Coastal dead zones in Indian Ocean

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1 Motivation and context

The ocean has lost about 2% of its dissolved oxygen in the past fifty years in response to global warming (Keeling et al., 2010; Levin, 2018; Ito et al., 2017; Schmidtko et al., 2017). A major concern is that this systematic de-oxygenation will expand tropical OMZs (Stramma et al., 2008). Low O_2 levels threaten the habitat, success and survival of marine life (e.g. fish, crustacean Vaquer-Sunyer and Duarte, 2008; Stramma et al., 2011; Altieri et al., 2017; Bertrand et al., 2011; do Rosário Gomes et al., 2014), including species vital to local and global marine ecosystem services, in terms of commercial value (tuna, billfishes, shrimp), catch volumes (anchovies and sardines) or tourism (coral reefs). The expansion of OMZs will also certainly exert a positive feedback on climate. Larger OMZs promote the production of nitrous oxide (Lam and Kuypers, 2011; Babbin et al., 2015; Yang et al., 2020), a powerful greenhouse gas, and reinforce the removal of biologically-available nitrogen, which in turn could limit the efficiency of the ocean's biological carbon sink (Gruber, 2004).

Observations indicate strong regional variations in the evolution of the OMZs. In the Pacific Ocean, the OMZ shrunk for most of the 20th century but expanded after 1970 (Deutsch et al., 2014; Stramma et al., 2008). In the northern Indian Ocean, parts of the OMZ are shrinking (north-west) whereas others are expanding (south) (Banse et al., 2014; Piontkovski and Al-Oufi, 2015; Queste et al., 2018). Looking to the 21st century, global de-oxygenation is projected to continue unless greenhouse gas emissions are rapidly curtailed (Bopp et al., 2013; Cabré et al., 2015; Bopp et al., 2017; Long et al., 2016). There is, however, **no consensus on how OMZs will evolve in the future**, with Earth-system models (ESMs) projecting dramatically different changes in OMZ volume between -10% and +15% (Cocco et al., 2012; Bopp et al., 2013; Cabré et al., 2015).

OMZs are found in "shadow zones" of the thermocline and intermediate layers located right below (approx. 100-1500 m). These regions combine weak ventilation, long water residence time (Pedlosky, 1987) and highly productive surface upwelling systems that boost respiration and O_2 biological demand at the subsurface (Paulmier and Ruiz-Pino, 2009) (Fig **??**). Global warming makes O_2 less soluble in surface waters and limits the transfer of these oxygenated waters to the ocean interior by increasing upper ocean stratification. Warming and enhanced stratification are, however, also expected to limit planktonic production, which could reduce O_2 biological demand and act as a stabilizing feedback on deoxygenation (Bopp et al., 2013). The strong variations in observed trends suggest that this balance between ventilation and biogeochemical feedbacks vary in space and time in the real ocean (Resplandy, 2018). Yet, uncertainties in the future OMZs show that ESMs disagree on the magnitude and timing of these ventilation and biological changes, and how strongly they offset each other. For instance, models that project a larger expansion of the equatorial Pacific OMZ by 2100 are models with larger weakening of the equatorial circulation (Shigemitsu et al., 2017; Busecke et al., 2019). Some ESMs also suggest that, after an initial expansion, OMZs might shrink due to the re-invigoration of ventilation in the 22nd century (Fu et al., 2018). **Improving our understanding of ventilation and biogeochemical feedbacks and constraining models using available observations is crucial to refine future projections of OMZs and anticipate their impacts.**

In coastal areas, anthropogenic eutrophication (excessive nutrient enrichment due to waste waters, fertilizers) exacerbates the effect of warming on de-oxygenation by promoting algal and microbial production which further consumes O_2 in coastal waters (Diaz and Rosenberg, 2008; Rabalais et al., 2010). In the past 50 years, more than 500 coastal hypoxic events ($O_2 < 60$ μM) or "dead zones" have been reported globally, mostly in the eutrophic American and European waters (Breitburg et al., 2018). **In the near future, the tropical Indian Ocean will be at greater risk of coastal hypoxia**. The OMZ in this region is expected to expand and eutrophication tied to population growth (urbanization, waste water, dependency on crops) is projected to increase (Seitzinger et al., 2010; Sinha et al., 2017). Reports of dead zones in the tropical Indian Ocean have increased in the past 20 years (Diaz and Rosenberg, 2008; Breitburg et al., 2018; Altieri and Gedan, 2015). Yet, dead zones are still sporadic, with dramatic extreme anoxic events (near-zero O_2) in certain years and no event reported in others (Naqvi et al., 2013), suggesting that natural variability still exerts a primary control on the occurrence of dead zones in the Indian Ocean (Vallivattathillam et al., 2017). **The challenge to predict coastal dead zones and their impacts for ecosystems and populations in the Indian Ocean is to quantify the effect of human perturbations but also of natural fluctuations, which can reinforce or dampen anthropogenic effects.** A major limitation so far has been to incorporate the wide range of spatio-temporal scales, from local coastal processes (river inputs, algal bloom dynamics on scales $<$ 100 km and 1 year) to basin and global processes (global warming, OMZ expansion, monsoon on scales $>$ 1000 km; 100 yrs). This research project seeks to provide a new foundation for our understanding of the Indo-Pacific OMZs and their future evolution, by examining the influence of ventilation (Obj-1), biogeochemical feedbacks (Obj-2) and assess the risk of coastal dead zones in Indian Ocean coastal waters (Obj-3).

2 Risk of coastal dead zones in the Indian Ocean

The OMZs in the northern Indian Ocean impinge on the coastal waters of countries accounting for more than a 1/4 of the world's population (India, Pakistan, Bangladesh *etc.*). The severe hypoxia of the continental shelf in this basin (Helly and Levin, 2004) promotes coastal denitrification (sedimentary and water column, Naqvi et al., 2006; Schwartz et al., 2009; Gaye et al., 2018), and in extreme cases induces coastal dead zones which influence benthic and pelagic communities. Dead zones have been reported in the Arabian Sea and the Bay of Bengal along the coasts of India, Malaysia, Burma and Thailand (Altieri and Gedan, 2015; Breitburg et al., 2018). In 2001, for instance, a dead zone along the western coast of India collapsed local shrimp fisheries and led to a 3- to 5-fold decline in demersal fish catch (Naqvi et al., 2013).

The sporadic nature of dead zones in the Indian Ocean suggests that natural variability is crucial to their occurrence. In a prior work in collaboration with the National Institute of Oceanography in India, we showed that shallow thermocline and oxycline (i.e. strong gradient in O_2 separating surface oxygenated waters from low O_2 waters below) during summer/fall upwelling preconditioned coastal hypoxia seasonally along the western Indian coast. Yet we found that interannual anomalies in oxycline during positive phases of the Indian Ocean Dipole (IOD) limited the seasonal invasion of low O_2 waters on the continental shelf and prevented coastal hypoxia (Vallivattathillam et al., 2017). This study which established a link between seasonal and interannual variability and coastal dead zones was however limited to a small portion of the western Indian coast (off of Goa) where seasonal oxygen data were available (15.5°N, 73.6°E) and relied on a relatively coarse model (25 km) to examine natural interannual variability unresolved by the data at the time. Here, we propose to leverage new interannual observations and expand this study of coastal dead zones to the entire northern Indian Ocean and incorporate the wide range of spatio-temporal scales, from local processes (river inputs, algal bloom dynamics and O_2 cross-shelf transport on scales $<$ 100 km and 1 year) to basin and global processes (global warming, OMZ expansion, Monsoon on scales $>$ 1000 km; 100 yrs). The objective is threefold:

- **Obj-3.1** Estimate how natural variability precondition coastal anoxia in the Indian Ocean (e.g. seasons, IOD, fine scale flow structures, coastal residence time and river loadings).
- **Obj-3.2** Quantify the re-enforcing role of anthropogenic activities (e.g. river loadings, aerosol deposition and warming-driven changes in monsoon).
- **Obj-3.3** Identify regions and conditions with higher risks of coastal dead zones.

▷ **Natural variability tied to seasonal monsoon and Indian Ocean Dipole.** The IOD is an east-west oscillation controlled by winds in the central equatorial Indian Ocean (Saji et al., 1999). Positive phases are characterized by a cooling and shallower thermocline in the eastern Indian Ocean (anomalous upwelling along Java) and by a warming and deeper thermocline in the central and western Indian Ocean. This equatorial signal propagates around the Bay of Bengal as coastal Kelvin wave, shallowing the thermocline along the eastern Indian coast in the Bay of Bengal. In the Arabian Sea, however, anomalous winds at the tip of India generate downwelling coastal Kelvin waves that deepen the thermocline (Suresh et al., 2016; Vallivattathillam et al., 2017). In Figure 1, we computed the month of shallowest seasonal oxycline on the northern Indian coastal shelf using hydrographic databases. Consistent with our prior result, the oxycline is shallowest in summer/fall off of Goa (Vallivattathillam et al., 2017) but also in most of the Arabian Sea and in the western Bay of Bengal. In contrast, the oxycline is shallowest in winter/spring in the eastern part of the Bay of Bengal. The added value of including Bio-Argo data is that they capture interannual IOD variability. Our preliminary results show that positive phase of the IOD limit the fall invasion of low O_2 waters on the shelf in the eastern Arabian Sea, while they reinforce the spring supply of low O_2 waters in the eastern Bay of Bengal (Fig 1, probability distribution in bottom panels).

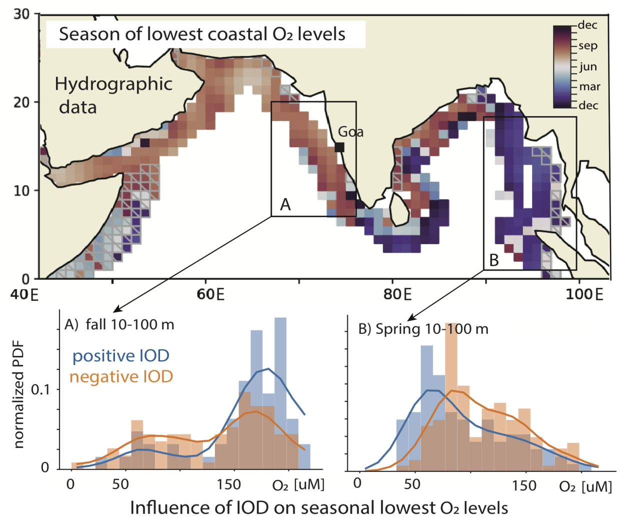

Figure 1: (Top) Month with shallowest seasonal oxycline, which corresponds to lowest O_2 levels on the shelf. Oxycline is shallowest in summer/fall in Arabian Sea and western Bay of Bengal and in winter/spring in the eastern Bay of Bengal. (Bottom) Probability distribution of oxygen levels on the shelf during fall in eastern Arabian Sea (box A) and spring in eastern Bay of Bengal (box B). Positive IODs limit the occurrence of low O_2 levels in eastern Arabian Sea but favor them in spring in eastern Bay of Bengal. Data are from bio-Argo, GO-SHIP and Wold Ocean Data Base (Talley et al., 2016; Bittig et al., 2019; Boyer et al., 2013).

▷ **Fine-scale flow structures and bathymetry.** Other key natural processes controlling O_2 on the shelf include fine scale flow structures associated with mesoscale eddies and bathymetry. Mesoscale eddies are known to promote algal blooms and control the supply of oxygen to the OMZ (Resplandy et al., 2011, 2012; Lachkar et al., 2016). In a recent study, we showed that resolving fine scale structures of the flow and bathymetry limited the ventilation of the shelf and increased the residence time of coastal waters on the western Indian shelf by 25 to 50% (Liu et al., 2019). Although unexplored, this effect could favor the retention of low O_2 upwelled waters with high respiration on the shelf and promote coastal dead zones. This hypothesis is supported by results from our regional Indian Ocean biophysical model (Resplandy et al., 2012), which shows O_2 level lower than 100μM trapped by eddies on the shelves in the eastern Arabian Sea and around the Bay of Bengal (Fig 2).

▷ **Eutrophication and anthropogenic changes.** Riverine nutrient loadings are projected to increase due to population growth (Seitzinger et al., 2010; Sinha et al., 2017). They are also expected to vary on interannual and multi-decadal time-scales due to variations in monsoonal precipitations. We used river loading data collected at stations recently released online by the Water Resources Information System of India (India-WRIS) to evaluate water and nitrogen runoff in 7 catchment areas in central and southern India (catchment data from NASA/USGS Hydro1k dataset). Each stations have more than 15-20 years of daily discharge measurements and 150 measurements of nitrogen concentrations in the past three decades. Preliminary analysis of this dataset suggests high interannual variability in nutrient loadings, well correlated with water discharge and upstream precipitation. On interannual time-scales, rainfall is expected to increase in central and northern India during positive IOD and in the western India during negative IOD (Behera and Ratnam, 2018). On longer time-scales, anthropogenic activities seem to weaken the monsoon but make it more erratic, with more extreme rainfalls (Singh, 2016). We propose to further explore the response of coastal oxygen to these interannual and future change in rainfall and nutrient loadings.

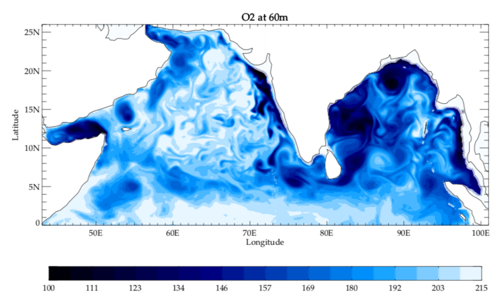

Figure 2: O_2 at 60 m depth [μM] in a high-resolution regional Indian Ocean simulation reveals intense variability at the mesoscale along the coast (Resplandy et al., 2012).

▷ **Proposed Research.** We propose to evaluate how natural (Obj-3.1) and anthropogenic (Obj-3.2) processes control the O_2 levels on the coastal shelf and identify regions at higher risk of coastal dead zones (Obj-3.3) using existing hydrographic data and a new regional Indian Ocean biophysical model based on MOM6-COBALT. My group has been working over the past year to develop a regional Indian Ocean model (30E-135E, 30S-30N) with an eddy-permitting resolution (25 km) and are developing an eddying configuration (10 km) to better resolve the topography, ocean circulation and biogeochemistry on the shelf. This regional model largely benefits from the expertise acquired when developing the older model of Resplandy et al. (2009, 2012). If needed, we could consider a nesting at even higher resolution (5 km) in key regions such as the eastern Arabian Sea and/or the eastern Bay of Bengal.

We will refine the analysis of hydrographic data (Fig 1) and leverage the extensive new data from the Second International Indian Ocean Expedition (IIOE-2, Hood et al., 2019; Hood and Beckley, 2019) to identify regions where seasonal and interannual variations favor low O_2 levels on the shelf and coastal dead zones. We will also use the global data base of coastal dead zones of Diaz et al. (2011) and Altieri et al. (2017) to identify location, season and IOD phase of reported events. We will complement this data-based analysis using a suite of regional model experiments. The comparison of the eddy-permitting and eddying simulation will inform on the influence of mesoscale eddies and coastal bathymetry. The relative contribution of biological and physical variations will be evaluated using the simulated oxygen budgets as in Resplandy et al. (2012), which my group coded in the MOM6-COBALT model (see example on carbon in Liao et al., 2020).

To examine the influence of eutrophication, we will expand the analysis started with the data released by India-WRIS to evaluate interannual variability in water discharge and nitrogen loadings in the 7 catchements, and use regional model experiments with climatological and time-varying regional model experiments to evaluate their impact on coastal O_2 . Future anthropogenic influences will be evaluated by extending the regional simulation using future atmospheric fields (e.g. rainfall, winds, temperature) and ocean fields (e.g. oxygen, temperature, salinity at model boundary) from GFDL-ESM4 under the mitigation (SSP245) and business as usual (SSP585) scenarios. Finally, we will identify regions with higher risk of coastal dead zones (O_2 <60 μM) and relate this risk to natural and anthropogenic factors (e.g. season, coastal geometry, riverine loadings, rainfall), a key steps towards anticipating their ecological and societal impacts.

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