A dynamic frontier

Dr Phil Williamson* reports on the latest research at one of our planet's busiest border crossings – the sea surface

Environmental interfaces are often taken for granted, yet can be disproportionately important. Although we mostly see what is on the surface of the Earth, life is near-equally distributed on either side of the air-land interface. At ~360 million km^2, the air-sea interface is nearly three times larger than the air-land boundary, and is arguably the Earth's most important frontier between its dynamic components.

Every day, on average slightly more than 2.5t of CO_2 is taken up by each 1km^2 of ocean, and slightly less than 2.5t of CO_2 is released. The 'average' 1km^2 doesn't actually exist, since the uptake and release are seasonally and geographically separated. Nevertheless, the difference of around 2% between oceanic ingoings and outgoings, together with the net transfer of other greenhouse gases, is crucial in determining the trajectory for future changes in atmospheric composition, and the effects of those changes for the global climate. As Charles Dickens observed, small differences between income and expenditure can result in either happiness or misery.

Crossing boundaries

The traditional organisation of research on a disciplinary basis has, unfortunately, hindered scientific understanding of what exactly is going on at the sea surface, and how the ocean affects the atmosphere and vice versa. Although funding boundaries within environmental science are now much less of a problem in the UK, nearly everywhere else oceanographers and atmospheric scientists are regarded as separate communities, served by different review committees and support schemes. Such separatism slowed the linking of atmospheric and oceanic circulations in global climate models.

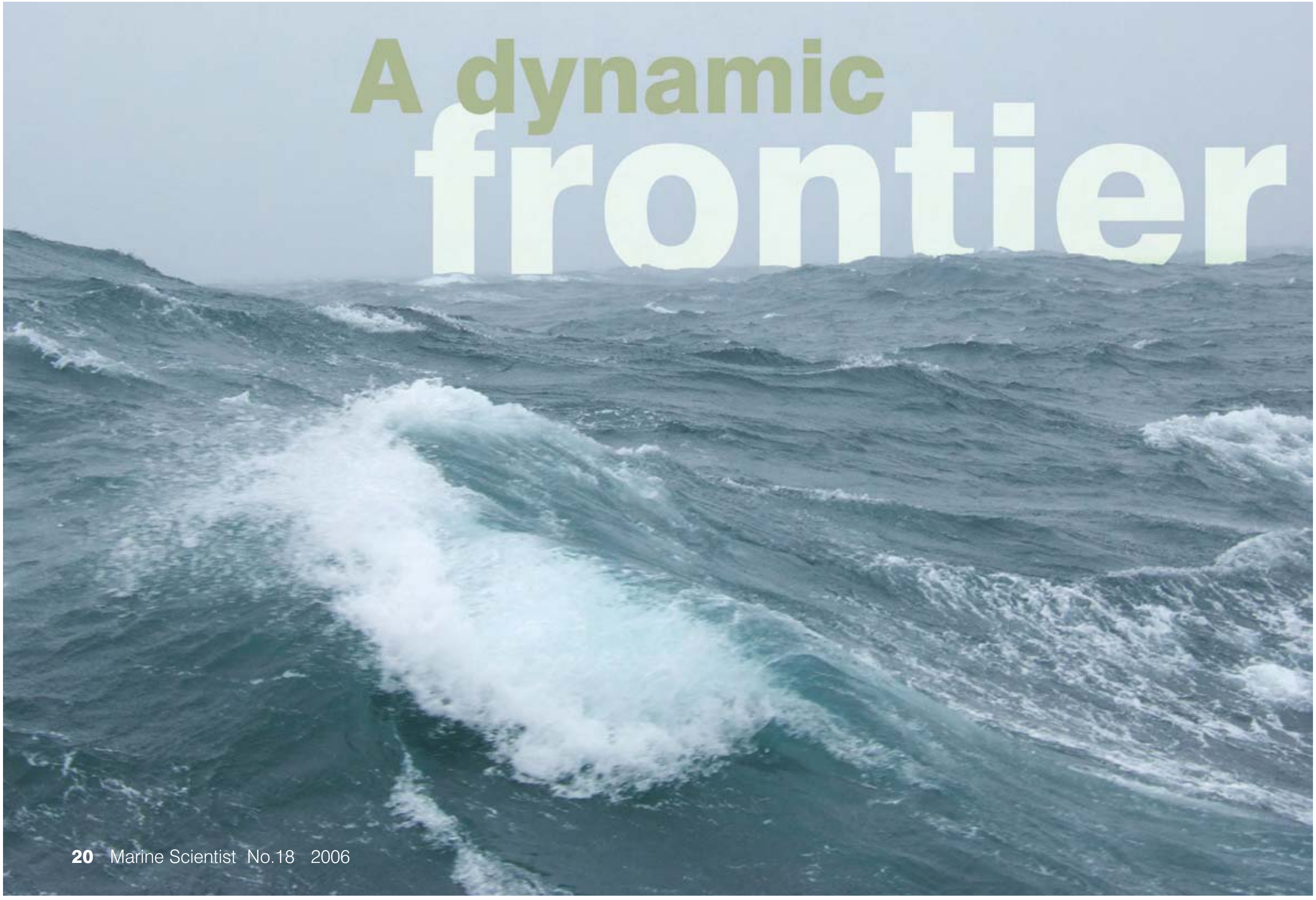
Until a decade or so ago, our lack of understanding of the processes occurring at the ocean-air boundary made it necessary to use arbitrary estimates of heat transferred between these realms to couple the atmosphere to the ocean in global climate models. Without such fixes, the first generation of general circulation models for climate prediction were inherently unstable, even in the absence of additional greenhouse gases produced by human activities.

Fixes and Fluxes

The basic physics of ocean circulation and air-sea energy fluxes is now (mostly) sorted at model grid cells of 10-100km. But the detailed behaviour of waves, turbulent mixing, bubbles, surface films, sea-spray and other momentum-exchange effects occurring at the nanometre to ~10m scale is still very uncertain. While global climate models do not need that level of resolution, they do increasingly require quantitative descriptions of the dominant processes — since they affect the carbon cycle and other links between physics, biology and chemistry that are now being included in Earth system models (see Box on next page).

International efforts

The international Surface Ocean — Lower Atmosphere Study (SOLAS; www.solas-int.org) has

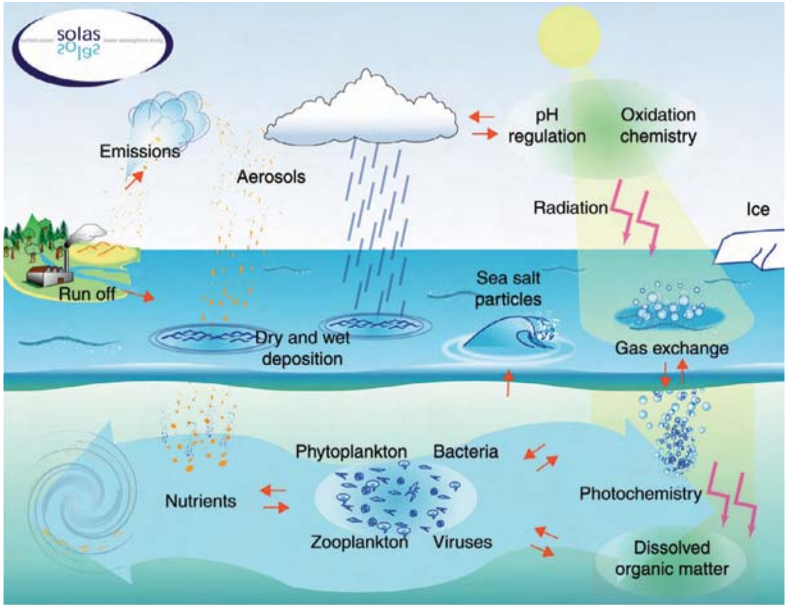


Stormy sea
Janina Woeltjen, UEA

Important biogeochemical interactions between the upper ocean and lower atmosphere include:

- **The production of DMS (dimethyl sulphide) by marine plankton.** After its release from the surface ocean as a gas, DMS is rapidly oxidised to a sulphate aerosol, contributing to cloud formation and the global sulphur cycle.
- **Ocean acidification, resulting from increasing atmospheric CO_2 being absorbed by the ocean.** Even small changes in pH affect the ability of corals, molluscs and other organisms to take up calcium, which they use in forming their exoskeletons. Major changes in biodiversity and ecosystem dynamics now seem inevitable as a result of changes in ocean acidity.
- **Changes in atmospheric nutrient inputs, via dust.** Past changes to the climate have involved links between global temperature, dust delivery to the ocean, marine productivity and the net take-up of carbon by the ocean.
- **Climatic forcing by sea-salt aerosols.** Air-borne droplets of seawater and salt particles affect solar heat absorption and transfer. They trigger chemical reactions, determining the lifetime of ozone and other trace gases in the lower atmosphere.

All these processes are, at present, poorly understood.



Factors affecting exchanges across the air-sea interface Credit: IGBP

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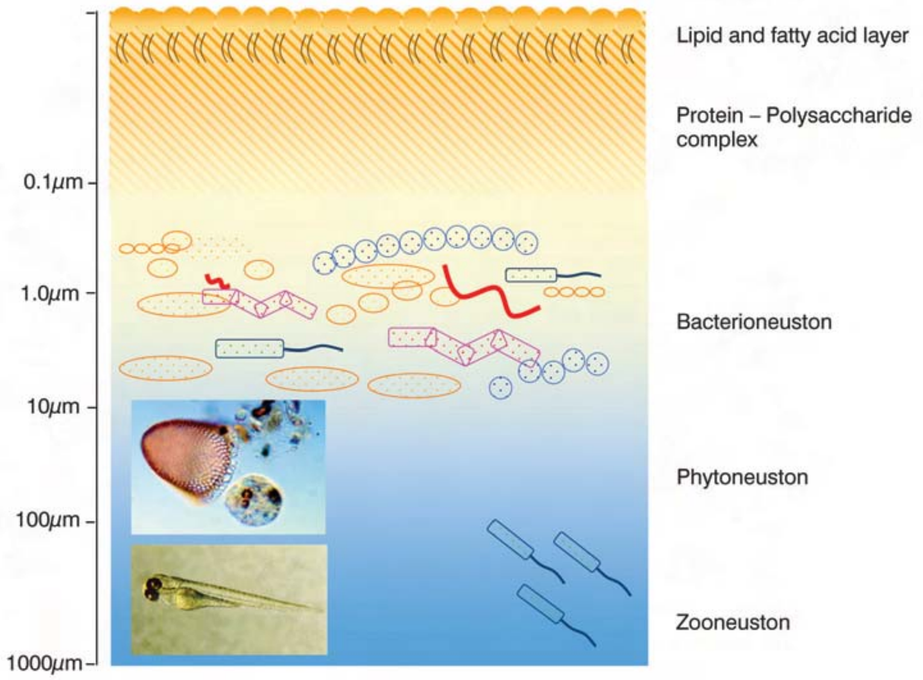
been developed to focus effort on events at the sea surface that provide some of the weakest links in developing realistic scenarios for future global change. SOLAS research covers not only exchanges of climatically-important trace gases across the air-sea interface, but also relevant feedbacks, production processes, transformations and photochemical reactions occurring above and below the waterline. Through the Natural Environment Research Council, the UK hosts the SOLAS International Project Office (at the University of East Anglia), and also supports a major national science contribution – UK SOLAS — currently involving 18 component projects and eight research cruises, at a total cost of around £10.5M over the period 2004-09.

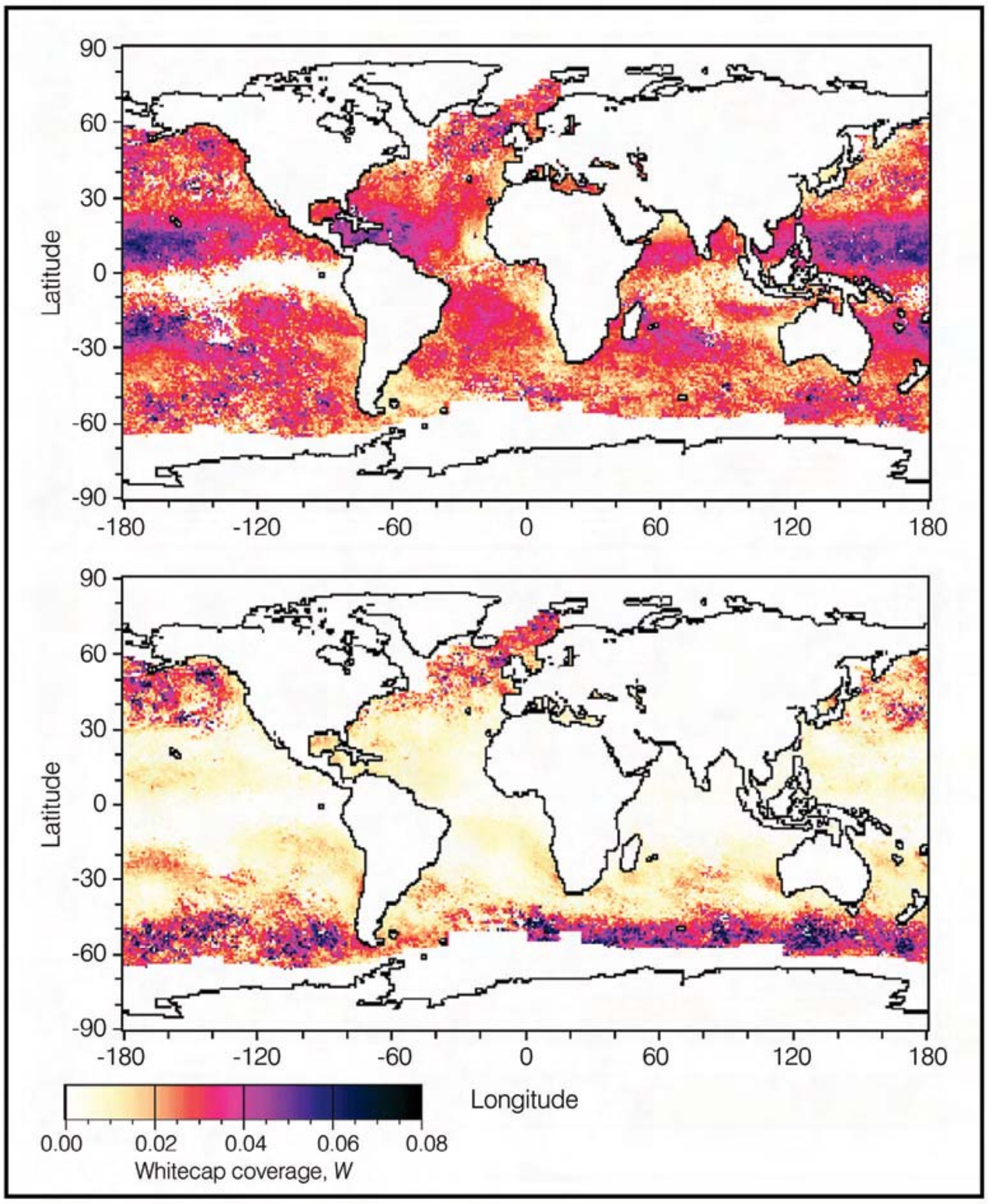
Crucial questions

As part of the recent Challenger Society Conference (Oban, September 2006), UK SOLAS scientists met with colleagues to discuss key unknowns and how they might be tackled. Dr Ian Brooks (University of Leeds) addressed the central question 'How do physical processes control the air-sea exchanges of interest to SOLAS?' His answer was that the movement of key trace gases (such as carbon dioxide, dimethyl sulphide, methane, ammonia and nitrous oxide) and volatile organic compounds (such as methyl iodide, and other organo-halides) is driven by concentration differences across the sea surface, and that transfer from aqueous to gaseous phases (or vice versa) increases with wind speed. Greater wind speeds also produce more sea-salt aerosols, as very fine spray.

But Brooks emphasised that wind isn't the only factor determining transfer rates. Measure-



Conceptual model of the sea surface Credit: M Cunliffe, modified from JT Hardy (1982)



There is currently wide mismatch between global estimates of whitecap coverage from satellite microwave measurements (upper map) and models based on wind-fields (lower map). One – or both – must be wrong. What actually happens is critical for global air-sea gas transfers and sea-salt aerosol production

Credit: MD Anguelova & F Webster (2006) JGR.

ments in the open ocean of gas transfers and aerosol production have shown 5-10 fold variability for the same wind speed. Breaking waves and whitecaps, rather than wind *per se*, seem to be more fundamental drivers — but then it gets complicated. It isn't easy to quantify the highly mobile, 3D features of the sea surface (especially under stormy conditions), nor to work out how they arise, depending on a complex combination of wind stress, fetch and direction; surface films; and near-surface currents and turbulence. Global comparisons between state-of-the-art model predictions and satellite-based estimates of whitecap coverage currently show major mismatches, particularly in the tropics.

Ocean observations

New observation techniques have been developed to improve wind-wave coupling models and our understanding of momentum exchange, whereby the energy of air movements is transferred to water movements. These approaches will be put to the test by Brooks and co-workers in two of the UK SOLAS cruises in the North Atlantic (in November-December 2006, and June-July 2007), deliberately seeking a wide range of physical conditions. The overall aim is to develop more realistic models, using them to scale-up from cruise-based measurements to regional and global estimates — and hence to explore how air-sea transfer rates will change in future climate scenarios.

Living layers

Research on sea surface biology was introduced by Dr Michael Cunliffe (University of Warwick), focusing on the structure and function of microbes in the microlayer — a surface layer around half the thickness of the full-stop at the end of this sentence. Some of the ocean's smallest inhabitants — bacteria, archaea and micro-algae — live in the microlayer, and act as gatekeepers for many air-sea exchanges. Thus their production (or uptake) of gases and volatile organic compounds determines the concentrations of these compounds in this layer of seawater in direct contact with the air. The top 5µm of ocean could, in theory, have a greater effect on atmospheric composition than the 5km of seawater below.

DNA sequencing for bacteria collected from the sea surface has been carried out by Warwick researchers. Preliminary results suggest that these are a distinct population, with a much reduced diversity. In North Sea samples, 9 different strains of bacteria or clone types were found in the surface microlayer (dominated by *Vibrio* spp and *Pseudoalteromonas* spp), compared with 46 clone types from a few centimetres deeper. Further work supported by UK SOLAS will test if this result is consistent over wider geographic scales and seasonal cycles.

Challenging convention

Drs Ruth Airs and Chris Gallienne (Plymouth Marine Laboratory, UK) provided other results that challenged the orthodox oceanographer's view of a homogenous 'upper mixed layer', separated by the thermocline (or thermal boundary layer) from colder, deep ocean waters. Off Northwest Spain on the *RRS Charles Darwin*, they collected a profile of eight samples from the top 2m of the sea, together with surface-film water from the top ~1mm. Such sampling would not be possible in the open ocean under rough sea conditions; fortunately wind speeds were 5 m/s for much of their research cruise.

During the calmer sea-states,

Other activities of the NERC-supported UK SOLAS programme include the recent start-up, with international co-funders, of an ocean-atmosphere observatory on the Cape Verde islands; an Arctic weather-ship time series, at station Mike (with the Norwegian Meteorological Office); ship and aircraft measurements of dust dynamics off NW Africa; and intensive studies of the production and fate of halocarbons, in both open ocean and coastal situations. The fieldwork has been developed in a modelling framework, and in the context of the wider, international SOLAS research effort. The *RSS Charles Darwin* research cruise off NW Spain was funded by Plymouth Marine Laboratory.

significant depth-related changes rapidly developed for many biologically-produced compounds, including chlorophyll and chemicals involved in DMS (dimethyl sulphide) production. These changes were seen as 'enrichment factors', meaning they were present in much higher concentrations in the surface-film water than in other upper-ocean samples. In the case of compounds known as mycosporine-like amino acids (MAAs), the concentration was several hundred times greater at the surface — a feature of particular interest because MAAs serve as UV protectants in both cyanobacteria and microalgae. Intense selective pressures are therefore, presumably, favouring species capable of surviving high light levels in a microhabitat of very small thickness but very large surface area. 'We expected that there might be some differences in the microlayer' said Airs, 'but the effects we found are far greater than have been observed before. It is even possible that microbes in the surface film might be providing a sunscreen for organisms living below'. ◎

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Near-surface sampling device, used to obtain water profiles from the top 2m
Credit: PML