The 4th Atmospheric Oxygen Workshop

Air-sea O2 flux and its influence on ocean oxygen cycle

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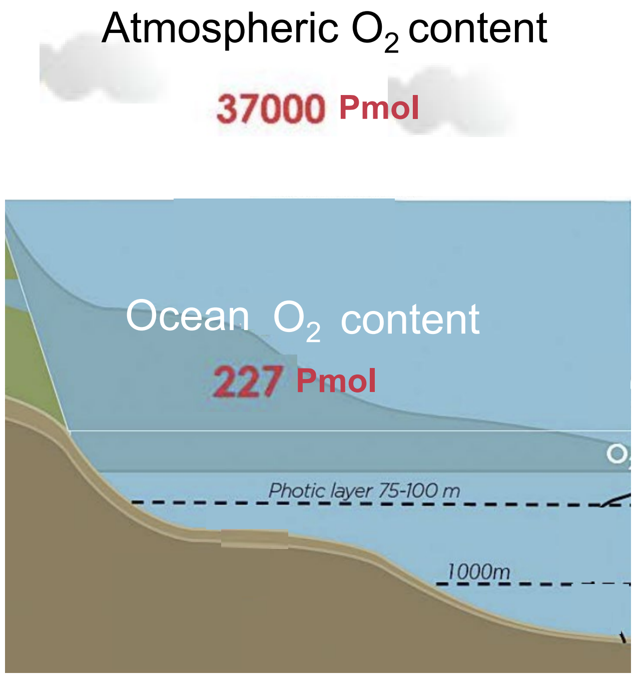
Dissolved oxygen in the ocean

The response of marine organisms to different dissolved oxygen conditions

Breitburg et al., *Science*, 2018



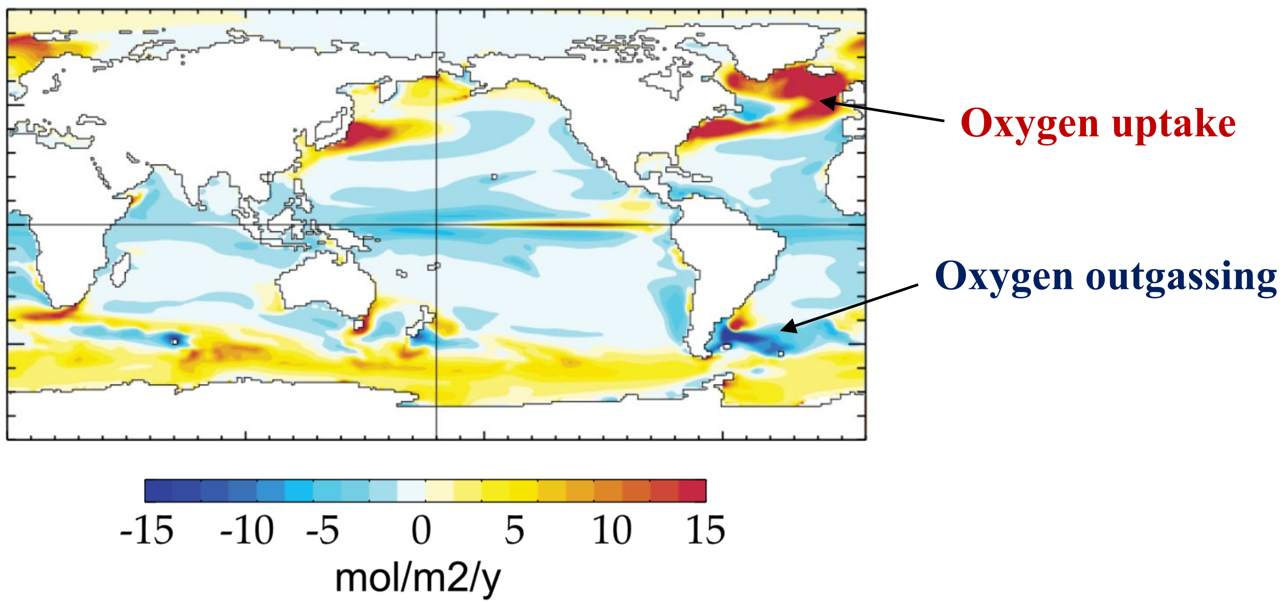
The oxygen content in ocean is ONLY about 0.6% of that in the atmosphere

1 Pmol = 10^{15} mol

Oxygen is a fundamental requirement for marine life from the seashore to the greatest depths of the ocean. However, the stock of oceanic oxygen is relatively small, which makes the ocean much more sensitive to changes in oxygen.

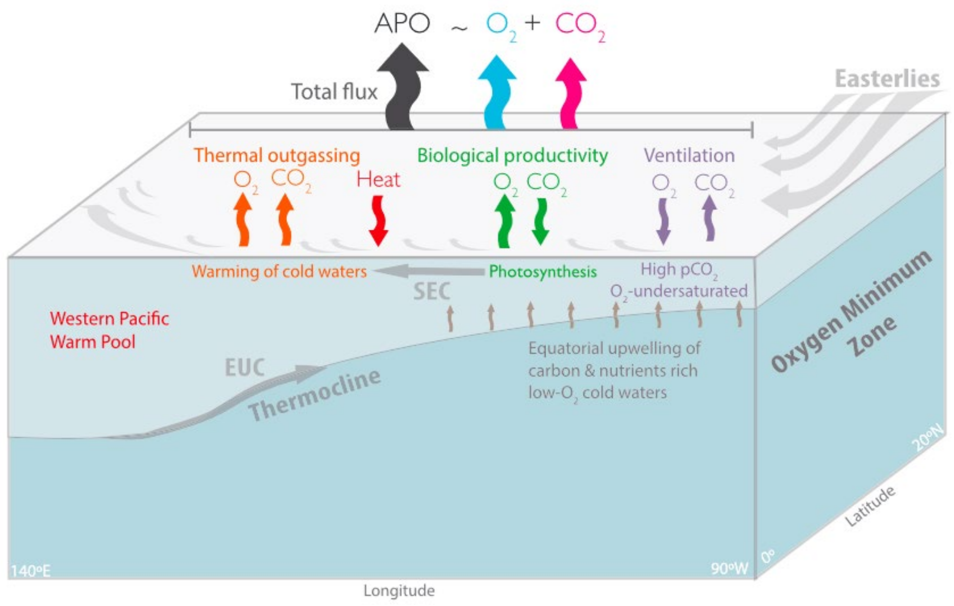
Air-sea O_2 flux: a crucial factor for oxygen distribution

Maps of annual air-sea O_2 flux simulated by climate model



Resplandy et al., *J. Geophys. Res. Oceans*, 2014

Schematic of major processes in the tropical Pacific

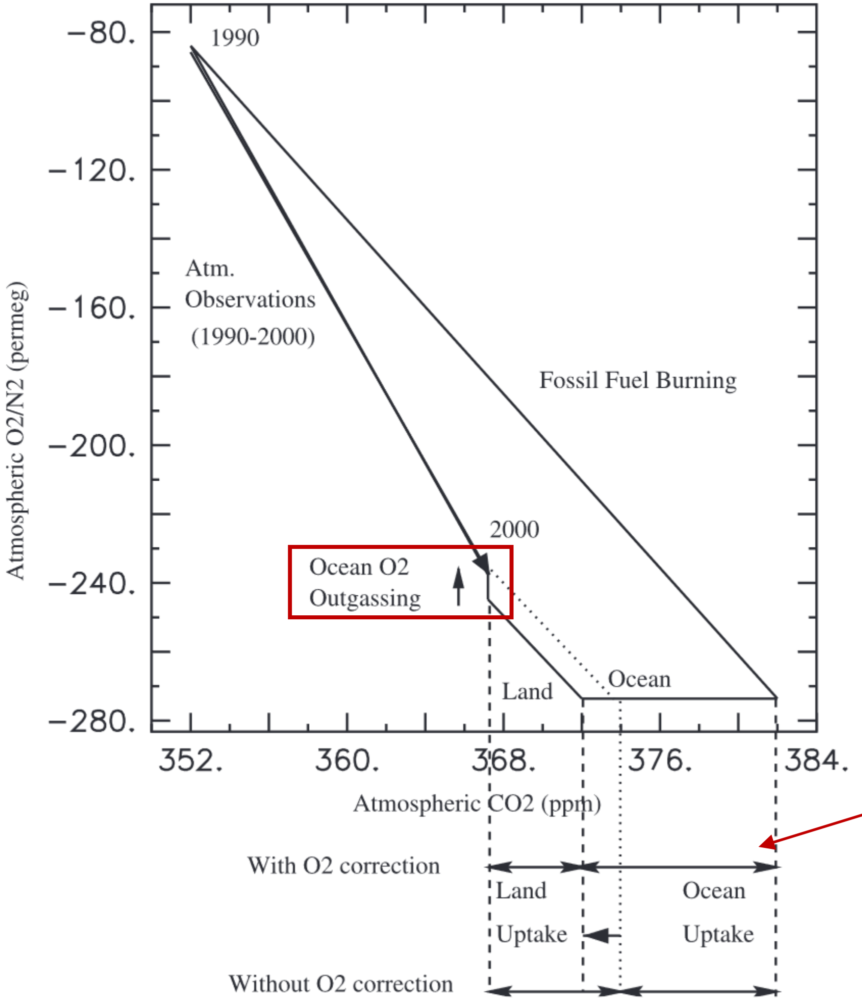


Eddebbar et al., *Global Biogeochem. Cycles.*, 2017

The air-sea O_2 flux plays an important role in the modifications of ocean O_2 content, influencing regional residence times and redistribution of oxygen.

Implications for carbon sink estimations

Diagram showing the calculation of the global ocean and land carbon sink using oxygen datasets



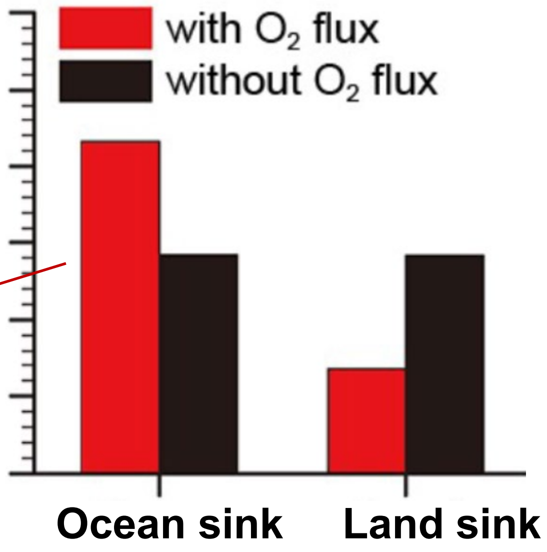
Bopp et al., *Glob. Biogeochem. Cycles.* 2002

$$\Delta CO_2 = F_{fossil} - S_{ocean} - S_{land}$$

- ΔCO_2: atmospheric CO_2 change
- F_{fossil}: Fossil fuel burning
- S_{ocean}: Ocean carbon sink
- S_{land}: Land carbon sink

$$\Delta O_2 = -\alpha_F F_{fossil} + \alpha_B S_{land} + F_{air-sea}$$

- ΔO_2: atmospheric O_2 change
- α_F: Oxidative ratio
- α_B: Exchange ratio for land biota
- $F_{air-sea}$: Air-sea O_2 flux



The accuracy of estimates for the oceanic and land carbon sinks is heavily dependent on the method used to calculate the global air-sea O_2 flux.

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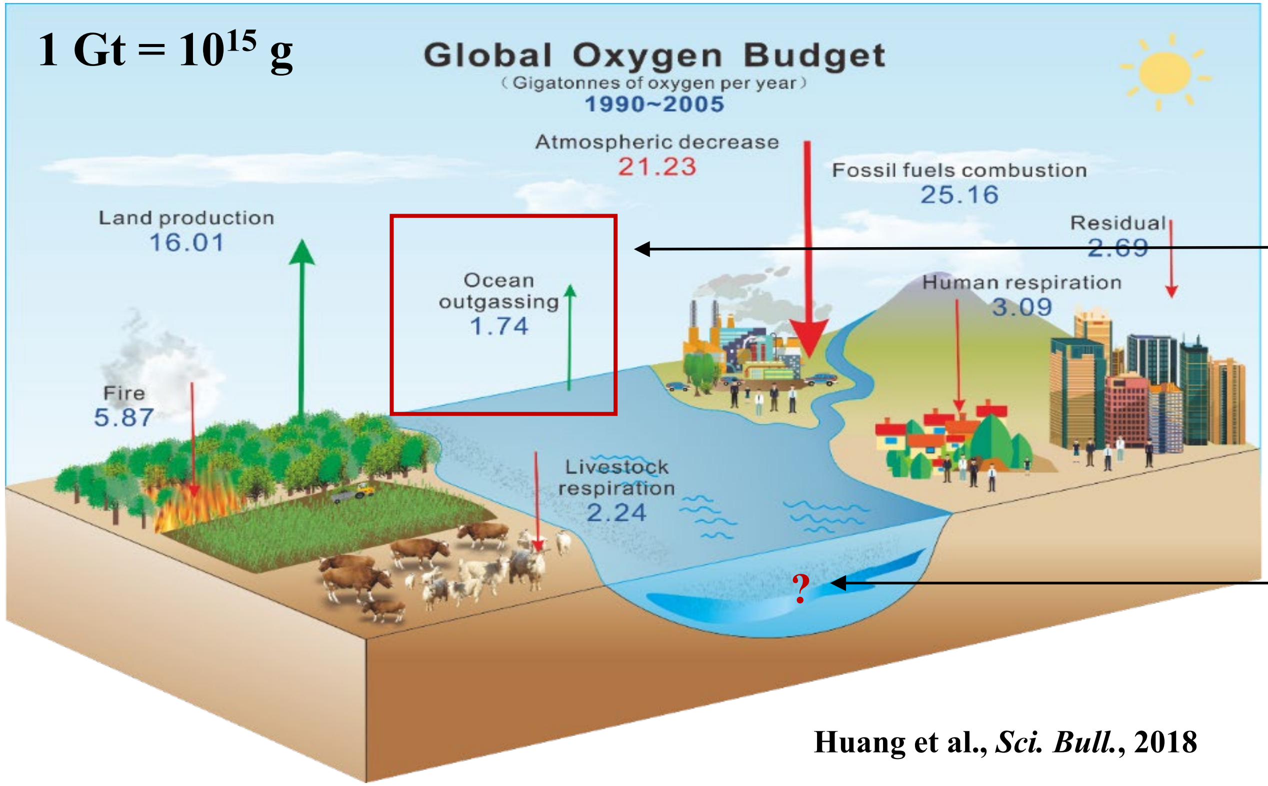
The O_2 budget in modern Earth (1990-2005)



Huang et al., *Sci. Bull.*, 2018

The ocean releases approximately 1.74 Gt of oxygen to the atmosphere annually

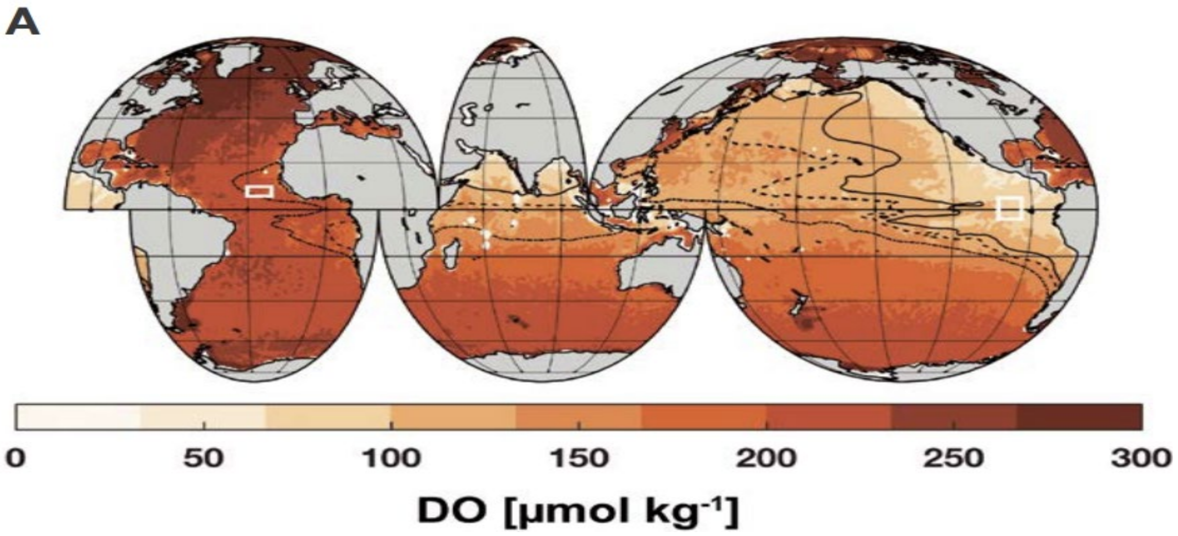
How is the oxygen inventory changing in the ocean?

From 1990 to 2005, the average annual total O_2 consumption was 38.99 Gt, while global terrestrial and oceanic ecosystems only released 17.76 Gt of O_2 to the atmosphere, resulting in a decrease of atmospheric O_2 at a rate of 21.23 Gt per year.

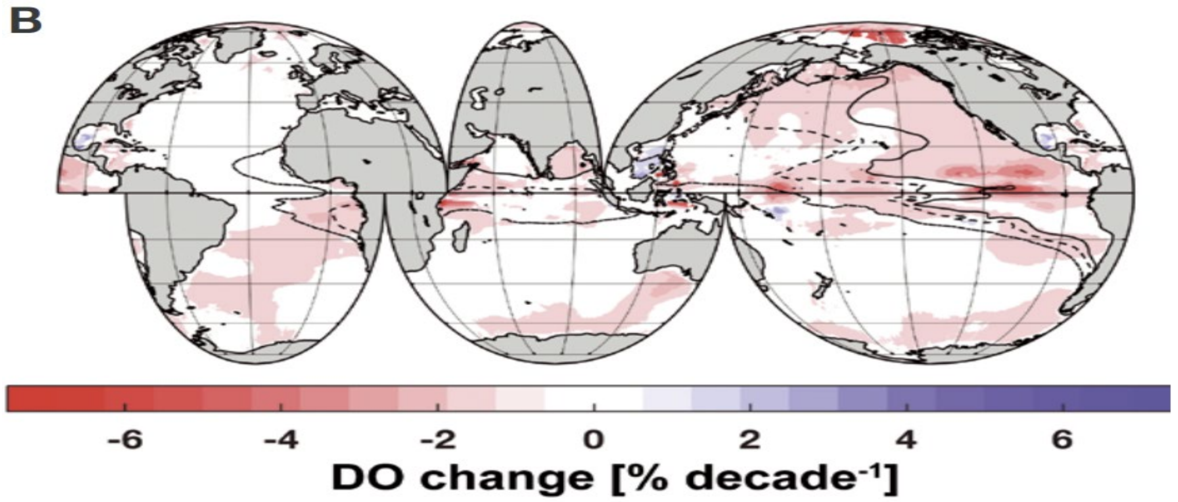
Ocean oxygen decline under climate change

Due to the impact of climate change, the oxygen content in the ocean is decreasing at an unprecedented rate (i.e. ocean deoxygenation). In the past 50 years, the ocean's oxygen inventory has decreased by approximately 2% of the total amount.

The spatial distribution of ocean oxygen content



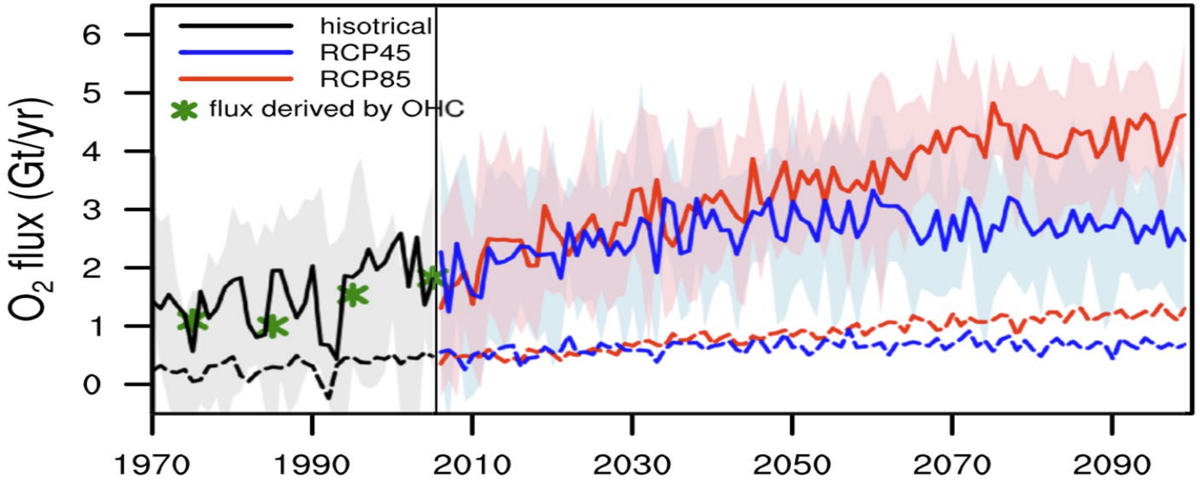
The dissolved oxygen change since the 1960s



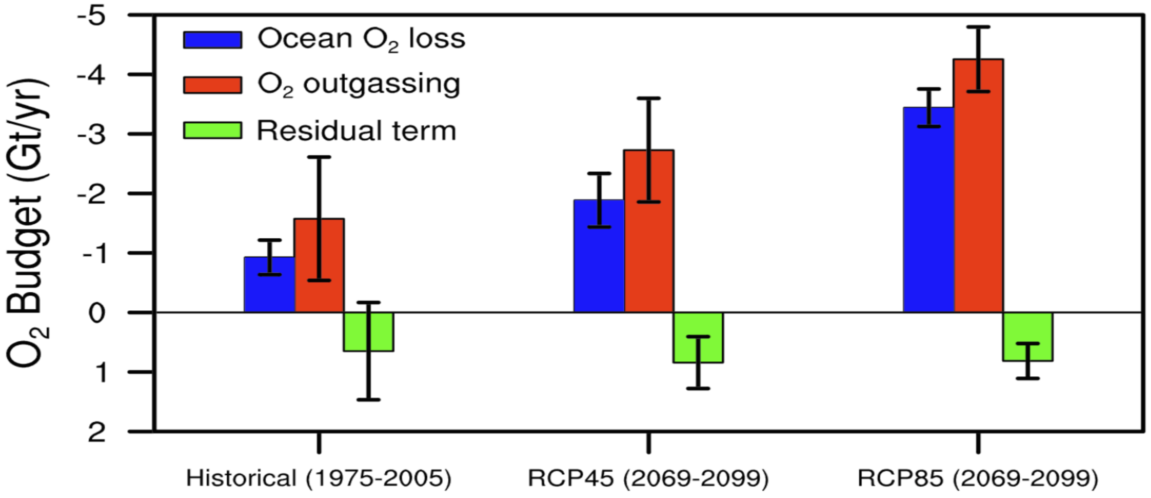
Schmidtko et al., *Nature* 2017

Air-sea O_2 flux and its influence on ocean O_2 budget

Global annual air-sea O_2 flux in CMIP5 models



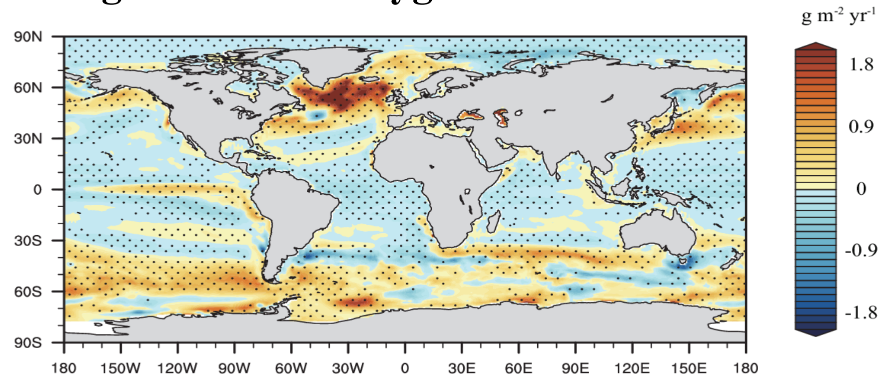
Ocean oxygen budget under climate change



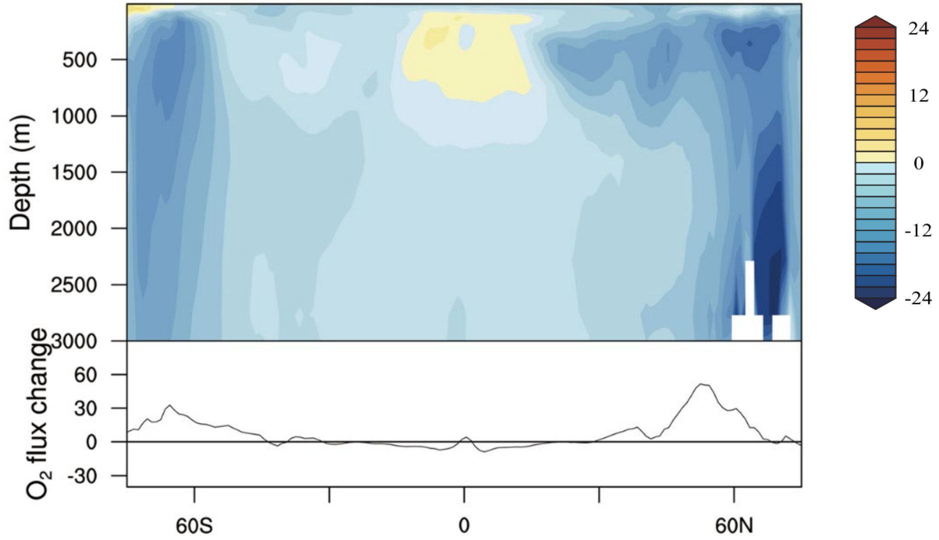
Model simulations indicate the amount of oxygen released by the ocean to the atmosphere will increase from 1.7 Gt/yr in the historical period to 2.8 Gt/yr (RCP4.5) or 4.3 Gt/yr (RCP8.5) by the end of this century. The rate of oxygen "escape" from the ocean is continuously increasing, which means that the decline in oceanic oxygen content will accelerate in the future.

Derivers of oxygen decline in the vast ocean

The changes in air-sea oxygen flux



Oxygen content and its relationship with O_2 flux



Mechanism of open ocean oxygen decline

Ocean Warming

- **Thermal change (~25%)** → **decrease of the oxygen solubility in seawater**
- **Dynamic change (~75%)**
  - **weakening of ventilation, Intensified stratification**
  - **Change in oceanic circulation**
  - → **Obstructed transport of oxygen in the ocean.**

→ **Enhanced oceanic outgassing**

***positive values indicate an oxygen outgassing from ocean to the atmosphere**

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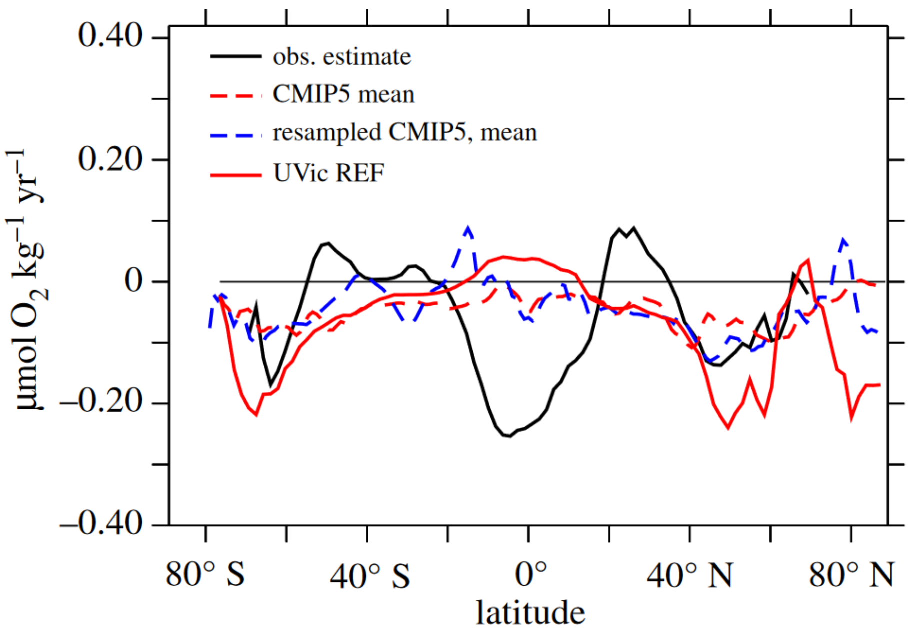
Discrepancies between model and observation

Current climate models do not reproduce observed patterns for oxygen changes in the ocean's thermocline and these **models underestimate the temporal variability of oxygen concentrations.**

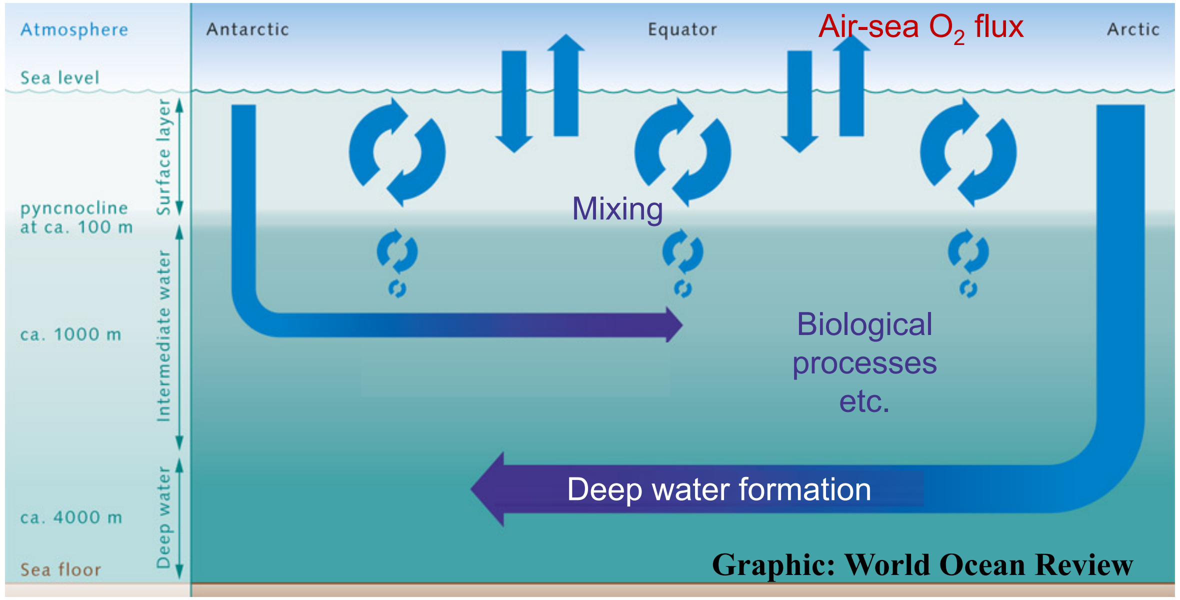
Mismatch of oxygen change between observation and models



Oschlies et al., *Phil. Trans. R. Soc. A*, 2017

Equation that governs ocean oxygen concentrations in the model

$$\frac{\partial O_2}{\partial t} = -\boldsymbol{u} \cdot \nabla O_2 + \nabla \cdot (\kappa \nabla O_2) + F_{air-sea} + J_{bio}$$



Graphic: World Ocean Review

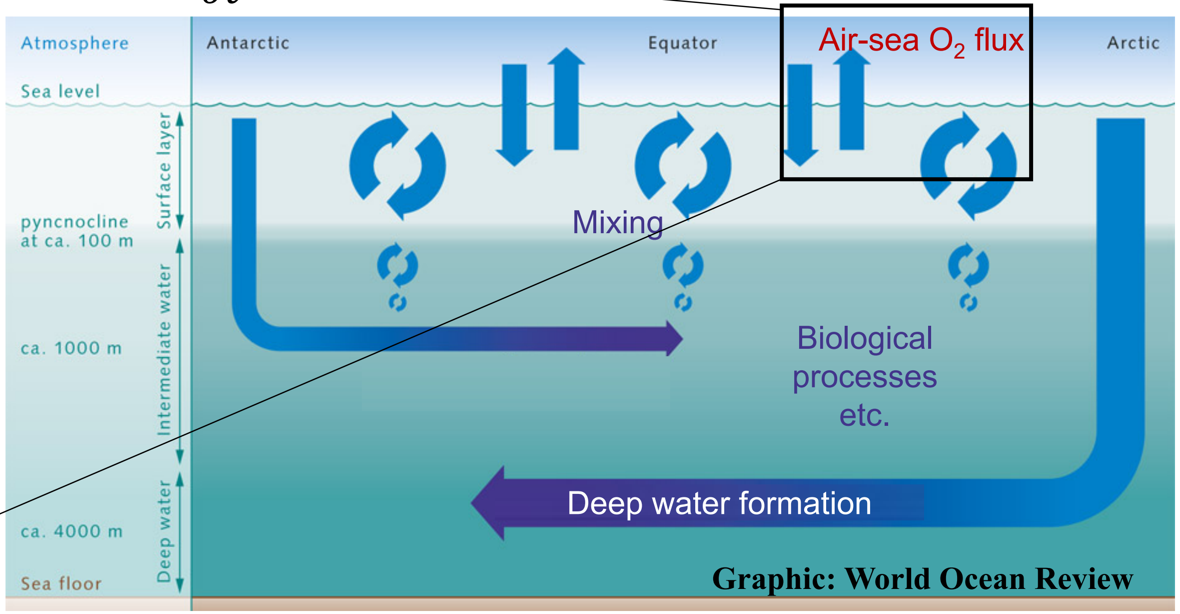
Discrepancies between model and observation

For the air-sea O_2 flux, most widely used parameterization in climate model is based on the concept of molecular diffusion across the sea-surface boundary layer, which lacks descriptions of gas transfer associated with collapsing bubble.

Bubbles in the sea-surface boundary layer

Equation that governs ocean oxygen concentrations in the model

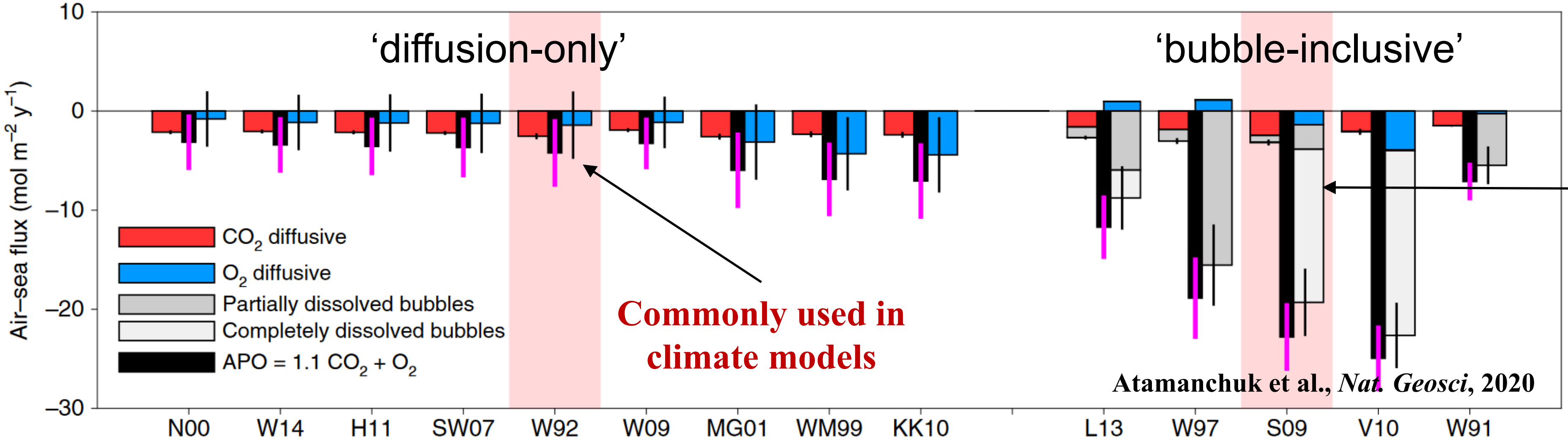
$$\frac{\partial O_2}{\partial t} = -\boldsymbol{u} \cdot \nabla O_2 + \nabla \cdot (\kappa \nabla O_2) + F_{air-sea} + J_{bio}$$



Graphic: World Ocean Review

Parameterizations for air-sea O_2 flux

Annual air–sea O_2 flux in the Labrador Sea for different parameterizations of gas exchange



An illustration of bubble-mediated processes

Diffusion-only scheme (W92)

$$F_{air-sea} = k([O_2] - [O_{2,sat}])$$

The flux depends on the concentration gradient and the gas transfer velocity

Bubble-inclusive scheme (L13)

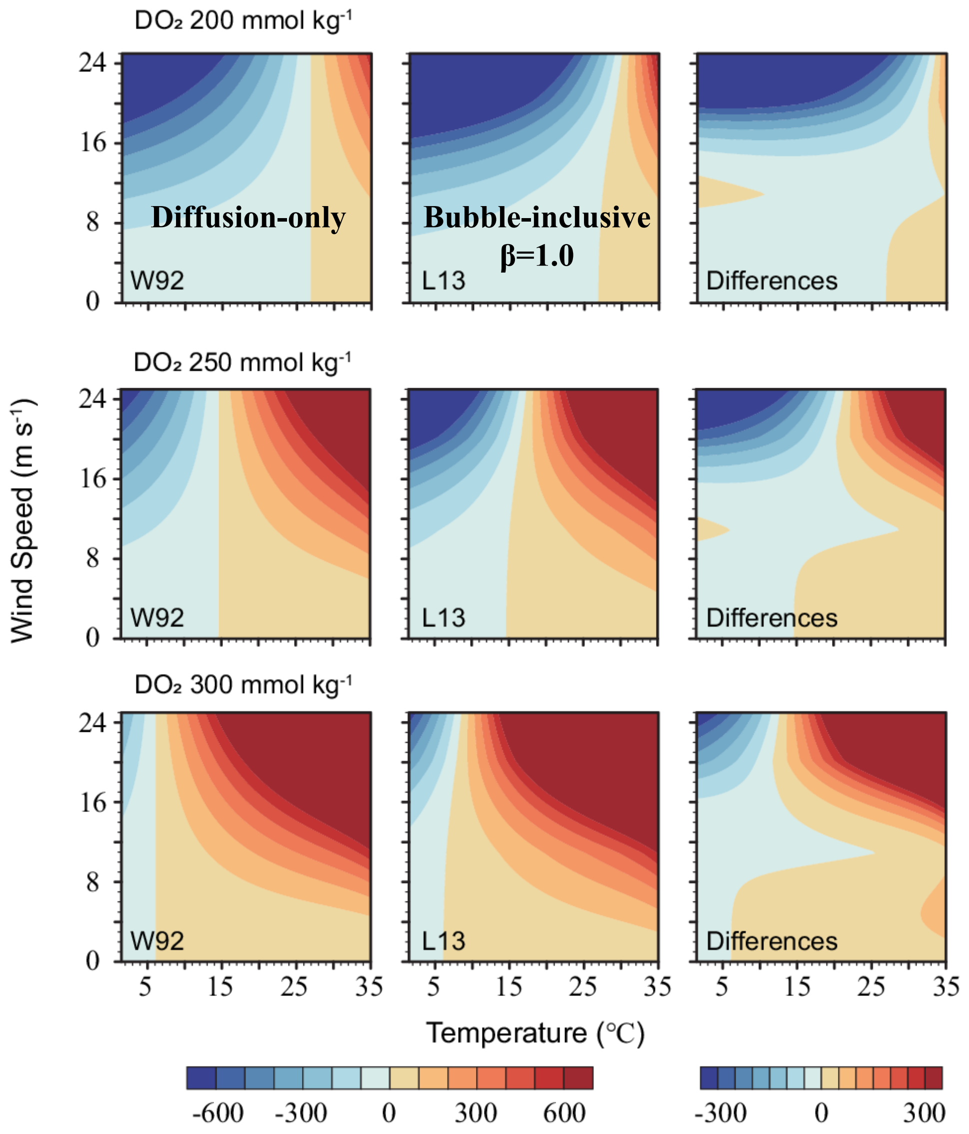
$$F_{air-sea} = F_s + \beta(F_c + F_p)$$

Diffusive contribution (F_s)

Bubble-mediated contribution ($\beta(F_c + F_p)$)

The flux obtained from 'diffusion-only' scheme are only one-third of those from 'bubble-inclusive' scheme. It reveals a need for evaluation of the protocols used for accounting for air–sea O_2 fluxes in current climate models.

Comparisons between W92 and L13



Diffusion-only scheme (W92)

$$F_{air-sea} = k([O_2] - [O_{2,sat}]) \qquad k = a(U_{10})^2 (\frac{S_{O_2}}{660})^{-0.5}$$

Bubble-inclusive scheme (L13)

$$F_{air-sea} = F_s + \beta(F_c + F_p)$$

Diffusive

$$F_S = 1.3\times 10^{-4} U_a^* \left(\frac{S_{O_2}}{660}\right)^{-0.5} ([O_2] - [O_{2,sat}]) \frac{\rho_w}{10^6}$$

Small bubbles

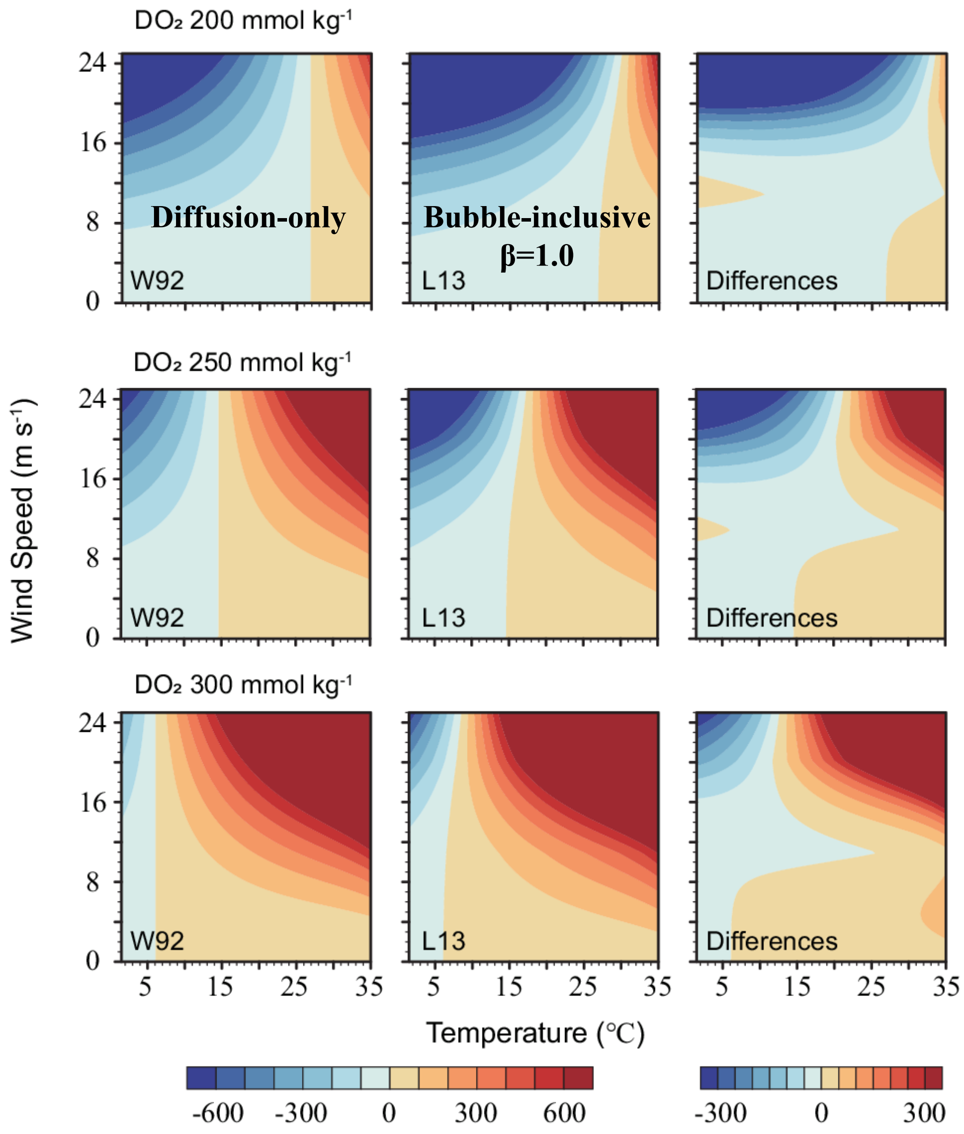
$$F_C = -5.56 \ (U_w^*)^{3.86} X_{O_2}$$

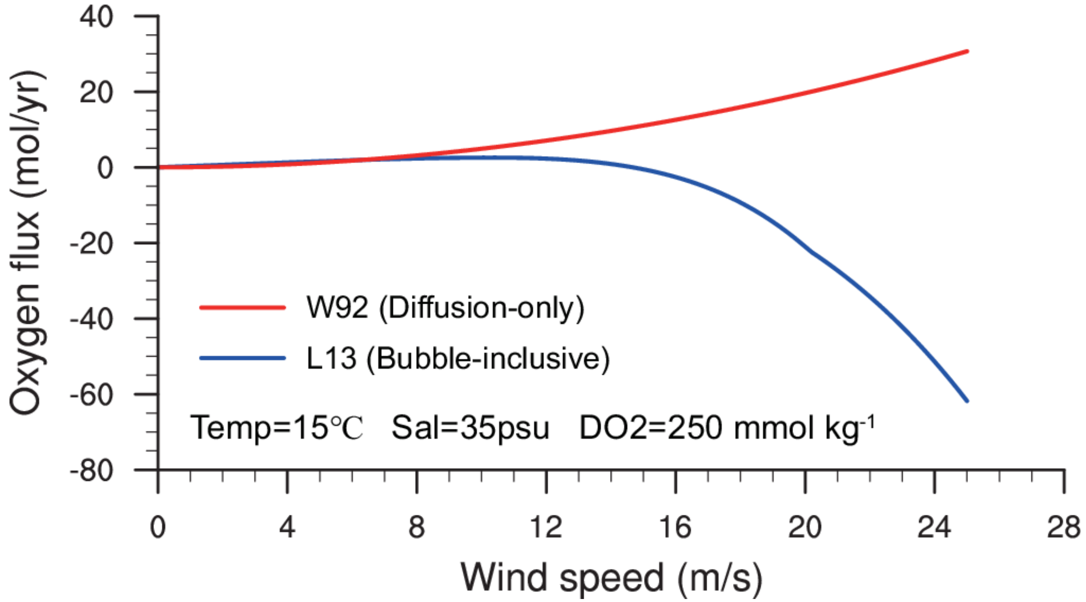
Large bubbles

$$F_P = 5.5 \ (U_w^*)^{2.76} \left(\frac{S_{O_2}}{660}\right)^{-2/3} \left([1+\Delta_P][O_2]\frac{\rho_w}{10^6} - [O_{2,sat}]\frac{\rho_w}{10^6}\right)$$

Note that β is the tuning factor which enhances or diminishes bubble flux contributions to net gas exchange

Comparisons between W92 and L13





For less soluble gases (e.g. O_2), there is an important contribution from bubble injection.

The difference between W92 and L13 is specifically significant at high wind-speed situations

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Integrating bubble-mediated parameterization into CESM

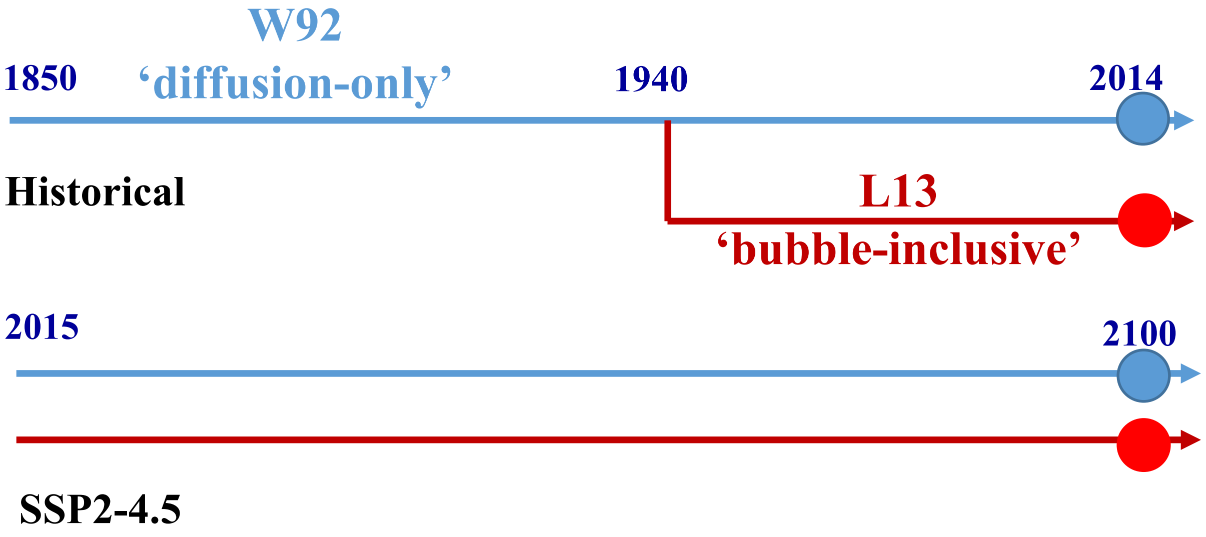
The Community Earth System Model

Community Earth System Model 2 (CESM2)

The latest release in the CESM family including many substantial science and infrastructure improvements since its previous version

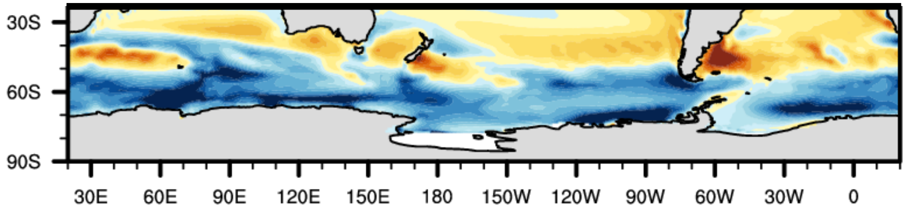
Graphic: National Center for Atmospheric Research

Model experiments design



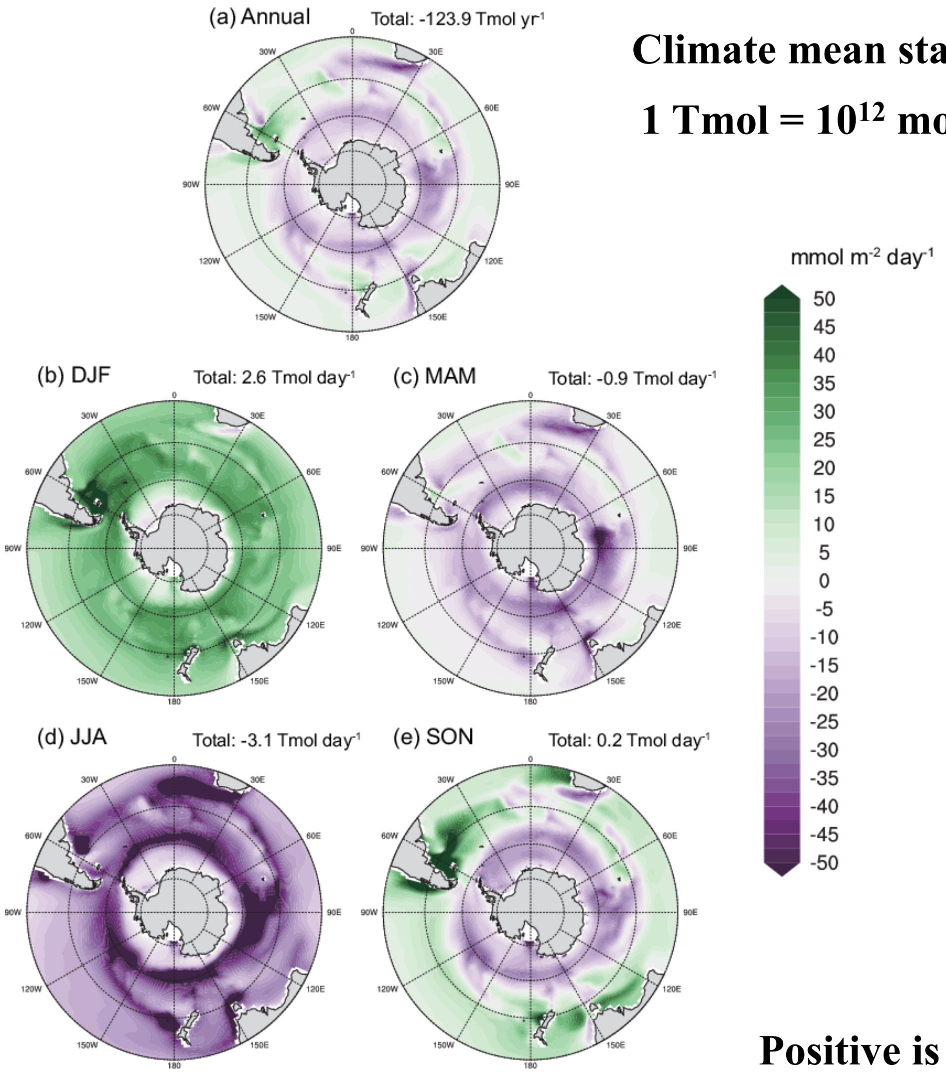
Focusing area: Southern Ocean

A crucial region for air-sea oxygen exchange, characterized by strong winds



Role of bubble in air-sea O_2 flux

The air-sea O_2 flux derived from bubble-inclusive scheme



Climate mean state

1 Tmol = 10^{12} mol

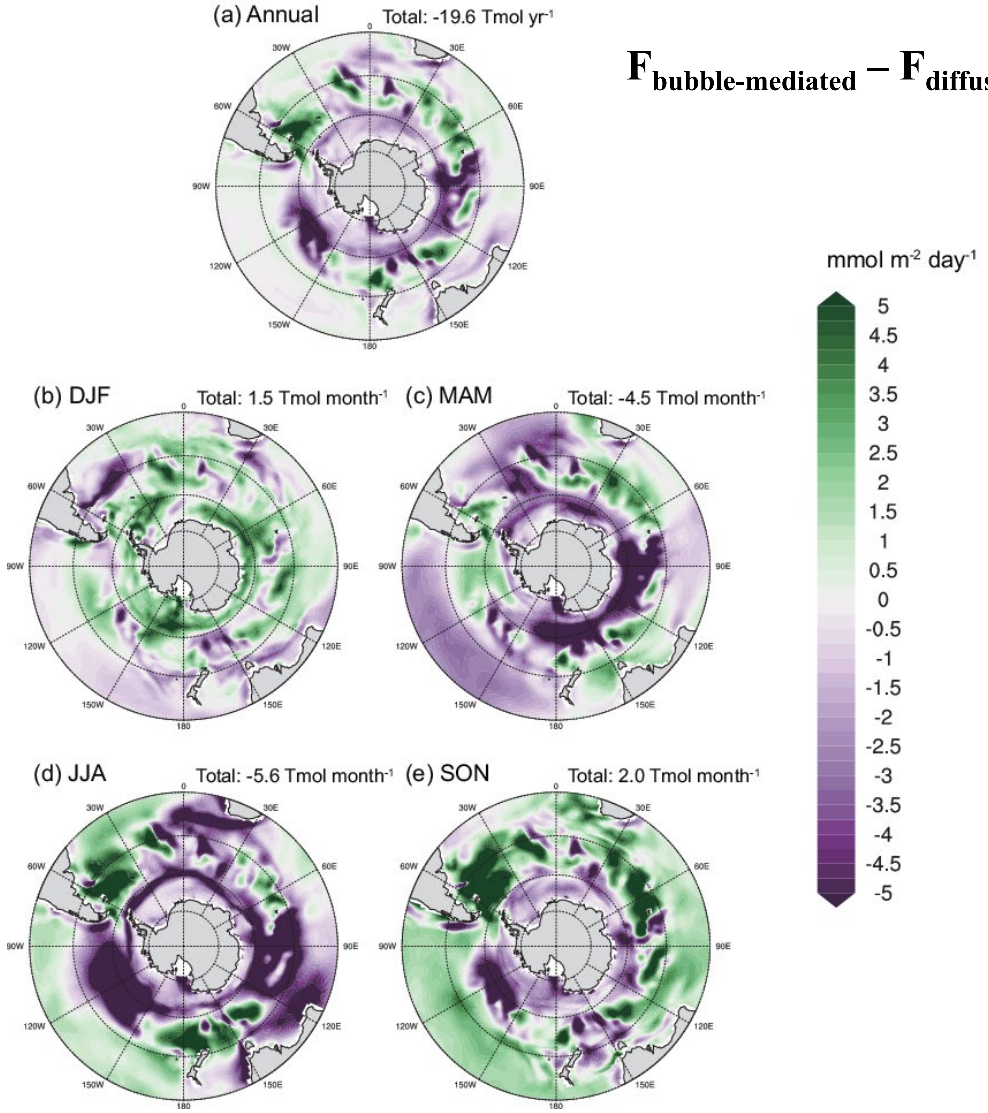
Positive is a flux to the atmosphere

The Southern Ocean exhibits a distinct oxygen uptake in Winter (JJA) and oxygen outgassing in Summer (DJF) .

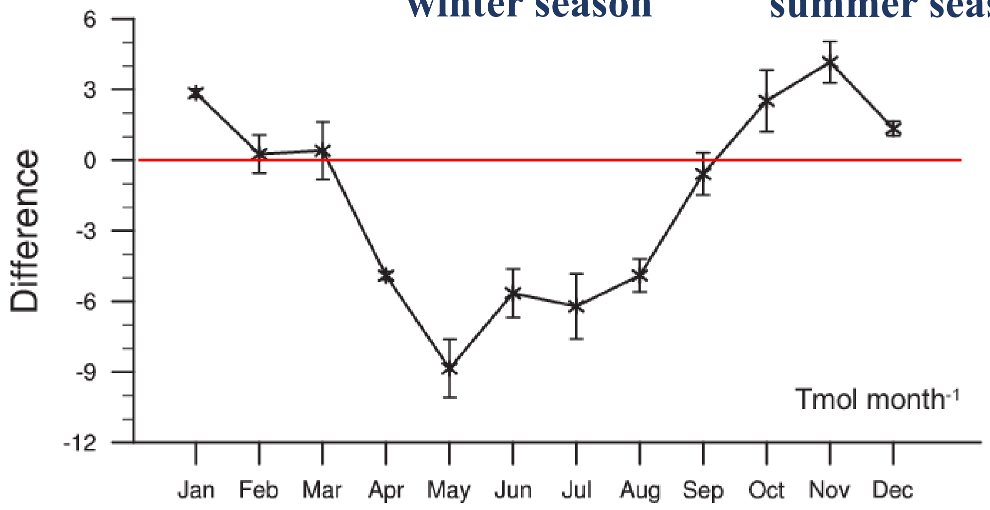
The annual air-sea O_2 flux is about -123.9 Tmol yr^{-1}, which indicates Southern Ocean as a net sink of oxygen.

Role of bubble in air-sea O_2 flux

Differences of air-sea O_2 flux between bubble-inclusive and diffusion-only models



$F_{bubble\text{-}mediated} - F_{diffusion\text{-}only}$

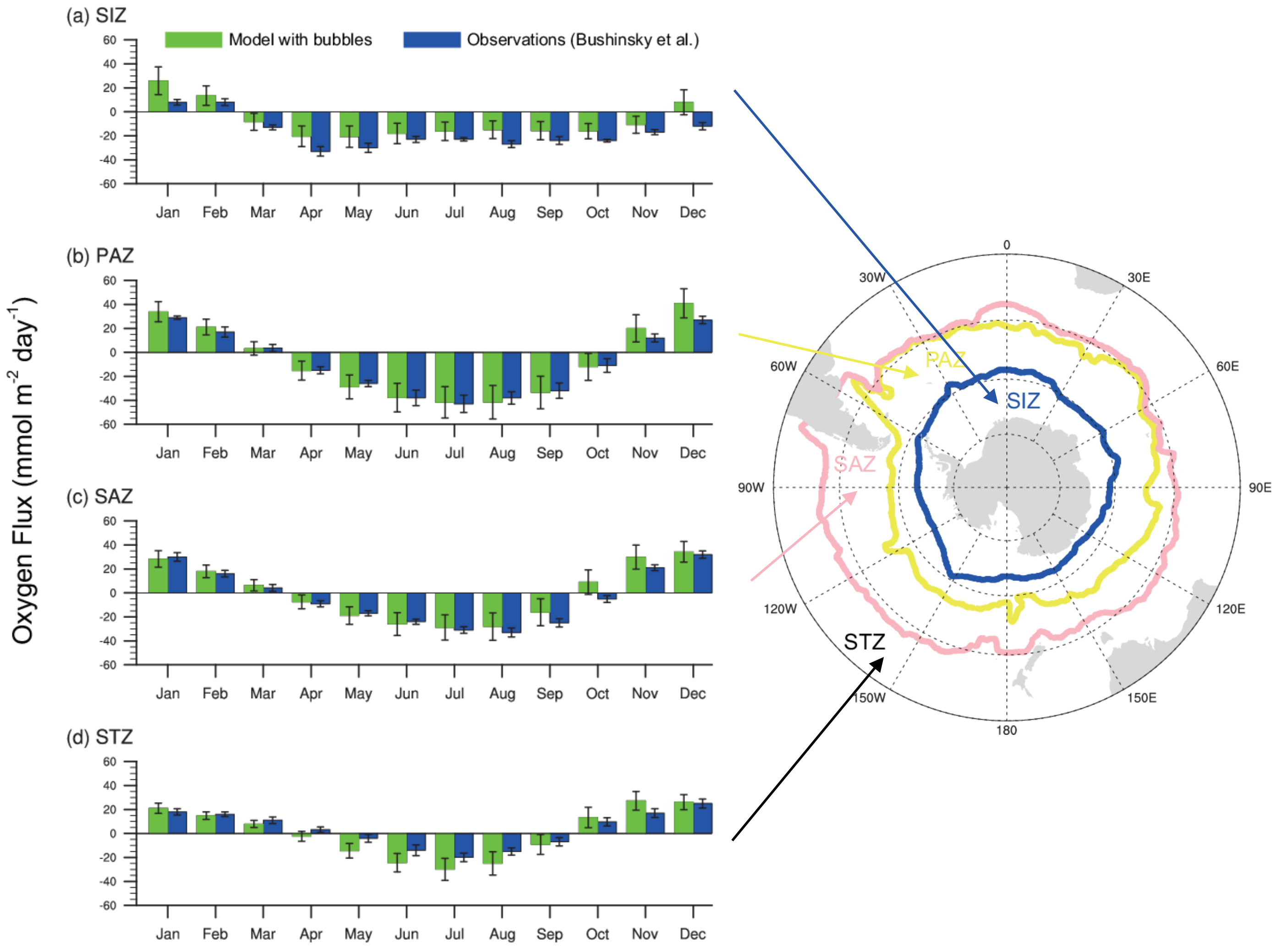


The bubble-mediated model shows an overall intensified oxygen uptake in the Southern Ocean on annual average.

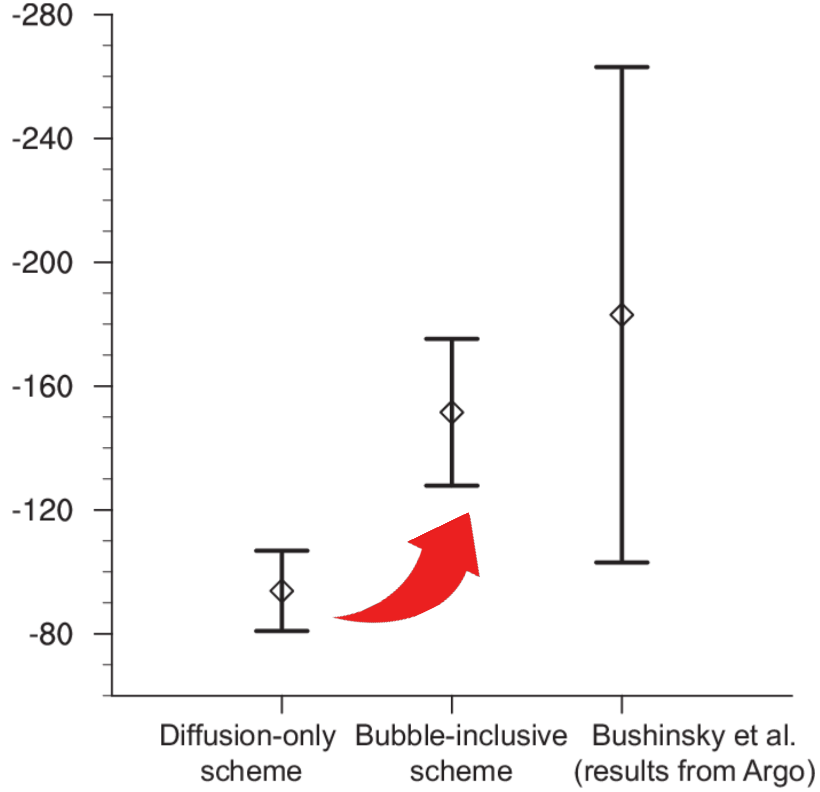
For seasonal cycle, stronger oxygen uptake and outgassing is found in winter and summer, respectively, which reinforces the seasonal variability.

Comparisons with flux derived from Argo floats

Monthly air-sea O_2 flux for the four Southern Ocean regions

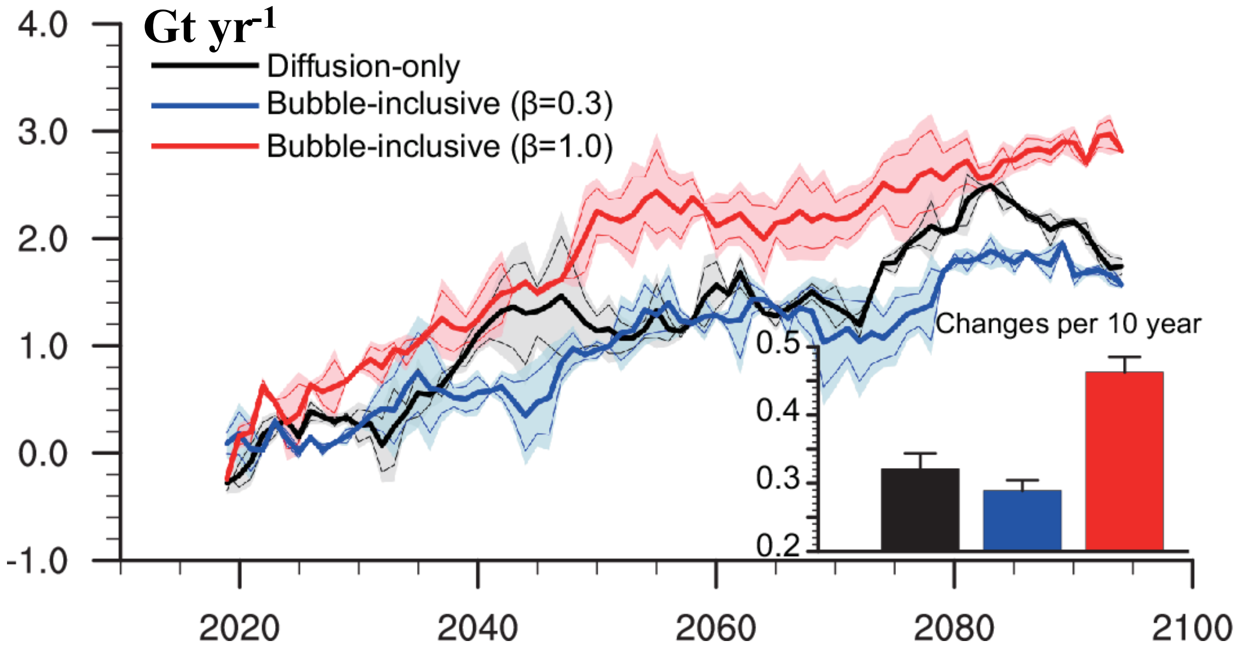


Annual air-sea O_2 flux in the Southern Ocean (Tmol yr^{-1})



Sensitivity of the flux to climate change

The annual air-sea O_2 flux anomaly in SSP2-4.5



$$F_{air-sea} = F_s + \beta(F_c + F_p)$$

Bubble-mediated contribution

Three experiments investigating the effects of bubbles were conducted:

1. Diffusion-only scheme

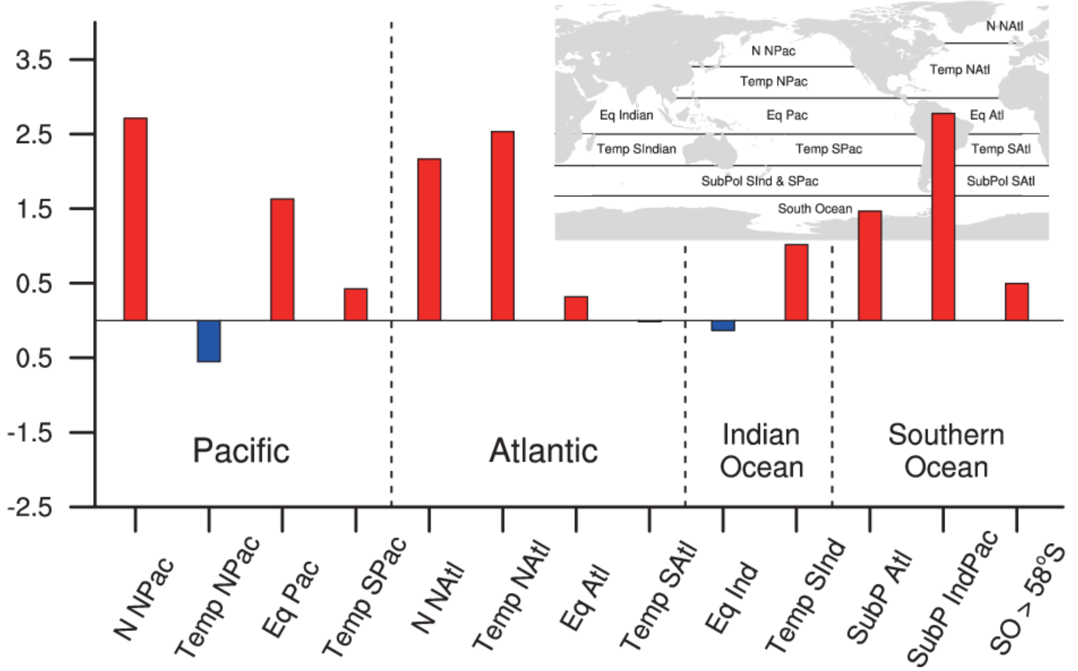
2. Bubble-inclusive scheme with β=0.3, which diminishes bubble flux contributions

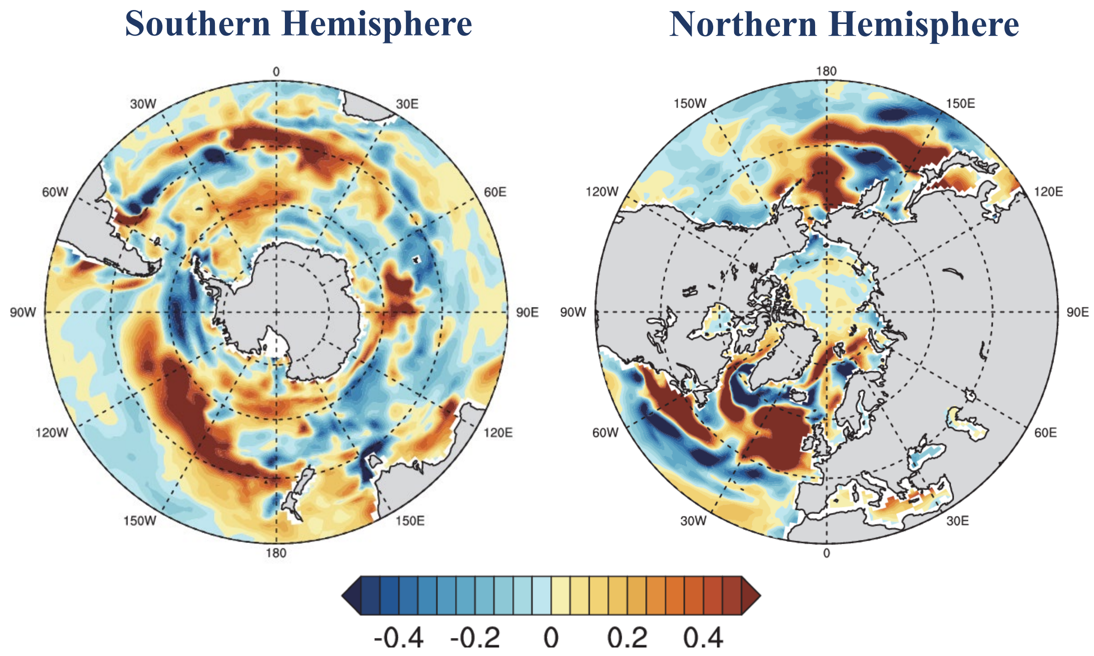
3. Bubble-inclusive scheme with β=1.0

The oxygen flux derived from the bubble-inclusive scheme is more sensitive to climate change, with a significantly higher linear trend compared to the flux from diffusion-only scheme.

Sensitivity of the flux to climate change

The differences in the response of the flux to climate change between bubble-inclusive and diffusion-only models.





The regions with a greater sensitivity to climate change in the bubble-inclusive model compared to the diffusion-only model are mainly situated in mid to high latitudes, particularly in the North Atlantic and Southern Ocean.

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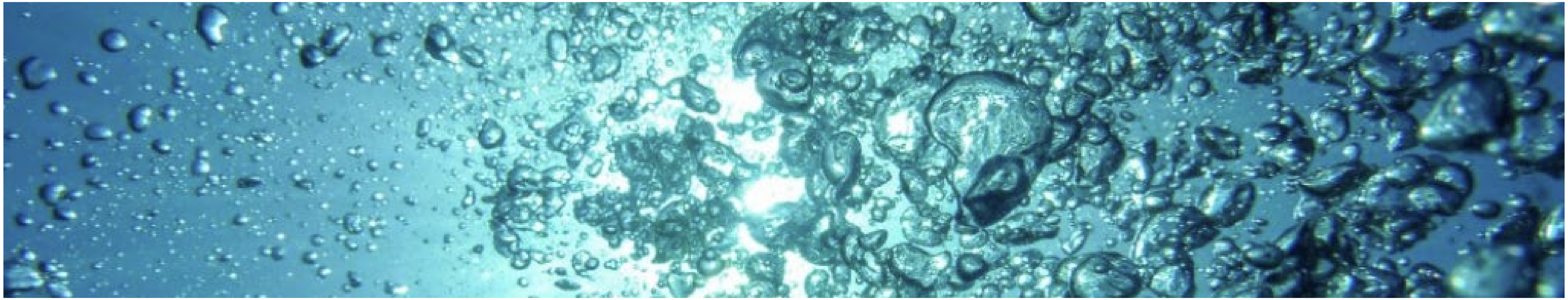
Summary and discussions

- The air-sea O_2 flux is crucial for ocean oxygen cycle which modifies ocean O_2 concentrations and residence times.
- Model simulations reveals an intensified oxygen uptake associated with bubble injection in the widespread Southern Ocean regions. A stronger response of the air-sea O_2 flux to global warming has been found under the bubble-mediated model.
- The absence of air-sea gas transfer descriptions associated with collapsing bubbles in current models might lead to a severe underestimate in sensitivity of ocean oxygen cycle to climate change



Thanks

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