

Atmospheric control of nutrient cycling and production in the surface ocean

Cecile Guieu, Cliff Law, Shigenobu Takeda, Doug Wallace

1. **Background and significance**

a) Significance

Nutrient availability is a primary control of ocean productivity and partitioning of carbon between the ocean and atmosphere, mediated by the limiting potential of elements N, P, Fe and Si as major metabolic requirements¹⁻³. It is established that both phytoplankton elemental composition and deep sea nutrient inventories are linked to nutrient availability via the Redfield ratio, but also increasingly recognized that phytoplankton nutrient stoichiometry is variable, with the canonical N:P ratio of 16:1 representing an average arising from multiple phytoplankton growth strategies³. As a result, variation in surface ocean nutrient supply may alter phytoplankton nutrient stoichiometry, modify current nutrient inventories and influence feedbacks to climate via air-sea exchange and the ocean carbon sink.

Atmospheric deposition is a major pathway for nutrient delivery⁴⁻⁵ with potential to alter ocean nutrient stoichiometry. Climate change and pollution influence the deposition of essential trace metals and macronutrients, and induce variation in nutrient limitation, biodiversity; primary productivity and air-sea gas fluxes⁵. In High-Nutrient, Low-Chlorophyll regions (~30% of the ocean) carbon fixation is limited by iron availability, with iron addition stimulating phytoplankton production, CO₂ drawdown and DMS and halocarbon production⁶. Atmospheric deposition also influences production and nitrogen-fixation in oligotrophic waters, with the latter process limited or co-limited by iron and phosphate⁷. Fixed nitrogen has an oceanic residence time of a few thousand years, and appears to be sensitive to both direct (N-deposition) and indirect (iron control on N-fixation) effects of deposition.

However, the links between atmospheric deposition, ocean productivity and nutrient cycling are poorly understood. Despite growing awareness of the variability of deposition and its complex influences on carbon and nitrogen fixation, aeolian nutrient supply is also not well represented in budgets and global models. As these models are the primary platform for prediction of ecosystem and carbon cycle responses to anthropogenic change, this shortcoming requires urgent refinement and testing in robust field studies.

b) Background information in the SOLAS Science Plan and Implementation Strategy

The interactions and feedbacks between atmospheric nutrient deposition and biological production is central to Activities 1.4 Iron and Marine Productivity and 1.5 Ocean-Atmosphere Cycling of Nitrogen, in the SOLAS Science Plan and Implementation Strategy⁸. SOLAS has a unique ability to address this issue due to its consideration of both atmospheric and oceanic chemistry and its broad disciplinary range.

Dust is the primary vector for atmospheric deposition of key trace metals into the ocean. We know little about the biological availability and fate of trace metals and macronutrients in dust and aerosols, the variation in physical-chemical characteristics of dust and aerosol delivery of nutrients varies from source to deposition, or how ocean biota adapt and respond to deposition events.

Correspondence has been reported between models, satellite data and measurement of dust and fixed nitrogen deposition rates^{4,5}, but the distribution and magnitude of dust and macronutrient delivery varies significantly^{5,9}. Some studies have show correlation between atmospheric deposition, upper ocean nutrient distributions and plankton diversity^{10,11}, but are limited to date, with no clear link observed in other studies^{12,13}. The balance between nutrient availability and cellular stoichiometric requirements controls fundamental aspects, such as the magnitude and location of nitrogen and carbon fixation, the responsive planktonic group, and the degree of feedback coupling. It is likely that marine organisms have developed specialised adaptations to deal with the variable nature and frequency of atmospheric nutrient inputs. As large regions of the ocean are currently undergoing significant change in atmospheric deposition, as a result of combustion and dust deposition, it is essential to improve our understanding and ability to predict how productivity, plankton community composition and the nature of nutrient cycling will respond.

2. Questions to be addressed

- How does the nutrient and trace metal content of the aerosol (e.g. dust) alter from initial uplift to uptake, and how does processing in the atmosphere and water influence nutrient supply and availability?
- What is the relative magnitude and spatial variability of organic and inorganic nutrient supply via aerosol deposition? Does the organic aerosol supply have an influence on the biota? Can we model this?
- How do temporal and spatial variations in atmospheric nutrient supply affect surface ocean plankton community structure and the associated biogeochemistry (e.g. N fixation; C-fixation; heterotrophic DOC utilization)? Insight into changes in microbial C:N:P stoichiometry is critical in determining how nutrient-biota interactions modulate, and are themselves modulated by, processes operating at scales ranging from algal photosynthesis to the global climate. How do planktonic communities respond to differing aerosol-borne nutrient stoichiometries under different nutrient limitation regimes?
- Are there identifiable adaptations and strategies that allow marine micro-organisms to compete for this variable nutrient source? Do molecular-biological approaches give insight into the potential for ecosystem response?
- How will future variation in the composition and magnitude of nutrient and trace metal deposition influence surface ocean carbon and nitrogen fixation, both at the event scale (dust storms) and over longer time scales (greenhouse world)?

3. What needs to be done to address the questions?

Spatial and temporal aerosol characterisation: spatial, seasonal and inter-annual variability of wet and dry deposition with emphasis on sources, particle size, chemical

speciation, reactivity, composition and determination of changes in the physical and chemical characterization during atmospheric transport. Platforms for wet and dry deposition and transport characterization should include time-series sites and increased use of research vessels and voluntary observing ships (VOS's), particularly those which allow for repeated sampling. To ensure global coherence and quality control, methodological intercalibration, sample sharing and common reference materials will be necessary.

Surface water transect surveys of “core” surface water properties (inorganic and organic nutrients at low concentrations, dissolved organic carbon, trace metals, plankton community composition including molecular biological characterization) and **key rate measurements** (e.g. primary and bacterial production, nitrogen fixation) will cover large regions encompassing gradients of atmospheric deposition and water properties and sampled in different seasons.

The transects should allow for experimental nutrient manipulation experiments to be conducted along the cruise track. These would be bottle incubations using multifactorial addition nutrient and trace metals additions to gain insight into proximal controls on plankton composition and process rates, with consistent water property and rate measurements with the surface water surveys.

Sample coverage for surface water properties and aerosol characteristics, can in principle, be increased by use of VOS's including naval, coastguard or commercial vessels that cover repeat lines or regions. Synergies and mutual interest between ocean basin transects planned by GEOTRACES and the issues underlying this White paper should be exploited.

The complex measurement and experimental programme would benefit from establishment of international “**biogeochemical SWAT teams**” with common equipment and shared methodologies that could be deployed at relatively short notice to sample appropriate transects of ocean basins (e.g. transits associated with redeployments of research vessels).

Transect surveys can be augmented by **Lagrangian studies** using tracers and/or drifting buoys to determine temporal responses and trends within the same body of water. *In situ* manipulation studies may be especially useful for addressing medium term, whole-ecosystem impacts of nutrient input. **Mesoscosms** offer potential for duplicate and repeat *in situ* manipulations in the same time and space and can be described by 1-D models, but deployment is limited to favourable sea-states and trace-metal clean techniques should be applied. Tracer-labelled ***in situ* manipulation** studies characterise the whole ecosystem response to perturbation, but cannot be easily duplicated.

Seasonal and interannual measurements and experiments at existing **time series stations** (e.g. HOTS, BATS, Cape Verde, DYFAMED) should be maintained and could become focal points for more detailed experimentation and process studies. The existing sites should be augmented by new time series stations in regions susceptible to dust deposition (eg. SW. Pacific, N.E. Pacific, off Patagonia and Corsica). The time-series data may be of particular use for the **development and testing of model parameterisations**.

Ocean measurements should be underpinned by **laboratory research** with critical areas for examination including the amount and form of bioavailable trace metals and

the biological mechanisms and adaptations associated with accessing episodically delivered nutrients. Information on cellular elemental and nutrient requirements and physiological/metabolic capabilities of different components of the plankton is essential.

The relative contribution of different factors is best explored using sensitivity analysis in dust deposition and transport models. **Satellite remote-sensing** tools for column dust and Aerosol Optical Depth are critical parameters for interpretation, modelling and prediction of dust deposition but require improvement for greater accuracy in evaluating dust concentration, composition and deposition rates.

Atmospheric and ocean data are important requirements for **robust model development**. The challenges are to develop more realistic models of deposition to the ocean, with more accurate representation of mechanisms and time scales of ocean response. Reliance on deposition and transport models requires thorough testing against in-situ and remote-sensing observations.

The geographic scale, level of effort and complexity of the observational and modelling approaches proposed here will require **research planning and collaboration** on an international and global scale, and benefit from cross-program **integration** with GEOTRACES.

4. *What is planned, possible and missing?*

See Table

5. *Required co-ordination and planning tasks*

International SOLAS needs to provide the international coordination required to establish a global program of observational work, experimentation and modelling similar to that outlined above. In some areas, there is considerable mutual interest and hence benefit of collaborative research with GEOTRACES.

The following strategy is proposed:

A scientific review article should be written for a high-profile journal summarising the state-of-the-art, identifying key unknowns and explaining their importance. SOLAS has recently proposed an IGBP Fast-Track Initiative to coordinate the writing of this paper to be led by Dr. Mark Moore of the National Oceanographic Centre in Southampton, UK. SOLAS should promote links between international activities, organizations and groups that are conducting or proposing measurement campaigns and modelling efforts that address this issue. Specifically, SOLAS should work with GEOTRACES to ensure that adequate biological measurements, experiments and nutrient measurements are made on GEOTRACES Survey cruises. SOLAS should also seek to develop observational approaches. A Whitepaper for the OceanObs '09 conference in Venice is in preparation that addresses biogeochemical measurements of the surface layer and lower atmosphere that can be made from surface ocean transects with research vessels and VOS. SOLAS is also contributing to a whitepaper being prepared by OceanSITES which addresses the need for long-term, biogeochemical measurements of the surface layer from an expanded network of fixed-point ocean time series.

To accelerate this scientifically, a joint OCB-SOLAS workshop could be proposed to which members of the Fast-Track Initiative writing team and representatives of the international projects and activities listed above could be invited. The purpose of the workshop would be to coordinate and compare measurement and experimental approaches, design and propose collaborative studies and initiate community modeling initiatives which address this topic. The workshop may make the first steps towards definition and assembly of the international SWAT teams.

Provisional Timeline:-

Planning phase 2009; Proposal writing end of 2009.

Initiation in 2010.

End date 2015

References

- ¹ Sarmiento et al. 2004
- ² Arrigo, 2005
- ³ Deutsch et al. 2006
- ⁴ Jickells et al., 2005
- ⁵ Duce et al., 2008
- ⁶ Boyd et al, 2007
- ⁷ Mills et al, 2004
- ⁸ SOLAS Science Plan and Implementation Strategy
- ⁹ Mahowald et al, 1999
- ¹⁰ Lenes et al, 2001
- ¹¹ Breiviere et al, 2006
- ¹² Johnson et al. 2003
- ¹³ Neuer et al., 2004