Oxygen Deficiency in the Water Column of the North Indian Ocean

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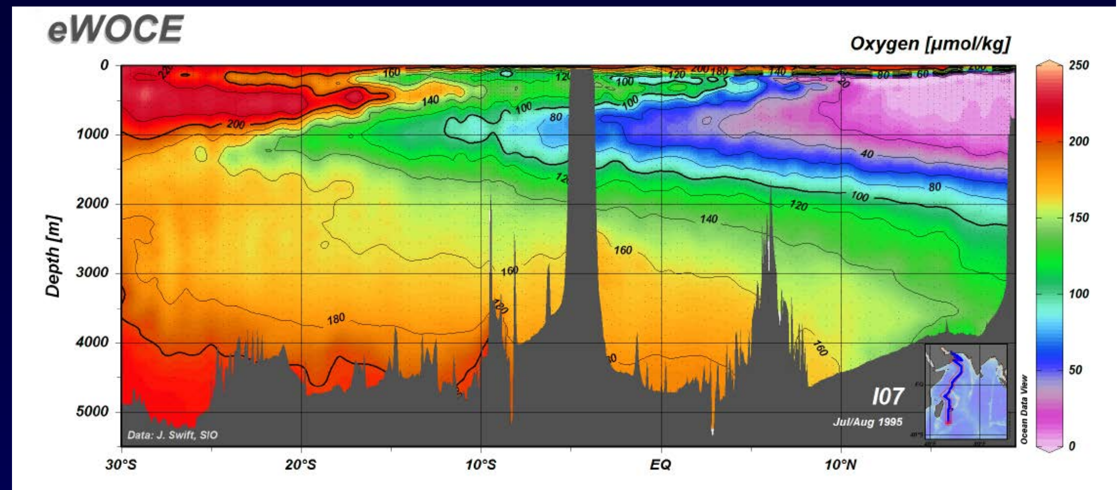
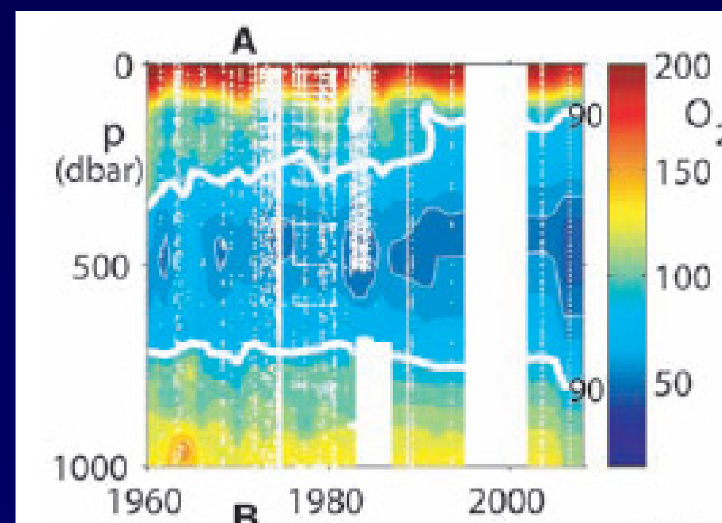
Why do we care about oxygen deficiency?

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).

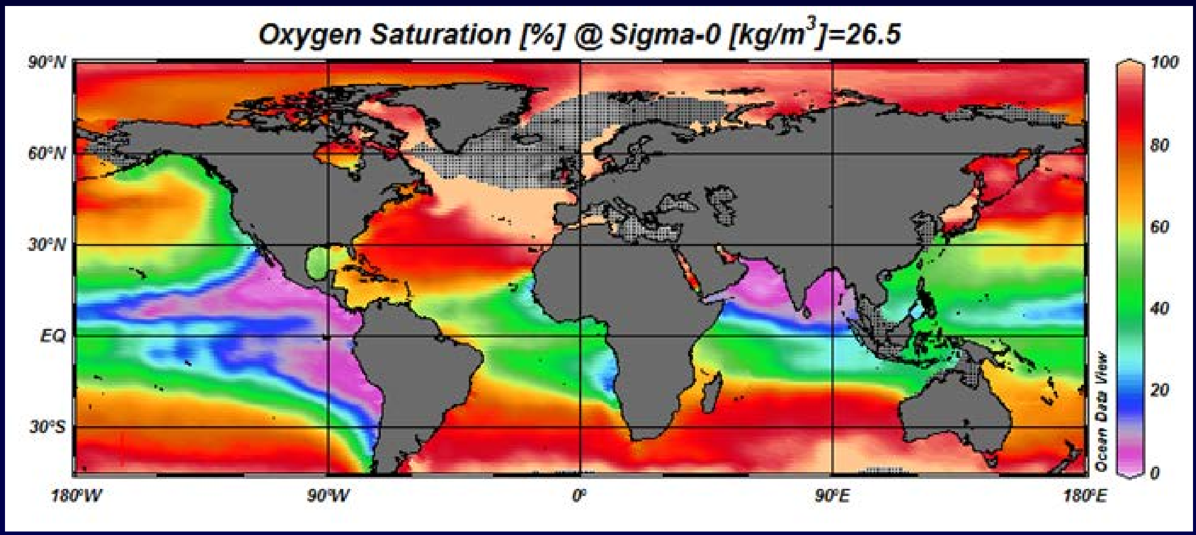
@ 0.09-0.37 µmol/kg/yr within 300-700 m in Pacific & Atlantic

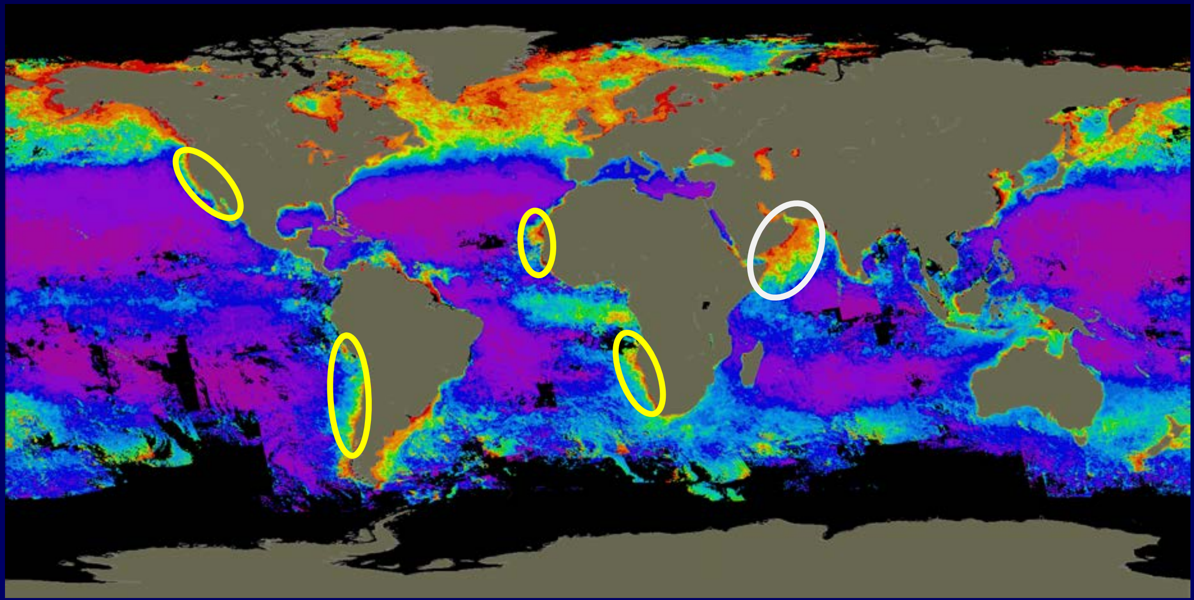
The OMZs - What is Unique about Indian Ocean?

- 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

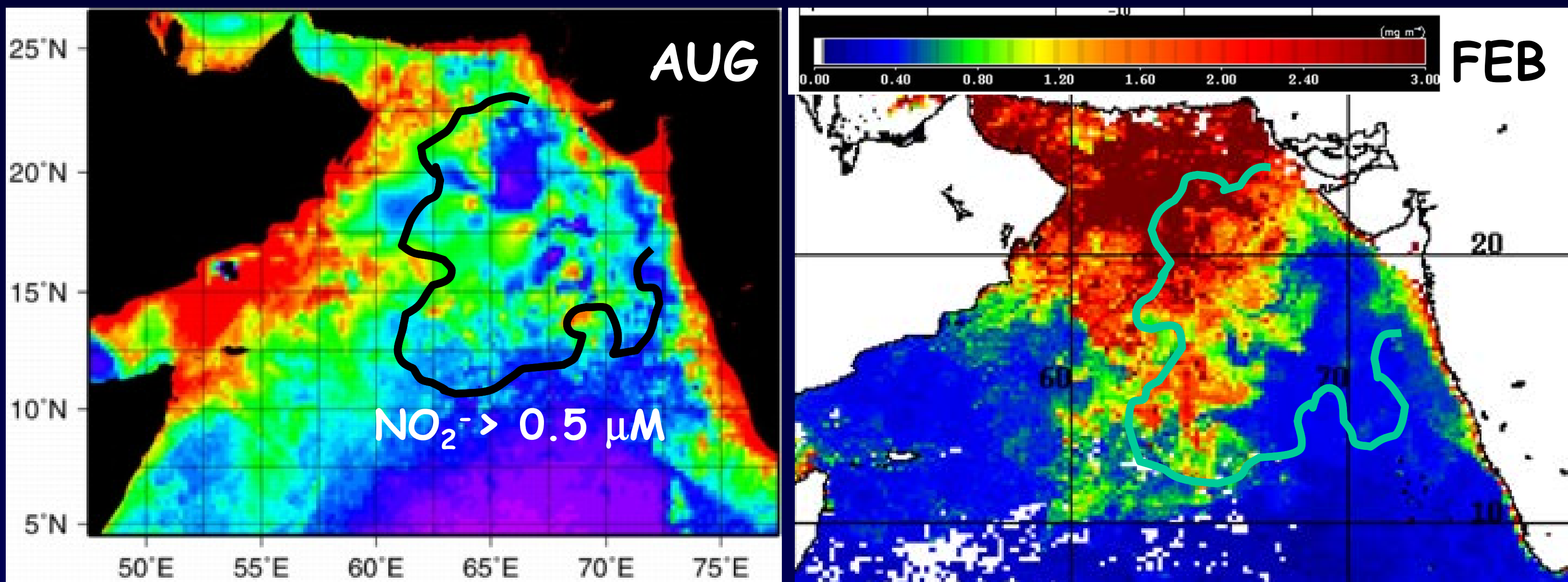
- Indian Ocean contains the only major western boundary upwelling centres in the world





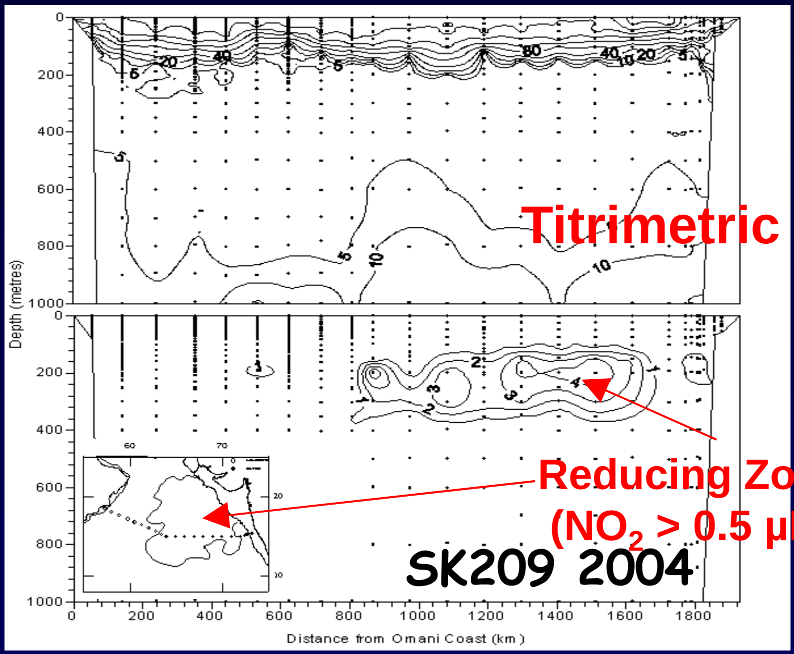
Global mean chlorophyll in July-August

Geographical variability of oxygen deficiency



- ➢ 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

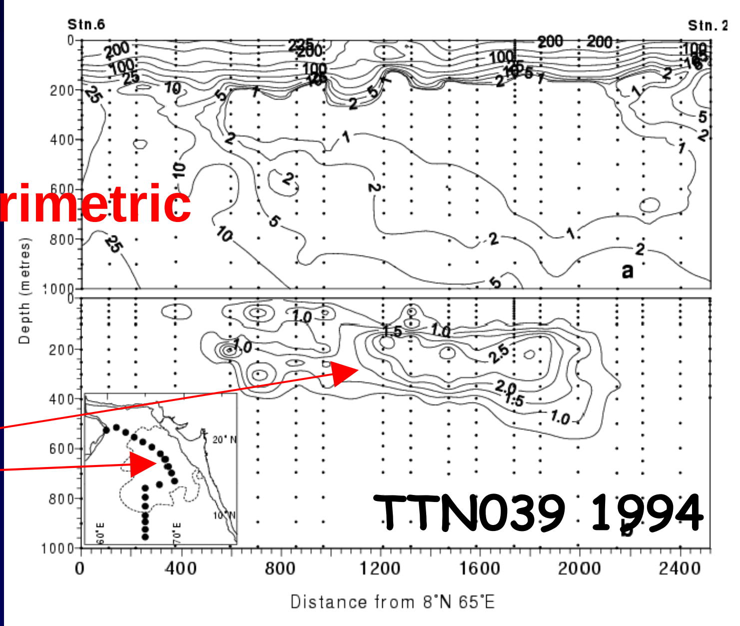
Secondary Nitrite Maximum (SNM)



O_2

Colorimetric

NO_2

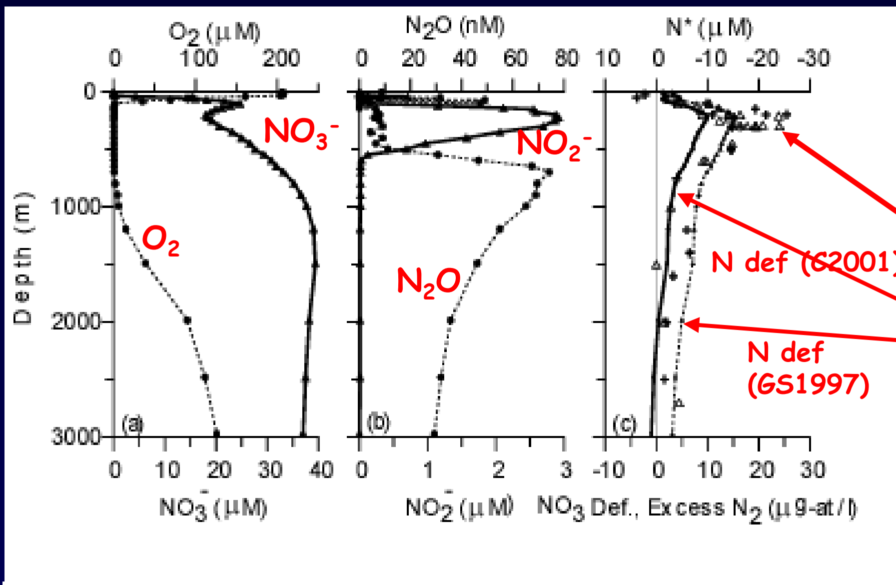


O_2 and NO_2^- distributions along two sections

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

- SNM zone ~ 3 x 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

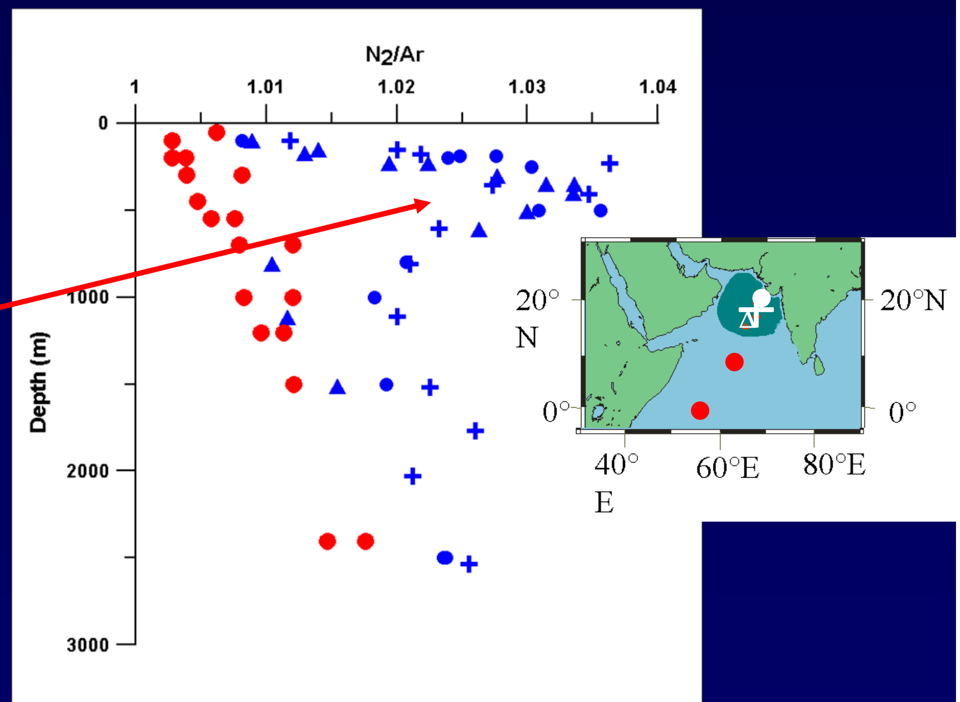
Large N-loss within the Arabian Sea OMZ



Naqvi et al., *Biogeosciences* (2006)

- Nitrate minimum, nitrite maximum and N_2O 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.

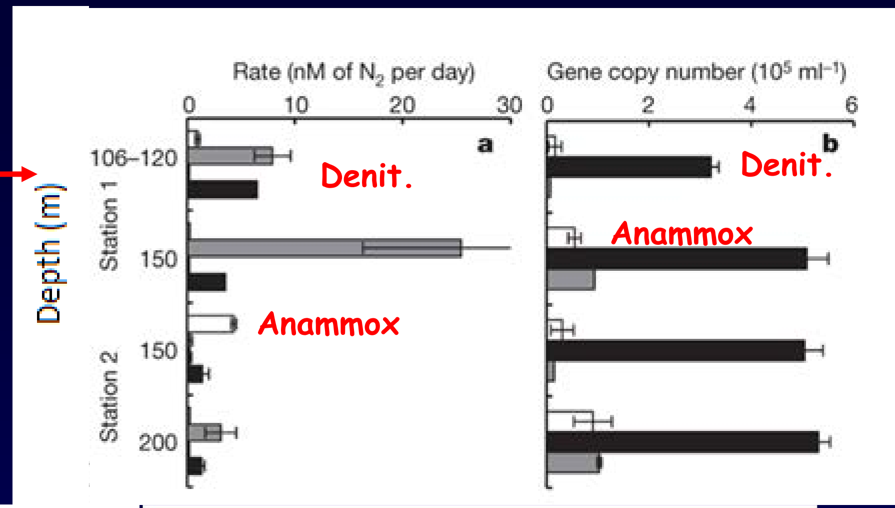
Much higher N_2/Ar ratio in water within the suboxic zone (blue symbols) than outside (red symbols)

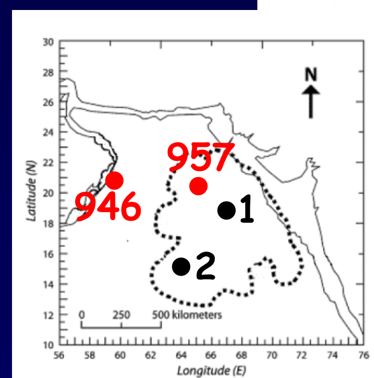


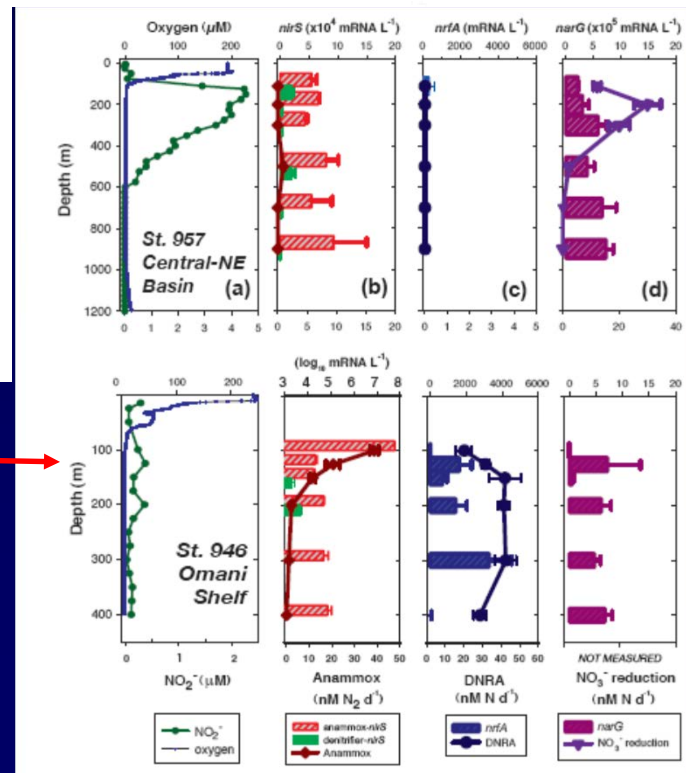
Devol et al., *DSR I*, 53: 1533-1547, 2006

Disagreement over nitrogen loss pathways

Denitrification ($NO_3 \rightarrow NO_2 \rightarrow NO \rightarrow N_2O \rightarrow N_2$) found to be more important than Anaerobic Ammonium Oxidation (Anammox: $NH_4 + NO_2 \rightarrow N_2 + H_2O$) by Ward et al. (*Nature*, 461: 78-81, 2009)



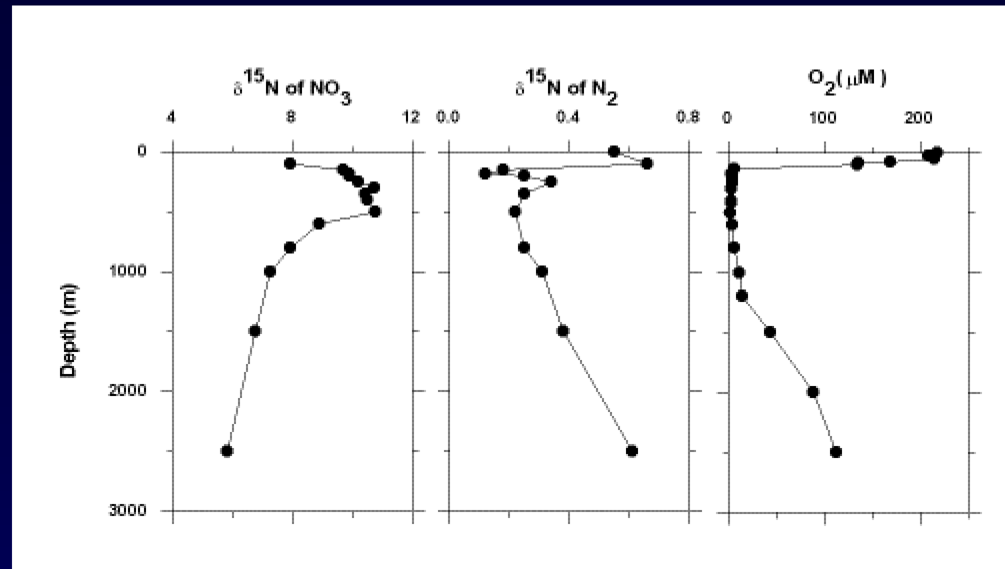


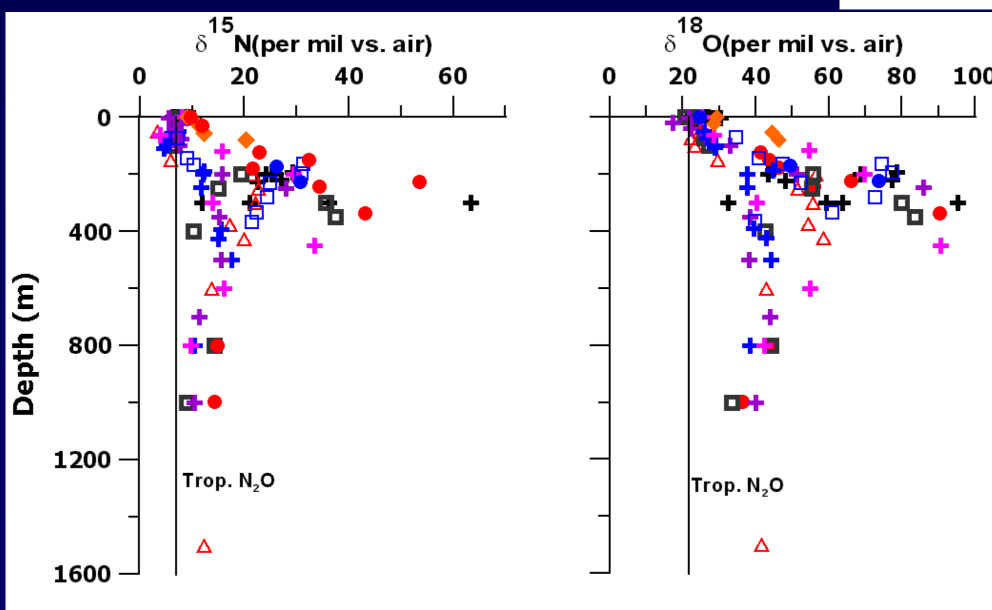


Anammox coupled with DNRA is the dominant mechanism of N loss off Oman but not in the open ocean OMZ (Lam et al., *Biogeosciences*, 8: 1565-1577, 2011)

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.

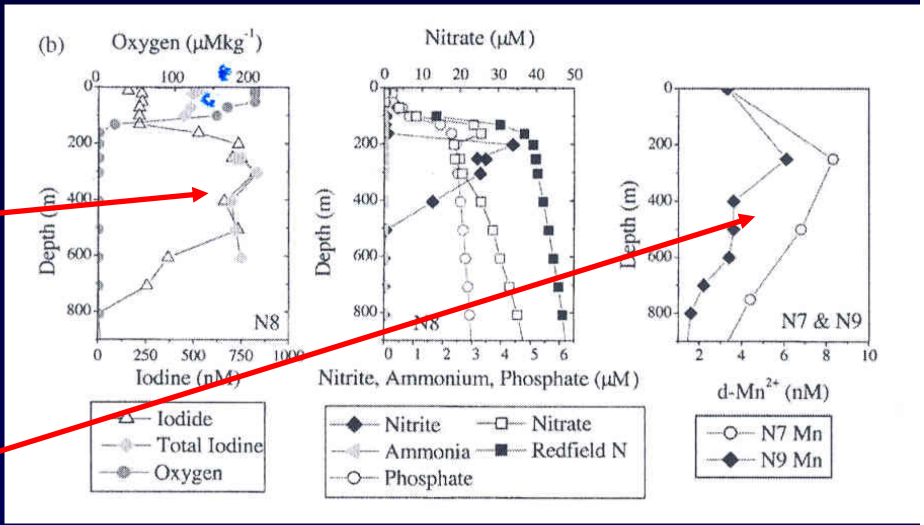




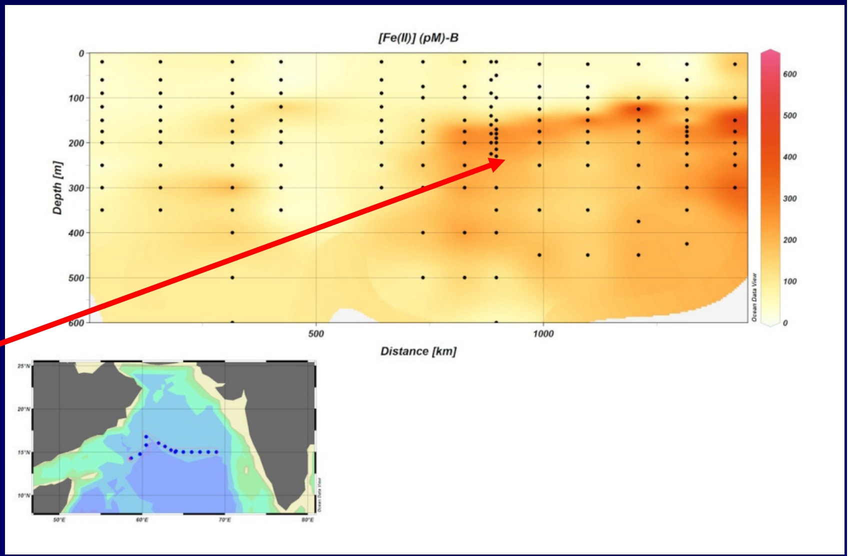
- Extremely large enrichment of ^{15}N and ^{18}O in N_2O. Upper and lower N_2O concentration maxima have different compositions – various formative pathways

Accumulation of reduced species of several polyvalent elements associated with SNM

Iodate (IO_3^-) reduced to iodide (I^-) by bacteria within SNM



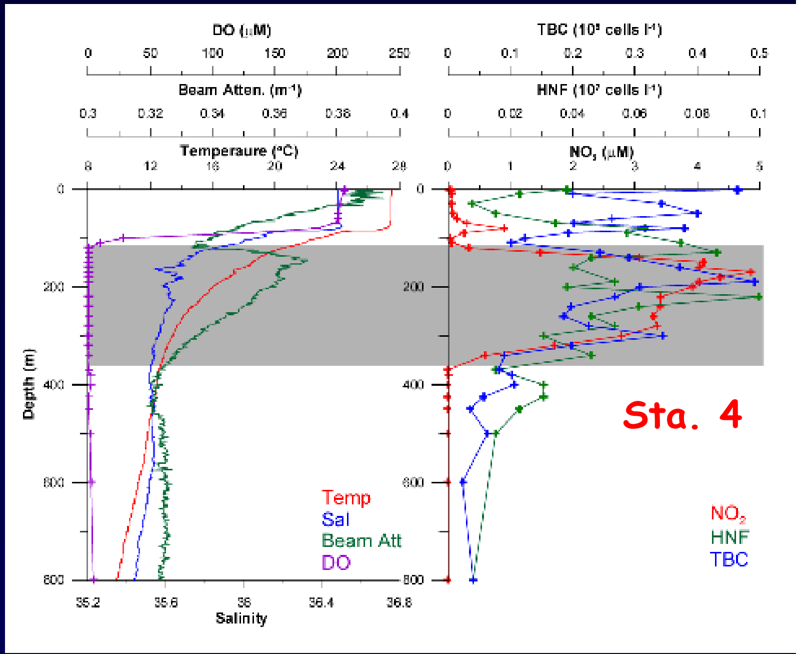
Dissolved Mn (Mn II) also exhibits a maximum within this zone (Farrenkopf & Luther, *DSR. II*, 49: 2303-2318, 2002) as does dissolved Fe (Fe II) (Moffett et al., *DSR I*, 54: 1341-1349, 2007) .

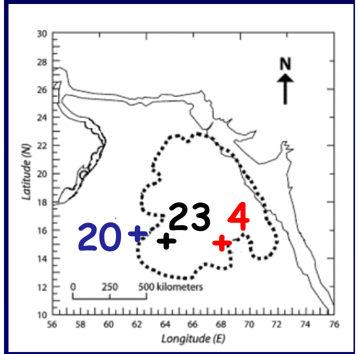


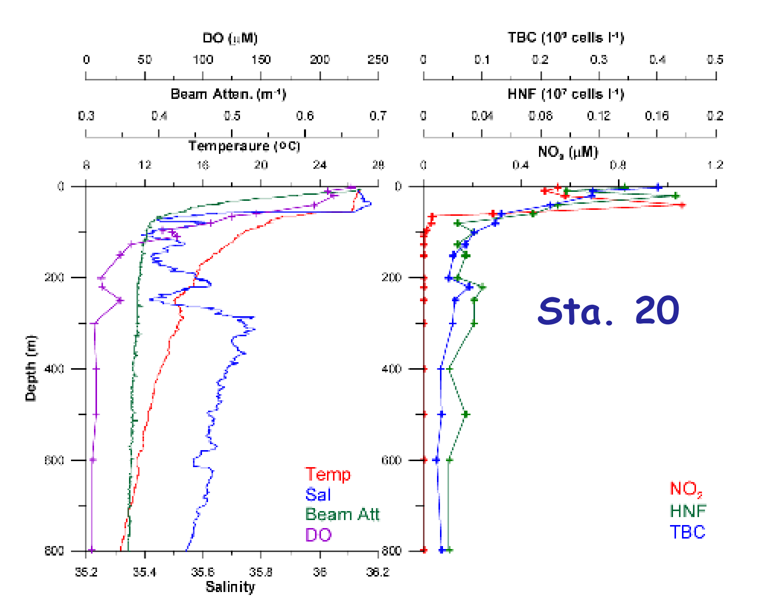
Traces of O_2 inhibit anaerobic pathways

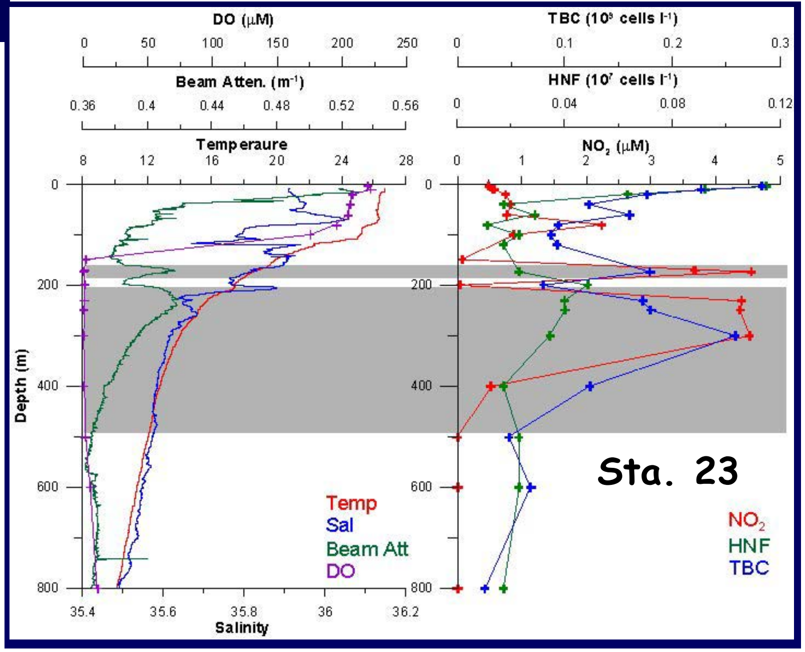
- Secondary nitrite maximum is associated with a particle maximum and a bacterial biomass maximum
- Heterotrophic nanoflagellates quite abundant within SNM - bacterial abundance not due to suppressed grazing

How do HNF respire?





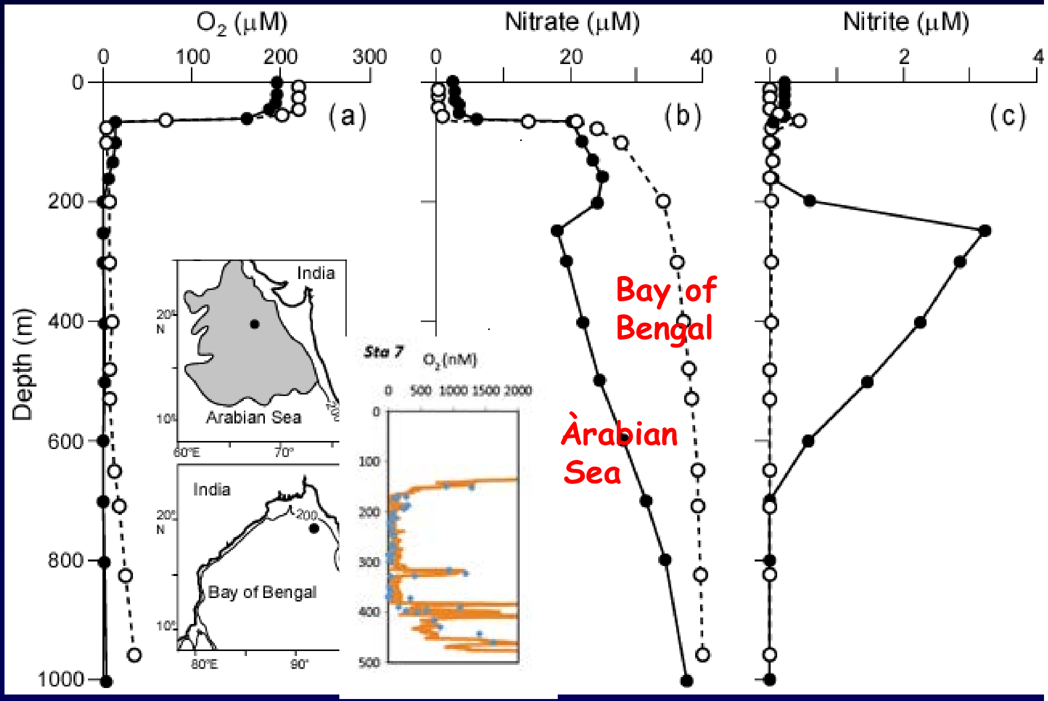




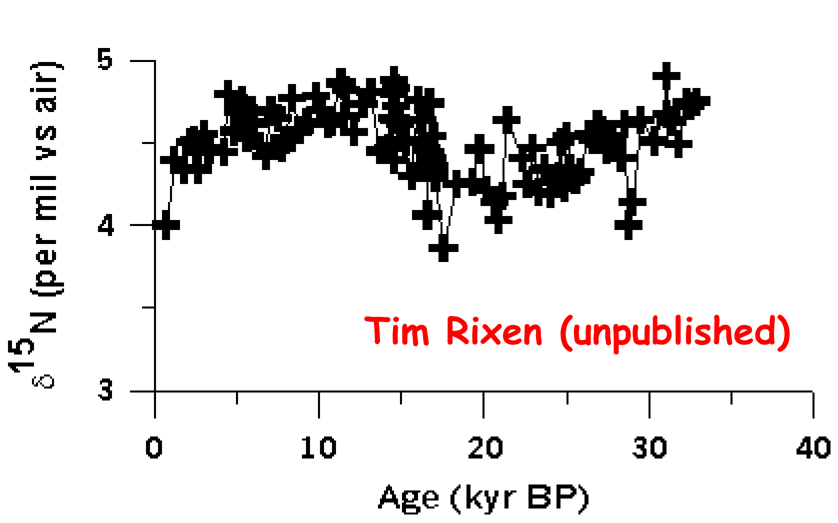
Bay of Bengal on verge of anoxia

- 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



Naqvi et al., *The Sea* (2006)



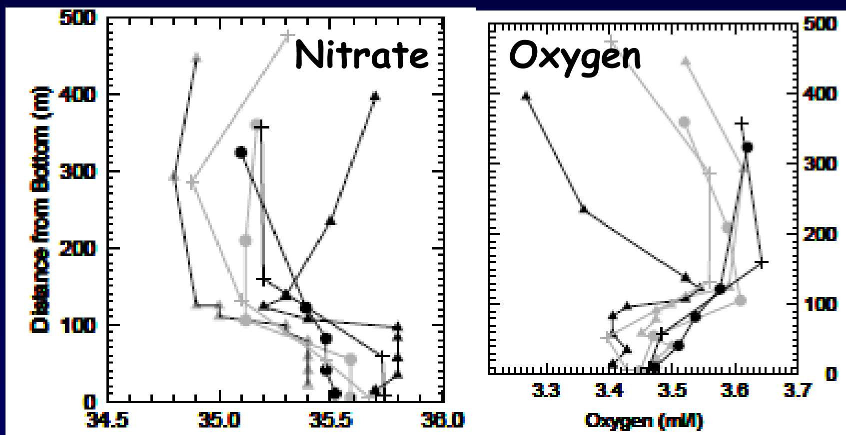
Sedimentary record suggests BoB was not strongly denitrifying over past 35 years

Why doesn't the Bay of Bengal turn anoxic?

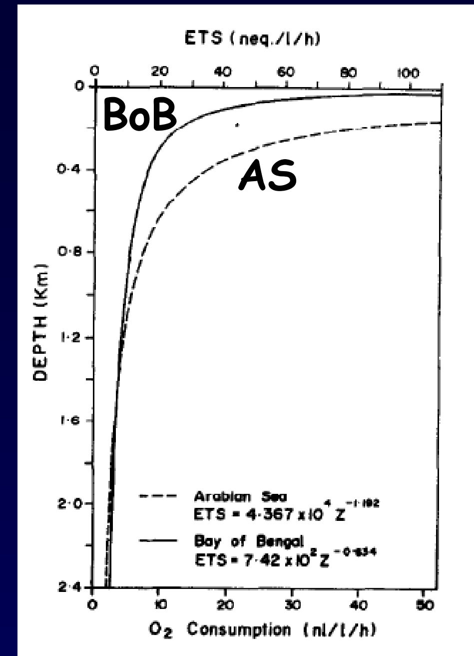
- Low respiration rates in water column

- Little upwelling, convective mixing -> Lower productivity

- Rapid sedimentation of particulate organic matter due to ballast provided by lithogenic material



Gordon et al., DSR II (2002)



Naqvi et al., DSR II (1996)

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 O_2 hard to remove? Similar conditions occur in Gulf of California and California Borderline Basins

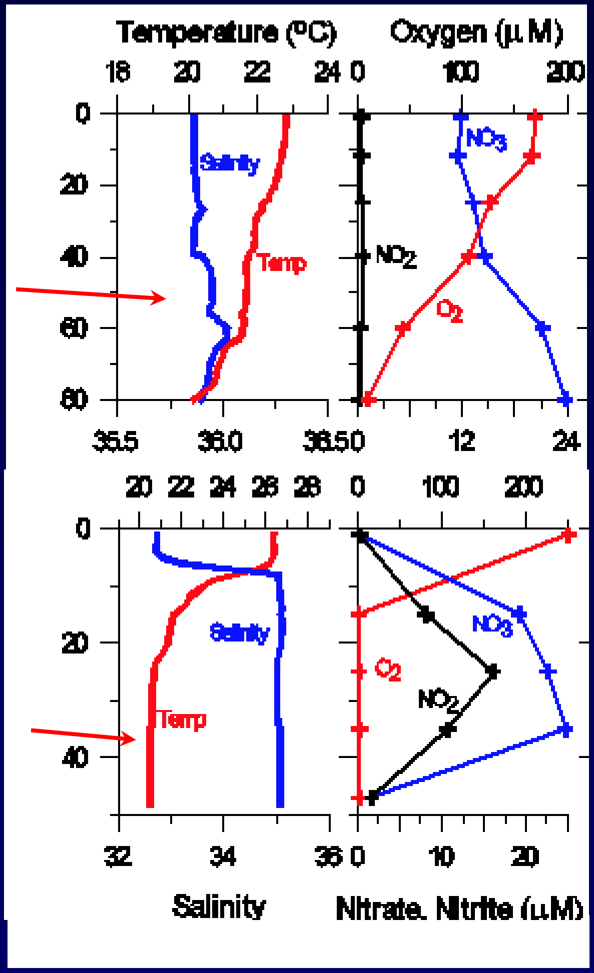
Oxygen deficiency in coastal waters – difference between the western and eastern Arabian Sea

- Strong upwelling brings up low O_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 stratificaion

Off Indian west coast



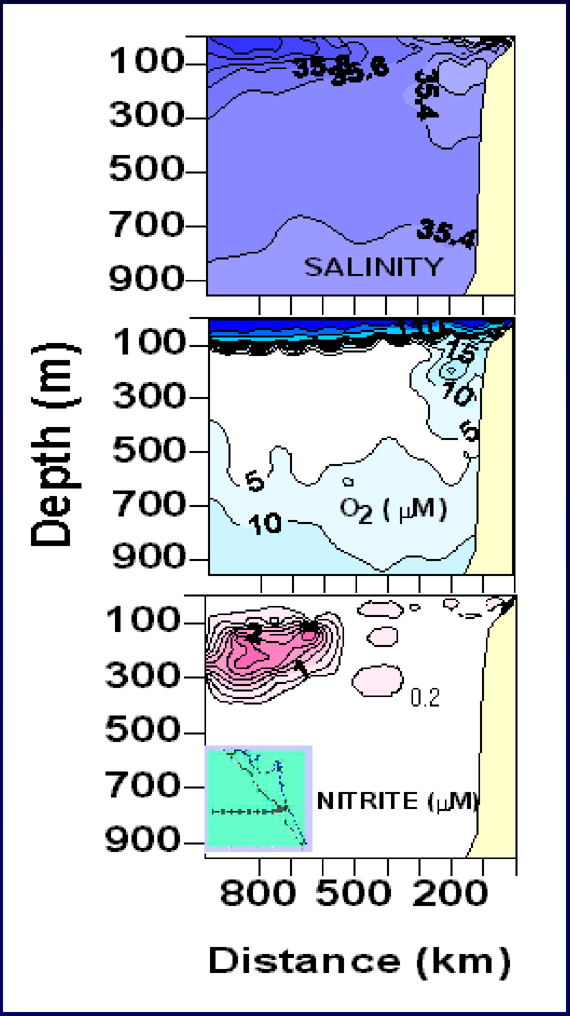
- Extreme conditions – complete N-loss and sulphate reduction

- **Not contiguous 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

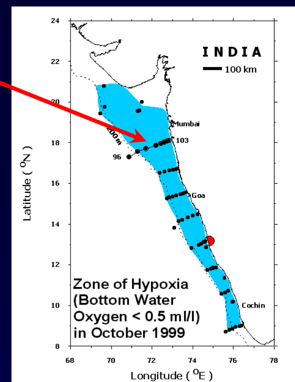


Offshore intensification of denitrification unique to Arabian Sea

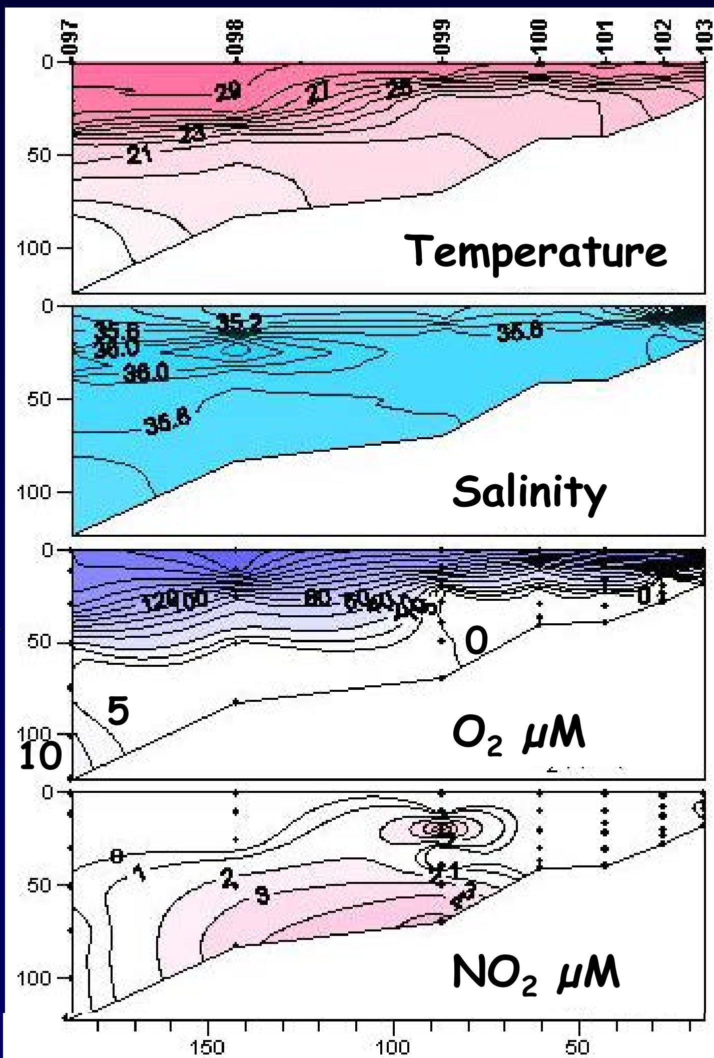
Intense Seasonal Anoxia off India

Property distributions off Bombay in October 1999

World's largest coastal low O_2 zone (area 200,000 km^2)



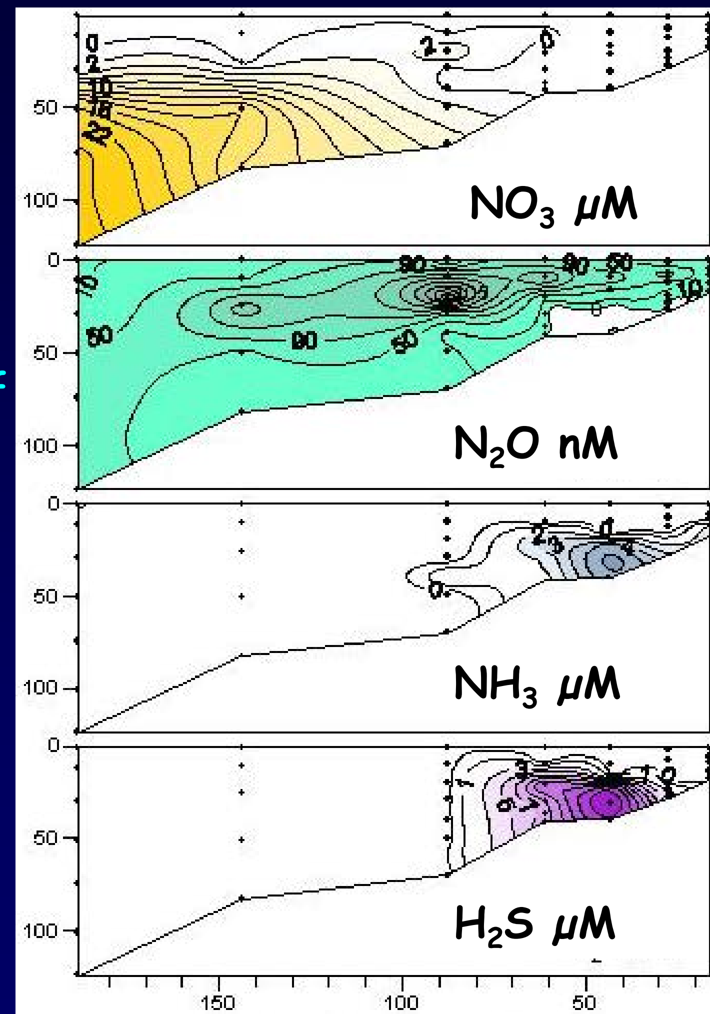
Depth in metres



Distance from coast (km)

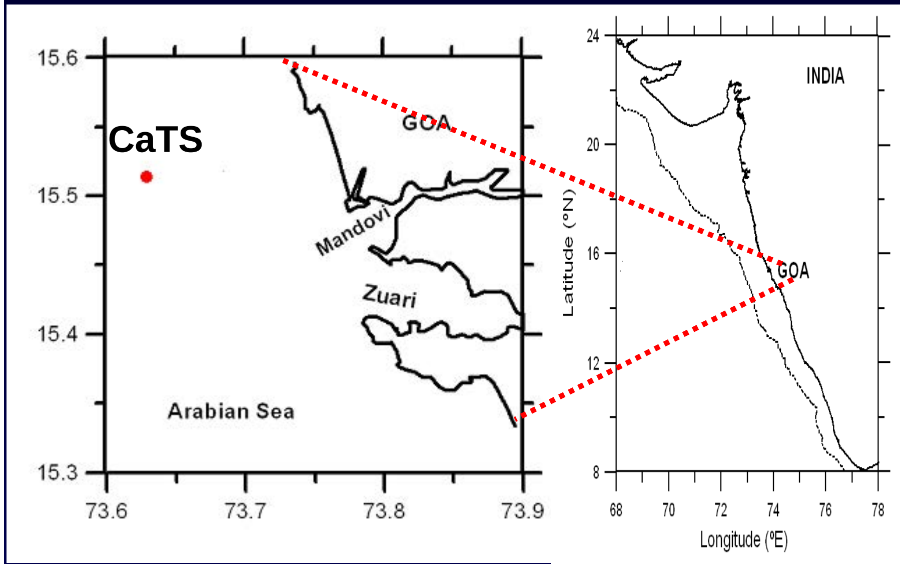
Outer shelf hypoxic, mid-shelf suboxic, inner shelf anoxic (sulphidic)

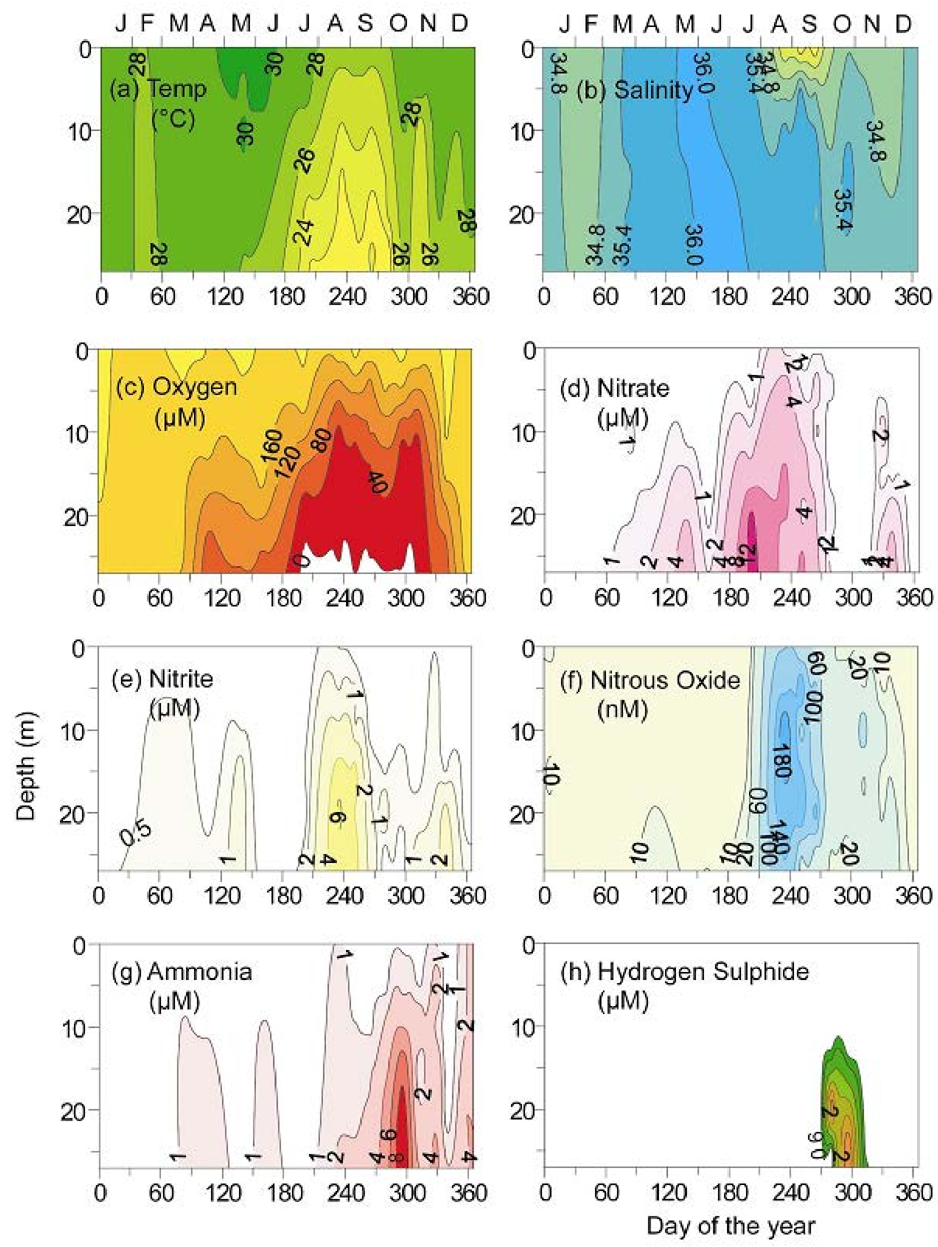
Huge buildup of N_2O



Distance from coast (km)

(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 O_2 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