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Figure 1: Participants of the workshops at the University of East Anglia, Norwich, United Kingdom.

Left to right - Back row: Athanasios Nenes, Eric Buitenhuis, David Turner, Andrew Rees, Martin Johnson, Laurent Bopp, Oliver Andrews, Isabelle Dadou, Nadine Goris, Natalie Mahowald (hiding!), Steve Archer
 Next row: Peter Croot, Rob Middag, Alex Baker, Robert Duce, Marion Gehlen, Frances Hopkins, Gill Malin, Parvatha Suntharalingam, Fiona Keng Seh Lin, Yuan Gao
 Next row: Cécile Guieu, Martine Lizotte, Rachel Shelley, Morgane Perron, Maria Kanakidou, Peter Liss,
 Front row: Hema Uskaikar, Akinori Ito, Manmohan Sarin, Stelios Myriokefalitakis, Cliff Law, Kitack Lee
 Missing: Tim Jickells. © Tim Jickells, UEA.

The focus of workshop 1 considered the changing atmospheric acidity and its effects on ocean biogeochemistry, utilising a wide range of approaches from fundamental chemistry, through modelling, to field work. The atmosphere has already been through a major phase of anthropogenic acidification due to the emissions of extra sulphur dioxide and nitrogen oxides to the atmosphere from combustion sources. This acidification has been offset to some extent by neutralisation associated with ammonia emissions which originate mainly from agriculture. Vigorous regulatory efforts over the last few decades have greatly decreased sulphur dioxide emissions, and the impact of nitrogen oxides control measures on cars indicate that those emissions have been stabilising. However, continuing intensification of agriculture has increased ammonia emissions. The combined effect of these changes in emissions is a steady reduction in

atmospheric acidification. This process has reduced acidity in many areas of the world and may even lead to alkaline rain. The solubility of several aerosol derived key ocean nutrients (particularly iron and phosphate) is very pH-sensitive and hence sensitive to changing atmospheric acidity. In consequence these changes have the potential to alter the inputs of bioavailable soluble nutrients in the future.

The other key context for the meeting was the changing nature of ocean acidity. Given that there has been a great emphasis on the air-sea exchange of CO₂ in many symposia, the focus in workshop 2 was on a range of other climatically important gases including halogen, nitrogen and sulphur species. These gases play a key role in controlling radiative forcing, atmospheric oxidising capacity and atmospheric chemistry.

As a result of increasing CO₂ concentrations in the atmosphere, the oceans are now demonstra-

As a result of increasing CO₂ concentrations in the atmosphere, the oceans are now demonstrably being acidified by CO₂ uptake.

bly being acidified by CO₂ uptake. This process will continue for decades, before hopefully the Paris Climate Agreement (United Nations Framework Convention on Climate Change, 2015) tackles the problem. While there were great advances in our understanding of the direct biogeochemical impacts of ocean acidification, the question addressed by workshop 2 was how ocean acidification may affect the production and air-sea exchange of trace gases, and whether this effect will mitigate or enhance global change pressures. Thus, the impacts of ocean acidification on ocean biogeochemistry and ecosystems, and how this in turn can affect air-sea exchange at both the global and regional scale were discussed. The workshop considered a wide range of approaches, from fundamental cellular pro-

cesses through ecosystem considerations to global models, and from laboratory to mesocosm and field studies. Also linkages to other global change stressors, particularly global warming and its ramifications for ocean circulation, were taken into account.

Given the intriguing symmetry of potentially important impacts of changing acidity (albeit in opposite directions) on both sides of the air-sea interface we wanted to host these two meetings in parallel to allow crossovers between the various experts. Hence, 25 scientists from around the world gathered in Norwich along with 8 locally based experts and discussed a wide range of issues around these respective themes. These discussions were done often as two separate groups, but with structured joint sessions, and also regular social interactions over shared refreshments.

The meetings featured rather informal presentations from experts, followed by intense discussion sessions, exploring the multiple topics and feedbacks evident in the complex air-sea interaction issues. The invited scientists were selected according to their expertise and interest in these areas, as well as to provide a wide spectrum of

knowledge, and ranged from modelers to experimentalists. We drew scientists from sixteen different countries and from a wide range of career stages, from senior scientists through to graduate students. The participants all seemed to leave Norwich full of enthusiasm for the process and the new scientific insights the groups had developed. The aim now is to write a series of papers synthesising these conclusions. By an interesting coincidence two papers (Jickells *et al.*, 2017; Sharples *et al.*, 2017) from



Figure 2: Prof. Dr. Tim Jickells, who is missing from figure 1. © Tim Jickells; UEA

a similarly sponsored and structured workshop (Duce *et al.*, 2008) were published at about the time of the workshop, which in turn revised work from an earlier workshop.

To conclude, we thank workshops sponsors and all the participants for travelling from near and far to participate, for leaving their families, day-to-day cares and duties (well the email still finds you!) and for embracing the excitement of this scientific dialogue, and we look forward to the speedy preparation of all of the promising manuscripts.

Robert Duce & Tim Jickells
(co-chairs of GESAMP WG 38)

Alex Baker, Cécile Guieu and Manmohan Sarin
(for workshop 1)

Parvatha Suntharalingam, Marion Gehlen,
Frances Hopkins and Martine Lizotte
(for workshop 2)

The outcomes of the workshops contribute to advance our knowledge of the Core Theme 3 “Atmospheric Deposition and Ocean Biogeochemistry” of the SOLAS 2015-2025 Science Plan and Organisation.

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Morgane Perron completed a Master degree in marine chemistry in France at the Institut Universitaire Européen de la Mer, Brest, France, in 2015. She started her PhD in 2016 at the Institute for Marine and Antarctic Studies, Hobart, Tasmania, to investigate the role of atmospheric dust as a vector of trace nutrient, e.g. iron, to Australian marine ecosystems.

Natural iron fertilization of the oceans around Australia, linking terrestrial aerosols to marine biogeochemistry

Perron, M.

Institute for Marine and Antarctic Studies, Hobart, Tasmania

morgane.perron@utas.edu.au

Atmospheric aerosols modulate global climate in numerous significant ways, impacting the Earth's radiative forcing or acting as cloud condensation nuclei or ice nuclei (Jickells *et al.*, 2005). Thereby, atmospheric aerosols have an indirect influence on global weather and being, for example, able to facilitate the occurrence of rainfall. Moreover, the atmospheric pathway has been highlighted as an important if not the main source of iron (Fe) and other key biogeochemical nutrients to the open ocean, where riverine input or sediment resuspension are rare (Duce and Tindale, 1991). Among these areas and in regard to our understanding of climate change, the Southern Ocean is of major interest because of its potential role in the carbon dioxide (CO₂) sequestration in deep ocean layers. However, iron scarcity in these so-called High Nutrient Low Chlorophyll regions limits greatly primary producers' growth. The southern hemisphere comprises only of a few potential dust sources, when compared to

the northern hemisphere (Mahowald *et al.*, 2005). Recently, studies have pointed out Australia's desert as a substantial and previously underestimated nutrient carrier to the southern hemisphere and particularly the Southern Ocean, either during the present time and/or during the Last Glacial Maximum (Luo *et al.* 2003). In Australia, mineral aerosols are produced by aeolian erosion of surface soils in the Lake Eyre and the Murray-Darling Basins arid regions. The country is characterised by highly episodic dust storms (Mackie *et al.*, 2008) that lift up and transport desert dust within specific air masses toward the surrounding coastal or open oceans (Fig. 3). After mixing with air masses, aerosols are finally deposited back to the earth (or ocean), either by dry settling or by wet deposition (rain) (Knippertz and Stuut, 2014). Figure 4 shows a schematic of the dust cycling (Bowie, pers. comm.). However, regarding this, Australia is still largely underexplored and the knowledge on the biogeochemical

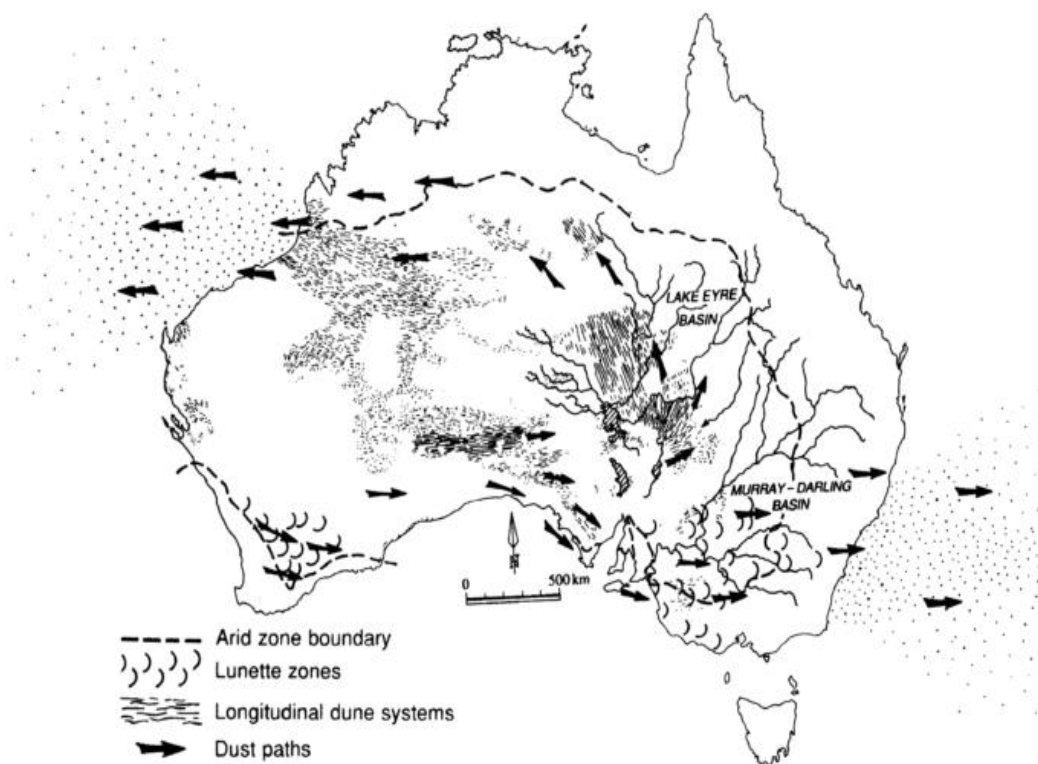


Figure 3: Australian arid zones and major dust pathways (Hesse and McTainsh, 2003)

processing of dust in the atmosphere on its way from the source area to the ocean remains limited. Current global model predictions on dust deposition and its impact on the marine ecosystems are computed against northern hemisphere parameters and do not represent the southern hemisphere processes well (Luo *et al.* 2003; Mahowald *et al.*, 2005). To answer the issues given

above, my PhD project involves an intense sampling activity all around the Australian coasts and the ambient waters. The aim of my study is to qualify and quantify the content of dust loading brought from the central Australian 'outback' to the ocean. By a series of leaching experiments (Baker *et al.* 2006; Bowie *et al.* 2010), we will determine the proportion of water soluble, potential-

ly bioavailable (labile), and refractory iron along with other trace nutrients in collected aerosol samples. This dataset will support or contradict the hypothesis of dust as an essential source of nutrients to the ocean in the study area. Finally, by this extensive dataset, we will be able to constrain dust cycle model parameters relative to the southern hemisphere, as well as model predictions

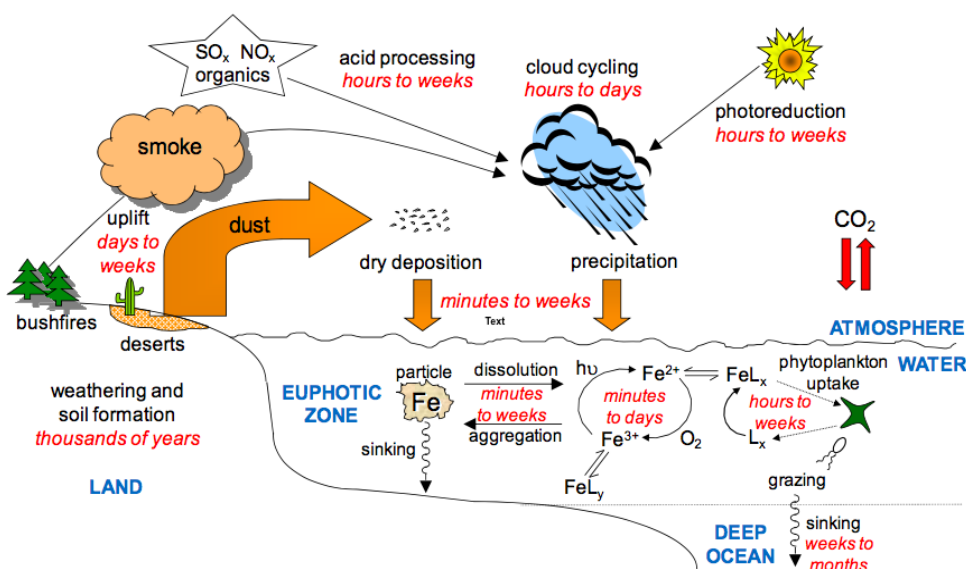


Figure 4: Schematic of air-sea exchanges of trace metals, with iron as an example (Bowie, pers. comm.)

of dust impact on southern hemisphere marine ecosystems, particularly in the Southern Ocean.

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Fiona Seh Lin Keng studied biotechnology at the University of Malaya, Malaysia, where she also conducted her master studies in the field of environmental science. In 2016, Fiona started her PhD at the Institute of Ocean and Earth Sciences, University of Malaya, focusing on the changing environmental effects on the emission of halocarbons by tropical seaweeds.

Will ocean acidification affect the biogenic emission of volatile short-lived halocarbons by marine algae?

Keng, F.S.L.* , Phang, S.M.

Institute of Ocean and Earth Sciences, and Institute of Graduate Studies, University of Malaya, Kuala Lumpur, Malaysia

*fionakeng@yahoo.com

Marine algae emit volatile halocarbons under stressed conditions during grazing, microbial attack, and exposure to varying environmental parameters, which include high light intensity, desiccation, and nutrient limitation, as well as variations in temperature, salinity, and carbon dioxide (CO_2). Phytoplankton in the open ocean has been reported to emit around 19 – 304 Gg Br yr^{-1} (Lim *et al.*, 2017), while marine macroalgae (seaweeds) from the South East Asian region (Fig. 5) were shown to emit between 6 – 224 mmol Br yr^{-1} (Leedham *et al.*, 2013). These halocarbons can affect atmospheric oxidation capacity and radiation balance, change the local climate and even contribute to the halogen pool in the upper troposphere/lower stratosphere. The emission of biogenic halocarbons by marine algae can be affected by ocean acidification. The rise in both, atmospheric CO_2 and eutrophication, affect the photosynthesis activity of the algae, decreases calcification in coralline algae and

change the physiology of the marine plants. An increase in the partial pressure of carbon dioxide (pCO_2) increases photosynthetic activities in non-calcified marine algae (Roleda *et al.*, 2015). The effect of halocarbons on photosynthesis has



Figure 5: *Kappaphycus* spp. red algae farms dominate the South East Asian region.

been linked, as halocarbons are produced from photosynthetic and photorespiratory products i.e. hydrogen peroxide, but these effects vary between different marine algae species (Fig. 6). The presence of halogens, hydrogen and dissolved organic matter in the seawater will produce polyhalogenated compounds, for example bromoform (CHBr_3) and dibromomethane (CH_2Br_2) through the reaction of haloperoxidases (Wever & van der Horst, 2013). Despite the observed correlation between photosynthesis and halocarbon emissions, mesocosm studies on phytoplankton in the arctic and brackish water

emissions peak between 2010-2020 and decline substantially thereafter), projections for the future global oceanic emissions indicate increased emissions of CHBr_3 , CH_2Br_2 and methyl iodide. These increases could be attributed to a potential increase of the sea surface temperature in the tropics and subtropics, intensified vertical transport, and sea-to-air fluxes by the end of the century (Ziska *et al.*, 2016). However, human influences, including seaweed cultivation which could be a significant contributor of CHBr_3 and CHBr_2 , were not included in the model. Challenges encountered for predicting the contribu-



Figure 6: Halocarbon research and sampling for laboratory incubations at the University of Malaya, Kuala Lumpur, Malaysia.

temperate communities, found no or little significant effect of increased pCO_2 levels on the halocarbon emissions by phytoplankton at levels up to those projected under the various Intergovernmental Panel on Climate Change (IPCC) scenarios for year 2100 (Hopkins *et al.*, 2013; Webb *et al.*, 2016). Taken into account the IPCC scenarios of the Representative Concentration Pathways 8.5 (global annual greenhouse gases emissions continue to rise throughout the 21st century) and 2.6 (global annual greenhouse gas

tion and significance of marine algal emission of halocarbons in the regional and global scale include: the species-specific responses of the algae towards changing environmental condition, the complex interactions between marine algae species at the community and ecosystem levels, the spatial and temporal variations of emissions, as well as the restricted availability to regional primary production, biomass, and species distribution data. Efforts are on-going to understand the response and adaptation of the marine algae

to the changing climate; the information obtained will facilitate better predictions of future marine biogenic halocarbon emissions.

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Contact

SOLAS International Project Office

GEOMAR Helmholtz Center for Ocean Research Kiel

solas@geomar.de

Editors:
Emilie Brévière
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