

Surface Ocean-Lower Atmosphere Study

UK SOLAS: Programme Final Report



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Programme Final Report

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Cover image by Glynn Gorick, commissioned for the UK SOLAS display "The Breathing Ocean" at the Royal Society 2008 summer science exhibition

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1. Programme Final Report: Overview

1.1 Programme objectives

The **overall aim of the UK SOLAS programme**, as approved by NERC Council in April 2003, was to advance the understanding of environmentally significant interactions between the atmosphere and the ocean, focussing on material exchanges that involve ocean productivity, atmospheric composition and climate. Within this remit, core issues have been the biogeochemical and physical processes in the upper ocean and lower atmosphere that control chemical exchanges across the air-sea interface.

The UK SOLAS Steering Committee subsequently identified seven **specific research objectives**, detailed in the programme's Science Plan (Annex 2). These were grouped in three related areas, as follows:

Ocean processes relevant to the atmosphere

- i) To identify important trace gas production and loss processes in the surface ocean
- ii) To determine the impact of dynamic physical, chemical and biological processes on marine trace gas production and breakdown, with emphasis on the microbial loop

Atmospheric processes relevant to the ocean

- iii) To improve understanding of the atmospheric transport, cycling and deposition of dust and nutrients
- iv) To assess the importance of marine sources of aerosols and influences on their dynamics
- v) To determine the role of trace gas emissions in modifying the oxidising capacity of the atmosphere

Ocean-atmosphere exchanges

- vi) To reduce the existing uncertainty in the air-sea fluxes of trace gases
- vii) To determine the role of sea surface microlayer in regulating material fluxes to the atmosphere.

The above overall aim and specific objectives were developed in the context of the international SOLAS programme, and its Science Plan and Implementation Strategy (IGBP Report 50, 2004; www.solas-int.org), that had been prepared with substantial UK involvement. The UK SOLAS aims and objectives were also consistent with the first NERC Strategy ("Science for a sustainable future", NERC 2002), that identified climate change and Earth's life-support systems as its major science priorities.

UK SOLAS was well underway by the time of the current, theme-based NERC Strategy ('Next Generation Science for Planet Earth', NERC 2007), involving a change in funding mechanisms. Nevertheless, the transition from Directed Programme to Research Programme was straightforward, and – as detailed in Section 1.3.2 below – UK SOLAS can be considered to have been well-aligned to NERC's new priorities and challenges, particularly for the themes of Climate System and Earth System Science.

1.2 Summary of activities

During its 'core' 6 year lifetime the UK SOLAS programme involved more than 120 researchers working on 28 projects at over 35 research organisations (Section 2 and Annex 5). Science activities were based on field campaigns, laboratory studies and modelling. Programme milestones are identified in [Table 1](#).

The programme's geographical focus was multi-regional; nevertheless, there was particular interest in the tropical east Atlantic (off north west Africa), and higher latitudes in the open north east Atlantic. Whilst an Atlantic focus was anticipated in the Science Plan (Annex 2), specific study areas were primarily determined by successful Round 1 projects, assessed on scientific merit; i.e., each research group identified the most appropriate fieldwork for its needs. Processes occurring in the open ocean, shelf seas and coastal regions were all of interest, although relatively few studies were carried out in UK waters.

Fieldwork and data management

Multidisciplinary and multi-institution fieldwork was central to the UK SOLAS programme. Main activities comprised:

- Eight major research cruises, on *RV Poseidon* (P0332, led by Eric Achterberg) and *RRS Discovery* (D313, Rob Upstill-Goddard; D317, Ian Brooks; D319, Gordon McFiggans; D320, Rob Upstill-Goddard; D325, Gill Malin; D326, Eric Achterberg; and D338, Carol Robinson)
- Three sets of research flights, two using the Met Office/NERC Bae-146 (operated by the Facility for Airborne Atmospheric Measurements, FAAM) and one using the NERC Dornier 228 (operated by the Airborne Research & Survey Facility, ARSF); projects led by Ellie Highwood and Ally Lewis respectively
- A 3-year time series on the Norwegian weathership *Polarfront* at Station Mike, led by Margaret Yelland

- An ongoing time series at the Cape Verde Atmospheric Observatory, initiated by Lucy Carpenter and Mike Pilling, now continued under National Centre for Atmospheric Chemistry, NCAS
- Campaign-based work at Roscoff, Brittany and mesocosm experiments at Bergen, Norway, led by Gordon McFiggans and Colin Murrell respectively.

The British Oceanographic Data Centre, BODC and the British Atmospheric Data Centre, BADC jointly provided data management services for the UK SOLAS programme, with emphasis on field data. UK SOLAS cruise reports and marine datasets are at www.bodc.ac.uk/projects/uk/uksolas with atmospheric datasets at <http://badc.nerc.ac.uk/data/solas>. Remote sensing data relevant to ship and aircraft campaigns off north west Africa was processed and collated by the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) <http://wwwdev.neodaas.ac.uk/supportedscience/uksolas.php>.

Laboratory analyses, modelling and data synthesis

In addition to ship- board experiments and observatory-based analyses, UK SOLAS fieldwork was supported by many laboratory-based studies. These included:

- Gas tank experiments for studying the physics of air-sea gas exchange
- Microbial ecology and molecular biology studies to determine the role of microbial diversity on trace gas production and loss, and effects on the sea surface microlayer
- Simulated cloud processing of desert dust samples, to investigate solubility changes of trace metals.

Modelling was carried out as a component of individual projects, to guide effort in field campaigns and process studies, and assist in knowledge synthesis. There was also a global modelling analysis with close links to the UK Met Office, led by Ken Carslaw, and a global-scale data synthesis project, led by Peter Liss.

National and international linkages

At the national level, close linkages were developed with four other NERC major activities (Oceans 2025; Quantifying and Understanding the Earth System, QUEST; Aerosol Properties, Processes and Influences on the Earth's Climate, APPRAISE; and the Centre for Excellence for the observation of air-sea interactions and fluxes, CASIX). Several UK SOLAS projects also involved collaborations with the UK Met Office/Hadley Centre. Attempts to stimulate private sector engagement through a Knowledge Transfer funding round were less successful, with such linkages limited to studentship co-support (by Commercial Microbiology Ltd).

International partnerships at the programmatic and institutional level included joint work with the German SOLAS programme, Surface Ocean Processes in the Anthropocene (SOPRAN); the Norwegian Meteorological Office; the Cape Verde Instituto Nacional de Meteorologia e Geofísica (INMG); and the African Monsoon Multidisciplinary Analyses (AMMA) project. Co-support was obtained from the European COST Action 735 'Tools for assessing global air-sea fluxes of climate and air pollution relevant gases' and the EU Tropical Eastern North Atlantic Time-Series Observatory (TENATSO) project.

Very many project- and individual-level collaborations with international colleagues also occurred in UK SOLAS, resulting in ~60% of UK SOLAS peer-reviewed publications (Section 4) having non-UK co-authors. Those linkages were greatly stimulated by the UK-hosted SOLAS International Project Office (IPO), with associated scientific guidance through workshops, conferences, website and publications (for details see Section 1.3.5, Table 4). NERC support for the SOLAS IPO was initially via the UK SOLAS programme.

Training

UK SOLAS directly funded 10 research studentships (PhDs) through CASE awards and studentships linked to research grants. Around 20 other research students participated in UK SOLAS research cruises.

UK SOLAS also supported the participation of a total of 28 young researchers in the 2005, 2007 and 2009 international SOLAS summer schools, held in Cargèse, Corsica. Nearly twice as many UK students applied for places on the summer school; the selection was made by an international SOLAS panel. The participation of a further 8 UK students will be directly supported by NERC in 2011.

Communications and wider engagement

Through NERC Swindon Office and university press offices, UK SOLAS has issued five press releases, resulting in wide media coverage. The programme has also been involved in displays at the Science Museum, London ('Chasing Saharan sandstorms' 2006; 'Atmosphere... exploring climate science', 2010 -) and exhibited its own display ('The Breathing Ocean') at the 2008 Royal Society Summer Science Exhibition.

Policy-related work has included UK SOLAS involvement in the 'Experiment Earth?' public dialogue on geoengineering; the provision of evidence and advice (through NERC/RCUK) to the House of Commons Science & Technology Committee; and co-authorship of a Unesco/IOC report on Ocean Fertilization. For further details on above, see Section 1.3.6 and Achievements 3.5 and 3.8.

Table 1. UK SOLAS schedule and milestones, 2004-2010. The programme's total duration was longer than originally planned (by ~1 year, with 6 component projects continuing in 2010-11) due to constraints on shiptime availability that required re-scheduling of elements of the field programme, with associated extensions of awards.

| 2004 | |
|-----------|---|
| Jan | • UK SOLAS Steering Committee established; appointment of UEA-hosted Science Coordinator |
| 19-20 Feb | • <i>1st Steering Committee meeting</i> |
| Mar-May | • Development of Science Plan and Implementation Plan |
| 20 May | • <i>2nd Steering Committee meeting</i> |
| 10 Jun | • First Announcement of Opportunity (AO) for project outlines; Science Plan published |
| 3 Aug | • Closing date for 1 st round outline bids |
| 23 Aug | • <i>3rd Steering Committee meeting</i> ; assessment of outlines |
| Sep-Oct | • Workshops to help develop full proposals (for shortlisted outlines); initial planning of field programme |
| 13-16 Oct | • UK SOLAS participation in international SOLAS Open Science Conference (Halifax, Canada) |
| 8 Nov | • Closing date for 1 st round full bids |
| 2005 | |
| 7-8 Apr | • <i>4th Steering Committee meeting</i> , including 1 st round proposal assessments |
| Jun | • 1 st round awards announced; additional AO for halogen dynamics component [Delay in announcement of awards due to reduction in funding available to the programme] |
| 12-13 Jul | • Programme launch meeting, with research users; Met Office, Exeter |
| Aug-Sep | • Participation of young UK SOLAS researchers in 2 nd international SOLAS summer school, Corsica |
| Sep-Oct | • Start of 1st round research grant awards and studentships |
| 15 Nov | • <i>5th Steering Committee meeting</i> ; assessment of halogen dynamics proposals |
| 10 Dec | • AO for Knowledge Transfer (CASE studentships and research grants) |
| 2006 | |
| Jan- Feb | • First research cruise on <i>RV Poseidon</i> (P0332); DODO flight campaign (with DABEX) off NW Africa |
| Mar -Apr | • Assessment of KT bids; UK SOLAS exhibit at the London Science Museum |
| 17-18 Jul | • 1st Annual Science Meeting for programme participants, Manchester. <i>6th Steering Committee meeting</i> ; finalisation of programme Data Management Plan |
| 25 Jul | • 2 nd AO for science projects, with emphasis on integrative activities |
| Jul-Aug | • First RHaMBLe field campaign held in Roscoff, Brittany |
| Sep-Oct | • 2nd DODO flight campaign (with AMMA) off NW Africa; start of measurements at Cape Verde atmospheric observatory and on Norwegian weather ship <i>Polarfront</i> |
| Oct | • Closing date for 2 nd AO for science projects |
| Nov -Dec | • Research cruise on <i>RRS Discovery</i> for DOGEE and SEASAW projects (D313; uncompleted) |
| 2007 | |
| 8-10 Jan | • Workshop on monitoring and modelling (with QUEST and ACCENT), Cape Verde |
| Jan-Jun | • Three UK SOLAS research cruises on <i>RRS Discovery</i> , for SEASAW (D317), RHaMBLe (D319) and DOGEE-II (D320) |
| 31 Jan | • <i>7th Steering Committee meeting</i> ; assessment of 2 nd round science proposals |
| 6-9 Mar | • UK SOLAS participation in international SOLAS Open Science Conference (Xiamen, China) |
| Apr | • Start of 2nd round awards |
| Sep | • 2nd Annual Science Meeting for programme participants, Leeds; <i>8th Steering Committee meeting</i> |
| Oct-Nov | • Participation of young UK SOLAS researchers in 3 rd international SOLAS summer school, Corsica |
| Nov-Dec | • Research cruise on <i>RRS Discovery</i> (D325) for INSPIRE project |
| Dec | • AO for bids under 'Knowledge Transfer, Synthesis and Dissemination' |

| 2008 | |
|-----------|--|
| 22 Jan | • Closing date for final KT/Synthesis AO |
| Jan-Feb | • Research cruise on <i>RRS Discovery</i> (D326) on Saharan dust deposition |
| May- Jun | • Bergen mesocosm experiment |
| Jun- Jul | • “The Breathing Ocean” display at the Royal Society Summer Science exhibition, London |
| 6-8 Oct | • 3rd Annual Science Meeting for programme participants, Southampton <i>9th Steering Committee meeting</i> |
| 2009 | |
| Apr- May | • Research cruise on <i>RRS Discovery</i> (D338) for ICON project |
| 3-15 Aug | • Participation of young UK SOLAS researchers in 4 th international SOLAS summer school, Corsica |
| 16-19 Nov | • Presentations on UK SOLAS science at international SOLAS Open Science Conference (Barcelona) |
| 2010 | |
| March | • Rampdown of NERC support for SOLAS international Project Office (transfer of Executive Officer post to IfM-GEOMAR, Kiel). Newsletter, website and COST coordination continue at UEA, to March 2012 |
| 22-23 Mar | • UK SOLAS finale event , “The Breathing Ocean”, Meteorological Office, Exeter. <i>10th Steering Committee meeting</i> . Most awards now ended, although data management still ongoing. |
| 31 May | • End of contract for UK SOLAS Science Coordination support at UEA |
| Apr -Dec | • Main period for submission of project final reports and publication of peer-reviewed UK SOLAS papers. Preparation of programme final report. |

1.3 Summary of outputs, outcomes and impacts

This section provides an overview of the range of achievements of the UK SOLAS programme, covering both scientific outputs and outcomes, and its wider societal legacy. Such achievements are summarised here under six headings:

- Main science outputs in relation to programme objectives
- Contribution to NERC Strategy and Theme Challenges
- Publications summary
- Data sets and data products
- Deliverables and achievements of the SOLAS International Project Office
- Policy-related knowledge exchange and impacts.

Specific non-technical examples of high impact achievements are given in Section 3, and a listing of UK SOLAS publications 2005-2010 is given in Section 4. Additional details can be found in the Final Reports of individual projects.

1.3.1 Main science outputs in relation to programme objectives

Objective (i): To identify important trace gas production and loss processes in the surface ocean

Relevant projects include: Impact of coastal upwelling on the air-sea exchange of climatically important gases (ICON); Investigation of near-surface production of iodocarbons - rates and exchange (INSPIRE); Air-sea Oxygenated Volatile Organic Compound (OVOC) fluxes: Seawater sources/sinks and role of the microlayer; Joint SOLAS Bergen mesocosm experiment; Roles of DMSP and GBT in protection from photoinhibition/ photoxidative stress and consequences for DMS and NH₃ production; Denitrification in the bacterioneuston

Many UK SOLAS projects addressed this objective. The **ICON** project (led by Carol Robinson) investigated the influence of coastal/shelf upwelling (20-200 km off NW Africa) on the air-sea exchange of climatically important biogenic gases (CH₄, N₂O, CO₂, DMS/DMSP). Such upwelling can result in high concentrations of these gases – with their air-sea fluxes strongly influenced by spatial and temporal variability in plankton community structure and productivity (stimulated by the high nutrient contents of the upwelled water) and light-driven breakdown of both upwelled and recently-produced dissolved organic matter.

ICON researchers successfully tracked upwelled filaments by combining tracker buoys, real time monitoring of SF₆ tracer patches and remote sensing data supplied by NEODAAS. An unexpected finding was that peak

chlorophyll concentrations occurred at the boundaries between high nutrient, upwelling water and older, low nutrient waters, not in the centre of the former as had been predicted. Because of the late scheduling (2009) of the ICON cruise within the UK SOLAS programme, the main outputs of this project have yet to be published. However ~40 peer reviewed publications are in preparation.

In conjunction with the **Deep Ocean Gas Exchange Experiment (DOGEE)** (led by Rob Upstill-Goddard), the **Air-sea OVOC fluxes** project (led by Phil Nightingale) made the first ever total methanol oxidation rate measurements, off north west Spain. Comparison of measured oxidation rates with uptake into cellular biomass suggested that methanol is mostly used by microbes as a source of carbon rather than of energy. Results also showed the contribution of methanol to bacterial carbon demand was <10% for shelf stations, but as high as 58% for nutrient limited areas. This suggests that methanol could be a significant source of organic carbon for marine bacteria in oligotrophic areas (see Achievement 3.4).

Trace gas production and loss within the sea surface microlayer is discussed below under objective (vi).

Objective (ii): To determine the impact of dynamic physical, chemical and biological processes on marine trace gas production and breakdown, with emphasis on the microbial loop

Relevant projects include: Joint SOLAS Bergen mesocosm experiment; Roles of DMSP and GBT in protection from photoinhibition/ photooxidative stress and consequences for DMS and NH₃ production; Role of algal-bacterial interactions in determining dimethylsulphide fluxes to the atmosphere (ALBA); Impact of coastal upwelling on the air-sea exchange of climatically important gases (ICON); Air-sea OVOC fluxes: Seawater sources/sinks and role of the microlayer; Denitrification in the bacterioneuston; Quantifying dust and upwelling influences on DMS production and fluxes in the tropical NE Atlantic (DUST-UP); Impact of atmospheric dust-derived metal and nutrient inputs on tropical North Atlantic near-surface microbiota

The project **Role of algal-bacterial interactions in determining dimethylsulphide fluxes to the atmosphere** (ALBA, led by David Green) showed that many different bacterial types can oxidise DMS to DMSO, especially when an energy source, such as glucose, is available. Thus this DMS loss pathway may be more important to our understanding of the DMS-climate system than previously suspected. Furthermore, DOC concentration and biological availability may be crucial parameters affecting surface ocean DMS concentrations.

In the project **Roles of DMSP and GBT in protection from photoinhibition/ photooxidative stress and consequences for DMS and NH₃ production** (led by Stephen Archer) cultures of the phytoplankton *Emiliana huxleyi* were acclimatised to high and low light conditions before exposing the cells to acute levels of light and ultraviolet radiation. *E. huxleyi* responded by adjusting its DMSP cell content at rates similar to other photoacclimation strategies used to optimise photosynthesis in the dynamic light environment, thus supporting the hypothesis that DMSP plays a photo-physiological role. However, in experimental studies on the UK SOLAS research cruise D326, natural phytoplankton from the tropical North Atlantic did not show increased DMSP synthesis were exposed to levels of light and UV sufficient to elevate oxidative stress. Thus DMSP's importance as an antioxidant remains unproven.

Glycine betaine (GBT) is also a hypothesised antioxidant, but measurements to date of its concentration have been highly uncertain. UK SOLAS researchers developed a new analytical approach, increasing the detection limit by 3-orders of magnitude. This method was then used to measure GBT concentrations for the first time in an open ocean environment.

The **Joint SOLAS Bergen mesocosm experiment** (led by Colin Murrell) brought together a very wide range of biogeochemical expertise to determine the biological and chemical changes taking place in Norwegian fjord mesocosms during the course of a phytoplankton bloom. Quantified trace gas fluxes included N₂O, DMS and various volatile organic iodine compounds, nearly all of which showed increased fluxes during the course of, or following the bloom.

Objective (iii): To improve understanding of the atmospheric transport, cycling and deposition of dust and nutrients

Relevant projects include: Dust outflow and deposition to the ocean (DODO); Impact of atmospheric dust-derived metal and nutrient inputs on tropical North Atlantic near-surface microbiota; Quantifying dust and upwelling influences on DMS production and fluxes in the tropical NE Atlantic (DUST-UP); Climatology of atmospheric iron inputs to the Atlantic Ocean (IRONMAP); Pathways of Fe in mineral aerosols from Saharan soils to the marine environment

The **DODO** project (led by Ellie Highwood) undertook aircraft campaigns from Dakar in February and August 2006, with the former linked to the first UK SOLAS cruise on *RV Poseidon*. During these campaigns an enhanced dust sampling system with very low particle loss rates was deployed, providing new information on the size, composition, optical properties and iron content of desert dust in both wet and dry seasons. The

success of this system led to its use in the NERC-funded Fennec consortium project, Dust processes and the western Sahara 'heat low' (2010-12).

In particular, iron, silicate and calcium contents were highly dependent on source area (e.g. Sahelian regions vs western Sahara), whilst changes in the relative proportion of coarse mode particles and the refractive index occurred during atmospheric transport and processing. As dust moved over the ocean to Cape Verde some mixing with nitrate aerosol was apparent, and after long range transport to the UK (Mace Head) both sulphate and nitrate were present in the dust.

The atmospheric processing of dust was studied experimentally in **Pathways of Fe in mineral aerosols from Saharan soils to the marine environment** (led by Michael Krom), confirming the potential for major changes in iron solubility. Iron nanoparticles can be formed upon exposure of dust to acid conditions, with an associated increase in iron solubility. Trace metals, eg chromium, have also been found associated with these nanoparticles both in laboratory simulations and in field samples.

The **IRONMAP** project (led by Alex Baker) combined ocean basin scale air mass climatologies with chemical aerosol and dust data collected during 15 large scale cruises which took place over 10 years (SOLAS and non-SOLAS studies). New estimates were thereby obtained of wet and dry deposition of iron, nitrogen and phosphorous to the Atlantic ocean.

Data from the **Impact of atmospheric dust-derived metal and nutrient inputs on tropical North Atlantic near-surface microbiota** (led by Eric Achterberg) strongly indicate that upwelling, rather than dust deposition, is the main factor driving increased productivity off the western coast of Africa. Nevertheless, over a wider area dust-delivered iron may be very important for N₂ fixation. Incubation experiments suggest that high copper content in some dust sources may have an inhibitory effect on phytoplankton growth.

Objective (iv): To assess the importance of marine sources of aerosols and influences on their dynamics

Relevant projects include: Reactive Halogens in the Marine Boundary Layer (RHAMBLe); Aerosol characterisation and modelling in the marine environment (ACMME); Field observations of sea spray, gas fluxes and whitecaps (SEASAW); Chemical and physical structure of the lower atmosphere of the tropical eastern North Atlantic; Investigation of near-surface production of iodocarbons - rates and exchange (INSPIRE); Global modelling of aerosols and chemistry (GLOMAP); Transformations, volatilisation and speciation of organic and inorganic iodine in the marine environment

Unique information on aerosol dynamics and reactive atmospheric chemistry has been obtained from multi-platform studies in UK SOLAS; in particular, the data sets obtained from simultaneous measurements at the **Cape Verde Atmospheric Observatory (CVAO)** and on *RRS Discovery* as part of **RHAMBLe**, **SEASAW** and **ACCME** projects (led by Gordon McFiggans, Ian Brooks and James Allan respectively). For example, the first direct eddy covariance flux estimates of size-resolved aerosol over the open ocean were made during the **SEASAW** study. In **Chemical and physical structure of the lower atmosphere of the tropical eastern North Atlantic** (led by Ally Lewis), the NERC Dornier aircraft was used to determine the vertical distribution of reactive trace gases at Cape Verde and near to the **RHAMBLe** cruise paths.

The coastal component of **RHAMBLe**, carried out in Roscoff bay provided direct observational linkage between new particle formation and reactive halogens, resulting in the development of a new parameterisation for use in large-scale models.

During the **INSPIRE** cruise (led by Gill Malin) a new thermo-extraction spectrophotometric method was used to analyse the total and water-soluble iodine in bulk marine aerosols from the NE Atlantic. High iodine levels were found in air masses with low atmospheric O₃ levels and with long residence times over the high chlorophyll waters in the West African upwelling.

The **GLOMAP** modelling project (led by Ken Carslaw) has, for the first time, quantitatively linked the seasonal cycle of cloud condensation nuclei (CCN) in the marine boundary layer with DMS dynamics using a global aerosol microphysics model. The sensitivity of CCN to local DMS emissions is lower (but the effect more widespread, over thousands of km) than previously thought due to long range transport of aerosol through the global free troposphere (see Achievement 3.3).

GLOMAP also found that there is a significant source of marine organic aerosol (comparable in magnitude to the fossil fuel organic carbon source), and that stratospheric ozone depletion has driven increases in southern hemisphere winds - leading to increased sea spray, aerosols and CCN concentrations. The change in summertime forcing of - 0.7 W m⁻² is comparable in magnitude, but opposite in sign, to the greenhouse gas forcing over the same period.

Objective (v): To determine the role of trace gas emissions in modifying the oxidising capacity of the atmosphere

Relevant projects include: Chemical and physical structure of the lower atmosphere of the tropical eastern North Atlantic; Reactive Halogens in the Marine Boundary Layer (RHAMBLe); Oxidative ability of the mid-Atlantic lower troposphere; Seasonal oxidant observations; Transformations, volatilisation and speciation of organic and inorganic iodine in the marine environment

The **CVAO** has been central to many of the projects involved with this objective. Collective data has greatly improved our understanding of how ocean-produced reactive halogens affect the photochemistry of the tropical marine boundary layer. In particular, the realisation that tropospheric O₃ destruction is enhanced by halogen oxide reactions and is 50% greater than predicted in climate models. Due to the tight coupling of ozone photochemistry and methane cycles this has major implications for modelling approaches to simulating atmospheric methane (see Achievement 3.2).

In temperate, coastal waters the stress-related physiological basis for iodine release by macroalgae (kelp) was investigated by the project **Transformations, volatilisation and speciation of organic and inorganic iodine in the marine environment** (led by Lucy Carpenter), resulting in a high profile publication (Küpper et al 2008) - rated by the US Discover magazine as one of the top 100 science stories for that year.

Objective (vi): To reduce the existing uncertainty in the air-sea fluxes of trace gases

Relevant projects include: Deep ocean gas exchange experiment (DOGEE); Impact of coastal upwelling on the air-sea exchange of climatically important gases (ICON); Field observations of sea spray, gas fluxes and whitecaps (SEASAW); High wind air-sea exchanges (HiWASE)

The **DOGEE** project achieved most of its aims although technical problems and bad weather during its first cruise (D313) and the discovery of a previously unrecognised source of contamination to open path LICOR CO₂ measurements delayed the linkage of CO₂ fluxes and wave-related impacts. A new algorithm was developed to correct these measurements and all affected UK SOLAS data are being corrected via a PhD studentship.

DOGEE has led to improved parameterisations of gas transfer velocity (k) for both soluble (e.g. DMS) and low solubility gases (e.g. N₂O and CO₂). Solubility is an important consideration in air-sea gas transfer rates that had previously not been fully taken into account. For DMS, near-surface gradients can also influence estimates of k , with implications for air-sea fluxes based on single-depth DMS concentration measurements. Surfactant effects were also shown to be important for the air-sea exchange of trace gases,

HiWASE (led by Margaret Yelland) used a unique combination of instruments, mostly automated, to measure CO₂ flux and hence characterise the main forcing parameters, such as sea state, wave breaking and whitecap fraction. HiWASE greatly extended the previously sparse measurements of open-ocean air-sea CO₂ flux at high wind speeds (see Achievement 3.1). Together, **HiWASE**, **SEASAW** and **DOGEE** much improved our quantitative understanding of the relationship between whitecap fraction and wind speed, directly affecting air-sea transfer of gases via bubble formation; these studies also tested algorithms for satellite-based retrieval of the whitecap fraction.

Objective (vii): To determine the role of sea surface microlayer in regulating material fluxes to the atmosphere

Relevant projects include: Deep ocean gas exchange experiment (DOGEE); Impact of coastal upwelling on the air-sea exchange of climatically important gases (ICON); The role of the bacterioneuston in air-sea gas exchange; The joint SOLAS Bergen mesocosm experiment; Air-sea OVOC fluxes; Denitrification in the bacterioneuston

Production and consumption of greenhouse gases within the sea surface microlayer, and the influence of this layer on the air-sea exchange of such gases, was investigated on several UK SOLAS cruises, e.g. **DOGEE** (D313, D325) and **ICON** (D338). Detailed characterisation of the microlayer was carried out by two projects, **The role of the bacterioneuston in air-sea gas exchange** and **The Joint SOLAS Bergen mesocosm experiment** (both led by Colin Murrell).

Microlayer sampling practices were evaluated and new techniques were developed, using a remote controlled catamaran to collect a surface film ~50 µm thick. Molecular analyses of microbial biodiversity based on 16S rRNA showed that microlayer-specific bacterial populations exist (see Achievement 3.7), and that their recruitment to the microlayer is non-random in estuarine, open ocean and in fjord mesocosm environments.

1.3.2 Contribution to NERC Strategy and Theme Challenges

Through the science outputs summarised above, UK SOLAS is considered to have made a substantial contribution to the delivery of the current NERC mission. Thus it has promoted and supported high quality strategic and applied research, whilst also advancing knowledge required by policy makers and other end-users, in areas that closely match many of specific challenges identified as priorities in NERC's current science strategy (Table 2).

| Table 2. NERC theme challenges (2010 update) addressed by UK SOLAS. XXX, very close match, high contribution to theme delivery; XX, good match, significant contribution; X, modest match and contribution. | | |
|--|--------------|--|
| NERC Theme/Challenge | match | UK SOLAS contribution |
| CLIMATE SYSTEM | | |
| Develop high-resolution regional predictions for decision making | XXX | New climate system model components and improved processes, (with MetOffice/Hadley Centre and others) to reduce and quantify uncertainty; new datasets for model testing |
| Enabling society to develop mitigation and adaptation strategies through climate science | X | International partnerships in developing coupled models; capacity building, with enhanced relationships with developing countries |
| Improve and expand observations to validate climate change detection and prediction | XX | New time series (eg Cape Verde Observatory) to test theory and models; collation and re-analysis of global data sets |
| Increase knowledge of the physical, chemical and biological feedback processes | XXX | Process studies on production and fate of marine biogases (eg halogens, DMS and VOCs); impact of marine emissions on oxidising capacity and climate |
| Key processes determining the sensitivity of the climate system | XX | Improved representations of basic processes and feedbacks relating to ocean-atmosphere interactions |
| Natural variability and the link with climate change | X | Better understanding of spatial and temporal variability affecting and affected by ocean-atmosphere interactions |
| The changing water cycle | X | Improved parameterisation of ocean heat budgets; role of marine aerosols in cloud formation |
| Assess climatic implications of geo-engineering to intentionally alter the global carbon cycle and/or climate | XX | Process-based understanding relevant to potential geoengineering via ocean fertilization and/or cloud-based solar radiation management |
| EARTH SYSTEM SCIENCE | | |
| Biogeochemical fluxes and feedbacks in the cryosphere, ocean, atmosphere and Earth surface system <i>[previously 11 separate challenges, now combined]</i> | XXX | Impacts of high CO ₂ on upper ocean chemistry and biology; feedbacks to climate and air quality; production and loss of climatically relevant biogases; particle formation and reactivity in the marine boundary layer; chemical interactions with ozone and halogens in marine boundary layer; observations and modelling of air-sea fluxes of key elements, including iron and trace metals; interactions between physically-driven hydrodynamic processes (at range of scales), upper ocean biology and chemical fluxes; |
| ENVIRONMENT, POLLUTION & HUMAN HEALTH | | |
| Process studies and enhanced models of the dynamics of transport and transformation of environmental pollutants | X | Oxidative capacity of marine atmosphere |
| TECHNOLOGIES | | |
| Remote sensing and Earth observation | XX | Sea surface physics and biogeochemistry; atmospheric composition |
| Intelligent field sensors and networks of sensors | X | New measurements techniques for marine and atmospheric observatories and process studies |
| Informatics, models and data | XX | Global data collation, synthesis, management and analysis |

1.3.3 Publications summary

To date (February 2011), the UK SOLAS programme has been fully or partly responsible for 133 peer-reviewed science publications, and at least 205 non peer-reviewed publications. Annual totals for 2005-2010 are shown in [Figure 1](#) and a full title listing (including a few 2011 publications) is given in Section 4.

This information is primarily derived from the programme's collated Output and Performance Measures (OPM) returns, as annually collated in NERC's Research Outputs Database (ROD). However, additional

2010 publications are likely, since not all projects have yet submitted their 2010 ROD returns (March deadline). An additional 50-70 peer-reviewed publications might be expected in 2011-2013, assuming that a near-normal distribution applies to the timing of their production – as typically occurs for a major research programme – and that 2010 is the ‘peak year’.

For 2010 peer-reviewed publications, UK SOLAS researchers were lead authors for 75% of those papers. A relatively high proportion (60%) included a non-UK co-author.

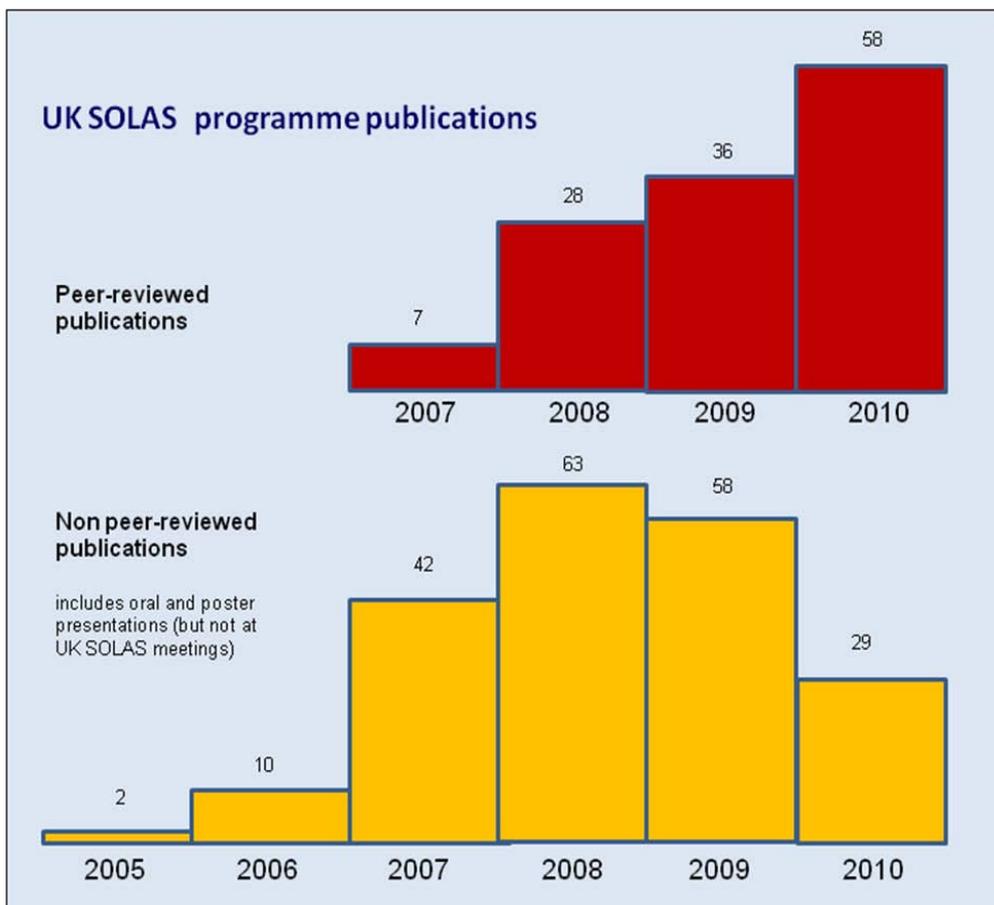


Figure 1. Summary of peer-reviewed and non peer-reviewed publications arising from the UK SOLAS programme, 2005-2010. Data for 2010 likely to be incomplete.

1.3.4 Data sets and data products

Many large, high quality data sets were produced by the UK SOLAS programme. The long-term post programme exploitation of data has been promoted by:

- The involvement of relevant national Data Centres (British Oceanographic Data Centre, BODC and British Atmospheric Data Centre, BADC) in programme management, through Steering Committee membership (BODC), participation in UK SOLAS meetings, and visits to research groups
- Development and wide dissemination of the UK SOLAS Data Management Plan, Data Policy and Metadata Protocol (Annex 4)
- Creation of integrated databases for fully-archived data at BODC www.bodc.ac.uk/projects/uk/uksolas (UK SOLAS data centre) and BADC <http://badc.nerc.ac.uk/data/solas>.
- Lead role in the creation of an international SOLAS metadata portal <http://tinyurl.com/46xnf9>, as part of NASA’s Global Change Master Directory.

A UK SOLAS Knowledge Transfer (KT) award (“Global data synthesis of air-sea fluxes of gases and aerosols for policy directed modelling and assessment of climate change and prediction”, led by Peter Liss) and strong UK SOLAS involvement in the European Cost Action 735 (“To develop tools for assessing global air-sea fluxes of climate and air pollution relevant gases”) assisted in ensuring that relevant end users are aware of, and can access, SOLAS data sets.

Thus the closely linked KT award and COST Action 735 focussed effort on converting UK SOLAS and international SOLAS data into readily-accessible data products, useful to end users, including climate modellers and scientists/companies working with remote sensing applications. This work was further developed by NERC Knowledge Exchange support for a SOLAS Project Integration Officer, to coordinate the preparation of SOLAS-derived data products.

Examples of major data sets and data products are given in [Table 3](#). UK SOLAS has also contributed to the ongoing development of the Halocarbons in the Ocean and Atmosphere (HalOcat) database, led by IFM-GEOMAR (<https://halocat.ifm-geomar.de>).

| Table 3. Major UK SOLAS data products, including those produced in partnership with other activities | |
|---|--|
| Cape Verde Atmospheric Observatory | Wide range of trace gases, including CO ₂ , O ₃ , NO, NO _x , VOCs and halocarbons; also met data and aerosol characterisation. From September 2006, now continued via NCAS. Data archived with WMO-GAW and BADC. http://ncasweb.leeds.ac.uk Supporting remote-sensing data for periods of UK SOLAS field campaigns: http://wwwdev.neodaas.ac.uk/supportedscience/uksolas.php |
| Polarfront time series: Norwegian Sea (HiWASE) | A three year time series including data of the turbulent air-sea fluxes of sensible and latent heat, momentum and CO ₂ . http://noc.soton.ac.uk/ooc/CRUISES/HiWASE/index.php |
| Ironmap | Database of aerosol chemistry (wet and dry deposition data) for iron, nitrogen and phosphorus for the Atlantic Ocean, based on 12 research cruises. Currently being used to validate Met Office biogeochemical models. Contact: Alex.baker@uea.ac.uk |
| Dimethylsulphide (DMS) global climatology | Global database of > 47000 measurements of DMS water concentrations and air-sea fluxes. The flux climatology indicates a 16-18% increase in global DMS flux estimates compared to previous work. Facilitated by the NERC- funded SOLAS Project Integration Officer Lana et al. (2011) <i>Global Biogeochemical Cycles</i> , 25, GB1004 |
| MEMENTO: Marine methane & nitrous oxide database | Global database of marine and atmospheric methane and nitrous oxide data; facilitated by the NERC funded SOLAS Project Integration Officer Bange HW et al (2009) <i>Environmental Chemistry</i> 6, 195-197 |

1.3.5 Deliverables and achievements of the SOLAS International Project Office

The co-location at the University of East Anglia of the UK SOLAS Science Coordinator and the SOLAS International Project Office has greatly facilitated productive interactions between the two activities. There have also been close administrative and financial linkages. Thus NERC support for the SOLAS International Project Office (IPO) was initially awarded in August 2002, on a provisional, low-level basis and subject to approval of a single full proposal for both the IPO and a national SOLAS programme. The total UK SOLAS budget subsequently included IPO support, with an overview management role both by NERC Swindon Office and the UK SOLAS Steering Committee.

The work of the IPO has however, been directed by the international SOLAS Scientific Steering Committee, co-sponsored by the International Geosphere-Biosphere Programme (IGBP), the Scientific Committee on Oceanic Research (SCOR) the World Climate Research Programme (WCRP), and the International Commission on Atmospheric Chemistry and Global Pollution (ICACGP). Dr Jeff Hare was appointed SOLAS IPO Executive Officer in 2005, succeeded in 2008 by Dr Emilie Breviere. In early 2010, lead IPO functions were transferred to IfM-GEOMAR, Kiel, with German funding; NERC has, however, maintained support for a nodal office of the SOLAS IPO until March 2012, with responsibility for communications (website and newsletter) and implementation of COST Action 735.

NERC support for IPOs is provided on the basis that they address the following generic objectives:

- Support vibrant, integrated research communities in which UK scientists can participate
- Encourage UK leadership and influence in setting agendas and priorities for international research, helping to deliver and inform NERC's own strategic priorities
- Facilitate coordination of research worldwide to advance science at international level, providing opportunities for UK science that the UK cannot deliver alone
- Help deliver new knowledge
- Help deliver knowledge exchange that supports NERC priorities
- Support NERC's contribution to international sustainable development goals.

[Table 4](#) provides information on the SOLAS IPO's achievements to date, summarising how each of its seven main activities have contributed to the above generic objectives (primarily via interactions with UK SOLAS).

Table 4. Achievements of the SOLAS International Project Office (2003-2010) in context of the IPO's main activities (1) – (7) and NERC's generic objectives for IPOs

| | |
|---|--|
| <p>1. Preparation, publication and delivery of the SOLAS Science Plan and Implementation Strategy (2004). The IPO edited the Science Plan and subsequently facilitated its delivery, working with the SOLAS Scientific Steering Committee and the international community, to initiate and support priority activities.</p> <p>The SOLAS Science Plan defined the international research agenda for biogeochemical air-sea interactions, identifying key knowledge gaps. These included ocean acidification; effects of iron on marine productivity; geographic and sub-decadal variability of air-sea CO₂ fluxes) and the role of biogenic gases and aerosols in climate change.</p> | |
| <p><i>Support research communities with UK participation</i></p> | <p>Strong synergisms have been developed between the NERC-funded UK SOLAS directed programme and international SOLAS activities.</p> <p>For example, SOLAS links enabled UK researchers to: i) participate in German and US research cruises and other field campaigns (and vice versa); ii) install sensors on the Norwegian weather ship <i>Polarfront</i>, to obtain a unique three year time series on air-sea fluxes; iii) establish (with Germany and other partners) the Cape Verde Ocean-Atmosphere Observatory (now NCAS supported, as National Capability); and iv) obtain access to other nations' facilities (eg Bergen mesocosms), equipment (ASIS profiling sampler used on UK SOLAS cruises) and datasets (e.g. UK modellers using Australian and Irish atmospheric monitoring data).</p> |
| <p><i>Encourage UK leadership/influence re NERC priorities</i></p> | <p>The international SOLAS Science Plan was prepared under UK Chairmanship (Peter Liss), and had strong UK involvement (4 out of 18 authors). Also two other UK members of international SOLAS Scientific Steering Committee (Tim Jickells; Roland von Glasow)</p> <p>In addition to guiding the UK SOLAS research agenda, the SOLAS Science Plan influenced the development of at least five other NERC activities: Centre for Observations of Air-Sea Interactions and Fluxes (CASIX); Aerosol Properties, Processes & Influences on Earth's Climate (APPRAISE); Quantifying & Understanding the Earth System (QUEST); Oceans 2025 (NERC marine strategic programme); and the UK Ocean Acidification research programme (UKOARP).</p> |
| <p><i>Facilitate research coordination with UK opportunities</i></p> | <p>Examples of SOLAS coordination role (facilitated by IPO) include: i) support for global data synthesis and integration (primarily via COST Action 735, see below); ii) development of ocean acidification research in Europe (via EPOCA, European Project on Ocean Acidification; with strong UK involvement) and worldwide (via SOLAS-IMBER Working Group on Ocean Acidification, with UK representation) and iii) unified approaches to governments/agencies for collaborative work and diplomatic approvals (e.g. via EU TENATSO project promoting regional involvement in Cape Verde observatory, and facilitating work in Mauritanian territorial waters).</p> |
| <p><i>New knowledge</i></p> | <p>Major knowledge advances achieved via collective effort of SOLAS programme include: i) quantification of role of marine biogenic gases (including dimethyl sulphide, DMS) in atmospheric chemistry and cloud formation); ii) recognition of importance of dust-derived iron for microbial nitrogen fixation; iii) molecular characterisation of sea surface microlayer; and iv) improved global estimates of air-sea CO₂ exchanges and the factors controlling such fluxes.</p> |
| <p><i>Knowledge exchange</i></p> | <p>SOLAS KE achieved via i) national links to governmental bodies involved with climate policy (Defra, DECC and MetOffice/Hadley Centre for UK; European links via COST); ii) policy papers and other inputs to IOC, UN and ICSU bodies, directly and via SOLAS sponsors; iii) lead and contributory authorship of IPCC Fourth Assessment (2007); and iv) advisory role in regulation of ocean-based geoengineering (via IOC and London Convention/ Protocol).</p> |
| <p><i>International sustainable development</i></p> | <p>The IPO actively promotes SOLAS involvement by developing countries, via capacity-building initiatives. For example, via travel funds for participation in SOLAS training (Summer School), SOLAS regional meetings, Conferences and workshops, and other events and activities.</p> |
| <p>2. Develop and maintain international SOLAS network of networks. The SOLAS network provides two-way communication between the IPO and the global SOLAS research community, through national contacts and nationally-funded programmes and projects.</p> | |
| <p><i>Support research communities with UK participation</i></p> | <p>SOLAS database includes ~1600 researchers and research users in 77 countries, with 26 national networks.. Annually-updated, online national reports and SOLAS News articles provide UK researchers with key contacts and latest information on worldwide research opportunities</p> |
| <p><i>Encourage UK leadership/influence re NERC priorities</i></p> | <p>UK national reports and contacts made available to very wide audience, with known influence in stimulating new collaborations. Information on international activities made available to UK SOLAS Steering Committee and others</p> |
| <p><i>Facilitate research coordination with UK opportunities</i></p> | <p>Linkages between the IPO, the Scientific Steering Committee and the SOLAS network provide the backbone for international planning, coordination and implementation of the programme – and the UK's full engagement in it.</p> |
| <p><i>New knowledge</i></p> | <p>More than 600 SOLAS publications in 2006-10 (list at http://solas-int.org/science/publications/publications.html), including 25 in <i>Science</i>, <i>Nature</i>, <i>Nature Geo-science</i> and <i>PNAS</i> (11 with UK authors/co-authors); also two special issues of <i>Deep Sea Research Part II</i></p> |
| <p><i>Knowledge exchange</i></p> | <p>See above. UK SOLAS KE work closely aligned to international effort, eg via COST</p> |

| | |
|--|--|
| <i>International sustainable development</i> | Well-developed SOLAS networks in India, China, Southern Africa, Brazil, Chile and SE Asia (also SSC members from several of those countries/ regions). |
| 3. Communicate SOLAS science to international research and policy community , through website, SOLAS news and e-bulletins. | |
| <i>Support research communities with UK participation</i> | Well-visited website www.solas-int.org . Twelve issues of SOLAS News to date, each 20-48 pages; hardcopy and online, and including > 25 UK articles and reports |
| <i>Encourage UK leadership/influence re NERC priorities</i> | Information on UK activities made available to very wide audience, with opportunity for influence. Also vice versa, as above. |
| <i>Facilitate research coordination with UK opportunities</i> | International balance in IPO communications is crucially important. Nevertheless, the UK is very well-positioned to promote its interests. |
| <i>Knowledge exchange</i> | IGBP website and publications also used to communicate SOLAS science to research users |
| 4. Organisation of major international science meetings. SOLAS Open Science Conferences held in Halifax, Canada (2004), Xiamen, China (2007) and Barcelona (2009). Reports in SOLAS News 1, 5 and 10. | |
| <i>Support research communities with UK participation</i> | Open Science Conferences (OSCs) attended by 200-250 participants, from >25 countries. At Xiamen, the UK contributed 29 posters (out of 219), 4 oral overviews (out of 21) and led/co-led 6 discussion groups. At Barcelona, the UK authored/co-authored 52 posters (out of 191), gave 5 plenary talks (out of 28) and led/co-led 5 discussion groups |
| <i>Encourage UK leadership/influence re NERC priorities</i> | Outputs from ocean fertilization discussion session at Barcelona OSC used in planning the NERC-led Public Dialogue on Geoengineering |
| <i>Facilitate research coordination with UK opportunities</i> | OSCs provide the opportunity for initial planning of large-scale studies on international basis |
| <i>New knowledge</i> | New knowledge tested (and generated) by exposure of results to international discussion |
| <i>Knowledge exchange</i> | The Barcelona OSC (held at a Science Museum) included a public evening event with UK speaker; also discussions sessions on geoengineering, ship plumes and developing SOLAS- ESA links. Wide range of research user participants. |
| <i>International sustainable development</i> | IPO-arranged sponsorship, via SCOR and others, for developing countries' participation in OSCs (total ~23 at Halifax; ~65 at Xiamen, and ~20 at Barcelona). |
| 5. Organisation of SOLAS Summer Schools for PhD students and early career scientists. Held in Corsica in 2003, 2005, 2007 and 2009, each with ~70 students. Reports in SOLAS News 2, 6 and 10. | |
| <i>Support research communities with UK participation</i> | NERC-sponsored attendance (via UK SOLAS) of 8-10 students at 2005, 2007 and 2009 Summer Schools. Eight students selected for NERC support in 2011. |
| <i>Encourage UK leadership/influence re NERC priorities</i> | 4-5 high profile UK lecturers involved in each Summer School |
| <i>Knowledge exchange</i> | Textbook developed from Summer Schools published in 2009 (AGU Geophysical Monograph 187). UK authorship of 7 (out of 17) chapters. |
| <i>International sustainable development</i> | IPO-arranged sponsorship, via SCOR, APN, IAI, EU and others, for developing countries' participation in Summer Schools |
| 6. Development and implementation of COST Action (European Cooperation in Science & Technology action 735; 2006-11, "Tools for assessing air-sea fluxes of climate and air-pollution relevant gases". EU/ ESF funded; UK Chair. Delivery by IPO, with support from UK SOLAS KT award. | |
| <i>Support research communities with UK participation</i> | 17 countries have signed MoU for formal collaboration on science-policy activities in SOLAS area; 8 non-EU countries also involved. |
| <i>Facilitate research coordination with UK opportunities</i> | Ten workshop meetings held to date (6 UK-hosted); total participation 187, (42 from UK). Three other workshops in prep. Also 11 Short Term Scientific Missions, 7 with UK researchers or UK hosts, to support working visits between COST countries. |
| <i>Knowledge exchange</i> | Workshops cover policy-relevant topics and include governmental participants (from meteorological offices, ESA and similar). |

| | |
|---|---|
| 7. Joint work with other global change programmes and activities , primarily through IGBP (International Geosphere-Biosphere Programme); eg via multi-project Fast Track Initiatives also with SCOR (Scientific Committee on Oceanic Research) and ICSU (International Council for Science). | |
| <i>Support research communities with UK participation</i> | IPO-developed SOLAS linkages and joint initiatives provide many additional national, European and international opportunities for high-level involvement by UK researchers; eg UK-hosted workshop on Megacities and the Coastal Zone. |
| <i>Facilitate research coordination with UK opportunities</i> | Work with IMBER (Integrated Marine Biogeochemistry and Ecosystem Research) on ocean acidification; and with WMO-GAW (World Meteorological Organisation-Global Atmospheric Watch) and IOCCP (International Ocean Carbon Coordination Project) on global monitoring |
| <i>New knowledge</i> | Interdisciplinary synthesis and integration within and between global change programmes generates new understanding of Earth system interactions |
| <i>Knowledge exchange</i> | SOLAS work with IOC (Intergovernmental Oceanographic Commission), IMO (International Maritime Organization) and CBD (Convention on Biodiversity) on regulation of ocean fertilization. |
| <i>International sustainable development</i> | Capacity building activities (with UK involvement) include SOLAS-IMBER Southern Africa Meeting (2008); and SOLAS-ACCENT Cape Verde workshop (2007) |

1.3.5 Policy-related knowledge exchange and impacts

Predictive climate modelling

The importance of UK SOLAS datasets, data products and parameterizations for predictive climate modelling was recognised not only at the start but also at the end of the programme, with the programme launch (July 2005) and finale event (March 2010) both being held jointly with the UK Met Office and Hadley Centre. Whilst 20 years or so ago, the physical coupling between ocean and atmosphere, with associated fluxes of heat and energy, represented the major uncertainty in climate modelling, subsequent attention has increasingly focussed on the potential for biogeochemical feedbacks – via effects on atmospheric chemistry, aerosols and greenhouse gases – that might arise from either marine or terrestrial ecosystems (Figure 2).

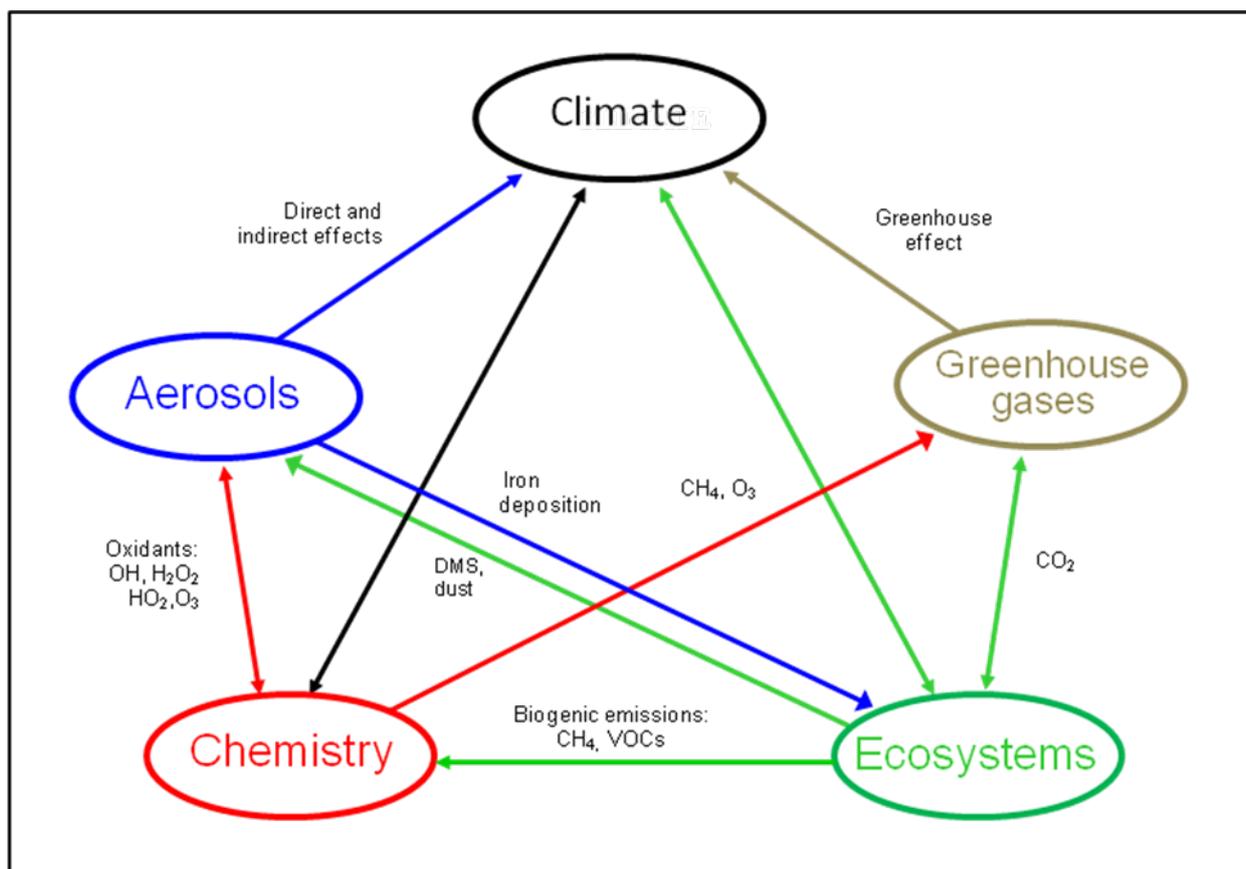


Figure 2. Biogeochemical feedbacks and interactions in the climate system, as represented in the HadGEM2-ES global model, developed with UK SOLAS inputs. Figure based on Met Office presentation by Olivier Boucher at UK SOLAS finale event (omitting role of human emissions and land-use changes).

The following areas represent significant increases in predictive modelling capabilities part or fully facilitated by UK SOLAS awards or knowledge exchange:

- New dust uplift scheme derived from DODO study and implemented in several versions of the UM (limited area model, HadGAM2) and compared against existing dust schemes.
- Improved parameterisation of reactive atmospheric chemistry in tropical marine boundary layer, from Cape Verde data, affecting tropospheric ozone and NO_x concentrations and global lifetime of methane (see Achievement 3.2)
- Quantification of role of iodine in particle formation, and the physiological basis of its biogenic release in the coastal zone
- Improved estimates of global DMS fluxes, and the relative climatic importance of DMS, sea spray and marine organics through the production of cloud condensation nuclei (see Achievement 3.3).

The above work complemented other collaborations between NERC and the Met Office (e.g. via QUEST and APPRAISE) and helped establish more recent initiatives developed under NERC's current strategy, e.g. Joint Climate and Weather Research Programme (TAP 1); Aerosols and Clouds, and Understanding and Predicting the Ocean Boundary Layer (TAP 2); and Greenhouse Gas Emissions and Feedbacks (proposed for TAP 3).

Ocean fertilization – and its potential for geoengineering

The UK SOLAS programme did not include any large-scale ocean fertilization experiments, and was not explicitly designed to test whether either deliberate nutrient addition to the ocean or enhanced upwelling (via 'ocean pipes') might enhance longterm CO₂ drawdown, and hence reduce or reverse the rate of future global warming. Nevertheless, the programme did investigate many of the relevant natural processes, and the UK SOLAS community provided the main grouping of national expertise on these issues. Programme representatives were therefore able to provide policy-relevant advice on ocean-based geoengineering, whilst making significant contributions to the national and international debate on the scientific feasibility of other schemes. These activities included:

- Participation in the 2009 sessions of Technical Working Group of the London Convention/London Protocol, to develop scientific framework for approval of ocean fertilization research
- Involvement in drafting NERC/RCUK written evidence, provision of oral evidence and commenting on government responses, for enquiries by House of Commons Innovation, Universities, Science and Skills Committee (for Geoengineering section of "Engineering: turning ideas into reality" 2009) and Science and Technology Committee (for report "The regulation of geoengineering" 2010)
- Keynote presentation on geoengineering at the 3rd SOLAS Open Science Conference (Barcelona; November 2009) and the participation of many UK SOLAS researchers in an associated discussion session on iron fertilization (www.solas-int.org/news/conferencemeetings/OSC2009/Fertilisation.pdf)
- Participation in planning and implementation of the NERC-led Public Dialogue "Experiment Earth?", (Ipsos MORI, 2010; www.nerc.ac.uk/about/consult/geoengineering.asp) to assess public acceptability of geoengineering research
- Co-authorship and editing of "Ocean Fertilization: Scientific Summary for Policy Makers" (Wallace et al, 2010; <http://unesdoc.unesco.org/images/0019/001906/190674e.pdf>); a joint initiative between UNESCO's Intergovernmental Oceanographic Commission (IOC) and international SOLAS, with involvement in associated discussions at 43th IOC Executive Council. For additional information, see Achievement 3.5.

Contribution to UK Marine Monitoring and Assessment Strategy

UK SOLAS researchers contributed data and assisted in the editing of the "Ocean Processes" section of Charting Progress 2: the State of UK Seas (Defra/UKMMAS, 2010). Information and practices from the HiWASE project were also included in the Marine Monitoring Protocols Database, developed by the Water Research Centre (WRC) under contract to Defra.

1.4 Problems encountered

Research cruises

The main setbacks experienced by UK SOLAS were due to the increasing unreliability and other uncertainties relating to its main fieldwork platform *RRS Discovery*, affecting ship-scheduling. There were also technical problems during research cruises. In particular:

- The ICON cruise had to be twice re-programmed (from May 2006 to May-June 2008, and finally to April-May 2009), with the suspension and re-start of the associated research grant. This postponement had

knock-on effects for other linked projects (e.g. DUST-UP, Air-sea OVOC fluxes and Saharan dust deposition), data management and the overall duration of the UK SOLAS programme.

- The first DOGEE cruise (D313) suffered downtime not only due to severe weather but also due to winch and engine problems. As a result, the cruise ended early; the main experiment was aborted, equipment losses occurred and science objectives were only partly met. Details are given in the D313 cruise report, available via www.bodc.ac.uk/projects/uk/uksolas/cruise_programme
- Other research cruises involving *RRS Discovery* were re-arranged, and experienced technical failures (although of a less serious nature).
- When the re-scheduled ICON cruise did eventually take place, it was nearly thwarted by the initial inability of NERC's National Marine Facilities- Sea Systems Operations and the Foreign and Commonwealth Office to obtain diplomatic clearance to work in Mauritanian waters. This problem was, however, resolved whilst ICON was at sea, involving the PI's direct contact (facilitated by international SOLAS) with the Institut Mauritanian de Recherches Oceanographique et des Peches (IMROP) and the Mauritanian Minister of Fisheries.

The adverse impacts of all but the last of the above scheduling and technical problems for the UK SOLAS programme were significant. Yet they did not jeopardise the overall success of the programme, due to the flexibility of PIs and their research teams; the exceptional work¹ of the UK SOLAS Logistics Coordinator (Malcolm Woodward); the high standards of the ship's crews; and NERC's decision to supplement research grant awards to cover additional costs arising from the ICON cruise rescheduling. However, a proposed 're-run' of the first DOGEE cruise was not approved by NERC (due to its high cost implications). There were also concerns raised by PIs and the UK SOLAS Steering Committee that NERC could have done more to address the ship-scheduling problems on a programmatic basis, rather than considering the platform needs of each cruise separately.

Finances

At the start of UK SOLAS (early 2005), NERC reduced the programme's budget by £1.5m (~10%) as part of an overall re-prioritisation exercise. Because only a relatively small proportion of programme funds had then been committed, the effects were manageable. However, several Round 1 research grant awards could not be fully funded, and the associated period of financial uncertainties resulted in a 3 month delay in award announcements, affecting their start dates and staff recruitment.

During the course of the programme other financial issues inevitably arose, several relating to unexpected additional costs for the Cape Verde Atmospheric Observatory. These problems were generally resolved to the satisfaction of those concerned. At its conclusion, the UK SOLAS programme 'balanced its books' with regard to total spend and total budget.

Programme management

During the course of its lifetime, UK SOLAS was served by four programme administrators at NERC Swindon (Sarah Collinge, Sophie Hodgson, Frances Collingborn and Kay Heuser; Michal Filtness subsequently provided post-programme support). Whilst individual postholders were highly competent, the turnover of those responsible for day-to-day programme management did inevitably result in some inefficiencies with regard to 'programme memory' and maintaining close working links with the Steering Committee and programme participants.

Changes also occurred in membership of the UK SOLAS Steering Committee (Annex 1). However, some turnover in a group of that size can be expected, and there were benefits arising from the involvement of new expertise. Overall continuity was provided by the programme maintaining the same Steering Committee Chair (Howard Cattle), Science Coordinator (Phil Williamson) and NERC Programme Manager (Mike Webb).

Risk management

The UK SOLAS programme did not have a formal structure of risk management through regular quantitative assessment of risk likelihood and impact, with associated formulation of anticipatory mitigation actions. Steering Committee members were, however, kept informed of relevant issues and gave advice on how deleterious impacts could be minimised. It is debatable whether any different approach by UK SOLAS management might have enhanced overall programme effectiveness, since the both causes of the problems and the means to ameliorate their adverse consequences were essentially beyond its control.

¹ Including the tracking and retrieval (from a fisherman's garage in Orkney) of a state-of-the-art instrumented float, that had to be abandoned by D313; "Google Earth locates marine equipment", *Planet Earth*, spring 2007, p7.

1.5 Conclusions

UK SOLAS has not been externally evaluated, and its Steering Committee has not itself carried out a structured review of the programme's scientific and management performance. Nevertheless, the following conclusions are considered to provide a fair assessment of UK SOLAS strengths and weaknesses, based on information provided by programme PIs in their final reports, discussions of the Steering Committee during the course of the programme, and independent feedback received after the programme's finale event, from research users and the international community.

- i) UK SOLAS has clearly met its own overall goal and specific research objectives, delivering internationally-competitive science with high societal impact. It has also provided a very good fit to NERC's developing strategic priorities, particularly for the themes of Climate System and Earth System Science. Whilst not all component projects achieved all of their project objectives, the reasons for such shortcomings were largely outside the researchers' control.
- ii) The programme can be considered to have been highly successful in: promoting multidisciplinary research (biological, physical and chemical); bringing together the marine and atmospheric research communities; integrating laboratory, field and modelling studies; and involving very extensive, high quality community engagement by leading research groups in universities, NERC Centres and Collaborative Centres.
- iii) The close linkage between UK SOLAS and the international SOLAS programme has been a major strength, stimulating and facilitating productive collaborations on a worldwide scale whilst also providing cost-effective access to unique research platforms and other infrastructure. UK-hosting of the SOLAS International Project Office has provided excellent added value in that regard, greatly benefitting the programme whilst also satisfying NERC's generic objectives for IPO support.
- iv) The planned UK SOLAS fieldwork was ambitious, based on eight research cruises. Unfortunately these became over-reliant on the availability of a single platform, *RRS Discovery* (although alternative research vessels would have been acceptable to the programme). Nevertheless, the cruise programme was eventually completed, albeit over a longer timeframe than originally intended. The outcomes of other fieldwork – based on the Cape Verde and *Polarfront* time series, the Roscoff campaign and the Bergen mesocosm study – all met (or exceeded) expectations, despite their own complex logistics, requiring new scientific partnerships and skilful international diplomacy.
- v) UK SOLAS benefitted from engagement with many national and international partners and stakeholders, with research-users mostly being policy-related. The low level of private sector involvement was not due to lack of effort by the programme: a Knowledge Exchange facilitator was supported in 2004-05 as part of the UK SOLAS Science Coordination team, specifically to encourage KE (then KT, Knowledge Transfer) engagement by a broad spectrum of marine industries. However, the overall outcome was to strengthen UK SOLAS links with its existing main external partner/research user, the UK Met Office, whilst also extending such relationships on a European/international scale (through the COST Action).
- vi) For the research community, the programme's legacy is primarily in its peer-reviewed publications: 130 to date and likely to increase by a further ~50%. Very many of these are in high profile journals and/or have been highly cited (e.g. 64 citations to date for Read et al's 2008 *Nature* paper). The programme's datasets and data products are also tangible outcomes, that will have wide impact. Whilst they may not deliver immediate economic benefit, such information is crucial to developing robust prediction of future climate, with financial implications of many millions (or possibly billions) of dollars.
- vii) UK SOLAS has also played an important role in helping to develop NERC's own science agenda, stimulating complementary initiatives (e.g. components of Oceans 2025, providing co-support for the final UK SOLAS cruise); follow-on observational programmes (e.g. NCAS continued support for the Cape Verde Atmospheric Observatory); policy advice at the national and international level (e.g. on ocean fertilization); and contributing to the development of related research programmes (e.g. UK Ocean Acidification Research Programme).
- viii) The multidisciplinary, field-based UK SOLAS programme was particularly suitable for PhD students, thereby contributing to NERC's training mission. Ten research studentships were directly supported by UK SOLAS, with many others also participating in research cruises. Around 30 students and young researchers have been supported to date at the international SOLAS summer schools, held in Corsica.
- ix) Programme management for UK SOLAS retained the original, Directed Programme arrangements, comprising a single Steering Committee (rather than the separation of a Programme Advisory Group and Executive Board). The UK SOLAS Science Coordinator provided the main interface between NERC Swindon and programme participants, whilst working to make the programmatic whole greater than the sum of its parts. On the basis that this was achieved, despite some setbacks, such a management model can be considered fit for purpose.

2. UK SOLAS awards

2.1 Research grants

Total value £6,360k. Proposal abstracts online via NERC Grants on the Web:

http://gotw.nerc.ac.uk/list_them.asp?them=Surface+Ocean+Lower+Atmosphere+Study+SOLAS

| PI and Co-Is | Project title, NERC code; <i>funding round</i> | Award value | Start-end dates |
|--|--|-------------|--------------------------|
| Eric Achterberg (NOC/So'ton) DA Purdie, MV Zubkov & P Statham (NOC/So'ton); T Jickells & AR Baker (UEA) | The impact of atmospheric dust derived metal and nutrient inputs on tropical North Atlantic near surface plankton microbiota NE/C001931/1; NE/C001737/1 <i>1st round</i> | £464,555 | 22 Sep 05- 21 Mar 10 |
| James Allan (Manchester) GB McFiggans, DO Topping & PI Williams (Manchester) | ACMME: Aerosol characterisation and modelling in the marine environment NE/E011454/1 <i>2nd round</i> | £77,522 | 27 Apr 07 - 26 Aug 09 |
| Icarus Allen (PML) S Archer & PD Nightingale (PML); J Holt (POL) | DUST-UP: Quantifying dust and upwelling influences on DMS production and fluxes in the tropical NE Atlantic NE/E011314/1; NE/E011306/1 <i>2nd round</i> | £182,265 | 1 May 07 – 31 Aug 10 |
| Stephen Archer (PML) GJC Underwood, NR Baker & R Geider (Essex); CA Llewellyn (PML) | Roles of DMSP and GBT in protection from photoinhibition/ photooxidative stress and consequences for DMS and NH ₃ production NE/C51715X/1; NE/C517168/1 <i>1st round</i> | £357,205 | 1 Oct 05- 30 Jun 09 |
| Alex Baker (UEA) TG Bell & CA Adams (UEA) | A climatology of atmospheric iron inputs to the Atlantic Ocean NE/G000239/1 <i>Concluding KT/synthesis round</i> | £49,541 | 1 Oct 08 – 31 May 09 |
| Ian Brooks (Leeds) MH Smith & JB McQuaid (Leeds); MA Srokosz (NOC) | SEASAW: Field observations of sea spray, gas fluxes and whitecaps NE/C001869/1; NE/C001869/1 <i>1st round</i> | £454,285 | 16 Feb 06 – 4 Jan 10 |
| Ian Brooks (Leeds) Margaret Yelland (NOC/So'ton) | Physical air-sea exchange: synthesis and dissemination NE/G000107/1; NE/G000115/1 <i>Concluding KT/synthesis round</i> | £39,661 | 29 Jul 08- 31 May 11 |
| Lucy Carpenter (York) FC Küpper (SAMS) | Transformations, volatilisation and speciation of organic and inorganic iodine in the marine environment NE/D006538/1; NE/D006546/1 <i>1st round: halogens</i> | £123,435 | 19 Oct 06- 30 Nov 09 |
| Lucy Carpenter (York) W Bloss (B'ham), MJ Evans, DE Heard & T Ingham (Leeds); JR Hopkins, JD Lee & AC Lewis (York) | Seasonal oxidant observations in the tropical North Atlantic atmosphere NE/E011330/1; NE/E011403/1 <i>2nd round</i> | £196,922 | 1 May 07- 31 Jan 10 |
| Ken Carslaw (Leeds) M Chipperfield (Leeds) | Global modelling of aerosols and chemistry in support of SOLAS-UK NE/C001915/1 <i>1st round</i> | £164,947 | 3 Jan 06 – 2 Oct 09 |
| David Green (SAMS) MC Hart, & AD Hatton (SAMS) | ALBA: Role of algal-bacteria interactions in determining DMS fluxes to the atmosphere NE/C51725X/1 <i>1st round</i> | £168,621 | 21 Oct 05- 20 Apr 09 |
| Jacqueline Hamilton* (York) A Lewis, JR Hopkins, & JD Lee (York) [*PI initially AR Lewis] | Chemical and physical structure of the lower atmosphere of the tropical eastern North Atlantic NE/E01111X/1 <i>2nd round</i> | £33,829 | 1 Apr 07- 31 Mar 09 |
| Ellie Highwood (Reading) H Coe, DJ Vaughan, JR Lloyd & PI Williams (Manchester); RM Harrison (B'ham) | DODO: Dust outflow and deposition to the ocean NE/C517276/1; NE/C517292/1; NE/C517284/1 <i>1st round</i> | £300,191 | 1 Oct 05 – 30 Apr 09 |
| Michael Krom (Leeds) LG Benning, K Carslaw & GW Mann (Leeds); T Jickells & AR Baker (UEA) | Developing new understandings of the fundamental pathways of Fe in mineral aerosols from Saharan soils to the marine ecosystem in surface seawater NE/E011470/1; NE/E011411/1 <i>2nd round</i> | £208,051 | 1 May 07 – 30 Apr 09 |

| | | | |
|---|--|----------|-------------------------|
| Peter Liss (UEA) J Gunson (MetO), J Brown (BODC) | Global data synthesis of air-sea fluxes of gases and aerosols for policy-directed modelling and assessment of climate change and pollution NE/E001696/1 <i>KT round</i> | £232,916 | 15 Nov 06- 14 May 10 |
| Gill Malin (UEA) C Hughes, P Liss & M Martino (UEA); PD Nightingale, S Archer, JI Allen & T Smyth (PML) | INSPIRE: Investigation of near-surface production of iodocarbons - rates and exchange NE/D006511/1; NE/D00649X/1 <i>1st round: halogens</i> | £276,407 | 16 Dec 06 -15 Jan 11 |
| Gordon McFiggans (Manchester) MW Gallagher (Manchester), S Ball (Leicester), L Carpenter (York); D Heard & JMC Plane (Leeds); W Bloss (Leeds/B'ham) | RHaMBLE: Reactive halogens in the marine boundary layer NE/D006570/1; NE/D006589/1; NE/D006562/1; NE/D006554/1; NE/D00652X/1 <i>1st round; halogens</i> | £380,627 | 7 Mar 06- 6 Jun 08 |
| Gordon McFiggans (Manchester) | Integration and synthesis of current research into the formation, evolution and roles of cloud condensation nuclei in the marine environment NE/G000247/1 <i>KT round</i> | £49,878 | 1 Aug 08 – 31 Jul 09 |
| Paul Monks (Leicester) | Oxidative ability of the mid-Atlantic lower troposphere NE/E011357/1 <i>2nd round</i> | £96,613 | 1 Oct 07 – 31 Jul 09 |
| Colin Murrell (Warwick) R Upstill-Goddard (Newcastle), H Schaefer (Warwick) | The role of the bacterioneuston in air-sea gas exchange NE/C001923/1; NE/C001885/1 <i>1st round</i> | £281,759 | 1 Oct 05 – 31 Oct 08 |
| Colin Murrell (Warwick) E Baggs (Aberdeen) H Schaefer (Warwick), R Upstill-Goddard (Newcastle) | Joint SOLAS Bergen mesocosm experiment NE/E011446/1; NE/E011438/1; NE/E011527/1 <i>2nd round</i> | £131,552 | 1 Jan 08 – 31 Oct 09 |
| Phil Nightingale (PML) SM Turner, D Oram & PS Liss (UEA) | Air-sea OVOC fluxes: Seawater sources/sinks and role of the microlayer NE/C517192/1 <i>1st round</i> | £156,555 | 1 Nov 05- 31 Oct 09 |
| Phil Nightingale (PML) S Archer (PML) | A comparison of sea to air DMS flux measurements and the possible role of near-surface gradients NE/E011489/1 <i>2nd round</i> | £99,720 | 1 Apr 07 - 30 Jun 09 |
| Carol Robinson (PML) EP Achterberg (NOC/So'ton); AP Rees, NJP Owens & R Torres (PML) | ICON: The impact of coastal upwellings on air-sea exchange of climatically important gases NE /C517176/1; NE/517184/1; NE/C517176/2 <i>1st round</i> | £811,574 | 7 Nov 05 – 11 Oct 10 |
| Rob Upstill-Goddard (Newcastle) PD Nightingale (PML); TG Leighton (So'ton); AJ Watson (UEA); MA Srokosz (NOC SOUTHAMPTON) | DOGEE: The UK SOLAS deep ocean gas exchange experiment NE/C001702/1; NE/C001834/1; NE/C001745/1; NE/C517341/1 <i>1st round</i> | £489,931 | 1 Oct 05- 31 Oct 09 |
| Malcolm Woodward (PML) | UK SOLAS programme – Marine science research facilitation officer (cruise logistics) NE/E014208/1 | £56,893 | 10 Nov 06- 9 Nov 08 |
| Margaret Yelland (NOC/So'ton) AJ Watson (UEA) | HiWASE: High wind air-sea exchanges NE/C001826/1 <i>1st round</i> | £396,610 | 1 Jul 06 - 28 Feb 11 |
| Margaret Yelland (NOC/So'ton) RW Pascal & BI Moat (NOC/So'ton) | Extension of the HiWASE measurement program at Station Mike NE/G000123/1 <i>Concluding KT/synthesis round</i> | £47,556 | 1 Jun 09 – 4 Jan 10 |

2.2 Contracts total value £1885k

| Institution; lead contacts | Contract title/purpose | Contract value | Start-end dates |
|---|--|----------------|------------------------|
| British Oceanographic Data Centre (BODC) Juan Brown & Gwen Moncoiffe | Data management for the UK SOLAS programme | £692,790 | 1 Aug 05- 31 Apr 11 |

| | | | |
|---|---|-----------------------------|----------------------|
| Distributed Institute for Atmospheric Composition (DIAC)* Mike Pilling (Leeds) & Lucy Carpenter (York) [*now the National Centre for Atmospheric Science (NCAS)] | Establishment and maintenance of Cape Verde atmospheric observatory | £837,249 | 1 Aug 05 - 31 Apr 10 |
| NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS, at PML) Steven Groom & Jamie Shutler | Remote sensing services for UK SOLAS | £75,100 | 1 Oct 05- 31 Mar 10 |
| University of East Anglia: School of Environmental Sciences Phil Williamson | Science coordination services for NERC directed programme UK SOLAS | £279,753 (excl PW's salary) | 1 Feb 04- 31 May 10 |

2.3 CASE Studentships (not tied to Research Grants)

| Supervisors | Student | Project title | Start-end dates |
|---|---------------------|---|----------------------|
| K Carslaw & G Mann (Leeds); O Boucher & J Gunson (MetO) | Matt Woodhouse | Oceanic DMS emissions and dust deposition feedbacks in the Earth's climate system | 1 Oct 06 - 30 Sep 09 |
| E Baggs & U Witte (Aberdeen) I Spark & S Maxwell (Commercial Microbiology Ltd) | Marie-Therese Moore | Denitrification in the bacterioneuston: the role of algal C in driving N ₂ O reduction | 1 Oct 06 - 30 Sep 09 |

3. Examples of science achievements and impacts

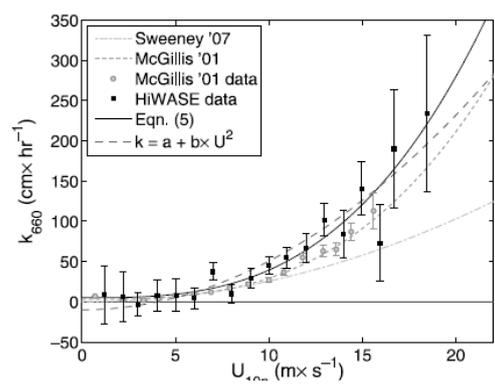
Highlights identified in 2010 UK SOLAS Report to international SOLAS

3.1 Now we know what happens when the wind blows

The rate at which CO₂ moves across the air-sea interface is critical for modelling the carbon cycle and its sensitivity to climate change. The transfer velocity coefficient (*k*) increases with wind speed, and various empirical relationships have been derived to describe this relationship. These different relationships agree reasonably well at low wind speeds, for which it is relatively easy to collect data; however, they differ greatly at high wind speeds – the conditions that determine most ‘real world’ CO₂ fluxes, yet are the most difficult to investigate. The HiWASE study, supported by the UK SOLAS programme in collaboration with the Norwegian Meteorological Office, has now provided ^{1,2} the largest set of directly-measured air-sea CO₂ flux data for the open ocean. Measurements were made on the weather ship *Polarfront* over a 3 year period, using the eddy covariance technique and the Autoflux autonomous system. The collection of data at wind speeds up to 19 m per sec (70 km per hr) has provided a major advance in quantifying the wind speed dependence of *k*, whilst indicating that additional factors, such as sea state and bubbles, also seem to be important. A new study, WAGES (Waves, Aerosol and Gas Exchange Study)³ will use the Autoflux system on *RRS James Clark Ross* to extend the geographic coverage of the high-wind dataset.



Photo: the Norwegian ocean weather ship *Polarfront* (no longer in service). **Figure:** the new relationship between CO₂ transfer velocity (*k*₆₆₀) and wind speeds, with 12 data points for the 18.5 m s⁻¹ grouping.



1. Prytherch J, Yelland MJ, Pascal RW, Moat BI, Skjelvan I, & Srokosz M. 2010. Open ocean gas transfer velocity derived from long-term direct measurements of the CO₂ flux. *Geophysical Research Letters*, 37, L23607.
2. www.noc.soton.ac.uk/ooc/CRUISES/HIWASE
3. <http://homepages.see.leeds.ac.uk/~lecimb/WAGES/>

3.2 Methane lifetime reduced by trace gases from tropical Atlantic

Global models of atmospheric chemistry are now reasonably skilful, but don't get everything right. Considerable uncertainties still surround the marine emissions of many reactive trace gases (halogens, oxidised nitrogen, carbonyls and isoprene) that together affect the lifetimes of ozone, methane and short-lived radicals, and also play a role in aerosol production. These knowledge gaps are greatest in tropical regions, where high quality measurements of such atmospheric components – that may only occur at part-per-trillion levels – are sparse. The Cape Verde Atmospheric Observatory¹ (Observatório Atmosferico de Cabo Verde, Humberto Duarte Fonseca; a joint initiative by the UK, Cape Verde and Germany, with EU co-support) has helped fill those gaps. Results² published in 2010 include an analysis of OH and HO₂ concentrations, and their control by the marine-emitted halogens IO and BrO. Halogen-mediated effects help explain the observed daily cycle of O₃ destruction at the Cape Verde site; they also reduce by 9% the estimated lifetime of methane. Ship and aircraft-based measurements^{3,4} complemented the ground-based studies; they provided data on vertical distributions and wider spatial variability – with the latter indicating that the Cape Verde observatory was representative of the tropical North Atlantic. However, ship-based measurements of a range of volatile organic iodine compounds showed that only 10-25% of the observed IO levels could be accounted for, indicating that significant iodine sources have yet to be identified^{4,5}.



Photo: The Cape Verde Atmospheric Observatory (Observatório Atmosferico de Cabo Verde: Humberto Duarte Fonseca). In 2010, a new, wooden 30m tower was constructed, replacing the 4-year old metal tower that had become badly corroded. Improvements were also made to the container-based sampling air-sampling systems. (Image: Luis Mendes)

1. <http://ncasweb.leeds.ac.uk/capeverde>
2. Whalley LK, Furneaux KL, Goddard A, Lee JD, Mahajan A, Oetjen H, Read KA, Kaaden N, Carpenter LJ, Lewis AC, Plane JMC, Satzman ES, Wiedensohler A, & Heard DE. 2010. The chemistry of OH and HO₂ radicals in the boundary layer over the tropical Atlantic Ocean. *Atmospheric Chemistry & Physics*, 10, 1555-1576.
3. Lee JD, McFiggans G and 44 others. 2010. Reactive Halogens in the Marine Boundary Layer (RHAMBLE): the tropical North Atlantic experiments. *Atmospheric Chemistry & Physics*, 10, 1031-1055.
4. Jones CE, Hornsby KE, Sommariva R, Dunk RM, von Glasow R, McFiggans G & Carpenter LJ. 2010 Quantifying the contribution of marine organic gases to atmospheric iodine. *Geophysical Research Letters*, 37, L18804.
5. Mahajan AS, Plane JMC, Oetjen H, Mendes L, Saunders RW, Saiz-Lopez A, Jones CE, Carpenter LJ & McFiggans GB. 2010. Measurement and modelling of tropospheric reactive halogen species over the tropical Atlantic Ocean. *Atmospheric Chemistry & Physics*, 10, 4611-4624.

3.3 Gaia feedback questioned: weak role of DMS in future climate change

The potential role of dimethyl sulphide (DMS) in climate processes has been much debated since the CLAW hypothesis was first published by Charlson, Lovelock, Andreae and Warren in 1987, and subsequently featured as a key feedback in James Lovelock's Gaia hypothesis. Recent analyses co-supported by the UK SOLAS programme and the UK Meteorological Office indicate that the global abundance of cloud condensation nuclei (CCN) – and hence cloud formation – is relatively insensitive to changes in marine DMS emissions¹. The study used an aerosol microphysics model to explore the CCN-DMS relationship using multiple present-day and future sea-surface DMS climatologies. For future, globally-warmed scenarios, a 10% change in DMS flux was found to cause a ~1% change in global mean CCN at the sea surface. For the southern hemisphere, the effect of a 10% change was 2%. Such potential changes in CCN abundances are of comparable magnitude to current interannual differences due to variability in windspeed. Other feedback factors affecting aerosol formation, such as sea-spray and associated transfer of organic material, would seem of much greater importance².

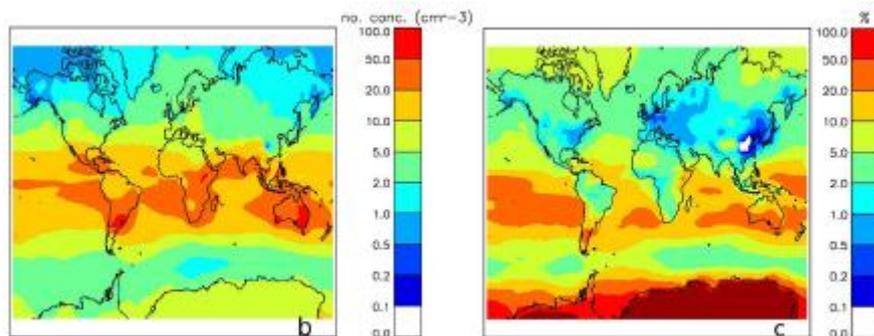


Figure: Left, model-based estimate of the absolute contribution of DMS to CCN; right, the fractional contribution of DMS to CCN. From Woodhouse et al, 2010.

1. Woodhouse MT, Carslaw KS, Mann GW, Vallina SM, Vogt M, Halloran PR & Boucher O. 2010. Low sensitivity of cloud condensation nuclei to changes in the sea-air flux of dimethyl-sulphide. *Atmospheric Chemistry & Physics* 10, 7545-7559.
2. Carslaw KS, Boucher O, Spracklen DV, Mann GW, Rae JGL, Woodward S & Kulmala M. 2010. A review of natural aerosol interactions and feedbacks within the Earth System. *Atmospheric Chemistry & Physics* 10, 1701-1737.

3.4 Alcohol helps fuel marine productivity: first measurements of ethanol and propanol, and methanol turnover time in the ocean

Methanol and other oxygenated volatile organic compounds (OVOCs) significantly affect the oxidising capacity of the atmosphere, yet – because of the difficulty in measuring them – very little is known about their exchanges with the ocean. These technical problems have now been mostly overcome, with UK SOLAS researchers reporting that the North Atlantic may be an important source of ethanol and propanol, particularly in upwelling regions¹, whilst possibly providing a net sink for methanol². Experiments using ¹⁴C-labelled methanol showed its turnover time in the upper ocean to be 7-33 days, being metabolised by marine bacteria (and possibly some mixotrophic eukaryotes) not only as a significant energy source, but also use as a carbon source for incorporation into cellular biomass. Measurements for these studies have been made in coastal waters off Plymouth, on two UK SOLAS cruises and as part of the Atlantic Meridional Transect study, supported through the Oceans 2025 programme. The microbial uptake rates for acetone and acetaldehyde have also been measured for the first time.

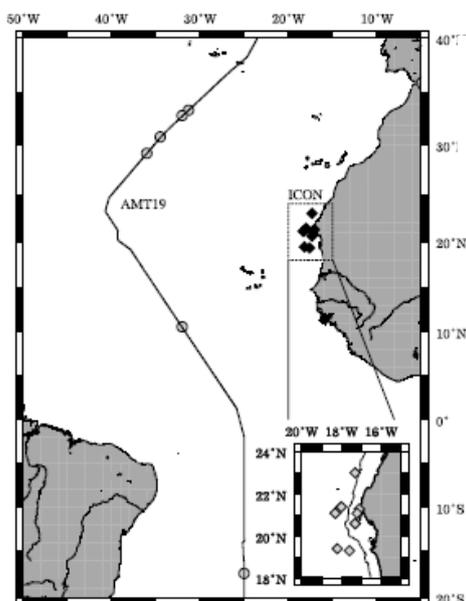


Figure: Sites for the measurement of ethanol and 1- and 2-propanol in the North and South Atlantic. Additional sites (not shown) were used for studies of methanol turnover.

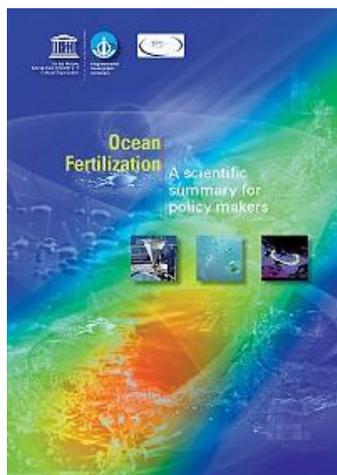


1. Beale R, Liss PS & Nightingale PD. 2010. First oceanic measurements of ethanol and propanol. *Geophysical Research Letters* 37, L24607
2. Dixon J, Beale R & Nightingale PD. 2010. Microbial methanol uptake in northeast Atlantic waters. *ISME Journal*, 1, 13

3.5 Ocean fertilization: from science to policy

Iron addition experiments in the 1990s helped develop the scientific rationale for the international SOLAS programme, increasing research attention to the natural atmospheric controls of ocean productivity. Those studies also stimulated wider public and policy interest in whether ocean fertilization might help solve the climate change problem, as a relatively natural form of geoengineering. A policy-directed assessment of the viability of such an approach has now been published¹ as a joint initiative between SOLAS and UNESCO's Intergovernmental Oceanographic Commission.

Anyone looking for an endorsement of early claims that a tanker full of iron could start the next ice age will be disappointed by this review. Best estimates of enhanced global carbon storage achievable by deliberate ocean fertilization over the next hundred years are now 25-75 billion tonnes (gigatonnes), an order of magnitude lower than estimates from the early 1990s – and two orders of magnitude less than cumulative carbon emissions under unconstrained scenarios.



Whilst the possibility remains that ocean fertilization might be adopted as one of many ways of achieving climate stabilisation, this option is not risk-free. And the cost of showing that it is working (and not causing unintended consequences) could be high. There are also critical questions regarding the international acceptability and governance of any geoengineering approach that might involve adverse environmental consequences, as shown by recent discussions by the Convention on Biological Diversity.

1. Wallace DWR, Law CS, Boyd PW, Collos Y, Croot P, Denman K, Lam PJ, Riebesell U, Takeda S & Williamson P. (2010) Ocean Fertilization. A Scientific Summary for Policy Makers. IOC/UNESCO, Paris (IOC/BRO/2010/2). 17 pp
<http://unesdoc.unesco.org/images/0019/001906/190674e.pdf>

3.6 Iodine in seaweed – an antioxidant and source of atmospheric particles

Large brown seaweed (kelp) of the genus *Laminaria* are the world's most effective bio-accumulators of iodine, an important element for thyroid function in humans. The chemical speciation and biological role of iodine in kelp had, however, remained enigmatic until now. UK SOLAS researchers at SAMS and the Universities of Manchester, York and Leicester have shown that seaweed iodine is stored in the form of iodide - single, negatively charged ions - which acts as the first known inorganic (and, in fact, the most simple) antioxidant in any living system.

When kelp experience stress (for example, when they are exposed to intense light, desiccation or atmospheric ozone during low tides, or a pathogen attack), they quickly release large quantities of iodide from stores inside the tissues. These ions detoxify ozone and other oxidants that could otherwise damage kelp, and, in the process, produce molecular iodine. Subsequently, iodine oxide and volatile halocarbons are formed; when these chemicals reach the atmosphere they can act as important sources of cloud condensation nuclei.



Measurements by UEA researchers on the UK SOLAS "Inspire" research cruise in the tropical North Atlantic have shown that the sea surface of the open ocean also contributes to the iodine cycle, through the release of a range of short-lived volatile organoiodine compounds (CH_2I_2 , CHClI_2 and CHI_3). Both photochemistry and biological processes are likely to be involved – with the latter driven by micro-algae (phytoplankton).

Photo: Measuring iodine release from seaweed at Roscoff, France, as part of the UK SOLAS RHAMBLE field campaign

3.7 Life is different at the sea surface

The ocean teems with microbial life - with millions of viruses, bacteria, archaea and micro-algae in every millilitre. Whilst it has long been known that such organisms play a major role in the global cycling of carbon and other elements, UK SOLAS has shown that microbes living in the sea surface microlayer (the top mm or so) form a distinct community – with potential for a disproportionately high influence on trace gas transfers between the bulk ocean and the atmosphere.

Researchers at the Universities of Warwick and Newcastle used a range of molecular techniques (PCR-based DNA profiling, clone library analysis, DGGE and functional gene probes) to investigate the ocean 'biofilm' – by area, if not in volume, the largest single habitat on Earth. Analysis of samples from the open ocean, estuaries, fjords and coastal waters (from the North Sea to Hawaii) consistently showed that bacterial communities in the microlayer are different from those in the water immediately beneath. The explanation is likely to be that the sea surface is a more extreme environment, subject to higher UV and chemical stresses; as a result, the well-adapted groups flourish whilst others do not survive. Although breaking waves or other surface disturbance will mix the microlayer with underlying water, tank experiments indicate that its distinct characteristics are rapidly re-formed.

Methane oxidation in the microlayer was investigated using analysis of the *mox* gene that codes for methane monooxygenase. Results revealed a high abundance of sequences from *Methylomonas*-like species, specific to the estuarine microlayer. The biogeochemical consequences of a distinct sea-surface microbiology was studied experimentally at the Bergen mesocosm facility in May 2008.

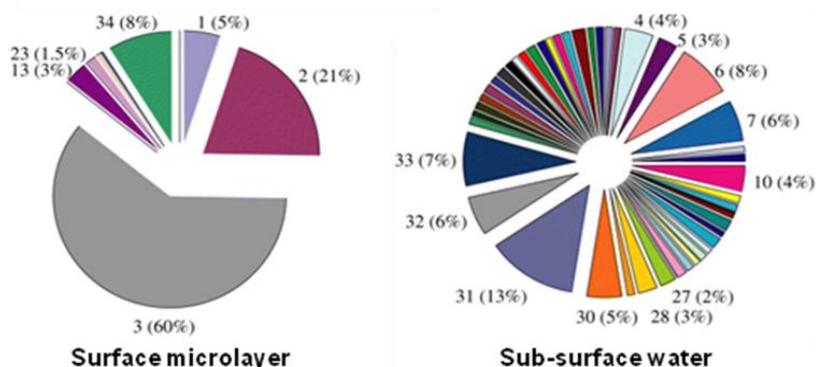


Figure: microbial biodiversity is much reduced (and very different) at the sea surface, left, than at just a few cm below, right.

3.8 UK SOLAS science on display

A display called "The Breathing Ocean" was selected for inclusion in the Royal Society's 2008 summer science exhibition, where it was seen by over 4,000 visitors. It included algal cultures, a digital globe, an ocean quiz and animated films, and was presented by UK SOLAS researchers from University of East Anglia, Southampton, York, Leicester and Plymouth Marine Laboratory. The display had its own website (with more than 15,000 visits) and was subsequently re-exhibited at Norwich Forum.



Photo: State-of-the-art digital graphics were used to introduce the global carbon cycle to visitors at The Breathing Ocean display at the Royal Society's summer science exhibition.

Two years earlier, the Science Museum, London, featured UK SOLAS in a special exhibit "Scientists chase Saharan sandstorms at sea". The display opened just two weeks after the end of the programme's first cruise, and includes an atmospheric dust collector, oceanographic sampling gear and video clips of the researchers involved. The Principal Scientist, Eric Achterberg, and others on the cruise participated in "meet the scientists" sessions, providing an informal account of their work to several hundred visitors. More recently (Oct-Dec 2010), UK SOLAS provided advice to the Science Museum for its new interactive gallery "Atmosphere... exploring climate science".

4. UK SOLAS publications

The publications listed below have arisen directly or indirectly from the NERC-supported UK SOLAS programme. Dates for peer-reviewed publications relate to print/final version publication for papers initially published online in discussion version. "Not peer-reviewed" includes websites, posters, displays and talks, but excludes presentations given at UK SOLAS meetings or workshops. Listing for 2010 incomplete (awaiting 2010 project OPM-ROD returns); updated version will be made available via www.bodc.ac.uk/projects/uk/uksolas/knowledge_transfer/.

2005

Not peer-reviewed (n = 2)

NERC. Website established for NERC-funded SOLAS programme, including Science Plan www.nerc.ac.uk/research/programmes/solas

SOLAS International Project Office. Website established for UK activities contributing to international SOLAS www.uea.ac.uk/env/solas/aboutsolas/organisaandstructure/solasnetwork/uk.html

2006

Not peer-reviewed (n = 10)

BODC. Website established for programme data management, including cruise reports www.bodc.ac.uk/projects/uk/uksolas

Carpenter LJ, Read KA *et al.* Website established for Cape Verde atmospheric observatory, www.york.ac.uk/capeverde
Cunliffe M "Microbial biogeography and community structure in the sea surface microlayer" Oral presentation at Challenger Conference, Oban, 12 Sept

Groom S, Shutler J & Miller P. Website established for UK SOLAS remote sensing services via NEODAAS www.npm.ac.uk/rsg/projects/mceis/c0

McFiggans G, Ball S, Bloss B, Carpenter L, Heard D & Plane J. 2006. The science behind the coastal studies within the RHaMBLe project. *SOLAS news*, 3, 18-19.

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Allan JD, Coe H, McFiggans GB, Williams PI, Flynn M, Bower K, Crosier J, Good N, Irwin M & Topping D. "The search for marine organic aerosols". Oral presentation at:

- Royal Meteorological Society Conference, Edinburgh, 3 -8 September
- American Association of Aerosol Research Annual Conference, Reno, Nevada, 24-28 September

Bloom A, Brooks IM, Hill MK, Schwierz CB, Norris SJ, Telszewski M, Yelland MJ, Moat BI *et al.* "CO₂ flux measurements during SEASAW". Oral presentation at AMS 15th Conference on Air-Sea Interaction, Portland, Oregon, 20-24 Aug

Breider T "Coupled sulfur/halogen chemistry and aerosol modelling in a 3D chemistry transport model (CTM)". Poster at 3rd international SOLAS Conference, Xiamen, 6- 9 March

Brooks IM. "The Sea Spray Gas Flux and Whitecaps Study (SEASAW)". Article in FluxNews (Newsletter of WCRP Working Group on Surface Fluxes)

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Brooks IM, Hill MK, Yelland, MJ, Moat BI & Pascal RW. "Ship based turbulence measurements under heavy seas: measurement, motion correction and interpretation". Oral presentation at AMS 15th Conference on Air-Sea Interaction, Portland, Oregon, 20-24 August

Brooks IM, Norris SJ, Hill MK, Smith MH, Brooks BJ, Lingard JJJ. "Measurements of sea salt aerosol fluxes over the North Atlantic". Oral presentation at UKAAN workshop: Air quality to climate change: Implication of and for aerosol, Reading, 6-7 June

Coles DGH & Leighton TG. "Autonomous spar-buoy measurements of bubble populations under breaking waves in the Sea of the Hebrides". Oral presentation and Proceedings paper (p 543-8), 2nd International Conference on Underwater Acoustic Measurements, Technologies and Results, Heraklion, Crete, 25-29 June

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Dall'osto M "Characterisation of airborne particles by aerosol time-of-flight mass spectrometry across different locations at sea". Poster at 3rd international SOLAS Conference, Xiamen, 6- 9 March

Dixon J "Methanol in seawater". Poster at 3rd international SOLAS Conference, Xiamen, 6- 9 March

Harrison E "Reformation and stabilisation of the sea surface microlayer". Poster at 3rd international SOLAS Conference, Xiamen, 6-9 March

Huebert B, Blomquist B & Archer S. "DMS transfer velocity functionality from DOGEE". Oral presentation at AGU Fall Meeting, San Francisco, 10-14 December

Hughes C "Investigation of the Near-Surface Production of Iodocarbons: Rates and Exchanges (INSPIRE)". Poster at 3rd international SOLAS Conference, Xiamen, 6- 9 March

Lingard JJJ, Brooks BJ, Norris SJ, Brooks IM & Smith MH. "Physicochemical characterisation of marine boundary layer airborne aerosol particles during the sea spray, gas fluxes and whitecaps (SEASAW) experiment." Oral presentation at 17th International Conference on Nucleation and Atmospheric Aerosols, Galway, Ireland, 13-17 August

Moat BI, Pascal RW, Srokosz MA, Coles DGH, Comben DH, Cansdale AG, Leighton TG, Yelland MJ, Waddington I & Woolf DK. "Measurements of breaking waves using a unique free-floating spar buoy" Oral presentation at AMS 15th Conference on Air-Sea Interaction, Portland, Oregon, 20-24 August.

Moncoiffé G "Data management for the UK SOLAS programme". Poster at 3rd international SOLAS Conference, Xiamen, 6-9 March

Murrell C "The microbiology of the sea surface microlayer – the bacterioneuston". Invited oral presentation at 3rd international SOLAS Conference, Xiamen, 6-9 March

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Norris SJ, Brooks IM, Smith MH, Hill MK, Brooks BJ & de Leeuw G. "In situ measurements of aerosol production from individual whitecaps during SEASAW" Oral presentation at AMS 15th Conference on Air-Sea Interaction, Portland, Oregon, 20-24 August

Norris SJ, Brooks IM, Hill MK, Brooks BJ, Smith MH & Lingard JJJ. "Eddy correlation measurements of sea-spray aerosol fluxes during SEASAW". Oral presentation at AMS 15th Conference on Air-Sea Interaction, Portland, Oregon, 20-24 August

Patey M "Macro and nanomolar nutrient measurements in a dust-affected region of the North Atlantic". Poster at 3rd international SOLAS Conference, Xiamen, 6- 9 March

Powell C "Aerosol deposition in the tropical North Atlantic". Poster at 3rd international SOLAS Conference, Xiamen, 6- 9 March

Robinson C "The impact of coastal upwellings on air-sea exchange of climatically important gases". Poster at 3rd international SOLAS Conference, Xiamen, 6-9 March

Salter M "Determination of surface active substances in sea surface microlayer samples from the North Sea and Blyth Estuary". Poster at 3rd international SOLAS Conference, Xiamen, 6-9 March

Upstill-Goddard RC *et al.* "RRS Discovery Cruise D313, 7 November - 6 December 2006: DOGEE-SOLAS and SEASAW; high wind gas and aerosol fluxes in the North East Atlantic Ocean" Cruise Report, online via BODC

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Williamson P "UK SOLAS: measuring, monitoring and modelling in the North Atlantic". Poster at 3rd international SOLAS Conference, Xiamen, 6-9 March

Williamson P. Letters published in The Times, The Guardian and The Independent on proposed 'ocean pipes' geoengineering technology

- Woodhouse M “Oceanic DMS emissions and climate feedbacks”. Poster at 3rd international SOLAS Conference, Xiamen, 6-9 March
- Yelland M J, Pascal RW, Taylor PK, Moat BI, Skjelvan I & Neill CC. “High Wind Air-Sea Exchanges (HiWASE) - Continuous air-sea flux measurements at Station Mike” Oral presentation at AMS 15th Conference on Air-Sea Interaction, Portland, Oregon, 20-24 August
- Yelland MJ, Bjorheim K, Gommenginger C, Pascal RW & Moat BI. “*In situ* wave measurements at Station Mike”. Oral presentation at:
- Joint Scientific and Technical Symposium on Storm Surges; Seoul, Rep of Korea. 2-6 October
 - Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology, 10th International workshop on wave hindcasting and forecasting & coastal hazard assessment; Hawaii, 11-16 November
- Yelland M J, Bjorheim K, Gommenginger C, Pascal RW & Moat BI. “Future exploitation of *in situ* wave measurements at Station Mike” Oral presentation at:
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- Yelland MJ, Gommenginger C, Pascal RW, Moat BI, Bjorheim K, Skjelvan I & Neill CC. “Continuous salinity, SST and wave measurements at Station Mike”. Poster presented at ESA Cal/Val workshop for the Soil Moisture and Ocean Salinity Mission, Rome, 29-31 October

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- Hill MK, Brooks BJ, Norris SJ, Smith MH, Brooks IM & de Leeuw G. 2008. A compact lightweight aerosol spectrometer probe (CLASP). *Journal of Atmospheric and Oceanic Technology*, 25, 1996-2006.
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- Brooks IM "Field observations of sea spray, gas fluxes and whitecaps". [Article](#) in *e-Strategies*, knowledge exchange periodical for policy makers
- Brooks IM, Hill MK, Norris SJ & Brooks BJ. "CLASP : An Optical Particle Counter for Eddy-Correlation Measurements of Sea-Spray Aerosol Fluxes". [Poster](#): OceanSensors'08, Warnemünde, Germany, 31 March- 4 April
- Chance R, Hamilton JF & Carpenter LJ. "The use of liquid chromatography-tandem mass spectrometry to characterise marine organic matter". [Poster](#) at Challenger Conference, Bangor, 8-11 September
- Chance R, Carpenter L, Hamilton J, Ward M, Wilson J, Küpper FC & Gachon C. "Exploring the use of liquid chromatography-tandem mass spectrometry to characterise marine organic matter". [Oral presentation and conference abstract](#).
- Chance R. "Iodine in the marine environment". [Oral presentation](#).
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- Griessbaum F, Moat BI, Narita Y, Yelland MJ, Klemm O & Uematsu M. "Uncertainties in CO₂ transfer velocities due to bias in shipboard wind measurements caused by airflow distortion". [Poster](#): EGU General Assembly, Vienna, 13-18 April
- Harrison E, Upstill-Goddard R & Murrell C. "The SOLAS Bergen mesocosm experiment 2008: The role of the sea surface microlayer in air-sea gas exchange". [Poster](#) at Challenger Conference, Bangor, 8-11 September

Hill PG, Zubkhov MV & Purdie D. "Microbial response to Aeolian nutrient enrichment in the north east subtropical Atlantic". Poster at Challenger Conference, Bangor, 8-11 September

Huebert BJ, Blonquist B, Yang M, Archer SD, Stephens JA & Nightingale PD. "Determination of the air-sea gas transfer of DMS during the DOGEE experiment". Oral presentation and abstract, Challenger Conference, Bangor, 8-11 Sept

Hughes C, Martino M, Turner SM, Liss P & Malin G. "Controls on photochemical iodomethane production in seawater". Oral presentation and abstract, Challenger Conference, Bangor, 8-11 September

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Lee JD, Read KA, Lewis AC & Carpenter LJ. "The Cape Verde Atmospheric Observatory: Greenhouse and trace gas measurements in a global context." Oral presentation.

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Malin G, Hughes C, Martino M, Liss P, Nightingale P, Allen JI, Archer S & Smyth T. "Investigation of near-surface production of iodocarbons- rates and exchanges (INSPIRE)". Oral presentation and conference abstract.

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Pascal RW, Moat BI, Srokosz MA, Waugh E, Coles DGH, Comben DH, Cansdale AG, Leighton TG, Yelland MJ, Waddington I & Woolf DK. "Measurements of breaking waves using a unique free-floating spar buoy". Poster presentation

Patey M, Rijkenberg M, Stinchcombe M & Achterberg E. "Trace metal and nutrient solubility in dust collected at the Cape Verde atmospheric observatory". Poster at Challenger Conference, Bangor, 8-11 September

Prytherch J, Yelland MJ, Pascal RW, Taylor PK, Moat BI, Skjelvan I & Neill C. "High wind air-sea exchanges (HiWASE) – Initial turbulent CO₂ flux results from station Mike". Poster: 13th Challenger Society conference, Bangor, 8-11 Sept

Rijkenberg M, Achterberg E *et al* "Chasing Saharan dust storms II: *RRS Discovery* 326, 5 January – 5 February 2008". Cruise Report, online via BODC

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Smyth, T. "UV light penetration of the oceans: measurements and modelling using a coupled atmospheric in-water UV radiative transfer approach". Oral presentation, poster presentation and conference abstract.

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Weller RA, Bradley F, Brooks IM, Edson J & Fairall C. "Sensors for fluxes at the sea surface. Physical: energy, heat, water, salt". Oral presentation: OceanSensors'08, Warnemünde, Germany, 31 March – 4 April

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Yelland MJ, Hydes D, Byfield V, Campbell J, Challenor P, Childs D, Cromwell D, Fangohr S, Gommenginger C, Hartman M, Kent E, Moat B, Pagnani M, Pascal R, Saw K, Wyatt J, "SNOMS - SWIRE NOCS Ocean Monitoring System". Oral presentation to the SWIRE group. 14 April

Yelland MJ, Gommenginger C, Pascal RW, Moat BI & Bjorheim K. "In situ wave measurements at Station Mike" Poster at:

- OceanSensors'08, Warnemünde, Germany, 31 March-4 April
 - 2nd joint GOSUD/SAMOS Workshop, Seattle, USA, 10-12 June
 - Opening of the Meteorological Office at NOC Southampton, 26 September
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 - 4th NERC Technology Forum, SAMS, Oban 12-14 May
 - 2nd joint GOSUD/SAMOS Workshop, Seattle, USA, 10-12 June
 - Opening of the Meteorological Office at NOC Southampton, 26 September
 - FerryBox08 Conference, NOC Southampton, 29-30 September
- Yelland MJ, Bjorheim K, Gommenginger CP, Pascal RW & Moat BI. "Exploiting *in situ* ocean wave measurements at Station Mike". Oral presentation at EGU General Assembly, Vienna, 13-18 April
- Yelland MJ, Pascal RW, Taylor PK & Moat BI. "AutoFlux - an autonomous system for the direct measurement of the air-sea fluxes of CO₂, heat and momentum". Oral presentation at Oceanology International IO08, London, 11-13 March

2009

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- Baker, A "Field observations of nutrient deposition to the Atlantic Ocean" Plenary oral presentation at SOLAS OSC, Barcelona 16-19 November
- Bange H, Bell T, Cornejo M, Freing A, Uher G, Upstill-Goddard R & Zhang G "MEMENTO (MarinE MethanE and NiTrous Oxide database): Towards a global database of oceanic menthane and nitrous oxide data" Poster at SOLAS OSC, Barcelona 16-19 November

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- Beale R, Dixon JL, Nightingale PD & Liss PS "Development of Membrane Inlet Proton Transfer Reaction / Mass Spectrometry (MI-PTR/MS) method to quantify Oxygenated Volatile Organic Compounds (OVOCs) in sea water & results from the Mauritanian Upwelling in April-May 2009" Poster at SOLAS OSC, Barcelona 16-19 November
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- Goddjin-Murphy L "Feasibility study of global observations of whitecap coverage, for improved estimation of CO₂ fluxes" Poster at SOLAS OSC, Barcelona 16-19 November
- Griessbaum F, Moat BI, Narita Y, Yelland MJ, Klemm O, Uematsu M "Uncertainties in wind speed dependent CO₂ transfer velocities due to airflow distortion at anemometer sites on ships" Poster at SOLAS OSC, Barcelona 16-19 November
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- Hill, P "Effect of wind-mixing and dust deposition on bacterioplankton community structure in the vicinity of the Cape Verde islands" Poster at SOLAS OSC, Barcelona 16-19 November
- Hopkins FE "Ocean acidification and marine biogenic trace gas production" Plenary oral presentation at SOLAS OSC, Barcelona 16-19 November
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- Kimmanse S, Hopkins J, Stephens J, Tarran G, Stefels J & Archer S "When the going gets tough, the tough produce DMSP; or do they?" Poster at SOLAS OSC, Barcelona 16-19 November
- Lana A, Bell TG, Simó R, Vallina SM, Ballabrera-Poy J, Kettle AJ, Dachs J, Bopp L, Saltzman ES, Stefels J, Johnson JE & Liss PS "An updated climatology of surface dimethylsulphide concentrations and emission fluxes in the global ocean" Poster at SOLAS OSC, Barcelona 16-19 November
- Lee J, Lewis A, Read K, Hopkins J & Carpenter L "Chemical and physical structure of the lower atmosphere of the tropical eastern North Atlantic" Poster at SOLAS OSC, Barcelona 16-19 November
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- Read KA, Lewis AC, Lee JD, Neves LM & Carpenter LJ "A UK SOLAS observatory at Cape Verde" Poster at SOLAS OSC, Barcelona 16-19 November
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- Shi Z, Krom MD, Bonneville S, Mann G, Carslaw K & Benning LG "Developing new understandings of the fundamental pathways of Fe in mineral aerosols from Saharan soils to the marine ecosystem in surface seawater" Poster at SOLAS OSC, Barcelona 16-19 November
- Stefels J, Archer SD & Elzenga JTM "Production and loss rates in natural phytoplankton communities from the tropical Atlantic using stable isotope additions" Poster at SOLAS OSC, Barcelona 16-19 November
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- Williamson P. "What the Brits have been up to: an overview of UK SOLAS". Oral presentation at SOLAS Ireland science conference, Galway, 14 December
- Woodhouse M, Carslaw K, Mann G & Boucher O "Sensitivity of atmospheric aerosol to regional changes in oceanic DMS flux" Poster at SOLAS OSC, Barcelona 16-19 November
- Woolf D, Developing mechanistic models of air-sea exchange. Poster at SOLAS OSC, Barcelona 16-19 November
- Yelland MJ, Holliday NP, Skjelvan I, Østerhus S, and Conway TJ. Continuous observations from the weather ship Polarfront at Station M. Poster at OceanObs 09: Sustained Ocean Observations and Information for Society, Venice, 21-25 September.

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5. Acronyms and abbreviations

Acronyms and abbreviations are generally given in full when used for the first time in this document. The following listing is intended to cover those that may not have been explained, as well as those frequently re-used. It does not claim to be comprehensive.

| | |
|------------|---|
| ACCENT | Atmospheric Composition Change: European Network of Excellence <i>EU programme</i> |
| ACCME | Aerosol Characterisation and Modelling in the Marine Environment <i>UK SOLAS project</i> |
| IAI | Inter-American Institute for Global Change Research |
| ALBA | Role of algal-bacteria interactions in determining DMS fluxes to the atmosphere <i>UK SOLAS project</i> |
| AO | Announcement of opportunity |
| APN | Asian-Pacific Network for Global Change Research |
| APPRAISE | Aerosol Properties, Processes and Influences on the Earth's Climate |
| AMMA | African Monsoon Multidisciplinary Analyses |
| CBD | Convention on Biological Diversity |
| COST | European Cooperation in Science and Technology <i>EU-ESF programme:</i> |
| CVAO | Cape Verde Atmospheric Laboratory |
| DMS | Dimethylsulphide |
| DODO | Dust outflow and deposition to the ocean <i>UK SOLAS project:</i> |
| DOGEE | Deep Ocean Gas Exchange Experiment <i>UK SOLAS project</i> |
| ESA | European Space Agency |
| ESF | European Science Foundation |
| EU | European Union |
| GLOMAP | Global Modelling of Aerosols and Chemistry <i>UK SOLAS project</i> |
| HiWASE | High wind air-sea exchanges <i>UK SOLAS project</i> |
| ICACGP | International Commission on Atmospheric Chemistry and Global Pollution |
| ICON | Impact of coastal upwelling on the air-sea exchange of climatically important gases <i>UK SOLAS project</i> |
| ICSU | International Council of Scientific Unions |
| IfM-GEOMAR | Leibniz Institute of Marine Sciences at the Christian-Albrechts Universität zu Kiel |
| IGBP | International Geosphere Biosphere Programme |
| INMG | Nacional de Meteorologia e Geofísica (Cape Verde) |
| IOC | Intergovernmental Oceanographic Commission |
| IOCCP | International Ocean Carbon Coordination Project |
| IMBER | Integrated Marine Biogeochemistry and Ecosystem Research |
| INSPIRE | Investigation of near-surface production of iodocarbons - rates and exchange <i>UK SOLAS project</i> |
| IPCC | Intergovernmental Panel on Climate Change |
| IPO | International Project Office |
| KE (KT) | Knowledge exchange (knowledge transfer) |
| MEMENTO | Marine Methane and Nitrous Oxide database |
| NCAS | National Centre for Atmospheric Science |
| NEODAAS | NERC Earth Observation Data Acquisition and Analysis Service |
| NOC | National Oceanography Centre |
| OSC | Open Science Conference |
| PML | Plymouth Marine Laboratory |
| RHaMBLe | Reactive Halogens in the Marine Boundary Layer <i>UK SOLAS project</i> |
| ROD | NERC Research Output Database |
| SAMS | Scottish Association for Marine Science |
| SCOR | Scientific Committee on Oceanic Research |
| SEASAW | Field observations of sea spray, gas fluxes and whitecaps <i>UK SOLAS project</i> |
| SML | Sea surface microlayer |
| SOLAS | Surface Ocean Lower Atmosphere Study |
| SOPRAN | Surface Ocean Processes in the Anthropocene |
| SOS | Seasonal oxidant observations in the tropical North Atlantic atmosphere (also known as 'Seasonal Oxidant Study') <i>UK SOLAS project</i> |
| TENATSO | Tropical Eastern North Atlantic Time-Series Observatory <i>EU programme</i> |
| UEA | University of East Anglia |
| UKMMAS | UK Marine Monitoring and Assessment Strategy |
| WCRP | World Climate Research Programme |
| WMO-GAW | Global Atmospheric Watch of World Meteorological Organisation |

ANNEXES

Annex 1

UK SOLAS Programme Management

The **UK SOLAS Steering Committee** provided science direction, recommended the allocation of financial resources (with additional, independent expertise for proposal assessments), and guided the progress of the programme. The Committee met on 10 occasions between February 2004 and March 2010. Sub-groups were formed as necessary to advise on specific aspects of programme development. Members whose names are given in bold below served for the full period.

The Swindon-based **NERC Programme Managers** and **Programme Administrators** for UK SOLAS, also identified below, were responsible for programme overview, budget management, proposal assessment procedures, award administration and arranging major meetings.

The **UK SOLAS Science Coordinator**, based at the University of East Anglia, was responsible for overall programme integration and its productive implementation, working with the Steering Committee and Swindon Office on programme strategy; programme promotion; development of multi-project fieldwork; communication with researchers and research users; liaison with other relevant national and international activities; and aspects of award administration, progress monitoring, data management and knowledge transfer. The Science Coordinator post was part-time (10-30%), with assistance by other individuals as indicated below.

| | | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|--|------|------|------|------|------|------|------|
| UK SOLAS Steering Committee members | Dr Howard Cattle (CLIVAR/NOC) Chair | | | | | | | |
| | Prof Stephen Belcher (Reading) | | | | | | | |
| | Dr Juan Brown (BODC) | | | | | | | |
| | Prof John Burrows (Bremen/CEH) | | | | | | | |
| | Prof Lucy Carpenter (York) | | | | | | | |
| | Prof Peter Cox (Met Office/CEH/Exeter) | | | | | | | |
| | Dr Jim Gunson (Met Office) | | | | | | | |
| | Dr Angela Hatton (SAMS) | | | | | | | |
| | Prof Peter Liss (UEA) | | | | | | | |
| | Prof Colin Murrell (Warwick) | | | | | | | |
| | Prof Mike Pilling (Leeds) | | | | | | | |
| | Prof Tony Slingo (Reading) | | | | | | | |
| | Prof Mike Smith (Leeds) | | | | | | | |
| | Prof Steve Thorpe (Bangor/retired) | | | | | | | |
| Prof Rob Upstill-Goddard (Newcastle) | | | | | | | | |
| Prof Doug Wallace (IFM-GEOMAR, Kiel) | | | | | | | | |

| | | | | | | | | |
|------------------------------|---------------------------|--|--|--|--|--|--|--|
| Programme Managers | Dr Mike Webb | | | | | | | |
| | Dr Andrew Kaye | | | | | | | |
| Programme Administrators | Dr Sarah Collinge | | | | | | | |
| | Sophie Hodgson | | | | | | | |
| (all at NERC Swindon Office) | Dr Frances Collinborn | | | | | | | |
| | Kay Heuser | | | | | | | |
| | Michal Filtness | | | | | | | |
| Science Coordinator | Dr Phil Williamson | | | | | | | |
| Assisted by: | Dr Claire Hughes | | | | | | | |
| | Dr Martin Johnson (KT/KE) | | | | | | | |
| (all at UEA) | Georgia Bayliss-Brown | | | | | | | |
| | Dr Chris Adams | | | | | | | |

A2.1 Context

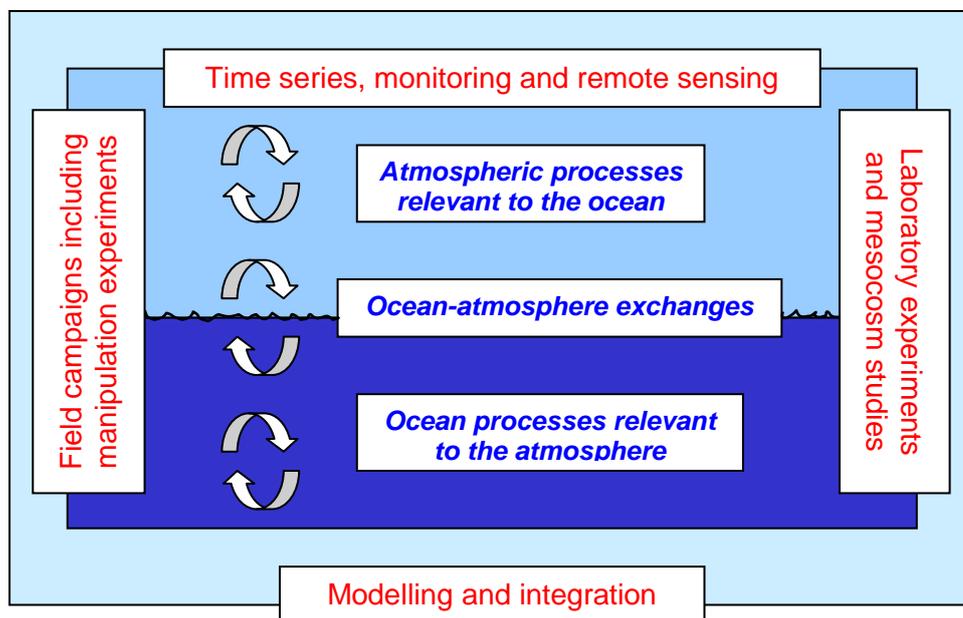
The overall aim of the UK SOLAS directed programme is to advance understanding of environmentally significant interactions between the atmosphere and ocean, focusing on material exchanges that involve ocean productivity, atmospheric composition and climate. The knowledge obtained will not only improve the predictability of climate change but will also give insights into the distribution and fate of persistent pollutants and other future environmental conditions – thereby helping to develop appropriate policy responses. The programme is funded by the Natural Environment Research Council at the level of £12.1m [*original award*], including management costs, over the period 2004-2009.

The NERC-supported programme provides the main national science contribution to the international SOLAS initiative (SOLAS, 2004; www.solas-int.org), with similar research goals. This Science Plan emphasises elements identified in the original UK SOLAS thematic proposal, particularly those that: require an interdisciplinary approach; build on existing strengths of the UK community of atmospheric scientists, oceanographers, microbiologists and modellers (as developed by ACSOE, PRIME, M&FMB and COAPEC; see Appendix 1 for acronyms); and complement other major NERC programmes and initiatives (such as RAPID, QUEST, CASIX, AMT and NCAS). Other SOLAS-relevant activities carried out by UK researchers can also be formally recognised as part of the international effort; however, they are not constrained by this Science Plan, and may cover additional topics.

Core issues for UK SOLAS are the biogeochemical and physical processes in the upper ocean and lower atmosphere that control chemical exchanges across the air-sea interface. These research problems will be investigated by hypothesis-driven studies, using ship and aircraft campaigns supplemented, as appropriate, by laboratory and mesocosm experiments. The spatial and temporal scaling-up of the process-oriented fieldwork will be achieved by remote sensing, time-series measurements, monitoring studies, and modelling, from local to basin-wide and global scales. Implementation issues are addressed in detail in the UK SOLAS Implementation Plan.

The linkages between the main components of the UK SOLAS programme are summarised conceptually in the figure below. Although highly simplified, this shows the need for a well-structured, integrated and community-wide approach, to address the dynamic behaviour of the coupled atmosphere/ocean system within an Earth System framework (NERC, 2002; Houghton *et al*, 2001).

Conceptual summary of UK SOLAS science structure



A2.2 Programme goals

Three 'high level' goals for UK SOLAS are:

- To advance our quantitative understanding of the mechanisms that control the rates of air-sea exchanges of gases, dust, nutrients, aerosols and solar radiation, and to use this information to improve estimates of air-sea exchanges.
- To evaluate how these exchanges impact the chemistry of the marine atmospheric boundary layer, the biogeochemistry of the ocean mixed layer, and feedback between the ocean and the atmosphere.
- To quantify the implications of these boundary-layer processes on the global climate system through developing improved predictive modelling capabilities.

UK SOLAS goals provide an over-arching framework for the programme, and the basis for the more specific objectives and approaches presented below. It is likely that many of the component projects – i.e. research grant and training awards – supported through UK SOLAS will relate to more than one specific objective or approach, and interactions between component studies are strongly encouraged. Alternative science classifications are equally valid: indeed, an 'elemental' cross-cutting approach (based on air-sea cycling of, say, sulphur, iron, nitrogen, carbon or iodine, in both organic and inorganic forms) may prove useful for subsequent programme-wide integration and synthesis.

Whilst UK SOLAS is primarily directed at natural processes, some consideration of directly-produced anthropogenic emissions (e.g. combustion products from ship engines) may be relevant to budgets, modelling and chemical reactions in the marine atmosphere.

A2.3 Research problems: processes and fluxes

A2.3.1 Ocean processes relevant to the atmosphere

Objective i) To identify important trace gas production and loss processes in the surface ocean

For most trace gases, we have inadequate understanding of the dynamic processes affecting their generation (involving phytoplankton, zooplankton, bacteria, archaea, viruses and photochemistry) and breakdown (biological and photochemical). The balance between these production and loss rates not only determines the concentrations of dissolved trace gases in the upper ocean, but also is a major factor controlling their emission or uptake, hence affecting atmospheric concentrations. UK SOLAS will identify important production and loss processes for gases known to be climatically-important, e.g. DMS, N₂O, CH₄ and CO₂, also for other gases, such as alkyl nitrates, organo-halogens and oxygenated organics (Chuck *et al.*, 2002; O'Dowd *et al.*, 2002), that are relevant to wider air-quality considerations. For example, the diversity, abundance and activity of the major groups of microorganisms that are involved in trace gas biogeochemistry will be identified using conventional microbiology and molecular techniques, coupled with trace gas measurements (Malmstrom *et al.*, 2004; Bodrossy *et al.*, 2003). In addition, important chemical processes involved in trace gas production and loss such as photochemistry (Moore & Zafiriou, 1994) will be investigated.

UK SOLAS research addressing this objective will contribute to international SOLAS Focus 1 (Activities 1.2, 1.3), Focus 2 (Activity 2.2) and Focus 3 (Activity 3.3).

Objective ii) To determine the impact of dynamic physical, chemical and biological processes on marine trace gas production and breakdown,, with emphasis on the microbial loop

Knowledge of the influence of physical, chemical and biological variations on trace gas dynamics is required to estimate present-day concentration fields and assess how these distributions are altered by regional (e.g. rain and dust deposition of Fe and N) and global (e.g. increased atmospheric CO₂, temperature and solar radiation) perturbations. For example, changes in the size structure, composition and ecological role of pelagic communities (both autotrophic and heterotrophic) are likely consequences of environmental change (eg Karl *et al.*, 2001, Beaugrand & Reid, 2003). Hence it is important to quantify the production/consumption rates of key trace gases by different taxa of marine organisms, and assess how the various components of the microbial loop respond to physical and chemical changes in environmental conditions. In addition, DMS production has recently been linked to a specific algal stress response (Sunda *et al.*, 2002) which may be induced by changes in the Earth's radiation budget. These interactions may involve complex ocean-atmosphere feedback loops: for example, the role of DMS in regulating the level of solar radiation reaching the Earth's surface, (Charlson *et al.*, 1987). Whilst the potential for such effects is now widely recognised, there are major uncertainties regarding their quantitative importance during the next 50-100 years. UK SOLAS will investigate how environmental variation influences trace gas dynamics in surface waters and related feedback processes, through laboratory, mesocosm or field-based perturbation studies (see below).

This work will contribute to international SOLAS Focus 1 (Activities 1.2, 1.3), Focus 2 (Activity 2.2) and Focus 3 (Activity 3.3).

A2.3.2 Atmospheric processes relevant to the ocean

Objective iii) To improve understanding of the atmospheric transport, cycling and deposition of dust and nutrients

The lower atmosphere connects processes occurring on land and in the rest of the atmosphere to the ocean. These connections are two-way, delivering and receiving materials. Atmospheric deposition of dust provides nutrients that may be lacking from the surface ocean, with the potential to significantly enhance primary production, both directly and indirectly (the latter via Fe effects on N₂ fixation; Falkowski *et al.*, 1998). However, predictions of biological responses are hindered by limitations in our understanding of atmospheric transport, cycling and deposition processes (Jickells & Spokes, 2001). For example, it is known that iron is supplied to the surface oceans by desert dusts (e.g. Baker *et al.*, 2003) but accurate measurements, and even estimation, of this flux is very difficult. In addition, wet atmospheric nitrogen deposition may be a substantial fraction of the total

(biologically active) nitrogen flux to the pelagic ocean; however, its sources and chemical form are not well known (Cornell *et al*, 1995, 2003). An improved understanding of how atmospheric deposition influences biogeochemistry is required, to allow predictions of how such processes will alter with future global change. UK SOLAS will address issues relating to the temporal and spatial variability of these depositions, other (micro-) nutrients involved, and their chemical transformations.

This work will contribute to international SOLAS Focus 2 (Activity 2.3).

Objective iv) To assess the importance of marine sources of aerosols and influences on their dynamics

Aerosols provide a major contribution to the uncertainty in total anthropogenic mean radiative forcing relative to pre-industrial times. Globally-averaged, aerosol forcing is estimated to be between -0.3 and -3.0 W m⁻² (direct and indirect), and our scientific understanding of such effects is classified as 'very low' by IPCC (Houghton *et al*, 2001). The direct climatic role of aerosols is due to the scattering and absorption of solar and thermal radiation, while indirect effects arise from their modification of micro-physical properties, contribution to cloud formation and effects on cloud properties. The sea-air transfer of trace gases and production of sea-spray are known to cause significant changes to aerosol properties above the ocean. UK SOLAS will investigate processes involving both sea-salt and non-sea-salt (nss) aerosols produced through ocean-atmosphere interactions

The ocean emits large quantities of sea-salt aerosols by spume droplets and the bursting of whitecap bubbles. In addition to their role as highly-efficient cloud condensation nuclei and their direct and indirect impacts upon the atmospheric radiation field, these particles release gases (e.g. volatile organic compounds, sulphur and halogen species) and provide surfaces for heterogeneous chemical reactions. In turn, the characteristics of these aerosols reflect their source and subsequent physical and chemical processing (Chameides & Stelson, 1992, O'Dowd *et al*, 1997). The exchange of sea-salt aerosol between the ocean and the atmosphere is regulated by a variety of physical forcings, which will be subject to climate-induced changes and which, in turn, feed back to the global climate. UK SOLAS will carry out investigations in to the source strengths, distributions and removal rates of sea-salt aerosols to reduce the substantial uncertainty in current estimates of the production and removal rates of both sea-salt and nss aerosols. For climate forcing, it is especially important to extend flux estimates to the smaller particle sizes (~0.1µm) important as cloud condensation nuclei. Furthermore, the extent to which organic compounds present in seawater, often as a surface film, influence particle production and microphysics, as well as the characteristics of the resultant aerosol, needs to be established.

In terms of nss aerosols, UK SOLAS is expected to investigate the production of new atmospheric particles by nucleation of volatile organic compounds and low-volatility products of iodine and sulphur. Sulphate derived from the oxidation of dimethylsulphide (Liss *et al*, 1997) and oxidized photolysis products (i.e. IO and OIO) of biogenic iodine (O'Dowd *et al*, 2002) are both known to be involved in new particle formation over the ocean. However, the degree to which this process leads to new aerosols or the growth of existing particles is uncertain. For example, what fraction of such aerosols acts as cloud condensation nuclei under the conditions typical of clouds in the marine atmosphere is a key question surrounding this research area. Burkholder *et al* (2004) used a modeling approach to show that observed IO and OIO concentrations are unlikely to result in significant aerosol production, whilst Hewitt *et al* (1997) found that a substantial fraction of the sulphate formed from DMS oxidation is neutralized by reaction with ammonia, forming ammonium sulphate aerosol. In addition, interactions between halogen and sulphur chemistry have been suggested to influence new particle formation in the marine boundary layer but have received little attention. For example, modelling studies have suggested that reactions between DMS and oxidation products of biogenic-bromine (i.e. BrO) reduce CCN formation (von Glasow *et al*, 2002). UK SOLAS will improve knowledge of the reaction rates and pathways for the oxidation and photolysis processes required for climate-relevant modelling of particle concentrations and their effects.

This work will contribute to international SOLAS Focus 1 (Activities 1.1, 1.3) and Focus 2 (Activity 2.3).

Objective v) To determine the role of trace gas emissions in modifying the oxidising capacity of the atmosphere

The atmosphere's oxidising capacity, i.e. its ability to process trace gases and hence the magnitude of their radiative impact, depends on the concentrations of oxidising species such as OH and ozone. There are several marine influences leading to the modification of tropospheric ozone and OH, which result in changes in the lifetime of reactive greenhouse gases and other climatically significant gases such as DMS. A particularly important influence results from the release of active halogen species from sea salt aerosol (Cl and Br) and from alkyl iodides and bromides, and their subsequent photochemistry in the lower atmosphere (reviewed by Platt & Honninger, 2003). Quantification of the effect of reactive halogen on the atmosphere's oxidising capacity is a high priority for UK SOLAS.

This work will contribute to international SOLAS Focus 1 (Activities 1.1, 1.3) and Focus 2 (Activity 2.3).

A2.3.3 Ocean-atmosphere exchanges

Objective vi) To reduce the existing uncertainty in the air-sea fluxes of trace gases

Air-sea fluxes are routinely calculated from the product of the concentration difference across the interface (ΔC) driving the exchange and the physical transport term, the gas transfer velocity (k) (eg Liss & Slater, 1974). Accurate quantifications of both ΔC and k are problematic and represent fundamental limitations on air-sea flux calculations over a range of scales.

Much of our present understanding of the controls on k is derived from theoretical work (e.g. Liss & Slater, 1974) and wind tunnel studies (Wanninkhof & Bliven, 1991), assuming that k is proportional to wind speed. However, the uncertainty for CO_2 is a factor of about two when k is parameterised in terms of wind-speed alone (Nightingale & Liss, 2004) – neglecting the possible effects of waves, bubbles, biologically-derived surfactants, rain and other physical variables. Studies indicating that such parameters affect k include Upstill-Goddard *et al* (2003) and Frew *et al* (1990); the latter observed a 55-70% reduction in air-sea gas exchange in the presence of phytoplankton-generated surfactants. However, these effects are insufficiently understood to be quantified in models or routinely incorporated into flux calculations.

The concentrations of reactive gases may exhibit significant vertical and horizontal structure in both the surface ocean and lower atmosphere, creating difficulties in calculating fluxes based on ΔC . Temperature gradients are important in this context: for example, Robertson & Watson (1992) calculated that the 'cool skin' effect at the sea surface may increase global CO_2 uptake by the oceans by c 40%. UK SOLAS will improve the assessment of appropriate values of ΔC by developing better understanding of the controlling physical, chemical and biological processes – to be achieved by 'direct' measurements at similar spatial/temporal resolution to the variation in environmental forcing. Sections 3.1 (marine processes), 3.2 (atmospheric processes) and the role of the microlayer (see below) are also relevant in this context.

This work will contribute to international SOLAS Focus 2 (Activity 2.1).

Objective vii) To determine the role of the sea surface microlayer in regulating material fluxes to the atmosphere.

The sea surface microlayer has unique microbiological, chemical and physical characteristics (Liss & Duce, 1997). For example, DMS concentrations in the top few mm may be twice as high as in underlying water samples (Yang, 1999). Microlayer water (and its contents, including bacteria; Leck & Bigg, 1999) is particularly likely to be introduced into the atmosphere as an aerosol, through bubble-bursting associated with breaking waves (film and jet droplets), mechanical tearing (spume droplets) and spilling over of wave crests (splash droplets). Furthermore, under calmer conditions, trace gases must pass through this interface when exchanging between the ocean and atmosphere – and, as indicated above, the transfer velocity k may be affected by surface film properties. Such microlayer effects are difficult to investigate, and hence poorly understood. Nevertheless, better knowledge of the properties of this interfacial boundary is vital for determining the role of ocean-atmosphere exchanges in global biogeochemistry. UK SOLAS will increase our understanding of the importance of the microlayer on surface ocean – lower atmosphere biogeochemistry. For example the development and use of phylogenetic and functional gene probes to determine microbial population structure and dynamics at the microlayer will allow a better understanding of the role of this novel community in regulating air-sea gas exchange.

This work will contribute to international SOLAS Focus 2 (Activity 2.1).

A2.4 Research approaches: techniques and tools

The science-based specific objectives (i)- (vii) above will be addressed through linked fieldwork and laboratory experiments. Our understanding of the underlying processes will be further developed and tested through monitoring studies, remote sensing, modelling and data assimilation, as detailed below.

A2.4.1 Aircraft and ship-based fieldwork, including manipulation experiments

Approach i) To conduct large-scale, multidisciplinary field campaigns based on hypothesis-testing and including simultaneous measurements in the surface ocean and lower atmosphere

Field experiments using state of the art techniques will directly address the issue of air-sea exchange, with major campaigns expected to be carried out in collaboration with the international SOLAS effort. Available techniques include multiple tracer releases, as pioneered by the UK (Watson *et al*, 1991), and micro-meteorological techniques such as eddy correlation (as recently verified at sea for CO_2 ; McGillis *et al*, 2001). UK SOLAS provides the opportunity to develop the latter technique further, in conjunction with eddy accumulation and boundary layer gradient methods, to measure the fluxes of a range of gases and particles from ships, autonomous vehicles and/or from fixed platforms. By deploying these approaches simultaneously, together with physical observations, a quantitative assessment of their accuracy will be possible, which should greatly improve our ability to specify k under different sea states and with different surface film conditions (Nightingale *et al*, 2000); see 3.3 above.

In addition to studies of 'undisturbed' conditions, field manipulation experiments are envisaged. These experiments could include: addition of real or artificial dust, or selected elements, to the surface ocean; investigation of the effect of specific rain events; and the induction of small scale ocean upwelling (as being developed by Japan SOLAS). Such perturbation studies demand a highly interdisciplinary and often Lagrangian

approach. To maximise their benefits, coordinated use of aircraft, ships and ground-based platforms is needed, preferably for at least 6-8 weeks. Purposeful tracers (eg SF₆) may be part of manipulation experiments, or as part of 'observational' process studies – not only to follow surface water movements, but also (potentially) for air mass tracking, to investigate the evolution of chemical reactions in the atmosphere under *in situ* conditions.

Atmospheric studies will make use of the new aircraft instruments available for measuring the physical and chemical nature of aerosols, radicals (OH, HO₂, RO₂), hydrocarbons and oxygenated and halogenated VOCs, as well as a full suite of 'standard' chemical species. In addition, deployment of a medium-sized tethered balloon would allow studies of boundary-layer structure and the altitude dependence of selected atmospheric constituents (Moore *et al*, 2003). A wide range of ground-based instruments is expected to be available for physical and chemical measurements, including wind and O₃ profilers.

The above measurements will be supported by meteorological data, derivations of air mass back trajectories, satellite data on ocean surface characteristics and atmospheric properties (see 4.3) and calculations based on chemistry/transport models (CTMs). Coupled with flux measurements to determine the local sea to air fluxes, this will allow assessment of the regional contribution to atmospheric composition at the measurement site. The resulting datasets are expected to be used in conjunction with detailed chemistry box models, incorporating both gas and aerosol phases, and CTMs to develop our understanding of the influence of ocean fluxes on aerosol formation, composition and evolution, and on gas phase processing.

Joint field campaigns with other UK and non-UK research programmes will be considered where appropriate. For example, working with international SOLAS and IGAC projects, the latter including the African Monsoon Multidisciplinary Analysis (AMMA) that has UK involvement and an overlapping timescale with UK SOLAS.

A2.4.2 Laboratory and mesocosm work

Approach ii) To investigate key processes in greater detail through controlled, small-scale studies in the laboratory and mesocosms

Although results obtained from laboratory and mesocosm investigations are not necessarily transferable to the open ocean, they can provide important process information to guide field and modelling studies. For example, knowledge of the precursors and processes involved in the production of DMS in the pelagic environment was elucidated through laboratory studies (reviewed by Malin *et al*, 1994). UK SOLAS is therefore expected to use this type of research to investigate the sources and sinks (biological and chemical) of trace gases, the role of the sea surface microlayer in determining fluxes to and from the atmosphere (eg Upstill-Goddard *et al* 2003) and liquid phase chemical processes in the near-surface layers of the ocean. Laboratory and mesocosm experiments may also provide opportunities for perturbation studies (eg the response of surface ocean processes to doubled CO₂) where investigations in the 'free' pelagic environment are not possible.

Laboratory measurements relating to atmospheric processes may also provide kinetic data for gas phase and heterogeneous reactions which determine reactive halogen release; the production and loss of ozone; free radical steady states; and gas-to-particle conversion (including nucleation of aerosols). Data are required for the microphysical parameters controlling aerosol growth, scavenging and radiative properties. Standard techniques of cloud and aerosol physics, gas and liquid phase kinetics and physical chemistry, including advanced optical and mass spectrometric measurements are expected to be used. Such studies need to be targeted to produce transferable physico-chemical data and parameterisations for use in numerical models of the ocean-atmosphere interface region.

In addition, some experiments may cover both the aqueous and gaseous phases. For example, recent work by McFiggans *et al* (2004) showed how trace gas emissions from macro-algae (seaweeds) influence atmospheric particle formation in the presence of ozone. Studies of this type are important in demonstrating the links between ocean and atmosphere processes.

5.4.3 Time series studies, monitoring and remote sensing

Approach iii) To develop time series for marine and atmospheric observations (e.g. with AMT and CASIX) and, if feasible, establish a monitoring station at an open ocean site (with research users)

While intensive field campaigns can provide insights into the mechanisms of atmosphere-ocean interactions, they only provide snap-shots of seasonal changes, and cannot resolve annual and longer-term variability in oceanic trace production/consumption and aerosol concentrations over the oceans. Furthermore, their spatial coverage is necessarily limited. Observations at appropriate time-scales, preferably at the regional scale, are required to fully address these issues – both to develop models, e.g. on source emission processes, and to test their ability to hindcast and predict real-world events.

UK SOLAS access to NERC research ships and aircraft is likely to be limited to 2006-2008, and fieldwork may not necessarily be in the same geographical location each year. Hence there is a strong case to widen temporal coverage via links to other, ongoing programmes. The Atlantic Meridional Transect (AMT) observational series started in 1995, has involved 14 cruises to date (May 2004) and currently receives NERC consortium support (2002-06). AMT science aims (see www.pml.ac.uk/amt) closely match those of UK SOLAS – providing considerable scope for joint work, building on existing marine datasets and expanding the range of atmospheric data collected.

Additional partnership arrangements with the Centre for Observation of Air-Sea Interactions and Fluxes (CASIX, www.pml.ac.uk/casix) would provide further added-value to the UK SOLAS programme. CASIX expertise includes the acquisition, processing and interpretation of remote sensing data relevant to marine processes. UK SOLAS will not try to replicate such activities. Instead, the programme intends to collaborate with CASIX in collecting 'ground truth' data over large spatial scales and the associated analyses.

There is a global lack of open-ocean, marine and atmospheric monitoring sites that record a comprehensive suite of biogeochemical measurements relevant to SOLAS science. Although northern hemisphere datasets for atmospheric parameters are available for Mace Head (west Ireland) and Weybourne (north Norfolk), with some associated research cruises and aircraft campaigns, these sites are subject to strong coastal and terrestrial influences (Carpenter *et al*, 1999; O'Dowd *et al*, 2002). UK SOLAS will therefore investigate the possibility of establishing a new monitoring station and, if viable, seek to establish such a facility – initially to be closely linked to programme field campaigns, and subsequently (with co-support) having a significantly longer lifetime. Possible sites are the Cape Verde Islands, Ascension Island and Bermuda; consideration may also be given to Brazilian islands (eg Ilha Fernando do Noronha), the Falklands and South Georgia.

A2.4.4 Modelling and integration

Approach iv) To develop a suite of complementary models with the varying degrees of sophistication that are required to describe the processes, interactions and feedbacks relevant to UK

Much of this effort is likely to involve close collaboration between the NERC scientific community (including BODC and BADC) and researchers at the Hadley Centre/Met Office. In order to maximise the scientific outcomes of the modelling component of UK SOLAS, extensive consultation between modellers and experimental scientists will be a prime consideration during planning of the fieldwork activities. Novel observations will need to offer a global perspective, consistent with the international SOLAS strategy. The incorporation of other relevant datasets, both historical and contemporary, into the modelling effort will enhance the value of new data. Recent examples include a compilation of ocean DMS measurements (Kettle *et al*, 1999), and information on upper ocean biogeochemistry for Atlantic transects via AMT cruises.

Existing data sets may, however, require modification/reworking to provide the necessary global perspective. UK SOLAS is therefore expected to support initiatives to identify existing relevant datasets, and/or compile new ones from existing measurements, reassembling these into forms suitable for both refining current parameterisations and models, and for developing new ones. These activities will be closely linked to the NERC programme on Quantifying and Understanding the Earth System (QUEST; www.nerc.ac.uk/funding/thematics/quest) and tested as appropriate in the Hadley Centre climate model.

A2.5 Data management

UK SOLAS will follow NERC policy regarding data management, to ensure the longterm availability of data collected and thereby maximise the application and exploitation of programme results. NERC Designated Data Centres (BADC and BODC) will be engaged early in programme planning and project implementation, and subsequently used for data checking and archiving – with costs covered from programme funds. After a period of sole access by PIs for publication preparation, data will be made available to other programme participants and the wider community. For further details, see UK SOLAS Data Management policy [*Annex 4*].

A2.6 Training

The interdisciplinarity, multi-institute and international nature of UK SOLAS offers excellent opportunities for younger researchers, and it is anticipated that a significant number of research studentships (for PhD training) will be supported. The participation of students in international SOLAS activities (e.g. SOLAS science conferences and Summer Schools) will also be strongly encouraged.

A2.7 Work with research users and wider links

A major aim of the UKSOLAS programme will be to develop working relations with a wide range of business, governmental and non-governmental research users to play a major role in international SOLAS; and to establish appropriate links with related initiatives. The NERC Knowledge Transfer (KT) scheme will be used for this purpose, considering KT as a two-way process between academics and wider stakeholders, i.e. bringing knowledge from the latter into the programme as well as providing them with science results.

As already indicated above, UK SOLAS is strongly connected to international SOLAS. For example, Peter Liss is the first chair of the SOLAS Scientific Steering Committee (2001-04, with possibility of renewal), and the SOLAS International Project Office and UK SOLAS Science Coordination team are co-located at UEA. In addition, UK SOLAS has good contacts with other SOLAS programmes (e.g. Canada, Germany), and either already has or is developing liaisons with other relevant international activities, such as AMMA, CLIVAR, ITOP and OASIS.

A2.8 Project management

The UK SOLAS Steering Committee (Chair: Howard Cattle) provides science direction and advice. The NERC Programme Administrator is Sarah Collinge; the NERC Science and Innovation Managers are Mike Webb and Andrew Kaye; and the Science Coordination team is Phil Williamson and Claire Hughes (UEA).

Acronyms

| | |
|--------|--|
| ACSOE | Atmospheric Chemistry Studies in the Oceanic Environment (NERC thematic programme) |
| AMMA | African Monsoon Multidisciplinary Analysis |
| AMT | Atlantic Meridional Transect (NERC consortium project) |
| BADC | British Atmospheric Data Centre |
| BODC | British Oceanographic Data Centre |
| CASIX | Centre for the observation of Air-Sea Interactions and Fluxes |
| CLIVAR | Climate Variability and Prediction Research Programme |
| COAPEC | Coupled Ocean-Atmosphere Processes and European Climate (NERC directed programme) |
| CTM | Chemical Transport Model |
| DMS | Dimethylsulphide |
| IGAC | International Global Atmospheric Chemistry project |
| IPCC | International Panel for Climate Change |
| ITOP | Inter-continental Transport of Ozone and Precursors |
| M&FMB | Marine and Freshwater Microbial Biodiversity (NERC directed programme) |
| NCAS | NERC Centres for Atmospheric Science |
| OASIS | Ocean-Atmosphere-Sea-Ice-Snowpack Interactions Project |
| PRIME | Plankton Reactivity in the Marine Environment (NERC thematic programme) |
| QUEST | Quantifying the Earth System |
| RAPID | Rapid Climate Change (NERC directed programme) |
| SOLAS | Surface Ocean – Lower Atmosphere Study |
| UEA | University of East Anglia |
| VOC | Volatile Organic Carbon |

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*This Implementation Plan provided the strategy by which the objectives of the Science Plan [Annex 2] were implemented. It includes the **UK SOLAS Knowledge Transfer Plan** (Box A3.1) and the **UK SOLAS Communications Strategy** (Box A3.2). Such documents were developed by the UK SOLAS Steering Committee and Science Coordinator, mostly in 2004-05, and were available online during the duration of the UK SOLAS programme via www.nerc.ac.uk.*

A3.1 Introduction

The UK Surface Ocean-Lower Atmosphere Study (UK SOLAS) is a NERC directed programme which aims to advance understanding of environmentally significant interactions between the atmosphere and ocean, focusing on material exchanges that involve ocean productivity, atmospheric composition and climate. UK SOLAS is a component of the UK IGBP effort and provides the main national science contribution to the international SOLAS initiative with a similar research goal. The scientific objectives and main approaches of the NERC programme are defined in the UK SOLAS Science Plan [Annex 2].

The aims of UK SOLAS have been met through research grants and other awards, following submission of project-based funding bids in response to Announcements of Opportunity (AO). The programme strongly encouraged collaborations between different research groups and disciplines, both within the programme and through partnerships with other relevant national and international activities.

A3.2 Programme management

The UK SOLAS Steering Committee (chaired by Dr Howard Cattle) provides science direction, recommends the allocation of financial resources, and guides the progress of the programme. Details of its membership are provided elsewhere [Annex 1 of this Report]. Independent experts participating in research grant assessment meetings had included Prof Hartmut Hermann (IfT Leipzig), Prof Maurice Lévassieur (Laval), Colin O'Dowd (Galway) and Dr Dudley Shallcross (Bristol),

The policy-related responsibilities of the NERC Programme Administrator and NERC Programme Manager include programme overview, budget management, arrangements for meetings, and award administration.

The Science Coordinator is Dr Phil Williamson, based at the University of East Anglia. His role is to assist the Steering Committee and Swindon Office with: programme strategy and programme promotion; development of well-integrated fieldwork; communication with researchers and research users; liaison with other relevant national and international activities; and aspects of proposal assessment, award administration, progress monitoring, data management and knowledge transfer.

A3.3 The UK SOLAS community

The programmatic framework of UK SOLAS has brought together a wide range of scientific disciplines (including marine biogeochemists, atmospheric chemists, microbiologists, physical oceanographers, modellers and climatologists) to address important research issues that were not being tackled by other projects, and that required a coordinated approach. To help foster a UK SOLAS community, the programme gave high priority to:

- workshops and meetings that provided a platform for interdisciplinary discussion, for active involvement of younger scientists and for engagement with research users
- development and implementation of a communication strategy that ensured wide awareness of the aims and achievements of the programme
- facilitation of collaboration at both national and international levels.

A3.4 Funding for science

The development and selection of component science projects was based on two main funding rounds, each preceded by well-publicised Announcements of Opportunity (AOs) that included information on the funds available. The first AO involved a Project Outline stage, to assist in the development of well-focussed and complementary full proposals. Timetables for the funding rounds are summarised under Section A3.13 below.

Proposals may have involved a single investigator (PI), or several investigators (PI and Co-Is) in the same institution, or several groups in different institutions (one PI and several Co-Is, with 'split award' arrangements) together with non-academic or international partners. Standard NERC rules regarding investigator and institution eligibility applied unless notified otherwise at the AO stage. Any other special considerations were also identified then (eg specific priorities, if applicable; or factors affecting timing/duration of awards). Feedback guidance from the Steering Committee was provided on outlines and following assessment of full proposals.

A3.5 Training

PhD training was directly provided to a total of 10 scientists through both 'tied studentship' awards (linked to first round UK SOLAS research grant proposals) and CASE studentships (collaborative awards, with research-user partners) supported through the Knowledge Transfer funding round; see below.

Provision was made so that additional non-UK SOLAS funded PhD candidates could also participate in UK SOLAS research cruises and field campaigns when their participation furthered the goals of the campaign.

Travel funding was provided to research students and other young scientists to assist their participation in the first international SOLAS science conference in Halifax, Canada (Oct 2004). Similar assistance was provided for their attendance at both the 2nd international conference in Xiamen, China (March 2007) and the 3rd international conference in Barcelona, Spain (Nov 2009). Additional short-term training support was made available for postgraduate students with SOLAS-related interests to attend the biennial international SOLAS summer school. NERC has agreed to continue this support for SOLAS-related early career researchers to attend the 2011 Summer School. No NERC fellowships have been supported via UK SOLAS.

A3.6 Knowledge Transfer

Knowledge Transfer (KT) activities [*now known as Knowledge Exchange*] are an integral part of NERC's mission, for which directed programmes have particular responsibilities. The expectation is that around 5% of the UK SOLAS budget will be used for this purpose. A KT plan (Box A3.1, below) was developed at the planning stage of the programme. Adoption of this plan and initial planning of KT activities was assisted by a KT Facilitator (Martin Johnston) supported for 9 months in 2004/05. A KT-specific funding round was held in late 2005-early 2006, resulting in two CASE studentships and a KT project on global SOLAS data integration and synthesis (with the Met Office; also in partnership with QUEST and CASIX). A second KT-specific funding round was held in late 2007-early 2008, through which four KT awards were made. Section 1.4 of this report details some specific examples of SOLAS KT activities.

Box A3.1 UK SOLAS Knowledge Transfer plan

Background

NERC defines Knowledge Transfer (KT) [*now known as Knowledge Exchange*] as the process by which knowledge, expertise and skilled people transfer between the science base and user communities, thereby contributing to UK economic competitiveness, the effectiveness of public services and policy, and the quality of life. This definition relates to the four main types of knowledge produced by NERC-funded scientists:

- knowledge presented in scientific papers or at scientific meetings
- knowledge that can be commercialised (eg through ownership of intellectual property)
- tacit knowledge ('know-how') relating to the methodologies used in scientific studies
- information that by itself does not merit scientific publication, but could be valuable to other researchers or research-users.

Activities to specifically promote KT include:

- cooperation in education and training
- people and knowledge flow
- collaborative research with users
- commercialising science.

Knowledge transfer can also be considered to include information transfer from one part of the science base to another, and the transfer of knowledge from the science base to the general public. However, the former process is such an essential part of research that it does not require special attention as KT, whilst for NERC the latter is primarily covered by Science and Society activities.

Since 2003 NERC has allocated additional resources to KT activities. KT funds are being spent across NERC's research centres, directed programmes and specific KT initiatives. A NERC KT plan, approved in December 2004, includes targets for increasing: interaction with business and public service; collaborative research with public and private sectors; commercialisation of research (patents, spin-out companies and entrepreneurship training); co-operative training; and people exchange between the science and engineering base and users.

NERC directed programmes are expected to allocate at least 5% of their budget for KT support, based on recommendations by the programme Steering Committee. For UK SOLAS, the KT funding line is currently ~£500k. The development of this KT Plan for UK SOLAS has been assisted by discussions with the Swindon Office KT team, and with the Technology Translators/KT Facilitators for other NERC programmes, including QUEST, RAPID and the Marine & Freshwater Microbial Biodiversity (M&FMB) programme.

The nature of UK SOLAS research

Programme goals, objectives and approaches provide the framework for identifying and promoting user interest, in both the public and private sectors. For UK SOLAS, the main goals are:

- To advance our quantitative understanding of the mechanisms that control the rates of air-sea exchanges of gases, dust, nutrients, aerosols and solar radiation, and to use this information to improve estimates of air-sea exchanges.
- To evaluate how these exchanges impact the chemistry of the marine atmospheric boundary layer, the biogeochemistry of the ocean mixed layer, and feedback between the ocean and the atmosphere.
- To quantify the implications of these boundary-layer processes on the global climate system through developing improved predictive modelling capabilities.

Seven objectives (UK SOLAS Science Plan) define in greater detail what the programme expects to achieve through component research awards, each having its own project-specific objectives:

- To identify important trace gas production and loss processes in the surface ocean
- To determine the impact of dynamic physical, chemical and biological processes on marine trace gas production and breakdown, with emphasis on the microbial loop
- To improve understanding of the atmospheric transport, cycling and deposition of dust and nutrients
- To assess the importance of marine sources of aerosols and influences on their dynamics
- To determine the role of trace gas emissions in modifying the oxidising capacity of the atmosphere
- To reduce the existing uncertainty in the air-sea fluxes of trace gases
- To determine the role of the sea surface microlayer in regulating material fluxes to the atmosphere.

In addition, four main approaches are set out in the programme's Science Plan:

- To conduct large-scale, multidisciplinary field campaigns based on hypothesis-testing and including simultaneous measurements in the surface ocean and lower atmosphere
- To investigate key processes in greater detail through controlled, small-scale studies in the laboratory and experimental mesocosms
- To develop time series for marine and atmospheric observations and, if feasible, establish a monitoring station at an open ocean site
- To develop a suite of complementary models with the varying degrees of sophistication that are required to describe the processes, interactions and feedbacks relevant to UK SOLAS.

The programme's geographical focus was not explicitly defined in the UK SOLAS Science Plan, but was determined by successful Round 1 projects, assessed on scientific merit; i.e., each research group identified the most appropriate fieldwork for its needs. Two main areas of interest emerged: the tropical NE Atlantic (off NW Africa), and higher latitudes in the open NE Atlantic. Whilst processes occurring both outside and within territorial waters (of the UK and other nations) are of interest, emphasis is on the former.

The above features of UK SOLAS make it unlikely that many near-market research products will arise as programme deliverables. That does not mean that there are no potential applications; nevertheless, it would be unrealistic to expect major short-term commercial outputs from NERC's investment in the programme.

Summary of activities initiated by UK SOLAS KT Facilitator (2004-05)

In addition to a science-based network of ~300 researchers (only a minority of whom are recipients of UK SOLAS support), a database of more than 60 KT research user contacts in around 30 organisations has been established.

For the programme's first funding round (closing date: November 2004), users were encouraged to establish links with PIs, and become involved as project partners in the full bids. Although 13 proposals (out of 27) had international academic partners, only three research grant and studentship proposals included project partners from non-academic UK institutions. Possible reasons for this relatively low level of UK research user involvement were as follows:

- Benefits to be derived from programme involvement were perceived as relatively diffuse
- The first funding call was not specifically directed at KT activities
- In the absence of specific targeting, it can be difficult for research users to justify the time and effort needed for the collaborative planning of projects that may fail to obtain funding.

It has been the experience of other directed programmes that the development of KT activities works best as an iterative process. Exposure of research users to programme projects and PIs (and vice versa) is an important factor in stimulating collaborative linkages and other interests that can be further encouraged. For UK SOLAS, the need for the remainder of the programme is to sustain the broad user interest that does exist, and to develop some specific projects with research users as KT activities.

Plans for UK SOLAS KT activities 2006-2010

Broad research user interest in the UK SOLAS programme will be sustained by:

- Maintaining information flow to research users on the database, informing them (by email and website) of programme developments, such as fieldwork schedules, open science meetings, international links and major research findings
- Arranging user-focussed events that might either be held jointly with other NERC programmes (such as RAPID or QUEST, since there is considerable overlap with their user databases) or linked to the UK SOLAS annual science meeting
- Stimulating one-to-one discussions between users and PIs where close matching of interests seems likely.

More specific initiatives for research user engagement in UK SOLAS (involving a competitive KT proposal process) are as follows:

- *Cooperation in education and training.* This could best be achieved by a UK SOLAS research studentship competition through the CASE scheme (Cooperative Awards in Sciences of the Environment), on the basis that 2-3 such awards might be supported. Such studentships would need to start in Autumn 2006 for completion before the overall programme end-date; hence - for recruitment of high quality students - the project approval process will need to be completed by March-April 2006.
- *People and knowledge flow.* In the UK SOLAS context, such a KT activity might involve a researcher already funded on a research grant spending 1-6 months with a (non-academic) research user, associated with an extension to the research award period. Alternatively, the working visit might be by the research user to the grant-holder's institution, assisted by the KT award to the HEI. For such arrangements, some co-support by the user organisation would be expected, either directly or in kind.
- *Collaborative research with users.* This category of KT activity needs to be explicitly driven by research user needs - and preferably involving significant co-funding by the user. Whilst science quality remains an important consideration for assessing the excellence of the proposed work, the level of user engagement and 'added value' issues are also key considerations.

In December 2007 a UK SOLAS call for 'Knowledge Transfer, Synthesis and Dissemination' was launched and as a result of this four awards were made in 2008.

The UK SOLAS Science Coordinator has responsibility for developing KT activities in the programme, in close liaison with the Steering Committee, the Programme Administrator and the Swindon Office KT team.

A3.7 Requirements for ship time, services and facilities

UK SOLAS made use of a wide range of NERC services and facilities for fieldwork and laboratory-based modelling studies. Those of major interest to the programme included: Research Ships Unit (RSU), Facility for Airborne Atmospheric Measurements (FAAM), Remote Sensing Data Analysis Service (RSDAS), and High Performance Computing (HPC).

Separate applications for access to these facilities were made when appropriate, either by individual project PIs or on a programme-wide basis. In total there were 8 research cruises and 3 research flight campaigns which made use of NERC facilities. In addition, the part NERC funded SOLAS IPO facilitated UK use of foreign national facilities eg placement of equipment and researchers on the Norwegian weather ship *MS Polarfront* during the HiWASE project.

A3.8 Data management

NERC policy requires all directed programmes to properly manage the data they collect. UK SOLAS devoted an adequate proportion of its budget and planning effort to ensure that datasets collected by the programme are managed in accordance with this policy, so that they can be exploited scientifically and commercially beyond the lifetime of the programme. As UK SOLAS involves both atmospheric and oceanographic studies, both BADC and BODC are involved in data management - with BODC leading the 'UK SOLAS Data Centre' (SDC). The UK SOLAS Data Management Plan [*Annex 4 of this Report*] provides information on these arrangements, including metadata protocols.

A3.9 Progress monitoring and reporting

Formal monitoring of the progress of individual projects has been carried out as part of the NERC annual Output Performance Measures (OPM) exercise. Results (together with additional information) were collated and incorporated in to both written and oral annual progress reports to the Steering Committee, to NERC and to the international SOLAS programme.

A3.10 Communication

NERC is keen that all interested parties (including the general public) are aware of its research activities and their societal importance. The UK SOLAS programme has drawn together researchers from a wide range of disciplines including marine biogeochemistry, physical oceanography, atmospheric chemistry and mathematical modelers to achieve its aims. To help achieve effective communications across these traditionally distinct disciplines, the UK SOLAS Science Coordinator has (with advice from the Steering Committee and the NERC Communications Team) developed and implemented a communication strategy to promote wider outreach for the programme and facilitate successful cross-discipline dialogue.

Box A3.2 UK SOLAS Communication Strategy

Key objectives of the communication strategy

- To raise awareness of the goals and outcomes of the programme
- To gain national and international recognition for UK SOLAS science
- To break down barriers between traditional disciplines

Key messages of UK SOLAS

- The significance of key processes occurring at the sea surface
- The contribution made by the programme to our overall understanding of the Earth system
- The importance of a multidisciplinary approach

Key audiences

*Scientific community
(national and international)*

- SOLAS community
- Wider community

*Government sector
(eg Defra, Met Office)*

- Scientists
- Policy makers

Private sector

- Marine Technology
- Pollution control
- Consultants

Public

- Teachers
- Young people

Action planning

- Establish academic and user mailing lists to relay news and information
- Employ a Knowledge Transfer Facilitator to establish a UK SOLAS user network
- Publish information on the NERC/UK SOLAS website
- Participation/presentation at relevant science meetings
- Produce UK SOLAS leaflet and other publicity material for circulation
- Attendance at popular science exhibitions (eg Royal Society) and careers fairs
- Press releases/media interviews where appropriate

Obstacles and risks

- Lack of a common science language between disciplines
- Generating private sector interest in a research area that is not directly applied
- Identifying opportunities to communicate with the public

Budget

- £100k of programme budget dedicated to science meetings
- £600k for Knowledge Transfer activities (eg engage stakeholders).
- Support for attendance of scientists/ students/ programme managers at national/ international meetings and Summer Schools
- Additional undefined costs associated with publicity material and exhibitions.

Examples of activities and outcomes

Press releases and public events

- Numerous press notices from NERC and science institutions as well as other media liaison including >20 articles and reports in SOLAS News which is distributed both online and in hardcopy by the SOLAS IPO.
- Further media interest in UK SOLAS fieldwork was initiated by arranging for a Guardian journalist to accompany Eric Achterberg's 2006 cruise on the *RV Poseidon* with a feature article published 13 February 2006. This stimulated interest by the Science Museum, London, resulting in a special exhibit "Scientists chase Saharan sandstorms at sea".
- Public events such as this and 'The Breathing Ocean' exhibit at the 2008 Royal Society Summer

Science exhibition facilitated public engagement and dissemination of SOLAS science concepts to a very wide audience. Such activities have been linked to KT initiatives and the wider exploitation of research results.

- Where appropriate specific projects held public engagement events; one example of this was a public meeting held at the Station Biologique in Roscoff during the RHaMBLe field experiment carried out in Roscoff Bay.
- Also during RHaMBLe SOLAS scientists appeared on BBC Radio 4 Material World, French TV, a podcast for the Discovery channel and in two French newspaper articles.

Summer School

- NERC Support was made available for early career and PhD SOLAS researchers to attend the biennial International SOLAS Summer School, Corsica. The Summer School courses have since been the base for the SOLAS textbook (AGU Geophysical Monograph 187) with UK researchers contributing 7 out of 17 chapters assisting the transport of SOLAS science directly into the classroom at degree and postgraduate level. This forum also facilitated networking and communication of UK SOLAS science to international colleagues.

Conferences and Finale Event

- Strong participation by UK researchers in the biennial International SOLAS Open Science Conferences (OSC) has led to successful communication of UK SOLAS science to the wider SOLAS community. The main UK participation at each OSC was as follows: At Xiamen, the UK contributed 29 posters (out of 219), 4 oral overviews (out of 21) and led/co-led 6 discussion groups. At Barcelona, the UK authored/co-authored 52 posters (out of 191), gave 5 plenary talks (out of 28) and led/co-led 5 discussion groups. Moreover, the OSCs included public workshops and discussions allowing SOLAS science to reach and stimulate debate with the interested general public.

The end of programme event was held at the Met Office and consisted of two days, the first of these being a science discussion day aimed at both the UK SOLAS community and other research users with a large input from Met Office researchers. The second day of the event was a more traditional end of programme meeting with invited participants from both SOLAS and non-SOLAS scientists, NGOs, NERC, Defra, the EA and a range of other interest groups. Together these two days allowed the dissemination of UK SOLAS science to a very wide community.

A3.11 Links to International SOLAS

The national SOLAS community has established strong working links with SOLAS activities taking place worldwide, and has played a major role in international science activities. Many of these connections were developed through close contact between the UK SOLAS Science Coordinator and the SOLAS IPO (co-located at UEA), the involvement of UK representatives at international SOLAS meetings, and the active encouragement of wider collaborations. [For a summary of these activities, see Section 1.3.5 and Table 4 of this Final Report].

A3.12 Links to other research programmes

In addition to international SOLAS, UK SOLAS has made connections to other relevant UK and international research projects, to promote complementarity and avoid duplication of effort. Initial attention for UK-based linkages was directed at maximising synergies with the Atlantic Meridional Transect (AMT; subsequently a component of the Oceans 2025 programme), the Centre for Air-Sea Interactions and Exchanges (CASIX), Quantifying the Earth System (QUEST), the African Monsoon Multidisciplinary Analysis (AMMA; UK contribution to international programme supported via a NERC consortium award) and Aerosol Properties, Processes and Influences on the Earth's Climate (APPRAISE).

Linkages at the European level included those with Atmospheric Composition Change: European Network of Excellence (ACCENT), the Tropical Eastern North Atlantic Time-Series Observatory (TENATSO), and COST Action 735.

*This Data Management Plan includes the **UK SOLAS Data Policy** (Box A4.1) and **UK SOLAS Metadata Protocols** (Box A4.2). It was developed in 2004-06 jointly by the UK SOLAS Steering Committee, Science Coordinator, the British Oceanographic Data Centre (BODC) and the British Atmospheric Data Centre (BADC). Project-specific data management plans were also developed but are not presented here.*

A4.1 Introduction

NERC requires all Directed Programmes to plan and implement a data management scheme. The planning must cover the practical arrangements while the programme is running and the subsequent maintenance and long-term curation of the data sets. The latter is increasingly important in view of the Environmental Information Regulations, which place a duty on Government funded bodies to make all publicly funded data readily and easily available.

The NERC Data Policy requires that all data are lodged with the appropriate NERC Designated Data Centre. In the context of the UK SOLAS programme these are the British Oceanographic Data Centre (BODC) and the British Atmospheric Data Centre (BADC), the respective Designated Data Centres for marine and atmospheric sciences. The minimum required standards of stewardship are summarised in Section A4.3.

NERC provides funding to the Data Centres for basic infrastructure support and the long-term maintenance and curation of NERC's data assets. Directed Programme budgets include the funds necessary for within-programme data management during their lifetimes.

An integral part of the Data Plan is an obligation upon UK SOLAS Principal Investigators (PIs) to ensure that data management is undertaken in a suitable way, and that adequate consideration is given to the 'data side' of their work. The programme's data policy (specifying required actions) is given in Box A4.1. Individual project 'data management plans' (not provided here) cover staff responsibilities, data collection policies, data standards, resourcing of data management, data quality and quality assurance.

This plan has been formulated following a review of the specified resource requirements and outputs set out in the project proposals and discussions between BODC/BADC, the UK SOLAS Science Coordinator, and project PIs in order to assess the scale of data collection/production. Data include observational and modelling products, biological, chemical and geophysical samples, with requirements to link to third party datasets.

A4.2 The role of the UK SOLAS Data Centre (SDC)

Submission of and access to data will be through a common 'portal' and for the purposes of the UK SOLAS directed programme, the term UK SOLAS Data Centre (SDC) will refer to BADC and BODC. Data management costs have been allocated in the UK SOLAS budget for SDC services. Note that the SDC does not have data management responsibilities for non-programmatic science contributions to national SOLAS activities, i.e. SOLAS-relevant projects and activities supported by other funding mechanisms (NERC and non-NERC).

Given the complex and broad range of data encompassed by the UK SOLAS programme the nature of the data management will vary between projects. The basis of this has been agreed with PIs following an initial dialogue with the SDC and UK SOLAS Science Coordinator.

The SDC will be the focal point for PIs regarding data issues. The SDC website will contain inventories providing comprehensive up to date information about the status of all project data sets and model runs, so that all UK SOLAS participants can easily request available data. The SDC will service data requests by UK SOLAS participants.

Following the completion of UK SOLAS, the SDC will ensure that data are passed to the appropriate International Data Centres (through international SOLAS and other bodies), ensuring that NERC meets its international obligations.

A4.3 Minimum standards of stewardship for NERC data

To comply with the NERC Data Policy (www.nerc.ac.uk/data/policy.shtml) the following minimum standards are expected to apply when (digital) datasets form part of NERC's enduring data resource:

- i) The ownership and Intellectual Property Rights to the data set must be established, and NERC's policy towards exploiting and making it available to third parties agreed
- ii) The data set must be catalogued to the level of detail required by a NERC Designated Data Centre, so that it can be mentioned in web-based NERC data catalogues
- iii) Formal responsibility for the custody of the data set must be agreed
- iv) Data must be fully "worked up" (i.e. calibrated, quality-controlled etc.) with sufficient associated documentation to be of use to third parties without reference to the original collector
- v) Technical details of how the data are to be stored, managed and accessed must be agreed and documented
- vi) The technological implications must be established (digital data stewardship implies the need for an underlying infrastructure of IT equipment and support)

- vii) The resources needed to carry out these intentions over the planned life of the data, in terms of staff (whether in project teams or the Data Centre) and IT equipment/infrastructure must be estimated and sources identified
- viii) A review mechanism must exist to reconsider periodically the costs and benefits of continuing data maintenance
- ix) The intention to destroy or put at risk data should be publicised in advance, allowing time for response by interested parties.

The above requirements will be looked after 'automatically' for the UK SOLAS data sets managed by BODC and BADC. Nevertheless, PIs need to be aware of this framework.

A4.4 Data and sample acquisition

UK SOLAS data cover a broad subject area, including oceanographic and atmospheric information, and the generation of model output. It is not the intention to specify here the details of how these data will be collected, described and delivered to the data centres. However, a number of generic principles need to be adhered to.

Processed and project-specific data must be provided to the SDC by the Principal Investigator, field campaign leaders (research cruises and research flights) and project teams as they become available, not in the concluding few months or weeks of projects. However, great importance is given, both by the programme and by the SDC, to protecting the interests of data originators, and restrictions on the wider availability of the SDC-held data sets will therefore apply (see Data Policy: Box A4.1).

A well structured and user-friendly identification system is essential for cruise-based data collection and sample labelling. Such arrangements are traditionally the responsibility of the cruise Principal Scientist. However, in order to assist the PIs and SDC, a representative of the SDC should be invited to attend pre-cruise planning meetings.

Station identifiers, navigational information and "basic" oceanographic data (for which the SDC will have quality-control responsibilities) must be provided to the SDC by the Principal Scientist immediately after a cruise. Normal practice, as for other Directed Programmes, will be for the SDC to meet the ship when it docks in the UK and to take delivery of this material together with a copy of the logs, calibration data and sensor information. If a cruise terminates in a foreign port it will be necessary for the PI and a representative of the SDC to meet immediately on return of the PI to the UK. A copy of the Cruise Summary Report (ROSCOP form) should be provided to the SDC by the Principal Scientist within one working week of the end of the cruise. A copy of the full cruise report should also be sent to the SDC, electronically, as soon as it is completed. The SDC will then assist in making this more widely available (e.g. via a link from the main programme website).

For projects collecting biological, chemical or geophysical samples it is the PI's responsibility to ensure that appropriate sample management measures are in place. However, it is important that the necessary collection details are provided to the SDC to form part of the overall project information.

For model data, information accompanying submitted data should include the model name and version number and a brief description of the model's general aim. Broad principles relating to model metadata are given in A4.5 and discussed further in Box A4.2. Detailed arrangements for submission and serving will be agreed with individual PIs.

A4.5 Metadata

Metadata are a crucial part of any data archive since they ensure that the data can be understood at a later date. To guarantee the UK SOLAS data archive quality, full documentation on all validated raw and processed data, as well as on models and model results, must be provided to the SDC. It is therefore essential that metadata are submitted at the same time as the data sets to which they pertain. The responsibility for producing the metadata will lie with project PIs and the SDC. A metadata protocol is outlined in Box A4.2.

In addition to the standard metadata, investigators are encouraged to archive all relevant information electronically, including references, papers, reports, etc., unless agreed otherwise between the PIs and the SDC.

A4.6 Data formats and data media

Digital data should be collected and stored using standard, widely available software products and their related data formats. Whilst the SDC has experience in handling a very wide range of software, formats and media, Investigators should discuss with them at an early stage the proposed use of any data-handling or storage protocols that might be regarded as "non-standard".

In general, model data should be formatted in CF-compliant NetCDF files, although there will be exceptions (particularly PP and HDF will also be accepted). Documentation on formats and conventions is available (www.badc.nerc.ac.uk/help/formats/index.html), which also provides links to downloadable free software packages to support NetCDF access.

Submission of data will generally be via CD-ROM, as a Word/Excel e-mail attachment or by FTP. In some instances (e.g. some of the atmospheric model output) an automatic web-based file uploader will be available. At an early stage PIs should discuss the options with the SDC. CD-ROMs and or DVDs are currently the preferred means for making integrated data products from directed programmes available to the wider research community.

However, there may be a preference towards a web-based final data product as UK SOLAS progresses. The UK SOLAS Steering Committee will review and decide on this at a later stage in the programme.

A4.7 Data back-up policy

The consequences of losing data, due to insufficient or inappropriate provision for their back-up, are potentially catastrophic in the case of large data collections, and cumulatively serious in the case of smaller data sets. Rigid daily back-up programmes operated at the SDC safeguard major digital databases. Provision and support of backup strategies for digital data stored locally are the responsibility of individual PIs or their delegates. Project PIs and Co-Is are responsible for providing appropriate backup for digital data stored locally or via other organisations.

As far as possible, analogue data (such as photographs) should be "disaster proofed" by transferring them into digital form, e.g. by scanning. Such duplication is not a waste of effort, even though the original, analogue version may have a longer lifetime than the format/media used for the digital transcription. Such data may then be included on a programme CD-ROM or DVD. BODC has considerable experience in managing and publishing image data.

PIs should be aware that timely deposit of data with the SDC provides additional security for the project data.

A4.8 Protection of data originator's Intellectual Property Rights (IPR)

The Steering Group and the SDC recognise the need to ensure reasonable protection of project scientist IPR. The UK SOLAS Data Policy (Annex 1, below) addresses this and is intended to provide an appropriate balance between the protection of data originators' IPR and the potential benefits that may arise via data use by the programme, the wider research community and other interested parties.

Box A4.1 UK SOLAS Data Policy

Introduction

Data collected within UK SOLAS will comply with NERC data policy (www.nerc.ac.uk/data/policy.shtml), to ensure that the data will contribute to a key NERC resource, which will continue to be exploited both scientifically and commercially long after the formal end of the programme. The management of the data collected within the UK SOLAS programme will be the responsibility of the relevant NERC Designated Data Centres (BODC or BADC), and funds have been made available from the UK SOLAS budget to support this activity.

Data management arrangements for the UK SOLAS directed programme are expected to:

- Encourage UK SOLAS dissemination of scientific results
- Protect the rights of the individual scientists
- Treat all the involved researchers equitably
- Ensure the quality of the data in the UK SOLAS data archive.

However, these aims can conflict at times, and it is intended that the programme's Data Management Policy and associated protocols resolve these conflicts fairly. It is recognised that this may not always be achieved to everyone's complete satisfaction; thus individual interests could clash with those of the UK SOLAS programme. To try to meet these aims, all PIs involved in UK SOLAS, in accordance with and on behalf of their Co-Investigators, have agreed to abide by the following conditions as part of the acceptance of their grant awards.

UK SOLAS Data Policy

The following data policy framework applies to UK SOLAS, in line with other NERC thematic/ directed programmes. Subject to Steering Committee overview and any special considerations that may apply to Observatory-based datasets (main issues outlined below), it applies to all UK SOLAS research grants, studentships and contracts:

- a) Data (include present-day observations, model output, data syntheses, data-model syntheses, model codes and information on actual samples) should be lodged with the appropriate Data Centre on acquisition*, together with such metadata as are defined under the UK SOLAS data management plan. [*The time-scale may vary between data types (for example, real-time data could go directly to a data centre) but the overall aim is to keep the time-scale as short as possible and certainly less than 6 months. This is to ensure that data acquired during UK SOLAS are available to the UK SOLAS community within the lifetime of the programme].
- b) Data will be embargoed for 1 year from acquisition, allowing the PI and co-workers to exploit them in the first instance. The metadata will not be embargoed, to allow the wider community to be aware of work being carried out under UK SOLAS and facilitate community building.
- c) With the exception of studentship-related data (see below), data will be made available by the SOLAS Data Centre to the UK SOLAS community after 1 year, and to everyone after 2 years.
- d) In the case of PhD students supported by UK SOLAS, data central to the student's study will not be released by the SOLAS Data Centre for the duration of the studentship without prior agreement between the Data Centre, the UK SOLAS Science Coordinator and the student's supervisor. On cessation of the studentship funding all three parties will consult before allowing wider access to the data relating to the studentship. This is intended to protect a student's intellectual property, but does not imply that he/she has exclusive rights to UK SOLAS data.

- e) Anyone making further scientific use of UK SOLAS data within 3 years of them being lodged at the Data Centre will be required to include the PI and/or co-workers (as appropriate) as co-author/s on any resulting papers, if the PI and/or co-workers so desire.
- f) Any corrections, improvements or amendments to data must be lodged with the appropriate data centre as soon as possible.
- g) PIs making use of UK SOLAS data are responsible for ensuring that the data used in publications are the best available at the time.
- h) Data submitted to the Data Centre must be in the data format agreed between the Data Centre and PI. In addition, all agreed metadata must be supplied to the Data Centre.
- i) During the time when data are restricted from the public domain, no data will be transferred to parties outside the programme without the explicit agreement of the originator. In addition, guidance will need to be sought from the Science Coordinator and the Steering Committee if major data transfers are involved, to avoid compromising the interests of other programme participants.
- j) In the event of dispute, the final decision rests with the UK SOLAS Science Coordinator and Steering Committee
- k) PIs and/or co-workers failing to comply with the UK SOLAS data policy would be subject to appropriate sanctions.
- l) For datasets arising from the UK SOLAS Observatory on Cape Verde, special considerations will apply. Current arrangements are as follows:
 - For observations and short-term experiments requiring limited post processing, DIAC data will be delivered to BADC within 30 days of collection, with unvalidated data potentially available to UK SOLAS researchers in real-time or on a daily basis, dependent on data bandwidth connections on site.
 - Final data from instrumentation requiring extensive post processing, such as GC instruments, will be available 3 months after raw data collection.
 - Final validated data will be lodged for archiving at BADC in NASA AMES format.
- m) Arrangements for Observatory datasets involving international collaborators, and the timescale for public dissemination (via a dedicated web site) are issues that are still under discussion. A review of Observatory data management arrangements will be made after atmospheric measurements and data transfer protocols are routinely in operation.

Box A4.2 UK SOLAS Metadata Protocol

Introduction

The term *metadata* encompasses all the information necessary to interpret, understand and use a given dataset. *Keyword metadata* more particularly apply to information (keywords) that can be used to identify and locate the data that meet the user's requirements (via a Web browser, a Web based catalogue, etc). *Detailed metadata* include the additional information necessary for a user to work with the data without reference back to the data provider. The metadata required by the UK SOLAS programme include both keyword and detailed metadata.

Metadata pertaining to observational data, for example, include details about **how** (with which instrument or technique), **when** and **where** the data have been collected, by **whom** (including affiliation and contact email, address or telephone number) and in the framework of which research project.

In the case of all submitted data, the SDC needs to know how the values were arrived at. The derivation process must be stated: all processing and calibration steps should be described and calibration values supplied. The nature and units of the recorded variables are essential, as well as the grid or the reference system. The SDC requests that as much information as possible about fieldwork instrumentation be included, e.g. serial number, copies of manufacturer's calibration sheets, and recent calibrations, if applicable.

Metadata pertaining to model output should include the name of the model, the conditions of the calculation, the nature of its output, the geographical domain over which the output is defined (when applicable). Specific conditions applying to the model or the experiment may be mentioned. Metadata also include information on the format in which the data are stored, and the order of the variables, to allow potential users to read them. Metadata pertaining to software models include the key points of the theory on which the model is based, the techniques and computational language used, and references.

The following lists the minimum metadata required to accompany data files submitted to the UK SOLAS Data Centre (SDC). Since there is a large range of data types within UK SOLAS, the SDC will liaise with project workers submitting data on a case-by-case basis to ensure that metadata formats are appropriate and to gain additional relevant information as necessary.

Metadata for tables of numbers (observations or model output)

Metadata for numerical information include the following, some of which may be applicable in specific cases only:

- *Information about the experiment*
 - Date when fieldwork, experiment or model simulation started
 - Site or trajectory bounding box or domain limits
 - Platform (e.g. ship, cruise number)
 - Instrumentation (instrument make, model and serial number)
 - Model name.
- *Information about the experimenter(s)*
 - Names, affiliation, contact address, e-mail, telephone number
 - Programme name, research project number.
- *Information about the independent variables (spatio-temporal grid)*
 - Names, units, domain of definition of independent variables
 - Interval values when appropriate.
- *Information about the data, including processing level*
 - Version number
 - Date of last revision
 - Processing level (nature of raw data, derivation method: processing steps, calibrations applied).
 - Nature, name, units, scaling factors of dependent variables.
- *Information about data storage*
 - Number of files of the entire dataset
 - File number of current file.
- *Information about data format*
 - Type of format e.g. ASCII, Excel, Matlab, NetCDF.
- *Additional information*
 - May include particular conditions of experiment or model run, model boundary conditions, article reference, and sources of further information.

Ideally, each data file should include a header containing the metadata. If there is a large amount of information (e.g. description of many processing steps, calibration techniques), then a separate text file can be used instead.

Metadata for software

Metadata pertaining to a model should include the following:

- *Information on the model*
 - Brief description of model general aim
 - Model structure
 - Physical processes involved, including equation set
 - Algorithmic implementation techniques used
 - Spatio-temporal coverage when applying
 - Boundary conditions, including reference(s)
 - Initial conditions, including reference(s)
 - Program language
 - Input nature and format
 - Output nature and format
 - Summary of model validation, or appropriate reference(s)
 - Summary of results from former studies conducted with the model, or appropriate reference(s).
- *Information on the author(s)*
 - Names, affiliation, contact address, e-mail, telephone number.
 - Programme name, research project number.

Metadata relative to software can be included as comments in the top section of the source file or can alternatively be provided as a separate text file.

There is no particular requirement regarding software metadata formatting.

Additional documentation

Any additional documentation on recorded data or images, whether pertaining to a single data file or a whole dataset, that would not find its place into the structures described above (because it does not fall into any described category or because it is too voluminous) may be submitted to the SDC in the form of a text file that will be stored in the UK SOLAS archive documentation directory. These documents may for example include technique description, possible use of the data, study conclusions, etc.

Annex 5**UK SOLAS science providers****A5.1 UK research institutions**

| Institute/Department | Address |
|--|--|
| British Atmospheric Data Centre (BADC) | The British Atmospheric Data Centre, STFC Rutherford Appleton Laboratory, Chilton, nr Didcot OX11 0QX Tel: +44 (0) 1235 44 64 32 |
| British Oceanographic Data Centre (BODC) | British Oceanographic Data Centre, Joseph Proudman Building 6 Brownlow Street, Liverpool L3 5DA, UK Tel: +44 (0) 151 795 4884 |
| Commercial Microbiology Ltd | Commercial Microbiology Ltd, Kettock Lodge: Campus 2, Aberdeen Science Park, Bridge of Don, Aberdeen AB22 8GU Tel: +44 (0)1224 706062 |
| Meteorological Office | Met Office, FitzRoy Road, Exeter EX1 3PB Tel: 0870 900 0100 or +44 (0)1392 885680 |
| National Centre for Atmospheric Science (NCAS) <i>Previously: Distributed Institute for Atmospheric Composition (DIAC)</i> | NCAS, School of Earth and Environment, University of Leeds Leeds LS2 9JT Tel: +44 (0)113 3435158 |
| National Oceanography Centre (NOC) Southampton | National Oceanography Centre, Waterfront Campus, European Way, Southampton SO14 3ZH Tel: +44 (0)23 8059 6666 |
| National Oceanography Centre (NOC) Liverpool | National Oceanography Centre, Joseph Proudman Building 6 Brownlow Street, Liverpool L3 5DA Tel: +44 (0)151 795 4800 |
| NERC Earth Observation Data Acquisition and Analysis (NEODAAS) | NEODAAS-Plymouth, Plymouth Marine Laboratory, Prospect Place The Hoe, Plymouth PL1 3DH; email: info@neodaas.ac.uk |
| North Highland College Environmental Research Institute (ERI) | Environmental Research Institute, North Highland College Castle Street, Thurso, Caithness KW14 7JD Tel: +44(0)1847 8895 74/89 |
| Plymouth Marine Laboratory (PML) | Plymouth Marine Laboratory, Prospect Place, The Hoe Plymouth PL1 3DH Tel: +44 (0)1752 633 100 |
| Scottish Association for Marine Science (SAMS) | SAMS, Scottish Marine Institute, Oban, Argyll PA37 1QA Tel: +44 (0)1631 559000; email: info@sams.ac.uk |
| University of Aberdeen School of Biological Sciences | Institute of Biological and Environmental Sciences, Zoology Building Tillydrone Avenue, Aberdeen AB24 2TZ Tel: +44 (0)1224 272 678 |
| University of Birmingham Geography, Earth & Environmental Sciences | Geography, Earth and Environmental Sciences, University of Birmingham Edgbaston, Birmingham B15 2TT |
| University of Bristol School of Chemistry | School of Chemistry, University of Bristol, Cantocks Close Bristol BS8 1TS Tel: +44 (0)117 9289186 |
| University of Cambridge Department of Chemistry | Department of Chemistry, University of Cambridge, Lensfield Road Cambridge CB2 1EW Tel: +44 (0)1223 336300 |
| University of East Anglia (UEA) School of Environmental Sciences | School of Environmental Sciences, University of East Anglia Norwich NR4 7TJ Tel: +44 (0)1603 592542 |
| University of Essex Department of Biological Sciences | Department of Biological Sciences, University of Essex, Wivenhoe Park Colchester CO4 3SQ |
| University of Leeds Department of Chemistry | School of Earth and Environment, University of Leeds, Leeds LS2 9JT Tel: +44 (0)113 343 6461; email: enquiries@see.leeds.ac.uk |
| University of Leicester Department of Chemistry | Department of Chemistry, University of Leicester, Leicester LE1 7RH Tel: +44(0)116 252 2100 Email: chemistry@le.ac.uk |

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|---|---|
| University of Manchester School of Earth, Atmospheric and Environmental Sciences | School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester M13 9PL Tel: +44(0)161 306 9360 |
| University of Newcastle School of Marine Science and Technology | School of Marine Science and Technology, Armstrong Building, Newcastle University, Newcastle upon Tyne NE1 7RU Tel: +44 (0) 191 222 6718; email: marine@ncl.ac.uk |
| University of Reading Department of Meteorology | Department of Meteorology, University of Reading, Earley Gate, PO Box 243, Reading, RG6 6BB Tel: +44 (0)118 378 8950; email: infosec@met.reading.ac.uk |
| University of Southampton Institute of Sound and Vibration Research | Institute of Sound and Vibration Research, University Road. Highfield Southampton S017 1BJ Tel: +44 (0)23 8059 2294; email: enquiries@isvr.soton.ac.uk |
| University of Southampton School of Ocean and Earth Sciences | School of Ocean and Earth Science, University of Southampton Waterfront Campus, European Way, Southampton SO14 3ZH Tel: +44 (0)23 8059 2011; email: soes@noc.soton.ac.uk |
| University of Warwick School of Life Sciences | School of Life Sciences, Gibbet Hill Campus, University of Warwick Coventry CV4 7AL Tel: +44 (0)24 7657 4251 |
| University of York Department of Chemistry | Department of Chemistry, University of York, Heslington, York YO10 5DD Tel: +44 (0) 1904 432511 |

A5.2 Main non-UK research partner institutions

| Institute/Department | Address |
|--|--|
| Instituto Nacional de Meteorologia e Geofisica (INMG) | Instituto Nacional de Meteorologia e Geofisica, Mindelo, Sao Vicente, Cape Verde |
| Leibniz Institute of Marine Sciences at the Christian-Albrechts Universität zu Kiel | IFM-GEOMAR, Düsternbrooker Weg 20, 24105 Kiel, Germany |
| Leibniz Institute for Tropospheric Research, Leipzig | Leibniz-Institut für Troposphärenforschung, Permoserstraße 15, 04318 Leipzig, Germany |
| Max Planck Institute for Biogeochemistry, jena | Max Planck Institute for Biogeochemistry, PO Box 10 01 64, 07701 Jena Germany |
| Norwegian Meteorological Institute Forecasting Division of Western Norway | Meteorologisk institutt , Allégaten 70, 5007 Bergen, Norway |
| Royal Netherlands Institute for Sea Research (NIOZ) | Nederlands Instituut voor Onderzoek der Zee, PO Box 59, NL-1790 AB Den Burg, The Netherlands |
| University of Colombia: Lamont Doherty Earth Observatory Dept of Earth and Environmental Sciences | Lamont Doherty Earth Observatory, PO Box 1000, 61 Route 9W Palisades, New York 10964-1000, USA |
| University of Hawaii at Manoa Department of Oceanography | Department of Oceanography, University of Hawaii at Manoa, 1000 Pope Road, Honolulu, HI 96822, USA |
| University of Miami Rosentiel School of Marine & Atmospheric Science | Rosentiel School of Marine & Atmospheric Science, Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149 1, USA |
| University of Montana Department of Chemistry and Biochemistry | Department of Chemistry and Biochemistry, University of Montana, Missoula, MT 59812, USA |
| University Pierre and Marie Curie Station Biologique De Roscoff | Station Biologique de Roscoff, Place Georges Teissier, BP74 29682 Roscoff Cedex, France |
| University of Rhode Island Graduate School of Oceanography | Graduate School of Oceanography, Narragansett Bay Campus 215 South Ferry Road, Narragansett, RI 02882, USA |
| CSIC Institute of Marine Research (Instituto Investigaciones Marinas de Vigo) | Instituto de Investigaciones Marinas de Vigo, C/Eduardo Cabello 6, Vigo. Pontevedra. E-36208, Spain |

A5.3 UK SOLAS PIs, Co-Is, researchers and co-workers

Information on host institution applicable to period of UK SOLAS work. This section also serves as detailed acknowledgements to the research community for their direct and indirect inputs to this report. Apologies to individuals who may have been omitted from this list, or whose multiple contributions to UK SOLAS planning and implementation may be insufficiently credited.

| Name | Institution | Role |
|--------------------------|--|-------------------------------------|
| Prof Eric Achterberg | University of Southampton | PI, cruise PS |
| Dr Christopher Adams | University of East Anglia | Co-I; Assistant Science Coordinator |
| Dr Ruth Airs | Plymouth Marine Laboratory | Researcher |
| Dr James Allan | University of Manchester | PI |
| Dr Icarus Allen | Plymouth Marine Laboratory | PI, Co-I |
| Dr Jenny Andrew | British Oceanographic Data Centre | Data manager |
| Dr Steve Archer | Plymouth Marine Laboratory | PI, Co-I |
| Dr Elizabeth Baggs | University of Aberdeen | Student supervisor |
| Dr Alex Baker | University of East Anglia | PI, Co-I |
| Prof Neil Baker | University of Essex | Co-I |
| Philip Balitsky | University of Rhode Island | Cruise participant |
| Dr Stephen Ball | University of Leicester | Co-I |
| Beatriz Barreira | CSIC Instituto Investigaciones Marinas de Vigo | Cruise participant |
| Georgia Bayliss-Brown | University of East Anglia | Assistant Science Coordinator |
| Rachael Beale | Plymouth Marine Laboratory | Student |
| Cory Beatty | University of Montana | Cruise participant |
| Amanda Beesley | Plymouth Marine Laboratory | Cruise participant |
| Prof Stephen Belcher | University of Reading | SC member |
| Dr Thomas Bell | University of East Anglia | Co-I, researcher |
| Dr Liane Benning | University of Leeds | Co-I |
| Ailsa Benton | University of Cambridge | Cruise participant |
| Mr Anthony Bloom | University of Leeds | Student (MRes) |
| Dr William Bloss | University of Birmingham | Co-I |
| Dr Olivier Boucher | UK Met Office | Research partner |
| Tom Breider | University of Leeds | Research student |
| Ester Brito | INMG Cape Verde | Research partner |
| Dr Ian Brooks | University of Leeds | PI, cruise PS |
| Dr Barbara Brooks | University of Leeds | Researcher |
| Ian Brown | Plymouth Marine Laboratory | Cruise participant |
| Dr Juan Brown | British Oceanographic Data Centre | Co-I; SC member |
| Prof John Burrows | University of Bremen | SC member |
| Prof Lucy Carpenter | University of York | PI, Co-I; SC member |
| Prof Ken Carslaw | University of Leeds | PI |
| Dr Howard Cattle | NOC Southampton | SC Chair |
| Dr Rosie Chance | University of York | Researcher |
| Prof Martyn Chipperfield | University of Leeds | Co-I |
| Darren Clarke | Plymouth Marine Laboratory | Cruise participant |
| John Cluderay | Royal Netherlands Inst of Sea Research; NIOZ | Cruise participant |
| Dr Hugh Coe | University of Manchester | Co-I |
| David Coles | University of Southampton | Cruise participant |
| Roisin Commane | University of Leeds | Cruise participant |
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| Denise Cummings | Plymouth Marine Laboratory | Cruise participant |
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| Dr Manuel Dall'Osto | Birmingham | Researcher |

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| Rachel Dunk | University of York | Cruise participant |
| Dr Matthew Evans | University of Leeds | Co-I |
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| Prof. Richard Geider | University of Essex | Co-I |
| Dr Laura Goldson | Plymouth Marine Laboratory | Cruise participant |
| Nicholas Good | University of Manchester | Cruise participant |
| Stephen Groom | Plymouth Marine Laboratory | Remote sensing services |
| Dr Jim Gunson | UK Met Office | Co-I; SC member |
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| Carolyn Harris | Plymouth Marine Laboratory | Cruise participant |
| Prof. Roy Harrison | University of Birmingham | Co-I |
| Stephen Harrison | NOC Southampton | Cruise participant |
| Dr Mark Hart | Scottish Association for Marine Science | Co-I |
| Dr Angela Hatton | Scottish Association for Marine Science | Co-I; SC member |
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| Dr Dwayne Heard | University of Leeds | Co-I |
| Prof Martin Heimann | Max-Planck-Institute for Biogeochemistry | Research partner |
| Prof Hartmutt Hermann | Leibniz-Inst für Troposphärenforschung, Leipzig | Research partner |
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| Dr Ellie Highwood | University of Reading | PI |
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| Dr Frithjof Küpper | Scottish Association for Marine Science | Co-I |

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| Gareth Lee | University of East Anglia | Cruise participant |
| Dr James Lee | University of York | Co-I |
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| Dr Simon O'Doherty | University of Bristol | Researcher |
| Dr David Oram | University of East Anglia | Co-I |
| Lisa Oswald | University of Hawaii | Cruise participant |
| Dr Robin Pascal | NOC Southampton | Co-I |
| Matt Patey | NOC Southampton | Research student |
| Prof Mike Pilling | University of Leeds | Contract PI; SC member |
| Prof John Plane | University of Leeds | Co-I |
| Claire Powell | University of East Anglia | Research student |
| Dr Duncan Purdie | University of Southampton | Co-I |
| Mike Rebezo | University of Miami | Cruise participant |
| Dr Andy Rees | Plymouth Marine Laboratory | Co-I |
| Dr Micha Rijkenberg | NOC Southampton | Researcher |
| Dr Carol Robinson | University of East Anglia | PI; cruise PS |
| Dr Matt Salter | University of Newcastle | Researcher |
| Dr Hendrik Schäfer | University of Warwick | Co-I |

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|-----------------------------|---|--------------------------------------|
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| Rachel Shelley | University of Plymouth | Cruise participant |
| Dr Zongbo Shi | University of Leeds | Researcher |
| Dr Jamie Shutler | Plymouth Marine Laboratory | Remote sensing services |
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| Paul Smith | University of Leeds | Research student |
| Prof Michael Smith | University of Leeds | Co-I; SC member |
| Dr Tim Smyth | Plymouth Marine Laboratory | Co-i |
| Dr Meric Srokosz | NOC Southampton | Co-I |
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| John Stephens | Plymouth Marine Laboratory | Cruise participant |
| Mark Stinchcombe | NOC Southampton | Cruise participant |
| Glenn Tarran | Plymouth Marine Laboratory | Cruise participant |
| Dr Maciej Telsewski | University of East Anglia | Cruise participant |
| Prof Steve Thorpe | Bangor/retired | SC member |
| Dr Gavin Tilstone | Plymouth Marine Laboratory | Cruise participant |
| Dr David Topping | University of Manchester | Co-I |
| Dr Ricardo Torres | Plymouth Marine Laboratory | Co-I |
| Dr Ian Totterdell | UK Met Office | Research partner |
| Dr Sue Turner | University of East Anglia | Co-I |
| Prof Graham Underwood | University of Essex | Co-I |
| Prof Robert Upstill-Goddard | University of Newcastle | PI, Co-I; SC member |
| Prof David Vaughan | University of Manchester | Co-I |
| Prof Doug Wallace | IfM-GEOMAR Kiel | SC member |
| Roisin Walsh | University of Bristol | Cruise participant |
| Dr Brian Ward | Univ of Rhode Island; University of Galway | Research partner, cruise participant |
| Prof Andrew Watson | University of East Anglia | Co-I |
| Alfred Wiedensohler | Leibniz-Inst für Troposphärenforschung, Leipzig | Research partner |
| Dr Paul Williams | University of Manchester | Co-I |
| Dr Phil Williamson | University of East Anglia | Science Coordinator |
| Prof Ursula Witte | University of Aberdeen | Student supervisor |
| Janina Woeltjen | University of East Anglia | Research student |
| Matt Woodhouse | University of Leeds | Research student |
| Malcolm Woodward | Plymouth Marine Laboratory | Cruise logistics coordinator |
| Dr David Woolf | UHI Thurso | Research partner |
| Dr Alexandra Xylouri | University of Leeds | Cruise participant |
| Dr Margaret Yelland | NOC Southampton | PI |
| Dr Dickon Young | University of Bristol | Research partner |
| Dr Henk Zemmerlink | Royal Netherlands Inst of Sea Research; NIOZ | Cruise participant |
| Dr Mike Zubkov | NOC Southampton | Co-I |