Oxygen Deficiency in the Water Column of the North Indian Ocean

Wajih Naqvi
National Institute of Oceanography
Dona Paula, Goa
Why do we care about oxygen deficiency?

Oxygen depletion occurs to varying extent in all oceanic areas, but nearly anoxic conditions are restricted to a few regions.

Oxygen minimum zones (OMZs) are sites of important biogeochemical transformations that control ocean productivity & atmospheric composition. \( O_2 \) deficiency also impacts marine life.

Ocean Deoxygenation: Oceans are losing oxygen; OMZs are expanding (Stramma et al., Science, 320:655-658, 2008).

@ 0.09-0.37 \( \mu \text{mol/kg/yr} \) within 300-700 m in Pacific & Atlantic
The OMZs - What is Unique about Indian Ocean?

- Intense oxygen minimum zones occur in the north, not in the east; greater interaction with continental margins
  - due to low-latitude northern boundary, porous eastern boundary
    → unusual circulation: monsoon reversal, restricted subsurface ventilation in the north
- Indian Ocean contains the only major western boundary upwelling centres in the world
OMZ thickest and most intense in Arabian Sea due to high productivity resulting from summer upwelling and winter convection

Anoxic (reducing) conditions prevail only within a well-defined area in the central/NE Arabian Sea distinguished by nitrite accumulation

Reducing zone geographically separated from areas of highest productivity
- Better ventilation in the western Arabian Sea
- Shallower mineralization of OM offshore due to Fe and Si deficiency

Reducing zone remarkably stable on multi-decadal time scale despite slight fluctuations of the western boundary
Secondary Nitrite Maximum (SNM)

- Water outside SNM slightly oxygenated, but anoxic within this zone ($O_2$ below detection (<10 nM) of STOX sensor)

- SNM zone ~ $3 \times 10^{14}$ m$^3$ (~3% of the volume of AS), supports 1/3 of global oceanic water column N-loss; volume of nearly-anoxic water much larger – vulnerable to climate change
Large N-loss within the Arabian Sea OMZ

- Nitrate minimum, nitrite maximum and N$_2$O minimum in the upper OMZ indicate N loss
- Excess N$_2$ derived from N$_2$/Ar compares well with N loss computed from O$_2$ and phosphate data.

Naqvi et al., *Biogeosciences* (2006)

Much higher N$_2$/Ar ratio in water within the suboxic zone (blue symbols) than outside (red symbols)

Devol et al., *DSR I*, 53: 1533-1547, 2006
Disagreement over nitrogen loss pathways

Denitrification
\[(\text{NO}_3^– \rightarrow \text{NO}_2^- \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2)\]
found to be more important than
Anaerobic Ammonium Oxidation
(Anammox: \(\text{NH}_4^+ + \text{NO}_2^- \rightarrow \text{N}_2 + \text{H}_2\text{O}\)) by Ward et al. (Nature, 461: 78-81, 2009)

Anammox coupled with DNRA is the dominant mechanism of N loss off
Oman but not in the open ocean OMZ
(Lam et al., Biogeosciences, 8: 1565-1577, 2011)
Isotopic signatures of denitrification

- Preferential reduction of $^{14}$NO$_3^-$ over $^{15}$NO$_3^-$ causes enrichment of $^{15}$N in NO$_3^-$ and depletion in N$_2$; fractionation factor computed from field data (~25 per mil) close to lab value.

- Extremely large enrichment of $^{15}$N and $^{18}$O in N$_2$O. Upper and lower N$_2$O concentration maxima have different compositions – various formative pathways.
Accumulation of reduced species of several polyvalent elements associated with SNM

Iodate (IO$_3^-$) reduced to iodide (I$^-$) by bacteria within SNM

Dissolved Mn (Mn II) also exhibits a maximum within this zone (Farrenkopf & Luther, *DSR. II*, 49: 2303-2318, 2002) as does dissolved Fe (Fe II) (Moffett et al., *DSR I*, 54: 1341-1349, 2007).
Traces of $O_2$ inhibit anaerobic pathways

- Secondary nitrite maximum is associated with a particle maximum and a bacterial biomass maximum
- Heterotrophic nanoflagellates quite abundant within SNM - bacterial abundance not due to suppressed grazing

How do HNF respire?
Bay of Bengal on verge of anoxia

- Minimum $O_2$ in BoB in 10-100 nM range
- No SNM
- Slight $N_2$ excess, $^{15}N$ enrichment in nitrate
- Microbial populations similar to other OMZs
- Low denitrification and Anammox activities

Bristow et al., in review


Sedimentary record suggests BoB was not strongly denitrifying over past 35 years
Why doesn't the Bay of Bengal turn anoxic?

- Low respiration rates in water column
  - Little upwelling, convective mixing -> Lower productivity
  - Rapid sedimentation of particulate organic matter due to ballast provided by lithogenic material

More fresh material reaches the seafloor in BoB

- Subtle differences in physics (better oxygenation of OMZ through vertical mixing?)

A metabolic hole in BoB water column? Oxygen too low to support aerobic respiration (kinetic control), but enough to inhibit anaerobic respiration (thermodynamic control)

Traces of O₂ hard to remove? Similar conditions occur in Gulf of California and California Borderline Basins

Gordon et al., DSR II (2002)

Naqvi et al., DSR II (1996)
Oxygen deficiency in coastal waters – difference between the western and eastern Arabian Sea

- Strong upwelling brings up low O\textsubscript{2} water over the shelf in western Arabian Sea, but reducing conditions do not develop due to quick ventilation
  
  Off Omani coast

- Upwelling weaker off India, longer residence time of upwelled water over shelf; upwelled water capped by a warmer, fresher layer arising from monsoon precipitation – very strong near surface thermohaline stratification
  
  Off Indian west coast

- Extreme conditions – complete N-loss and sulphate reduction

- Not contiguousous with the open ocean suboxic zone
West India Undercurrent

Flows along the margin (~100–400 m) during the period of upwelling (May–November)

- Core of undercurrent fresher (by > 0.3) and more oxygenated (>10 μM) than waters at same depth offshore
- Maintains O$_2$ concentrations marginally above the threshold (~1 μM) for denitrification off Indian margin
- Large impact on biogeochemistry

Offshore intensification of denitrification unique to Arabian Sea
Intense Seasonal Anoxia off India

Property distributions off Bombay in October 1999

World's largest coastal low $O_2$ zone (area 200,000 km²)

Outer shelf hypoxic, mid-shelf suboxic, inner shelf anoxic (sulphidic)

Huge buildup of $N_2O$

(Naqvi et al., Nature, 2000)
Annual cycle of hydrographic and chemical parameters at the Candolim Time Series (CaTS) location (depth 28 m) off Goa.

Large inter-annual variability; no long-term trend. Exact causes of the variability is not known, but IOD/ENSO play a role.
Response to human induced changes

- Oceanic OMZs and coastal hypoxic zones are expanding globally (Stramma et al., 2008; Diaz and Rozenburg, 2008).

- No clear evidence for expansion of low O₂ systems in the Indian Ocean over the past 4 decades despite their potential vulnerability to human induced changes (large nutrient loading?)

- Will the large volume of nearly-anoxic waters in the North Indian Ocean, especially in BoB, turn anoxic in response to eutrophication and/or slowdown of mid-depth circulation in future?

- It will have a large impact on biogeochemical cycling.
Thank You