Reduced CO_2 uptake and growing nutrient sequestration from slowing overturning circulation

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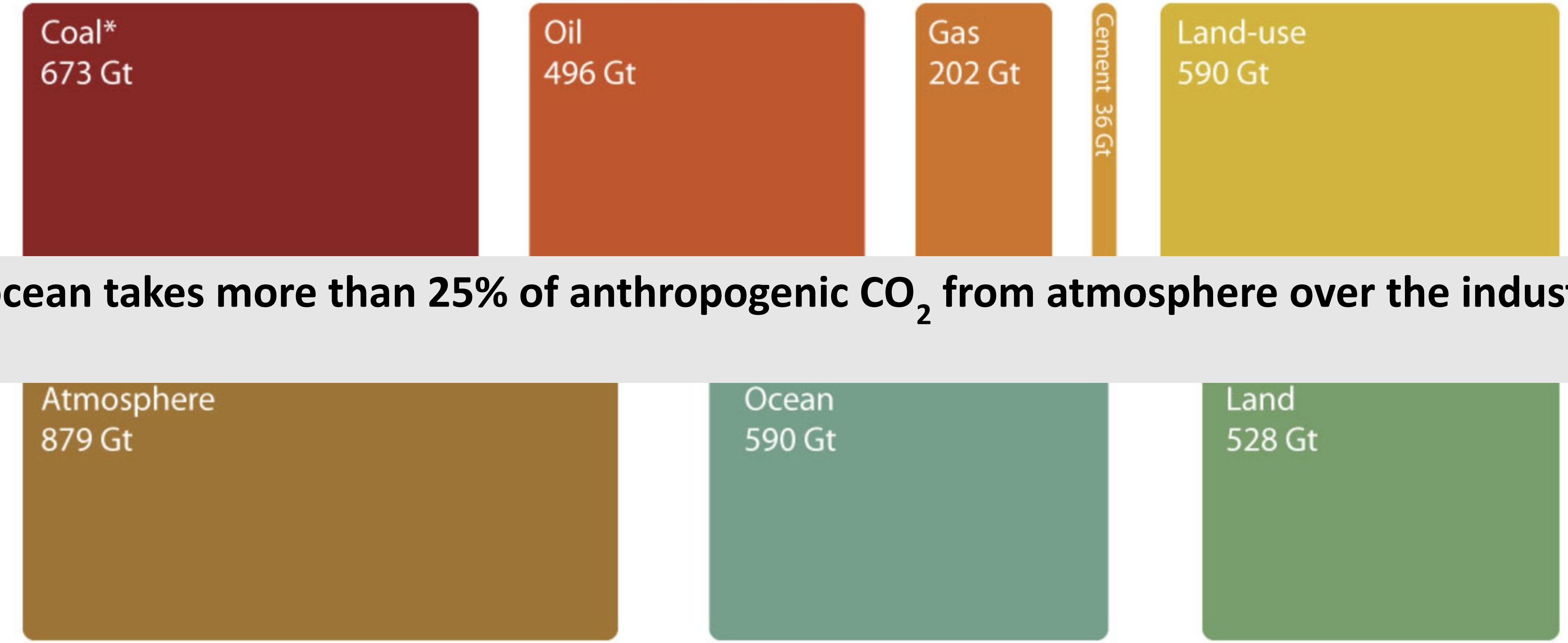
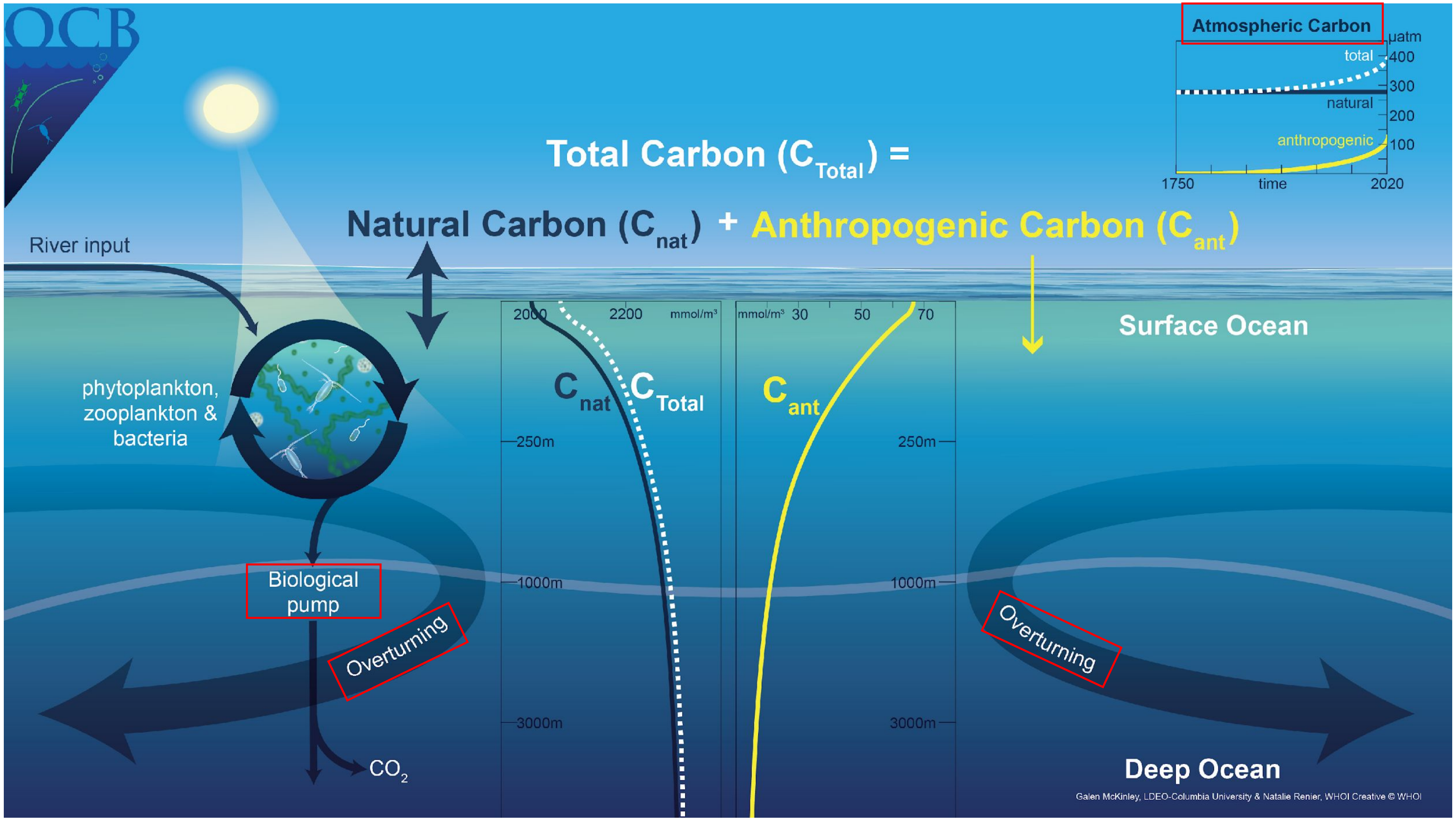
The ocean takes more than 25% of anthropogenic CO_2 from atmosphere over the industrial era!



Where our carbon emissions have gone: carbon emission sinks 1750-2012 (Gt CO_2)

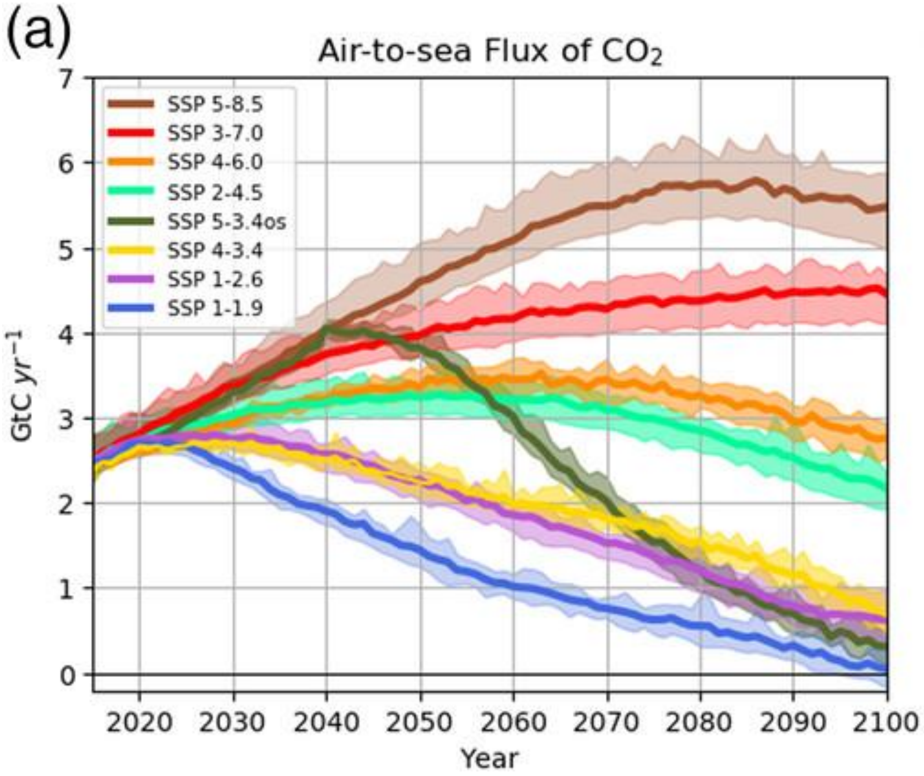
Notes: Both emissions and sinks sum to 1,997 Gt CO2. Land, ocean and atmospheric sinks represent the increased carbon dioxide absorption due to human emissions between 1750 and 2012. *Coal emissions are mostly coal but also include signficant biomass emissions. Gas emissions include a small volume of flaring emissions. Land use change emissions are the net change in carbon stocks resulting from human-induced land use, land use change and forestry activities.

Background



The atmospheric CO_2 is the first driver of the ocean carbon sink. However, ocean circulation patterns also affect the ocean carbon sink by multiple ways.

Scientific question and Methods



(Laddicoat et al., 2021, *Journal of Climate*)

- There are great uncertainties of the size of ocean carbon sink across CMIP6 climate models under each climate scenario.
- Under each climate scenario, the atmospheric CO_2 in each model is the same. The large uncertainties are driven by ocean processes.
- Three climate scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5.
- Models: CMIP6 + CESM1.0 (BGC) from CMIP5

How do circulation changes affect the ocean carbon sink in CMIP6 models under climate change?

Results: The slowdown of meridional overturning circulation

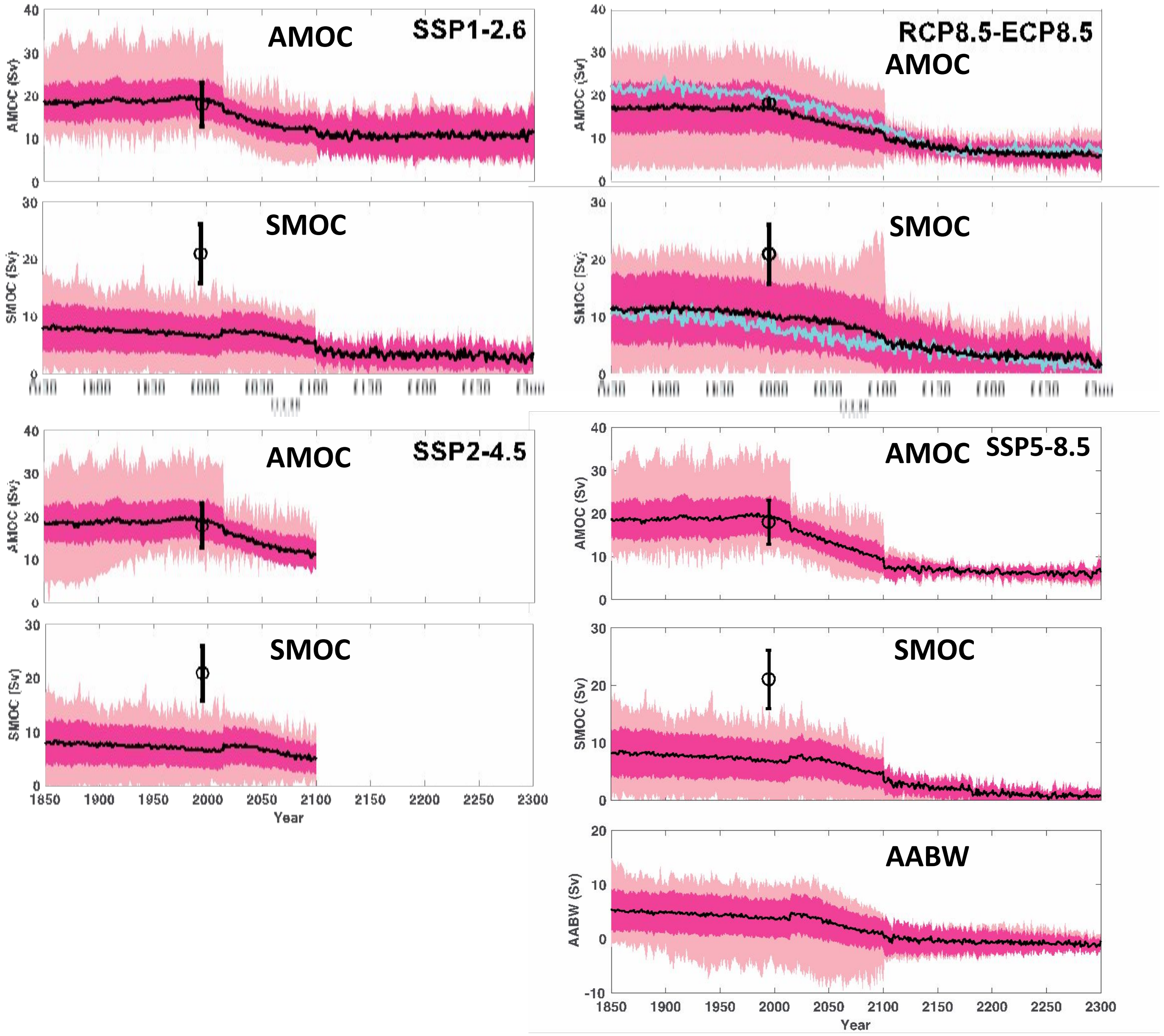
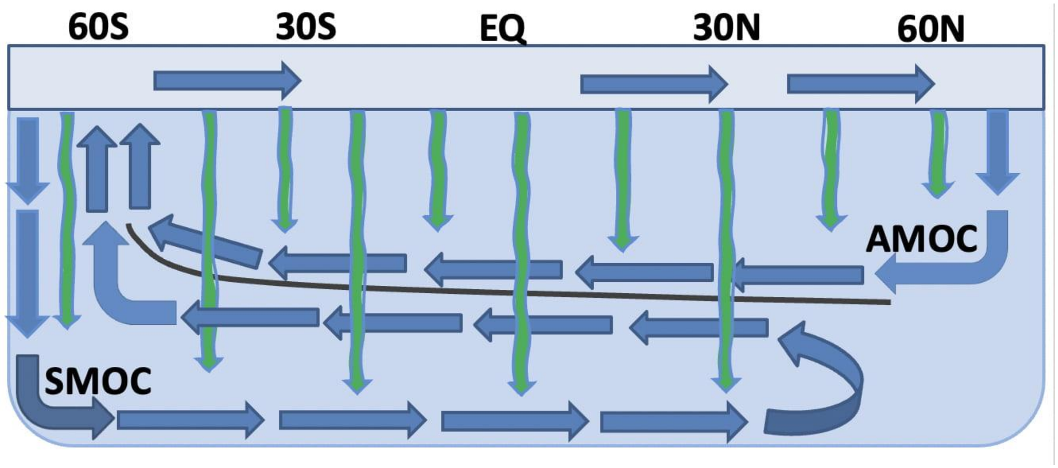


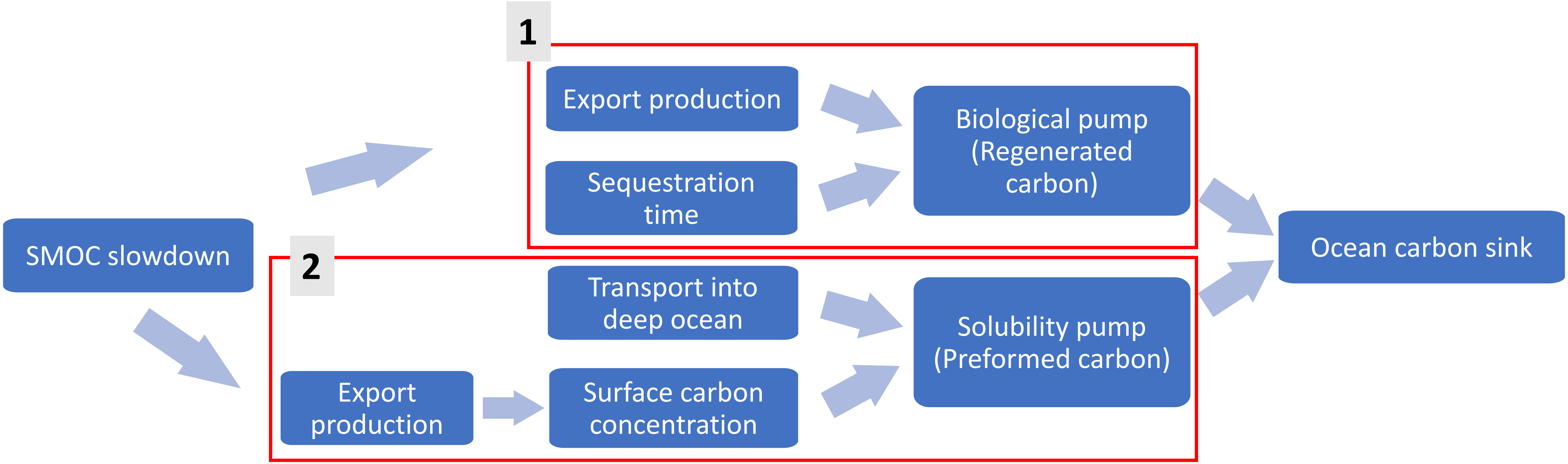
Figure 1. The slowdown of meridional overturning circulation under multiple climate scenarios.

- The meridional overturning circulation (MOC) slows down both in the upper and abyssal cells.
- The slowdown depends on the scenario: The MOC slows more under high-end scenario and less under moderate scenarios.
- To the year 2300, there are only ~5 Sv AMOC left under SSP5-8.5 scenario, and the SMOC almost fully shuts down.



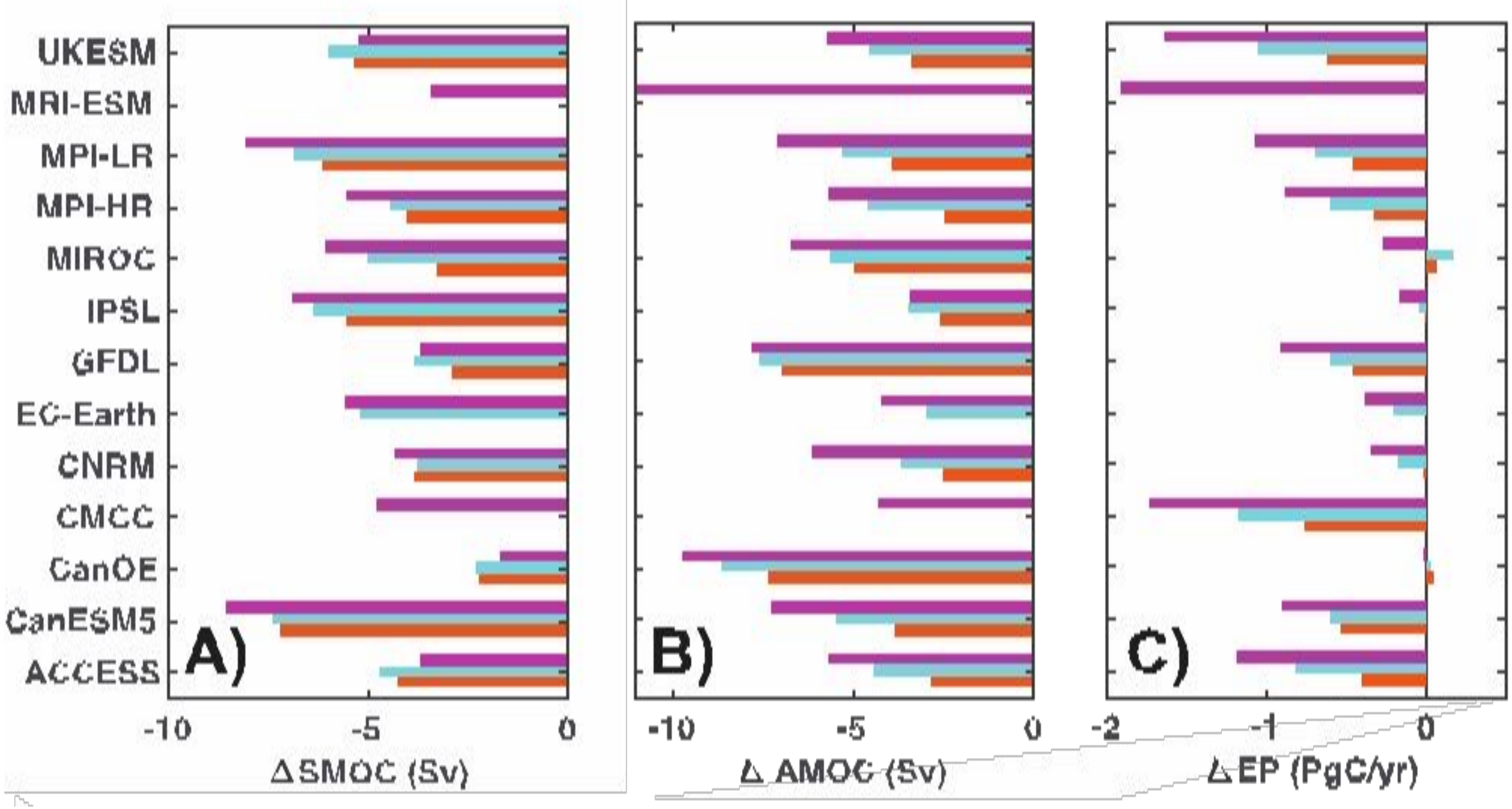
(Ref: Dr. Keith Moore)

Results: Impacts of MOC slowdown on the ocean carbon sink



In this study, we separately explore how SMOC slowdown affects the size of ocean carbon sink through the 1) biological pump (regenerated carbon) and 2) the solubility pump (preformed carbon).

Results: Impacts of MOC slowdown on the ocean carbon sink



- Almost all CMIP6 models show the larger slowdown of AMOC and SMOC under high-end warming scenarios than moderate warming scenarios (Panel A and B).
- Almost all CMIP6 models show decreasing biological carbon export (Panel C), with larger declines under stronger warming.

Results: Impacts of MOC slowdown on the ocean carbon sink

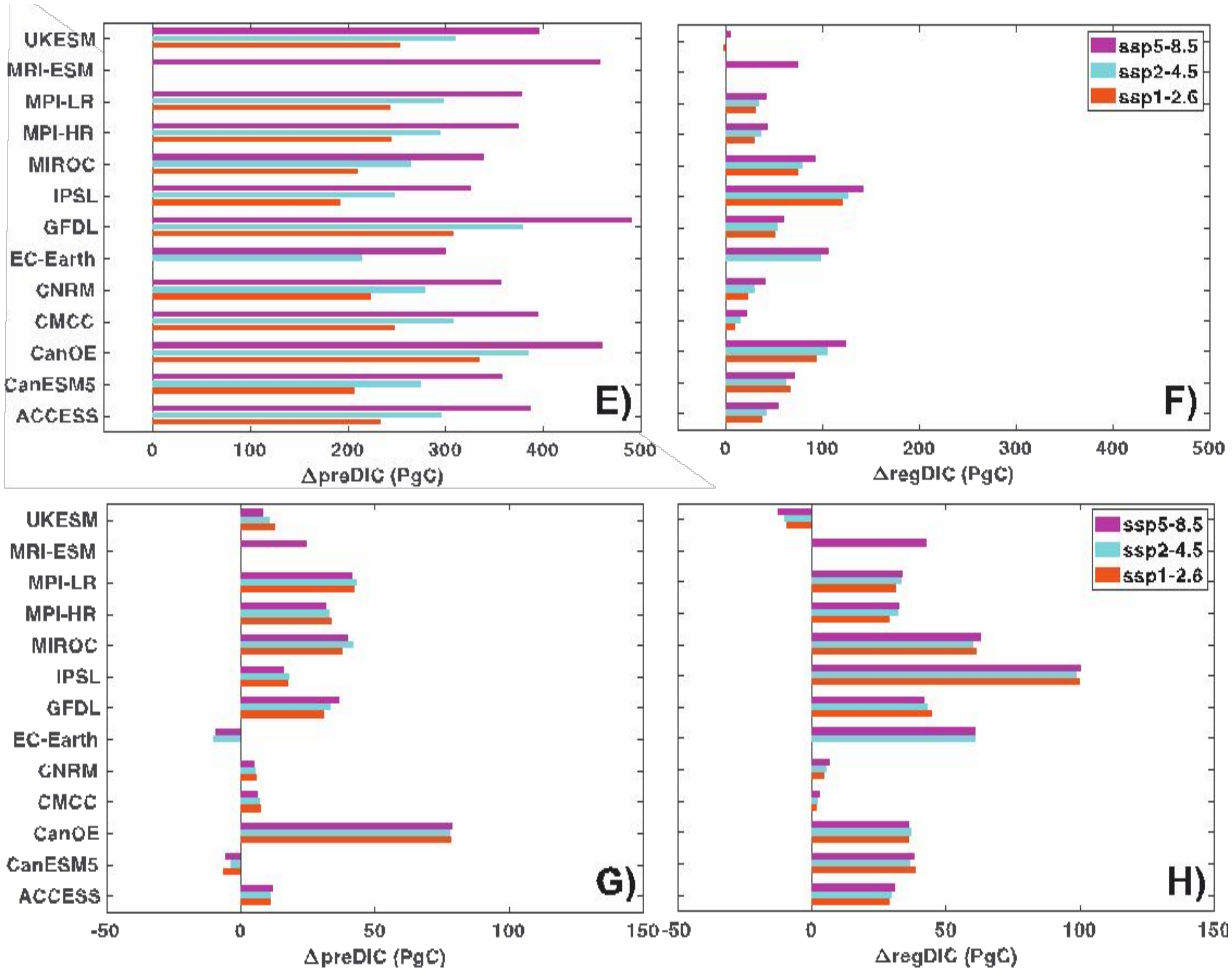


Figure 2. Changes in meridional overturning and carbon storage by 2100.

- Almost all CMIP6 models show increasing preformed carbon (Panel E and G) and regenerated carbon (panel F and H).
- Preformed carbon accumulates more in the intermediate depth (100-2000m) (panel E);
- Regenerated carbon accumulates more in the deep ocean (>2000m) (panel H).

Results: Impacts of MOC slowdown on the ocean carbon sink

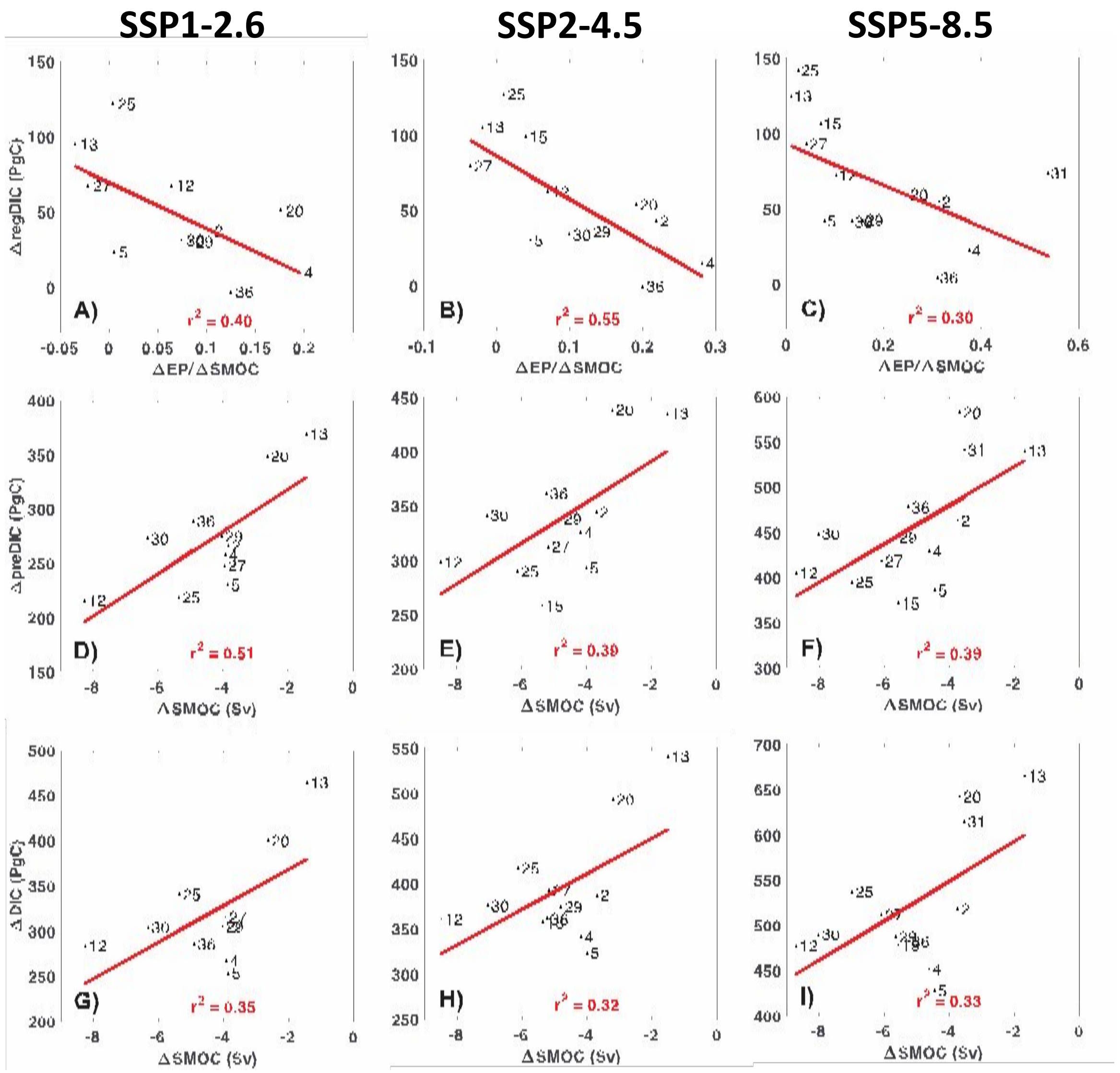


Figure 3. Slowing SMOC rates reduce ocean carbon uptake. The full water column storage of regenerated dissolved inorganic carbon (top row, A-C), preformed DIC (middle row, D-F), and total DIC (bottom row, G-I) by year 2100 (2080-2099 compared to 1850-1869).

- The relative change of export production and SMOC shows negative correlation with the accumulation of regenerated carbon.
- The more slowdown of SMOC -> less accumulation of preformed carbon.
- Net effect: The slowdown of SMOC reduces the size of ocean carbon sink.

CESMv1 + offline transport model (transport matrix method [TMM])

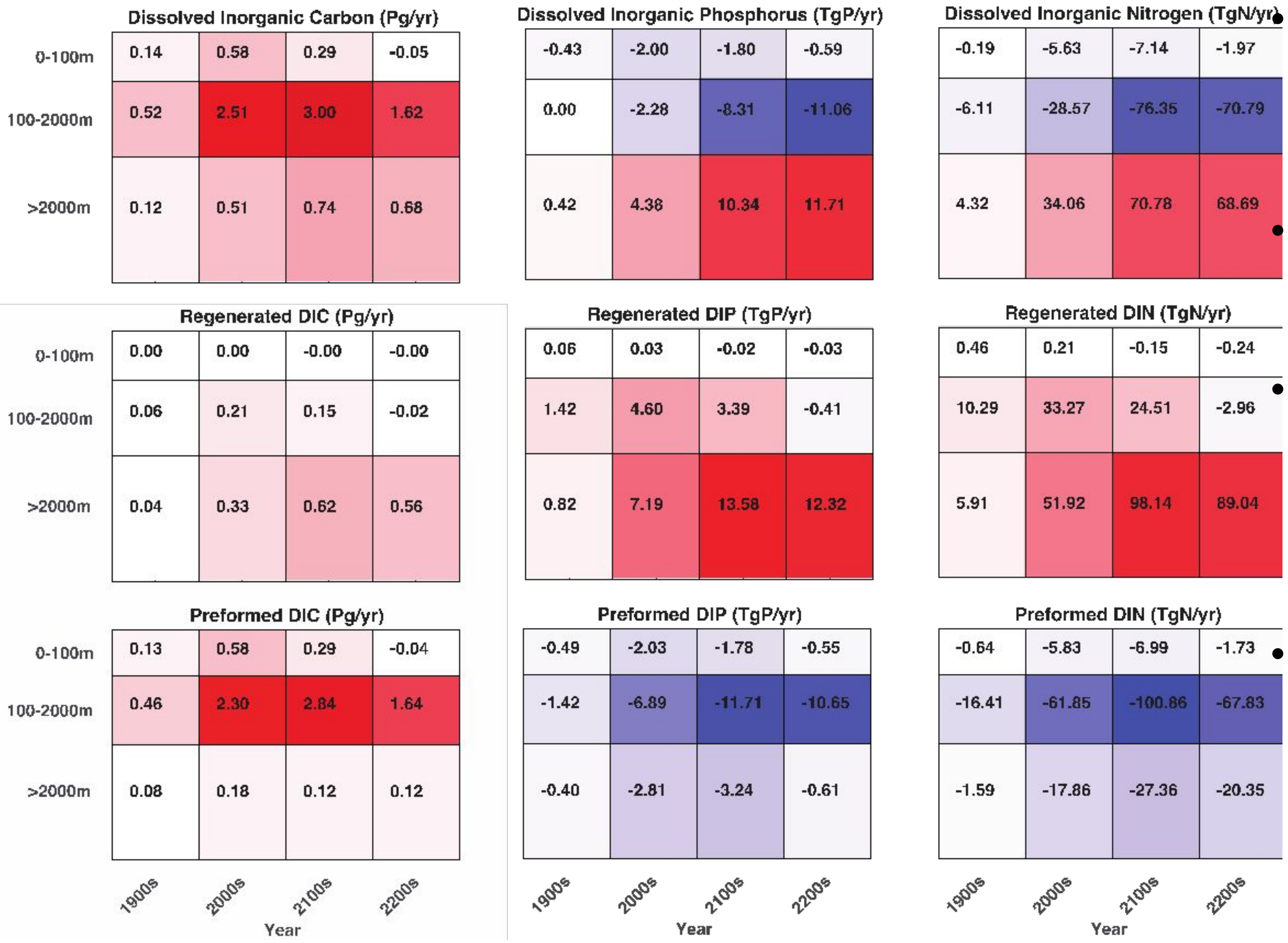


Figure 4. The dissolved inorganic carbon, phosphate and nitrate accumulation rates for each century.

- The accumulation of DIC is initially much larger in surface waters than at depth, due to direct uptake of anthropogenic CO_2 from the atmosphere.
- The strongest accumulation rate progressively shifts to intermediate-depth waters.
- Preformed DIC dominates accumulation at intermediate depths (100–2,000 m), but little has reached the deep ocean, even by 2300, largely due to slowing MOC.
- MOC slowdown sequesters more nutrients in the deep ocean -> Reduce the nutrients supplied to the surface -> Reduce the export production.

Results: Impacts of MOC slowdown on the nutrients and regenerated carbon

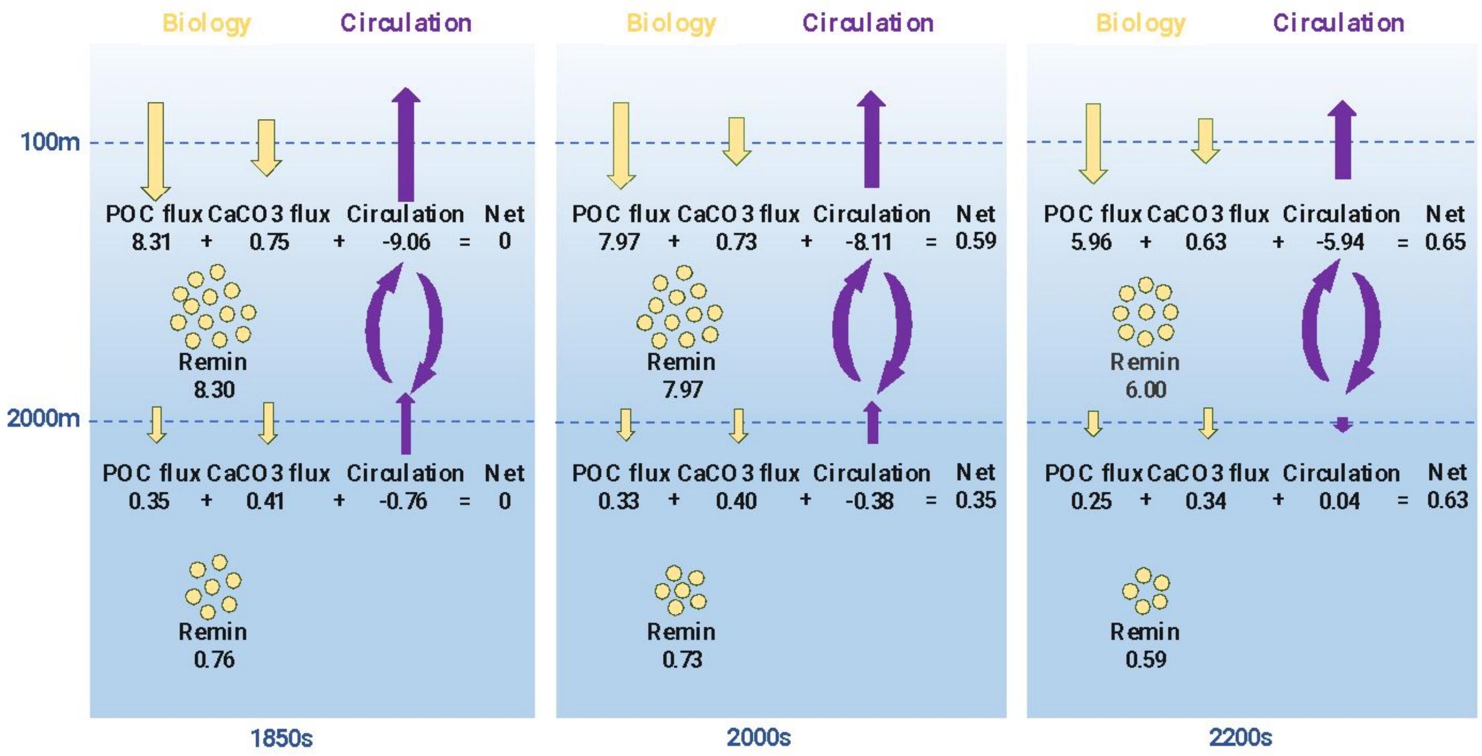
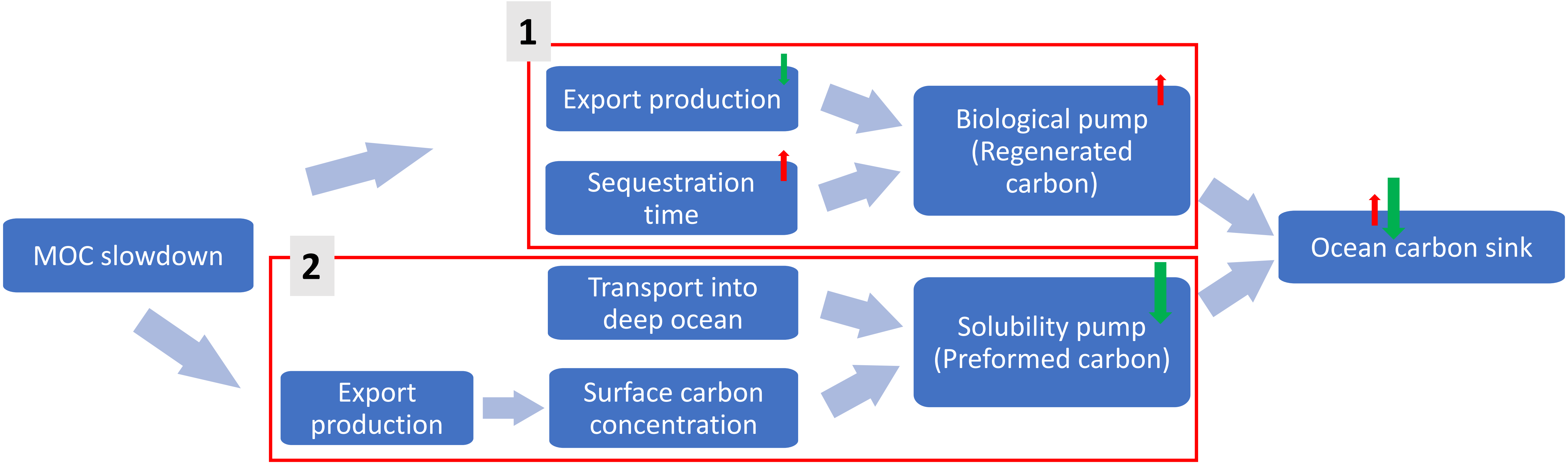


Figure 5. Biological export and changing circulation contributions to regenerated carbon storage under RCP8.5-ECP8.5 climate scenario.

- MOC slowdown -> Sequester nutrients in the deep ocean -> Decrease export production
- MOC slowdown -> Increase sequestration time -> Less carbon removal from the atmosphere
- Net effect: MOC slowdown -> more regenerated carbon at depth

Summary and Conclusion



- The slowdown of MOC depends on the scenario: MOC slows more on high-end scenarios, less under moderate scenarios.
- The slowdown of SMOC decreases export production but increases the carbon sequestration time,
  and the net effect is to accumulate more regenerated carbon in the ocean.
- The slowdown of SMOC reduces the accumulation of preformed carbon in the oceans, but the specific mechanisms are not well understood.

- **Net effect: The slowdown of SMOC reduces the ocean carbon sink, and explains ~1/3 of spread across CMIP6 models.**