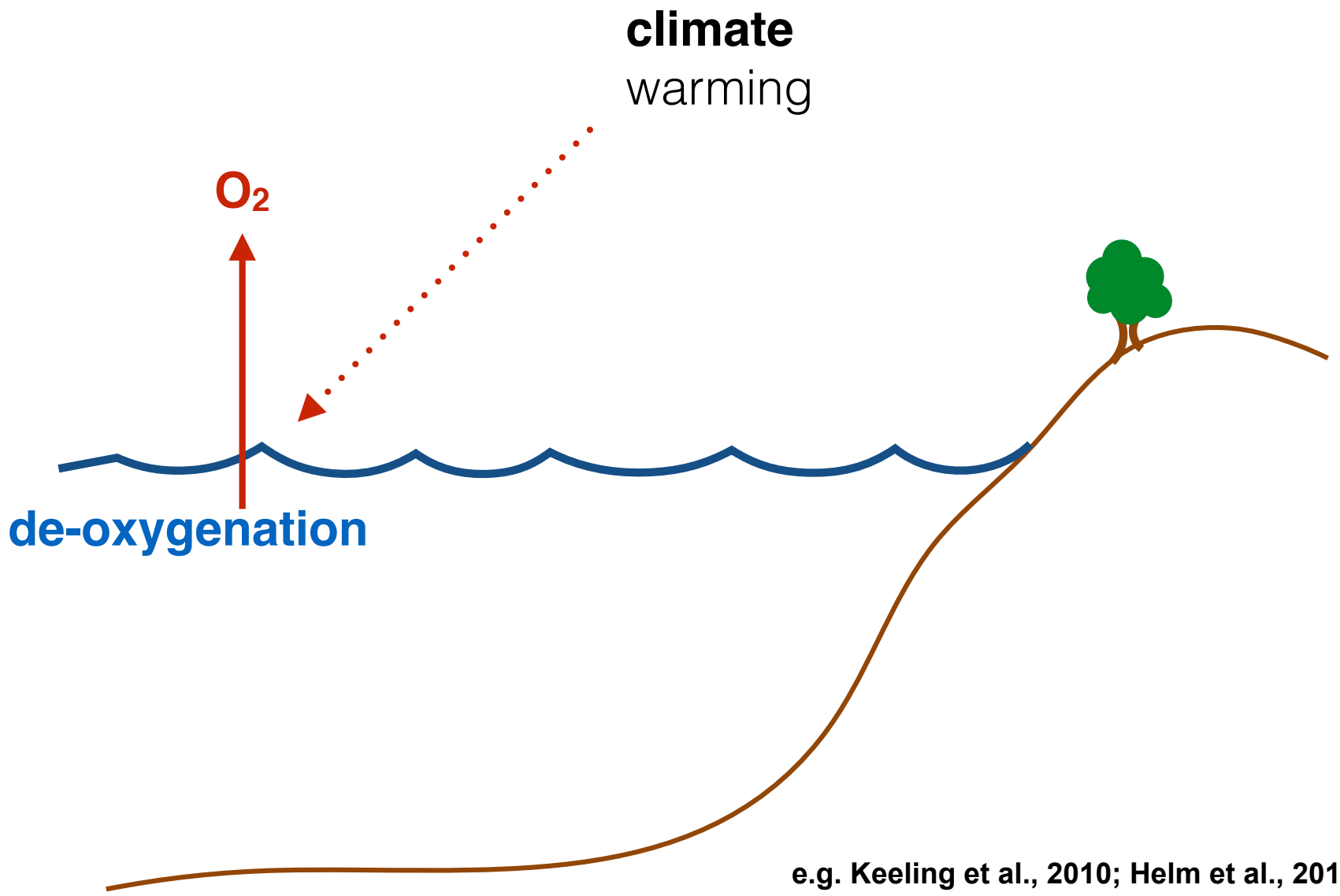
# Ventilation and oxygen variability and change

Laure Resplandy
Princeton University

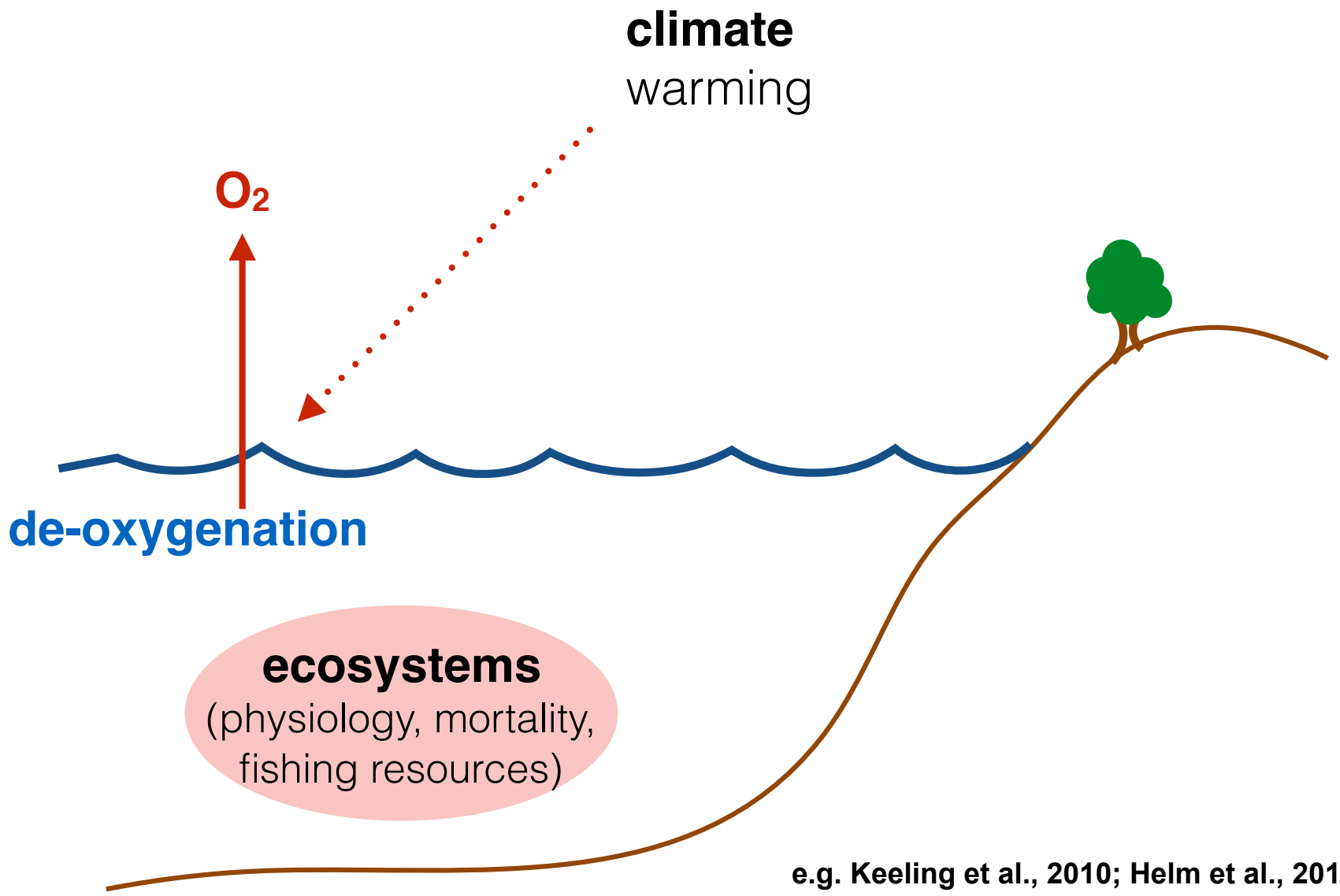

**Indian Ocean Science Workshop, Sept 2017**

# Ocean oxygenation and societal impacts




e.g. Keeling et al., 2010; Helm et al., 2011

# Ocean oxygenation and societal impacts

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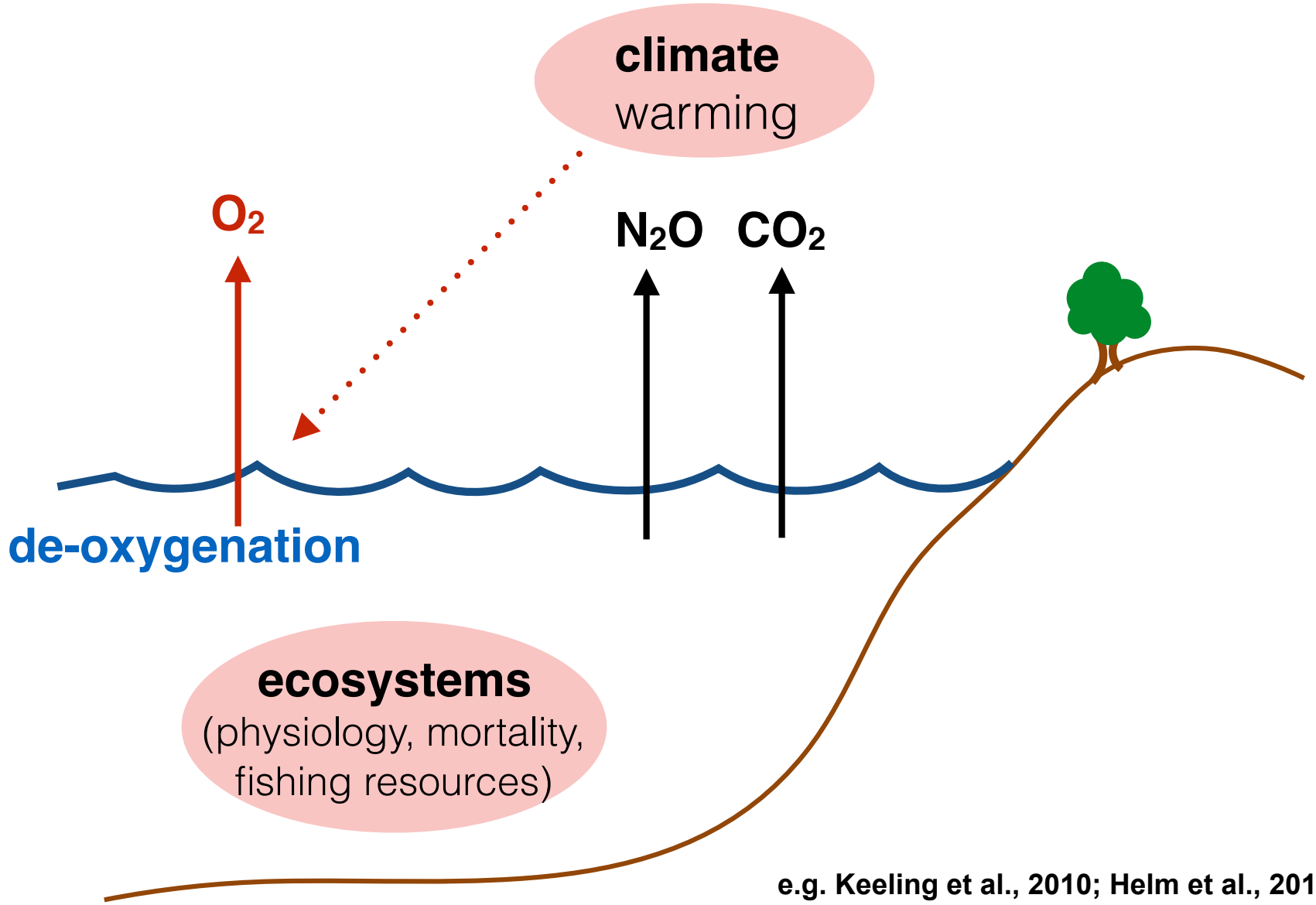
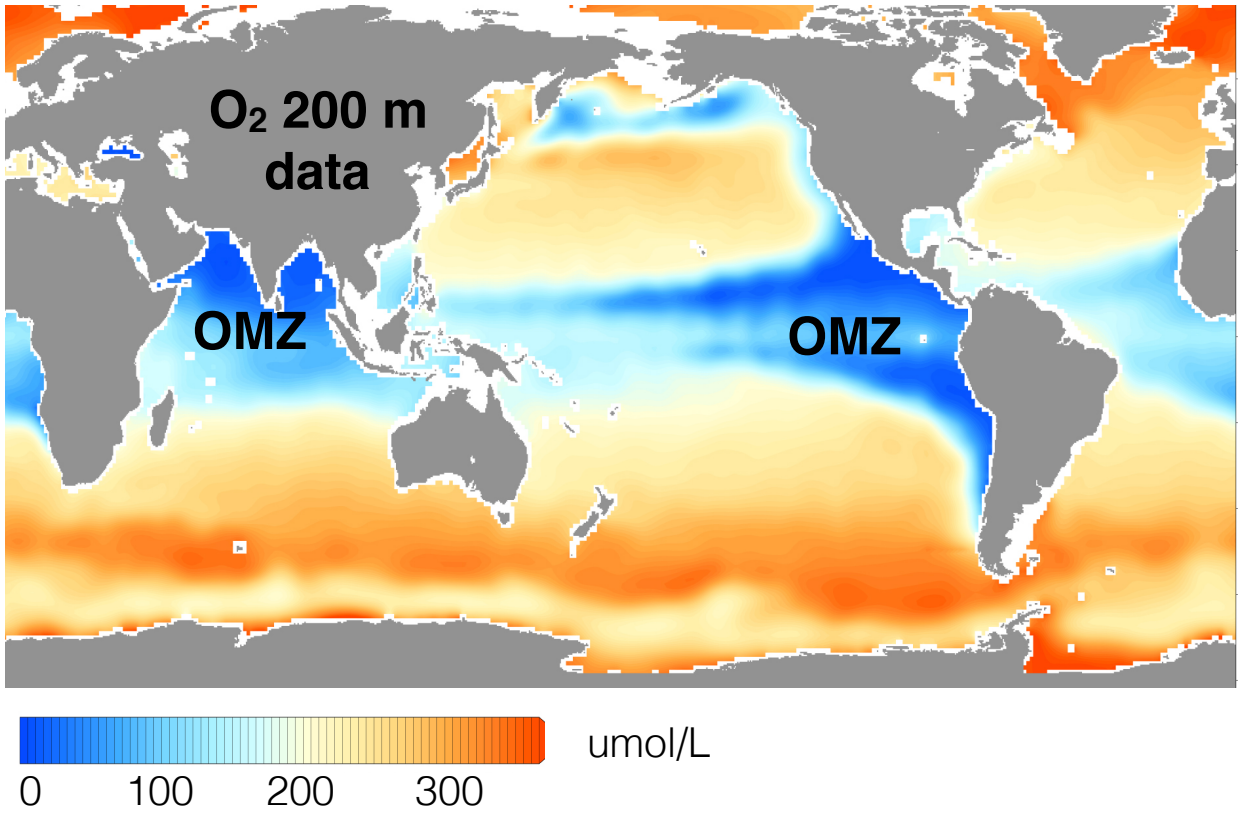
# Ocean oxygenation and societal impacts




e.g. Keeling et al., 2010; Helm et al., 2011

# Indian Ocean hosts major oxygen minimum zone




*anthropogenically-forced trend* ***should already be evident*** *in parts of Indian Ocean* **Long et al., GBC 2016**

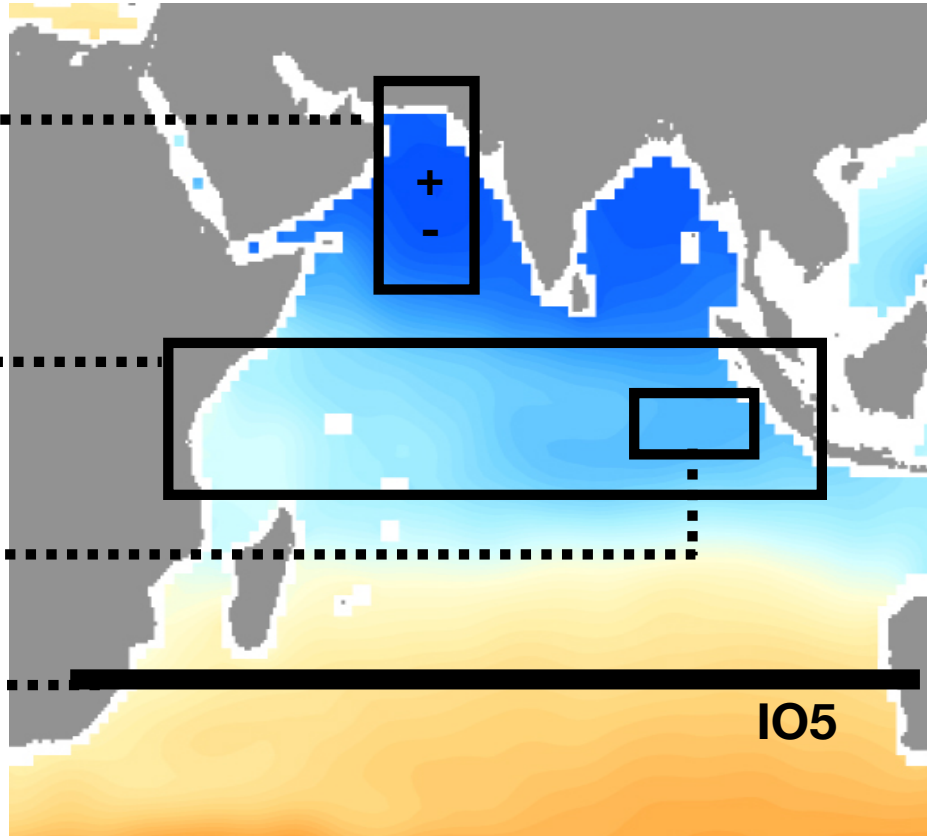
# What observations tell us ….

**Disparate trends (40 yrs)**
Banse et al., Biogeosciences 2014

**Weak O2 decrease (60 years) significant?** Schmidtko et al., Nature 2017

**No trend (50 years)**
Stramma et al., Science 2017

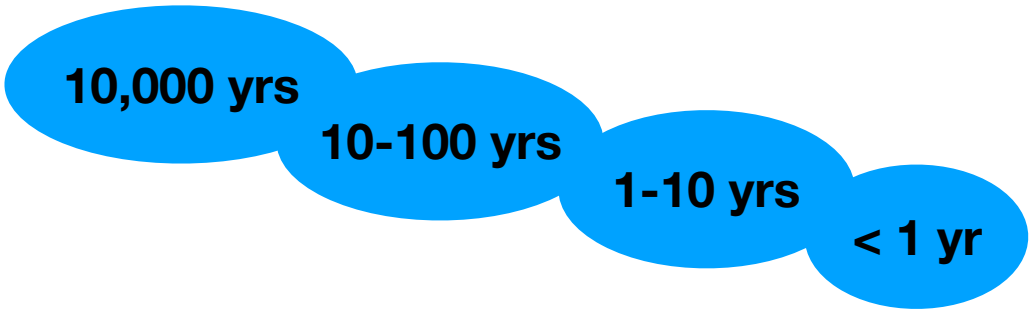
**No significant trend (1987-2009)** Fine et al., JGR 2017



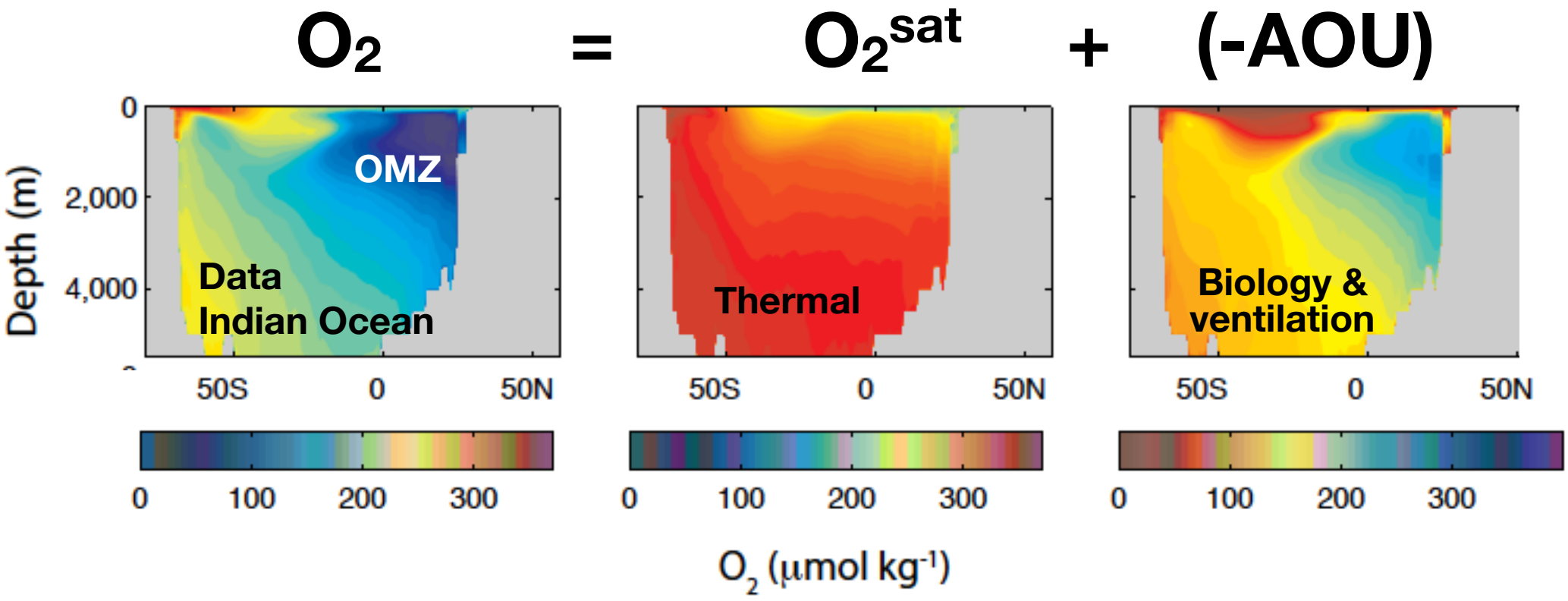

## No significant trend observed in Indian Ocean

## Why are ventilation and $O_2$ trends so difficult to detect?

## What can we learn on processes looking at variability from global multi-millennia scale to sub-seasonal mesoscale?

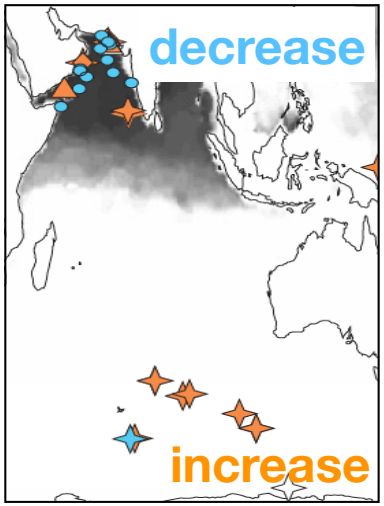


# Apparent oxygen utilization controls $O_2$ distribution in Indian Ocean

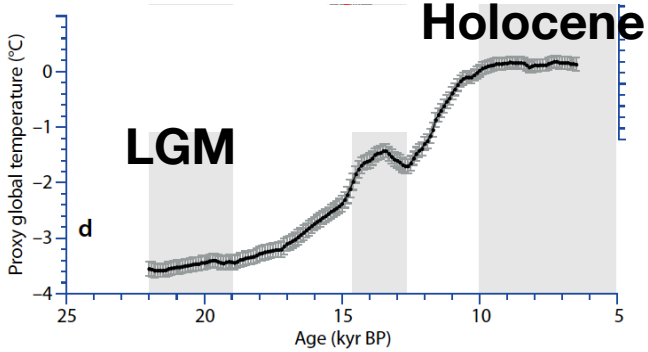



Jaccart et al., Oceanogr. 2014

# Indian OMZ strengthened during last deglaciation warming

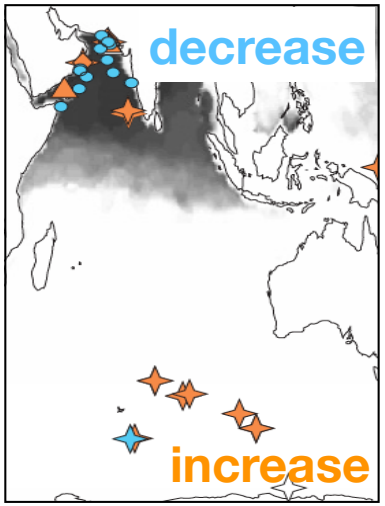



10,000 yrs

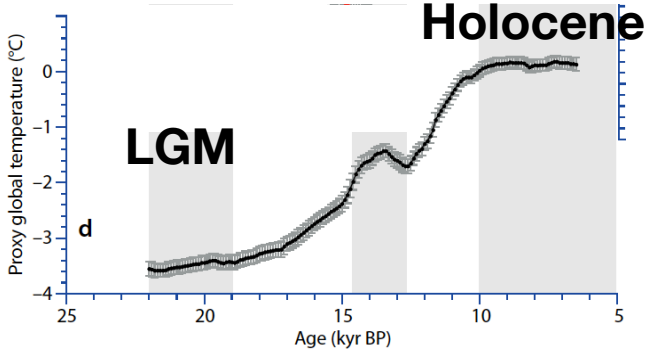



Jaccart and Galbraith, Nature Geo 2011

# Indian OMZ strengthened during last deglaciation warming

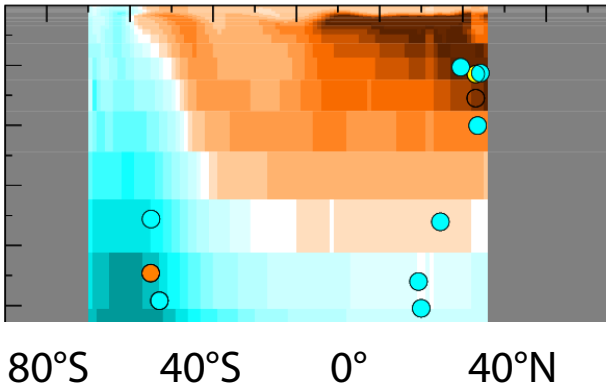



10,000 yrs

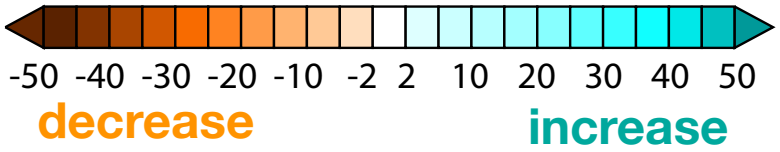



Jaccart and Galbraith, Nature Geo 2011

$\Delta O_2$



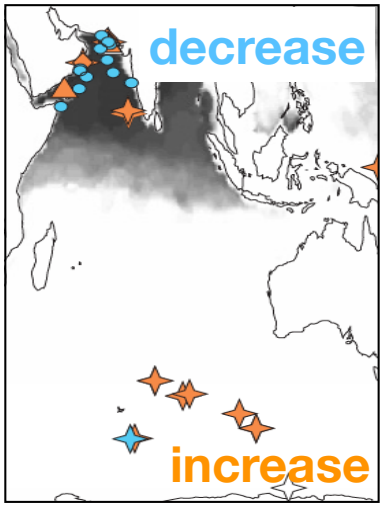
80°S 40°S 0° 40°N



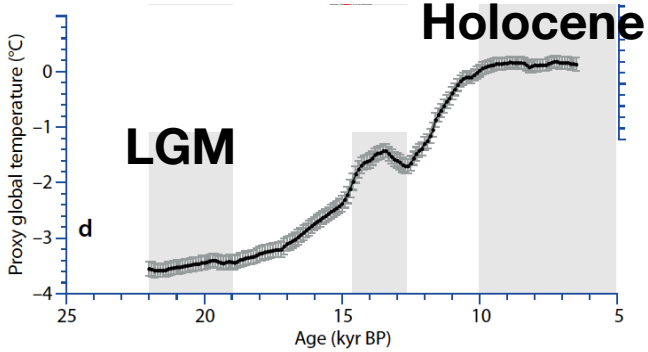

(MidHolocene - LGM)
(mmol $m^{-3}$)

Bopp, Resplandy et al., Royal Society 2017

# Indian OMZ strengthened during last deglaciation warming




10,000 yrs

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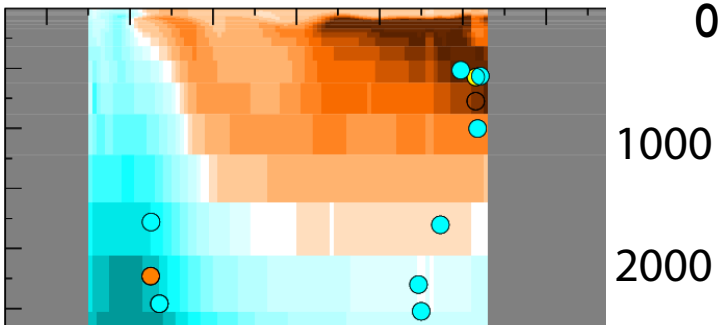
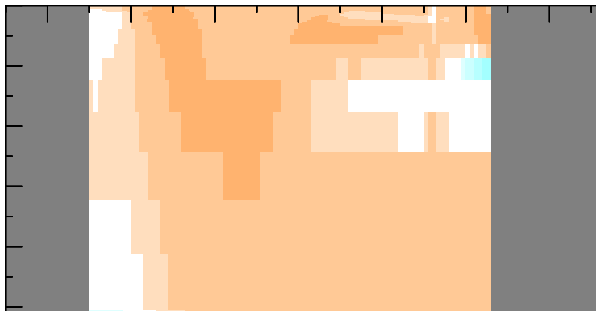
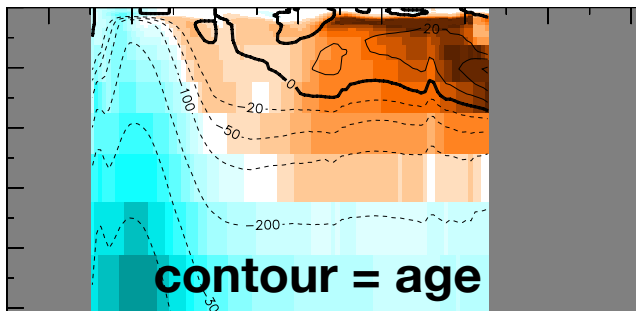
$\Delta O_2$

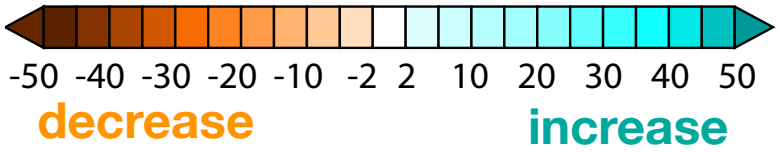



thermal




Bio/ventilation (-AOU)




(MidHolocene - LGM)
(mmol $m^{-3}$)

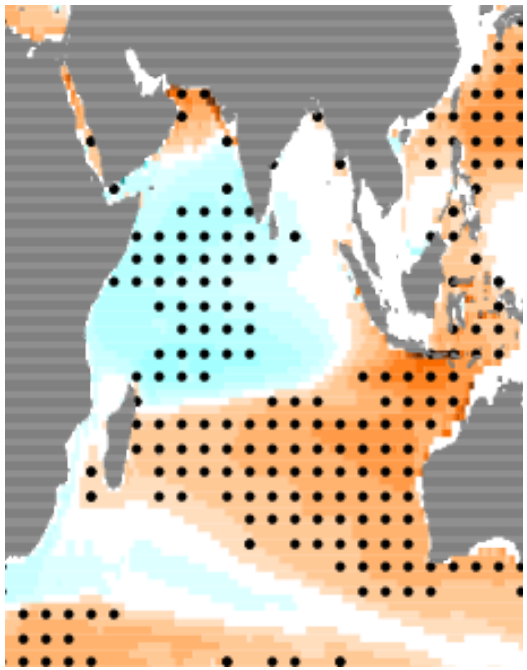
## Ventilation control and thermal re-enforcement in OMZ

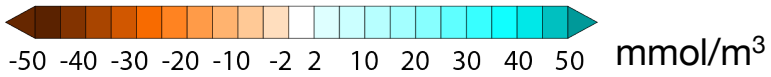
Bopp, Resplandy et al., Royal Society 2017

# Can earth system models help to understand observed anthropogenic trend? (or the lack of it)

10-100 yrs

$\Delta O_2$






**$O_2$ decrease** **$O_2$ increase**

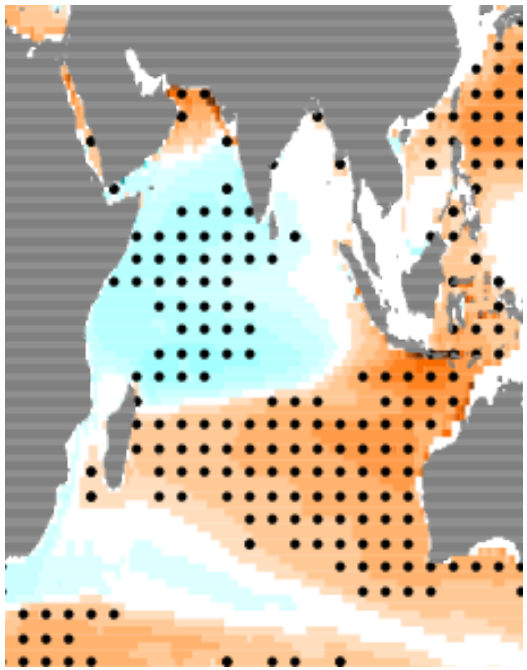
**RCP8.5 (Business as usual) 1990 to 2090**
**200 to 600 m**

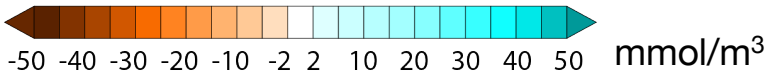

Bopp, Resplandy et al., Biogeosciences 2013
Bopp, Resplandy et al., Royal Society 2017

# Can earth system models help to understand observed anthropogenic trend? (or the lack of it)

10-100 yrs

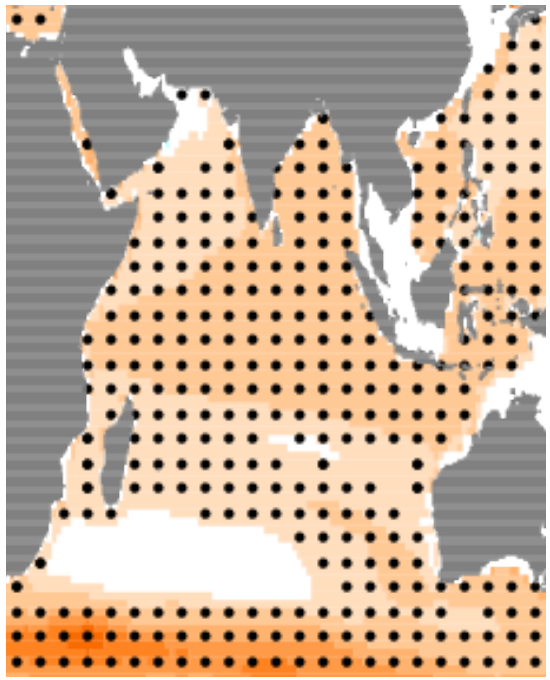
$\Delta O_2$



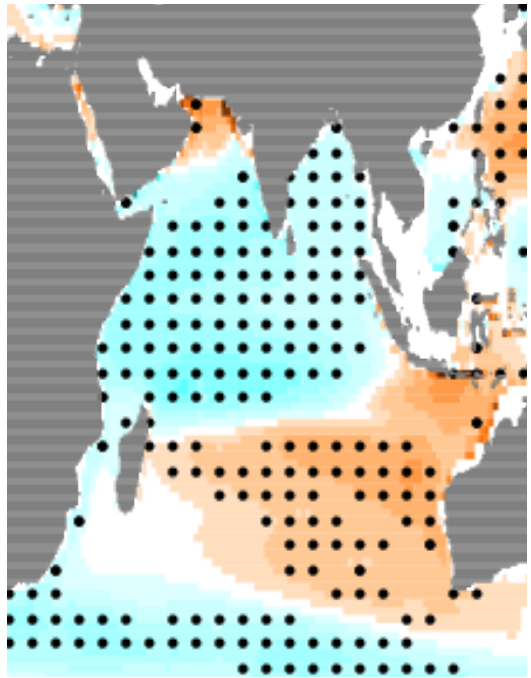



**$O_2$ decrease** **$O_2$ increase**

**Thermal ($O_2^{sat}$)**



**Bio/ventilation (-AOU)**



**Ventilation controls $O_2$ but partial compensation with thermal changes limits robustness … and detection**

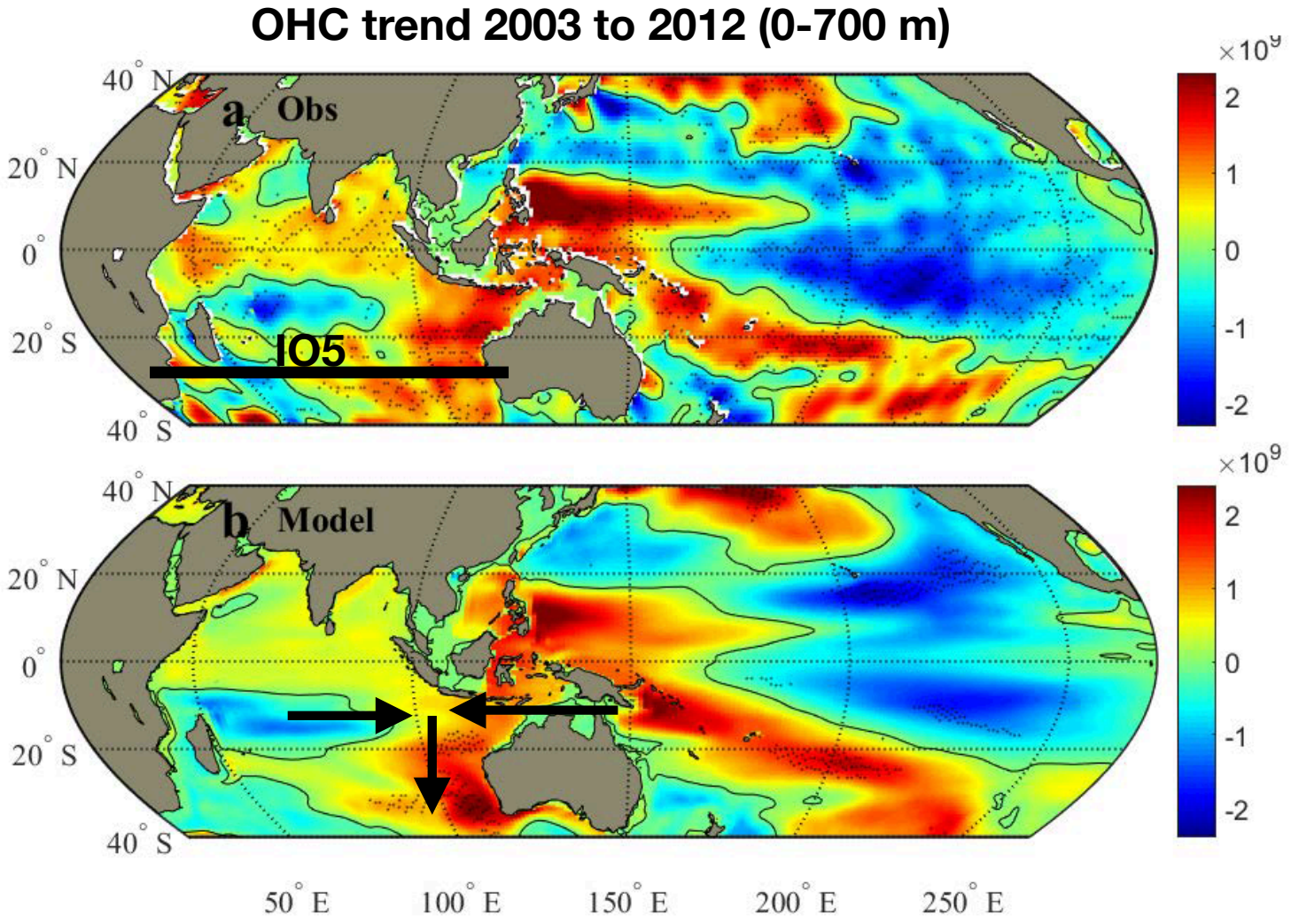

Bopp, Resplandy et al., Biogeosciences 2013
Bopp, Resplandy et al., Royal Society 2017

# Strong modulation of ventilation on decadal time-scales obscures anthropogenic trends

1-10 yrs

**Observations Levitus**

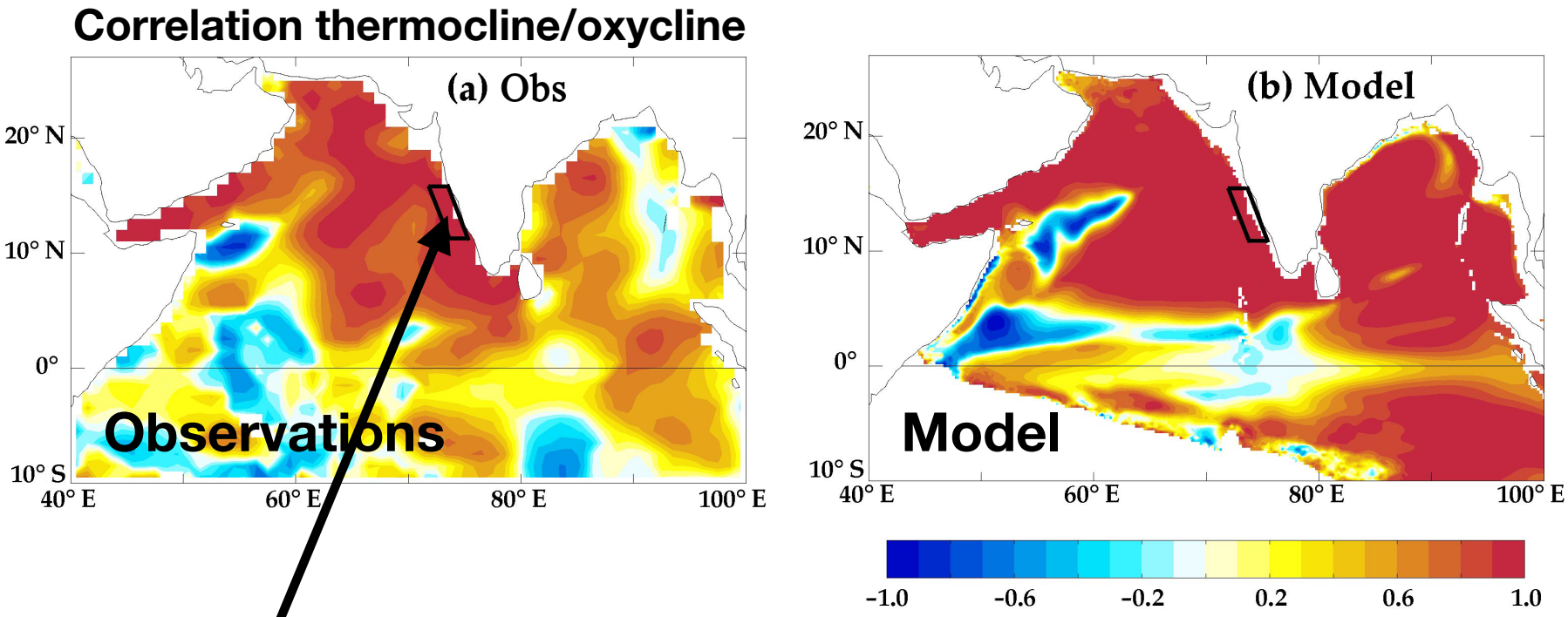
**Ocean CESM models**




Liao et al., to be submitted 2017

# Strong modulation of $O_2$ on interannual time-scales obscures anthropogenic trends

1-10 yrs

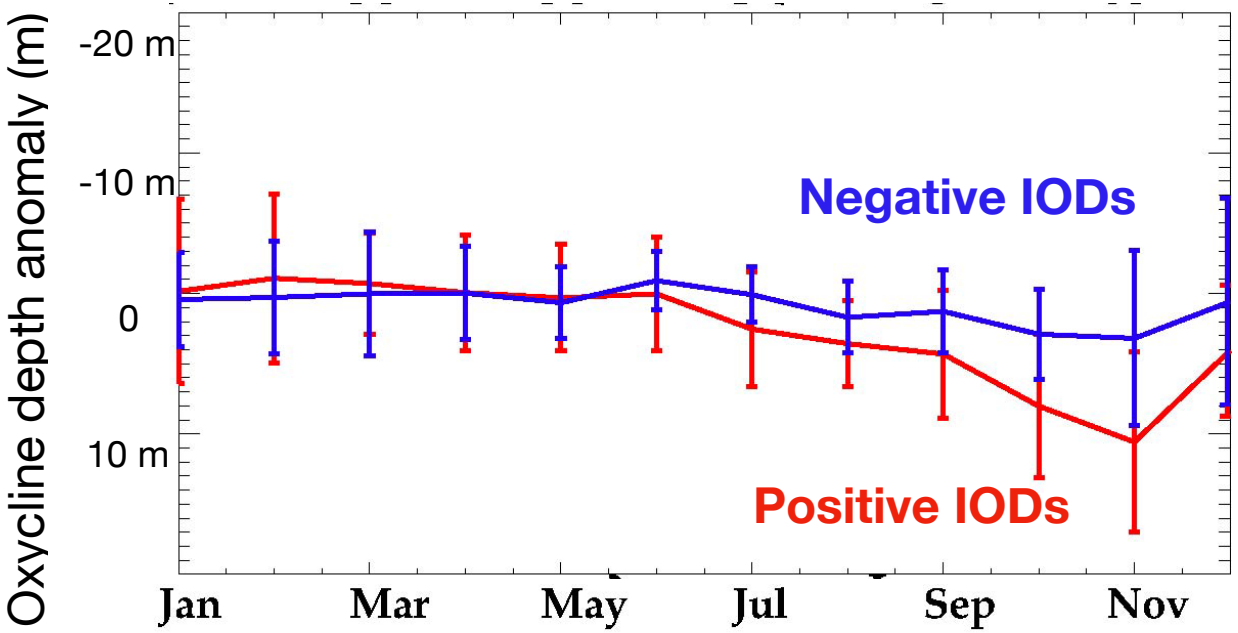



**observed coastal anoxia**
(Naqvi et al. 2009)

Vallivattathillam et al., Biogeosciences 2017

# Strong modulation of $O_2$ on interannual time-scales obscures anthropogenic trends

1-10 yrs




Deeper oxycline
downwelling coastal
Kelvin waves

## Indian Ocean Dipole preconditions coastal anoxia

## Consistent with observed anoxic events (neg. or no IOD)

**1998, 1999, 2001, 2002, 2004, 2005** (Naqvi et al. 2009)

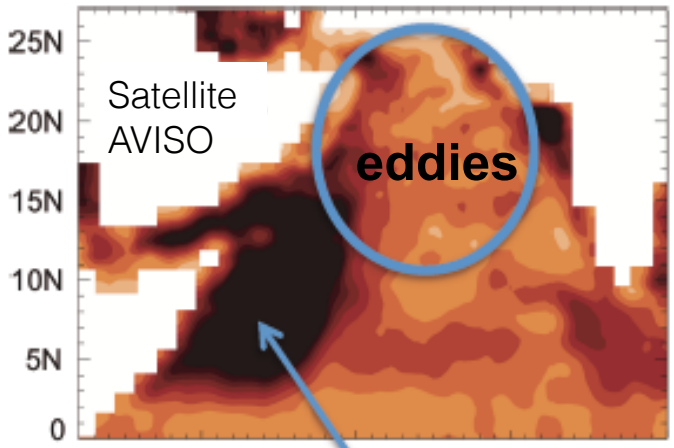
Vallivattathillam et al., Biogeosciences 2017

# Eddies decouple biology from ventilation

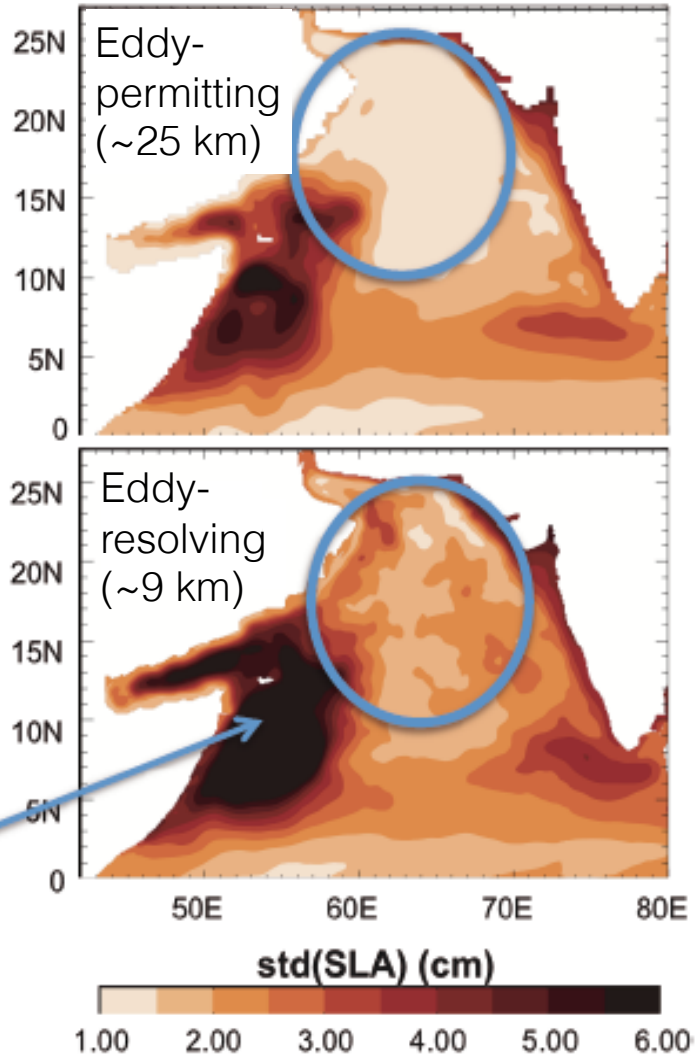
< 1 yr

## Sea level anomaly variations

### Observations




### Models




**Great Whirl**

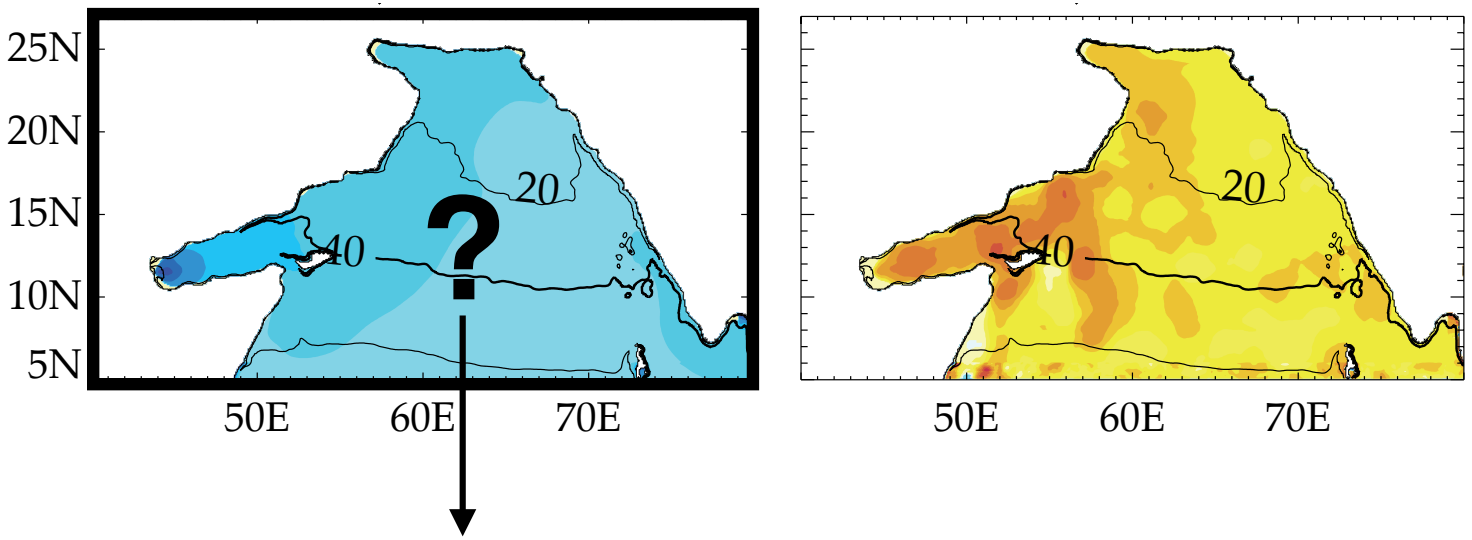
Resplandy et al., JGR 2011

# Eddies decouple biology from ventilation

$$\left(\frac{\partial O_2}{\partial t}\right) = \left(\frac{\partial O_2}{\partial t}\right)_{\text{Bio}} + \left(\frac{\partial O_2}{\partial t}\right)_{\text{Circ}}$$

**long-term mean**

200:1500 m




nutrient supply

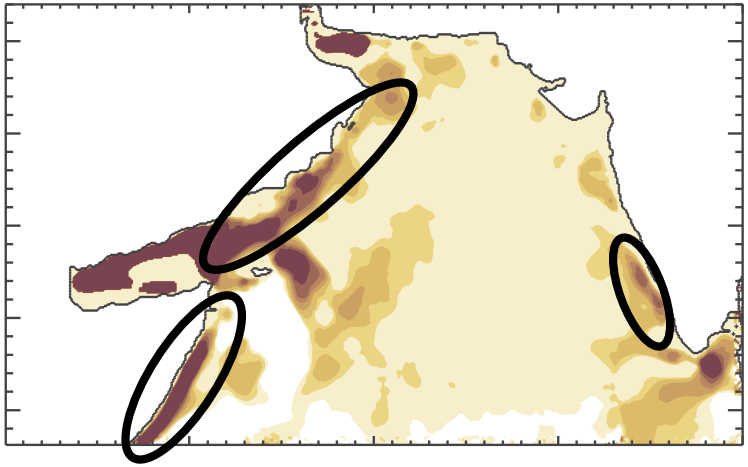
**consumes $O_2$** micromol / L / month **supplies $O_2$**

-0.40 -0.20 0.00 0.20 0.40

Resplandy et al., Biogeosciences 2012

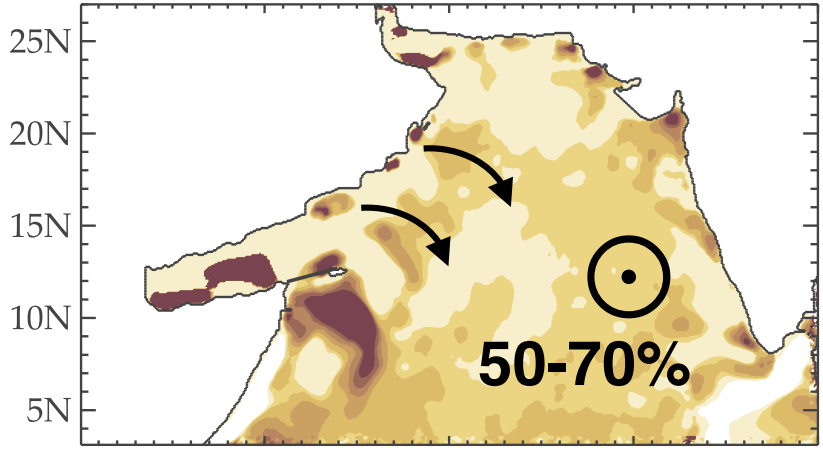
# Eddies crucial to offshore biological production

**Mean circulation**



**3 coastal upwelling**

**Eddies & filaments**




**horizontal & vertical transport of nutrients**

**nutrient supply**
[umol/m$^2$/d]

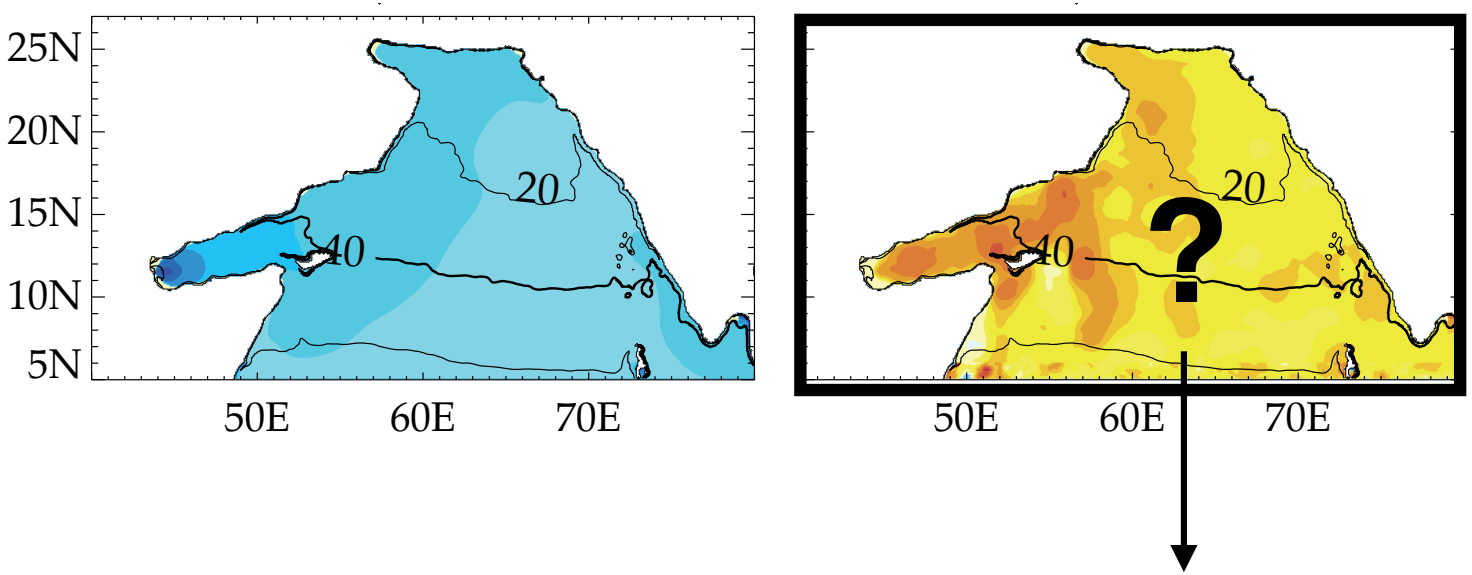

Resplandy et al., JGR 2011

# What are the processes controlling OMZ permanence?

$$\left(\frac{\partial O_2}{\partial t}\right) = \left(\frac{\partial O_2}{\partial t}\right)_{\text{Bio}} + \left(\frac{\partial O_2}{\partial t}\right)_{\text{Circ}}$$

**long-term mean**

200:1500 m




$O_2$ supply

**consumes $O_2$**

micromol / L / month

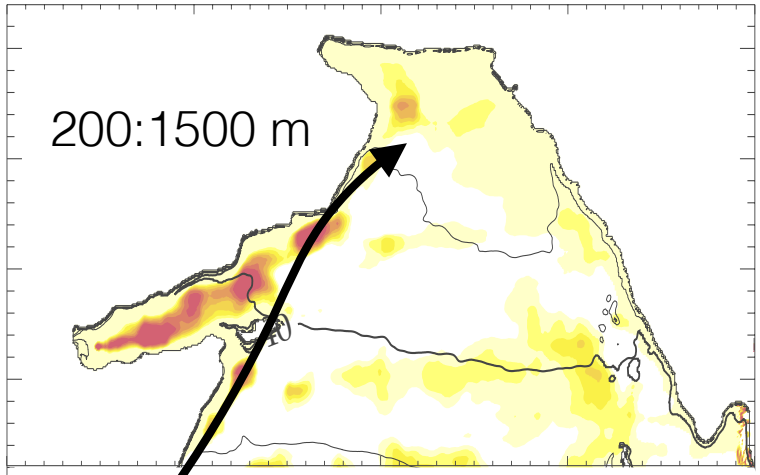
-0.40 -0.20 0.00 0.20 0.40

**supplies $O_2$**

Resplandy et al., Biogeosciences 2012

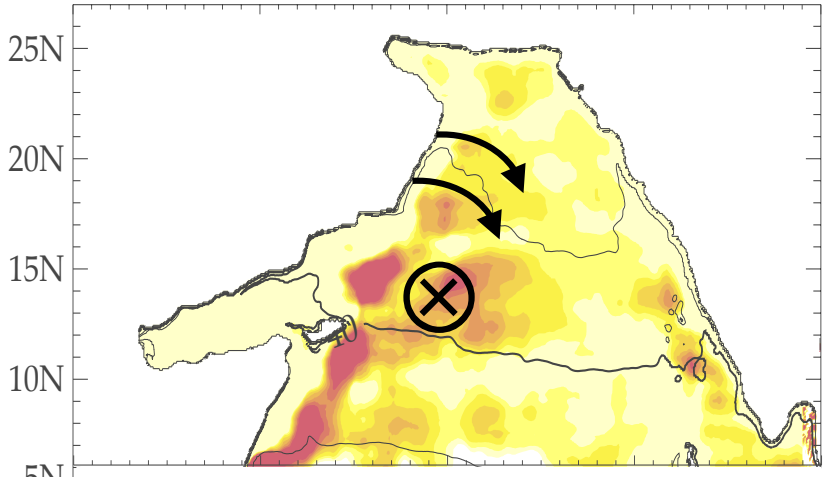
# Eddies supply $O_2$ offshore western boundary

**Mean circulation**



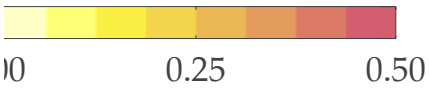

**Somali Current**

**Eddies & filaments**




**horizontal & vertical transport of $O_2$**

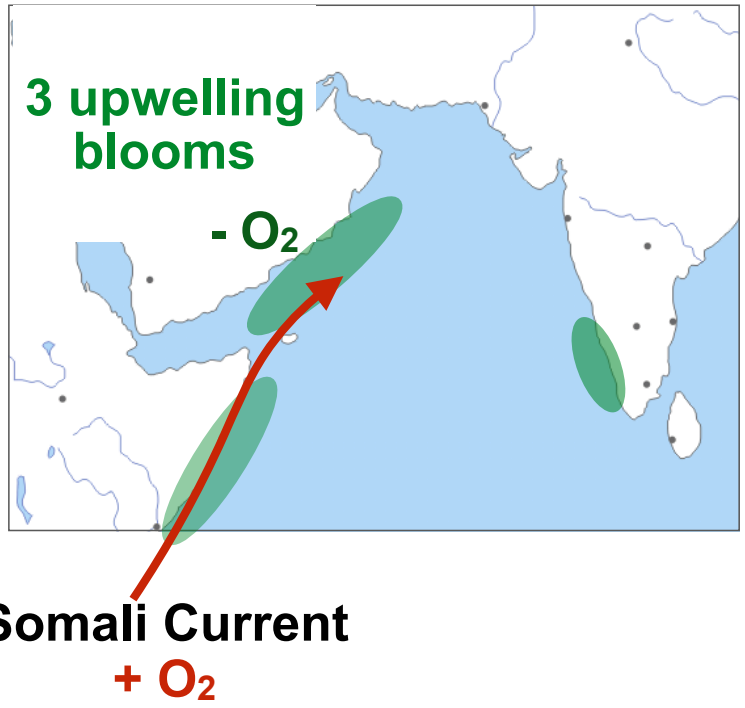
**$O_2$ supply**
[umol/L/month]



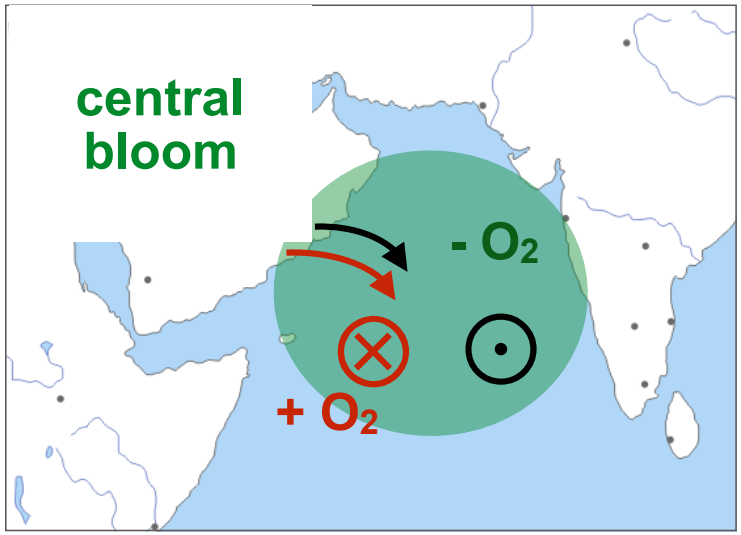

Resplandy et al., Biogeosciences 2012

# Eddies decouple $O_2$ circulation supply from biological consumption

**Mean circulation** in coarse models




**Eddies & filaments** not in coarse models




Resplandy et al., JGR 2011
Resplandy et al., Biogeosciences 2012

# Conclusions

**Ventilation controls $O_2$ changes and variability across time-scales**

**No significant trend in observations and some disagreement across models:**

- robust but opposed trends from thermal & ventilation changes => weak & uncertain trends
- obscured by variability
- key processes still undersampled or missing in global models