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**OceanFlux Greenhouse Gases Evolution**

**Scientific Impact Assessment Report**

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STSE OceanFlux Greenhouse Gases Evolution

Scientific Impact Assessment Report (SIAR)

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# Introduction

Since the beginning of the industrial revolution humans have released approximately 500 billion metric tons of carbon into the atmosphere from burning fossil fuels, cement production and land-use changes. About 30% of this carbon dioxide (CO2) has been taken up, or absorbed, by the oceans. However the exact amount that the oceans annually absorb (sink) and whether or not this sink is tracking the increasing atmospheric levels is unclear.

Space observations from satellite Earth observation (EO) play an important role in this area of science through providing quasi-synoptic, reproducible and well-calibrated measurements for investigating processes on global scales.

*OceanFlux-Evolution* builds upon the successes of OceanFlux Greenhouse Gases (GHG). *OceanFlux-Evolution* will exploit and build upon the methods and tools developed in OceanFlux Greenhouse Gases to further evaluate the role of the global oceans in cycling carbon, sulphur and nitrogen. We propose to achieve this by bringing together multidisciplinary expertise and capability in:

* Air-sea gas exchange (carbon, sulphur and nitrogen cycles)
* Marine carbonate chemistry (*in situ* and numerical modelling)
* Marine EO (active and passive sensors)
* Algorithm development and validation
* Efficient data processing

A highly skilled and experienced international multidisciplinary team has been constructed under the leadership of Dr Jamie Shutler from the University of Exeter (UoE, UK) who will be the science and management lead.

The main results and outputs from this project will be:

* Validated algorithms for studying air-sea gas interactions using Earth Observation.
* Datasets for the international SOLAS community to access and exploit (with uncertainty estimates).
* A number of key peer reviewed publications.

An end of project workshop and a clear framework for future ESA involvement in SOLAS related studies.

## Purpose and Scope

This is the Scientific Impact Assessment Report (SIAR) (deliverable D170) for the OceanFlux Greenhouse Gases Evolution project. It is intended to satisfy the original requirements for the SIAR as specified by the ESA [SoW]. This document describes the achievements, successes and advancements made by the project. It provides a compendium of the outputs of the project, in the form of papers (published, in review or in draft form) arising from the project. It also supports the Scientific Roadmap by providing a more detailed explanation of the underpinning science.

## Structure of this Report

The report is structured as follows:

* Section 1 (this section) the introduction gives an overview of the project aims and objectives.
* Section 2 describes the scientific impact assessment report.
* Section 3 lists all of the references.

## Contributions

The table below details the people who contributed to this report and the sections that they contributed to.

Table 1 Table of contributions.

|  |  |  |
| --- | --- | --- |
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| Section 2 | Jamie Shutler (UoE) |  |
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## Reference documents

This document makes reference to the documents listed in Table 2.

Table 2: Documents Referred to in this Report

| Reference | Document |
| --- | --- |
| [SoW] | OceanFlux GHG Evolution Statement of Work  **RFQ/3-14125/14/I/LG** |
| [RB] | The OceanFlux GHG Evolution Reference Baseline |
| [DARD] | The OceanFlux GHG Evolution Data Access Requirements Document |
| [ATBDv2] | The OceanFlux GHG Evolution Algorithm Theoretical Basis Document |
| [DUG] | The OceanFlux GHG Evolution Dataset User Guide |
| [ODSv2] | The OceanFlux GHG Evolution Output Data Set version 2 |
| [WKP] | The OceanFlux GHG Evolution workshop proceedings and report |

## Definitions and acronyms

|  |  |
| --- | --- |
| AATSR | Advanced Along Track Scanning Radiometer (ESA instrument) |
| ATBD | Algorithm theoretical basis document |
| AT | Total alkalinity |
| AVHRR | Advanced Very High Resolution Radiometer (NOAA instruments) |
| CARINA | CARbon dioxide IN the Atlantic Ocean |
| CCI | ESA Climate Change Initiative |
| Chl | Chlorophyll-a |
| CMIP5 | Climate Model Inter-comparison Project 5 |
| CO2 | Carbon dioxide |
| DIC | Dissolved inorganic carbon |
| ECMWF | European Centre for Medium-Range Weather Forecasts |
| Envisat | Environmental monitoring satellite |
| EO | Earth observation |
| EOS | Earth Observing System |
| ERSEM  ERI | European Regional Seas Ecosystem Model (and now global oceans ecosystem model) Environmental Research Institute Thurso |
| ESA | European Space Agency |
| EUMETSAT | European Organization for the Exploitation of Meteorological Satellites |
| FTP | File transfer protocol |
| GLODAP | Global Ocean Data Analysis Project |
| GOA-ON | Global Ocean Acidification Observing Network |
| GOOS  HWU | Global Ocean Observing System  Heriot Watt University |
| IPCC | Intergovernmental Panel on Climate Change |
| ITT  IOPAN | ESA invitation to tender  Polish Academy of Sciences |
| KO | Project kick off (November 2012) |
| LDEO | Lamont Doherty Earth Observatory |
| MERIS | Medium Resolution Imaging Spectrometer (ESA instrument) |
| MLD | Mixed layer depth |
| MODIS | Moderate Resolution Imaging Spectrometer (NASA instrument) |
| NASA | National Aeronautics and Space Administration (US) |
| NEMO | Generalised European oceanic physics modeling framework |
| NIVA | Norsk Institutt for Vannforskning, Norway |
| NOAA | National Oceanographic and Atmospheric Administration (US) |
| NSF | US National Science Foundation |
| npCO2 | pCO2 normalized to a standard temperature |
| OA | Ocean acidification |
| OAPS | Ocean Acidification Product Suite |
| OSI-SAF | EUMETSAT Ocean & Sea Ice Satellite Application Facility |
| pCO2 | Partial pressure of CO2 |
| pH | Acidity (or basic) scale |
| PIC | Particulate inorganic carbon |
| PML | Plymouth Marine Laboratory |
| PMP | Project Management Plan |
| POC | Particulate organic carbon |
| RA2 | Radar altimeter 2 (ESA instrument) |
| Rrs | Remote sensing reflectance |
| SCOT | ESA special conditions of tender |
| SMOS | Soil Moisture and Ocean Salinity (ESA satellite) |
| SOCAT | Surface Ocean CO2 Atlas |
| SOM | Self organizing map |
| SOOP | Ship of Opportunity Programme |
| SoW | ESA statement of work |
| SSM/I | Special Sensor Microwave/Imager |
| SSS | Sea surface salinity |
| SST | Sea surface temperature |
| STSE | Support to Science Element |
| Sv | Sverdrups (a unit of volume transport) |
| US  UoE | United States of America  University of Exeter |
| WP | Work package |
| WPD | Work package description |
| WOA | World Ocean Atlas |
| ΔpCO2 | Difference between in-water pCO2 and atmospheric pCO2 |
| ΩA | Aragonite saturation state |

# Introduction to atmosphere-ocean gas fluxes

The ocean and atmosphere are major components of the Earth’s surface, with reactions within and between them controlling many of the properties of the Earth’s system. The air-sea interface represents a vital link between the oceans and the atmosphere by acting as the conduit for the transfer of heat, momentum, aerosols, and gases between the two phases. In particular, the flux of gases such as oxygen (O2), dimethyl sulfide (DMS), carbon dioxide (CO2), and volatile iodocarbons (VICs) across the interface is of fundamental importance to studies of marine productivity, biogeochemical cycles, atmospheric chemistry, Earth’s climate, and human health. Furthermore, the surface exchange of heat and momentum is responsible for the dynamic circulation of the atmosphere and oceans. It is therefore important to quantify contemporary air-sea fluxes of gases and also to provide the understanding necessary to project possible future changes in these fluxes.

Thus far, the air-sea exchange of CO2 has received the most attention amongst marine gases, partly because the net flux of CO2 from the atmosphere to the ocean represents about a third of the annual release of anthropogenic CO2 to the atmosphere (Le Quéré et al., 2013, Sabine et al., 2004) and because this flux is superimposed on a much larger natural flux of CO2 that is cycled annually between the ocean and atmosphere (Watson and Orr, 2003). More recently there has been an increasing awareness that the net flux of CO2 into the ocean is reducing the pH of the world’s surface oceans (Santana-Casiano et al. 2007); the effect of this increasing acidification on marine productivity (Riebesell and Tortell 2011) and possible feedbacks to the atmosphere via alterations to the exchange of climate-active gases across the air-sea interface (Hopkins et al. 2011) are as yet unclear.

In addition to CO2, the ocean also acts as a large reservoir of other biogenic gases with high greenhouse gas warming potentials, particularly nitrous oxide (N2O) and methane (CH4). Currently, concentrations of CH4 and N2O in most of the world’s surface oceans are close to equilibrium with respect to the atmosphere ie they do not act as a significant source or sink (e.g Forster et al. 2009). Instead, the main marine sources of N2O and CH4 are thought to be from upwelling areas and coastal seas (Bange 2006, Kelley and Jeffrey 2002, Upstill-Goddard et al. 2000). However, there is increasing concern that the global marine flux of both of these greenhouse gases to the atmosphere might alter in response to a changing ocean. In addition to an increase in the acidity of the ocean, global warming is likely to result in changes to stratification in the surface ocean and a reduction in O2 concentrations due to solubility effects (Gruber 2011). Production of N2O and CH4 is linked to both nutrient supply (Duce et al. 2008) and to reduced oxygen concentrations (Codispoti 2010, Paulmier et al. 2008); hence the magnitude of the marine source strength of both of these greenhouse gases may alter.

The oceans also act as a source of other biogenic gases that are thought to be important in atmospheric chemistry and hence climate. For example, DMS is produced in almost all of the world’s oceans (Liss et al. 1997) and is emitted to the atmosphere. One of its oxidation products in the troposphere is sulphur dioxide, which can itself be further oxidized to sulphuric acid and then form aerosol sulphate (Plane, 1989). DMS is therefore thought to be a major source of atmospheric acidity, particularly in remote areas away from anthropogenic influence (Keene et al., 1998), and may also act as a source of cloud condensation nucleii (CCN) (Andreae et al., 1995). This link led to the CLAW hypothesis (named after the four authors of Charlson et al., 1987), the idea that phytoplankton may influence global climate. The hypothesis has stimulated much research but remains controversial (Quinn and Bates 2011), and has yet to be successfully tested.

Volatile iodine, bromine and even chlorine containing species are known to be produced in seawater via a combination of biological and photochemical mechanisms (Hughes et al 2011, Nightingale et al. 1995, Richter and Wallace 2004). These gases are believed to play an important role in the oxidation chemistry of the atmosphere, particularly above the remote oceans away from the continents. Brominated compounds (such as dibromomethane and tribromomethane) have been identified as a major source of reactive bromine to the stratosphere, whereas iodinated compounds (such as iodomethane and chloroiodomethane) are generally much shorter lived and play a significant role in tropospheric oxidation chemistry (Carpenter 2003). Bromocarbons are typically thought to be produced in the more productive coastal regions, especially by macroalgae, (Fogelqvist et al 1985) although these areas are relatively minor in size compared to the open oceans. Iodocarbons are believed to be produced across a wide range of marine environments (Carpenter et al. 2012).

A range of other environmentally relevant gases are produced and consumed in seawater for which the air-sea flux is thought to play an important role in modulating their atmospheric concentrations. Examples include oxygenated volatile organic compounds (OVOCs ie low molecular weight alcohols, aldehydes, ketones, and peroxides), isoprene, ammonia, carbon monoxide (Carpenter et al. 2012). These gases are involved in tropospheric and stratospheric oxidation chemistry via the formation and destruction of hydroxyl radicals, ozone, peroxyacetyl nitrate and nitrogen oxides and are thought to be involved in secondary organic aerosol formation (Jacob et al., 2005; Singh et al., 1995).

Finally, the transfer of gases from the ocean to the atmosphere and subsequent deposition to land is an important pathway in biogeochemical cycles. Sulphur is an element that is essential to life and for many years it had been predicted that there that there must be a major source of volatile sulphur from the oceans to the land via the atmosphere in order to balance the loss from the land via weathering (Eriksson, 1959). The sea to air flux of DMS is therefore important in re-supplying the sulphur to the terrestrial environment where it is essential for plant growth (e.g. Zhao et al., 1999). Furthermore, about 30% of the world’s population is thought to be at risk for iodine deficiency disorders that impair mental development due to low levels of iodine in soils away from coastal areas. The main source of iodine to land is as volatile iodine compounds produced in the ocean and transferred to the atmosphere across the air–sea interface.

Therefore understanding the pathways, sources, sinks, and impact of these gases on the Earth’s climate system is essential for monitoring climate and predicting future scenarios. Space observations have an important role to play in such research through providing quasi-synoptic, reproducible and well-calibrated measurements for driving, parameterising and enhancing climate models (e.g. Battrick*,* 2006). Indeed, Earth observation is potentially the only way of reliably monitoring global air-sea fluxes.

The flux of gases between the atmosphere and the ocean (air-sea) is controlled by wind speed, sea state, sea surface temperature and surface processes including any biological activity (figure 1). The air-sea flux of gases can in some cases be inferred indirectly, but most flux estimates depend on a calculation using a standard bulk air-sea gas transfer equation e.g. Takahashi et al.,(2009). For each gas, this calculation depends upon both measurements of the gas concentration in both the surface ocean and the lower atmosphere and upon formulae and resulting “transfer coefficients” that describe the “rate constants” for transfer across the sea surface.

|  |
| --- |
|  |
| Figure 1 The air-sea flux of gases and the various processes that are believed to control these fluxes (Jayne Doucette, Woods Hole Oceanographic Institution, and Wade McGillis, Columbia University). |

It is extremely difficult to measure directly air-sea gas fluxes in-situ as the fluxes are generally much lower than over land and corrections for ship’s motion have to be made. Currently direct measurements of air-sea fluxes of CO2 (e.g. McGillis et al. 2001), DMS (e.g Huebert et al. 2004), ozone (Helmig et al. 2012) and some OVOCS (Yang et al. 2013) have been reported in the literature. As a result, the magnitude of the air-sea flux of a particular gas has usually been calculated from the product of the concentration difference between the two phases that drives the flux and the gas transfer coefficient.

Concentrations of relevant compounds in seawater and air are relatively routine to determine although, as most gases of interest are produced and/or destroyed within the ocean or atmosphere, the challenge is to capture the spatial and temporal variability in their concentrations fields. Rather less progress has been made in understanding the basic mechanisms behind air-sea gas transfer rates and in being able to measure and parameterise gas transfer rates in the field, although laboratory/field experiments and theory suggest that a range of variables influence air-sea gas transfer (see Figure 1).

The simplest model of air-sea gas transfer is the two-film model (Liss and Slater, 1974; Whitman, 1923). The model assumes that the main bodies of air and water are well-mixed such that the concentration of any particular gas is uniform in both phases. This does not mean that the gas is inert but that the rate of mixing is greater than the rate of any production or destruction process that may be operating. Transfer through the two thin films is relatively slow and requires molecular diffusion. Note that this simple model also assumes that any production or destruction processes that may occur in the thin films are slow compared to molecular diffusion. The net flux of gas through one film is then given by the product of the concentration difference across the film that drives the flux and a kinetic (or rate) term known as the gas transfer coefficient (*k*). The gas transfer coefficient is also known as a piston velocity, or more commonly transfer velocity, as it has dimensions of length per unit time. Given the assumptions above, then

*F = kw* (*Cwi-Cw*) *= ka* (*Ca – Cai*) (1)

Where *Ca*is the concentration in the bulk air, *Cw* is the concentration in the bulk seawater and *Cai* and *Cwi* represent the concentrations at the interface in the gas and liquid phases respectively. If the gas obeys Henry’s Law then the relationship between *Cai* and *Cwi* is given by,

*Cai = H/Cwi* (2)

It can then be shown that

*F = Kw (Ca/H – Cw) = Ka (Ca – H.Cw)* (3)

where 1/*Kw =* 1/*kw +* 1/*H.ka*

and 1/*Ka = H/kw +* 1/*ka.* (4)

The flux of gas across the air-water interface is therefore given by the concentration difference between the bulk air and bulk seawater (*ΔC*) after correcting for solubility (i.e. the degree of disequilibrium between the two phases) and an overall transfer velocity that is itself dependent on the individual transfer velocities in the air and water.

In practice, for most sparingly soluble gases,( i.e. high *H*) the rate limiting step (or main resistance) is transfer through the water side thin film as molecular diffusion through water is considerably slower than in air. Examples of these gases are O2, CO2, methane (CH4), methyl bromide (CH3Br) and sulfur hexafluoride (SF6). In these cases, the term 1/*kw* therefore dominates and equation 3then simplifies to the more familiar expression for estimating air/sea gas fluxes i.e.

*F = kw (Ca/H – Cw)* (5)

For some gases that either react with water, or are highly soluble, the 1*/H.ka* term dominates. These gases include hydrogen chloride, sulfur dioxide (SO2), water and probably ammonia (NH3). In these cases the main resistance to transfer is in the air-side thin film and *Kw* can be approximated by the term *H.ka*.

So, CO2 is water-side controlled and so by using equation 5 the air-sea flux can be determined using a single gas transfer velocity, *k*:

*F = k (αw pCO2w - αs pCO2a )* (6)

where *α* is the solubility of the gas in water at depth (*αw*) and at the sea skin (*αs*), *pCO2* is the partial pressure of CO2 in the water (*pCO2w*) and air (*pCO2a*) and *k* is the gas transfer or piston velocity.

# Introduction to the Scientific Impact Assessment Report

Recognising the societal challenges of rising CO2 levels, and ever-increasing satellite remote-sensing measurement capabilities, in 2006 the International Surface Ocean and Lower Atmosphere Study (SOLAS) and the European Space Agency (ESA) formed a collaboration to exploit satellite observations for atmosphere-ocean exchange research. By combining satellite observations with in-situ and modelling approaches, the resulting OceanFlux projects, specifically those focused on Greenhouse Gases, have made significant scientific advances and increased our understanding of atmosphere-ocean exchange. Moreover, these projects continue to develop new capabilities for space based ocean-monitoring, helping to expand the frontiers of atmosphere-ocean exchange research.

This Scientific Impact Assessment Report (SIAR) is based around a number of publications produced by the OceanFlux Greenhouse Gases (GHG) Evolution project. Each of the subsections below describe one aspect of the scientific work and refer to journal publications which are either in-preparation, in-review or published. OceanFlux GHG Evolution was focussed primarily on interfacial transfer rates and thus upon concentrations on either side of the sea surface, and air-sea transfer coefficients. The significance of OceanFlux GHG Evolution extends more broadly for example to the global marine cycling of carbon. The position of OceanFlux GHG Evolution in the broader context of marine carbon cycling is illustrated in Figure 2. A wide range of scientific activities are relevant to marine carbon cycling. For example, the international SOLAS program spans the interface taking in processes also in the lower atmosphere and in the upper ocean. The international IMBER program overlaps with SOLAS in the upper ocean but is primarily concerned with marine biogeochemical cycles and ecosystems including the exchange of carbon between the upper ocean and the deep ocean.



Figure 2. A schematic of marine carbon cycling indicating the scope of OceanFlux GHG and of the large international programs SOLAS and IMBER.

The specific focus of OceanFlux GHG Evolution is encapsulated in the air-sea gas flux equation (see Figure 2), but there are aspects of OceanFlux GHG Evolution touch upon and link to the deep ocean. The determination of the global fluxes, F, of carbon dioxide and other greenhouse gases is the primary objective and to reach that goal, the various parameters on the right-hand side of the equation must first be determined. OceanFlux GHG expends much of its effort in the determination of the transfer velocity, k. Transfer is primarily a result of stirring at and near the interface by the wind, but the process is complicated by wave physics generally, by breaking waves and bubbles at high wind speeds and by surfactants and convection at low wind speeds. The net flux, F, is also proportional to the concentration difference across the interface, written in Figure 2 as the product of solubility, α, and partial pressure, p, at either side of the interface. OceanFlux GHG Evolution depends on measurements and archiving of partial pressures external to the project. In particular, it relies on SOCAT to provide measurements of oceanic partial pressure of carbon dioxide. OceanFlux GHG Evolution has devoted more of its own resource to the determination of solubilities (dependent on temperature and salinity) and to the correct calculation of the concentration difference, in consolidating methodologies for studying this exchange and identifying and characterising uncertainties encapsulated in these methodologies and calculations.

The outputs are ordered in this document by category, starting with papers on the background and processing methods, followed by several outputs pertaining to the transfer velocity and then uncertainties. Several “special cases” follow later, looking at the particular effects of temperature gradients, rain, and sea ice on air-sea fluxes. Finally a few “associated papers” are reported; the chosen outputs do not directly arise from the project, but are relevant, involve project personnel and are contemporary to the project.

# Air-sea fluxes of CO2 in the presence of temperature and salinity gradients

**Publication**

Woolf DK, Land PE, Shutler JD, Goddijn-Murphy LM, Donlon CJ (2016), On the calculation of air-sea fluxes of CO2 in the presence of temperature and salinity gradients, *Journal of Geophysical Research-Oceans*, doi: 10.1002/2015JC011427

**Abstract**

The presence of vertical temperature and salinity gradients in the upper ocean and the occurrence of variations in temperature and salinity on time scales from hours to many years complicate the calculation of the flux of carbon dioxide (CO2) across the sea surface. Temperature and salinity affect the interfacial concentration of aqueous CO2 primarily through their effect on solubility with lesser effects related to saturated vapor pressure and the relationship between fugacity and partial pressure. The effects of temperature and salinity profiles in the water column and changes in the aqueous concentration act primarily through the partitioning of the carbonate system. Climatological calculations of flux require attention to variability in the upper ocean and to the limited validity of assuming “constant chemistry” in transforming measurements to climatological values. Contrary to some recent analysis, it is shown that the effect on CO2 fluxes of a cool skin on the sea surface is large and ubiquitous. An opposing effect on calculated fluxes is related to the occurrence of warm layers near the surface; this effect can be locally large but will usually coincide with periods of low exchange. A salty skin and salinity anomalies in the upper ocean also affect CO2 flux calculations, though these haline effects are generally weaker than the thermal effects.

**Status: Published**

# Global climatology of fCO2 (version 1.0)

**Publication**

Goddijn-Murphy, L.M., D.K. Woolf, P.E. Land, J.D. Shutler, C.J. Donlon (2015), The OceanFlux Greenhouse Gases methodology for deriving a sea surface climatology of CO2 fugacity in support of air-sea gas flux studies, *Ocean Science*, 11, 519-541, doi:10.5194/os-11-519-2015

**Abstract**

Climatologies, or long-term averages, of essential climate variables are useful for evaluating models and providing a baseline for studying anomalies. The Surface Ocean CO2 Atlas (SOCAT) has made millions of global underway sea surface measurements of CO2 publicly available, all in a uniform format and presented as fugacity, *f*CO2. As *f*CO2 is highly sensitive to temperature, the measurements are only valid for the instantaneous sea surface temperature (SST) that is measured concurrently with the in-water CO2 measurement. To create a climatology of *f*CO2 data suitable for calculating air–sea CO2 fluxes, it is therefore desirable to calculate *f*CO2 valid for a more consistent and averaged SST. This paper presents the OceanFlux Greenhouse Gases methodology for creating such a climatology. We recomputed SOCAT's *f*CO2 values for their respective measurement month and year using monthly composite SST data on a 1° × 1° grid from satellite Earth observation and then extrapolated the resulting *f*CO2 values to reference year 2010. The data were then spatially interpolated onto a 1° × 1° grid of the global oceans to produce 12 monthly *f*CO2 distributions for 2010, including the prediction errors of *f*CO2 produced by the spatial interpolation technique. The partial pressure of CO2 (*p*CO2) is also provided for those who prefer to use *p*CO2. The CO2 concentration difference between ocean and atmosphere is the thermodynamic driving force of the air–sea CO2 flux, and hence the presented *f*CO2 distributions can be used in air–sea gas flux calculations together with climatologies of other climate variables.

**Status: published**.

# The open source FluxEngine toolbox (version 2)

During the lifetime of the OceanFlux GHG Evolution project the first open source FluxEngine journal paper has been published and version 1 of the software was released on github. The software has now been extended to include other gases, arctic capability and other additional functionality. The two papers described below give an overview of these advancements.

In addition, the FluxEngine toolbox is **now being used** and extended **within two UK government funded research projects**, and **will be used within** **three further (funded) research projects** (two EU and one UK). It is also being used within **3 PhD research projects** (two UK and one in Poland).

Data generated by the FluxEngine have now been used within **4 published journal** papers.

**Publication**

Shutler JD, Land PE, Piolle J-F, Woolf DK, Goddijn-Murphy L, Paul F, Girard-Ardhuin F, Chapron B, Donlon CJ (2016), FluxEngine: a flexible processing system for calculating atmosphere-ocean carbon dioxide gas fluxes and climatologies, *Journal of Atmospheric and Oceanic Technology*, doi: 10.1175/JTECH-D-14-00204.1.

**Abstract**

The air–sea flux of greenhouse gases [e.g., carbon dioxide (CO2)] is a critical part of the climate system and a major factor in the biogeochemical development of the oceans. More accurate and higher-resolution calculations of these gas fluxes are required if researchers are to fully understand and predict future climate. Satellite Earth observation is able to provide large spatial-scale datasets that can be used to study gas fluxes. However, the large storage requirements needed to host such data can restrict its use by the scientific community. Fortunately, the development of cloud computing can provide a solution. This paper describes an open-source air–sea CO2 flux processing toolbox called the “FluxEngine,” designed for use on a cloud-computing infrastructure. The toolbox allows users to easily generate global and regional air–sea CO2 flux data from model, in situ, and Earth observation data, and its air–sea gas flux calculation is user configurable. Its current installation on the Nephalae Cloud allows users to easily exploit more than 8 TB of climate-quality Earth observation data for the derivation of gas fluxes. The resultant netCDF data output files contain >20 data layers containing the various stages of the flux calculation along with process indicator layers to aid interpretation of the data. This paper describes the toolbox design, which verifies the air–sea CO2 flux calculations; demonstrates the use of the tools for studying global and shelf sea air–sea fluxes; and describes future developments.

**Status: published.**

**Publication**

Ashton, I., Shutler, J. D., Land, P. E., Nightingale, P. N., Rees, A. P., Piolle, J. F., Woolf, D. K., Goddijn-Murphy, L., Paul, F., Girard-Ardhuin, F., Chapron, B., Donlon, C. J., (in-draft) Recent Updates to the FluxEngine: Improving ocean-atmosphere carbon dioxide gas fluxes and climatologies

**Abstract**

The role of the oceans in taking up atmospheric carbon dioxide (CO2) and other greenhouse gases is a critical part of the climate system and a major influence on oceanic biogeochemical processes. Estimations of sea-air gas flux are a critical component in understanding the global carbon cycle. More accurate estimations at higher resolution can improve our understanding of this process and support more detailed predictions of the impact of rising CO2 levels on our global climate system. The FluxEngine is an open source processing toolbox that allows users to easily generate global and regional air-sea CO2 flux estimates from model, in-situ and Earth observation data. Verification of the system and the range of configurations available have been described in Shutler et al., (2105). This paper directly follows on, describing capabilities of the toolbox not previously discussed and providing illustrative examples of FluxEngine in use. Specifically, operating the system with different data sets is demonstrated using Surface Ocean CO2 Atlas (SOCAT) and in-situ data sets. The geographical flexibility of the system is shown using results from running the calculations on a high-resolution Arctic grid, reported for different areas within the Arctic region. The paper also includes a demonstration of updates that support the estimation of air-sea flux of other gases, including Nitrous Oxide and Methane. While the case studies presented offer valuable information in their own right, the paper overall demonstrates the flexibility of the toolbox and the breadth of its potential contribution to sea-air gas flux research.

**Status: in-draft.**

# Impact of rain on global and regional air-sea gas fluxes

**Publication**

Ashton IG, Shutler JD, Land PE, Woolf DK, Quartly GD (2016), A Sensitivity Analysis of the Impact of Rain on Regional and Global Sea-Air Fluxes of CO2. PLoS ONE 11(9): e0161105. doi:10.1371/journal.pone.0161105

**Abstract**

The global oceans are considered a major sink of atmospheric carbon dioxide (CO2). Rain is known to alter the physical and chemical conditions at the sea surface, and thus influence the transfer of CO2 between the ocean and atmosphere. It can influence gas exchange through enhanced gas transfer velocity, the direct export of carbon from the atmosphere to the ocean, by altering the sea skin temperature, and through surface layer dilution. However, to date, very few studies quantifying these effects on global net sea-air fluxes exist. Here, we include terms for the enhanced gas transfer velocity and the direct export of carbon in calculations of the global net sea-air fluxes, using a 7-year time series of monthly global climate quality satellite remote sensing observations, model and in-situ data. The use of a non-linear relationship between the effects of rain and wind significantly reduces the estimated impact of rain-induced surface turbulence on the rate of sea-air gas transfer, when compared to a linear relationship. Nevertheless, globally, the rain enhanced gas transfer and rain induced direct export increase the estimated annual oceanic integrated net sink of CO2 by up to 6%. Regionally, the variations can be larger, with rain increasing the estimated annual net sink in the Pacific Ocean by up to 15% and altering monthly net flux by > ± 50%. Based on these analyses, the impacts of rain should be included in the uncertainty analysis of studies that estimate net sea-air fluxes of CO2 as the rain can have a considerable impact, dependent upon the region and timescale.

**Status: published.**

# Reconciling methodologies in Arctic air-sea gas fluxes

Polar seas are areas of deep water formation, where surface carbon is transported to the deep ocean and as such, are particularly important to the global carbon cycle. The Arctic Ocean comprises ~4% of the worlds oceans by area and ~1% by volume. Nevertheless, it is thought to contribute 5-14% to the total oceanic sink for anthropogenic CO2 of (Bates and Mathis, 2009). The most common approach to estimating air-sea gas flux in areas affected by sea ice is to assume that sea ice acts as a cap (or partial cap) on air-sea gas transfer. Where sea ice occurs in a study area, the estimate of the gas flux is generally linearly scaled based on the percentage of free ice within each computational cell, with the rate of flux retained as equivalent to the open ocean (land et al., 2013; Takahashi et al., 2009). However, in-situ measurements in areas of partial ice-cover have identified CO2 fluxes 1–2 orders of magnitude higher than those expected under similar conditions in the open ocean (Else *et al.* 2011), suggesting that the linear scaling of open ocean conditions is providing an underestimate. More recent work to parameterise the gas transfer processes within areas effected by ice appear (Loose et al., 2015) to be at odds with recent published measurements in such areas (Butterworth et al., 2016). Here we have used EO and the FluxEngine to identify where these apparently different viewpoints actually overlap and under what conditions they actually agree.

**Publication**

Ashton, I., Shutler, J. D., Chapron, B., Woolf, D., et al., (in-draft) Reconciling estimations of air-sea gas exchange in areas of sea ice.

**Abstract**

Conventional estimations of air–sea gas exchange become inaccurate in areas affected by sea ice, which represents a source of uncertainty in global estimations of CO2 budgets. The presence of ice floes changes the effect of surface winds on the local wave conditions, modifies the properties of surface waters and alters surface turbulence and hence gas exchange. Natural variability in the physical properties of sea-ice, coupled with limited in-situ data mean that there is no consensus as to the effect of these processes on air-sea gas exchange and the subsequent impact on global estimates is unknown. Here, we review the methods and measurements available and rectify apparent discrepancies in the literature through examination of uncertainties. The analysis draws on recent, high resolution, satellite derived data for the polar seas surface ocean conditions to give spatial estimates from each approach and to draw tentative conclusions as to the potential impact of sea ice on regional estimations of air-sea CO2 exchange.

**Status: in-draft**

# Impact of hurricanes on air-sea CO2 gas fluxes

There are two main effects related to hurricanes that can influence ocean CO2 concentrations, and in turn air-sea CO2 fluxes: wind speed, and changes in mixed layer depth. All changes alter the intensity of air-sea CO2 fluxes, albeit in different ways. A change in wind speed has a direct effect on the flux (the direction of which can vary temporally), whilst the upwelling of colder, deeper waters lead to sea surface temperature (SST) changes, altering both surface ocean pCO2 and the flux rate. A significant change in the mixed layer depth also brings material to the surface that is normally held away by stratification, e.g. carbon and nutrients. Figure 3 shows the large region of the north Atlantic that are impacted each year by Hurricanes. Figure 4 shows the difference between atmospheric pCO2 and the in water pCO2 (DpCO2) in the latitudinal regions effected by hurricanes for the year 2000. From this you can see the hurricanes tracks that move across the Atlantic and through time will have differing effects on the localised airs-sea fluxes (due to the differing signs of the DpCO2). Figure 4 shows that hurricanes do not always form in areas of supersaturated in water pCO2.

We determined the monthly background sea-air CO2 flux using a climatology of surface ocean pCO2, e.g. Takahashi et al., (2009). For the Atlantic basin, we then estimated the direct change of sea-air CO2 flux due to hurricane high wind events, and the indirect effect of the hurricane cold wake’s decrease in temperature. These results are shown in Figure 5 for each component of the flux calculation. This shows that the effect that hurricanes have on the climatological mean sea-air CO2 flux varies significantly from year to year. Finally, we determined the change in nutrient concentrations due to the entrainment of deep water by hurricanes, estimated from the cold-wakes’ temperature reductions; these nutrient entrainments also show significant inter-annual variability. The results illustrate that you cannot simply extrapolate the results from a small number of hurricanes to those across a complete time series. The importance of each component (DpCO2, wind and cold wake) also varies between years, so all components should be included in any analysis of the impacts of hurricanes on air-sea CO2 gas fluxes.

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| **Figure 3** Number of hurricanes per location in the North Atlantic between 1851-2015 (output from the Atlantic Hurricane database, HURDAT2). |

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| **Figure 4** DpCO2 in the longitudal regions where hurricanes occur for year 2000, derived from from the Takahashi et al., (2009) climatology of air-sea gas fluxes. |

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| E:\documents\U_a_meetings\2016_09_Air_sea_flux_Brest\Schuster_et_al\delta_flux_3.png |
| **Figure 5** Interannual change in air-sea flux of CO2 (in PgC yr-1) due to DpCO2 (blue), wind speed (black) and cold wake (red). |

# Global inter-annual variability

**Publication**

Rödenbeck, C., Bakker, D. C. E., Gruber, N., Iida, Y., Jacobson, A. R., Jones, S., Landschützer, P., Metzl, N., Nakaoka, S., Olsen, A., Park, G.-H., Peylin, P., Rodgers, K. B., Sasse, T. P., Schuster, U., Shutler, J. D., Valsala, V., Wanninkhof, R., and Zeng, J. (2015) Data-based estimates of the ocean carbon sink variability – first results of the Surface Ocean pCO2 Mapping intercomparison (SOCOM), *Biogeosciences*, 12, 7251-7278, doi:10.5194/bg-12-7251-2015.

**Abstract**

Using measurements of the surface-ocean CO2 partial pressure (*p*CO2) and 14 different *p*CO2 mapping methods recently collated by the Surface Ocean *p*CO2 Mapping intercomparison (SOCOM) initiative, variations in regional and global sea–air CO2 fluxes are investigated. Though the available mapping methods use widely different approaches, we find relatively consistent estimates of regional *p*CO2 seasonality, in line with previous estimates. In terms of interannual variability (IAV), all mapping methods estimate the largest variations to occur in the eastern equatorial Pacific. Despite considerable spread in the detailed variations, mapping methods that fit the data more closely also tend to agree more closely with each other in regional averages. Encouragingly, this includes mapping methods belonging to complementary types – taking variability either directly from the *p*CO2 data or indirectly from driver data via regression. From a weighted ensemble average, we find an IAV amplitude of the global sea–air CO2 flux of 0.31 PgC yr−1 (standard deviation over 1992–2009), which is larger than simulated by biogeochemical process models. From a decadal perspective, the global ocean CO2 uptake is estimated to have gradually increased since about 2000, with little decadal change prior to that. The weighted mean net global ocean CO2 sink estimated by the SOCOM ensemble is −1.75 PgC yr−1 (1992–2009), consistent within uncertainties with estimates from ocean-interior carbon data or atmospheric oxygen trends.

**Status: published.**

# Reconciling empirical and mechanistic models of air-sea gas transfer

**Publication**

Goddijn-Murphy L, Woolf DK, Callaghan AH, Nightingale PD, Shutler JD (2015), A reconciliation of empirical and mechanistic models of the air-sea gas transfer velocity, *Journal of Geophysical Research-Oceans*, doi:10.1002/2015JC011096

**Abstract**

Models of the air-sea transfer velocity of gases may be either empirical or mechanistic. Extrapolations of empirical models to an unmeasured gas or to another water temperature can be erroneous if the basis of that extrapolation is flawed. This issue is readily demonstrated for the most well-known empirical gas transfer velocity models where the influence of bubble-mediated transfer, which can vary between gases, is not explicitly accounted for. Mechanistic models are hindered by an incomplete knowledge of the mechanisms of air-sea gas transfer. We describe a hybrid model that incorporates a simple mechanistic view—strictly enforcing a distinction between direct and bubble-mediated transfer—but also uses parameterizations based on data from eddy flux measurements of dimethyl sulphide (DMS) to calibrate the model together with dual tracer results to evaluate the model. This model underpins simple algorithms that can be easily applied within schemes to calculate local, regional, or global air-sea fluxes of gases.

**Status: published.**

# Towards a calibrated model of bubble mediated air-sea gas transfer

There are a number of approaches that are clear routes to developing a calibrated bubble mediated transfer parameterisation. The first OceanFlux-GHG project assessed the potential of relying on a wave model to provide whitecapping data and this is one approach that is provided within the FluxEngine. However, this first approach was not included in the OceanFlux-GHG project ensemble runs as the outputs appeared to be excessively high. A second approach is to tune the existing un-calibrated model (direct + bubble mediated) so that its output approaches those of a large *in situ* dataset of gas transfer velocity measurements. This work is described in the previous section (section 11) of this report.

A third option, and the one described here is to find a more accurate parametric approach and to find the EO data that can support that approach.

Tom Bell from PML provided his co-incident in situ CO2 and DMS flux data that were collected in the North Atlantic in 2011. An overview o these in situ data is shown in Figure 6a. Figure 6b-e show the relationship of the bubble mediated component of these data (kCO2 minus kDMS) to that of an example whitecapping parameterisation and different functions of wind speed at 10m (U10). Based on this analysis an initial parameterisation of the bubble mediated gas transfer was derived by the OceanFlux evolution team as kb = 0.175 U102 (R2 = 0.63, N=72, Figure 6e). This initial parameterisation assumes that the bubble mediated gas transfer is zero for DMS. Tom Bell and his collaborators have since submitted their own analysis of these data for review (Bell et al., 2017) and their results and methods are consistent with these initial results. The OceanFlux analysis and that of Bell et al., supports the premise that a calibrated bubble-mediated gas transfer (kb) parameterisation is achievable using parameters that are retrievable using satellite remote sensing. i.e. through exploiting remotely sensed observations of wind-speed or whitecapping. However, it is noted that this approach is still using a proxy (e.g. wind speed) for describing the turbulence and exchange at the water surface, rather than a direction observation of the exchange.

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| **a** | **b** |
| **c** | **d** |
| **e** | |
| **Figure 6** In situ bubble mediated transfer for multiple gases. Wind speed at 10m (U10) on the x axes is in ms-1 and gas transfer kDMS or kCO2 is in cm hr-1 .a)coincident in situ sea-air fluxes of CO2 and DMS provided by Tom Bell at PML (red is CO2, blue is DMS) and their relationship to b) whitecapping, c) U10, d) U102 and e) an initial parameterisation of bubble mediated transfer against U10 derived from these data (kb = 0.175 U102). | |

# Effect on air-sea gas fluxes of gas transfer parameterisation choice (N. Atlantic, Arctic)

**Publication**

Wrobel, I., Piskozub, J. (2016) Effect of gas-transfer velocity parameterization choice on air–sea CO2 fluxes in the North Atlantic Ocean and the European Arctic, Ocean Science, 12, 1091-1103, doi:10.5194/os-12-1091-2016.

**Abstract**

The oceanic sink of carbon dioxide (CO2) is an important part of the global carbon budget. Understanding uncertainties in the calculation of this net flux into the ocean is crucial for climate research. One of the sources of the uncertainty within this calculation is the parameterization chosen for the CO2 gas-transfer velocity. We used a recently developed software toolbox, called the FluxEngine (Shutler et al., 2016), to estimate the monthly air–sea CO2 fluxes for the extratropical North Atlantic Ocean, including the European Arctic, and for the global ocean using several published quadratic and cubic wind speed parameterizations of the gas-transfer velocity. The aim of the study is to constrain the uncertainty caused by the choice of parameterization in the North Atlantic Ocean. This region is a large oceanic sink of CO2, and it is also a region characterized by strong winds, especially in winter but with good in situ data coverage. We show that the uncertainty in the parameterization is smaller in the North Atlantic Ocean and the Arctic than in the global ocean. It is as little as 5 % in the North Atlantic and 4 % in the European Arctic, in comparison to 9 % for the global ocean when restricted to parameterizations with quadratic wind dependence. This uncertainty becomes 46, 44, and 65 %, respectively, when all parameterizations are considered. We suggest that this smaller uncertainty (5 and 4 %) is caused by a combination of higher than global average wind speeds in the North Atlantic (> 7 ms−1) and lack of any seasonal changes in the direction of the flux direction within most of the region. We also compare the impact of using two different in situ *p*CO2 data sets (Takahashi et al. (2009) and Surface Ocean CO2 Atlas (SOCAT) v1.5 and v2.0, for the flux calculation. The annual fluxes using the two data sets differ by 8 % in the North Atlantic and 19 % in the European Arctic. The seasonal fluxes in the Arctic computed from the two data sets disagree with each other possibly due to insufficient spatial and temporal data coverage, especially in winter.

**Status: published.**

# Ensemble estimates of global sea-air CO2 fluxes

**Publication**

David K. Woolf, Jamie D. Shutler, Lonneke Goddijn-Murphy, Mark Warren, Ian Ashton, Craig J. Donlon, Phil D. Nightingale, Peter E. Land, Ricardo Torres, Bertrand Chapron, Jean-Francois Piolle, Sylvain Herledan, Jenny Hanafin, Fanny Girard-Ardhuin, Fabrice Ardhuin, John Prytherch, Ben Moat, Margaret Yelland, Ute Schuster, Andy Watson (in-draft) The contemporary air-sea flux of carbon dioxide, II Scenario and ensemble estimates of global fluxes in the OceanFlux climatology.

**Abstract**

A global flux of CO2 of ~80 Pg C yr-1 is exchanged between atmosphere and ocean annually with a net flux in recent years of ~2 Pg C yr-1 into the oceans. While other methods are available to estimate global and basin-scale fluxes, regional and sub-seasonal estimates are only practical through application of an air-sea flux equation that requires concentrations in atmosphere and ocean and estimates of transfer velocity. Uncertainties arise throughout the calculation and the propagation of these errors through to a final flux estimate of flux. Various data sets (in situ, Earth Observation and modelling) and algorithms are used to compute air-sea gas flux. Fluxes are calculated at monthly and one-degree resolution for a reference year of 2010, but the analysis presented here focuses on annual fluxes for the global oceans. A large number of calculations are presented representing different scenarios and formal ensembles. The results suggest relatively high uncertainty in global and regional carbon dioxide flux. For a reference year of 2010, we estimate a net global flux from air to sea of 2.0 Pg C yr-1, but with a high bias uncertainty. An optimistic interpretation of existing uncertainty in gas transfer velocities leads to a bias uncertainty of ~0.5 Pg C yr-1, while a more pessimistic interpretation implies a bias uncertainty > 1 Pg C yr-1. Similarly, a set of simulated upper ocean CO2 fields created by a bootstrap method are also used to study the uncertainty in flux. Some ensemble members suggest a large uncertainty in global net flux. Some of the scenarios and ensemble members may be contradicted by global and regional estimates by other methods, but they cannot be easily dismissed directly.

**Status: In draft.**

# Physical processes at the ocean surface and its borders with the atmosphere and sea ice

**Publication**

Shutler JD, Quartly GD, Donlon CJ, Sathyendranath S, Platt T, Chapron B, Johannessen JA, Girard-Ardhuin F., Nightingale PD, Woolf DK, Høyer JL (2016), Progress in satellite remote sensing for studying physical processes at the ocean surface and its borders with the atmosphere and sea ice, *Progress in Physical Geography*, 40: 215-246, doi:10.1177/0309133316638957

**Abstract**

Physical oceanography is the study of physical conditions, processes and variables within the ocean, including temperature–salinity distributions, mixing of the water column, waves, tides, currents and air–sea interaction processes. Here we provide a critical review of how satellite sensors are being used to study physical oceanography processes at the ocean surface and its borders with the atmosphere and sea ice. The paper begins by describing the main sensor types that are used to observe the oceans (visible, thermal infrared and microwave) and the specific observations that each of these sensor types can provide. We then present a critical review of how these sensors and observations are being used to study: (i) ocean surface currents, (ii) storm surges, (iii) sea ice, (iv) atmosphere–ocean gas exchange and (v) surface heat fluxes via phytoplankton. Exciting advances include the use of multiple sensors in synergy to observe temporally varying Arctic sea ice volume, atmosphere–ocean gas fluxes, and the potential for four-dimensional water circulation observations. For each of these applications we explain their relevance to society, review recent advances and capability, and provide a forward look at future prospects and opportunities. We then more generally discuss future opportunities for oceanography-focused remote sensing, which includes the unique European Union Copernicus programme, the potential of the International Space Station and commercial miniature satellites. The increasing availability of global satellite remote-sensing observations means that we are now entering an exciting period for oceanography. The easy access to these high quality data and the continued development of novel platforms is likely to drive further advances in remote sensing of the ocean and atmospheric systems.

**Status: published.**

# List of all publications

The OceanFlux GHG Evolution scientific publications are listed below. Authors who are project team members are shown in bold.

## Journal publications (published)

1. **Woolf DK, Land PE, Shutler JD, Goddijn-Murphy LM, Donlon CJ** (2016), On the calculation of air-sea fluxes of CO2 in the presence of temperature and salinity gradients, *Journal of Geophysical Research-Oceans*, doi: 10.1002/2015JC011427
2. **Goddijn-Murphy, L.M., D.K. Woolf, P.E. Land, J.D. Shutler, C.J. Donlon** (2015), The OceanFlux Greenhouse Gases methodology for deriving a sea surface climatology of CO2 fugacity in support of air-sea gas flux studies, *Ocean Science*, 11, 519-541, doi:10.5194/os-11-519-2015
3. **Ashton IG, Shutler JD, Land PE, Woolf DK**, Quartly GD (2016), A Sensitivity Analysis of the Impact of Rain on Regional and Global Sea-Air Fluxes of CO2. PLoS ONE 11(9): e0161105. doi:10.1371/journal.pone.0161105
4. **Shutler JD, Land PE, Piolle J-F, Woolf DK, Goddijn-Murphy L, Paul F, Girard-Ardhuin F, Chapron B, Donlon CJ** (2016), FluxEngine: a flexible processing system for calculating atmosphere-ocean carbon dioxide gas fluxes and climatologies, *Journal of Atmospheric and Oceanic Technology*, doi: 10.1175/JTECH-D-14-00204.1.
5. **Shutler JD**, Quartly GD, Donlon CJ, Sathyendranath S, Platt T, **Chapron B**, Johannessen JA, **Girard-Ardhuin F.**, **Nightingale PD**, **Woolf DK**, Høyer JL (2016), Progress in satellite remote sensing for studying physical processes at the ocean surface and its borders with the atmosphere and sea ice, *Progress in Physical Geography*, 40: 215-246, doi:10.1177/0309133316638957
6. Wrobel, I., **Piskozub, J.** (2016) Effect of gas-transfer velocity parameterization choice on air–sea CO2 fluxes in the North Atlantic Ocean and the European Arctic, Ocean Science, 12, 1091-1103, doi:10.5194/os-12-1091-2016.
7. **Goddijn-Murphy L, Woolf DK**, Callaghan AH, **Nightingale PD, Shutler JD** (2015), A reconciliation of empirical and mechanistic models of the air-sea gas transfer velocity, *Journal of Geophysical Research-Oceans*, doi:10.1002/2015JC011096
8. Rödenbeck, C., Bakker, D. C. E., Gruber, N., Iida, Y., Jacobson, A. R., Jones, S., Landschützer, P., Metzl, N., Nakaoka, S., Olsen, A., Park, G.-H., Peylin, P., Rodgers, K. B., Sasse, T. P., **Schuster, U., Shutler, J. D**., Valsala, V., Wanninkhof, R., and Zeng, J. (2015) Data-based estimates of the ocean carbon sink variability – first results of the Surface Ocean pCO2 Mapping intercomparison (SOCOM), *Biogeosciences*, 12, 7251-7278, doi:10.5194/bg-12-7251-2015.

## Journal papers (in-draft)

9. **David K. Woolf, Jamie D. Shutler, Lonneke Goddijn-Murphy, Mark Warren, Ian Ashton, Craig J. Donlon**, **Phil D. Nightingale, Peter E. Land**, Ricardo Torres, **Bertrand Chapron, Jean-Francois Piolle, Sylvain Herledan**, Jenny Hanafin, **Fanny Girard-Ardhuin**, Fabrice Ardhuin, John Prytherch, Ben Moat, Margaret Yelland, **Ute Schuster, Andy Watson, Piskozub, J.** (in-draft) The contemporary air-sea flux of carbon dioxide, II Scenario and ensemble estimates of global fluxes in the OceanFlux climatology

1. Ashton, I., Shutler, J. D., Chapron, B., Woolf, D., et al., (in-draft) Reconciling estimations of air-sea gas exchange in areas of sea ice.
2. Ashton, I., Shutler, J., et al., (in-draft) FluxEngine: updates and extensions to a handle arctic regions, non-regular grids, N2O and CH4.

## Technical report

12. **Quilfen, Y., Chapron, B., Girard-Ardhuin, F.** (2016) Remote sensing derived upwelling estimates, Ifremer Technical report.

## Conference proceedings or abstracts

13. Wrobel, I., **Piskozub, J.** (2016) Comparing momentum and mass (aerosol source function) fluxes for the North Atlantic and the European Arctic using different parameterizations, *EGU General Assembly*, Vienna.

14. Wrobel, I., **Piskozub, J.** (2016) Why different gas flux velocity parameterizations result in so similar flux results in the North Atlantic?, *EGU General Assembly*, Vienna.

15. **Shutler, J. D.** (2016) The ESA OceanFlux Greenhouse Gases Evolution project, *Air-sea Gas fluxes: progress and future prospects*, Brest, France.

16. **Shutler, J.D. Land, P. E.,** Findlay, H., **Girard-Ardhuin, F., Piolle, J.-F.** Reul, N., **Chapron, B.,Quilfen, Y,** Salisbury, J., Vandemark, D., Bellerby, R., Bhadury, P., Sabia, R., **Fernandez, D** (2016) The other CO2 problem from a different angle: Studying Ocean Acidification using satellite Earth observation, *Air-sea Gas fluxes: progress and future prospects*, Brest, France.

17. **Woolf, D.K.** (2016) The importance and challenges of regional scale analyses, *Air-sea Gas fluxes: progress and future prospects*, Brest, France.

18. **Goddijn-Murphy L.** (2016) The retrieval of air-sea gas transfer velocity from space using the hybrid model, *Air-sea Gas fluxes: progress and future prospects*, Brest, France.

19. **Ashton, I.** (2016) Gas exchange in polar seas, *Air-sea Gas fluxes: progress and future prospects*, Brest, France.

20. **Nightingale, P. D.** (2106) Measurements of air-sea gas transfer in upwelling filaments off Mauritania, *Air-sea Gas fluxes: progress and future prospects*, Brest, France.

21. Wrobel, I., **J. Piskozub.** (2015) Regional scale climatology of global change carbon dioxide flux on the ocean surfacefor North Atlantic and the Arctic. *IUGG General Assembly, June 22-July 2 2015,* Prague, the Czech Republic.

# News and media

The ESA OceanFlux project has faced many barriers since its inception, including theoretical understanding, technological complexities and an understanding of the full role that satellites can play in this important area of climate science. The significant advances that the project has made over the last 5 years means that we are now in an excellent position to demonstrate the advantages that satellites can provide. Therefore, we have now begun exposing our work to the general public. Our first press release was linked to the publication of the FluxEngine open source toolbox and some initial results that were included in the publication that focused on European seas. ESA’s press release resulted in BBC news article (figure 7) and 10 other news outlets, 1 blog, 4 twitter feeds, 2 facebook pages. A summary of the coverage is here: <https://www.altmetric.com/details/4969088#score>

ESA press release: Sentinel 3 and the ocean carbon conundrum

<http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-3/Sentinel-3_and_the_ocean_carbon_conundrum>

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| **Figure 7** The BBC news article ‘How European waters soak up carbon dioxide’ can be found here: <http://www.bbc.co.uk/news/science-environment-35654938> |

# Scientific workshop

The second “air-sea gas flux: Progress and Future prospects’ science workshop was held during 6-9 September 2016 in Brest, France.

The Scientific workshop was organized by the OceanFlux Greenhouse Gases Evolution project as a forum to bring the international and interdisciplinary air-sea gas flux scientific community together to present recent advances, report results from key initiatives and importantly to identify new goals, challenges and opportunities. The key focal point of the workshop was the synergistic use of models, in situ and remote sensing data and techniques for studying, and furthering this important area of climate research.

**106 participants from 18 countries and 5 continents** (figure 8) attended the four day workshop. Importantly much of the work and advances that were presented here in 2016 were identified as opportunities and challenges at the first workshop that was held 3 years ago in 2013.

The workshop was a great success.

The open discussion sessions within the workshop allowed areas of scientific importance to be debated and the identification of new opportunities. The discussions during and at the end of the workshop have provided clear avenues for future work that fit both within the International SOLAS plans and aims, and are within the scope of work that the European Space Agency are keen to support.

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| **Figure 8** The workshop participants on day 3. |

Here is a synopsis of the outcomes and conclusions from the discussion sessions. The full report and minutes from the discussions are within the [WKP] deliverable:

It is clear that the understanding of air-sea exchange in extreme conditions (cyclones, hurricanes, polar lows) has advanced, but more work needs to be done to fully characterize their impact. The potential of a multi-agency experiment towards creating fiducial reference measurements (e.g. building upon the approach of the Atlantic Meridional Transect (AMT) for EO cruise this year) collecting standardized remote sensing parameters from ships and aircraft (comparable to those observed from space) and air-sea fluxes and exchanges of multiple gases would provide the basis for the advancement beyond simple proxies for characterizing air-sea gas exchange. Previous efforts (e.g. SO Gasex) and formal structures (including the Galway Statement on Atlantic Ocean Cooperation, an EU – Canada – US Research alliance) illustrate that a multi-agency experiment could be possible. Continued cross-disciplinary collaboration, including the sharing of software tools, practices, observations, ancillary data and further workshops (e.g. every 3 years) is also needed and encouraged. The complexities of polar air-sea exchange research illustrates an opportunity for remote sensing to help consolidate and identify complementarities between existing divergent approaches in polar regions. The continued development of a "marine carbon observing system" that incorporated remote sensing was strongly endorsed by delegates. New novel areas where remote sensing could be used in synergy with in situ and models to further the science were also discussed (e.g. microwave sensors onboard vessels during cruises, drone/satellite data to investigate the footprint and origin of eddy covariance flux observations, exploitation of atmospheric potential oxygen methods and links with remote sensed primary production). Whilst the impact of large river systems, such as the Amazon and those in the Arctic, as yet to be fully evaluated in terms of air-sea gas exchange and appears to be an area where remote sensing approaches could play a major role.

# When the oceans breathe in (Royal Society Summer exhibition)

As a direct result of the Scientific Workshop and based on initial discussions held at the workshop, a bid was submitted to the Royal Society Summer exhibition to have an OceanFlux and oceans focussed exhibition.

The Royal Society summer exhibition is held each year, lasts 7 days and annually attracts thousands of visitors. The 7 day programme also includes invite only events for government and policy makers, providing an ideal opportunity to promote the work and advances of the OceanFlux GHG Evolution project. Here is the summer exhibition website: <https://royalsociety.org/science-events-and-lectures/summer-science-exhibition/>

This bid was submitted by the project team and Dr Helen Czerski. Dr Cerski is a media facing scientist and broadcaster based at the University College London and she has previously presented and/or been involved in >20 scientific focussed television programmes since 2012.

The bid was designed to begin to address the need to promote the oceans and the importance of monitoring their health to the wider public and governmental policy makers. Below is the main text from the proposal to the Royal Society that gives an introduction to the subject, the reasoning for its importance and what the planned exhibit would include. The team are awaiting the outcome of this bid.

**When the oceans Breathe in**

The global carbon cycle is being altered by human activities through the unprecedented production of carbon dioxide (CO2) from fossil fuel combustion. Improved understanding of the global sources, pathways, and sinks of CO2 is essential for monitoring and projecting future climate. Within the carbon cycle the oceans play a vital role, absorbing about a third of anthropogenic CO2 emissions and limiting the rise in atmospheric CO2 concentrations. However, this net flux of CO2 into the oceans reduces the pH of the world’s surface oceans (known as ocean acidification), the effects of which on marine life, marine food-web and ultimately the human food supply remain unclear.

Earth’s vast oceans are breathing. Gases like carbon dioxide and oxygen are constantly exchanged with the atmosphere, and the process is invisible but gigantic. Some regions of the ocean breathe in, while others breathe out. How and where this happens matters for our climate and how it may be changing.

When you look down on our planet from space, the oceans dominate the view. But it’s easy for most of us to forget that this vast blue expanse exists. The oceans are the engine of our planet’s system. It’s a topic that isn’t discussed very often, but it’s becoming essential knowledge for everyone. Stewardship of both our oceans and our atmosphere is now a major challenge for humanity. The breathing process is the link between these two vast reservoirs, and to rise to the challenges of the future we need to understand it.

This exhibit would tell the story of how and where our ocean breathes, and why it matters. The oceans produce about half our planet’s oxygen. But they also take up around a third of the extra carbon dioxide that humans are putting into the air, acting as a storehouse that slows down the greenhouse effect. It’s not a free lunch. That extra carbon dioxide is changing our oceans, and we don’t know whether the oceans will continue to take up CO2 in the same way in the future.

The ocean is a fantastically varied environment. There are storms and periods of flat calm. There are gigantic drifting regions full of life, and almost empty deserts. All of this affects how and when the oceans breathe. An increase in storms or a warming of the ocean could have different effects in different places. This exhibit will allow the public to explore the consequences of those changes for themselves, and to appreciate that although the oceans are vast, they’re not too big for humans to change them. We hope that when the public leave the exhibit, they’ll be able to look out over the seas and appreciate the invisible breathing processes happening right in front of their eyes.

We will develop a visual computer simulation of the ‘Oceans breathing’ that the public can interact with via a large screen and tablets, based on ESA OceanFlux research. Visitors will be able to tweak aspects of the simulation (temperatures, storms, CO2 emissions etc.) and see the consequences for oceanic CO2 uptake and humanity, including fictional news headlines. Visitors will see how increasing CO2 emissions can affect the oceans, marine life, temperatures on Earth and ultimately our lives.

We will construct an interactive wave tank to illustrate the small-scale processes responsible for gas uptake by the ocean. This will use a colour reactive liquid so you can see how waves and bubbles drive gas into the water. A bubble camera will allow the public to see the exchange up close. Interactive scale models of existing satellites, daily satellite images and an instrument measuring CO2 throughout the day will be displayed We will develop a website version of ‘Oceans breathing’ that visitors can explore online. It will illustrate how increasing atmospheric CO2 affects the oceans, marine life and the temperature on Earth.

ESA will provide an exciting video tour of ESA facilities and satellite development, including time-lapse video of a satellite being built.

We can provide an animation that explains how satellites are used to study and monitor atmosphere-ocean gas exchange (<http://www.esa.int/spaceinvideos/Videos/2016/02/Carbon_flux>).

We will create global animations of satellite images showing the seasonal progression in the oceans and how the movement of gases between the oceans and atmosphere changes through time.

The team putting this exhibit together has an ideal combination of experience and skills, and we are confident that we can work together to make a very memorable exhibit, on an important topic that is very rarely talked about.

Over the last 5 years Jamie Shutler has been involved in, and helped drive, ESA’s vision to support and accelerate our knowledge of atmosphere-ocean interaction. He leads the ESA OceanFlux project and has previously worked with the majority of the team. Helen Czerski, is an active researcher in this area and a regular science presenter for the BBC and frequently writes and talks about the ocean. The overall shape of the exhibit will be guided by her experience. Andy Watson (FRS) and Craig Donlon have extensive high-level experience of talking about these issues to policy-makers. Adrian Callaghan studies ocean wave breaking in the laboratory and at sea, a process that is the driving force behind bubble-mediated gas exchange in the global oceans. In January 2017, he will begin a 2-year Royal Society Eric Shooter Fellowship and participation in the Summer Science Exhibition will provide an excellent opportunity to showcase Royal Society funded research related to atmosphere-ocean exchange. Phil Nightingale leads atmosphere-ocean exchange research at Plymouth Marine Laboratory and has previously taken part in the Summer Science Exhibition.

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