Using a Limited-Domain Transport Matrix Technique to Study the Oxygen Concentrations in the Indian Ocean

Ann Bardin
François Primeau
Keith Moore
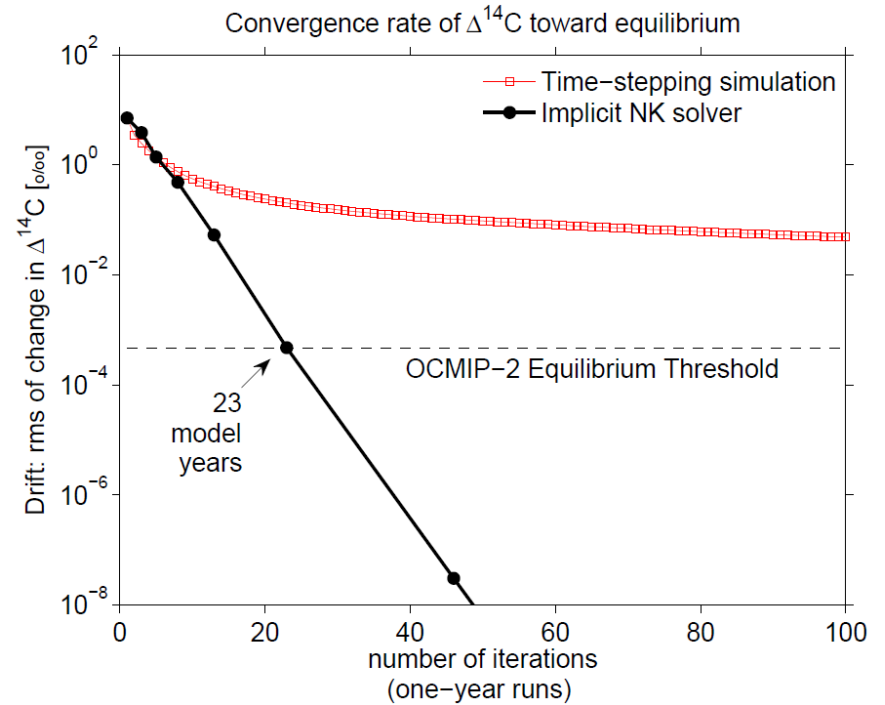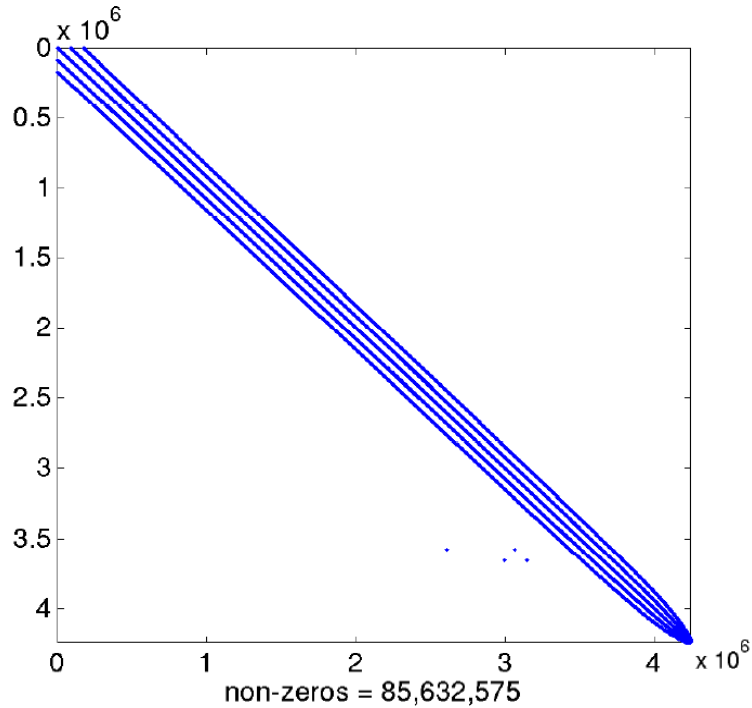
For CESM Ocean Modeling Working Group
January, 2015

Agenda

Previously,

- ^{14}C Age dating of the ocean using a Global offline model

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→ Now,
with a regional offline model, determine external vs. internal biases in circulation and biological processing

- How does this work?

- What are the effects of moving the southern boundary?

- From which boundaries do the OMZ sources of water and

  oxygen come?

- Can we determine circulation vs. biological processing biases?

Regional Boundaries

WOA13 O_2, at depth 5 m

ITF Boundary
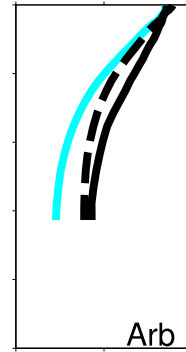
Southern Boundary

$[O_2]$ mmol m^{-3}
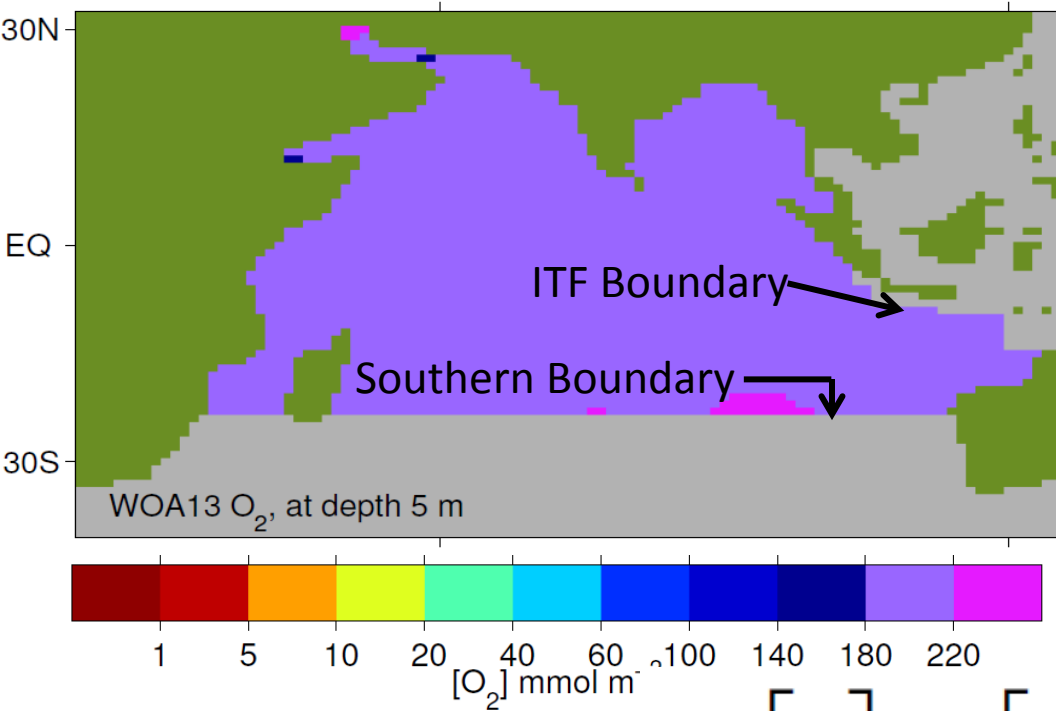
How to set up the boundary conditions such that it appears as if the global ocean is present?

$$\frac{\partial c}{\partial t} + \mathbf{T}c + S = 0$$

$$\frac{\partial}{\partial t}\begin{bmatrix} c_i \\ c_e \end{bmatrix} + \begin{bmatrix} \mathbf{T}_{ii} & \mathbf{T}_{ie} \\ \mathbf{T}_{ei} & \mathbf{T}_{ee} \end{bmatrix}\begin{bmatrix} c_i \\ c_e \end{bmatrix} + \begin{bmatrix} S_i \\ S_e \end{bmatrix} = 0$$
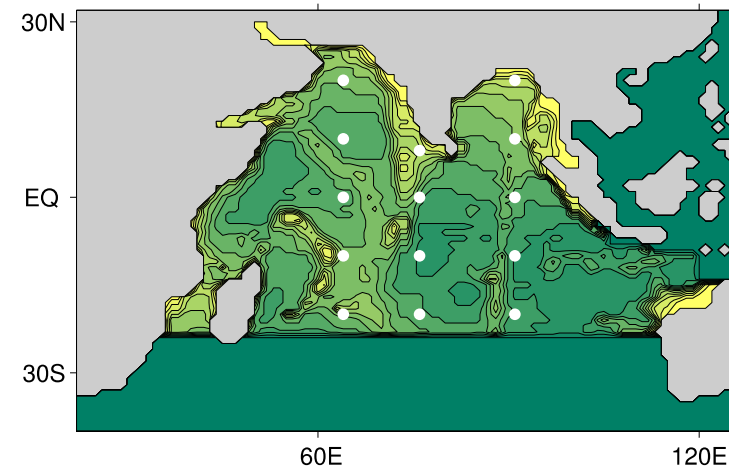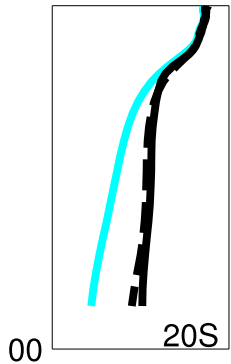
$$\frac{\partial c_i}{\partial t} + \mathbf{T}_{ii}c_i = -\mathbf{T}_{ie}c_e - S_i$$

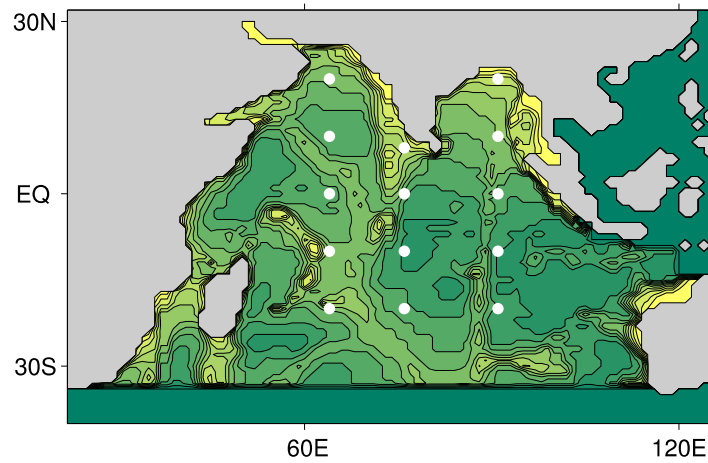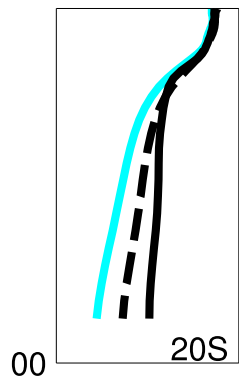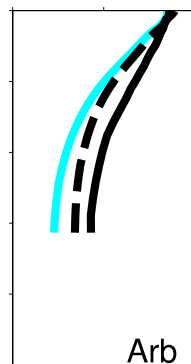# Distinguishing Regional Circulation Bias
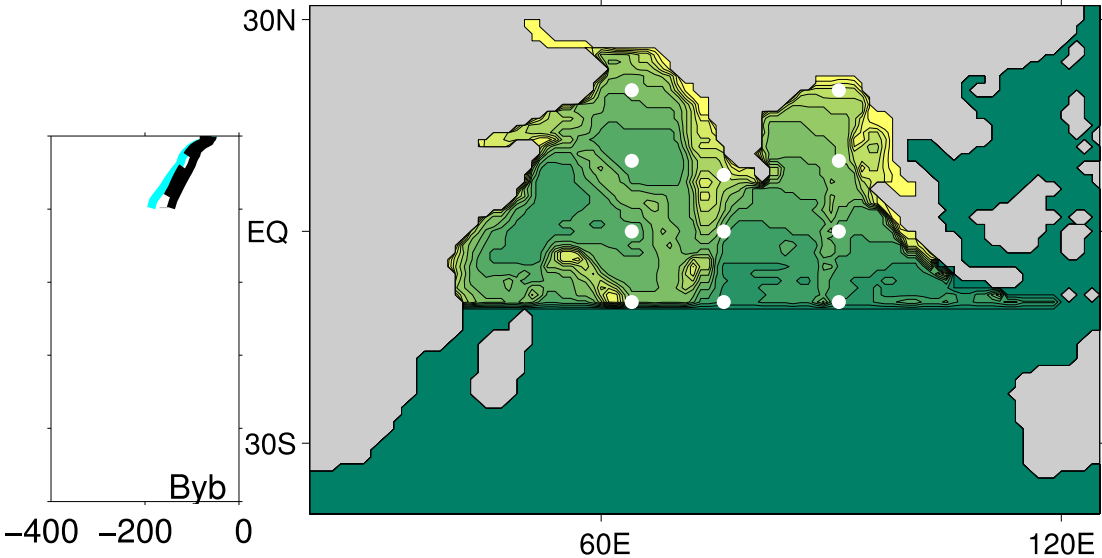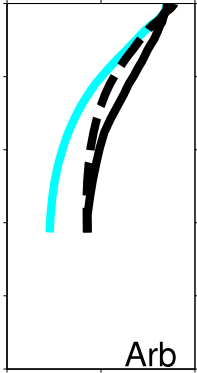# from Global Circulation Bias

Comparison of

- ^{14}C Global simulation,
- Regional simulation using observational boundary values, and
- GLODAP gridded observations

What happens if we move the boundary to 35S ?

What happens if we move the boundary to 12S ?
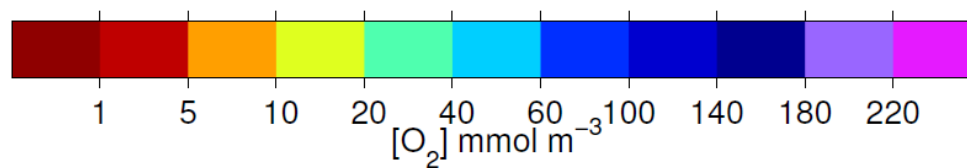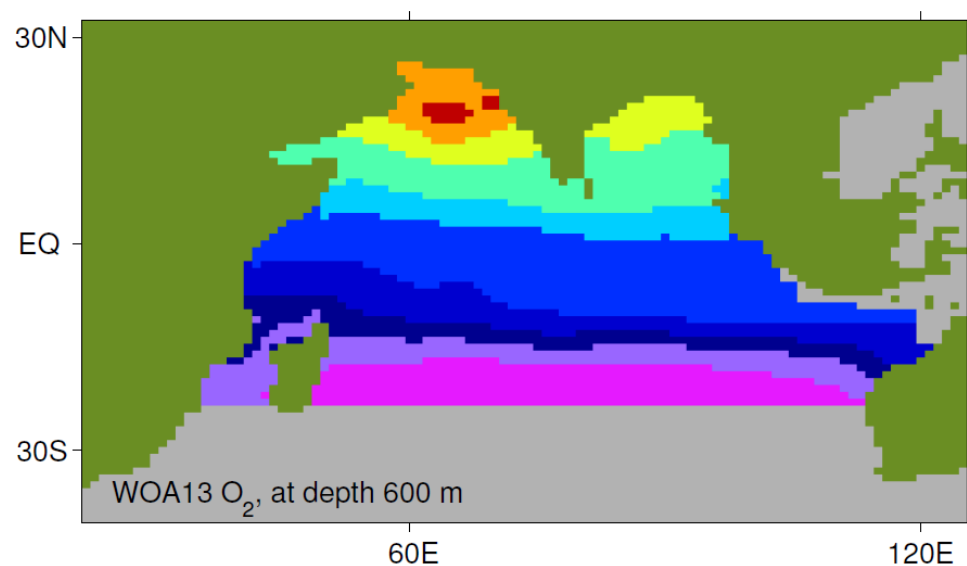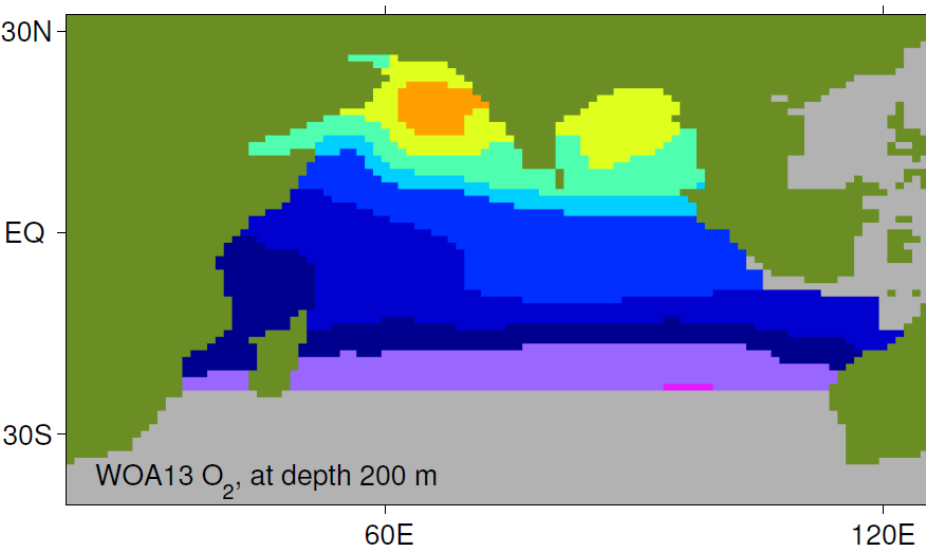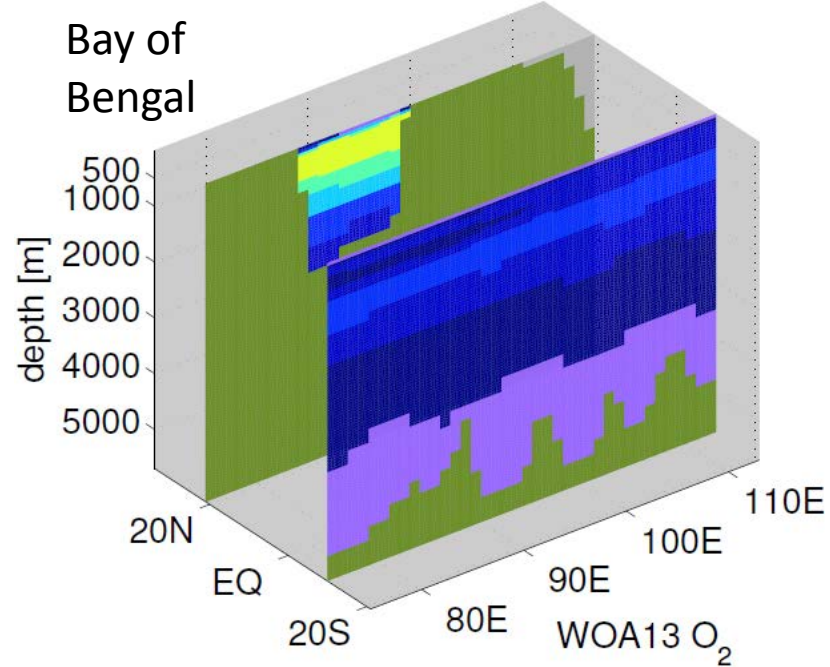
Agenda

Previously,
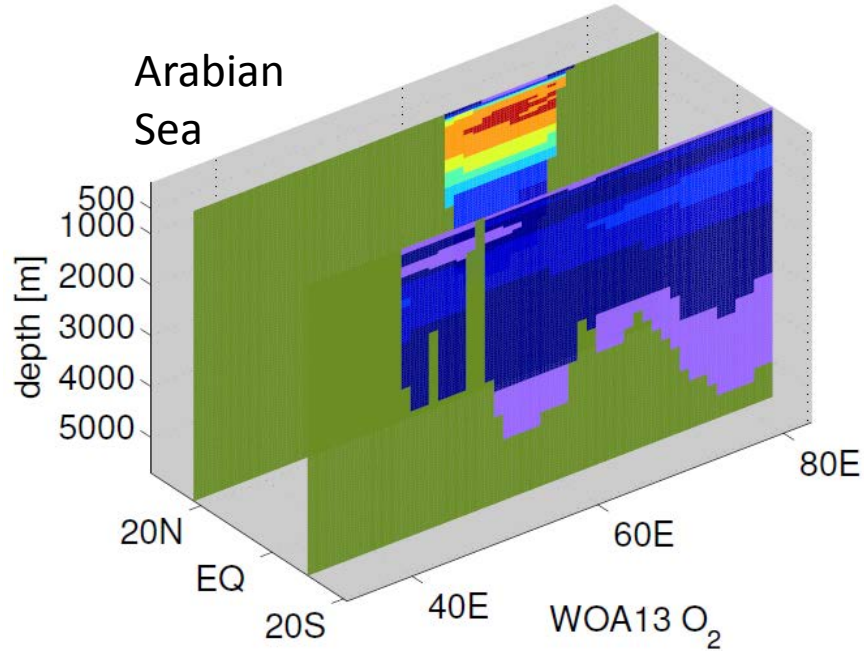
- ^{14}C Age Dating of the ocean using a Global offline model

Now, with a regional offline model, determine external vs. internal biases in circulation and biological processing
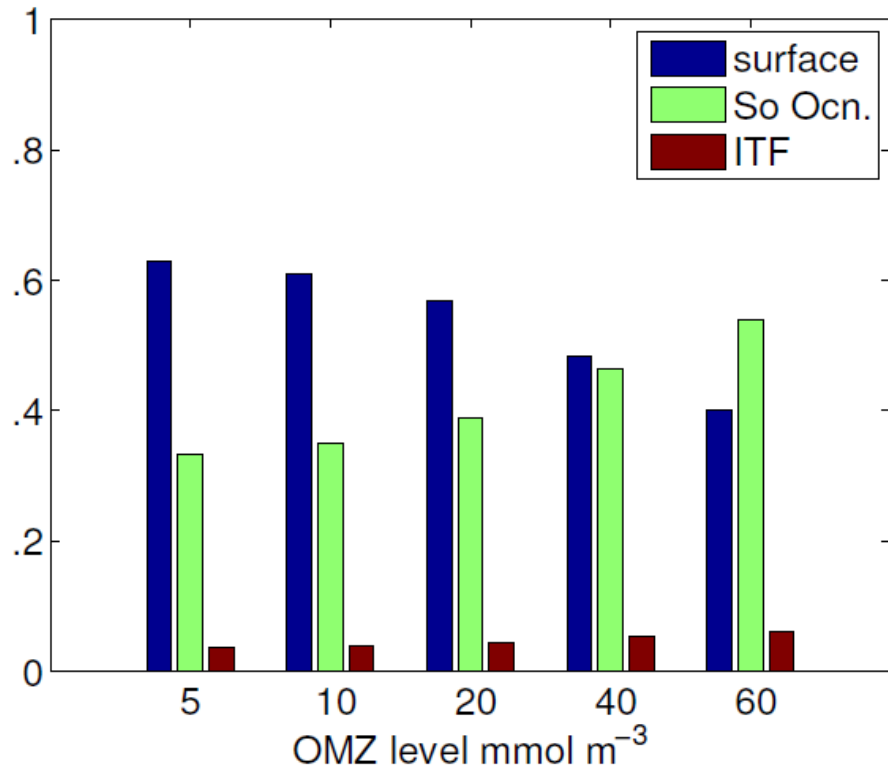
- How does this work?

- What are the effects of moving the southern boundary?

- From which boundaries do the OMZ sources of water and oxygen come?

- Can we determine circulation vs. biological processing biases?

Arabian Sea — WOA13 O_2

Bay of Bengal — WOA13 O_2

WOA13 O_2, at depth 200 m

WOA13 O_2, at depth 600 m

$[O_2]$ mmol m^{-3}

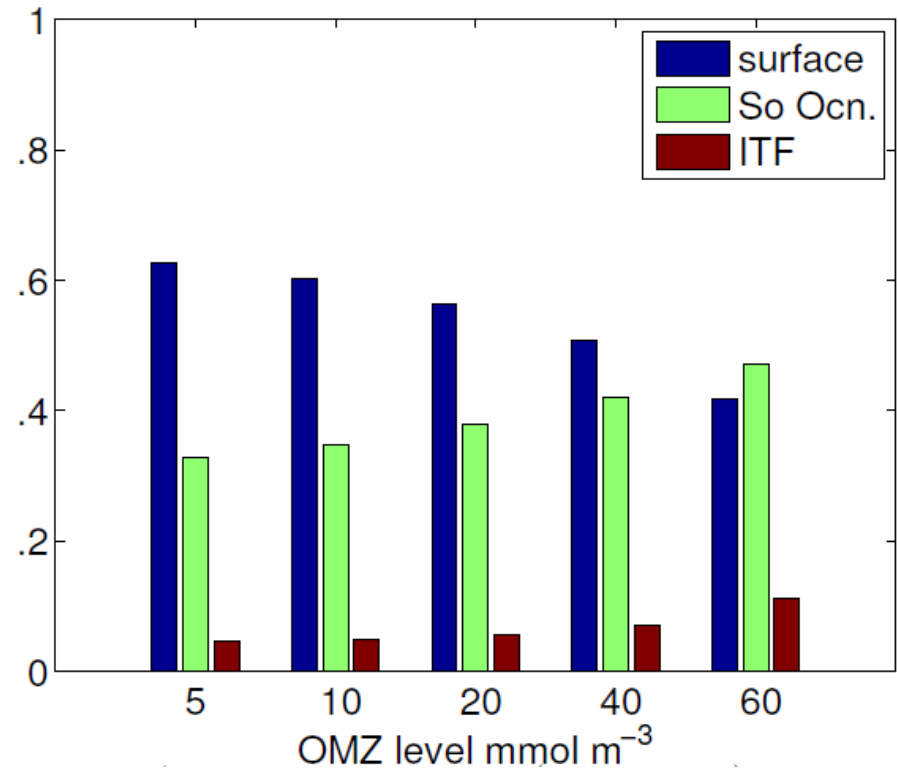1   5   10   20   40   60   100   140   180   220

Which boundaries are the biggest ventilation sources of the OMZs?
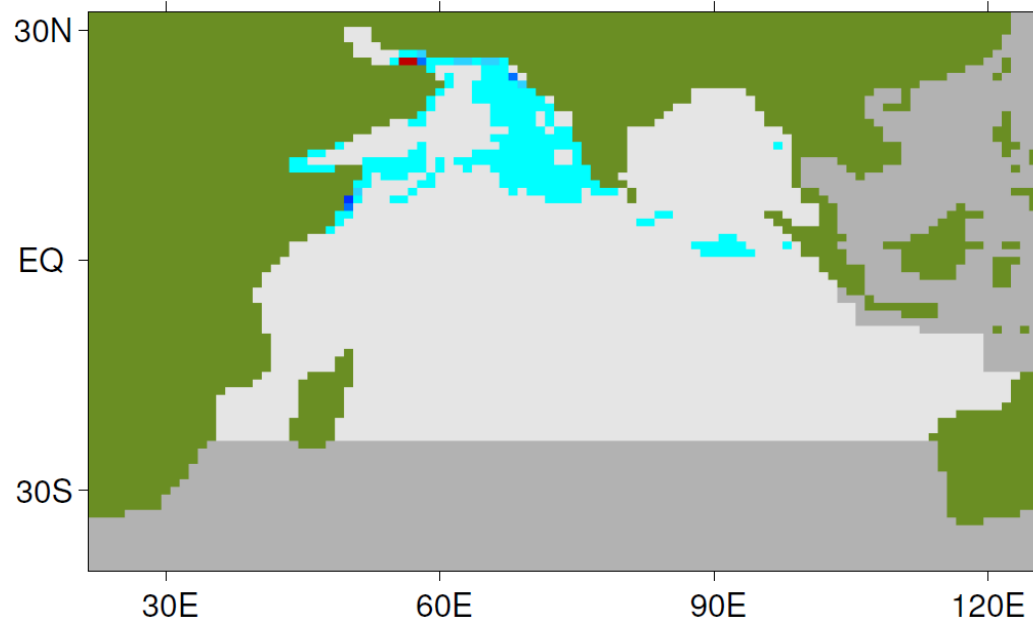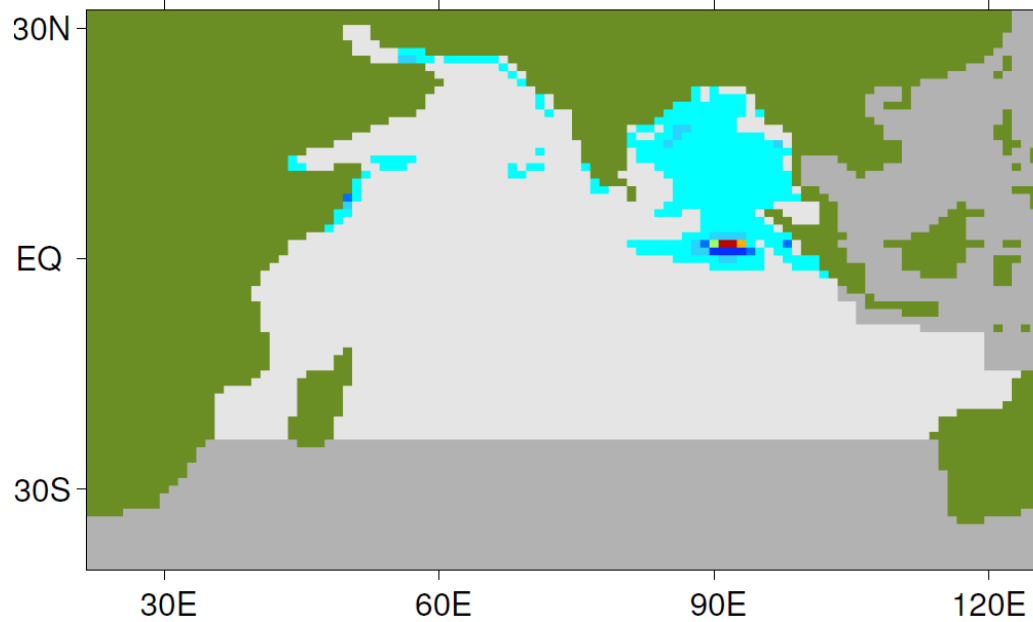

Arabian Sea

Bay of Bengal

What is the ventilation source pattern on the surface ?

For the
Arabian Sea
20 mmol m^{-3}
OMZ

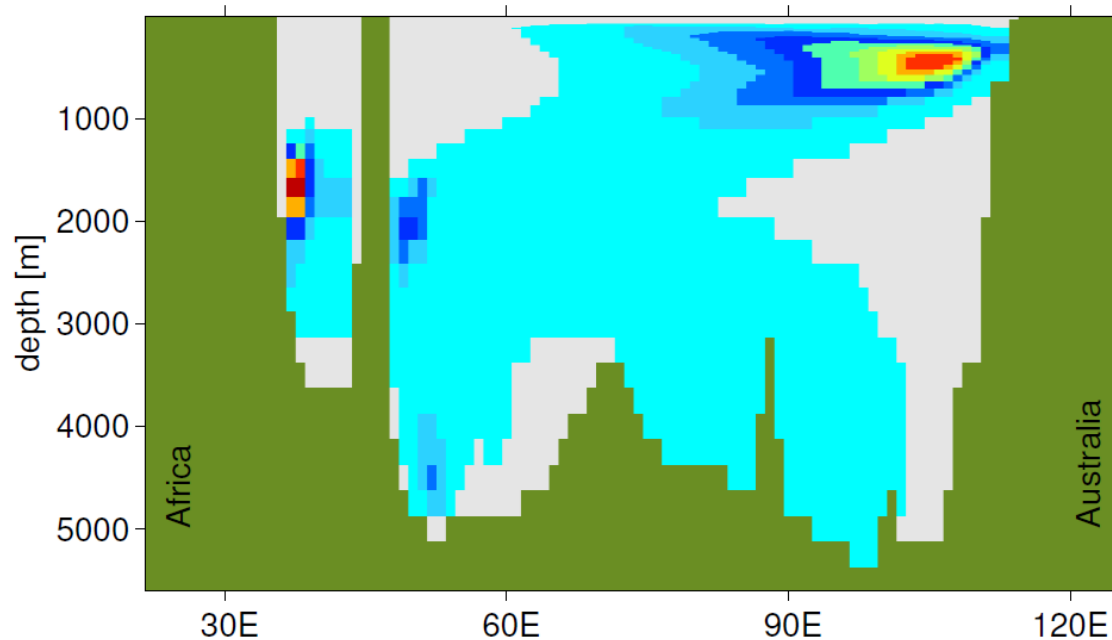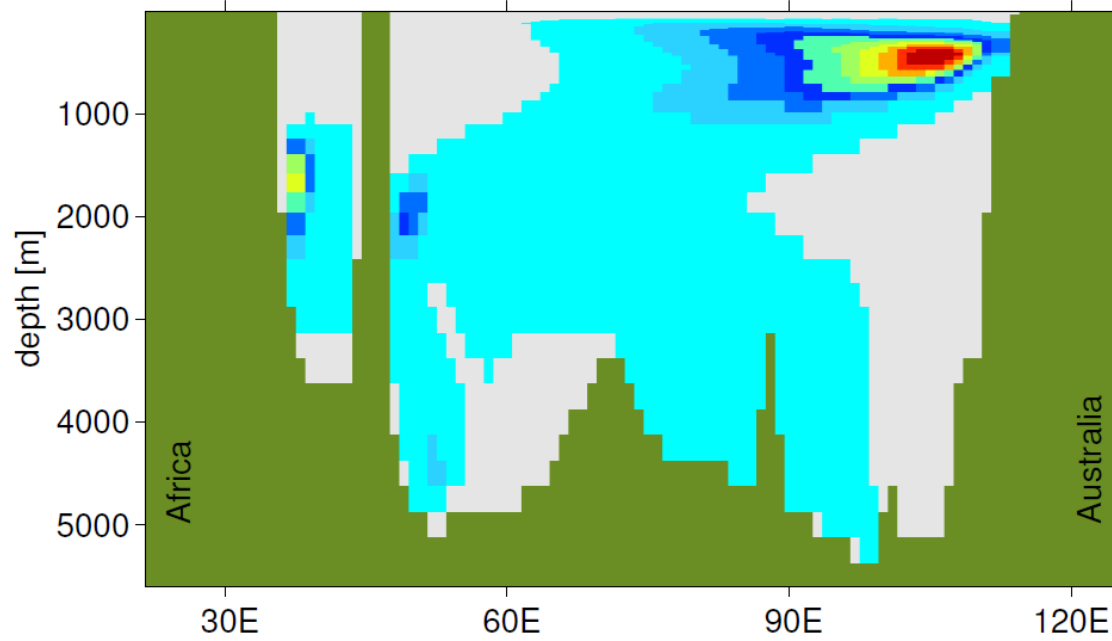For the
Bay of Bengal
20 mmol m^{-3}
OMZ

source fraction, normalized by its maximum

What is the ventilation source pattern on the Southern Boundary?
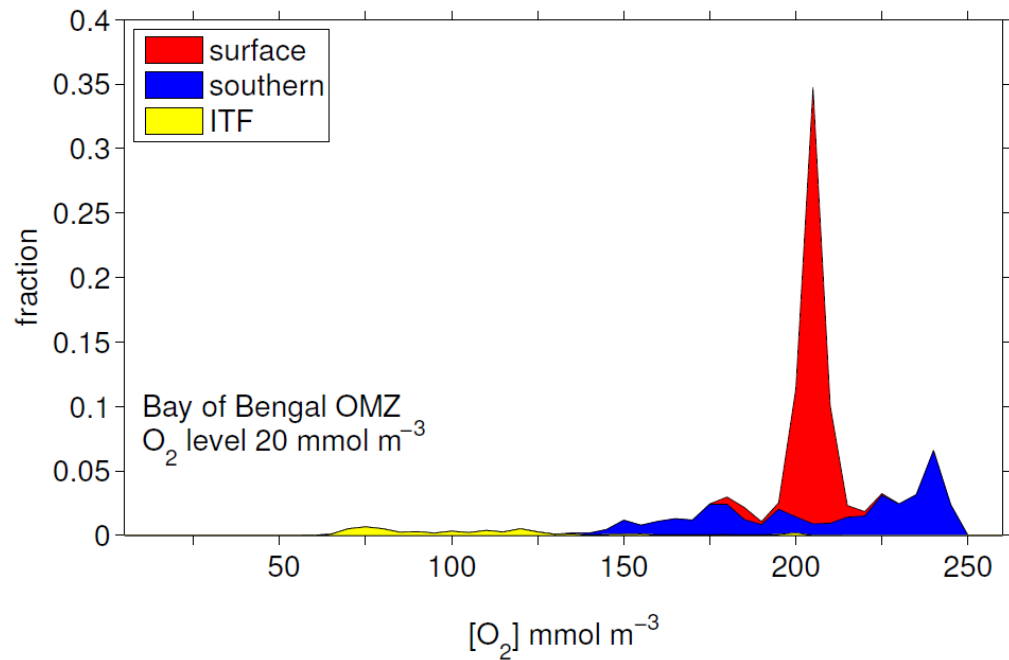
For the
Arabian Sea
20 mmol m^{-3}
OMZ

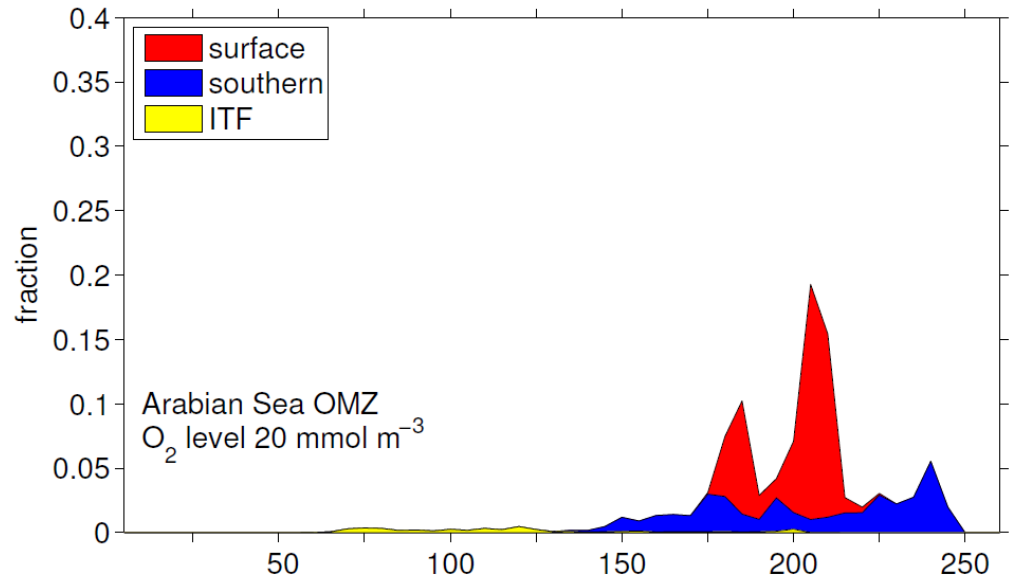For the
Bay of Bengal
20 mmol m^{-3}
OMZ

source fraction, normalized by its maximum

Oxygen Source Distribution

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With a regional offline model, determine external vs. internal biases in circulation and biological processing

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→ • Can we determine circulation vs. biological processing biases?

Regional Oxygen Model with Biology

- Biological component for O_2
    - Use BEC model O_2 production and consumption output variables from CMIP5 CESM simulation

- CMIP5 simulation
    - ocean-atmosphere coupled simulation for IPCC scenario RCP8.5 (business as usual)
    - Present day conditions: 1990s
    - Forcings and spin-up are different from that for the parent of offline model

Comparing Regional BEC Bias
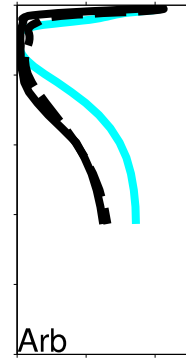# with Global BEC Bias -1
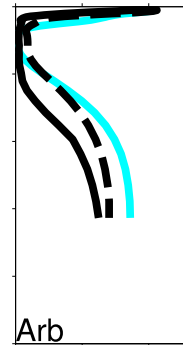
Comparison:

- Global BEC CMIP5 O_2 ,

- Regional Model with **Global BEC CMIP5 O_2 boundaries**, and
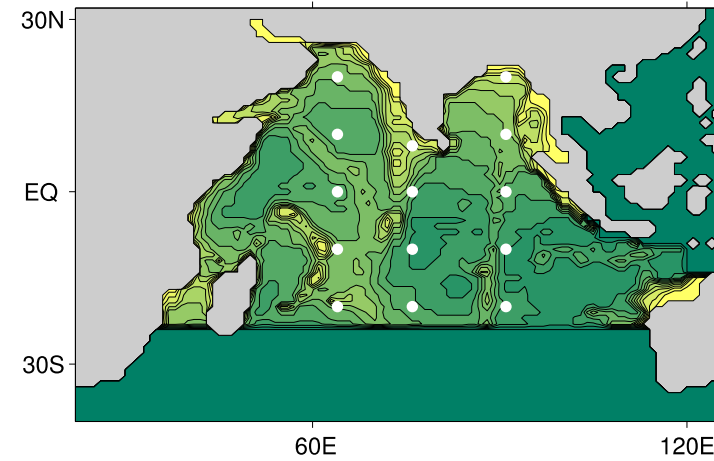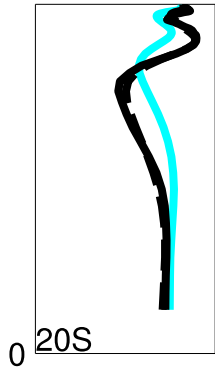
- WOA13 O_2 observations
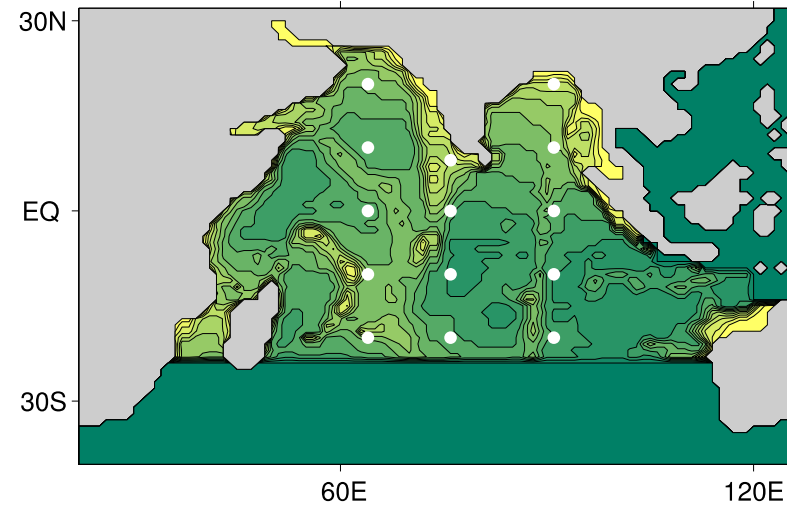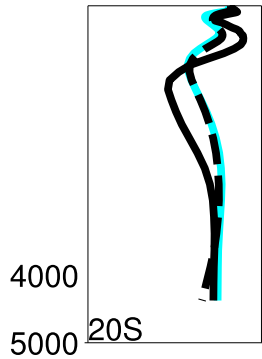
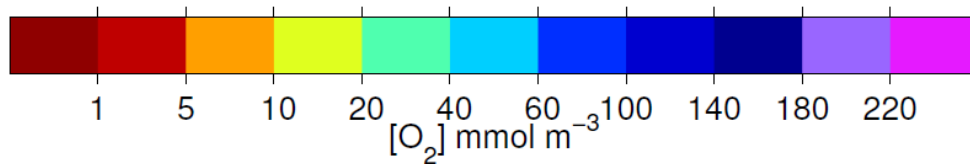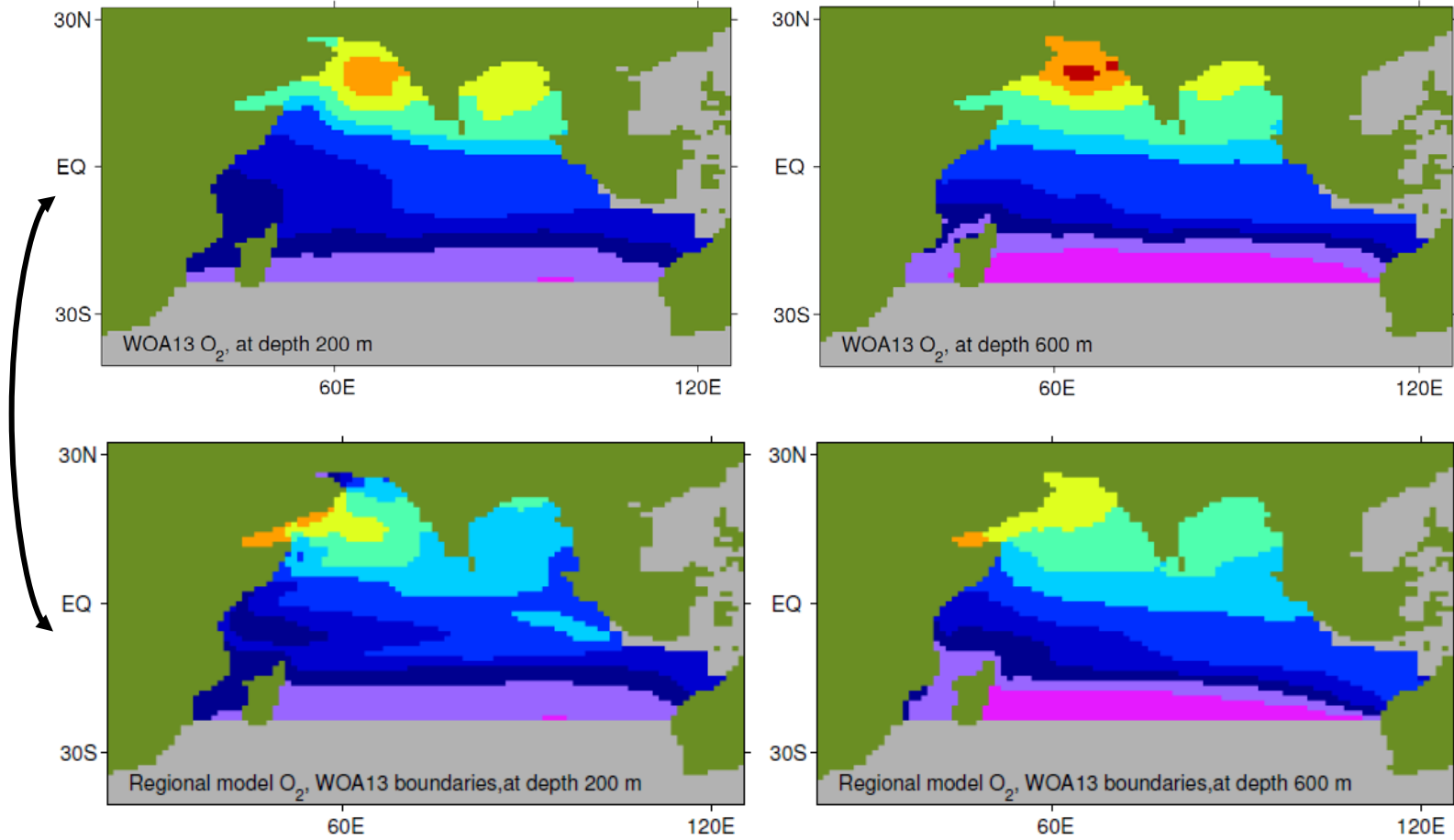# Comparing Regional BEC Bias
with Global BEC Bias -2

Comparison:

- Global BEC CMIP5 O_2,
- Regional Model with **WOA13 O_2 boundaries**, and
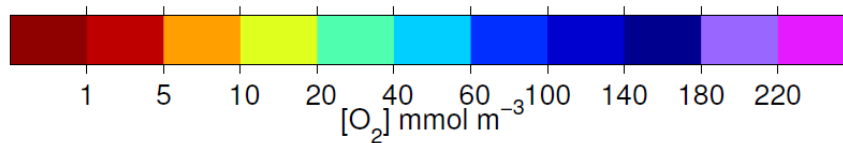- WOA13 O_2 observations

Difference:
If circulation OK, then biology

WOA13 O$_2$, at depth 200 m

WOA13 O$_2$, at depth 600 m

Regional model O$_2$, WOA13 boundaries, at depth 200 m

Regional model O$_2$, WOA13 boundaries, at depth 600 m

1   5   10   20   40   60   100   140   180   220

[O$_2$] mmol m^{-3}

Difference: If circulation OK, then biology

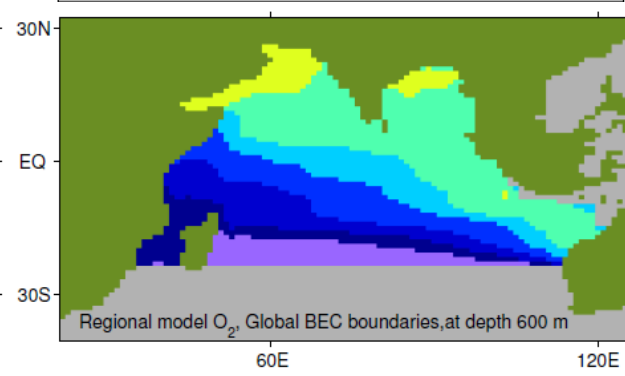Difference: Regional versus External bias

WOA13 O$_2$, at depth 200 m

WOA13 O$_2$, at depth 600 m

Regional model O$_2$, WOA13 boundaries, at depth 200 m

Regional model O$_2$, WOA13 boundaries, at depth 600 m

Regional model O$_2$, Global BEC boundaries, at depth 200 m

Regional model O$_2$, Global BEC boundaries, at depth 600 m

1 5 10 20 40 60 100 140 180 220
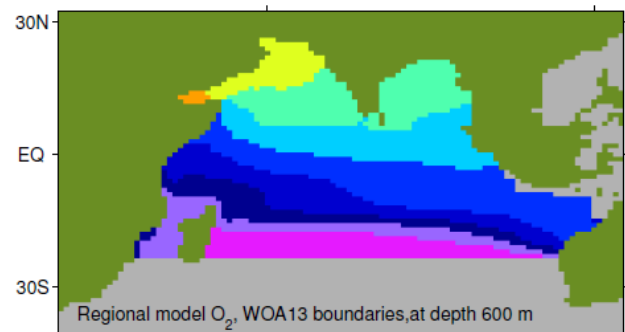
[O$_2$] mmol m^{-3}
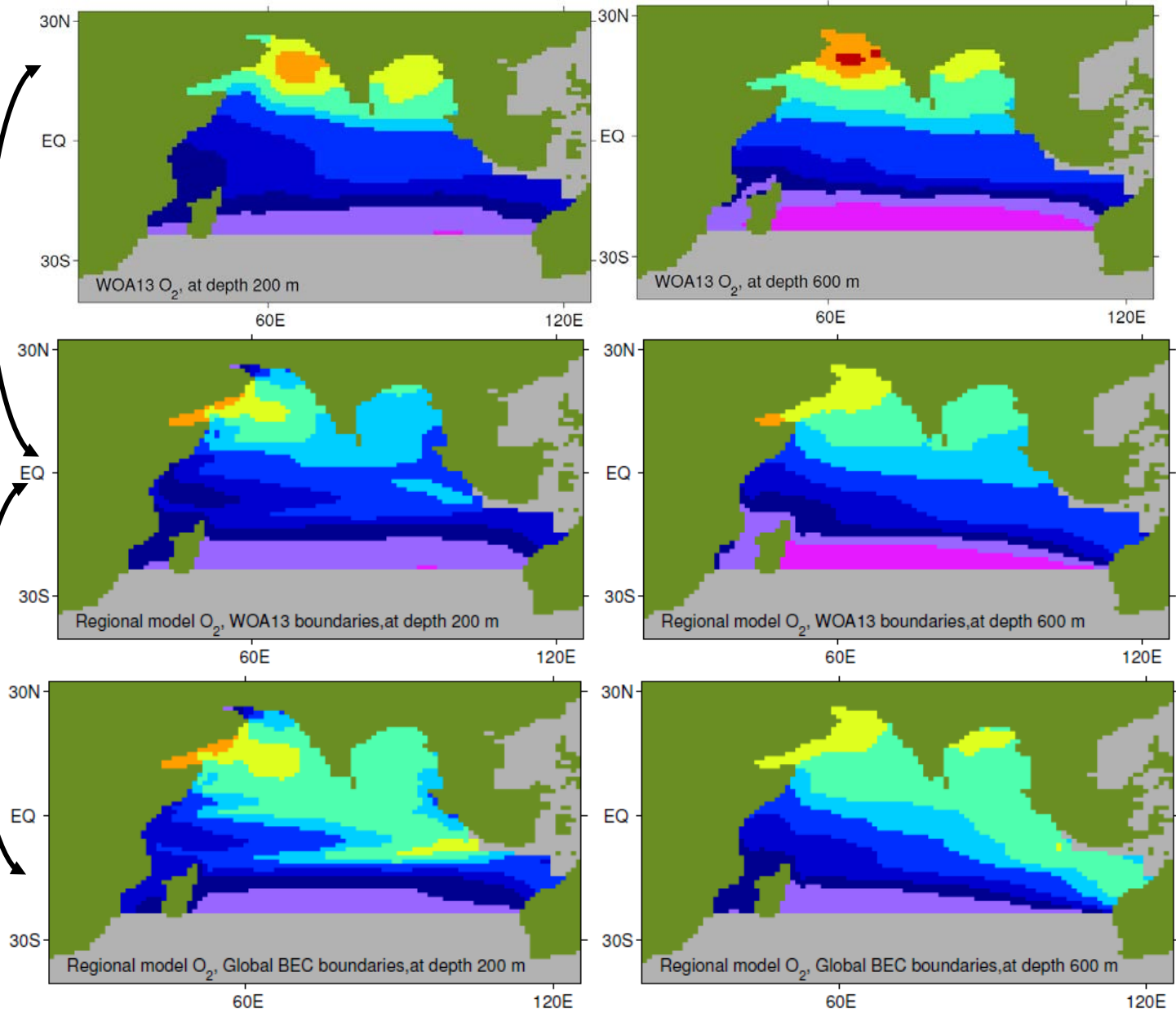
Difference:
If circulation OK, then biology

Difference:
Regional versus External bias

Difference:
Regional model circulation versus Global CMIP5 circulation

WOA13 O$_2$, at depth 200 m

WOA13 O$_2$, at depth 600 m

Regional model O$_2$, WOA13 boundaries, at depth 200 m

Regional model O$_2$, WOA13 boundaries, at depth 600 m

Regional model O$_2$, Global BEC boundaries, at depth 200 m

Regional model O$_2$, Global BEC boundaries, at depth 600 m

BEC model O$_2$, at depth 200 m

BEC model O$_2$, at depth 600 m

1   5   10   20   40   60   100   140   180   220

[O$_2$] mmol m^{-3}
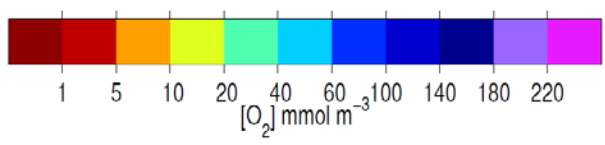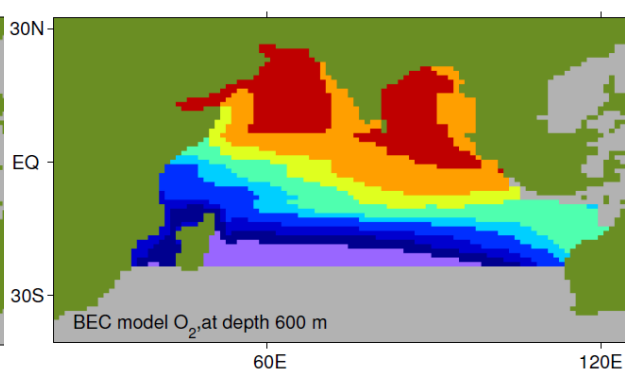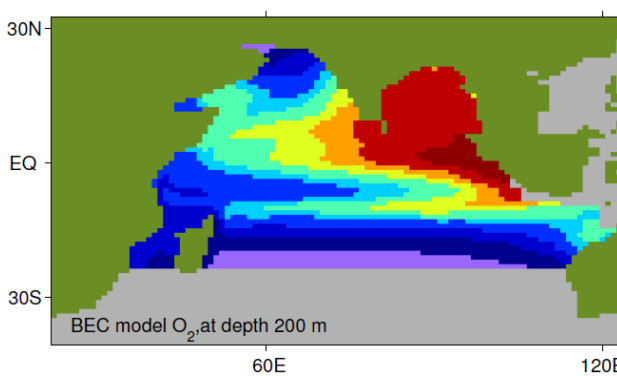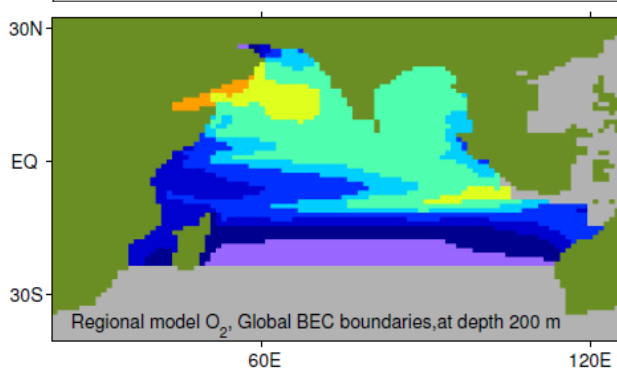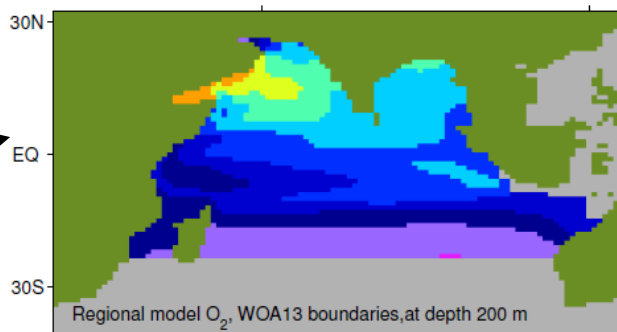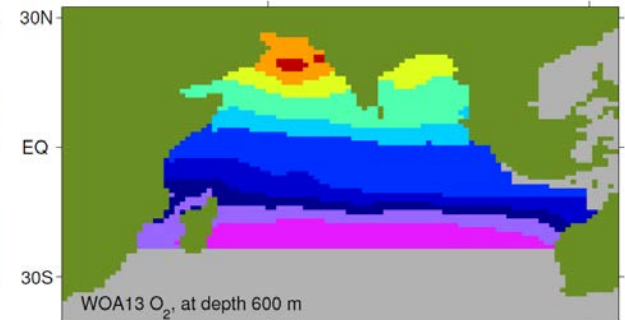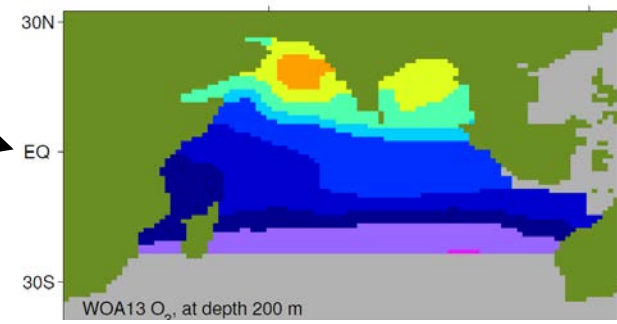
Conclusions

The regional model capability has the potential to provide a platform for further circulation and biogeochemical studies.
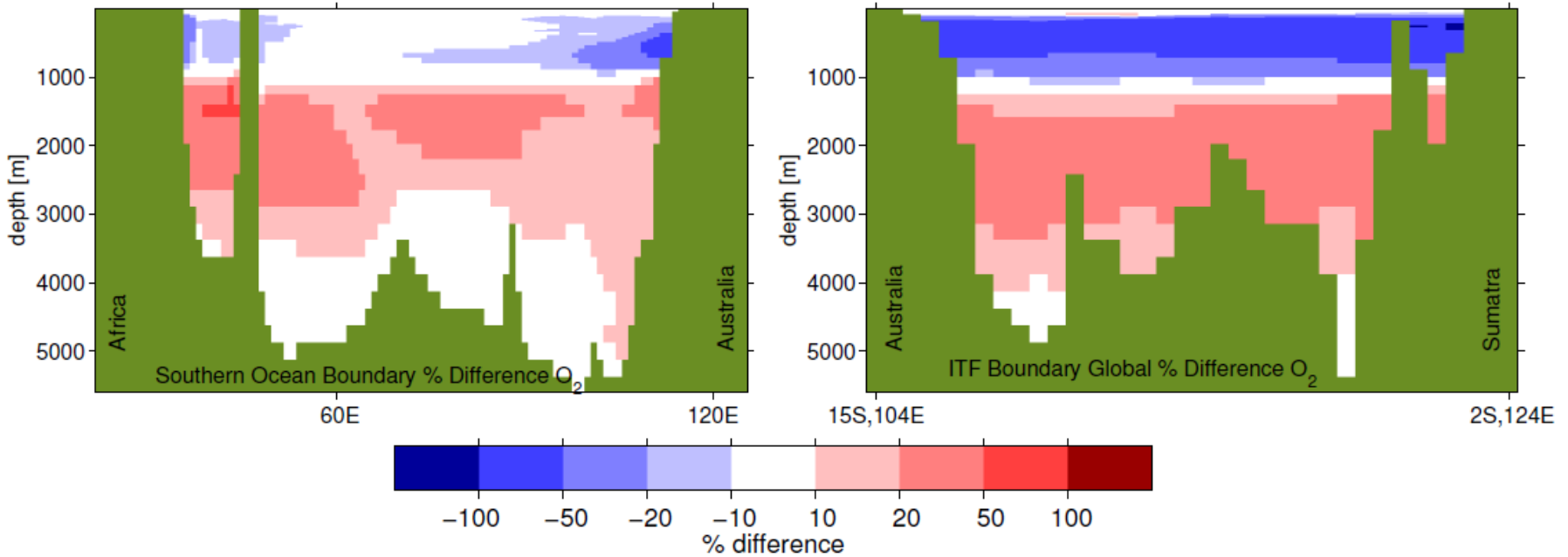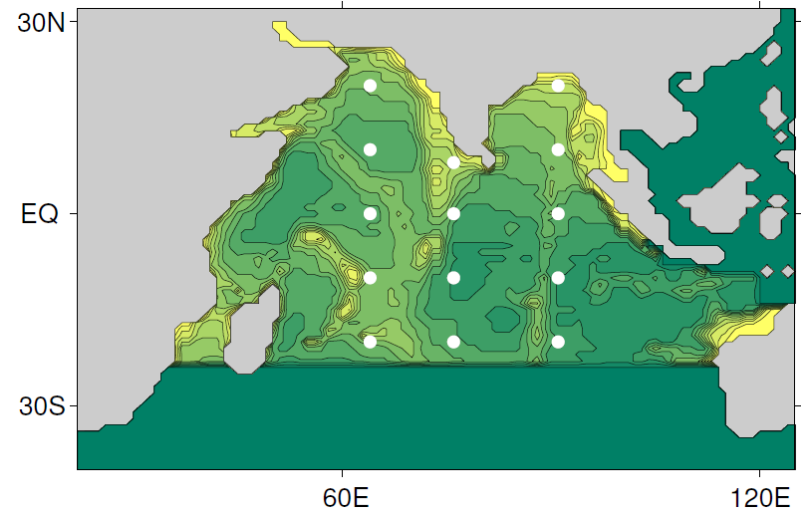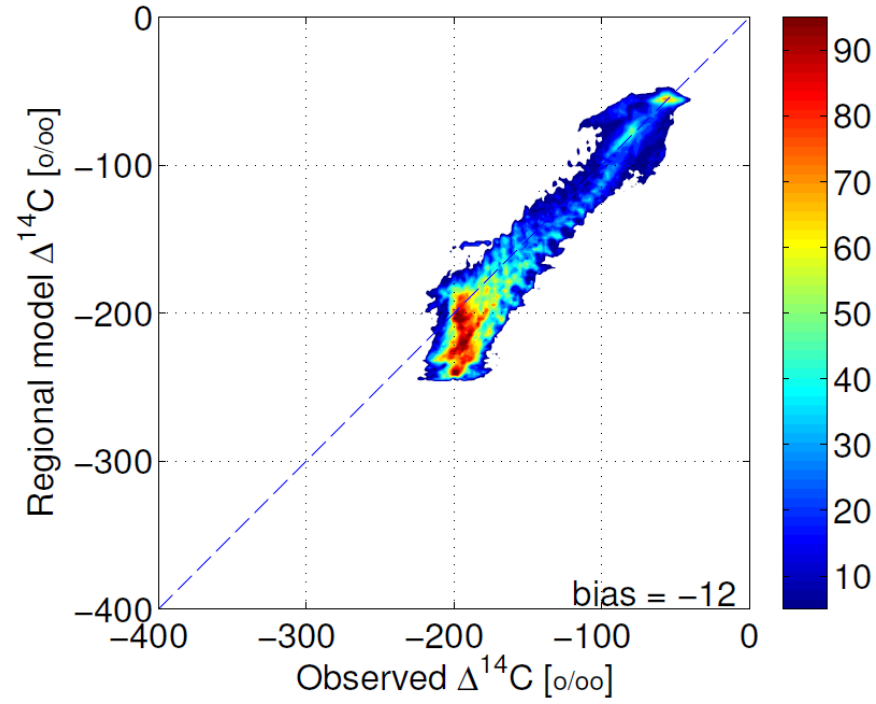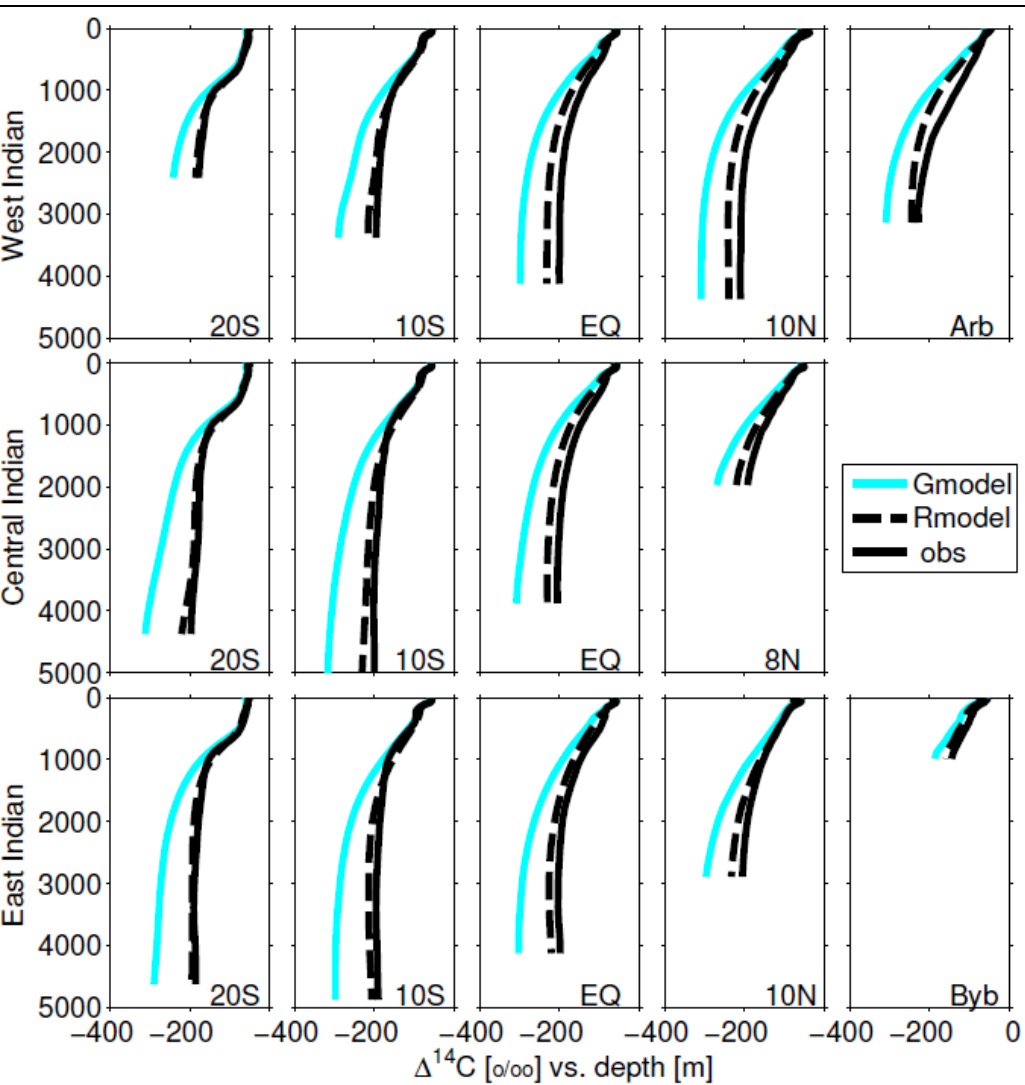
Thank you for listening

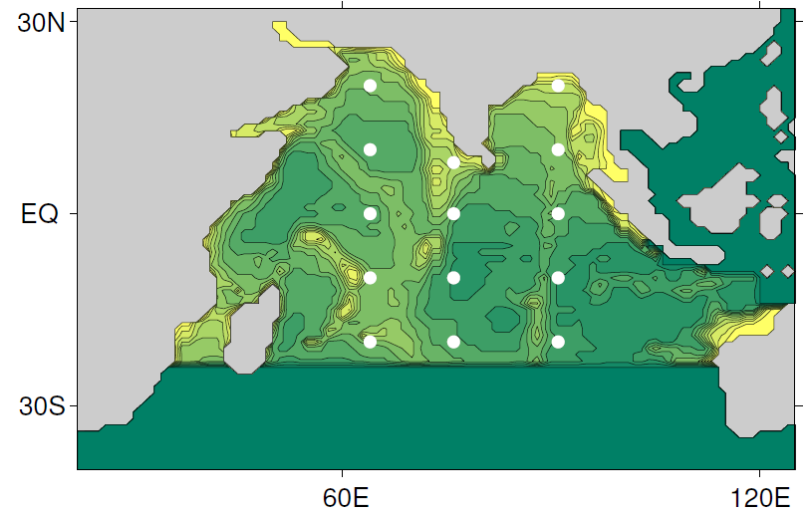# RMS of log[O₂] Comparisons
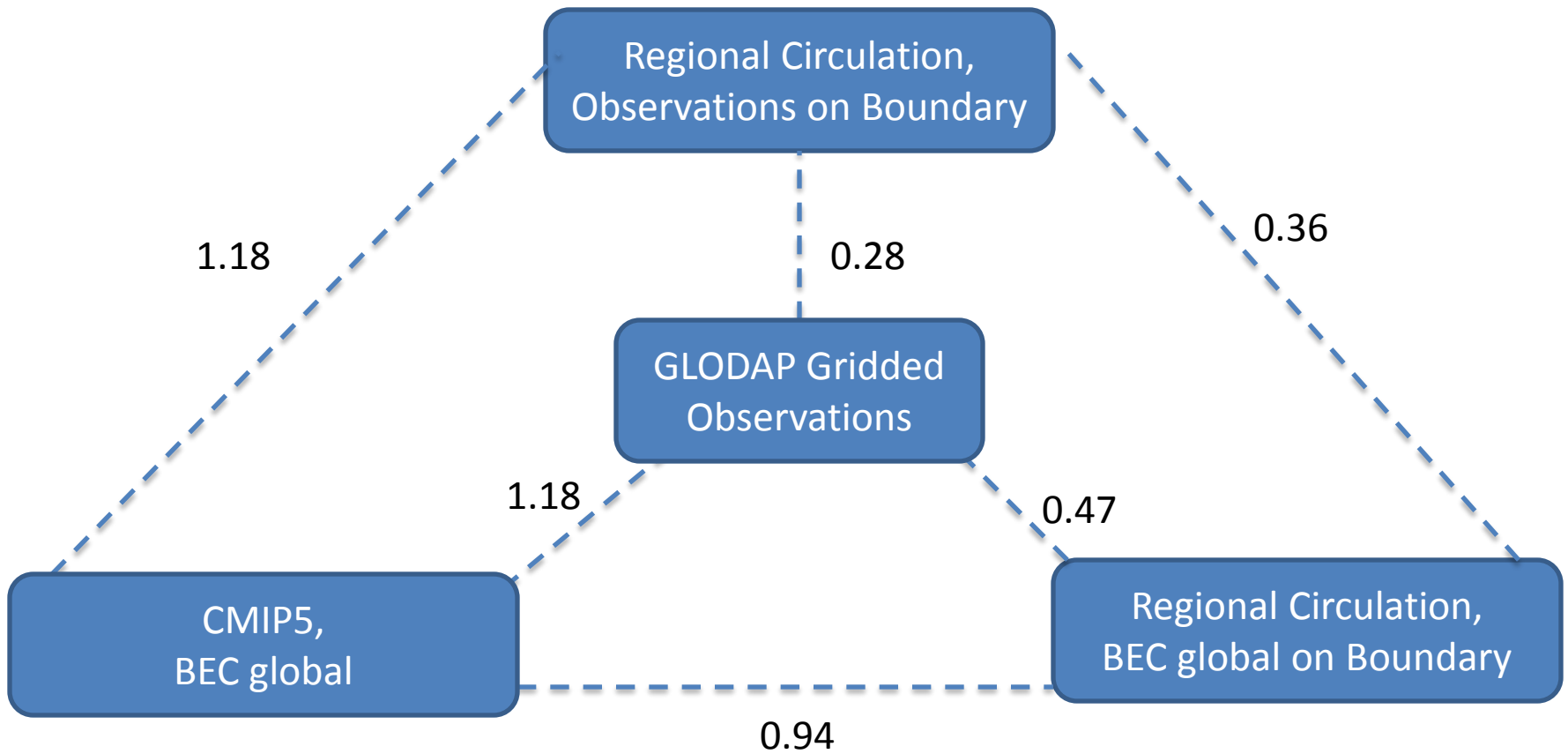
How different are the O$_2$ boundary values?
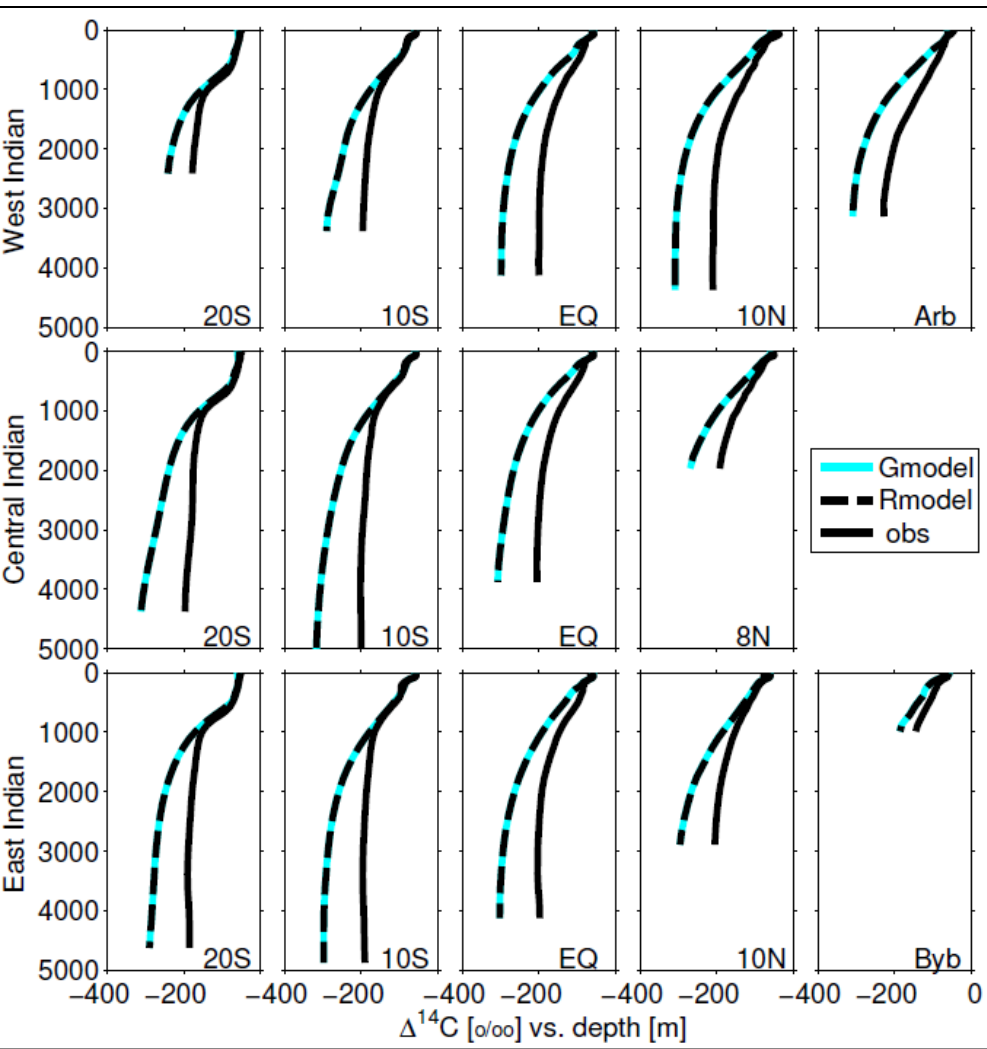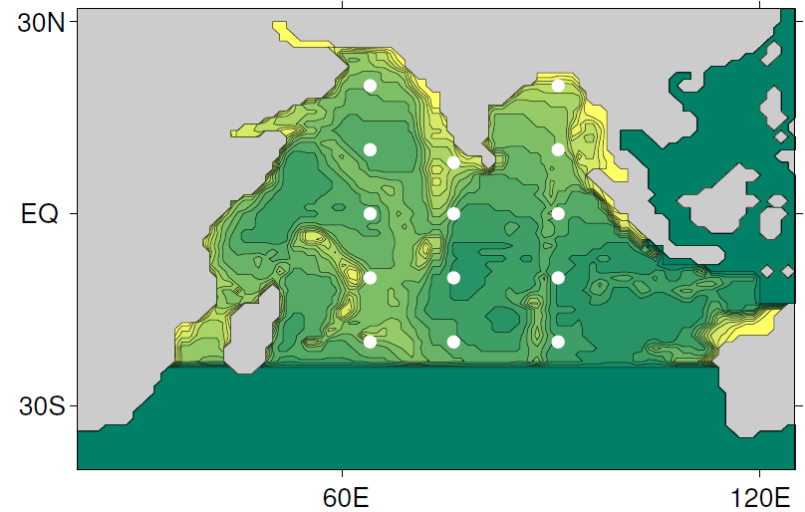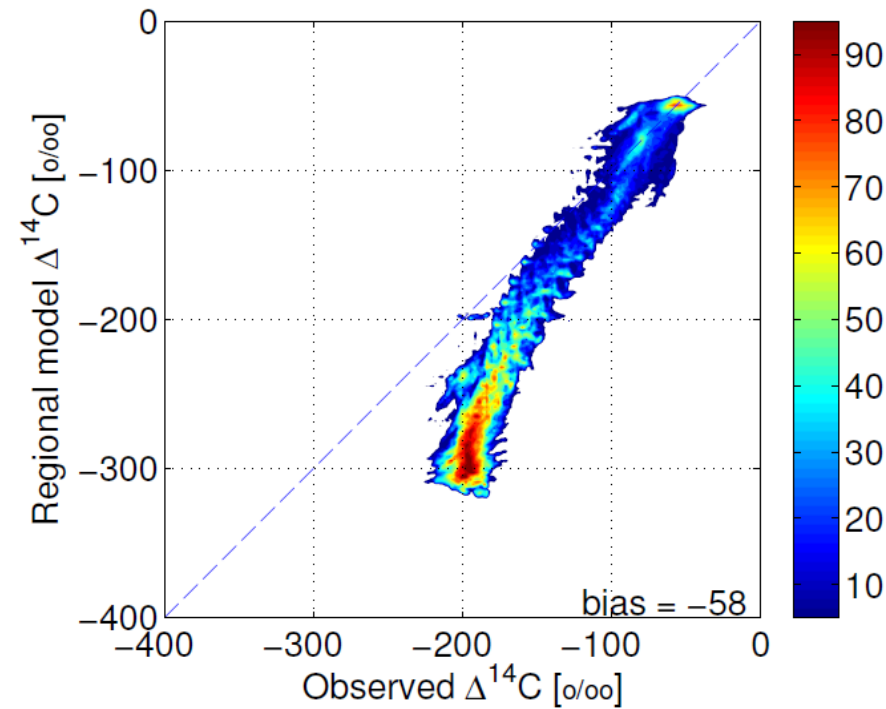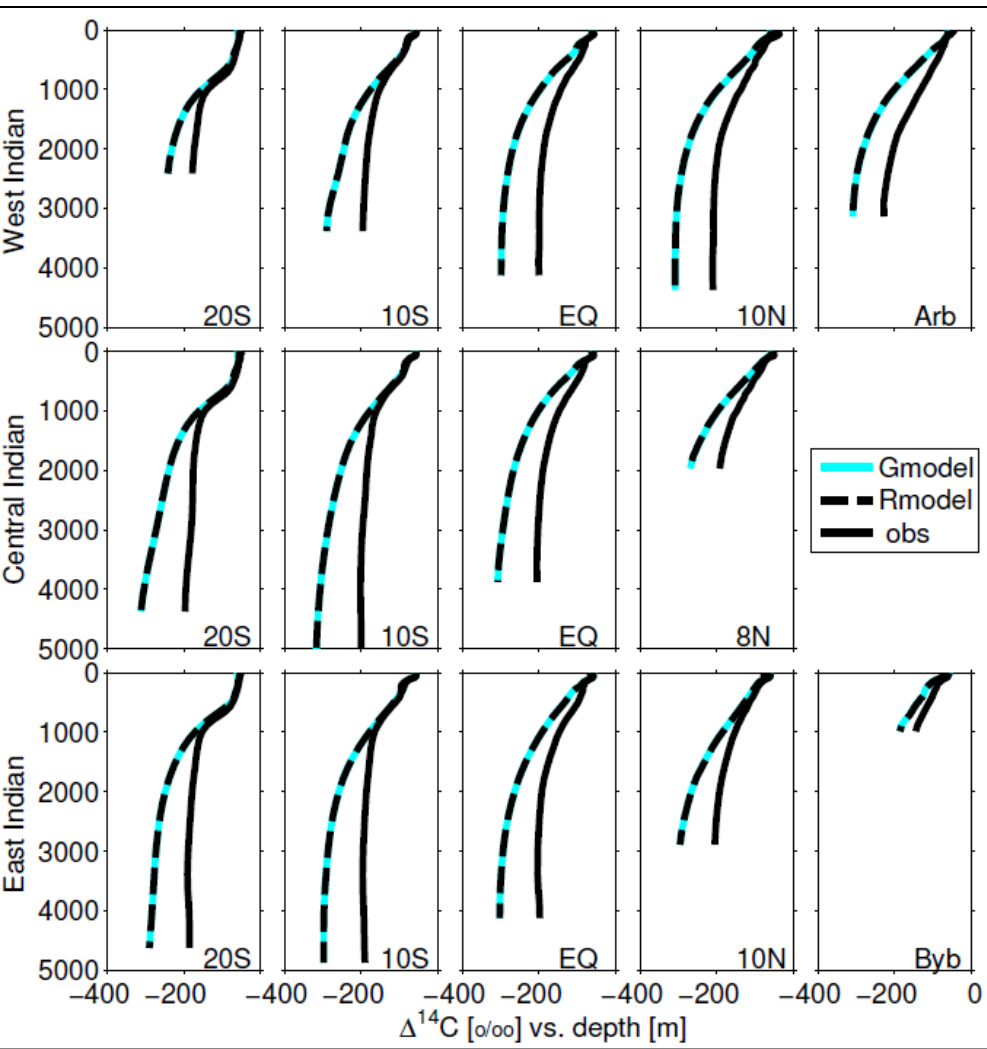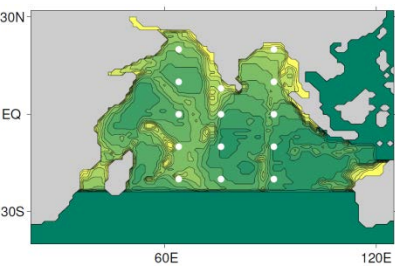
GLODAP observational ^{14}C Boundaries

Global Simulation ^{14}C Boundaries
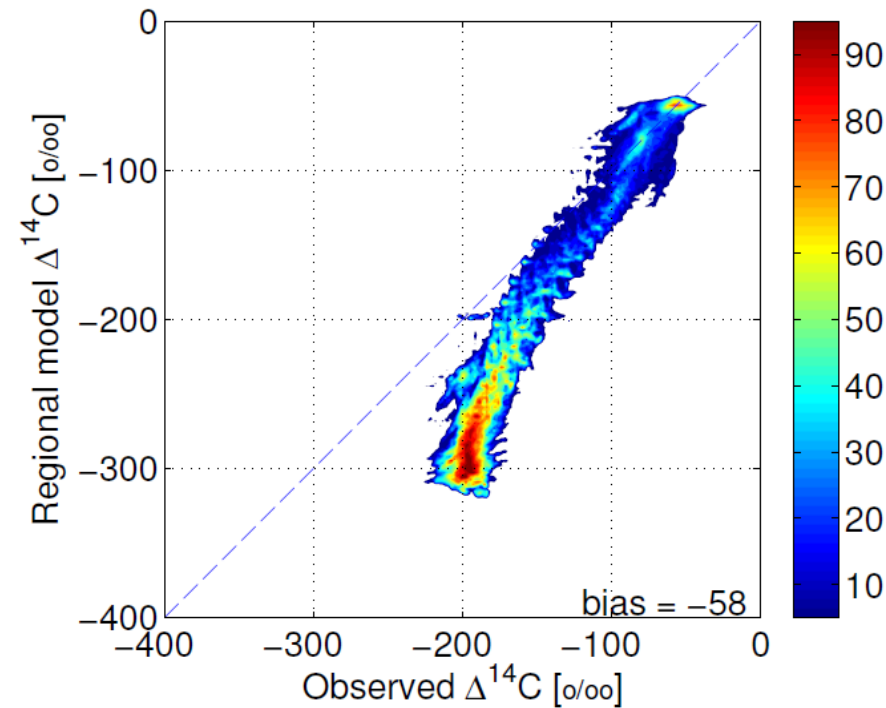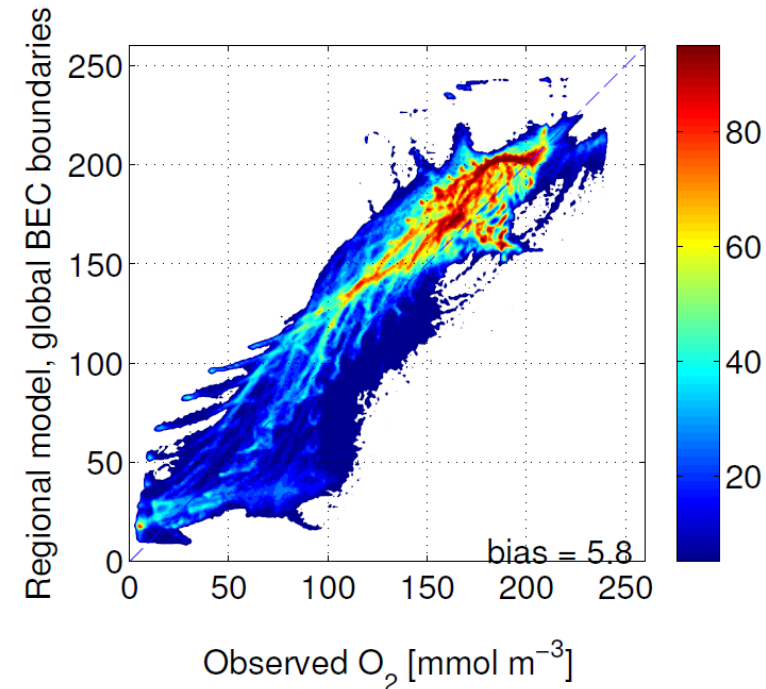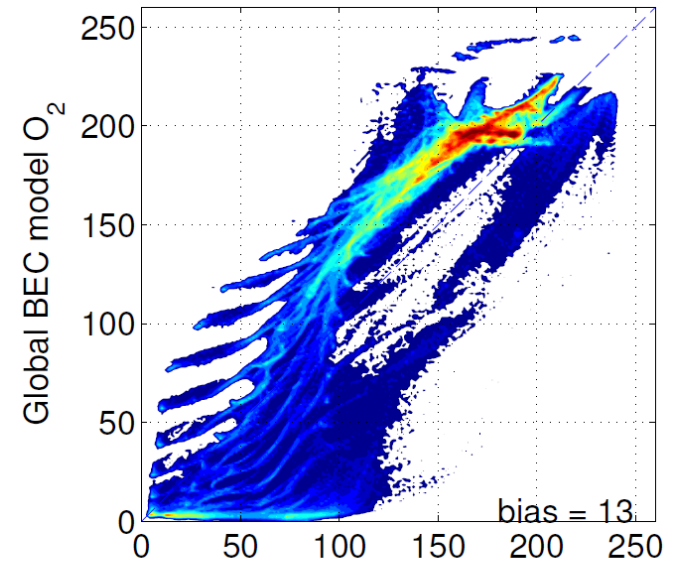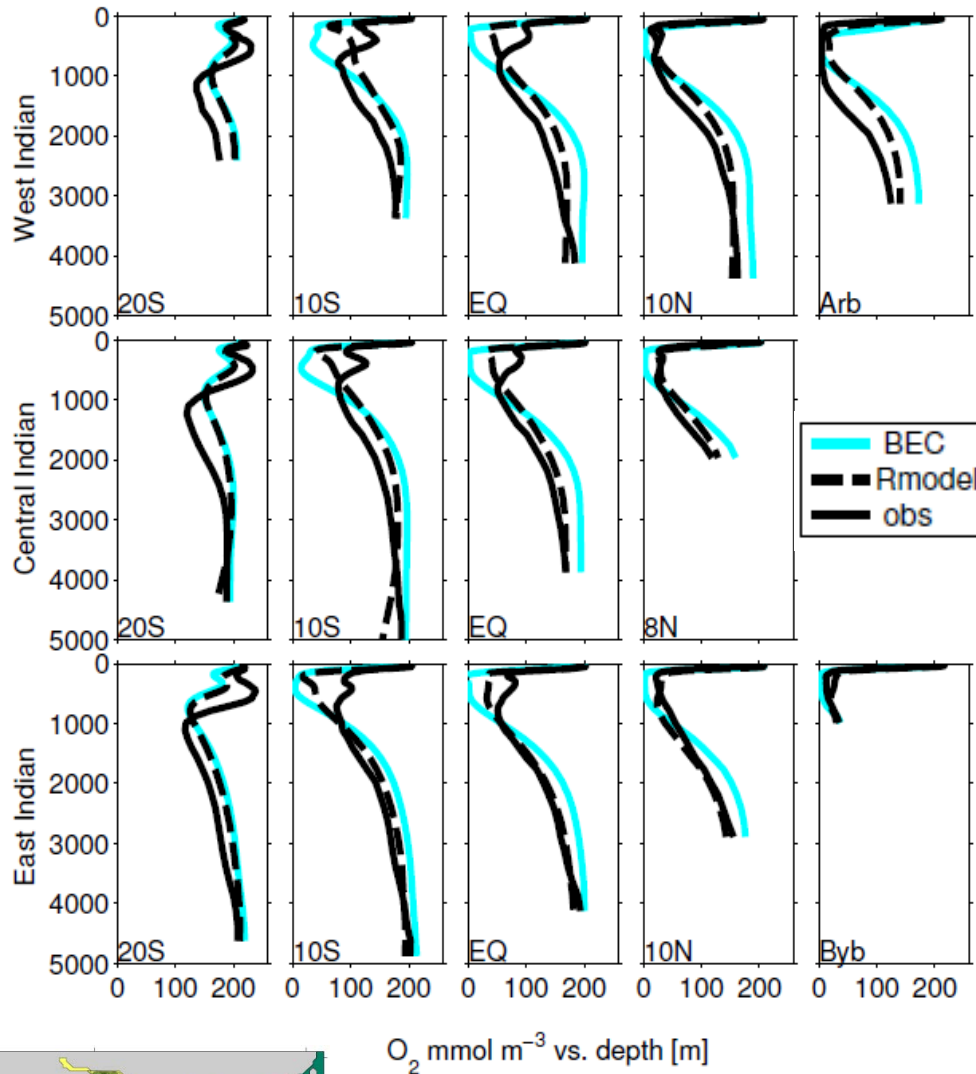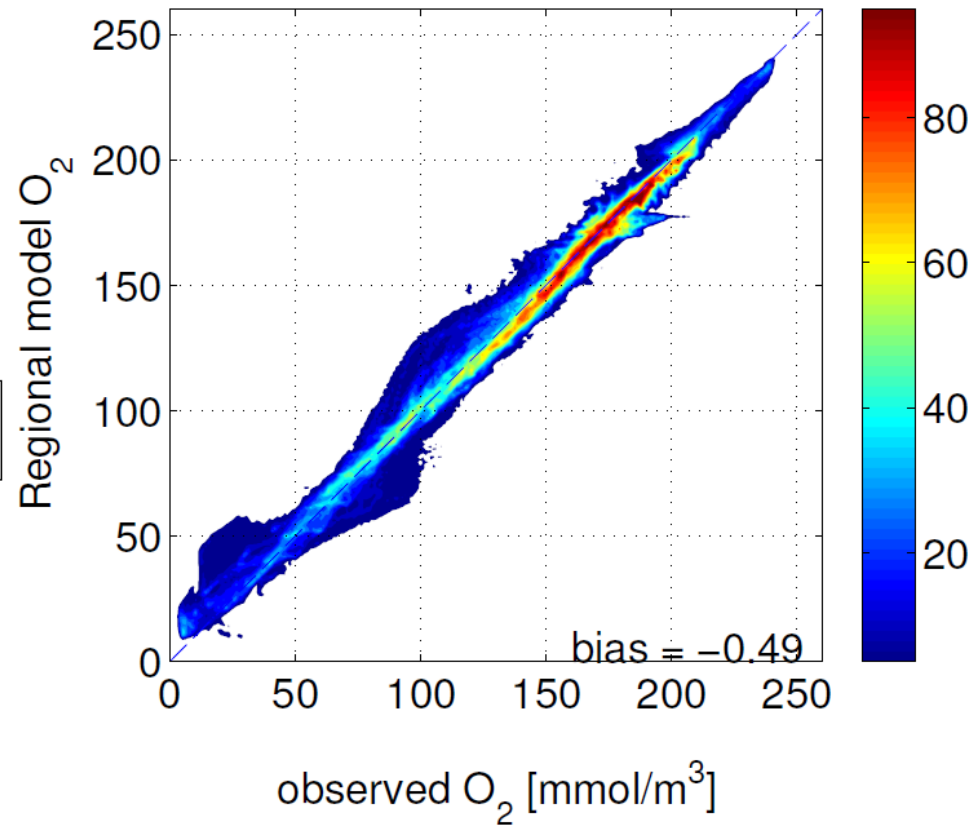
Global Simulation ^{14}C Boundaries

CMIP5 BEC Global Simulation O$_2$ Boundaries

O$_2$ mmol m^{-3} vs. depth [m]

Observed O$_2$ [mmol m^{-3}]

WOA13 observational O$_2$ Boundaries

O$_2$ mmol m^{-3} vs. depth [m]

bias = −0.49

observed O$_2$ [mmol/m^3]

Regional model O$_2$
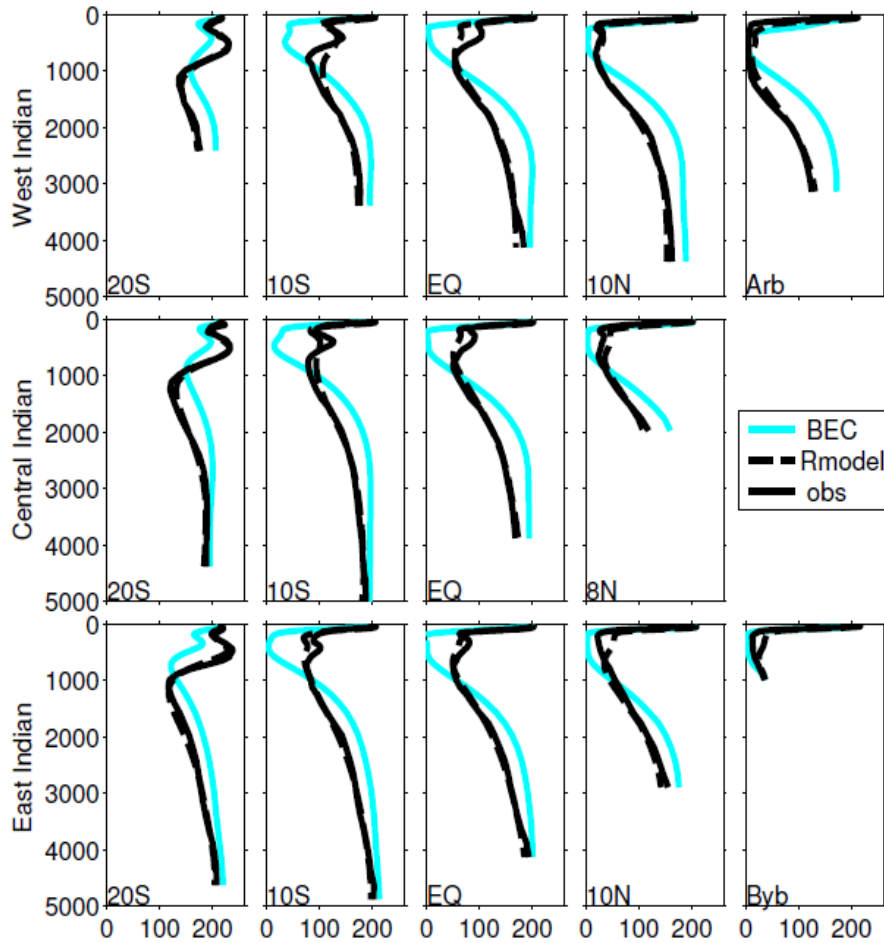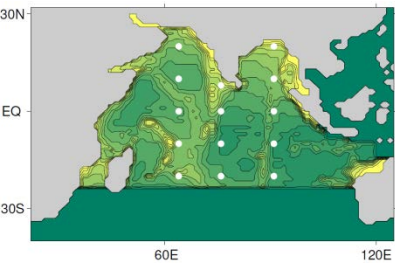
Model Equilibrium Δ^{14}C vs. GLODAP Observations at 3000 m
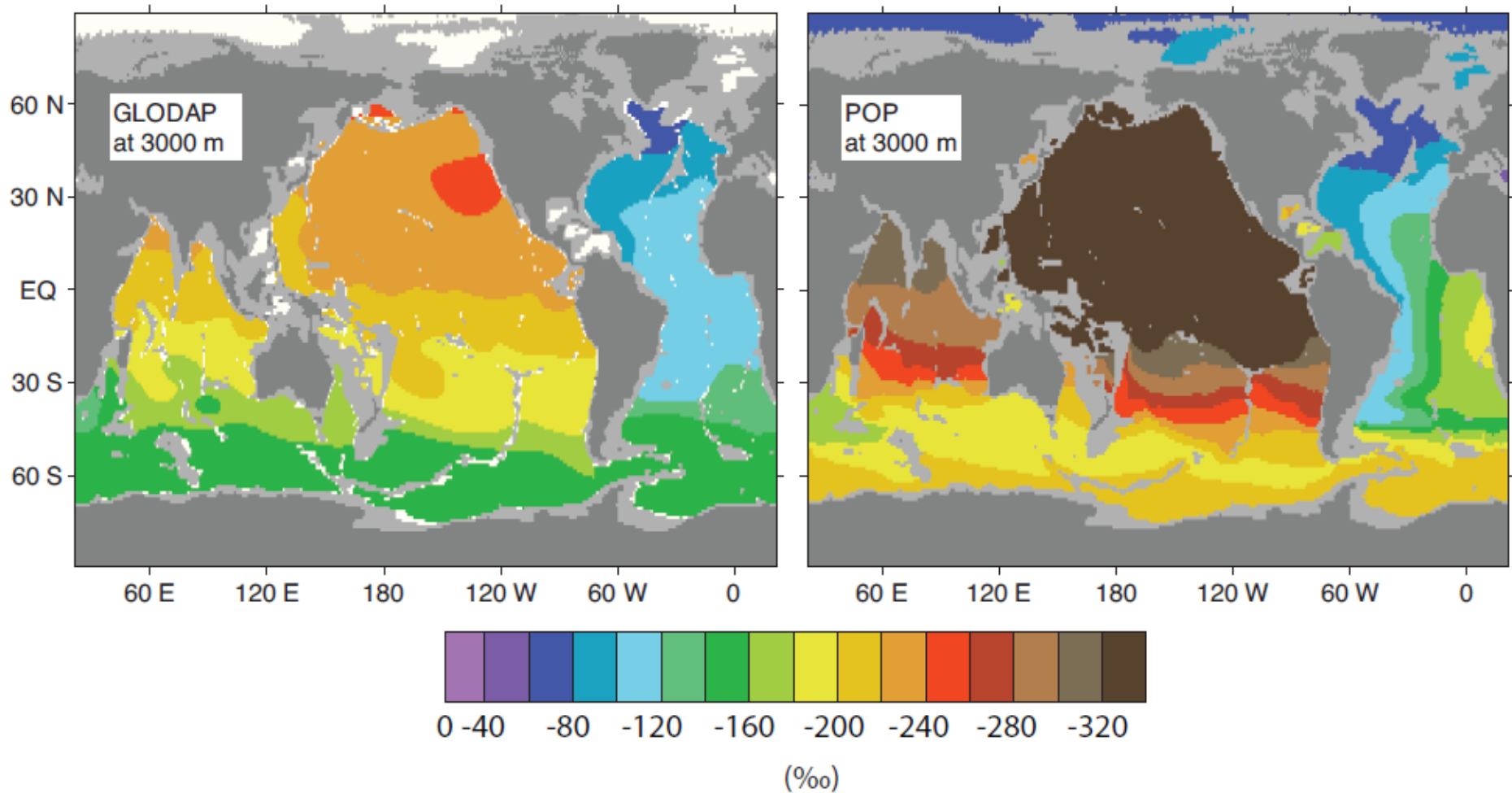
Record OGCM circulation fields for transport matrix

- Advection and horizontal diffusion fields were recorded using an Impulse-Response Function (IRF) .

Time t   Time t +Δt

Col 7   Col 8
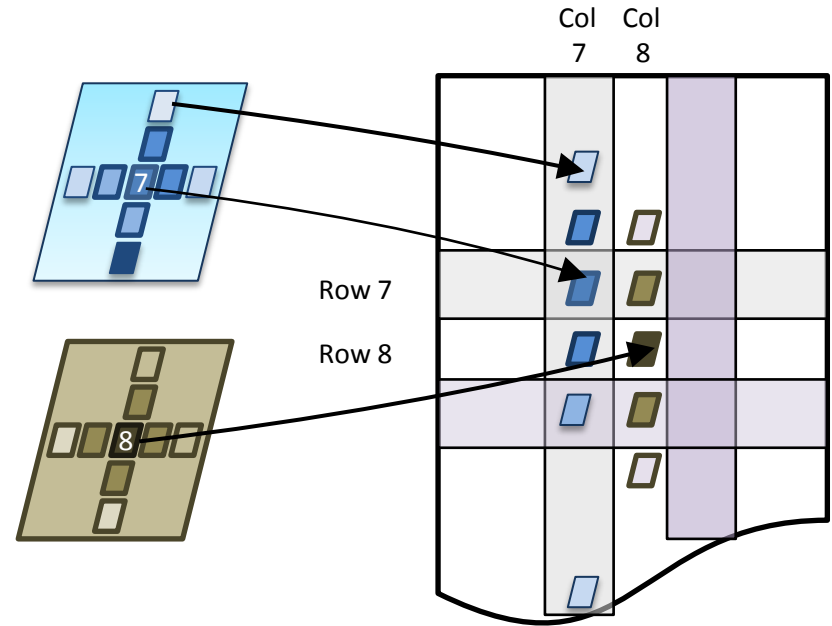
Row 7

Row 8
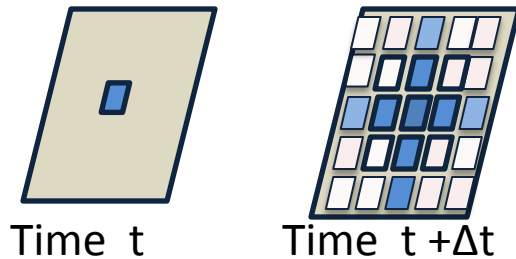
- Recoded monthly-averaged values for each impulse tracer were used to create the advection and horizontal diffusion operators.

- The vertical diffusion operator was calculated from recorded coefficients.

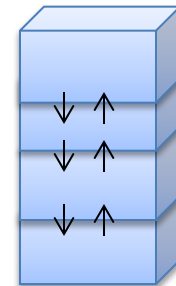# Implicit Newton-Krylov solver (nsoli.m) iteratively solves for seasonal-cycle equilibrium

- Each iteration requires a 1-year seasonal-cycle run

- Offline transport time-stepping uses
    3rd-degree Adams-Bashforth for advection,
    Euler -forward for horizontal diffusion,
    Euler-backward for vertical diffusion,
    and accounts for sea-surface height changes.

- Calculate the difference between the beginning and end of the year $(X_{n+1} - X_n)$

- But – for a faster solution, apply a preconditioner

Motivation for oxygen study

Predicted loss of oxygen from the ocean due to climate change (Bopp 2002; Matear and Hurst 2003; Stramma 2008; Bopp 2013)

Observations suggest that a loss of oxygen is already underway (Whitney 2007; Chan 2008; Stramma 2012)

Ocean general circulation models of the IPCC class have biases even when simulating present-day conditions, especially at low oxygen values (Bopp 2013)

Volume of water in Oxygen Minimum Zones (OMZs) is predicted to increase or decrease in CMIP5 study (Bopp 2013)

Oxygen is a very integrative quantity of

- the circulation

- biological production and consumption

- air-sea gas exchange

Conclusions

- The circulation differences between the regional model and the CMIP5 simulation make a significant difference in the results.

- The regional model with observations on the border give the least bias compared to observations, but there are still significant misfits at low oxygen concentrations.

- The regional model capability has the potential to provide a platform for further circulation and biogeochemical studies.

Regional ¹⁴C simulation with observational boundary values vs. Global Simulation
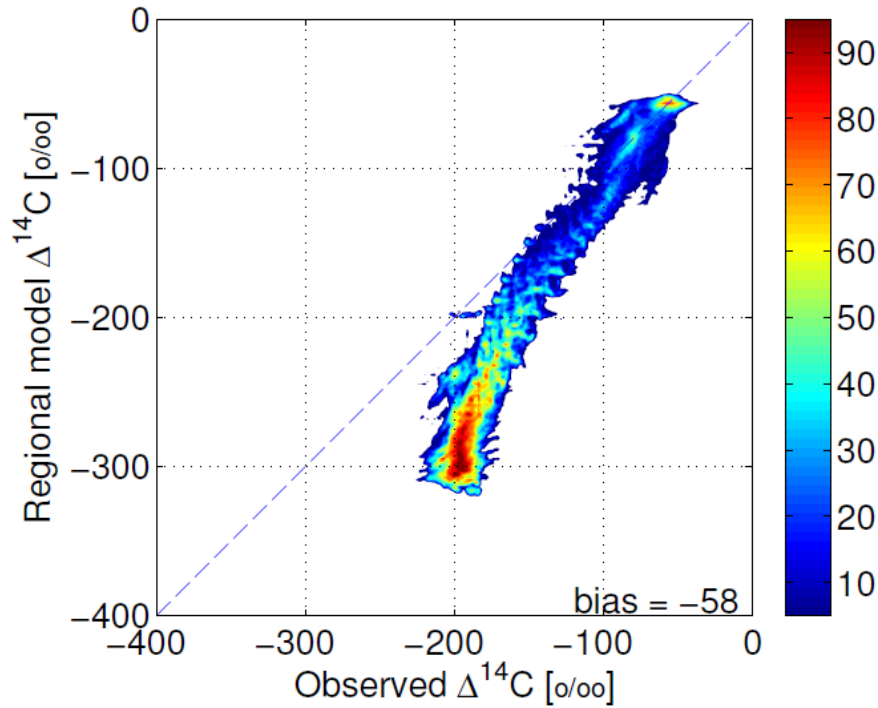
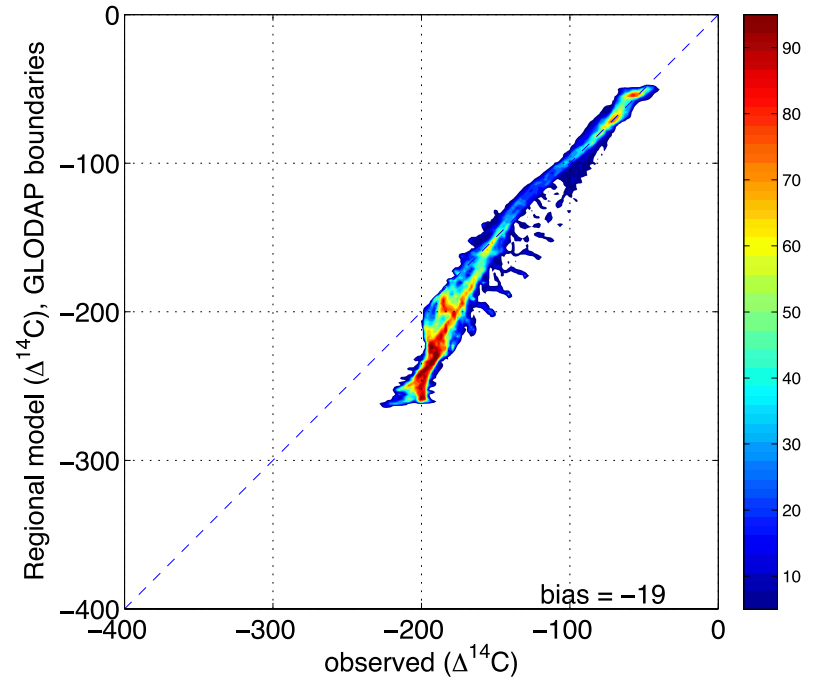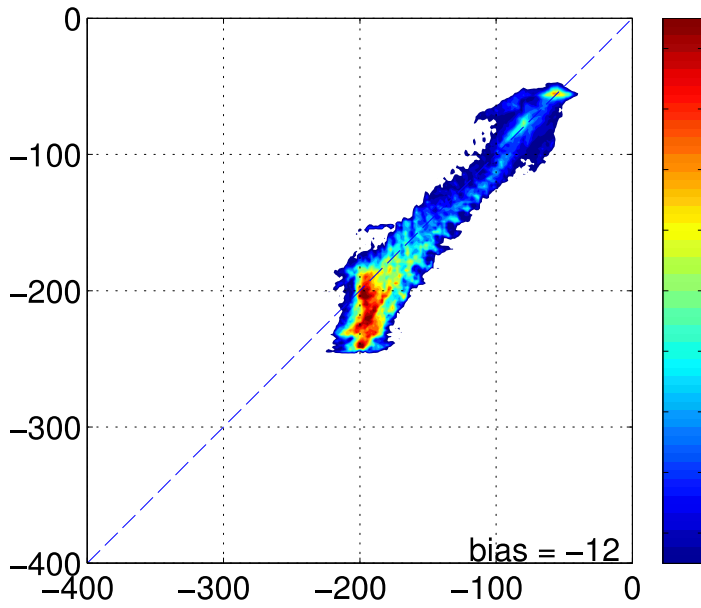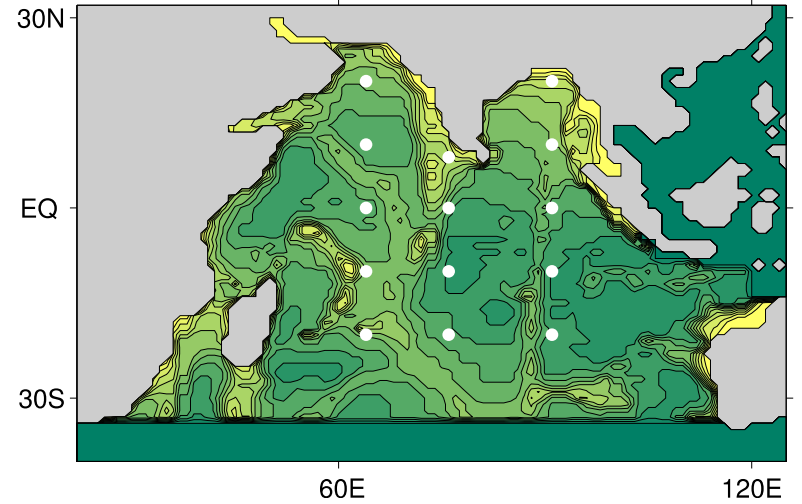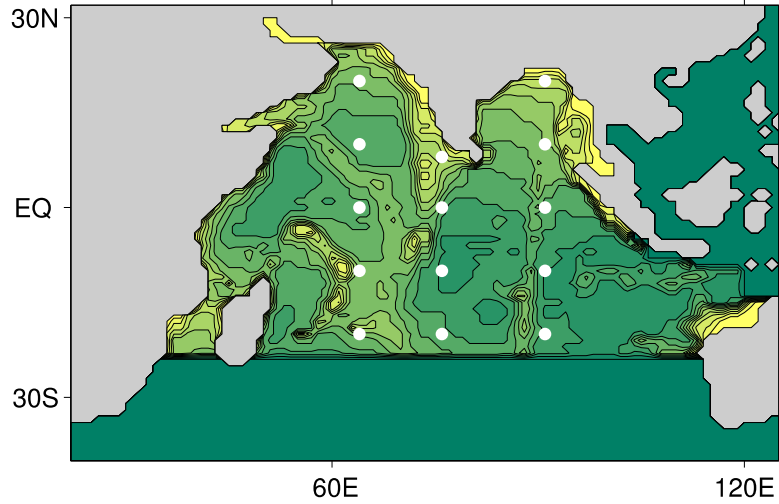Global Simulation
¹⁴C Boundaries
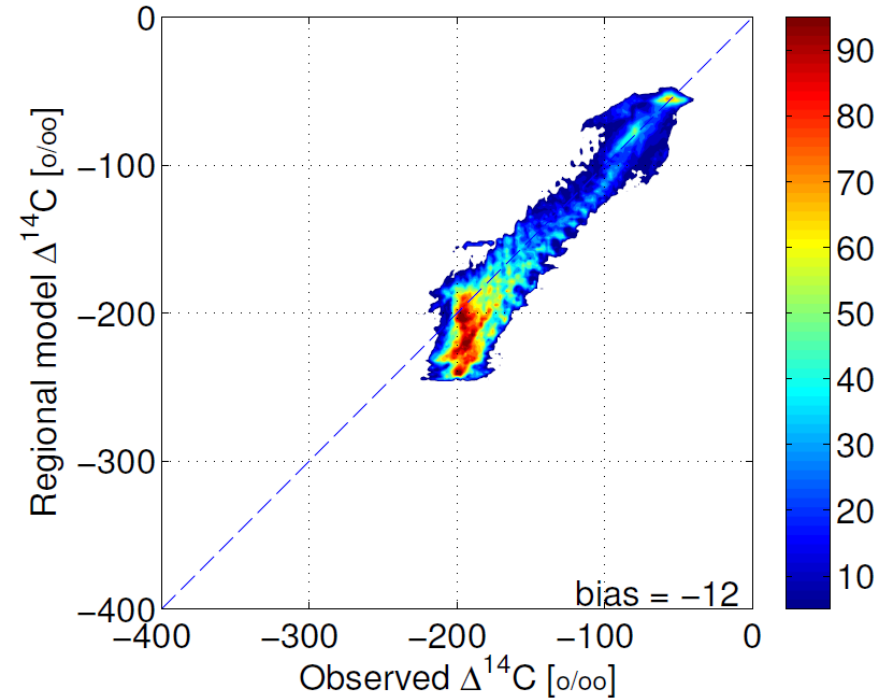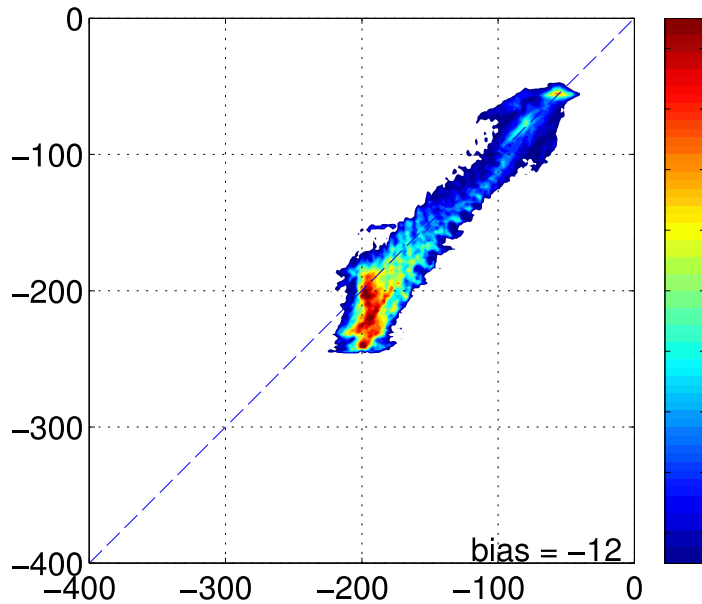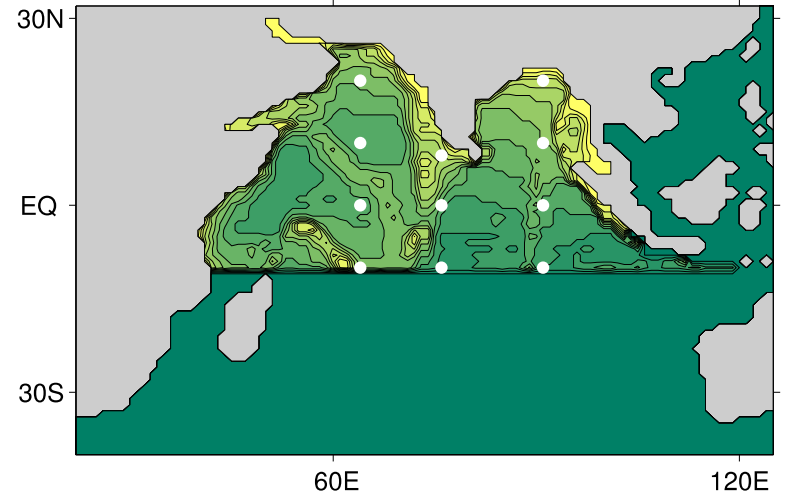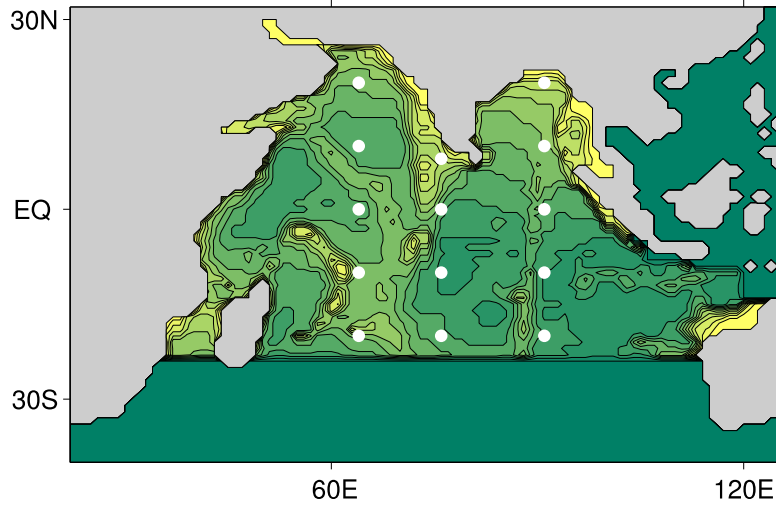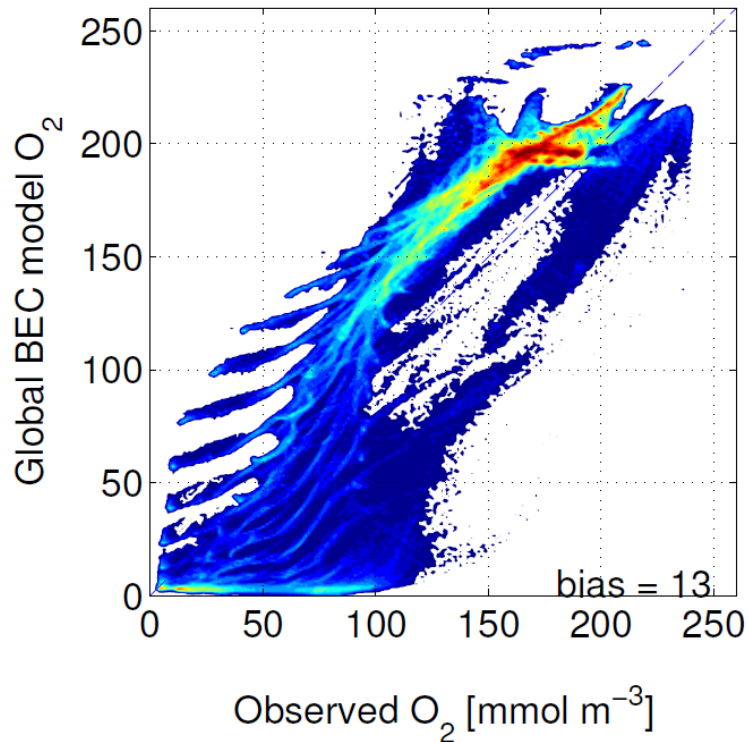
GLODAP observational
¹⁴C Boundaries

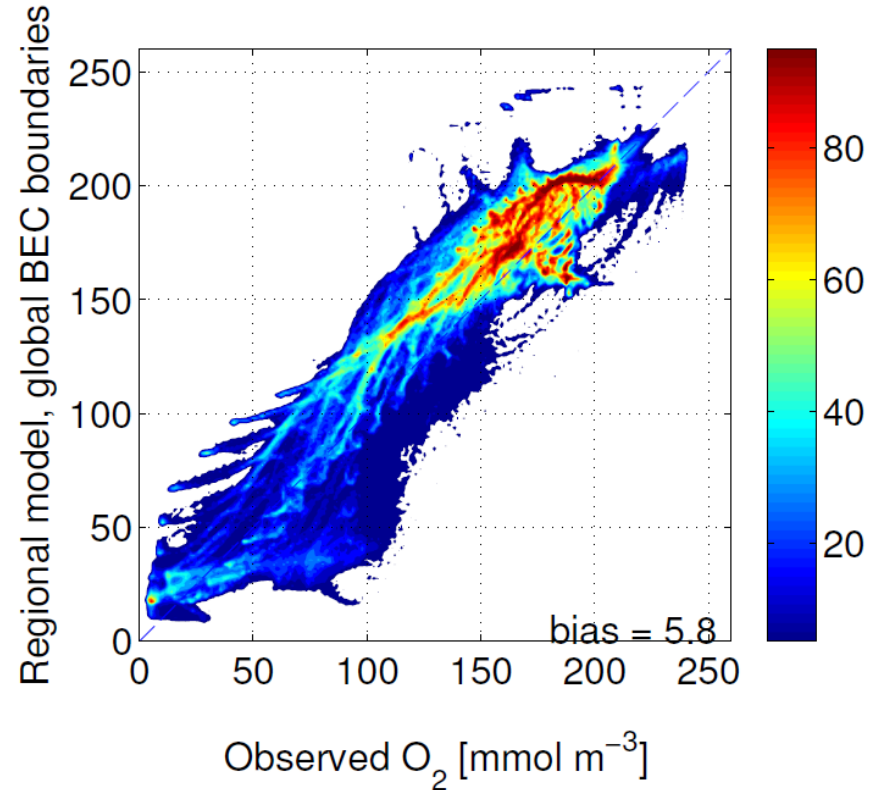# What happens if we change the boundary to 35S ?

What happens if we change the boundary to 11S ?
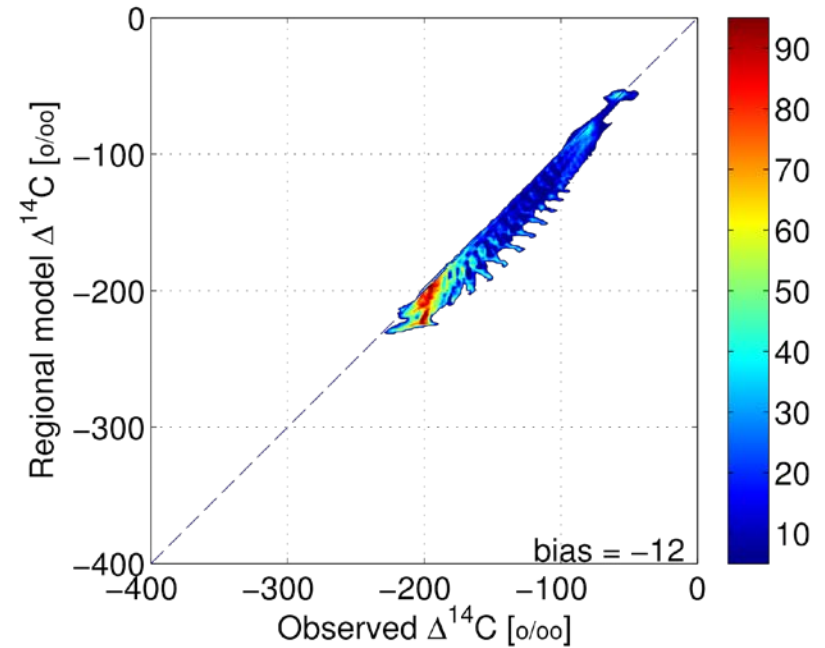
Comparison: Global CMIP5 O_2 versus Regional Model with Global CMIP5 O_2 boundaries
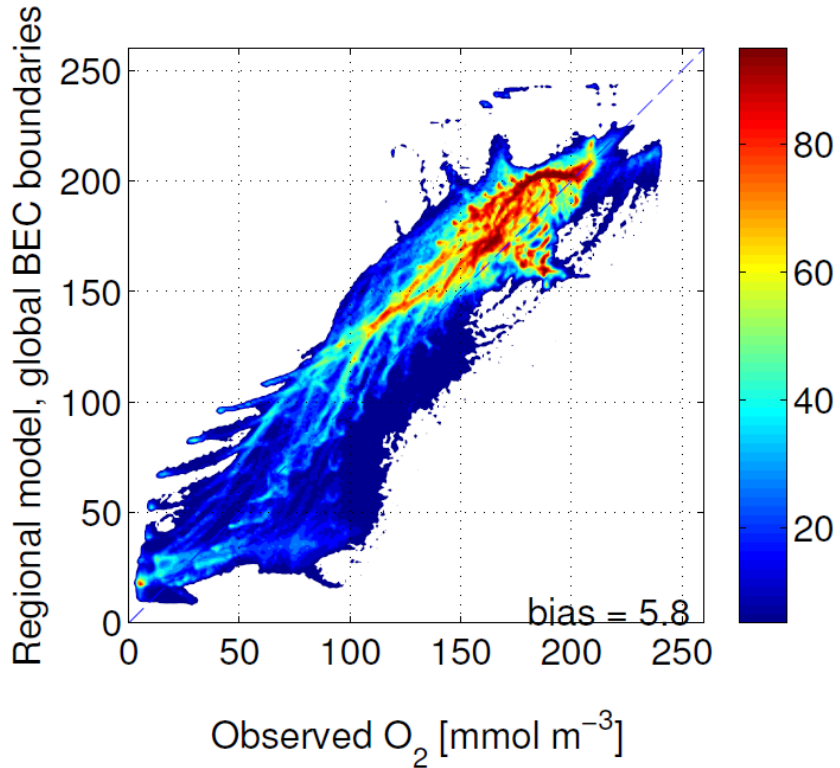

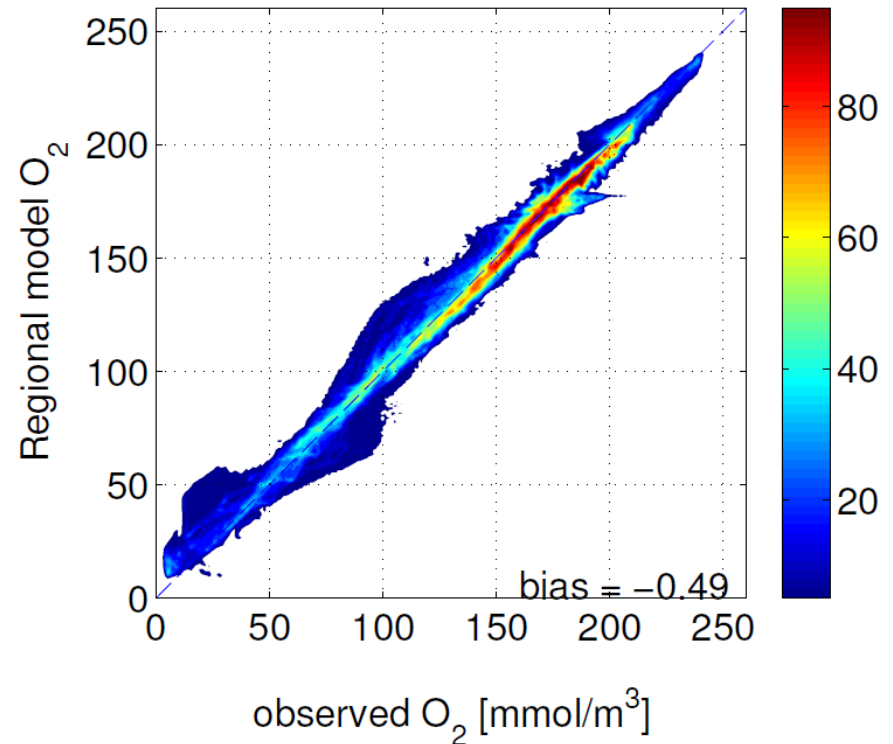Global CMIP5 BEC Simulation
O_2 in the region

CMIP5 BEC Simulation
O_2 Boundaries on Regional Model

Comparison:
Regional Model with Global CMIP5 O_2 boundaries versus observational O_2 boundaries

CMIP5 BEC Simulation O_2 Boundaries on Regional Model

Observational O_2 Boundaries on Regional Model