



ESA Support to Science Element

**OceanFlux Greenhouse Gases Evolution**

**Reference Baseline**

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**Deliverable: D-60**

**FINAL**

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STSE OceanFlux Greenhouse Gases Evolution

Reference Baseline

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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 of the Reference Baseline

This is the Reference Baseline (RB) (deliverable D60) for the Ocean Flux Greenhouse Gases Evolution project. It is intended to satisfy the original requirements for a Reference Baseline specified by the ESA [SoW]. Primary *in situ* data sources, EO products, model outputs and model systems are identified. Candidate regions of interest follow largely from the location of available data. Approaches to manipulating and integrating data streams are considered. The proposed features of products and the methods to achieve them are discussed. The delivery of products through the web portal will be outlined.

The purpose of this report is to:

* Present a balanced view of existing understanding to the calculation carbonate parameters from space.
* Assess the reasonable expectation for the project (particularly the achievable outputs).
* Provide an analysis of requirements for the project in several sub-headings
  + Clarifications of fundamental understanding that must underpin reliable and accurate outputs
  + The data required to arrive at suitable parameterizations
  + Data, EO products and model outputs required as inputs to model systems
* Compile and analyse data and model output relevant to the project
  + Data type
  + Methodology
  + Accuracy
  + Temporal and Spatial Coverage
  + Availability and Restrictions on Use
* Outline the tasks involved in completing the project satisfactorily
  + Identify regions of interest.
  + Identify specific products.
  + Identify delivery mechanisms.
  + Identify routes for outreach.

## 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 gives an overview of atmosphere-ocean gas exchange theory and implications.
* Section 3 gives a summary project overarching requirements and tradeoffs.
* Section 4 gives an overview of the planned outputs and products.
* Section 4 gives the data requirements for planned outputs and products.
* Section 6 gives the requirements for the technical implementation.
* Section 7 details the requirements for the project website.
* Section 8 gives the requirements for the project outreach.
* Section 9 gives the requirements on the schedule
* Section 10 gives the mapping of the requirements to the [SoW].
* Section 11 contains the references.
* Section 12 in the annex containing the literature review.

## 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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| Section 10 | Jamie Shutler (UoE) |  |
| Section 11 | Jamie Shutler (UoE) |  |
| Section 12 | Jamie Shutler (UoE) | All. |

## 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] | This document (Reference Baseline) |
| [RB-Annex2] | Literature review. |

## 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 exchange

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.

# Summary of OceanFlux GHG Evolution requirements

The requirements presented in this document have come from the following sources:

1. The original statement of work [SoW].
2. Internal discussions within the OceanFlux GHG Evolution project team and the ESA technical officer.
3. The submitted project proposal (response to the original ESA RFQ).

**The decisions made within this [RB] are guided by the main literature review that is in [RB-Annex2] of this document.**

## ESA’s high level objectives

ESA’s requirements were summarized in the [SoW]. ESA’s high-level objectives for OceanFlux GHG Evolution are to:

***Generate and demonstrate the impact of improved estimates of air-sea CO2 and other ocean-atmosphere gas fluxes using EO data for use by SOLAS and other air-sea gas transfer scientific communities.***

## Key requirements

The key requirements are listed in the original [SoW]. Below is a copy of these requirements:

1. **Extend the *OceanFlux Evolution* FluxEngine** to include other gasses including at least DMS, O2 and N2O and create V1.0 climatologies for each gas.
2. **Work together with the Surface Ocean CO2 Climatology (SOCAT) project** [RD-7] team to help develop and apply SOCAT V3.0 data within the FluxEngine to generate improved global and regional estimates of CO2 flux.
3. Work together with the international community to **maximise the number of ocean and atmosphere pCO2 data available to the Flux Engine** in difficult areas including coastal, sea ice and open ocean upwelling areas, the Mediterranean Sea, the Black Sea and Arctic Ocean and other areas relevant to the OceanFlux Evolution project.
4. **Implement the NOAA-COARE model [e.g. RD-37] and other relevant air-sea gas transfer models** within the FluxEngine, validate the new algorithm(s) using sensitivity experiments/validation analysis and produce new gas flux climatologies based on the new algorithms.
5. **Improve and validate parameterisations of bubble mediated gas transfer** (i.e. solidify the scientific case) and implement the result into the FluxEngine including:
   1. Specification of latitudinal variation in the parameterisation,
   2. Investigate the impact of seawater foam-thickness on the parameterisation,
   3. Investigate the impact of breaking waves on the parameterisation,
   4. Investigate the role and impact of other relevant processes to the parameterisation.
6. **Investigate the role and impact of wind/wave parameters on the spread of direct and indirect gas transfer method k curves at moderate to high wind speed**. *i.e* can fetch/wind/Hs etc explain the spread of experimental data used to define k curves?
7. **Develop a strategy and implement method(s) within the Flux Engine to properly handle significant local/regional events** that are not properly represented in spatio-temporal average gas flux products including:
   1. upwelling events (coastal and equatorial),
   2. strong extra-tropical cyclones (ETC) and Tropical Cyclones (TC),
   3. significant biological blooms,
   4. diurnal SST variability
   5. precipitation
   6. other local/regional events of significance to air-sea gas transfer.
8. **Convene an *OceanFlux Evolution* scientific user group** to assist the project during validation and exploitation of the output final products..
9. **Design, implement and publish the results form a series of well-defined “Crowd Sourced” scientific ensemble experiments** using the FluxEngine system to better understand and improve knowledge of uncertainties in air sea gas transfer products.
10. **Produce and investigate global gas flux estimates and trends using the FluxEngine system** by fully exploiting the natural variability captured by EO data (as specified in [REQ-7]) over a 10-year (or longer) time series.
11. **Produce and investigate regional gas flux estimates and trends using FluxEngine system in the North Atlantic Ocean** (where ocean pCO2 are more prolific)
12. **Define and implement methods that quantify uncertainty in all *OceanFlux Evolution* output products.**
13. **Produce and investigate regional gas flux estimates using the FluxEngine system in the in the Arctic Ocean** (characterised by new open water/fetch conditions).
14. **Conduct a thorough scientific analysis of resulting gas flux products** generated by the project and submit peer-review journal articles to relevant scientific journals. The project shall target the needs of the SOLAS community and the potential Intergovernmental Panel for Climate Change (IPCC) Assessment Review.
15. **Develop a suite of diagnostic metrics and assessments** that can be used to monitor improvements to *OceanFlux Evolution* products.
16. **Provide example code to read and display *OceanFlux Evolution* products**, diagnostics, documentation for Masters students improved interface to the FluxEngine system)
17. **Provide tools to promote and manage *OceanFlux Evolution* science users** including dedicated graphics and “media-ready” web resources, strong links and interactions with SOLAS and SOCAT, a professional web interface focussed on “the sale of OceanFlux Evolution products”, a user feedback and bug tracking system and other capabilities required to promote and develop the *OceanFlux Evolution* outcomes.
18. **Convene and hold a major air-sea gas transfer scientific workshop** to report results from the project and to seek feedback form the international scientific community.
19. **Fully exploit as much as possible suitable ESA data including Copernicus Sentinel satellites**. It is recognized that the work to be performed will require access to non-ESA data sets and the Contractor shall exploit both ESA and non-ESA EO mission data, as and where appropriate to the work to be carried out. This project requires the use of historical data and the Contractor is encouraged to exploit the historical archives of ESA.
20. Building on the outputs, knowledge and tools developed by the project, **provide a roadmap of future activities** based on the requirements of SOLAS and the international air-sea gas transfer, IPCC and other relevant communities.
21. **Submit peer-review journal articles** to relevant scientific journals reporting scientific developments by the project.
22. **Manage the *OceanFlux Evolution* project according to cost and schedule.**

# Scientific output and product requirements

## Study regions

OceanFlux GHG Evolution has three main areas of interest. These are Global oceans, Arctic Ocean and the Atlantic. The global ocean will predominantly be used for the project CO2 climatology and inputs to the Global Carbon Project. The Arctic region will be used for the Arctic study on gas fluxes within ice flows. The Atlantic region will be used for characterising the modified SST (and thus fCO2, gas transfer and CO2 flux) due to tropical cyclones.

The information on each region is summarised in Table 3.

Table 3: Definitions of the OceanFlux GHG Evolution areas of interest.

|  |  |  |  |
| --- | --- | --- | --- |
| **Ocean(s) of interest** | **Area name** | **Boundaries** | **Notes** |
| Global | Global area | 90oS to 90oN  180oW to 180oE | Global coverage at 1o × 1o (~111 km) spatial resolution. Regular geographic grid. |
| Arctic | Barents Sea | International Hydrographic Office definition for the Barents Sea. | 50 km× 50 km spatial resolution.  Polar stereographic projection. |
| Atlantic | Atlantic | International Hydrographic Office definition for the Barents Sea. | Global coverage at 1o × 1o (~111 km) spatial resolution. Regular geographic grid. |

## Main data outputs

The main data output from OceanFlux GHG Evolution will be calibrated and validatated datasets including an update to the OceanFlux GHG CO2 climatology.

The OceanFlux GHG Evolution project will generate an updated version of the OceanFlux GHG CO2 Climatology (v0.95). This will exploit the most up to date version of SOCAT (most likely v3 – determined as the version available within KO to KO+6).

All data will be provided in NetCDF format, will be easily downloadable from the project website and will contain attribute layers and information on data uncertainties (to aid user interpretation and use of these data).

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| **OceanFluxGHGEvolution-RB-REQ-1: Main outputs - data** | |
| The OceanFlux GHG Evolution project will produce data for these areas of interest in CF 1.6 compliant NetCDF4 format:   * 1. Global - monthly 1o × 1o (regular geographic grid)   2. The Barents Sea (Arctic) - monthly ~50 km × ~50 km (polar stereographic projection).   3. The Atlantic (Atlantic) – monthly 1o × 1o (regular geographic grid)   Each dataset will include attribute layers within the NetCDF files including suitable land masks, quality control layers. The meta data within the each data will describe the uncertainty information and reference to any relevant documents and contact points for further information. | |
| **Verification method** | Inspection |

## Scientific study outputs

OceanFlux GHG Evolution will carry out a series of scientific studies, answering the requirements in the [SoW] and these will be written up and submitted as scientific journal papers.

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| **OceanFluxGHGEvolution-RB-REQ-2: Main outputs - publications** | |
| The OceanFlux GHG Evolution project will produce at least 5 scientific journal publications. | |
| **Verification method** | Inspection |

## The need for an EO-derived total gas transfer relationship

There are a number of approaches that are clear routes to developing a calibrated bubble mediated transfer parameterisation. OceanFlux-GHG 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 project ensemble runs. 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. A third option is to find a more accurate parametric approach and to find the EO data that can support that approach.

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| **OceanFluxGHGEvolution-RB-REQ-3: Bubble mediated transfer** | |
| The OceanFlux GHG Evolution project will develop a bubble mediated gas transfer relationship that can be exploited within the OceanFlux CO2 climatology. | |
| **Verification method** | Inspection |

## The impact of unhandled regional events

The OceanFlux-GHG CO2 climatology is based around the use of monthly mean fields of the various components of the gas flux equation (Equation 6). This approach assumes that we are only interested in the mean (or average) conditions during each month, or that the mean of the flux is accurately calculated from the product of component means. However, specific episodic events can occur in different regions of the globe and these events may have a significant effect on the monthly mean fields and/or the monthly CO2 fluxes, even though they only occur over sub-monthly time scales. Currently the impacts of these events are not explicitly captured within the net sink estimates derived from the OceanFlux-GHG CO2 climatology. Therefore it is important to fully characterize the impact of the events and to then either i) add a suitable correction into the climatology methods to account for these events and/or ii) include the events in the uncertainty analysis. The background and issues involved for each of the regional events to be studied within *OceanFlux-Evolution* are described below. These regional events are i) tropical cyclones, ii) diurnal SST variability, iii) precipitation, iv) upwelling and v) arctic fluxes within areas of broken ice.

### Tropical cyclones

Tropical cyclones have profound effects on the air-sea flux of CO2, firstly by the significant increase in wind speed, and secondly by the ‘cold wake’ caused by the increased vertical mixing under the cyclone. The cold wake results in a change in the partial pressure of CO2 in the seawater. As the cyclones pass over they entrain (or upwell) subsurface water into the mixed layer depth. Currently it is unclear whether globally tropical cyclones cause an increase or a decrease in the tropical outgassing of CO2. Within *OceanFlux\_Evolution*, the effect of high wind speed events will be studied using the air-sea flux CO2 climatology, resulting in an estimation of the global mean effect and its uncertainty.

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| **OceanFluxGHGEvolution-RB-REQ-4: High wind speed events and tropical cyclones** | |
| The OceanFlux GHG Evolution project will determine the mean global effect of tropical cyclone induced winds on the air-sea flux CO2 climatology, and estimate its uncertainty. A report will be written to detail this work and results. | |
| **Verification method** | Inspection |

### Diurnal SST variability

During the day, the upper 2 m of the ocean typically absorbs about 50% of the solar radiation reaching its surface. At night this layer then cools, losing heat to the atmosphere through radiative latent and sensible heat fluxes. This diurnal heating and cooling can lead to significant variations in the sea surface temperature (SST).

The FluxEngine and the extensive SST dataset that is already held on the IFREMER Nephelae cloud platform (e.g. GHRSST data archive) provides the ideal platform for investigating the impact of diurnal variations on global air-sea CO2 gas fluxes.

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| **OceanFluxGHGEvolution-RB-REQ-5: Diurnal variations in SST** | |
| The OceanFlux GHG Evolution project will characterise the impact of the SST diurnal cycle on the global and region air-sea CO2 gas fluxes using the FluxEngine and a range of different datasets including SEVIRI hourly data. This information will be used within the updated uncertainty analysis within the OceanFlux CO2 climatology. | |
| **Verification method** | Inspection |

### Precipitation

Rain can influence air-sea gas exchange by increasing surface turbulence (gas transfer velocity), direct wet deposition of CO2 to the surface waters, chemical dilution of the surface salinity and partial pressure of CO2 (pCO2) and through altering the temperature of surface waters. These latter two aspects can in turn alter the solubility of the gas and the change in temperature will in turn have a small impact on the gas transfer velocity.

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| **OceanFluxGHGEvolution-RB-REQ-6: Precipitation functionality in FluxEngine** | |
| The OceanFlux GHG Evolution project will include the ability to parameterise rain driven gas transfer within the FluxEngine software, including the ability to select this configuration through the web portal. This information will be used within the updated uncertainty analysis within the OceanFlux CO2 climatology. | |
| **Verification method** | Inspection |

### Upwelling events

Clearly episodic upwelling events will affect the air-sea CO2 fluxes and these effects may not be fully captured within the FluxEngine monthly mean estimates and the project CO2 climatology. The FluxEngine provides the framework to investigate the impact of this upwelling on the regional air-sea CO2 flux.

Offshore, the upwelling/down-welling occurrence is mainly due to curl-driven Ekman pumping processes, while near-shore upwelling and down-welling are due to both near-shore Ekman transport (due to alongshore wind stress) and curl-driven Ekman pumping under the assumption that we ignore the impact of Kelvin waves and similar effects. The fields describing the curl-driven Ekman pumping and near-shore Ekman transport can be computed from the mean monthly ASCAT scatterometer wind stress fields for the time period 2007 up to now (or/and from other instruments like QuikScat for reference/comparison purpose) e.g. Risien and Chelton, 2008. These data can be used to perform a sensitivity analysis to quantify the impact that upwelling can have on regional and global pCO2 and air-sea fluxes.

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| **OceanFluxGHGEvolution-RB-REQ-7: Upwelling** | |
| The OceanFlux GHG Evolution project will use the FluxEngine and SMOS+ storms, ASCAT and QuickScat data to study the impact of upwelling in the Atlantic on SST and fCO2. A sensitivity analysis of the impact of the upwelling events on the SST and fCO2, and the resultant impact on the net CO2 gas fluxes will be performed. A report will be written to detail this work and results. | |
| **Verification method** | Inspection |

### Arctic CO2 gas transfer within areas of broken ice

The Arctic Ocean covers a relatively small area (~10.7×106 km2) of the global ocean and ~53% of Arctic waters are broad and shallow (< 200m) continental shelves. Consequently the Arctic Ocean contributes only ~1% to the global ocean volume but it is nevertheless thought to account for 5-14% of the total oceanic sink for anthropogenic CO2 (Bates and Mathis, 2009). Currently rather crude and simplistic estimates of gas transfer within ice flows are used within studies. This situation is due to the difficulty of monitoring air-sea gas transfer and fluxes within dangerous ice flows.

Cryosat and Sentinel 1A when operated in SAR mode is able to provide backscatter (sigma0) and thus wind speed data within the regions of open water that exist in amongst the melting sea ice. The combination of Cryosat data, Sentine 1A data and the FluxEngine provides the framework for the first to characterise air-sea gas transfer within regions of melting sea ice. Such work would link with previous OceanFlux-GHG Arctic studies (e.g. Land et al., 2013). The discussion part of this study will then use the results from the literature to allow us to postulate and estimate the impact of this between-ice gas transfer on the Arctic net CO2 gas fluxes.

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| **OceanFluxGHGEvolution-RB-REQ-8: CO2 gas transfer within ice flows** | |
| The OceanFlux GHG Evolution project will use Cryosat, Sentinel 1A and historical ERS data to characterise gas transfer between broken ice in the Barents sea. We will use the FluxEngine and selection of gas transfer relationships for the characterisation resulting in an estimate of the impact of this gas transfer on Arctic CO2 fluxes. | |
| **Verification method** | Inspection |

## Trend analyses

The global ocean is considered a true net sink of anthropogenic CO2, although it is currently not clear if the global oceanic sink is following the increasing atmospheric levels of CO2. Within OceanFlux-Evolution, mechanisms will be determined through which the estimation of the long-term trend can be improved, and its uncertainty determined, both for the global ocean and for the North Atlantic as a sub-region.

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| **OceanFluxGHGEvolution-RB-REQ-9: Global air-sea flux trend** | |
| The OceanFlux GHG Evolution project will determine the mechanisms through which the determination of the global air-sea flux trend can be improved. A report will be written to detail this work and results. | |
| **Verification method** | Inspection |

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| **OceanFluxGHGEvolution-RB-REQ-10: North Atlantic air-sea flux trend** | |
| The OceanFlux GHG Evolution project will determine the mechanisms through which the determination of the North Atlantic air-sea flux trend can be improved. | |
| **Verification method** | Inspection |

## An updated OceanFlux GHG CO2 Climatology and uncertainty analysis

One of the major outputs of the OceanFlux-GHG project was the creation of a new and advanced global climatology of air-sea CO2 gas fluxes (v0.95) and its associated uncertainty analysis. This CO2 climatology was based on advancements in EO algorithm development made within OceanFlux-GHG and made extensive use of the international SOCAT fCO2 database. The methods for the OceanFlux-GHG CO2 climatology were deliberately simple so a number of improvements to these methods can be investigated. Equally the uncertainty analysis identified all of the major components, but not all components were thoroughly investigated (due to time constraints). Instead the work focussed on those aspects that were considered most important to initially understand and quantify.

### Uncertainties

The uncertainties in global, regional and local estimates of air-sea gas flux estimates cannot be simply calculated from the propagation of known measurement errors, but are a complicated function of numerous types of uncertainty that arise in any knowledge system. The total uncertainty in the net global flux of CO2 (approximately 1 Pg C/year) estimated by Takahashi et al. (2009) and accepted in the latest IPCC reports (Ciais et al., 2013; Rhein et al., 2013) is probably correct, but that figure is not supported by a thorough study and explanation of uncertainties in the bulk air-sea gas flux equation. As part of the first OceanFlux GHG project, Woolf et al. (2015a) have firstly set out a framework for identifying and following all types of uncertainty; and secondly have reviewed the most important sources of uncertainty in global, regional and local gas fluxes.

For the global net air-sea flux of CO2, the following can be identified as contributing very significantly to the uncertainty in the final net flux value (of 2 ± 1 Pg C year-1 for 2010).

(1) Uncertainties in the structure and parameters of traditional gas transfer velocity models (polynomial dependence on wind speed; Sc-1/2). Those uncertainties can be classified as (a) “Type I” uncertainties arising from the necessary limitations of the experimental method most widely preferred (Dual Tracer), and (b) “Type II” uncertainties in expertly combining knowledge from two or more experimental methods.

(2) Uncertainties in gas transfer velocity model structure beyond that described in (1). Thus models can (a) not be polynomial in wind speed; (b) express a “forcing dependence” not expressible simply in terms of wind speed (e.g. wave height or surfactant occurrence might also be necessary inputs); (c) depend on the physicochemical properties of the water and dissolved gas, other than as Sc-1/2.

(3) Unaccounted for asymmetries in gas exchange. A complete model should account for the necessary asymmetry in bubble-mediated gas exchange (invasion favoured over evasion) and correctly deal with the effects of thermal and haline gradients.

(4) Uncertainty arising from sparse sampling. That uncertainty in the context of CO2.is mainly related to the limited number of cruises providing acceptable upper ocean CO2 data, especially in relatively remote oceanic regions,

(5) Uncertainty and ambiguity in “climatological values” of CO2 flux. The calculation of fluxes “referenced” to a specific year has been a pragmatic, but this is also an unsatisfactory response to the sparse data problem described in (4). There is no satisfactory solution for poorly sampled oceans, but an uncertainty analysis should include the uncertainty in assumed secular trends. For better sampled oceans, such as the North Atlantic, climatological values should simply be avoided and calculations should be on an individual year basis.

Again as part of the first OceanFlux GHG project, Woolf et al., (2015b) have explored (1) and (4). Also the architecture for (2) and (3) was constructed within FluxEngine to explore (2) and (3) but that architecture would benefit from review and extension.

Most of (1) to (5) are significant both to more local calculations of flux and to other poorly soluble gases, but with some variation in importance. For example, it is anticipated that for North Atlantic air-sea flux of CO2, (1) and (2) are likely to be much more important than (3) – (5).

The OceanFlux GHG Evolution project will adopt and develop the architecture developed around FluxEngine to elucidate true uncertainties in air-sea gas fluxes. All new CO2 calculations will benefit from extended SOCAT data (ie more recent versions). For (1), the original study was quite satisfactory but can be updated. For (2) and (3), some architecture exists, but new architecture and calculations will be based on the research within OceanFlux GHG Evolution (by IOPAN/HWU) on bubble-mediated transfer. For (4), the first study used a bootstrap method of selecting cruises, but we omitted to keep the index of each cruise selected, which made interpretation difficult; that will be rectified. For (5), it will be necessary to construct various “referenced” data sets based on different assumptions of oceanic trends.

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| **OceanFluxGHGEvolution-RB-REQ-11: Uncertainties in air-sea CO2 gas fluxes (1)** | |
| The OceanFlux GHG Evolution project will adopt and develop the architecture developed around FluxEngine to elucidate true uncertainties in air-sea gas fluxes.  Uncertainties in the structure and parameters of traditional gas transfer velocity models (polynomial dependence on wind speed; Sc-1/2). Those uncertainties can be classified as (a) “Type I” uncertainties arising from the necessary limitations of the experimental method most widely preferred (Dual Tracer), and (b) “Type II” uncertainties in expertly combining knowledge from two or more experimental methods.  The information in the original OceanFlux GHG study will be updated based on the new SOCAT data. This information will be included in the paper describing the updated CO2 climatology | |
| **Verification method** | Inspection |

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| **OceanFluxGHGEvolution-RB-REQ-12: Uncertainties in air-sea CO2 gas fluxes (2)** | |
| The OceanFlux GHG Evolution project will adopt and develop the architecture developed around FluxEngine to elucidate true uncertainties in air-sea gas fluxes.  Uncertainties in gas transfer velocity model structure beyond that described in OceanFluxGHGEvolution-RB-REQ-12. Thus models can (a) not be polynomial in wind speed; (b) express a “forcing dependence” not expressible simply in terms of wind speed (e.g. wave height or surfactant occurrence might also be necessary inputs); (c) depend on the physicochemical properties of the water and dissolved gas, other than as Sc-1/2.  Unaccounted for asymmetries in gas exchange. A complete model should account for the necessary asymmetry in bubble-mediated gas exchange (invasion favoured over evasion) and correctly deal with the effects of thermal and haline gradients.  New architecture and calculations will be based on the research within OceanFlux GHG Evolution (by IOPAN/HWU) on bubble-mediated transfer. This information will be included in the paper describing the updated CO2 climatology | |
| **Verification method** | Inspection |

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| **OceanFluxGHGEvolution-RB-REQ-13: Uncertainties in air-sea CO2 gas fluxes (3)** | |
| The OceanFlux GHG Evolution project will adopt and develop the architecture developed around FluxEngine to elucidate true uncertainties in air-sea gas fluxes.  Uncertainty arising from sparse sampling. That uncertainty in the context of CO2.is mainly related to the limited number of cruises providing acceptable upper ocean CO2 data, especially in relatively remote oceanic regions,  Information on which cruises were removed from he bootstrap experiments will be kept and analysed. This information will be included in the paper describing the updated CO2 climatology. | |
| **Verification method** | Inspection |

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| **OceanFluxGHGEvolution-RB-REQ-14: Uncertainties in air-sea CO2 gas fluxes (4)** | |
| The OceanFlux GHG Evolution project will adopt and develop the architecture developed around FluxEngine to elucidate true uncertainties in air-sea gas fluxes.  Uncertainty and ambiguity in “climatological values” of CO2 flux. The calculation of fluxes “referenced” to a specific year has been a pragmatic, but this is also an unsatisfactory response to the sparse data problem described in OceanFluxGHGEvolution-RB-REQ-14. There is no satisfactory solution for poorly sampled oceans, but an uncertainty analysis should include the uncertainty in assumed secular trends. For better sampled oceans, such as the North Atlantic, climatological values should simply be avoided and calculations should be on an individual year basis  We will construct various “referenced” data sets based on different assumptions of oceanic trends. This will be exploited within OceanFluxGHGEvolution-RB-REQ-10 and OceanFluxGHGEvolution-RB-REQ-11. | |
| **Verification method** | Inspection |

### CO2 climatology

Figure 2 below gives an overview of the options within the FluxEngine for generating the project CO2 climatology.

An updated CO2 climatology would benefit from recent updates to i) SOCAT dataset, ii) EO datasets, iii) more advanced in-water fCO2 correction, iv) more advanced interpolation (kriging) techniques and v) advances in the uncertainty analysis.

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| Figure 2 Schematic of processing for the flux climatologies. |

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| **OceanFluxGHGEvolution-RB-REQ-15: OceanFlux GHG Evolution CO2 climatology** | |
| The OceanFlux GHG Evolution project will develop a version 1 of the OceanFlux Greenhouse Gases CO2 climatology. It will include and exploit:  1. An updated version of SOCAT (v3).  2. The new version of the ESA SST CCI datasets and its sub-skin SST estimate.  3. More advanced interpolation scheme using 3D kriging (2D + time).  4. Updates to the in-water fCO2 correction scheme (e.g. complete automation).  5. An updated uncertainty analysis. | |
| **Verification method** | Inspection |

## Technical extensions to the FluxEngine

A number of technical developments will be required within OceanFlux GHG Evolution. These developments arise from the need to encourage greater community use of the FluxEngine and also to allow greater flexibility for studies to be carried out within the project. The reasoning for each of these developments is described below.

Extensions to include other gases will increase the uptake and use of the FluxEngine by the international community and to support CO2 research. The capability to study additional gases (in addition to CO2) is likely to support the CO2 research. For example the direct gas transfer algorithms developed within OceanFlux-GHG were actually calibrated using DMS data (and not CO2). Another example of the benefits of studying multiple gases is that the nitrogen and carbon cycles are highly interlinked, meaning that understanding the behaviour of N2O (for example) can support the interpretation of CO2 data.

### NOAA-COARE

Most parameterisations of gas transfer are empirical and depend only on wind speed, but the effect of this is to combine many different wind dependent processes into a simple parameterisation. It also neglects buoyancy driven transfer that may be dominant at low wind speed. The NOAA COARE bulk flux model arose from the COARE field programme in 1992-3 (Fairall et al., 1996a;Fairall et al., 1996b). It was originally developed for studying bulk heat fluxes, and was later extended to calculate fluxes of CO2 (Fairaill et al., 2000;Hare et al., 2004), DMS (Blomquist et al., 2006) and other gases (Fairall et al., 2011). The COARE model is a physically based model of gas transfer, and is considered to be at the forefront of gas transfer modeling. It can provide gas transfer velocities for 79 different gases and it has been extensively used in air-sea gas flux studies (e.g. Kettle et al., 2009). Therefore to increase the international use of FluxEngine (especially by US scientists), the COARE gas transfer parameterisation needs to be added into the suite of available gas transfer velocity parameterisations. Adding this capability will allow the parameterisation to be exploited within the *OceanFlux-Evolution* uncertainty analysis and it will also provide additional capability to calculate gas transfer velocities for other gases such as N2O, CH4 and OVOCs.

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| **OceanFluxGHGEvolution-RB-REQ-16: FluxEngine technical developments (1)** | |
| The OceanFlux GHG Evolution project will extend the FluxEngine to enable and include NOAA COARE gas transfer parameteristion. | |
| **Verification method** | Inspection |

### Dimethyl-sulphide (CH4-S-CH4 or DMS)

The global oceans are the largest natural source of atmospheric sulphur through the emission of the gas dimethylsulphide (DMS). The generation of DMS is thought to be linked to the growth and decay of phytoplankton. Once in the atmosphere the DMS gas forms acids that contribute to the pool of cloud condensation nuclei that are necessary for the formation of clouds. These condensation nuclei can affect the Earth’s radiation budget (and thus climate) by scattering sunlight and influencing cloud physics and albedo. In general, DMS concentrations are larger at high latitudes, with a trend toward higher concentrations in summer. Kettle et al. (1999) assembled a database of all available seawater DMS concentrations, about 15000 individual measurements at that time and more recently Lana et al. (2011) increased this database to more than 47000 observations to create a monthly climatology. Recent work (Land et al., submitted) developed methods for using Envisat EO data and this climatology to study sea-air DMS fluxes. Land et al used the Lana et al. (2011) climatology and then assumed the atmospheric concentration of DMS to be 1/400 of the in-water concentration (an assumption that was based on field data from 10 open ocean cruises). Solubility, Schmidt numbers and air side transfer velocity used the modeling methods of Johnson (2010) and the water side transfer velocity used the OceanFlux-GHG algorithm (Goddijn-Murphy et al., 2012). Collectively this meant that they derived sea-air fluxes of DMS using a combination of EO, *in situ* data and a model.

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| **OceanFluxGHGEvolution-RB-REQ-17: FluxEngine technical developments (2)** | |
| The OceanFlux GHG Evolution project will extend the FluxEngine to enable and include DMS gas capability following the methods in Land et al., (2013). | |
| **Verification method** | Inspection |

### Methane (CH4), Nitrous-oxide (N2O)

CH4 and N2O are both climatically important gases and they are both water-side controlled gases Therefore equation 6 can be used to parameterise the gas flux. Fortunately both of these gases have similar gas transfer velocity parameterisations to that of CO2 and the NOAA-COARE model is able to provide estimates for these gases. Therefore some means to derive the in-water fugacity of these gases is all that is required to enable the FluxEngine to be extended to calculate air-sea CH4 and N2O fluxes. International efforts are currently collating climatologies for these gases and the data are soon to be available (e.g. the MEMENTO Database).

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| **OceanFluxGHGEvolution-RB-REQ-18: FluxEngine technical developments (3)** | |
| The OceanFlux GHG Evolution project will extend the FluxEngine to enable and include Methane and nitrous oxide gas transfer parameterisations. Where possible basic climatologies will be produced and a technical note will be written to describe these climatologies. | |
| **Verification method** | Inspection |

### Handling regional events

A number of technical developments will be needed to enable the work on regional events (diurnal variability, precipitation, cyclones, upwelling) to be carried out. These are likely to be small additions to the FluxEngine to allow sensitivity analyses to be carried out. Updates to the FluxEngine will need to be carried out for the Arctic regional study as the analysis will need to be run at a higher spatial resolution than the current 1o × 1o resolution at which the global analyses are carried out. Further updates to the FluxEngine will be needed to implement the calibrated bubble mediated gas transfer algorithm and to evaluate new ensemble scenarios identified within the uncertainty analyses.

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| **OceanFluxGHGEvolution-RB-REQ-19: FluxEngine technical developments (4)** | |
| The OceanFlux GHG Evolution project will extend the FluxEngine to enable and include small extensions to allow the regional studies to be carried out. | |
| **Verification method** | Inspection |

### Additional FluxEngine tools and extensions

The development and provision of additional tools to allow the FluxEngine output data to be easily plotted and compared with other datasets is likely to increase the use of the FluxEngine by the international scientific community. These tools will make it easier for the users to exploit and analyse the datasets. These tools could also be used by the project team for reports and publications. Similarly to enable the crowd sourced ensemble to be generated (and to encouraged wide participation in this experiment) will require the FluxEngine interface to be improved and the ability to initiate the processing (and monitor its progress) through the web interface will be required. An internal consistency matrix will also be included to aid error checking and interpretation of the FluxEngine outputs.

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| **OceanFluxGHGEvolution-RB-REQ-20: FluxEngine technical developments (5)** | |
| The OceanFlux GHG Evolution project will extend the FluxEngine to enable and include:   1. Small extensions to allow the regional and sensitivity studies to be carried out. 2. Additional tools to support outreach and external use of the FluxEngine. e.g. help information like example code or tools to read and display OceanFlux data. 3. Extensions to allow the updated CO2 climatology to be produced. 4. Consistency matrix for all outputs and diagnostic metrics. | |
| **Verification method** | Inspection |

## Crowd sourcing experiment

Crowdsourcing is the process of obtaining needed services, ideas, or content by soliciting contributions from a large group of people, and especially from an online community, rather than from traditional employees or suppliers. It involves the outsourcing of a task (once performed by a small number of people) to a large network. The technique can be used to tackle intractable and laborious problems, by creating and bringing together communities.

The FluxEngine provides an ideal platform for performing a crowdsourcing experiment and such an experiment will provide insight into community parameterisation preferences and the reasons for these choices and insight into sources of uncertainty.

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| **OceanFluxGHGEvolution-RB-REQ-21: Crowd sourcing experiment** | |
| The OceanFlux GHG Evolution project will organise and run a crowd sourcing experiment that uses the FluxEngine to study uncertainties in air-sea gas flux calculations. Depending upon the results and conclusions drawn from these experiments, the results will be written up into a technical note or journal paper. | |
| **Verification method** | Inspection |

# Requirements on data for the project outputs

OceanFlux GHG Evolution will exploit the vast amount of EO, *in situ* and model data that both partners already hold. We will exploit the large amount of data storage and processing capability available at both PML and IFREMER. Any required datasets that are not already held by the partners will be obtained and stored in standardised formats.

All data (where IPR agreements allow) will be made available through the project website by exploiting the IFREMER web based data access tools previously used within other the first ESA OceanFlux GHG project. These allow users to browse and access data and associated metadata easily using a web browser.

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| OceanFluxGHGEvolution-RB-REQ-22: Data access | |
| The OceanFlux GHG Evolution project will make all data available through the project website. Data will be made available once all scientific work has been completed and the quality of these data have been verified. | |
| **Verification method** | Inspection (quality controlled using ESA recommendations) |

## Earth observation data

The primary EO parameters used in this work will be Sea surface temperature (SST), Sea surface salinity (SSS), chlorophyll-a, wind speed, sea state data and sea ice extent.

The table below lists all of the EO data that the consortium will require. The data listed below includes ESA historical datasets, third party missions and data from ESA Climate Change Initiative (CCI, Ocean colour and SST) and ESA Glob projects (GlobWave). If available we will also exploit Sentinel 1 and Sentinel 3 data.

Table 4 satellite Earth observation datasets to be used by OceanFlux GHG Evolution.

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| **No.** | **Sensor/name (version)** | **Spatial resolution (temp. resolution)** | **Temporal period** | **Geographic coverage** | **Parameters** | **References** | **Data held** |
| **1.** | Cryosat-2 (GlobWave GDR) | ~300 m along track, ~4 km across track (daily, monthly) | 2010-present | Global | U10, Ice thickness | Laxon et al. (2013) | Yes |
| **2.** | SMOS (CATDS v2) | 0.25o × 0.25o (monthly)  0.5o × 0.5o (daily) | 2010-present | Global | SSS, U10 | Font et al. (2010) | Yes |
| 3. | SEVIRI | 0.05o × 0.05o (hourly) | 2002-present | Central East Atlantic | SST, SSI, DLI |  |  |
| 4. | ESA SST CCI (ARC v1.1.1) | 0.1o × 0.1o (monthly) | 1992-2012 | Global | SSTskin, SSTsub | Merchant et al. (2012) | Yes |
| 5. | ESA Ocean Colour CCI (v0.95) | 4 × 4 km (daily, monthly) | 1997-2012 | Global | Rrs, chl | Brewin et al. (2012) |  |
| 6. | ESA GlobWave multi-sensor merged (GlobWave GDR) | (daily, monthly) | 1992-present day (ie monthly near real time feed needed) | Global | U10, wind direction | [www.globwave.info](http://www.globwave.info) | Yes |
| 7. | OSI-SAF | 25 × 25 km (daily, monthly) | 1987-present | Global (Arctic and Antarctic) | %age ice cover | [www.osi-saf.org](http://www.osi-saf.org) | Yes |
| 8. | SSM/I | 12.5 × 12.5 km (daily, monthly) | 1991-present | Global (Arctic and Antarctic) | %age ice cover | [http://cersat.ifremer.fr](http://cersat.ifremer.fr/) | Yes |
| 9. | OSTIA | 0.05o × 0.05o | 2007-present day (ie monthly near real time feed needed) | Global | SST | http://www.myocean.eu/web/69-myocean-interactive-catalogue.php/?option=com\_csw&view=details&product\_id=SST\_GLO\_SST\_L4\_NRT\_OBSERVATIONS\_010\_001 | Yes |
| 10. | ODYSSEA | 0.1o × 0.1o | 2006-present day (ie monthly near real time feed needed) | Global | SST | http://www.ifremer.fr/cersat1/exp/productscatalog/details?id=CER-SST-MED-1D-002-ODY-MGD | Yes |
| 11. | CCMP | 0.25o × 0.25o | 1987-present | Global | U10 | http://podaac.jpl.nasa.gov/Cross-Calibrated\_Multi-Platform\_OceanSurfaceWindVectorAnalyses | No. |

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| --- | --- |
| OceanFluxGHGEvolution-RB-REQ-23: Earth observation data | |
| The OceanFlux GHG Evolution project will use and exploit the following satellite Earth observation data (full details are in table 4). These data will be made available (and provided in the 1° × 1° degree format) for the FluxEngine.  Sea surface salinity data:   * SMOS (CATDS v2) salinity data. * Aquarius salinity data.   Sea surface temperature data:   * SEVIRI SST data. * ESA SST CCI (ARC v1.1.1) data. * OSI-SAF SST data. * SSM/I SST data. * OSTIA SST data. * ODYSSEA SST data.   Sea state data:   * ESA GlobWave multi-sensor merged wind and wave data * NASA/NOAA CCMP (Cross Calibrated Multi-platform Ocean Wind) data.   Ocean Colour data:   * ESA Ocean Colour CCI (v0.95) data. | |
| **Verification method** | Inspection (quality controlled using ESA recommendations) |

## Climatology data

The project also has access to and will exploit the following global climatological datasets:

Table 5 Climatology data to be used by OceanFlux GHG Evolution.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **No.** | **Dataset source** | **Parameters** | **Reference** | **Access secured** |
| 1. | ESA OceanFlux GHG | pCO2 + all associated parameters | [www.oceanflux-ghg.org](http://www.oceanflux-ghg.org) | Yes |
| 2. | LOCEAN/IFREMER | MLD | [www.ifremer.fr/cerweb/deboyer/mld](http://www.ifremer.fr/cerweb/deboyer/mld) | Yes |
| 3. | Community DMS climatology | DMS concentrations, SSS | Lana et al., 2011 | Yes |
| 4. | MEMENTO | CH4 and N2O concentrations and associated parameters. | [www.memento.geomar.de](http://www.memento.geomar.de)  Bange et al., 2009 | negotiating |
| 5. | LDEO pCO2 climatology | pCO2, SST | <http://cdiac.ornl.gov/oceans/LDEO_Underway_Database/> | Yes |

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| --- | --- |
| OceanFluxGHGEvolution-RB-REQ-24: Climatology data as inputs | |
| The OceanFlux GHG Evolution project will use and exploit the following climatology data (full details are in table 5). These data will be made available (and provided in the 1° × 1° degree format) for the FluxEngine.   * ESA OceanFlux Greenhouse Gases air-sea CO2 flux climatology v0.95 * LOCEAN/IFREMER Mixed layer depth climatology. * Community DMS climatology (Lana et al., 2011). * MEMENTO climatology (Bange et al., 2009). * Takahashi et al., 2009 air-sea CO2 flux climatology | |
| **Verification method** | Inspection (quality controlled using ESA recommendations) |

## Modeled data

The following model data are also available for the project. PML have previous experience in using these International Panel on Climate Change (IPCC) Climate Modelling Inter-comparison Project 5 (CMIP5) datasets.

Table 6 Model data to be used by OceanFlux GHG Evolution.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **No.** | **Model** | **Spatial resolution (temp. resolution)** | **Temporal period** | **Geographic location** | **Parameters** | **References** | **Access secured** |
| 1. | IPCC CMIP5  Multiple model datasets e.g. HadGEM2-ES and  FIO-ESM | 1o × 1o degree (monthly) | 1951-2100 | Global | pCO2, AT, DIC, pH | Taylor et al. (2012) | Yes |
| 2. | IOWAGA WavWatch III simulations | 0.5o × 0.5o degree (3 hourly) | 1991-2011 | Global | Various parameters including dissipation rate, wave spectral shape, breaking probabilities and spectral scales. | <http://wwz.ifremer.fr/iowaga> | Yes |

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| OceanFluxGHGEvolution-RB-REQ-25: Model data | |
| The OceanFlux GHG Evolution project will use and exploit the following model data (full details are in table 6). Where required these data will be made available (and provided in the 1° × 1° degree format) for the FluxEngine.   * IPCC CMIP5 outputs (for a selection of business as usual model runs). * IOWAGA model simulations. | |
| **Verification method** | Inspection (quality controlled using ESA recommendations) |

## Wind speed datasets

A large number of different wind datasets are available as derived from altimeter, models and scatterometers. OceanFlux GHG Evolution will make full use of the inter-calibrated datasets from GlobWave and the SMOS wind data from SMOS+ Storms (specifically for the Amazon Plume region).

|  |  |
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| OceanFluxGHGEvolution-RB-REQ-26: Wind speed and sea state | |
| For each of the wind and sea state data products listed in OceanFluxGHGEvolution-RB-REQ-23, the OceanFlux GHG Evolution project will generate and provide the following using the grids specified in OceanFluxGHGEvolution-RB-REQ-1:  a) Mean and median wind speed and sea state.  b) Second and third order moments of wind speed and sea state. | |
| **Verification method** | Inspection (quality controlled using ESA recommendations) |

## Sea surface temperature and salinity data

A number of different temperature datasets are required to accompany the estimates of pCO2 at different depths. Sea surface skin data from AATSR can be provided by ESA. AVHRR and MODIS SST data (corrected to skin values) are available from NOAA and NASA respectively. These data are detailed in the satellite Earth observation data in Table 1.

Salinity climatology data can be provided by the Takahashi et al 2009 climatology, which is freely available. Salinity data are now available from ESA SMOS and NASA Aquarius.

Upper ocean salinity is available via the World Ocean Atlas 2013 and the Takahashi database.

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| OceanFluxGHGEvolution-RB-REQ-27: Sea surface temperature data | |
| The OceanFlux GHG Evolution project will make use of the Sea surface temperature dataset listed in OceanFluxGHGEvolution-RB-REQ-23.  Where necessary these data will be re-gridded to the grids and temporal resolutions specified in OceanFluxGHGEvolution-RB-REQ-1. Where this re-gridding is done, OceanFlux GHG Evolution will provide:  a) Mean and median SST.  b) Second and third order moments of SST. | |
| **Verification method** | Inspection (quality controlled using ESA recommendations) |

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| OceanFluxGHGEvolution-RB-REQ-28: Sea surface salinity data | |
| The OceanFlux GHG Evolution project will make use of the Sea surface salinity dataset listed in OceanFluxGHGEvolution-RB-REQ-23. In addition to these, the project will also use and make available:   1. Takahashi et al 2009 Salinity climatology. 2. World Ocean Atlas 2013.   Where necessary these data will be re-gridded to the grids and temporal resolutions specified in OceanFluxGHGEvolution-RB-REQ-1. Where this regridding is done, OceanFlux GHG Evolution will provide:  a) Mean and median salinity.  b) Second and third order moments of salinity. | |
| **Verification method** | Inspection (quality controlled using ESA recommendations) |

## In situ carbon dioxide data

In addition to the in situ data listed below to support the bubble mediated gas transfer research within OceanFlux GHG Evolutionwe will collate all available *in situ* datasets of gas fluxes (especially CO2 but other gases may be also useful) where fluxes were measured at the same time as the air and in-water partial pressures of the gas. The project partners already hold many of these datasets, but we are also seeking further datasets. The project has access to the following *in situ* data:

Table 7 in situ carbon dioxide data that OceanFlux GHG Evolution will use.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **No.** | **Dataset name** | **Temporal period** | **Geographic location** | **Parameters** | **N** | **References** | **Access secured** |
| 1. | SOCAT v2.0 | 2005-2011 | Global | fCO2W, SSS, SST | 10,000,000+ | Bakker et al. (2014) | Yes |
| 2. | LDEO v2012 | 1980-present | Global | pCO2W, SSS, SST | 6,700,000+ | Takahashi et al. (2013) | Yes |
| 3. | IOPAN |  | Baltic sea and North Sea | pCO2W, SSS, SST | 1000+ | IOPAN in-house dataset. | Yes |
| 4. | OceanFlux-GHG algorithm development dataset. | 2003-2010 | Global | Coincident DMS (gas transfer) and EO sea state | 179 | Goddijn-Murphy et al., 2012; Goddijn-Murphy et al., 2013 | Yes |

N = approximate number of data points

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| **OceanFluxGHGEvolution-RB-REQ-29: Carbonate system data** | |
| The OceanFlux GHG Evolution project will use all available in situ and climatological carbonate system data as listed in OceanFluxGHGEvolution-RB-REQ-29 to OceanFluxGHGEvolution-RB-REQ-25.  In addition to these the project will also use:   * SOCAT (v2 and v3) data. * LDEO v2012 database * IOPAN in situ dataset. | |
| **Verification method** | Inspection |

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| **OceanFluxGHGEvolution-RB-REQ-30: Carbon Dioxide** | |
| The OceanFlux GHG Evolution project will use the following carbon dioxide datasets:   * + 1. Fugacity in the upper ocean standardized to 2010 as a derived product from the SOCAT data (OceanFlux GHG v0.95 dataset)     2. Base of the microlayer CO2 concentration (derived from fugacity and an appropriate sea surface temperature) (OceanFlux GHG v0.95 dataset)     3. Atmospheric partial pressure of CO2 (derived from atmospheric dry fraction, atmospheric pressure and saturated vapour pressure) (OceanFlux GHG v0.95 dataset)     4. Surface CO2 concentration (derived from atmospheric partial pressure and surface skin solubility). (OceanFlux GHG v0.95 dataset) | |
| **Verification method** | Inspection |

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# Technical implementation requirements

The following sections specify the requirements for the OceanFlux GHG Evolution technical implementation.

## Cloud computing

OceanFlux GHG Evolution shall provide a processing capability for reprocessing datasets or testing new algorithms.

This processing capability shall be available, and restricted, to all members of OceanFlux GHG Evolution team. The platform shall provide a suitable environment and tools to these members for them to run or test the data processing.

Members of OceanFlux GHG Evolution shall be able to initiate processing on the processing platform. Tools shall be provided to distribute and run any data processing (using an efficient batch approach) on a sequence of input data.

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| **OceanFluxGHGEvolution-RB-REQ-31: Cloud computing** | |
| The OceanFlux GHG Evolution project will provide cloud computing capability to members of the OceanFlux GHG Evolution team.  This capability will allow the team to re-process the data for the different regions of interest. | |
| **Verification method** | Inspection |

## Data types and formats

Existing input datasets relevant for OceanFlux GHG Evolution shall not be re-formatted if they are already available in NetCDF3 or NetCDF4 format.

All in situ data will be converted to NetCDF format. These data will follow and extend the data model defined by the ESA GlobWave project for ocean and meteorological buoy data (the GlobWave product user guide can be found at: http://www.globwave.org/content/download/3289/24478/file/GlobWave\_D.5\_PUG\_v1.2.pdf).

The global datasets produced by OceanFlux GHG Evolution will use:

* Common projection and 1o ×1o or 0.5o × 0.5o spatial resolution (regular geographic grid and polar stereographic for the Arctic region)
* NetCDF4\_CLASSIC (CF 1.6 compliant) including internal zlib compression. ie no usage of the new NETCDF4 features (such as groups etc..) shall be handled.

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| **OceanFluxGHGEvolution-RB-REQ-32: Data types and formats** | |
| The OceanFlux GHG Evolution project will provide EO, model and *in situ* data in consistent NetCDF 4 Classic formats complying to CF 1.6 conventions. | |
| **Verification method** | Inspection |

## Meta data requirements

The OceanFlux GHG Evolution output data sets shall include global and variable attributes complying to the CF convention. The GHRSST GDS v2 specification will be used as a basis for the relevant list of metadata.

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| **OceanFluxGHGEvolution-RB-REQ-33: Meta data** | |
| The OceanFlux GHG Evolution project will follow the CF 1.6 conventions for all NetCDF4 data that the project produces. This will include quality level data. | |
| **Verification method** | Inspection |

## Data delivery and access

The datasets produced by (or collected for) OceanFlux GHG Evolution shall be available through ftp access to all authorized users. A login/password shall be delivered by CERSAT help desk to any interested users.

Local access to the online archive will be possible from the Nephelae cloud platform of CERSAT allowing for direct remote processing without the need to download any data.

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| **OceanFluxGHGEvolution-RB-REQ-34: Data delivery and access** | |
| The OceanFlux GHG Evolution project will make all novel datasets available through an ftp server (linked from the project website). Data will be released to people external to the project once all scientific analyses have been completed. See also OceanFluxGHGEvolution-RB-REQ-22. | |
| **Verification method** | Inspection |

## Software development

All algorithm development will use Python and appropriate open source wrappers. All software developed within OceanFlux GHG Evolution will be made open source upon the completion of any scientific analyses.

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| **OceanFluxGHGEvolution-RB-REQ-35: Software development** | |
| All software algorithm development will use Python and be made open source upon the completion of the scientific work within the project. | |
| **Verification method** | Inspection |

# Requirements of the web portal

The OceanFlux GHG Evolution GHG project shall develop, operate and maintain a central web portal that shall provide a single entry point to all aspects of the project. It will be maintained for at least 2 years after the completion of the project.

The aim of the OceanFlux GHG Evolution web portal is to:

* Provide users with a resource to make full and easy use of the OceanFlux GHG Evolution outputs.
* Establish and maintain connections with the OA community and other relevant project teams.
* Actively promote the results of the project.

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| **OceanFluxGHGEvolution-RB-REQ-36: Web portal contents** | |
| The OceanFlux GHG Evolution web portal shall contain at least the following contents:   1. information about the project, including objectives, work packages list, latest news and news archive, documents and presentation for all the project meetings in PDF format, list of OceanFlux GHG Evolution main team members, contacts of the project manager, links to international community linked to the project 2. a page announcing meetings. 3. descriptions and links to sources of data used in the project (satellite, *in situ*, models) and products developed during the project. 4. access to project documentation. | |
| **Verification method** | Inspection |

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| **OceanFluxGHGEvolution-RB-REQ-37: Web portal lifetime** | |
| The web portal shall be maintained and updated for the duration of the project and at least two years after the end of the project. The contents of the web portal shall be reviewed at least once per month. | |
| **Verification method** | Inspection / testing |

## Project documentation

All internal project documentation shall be made available on the website, however this should not be publically available.

The web portal shall provide a restricted (and secure) project area containing internal documentation such as deliverables, meeting minutes, monthly reports, project management plan, etc… The project documents will be placed in the secure area as they become available.

Some internal documents will be provided to the external community following mutual agreement between ESA and all members of the consortium.

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| **OceanFluxGHGEvolution-RB-REQ-38: Project documentation** | |
| The web portal shall provide a password protected project section containing project internal documentation, such as all draft document deliverables, RIDs, meeting minutes, actions database, monthly reports, project management plan, etc. | |
| **Verification method** | Inspection / testing |

## Data delivery and access

The OceanFlux GHG Evolution project will allow easy access to the project products and results. The OceanFlux GHG Evolution data information shall be available through the website. This will include links to any documentation and information on how to access any datasets.

OceanFluxGHGEvolution-RB-REQ-22 and OceanFluxGHGEvolution-RB-REQ-34 define the quality and the access requiremenst for all OceanFlux GHG Evolution data.

# Community, promotion and outreach requirements

## Promotion of the project

The OceanFlux GHG Evolution project intends to disseminate the results of the project to as wide a community as possible and a number of mechanisms are planned in order to achieve this including:

1. Develop and maintain a contacts directory of all members of the project.
2. Actively maintain connections with relevant international communities (e.g. International SOLAS office).
3. Develop and maintain a web portal.
4. Actively promote the results through the web portal, publishing peer-reviewed papers and presenting results at international conferences.
5. Convene and hold an international workshop were the results from OceanFlux GHG Evolution are presented and the international community can present their work.
6. In conjunction with the international community collate and write a scientific roadmap to identify and focus future research activitities.

The mechanisms by which the OceanFlux GHG Evolution project shall promote and disseminate the results of the project are detailed below.

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| **OceanFluxGHGEvolution-RB-REQ-39: Directory and mailing list** | |
| The OceanFlux GHG Evolution project will maintain a directory and mailing list which shall contain contact details of:   1. All members of the project team. 2. Potential users of the project output. 3. All project supporters. | |
| **Verification method** | Inspection |

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| **OceanFluxGHGEvolution-RB-REQ-40: Peer-reviewed publications** | |
| The OceanFlux GHG Evolution project will develop and submit papers to appropriate international (peer-reviewed) science journals. The publications shall acknowledge the support of the ESA STSE programme and use of ESA data. | |
| **Verification method** | Inspection |

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| **OceanFluxGHGEvolution-RB-REQ-41: Present results of the study** | |
| The OceanFlux GHG Evolution project will present the study and results at relevant international events, including future ESA and SOLAS meetings and other international symposia during the lifetime of the project and the project scientific workshop. | |
| **Verification method** | Inspection |

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| **OceanFluxGHGEvolution-RB-REQ-42: Promote results of the study** | |
| The OceanFlux GHG Evolution project will actively promote the results of the study and distribute freely all data, reports and experimental output data to:   1. International SOLAS office. 2. Other relevant scientific communities including the Global Ocean Acidification Observing Network (GOA-ON). More details will be given in the technical specification and later deliverables. 3. Project supporters. | |
| **Verification method** | Inspection |

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| --- | --- |
| **OceanFluxGHGEvolution-RB-REQ-43: Convene and hold an international workshop** | |
| The OceanFlux GHG Evolution project will convene and hold an international workshop where the results from the project will be presented. The workshop will also provide a stage for the international community to present their work and open discussions to identify future avenues of scientific investigation for supporting SOLAS relate science. | |
| **Verification method** | Inspection |

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| **OceanFluxGHGEvolution-RB-REQ-44: Scientific roadmap** | |
| The OceanFlux GHG Evolution project will use all project meetings and the project Scientific workshop to identify future avenues of scientific investigation for supporting SOLAS relate science. All of the information from the open discussions at the workshop and meetings will be collated into a clear strategy for future scientific focus identifying where satellite Earth observation can help further SOLAS related science. | |
| **Verification method** | Inspection |

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| **OceanFluxGHGEvolution-RB-REQ-45: Dedicated graphics and media information** | |
| The OceanFlux GHG Evolution project will collate imagery (with copyright ownership) and media ready content for use by the project team and for use within any project press releases. | |
| **Verification method** | Inspection |

## The importance of the community

There is a clear need for *OceanFlux-Evolution* to link with international efforts including those of the Surface Ocean CO2 Atlas (SOCAT) and the Global Carbon Project (GCP). Linking with, and supporting, these international initiatives will highlight the importance of the work and ensure that the outputs from *OceanFlux-Evolution* are fully exploited and included in international publications such as the reports from the IPCC.

### Surface Ocean CO2 ATlas (SOCAT)

SOCAT brings together global observations of fCO2 in the sea surface, and rigorously quality controls them at 2nd QC level. Version 3 is going to be made public in September 2015, whilst version 4 will be in progress by then. We will continue to participate in this process, and aim to improve the automation of submission and quality control of data, working towards a more timely public release of the data set in the future.

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| **OceanFluxGHGEvolution-RB-REQ-46: SOCAT** | |
| The OceanFlux GHG Evolution project will contribute to the continuation of the 2nd level quality control within SOCAT. | |
| **Verification method** | Inspection |

### Global Carbon Project (GCP)

Each year the Global Carbon Project (Le Quiere et al., 2014) produces a synthesis publication detailing the global trends in CO2 emissions and uptake. This covers the complete carbon cycle across the land, oceans and atmosphere. To date the synthesis work has focussed on model driven estimates, although the most recent report has included some observational work from *in situ* networks, but no satellite Earth observation derived data. They (the GCP) are keen to included further observations derived datasets, including that of EO. Providing datasets to, and being involved in The Global Carbon Project will provide a direct exploitation of the project outputs and in the medium to long term will increase the projects visibility within the gas fluxes academic and wider climate research communities.

For OceanFlux GHG Evolution to partake in this work up to date air-sea gas flux data is required ie to participate in the next study, data for 2013 will be required. This means that EO data up to and including 2013 are required by the project to enable us to take part in the next GCP synthesis. Assumptions made to generate the updated CO2 climatology will also need to take into account the ability to generate flux data for 2013. Realistically the project will be able to contribute to the 2015 or 2016 Global Carbon Project synthesis studies, so the project will need to keep all critical EO data (sea state and SST) as close to real time as possible.

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| **OceanFluxGHGEvolution-RB-REQ-47: Ensuring participation in the Global Carbon Project** | |
| The OceanFlux GHG Evolution project will ensure that GlobWave merged data (for sea state parameters) and ODYSSEA and OSTIA SST data up to an including 2015 (and beyond) are available.  The OceanFlux GHG Evolution project will submit data to the Global Carbon Project for inclusion in their synthesis report. | |
| **Verification method** | Inspection |

# Requirements on the schedule

Access to the Nephalae cloud data processing and project datasets will be given to the project team by KO+4. This will allow the team to access the EO and model data as they are collated and allow them to start writing and testing the Python implementation of the different carbonate algorithms.

All *in situ* data need to be collated and catalogued (including their support meta data) in advance of beginning the generation of the matchup database.

All data need to have been collated by KO+6 to allow the algorithm development, data extraction and algorithm evaluation work to start.

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| **OceanFluxGHGEvolution-RB-REQ-48: Requirements on the schedule (1)** | |
| All OceanFlux GHG Evolution project team members will be given access to the Nephalae cloud by KO+4. | |
| **Verification method** | Inspection |

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| --- | --- |
| **OceanFluxGHGEvolution-RB-REQ-49: Requirements on the schedule (1)** | |
| All *in situ* data will be collated and catalogued (including their support meta data) in advance of beginning the generation of the matchup database. This needs to be complete by KO+6. | |
| **Verification method** | Inspection |

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| --- | --- |
| **OceanFluxGHGEvolution-RB-REQ-50: Requirements on the schedule (1)** | |
| All OceanFlux GHG Evolution project data (EO, model and in situ) will be collated by KO+6. | |
| **Verification method** | Inspection |

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# Annex-1 mapping to SoW requirements

The following table shows the mapping of the requirements in this [RB] document to those of the original [SoW].

|  |  |  |
| --- | --- | --- |
| **SOW Requirement/objective/task** | **RB Requirement** | **Notes** |
| **Description** | **ID** |
| [REQ-1] Extend the *OceanFlux Evolution* FluxEngine to include other gasses including at least DMS, O2 and N2O and create V1.0 climatologies for each gas. | OceanFluxGHGEvolution-RB-REQ-16 OceanFluxGHGEvolution-RB-REQ-17 OceanFluxGHGEvolution-RB-REQ-18 |  |
| [REQ-2] Work together with the Surface Ocean CO2 Climatology (SOCAT) project team to help develop and apply SOCAT V3.0 data within the FluxEngine to generate improved global and regional estimates of CO2 flux. | OceanFluxGHGEvolution-RB-REQ-20 OceanFluxGHGEvolution-RB-REQ-24 OceanFluxGHGEvolution-RB-REQ-46 OceanFluxGHGEvolution-RB-REQ-47 |  |
| [REQ-3] Work together with the international community to maximise the number of ocean and atmosphere pCO2 data available to the Flux Engine in difficult areas including coastal, sea ice and open ocean upwelling areas, the Mediterranean Sea, the Black Sea and Arctic Ocean and other areas relevant to the OceanFlux Evolution project. | OceanFluxGHGEvolution-RB-REQ-46 |  |
| [REQ-4] Implement the NOAA-COARE model [e.g. RD-37] and other relevant air-sea gas transfer models within the FluxEngine, validate the new algorithm(s) using sensitivity experiments/validation analysis and produce new gas flux climatologies based on the new algorithms. | OceanFluxGHGEvolution-RB-REQ-16 OceanFluxGHGEvolution-RB-REQ-17 OceanFluxGHGEvolution-RB-REQ-35 |  |
| [REQ-5] Improve and validate parameterisations of bubble mediated gas transfer (i.e. solidify the scientific case) and implement the result into the FluxEngine including:   * 1. Specification of latitudinal variation in the parameterisation,   2. Investigate the impact of seawater foam-thickness on the parameterisation,   3. Investigate the impact of breaking waves on the parameterisation,   4. Investigate the role and impact of other relevant processes to the parameterisation. | OceanFluxGHGEvolution-RB-REQ-3 OceanFluxGHGEvolution-RB-REQ-26 OceanFluxGHGEvolution-RB-REQ-27 OceanFluxGHGEvolution-RB-REQ-30 |  |
| [REQ-6] Investigate the role and impact of wind/wave parameters on the spread of direct and indirect gas transfer method k curves at moderate to high wind speed. *i.e* can fetch/wind/Hs etc explain the spread of experimental data used to define k curves? | OceanFluxGHGEvolution-RB-REQ-3 |  |
| [REQ-7] Develop a strategy and implement method(s) within the Flux Engine to properly handle significant local/regional events that are not properly represented in spatio-temporal average gas flux products including:   1. upwelling events (coastal and equatorial), 2. strong extra-tropical cyclones (ETC) and Tropical Cyclones (TC), 3. significant biological blooms, 4. diurnal SST variability 5. precipitation 6. other local/regional events of significance to air-sea gas transfer. | OceanFluxGHGEvolution-RB-REQ-19 OceanFluxGHGEvolution-RB-REQ-20 OceanFluxGHGEvolution-RB-REQ-4 OceanFluxGHGEvolution-RB-REQ-5 OceanFluxGHGEvolution-RB-REQ-6 OceanFluxGHGEvolution-RB-REQ-7 |  |
| [REQ-8] Convene an *OceanFlux Evolution* scientific user group to assist the project during validation and exploitation of the output final products. | OceanFluxGHGEvolution-RB-REQ-40 OceanFluxGHGEvolution-RB-REQ-42 |  |
| [REQ-9] Design, implement and publish the results form a series of well-defined “Crowd Sourced” scientific ensemble experiments using the FluxEngine system to better understand and improve knowledge of uncertainties in air sea gas transfer products. | OceanFluxGHGEvolution-RB-REQ-2 OceanFluxGHGEvolution-RB-REQ-21 OceanFluxGHGEvolution-RB-REQ-22 OceanFluxGHGEvolution-RB-REQ-31 OceanFluxGHGEvolution-RB-REQ-34 OceanFluxGHGEvolution-RB-REQ-40 |  |
| [REQ-10] Produce and investigate global gas flux estimates and trends using the FluxEngine system by fully exploiting the natural variability captured by EO data (as specified in [REQ-7]) over a 10-year (or longer) time series. | OceanFluxGHGEvolution-RB-REQ-9 OceanFluxGHGEvolution-RB-REQ-15 |  |
| [REQ-11] Produce and investigate regional gas flux estimates and trends using FluxEngine system in the North Atlantic Ocean (where ocean pCO2 are more prolific) | OceanFluxGHGEvolution-RB-REQ-10 OceanFluxGHGEvolution-RB-REQ-15 |  |
| [REQ-12] Define and implement methods that quantify uncertainty in all *OceanFlux Evolution* output products. | OceanFluxGHGEvolution-RB-REQ-11 OceanFluxGHGEvolution-RB-REQ-12 OceanFluxGHGEvolution-RB-REQ-13 OceanFluxGHGEvolution-RB-REQ-14 OceanFluxGHGEvolution-RB-REQ-15 |  |
| [REQ-13] Produce and investigate regional gas flux estimates using the FluxEngine system in the Arctic Ocean (characterised by new open water/fetch conditions). | OceanFluxGHGEvolution-RB-REQ-8 |  |
| [REQ-14] Conduct a thorough scientific analysis of resulting gas flux products generated by the project and submit peer-review journal articles to relevant scientific journals. The project shall target the needs of the SOLAS community and the potential Intergovernmental Panel for Climate Change (IPCC) Assessment Review. | OceanFluxGHGEvolution-RB-REQ-2 OceanFluxGHGEvolution-RB-REQ-31 OceanFluxGHGEvolution-RB-REQ-40 OceanFluxGHGEvolution-RB-REQ-46 OceanFluxGHGEvolution-RB-REQ-47 |  |
| [REQ-15] Develop a suite of diagnostic metrics and assessments that can be used to monitor improvements to *OceanFlux Evolution* products. | OceanFluxGHGEvolution-RB-REQ-20 OceanFluxGHGEvolution-RB-REQ-31 OceanFluxGHGEvolution-RB-REQ-32 OceanFluxGHGEvolution-RB-REQ-33 |  |
| [REQ-16] Provide example code to read and display *OceanFlux Evolution* products, diagnostics, documentation for Masters students improved interface to the FluxEngine system) | OceanFluxGHGEvolution-RB-REQ-20 |  |
| [REQ-17] Provide tools to promote and manage *OceanFlux Evolution* science users including dedicated graphics and “media-ready” web resources, strong links and interactions with SOLAS and SOCAT, a professional web interface focussed on “the sale of OceanFlux Evolution products”, a user feedback and bug tracking system and other capabilities required to promote and develop the *OceanFlux Evolution* outcomes. | OceanFluxGHGEvolution-RB-REQ-34 OceanFluxGHGEvolution-RB-REQ-36 OceanFluxGHGEvolution-RB-REQ-37 OceanFluxGHGEvolution-RB-REQ-38 OceanFluxGHGEvolution-RB-REQ-42 OceanFluxGHGEvolution-RB-REQ-45 OceanFluxGHGEvolution-RB-REQ-22 |  |
| [REQ-18] Convene and hold a major air-sea gas transfer scientific workshop to report results from the project and to seek feedback form the international scientific community. | OceanFluxGHGEvolution-RB-REQ-41 OceanFluxGHGEvolution-RB-REQ-43 |  |
| [REQ-19] Fully exploit as much as possible suitable ESA data including Copernicus Sentinel satellites. It is recognized that the work to be performed will require access to non-ESA data sets and the Contractor shall exploit both ESA and non-ESA EO mission data, as and where appropriate to the work to be carried out. This project requires the use of historical data and the Contractor is encouraged to exploit the historical archives of ESA. | OceanFluxGHGEvolution-RB-REQ-23 OceanFluxGHGEvolution-RB-REQ-24 OceanFluxGHGEvolution-RB-REQ-24 OceanFluxGHGEvolution-RB-REQ-27 OceanFluxGHGEvolution-RB-REQ-28 OceanFluxGHGEvolution-RB-REQ-29 OceanFluxGHGEvolution-RB-REQ-30 |  |
| [REQ-20] Building on the outputs, knowledge and tools developed by the project, provide a roadmap of future activities based on the requirements of SOLAS and the international air-sea gas transfer, IPCC and other relevant communities. | OceanFluxGHGEvolution-RB-REQ-44 |  |
| [REQ-21] Submit peer-review journal articles to relevant scientific journals reporting scientific developments by the project. | OceanFluxGHGEvolution-RB-REQ-2 OceanFluxGHGEvolution-RB-REQ-40 |  |
| [REQ-22] Manage the *OceanFlux Evolution* project according to cost and schedule. | OceanFluxGHGEvolution-RB-REQ-38 OceanFluxGHGEvolution-RB-REQ-48 OceanFluxGHGEvolution-RB-REQ-49 OceanFluxGHGEvolution-RB-REQ-50 |  |

# Annex-2 Review

The information in the following sections was collated and used to underpin the decisions within the main document.

**Parameterising a bubble mediated gas transfer relationship**

In order to create a parametrization of bubble effect on air-sea gas transfer velocity one needs to parametrize the volume of bubbles created by wave breaking. One proxy commonly used for this is whitecap coverage. Most of its parametrization are wind speed dependent. A good review was provided by Angueolova and Webster (2006). From the review it was clear that the parametrizations are converging about the cubed power law. More recent papers also tend to propose variants of the cubed power law (Lafon et al. 2007, Sugihara et al. 2007) but also adding corrections for wave age dependance (Lafon et al 2007, Callaghan et al. 2008a) replacing wind speed with neutral wind speed (Callaghan et al. 2008b) or using energy dissipation instead of wind speed (Hwang and Sletten 2008). An approach avoiding using whitecap coverage and replacing it with a form of Reynolds number has been also proposed (Woolf 2005). A recent paper (Goddijn-Murphy et al. 2011) reviews all the approaches.

Another aspect affecting bubble effect on gas-transfer velocity are surfactants. They are present not only on the sea surface but also provide coating for bubbles affecting gas transfer to and from them. A review of present knowledge about sea surface microlayer microbiology was provided by Cunliffe et al. (2011). Frew et al (2004) tried to estimate the surfactant effect on gas transfer velocity. Tsai and Liu (2003) tried to estimate the global impact on gas air-sea exchange. A more recent study (Wurl et al. 2011) tried to create a global climatology of microlayers basing on the measurements available. Salter et al. (2011) described results of a controlled surfactant release on air-sea gas fluxes, providing the best data available up to now. Some recent reviews (Cunliffe et al. 2013, Garbe et al. 2014) discussed the state of knowledge on the effect of surfactants on air-sea interaction (although not in the context of bubbles) concluding the effect is still poorly constrained.

Any new parametrization would need verification using existing data sets. The best data sets involving eddy correlation measurements exist for DMS (Bell et al. 2012, Bell et al. 2013, Land et al. 2014). However due to the high solubility of DMS in sea water such data are not useable for studying the effect of bubble processes (Goddijn-Murphy et al. 2012, Garbe et al. 2014). Even as there exists a theory based estimation of the bubble effect for CO2 (Johnson 2010), few empirical data exist to validate the approach with the possible exception of the recent methanol and acetone measurements of Yang et al. (2014).

**Diurnal warming**

During the day, the upper 2 m of the ocean typically absorbs about 50% of the solar radiation reaching its surface. At night this layer then cools, losing heat to the atmosphere through radiative latent and sensible heat fluxes. This diurnal heating and cooling can lead to significant variations in the sea surface temperature (SST) (e.g., Stuart-Menteth et al., 2003; Gentemann et al., 2003) and thus also causes significant diurnal variations in the highly temperature sensitive carbonate parameters and air-sea CO2 fluxes.

Olsen et al. (2004) used AVHRR daytime and nighttime SST data to estimate the global effect of diurnal warming on CO2 fluxes. They estimated it to cause the global ocean uptake of CO2 to be more than twice as large during the night as during the day. Kettle et al. (2009) used a combination of EO from hourly SEVIRI SST data and models to study the impacts of diurnal cycles on air-sea CO2 fluxes over the central Atlantic. They concluded that neglecting this warming in the central Atlantic has a large effect on the estimated regional annual CO2 flux.

**Upwelling events (coastal, equatorial and cyclones)**

Through the process of wind driven upwelling dense cooler water, with a higher concentration of CO2 is upwelled (drawn up) from depth to the ocean surface. The higher concentration of CO2 within the upwelled water means that it is more acidic than the surrounding surface waters and so can have significant impacts on a region and ecosystem (Feely et al., 2008). This phenomenon is known to occur in a number of places around the world. Examples include the western coast of Portugal (e.g. Fiuza 1983) and large sections of the African coastline (e.g. Benguela). In many of these regions the cold water also contains higher concentrations of nutrients that help to increase phytoplankton growth, which in turn supports marine life and fisheries. Several studies have also shown that wind-driven upwelling occurs in open (ice-free) water along the continental shelf of the Beaufort Sea, which brings high pCO2 (low pH) deeper waters up onto the shelf, driving down the aragonite saturation state and causing outgassing of CO2 to the atmosphere (Mathis et al., 2012; Pickart et al., 2009;2011). Early work within OceanFlux-GHG highlighted instances of cooler upwelled water within the SOCAT database in the Galapagos Islands, since the monthly mean sea skin temperature was vastly different to the SST from the *in situ* dataset. As previously mentioned tropical cyclones or hurricanes are also known to causing upwelling of water in their path and Figure 5 shows evidence of cooler upwelled water (areas of blue) due to hurricane Katia in 2011 as viewed by the SMOS and Aquarius satellite sensors.

**Precipitation**

Rain can influence air-sea gas exchange by increasing surface turbulence (gas transfer velocity), direct wet deposition of CO2 to the surface waters, chemical dilution of the surface salinity and partial pressure of CO2 (pCO2) and through altering the temperature of surface waters. These latter two aspects can in turn alter the solubility of the gas and the change in temperature will in turn have a small impact on the gas transfer velocity.

Early work (Ho et al., 1997; Ho et al., 2000; Ho et al., 2004) highlighted how rain can significantly enhance gas transfer, provided the first parameterisation of rain-driven gas transfer velocity for freshwater environments and studied the physical mechanisms underlying this enhancement. The role of rain-induced turbulence as the main reason for rain enhanced gas transfer in saltwater systems was shown by a later study (Zappa et al., 2009). The combined effect of wind and rain has been studied in both the laboratory and in the field (Ho et a., 2007). Within the laboratory, rain was seen to alter the wind profile and dampen surface waves and rain and wind effects were seen to combine linearly to influence gas transfer velocity. Komori et al (2007) concluded that the global effect of rainfall on net air-sea fluxes was to increase the sink of atmospheric CO2 by <5%. Following this Turk et al., (2010) used laboratory derived parameterisations of wet deposition, rain induced k and surface pCO2 dilution to study their impact on air-sea fluxes in the western equatorial Pacific ocean through the use of a 1 dimensional model. More recently, Harrison et al., (2012) performed a number of experiments in the laboratory to show that rain can contribute significantly to the total air-sea gas flux at low wind speeds, whereas at higher wind speeds the effects become negligible. They also showed that rain and wind effects combine nonlinearly to enhance air-water gas exchange. OceanFlux-GHG built upon and extended the work of Komori et al., (2007) by applying recent conclusions and parameterisations to characterise the potential global and regional impacts that rain could have on monthly time scales.

Work prior to OceanFlux-GHG supports the need to study rainfall for regional fluxes, but for globally-integrated net fluxes it can be ignored. The work within OceanFlux-GHG showed that the impacts of rain should be included in the uncertainty analysis of studies that estimate net air-sea fluxes of CO2 as the rain can have a considerable impact on the fluxes, dependent upon the region and timescale. The inclusion of the ability to parameterise rain impacts within the FluxEngine is clearly needed.

**Tropical cyclones high wind speed events**

Tropical cyclones have profound effects on the air-sea flux of CO2, firstly by the significant increase in wind speed, and secondly by the ‘cold wake’ caused by the increased vertical mixing under the cyclone. The change in temperature results in a change in the partial pressure of CO2 in the seawater. As the cyclones pass over they entrain (or upwell) subsurface water into the mixed layer depth (Mahadevan et al., 2011).

Bates et al. (1998) found that Hurricane Felix in the Sargasso Sea (a region of CO2 outgassing) decreased pCO2w and SST, which between them reduced the difference in the atmospheric and oceanic partial pressure from +65 μatm to +15 μatm, thus reducing the regional out gassing of CO2. However, the increase in wind speed dominated the overall effect on the fluxes, resulting in a net outgassing effect over the duration of the hurricane of 40-135 mmol CO2 m-2. From this single field study they then estimated that hurricanes between 40°S and 40°N decrease the oceanic sink of atmospheric CO2 by 40-510 TgC yr-1, which assuming an oceanic sink of 2 PgC yr-1 equates to up to a 25% reduction in the global oceanic sink. In contrast Perrie et al. (2004) used a combined modeling and *in situ* study to estimate the effect on air-sea CO2 flux of Hurricane Gustav, which made landfall in Nova Scotia around 45°N in 2002. They estimated an increase in the sink with a peak of 2.1 mmol CO2 m-2 hr-1, hence concluding that mid-latitude storms with hurricane wind speeds were able to slightly increase the oceanic sink of CO2.

Due to the obvious difficulty in measuring fluxes within cyclones, there are only a limited number of studies characterizing the gas transfer velocity within hurricanes. Novel work by McNeil and D'Asaro (2007) using instruments dropped from aircraft in the predicted paths of hurricanes enabled the gas transfer velocity for nitrogen (N2) and oxygen (O2) to be determined. They highlighted and warned against studies using standard gas transfer relationships (e.g. Wanninkhof and McGillis, 1999) when studying air-sea gas fluxes due to hurricanes. Their work also enabled the first estimate of the hurricane bubble injection flux of CO2 as 0.26 mmol CO2 m-2 hr-1.

The cyclone-induced increases or decreases in the total CO2 gas flux are dependent on the dominating influence, e.g. increased efflux due to increases wind speed (Bates et al., 1998) and entrainment of deeper waters with higher carbon content versus decreased efflux due to lower sea surface temperature in the cold wake (Wanninkhof et al., 2007;D'Asaro et al., 2007) and potential phytoplankton blooms due to entrainment of deeper waters with higher nutrient content.

The datasets from the ESA SMOS+ storm project has recently processed the complete SMOS archive to study all hurricanes in the North Atlantic since the launch of the SMOS instrument. This provides an extensive dataset from which the effect of hurricanes on air-sea CO2 fluxes could be studied. We will build on this work by studying the high wind speed effects of tropical cyclones on the air-sea CO2 flux.

**Trends**

Understanding any trend in the oceanic sink of CO2 is key for enabling improved modelling of future climate scenarios and to guide government policy on reducing CO2 emissions (e.g. Le Quere et al., 2014). Current work to study trends and variability in ocean CO2 uptake, whilst advanced, are based mainly on modelling studies, with some studies including *in situ* data (e.g. Schuster et al., 2013). Therefore it is clear that information from all sources of data, *in situ*, models, and EO, should be exploited to study these trends and variability.

Compared to most of the major oceans, the pCO2 observations for the North Atlantic are more prolific and new data are being systematically collected (e.g. Bakker et al., 2014). As a result Watson et al., (2009) illustrated that the North Atlantic CO2 sink could be estimated and monitored to a precision of 10%. This work used solely *in situ* data to study the variability of the sink. Clearly more recent *in situ* data and EO data could be exploited to further this work towards studying the recent variability and any underlying trends in this region.

Improved estimates of the oceanic CO2 sink can be achieved; combining different methods will also improve the total (ocean and land) sink in e.g. the Northern Hemisphere.

### Arctic CO2 gas transfer within areas of broken ice

The Arctic Ocean covers a relatively small area (~10.7×106 km2) of the global ocean and ~53% of Arctic waters are broad and shallow (< 200m) continental shelves. Consequently the Arctic Ocean contributes only ~1% to the global ocean volume but it is nevertheless thought to account for 5-14% of the total oceanic sink for anthropogenic CO2 (Bates and Mathis, 2009), largely due to strong seasonal biological drawdown (Takahashi et al., 2009). Given this disproportionate contribution, its susceptibility to environmental changes that include rapid warming well above the global average (Polyakov et al., 2010;Purkey and Johnson, 2010), accelerating sea ice retreat (Kwok et al., 2009), increasing freshwater inputs (Dai et al., 2009) and changes to ecosystem structure and primary productivity (Arrigo et al., 2008;Pabi et al., 2008) affords the Arctic Ocean an important role in future ocean CO2 uptake.

The high uncertainty in the size of the Arctic Ocean CO2 sink reflects a paucity of coordinated *in situ* measurement campaigns and difficulties of logistical support in a remote and hostile environment, especially during winter ice cover (Bates and Mathis, 2009). Moreover, the heterogeneous nature of Arctic waters, especially on the continental shelves, will likely confound future efforts that may aim to improve this estimate by extrapolating from temporally and spatially limited *in situ* data alone. Clearly EO has a role to play in providing data to study the fluxes in these regions. Despite this, few studies have used EO data to estimate CO2 fluxes in Arctic oceans. Boutin et al. (2002) used EO wind data with climatological SST and fixed salinity to derive sea-air fluxes of CO2 at the global scale, which included the Arctic oceans. Arrigo et al. (2010) used EO ice cover and chlorophyll with model SST, salinity and wind speed and empirical relationships to estimate pCO2w and hence CO2 flux in the Arctic Ocean. OceanFlux-GHG (Land et al., 2013) used EO SST and wind speed with EO-derived sea ice fraction and climatological pCO2 and salinity to estimate CO2 fluxes in three Arctic seas.

As Arctic sea ice melts, large areas of open water are exposed in amongst the ice and these regions of open water can exchange CO2 with the atmosphere. This boundary CO2 flux has not been studied using *in situ* or remote sensing and so these regions of open water and the resultant air-sea fluxes are largely ignored within recent studies. The majority of recent studies use large spatial scale data so the regions in amongst sea ice are ignored or averaged out. This situation is not surprising as these regions are difficult to access for *in situ* studies and previous EO sensors were unable to make retrievals within areas of sea ice. A laboratory study by Loose et al (2009) and an *in situ* study of an Arctic polynya by Else et al (2011) both suggest that the flux from partially ice covered regions is greater than expected from a simple proportionality with open water area. It seems that flux is concentrated in the open water areas between ice covered areas.

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