ESA Support to Science Element

OceanFlux Greenhouse Gases Evolution

Workshop Proceedings and Report

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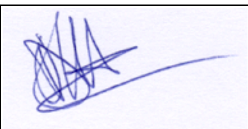
Lead Authors (PML)	Jamie Shutler (University of Exeter, UoE) Scientific lead	
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AMENDMENT HISTORY

Version	Date	Change Description	Author
1.0	29/11/2016	Structure and content	Jamie Shutler
1.1	13/03/2017	Added section on key conclusions from presentations and sessions	Jamie Shutler

DISTRIBUTION

Name	Company
Jamie Shutler	University of Exeter (UoE)
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Craig Donlon	European Space Agency (ESA)

Contents

1. 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 (CO_2) has been taken up, or absorbed, by the oceans. However the exact amount that the oceans annually absorb (sink) and whether or not this sink is tracking the increasing atmospheric levels is unclear.

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

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

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

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

The main results and outputs from this project will be:

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

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

Purpose and Scope

This is the Workshop Proceedings and Report (WKP) (deliverable D180) for the OceanFlux Greenhouse Gases Evolution project. It is intended to satisfy the original requirements for the WKP as specified by the ESA [SoW]. This document describes the International workshop (held in Brest, September 2016), the participants and the results from the discussions that took place during the workshop.

Structure of this Report

The report is structured as follows:

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

Contributions

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

Table 1 Table of contributions.

Section	Primary author(s)	Contributing author(s)
Section 1	Jamie Shutler (UoE)	
Section 2	Jamie Shutler (UoE)	
Section 3	Jamie Shutler (UoE)	David Woolf, Jacek Piskozub, Bertrand Chapron, Fanny Girard-Ardhuin, Andy Watson, Steve Jones, Ute Schuster, Mark Warren, Phil Nightingale, Peter Land, Lonneke Goddijn-Murphy

Reference documents

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

Table 2: Documents Referred to in this Report

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

Definitions and acronyms

AATSR	Advanced Along Track Scanning Radiometer (ESA instrument)
ATBD	Algorithm theoretical basis document
A_T	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
CO_2	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	European Regional Seas Ecosystem Model (and now global oceans ecosystem model)
ERI	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	Global Ocean Observing System
HWU	Heriot Watt University
IPCC	Intergovernmental Panel on Climate Change
ITT	ESA invitation to tender
IOPAN	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
$npCO_2$	pCO_2 normalized to a standard temperature
OA	Ocean acidification
OAPS	Ocean Acidification Product Suite
OSI-SAF	EUMETSAT Ocean & Sea Ice Satellite Application Facility
pCO_2	Partial pressure of CO_2
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 CO_2 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	United States of America
UoE	University of Exeter
WP	Work package
WPD	Work package description
WOA	World Ocean Atlas
ΔpCO_2	Difference between in-water pCO_2 and atmospheric pCO_2
Ω_A	Aragonite saturation state

2. Introduction to the workshop proceedings and report

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

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

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

The open discussion sessions within the workshop allowed areas of scientific importance to be debated and the identification of new opportunities. Topics discussed included the potential for multi-agency experiments, the need for fiducial reference measurements and the need for continued cross-disciplinary collaboration including the sharing of tools. These discussions took place during and at the end of the workshop, and have provided clear avenues for future work, that fit within the International Surface Ocean and Lower Atmosphere Study (SOLAS) scientific plans, aims and priorities, whilst also being relevant for agencies like the European Space Agency to support.

The workshop was a great success and this document is the workshop proceedings and report.

The workshop participants on day 3.

Aims and purpose

The atmosphere-ocean (air-sea) exchange of climate active gases, such as CO_2, N_2O, CH_4, DMS and CH_3Br is a critical part of the climate system and a major factor in the biogeochemical function of the oceans. More accurate and higher resolution calculations of these gas fluxes are required if we are to fully understand and predict the chemistry of our atmosphere and hence future climate. This endeavour requires the maintenance of major observing systems (shipboard, satellite-borne and land-based) and a deep understanding of the transfer processes. It is a challenging task that requires interdisciplinary collaboration and cost-effective solutions.

The European Space Agency (ESA) and the International Surface Ocean Lower Atmosphere Study (SOLAS) community came together in 2010 to support a new initiative in this area and the OceanFlux Greenhouse gas projects arose (http://www.oceanflux-ghg.org). At the same time, there have been enormous efforts internationally on collecting and collating data, strengthening and organising the measurement of dissolved gases (e.g. by LDEO and SOCAT) and exploring new methods of measuring and modelling the transfer processes and exchange coefficients.

In 2013, the first Air-sea Gas Fluxes workshop was held (http://www.oceanflux-ghg.org/Workshop/Workshop2013). The workshop was a great success and the participants identified the need for this interdisciplinary community to meet again in the future. Many advances have been made since 2013, so the project team invited the community back to a second international workshop in France in September 2016 to present recent advances and identify future goals and prospects.

Progress from the most recent OceanFlux project research was be presented. Renowned international scientists and groups presented overviews and results from key initiatives. Oral and poster presentations were given on **all aspects of air-sea gas transfer of any climatically important gases, including reactive gases.** We especially encouraged research focusing on: Arctic and marginal ice zones, extreme winds, atmospheric modeling, inversion techniques and heat fluxes. The workshop presented a picture of the existing capability in studying air-sea gas fluxes. Importantly, we also looked ahead to new challenges and opportunities. The European Space Agency and other funding agencies are setting their own priorities and strategies. This workshop was an important opportunity to rationalize and explain the priorities of the scientific community.

The ultimate aim of the workshop was to facilitate and accelerate the research and technology development necessary for an accurate evaluation of the air-sea flux of climate active gases, by identifying key challenges and opportunities and setting appropriate priorities for the scientific community and for supporting and guiding agencies (notably space agencies). The specific aims of the workshop were:

1. Identifying key challenges facing the air-sea gas flux community:

- Maintaining the ship-based observing system.
- Maintaining the marine earth observation capability.
- Addressing remaining gaps in fundamental knowledge.
- Understanding and addressing the full set of uncertainties.

2. Identifying opportunities and setting priorities:

- The requirements of the climate science and policy communities.
- New Earth observation technologies and missions.
- New measurement techniques and opportunities for more autonomous measurements.
- New modelling and statistical techniques.
- The rapidly expanding capacity of cloud and other computing architecture.

Organisation and committees

We had two committees for the organisation of the workshop:

- The **scientific steering committee** for defining the goal of the workshop, inviting people, reviewing the abstracts and building the agenda.
- The **organizing committee** for running the workshop and logistics.

Scientific steering committee members:

- Jamie Shutler, University of Exeter, UK (Chair)
- David Woolf, Heriot Watt University, UK
- Bertrand Chapron, Ifremer, France
- Jacek Piskozub, IOPAN, Poland
- Lonneke Goddijn-Murphy, Environmental Research Institute, Thurso, UK
- Andy Watson, University of Exeter, UK
- Craig Donlon, European Space Agency, The Netherlands
- Dorothee Bakker, University of East Anglia, UK
- Ute Schuster, University of Exeter, UK
- Phil Nightingale, Plymouth Marine Laboratory, UK
- Christian Roedenbeck, Max Planck Institute for Biogeochemistry, Germany
- Rik Wanninkhof, NOAA, US
- Chris Fairall, NOAA, US
- Magdalena Anguelova, Naval Research Laboratory, US
- Christa Marandino, GEOMAR, Germany
- David Ho, University of Hawaii, US
- Bill Asher, University of Washington, US
- Jacqueline Boutin, LOCEAN, France

Organizing committee members:

- Fanny Girard-Ardhuin, Ifremer, France
- Francine Loubrieu, Ifremer, France
- Audrey Abiven, Ifremer, France
- Denise Guillerm, Ifremer, France
- Swen Jullien, Ifremer, France
- Jamie Shutler, University of Exeter, UK
- Craig Donlon, European Space Agency, The Netherlands

- Diego Fernandez, European Space Agency, Italy
- Roberto Sabia, European Space Agency, Italy

Main tasks

The workshop logistics were organized at Ifremer in Brest, France. The main tasks included:

- identify key participants and advertise them (through other workshops, email lists, etc…).
- organize the local organization (booking of the facilities, logistical issues, accommodation and travel options…).
- manage the registration, submission of abstracts and communicate with the participants.
- oversee the selecting of oral and poster presentations (20 posters, 62 talks).
- organize the programme of the workshop.
- organize the grant applications.
- select grant awardees among the grant applications.
- organize media outputs during the workshop.
- make the presentations available on the project website.

A website has been dedicated to the workshop and it can be found here:

http://www.oceanflux-ghg.org/Workshop

Invitations

From within the OceanFlux GHG Evolution budget we were able to provide travel support to invited speakers:

- Dr James Butler, Director of the Global Monitoring Division, National Oceanographic and Atmospheric Administration (NOAA, US).
- Professor Sarah Gille, Scripps Institution of Oceanography, Southern Ocean Carbon and Climate Observations and Modelling (SOCCOM, US).
- Dr Brian Ward, Member of the International SOLAS Executive Committee (Ireland).

Thanks to additional support from ESA, we were also able to provide travel support for young researchers and early career scientists. 27 applicants applied and 7 were selected for awards. These were:

- Mr Matei (UK)
- Mr Markusewski (Poland)
- Mr Yang (UK/China)
- Mrs Pereira (UK)
- Mr Saket (Australia)
- Mr Butterworth (USA)
- Mr Hackerott (Brazil)

Workshop programme

Sessions overview and detailed agenda of the workshop are in the following table. There were oral presentations, sessions dedicated to discussions and two posters sessions.

Day 1 - Sept 6 – Tuesday		
08:10 - 08:50	Bus for Ifremer	
08:50 - 09:30	*Registration in the Hall*	
Welcome - Lucien Laubier Conference Room		
09:30 - 09 :40	Welcome	Jamie SHUTLER, Uni. of Exeter. UK. Diego FERNANDEZ, ESA, Italy
09:40 - 09:45	Welcome to Ifremer	Bertrand CHAPRON, Ifremer, France.
Session 1 Updates from International initiatives ***Chair : Phil Nightingale***		
09:45 - 10:15 **Keynote**	Surface Ocean Lower Atmosphere Study (SOLAS): Air-sea interface and fluxes of mass and energy	Brian WARD, AirSea Laboratory NUIG, Ireland
10:15 - 10:35	ICOS Ocean Thematic Center a tool to secure long term funding for ocean carbon system observation systems	Truls JOHANNESSEN, Geophysical Institute and the ICOS Ocean Thematic Centre, Norway.
10:35 - 10:55	The Surface Ocean CO_2 Atlas (SOCAT) enables quantification of the ocean carbon sink and ocean acidification	Dorothee BAKKER, Uni. of East Anglia, UK.
10:55 - 11:15	The ESA OceanFlux Greenhouse Gases Evolution project	Jamie SHUTLER, Uni. of Exeter, UK.
11:15 - 11:30	*Coffee break*	
Session 2 Regional processes in time or space ***Chair :***		
11:30 - 11:50	Air exposure of coral causes significant dimethylsulfide (DMS) emissions	Tom BELL, Plymouth Marine Laboratory, UK.

11:50 - 12:10	Strengthening trade winds and an enhanced Equatorial Pacific carbon source	Sarah SCHLUNEGGER, Princeton Uni., US.
12:10 - 12:30	Filling the gap of in situ CO_2 fluxes during low wind conditions	Mariana RIBAS RIBAS, Uni. of Oldenberg, Germany.
12:30 - 12:50	The other CO_2 problem: Studying Ocean Acidification using satellite Earth observation in the Amazon plume, Caribbean, Bay of Bengal, Arctic and globally	Jamie SHUTLER, Uni. of Exeter, UK.
13:00 - 14:00	*Lunch at Ifremer restaurant*	
Session 3 Resolving differences and exploiting linkages between regional and global air-sea exchange ***Chair :***		
14:00 - 14:20	Are open-ocean wind speed/gas exchange parameterizations applicable to coastal and inland waters?	David HO, Uni. of Hawaii, US.
14:20 - 14:40	On the fetch dependency of air-water gas exchange	Angelika KLEIN, IUP Germany,
14:40 - 15:00	Mind the Gap; Regional scale analyses are key to connecting process studies and global inventories	David WOOLF Heriot Watt Uni., UK.
15:00 - 15:20	Hourly to decadal variability of sea surface carbon parameters in the north western Mediterranean Sea	Jacqueline BOUTIN, LOCEAN/CNRS, France.
15:20 - 15:40	The effect of changing wind speeds on global air-sea CO_2 fluxes	Rik WANNINKHOF, NOAA, US.
15:40 - 16:00	Data-based estimates of the ocean carbon sink variability results of the Surface Ocean pCO_2 Mapping intercomparison (SOCOM)	Christian RODENBECK, MPI BGC, Germany.
Session 4 : First poster session and Welcome Cocktail ***16:00 – 18:30***		
18:30	Bus for Brest City Centre	

Day 2 - Sept 7 – Wednesday		
08:10 - 08:50	Bus for Ifremer	
Session 5 Multiple simultaneously measured gases I ***Chair : Dorothee Bakker***		
9:00 - 9:30 **Keynote**	Challenges in evaluating the influence of the ocean on atmospheric composition	Jim BUTLER, NOAA, US.
9:30 - 09:50	A newly developed equilibration system for continuous sea surface CO_2, CH_4 and N_2O measurements characterization and results from two cruises in the Benguela upwelling system	Jan WERNER, Institute for Baltic Sea Research, Germany
09:50 - 10:10	Measurements of air-sea gas transfer in upwelling filaments off Mauritania	Phil NIGHTINGALE, Plymouth Marine Laboratory, UK.
10:10 - 10:30	Air-Sea Fluxes of CO_2 and CH_4 from the Penlee Point Atmospheric Observatory on the South West Coast of the UK	Mingxi YANG, Plymouth Marine Laboratory, UK.
10:30 - 10:50	MEMENTO, the marine N_2O and CH_4 database: towards a new estimate of global CH_4 and N_2O emissions	Annette KOCK, GEOMAR, Germany.
10:50 - 11:20	*Coffee break & posters in the Hall*	
Session 6 Multiple simultaneously measured gases II ***Chair : Jim Butler***		
11:20 - 11:40	Air-sea gas transfer velocity for gases of different solubility (CO_2, O_2, H_2O and CH_4)	Anna RUTGERSSON, Uppsala Uni., Sweden.
11:40 - 12:00	Continuous measurement of CH_4 and pCO_2 in the Baltic Sea using off- axis integrated cavity output spectroscopy on a voluntary observation ship	Gregor REHDER, Leibniz Institute for Baltic Sea Research Warnemunde, Germany.
12:00 - 12:50 **(50 mins)**	**Open Discussion I (Multiple Gases): Can we do more with multiple gases? , what is needed to exploit them further? Should we be using Satellite observed atmospheric gas measurements?**	
13:00 - 14:00	*Lunch at Ifremer restaurant*	
Session 7 Physical controls on exchange - slicks, vertical water structure, motion, spray and heat ***Chair : Sarah Gille***		
14:00 - 14:20	Effect of surface contamination on isotropic-turbulence-driven interfacial gas transfer	Jan WISSINK, Brunel Uni. London, UK.

14:20 - 14:40	Towards improved estimate of turbulent heat flux over Global Oceans	Abderrahim BENTAMY, Ifremer, France.
14:40 - 15:00	Spatially-coherent organized motion in the upper ocean turbulent boundary layer: Langmuir circulation and ramp-like structures	Alexander SOLOVIEV, Nova Southeastern Uni., US.
15:00 - 15:20	Surfactant enrichment factors in the surface microlayer of the Atlantic Ocean: implications for air-sea gas exchange	Bita SABBAGHZADEH, Newcastle University, UK.
15 :20 -15 :30	*Short break*	
15:30 - 15:50	Surfactant control of air-sea gas exchange along an offshore coastal and open ocean transect: results from a laboratory gas exchange tank	Ryan PEREIRA, Heriot Watt Uni, UK.
15:50 - 16:10	Effects of near surface ocean gradients upon shelf sea air/sea gas exchange estimate	Richard SIMS, Plymouth Marine Laboratory, UK.
16:10 - 16:30	White cap measurements and parameterizations based on the dissipation source term	Oyvind BREIVIK, Met Norway, Norway
Session 8 : *Second poster session and coffee break* ***16:30 - 18:30***		
18:30 - 20:30 20:30	**Crepes at the Ifremer restaurant** Bus departure for Brest city	

Day 3 - Sept 8 – Thursday		
08:10 - 08:50	Bus for Ifremer	
Session 9 Novel measurements, techniques and datasets ***Chair : Christa Marandino***		
9:00 - 9:20	Copernicus and the Sentinels – New advances, satellite sensors and opportunities	Craig DONLON, ESA, The Netherlands.
9:20 - 9:40	Laboratory measurements of CO_2 transfer by capillary waves	Philippe BARDET, George Washington Uni., US.
9:40 - 10:00	Optical Measurement of very near-surface currents	Brian HAUS, Uni. of Miami, US.

10:00 - 10:20	Comparison of bubble plume data with wind/wave parameters, foam measurements, and carbon dioxide concentration	Adrian MATEI, Uni. College London, UK.
10:20 - 10:40	Eddy-Correlation fluxes measurements using the OCARINA autonomous platform during the BBWAVES 2015 cruise.	Louis MARIE, Ifremer, France.
10:40 - 11:10	*Coffee break & posters in the Hall*	
Session 10 ***Beyond proxies for parameterising gas exchange*** ***Chairs : Bertrand Chapron and Rik Wanninkhof***		
11:10 - 11:30	The retrieval of air-sea gas transfer velocity from space using the hybrid model	Lonneke GODDIJN-MURPHY, Environnemental Research Institute, UK.
11:30 - 11:50	Horizontal distribution of air-sea exchange parameters inferred from satellite images of sea surface roughness	Nicolas RASCLE, Ifremer, France.
11:50 - 12:50 **(1 hour)**	**Open discussion II (beyond proxies)** ***Can we now move beyond proxies for parameterising gas exchange?***	
13:00 - 14:00	*Lunch at Ifremer restaurant*	
Session 11 ***High latitude and Polar studies*** ***Chair : Brice Loose and Jamie Shutler***		
14:00 - 14:30 **Keynote**	Heat and carbon air-sea exchange in the Southern Ocean	Sarah GILLE, Scripps Institution of Oceanography, US.
14:30 - 14:50	Air-sea exchange of carbon dioxide in the Southern Ocean and Antarctic marginal ice zone	Brian BUTTERWORTH, Atmospheric Sciences Research Center, US.
14:50 - 15:10	Atmosphere-ocean gas transfer within areas of broken sea ice	Ian ASHTON, University of Exeter, UK.
15:10 - 15:30	Air-sea fluxes of CO_2 over a high latitude fjord in Greenland	Lise Lotte SORENSEN , Aarhus University, Denmark.
15:30 - 16:20 **(50 mins)**	**Open Discussion III: (polar regions)** ***Where can we gain most through synergy in Polar regions? Can we do more to study the links and flows between land-ocean-atmosphere?***	
16:20 - 16:50	*Coffee break & posters in the Hall*	

Session 12 ***Wave breaking*** ***Chair : Jacek Piskozub***		
16:50 - 17:10	On the variation of the effective breaking strength in oceanic sea states and its application to gas transfer	Chris ZAPPA, Columbia Uni., US.
17:10 - 17:30	Improved insights into whitecap foam evolution from laboratory breaking waves	Adrian CALLAGHAN, Scripps Institution of Oceanography, US.
17:30 - 17:50	Parameterizations of whitecap fraction: status update	Magdalena ANGUELOVA, Naval Research Laboratory, US.
17:50 - 18:10	Modulation of air-sea fluxes by microscale breaking waves	Peter SUTHERLAND , Ifremer, France.
18:20	Bus for Brest City Centre	

Day 4 – Sept 9 – Friday		
08:10 - 08:50	Bus for Ifremer	
Session 13 High winds ***Chair : David Woolf***		
09:00 - 09:20	Wind and wave forcing of gas transfer velocity from HIWINGS“ Results from the 2013 High Wind Gas Exchange Study in the Labrador	Chris FAIRALL, NOAA ESRL/PSD, US.
09:20 - 09:40	Detailed bubble plume measurements from the HiWINGS campaign, and reflections on the maximum possible contribution of subsurface bubble plumes to gas fluxes	Helen CZERSKI, Uni. College London, UK.
09:40 - 10:00	Air entrainment, and the dynamics and statistics of breaking waves: implications for field measurements of gas transfer	Ken MELVILLE, Scripps Institute of Oceanography, US.
10:00 - 10:20	How do tropical cyclones affect the global air-sea flux of CO_2 ?	Ute SCHUSTER, Uni. of Exeter, UK.
10:20 - 10:40	Performance of simple, single-parameter to complex, physical-based models of gas transfer velocity under high winds in varying sea state	Sophia BRUMER, Columbia Uni., US.
10:40 - 11:00	Investigating the mechanisms of air-sea gas exchange at hurricane wind speeds in wind/wave tunnel experiments	Kerstin KRALL, Institute of Environmental Physics, Germany.

11:00 - 11:20	*Coffee break*	
Session 14 ***Wave breaking and high winds*** ***Chair :***		
11: 20 - 11:40	Sea spray production by bag-breakup mode of fragmentation of the air-water interface at strong and hurricane wind	Yuliya TROITSKAYA, IAP RAS, Russia.
11:40 - 12:00	The distribution of sea spray spume particles observed above actively breaking wind- waves in the laboratory	David G.ORTIZ-SUSLOW, Uni. of Miami, US.
Session 15 ***Open Discussion*** ***Chair : Craig Donlon and Jamie Shutler***		
12:00 - 13:00 **(1 hour)**	**Open discussion IV (Continuing relationship) – The continuing ESA-SOLAS relationship, where and what next? What are the next frontiers? Should we continue with this workshop series? How can we raise the profile of this work? Collaborations with non-European partners and agencies (e.g. US).**	
13:00	*End of the meeting*	
13:00 - 14:00	*Lunch at Ifremer restaurant*	

Publications from the workshop

The program and the presentations are available on the website:
http://www.oceanflux-ghg.org/Workshop/Agenda/

Key conclusions from each presentation and session

Below are the key conclusions from each presentation. This information that has been collated from the presentation slides that are archived on the OceanFlux project website. Some presenters did not provide the slides for general distribution and some slides did not contain information on the conclusions of the work. In both of these cases, no conclusions are listed below. Slight changes to the presenters and order of presentations occurred (due to last minute cancellations and travel issues) so not all of the presentation conclusions below are listed in the final programme (given in the previous section of this report).

Session 1 Updates from international initiatives

Johannessen:

Title: ICOS Ocean Thematic Center a tool to secure long term funding for ocean carbon system observation systems

The integrated carbon observing system Ocean Thematic Center now exists. Run as a partnership between UK, Norway and Germany. Intention is to determine regional air-sea CO_2 fluxes on seasonal timescales to within 0.2 Pg year^{-1}

Bakker:

Title: The Surface Ocean CO_2 Atlas (SOCAT) enables quantification of the ocean carbon sink and ocean acidification

Surface Ocean CO_2 atlas (SOCAT) data collection and release is now aligned with the global carbon project. SOCATv4 has been released based on a more automated quality control methods. V5 will be available in 2017 (and will include additional carbonate parameters). Now >140 peer reviewed papers that have used SOCAT data. SOCAT was included in the 2016 global carbon budget assessment.

Shutler:

Title: The ESA OceanFlux Greenhouse Gases Evolution project

Two ESA oceanflux projects have been funded, resulting in advances in understanding, methods, gas exchange parameterisations, open source tools, open source data and 12 journal publications. These tools and data are now being used within undergraduate teaching, 3 PhDs, 3 other (non-ESA) funded projects and will support ICOS activities within two EU initiatives.

Session 2: regional processes in time and space

Bell:

Title: Air exposure of coral causes significant dimethylsulfide (DMS) emissions

Corals are a large but poorly understood source of sulphur in the tropics. Corals can produce and consume reduced sulphur species at high rates. Aerial exposure of corals may have a potentially important impact on DMS and atmospheric chemistry in the tropics.

Schlunegger:

Title: Strengthening trade winds and an enhanced Equatorial Pacific carbon source

Initial condition large ensemble and multi-model experiments with Earth System models indicate natural variability has produced much of the data-based regional trends in the ocean carbon sink over the past 2 decades. Model bias in decadal variability of Equatorial Pacific wind stress is a candidate cause of the disagreement between data-based estiamtes and modelled trends in the ocean carbon sink in this region.

Ribas Ribas:

Title: Filling the gap of in situ CO_2 fluxes during low wind conditions

New drifting buoy is a powerful tool to improve our understanding of gas transfer velocity through in situ measurements. Integrated system described can be use to correct for artificial turbulence due to buoy's movement. High temporal (every 40 minutes) and spatial resolution measurements are possible. Providing new insights into k parameterisation, especially for low wind speeds. Demonstrated by deployment in the Baltic Sea during the summer.

Shutler:

Title: The other CO_2 problem: Studying Ocean Acidification using satellite Earth observation in the Amazon plume, Caribbean, Bay of Bengal, Arctic and globally

The salinity-alkalinity relationship can be explored using satellite observations. Globally satellite driven methods perform as well as all other methods (Earth System Model and in situ). In the Caribbean satellite results are near identical to that of in situ methods. In the Amazon plume region satellite observations can outperform other methods. We are now preparing the data for public release.

Session 3: Resolving differences and exploiting linkages between regional and global air-sea exchange

Klein:

Title: On the fetch dependency of air-water gas exchange

Annular aeolotron gives interesting insight into the fetch dependency of air-sea gas transfer. With its basic geometry, measurements at short fetches (0-27 m) and infinite fetch can be simulated. Predominant wavelength with finite fetch leads to early onset of microscale breaking. Now plan to develop the capability to determine the local gas transfer velocity and compare the results with active thermography.

Woolf:

Title: Mind the Gap; Regional scale analyses are key to connecting process studies and global inventories

The success of models of K at regional and seasonal scales is essential but unproven. Validation of fluxes and transfer velocities at regional and seasonal scales is essential e.g. by revisiting previous work (new air-sea flux calculations and deep open measurements and choice of region). New tracers and validation work is needed. Deep ocean validation is intrinsically 'multi-year' but there is a need for seasonal validation. Focussed laboratory experiments on the effect of wave development are needed.

Boutin:

Title: Hourly to decadal variability of sea surface carbon parameters in the north western Mediterranean Sea

During summer the western Mediterranean Sea is very stratified, therefore there is a need to measure the pCO_2 as close as possible to the surface otherwise strong impact of inertial waves. Monitoring high frequency variations is also needed (due to the high influence of wind). For the first time surface ocean measurements support the hypothesis of another source of anthropogenic carbon than the atmosphere in the Mediterranean Sea – source from the Atlantic Ocean through the Gibraltar Straight. Clear importance and need for long-term monitoring of high frequency variability of pCO_2.

Wanninkhof:

Title: The effect of changing wind speeds on global air-sea CO_2 fluxes

Global winds in the CCMP-2 product have increased by about 0.4 ms^{-1} over 26 years. Largest regional change is in the Equatorial Pacific with an increase in 0.7 ms^{-1}. Cange in global air-sea CO_2 fluxes is relatively small due to the compensation of increases and decreases. Difference in quadratic and polynomial parameterisations has a small effect on the trend in global scale fluxes with quadratic showing an increase in efflux and hybrid model showing no trend. Effect of changes in wind is generally much smaller than impacts of changing $DpCO_2$ on fluxes with the direction of the trend (~0.015 Pc C $decade^{-1}$) being opposite and much smaller than the trend caused by changes of $DpCO_2$ (-0.15 – 0.35 Pg C $decade^{-1}$).

Roedenbeck:

Title: Data-based estimates of the ocean carbon sink variability results of the Surface Ocean pCO_2 Mapping intercomparison (SOCOM)

We have quantified the variability in ocean biogeochemistry from data. Multiple constraints (surface pCO_2, atmospheric CO_2, atmospheric O_2/N_2 and combined through a mixed-layer scheme). Yearly CO_2 flux is well constrained seasonally and the inter-annual variation is well constrained. Results are robust as they have been achieved using complementary methods.

Session 5: Multiple simultaneously measured gases I
Butler:

Title: Challenges in evaluating the influence of the ocean on atmospheric composition

Clear utility and advantage in studying a range of gases to understand exchange controls and parameterisations.

Yang:

Title: Air-Sea Fluxes of CO_2 and CH_4 from the Penlee Point Atmospheric Observatory on the South West Coast of the UK

Penlee point observatory is suitable for collecting eddy covariance measurements between coastal sea and atmosphere. CO_2 and CH_4 fluxes are highly variable. CH_4 flux appears to be tidal dependent. Picarro method has better precision and a lower flux detection limit than Los Gatos Research approach.

Kock:

Title: MEMENTO, the marine N_2O and CH_4 database: towards a new estimate of global CH_4 and N_2O emissions

N_2O is mainly supersaturated in the surface ocean with elevated emissions from upwelling areas, Southern ocean North Pacific (which are consistent with Nevison et al., 2004). N_2O emissions from Peru upwelling and West Indian shelf are one order of magnitude higher than from other upwelling areas. Areas with under-saturation are the high latitudes and subtropical gyres. CH4 emission estimate is based on bottom depth, leads to a conclusions that there is a small oceanic contribution to emissions.

Session 6: Multiple simultaneously measured gases II
Rutgersson:

Title: Air-sea gas transfer velocity for gases of different solubility (CO_2, O_2, H_2O and CH_4)

need more studies in a variety of basins and conditions for different gases to improve our understanding of the different processes controlling exchange. Limited size basin with land influence and non-wind driven processes are more important. Different solubility means that different processes act differently.

Session 7: Physical controls on exchange – slicks, vertical water structure, motion, spray and heat

Wissink:

Title: Effect of surface contamination on isotropic-turbulence-driven interfacial gas transfer

Surfactant transport is largely unaffected by the amount of diffusivity. Even low levels of contamination can have a large effect on interfacial gas flux. With increasing Reynolds numbers Ma/We (Marangoni number, Ma and Weber Number, We), the surface divergence becomes progressively damped. Resulting in a quick transition a K related to Schmidt^(-2/3) which is typical for a no-slip surface (shear). At lower Reynolds numbers Ma/We areas on the surface will develop with a zero surfactant concentration.

Bentamy:

Title: Towards improved estimate of turbulent heat flux over Global Oceans

The HeatFlux project now has a consolidated set of requirements for heat flux products, a standardized/consistent set of heat flux data and an ensemble data with uncertainty information. All is available through the project website (http://www.oceanheatflux.org) website includes on-in inter-comparisons, heat flux calculations and sensitivity tests.

Soloviev:

Title: Spatially-coherent organized motion in the upper ocean turbulent boundary layer: Langmuir circulation and ramp-like structures

We report a previously unknown mode of Langmuir circulation, which is coupled with ramp like structures. This coupled model is locked to the wind (but not wave) direction. Computational fluid dynamics model incorporating the wave-breaking turbulence has been able to reproduce both the Langmuir circulation and ramp like structures, coexisting in space but intermittent in time. Under developing seas (including high wind speed conditions), the new model can complement or compete with the traditional model of Langmuir circulation.

Sims:

Title: Effects of near surface ocean gradients upon shelf sea air/sea gas exchange estimate

The design of a near-surface ocean profiler improved the depth resolution with which gradients can be measured. Chemical gradients of CO2 have been observed. They appear small (1-2 uatm) and larger gradients are infrequent. Gradients appear to be correlated to favourable low wind high radiance conditions.

Breivik:

Title: White cap measurements and parameterizations based on the dissipation source term

The manual spatial separation of whitecap pixels (SSWP) method is found to accurately distinguish between stage A and stage B whitecaps. The Kraan et al., (1996) parameterisation is found to yield a good parameterisation of the total whitecap coverage. Re-running the wave model improved the results compared with using ERA-interim estimates with six-hourly resolution. The parameterisation is straightforward to implement as it only relies on integrated parameters.

Session 9: Novel measurements, techniques and datasets

Donlon:

Title: Copernicus and the Sentinels – New advances, satellite sensors and opportunities

Collectively the ESA Meteorological programme, the sentinel missions and the Earth Explorer missions provide and are continuing to provide a huge range of high quality observations and measurements that are directly applicable to studying and quantifying air-sea exchange. The Sentinels will continue to provide observations for the next 10-15 years (at least) and so these datasets are a potential goldmine for supporting air-sea exchange research and all data are open and freely available for use.

Haus:

Title: Optical Measurement of very near-surface currents

Wavenumber-frequency spectral analysis of short-scale ocean waves allows a glimpse of the near-surface current profile without disturbing the air-sea interface. This method can be performed aboard a moving vessel, offering remote determination of the near-surface current under certain conditions. Use of these techniques reveals a strong, near-surface current that may depart significantly from background flows, apparently orientating into the observed wind stress direction.

Marie:

Title: Eddy-Correlation fluxes measurements using the OCARINA autonomous platform during the BBWAVES 2015 cruise

New affordable IMUs can provide data of suitable accuracy for correction of turbulent measurements from even very small and dynamic platforms. The instantaneous signal (not just low-order statistics) now deserves to be looked at. OCARINA is a very good platform for such studies. The physics in stable boundary layers has more structure than self-similarity could easily account for. The Iroise Sea is a place where stable atmospheric boundary layers can readily be observed. The PDF of fluxes in non-Gaussian, but a generic PDF with this shape exists.

Session 10: Beyond proxies for parameterising gas exchange
Goddijn-Murphy:

Title: The retrieval of air-sea gas transfer velocity from space using the hybrid model

air-sea gas exchange can be retrieved using space measurements using a hybrid model. Performance has been shown to at least equal that of in situ approaches. Ko from satellite altimeter, Kb from the bubble model and whitecap. Whitecap can come from satellite winds, brightness temperature or a numerical model. Method is applicable to any gas.

Rascle:

Title: Horizontal distribution of air-sea exchange parameters inferred from satellite images of sea surface roughness

At scale <5km surface roughness is related to current gradients. Surface roughness variations occur mainly around fronts with divergence or strain in the wind direction. Observations during LASER 2016 shows large mean square slope variations at scales from 1 km down to 50 m. If transfer velocities are correlated to mean square slope (i.e. short waves), export towards the ocean interior might be concentrated around oceanic fronts. Therefore, oceanic fronts could account for regional/seasonal variations in gas transfer.

Session 11: High latitude and polar studies
Gille:

Title: Heat and carbon air-sea exchange in the Southern Ocean

Ocean heat content from Argo is consistent with seasonal cycle of air-sea heat flux. Long-term imbalance implies 0.5 Wm^{-2} input. Mechanisms governing fluxes need focussed approach; targeted by SOOS Working Group on air-sea fluxes; do we need more moorings?, user more satellite data?, or exploit wave gliders?

SOCCOM designed to study CO_2 flux. Biology plays a role, so change in CO_2 content doesn't imply CO_2 flux. Estimates of SOSE and from floats is not in agreement. Are more floats needed? What about Global? Infer fluxes from SOCCOM floats? This is also an objective for SOOS Working Group, but measurement methods and requirements will need discussion.

What would be transformative? Global biogeochemical Argo, new low-cost sensors for biogeochemical cycles? In situ process studies resolving eddy-scale fluxes of heat and gases, more global pCO_2 observations and biogeochemical Argo.

Butterworth:

Title: Air-sea exchange of carbon dioxide in the Southern Ocean and Antarctic marginal ice zone

First unattended eddy covariance CO2 fluxes in Southern Ocean and Antarctic sea ice zone. Quadratic dependence of open ocean gas transfer velocity on wind speed. Gas exchange in sea ice zone proportional to fraction of open water.

Ashton:

Title: Atmosphere-ocean gas transfer within areas of broken sea ice

The open source FluxEngine toolbox has now been extended to allow increased spatial resolution analyses and projections (e.g. polar stereographic at ~25 km spatial resolution) and it now includes additional physically derived gas transfer models (e.g. NOAA COARE and Loose et al., 2014). The FluxEngine toolbox provides an indeal platform for evaluating the sensitivity and impact of different gas transfer and flux parameterisations in polar regions. The spatial resolution of ice coverage datasets can introduce differences (errors) in the derived air-sea gas fluxes of between 0-9%. For 2012 the highest errors in the Arctic occur in July with the smallest in November.

Soerensen:

Title: Air-sea fluxes of CO_2 over a high latitude fjord in Greenland

We do see increased upward LE flux, downward H and low RH in periods with large upward CO_2 fluxes. Our data and measurement results are consistent with the theory of Andreas et al. In order to further test the theory we need measurements of sea spray fluxes for different particle sizes and low (minimum) water temperatures.

Session 12: wave breaking
Tournadre:

Title: What can we learn from Ku- and C-band surface backscatter?

Co-located dual Ku and C band satellite altimetry can be used to study air-sea exchange processes. Extensive archives exist (1992-present). These archives can be used to study the location and frequency of i) current-wave interactions (e.g. strong currents like the Gulf

Stream), ii) surface films (e.g. tropical equatorial regions), iii) wave fetch (e.g. southern ocean) and iv) rain freshening (indo-pacific equatorial).

Anguelova:

Title: Parameterizations of whitecap fraction: status update

Improvements in digital photography and processing algorithms can and are being applied to the problem of parameterising whitecap fraction. Data now have less noise and whitecap fraction parameterisation responses are now more closely clustered. New advances (e.g. measurements at different and multiple frequencies, from satellite, aeroplanes and ships, infra-red measurements) are leading to new measuring techniques and parameterisations that include more variables than ever before.

Sutherland:

Title: Modulation of air-sea fluxes by microscale breaking waves

Small scale breaking is dynamically important (e.g. for surface renewal, stress and dissipation). When small-scale breaking is included, wave dissipation can be balanced with dissipation by breaking, and measured wind stress can be balanced by momentum flux by breaking over a broad range of conditions. Energy is dissipated very near to the surface; the majority of the energy is dissipated at depths < Hs (significant wave height) from the sea surface. We have developed a new method to measure the turbulent kinetic energy (TKE) dissipation at the wavy sea surface.

Session 13: high winds
Ardhuin:

Title: Numerical wave modelling today and tomorrow

For numerical wave modelling, different forcing and parameterisations produce different results. There have been many rapid improvements in modelling wave-ice interactions. To improved small-scale variability in numerical modelling schemes requires realistic measurements of small-scale currents. These models can be used to investigate air-sea fluxes and whitecapping, but more validation work is needed. Large amount of model output is now freely available at ftp://ftp.ifremer.fr/ww3/HINDCAST

Reul: A new generation of extreme wind speed measurements from space borne L- and C-band passive radiometers

There is a clear satellite SMOS (L-band) brightness temperature signal associated with the passage of tropical cyclones. L-band signal is correlated with cyclone intensity, from Category 1 to Category 5. L-band observations provide the first non-atmosphere corrupted view of the ocean surface in these extreme conditions (wind retrieval with ~5 ms^{-1} accuracy up to wind speeds of 50 ms^{-1}. SMOS can retrieve important structural surface win features within hurricanes such as the radius of wind speed larger than 34, 50 and 64 knots. These are key parameters to monitor tropical cyclone intensification. An extensive database of storms has been developed for tropical and extra-tropical cyclones storms for 2009-2016 and is freely available to the international community. SMOS wind speed data assimilation experiments at the UK Met Office will be performed to investigate the data impact on storm track and intensity forecast skill.

Krall:

Title: Investigating the mechanisms of air-sea gas exchange at hurricane wind speeds in wind/wave tunnel experiments

Comparison between lab and field data confirms that the essential mechanisms are replicated in the lab. At high wind speeds (>35 ms^{-1}) a new regime exists with much steeper increase in the gas exchange transfer velocity (which agrees with previous studies). In fresh water, bubble effects for all gases are very small, likely negligible for CO2. In salt water, up to 95% increase in gas transfer velocity found for the lowest solubilities. No increase was found for solubilities about ~1. So bubble effects for CO_2 are likely be small, even in salt water. No limited transport velocity for DMS observed. These results have yet to be confirmed in the field (for real salt water).

Session 14: wave breaking and high winds

Troitskaya:

Title: Sea spray production by bag-breakup mode of fragmentation of the air-water interface at strong and hurricane wind

Statistical analyses of sequences of frames of high-speed video has enabled us to prove that the dominant spray generation mechanism in extreme wind is related to the bag-breakup fluid fragmentation regime. It activites at conditions corresponding to force 8 wind and manifests as spindrift. Starting from general principals of physics, we have developed the statistics of the bag-breakup events and determined the spray generation function, which is in good agreement with available experimental data. Giant droplets generated by bag-breakup significantly contribute to enthalpy and momentum flux: they increase the air-sea enthalpy flux at hurricane wind speeds, and they enable the explanation of non-monotonous dependence of surface drag coefficient on wind speed peaking at 35-40 ms^{-1}. Spray can be the main contributor to gas exchange in storms.

Key issues discussed in the open discussions

Four open discussion sessions were included in the main programme. Detailed minutes from these discussion sessions that occurred during the workshop are given in Annexes (Section 4) of this document. In addition to these there were also opportunities for further discussions during the two poster sessions. Here follows an analysis of the issues and topics that either provoked intensive discussions and/or issues that came up in discussion multiple times. The evidence for this analysis is found in Section 4 of this document.

1. Beyond proxies

There is now clear support from the community about the need to move away from relying on wind as a proxy for air-sea gas exchange. There are instances when this works well, but there are also considerable limitations in using this approach. Advancements in understanding (other descriptors of turbulence that out perform wind based approaches), and technology (e.g. ship borne mean square slope sensors) since the 2013 workshop mean that we are now in a good position to investigate better proxies and ultimately move towards a better understanding of the physics. Remote sensing has a clear role to play here in guiding the selection of ship borne measurements to be directly comparable to that observable from space and the ability to run large spatial scale sensitivity analyses to investigate the impact of new gas exchange relationships and understanding.

2. Polar regions (Arctic and Southern Oceans)

The polar-regions (Arctic and Southern Oceans) are critical for maintaining global oceanic and atmospheric circulation. Their cold waters have the potential to be significant sinks of CO_2, but how these waters and their sinks will change in the future is still unclear. The inhospitable and often dangerous nature of the Southern Ocean makes use of traditional observational platforms more difficult, enhancing the importance and impact of satellite observation efforts. Despite these issues, this area of science if often dominated by in situ and field studies. As is always the case, further evaluation of the quality of remote sensing data in these regions will help encourage future uptake and exploitation of remote sensing data. However, much more is possible now, such as the routine provision of air-sea exchange relevant observations to the international community, finer spatial scale evaluation of ice flows and the use of remote sensing data for sensitivity analyses to demonstrate how conflicting viewpoints within the international community overlap and complement each other. There is potential for any work to support and participate in the Year of Polar Prediction (YOPP, 2017-2018) activities and initiatives. The exploitation of Atmospheric potential Oxygen to estimate Arctic air-sea gas fluxes (primary production from remote sensing observations would be needed) is likely to provide a complementary approach to traditional gas transfer focussed methods and the enclosed nature of the Arctic provides an ideal place to exploit this approach.

3. High winds (including polar lows)

There is a continued need to understand and evaluate air-sea exchange in high winds (> 15 ms^{-1}) and related uncertainties. Global analyses (e.g. for GCP, IPCC) focus on monthly analyses that are likely to miss the impact of these events. The full impact of high wind systems (hurricanes, cyclones and polar lows) on the air-sea gas fluxes has yet to be determined and characterised. Impacts include modulated gas transfer, vertical mixing in the water column, cold wakes and entrainment of nutrients. (Note: The Oceanflux GHG

Evolution project has characterised the partial impacts of hurricanes in the north Atlantic demonstrating the potential of using EO for this sort of analysis). Polar lows have yet to be studied and may well have a greater impact than hurricanes (as they are more frequent and occur in waters considered to be important a CO2, due to its low temperature). This topic was also highlighted at the workshop in 2013 and advancements in instrumentation and analysis have now been made. However, much work is still needed. The early OceanFlux Evolution work has demonstrated that tools exist to investigate these issues (ranging from Earth Observation through in situ measurement, physical modelling and numerical modelling). Novel high wind instrumentation and datasets (including bubble plume data) now also exist (e.g. form the NASA/NERC HighWinds experiments).

4. Land-estuarine-ocean connections from large river systems (including the Arctic rivers)

The issues of freshwater inputs from large river systems and rain and their impact on CO_2 other gases was discussed. This links with Ocean Acidification research. The flow of dissolved organic matter (DOM) from land to the ocean will modulate the potential for the marine environment to take up CO_2 from the atmosphere. Large river systems that could be studies using remote sensing include the Amazon and those in the Arctic.

5. Marine carbon observing system and supporting SOCAT, GCP and ICOS

This topic was highlighted in the workshop in 2013 and some advances in this area have now been made. But more work is needed to help support efforts like the recent Paris agreement on climate change mitigation. There is therefore a continued need for a marine carbon observing system i.e. as part of, or to support, the International Carbon Observing System (ICOS). EO has a clear role to play in developing a capability. Programmes like Copernicus (EU), EOS (US) and also ESA Earth explorer satellites like SMOS have a role to play in this. The open source FluxEngine toolbox could be a component of such a system. Efforts towards the continued development of a "marine carbon observing system" was endorsed by delegates. The existing marine component lags behind other elements of the global carbon observing system and the importance of the ocean component in enabling the global budgets to be balanced needs to be demonstrated and highlighted to policy makers.

6. International cross-agency campaign towards a fudicial measurement dataset

The need and support for international cross-agency campaigns to fully evaluate new understanding and to underpin future advances was strongly endorsed by participants. Such a dataset could be steadily grown over multiple campaigns and used as a reference dataset for future advances. Platforms and initiatives already exist that could exploited to provide logistics and berths (e.g. the UK AMT programme runs a ship through the Atlantic each year and berths can be applied for). Novel and specialised instrumentation needed already exists within participant laboratories. This would enable the construction of a large fudicial dataset (including bubble cameras, mean square slope, SST vertical profiles (skin and foundation), fluxes from multiple gases, eddy covariance methods etc) for air-sea gas exchange to be exploited by the international scientific community. ESA, NASA, NOAA involvement will ensure that measurements relevant and directly comparable to remote sensing are collected (rather than proxies). The need for this was touched upon in the workshop in 2013, but community support for this is now (at the 2016 workshop) much stronger. This would also help underpin and support all key areas listed here, especially point 3 (a remote sensing based marine carbon observing system). Any experiments would benefit from a range of data collection techniques at varying temporal and spatial scales (e.g. microwave sensors onboard vessels during cruises, drone/satellite data to investigate the footprint and origin of eddy covariance flux observations).

7. Sharing of tools, software and use of standard formats

There is a clear need for the community to use standard techniques and data formats. Other scientific communities are doing this, whereas the flux community has been slow to follow this approach. The situation is improving, but further sharing of common tools will help accelerate scientific advances e.g. binning tools that both CO_2 (SOCAT) and N_2O/CH_4 (Momento) community use and/or need. This includes sharing/using common ancillary datasets.

8. Further scientific workshops to underpin interdisciplinary collaboration

A number of disciplinary communities are interested in the air-sea flux of CO_2. There is a clear need for the broader air-sea CO_2 flux community to meet frequently to learn from each others' work and advances. This workshop has re-highlighted the benefit of such communication. This approach can be used to help pool resources and focus effort (and to avoid duplication). This topic was also identified in the scientific workshop in 2013 and the beneficial nature of the scientific workshop series was highlighted again. The key to success was to avoid overlapping (in time) with other workshops. Note: some advances presented at the 2016 workshop were first identified as key foci at the 2013 workshop.

3. Conclusions

The discussions during and at the end of the workshop have provided clear avenues for future work that fit both within the International SOLAS plans and aims, and are within the scope of work that the European Space Agency are keen to support.

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

4. Annex 1 – Minutes from the discussion sessions

Open discussion I (Multiple gases)

Gregor Ryder: why not use N2O, CH4 measurements to look at k. would this be a useful multiple gas tracer experiment?

David Woolf: Helium3 if k is only dependent on Sc. If solubility is important then yes other gases are useful e.g. methane has 25% of the solubility of CO2.

Jamie Shutler: can we use EO data over the land (at the coast) for coastal estimate of CO2 sink? E.g. MingXi Yangs work at a land based observatory was able to estimate the Co2 sink for a portion of the UK coastal water.

Andy Watson: need fluxes at high precision so unlikely from EO. But you could look at changes in gases that are flowing over the ocean.

Christian Rodenbeck: need to overcome the fact that the EO data are column integrated values and the precision/accuracy of these data is quite low.

Jim Butler: complexity involved in movement at the integrated value (ie you are seeing the result of changes at different heights through the column).

Jim Butler: what can or needs to be done to improve existing databases and collation efforts in relation to multiple gases?

Gregor Ryder: should and do databases share data and overlap? Where should I send my data as I don’t really want to send it everywhere?

Dorothee Bakker: SOCAT is international and communicates with ICOS.

Tom Bell: keep data separate, should really be science driven.

Annette Kock: difficult to share daa between databases. Requires more cooperation between groups and databases.

Jamie Shutler: would sharing tools make things easier (rather than sharing data)?

Tom Bell: yes!

Rik Wanninkhof: sharing some parameters and data, sharing tools and ancillary parameters would all be useful.

Brice Loose: is this hard/difficult to actually do?

Dorothee Bakker: its difficult due to the time limitation on software developers. Ie someone has to actually write, test and fully evaluate any tools.

Jamie Shutler: using standard data formats is also important.

Christian Rodenbeck/Jim Butler: data quality controlling is more important than format.

Jim Butler where can we put data for sharing (i.e.. to share anciallary parameters and data)?

Craig Donlon: Oceanflux can act as a holding bay for ancillary data.

Ute Schuster: SOCAT, GLODAP – bottomup initiative, community coming together to make data available. Time and effort involved.

Jacqueline Boutin: salinity on CO2 not as accurate as needed for salinity measurements for EO verification, but should we co-ordinate with the salinity communities? Form links between datasets and different community efforts?

Christian Rodenbeck: one stop shop not needed. Some initiatives already exist. So work on data as this is the bottle neck.

?[male]? – Copernicus services provide data on different grids, spatial and temporal resolutions. Temporal resolutions are problematic.

Open discussion II (Beyond proxies)

Brian Haus : one side of a front can be breaking, the other could be slick. Has anyone tried to understand how they will average out? (from space).

MingXi Yang: aircraft data would be useful for understanding eddy covariance. E g. understanding the footprint of eddy covariance data.

Jamie Shutler: geolocation for aircraft data is challenging but is possible.

Brian Haus: has test data of eddy covariance and surface roughness.

Rik Wanninkhof: what description of turbulence is useful?

Bertrand Chapron: space/time scales are important, due to the whole system being dynamic.

Rik Wanninkhof: should be bypass need for k/transfer process and study the fluxes directly? E.e. atmospheric potential oxygen approach?

Bertrand Chapron: use the full electromagnetic spectrum and use a wave model to investigate and constrain measurements and approach.

Brian Ward: dissipation rate is important, rather than turbulence and in situ technology is available to measure the dissipation rate.

David Woolf: Scaling turbulence dissipation rate irrespective of the type of turbulence is not known.

Ken Melville: dissipation rage historically measured, not because it's the best thing to measure. For fluxes over the ocean the vertical velocity helps unpick component of turbulence.

Rik Wanninkhof: how to measure components in water from space (e.g. vertical motion).

Ken Melville: use drones to measure vertical turbulence in atmosphere with a turbulence probe. Need to measure fluxes directly.

Bertrand Chapron: yes, vertical motion is possible from Earth observation. We have a lot of options. Mean square slope, short wave and long breaking and the use of advanced models. Need to get wave modellers to include mean square slope or k in models.

Craig Donlon: we have lots of Earth observation data that are being used. we can start more work, but we are making progress.

Magdalena Anguelova: thickness measurements using passive microwave. Database of measurements from lab for different depths and emissivity.

Craig Donlon: air temperature needed for dissipation rates.

Fabrice Ardhuin: Satellite observations are needed to verify in situ fluxes. Need to be careful when using a wave model as modelled dissipation rates need validating. So in situ-model-earth observation is the obvious approach.

Rik Wanninkhof: should we be focussing on better proxies. Ie. Dissipation is just another proxy.

Craig Donlon: Earth observation is another tool. Need to use satellite data at the native spatial and temporal resolution (ie move away from gridding) and back to how electromagnetic spectrum responds to surface. Need in situ observations to understand quality and uncertainties. Need the community!

David Woolf: proxies. Now need better proxies. Need to investigate them. Turbulence is a observation of patchiness and this is important. Where does it come from? Capillary and large breaking waves. Need to move towards understanding the actual surface physics.

Alexander Soloviev: convection, shear and mean-shear(?) – 3 sources of turbulence. No icea on sheer and how it contributes to gas exchange. Could we solve this in the lab? Can be important near surface. Could be investigated using a model.

Rik Wanninkhof: regions and regimes (.e.g. turbulence), wind, is this important?

Bertrand Chapron: wave breaking and strong vertical flow (e.g. gulf stream) can vertical velocity (regimes where strong mixing – these are important).

Craig Donlon: area of biology are important.

David Woolf: South west monsoon (Indian Ocean) good area to test work.

Craig Donlon: Arctic ocean is becoming a focus for Europe.

Rik Wanninkhof: Arctic is important for gas exchange. There is an NSF programme focused on the Arctic.

Bertrand Chapron: Extremes (e.g. polar and hurricanes) are important.

Rik Wanninkhof: [optical] remote sensing can be limited if cloudy and in extreme conditions.

Sarah Gille: Southern ocean. Optical remote sensing is biased towards clear skies.

Jamie Shutler: important to understand the nuances of different observations. In situ data are also likely to be biased (towards times when people can take observations). So important to use all types of observation in synergy.

Jamie Shutler: what satellite and ship measurements are needed?

Adrian Callahan: penetration depth, surface measurements and ship measurements and linkages with Earth observation.

MingXi Yang: Seasonal and spatial biases need investigating. Transect studies across extreme gradients, better proxy, direct measurements between new proxies and gas fluxes.

Craig Donlon: how about an international Experiment to move things forward? Multi-agency international experiment? To start things off we could plan, identify priorities, approximate cost and people with kit.

Rik Wanninkhof: satellite and ship measurements. A lot of other platforms that we can use, drones, gliders, floats, mixed moorings. Holistic view on all possible measurements and we should take advantage of this.

Ken Melville: how about using time series gauge station as test sites?

Rik Wanninkhof: yes, huge benefit of using these.

Open discussion III (Polar regions)

Brice loose: sea ice completely dampens out the wave field, no non-linear terms in k and so k is reduced. Can relate mean square slope to TKE dissipation, relating it to upwelling velocity perturbation is better.

Need to measure the effect of sea ice on gas transfer, the ice acts like a coastline but is constantly moving. Radon deficit k estimates in open water agree, but it is might higher in areas of high ice concentration. Atmospheric community and water community results are different.

Surface ocean is highly stratified in marginal ice zone, this could increase in the future with ice melt. Permafrost melting makes small lakes, large methane emissions, need a good way to deal and take account of very low fetch of wind.

Polar analogue in the lab-aelotron with fake sea ice, air-sea ice chamber at UEA could be useful.

Fabrice Ardhuin: Model of sea-ice-air interaction. Shouldn't simplify to just a short fetch situation (like the coastal zone). Turbulence around ide flows are completely different from normal short fetch.

Magdalena Anguelova: need to obtain whitecap fractions amongst sea ice.

Truls Johannessen: Sensors around arctic basin could be used (e.g. Svalbard), Swedish group working in permafrost. Northern part of Svalbard with atmospheric stations. Permafrost melt measurements. Swedish group with lots of cruises. Lots going on. Important issue – what will happen when freshwater layer is removed and seawater is exposed to atmosphere.

Eric Saltzman: There is a joint US-Swedish cruise (on Oden) during the high arctic summer to study impacts of seawater biogenics on aerosol production. Opportunity for international collaboration.

Truls Johannessen: how about a vessel frozen into ice to look at air/sea/ice exchange?

Jim Butler: IASOA lots of Antarctic data and metadata from fixed stations which are a good background dataset for cruises. Ken Melville – could we do something with an A-GAGE station.

Brice Loose: DOM and DOC are important. DOM and denitrification are big topics in these regions.

Jamie Shutler: polar locations receive some of the higher repeat cycles for Earth observation as many platforms are polar orbiting. Excellent opportunity.

Ryan Piera: there have been some DOM/DOC flux focussed cruises in Canadian river systems (McKenzie et al). Lots of global rivers work being done on DOC and DOM fluxes, particularly round Spring period.

Brice Loose: upcoming Year of Polar Prediction (YOPP), MOSAIC polarstern is available for a 1 year for research, ocean-sea ice-ecosystem, EU open call coming soon for this.

Tom Bell: Opening up of NorthWest passage and shipping routes. Opportunities to observe as well as impacts upon the region.

Jamie Shuter: could the difference between different within sea-ice air-sea gas flux measurements be down to factors cancelling each other out (ie.e. the results are showing the same, but under some circumstances components cancel each other out?). The FluxEngine could be used to test for this.

Brian Butterworth: need more data to answer these questions. Would be good to test existing ideas.

David Woolf: The model of Brice et al., includes the mean square slope – wind relationship which is based on a cubic relationship. Its likely that in these conditions the relationship is linear. Not convinced that losing mean square slope and doing energy dissipation instead would be useful.

Brice Loose: yes, this relationship worked in the Arctic at $5ms^{-1}$ winds, but not sure it holds in the Antarctic in high wind conditions.

MingXi Yang: Keep in mind that keff assumes zero concentration under ice. What about the emissions from/through the ice itself?

Brice Loose: Great point. Brine exclusion could well push CO2 out of ice. Melting would produce freshwater that can retain/take up CO2.

Winter net source, summer melt low PIC results in a sink. Can we attribute the overall eddy covariance footprint flux to different sources?

David Woolf: surfactants often found in mixed ice zone. Need to add surfactants to the MOSAiC project.

MingXi Yang: Most of eddy covariance approaches have been designed for homogeneous sources, maybe sample at different heights to identify the different sources.

Tom Bell: could use terrestrial eddy covariance footprint to determine source or survey of flux footprint is another option.

Open discussion IV (The continuing relationship)

Andy Watson: ESA ministerial coming up in October 2016 and ESA need input from scientific communities on where to focus future efforts. Eddy covariance now able to work autonomously , better understanding of low and high wind scenarios, sea ice, should we have a large community experiment of inter-comparison to push things further forward?

Tom Bell: Need to move away from using wind speed as a proxy for gas exchange. What about a mean square slope and surfactant experiment coupled with wind speed.

Andy Watson: wind speed works really well on average (ie. Binned data).

Ken Melville: yes, the binned data looks good, but Lots of scatter in the data is not explained by wind speed alone. Drag coefficient versus wind speed.

?Mark Chalmers? friction velocity would be better than wind speed

MingXi Yang: Eddy covariance has natural variability, maybe this could be explained by combining it with remote sensing data. Natural variability in Eddy covariance - coupling with satellite would help to explain heterogeneity.

Adrian Callaghan: Exploit natural platforms with research vessels as part of a concerted field campaign. So use new technology to study waves, bubble. Platforms in the Meditteranean.

Andy Watson: Use an aircraft – cover larger areas.

Brian Ward: Discussion of field observations. Good to support and encourage new PIs. Should emphasise need for in situ data and approaches to ESA, e.g. some already being collected on AMT this year.

David Ho: NASA supported US (SO GasEx had a large NASA component) in situ dual tracer experiments in surfactant affected areas to parameterise for space observations. Phil's [Nightingale] talk with dual tracer – very interesting.

Helen Czerski: need to use standardised measurements in the sea surface – type of waverider or some other AUV for all to use in validation work.

Tom Bell: need field data to validate satellite observations. Measurements to validate satellites would satisfy ESA.

Ken Melville: Aircraft and wavegliders have the capability to get at/near the air/sea interface Aircraft with LIDAR, VIS/IR relatively small package. Also waveriders recently went through a category 3 tropical cyclone.

Gregor Rehder: Different regions have different properties: over versus under-saturation, with/without surfactants, high/low wind speeds. Use these to help understand the gas transfer. Region where k deviates from current parameterisations, surfactant/seasonal, look for correlations in baises with influx/outflux etc. Easy to fall prey to bias.

Brian Ward: The link between EU and USA should be emphasized to ESA. Could coordinate an EU/US/Canada activities. Craig donlon (ESA) wasn't aware of the US effort [Galway funding initiative].

Andy Watson: ESA NASA link.

Alex Soloviev: Bacteria are associated with surfactants. Difficult to see in ocean colour, but the slicks might be in SAR, need to distinguish between other types of slicks.

Christa Marandino: how about ships of opportunity with Eddy covariance systems? So fluxes measured on VOS lines would improve spatial and temporal coverage.

Andy Watson: Agreed.

Jamie Shutler: is there an appetite/need for another of these workshops?

Tom Bell: Yes! [laughter in hall] more productive than SOLAS meetings due to interdisciplinary nature. Three year gap between meetings is good.

David Ho: yes they are useful, but need coordination [with SOLAS and other meetings]. Scientific focus is good and appropriate. Need to make sure that we don't have gas exchange meetings every year (e.g. coordinate with the next air-sea transfer at the water surface meeting, penned or 2020 in UK).

Andy Watson: so coordinate with the next air-sea transfer at the water surface to be held in 2020. Phil Nightingale, Tom Bell and Jamie Shutler are organising this, so coordination should be ok.

Ken Melville: is Flow interference around research vessels collecitng eddy covariance data a problem?

Brian Ward: new work published last year shows that its better to use u* (wind stress) than u10 (wind speed) as it is less sensitive to this distortion/interference.

?Mark Chalmers?: Distortions very obvious in data, not in the mean but in the variance.

Tom Bell: breadth of workshop right or should it be more focussed?

Jamie Shutler: content of this workshop was based on the abstracts submitted.

Andy Watson: I enjoyed the wide focus, could do with more on biology and bacteria.

5. Annex 2 – Full list of participants

The table below gives a full list of the participants and their contact details.

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6. Annex 3 – Posters

Anguelova Magdalena, Michael H. Bettenhausen, John Prytherch, Ian M. Brooks, Magdalena D. Anguelova, Sarah J., Norris, Ivan B. Savelyev, Margaret J. Yelland, Robin W. Pascal, Dominic J. Salisbury. USA **Empirical model for sea spray production.**

Asseray M., M. N. Bouin, J.L. Redelsperger, L. Marié, D. Bourras, V. Garnier. France. **Impact of a SST front on the atmospheric boundary layer and turbulent fluxes.**

Bange H.W., S.T. Wilson and members of SCOR WG#143.Germany. **Dissolved N2O and CH4 measurements: working towards a global network of ocean time series measurements.**

Bell Thomas G - U.K. **Attribution of atmospheric sulfur dioxide over the English Channel to dimethylsulfide and changing ship emissions.**

Danielson Richard, Igor Esau, Abderrahim Bentamy, Antoine Grouazel, Johnny A. Johannessen, Jean-Francois Piolle, Normay. **A characterization of global analyses of surface heat flux in terms of a simple affine error model.**

Gutiérrez-Loza L. and F.J. Ocampo-Torres - Mexico. **The effect of the breaking waves on air-sea CO2 gas transfer in the coastal zone.**

Hackerott Joao A., Luciano P. Pezzi, Mostafa Bakhoday Paskyabi, Joachim Reuder, Ronald B. Souza, Ricardo de Camargo – Brazil.**Turbulent fluxes observed during the Air-Sea Interaction at Brazil-Malvinas Confluence (INTERCONF) 2014.**

Keraghel Mehdia Asma, Ferial Louanchi – Algeria. **Annual cycle reconstitution of pCO2 over the Western Mediterranean for the year 2011.**

Lennartz, S.T., von Hobe, M., Pozzer, A., Bruhl, C., Quack, B., Kruger, K., Marandino C.A. – Germany. **The role of oceanic emissions in the atmospheric budget of Carbonyl Sulfide.**

Markuszewski P., T. Petelski, P. Makuch, T. Zielinski, J. Piskozub, P. Pakszys, I. WrÃ³bel, V. Drozdowska, D. Gutowska, A. Rozwadowska – Poland. **Turbulent fluxes in near water boundary layer observation on board s/y Oceania in the European Arctic and Southern Baltic Sea areas.**

Paget C. Aaron, Jim Edson -USA. **Direct ASCAT and RapidScat Vector Winds Comparison.**

Pineau-Guillou L., F. Ardhuin, M.-N. Bouin, J.-L. Redelsperger, B. Chapron, J. Bidlot - France **Sensitivity to wind stress formulation in a coupled wave-atmosphere model.**

Piskozub Jacek, Iwona Wrobel - Poland. **Why different gas flux velocity parameterizations result in so similar flux results in the North Atlantic ?**

Porter J.G., W. De Bruyn, S. D. Miller, and E. S. Saltzman - USA. **Eddy covariance flux measurements of sulfur dioxide to the sea surface: Air-side resistance of a highly soluble gas.**

Rickard Philippa, Guenther Uher and Robert Upstill-Goddard.- UK. **Surfactant photo-reactivity and air-sea gas exchange.**

Saket Arvin, William L. Peirson, Michael L. Banner and Xavier Barthelemy - Australia. **Determining the onset of breaking: Laboratory investigations.**

Santini Marcelo F., Ronald B. Souza, Luciano P. Pezzi, J. Hackerott - Brazil.**Behavior and magnitudes of air-sea heat fluxes and MABL under two distinct atmospheric conditions at Brazil-Malvinas Confluence.**

Schulz Harry Edmar - Brazil .**Verifying the Random Square Waves statistics for 1D formulation of turbulence characteristics at gas-liquid interfaces.**

Stopa Justin E., Fabrice Ardhuin, Romain Husson, Bertrand Chapron, and Fabrice Collard - France. **Swell dissipation from 10 years of Envisat advanced synthetic aperture radar in wave mode.**

Tatsuki Tokoro, Tomohiro Kuwae – Japan. **Characteristics of coastal CO2 flux estimated from comparison of eddy covariance method with conventional method.**

Vanaki Sh.M., K. A. Suara , and R. J. Brown - Australia. **Use of drifter technology for measuring gas concentrations at air-sea interface in coastal waters.**

Wrobel Iwona., Drozdowska V., Gutowska D., Makuch P., Markuszewski P., Pakszys P., Petelski T., Piskozub J., Zielinski T., Institute of Oceanology Polish Academy of Sciences – Poland. **What is going on in the North Atlantic and European Arctic - future scenario.**

Zavarsky A., D. Booge, A. Fiehn, K. Kruger, T. Steinhoff, C. A. Marandino - Germany. **DMS flux in the Indian Ocean during summer monsoon.**

Zunino Patricia, Pascale Lherminier, Herlé Mercier, Xose A. Padin, Aida F. Ríos, Fiz F. Pérez - France. **Budgets of dissolved inorganic carbon in the eastern Subpolar North Atlantic in the 2000s from *in situ* data.**