Climatically-Active Gases In The Eastern Boundary Upwelling And Oxygen Minimum Zone (Omz) Systems

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ABSTRACT

The EBUS (Eastern Boundary Upwelling Systems) and OMZs (Oxygen Minimum Zone) contribute very significantly to the gas exchange between the ocean and the atmosphere, notably with respect to the greenhouse gases (hereafter GHG). From in-situ ocean measurements, the uncertainty of the net global ocean-atmosphere CO_2 fluxes is between 20 and 30%, and could be much higher in the EBUS-OMZ. Off Peru, very few in-situ data are available presently, which justifies alternative approaches for assessing these fluxes. In this contribution we introduce

***Index Terms*—** Air-Sea Interactions, Fluxes, Green House Gases, Satellite Retrieval, Partial differential equations

1. INTRODUCTION

The EBUS (Eastern Boundary Upwelling Systems) and OMZs (Oxygen Minimum Zone) contribute very significantly to the gas exchange between the ocean and the atmosphere [1, 2], notably with respect to the greenhouse gases (hereafter GHG). Invasion or outgasing fluxes of radiatively-active gases at the air-sea interface result in coupled or decoupled sink and source configurations [3]. From the in-situ ocean measurements, for example, the uncertainty of the net global ocean-atmosphere CO_2 fluxes is between 20 and 30%, and could be much higher in the EBUS-OMZ. Off Peru, very few in-situ data are available presently, which justifies alternative approaches for assessing the fluxes, and notably satellite, earth-observation data, and the outputs of modeling systems as well. Here we will focus on the Humboldt system off Peru (see Figure 1).

GHG vertical column densities (VCD) can be extracted from satellite spectrometers. The accuracy of these VCDs need to be highly accurate in order to make extraction of sources feasible. To this accuracy is extremely challenging,

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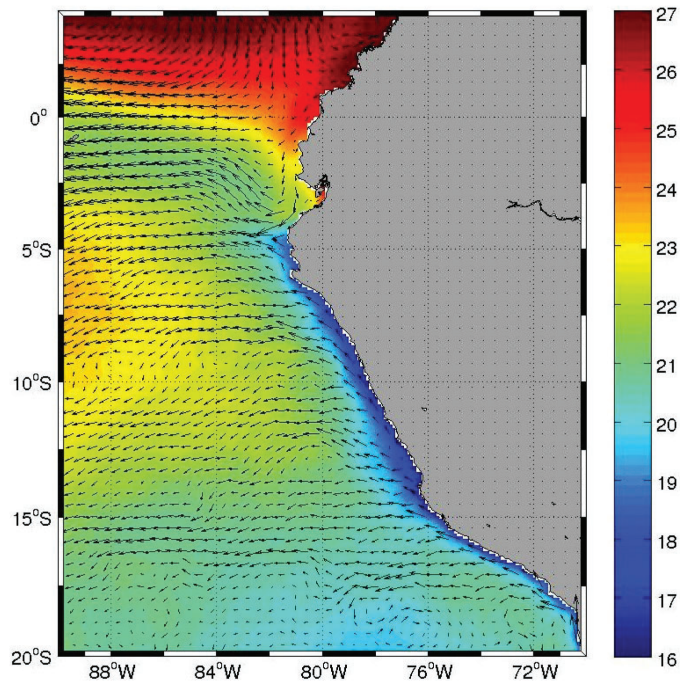

Fig. 1. Surface oceanic circulation together with Sea Surface Temperature, annual mean. Following [5].

particularly above water bodies, as water strongly absorbs infra red (IR) radiation. To increase the amount of reflected light, specular reflections (sun glint) can be used on some instruments such as GOSAT [4]. Also, denoising techniques from image processing may be used for improving the signal-to-noise ratio (SNR).

GHG air-sea fluxes determination can be inferred from inverse modeling applied to VCDs, using state of the art modeling, at low spatial resolution [6, 7]. Due to the long life-time of GHGs in the atmosphere, significant contributions of the VCDs may have been transported from far afield. in correctly choosing the boundary conditions of the inverse modeling approach, these effects can be separated. Only through this separation can the sources be determined accurately. These approaches will be tested on simulated data, which will make an assessment of the accuracy, limitations and requirements of the satellite instrument feasible.

For accurately linking sources of GHGs to EBUS and OMZs, the resolution of the source regions needs to be increased. This task develops on new non-linear and multiscale processing methods for complex signals [8] to infer a higher spatial resolution mapping of the fluxes and the associated sinks and sources between the atmosphere and the ocean. Such an inference takes into account the cascading properties of physical variables across the scales in complex signals. The use of coupled satellite data (e.g. SST and/or Ocean color) that carry turbulence information associated to ocean dynamics is taken into account at unprecedented detail level to incorporate turbulence effects in the evaluation of the air-sea fluxes.

Based on a parameterization, the transfer velocities K can be computed from satellite products. This leads to a measurement of p_{GHG}^{ocean}, which in turn will be validated by the output of a coupled physical biogeochemical model and in-situ measurements.

2. CONSTRAINING SURFACE FLUXES BY EO DATA

In the atmosphere, the temporal evolution of a tracer c is given by the equation :

$$\frac{\partial c}{\partial t} = -\mathbf{u}\nabla c + \frac{1}{\rho}\nabla\left(\rho T_d \nabla c\right) + \frac{1}{\rho} g + F, \tag{1}$$

with the concentration c, the wind field u, the density of air ρ, the turbulent diffusivity tensor T_d, the chemical transformation rate g and the net flux at the air-sea interface F.

Using optimal control and inverse problem modeling, in this contribution we will derive the mapping of F using Earth Observation and satellite data [6, 7]. It will estimate sources and sinks of gases, based on vertical column densities (VCD), at the spatial resolution of VCD data. For the retrieval of VCD of GHGs, we employ the approach detailed in [9]. This methods yields very accurate results due to its ability to simultaneously retrieve gas concentrations and particle scattering properties of the atmosphere using an efficient radiative transfer (RT) model [10].

Following [7], the underlying problem can be formulated as

$$\begin{aligned}
&\frac{\partial c}{\partial t} = \nabla \cdot (D\,\nabla c) - \mathbf{u}\cdot\nabla c + F,\\
&c(t_0, x) = c^0(x),\\
&c(t, x) = c^{in}(t, x) \quad \text{on } \Gamma_I,\\
&D\,\frac{\partial c}{\partial \nu} = 0 \quad \text{on } \Gamma_O,\\
&D\,\frac{\partial c}{\nu} - \bar{\beta}\, c = \gamma \quad \text{on } \Gamma_G.
\end{aligned} \tag{2}$$

Since the problem is ill-posed, we regularize it by introducing the Tikhonov functional given by

$$J(q, c) = \|c - C(c)\|_Z + \frac{\alpha}{2}\|F\|_Q. \tag{3}$$

The first term corresponds to the data term and includes given observations. Here $C(c)$ corresponds to the VCDs. The second term is the regularization term with a small parameter $\alpha \geq 0$. Thus, we aim at the solution of the following optimal control problem:

$$\text{Minimize } J(q, c) \tag{4}$$

subject to the state equation (2). The inverse problem is discretized using a $dG(0)cG(1)$ Galerkin discretization. Thus, for the temporal integration we employ the backward Euler method which corresponds to the discontinuous Galerkin method. A detailed description of the discretization scheme can be found in [11]. For the discretization in space we use piecewise trilinear functions. This corresponds to $\mathcal{Q}_1$ elements. To increase computational efficiency, the problem can be solved with a goal oriented adaptive grid refenement [7].

The relation between the net flux F and the partial pressure p_{GHG} of a GHG is of the form (for typical GHG such as CO_2, N_2O, CH_4):

$$F = \alpha K \left(p_{GHG}^{air} - p_{GHG}^{ocean}\right), \tag{5}$$

α being the gas solubility (which depends mostly of SST and salinity) and K is a function of wind, salinity, temperature, sea state, which can all be obtained from satellite data. Since p_{GHG}^{air} can be assumed to be constant over the upwelling region under study, the scalar p_{GHG}^{ocean} can then be obtained from inverse modeling and satellite data at VCD resolution.

The quantity p_{GHG}^{ocean} is a complex signal depending, at any spatial resolution, on sea surface temperature, salinity, chlorophyll concentration, dissolved inorganic carbon, alkalinity and nutrients concentrations. Both the biological pump, with chlorophyll a as a proxy, and the physical pump, driven by the temperature and salinity (e.g. solubility, water mass), govern the evolution of pGHG, when dealing with CO_2 for instance, in the surface ocean. For other GHG such as N_2O, the partial pressure of N_2O will also depend on the evolution of the various chemical forms of nitrogen and on the activity of the bacteria involved directly or indirectly in the major N transformation processes such as nitrification, denitrification, anammox, etc. It is therefore a competitive research challenge to use high resolution satellite data (at various spatial resolutions) coupled with low spatial resolution model outputs for p_{GHG}^{ocean} to derive a higher spatial resolution mapping of p_{GHG}^{ocean}.

Recent advances in non-linear and multiscale processing of complex and turbulent signals [12] allow to make use of cascading properties relevant to turbulence to assess high spatial resolution of scalar or vectorial quantities from low resolution satellite data and inference across the scales. The methodology makes use of the framework of reconstructible

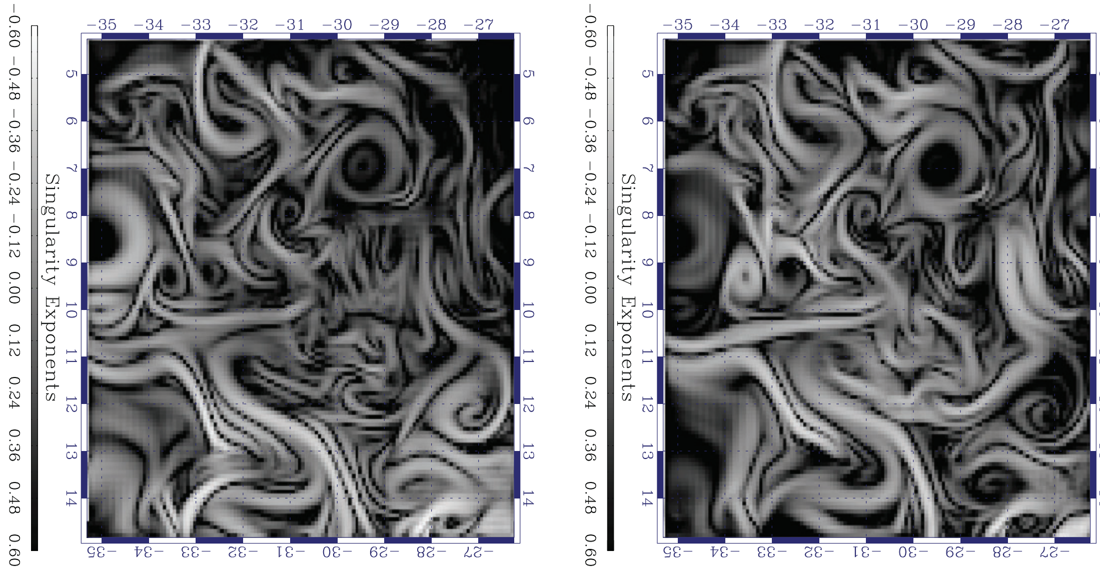

Fig. 2. Left : singularity exponents computed on simulated SST signal from the ROMS simulation model. Right: singularity exponents computed on simulated p_{CO2}^{ocean} signal from the ROMS simulation model. Note the similarity of coherent structures and the turbulent character of the p_{CO2}^{ocean} signal. These images are computed using the ROMS model and FluidExponents software. The p_{CO2}^{ocean} and SST signals used in the computation of the two images are averaged on a 5 days time interval.

systems and optimal wavelets, which shows a particular ability to perform fusion of satellite data acquired at different spatial resolutions [13], thus making it particularly appropriate for merging different kinds of satellite products. High resolution maps (resolving submesoscale features) will be provided at different timescales of interest, from intraseasonal to seasonal over the upwelling under study.

3. MULTISCALE PROPERTIES OF THE SIGNAL USED

As described in the previous section, p_{GHG}^{ocean} is a complex signal depending on temperature, salinity, chorophyll, dissolved inorganic carbon, alkalinity and nutrients concentrations. Such a signal is therefore expected to feature cascading, multiscale and other characteristic properties found in turbulent signals. We will present preliminary results which prove that a simulated p_{GHG}^{ocean} signal possesses the key signatures characteristic of complex multiscale signals, notably through a study of log-histograms and singularity spectrums. These characteristics prove that p_{GHG}^{ocean} signals are prone to be studied with the help of multiscale methods [8] to infer information along the scales.

The multiscale properties of a signal are well understood though the study of singularity spectrum and singularity exponents which give access to the determination of geometric subsets responsible of cascading properties [14, 8]. Figure 2 shows a computation of the singularity exponents on a simulated p_{CO2}^{ocean} signal obtained from the ROMS coupled physical/biogeochemical simulation model [15, 16, 17, 18]. The computation is performed using the FluidExponents software developed at INRIA. The spatial distribution of the singularity exponents underlines the complex distribution of fronts and vortices displayed by the p_{CO2}^{ocean} signal, which possesses turbulent characteristics. For comparison, we show in the same image the singularity exponents computed on the SST signal.

4. CONCLUSION

In this contribution we present a concerted effort to assess the influence Eastern Boundary Upwelling Systems on gas exchange between ocean and atmosphere. We link a coupled physical-biochemical model to parameters extracted from satellite remote sensing. A multiscale approach based on the singularity exponents is used to increase the resolution of our approach. We will present a framework as described above for determining sources and sinks of GHG from satellite remote sensing with the Peru OMZ as a test bed. First results of this analysis are very promising.

5. REFERENCES

[1] H. N. Waldron, P. M. S. Monteiro, and N. C. Swart, “Carbon export and sequestration in the southern benguela upwelling system: lower and upper estimates,” *Ocean Science*, vol. 5, no. 4, pp. 711–718, 2009.

[2] B. Hales, T. Takahashi, and L. Bandstra, “Atmospheric co2 uptake by a coastal upwelling system,” *Global Biogeochemical Cycles*, vol. 19, no. 1, pp. –, 2005.

[3] A. Paulmier, D. Ruiz-Pino, and V. Garçon, "The oxygen minimum zone (omz) off chile as intense source of co_2 and n_2o," *Continental Shelf Research*, vol. 28, pp. 2746–2756, 2008.

[4] A Butz, S Guerlet, O Hasekamp, D Schepers, A Galli, I Aben, C Frankenberg, J M Hartmann, H Tran, A Kuze, G Keppel-Aleks, G C Toon, D Wunch, P Wennberg, N Deutscher, D Griffith, R Macatangay, J Messerschmidt, J Notholt, and T Warneke, "Toward accurate CO_2 and CH_4 observations from GOSAT," *Geophysical Research Letters*, vol. 38, no. 14, pp. L14812, July 2011.

[5] Ivonne Montes, Francois Colas, Xavier Capet, and Wolfgang Schneider, "On the pathways of the equatorial subsurface currents in the eastern equatorial Pacific and their contributions to the Peru-Chile Undercurrent," *Journal Of Geophysical Research-Oceans*, vol. 115, pp. C09003, 2010.

[6] C. S. Garbe, R. Rannacher, U. Platt, and T. Wagner, *Optimal Control in Image Processing*, Springer-Verlag, Heidelberg, 2012, accepted.

[7] C. S. Garbe and J. Vihharev, "Modeling of atmospheric transport of chemical species in the polar regions," in *Proc. IEEE IGARSS 2012*. 2012, IEEE.

[8] A. Turiel, H. Yahia, and C. J. Perez-Vicente, "Microcanonical multifractal formalism - a geometrical approach to multifractal systems: Part i. singularity analysis," *Journal of Physics a-Mathematical and Theoretical*, vol. 41, no. 1, pp. –, 2008.

[9] A. Butz, O. P. Hasekamp, C. Frankenberg, and I. Aben, "Retrievals of atmospheric CO_2 from simulated space-borne measurements of backscattered near-infrared sunlight: accounting for aerosol effects," *Appl. Opt.*, vol. 48, pp. 3322, June 2009.

[10] Otto P Hasekamp and André Butz, "Efficient calculation of intensity and polarization spectra in vertically inhomogeneous scattering and absorbing atmospheres," *Journal of Geophysical Research*, vol. 113, no. D20, pp. D20309, Oct. 2008.

[11] K. Eriksson, D. Estep, P. Hansbo, and Johnson C., *Computational differential equations*, Cambridge University Press, Cambridge, 1996.

[12] H. Yahia, J. Sudre, C. Pottier, and V. Garçon, "Motion analysis in oceanographic satellite images using multiscale methods and the energy cascade," *Pattern Recognition*, vol. 43, no. 10, pp. 3591–3604, 2010.

[13] C. Pottier, A. Turiel, and V. Garçon, "Inferring missing data in satellite cholorophyll maps using turbulent cascading," *Remote Sensing of Environment*, vol. 112, pp. 4242–4260, 2008.

[14] A. Arneodo, F. Argoul, E. Bacry, J. Elezgaray, and J.F. Muzy, *Multifractales et Turbulence*, Diderot Editeur, Paris, France, 1995.

[15] P. Penven, *A numerical study of the southern Benguela circulation with an application to fish recruitment*, Ph.D. thesis, University de Bretagne Occidentale, Brest, France, 2000.

[16] P. Penven, J. R. E. Lutjeharms, P. Marchesiello, C. Roy, and S. J. Weeks, "Generation of cyclonic eddies by the agulhas current in the lee of the agulhas bank," *Geophysical Research Letters*, vol. 28, no. 6, pp. 1055–1058, 2001.

[17] J. Veitch, P. Penven, and F. Shillington, "The benguela: A laboratory for comparative modeling studies," *Progress in Oceanography*, vol. 83, no. 1-4, pp. 296–302, 2009.

[18] B. Le Vu, E. Gutkencht, E. Machu, J. Sudre, I. Dadou, and V. Garçon, "Physical and biogeochemical processes maintaining the oxygen minimum zone in the benguela upwelling system using an eddy resolving model," *XXX*, vol. To be submitted, pp. –, 2011.