: none"> <li>- presentation of a modeling analysis of the global DMS response to simulate climate change (marine food-web model, an atmosphere-ocean general circulation model (GCM), and an empirical dimethylsulfide (DMS) algorithm used)</li> <li>- predict the DMS seawater concentration and the DMS sea-to-air flux in 10° latitude bands from 70°N to 70°S under contemporary and enhanced greenhouse conditions (changes to nutrients not explicitly included)</li> <li>- strong regional variability in the simulated DMS flux response, with little change in the tropics and major increases predicted at high latitudes → future increases in stratification in the polar oceans will play a critical role in the DMS cycle and climate change</li> <li>- ecological data indicate that planktonic populations can respond extremely sensitively and quickly to ocean variability</li> </ul>	Global Biogeochemical Cycles, Vol. 18, GB2014; 2004 doi: 10.1029/2003GB002183
A.J. Gabric R. Cropp G.P. Ayers G. McTainsh R. Braddock	Coupling between cycles of phytoplankton biomass and aerosol optical depth as derived from SeaWiFS time series in the Subantarctic Southern Ocean	<ul style="list-style-type: none"> <li>- the Subantarctic Southern Ocean is a high-nutrient low-chlorophyll region → primary production is limited by deep mixing and the availability of iron (can be transported by Australian dust, particularly during the austral spring and summer)</li> <li>- coupling between satellite-derived (SeaWiFS) aerosol optical thickness and chlorophyll concentration in the upper ocean at monthly, weekly and daily timescales → episodic atmospheric delivery of iron is stimulating phytoplankton growth</li> </ul>	Geophysical Research Letters, Vol. 29, pp. 1112-1116; 2002 doi: 10.1029/2001GL013545
S. Gassó A.F. Stein	Does dust from Patagonia reach the sub-Antarctic Atlantic Ocean?	<ul style="list-style-type: none"> <li>- difficult to determine Patagonian dust by satellite measurements (clear sky condition needed, no black background (sea-ice), dust emission short lived) → combined approach of different satellite detectors aided by an aerosol transport model</li> <li>- observations confirm that dust advects through the SW Atlantic Ocean and can reach the area around the biological rich sub-Antarctic Ocean within 30 hours of emission</li> </ul>	Geophysical Research Letters, Vol. 34, L01801; 2007 doi: 10.1029/2006GL027693
<i>H.R. Gordon</i>	<i>Atmospheric correction of ocean color imagery in the Earth Observing System era</i>	<ul style="list-style-type: none"> <li>- <i>to realize an improvement in the retrieval of biologically important ocean parameters, e.g., the concentration of the photosynthetic pigment chlorophyll a, from this increased sensitivity, significantly better atmospheric correction than was applied to CZCS (coastal zone color scanner) is required</i></li> <li>- <i>inclusion of the effects of multiple scattering, which are strongly dependent on the aerosol size distribution, concentration, and absorption properties are</i></li> </ul>	<i>Journal of Geophysical Research, Vol. 102, no. D14, pp. 17,081-17,106; 1997</i> doi: 10.1029/96JD02443

		<p><i>necessary</i></p> <ul style="list-style-type: none"> <li>- <i>SeaWiFS, MODIS, and MISR algorithms are pre-requisites</i></li> <li>- <i>related issues such as the influence of aerosol vertical structure in the troposphere, polarization of the light field, sea surface roughness, and oceanic whitecaps on the sea surface are evaluated and plans for their inclusion in the algorithm are described</i></li> </ul>	
<p>C.O. Jo J.-Y. Lee K.-A. Park Y.H. Kim K.-R. Kim</p>	<p>Asian dust initiated early spring bloom in the northern East/ Japan Sea</p>	<ul style="list-style-type: none"> <li>- data for the TOMS aerosol index and SeaWiFS chlorophyll indicate that an early spring bloom in the northern East/Japan Sea can be initiated during the Asian dust event in association with precipitation (one month earlier than the bloom during non-dust event years)</li> <li>- normally initiated in this area as the surface mixed layer becomes shallower than critical depth, earlier bloom coincided with deepening of critical depth → supply of bio-available nutrients such as iron through wet deposition induces deepening of the critical depth, which results in an early initiation of the bloom</li> </ul>	<p>Geophysical Research Letters, Vol. 34, L05602; 2007 doi: 10.1029/2006GL027395</p>
<p>M.S. Johnson N. Meskhidze V.P. Kiliyanpilakkil S. Gassó</p>	<p>Understanding the transport of Patagonian dust and its influence on marine biological activity in the South Atlantic Ocean</p>	<ul style="list-style-type: none"> <li>- simulations (2009) indicate that the synoptic meteorological patterns of high and low pressure systems are largely accountable for dust transport trajectories over the SAO → South American dust plumes are elevated above the marine boundary layer → bulk concentration of mineral dust can quickly reach the HNLC waters of the SAO and Antarctica in ~3–4 days after emission from the source regions of Northern Patagonia</li> <li>- the effect of iron-laden mineral dust supply on surface ocean biomass is investigated by comparing predicted surface chlorophyll-<i>a</i> concentration ([Chl-<i>a</i>]) to remotely-sensed data</li> <li>- this study suggests that: <ul style="list-style-type: none"> <li>(1) atmospheric fluxes of mineral dust from Patagonia are not likely to be the major source of bioavailable iron to ocean regions characterized by high primary productivity</li> <li>(2) Patagonian dust plumes could still influence background [Chl-<i>a</i>] in the South Atlantic sector of the SO</li> </ul> </li> </ul>	<p>Atmospheric Chemistry and Physics, Vol. 11, pp. 2487-2502; 2011 doi: 10.5194/acp-11-2487-2011</p>

<p>M.S. Johnson N. Meskhidze F. Solmon S. Gassó P.Y. Chuang D.M. Gaiero R.M. Yantosca S. Wu Y. Wang C. Carouge</p>	<p>Modeling dust and soluble iron deposition to the South Atlantic Ocean</p>	<p>- the global chemical transport model GEOS-Chem (+ dust-iron dissolution scheme) was used - dissolved iron fraction of mineral dust over the SAO was small (on average only accounting for 0.57% of total iron) ↔ low ambient concentrations of acidic trace gases available for mixing with dust plumes, not enough to overcome the alkalinity buffer of Patagonian dust and initiate considerable acid dissolution of mineral-iron - sol-Fe deposited to the SAO was largely controlled by the initial amount of sol-Fe at the source region → Patagonian dust should have a minor effect on biological productivity in the SAO</p>	<p>Journal of Geophysical Research, Vol. 115, D15202, pp. 13; 2010 doi: 10.1029/2009JD013311</p>
<p>Y. Iwamoto K. Yumimoto M. Toratani A. Tsuda K. Miura I. Uno M. Uematsu</p>	<p>Biogeochemical implications of increased mineral particle concentrations in surface waters of the northwestern North Pacific during an Asian dust event</p>	<p>- mineral dust aerosols were scavenged by sea fog, and their deposition to the ocean increased the particle concentration in surface seawater - a general relationship for the solubility of iron from dust particles led to an estimate of 20 to 330 <math>\mu\text{g m}^{-2}</math> for the amount of bio-available iron delivered during the dust event (comparable to total dissolved iron added during an iron fertilization experiment in the northwestern North Pacific)</p>	<p>Geophysical Research Letters, Vol. 38, L01604, pp. 5; 2011 doi:10.1029/2010GL0459062011</p>
<p>A. Kumar M.M. Sarin</p>	<p><i>Aerosol iron solubility in a semi-arid region: Temporal trend and impact of anthropogenic sources</i></p>	<p>- 1-yr chemical data for the fine mode (<math>\text{PM}_{2.5}</math>) air-borne particulate matter in a semi-arid region of western India - inverse relationship between aerosol Fe and fractional Fe solubility (range: 0.06–16.1%) - increase in the solubility of iron, during wintertime, is marked by a uniform decrease in the mass fraction of mineral dust → advective transport of pollutants and Fe derived from combustion sources is one of the possible causes for the enhanced solubility of iron over a semi-arid region in western India</p>	<p>Tellus-B 62B, pp. 125-132 ; 2010 doi: 10.1111/j.1600-0889.2009.00448</p>
<p>A. Kumar M.M. Sarin</p>	<p><i>Atmospheric water-soluble constituents in fine and coarse aerosols from high-altitude site in western India: Long-range transport and seasonal variability</i></p>	<p>- one-year data set on water-soluble ionic species in <math>\text{PM}_{2.5}</math> (fine) and <math>\text{PM}_{10-2.5}</math> (coarse) aerosols from a high-altitude site in high-dust region of western India - the water-soluble ionic composition varied from 1.0 to 19.5 <math>\mu\text{g m}^{-3}</math> in the fine mode and constitutes 50, 39 and 31% of the aerosol mass during winter, summer and monsoon respectively, with dominant contribution from <math>\text{SO}_4^{2-}</math>, <math>\text{NH}_4^+</math> and <math>\text{HCO}_3^-</math> - twofold increase (relative to high-dust conditions in summer) in the abundances of <math>\text{nss-SO}_4^{2-}</math> and <math>\text{NH}_4^+</math> and their co-variability during wintertime → dominance of anthropogenic sources and long-range transport of combustion products - the water-soluble ionic composition varied from 0.1 to 24.8 <math>\mu\text{g m}^{-3}</math> in the coarse mode and constitutes 21% of the aerosol mass at annual average, with dominant</p>	<p>Atmospheric Environment, Vol. 44, pp. 1245-1254; 2010 doi: 10.1016/j.atmosenv.2009.12.035</p>

		<p>contribution from <math>\text{Ca}^{2+}</math> and <math>\text{HCO}_3^-</math></p> <ul style="list-style-type: none"> <li>- <math>\text{nss-SO}_4^{2-}/\text{NO}_3^-</math> mass ratio extreme variable during winter</li> <li>- high abundance of nitrate in the coarse mode, during all seasons → association with mineral dust</li> <li>- near quantitative neutralization of acidic species (<math>\text{NO}_3^-</math> and <math>\text{SO}_4^{2-}</math>) by <math>\text{NH}_4^+</math> in <math>\text{PM}_{2.5}</math> and mineral dust in <math>\text{PM}_{10-2.5}</math>, representing a dominant atmospheric chemical transformation process occurring in the high-dust semi-arid region</li> </ul>	
A. Kumar M.M. Sarin	Mineral aerosols from western India: Temporal variability of coarse and fine atmospheric dust and elemental characteristics	<ul style="list-style-type: none"> <li>- <math>\text{PM}_{2.5}</math> and <math>\text{PM}_{10}</math> samples collected in India (Jan–Dec-2007)</li> <li>- dominant and uniform contribution of mineral dust (60–80%) in the coarse mode relative to large temporal variability (11–75%) observed in the fine mode</li> <li>- coarse mass fraction: characteristic increase with the wind speed during summer months (Mar to Jun)</li> <li>- fine aerosol mass: temporal pattern associated with north-easterlies during wintertime (Oct–Feb)</li> <li>- relative enrichment of Fe in fine mode Fe/Al weight ratio during winter months due to the down-wind advective transport of combustion products derived from large-scale biomass burning, industrial and automobile emission sources (northern India)</li> <li>- relative enrichment of Ca and Mg in the coarse mode Ca/Al and Mg/Al weight ratios shows dominant contribution from carbonate minerals</li> </ul>	Atmospheric Environment, Vol. 43, pp. 4005-4013; 2009 doi:10.1016/j.atmosenv.2009.05.014
A. Kumar M.M. Sarin A.K. Sudheer	Mineral and anthropogenic aerosols in Arabian Sea-atmospheric boundary layer: Sources and spatial variability	<ul style="list-style-type: none"> <li>- chemical characteristics of aerosols in the Arabian Sea–atmospheric boundary layer (AABL) have been studied during the spring inter-monsoon (April and May 2006) based on the analysis of water-soluble constituents (<math>\text{Na}^+</math>, <math>\text{NH}_4^+</math>, <math>\text{K}^+</math>, <math>\text{Mg}^{2+}</math>, <math>\text{Ca}^{2+}</math>, <math>\text{Cl}^-</math>, <math>\text{NO}_3^-</math>, <math>\text{SO}_4^{2-}</math>), crustal elements (Al, Fe, Ca), and carbonaceous species (EC, OC)</li> <li>- the water-soluble species account for 35% of the total suspended particulate (TSP); with dominant contribution of <math>\text{Ca}^{2+}</math> and <math>\text{SO}_4^{2-}</math> followed by <math>\text{Na}^+</math> and minor contributions of <math>\text{K}^+</math>, <math>\text{Mg}^{2+}</math>, <math>\text{Cl}^-</math>, and <math>\text{NO}_3^-</math> (22 days cruise covering a latitudinal transect from 9°N to 22°N)</li> <li>- the abundances of <math>\text{Ca}^{2+}</math> and <math>\text{SO}_4^{2-}</math> do not exhibit any noticeable latitudinal distribution pattern but the non-sea-salt (nss) component constitutes 85–90% of their total concentration, indicating dominant transport from continental sources</li> <li>- a significant linear positive correlation among <math>\text{nss-Ca}^{2+}</math> and <math>\text{nss-SO}_4^{2-}</math>, and <math>\text{nss-Ca}^{2+}/\text{nss-SO}_4^{2-}</math> molar ratio averaging around 0.61 (range: 0.20–1.16) suggests uptake of anthropogenic <math>\text{SO}_4^{2-}</math> by mineral dust (<math>\text{CaCO}_3</math>)</li> <li>- on average, mineral dust accounts for 44% of the TSP (relatively high abundance occurring over the south Arabian Sea) and Fe/Al weight-ratio exhibit characteristic narrow range: 0.40–0.59</li> </ul>	Atmospheric Environment, Vol. 42, pp. 5169-5181; 2008 doi: 10.1016/j.atmosenv.2008.03.004

		- the impact of carbonaceous species (EC and OC) is nowhere pronounced in the AABL	
A.Kumar M.M. Sarin B. Srinivas	Aerosol iron solubility over Bay of Bengal: Role of anthropogenic sources and chemical processing	- chemical composition (involving water-soluble inorganic constituents, crustal elements and carbonaceous species) of size-segregated aerosols ( $PM_{10}$ and $PM_{2.5}$ ), collected from the marine atmospheric boundary layer (MABL) of the Bay of Bengal (BoB) has been studied (27th Dec 08–28th Jan 09) → factors controlling the spatio-temporal variability in the fractional solubility of aerosol iron - significant linear relationship among fractional Fe solubility [WS-Fe (%)] and $nss-SO_4^{2-}$ over N-BoB (characterized by higher abundance of aerosol iron ( $Fe_A$ ) and $SO_4^{2-}$ ) provides evidence for the acid processing of mineral dust during atmospheric transport from Indo-Gangetic Plain - temporal shift in the winds exhibit enhanced fractional solubility of aerosol Fe associated with the lower abundance of dust and $nss-SO_4^{2-}$ - observations suggest the dominance of combustion sources (biomass burning and fossil-fuel) in dictating the aerosol iron solubility over south Bay of Bengal → impact of the anthropogenic sources is also ascertained based on the covariance of WS-Fe with $K^+$ and OC (organic carbon); as well as enrichment factor of heavy metals (Pb and Cd) associated with the outflow from south-east Asia	Marine Chemistry, Vol. 121, pp. 167-175; 2010 doi: 10.1016/j.marchem.2010.04.005
P.J. Lam J.K.B. Bishop	The continental margin is a key source of iron to the HNLC North Pacific Ocean	- FeP = tracer for the delivery of total Fe, also retains the memory of its source through its chemical speciation - calculations show that subsurface Fe delivery from the shelf is likely as important a source of bioavailable iron to the HNLC WSP gyre than dust - this subsurface supply of iron is shallow enough to be accessible to the surface through winter upwelling and vertical mixing (key source of bioavailable Fe to the HNLC North Pacific) - strong lateral advection of labile Mn and Fe from redox-mobilized labile sources at the continental shelf supplemented by a more variable source of Fe from the upper continental slope	Geophysical Research Letters, Vol. 35, L07608; 2008 doi: 10.1029/2008GL033294
P.J. Lam J.K.B. Bishop C.C. Henning M.A. Marcus G.A. Waychunas I.Y. Fung	Wintertime phytoplankton bloom in the subarctic Pacific supported by continental margin iron	- first evidence of the delivery and importance of iron from the continental margin and its arrival at OSP in the open HNLC subarctic Pacific - the entire continental shelf from California to the Aleutian Islands may be a source of additional iron in winter to the North Pacific → degree of iron limitation in the subarctic Pacific is not constant through the year and productivity can be boosted by different natural iron sources in different seasons - the wintertime delivery of bioavailable iron to the subarctic Pacific may address the paradox of why wintertime chlorophyll levels in subpolar HNLC regions are so high despite light limitation - the effects of shelf were found to be limited to coastal regions because the	Global Biogeochemical Cycles, Vol. 20, GB1006; 2006 doi:10.1029/2005GB002557

		sedimentary iron was quickly scavenged out of the water column → the sensitivity of global ocean primary production to the shelf iron source was low - iron from shelf and continental sources is affecting the productivity of open ocean HNLC regions far (hundreds of kilometers) downstream	
C. Mahaffey R.G. Williams G.A. Wolff N. Mahowald W. Anderson M. Woodward	Biogeochemical signatures of nitrogen fixation in the eastern North Atlantic	- isotopic signal (low natural abundance of <sup>15</sup> N relative to <sup>14</sup> N) over the eastern North Atlantic (between 26°N and 32°N along 20°W) in spring 2000 leads together with phytopigment data and nitrate to phosphate ratios in the upper thermocline to the suggestion that nitrogen fixation provides a local dominant supply of nitrogen to phytoplankton over part of the eastern North Atlantic - biogeochemical proxies are coincident with enhanced atmospheric dust deposition → atmospheric dust events may spatially and temporally constrain the distribution of N <sub>2</sub> fixers	Geophysical Research Letters, Vol. 30, no. 6, 1300; 2003 doi: 10.1029/2002GL016542
N.M. Mahowald S. Kloster S. Engelstaedter J.K. Moore S. Mukhopadhyay J.R. McConnell S. Albani S.C. Doney A. Bhattacharya M.A.J. Curran M.G. Flanner F.M. Hoffman D.M. Lawrence K. Lindsay P.A. Mayewski J. Neff D. Rothenberg E. Thomas P.E. Thornton C.S. Zender	<i>Observed 20<sup>th</sup> century desert dust variability: impact on climate and biogeochemistry</i>	- reconstruction of desert dust variability over the 20th century based on observational and model synthesis - most important: North African, East Asian and Middle East/Central Asian sources - the results suggest that desert dust roughly doubled over the 20th century over much, but not all the globe - largest estimated differences: between the dusty 1980–1989 period compared to the relatively dust-free 1955–1964 period - including desert dust fluctuations in climate model simulations improves our ability to simulate decadal scale variability in global surface temperature, regional changes in temperature and precipitation and possibly explains the residual global carbon flux unexplained by other mechanisms	<i>Atmospheric Chemistry and Physics, Vol. 10, pp. 10875–10893; 2010</i> doi: 10.5194/acp-10-10875-2010
N. Mahowald K. Lindsay D. Rothenberg S.C. Doney J.K. Moore P. Thornton	<i>Desert dust and anthropogenic aerosol interactions in the Community Climate System Model coupled-carbon-climate model</i>	- the globally averaged climate and carbon is not significantly perturbed - the CCSM3.1 model has a slightly negative sensitivity to climate (i.e., more climate change means more carbon is taken up), due partly to the N-limitation in the land model, and partly due to a slow uptake by the oceans - the impact of aerosols onto the coupled-climate-carbon cycle may be largely explained by the globally averaged cooling from the aerosols, and is proportional	<i>Biogeosciences, Vol. 8, pp. 387–414; 2011</i> doi: 10.5194/bg-8-387-2011

<p>J.T. Randerson C.D. Jones</p>		<p><i>to the climate impact on the carbon cycle</i></p> <ul style="list-style-type: none"> <li>- there are globally significant changes in carbon which are likely to be due to changes in regional climate driven by aerosols, or by changes in diffuse and direct radiation</li> <li>- inclusion of realistic desert dust cycling does significantly impact the ocean biogeochemistry in our simulations, in terms of the nitrogen fixation and the ocean productivity</li> <li>- having interactive dust and anthropogenic aerosols is as important or more important as changes in carbon dioxide and the resulting climate changes to the nitrogen cycle and productivity in our model</li> <li>- many changes to ocean biogeochemistry seem to occur due to physical forcing of climate by aerosols instead of purely from the addition of iron</li> </ul>	
<p>E. Marañón A. Fernández B. Mouriño-Carballido S. Martínez-García E. Teira P. Cermeño P. Chouciño M. Huete-Ortega E. Fernández A. Calvo-Díaz X.A.G. Morán A. Bode E. Moreno-Ostos M.M. Varela M.D. Patey E.P. Achterberg</p>	<p>Degree of oligotrophy controls the response of microbial plankton to Saharan dust</p>	<ul style="list-style-type: none"> <li>- oligotrophy: lack of nutrients</li> <li>- different groups of phytoplankton and bacterioplankton responded differently to Saharan dust addition, although bulk abundance and biomass tended to remain unchanged</li> <li>- the relative increase in bacterial production, which was the dominant response to dust addition in ultraoligotrophic environments, became larger with increasing oligotrophy. In contrast, primary production, which was stimulated only in the least oligotrophic waters, became less responsive to dust as the ecosystem's degree of oligotrophy increased</li> <li>→ given the divergent consequences of a predominantly bacterial vs. phytoplanktonic response, dust inputs can, depending on the ecosystem's degree of oligotrophy, stimulate or weaken biological CO<sub>2</sub> drawdown</li> </ul>	<p>Limnology and Oceanography, Vol. 55(6), pp. 2339–2352; 2010 doi: 10.4319/lo.2010.55.6.2339</p>
<p>N. Meskhidze W.L. Chameides A. Nenes</p>	<p>Dust and pollution: A recipe for enhanced ocean fertilization?</p>	<ul style="list-style-type: none"> <li>- Fe solubilization in deliquesced mineral dust aerosols emanating from East Asia during the springtime outflow conditions is investigated with a Lagrangian box model of the gas and aqueous-phase chemistry (simulates scavenging, chemical reactions and dissolution of Fe-III oxides due to acid mobilization)</li> <li>- SO<sub>2</sub> pollutant emissions are a potential source of acidity to advecting dust from East Asia</li> <li>- only plumes with relatively high initial SO<sub>2</sub>-to-dust ratios are capable of delivering significant amounts of bioavailable Fe to the NPO</li> <li>- large dust advection episodes should have insignificant dissolved iron fraction</li> </ul>	<p>Journal of Geophysical Research, Vol. 110, D03301; 2005 doi:10.1029/2004JD005082</p>

		<p>(DIF) as the amount of SO<sub>2</sub> required to acidify such dust plumes is about an order of magnitude higher than what can typically be entrained in the plume during its advection</p> <ul style="list-style-type: none"> <li>- smaller dust plumes will generally have higher DIFs because they require lower amounts of SO<sub>2</sub> and, even if such small plumes may not cause algae blooms, they could still be important sources of dissolved Fe to the NPO</li> <li>→ future changes in SO<sub>2</sub>-pollutant emissions from East Asia may affect the productivity of the NPO</li> </ul>	
<p>N. Meskhidze A. Nenes W.L. Chameides C. Luo N. Mahowald</p>	<p>Atlantic Southern Ocean productivity: Fertilization from above or below?</p>	<ul style="list-style-type: none"> <li>- two sources of Fe for the surface waters of the SO have been proposed: (1) oceanic input (upwelling of nutrient-rich water, lateral flows from continental margins) (2) atmospheric input</li> <li>- upwelling of nutrient-rich water is the predominant source of bioavailable Fe in the surface waters of the south Atlantic Ocean</li> <li>- acidification of aeolian dust may be required to solubilize the large fraction of mineral-iron and make it bioavailable</li> </ul>	<p>Global Biogeochemical Cycles, Vol. 21, GB2006; 2007 doi:10.1029/2006GB002711</p>
<p>J.K. Moore O. Braucher</p>	<p>Sedimentary and mineral dust sources of dissolved iron to the world ocean</p>	<ul style="list-style-type: none"> <li>- fluxes from continental margins and mineral dust deposition are key sources of dissolved iron to the oceans ↔ primary production, biological carbon export and nitrogen fixation (global scale)</li> <li>- calculation of the relative importance of dust deposition vs. sedimentation (on an annual basis)</li> </ul>	<p>Biogeosciences, Vol. 5, pp. 631–656; 2008 doi: 10.5194/bg-5-631-2008</p>
<p>A. Nenes M.D. Krom N. Mihalopoulos P. Van Cappellen Z. Shi A. Bougiatioti P. Zampas B. Herut</p>	<p>Atmospheric acidification of mineral aerosols: a source of bioavailable phosphorus for the oceans</p>	<ul style="list-style-type: none"> <li>- deposition of atmospheric aerosols provides the major external source of phosphorus to surface waters ↔ primary productivity</li> <li>- but only a fraction of deposited aerosol phosphorus is watersoluble and available for uptake by phytoplankton</li> <li>- atmospheric acidification of aerosols is a prime mechanism producing soluble phosphorus from soil-derived minerals (expected where polluted and dust-laden air masses mix) → anthropogenic and natural acidic gas emissions may be a key regulator of ocean biogeochemistry</li> </ul>	<p>Atmospheric Chemistry and Physics Discussion, Vol. 11, pp. 6163-6185 ; 2011 doi: 10.5194/acpd-11-6163-2011</p>
<p>P. Parekh M.J. Follows E. Boyle</p>	<p><i>Modeling the global ocean iron cycle</i></p>	<ul style="list-style-type: none"> <li>- <i>simplest model representing a net scavenging of iron from the water column, and not attempting to explicitly represent the detailed processes, if the lifetime of dissolved iron with respect to scavenging is of the order of 100 years; broadly consistent with the observed data</i></li> <li>- <i>a more detailed model, including rapid scavenging and complexation with an organic ligand, of uniform total concentration can also fit the data over a range of parameter values</i></li> <li>- <i>based on this model it is argued, that a weaker ligand and greater total ligand concentration are more appropriate choices</i></li> </ul>	<p><i>Global Biogeochemical Cycles, Vol. 18, GB1002; 2004</i> doi:10.1029/2003GB002061</p>

		<p>- strong contrast between the scavenging-based models, in which the deep iron concentration and upwelling iron supply to the surface SO increase in concert with enhanced aeolian supply → phosphate can be completely drawn down</p> <p>- in the case where deep iron concentrations are controlled by complexation with an organic ligand, the drawdown of phosphate asymptotes toward a non-zero value which reflects the upper limit of deep dissolved iron imposed by the available ligand</p>	
<p>L. Patara N. Pinardi C. Corselli E. Malinverno M. Tonani R. Santoleri S. Masina</p>	<p>Particle fluxes in the deep Eastern Mediterranean basins: the role of ocean vertical velocities</p>	<p>- the relationship between deep sedimentary fluxes and ocean current vertical velocities in an offshore area of the Ionian Sea (deepest basin of the Eastern Mediterranean Sea) is analysed (1999-May 2001)</p> <p>- tight coupling is observed between the upper and deep traps and the estimated particle sinking rates are more than 200mday<sup>-1</sup></p> <p>→ direct effect of downward velocities in determining high sedimentation rates is excluded but upward velocities in the subsurface layers of the water column are positively correlated with deep particle fluxes</p> <p>→ upwelling would produce an increase in upper ocean nutrient levels (stimulating primary production and grazing) a few weeks before an enhanced vertical flux is found in the sediment traps</p> <p>- tight coupling between surface and deep layers through particle aggregation mechanisms → fast sinking rates of organic material in the deep ocean are connected to both lithogenic and biological aggregation mechanisms that transfer particles rapidly in the deep water column</p> <p>- two emerging fast sinking mechanisms have been captured:</p> <ol style="list-style-type: none"> <li>1. Pulses of primary production, triggered by upward current vertical velocities, followed by grazing and macrozooplankton-related biogenic flux that rapidly conveys the material in the deep ocean</li> <li>2. Large Saharan dust events that fertilize the upper ocean and possibly contribute to aggregation of organic material, thus producing high sedimentation fluxes</li> </ol>	<p>Biogeosciences, Vol. 6, pp. 333-348; 2009 doi: 10.5194/bg-6-333-2009</p>
<p>A.G. Ramos A. Martel G.A. Codd E. Soler J. Coca A. Redondo L.F. Morrison J.S. Metcalf A. Ojeda S. Suárez</p>	<p>Bloom of the marine diazotrophic cyanobacterium Trichodesmium erythraeum in the Northwest African Upwelling</p>	<p>- A T. erythraeum bloom such as that observed in August 2004 in the NW African Upwelling does not appear to have been recorded for the area previously → development due to the exceptionally warm weather and/or to the massive dust storms from the Sahara Desert observed in the NE Atlantic in August 2004</p>	<p>Marine Ecology Progress Series, Vol. 301, pp. 303-305; 2005 <b>doi: 10.3354/meps301303</b></p>

M. Petit			
N. Rastogi M.M. Sarin	<i>Chemistry of aerosols over a semi-arid region: Evidence for acid neutralization by mineral dust</i>	- evidence for quantitative neutralization of acidic constituents by mineral aerosols - ubiquitous alkaline-nature of rainfall events over this high dust region further attests to chemical data → regional-scale atmospheric transformation processes suggest the over estimation of negative radiative forcing (climate cooling) due to sulphate aerosols in the global climate models	Geophysical Research Letters, Vol. 33, L23815 GL027708; 2006 doi: 10.1029/2006GL027708
M.M. Sarin	Atmospheric dry deposition of N, P and Fe to the tropical Bay of Bengal	- N, P, Fe and their dry-deposition fluxes show significant spatio-temporal variability over north and south Bay of Bengal (N-BoB & S-BoB) - the aerosol $N_{\text{Inorg}}$ (Av. 185 nmol m <sup>-3</sup> ) is dominated by $NH_4^+$ (Av. 170 nmol m <sup>-3</sup> ) → aerosol- $NH_4^+$ concentration over Bay of Bengal has increased by a factor of three over the past one decade - the water-soluble organic nitrogen ( $N_{\text{Org}}$ ) accounts for no more than 15% of the total nitrogen ( $N_{\text{Tot}} = N_{\text{Inorg}} + N_{\text{Org}}$ ) and occurs mainly in the fine mode (PM <sub>2.5</sub> ) - the wet-deposition fluxes of N, P and Fe are not significant during the late NE-monsoon (Jan-March) when continental outflow dominates the widespread dispersal of pollutants over Bay of Bengal	unpublished, in progress
M.M. Sarin	Impact of Anthropogenic Sources on Aerosol Iron Solubility: Comparative Study from Tropical Bay of Bengal and Arabian Sea	- characteristic differences in the nature of mineral dust and chemical processing of alluvial dust by atmospheric acidic constituents (H <sub>2</sub> SO <sub>4</sub> , HNO <sub>3</sub> ) enhances the fractional solubility of Fe → comparison of the aerosol-Fe over Bay of Bengal and Arabian Sea - furthermore impact of biomass and fossil-fuel combustion sources → higher solubility	unpublished, in progress
F. Solmon P.Y. Chuang N. Meskhidze Y. Chen	Acidic processing of mineral dust iron by anthropogenic compounds over the north Pacific Ocean	- Atmospheric processing of mineral aerosol by anthropogenic pollutants may be an important process by which insoluble iron can be transformed into soluble forms (= available to oceanic biota) - production of soluble iron varies temporally and regionally depending on pollution-to-dust ratio (due to strong buffering by calcite) - ~30% to 70% of particulate soluble iron over the North Pacific Ocean basin can be attributed to atmospheric processing (especially chemical processing) - sensitivity tests suggest that doubling SO <sub>2</sub> emissions can induce a significant increase (13% on average, up to 40% during specific events) in dissolved iron production and deposition to the remote Pacific - half of the primary productivity induced by iron deposition in a north Pacific high-nutrient low-chlorophyll region is estimated to be due to soluble iron derived from anthropogenic chemical processing of Asian aerosol	Journal of Geophysical Research, Vol. 114, D02305; 2009 doi:10.1029/2008JD010417
A. Tagliabue L. Bopp O. Aumont	Ocean biogeochemistry exhibits contrasting responses to a large	- despite enforcing a climatically realistic dramatic reduction in the ocean deposition of aerosol Fe, we find that global NPP and FCO <sub>2</sub> only decline by around 3% ↔ spatial redistribution of NPP that accompanies a decline in aeolian	Biogeosciences, Vol. 5, pp. 11-24; 2008 doi: 10.5194/bg-5-11-2008

	scale reduction in dust deposition	<p>Fe input, as well as the lesser importance of aeolian Fe sources relative to continental shelf supply in the Pelagic Integration Scheme for Carbon and Ecosystem studies</p> <ul style="list-style-type: none"> <li>- dust deposition plays locally a role in sustaining diatom biomass in the ASO and could therefore be important in controlling the relative utilization of NO<sub>3</sub> and Si(OH)<sub>4</sub> and the associated marine food web; concomitant declines in denitrification stabilize the ocean DIN inventory (especially in the Pacific Ocean) and the excess NO<sub>3</sub> that arises from reduced bacterial consumption can act as a negative feedback on N<sub>2</sub> fixation</li> <li>- the denitrification– N<sub>2</sub> fixation feedback is controlled by changes in nutrients and NPP/carbon export, and its efficiency depends on the degree and timescales of deep-water ventilation above denitrification sites ↔ compensating for any dust mediated decline</li> <li>- change in air-sea CO<sub>2</sub> exchange between 1860 and 2100 is predominantly controlled by the change in atmospheric pCO<sub>2</sub> and the decline in dust deposition reduces cumulative uptake by only 4%</li> </ul>	
C. Theodosi Z. Markaki N. Mihalopoulos	Iron speciation, solubility and temporal variability in wet and dry deposition in the Eastern Mediterranean	<ul style="list-style-type: none"> <li>- Iron solubility ranged from 27.2% for pH between 4 and 5 (polluted rainwater) to 0.5% for pH close to 8 (Sahara dust episodes), indicating that Fe solubility, and therefore Fe bioavailability to ecosystems, is enhanced in the presence of acidic species</li> <li>- Dissolved Reactive Iron (DSRFe) levels deposited in the Eastern Mediterranean Sea were sufficient to account for the dissolved iron levels in seawater → dissolved iron in the Mediterranean Sea could be exclusively attributed to atmospheric deposition</li> <li>- during summer and autumn less than 5% of the deposited dissolved Fe is required for phytoplankton growth</li> </ul>	Marine Chemistry, Vol. 120, pp. 100-107; 2010 doi: 10.1016/j.marchem.2008.05.004
C. Theodosi Z. Markaki A. Tselepidis N. Mihalopoulos	The significance of atmospheric inputs of soluble and particulate major and trace metals to the eastern Mediterranean seawater	<ul style="list-style-type: none"> <li>- V, Cr, Fe and Pb were mainly associated with the particulate form (64–98%), whilst for Mn, Zn, Cu and Cd the soluble fraction represents 60–70% of the total input → significance of atmospheric inputs to the biogeochemical cycling of trace elements</li> <li>- the solubility of all studied metals was found to decrease with increasing pH values and increasing dust mass</li> <li>- Cr, Mn and Cu fluxes were higher during the dry season compared to those measured during the wet season (other metals: opposite trend; Fe and Zn are removed almost equally by wet and dry deposition)</li> </ul>	Marine Chemistry, Vol. 120, pp. 154-163; 2010 doi: 10.1016/j.marchem.2010.02.003
R. Young K. Carder P. Betzer	Atmospheric iron inputs and primary productivity:	<ul style="list-style-type: none"> <li>- major pulses of dust from Asia was followed by major increases in primary production → chemical analyses of the atmospheric particles showed that they were iron-rich (10-15%) and, further, that if only a small proportion (e.g. 10%) of</li> </ul>	Global Biogeochemical Cycles, Vol. 5, pp. 119-134; 1991 doi: 10.1029/91GB00927

<p>D. Costello R. Duce J. Ditullio N. Tindale E. Laws M. Uematsu J. Merrill R. Feely</p>	<p>phytoplankton responses in the North Pacific</p>	<p>this iron dissolved in the euphotic zone - at all depths, systematic decreases in production followed the initial surge in production, indicating that the phytoplankton may have evolved from being iron-limited to being nitrogen-limited - mineral particles with settling velocities equivalent to those of 14 to 18-<math>\mu</math>m-diameter spherical quartz particles were the most likely source for the iron stimulating the increases in primary production</p>	
<p>W. Yuan J. Zhang</p>	<p>High correlations between Asian dust events and biological productivity in the western North Pacific</p>	<p>- investigation of dust events at 11 meteorological stations in China and sediment-trap fluxes at KNOT (the Kyodo North Pacific Ocean Time-series station) (12.1997-04.2000) - Al flux has significant correlations (0.66–0.78) with dust events at a water depth of 924 m → Badain Juran Desert region is a primary source of eolian dust to the western North Pacific - high correlations between the dust events and opal flux, and PD (pennate diatoms) → dust events stimulate biological productivity, providing nutrients via processes such as particle floating, adsorption and coprecipitation - evident correlation between opal flux at 924 m and GHA (geopotential height anomalies) at 850 hPa level with about a 10-day time lag → atmospheric cyclone activities might also contribute to ocean productivity</p>	<p>Geophysical Research Letters, Vol. 33, L07603; 2006 doi: 10.1029/2005GL025174</p>

## Appendix 4

### List of Representative Papers that Address the Impact of Dust Deposition on Marine Biogeochemistry

**Abbreviations:**

AOD: aerosol optical depth  
 CCN: cloud condensation nuclei  
 DMS: Dimethyl sulfide  
 HNLC: high nitrate low chlorophyll  
 SIZ: sea-ice zone  
 SOA: South Atlantic Ocean  
 SO: Southern Ocean

authors	title	contents	publication
O. Aumont L. Bopp M. Schulz	What does temporal variability in aeolian dust deposition contribute to sea-surface iron and chlorophyll distributions?	<ul style="list-style-type: none"> <li>- global model of ocean biogeochemistry forced with daily fields of dust deposition to investigate impact of variability of dust deposition (1996-2001)</li> <li>- dust deposition explains a large part of the temporal variability of surface iron in the tropical regions and in part of the subarctic Pacific</li> <li>- while dust deposition is dominated by daily events, its impact on surface iron is maximal on interannual timescales</li> <li>- largest fluctuations of surface iron produced by dust occur in oligotrophic regions where phytoplankton growth is not primarily controlled by iron availability → variability of surface chlorophyll induced by aerosol iron is predicted to be very small everywhere</li> </ul>	Geophysical Research Letters, Vol. 35, L07607; 2008 doi: 10.1029/2007GL031131
A.R. Baker P.L. Croot	Atmospheric and marine controls on aerosol iron solubility in seawater	<ul style="list-style-type: none"> <li>- fraction of atmospheric deposited iron plays a keyrole for the productivity in many open ocean regions</li> <li>- basic idea and interactions of solubility of iron in seawater is presented</li> <li>- experimental methods for the determination of iron solubility is discussed</li> </ul>	Marine Chemistry, Vol. 120, Issues 1-4, pp. 4-13; 2008 doi: 10.1016/j.marchem.2008.09.003
J.K.B. Bishop R.E. Davis J.T. Sherman	Robotic Observations of Dust Storm Enhancement of Carbon Biomass in the North Pacific	<ul style="list-style-type: none"> <li>- investigations with two autonomous robotic profiling floats (subarctic North Pacific, 10 April 2001, 8 months) → records of carbon biomass variability from surface to 1000 meters below surface</li> <li>- marine biological response to dust event (passage of Gobi desert dust cloud) → near doubling of biomass in the mixed layer over a 2-week period</li> <li>→ temporal evolution of particulate organic carbon enhancement and an increase in chlorophyll use efficiency ↔ natural iron fertilization by the dust</li> </ul>	Science, Vol. 298, no. 5594, pp. 817-821; 2002 doi: 10.1126/science.1074961

<p>N. Cassar M.L. Bender B.A. Barnett S. Fan W.J. Moxim H. Levy II B. Tilbrook</p>	<p>The Southern Ocean Biological Response to Aeolian Iron Deposition</p>	<ul style="list-style-type: none"> <li>- gross primary production and net community production (comparable to export production) are compared with model estimates of dissolved iron over large areas of the Southern Ocean → export production is proportional to modeled input of soluble iron in aerosols (fertilization due to addition of aerosol iron)</li> <li>- aerosol iron input particularly enhances gross primary production over the large area of the Southern Ocean downwind of dry continental areas → sequestration of carbon dioxide</li> <li>→ may have been a major cause of the reduction of atmospheric CO<sub>2</sub> during the ice ages</li> </ul>	<p>Science, Vol. 317, no. 5841, pp. 1067-1070; 2007 doi: 10.1126/science.1144602</p>
<p>F. Chai M.-S. Jiang Y. Chao R.C. Dugdale F. Chavez R.T. Barber</p>	<p>Modeling responses of diatom productivity and biogenic silica export to iron enrichment in the equatorial Pacific Ocean</p>	<ul style="list-style-type: none"> <li>- Diatoms contribute to the initial increase of the total phytoplankton biomass due to iron enhancement, but decrease sharply after 10 days because of mesozooplankton grazing (grazing pressure prevents significant phytoplankton biomass accumulation)</li> <li>- increasing mesozooplankton grazing rate, the diatom increase due to iron addition stays at minimum level, but small phytoplankton tend to increase</li> <li>- larger size of the iron patch tends to produce a broader extent and longer-lasting phytoplankton blooms</li> <li>- modeled depth-time distribution of sinking biogenic silica (BSi) indicates that it would take more than 30 days after iron injection to detect any significant BSi export out of the euphotic zone</li> </ul>	<p>Global Biogeochemical Cycles, Vol. 21, GB3S90; 2007 doi: 10.1029/2006GB002804</p>
<p>S.C.Doney I. Lima R.A. Feely D.M. Glover K. Lindsay N. Mahowald J.K. Moore R. Wanninkhof</p>	<p>Mechanisms governing interannual variability in upper-ocean inorganic carbon system and air– sea CO<sub>2</sub> fluxes: Physical climate and atmospheric dust</p>	<ul style="list-style-type: none"> <li>- presentation of a systematic global analysis of the magnitude and processes governing carbon system variability on subannual to decadal time-scales</li> <li>- mechanisms governing interannual variability in the upper-ocean carbon system and air–sea CO<sub>2</sub> flux differ with region (major regions: Southern Ocean, tropical Indo-Pacific, and Northern Hemisphere temperate and subpolar latitudes)</li> <li>- Ocean circulation is the dominant underlying factor driving biogeochemical variability over most of the ocean</li> <li>- Variations in atmospheric iron deposition downwind of dust source regions generate substantial variability in ocean export production and air–sea CO<sub>2</sub> flux in HNLC in the Southern Ocean, equatorial Pacific and subpolar North Pacific</li> <li>- reduced global dust deposition (beginning in the mid 1990s) generates increased air–sea CO<sub>2</sub> outgassing in the Southern Ocean</li> </ul>	<p>Deep-Sea Research II, 56, pp. 640-655; 2009 doi: 10.1016/j.dsr2.2008.12.006</p>
<p>D.J. Erickson III J.L. Hernandez P. Ginoux W.W. Gregg C. McClain J. Christian</p>	<p>Atmospheric iron delivery and surface ocean biological activity in the Southern Ocean and Patagonian region</p>	<ul style="list-style-type: none"> <li>- iron is a limiting nutrient for biologic activity in many parts of the world ocean</li> <li>- correlation analysis to clarify the spatial response of chlorophyll concentrations to iron flux in oceanic biogeochemistry</li> <li>→ several regions between 40°S and 60°S show correlations from 0.6 to 0.95 (significant at the 0.05 level), particularly the Patagonian region</li> <li>- surface chlorophyll and iron flux follow similar patterns (chlorophyll may be</li> </ul>	<p>Geophysical Research Letters, Vol. 30, no. 12, pp. 1609-1613; 2003 doi: 10.1029/2003GL017241</p>

		displaced to different latitudes due to meridional ocean transport) - dust deposition of Fe may occur in one region and then ocean circulation moves the fertilized water mass away from the area of highest Fe flux → non-co-location of high CHL and high dust flux	
S. Fan W.J. Moxim H. Levy II	Aeolian input of bioavailable iron to the ocean	- soluble Fe fraction increases with transport time from the source region and with the corresponding decrease in dust concentration → small Fe solubility and large dust deposition near the sources → large Fe solubility corresponding to smaller dust deposition distant from source regions - anthropogenic emissions of SO <sub>2</sub> and NO should have caused a significant increase in hematite dissolution and soluble Fe input to the North Atlantic and North Pacific Oceans since the industrial revolution - re-mineralization of organic matter in the mixed layer does not lead to significant iron recycling	Geophysical Research Letters, Vol. 33, L07602; 2006 doi: 10.1029/2005GL024852
A.J. Gabric R.A. Cropp G.H. McTainsh B.M. Johnston H. Butler B. Tilbrook M. Keywood	Australian dust storms in 2002–2003 and their impact on Southern Ocean biogeochemistry	- 2002-2003 most active dust storm seasons in the last 40 years in Australia → large dust plumes advected over the adjacent SO → large scale natural dust fertilization in the Australian sector of the SO ↔ importance of dust derived nutrients in the marine carbon cycle of the SO - dust storm events that were advected south in late October, early November and January had a clear affect on AOD values in the 40°-45°S and 45°-50°S bands → strong coherence between the optical characteristics of the SO atmosphere and dust loading - satellite and field data on surface chlorophyll indicate a significant biological response (unusually strong south of 50°S), associated with a strong CO <sub>2</sub> drawdown	Global Biogeochemical Cycles, Vol. 24, GB2005; 2010 doi:10.1029/2009GB003541
A.J. Gabric J.M. Shephard J.M. Knight G. Jones A.J. Trevena	Correlations between the satellite-derived seasonal cycles of phytoplankton biomass and aerosol optical depth in the Southern Ocean: Evidence for the influence of sea ice	- the production of DMS is related to atmospheric sulfate aerosols in the upper ocean (confirmed through shipboard measurements, global modelling) - correlation between surface chlorophyll (CHL) and AOD is analysed - mean CHL and AOD time series (1997-2004) are strongly coherent in the band between 50°S and 60°S (with absence in the SIZ south of 60°S) - interannual variability in CHL occurs in the SIZ related to the variability in sea-ice production during the previous winter - clear latitudinal difference in the cross correlation between CHL and AOD, with the AOD peak preceding the CHL bloom by up to 6 weeks in the SIZ → substantial trace gas emissions (aerosol precursors) are being produced over the SIZ in spring (October–December) as sea ice melts	Global Biogeochemical Cycles, Vol. 19, GB4018, pp. 10; 2005 doi: 10.1029/2005GB002546
A.J. Gabric R. Simó R.A. Cropp	Modeling estimates of the global emission of dimethylsulfide under	- presentation of a modeling analysis of the global DMS response to simulate climate change (marine food-web model, an atmosphere-ocean general circulation model (GCM), and an empirical dimethylsulfide (DMS) algorithm used)	Global Biogeochemical Cycles, Vol. 18, GB2014; 2004 doi: 10.1029/2003GB002183

A.C. Hirst J. Dachs	<ul style="list-style-type: none"> <li>enhanced greenhouse conditions</li> </ul>	<ul style="list-style-type: none"> <li>- predict the DMS seawater concentration and the DMS sea-to-air flux in 10° latitude bands from 70°N to 70°S under contemporary and enhanced greenhouse conditions (changes to nutrients not explicitly included)</li> <li>- strong regional variability in the simulated DMS flux response, with little change in the tropics and major increases predicted at high latitudes → future increases in stratification in the polar oceans will play a critical role in the DMS cycle and climate change</li> <li>- ecological data indicate that planktonic populations can respond extremely sensitively and quickly to ocean variability</li> </ul>	
A.J. Gabric R. Cropp G.P. Ayers G. McTainsh R. Braddock	Coupling between cycles of phytoplankton biomass and aerosol optical depth as derived from SeaWiFS time series in the Subantarctic Southern Ocean	<ul style="list-style-type: none"> <li>- the Subantarctic Southern Ocean is a high-nutrient low-chlorophyll region → primary production is limited by deep mixing and the availability of iron (can be transported by Australian dust, particularly during the austral spring and summer)</li> <li>- coupling between satellite-derived (SeaWiFS) aerosol optical thickness and chlorophyll concentration in the upper ocean at monthly, weekly and daily timescales → episodic atmospheric delivery of iron is stimulating phytoplankton growth</li> </ul>	Geophysical Research Letters, Vol. 29, pp. 1112-1116; 2002 doi: 10.1029/2001GL013545
S. Gassó A.F. Stein	Does dust from Patagonia reach the sub-Antarctic Atlantic Ocean?	<ul style="list-style-type: none"> <li>- difficult to determine Patagonian dust by satellite measurements (clear sky condition needed, no black background (sea-ice), dust emission short lived) → combined approach of different satellite detectors aided by an aerosol transport model</li> <li>- observations confirm that dust advects through the SW Atlantic Ocean and can reach the area around the biological rich sub-Antarctic Ocean within 30 hours of emission</li> </ul>	Geophysical Research Letters, Vol. 34, L01801; 2007 doi: 10.1029/2006GL027693
C.O. Jo J.-Y. Lee K.-A. Park Y.H. Kim K.-R. Kim	Asian dust initiated early spring bloom in the northern East/ Japan Sea	<ul style="list-style-type: none"> <li>- data for the TOMS aerosol index and SeaWiFS chlorophyll indicate that an early spring bloom in the northern East/Japan Sea can be initiated during the Asian dust event in association with precipitation (one month earlier than the bloom during non-dust event years)</li> <li>- normally initiated in this area as the surface mixed layer becomes shallower than critical depth, earlier bloom coincided with deepening of critical depth → supply of bio-available nutrients such as iron through wet deposition induces deepening of the critical depth, which results in an early initiation of the bloom</li> </ul>	Geophysical Research Letters, Vol. 34, L05602; 2007 doi: 10.1029/2006GL027395
M.S. Johnson N. Meskhidze V.P. Kiliyanpilakkil S. Gassó	Understanding the transport of Patagonian dust and its influence on marine biological activity in the South Atlantic Ocean	<ul style="list-style-type: none"> <li>- simulations (2009) indicate that the synoptic meteorological patterns of high and low pressure systems are largely accountable for dust transport trajectories over the SAO → South American dust plumes are elevated above the marine boundary layer → bulk concentration of mineral dust can quickly reach the HNLC waters of the SAO and Antarctica in ~3–4 days after emission from the source regions of Northern Patagonia</li> <li>- the effect of iron-laden mineral dust supply on surface ocean biomass is</li> </ul>	Atmospheric Chemistry and Physics, Vol. 11, pp. 2487-2502; 2011 doi: 10.5194/acp-11-2487-2011

		<p>investigated by comparing predicted surface chlorophyll-<i>a</i> concentration ([Chl-<i>a</i>]) to remotely-sensed data</p> <p>- this study suggests that:</p> <p>(1) atmospheric fluxes of mineral dust from Patagonia are not likely to be the major source of bioavailable iron to ocean regions characterized by high primary productivity</p> <p>(2) Patagonian dust plumes could still influence background [Chl-<i>a</i>] in the South Atlantic sector of the SO</p>	
<p>M.S. Johnson N. Meskhidze F. Solmon S. Gassó P.Y. Chuang D.M. Gaiero R.M. Yantosca S. Wu Y. Wang C. Carouge</p>	<p>Modeling dust and soluble iron deposition to the South Atlantic Ocean</p>	<p>- the global chemical transport model GEOS-Chem (+ dust-iron dissolution scheme) was used</p> <p>- dissolved iron fraction of mineral dust over the SAO was small (on average only accounting for 0.57% of total iron) ↔ low ambient concentrations of acidic trace gases available for mixing with dust plumes, not enough to overcome the alkalinity buffer of Patagonian dust and initiate considerable acid dissolution of mineral-iron</p> <p>- sol-Fe deposited to the SAO was largely controlled by the initial amount of sol-Fe at the source region → Patagonian dust should have a minor effect on biological productivity in the SAO</p>	<p>Journal of Geophysical Research, Vol. 115, D15202, pp. 13; 2010 doi: 10.1029/2009JD013311</p>
<p>Y. Iwamoto K. Yumimoto M. Toratani A. Tsuda K. Miura I. Uno M. Uematsu</p>	<p>Biogeochemical implications of increased mineral particle concentrations in surface waters of the northwestern North Pacific during an Asian dust event</p>	<p>- mineral dust aerosols were scavenged by sea fog, and their deposition to the ocean increased the particle concentration in surface seawater</p> <p>- a general relationship for the solubility of iron from dust particles led to an estimate of 20 to 330 <math>\mu\text{g m}^{-2}</math> for the amount of bio-available iron delivered during the dust event (comparable to total dissolved iron added during an iron fertilization experiment in the northwestern North Pacific)</p>	<p>Geophysical Research Letters, Vol. 38, L01604, pp. 5; 2011 doi:10.1029/2010GL0459062011</p>
<p>P.J. Lam J.K.B. Bishop</p>	<p>The continental margin is a key source of iron to the HNLC North Pacific Ocean</p>	<p>- FeP = tracer for the delivery of total Fe, also retains the memory of its source through its chemical speciation</p> <p>- calculations show that subsurface Fe delivery from the shelf is likely as important a source of bioavailable iron to the HNLC WSP gyre than dust</p> <p>- this subsurface supply of iron is shallow enough to be accessible to the surface through winter upwelling and vertical mixing (key source of bioavailable Fe to the HNLC North Pacific)</p> <p>- strong lateral advection of labile Mn and Fe from redox-mobilized labile sources at the continental shelf supplemented by a more variable source of Fe from the upper continental slope</p>	<p>Geophysical Research Letters, Vol. 35, L07608; 2008 doi: 10.1029/2008GL033294</p>
<p>P.J. Lam J.K.B. Bishop</p>	<p>Wintertime phytoplankton bloom in</p>	<p>- first evidence of the delivery and importance of iron from the continental margin and its arrival at OSP in the open HNLC subarctic Pacific</p>	<p>Global Biogeochemical Cycles, Vol. 20, GB1006; 2006</p>

<p>C.C. Henning M.A. Marcus G.A. Waychunas I.Y. Fung</p>	<p>the subarctic Pacific supported by continental margin iron</p>	<ul style="list-style-type: none"> <li>- the entire continental shelf from California to the Aleutian Islands may be a source of additional iron in winter to the North Pacific → degree of iron limitation in the subarctic Pacific is not constant through the year and productivity can be boosted by different natural iron sources in different seasons</li> <li>- the wintertime delivery of bioavailable iron to the subarctic Pacific may address the paradox of why wintertime chlorophyll levels in subpolar HNLC regions are so high despite light limitation</li> <li>- the effects of shelf were found to be limited to coastal regions because the sedimentary iron was quickly scavenged out of the water column → the sensitivity of global ocean primary production to the shelf iron source was low</li> <li>- iron from shelf and continental sources is affecting the productivity of open ocean HNLC regions far (hundreds of kilometers) downstream</li> </ul>	<p>doi:10.1029/2005GB002557</p>
<p>C. Mahaffey R.G. Williams G.A. Wolff N. Mahowald W. Anderson M. Woodward</p>	<p>Biogeochemical signatures of nitrogen fixation in the eastern North Atlantic</p>	<ul style="list-style-type: none"> <li>- isotopic signal (low natural abundance of <sup>15</sup>N relative to <sup>14</sup>N) over the eastern North Atlantic (between 26°N and 32°N along 20°W) in spring 2000 leads together with phytopigment data and nitrate to phosphate ratios in the upper thermocline to the suggestion that nitrogen fixation provides a local dominant supply of nitrogen to phytoplankton over part of the eastern North Atlantic</li> <li>- biogeochemical proxies are coincident with enhanced atmospheric dust deposition → atmospheric dust events may spatially and temporally constrain the distribution of N<sub>2</sub> fixers</li> </ul>	<p>Geophysical Research Letters, Vol. 30, no. 6, 1300; 2003 doi: 10.1029/2002GL016542</p>
<p>E. Marañón A. Fernández B. Mouriño-Carballido S. Martínez-García E. Teira P. Cermeño P. Chouciño M. Huete-Ortega E. Fernández A. Calvo-Díaz X.A.G. Morán A. Bode E. Moreno-Ostos M.M. Varela M.D. Patey E.P. Achterberg</p>	<p>Degree of oligotrophy controls the response of microbial plankton to Saharan dust</p>	<ul style="list-style-type: none"> <li>- oligotrophy: lack of nutrients</li> <li>- different groups of phytoplankton and bacterioplankton responded differently to Saharan dust addition, although bulk abundance and biomass tended to remain unchanged</li> <li>- the relative increase in bacterial production, which was the dominant response to dust addition in ultraoligotrophic environments, became larger with increasing oligotrophy. In contrast, primary production, which was stimulated only in the least oligotrophic waters, became less responsive to dust as the ecosystem's degree of oligotrophy increased</li> <li>→ given the divergent consequences of a predominantly bacterial vs. phytoplanktonic response, dust inputs can, depending on the ecosystem's degree of oligotrophy, stimulate or weaken biological CO<sub>2</sub> drawdown</li> </ul>	<p>Limnology and Oceanography, Vol. 55(6), pp. 2339–2352; 2010 doi: 10.4319/lo.2010.55.6.2339</p>
<p>N. Meskhidze</p>	<p>Dust and pollution: A</p>	<ul style="list-style-type: none"> <li>- Fe solubilization in deliquesced mineral dust aerosols emanating from East Asia</li> </ul>	<p>Journal of Geophysical Research,</p>

<p>W.L. Chameides A. Nenes</p>	<p>recipe for enhanced ocean fertilization?</p>	<p>during the springtime outflow conditions is investigated with a Lagrangian box model of the gas and aqueous-phase chemistry (simulates scavenging, chemical reactions and dissolution of Fe-III oxides due to acid mobilization)</p> <ul style="list-style-type: none"> <li>- SO<sub>2</sub> pollutant emissions are a potential source of acidity to advecting dust from East Asia</li> <li>- only plumes with relatively high initial SO<sub>2</sub>-to-dust ratios are capable of delivering significant amounts of bioavailable Fe to the NPO</li> <li>- large dust advection episodes should have insignificant dissolved iron fraction (DIF) as the amount of SO<sub>2</sub> required to acidify such dust plumes is about an order of magnitude higher than what can typically be entrained in the plume during its advection</li> <li>- smaller dust plumes will generally have higher DIFs because they require lower amounts of SO<sub>2</sub> and, even if such small plumes may not cause algae blooms, they could still be important sources of dissolved Fe to the NPO</li> </ul> <p>→ future changes in SO<sub>2</sub>-pollutant emissions from East Asia may affect the productivity of the NPO</p>	<p>Vol. 110, D03301; 2005 doi:10.1029/2004JD005082</p>
<p>N. Meskhidze A. Nenes W.L. Chameides C. Luo N. Mahowald</p>	<p>Atlantic Southern Ocean productivity: Fertilization from above or below?</p>	<ul style="list-style-type: none"> <li>- two sources of Fe for the surface waters of the SO have been proposed:             <ol style="list-style-type: none"> <li>(1) oceanic input (upwelling of nutrient-rich water, lateral flows from continental margins)</li> <li>(2) atmospheric input</li> </ol> </li> <li>- upwelling of nutrient-rich water is the predominant source of bioavailable Fe in the surface waters of the south Atlantic Ocean</li> <li>- acidification of aeolian dust may be required to solubilize the large fraction of mineral-iron and make it bioavailable</li> </ul>	<p>Global Biogeochemical Cycles, Vol. 21, GB2006; 2007 doi:10.1029/2006GB002711</p>
<p>J.K. Moore O. Braucher</p>	<p>Sedimentary and mineral dust sources of dissolved iron to the world ocean</p>	<ul style="list-style-type: none"> <li>- fluxes from continental margins and mineral dust deposition are key sources of dissolved iron to the oceans ↔ primary production, biological carbon export and nitrogen fixation (global scale)</li> <li>- calculation of the relative importance of dust deposition vs. sedimentation (on an annual basis)</li> </ul>	<p>Biogeosciences, Vol. 5, pp. 631–656; 2008 doi: 10.5194/bg-5-631-2008</p>
<p>A. Nenes M.D. Krom N. Mihalopoulos P. Van Cappellen Z. Shi A. Bougiatioti P. Zarmpas B. Herut</p>	<p>Atmospheric acidification of mineral aerosols: a source of bioavailable phosphorus for the oceans</p>	<ul style="list-style-type: none"> <li>- deposition of atmospheric aerosols provides the major external source of phosphorus to surface waters ↔ primary productivity</li> <li>- but only a fraction of deposited aerosol phosphorus is watersoluble and available for uptake by phytoplankton</li> <li>- atmospheric acidification of aerosols is a prime mechanism producing soluble phosphorus from soil-derived minerals (expected where polluted and dust-laden air masses mix) → anthropogenic and natural acidic gas emissions may be a key regulator of ocean biogeochemistry</li> </ul>	<p>Atmospheric Chemistry and Physics Discussion, Vol. 11, pp. 6163-6185 ; 2011 doi: 10.5194/acpd-11-6163-2011</p>

<p>L. Patara N. Pinardi C. Corselli E. Malinverno M. Tonani R. Santoleri S. Masina</p>	<p>Particle fluxes in the deep Eastern Mediterranean basins: the role of ocean vertical velocities</p>	<p>- the relationship between deep sedimentary fluxes and ocean current vertical velocities in an offshore area of the Ionian Sea (deepest basin of the Eastern Mediterranean Sea) is analysed (1999-May 2001) - tight coupling is observed between the upper and deep traps and the estimated particle sinking rates are more than <math>200\text{mday}^{-1}</math> → direct effect of downward velocities in determining high sedimentation rates is excluded but upward velocities in the subsurface layers of the water column are positively correlated with deep particle fluxes → upwelling would produce an increase in upper ocean nutrient levels (stimulating primary production and grazing) a few weeks before an enhanced vertical flux is found in the sediment traps - tight coupling between surface and deep layers through particle aggregation mechanisms → fast sinking rates of organic material in the deep ocean are connected to both lithogenic and biological aggregation mechanisms that transfer particles rapidly in the deep water column - two emerging fast sinking mechanisms have been captured: 1. Pulses of primary production, triggered by upward current vertical velocities, followed by grazing and macrozooplankton-related biogenic flux that rapidly conveys the material in the deep ocean 2. Large Saharan dust events that fertilize the upper ocean and possibly contribute to aggregation of organic material, thus producing high sedimentation fluxes</p>	<p>Biogeosciences, Vol. 6, pp. 333-348; 2009 doi: 10.5194/bg-6-333-2009</p>
<p>A.G. Ramos A. Martel G.A. Codd E. Soler J. Coca A. Redondo L.F. Morrison J.S. Metcalf A. Ojeda S. Suárez M. Petit</p>	<p>Bloom of the marine diazotrophic cyanobacterium <i>Trichodesmium erythraeum</i> in the Northwest African Upwelling</p>	<p>- A <i>T. erythraeum</i> bloom such as that observed in August 2004 in the NW African Upwelling does not appear to have been recorded for the area previously → development due to the exceptionally warm weather and/or to the massive dust storms from the Sahara Desert observed in the NE Atlantic in August 2004</p>	<p>Marine Ecology Progress Series, Vol. 301, pp. 303-305; 2005 • doi: 10.3354/meps301303</p>
<p>M.M. Sarin</p>	<p>Atmospheric dry deposition of N, P and Fe to the tropical Bay of Bengal</p>	<p>- N, P, Fe and their dry-deposition fluxes show significant spatio-temporal variability over north and south Bay of Bengal (N-BoB &amp; S-BoB) - the aerosol <math>N_{\text{inorg}}</math> (Av. <math>185\text{ nmol m}^{-3}</math>) is dominated by <math>\text{NH}_4^+</math> (Av. <math>170\text{ nmol m}^{-3}</math>) → aerosol-<math>\text{NH}_4^+</math> concentration over Bay of Bengal has increased by a factor of three over the past one decade - the water-soluble organic nitrogen (<math>N_{\text{Org}}</math>) accounts for no more than 15% of the</p>	<p>unpublished, in progress</p>

		<p>total nitrogen (<math>N_{Tot} = N_{Inorg} + N_{Org}</math>) and occurs mainly in the fine mode (<math>PM_{2.5}</math>)</p> <ul style="list-style-type: none"> <li>- the wet-deposition fluxes of N, P and Fe are not significant during the late NE-monsoon (Jan-March) when continental outflow dominates the widespread dispersal of pollutants over Bay of Bengal</li> </ul>	
M.M. Sarin	Impact of Anthropogenic Sources on Aerosol Iron Solubility: Comparative Study from Tropical Bay of Bengal and Arabian Sea	<ul style="list-style-type: none"> <li>- characteristic differences in the nature of mineral dust and chemical processing of alluvial dust by atmospheric acidic constituents (<math>H_2SO_4</math>, <math>HNO_3</math>) enhances the fractional solubility of Fe → comparison of the aerosol-Fe over Bay of Bengal and Arabian Sea</li> <li>- furthermore impact of biomass and fossil-fuel combustion sources → higher solubility</li> </ul>	unpublished, in progress
F. Solmon P.Y. Chuang N. Meskhidze Y. Chen	Acidic processing of mineral dust iron by anthropogenic compounds over the north Pacific Ocean	<ul style="list-style-type: none"> <li>- Atmospheric processing of mineral aerosol by anthropogenic pollutants may be an important process by which insoluble iron can be transformed into soluble forms (= available to oceanic biota)</li> <li>- production of soluble iron varies temporally and regionally depending on pollution-to-dust ratio (due to strong buffering by calcite)</li> <li>- ~30% to 70% of particulate soluble iron over the North Pacific Ocean basin can be attributed to atmospheric processing (especially chemical processing)</li> <li>- sensitivity tests suggest that doubling <math>SO_2</math> emissions can induce a significant increase (13% on average, up to 40% during specific events) in dissolved iron production and deposition to the remote Pacific</li> <li>- half of the primary productivity induced by iron deposition in a north Pacific high-nutrient low-chlorophyll region is estimated to be due to soluble iron derived from anthropogenic chemical processing of Asian aerosol</li> </ul>	Journal of Geophysical Research, Vol. 114, D02305; 2009 doi:10.1029/2008JD010417
A. Tagliabue L. Bopp O. Aumont	Ocean biogeochemistry exhibits contrasting responses to a large scale reduction in dust deposition	<ul style="list-style-type: none"> <li>- despite enforcing a climatically realistic dramatic reduction in the ocean deposition of aerosol Fe, we find that global NPP and <math>FCO_2</math> only decline by around 3% ↔ spatial redistribution of NPP that accompanies a decline in aeolian Fe input, as well as the lesser importance of aeolian Fe sources relative to continental shelf supply in the Pelagic Integration Scheme for Carbon and Ecosystem studies</li> <li>- dust deposition plays locally a role in sustaining diatom biomass in the ASO and could therefore be important in controlling the relative utilization of <math>NO_3</math> and <math>Si(OH)_4</math> and the associated marine food web; concomitant declines in denitrification stabilize the ocean DIN inventory (especially in the Pacific Ocean) and the excess <math>NO_3</math> that arises from reduced bacterial consumption can act as a negative feedback on <math>N_2</math> fixation</li> <li>- the denitrification– <math>N_2</math> fixation feedback is controlled by changes in nutrients and NPP/carbon export, and its efficiency depends on the degree and timescales of deep-water ventilation above denitrification sites ↔ compensating for any dust</li> </ul>	Biogeosciences, Vol. 5, pp. 11-24; 2008 doi: 10.5194/bg-5-11-2008

		<p>mediated decline</p> <ul style="list-style-type: none"> <li>- change in air-sea CO<sub>2</sub> exchange between 1860 and 2100 is predominantly controlled by the change in atmospheric pCO<sub>2</sub> and the decline in dust deposition reduces cumulative uptake by only 4%</li> </ul>	
C. Theodosi Z. Markaki N. Mihalopoulos	Iron speciation, solubility and temporal variability in wet and dry deposition in the Eastern Mediterranean	<ul style="list-style-type: none"> <li>- Iron solubility ranged from 27.2% for pH between 4 and 5 (polluted rainwater) to 0.5% for pH close to 8 (Sahara dust episodes), indicating that Fe solubility, and therefore Fe bioavailability to ecosystems, is enhanced in the presence of acidic species</li> <li>- Dissolved Reactive Iron (DSRFe) levels deposited in the Eastern Mediterranean Sea were sufficient to account for the dissolved iron levels in seawater → dissolved iron in the Mediterranean Sea could be exclusively attributed to atmospheric deposition</li> <li>- during summer and autumn less than 5% of the deposited dissolved Fe is required for phytoplankton growth</li> </ul>	Marine Chemistry, Vol. 120, pp. 100-107; 2010 doi: 10.1016/j.marchem.2008.05.004
C. Theodosi Z. Markaki A. Tselepidis N. Mihalopoulos	The significance of atmospheric inputs of soluble and particulate major and trace metals to the eastern Mediterranean seawater	<ul style="list-style-type: none"> <li>- V, Cr, Fe and Pb were mainly associated with the particulate form (64–98%), whilst for Mn, Zn, Cu and Cd the soluble fraction represents 60–70% of the total input → significance of atmospheric inputs to the biogeochemical cycling of trace elements</li> <li>- the solubility of all studied metals was found to decrease with increasing pH values and increasing dust mass</li> <li>- Cr, Mn and Cu fluxes were higher during the dry season compared to those measured during the wet season (other metals: opposite trend; Fe and Zn are removed almost equally by wet and dry deposition)</li> </ul>	Marine Chemistry, Vol. 120, pp. 154-163; 2010 doi: 10.1016/j.marchem.2010.02.003
R. Young K. Carder P. Betzer D. Costello R. Duce J. Ditullio N. Tindale E. Laws M. Uematsu J. Merrill R. Feely	Atmospheric iron inputs and primary productivity: phytoplankton responses in the North Pacific	<ul style="list-style-type: none"> <li>- major pulses of dust from Asia was followed by major increases in primary production → chemical analyses of the atmospheric particles showed that they were iron-rich (10-15%) and, further, that if only a small proportion (e.g. 10%) of this iron dissolved in the euphotic zone</li> <li>- at all depths, systematic decreases in production followed the initial surge in production, indicating that the phytoplankton may have evolved from being iron-limited to being nitrogen-limited</li> <li>- mineral particles with settling velocities equivalent to those of 14 to 18-<math>\mu</math>m-diameter spherical quartz particles were the most likely source for the iron stimulating the increases in primary production</li> </ul>	Global Biogeochemical Cycles, Vol. 5, pp. 119-134; 1991 doi: 10.1029/91GB00927
W. Yuan J. Zhang	High correlations between Asian dust events and biological productivity in the	<ul style="list-style-type: none"> <li>- investigation of dust events at 11 meteorological stations in China and sediment-trap fluxes at KNOT (the Kyodo North Pacific Ocean Time-series station) (12.1997-04.2000)</li> <li>- Al flux has significant correlations (0.66–0.78) with dust events at a water depth</li> </ul>	Geophysical Research Letters, Vol. 33, L07603; 2006 doi: 10.1029/2005GL025174

	western North Pacific	<p>of 924 m → Badain Juran Desert region is a primary source of eolian dust to the western North Pacific</p> <ul style="list-style-type: none"><li>- high correlations between the dust events and opal flux, and PD (pennate diatoms) → dust events stimulate biological productivity, providing nutrients via processes such as particle floating, adsorption and coprecipitation</li><li>- evident correlation between opal flux at 924 m and GHA (geopotential height anomalies) at 850 hPa level with about a 10-day time lag → atmospheric cyclone activities might also contribute to ocean productivity</li></ul>	
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