Global budget imbalances in O_2 and APO

and

Constraining the Southern Ocean CO_2 sink variability with observation-based O_2 fluxes

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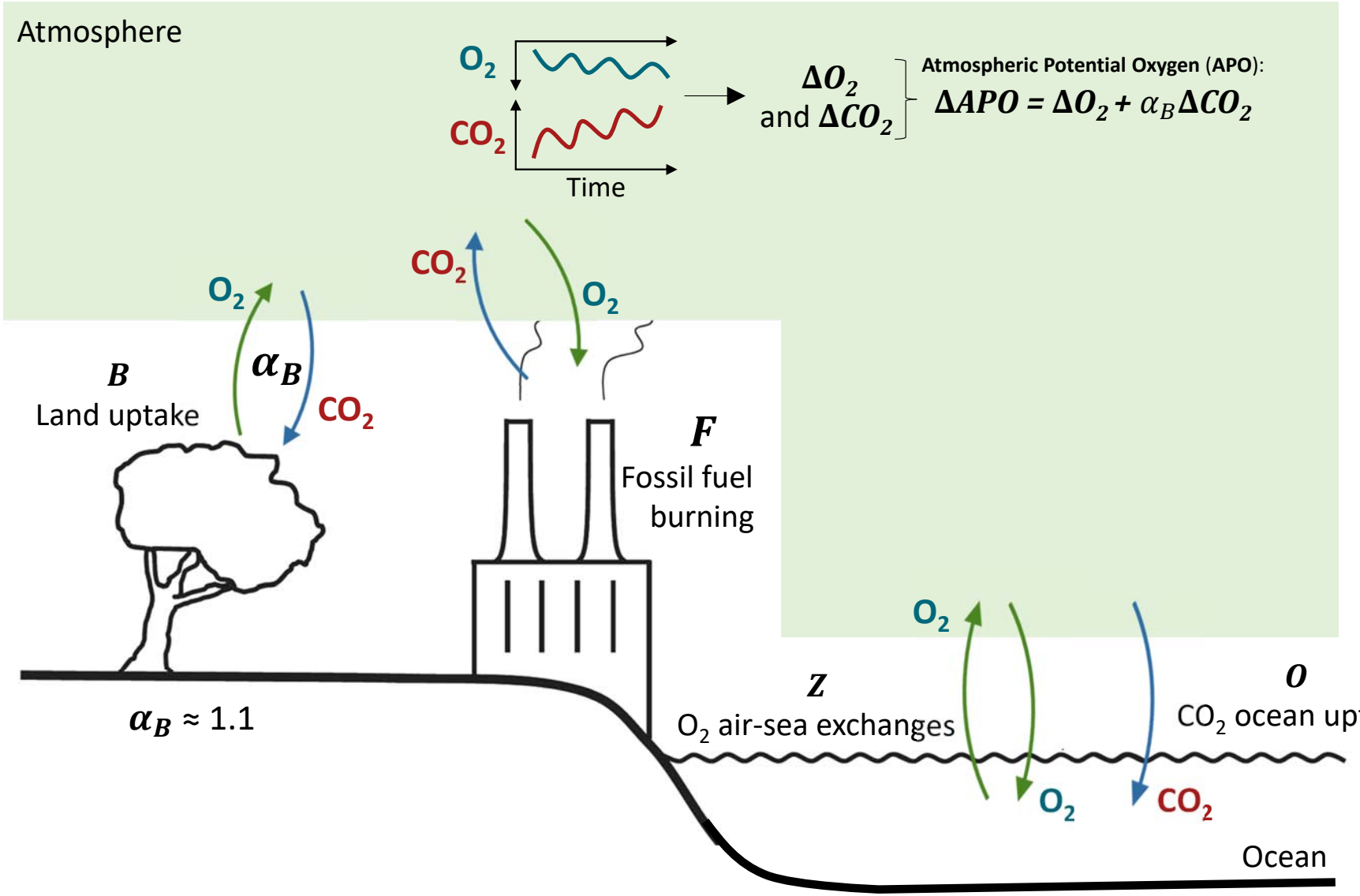
University of East Anglia

4C Climate-Carbon Interactions in the Current Century

Part A.

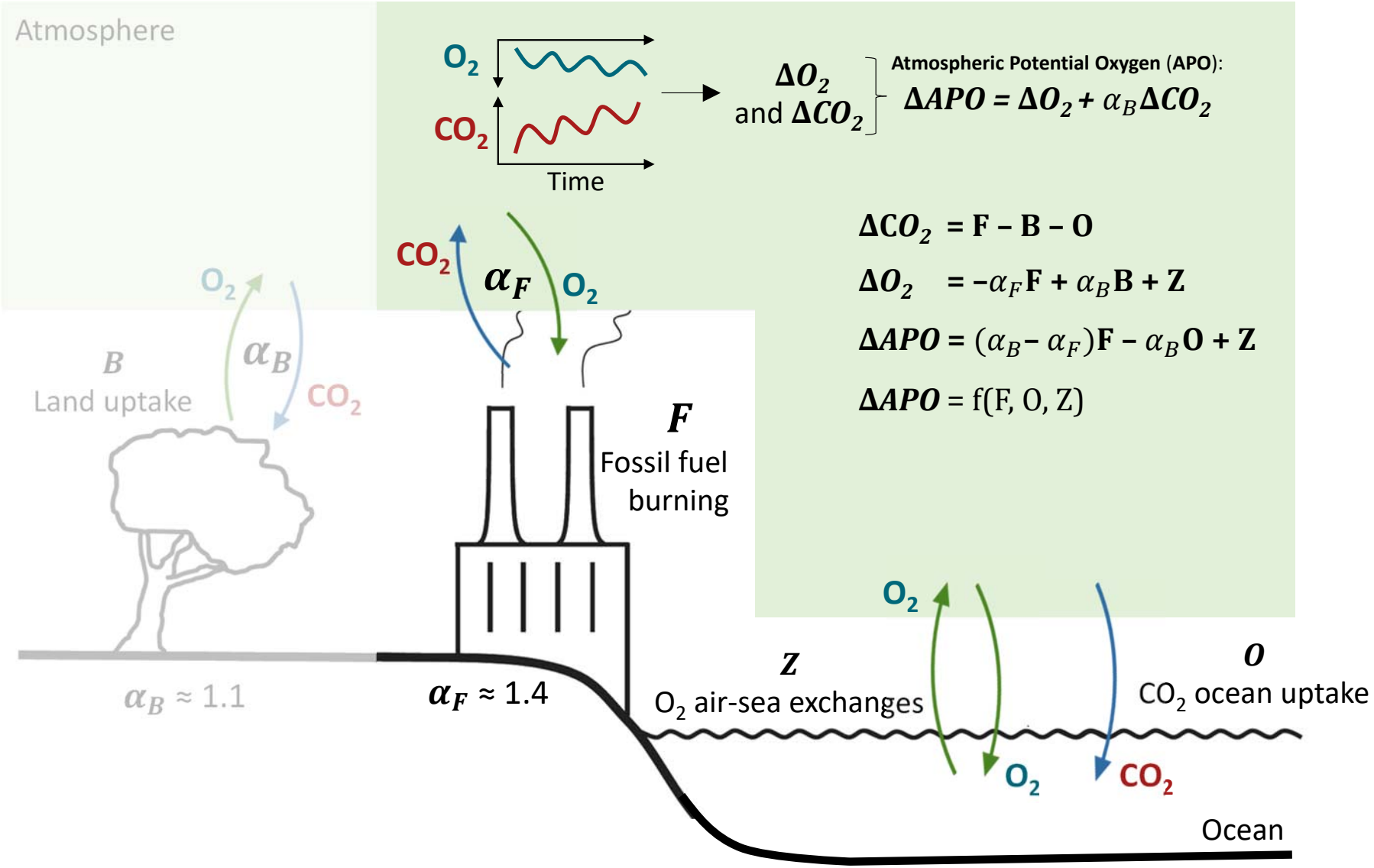
Global budget imbalances in O_2 and APO

New observational constraints on the global carbon cycle



Climate-Carbon Interactions in the Current Century

Global budgets of APO and O_2



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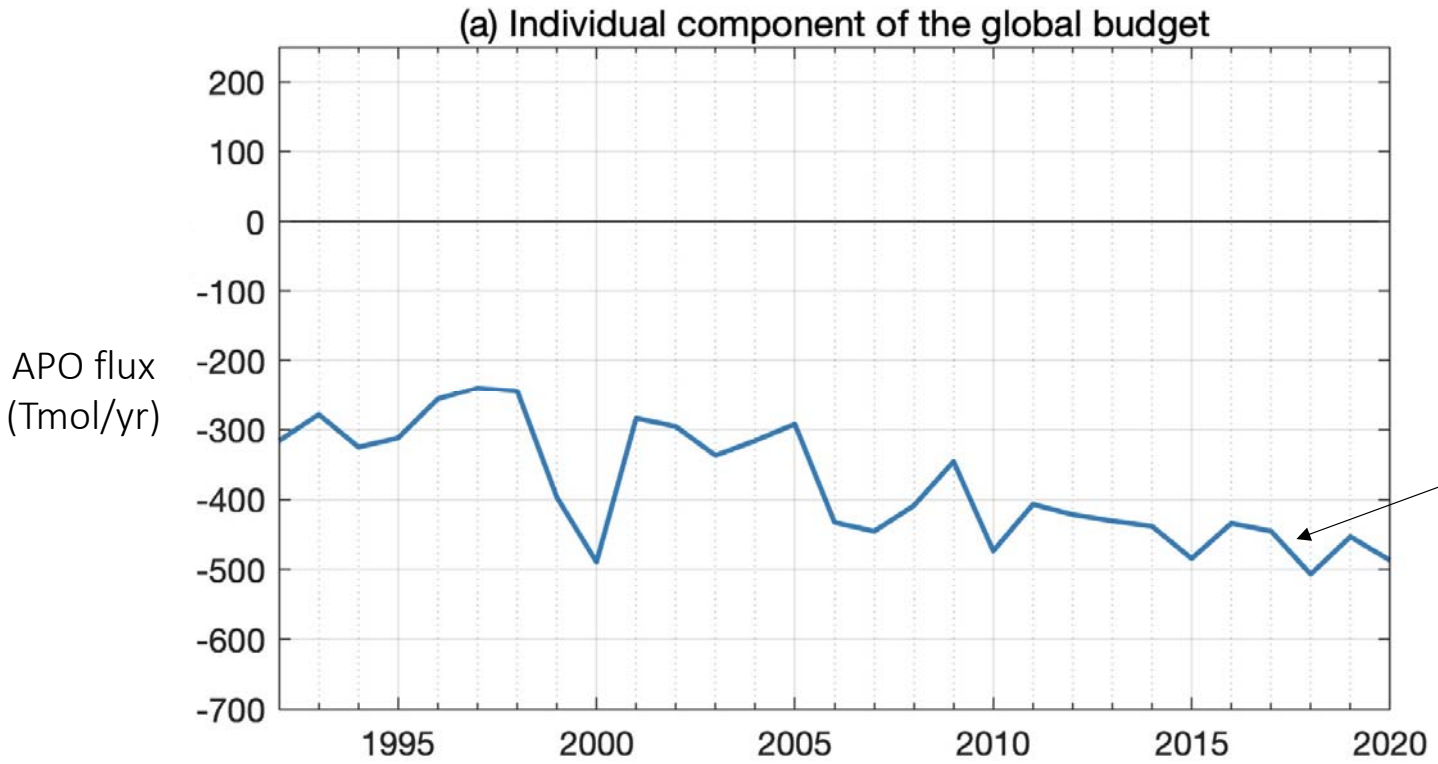
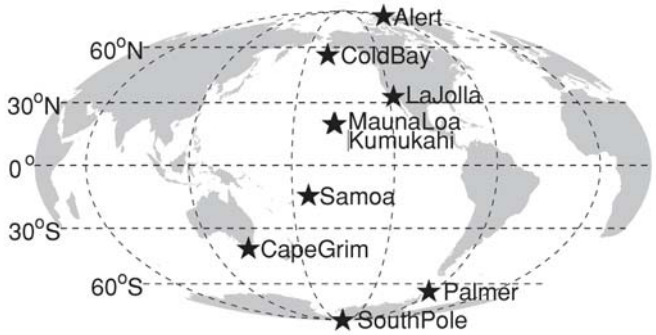
Global budget of APO



ΔAPO observed in the atmosphere



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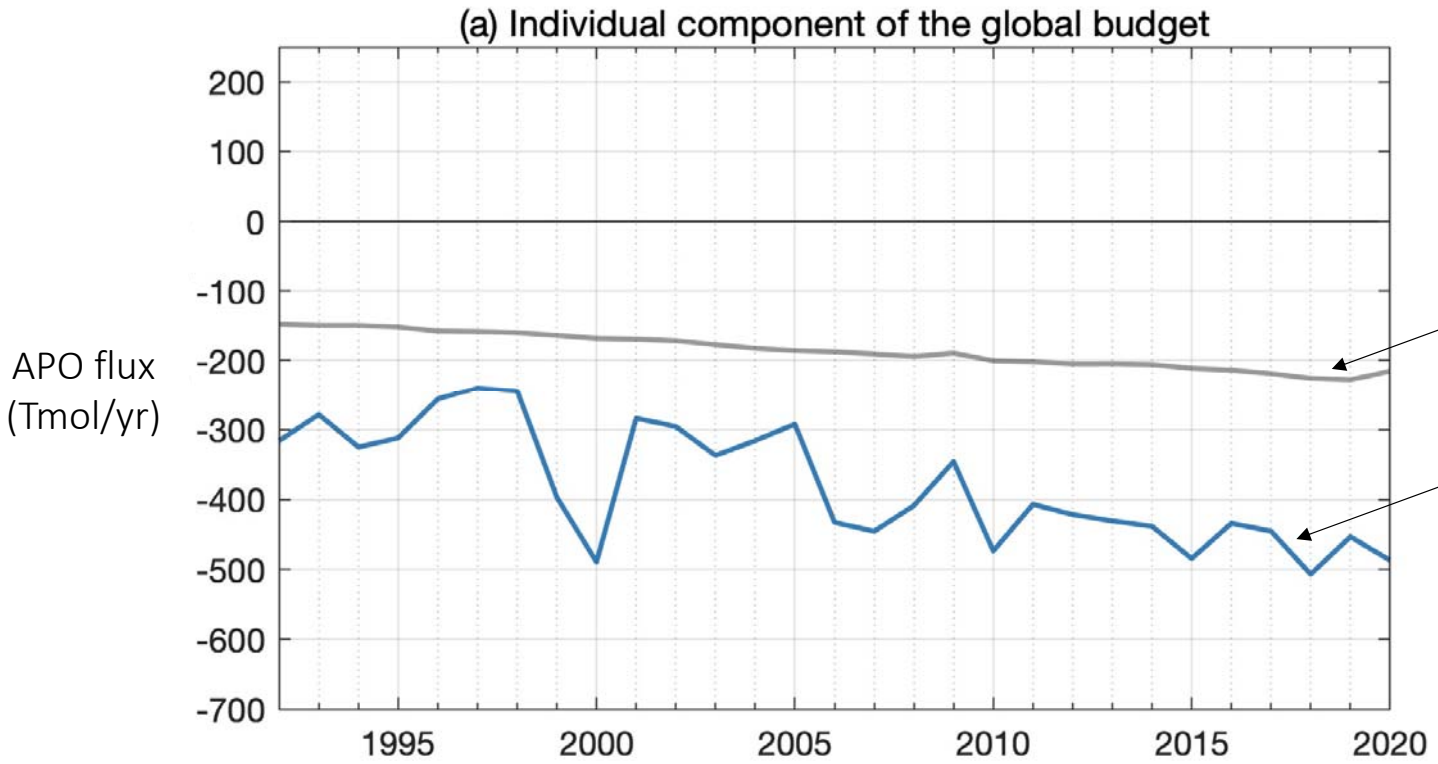
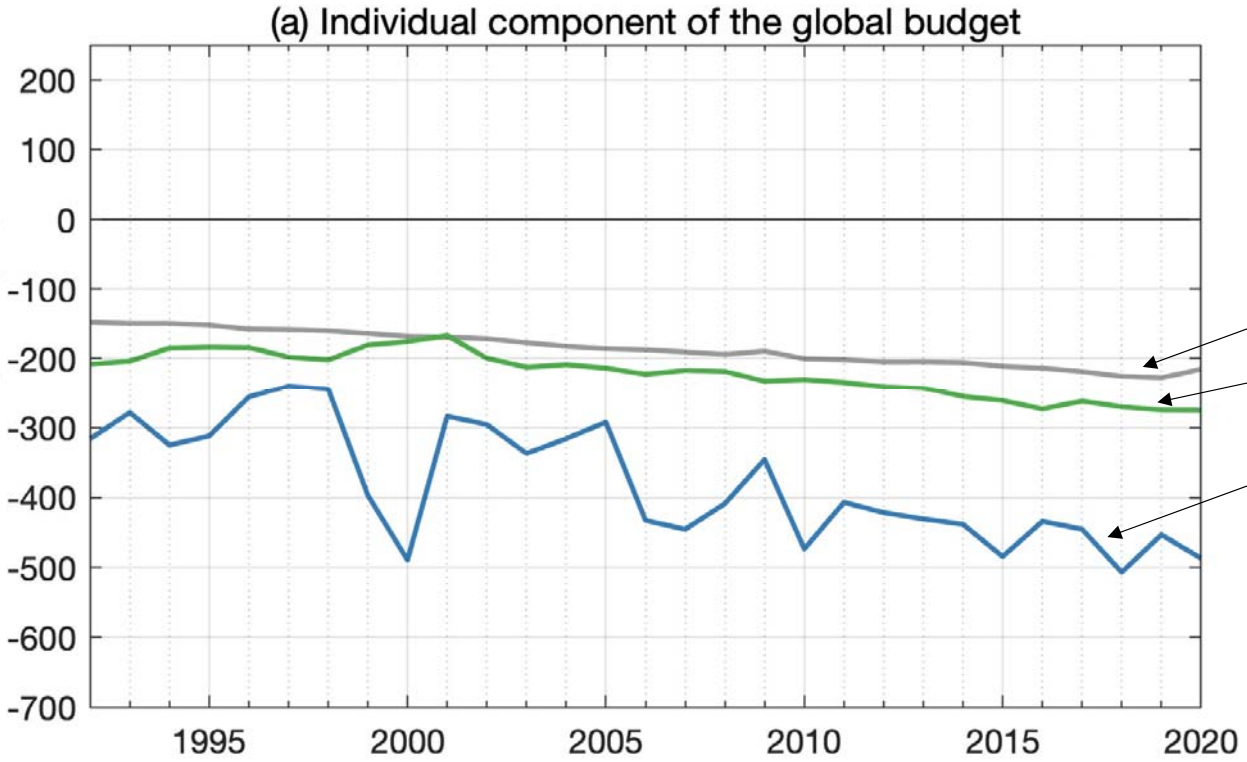
Global budget of APO



Climate-Carbon Interactions in the Current Century

Global budget of APO



APO flux (Tmol/yr)

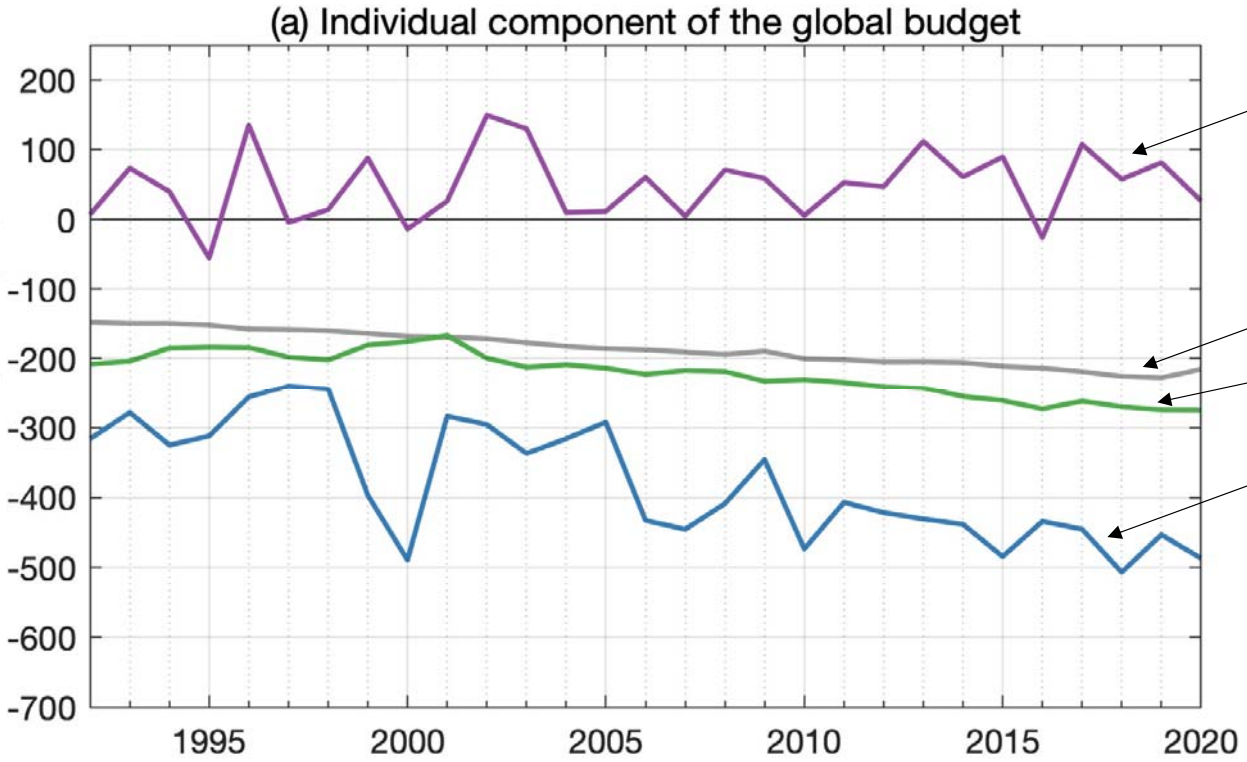
Fossil fuel

Ocean CO_2 sink (S_{OCEAN})

ΔAPO observed in the atmosphere

Climate-Carbon Interactions in the Current Century

Global budget of APO



O_2 air-sea exchange

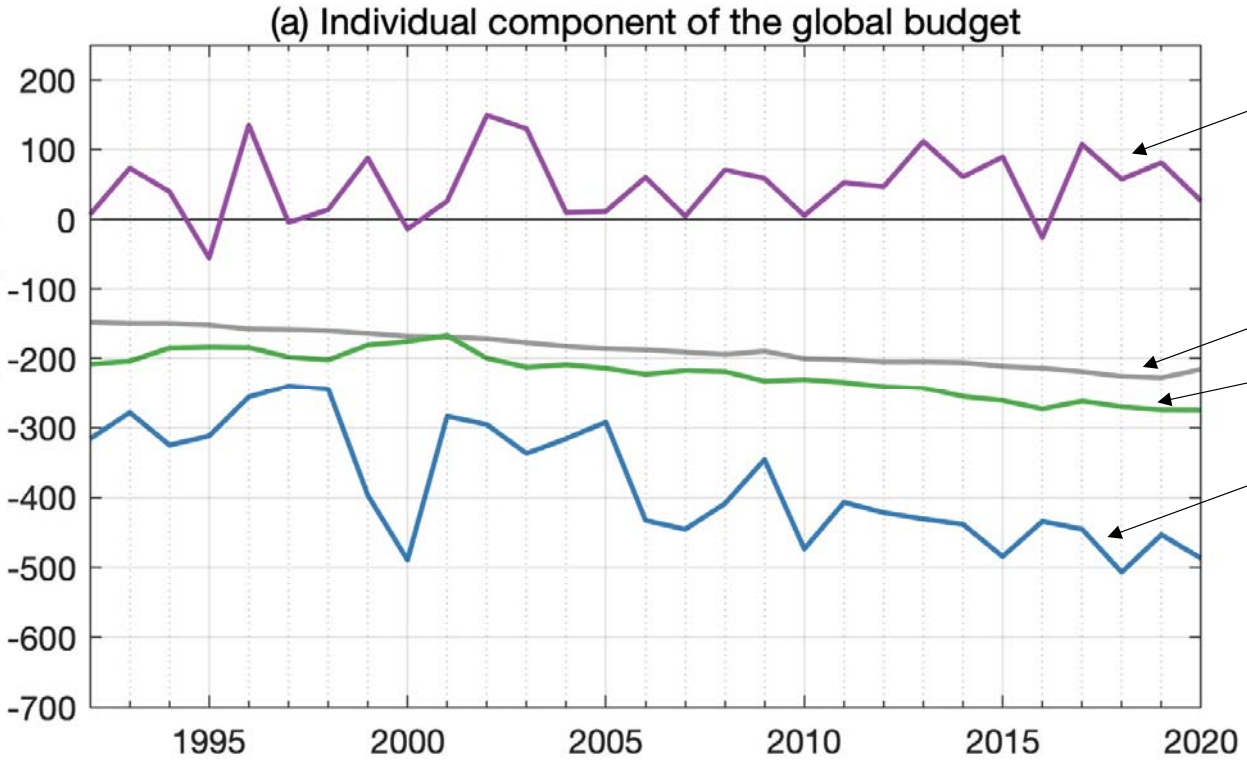
Fossil fuel

Ocean CO_2 sink (S_{OCEAN})

ΔAPO observed in the atmosphere

Climate-Carbon Interactions in the Current Century

Global budget of APO



O_2 air-sea exchange **(Z)**

Fossil fuel **(F)**

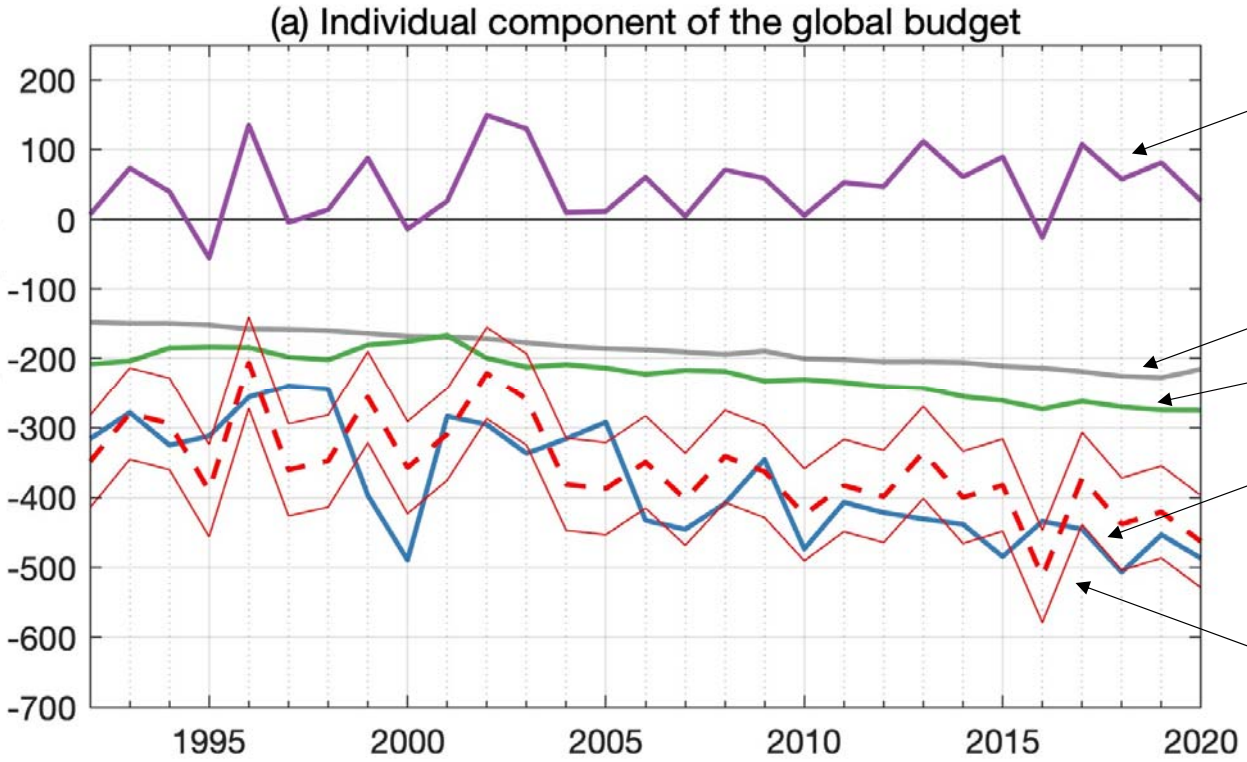
Ocean CO_2 sink (S_{OCEAN}) **(O)**

ΔAPO observed in the atmosphere

$$\Delta(\mathbf{APO}) = f(\mathrm{F}, \mathrm{O}, \mathrm{Z})$$

Climate-Carbon Interactions in the Current Century

Global budget of APO



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ΔAPO observed in the atmosphere

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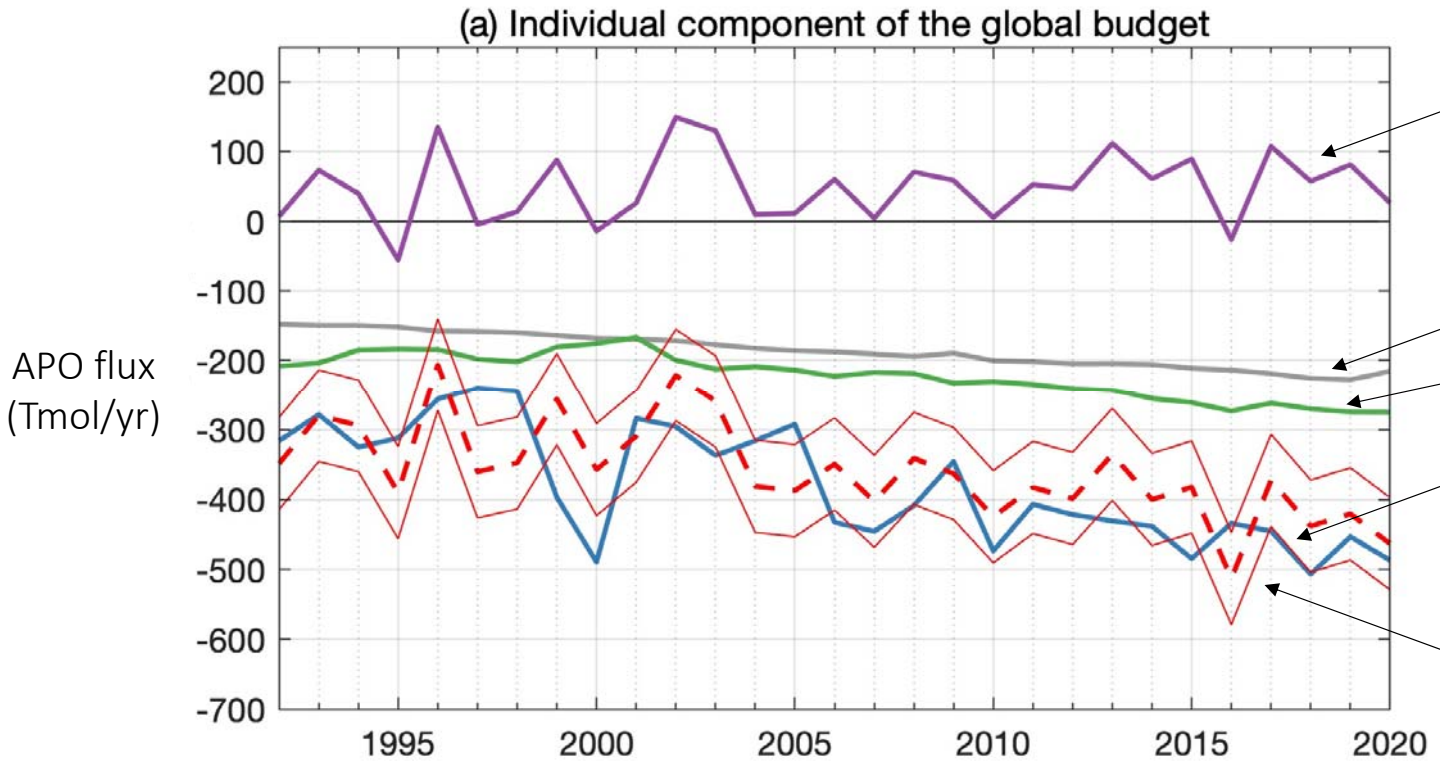
Climate-Carbon Interactions in the Current Century

Global budget of APO

Most of the interannual variability induced by the air-sea exchange of O_2

Mayot et al. (2023)



O_2 air-sea exchange **(Z)**

Fossil fuel **(F)**

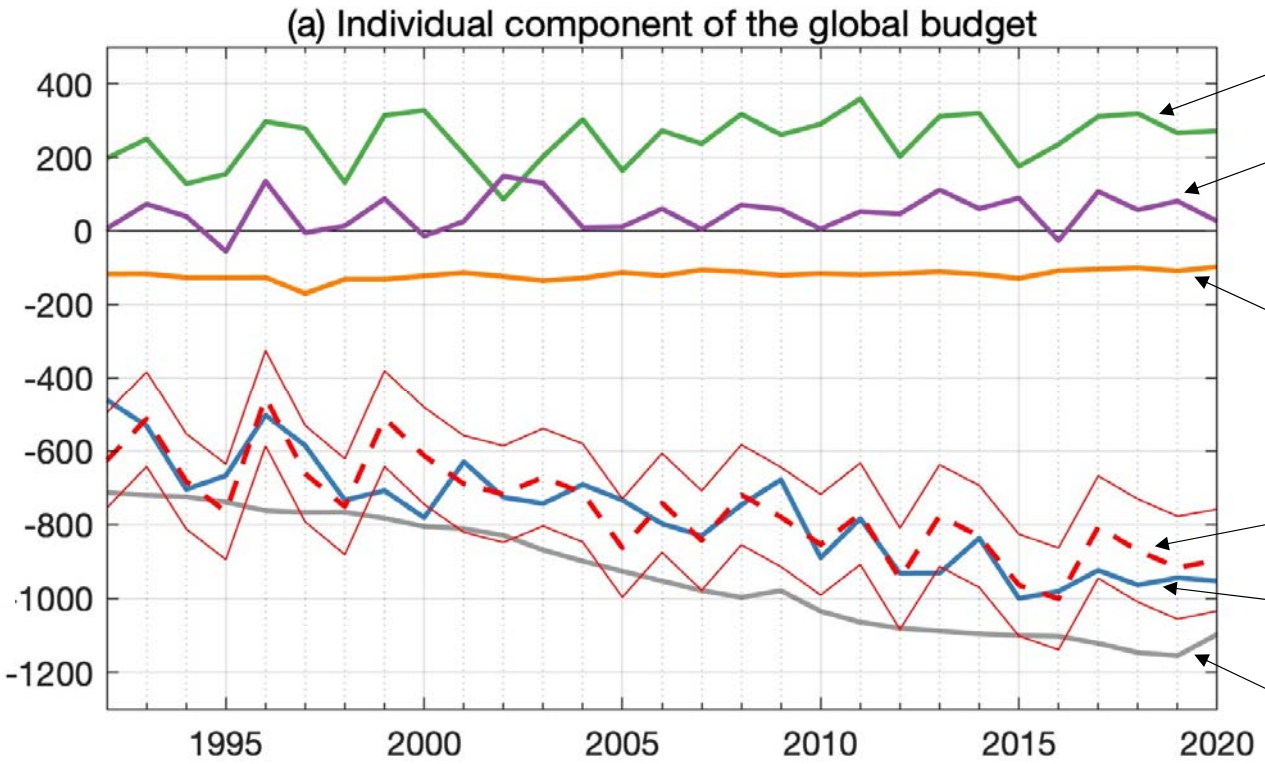
Ocean CO_2 sink (S_{OCEAN}) **(O)**

ΔAPO observed in the atmosphere

$$\Delta(\mathbf{APO}) = f(\mathrm{F}, \mathrm{O}, \mathrm{Z})$$

Climate-Carbon Interactions in the Current Century

Global budget of O_2



O_2 flux (Tmol/yr)

Land sink (S_{LAND}) **(B_{ii})**

O_2 air-sea exchange **(Z)**

Land use change **(B_i)**

$\Delta(\mathbf{O_2}) = f(\mathrm{F}, \mathrm{B}, \mathrm{Z})$

ΔO_2 observed in the atmosphere

Fossil fuel **(F)**

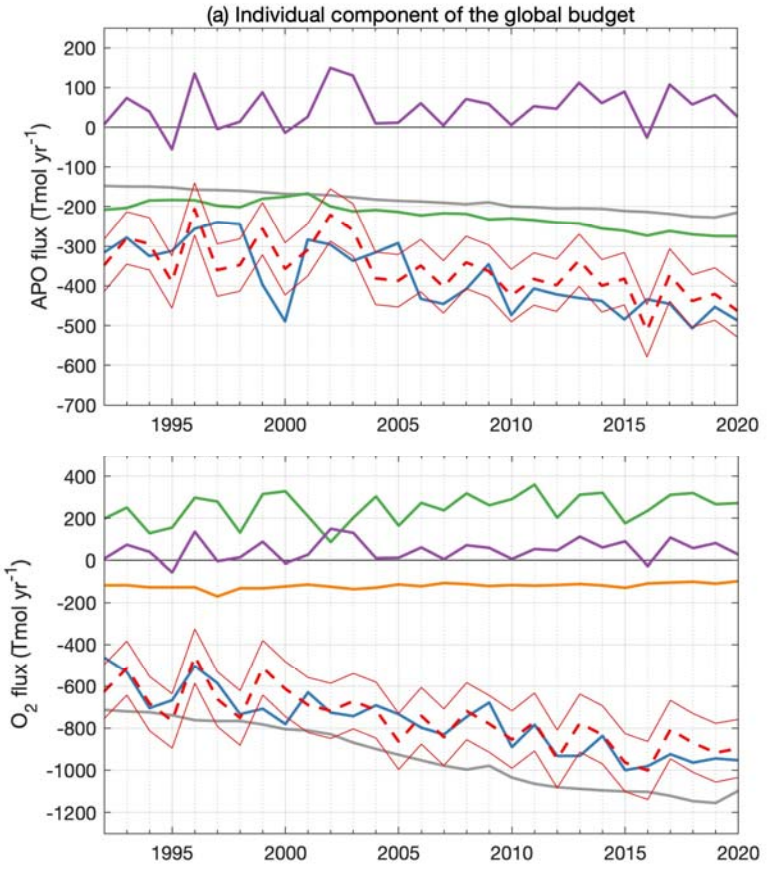
Climate-Carbon Interactions in the Current Century

Budget imbalance = BIM

$$\Delta CO_2 = F - B - O$$

$$\Delta O_2 = -\alpha_F F + \alpha_B B + Z$$

$$\Delta APO = (\alpha_B - \alpha_F)F - \alpha_B O + Z$$



Climate-Carbon Interactions in the Current Century

Budget imbalance = BIM

$$\Delta CO_2 = F - B - O \rightarrow (F - B - O) - \Delta CO_2 = CO_2 \text{ BIM}$$

$$\Delta O_2 = -\alpha_F F + \alpha_B B + Z \rightarrow (-\alpha_F F + \alpha_B B + Z) - \Delta O_2 = O_2 \text{ BIM}$$

$$\Delta APO = (\alpha_B - \alpha_F)F - \alpha_B O + Z \rightarrow ((\alpha_B - \alpha_F)F - \alpha_B O + Z) - \Delta APO = APO \text{ BIM}$$

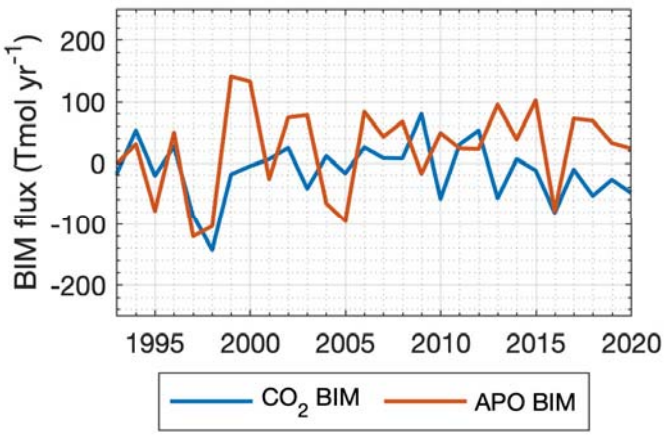
Climate-Carbon Interactions in the Current Century

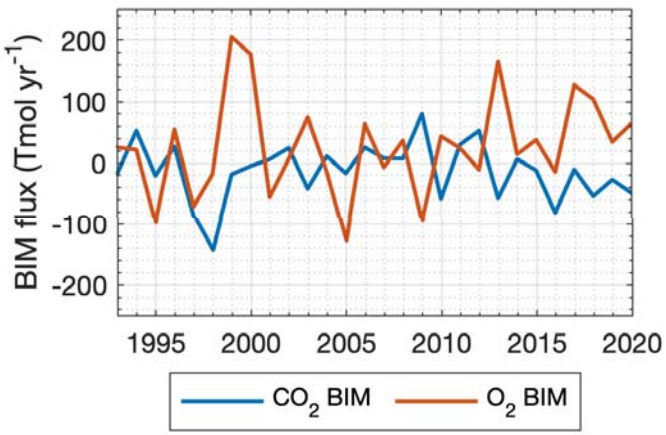
Budget imbalance = BIM

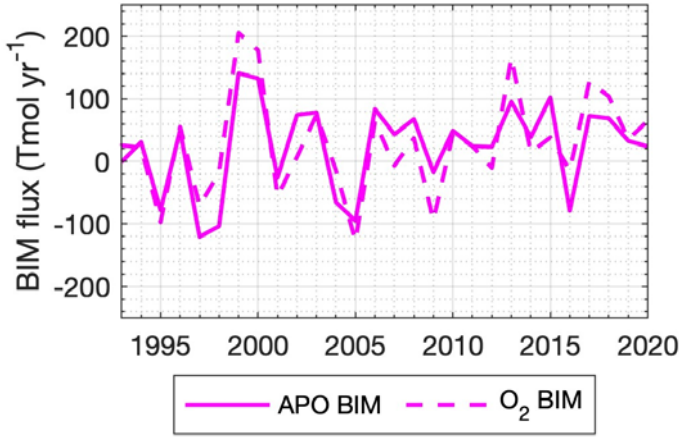
$$\Delta CO_2 = F - B - O \rightarrow (F - B - O) - \Delta CO_2 = CO_2\ BIM$$

$$\Delta O_2 = -\alpha_F F + \alpha_B B + Z \rightarrow (-\alpha_F F + \alpha_B B + Z) - \Delta O_2 = O_2\ BIM$$

$$\Delta APO = (\alpha_B - \alpha_F)F - \alpha_B O + Z \rightarrow ((\alpha_B - \alpha_F)F - \alpha_B O + Z) - \Delta APO = APO\ BIM$$







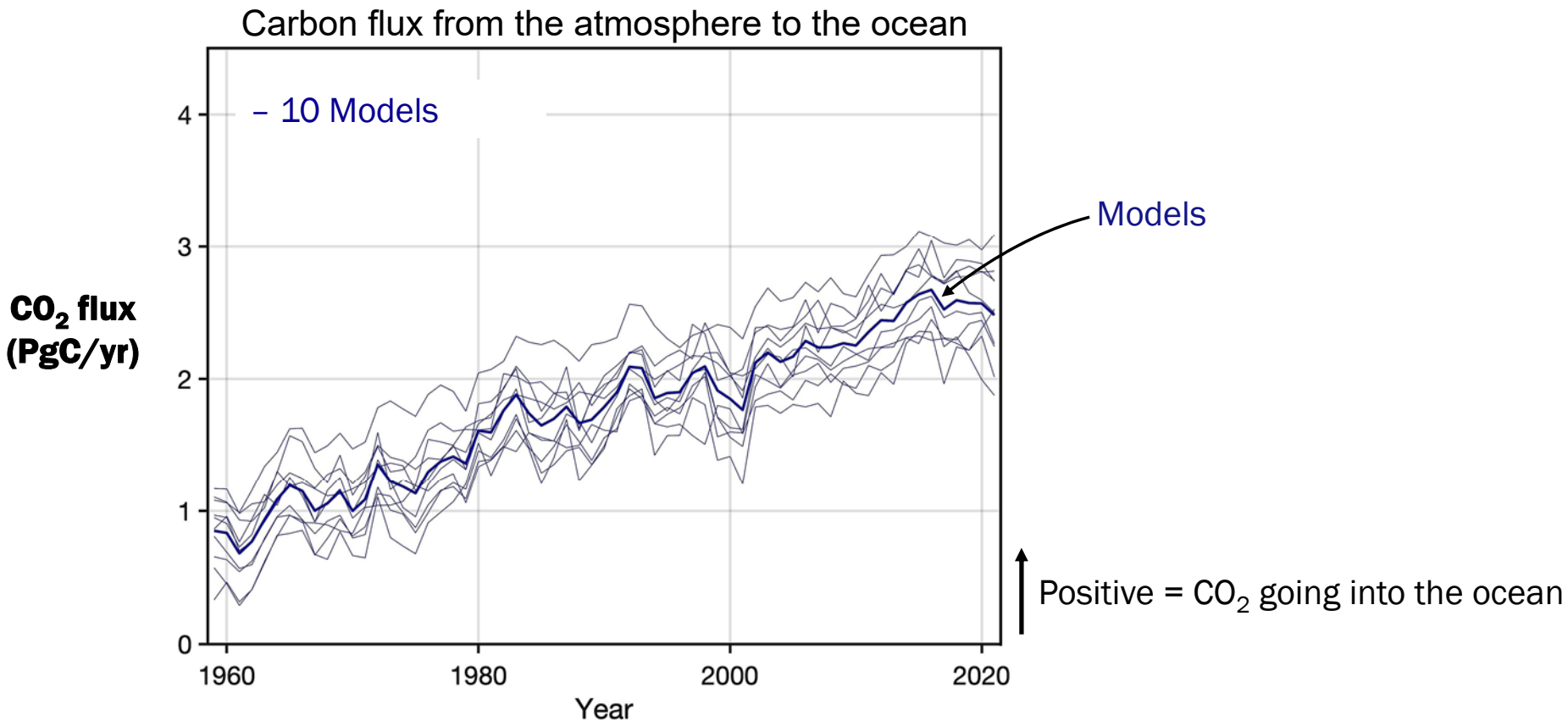
- The variability in BIMs of O_2 and APO is primarily induced by the oceanic O_2 component (= Z)
- Statistically significant increasing long-term trend in O_2 and APO BIMs
  - From overestimated sources of atmospheric O_2 and APO,
  - and/or underestimated consumption of atmospheric O_2 and APO

Climate-Carbon Interactions in the Current Century

Part B.

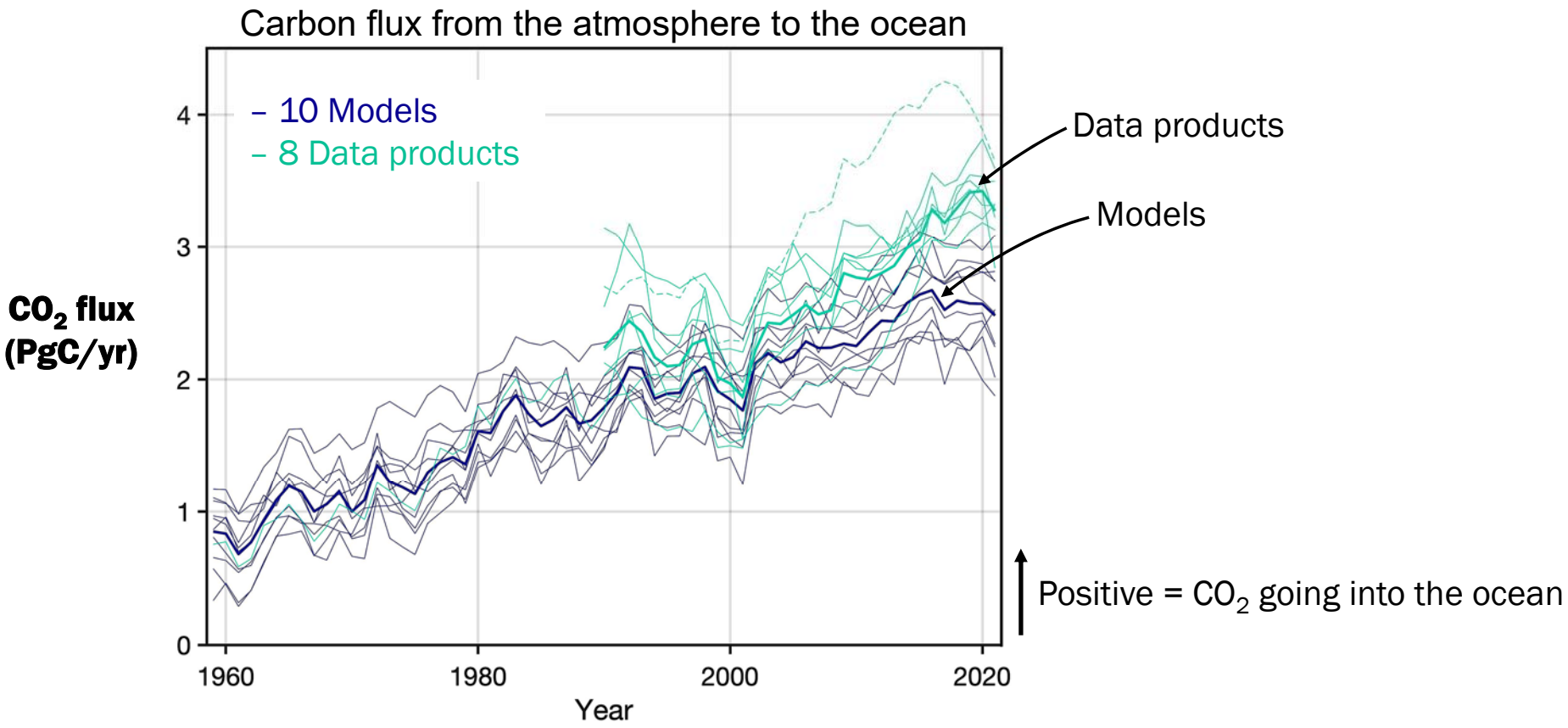
Constraining the Southern Ocean CO_2 sink variability with observation-based O_2 fluxes

Ocean CO_2 sink



Friedlingstein et al., ESSD (2022)

Ocean CO_2 sink



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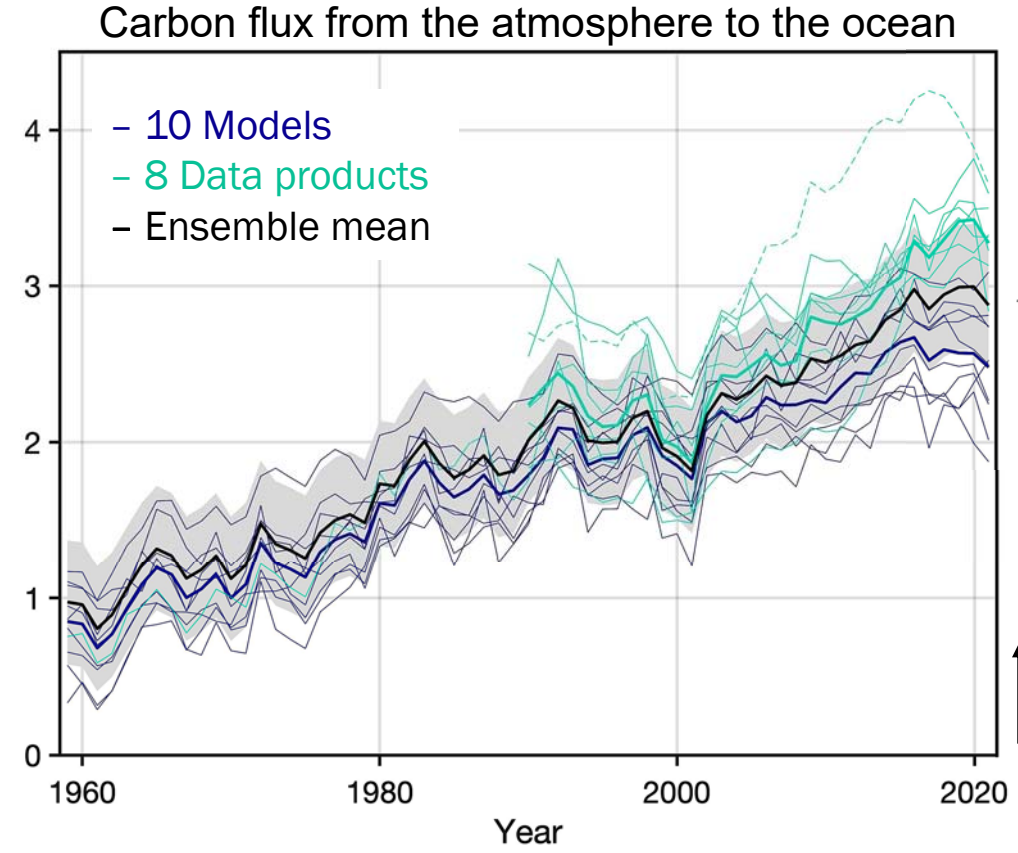
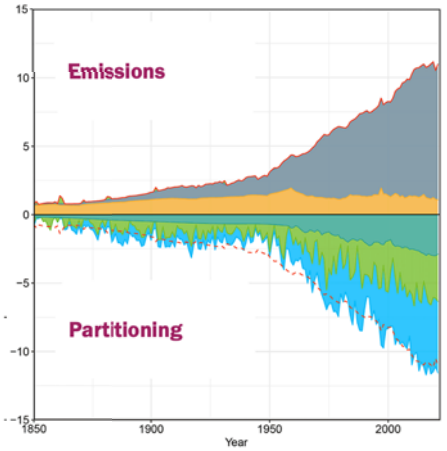
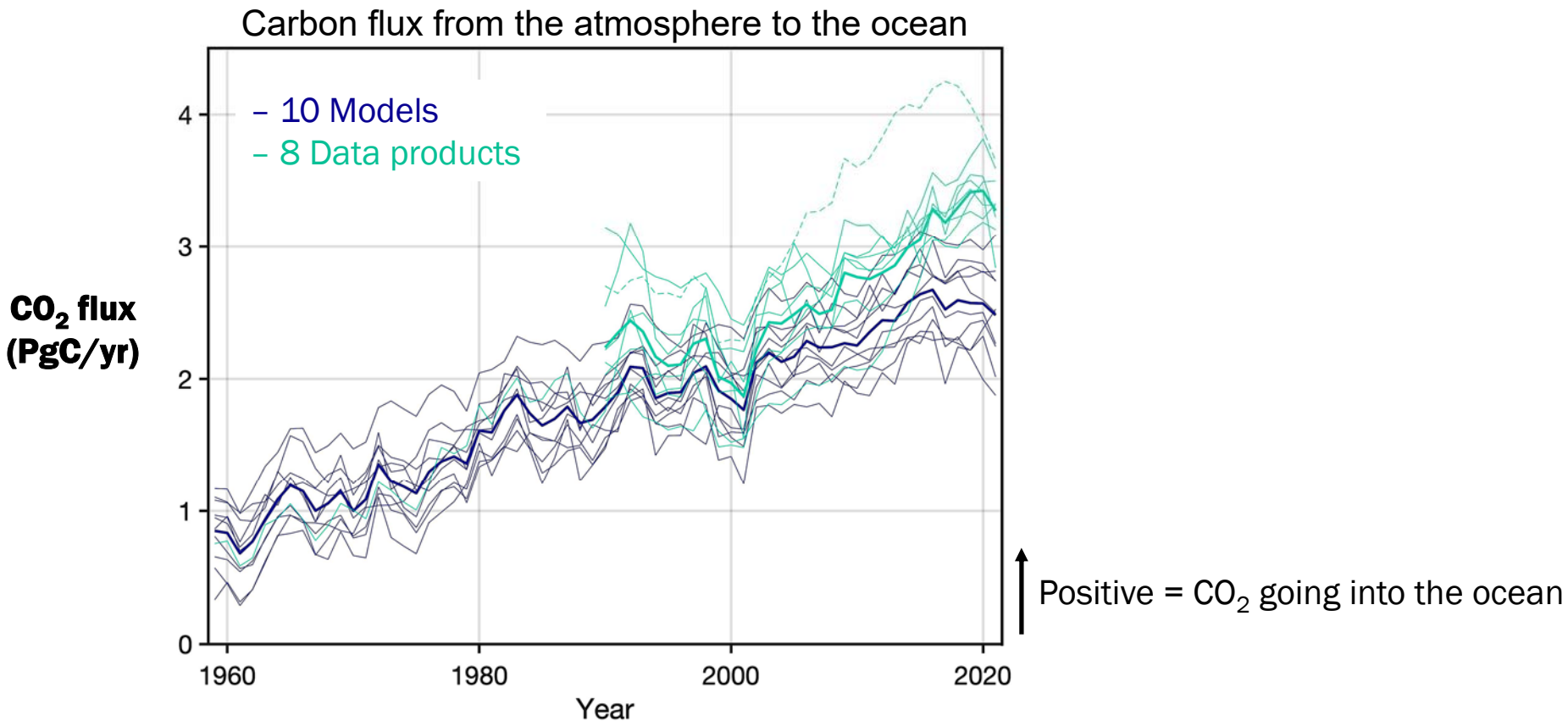




Positive = CO_2 going into the ocean

Friedlingstein et al., ESSD (2022)

Ocean CO_2 sink

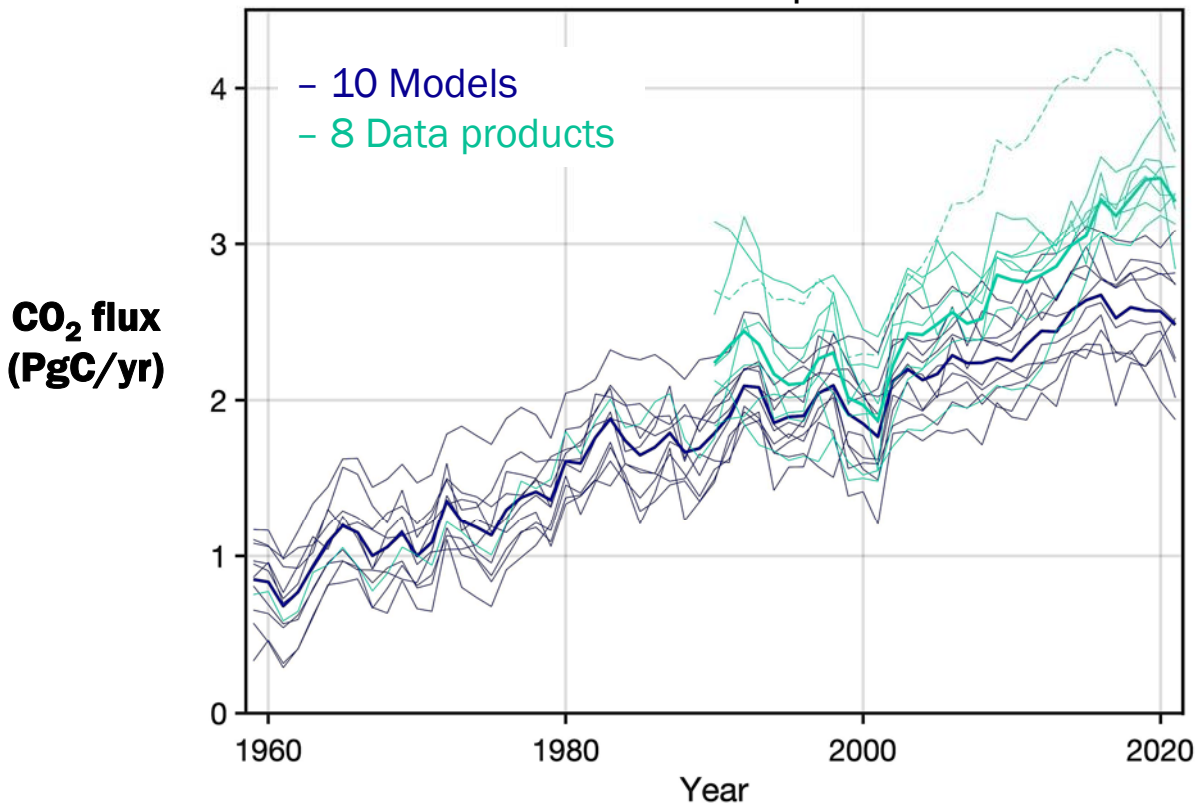


- **Substantial decadal variability in ocean CO_2 sink inferred from data products are not reproduced by models**

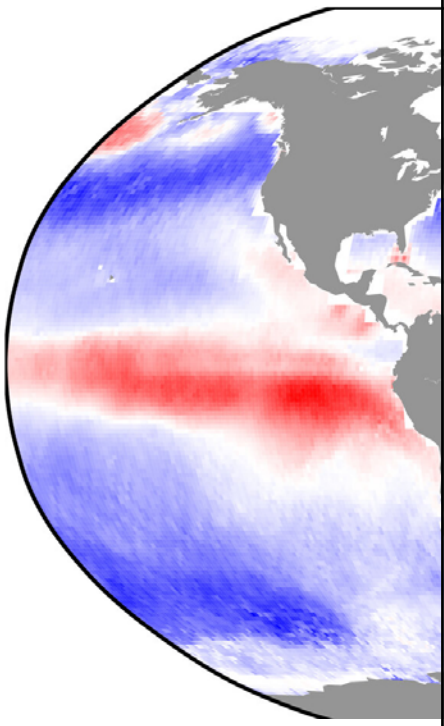
Friedlingstein et al., ESSD (2022)

Ocean CO_2 sink

Carbon flux from the atmosphere to the ocean



Monthly maps of CO_2 flux



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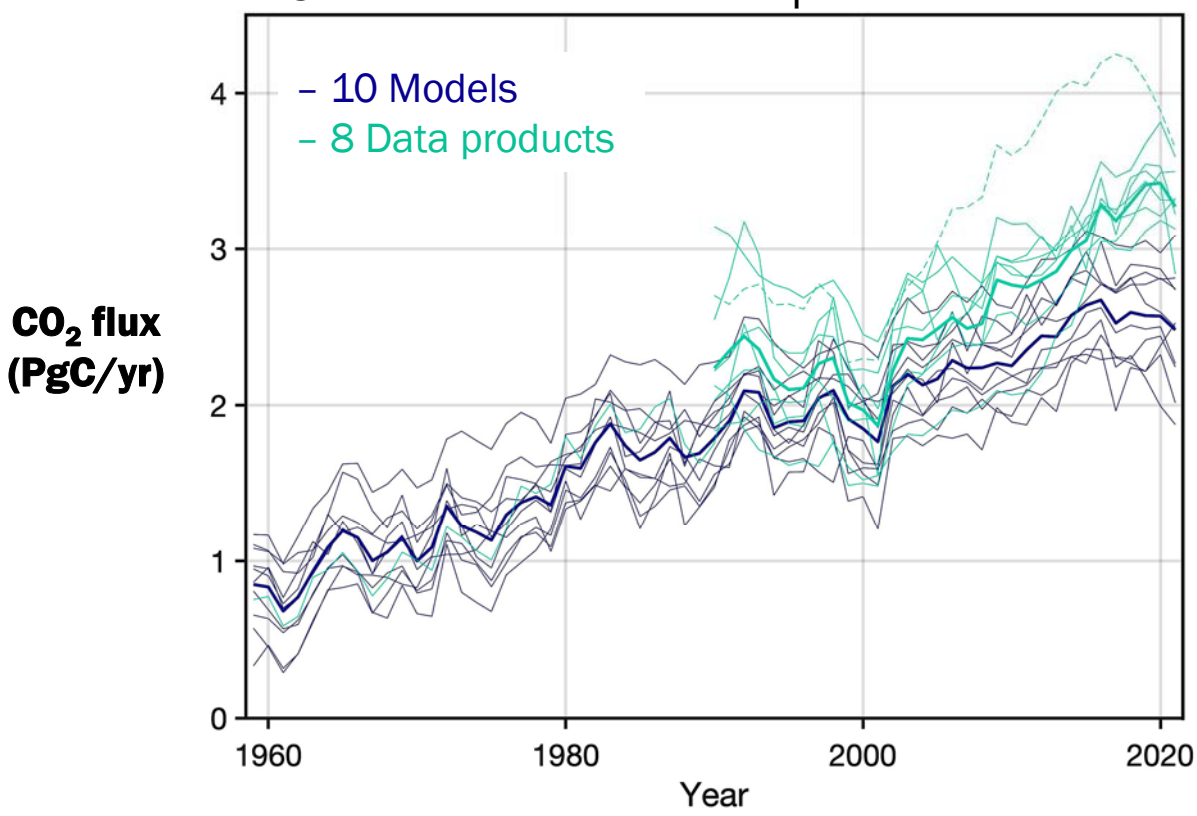

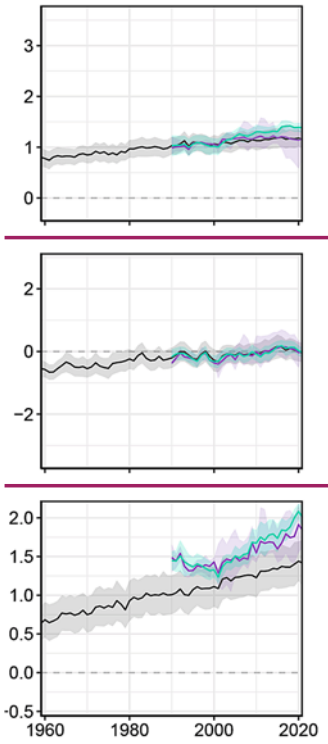

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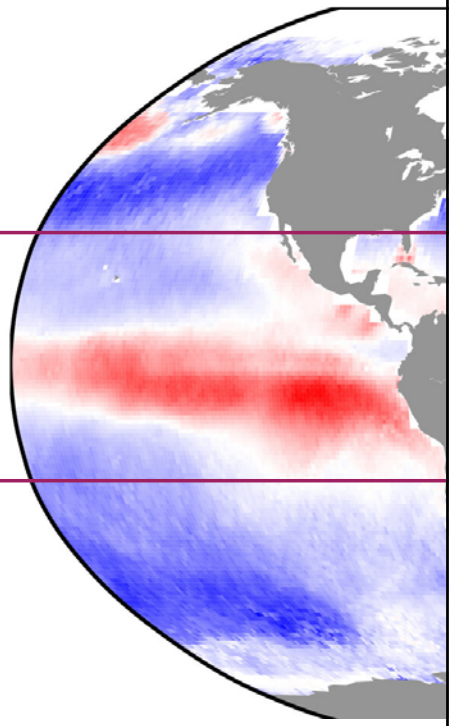


- Substantial decadal variability in ocean CO_2 sink inferred from data products are not reproduced by models
- Temporal variability in the Southern Ocean CO_2 sink remain uncertain and debated

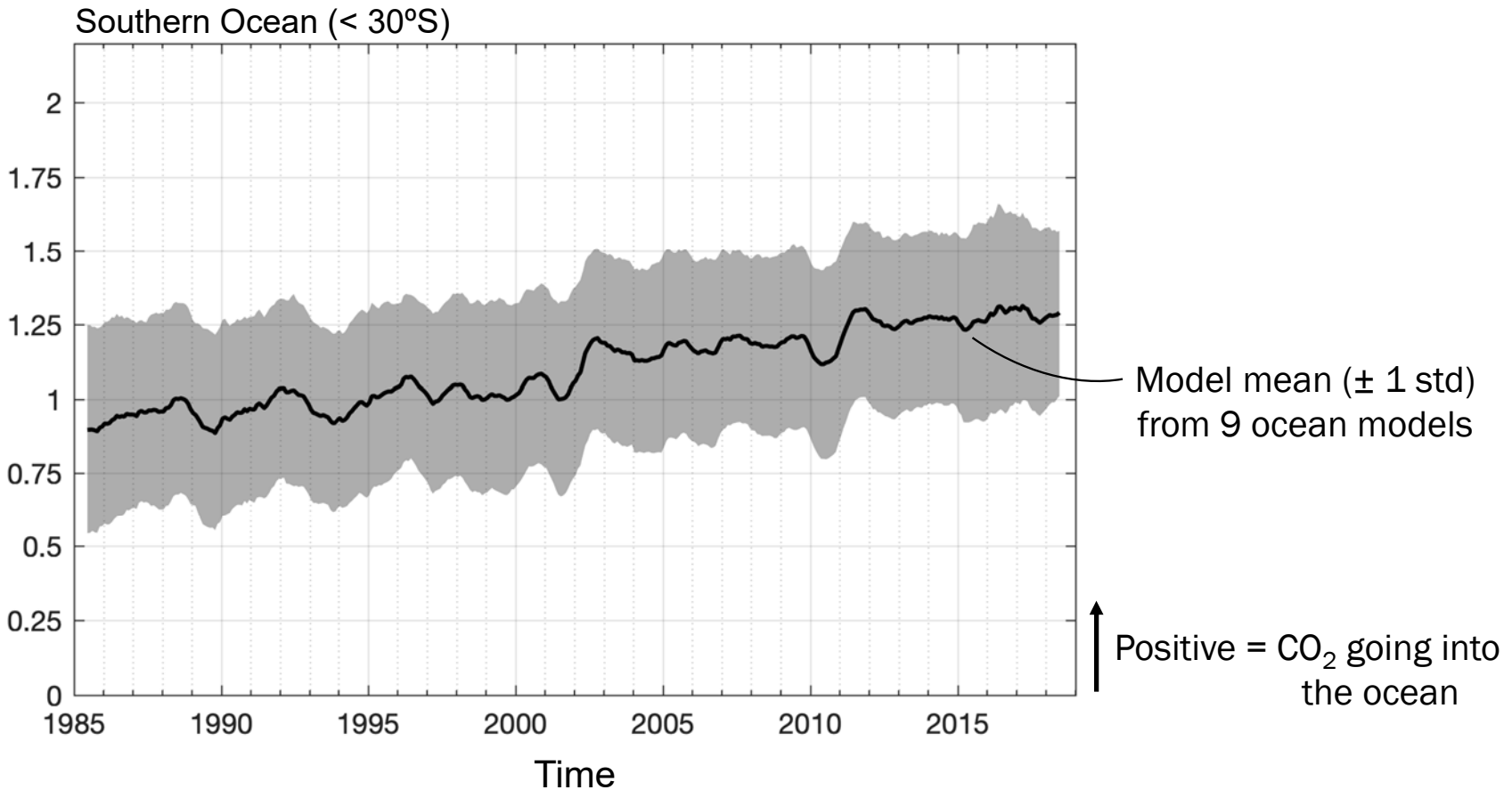
Friedlingstein et al., ESSD (2022)

Outline

(1) Climate-driven variability of the Southern Ocean CO_2 sink

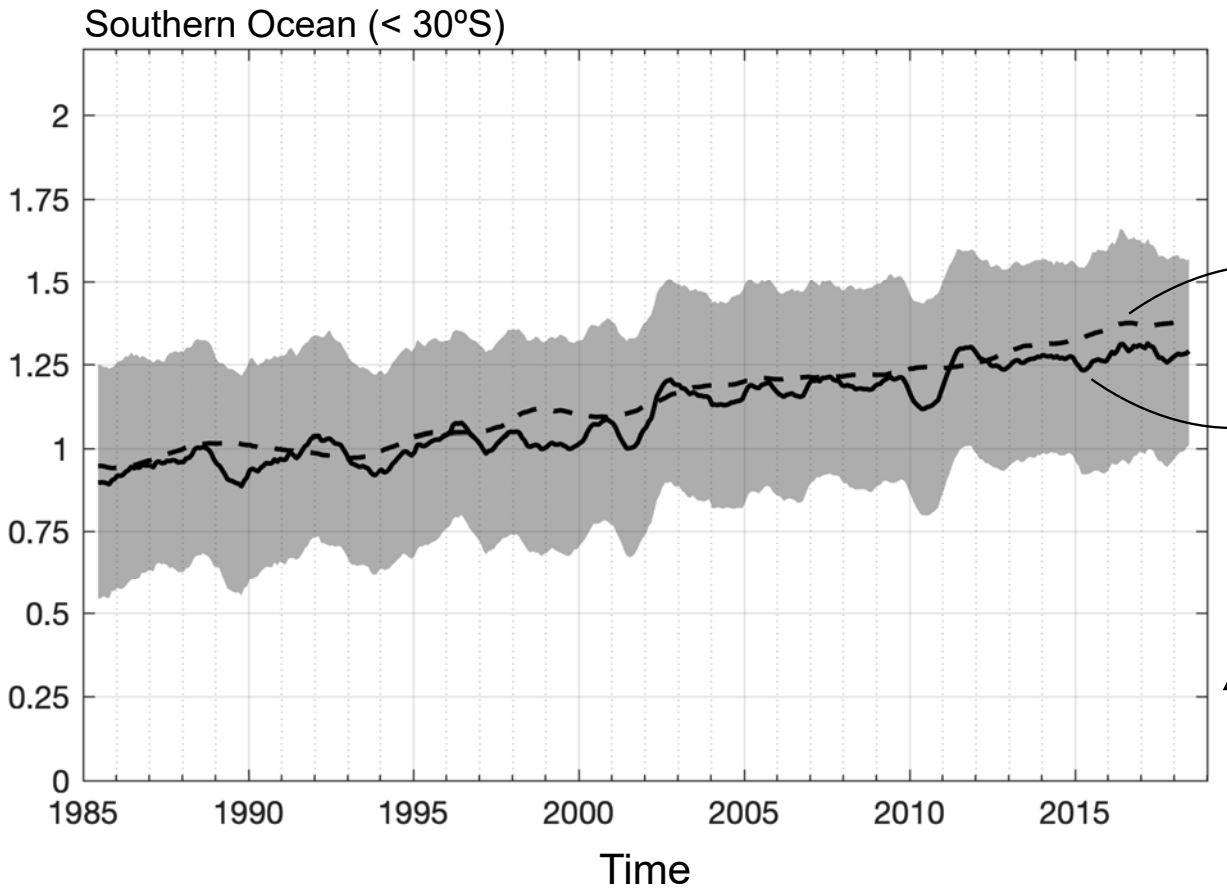
(2) Constraints on the variability of the oceanic CO_2 sink from observations and theory

Southern Ocean CO_2 sink



Mayot et al., Phil. Trans. Royal Soc. A (2023)

Southern Ocean CO_2 sink



CO_2 flux from the atmosphere to the ocean (PgC yr^{-1})

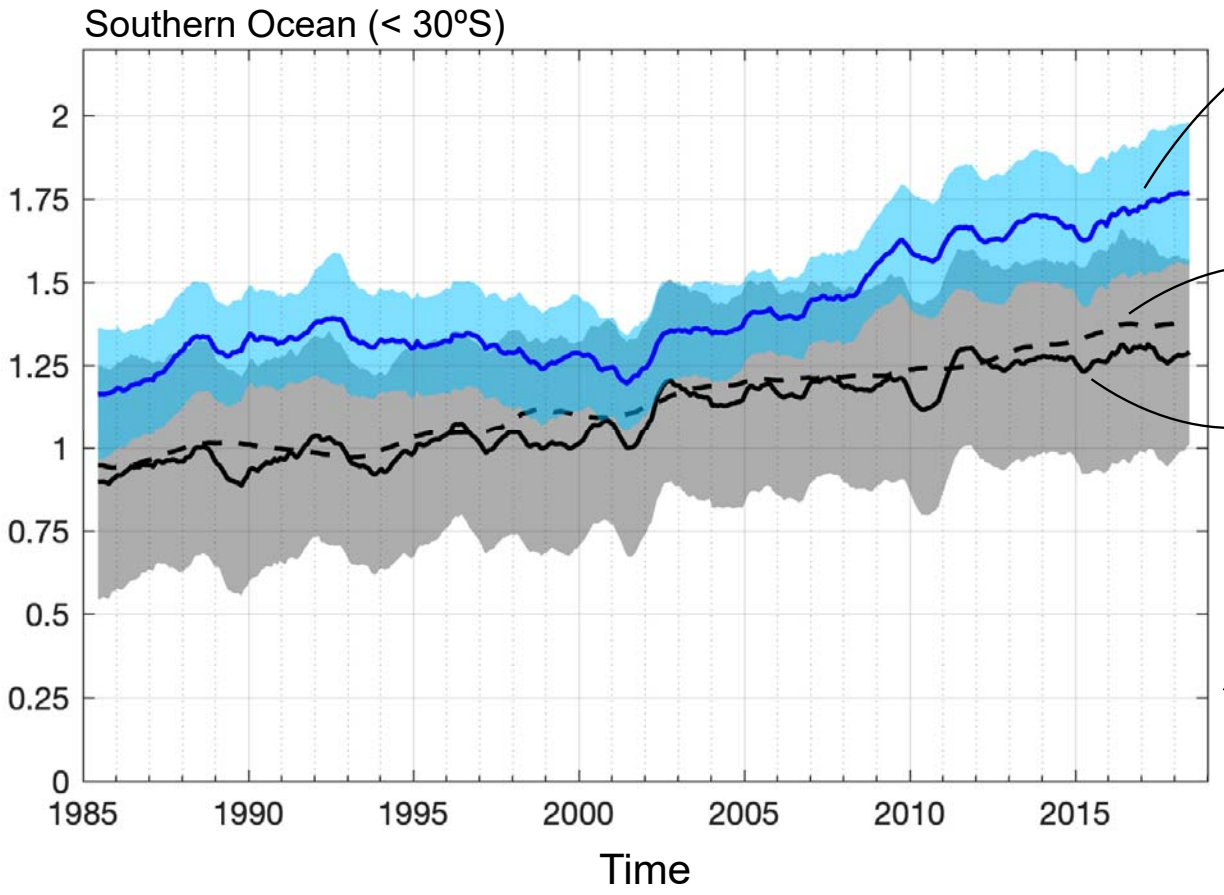
Flux in response to the atmospheric CO_2 increase only

Model mean (± 1 std) from 9 ocean models

Positive = CO_2 going into the ocean

Mayot et al., Phil. Trans. Royal Soc. A (2023)

Southern Ocean CO_2 sink



CO_2 flux from the atmosphere to the ocean (PgC yr^{-1})

Data-product mean (± 1 std), from 9 data-products

Flux in response to the atmospheric CO_2 increase only

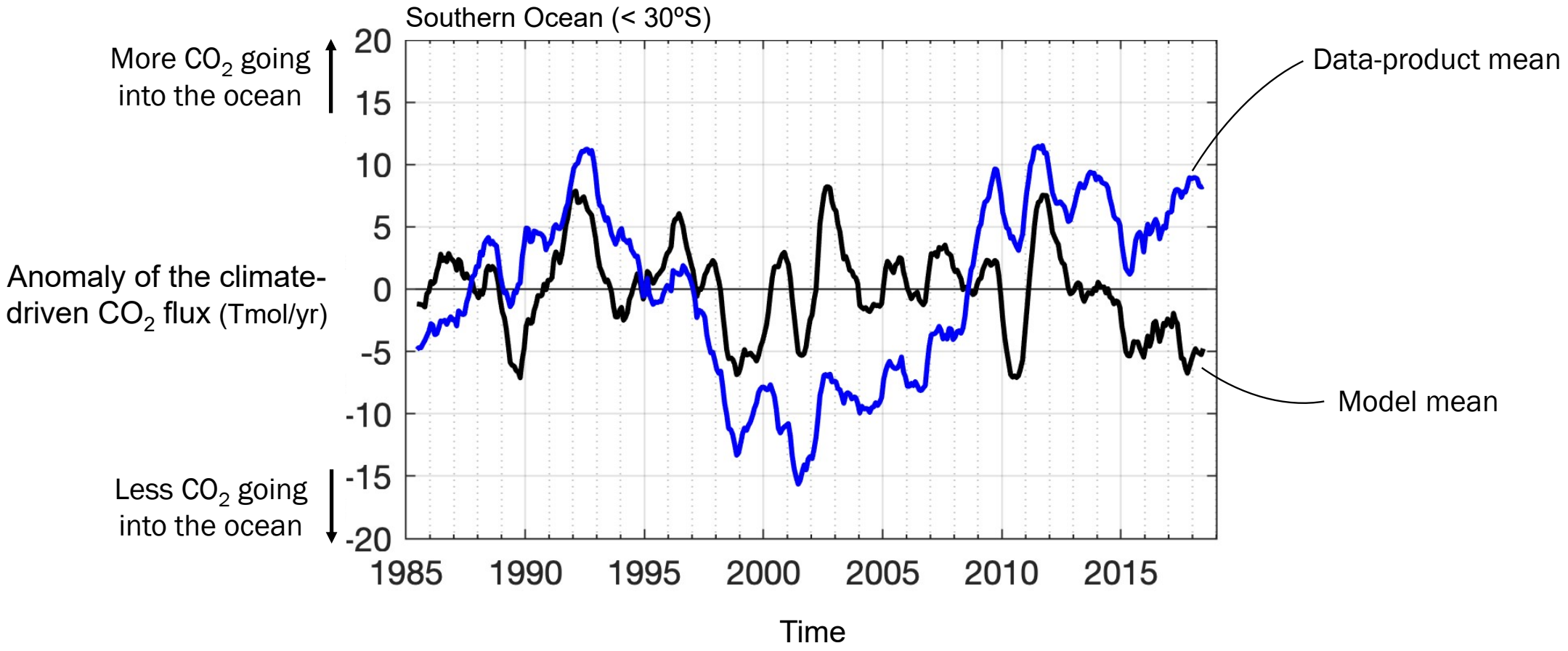
Model mean (± 1 std) from 9 ocean models

Positive = CO_2 going into the ocean

Climate-driven variability of the Southern Ocean CO_2 sink = **Model mean** (solid) – **Flux in response to the atm. CO_2 increase** (dashed)

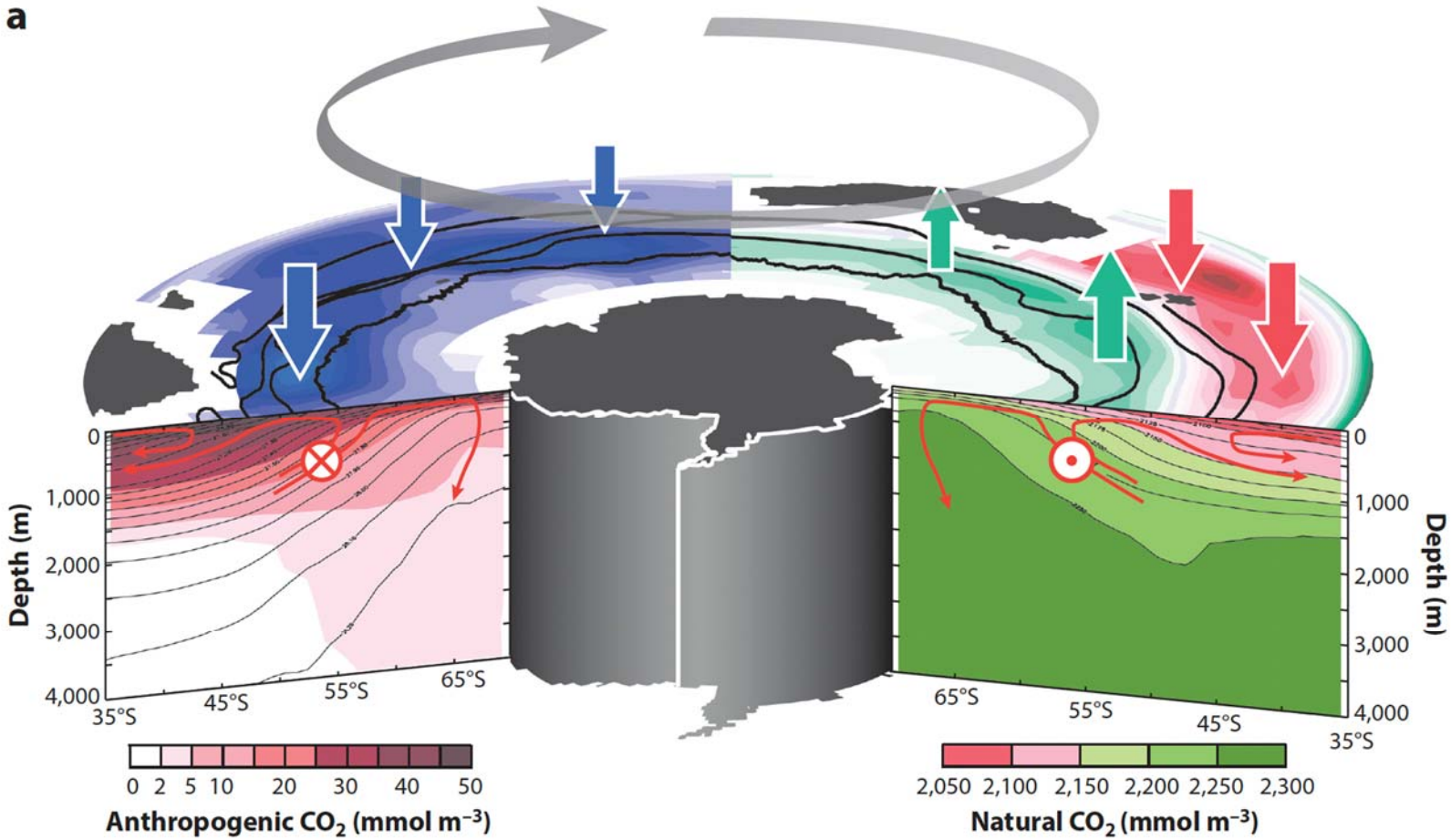
Mayot et al., Phil. Trans. Royal Soc. A (2023)

Climate-driven Southern Ocean CO_2 sink



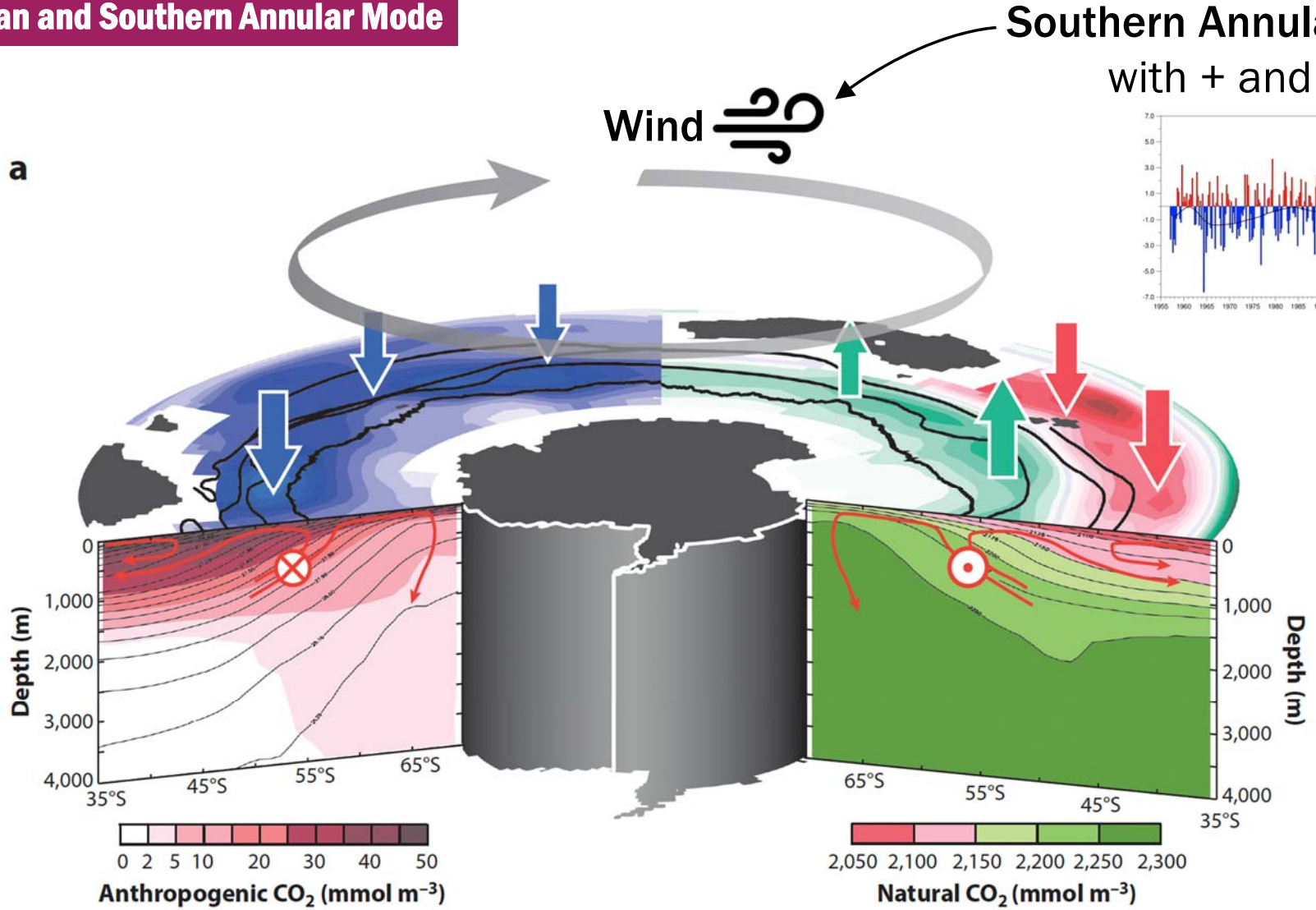
Mayot et al., Phil. Trans. Royal Soc. A (2023)

Southern Ocean and Southern Annular Mode



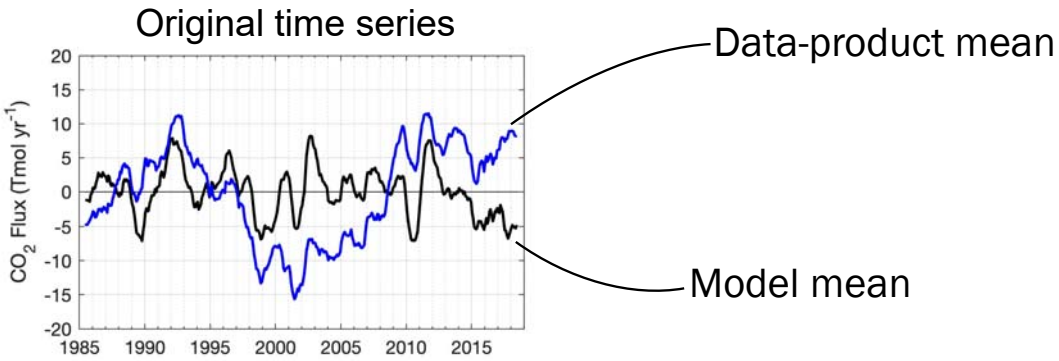
Gruber et al., Ann Rev Mar Sci (2019)

Southern Ocean and Southern Annular Mode



Gruber et al., Ann Rev Mar Sci (2019)

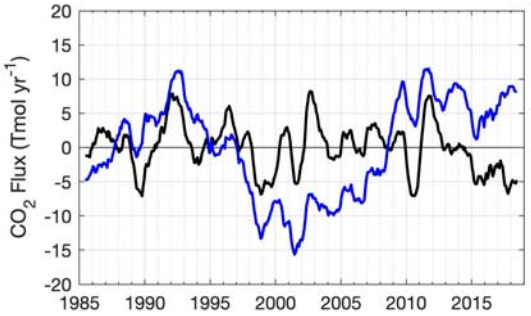
Temporal decomposition of the variability



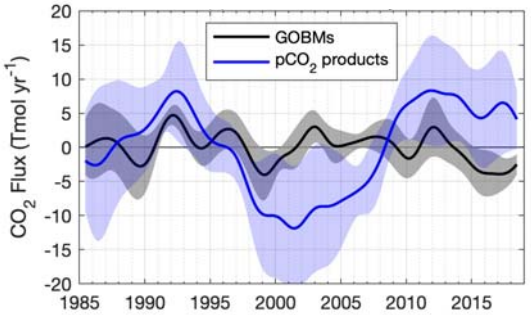
Mayot et al., Phil. Trans. Royal Soc. A (2023)

Temporal decomposition of the variability

Original time series



Decadal variability



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Temporal decomposition of the variability

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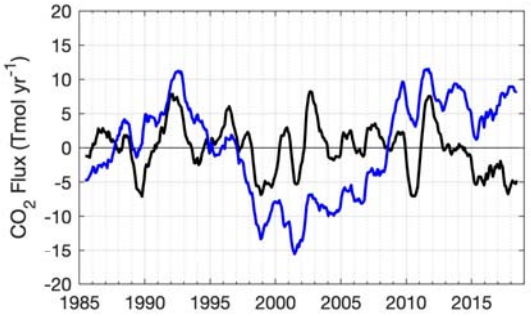

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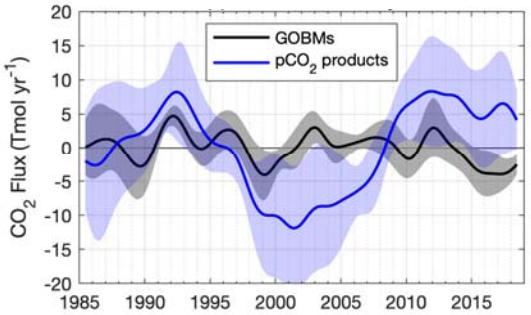
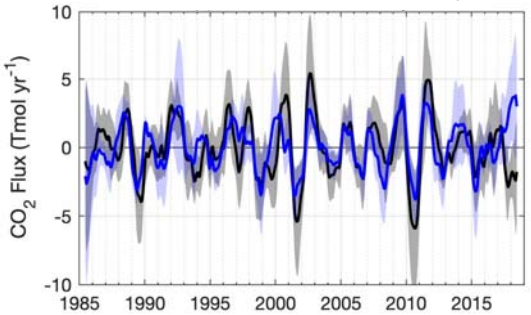
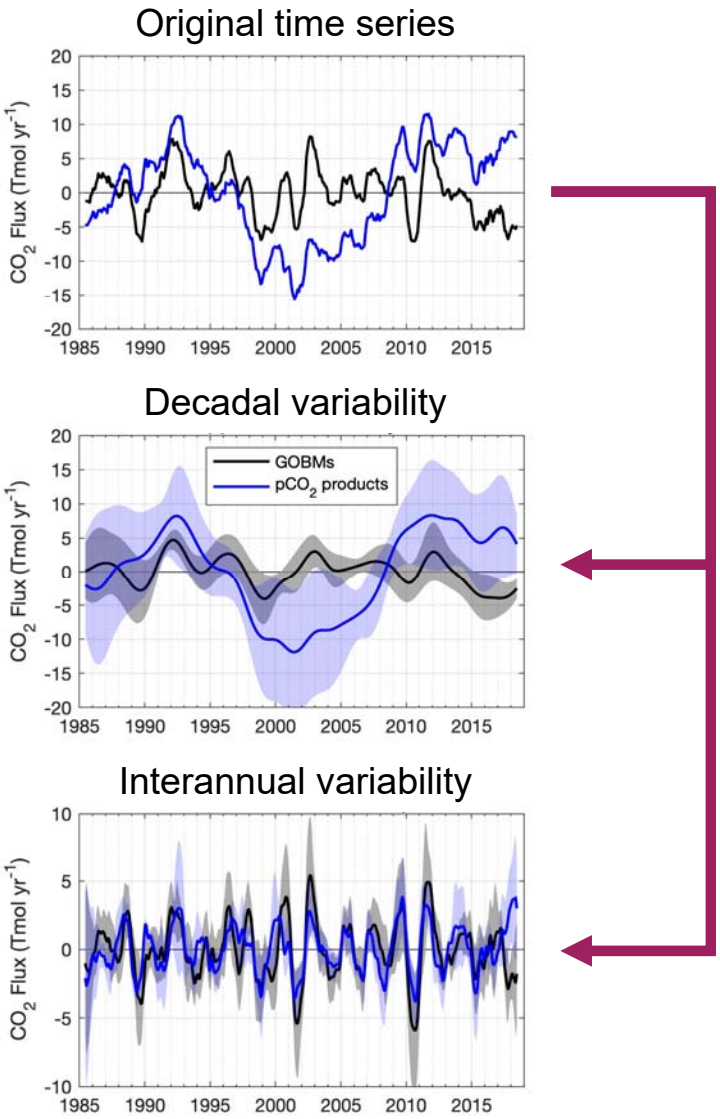


Interannual variability



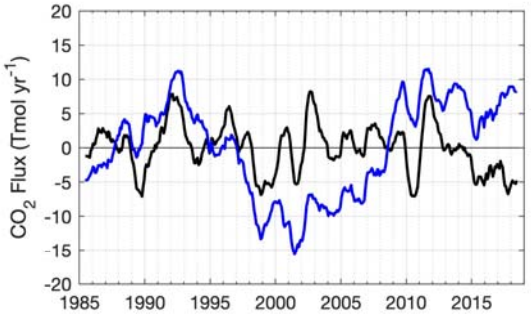
Temporal decomposition of the variability



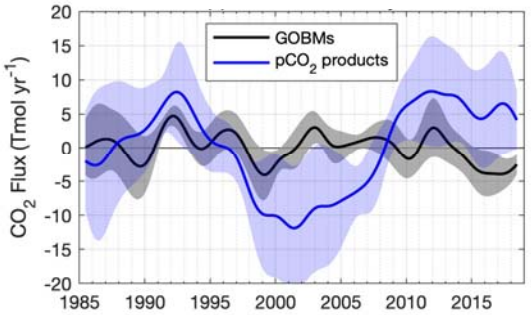
- Amplitude of the decadal variability is 3 times lower in models than in data products
- Models and data product have a similar interannual variability

Temporal decomposition of the variability

Original time series



Decadal variability



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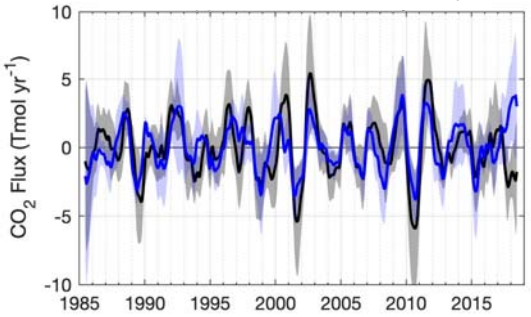


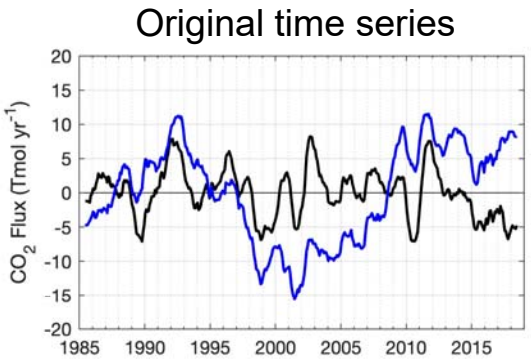
- Amplitude of the decadal variability is 3 times lower in models than in data products
- Models and data product have a similar interannual variability

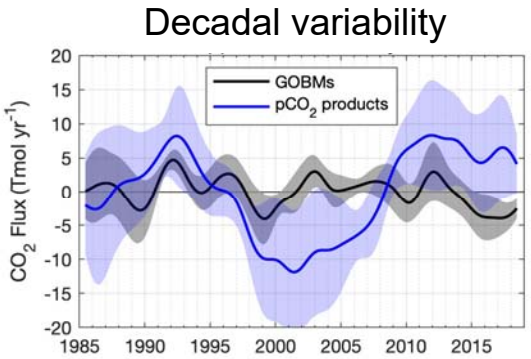
How to check this?

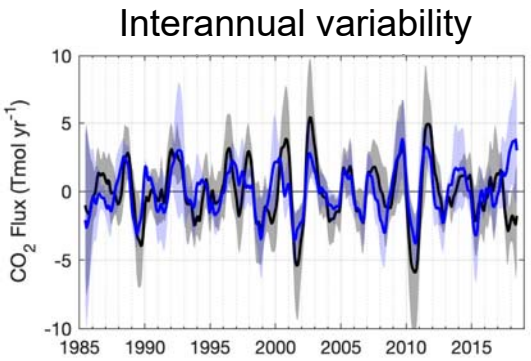
By looking at O_2 air-sea fluxes, because CO_2 and O_2 are affected by the same processes:

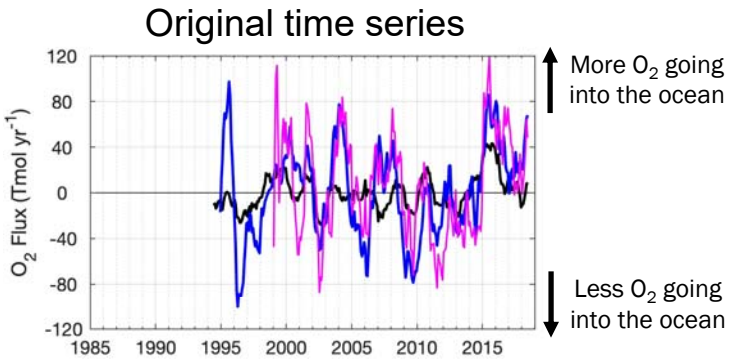
- photosynthesis & respiration
- ocean circulation
- air-sea gas exchange

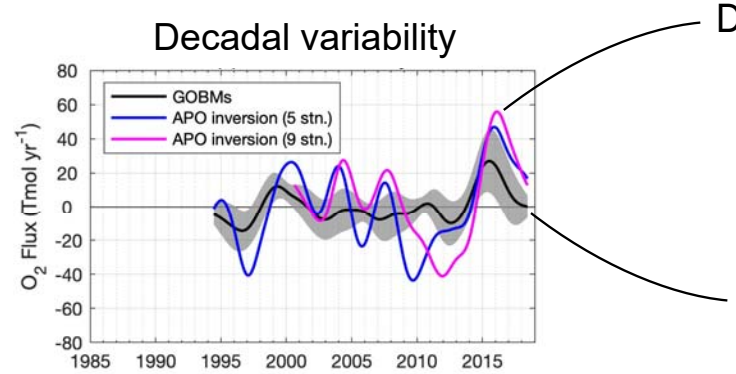
Temporal decomposition of the O_2 air-sea flux

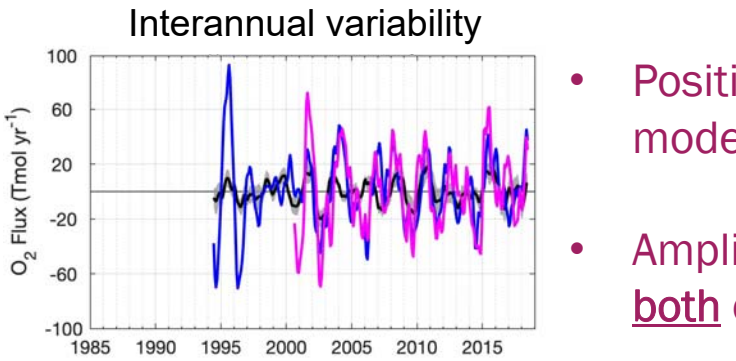






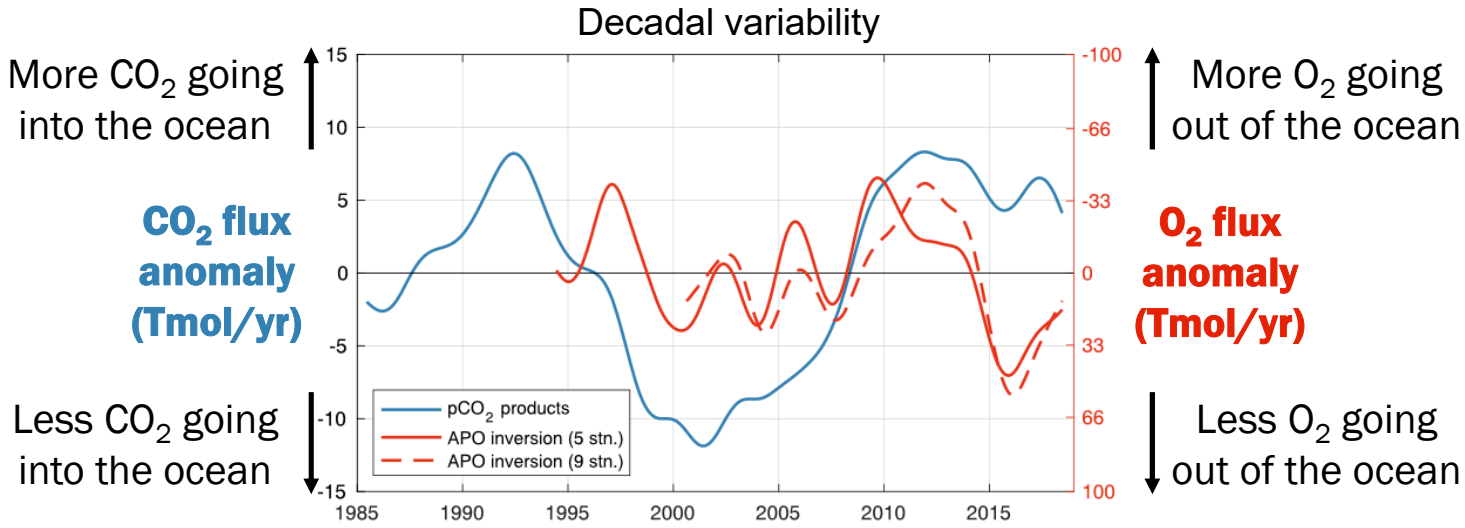






- Positive correlation between the models and data-based products
- Amplitude lower in models, for <u>both</u> decadal and interannual vari

Observed variability in O_2 and CO_2 fluxes



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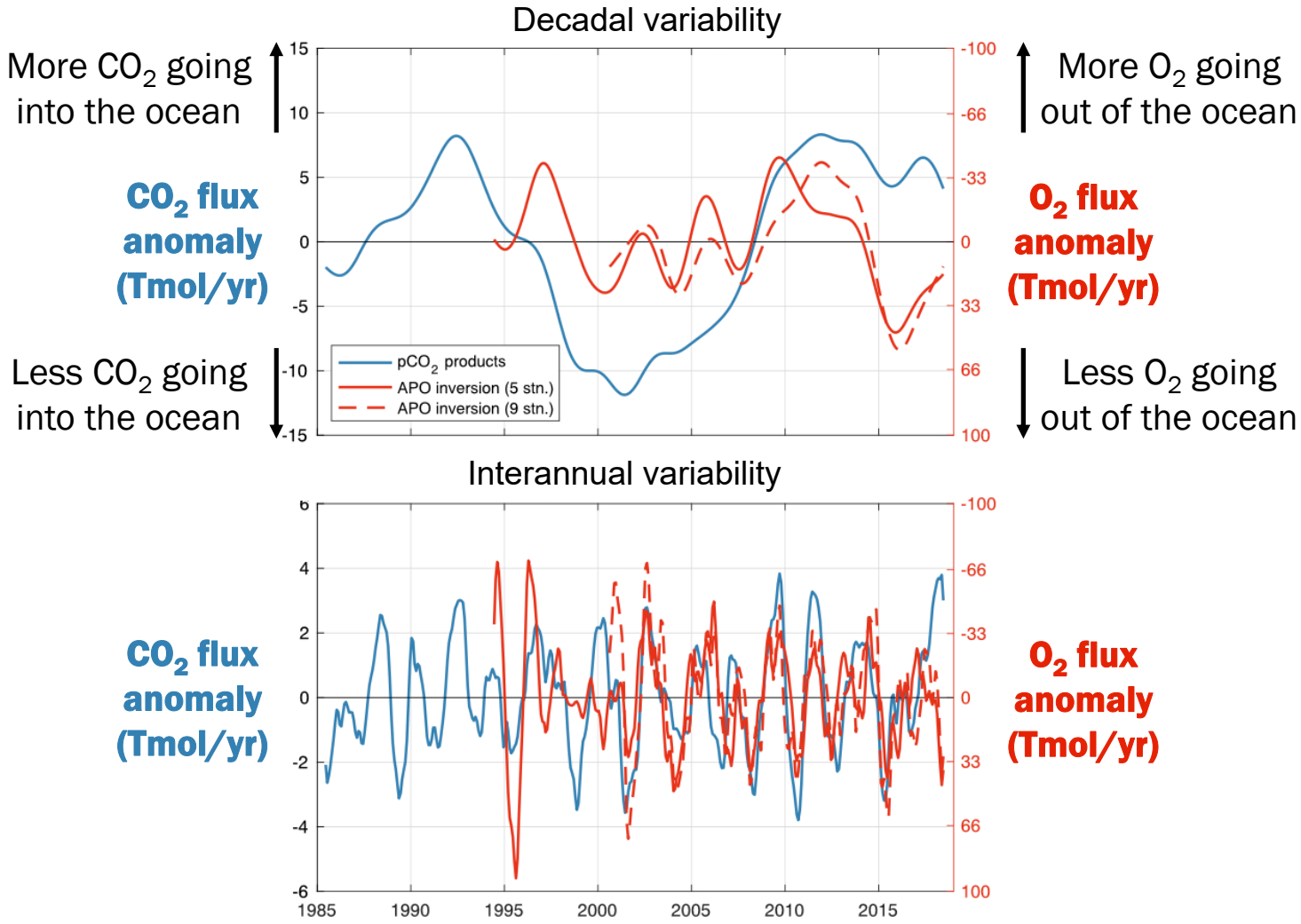
Observed variability in O_2 and CO_2 fluxes



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Observed variability in O_2 and CO_2 fluxes

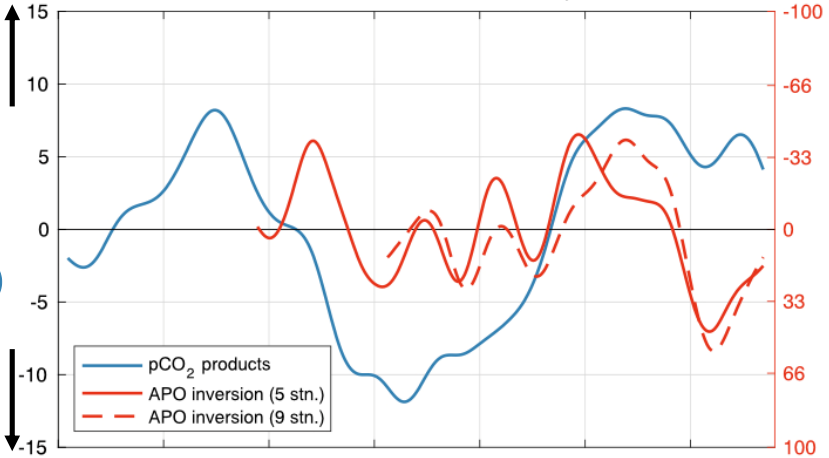
Decadal variability

More CO_2 going into the ocean

Less CO_2 going into the ocean

More O_2 going out of the ocean

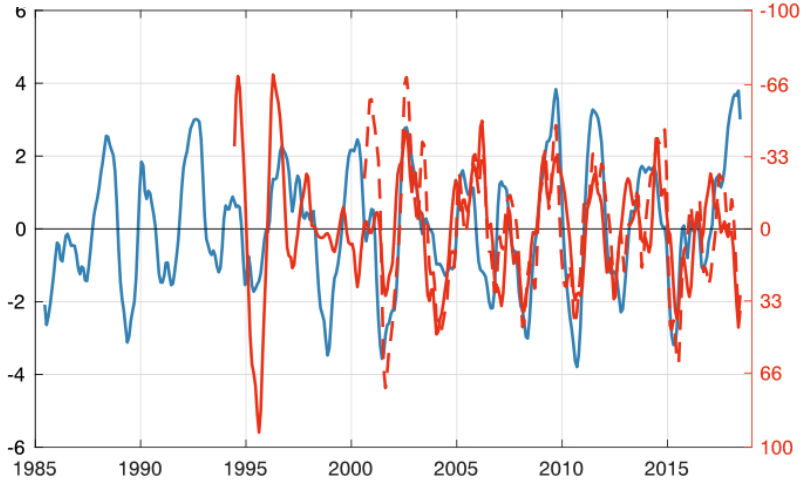
Less O_2 going out of the ocean



CO_2 flux anomaly (Tmol/yr)

O_2 flux anomaly (Tmol/yr)

Interannual variability



CO_2 flux anomaly (Tmol/yr)

O_2 flux anomaly (Tmol/yr)

> Observed decadal variations of the Southern Ocean CO_2 sink tend to be confirmed

> Data products and models tend to accurately represent the interannual variations of the Southern Ocean CO_2 sink

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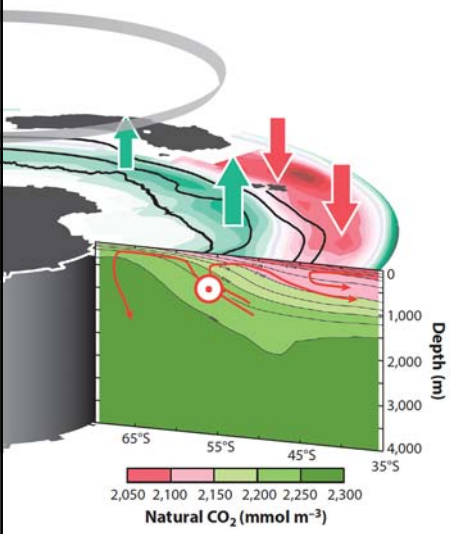
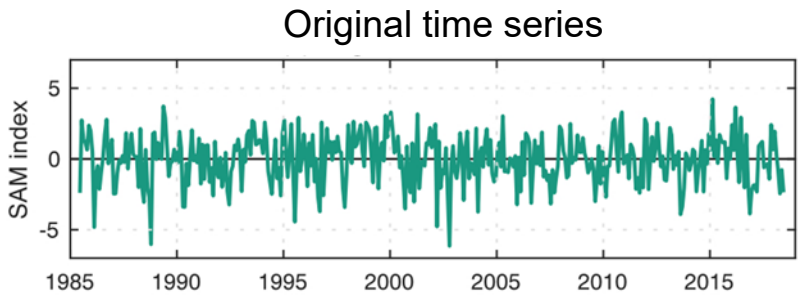
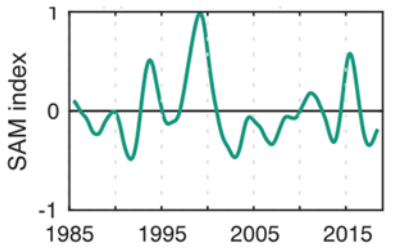
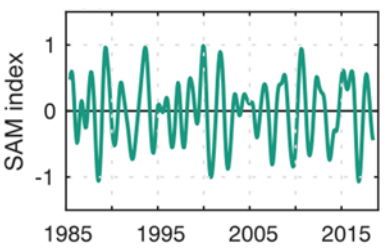
Southern Annular Mode and CO_2 sink









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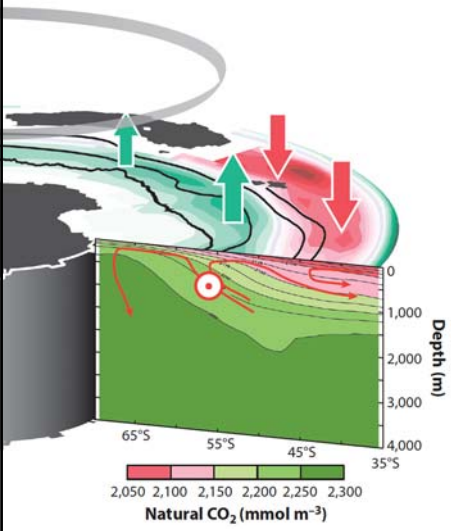
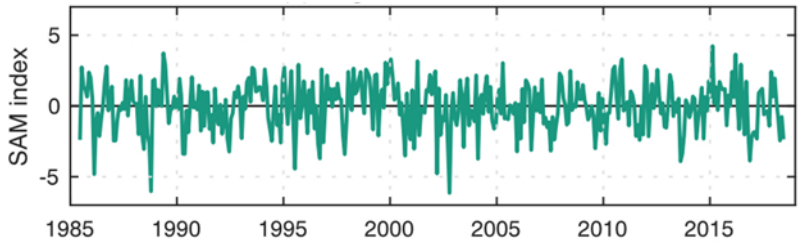
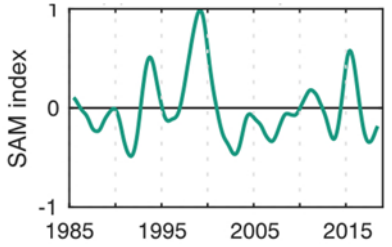
Southern Annular Mode and CO_2 sink



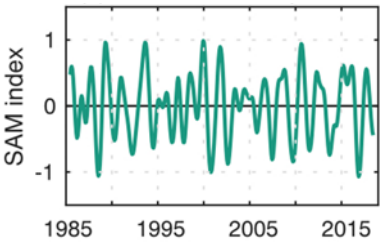
Original time series

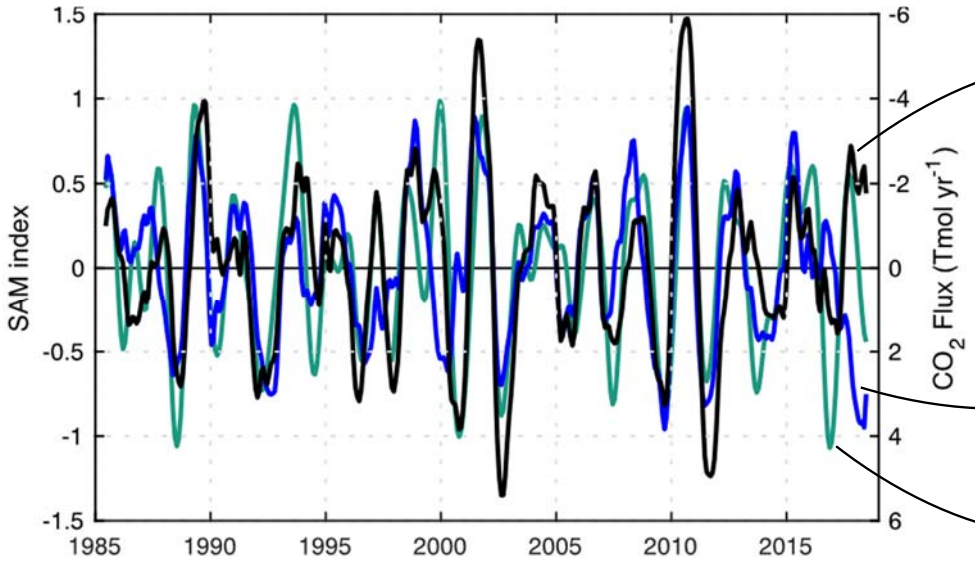


Decadal variability



Interannual variability





Model

> Interannual variability component – v. good SAM agreement

Data product

SAM

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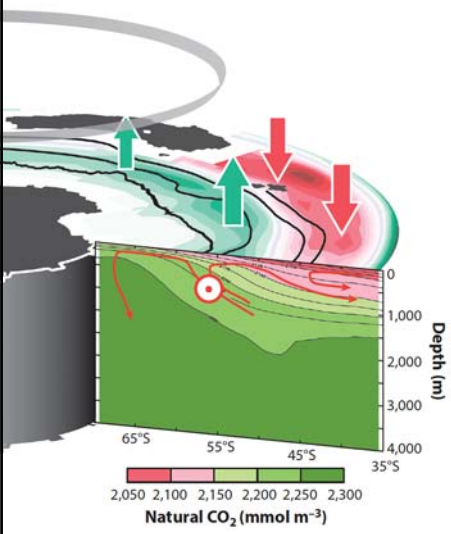
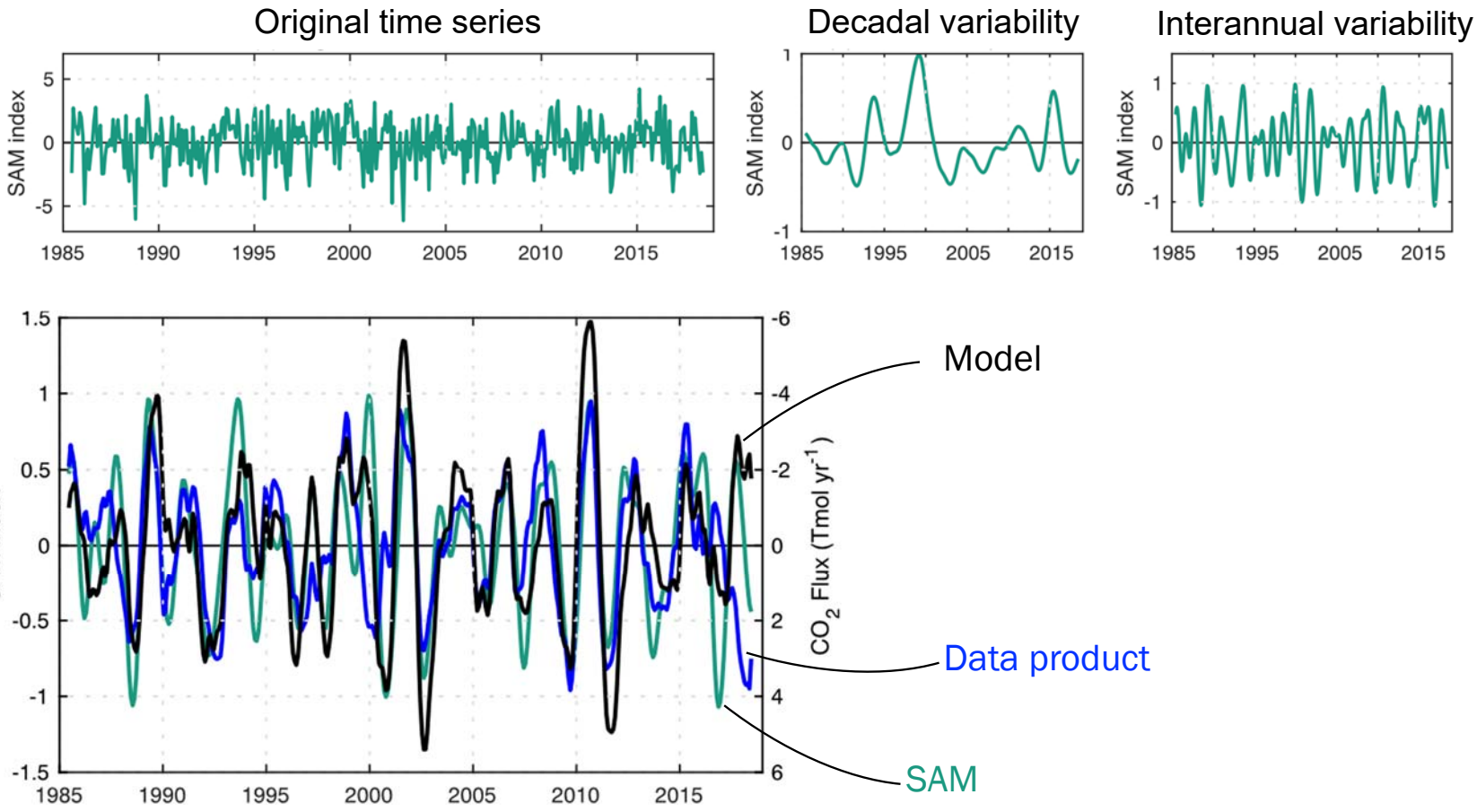
Southern Annular Mode and CO_2 sink





> Stronger (weaker) winds during years of positive (negative) SAM induce stronger (weaker) upwelling of deep waters and drive the short-term interannual variation of the Southern Ocean CO_2 sink.

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