GESAMP Working Group 38

<u>Report on two workshops on the changes in the acid/base balance of</u> <u>the atmosphere and ocean and their subsequent impacts on air/sea</u> <u>chemical exchange</u>

University of East Anglia, Norwich, United Kingdom

27 February - 2 March 2017

From 27 February to March 2 two workshops took place at the University of East Anglia (UEA), Norwich, United Kingdom under the auspices of GESAMP Working Group 38 and sponsored by WMO, NSF, SCOR, SOLAS, and UEA. These workshops focussed on the changes in the acid/base balance of the atmosphere and ocean, and their impacts on air-sea exchange.

Workshop 1 focussed on *Changing Atmospheric Acidity and its Impacts on the Oceanic Solubility of Nutrients* and Workshop 2 focussed on *The Impact of Ocean Acidification on Fluxes of Non-CO₂ Climate-Active Species*. These two themes recognise the importance of both atmospheric nutrient deposition to the biogeochemistry of the oceans and also the importance of the emissions of trace gases from the ocean for atmospheric chemistry and climate regulation. Given that there has been a great deal of focus on the air-sea exchange of CO₂ in many symposia, the focus here 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. The other key context for the meeting was the changing nature of the ocean and atmospheric acid/base balance and associated pH regime.

The atmosphere has already been through a major phase of anthropogenic acidification due to the emissions of extra SO₂ and NOx to the atmosphere from combustion sources. This acidification has been offset to some extent by neutralisation associated with ammonia emissions which come mainly from agriculture. Vigorous regulatory efforts over the last few decades have greatly decreased SO₂ emissions, and the impact of NOx control measures on vehicles have meant that NOx emissions from these 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 long term. The solubility of several key ocean nutrients (particularly iron and phosphorus),

which are mineral aerosol bound, is very sensitive to pH, and hence changing atmospheric acidity has the potential to change the inputs of bioavailable soluble nutrients in the future. Workshop 1 considered this issue and its effects on ocean biogeochemistry, utilising a wide range of approaches from fundamental chemistry, through modelling, to field work.

The oceans are now demonstrably being acidified by the uptake of CO_2 as this increases in concentration in the atmosphere. This process will continue for decades, before hopefully the Paris Climate agreement begins to control the problem. While there have been great advances in our understanding of the direct biogeochemical impacts of ocean acidification, the question considered by Workshop 2 was how this ocean acidification may affect the production and air-sea exchange of these trace gases, and whether this effect will mitigate or enhance global change pressures. Thus Workshop 2 considered 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. The workshop considered a wide range of approaches from fundamental cellular processes through ecosystem considered the links to other global change stressors, particularly global warming and its ramifications for ocean circulation.

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 to develop. So 25 scientists from around the world gathered in Norwich, UK along with 8 locally based experts and discussed a wide range of issues around these respective themes, often as two separate groups, but with regular social interactions over shared refreshments, and also some more structured joint sessions.

The meetings took the form of rather informal presentations from experts followed by very lengthy discussion sessions exploring multiple issues and feedbacks evident in these complex air-sea interaction issues. The invited scientists were selected for their expertise and interest in these areas, and also to provide a wide spectrum of expertise from modellers to experimentalists. We drew scientists from 16 different countries and also 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 from a similarly sponsored and structured GESAMP WG 38 workshop were published at about the time of the workshop; Sharples et al (2016) "What proportion of riverine nutrients reaches the open ocean?", <u>Global Biogeochemical Cycles 31</u>, doi:10.1002/2106GB005483 and Jickells et al., (2017) "A re-evaluation of the magnitude and impacts of anthropogenic nitrogen inputs on the ocean", <u>Global Biogeochemical Cycles 31</u>, doi:10.1002/2016GB00558. These papers in turn are based on an earlier similar workshop reported in Duce et al. (2008) "Impacts of atmospheric nitrogen on the open ocean", Science **320**, 893-897.

The following appendices provide the agendas of the two workshops, a tentative list of the peer-reviewed scientific papers that we expect to result from these workshops, a list of the workshop participants and their addresses, a list of the members of GESAMP Working Group 38, and a photo of the workshop participants.

We thank WMO, NSF, SCOR, SOLAS, and UEA for their strong financial and intellectual support for these workshops. We also thank all the participants for travelling from near and far to participate, for leaving their families, day-to-day cares and duties (well the e-mail still finds you!) and for embracing the excitement of this scientific dialogue, and we look forward to the speedy preparation of all of the promised manuscripts.

APPENDIX I

GESAMP Working Group 38

AGENDAS for two workshops on the changes in the acid/base balance of the atmosphere and ocean and their subsequent impacts on air/sea chemical exchange

University of East Anglia, Norwich, United Kingdom February 27 - March 2, 2017

AGENDA - Plenary Session for Both Workshops

Monday, February 27, Environmental Sciences Seminar Room

09:00 - 09:30 Introduction and local logistics - Tim Jickells, Co-Chair, WG 38 09:30 - 10:00 What is GESAMP? - Peter Kershaw, Chair GESAMP 10:00 - 10:30

- Working Group 38 and its activities Robert Duce, Co-Chair, WG 38
- Introduction to Workshop 1 Alex Baker, Co-Chair, Workshop 1
- Introduction to Workshop 2 Parv Suntharalingam, Tri-Chair Workshop 2

10:30 - Coffee and move to the Blackdale Building

AGENDA - Workshop #1

Changing Atmospheric Acidity and the Oceanic Solubility of Nutrients

Co-Chairs: Alex Baker and Manmohan Sarin

Terms of Reference:

- Review and synthesize the current scientific information on the solubility of aerosol associated key biogeochemical elements, the biogeochemical controls on aerosol solubility, and the pH sensitivity of those controls.
- Consider the likely changes in solubility of key species into the future and the potential biogeochemical consequences of such changes.
- Identify the key future research needs to reduce uncertainties in predictive capability in this area.
- Publish the results of this activity in the open peer-reviewed scientific literature.
- Interact with, and provide information to, leading relevant international groups including the Future Earth core projects SOLAS, IGAC and IMBER; SCOR, particularly its GEOTRACES program; and WMO programs such as GAW.

Monday, February 27 Blackdale Building

11:00 - 12:30 Introduction Alex Baker and Manmohan Sarin

12:30 - 13:15 Lunch

13:15 - 17:30 Initial discussion presentations

Underlying chemical controls on nutrient/trace element solubility David Turner

Potential changes in relevant emissions and their likely impact on atmospheric acidity Maria Kanakidou

Model schemes for simulating the influence of acidity of nutrient / trace element solubility **Thanos Nenes and Akinori Ito**

Modelled nutrient / trace element deposition fields Natalie Mahowald and Stelios Myriokefalitakis

Ocean regions likely to be impacted by atmospheric nutrient / trace element supply **Peter Croot and Cecile Guieu**

Tuesday February 28 Blackdale Building

09:00 - 10:30 Conclude discussion presentations (if necessary) and begin open discussion

- Where do we go from here?

- 10:30 10:45 Coffee break
- 10:45 12:30 Continuing evaluation of workshop science questions and how to

focus publications.

12:30 - 13:15 Lunch

13:15 - 15:30 We will continue with a flexible schedule, if appropriate splitting into smaller topic groups. The aim will be to go with the science flow, but with an ultimate goal of developing one or more topical review papers.

15:30 - 15:45 Tea break

15:45 - 17:30 Continuing discussions and end of day stock-take.

Wednesday March 1 Blackdale Building

- **09:00 10:30** Continuing discussions.
- 10:30 10:45 Coffee break
- 11:00 12:30 Continuing discussions
- 12:30 13:15 Lunch
- 13:15 15:30 Continuing discussions/planning.
- 15:30 15:45 Tea break

15:45 - 17:30 Continuing discussions/planning/writing and end of day stock-take.

Thursday March 2 Blackdale Building

09:00 - 12:30

- Discussion, assignment of writing tasks
- Report back to plenary session.

12:30 - 13:15 Lunch – Close of workshop

AGENDA - Workshop #2

Impact of Ocean Acidification on Fluxes of non-CO₂ Climate-Active Species

Tri-Chairs: Parv Suntharalingam, Marion Gehlen, and Frances Hopkins

Terms of Reference

- Review and synthesize the current science on the direct impacts of ocean acidification on marine production and emissions to the atmosphere of key species important for climate and atmospheric chemistry.
- Identify the primary needs for new research to improve process understanding and to quantify the impact of ocean acidification on these marine fluxes (i.e., provide recommendations on the specific laboratory process studies, field measurements and model analyses needed to support targeted research activities and improved understanding on this topic).
- Publish the results of this activity in the open peer-reviewed scientific literature.
- Provide input to and interact with national and international research programs on ocean acidification (e.g., UKOA, NOAA-OAP) and with relevant WMO programs (e.g., Global Atmosphere Watch (GAW)) to build on their recent relevant activity in achieving the above objectives.

Monday, February 27 Blackdale Building

12:30 - 13:15 Lunch

13:15 - 17:30 Initial discussion presentations

Introduction to Ocean-Acidification and non-CO₂ Trace-Gas Session

CHAIR: Parv Suntharalingam

• Introduction and workshop aims Parv Suntharalingam

Overview of recent progress in ocean acidification research

Talks of ~ 30 mins, including 5 mins for discussion

- Lessons learned from the UK Ocean Acidification research programme Phil Williamson
- Challenges and tools for ocean acidification research Cliff Law
- *Trace-gases (non-CO₂) and ocean acidification: Overview of experimental methodologies* **Frankie Hopkins**

Ocean acidification Impacts on Ocean Biogeochemistry and Ecosystems

Talks of ~ 30 mins, including 5 mins for discussion

- Ocean acidification: Biogeochemical Impacts and Feedbacks to the Earth System Marion Gehlen
- *Re-evalution of enhanced export production by carbon overconsumption under high CO*² **Kitack Lee**
- Indirect impact of ocean acidification on trace gases through pteropod mortality / aragonite dissolution Erik Buitenhuis

Tuesday February 28 Blackdale Building

09:00 - 12:30 Initial discussion presentations (continued)

Ocean Acidification Influences on Trace Gases

(CHAIR: Frankie Hopkins) Talks of 20 - 30 mins, including 5 mins for discussion

Metabolism of trace-gases: The importance of metals Colin Murrell

Reactive trace-gases: DMS and Halocarbons

- Effects of ocean acidification on marine DMS emissions: results from experimental studies **Steve Archer**
- Ocean acidification and DMS: what can we learn from cultures? Gill Malin
- Influence of ocean acidification on biogenic short-lived halocarbons by marine algae Fiona Keng

10:30 - 11:00 Coffee break

Methane, N_2O and the nitrogen cycle

- Impact of ocean acidification on N₂O and CH₄ Andy Rees
- Ocean acidification impacts on the nitrogen cycle Cliff Law
- Modelling impacts of ocean acidification on organic matter stoichiometry: Implications for marine nitrous oxide production **Oliver Andrews**
- Ammonia, pH and interactions with the sulfur cycle Martin Johnson
- Impact of deoxygenation and ocean acidification on N₂O and CH₄ Hema Naik

(Continue this session after lunch if needed)

13:30 - 17:30

<u>Trace-gas Synthesis for Workshop Paper</u>: Break-out groups to work on individual trace-gas sections of summary paper. Suggested breakout groups: (a) Short-lived species (DMS, Halocarbons); and (b) CH₄, N₂O

<u>Aims</u>: Produce summary from observational perspective for the different species, drawing on available observations, lab and in-situ studies. Identify information on process controls. Identify data gaps.

Wednesday March 1 Blackdale Building

09:00 - 10:30 Discussion presentations (continued)

Trace gases and multiple stressors

(CHAIR: Marion Gehlen)

Talks of 20 - 30 mins, including 5 mins for discussion

- Expected response of greenhouse gases to multiple stressors: thoughts on an experimental approach Andy Rees
- Expected response of trace gas emissions to multiple stressors: insights from ocean biogeochemical models Laurent Bopp
- Amplification of global warming through pH-dependence of DMS-production Nadine Goris:

10:30 - 11:00 Coffee

11:00 - 12:30

<u>Regions vulnerable to the impacts of ocean acidification: high latitudes</u>, coastal, and upwelling zones

(CHAIR : Frankie Hopkins)

Talks of 20 - 30 mins, including 5 mins for discussion

- Ocean acidification in the Arctic Ocean and its impacts on DMS cycling Martine Lizotte
- DMS concentrations in the polar oceans are resilient to short term ocean acidification Frankie Hopkins
- Nitrogen cycle dynamics in upwelling zones Isabelle Dadou

12:30 - 13:15 Lunch

13:15 - 17:30

Knowledge gaps and uncertainties, and future research needs

- Reports from Rapporteurs: Synthesis of key points from previous sessions
- Break-out sessions to work on the following for summary paper:
 - Main knowledge gaps, uncertainties and challenges
 - Future research needs: Observational programs, experimental methods, and requirements for improved model predictions

Contributors : All participants

Thursday March 2 Blackdale Building

09:00 - 12:30

- Workshop paper synthesis activities
- Report back to plenary session
- 12:30 13:15 Lunch Close of workshop

APPENDIX II

Draft Paper Titles and Lead Authors – Working Group 1

- **Changing atmospheric acidity as a modulator of ocean biogeochemistry** (Alex Baker Review)
- **The evolution of iron deposition over the ocean: A composite modeling view** (Stelios Myriokefalitakis)
- Evaluation of labile iron processing in atmospheric models (Akinori Ito)
- Evolution of atmospheric acidity impacts on nutrient deposition (Maria

Kanakidou/Thanos Nenes)

Controls and impacts of atmospheric nutrient solubility in the ocean (Peter Croot)

Impacts of the episodic atmospheric deposition on ocean biogeochemistry (Peter Croot)

Links between nutrient stoichiometry of atmospheric deposition and surface seawater (Natalie Mahowald/Maria Kanakidou)

Draft paper titles and lead authors - Working Group 2

- **Changing ocean acidity as a modulator of atmospheric biogeochemistry and climate** (Frances Hopkins Review)
- A synthesis of the DMS response to ocean acidification observed in mesocosm experiments (Steve Archer)
- **Ocean N2O emissions: current estimates and anthropogenically influenced changes** (Parvadhe Suntharalingam)

Ocean model internal variability assessment (Laurent Bopp)

Ammonia emissions and atmospheric acidity (Martin Johnson)

APPENDIX III

Participants at the GESAMP 38 Workshops

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APPENDIX IV

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APPENDIX V

Photo of Participants at the Two GESAMP WG 38 Workshops

