Title:

"Activity of the Minimum of Oxygen (OMZ) in the Pacific" (AMOP-SOLAS)

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1. Background and significance

a) Significance : Interest for the OMZs and focus in the East Pacific

In the past, the Oxygen Minimum Zones (OMZs), known as suboxic layers (O_2<20 μM), have contracted and expanded during cold and warm periods at paleoceanographical scales, respectively (Cannario and Kennett, 1999). In the present ocean, OMZs are potential traces of a primitive anoxic ocean in which Archean bacteria lived and reduced chemical anomalies occurred. But OMZs are also key players to understand the present unbalanced nitrogen cycle and the oceans' role on atmospheric greenhouse control. OMZs are the main areas of nitrogen loss (as N_2, N_2O; Codispoti et al., 2001) to the atmosphere through denitrification and anammox, and could even mitigate the oceanic biological sequestration of CO_2 (Paulmier et al., 2008). Local N_2 fixation may also occur in the OMZs, as suggested in Sigman et al. (2005) and Deutsch et al. (2001, 2007), although not yet confirmed from direct observations. In addition, OMZs are involved in the O_2 loss by the ocean and in the cycle of other very important climatic gases (Paulmier and Ruiz-Pino, 2008): i) the production of H_2S (Dugdale et al., 1977) and CH_4 (Cicerone and Oremland, 1988), episodically or for OMZs in contact with sediments; ii) potential DMS consumption due to higher bacterial activity (Kiene and Bates, 1990); and iii) unknown role on other trace gases as the emission of reactive halogen compounds (e.g. Saiz-Lopez et al., 2007).

Vertically, OMZs have been characterized by a O_2 profile very different from those found classically in all the oceans due to a O_2 minimum ~5 times shallower inducing an intense O_2 gradient called the oxycline, ~50 times more intense and an extension over several hundred meters. Horizontally, the main and most intense OMZs, often associated with an upwelling activity, are found in the Benguela system, in the North Indian Ocean (Arabian Sea; Bay of Bengal), and especially in the East Pacific (EP): in the South (ESP) and in the North Subtropical (ESTNP) and Tropical (ETNP). But it was recently hypothesized that OMZs will spread in the coming decades as consequence of the global climate change, and the feedback on the main atmospheric gases remains largely to be investigated and quantified. The project presented here focuses in the OMZ of the EP, a priority area because: i) the most extended (87% of the total OMZs) with one of the most intense OMZs in the ESP and ETNP (Paulmier and Ruiz-Pino, 2008); ii) in the same time, the most (ETNP) and the less (ESP) exposed to human influences and acidification (Doney et al., 2007).

b) Background information stated in the SOLAS Science Plan and Implementation Strategy

The objective of this project fits with the SOLAS overarching goals, i.e. to "understand the key biogeochemical-physical interactions and feedbacks between the ocean and atmosphere, and of how this coupled system affects and is affected by climate and environmental change". Indeed, the project has been developed to answer several open questions (listed below) concerning most of the main atmospheric gases. This set of questions deals mainly with SOLAS key Focus 1 concerning the Biogeochemical Interactions and Feedbacks between Ocean and Atmosphere, and also with Focus 3 concerning the Air-Sea Flux of CO_2 and Other Long-Lived Radiatively-Active Gases.

2. Questions to be addressed

1) Which is the role of the OMZs in the oceanic nitrogen loss (N_2, N_2O)? Can local N_2 fixation also be observed?
2) What are the mechanisms of production and consumption of N_2O, and can a net effect of the OMZs on the N_2O air-sea fluxes be quantified in a predictive sense, despite an extreme spatio-temporal variability?
3) Are the OMZs upwelling regions the highest oceanic CO_2 sources as compared to the other upwelling areas? Are the OMZs high Dissolved Inorganic Carbon (DIC) reserves or Carbon Maximum Zones (CMZs) because of the accumulation of the remineralization end-products only, or also because of higher rates and perhaps stronger efficiency for the oxycline-specific remineralization than in the oxygenated ocean?
4) Are the OMZs in contact with the continental shelves producing CH_4 only in the anoxic sediments, or also in the water column of the coastal OMZs? Which is then the effect of the OMZs on the atmospheric CH_4 concentrations?

From 1), 2), 3) and 4): Are the emissions of these most important long-lived radiatively-active gases N_2O, CO_2 and CH_4 coupled or decoupled during upwelling events, and which is the net greenhouse (GH) effect of the OMZs?

5) Are the OMZs producing H_2S only episodically, and is this production significant for the atmosphere?
6) Has the OMZs bacterial activity consuming DMS an impact on the oceanic emission of this gas to the atmosphere, which could play a significant role in the clouds formation?

7) Are the OMZs associated with upwelling important for other important trace gases as the reactive halogen compounds (molecular Cl, Br and I, halogen oxides and acids) in the troposhere and the halogen chemistry?

From 2) and 7): Have the OMZs a significant role on the atmospheric cycle for the tropospheric and stratospheric ozone (O_3) through halogen compounds and N_2O, respectively?

8) Finally, how much O_2 the ocean is losing in the OMZs, with which impact for the control of the relatively constant atmospheric O_2 level at larger paleoceanographical scales?

From these 8 questions:

- Is it possible to determine and quantify the overall role of the OMZs on the climatic change, taking into account the effect on the atmospheric GH gases, on the clouds formation, and on the control of O_3 and O_2?
- What are the different pathways of respiration coupled to other processes as anammox, and their role in the production of the different GH gases? In particular, which role is playing the shift from O_2-respiration to NO_3-, NO_2-, N_2O- and SO_4-reduction, methanogenesis, and even mechanisms using other electron acceptors, such IO_3 or Mn?

The main expected impact of AMOP deals with the potential influence of the OMZs on the climatic change (through CO_2 and N_2O) and environmental vulnerability (through the balance in oxygen and nitrogen). Indeed, the climatic variability as the warming phase, but also the modification of the ecosystems, for example associated with the fertilization of the ocean, would induce an expansion of the OMZs (Stramma et al., 2008), or even an apparition of new OMZs. In return, the OMZs have a direct feedback: already known but to be quantified with N_2O production, and to be specifically studied here with the intense remineralization in CO_2. In addition, the OMZs could present indirect and more complex feedback effect. For example, the nitrogen loss due to the denitrification and anammox processes would decrease the oceanic total nitrogen reserve, and then, according to the Falkowski's hypothesis (1997) decrease the total primary production and the oceanic CO_2 sequestration. In addition, the OMZ as a barrier to both vertical distribution and migration of zooplankton (e.g in ETNP: Fernández-Alámo and Färber-Lorda, 2006), could intensify the grazing pressure in the upper oxygenated surface layer and then, limit phytoplankton stocks and primary production.

3. What needs to be done to address the questions?

Initial work (AMOP-1): the first step of the project

Because the main biogeochemical anomalies concerning the carbon and nitrogen cycles are focused in the oxycline (Paulmier et al., 2006), one of the central hypothesis assumes that the oxycline could be the biogeochemical "engine" of the OMZ, as a border between the suboxia in the OMZ core and the oxygenated ocean in surface.

Hence the objective of the first step of the project (AMOP-1), focused in the ETNP, is to determine the control mechanisms of the OMZ bacterial activity concerning its intensity and variability, acting simultaneously on the oxygen, carbon and nitrogen cycle at the oxycline. Three components to be linked have been proposed: i) bulk measurement of the total bacterial community as O_2 consumption or CO_2 and N_2O production with a direct impact on the OMZ; ii) the present processes and bacteria involved; iii) the variability of environmental parameters such as the oxygenation of the oxycline.

This AMOP-1 is based on:

i) in situ observations focused at fixed stations off Mexico and off Colombia;

ii) experimentations in incubation based on isotopic (^{15}N) and molecular techniques;

iii) the elaboration of a conceptual model for the bacterial community.

AMOP-1 will begin in fall 2009 for an initial duration of 4 years until 2012. An application for financial support to the French ANR (National Agency for Research) has been performed in November 2008. In addition to AMOP-1, the German SFB754 program starts in 2008-2009 for 4 years (and possibility for 12 years), and is focused on the south component of the EP OMZ (ESP off Peru and Ecuador). Then, comparisons and parallel approaches of the EP OMZ are planned between AMOP-1 (ETNP) with an active Mexican and Colombian implication in the North and SFB-754 (ESP) with a significant Peruvian and Chilean contribution. Possibly German SOLAS (SOPRAN) could expand the focus for the Atlantic to include Eastern Pacific in 2010-2012.

4. What is planned, possible and missing?

The teams implied in AMOP-1 are summarized in Table below.

In addition, the CICESE in Mexico (F. Ocampo Torres: IMECOCAL[1]-PROCOMEX[2] programs) and U. del Valle in Colombia (A. Girardo: ERFEN[3]-INCODER[4] programs) will provide facilities for the cruises, and for the pre- and post-cruise short periods.

[1] : Investigaciones Mexicanas de la Corriente de California.

[2] : Programa Oceanográfico del Occidente de México.

The LEGOS, Toulouse, France (A. Paulmier; V. Garçon, …) will be in charge of the complementary modelling approach, and of the management of the project.

5. Needed co-ordination and planning tasks

Tentative time table for AMOP-1

Short-term (2009-2010):

Data acquisition for AMOP-1 (initial preparation phase of SOLAS international AMOP)

- In situ observations during 2 bi-annual cruises off Mexico and off Colombia,
- Hydrological stations to document the regional spatio-temporal variability of the ETNP;
- Fixed stations and laboratory experiments specifically adapted to understand the biogeochemical processes;
- Experimentations during incubations for the measurements of the production/consumption of the dissolved gases, for the determination of bacterial rates of the different processes (isotopic enrichment) and for the identification and quantification of the bacteria (molecular biology);
- Parallel approaches in the ESP: IFM-Geomar cruises (2008-2009) off Ecuador and Peru; Peruvian cruises (2009-2010).
- Preparation phase for the future SOLAS international AMOP cruises to be planned for 2011-2015.

Medium-term (2011-2012):

Analysis for AMOP-1 and start of SOLAS AMOP

- Elaboration of a conceptual model of the bacterial community for the ETNP OMZ from the specific *in situ* and experimental data;
- Joint interpretation of data (including remotely sensed data) together with simulations of the conceptual model;
- Oxygen, carbon and nitrogen budgets;
- Start of SOLAS international AMOP cruises (2011-2012), and acquisition of new synchronized data with homogenized protocols in the whole EP OMZs.

Long-term (2013-2015):

Analysis of SOLAS international AMOP data, parameterization and validation at large scale

- Analysis and interpretation of the SOLAS international AMOP data;

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[3] : Estudio Regional del Fenómeno El Niño.
[4] : Programs of the Instituto Colombiano de Desarrollo Rural.

- Parameterization of OMZ key-processes from different sensitivity tests of the conceptual model, to be included in global coupled physical/biogeochemical models;
- Validation at large scale based on long-time series (installation of new low oxygen and nutrients sensors on ARGO floats in the ETNP) and on intercomparisons with other OMZ system (e.g. in the East South Pacific: Peru and Chile).

References

Cannariato, K.G. and J.P., Kennett (1999). Climatically related millenial-scale fluctuations in strength of California margin oxygen-minimum zone during the past 60 k.y. *Geology*, 27, 975-978.

Cicerone, R., and R.S. Oremland (1988). Biogeochemical aspects of atmospheric methane. Global Biogeochemical Cycles 2,655-2,661.

Codispoti, L.A., Brandes, J.A., Christensen, J.P., Devol, A.H., Naqvi, S.W.A., Paerl, H.W., and T. Yoshinari (2001). The oceanic fixed nitrogen and nitrous oxide budgets: moving targets as we enter the anthropocene?. Sci. Mar. 65 (2), 85–105.

Deutsch, C., Gruber, N., Key, R. M., Sarmiento, J. L., and A. Ganaschaud (2001).Denitrification and N_2 fixation in the Pacific Ocean. *Glob. Biogeochem. Cycles* 15, 483–506.

Deutsch, C., Sarmiento, J. L., Sigman, D. M., Gruber, N., and J.P. Dunne (2007). Spatial coupling of nitrogen inputs and losses in the ocean. *Nature* 445, 163–167.

Doney, S.C., Mahowald, N., Lima, I., Feely, R.A., Mackenzie, F.T., Lamarque, J.F., and P.J. Rasch (2007). Impact of anthropogenic atmospheric nitrogen and sulfur deposition on ocean acidification and the inorganic carbon system, *PNAS*, 104 (37), 14580-14585.

Dugdale, R., Goering, J., Barber, R., Smith, R., and T. Packard (1977). Denitrification and hydrogen sulfide in Peru upwelling region during 1976. Deep-Sea Research 24, 601-608.

Falkowski, P.G. (1997). Evolution of the nitrogen cycle and its influence on the biological sequestration of CO_2 in the ocean. *Nature*, 387, 272-275.

Fernández-Alámo, M.A., and J. Färber-Lorda (2006) Zooplankton and the oceanography of the eastern tropical Pacific: A review. *Progress In Oceanography*, 69, 318-359.

Kiene, R.P., and T.S. Bates (1990). Biological removal of dimethylsulphide from seawater. Nature 345, 702-705.

Paulmier, A., Ruiz-Pino, D., Garçon, V., and L. Farias (2006). Maintaining of the East South Pacific Oxygen Minimum Zone (OMZ) off Chile. *Geophys. Res. Lett.*, 33, L20601, doi:10.1029/2006GL026801.

Paulmier, A., and D. Ruiz-Pino (2008). Oxygen Minimum Zones (OMZs) in the Modern Ocean. *Progress In Oceanography*, doi:10.1016/j.pocean.2008.05.001.

Paulmier, A., Ruiz-Pino, D., and V. Garçon, V. (2008). The Oxygen Minimum Zone (OMZ) off Chile as intense sources of CO_2 and N_2O. *Continental Shelf Research*, 10.1016/j.csr.2008.09.012

Saiz-Lopez, A., Mahajan, A.S., Salmon, R.A., Bauguitte,, S.J.-B., Jones, A.E., Roscoe, H.K., amd J.M.C. Plane (2007). Boundary Layer Halogens in Coastal Antarctica. *Science*, 317, 348-351.

Sigman, D. M., Granger, J., DiFiore, P. J., Lehmann, M. M., Ho, R., Cane, G., and A. van Geen (2005). Coupled nitrogen and oxygen isotope measurements of nitrate along the eastern North Pacific margin, *Global Biogeochem. Cycles*, 19, GB4022, doi:10.1029/2005GB002458.

Stramma, L., Johnson, G.C., Sprintall, J., and V. Mohrholz (2008). Expanding Oxygen-Minimum Zone in the Tropical Oceans. *Science*, 320, 655-658.