OPEN OCEAN AND COASTAL CO2 FLUXES FROM ENVISAT IN SUPPORT OF GLOBAL CARBON CYCLE MONITORING (OC-FLUX) - AN ESA STSE PROJECT

J. D. Shutler[*a], D. Woolf [b], N. Hardman-Mountford[a], P. Nightingale[a], C. Donlon[c]

[a]*Plymouth Marine Laboratory, Plymouth, U.K.*
[b]*Environment Research Institute, UHI Millenium Institute, Thurso, U.K.*
[c]*ESA/ESTEC, Noordwijk, The Netherlands.*
[*]*Corresponding author: jams@pml.ac.uk*

ABSTRACT
Increasing levels of atmospheric carbon dioxide (CO_2), from anthropogenic sources, are now of growing concern due to their impact on the global climate system. Research has shown that there is a strong link between increasing atmospheric CO_2 concentrations and the warming climate. The oceans are thought to absorb up to 25 % of the annual CO_2 emissions from burning fossil fuels. The rate at which CO_2 exchanges between the ocean and the atmosphere (termed air-sea fluxes) is related to wind speed, wave height and sea state. Understanding these exchanges is clearly of importance for understanding the global carbon cycle and for climate modelling. Earth observation (EO) is well placed to study and monitor air-sea fluxes. However, there remain large uncertainties in the current parameterisations of EO derived air-sea gas interactions, which can have profound effects on the resulting predictions from global carbon cycle models. The STSE project OC-flux is exploiting coincident Envisat data to provide a framework for analyzing a selection of these uncertainties.

1. INTRODUCTION

Increasing levels of atmospheric carbon dioxide (CO_2), caused by the burning of fossil fuels and biomass, are now of growing concern due to their impact on the global climate system. Currently, it is thought that the ocean system annually absorbs up to 25 % of the CO_2 from anthropogenic sources [1, 2]. This carbon 'sink' is increasing but is not keeping pace with the increasing carbon emissions (from both natural and anthropogenic sources). Levels of atmospheric CO_2 are strongly modulated by physical and biological processes across the whole of the Earth's land and water surfaces, illustrating the need for a holistic Earth system science approach to the problem. Understanding how the global carbon cycle works is essential for monitoring and projecting future scenarios, and their impacts on Earth's climate system. Space observations have a crucial role to play in this process through providing measurements for driving, parameterising and enhancing climate models [3].

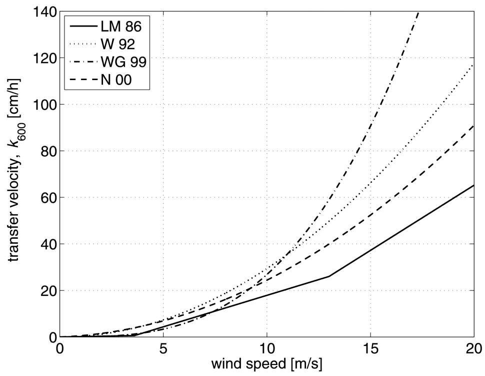

Figure 1: Gas transfer velocity k_{600} for CO_2 as a function of wind speed for a selection of relationships LM 86: [14], W92: [4], WG99: [15] and N00:[5] (figure from [10]).

If we are to fully understand the global carbon cycle then having the capability to study the exchange of climatically important gases between the ocean and atmosphere is of great importance. Additionally, the ability to monitor these air-sea fluxes is beneficial for the future management of the global carbon system. As a result, the estimation of air-sea fluxes of climatically important gases is a key goal of current climate research. One of the major sources of uncertainty in the calculation of air-sea fluxes on a global scale is the parameterisation of the gas transfer velocity, k. Improvement in the parameterisation of k is required because k controls the movement of gas particles across the air-water interface and is therefore a critical variable in global carbon cycle research. Earth observation (EO) is well placed to determine this parameter, and additionally, allows the estimation and monitoring of air-sea fluxes on a global scale. There are currently several approaches for estimating k from EO data. The majority of these approaches exploit the dependence of k on wind speed, deriving maps of k from winds determined via scatterometers and altimeters. These parameterisations are based on a series of transfer velocity-wind speed relationships e.g. [4, 5]. They all vary in their predictions of k, especially at higher wind speeds, as shown in figure 1 (k_{600} is the k for a Schmidt number of 600 which corresponds to CO_2 in fresh water at 20^{o}C). Furthermore, these purely wind-speed based parameterisations do not directly account for additional known aspects of air-sea gas exchange including the effects of dampening by biological slicks and films, wave breaking, bubble mediation and white capping. In contrast, [6] used a hybrid model to separate direct gas transfer from that of bubble-mediated gas transfer. Later, [7] proposed that the bubble-mediated component should depend on sea state and showed that this insight mimics the spread observed in current wind speed parameterisations. Further work has continued to move away from the reliance on wind speed as a proxy for gas transfer. [8, 9] related gas transfer velocity directly to sea surface roughness by using mean square slope $<s^2>$ determined from altimeter data using dual-frequency data. Altimeters view the surface below the sensor at vertical incidence and measure the radar return from a small footprint. From this return several parameters including surface wave height and mean square slope can be determined. [10] drew from the approaches of both [7] and [8] to develop a new single-frequency altimeter-based retrieval and applied this to TOPEX altimeter data. Figure 2 shows the direct gas transfer component relationship from [10] expressed as k_{600} against mean square slope $<s^2>$. Through the use of altimeter data these approaches are able to partially account for aspects including film damping and white capping, and provide a significant step forward.

Notwithstanding these advances, large uncertainties in the EO-derived gas transfer velocity parameterisations still exist and the choice of parameterisation is considered to be a significant factor affecting the total error budgets of global carbon models [11].

The air-sea flux of CO_2 can be determined from k using:

$$F = k\, s\, \Delta pCO_2 \qquad (1)$$

where k is the gas transfer velocity in cm/h, s is the solubility of the gas in water and ΔpCO_2 is the difference in partial pressure of the gas across the interface. The solubility follows a known relationship with SST and salinity and climatological values of ΔpCO_2 are available [11] based on 940,000 measurements of pCO_2 in surface waters. Recent work and advances for determining global CO_2 fluxes have used model or composite SST data to solve equation 1 e.g. [10]. These studies have concentrated on the long time series data from altimeters or scatterometers without coincident SST. The use of non-coincident SST data means that variations in sea surface skin temperature due to diurnal heating and cool skin effects are not captured. These variations are likely to affect the solubility (equation 1) and thus the calculated flux.

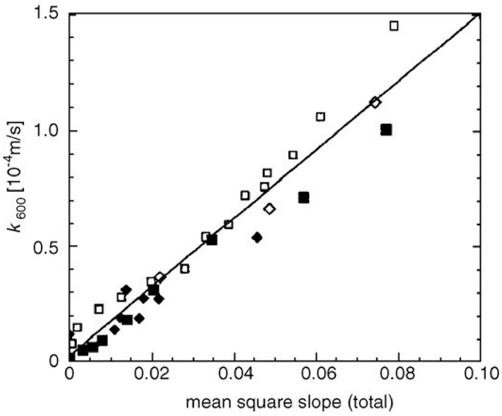

Figure 2: Gas transfer velocity k_{600} for varying mean square slope integrated over all wavelengths (figure from [10]).

Additionally, altimeters are unable to return valid signals very close to the coast, if land appears within the footprint then the data rendered unusable. Secondly, altimeters have a recognized tendency to return poor data in the first few seconds after the ground track has left land. Altimeters also suffer from poor spatial and temporal sampling compared to “swath” sensors. Scatterometers offer better sampling but are largely unusable within 50km of the coast, making these instruments more suited to the open ocean than coastal areas. In summary, current EO based CO_2 flux studies are unable to fully account for these coastal regions. Despite their relatively small area, accounting for just 7 % of the world ocean’s surface, coastal zones play an important part in the global carbon cycle and in buffering human impacts on marine systems. They are thought to support 10 -15 % of the world ocean net annual productivity and may be responsible for >40% of the annual carbon sequestration [12].

The ESA Support to Science Element project OC-flux is using coincident Envisat data to investigate aspects of uncertainties in current EO derived gas transfer velocity and thus CO_2 flux estimates. The methods developed within OC-flux will also be extended to be applicable to Sentinel 3 towards future monitoring of this important aspect of the global carbon cycle.

This paper describes the progress made with determining global air-sea transfer velocities from coincident Envisat RA2 and AATSR data. We present the methods developed and a selection of results for 2004.

Algorithm	Study	Dataset used	Temporal range	Mean transfer velocity [10^{-4} m s^{-1}]
W92	[10]	ERA-40 model data	1982-2001	0.497
WG99	[10]	ERA-40 model data	1982-2001	0.456
ALT1	[10]	TOPEX	1993-2001	0.511
This study	This study	Envisat	2004	0.517

Table 1: Mean total transfer velocities derived from this work in comparison to those from the published literature for the zonal coverage ±66°. Parameterisations are [4] (W92), [15] (WG99) and [10] (ALT1). Datasets include the ECMWF 40 year reanalysis (ERA-40) and NASA's Topography Experiment (TOPEX).

2. METHOD

All (global coverage) Envisat radar altimeter 2 (RA2) data for 2004 were processed using the ESA Basic Radar Altimeter Toolbox (BRAT) through the ESA Grid processing on Demand (G-POD) service. All (global coverage) level 2 Envisat Advanced Along Track Scanning Radiometer (AATSR) data for 2004 were quality filtered and binned using the ESA Earth Observation Toolbox and Development Package (BEAM). All pre-processed AATSR and RA2 data were then re-projected to a global 1° x 1° geographic grid using in-house re-projection tools [13]. The results were stored as NetCDF CF 1.0 data for future analysis. Daily maps of *k* were determined using the re-projected NetCDF data (AATSR and RA2) using the approach of [10]. This uses the hybrid model of [7] to determine the gas transfer velocity, *k*, which is defined as $k = k_d + k_b$, where k_d is the direct gas transfer and k_b is the bubble mediated transfer. The direct component, k_d, is determined using altimeter mean square slope, $\langle s^2 \rangle$. Reference [8] defined the mean square slope as:

$$\langle s^2 \rangle = \frac{\rho_{Ku}}{\sigma_{Ku}} \qquad (2)$$

with $\rho_{Ku} = 0.38$. k_d is then defined as:

$$k_d = \left(\frac{\alpha \rho_{Ku}}{\sigma_{Ku}} + b \right) (Sc/600)^{-1/2} \qquad (3)$$

with $\alpha = 1.49 \times 10^{-3}$, $b = 10^{-6}$. The Schmidt number, *Sc*, has a known temperature dependence and can be determined from AATSR data. From [7] the bubble mediated transfer is parameterized using:

$$k_b = c \frac{u_* H_S}{v_W} \qquad (4)$$

with $c = 2 \times 10^{-5}$. The significant wave height, *Hs*, and the friction velocity, u_*, can be determined from RA2 level 2 data. The kinematic viscosity of seawater, v_w, is parameterized as $v_w = 1.83 \times 10^{-6} \exp(-SST / T_0)$, with $T_0 = 36$ °C and SST is the sea surface temperature from the AATSR level 2 data. The method of [10] was then used to determine direct and bubble mediated transfer.

3. RESULTS AND DISCUSSSION

Validation of these methods is particularly difficult due to the complex methods needed to collect *in situ* gas transfer velocity measurements. The *in situ* datasets are often spatially and temporally sparse and collected during the more clement months of the year. For instance, validation using 75 *in situ* data points from [16] resulted in zero *in situ* versus Earth observation matchups. Figure 3 shows example coincident SST, mean square slope and the resultant gas transfer velocity data. Table 1 shows the global mean transfer velocity

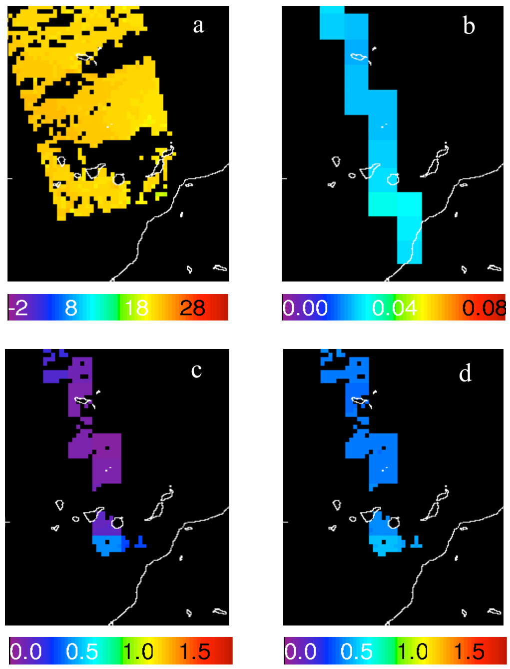

Figure 3: Example results from coincident Envisat data showing the Canary Islands on 22 July 2009 2223 UTC (regions of black pixels are land or no data). a) sea surface temperature (°C); b) mean square slope (total); c) bubble-mediated k_b (10^{-4} m s^{-1}) and d) direct k_d (10^{-4} m s^{-1}) gas transfer velocity.

for 2004 generated using the methods presented here, in comparison to those from the published literature. The results using Envisat data compare well with previous studies. Figure 4 shows the southern hemisphere (33° - 60° S) zonal mean k_b and k_d plotted for each month in 2004. These are area weighted means and the error bars show the upper and lower quartiles. In general the bubble mediated transfer, k_b, exhibits an increase in transfer rates during the southern hemisphere winter months. This corresponds with the increase in storm activity and wave height that would be expected during these periods. The decrease in the mean bubble mediated gas transfer during December 2004 (Figure 4b) is thought to be due to reduced Envisat AATSR data coverage (due to cloud). Figures 5 shows the global mean maps for 2004 of k_d, k_b and k. Figure 5a shows elevated levels in the tropics where trade winds will be evident. This is consistent with previous work as a combination of high winds and warm waters leads to high direct transfer velocities in regions of trade winds [10]. Figure 5b shows the elevated levels of bubble mediated transfer in the north Atlantic and southern ocean.

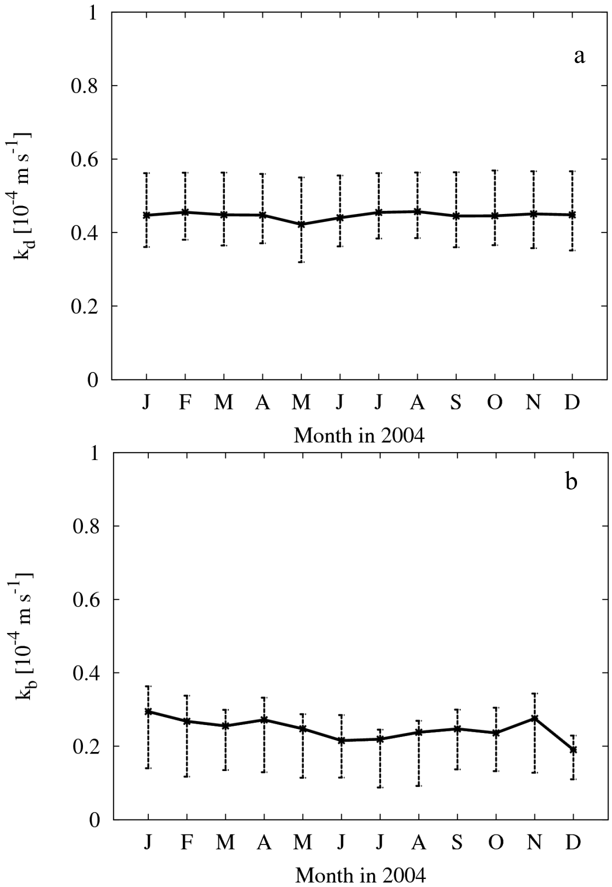

Figure 4: Gas transfer velocity for 2004 in the southern ocean (33° – 66° S), a) direct transfer k_d and b) bubble mediated k_b.

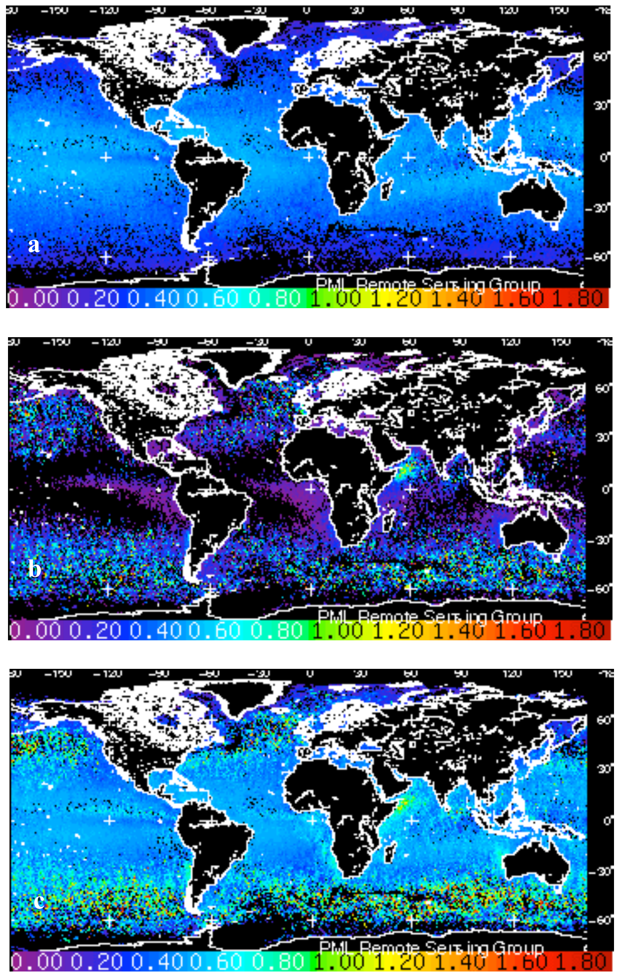

Figure 5: Mean gas transfer velocity derived from co-incident AATSR and RA2 data for all months in 2004; units are 10^{-4} ms^{-1}; a) direct k_d , b) bubble mediated k_b and c) total k.

4.CONCLUSIONS

We have demonstrated a method to derive the gas transfer velocity and CO_2 fluxes from Envisat data. This exploits coincident data from the Envisat RA2 and AATSR sensors and potentially enables the monitoring of CO_2 fluxes in near-real time. The next stage of this work is to process a longer time series of Envisat data allowing for a more comprehensive verification of the methods. This approach is being exploited within the OC-Flux project to investigate the uncertainties in current EO derived gas transfer velocity.

5. ACKNOWLEDGEMENTS

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