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Timing and magnitude of Southern Ocean sea ice/carbon cycle feedbacks

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- https://www.pnas.org/content/117/9/4498.abstract
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Timing and magnitude of Southern Ocean sea ice/carbon cycle feedbacks

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The Southern Ocean (SO) played a prominent role in the exchange of carbon between ocean and atmosphere on glacial timescales through its regulation of deep ocean ventilation. Previous studies indicated that SO sea ice could dynamically link several processes of carbon sequestration, but these studies relied on models with simplified ocean and sea ice dynamics or snapshot simulations with general circulation models. Here, we use a transient run of an intermediate complexity climate model, covering the past eight glacial cycles, to investigate the orbital-scale dynamics of deep ocean ventilation changes due to SO sea ice. Cold climates increase sea ice cover, sea ice export, and Antarctic Bottom Water formation, which are accompanied by increased SO upwelling, stronger poleward export of Circumpolar Deep Water, and a reduction of the atmospheric exposure time of surface waters by a factor of 10. Moreover, increased brine formation around Antarctica enhances deep ocean stratification, which could act to decrease vertical mixing by a factor of four compared with the current climate. Sensitivity tests with a steady-state carbon cycle model indicate that the two mechanisms combined can reduce atmospheric carbon by 40 ppm, with ocean stratification acting early within a glacial cycle to amplify the carbon cycle response.

Southern Ocean | sea ice | glacial cycles | carbon cycle

The Southern Ocean (SO) plays a critical role in the climate system, controlling the exchange of heat and gases between deep ocean water and atmosphere (1) (i.e., regulating the ventilation of the deep ocean). SO processes are thought to be the dominant driver of past variations in atmospheric carbon concentrations on orbital and millennial timescales (2, 3), an idea supported by the close correlation of the ice core reconstructions of atmospheric CO_2 and Antarctic temperature (4). The pool of carbon in the deep ocean is roughly 60× that in the atmosphere (5), and therefore, small perturbations to the flux of carbon into and out of the deep ocean can have large impacts on the atmosphere. While multiple processes are involved in carbon sequestration during glacial climates (2, 6), the regularity and orbital frequencies of the carbon record over glacial cycles imply that the driving mechanisms are dynamically linked. Moreover, those drivers are likely physical processes as changes in marine productivity occur relatively late within glacial cycles (7). Here, we focus on the physical mechanisms that could lead to decreased ventilation of the deep ocean during glacial climates, which broadly speaking, would require a decrease in some combination of 1) overturning circulation of deep ocean waters (8, 9), 2) mixing of abyssal water with the overlying waters (10–12), and 3) gas exchange between the atmosphere and deep waters after upwelling in the SO (13, 14).

The SO determines the ventilation of the deep ocean to the atmosphere both through upwelling of deep ocean water to the surface along isopycnals and through its influence on abyssal stratification and thereby, diapycnal mixing. The SO is where most deep ocean water returns to the surface as Circumpolar Deep Water (1) as part of a meridional circulation that is driven by surface momentum and density fluxes (15). The wind-driven Ekman circulation in the SO is largely compensated by eddy-induced transports (16), arising from baroclinic instabilities along the strongly sloped isopycnals, such that the residual overturning is primarily determined by the surface buoyancy forcing (17, 18). At high latitudes, the cold temperature limits the thermal expansion of seawater (19), and therefore, the surface buoyancy is dominated by freshwater fluxes, especially those associated with sea ice formation and melting (20).

Several studies have pointed to SO sea ice as a critical variable driving decreased deep ocean ventilation during glacial climates. Decreased air–sea gas exchange due to expanded sea ice coverage showed potential in a six-box model to significantly increase deep ocean carbon sequestration without producing deep ocean anoxia (13), although box models may be overly sensitive to perturbations (21). The increase of parameterized brine rejection from sea ice formation was shown to effectively stratify the deep ocean in an intermediate complexity climate model (10), and coupled general circulation model experiments have indicated that brine formation and shelf convection in the SO are key processes in shoaling the upper ocean meridional convection cell (22). Simplified dynamical scaling arguments (11) and idealized circulation model experiments (9) indicated that buoyancy forcing by sea ice could expand the pool of Antarctic Bottom Water during the Last Glacial Maximum (LGM), providing a larger and colder pool that would be more isolated from the atmosphere due to sea ice coverage and inhibited topographic mixing if the deep pool expanded above 2-km depth. However, diapycnal mixing in the SO may limit the impact of SO

Significance

Atmospheric carbon was sequestered in the ocean during glacial periods, but the processes responsible are not understood. Southern Ocean (SO) sea ice has been proposed as a link between several processes of carbon sequestration. This study analyzes the effect of SO sea ice on ocean ventilation in a 784,000-y climate model simulation. The results show that SO sea ice can dramatically reduce ocean ventilation by reducing the atmospheric exposure time of surface waters and by decreasing the vertical mixing of deep ocean waters. Sensitivity tests of the two mechanisms with a carbon cycle model show a 40-ppm reduction of atmospheric CO_2, half the glacial/interglacial difference, with ocean stratification playing the leading role in both magnitude and timing.

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The authors declare no competing interest.

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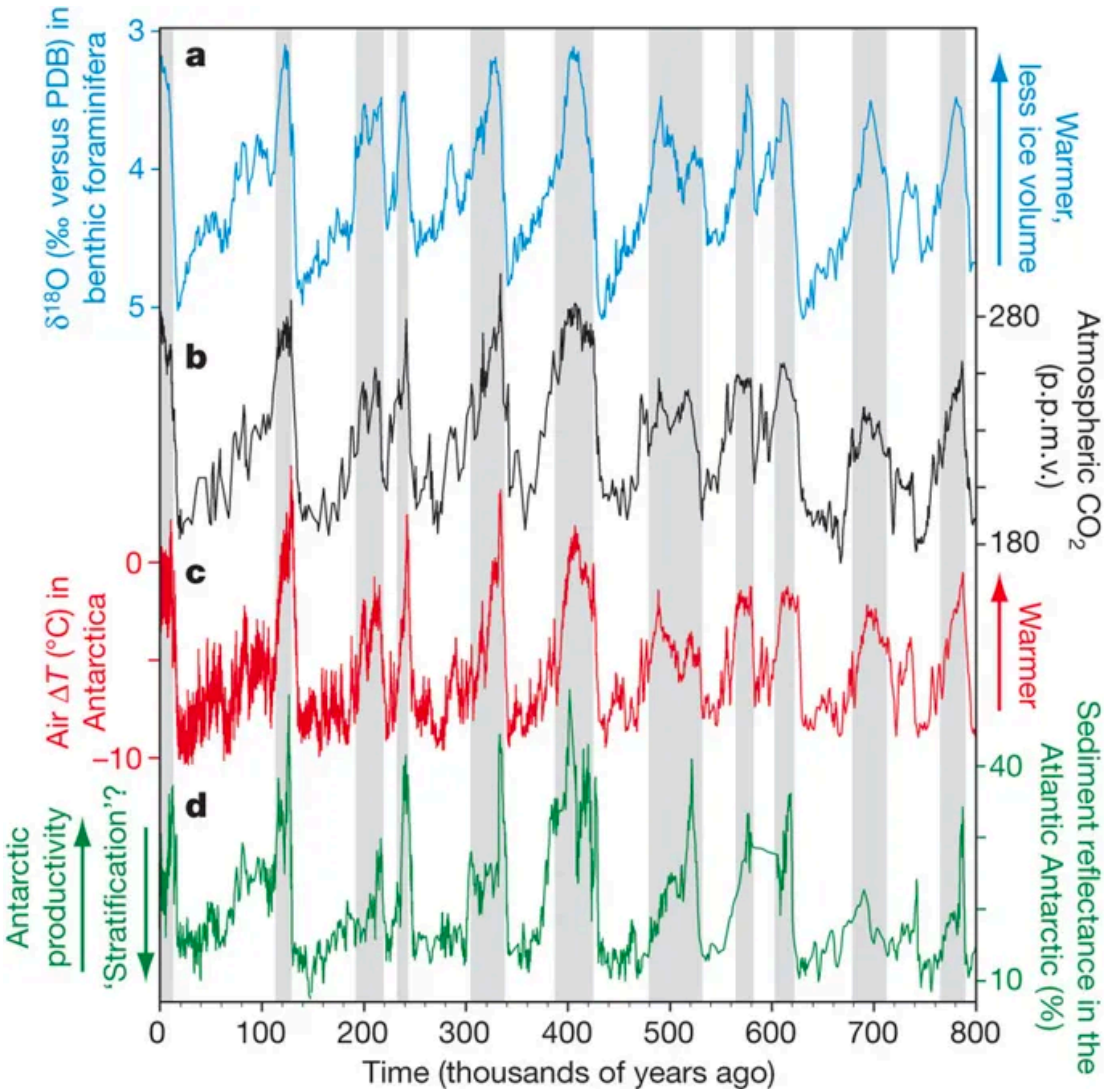
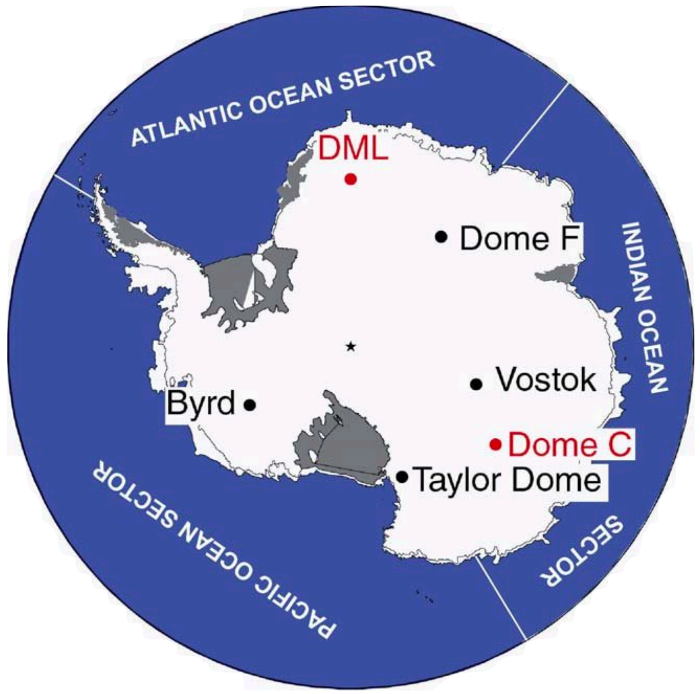
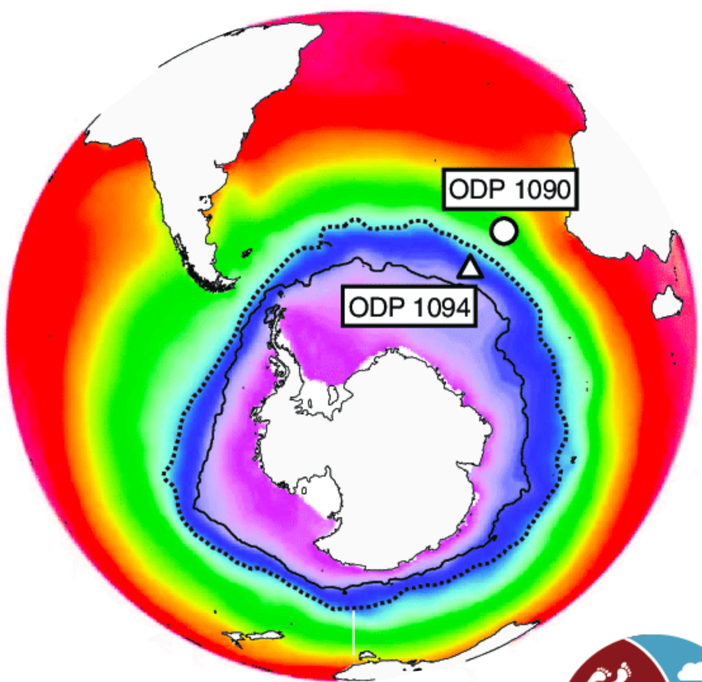
Big question: how does the ocean store and release atmospheric carbon over glacial cycles?

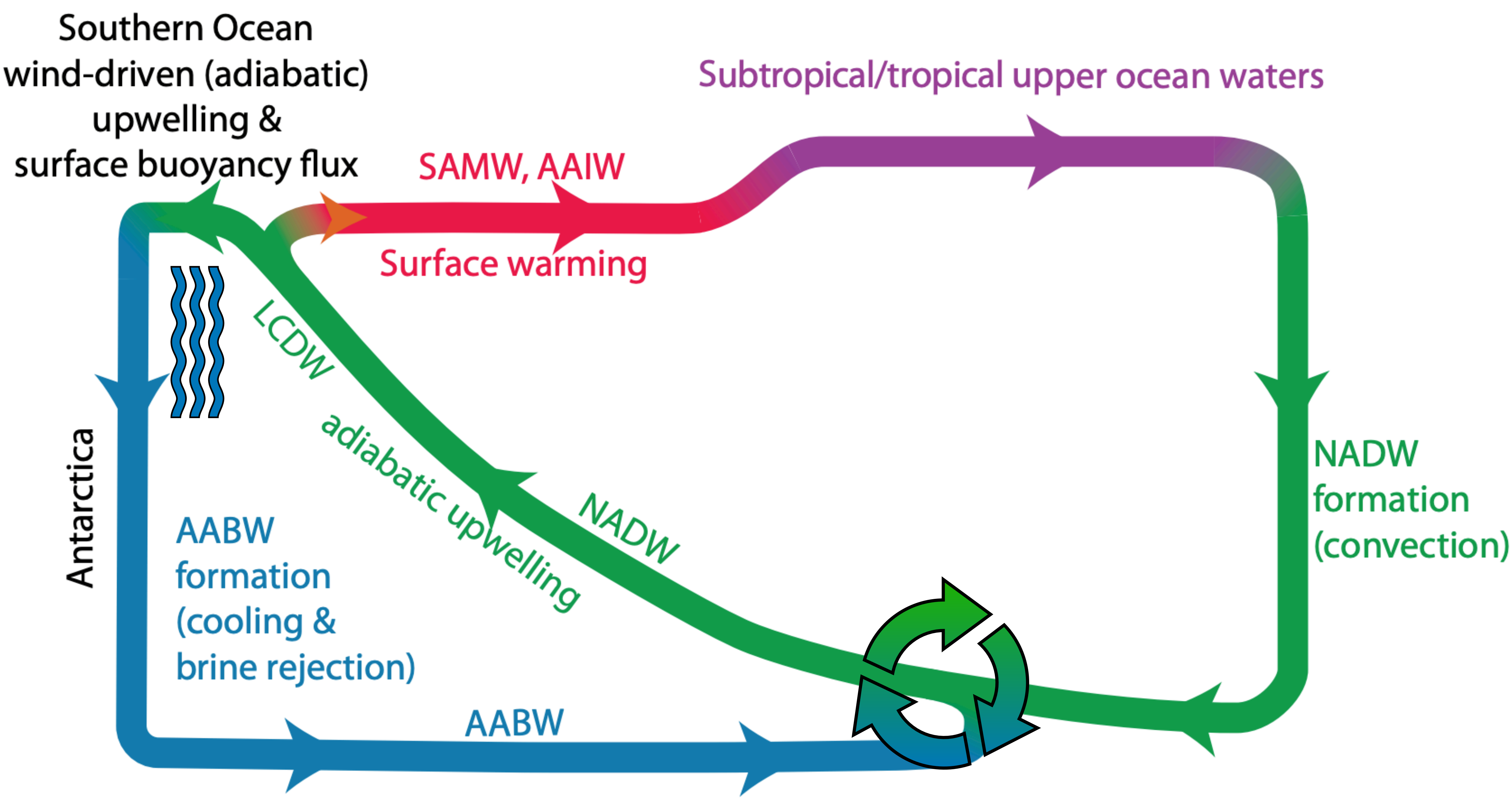






Sigman et al, *Nature*, 2010

The Southern Ocean may be key to the process, due to its impact on the ventilation of the deep ocean.



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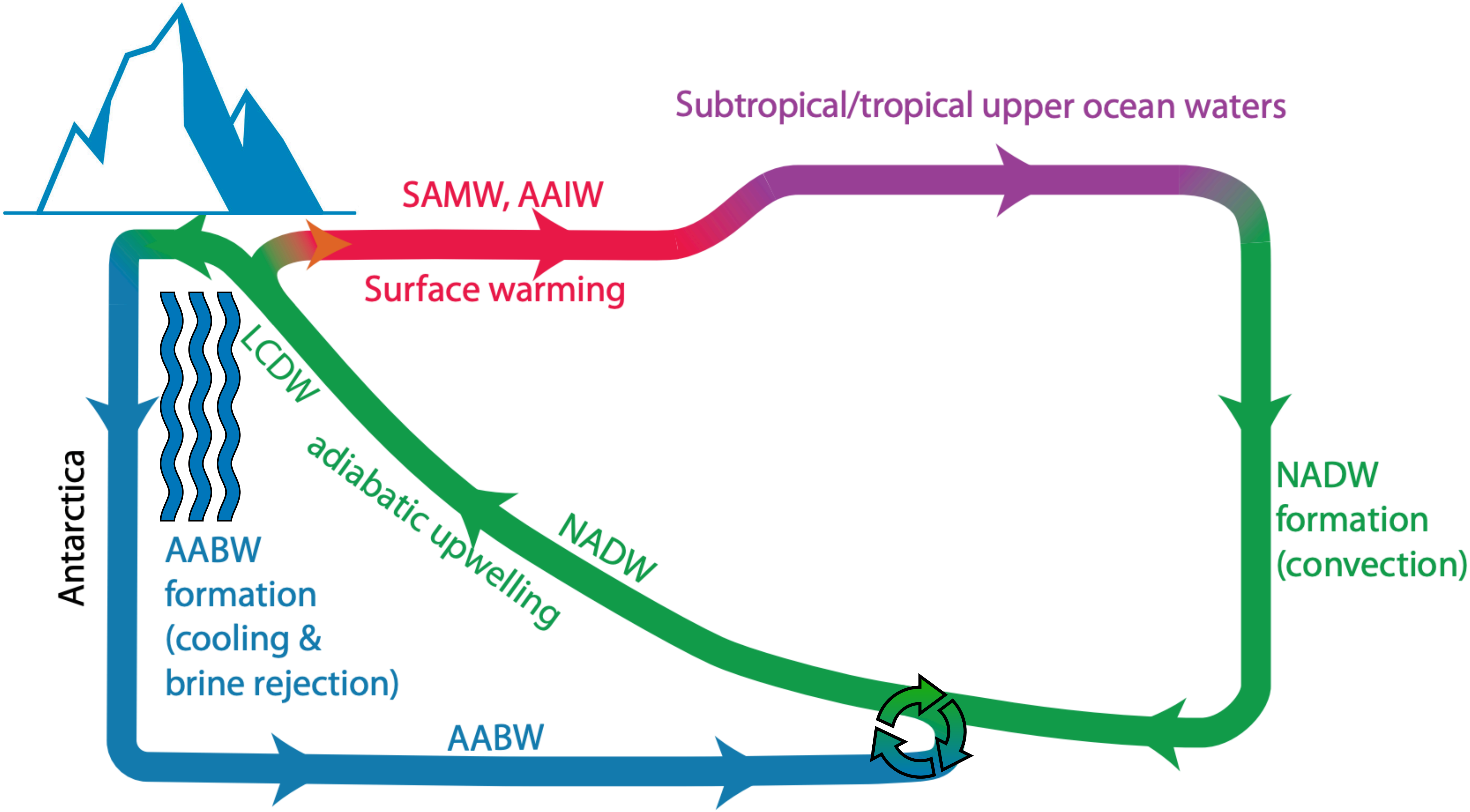


Talley, *Oceanography*, 2013

Method: 784,000 year transient experiment with the LOVECLIM intermediate climate model

Atmosphere
ECBILT
Global, spectral, quasi-geostrophic, T21

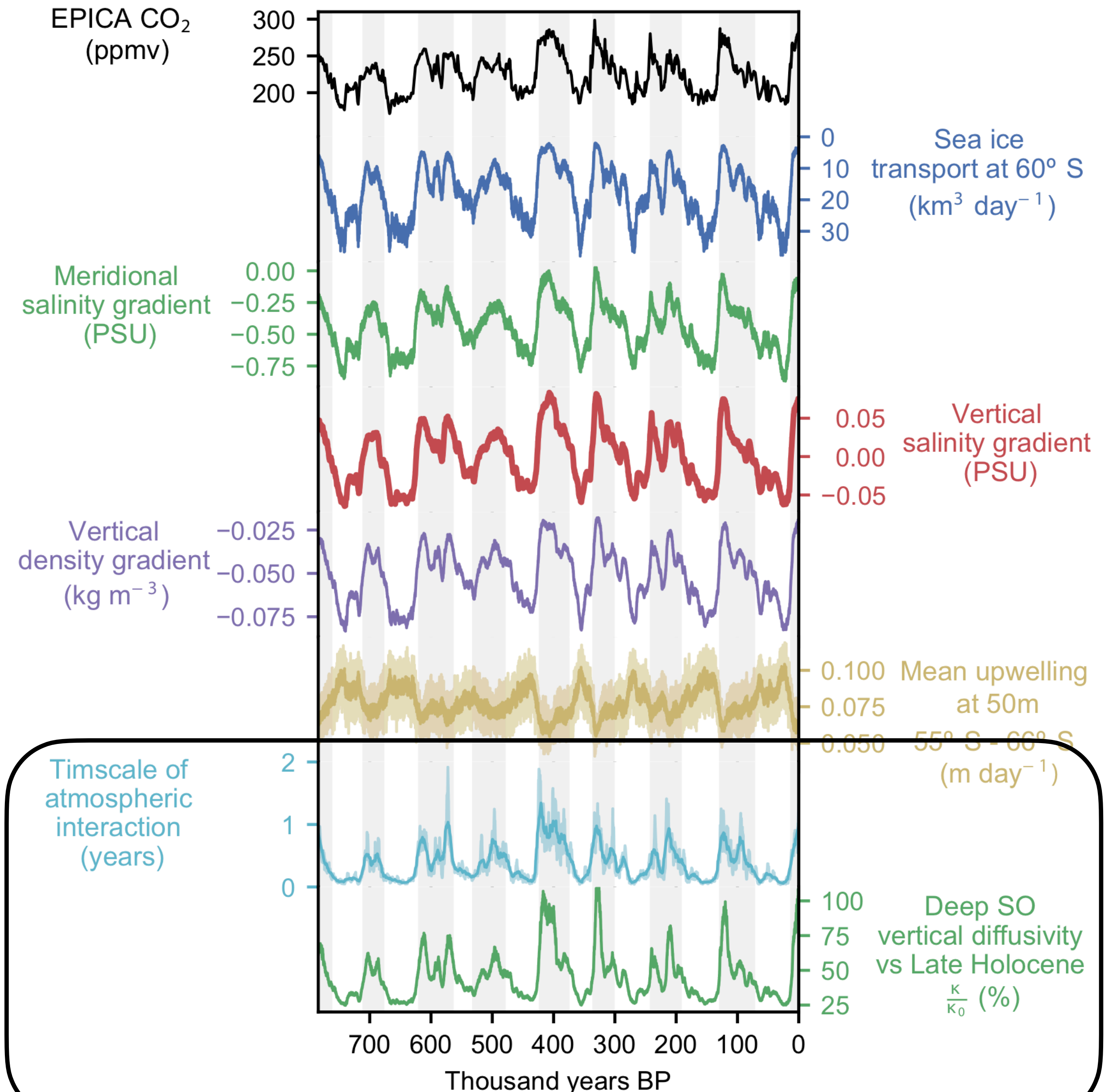
Forcing
5x orbital acceleration, greenhouse gases, and ice sheets from CLIMBER-2

Ocean & sea ice
Clio
Primitive-Equation, free surface GCM coupled to thermodynamic sea-ice model, ~3°X3° resolution

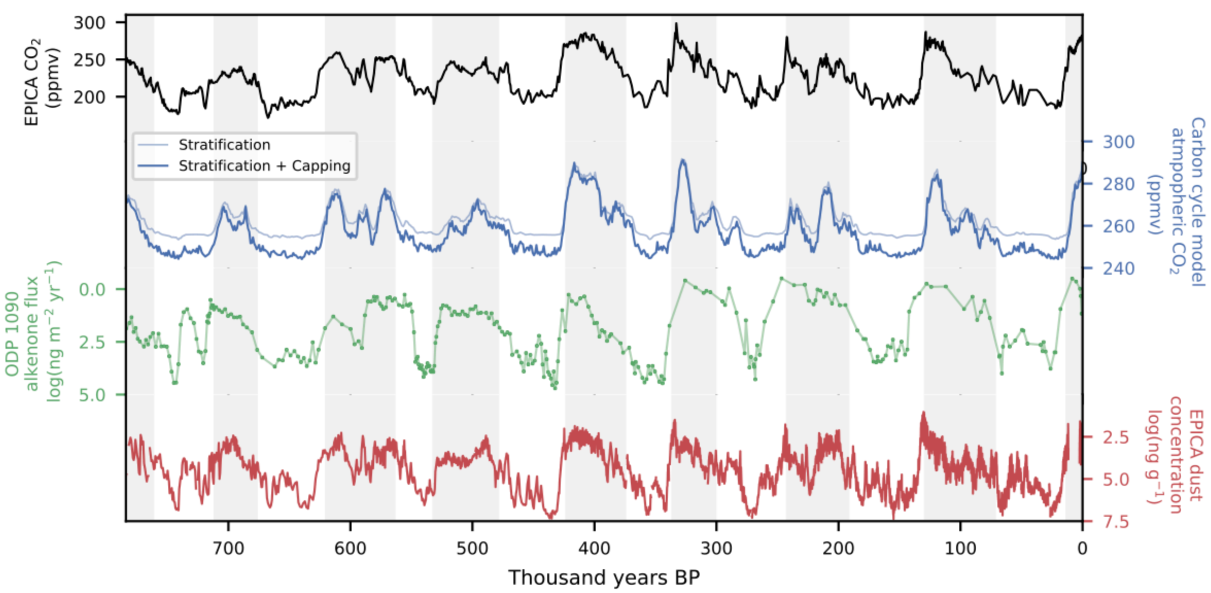
Vegetation
VECODE
Land cover model, fractional areas of grass, tress, & deserts

Method

LOVECLIM



Carbon cycle model

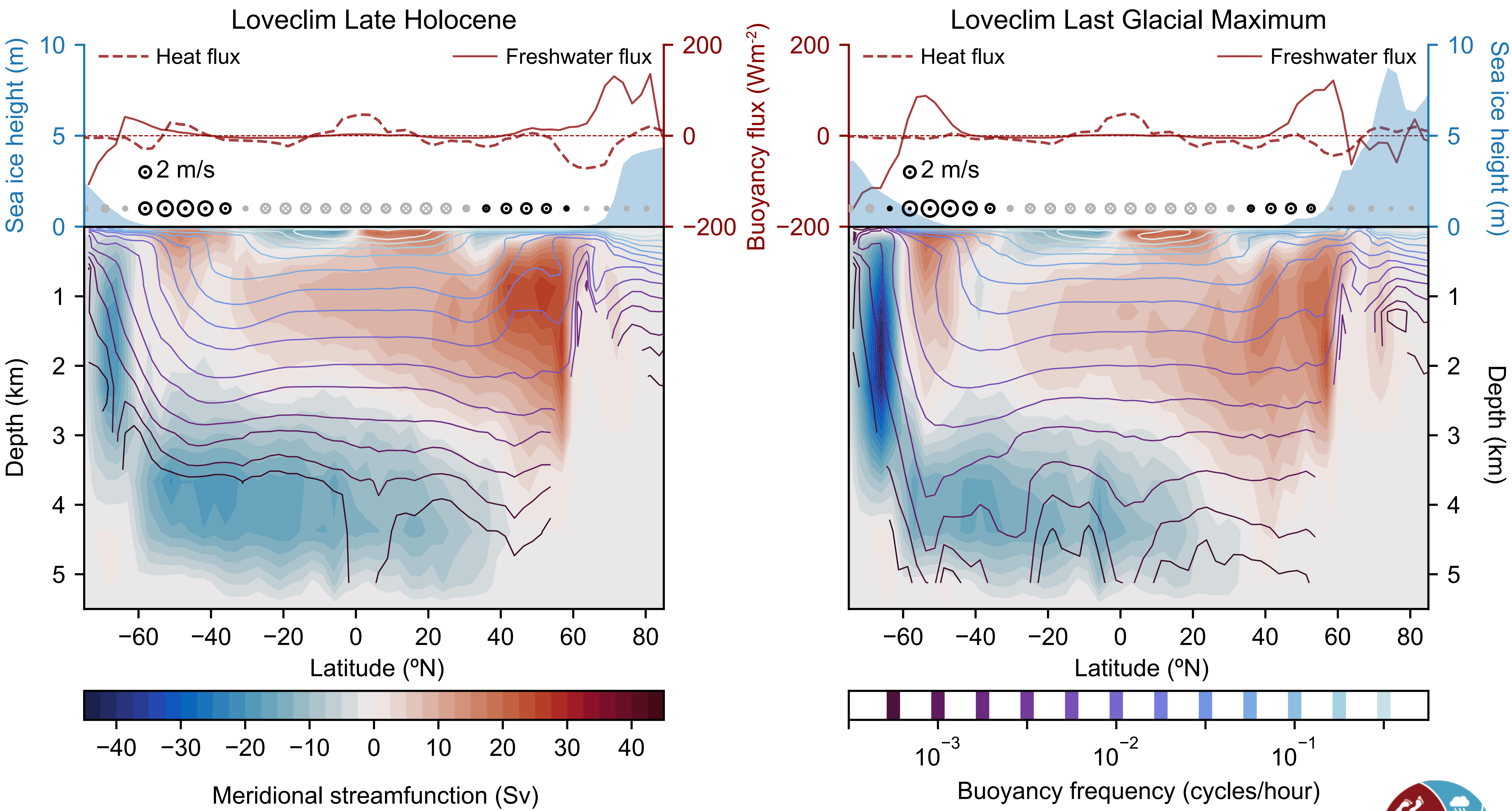


2) Test the impact of mechanisms in an offline carbon cycle model

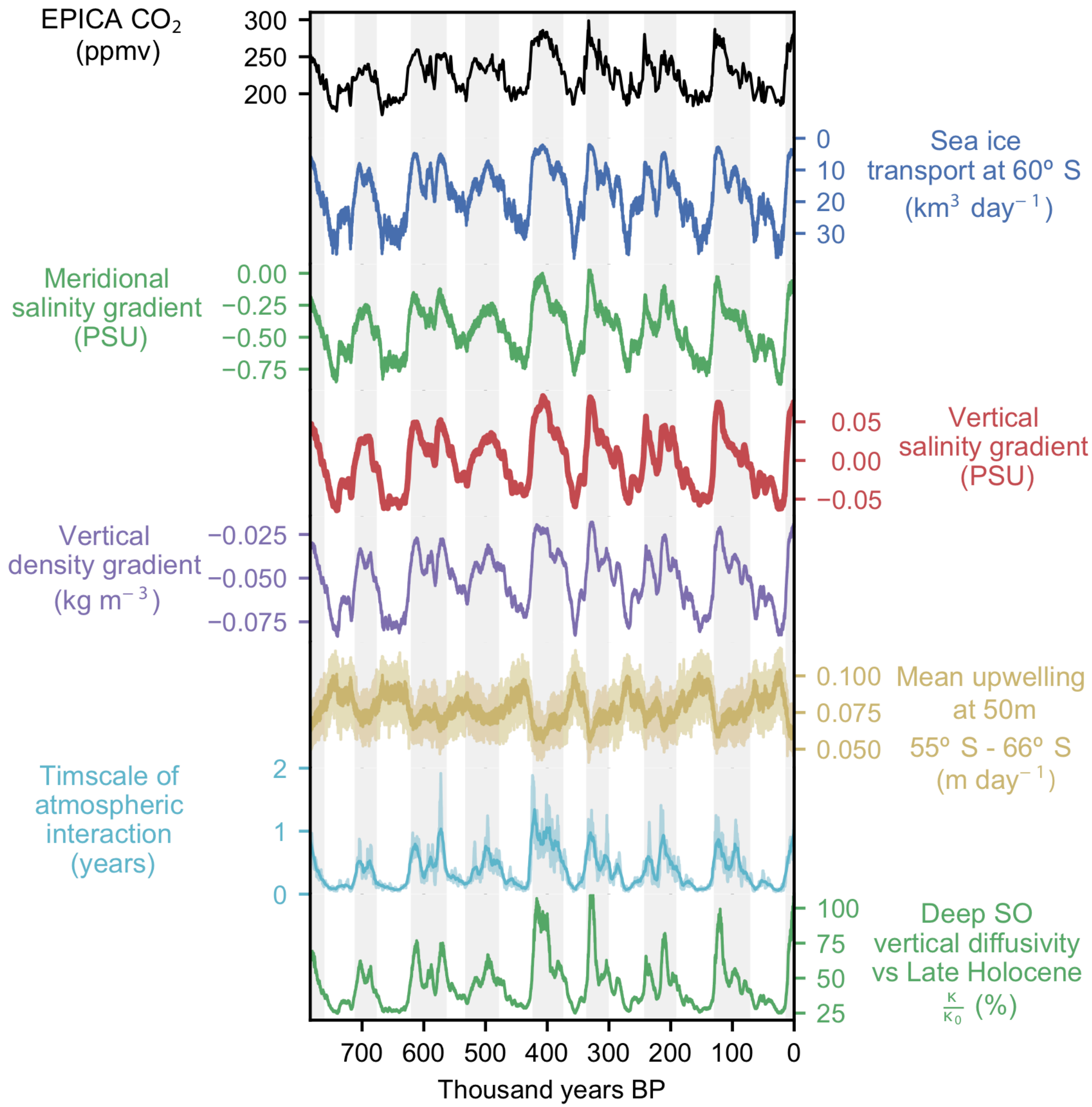
1) Identify physical mechanisms linking sea ice to deep ocean ventilation in LOVECLIM

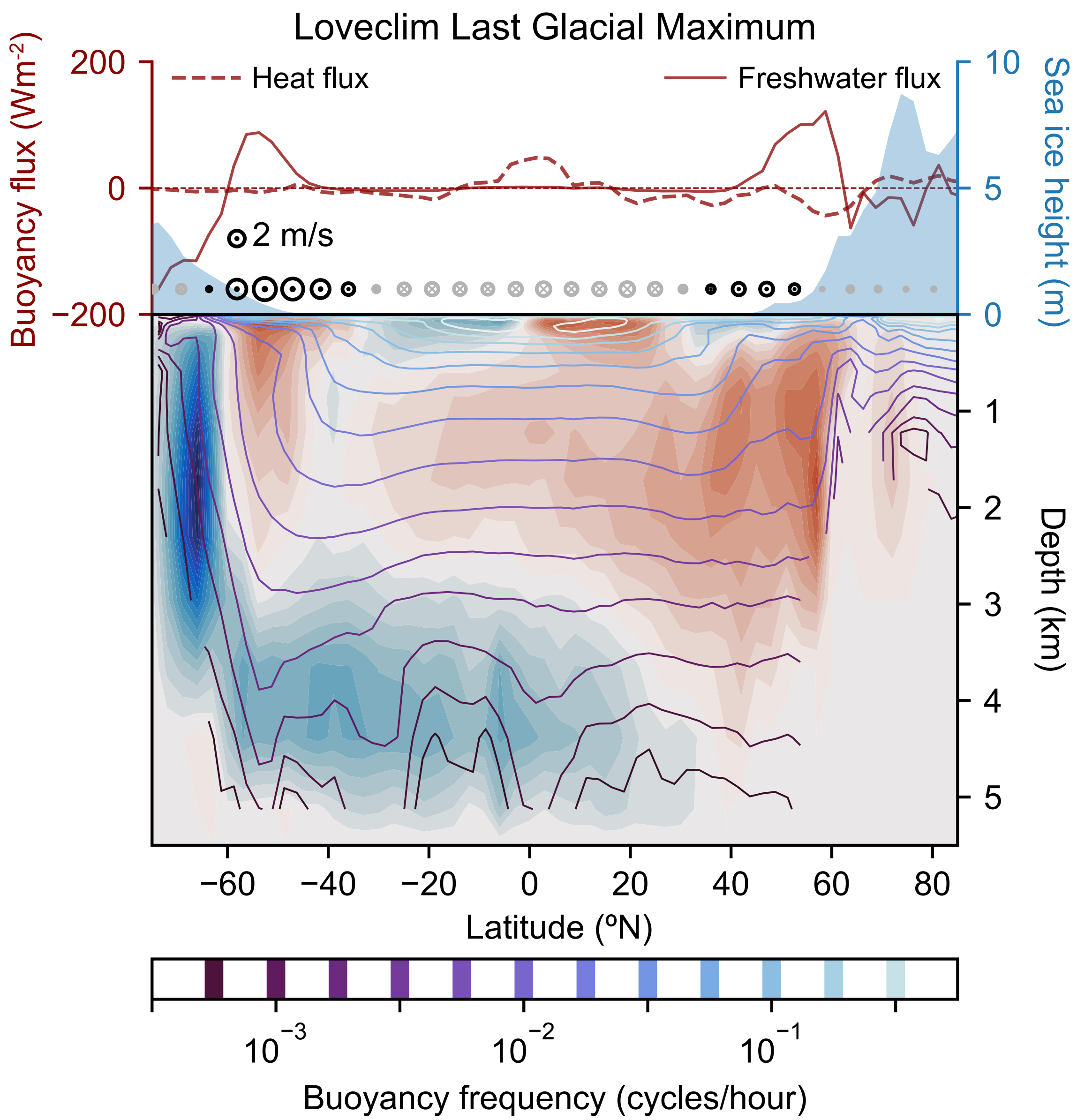
ICCP

LOVECLIM composites

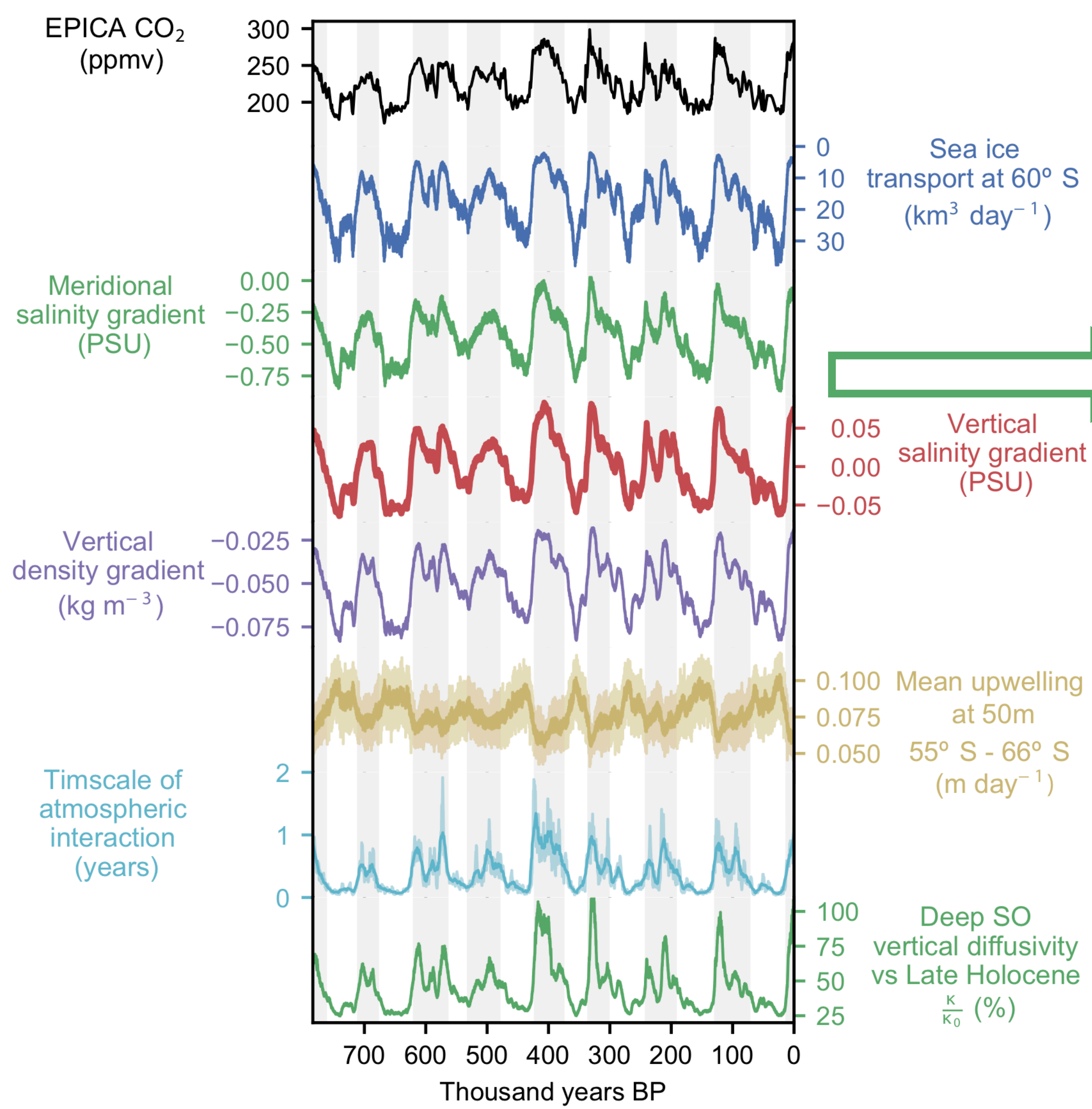


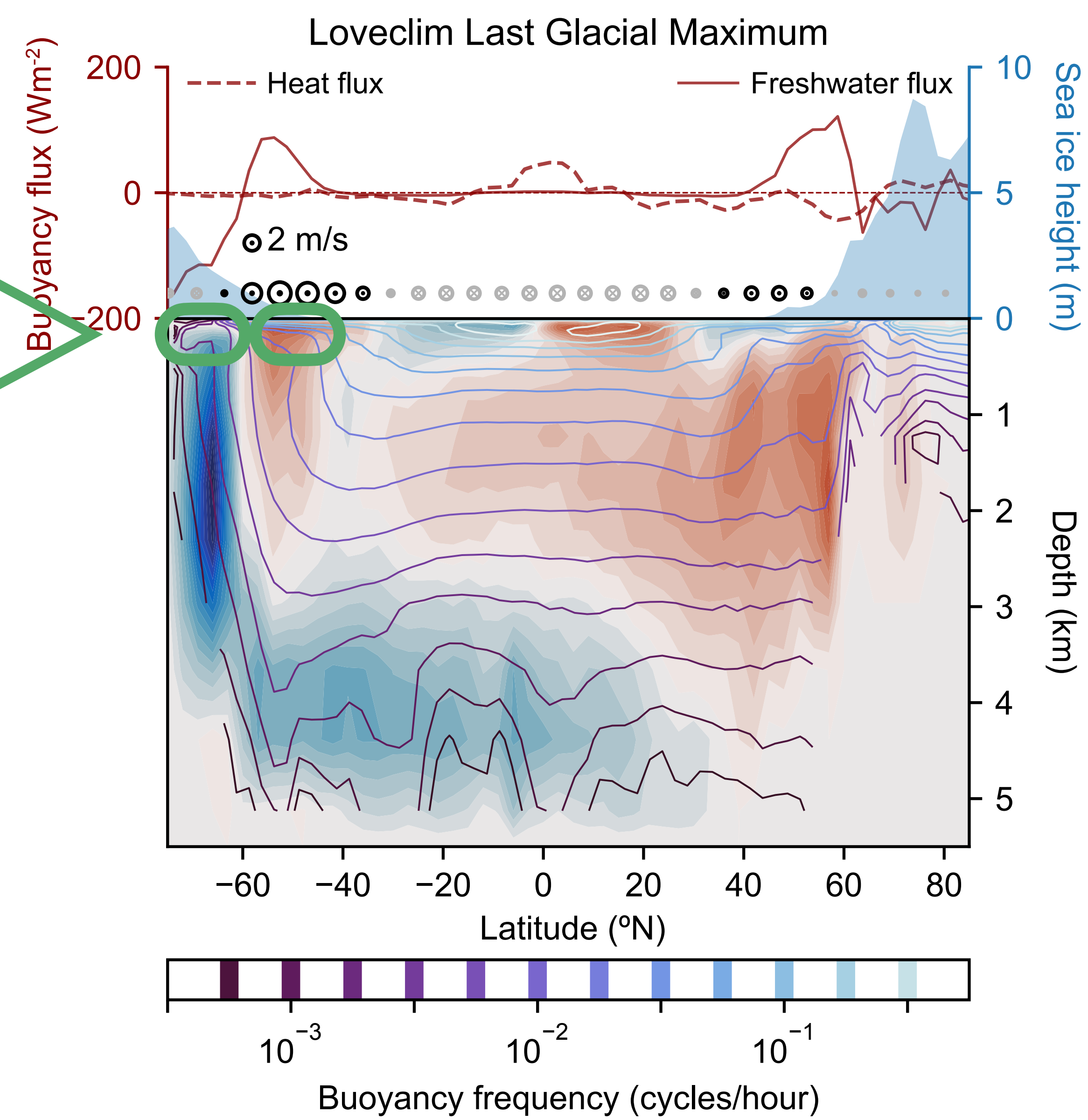
LOVECLIM time series



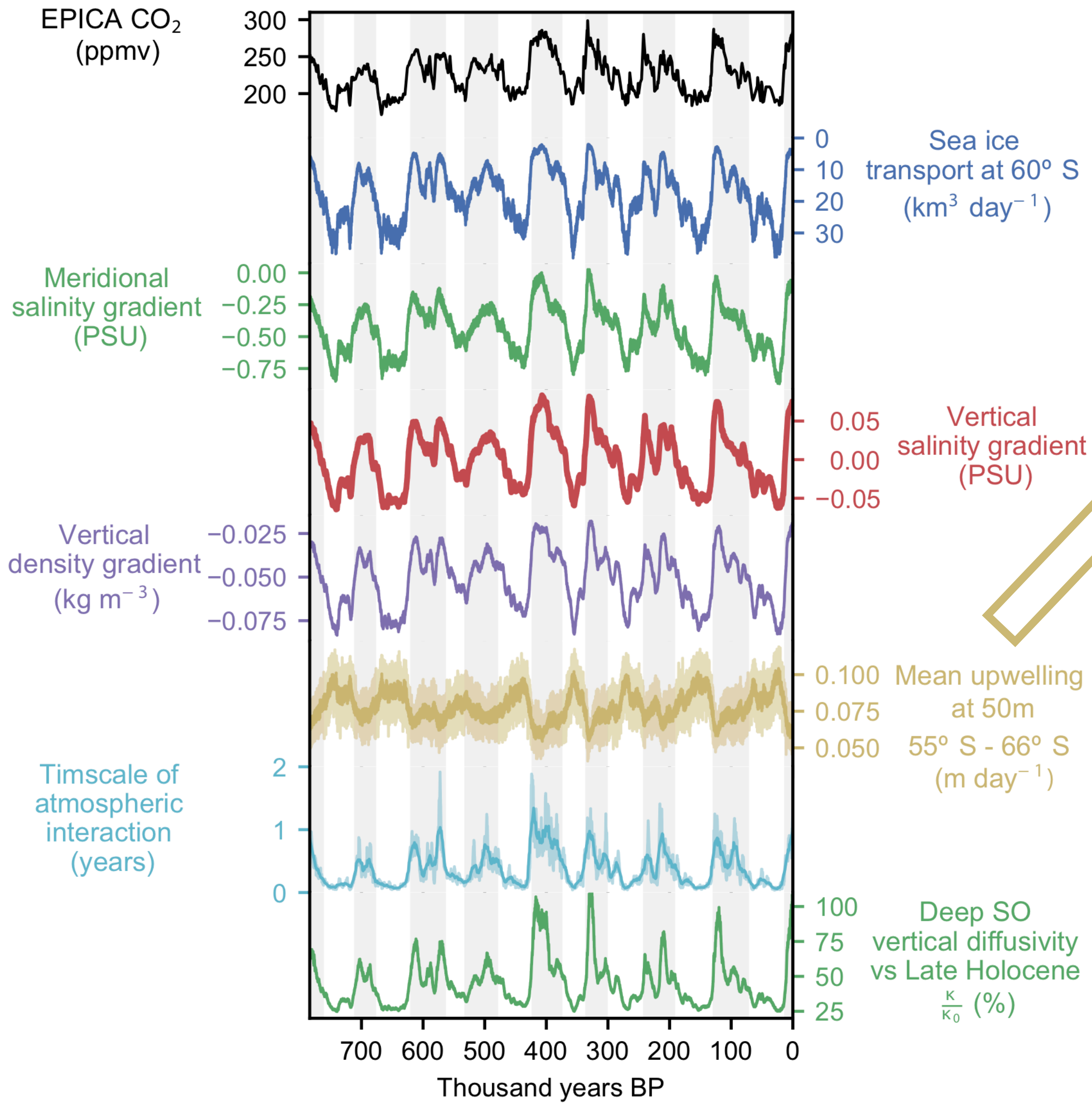


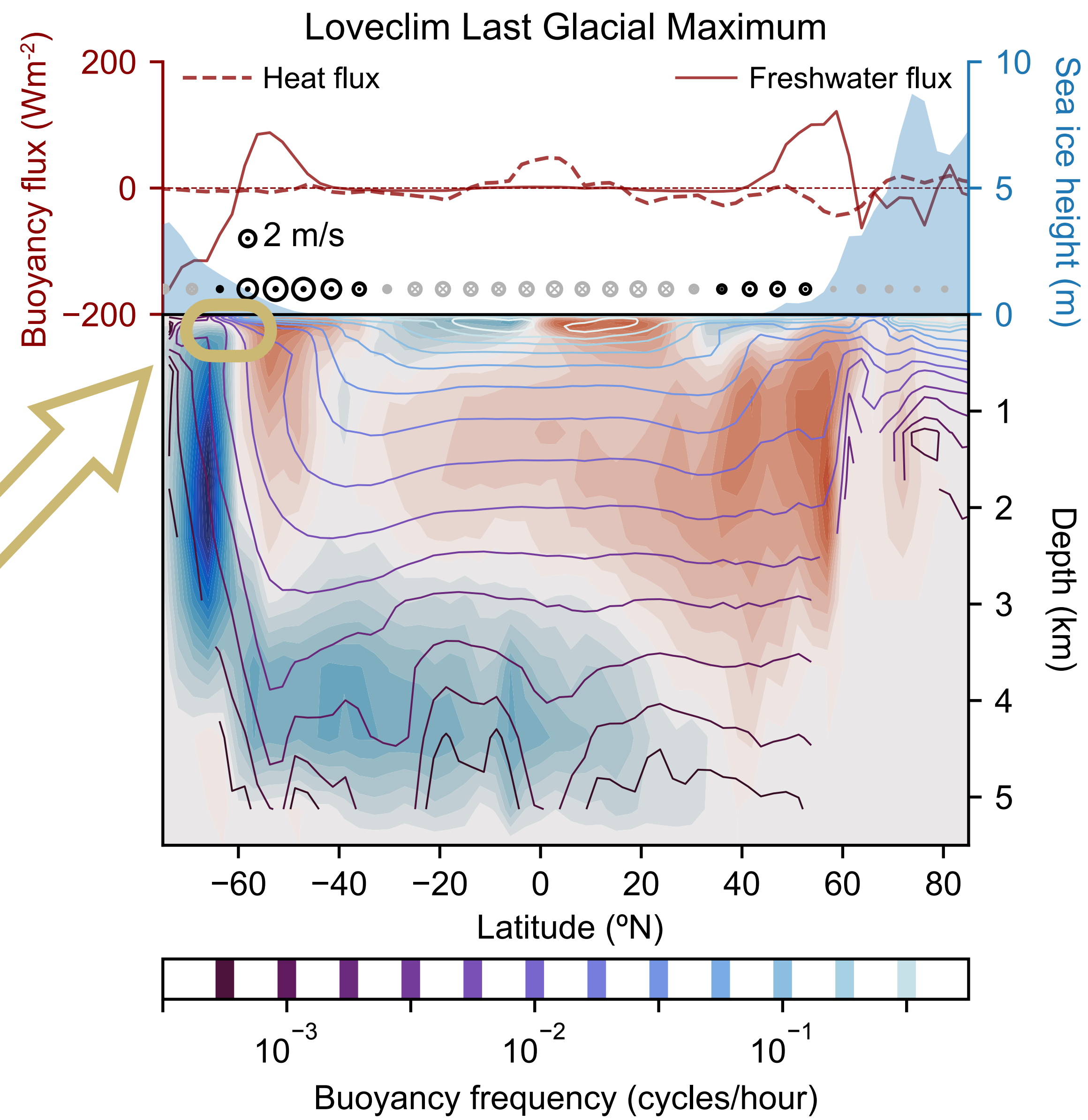
LOVECLIM time series



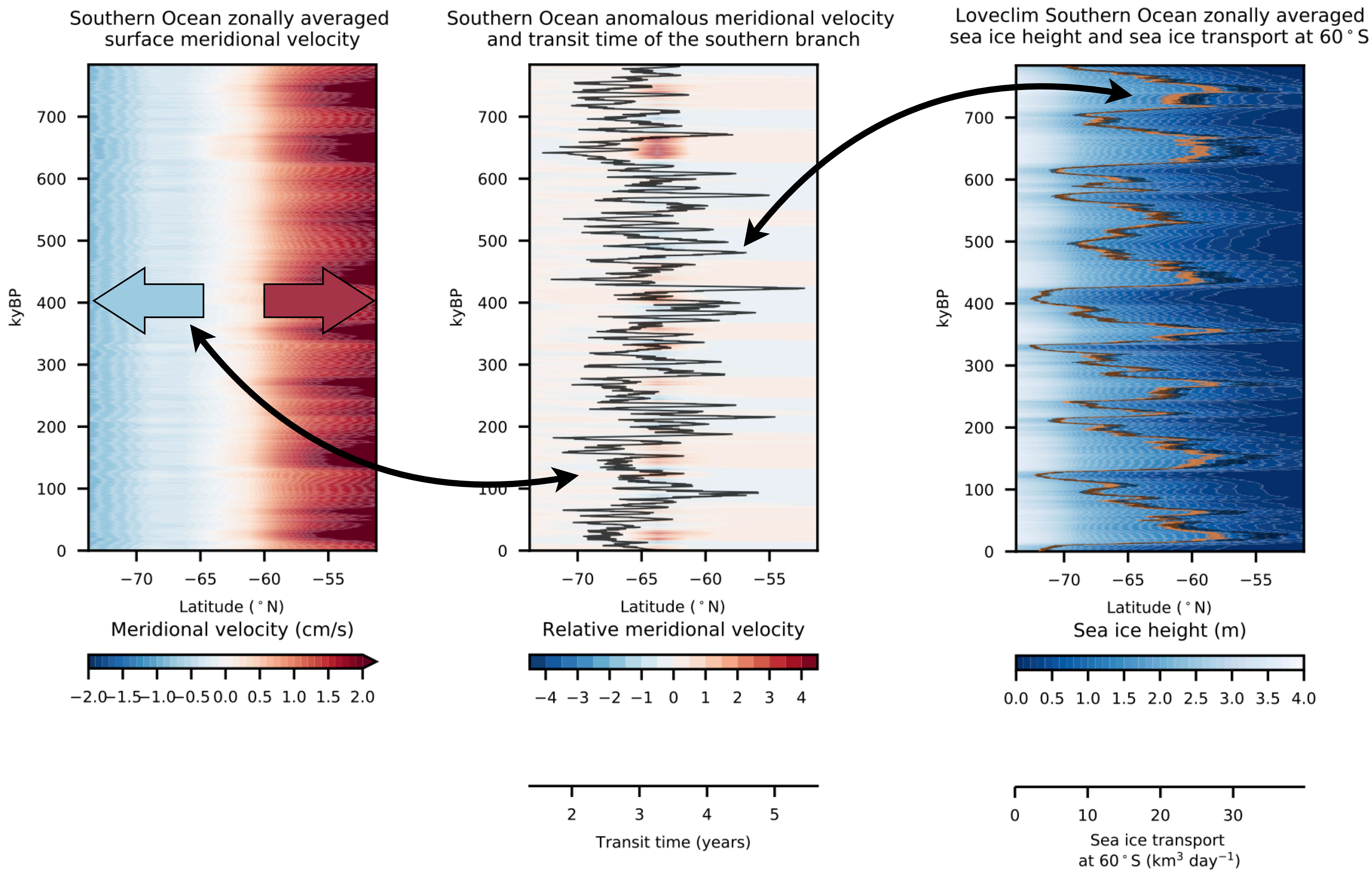


LOVECLIM time series

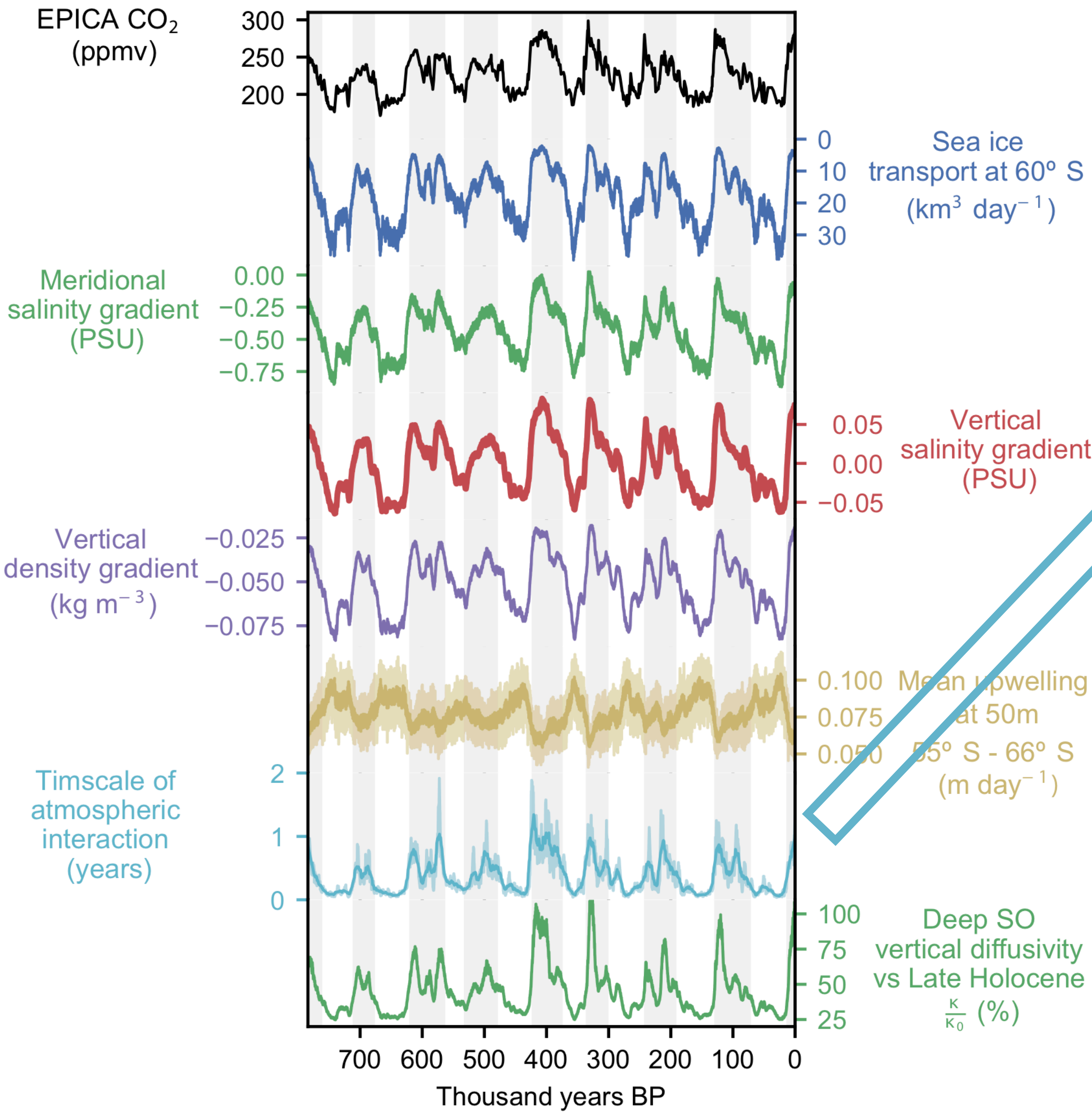


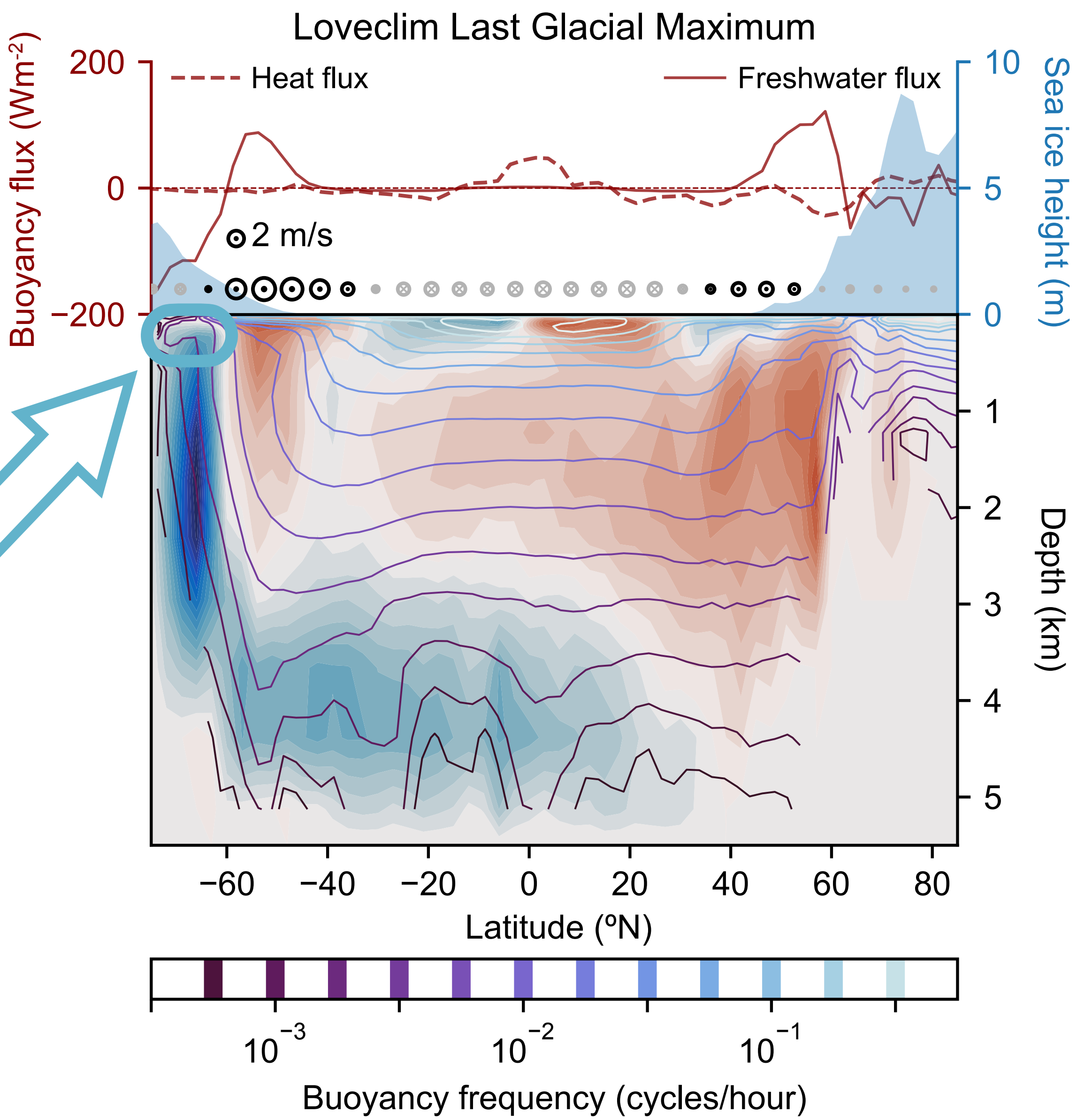


Timescale of atmospheric interaction

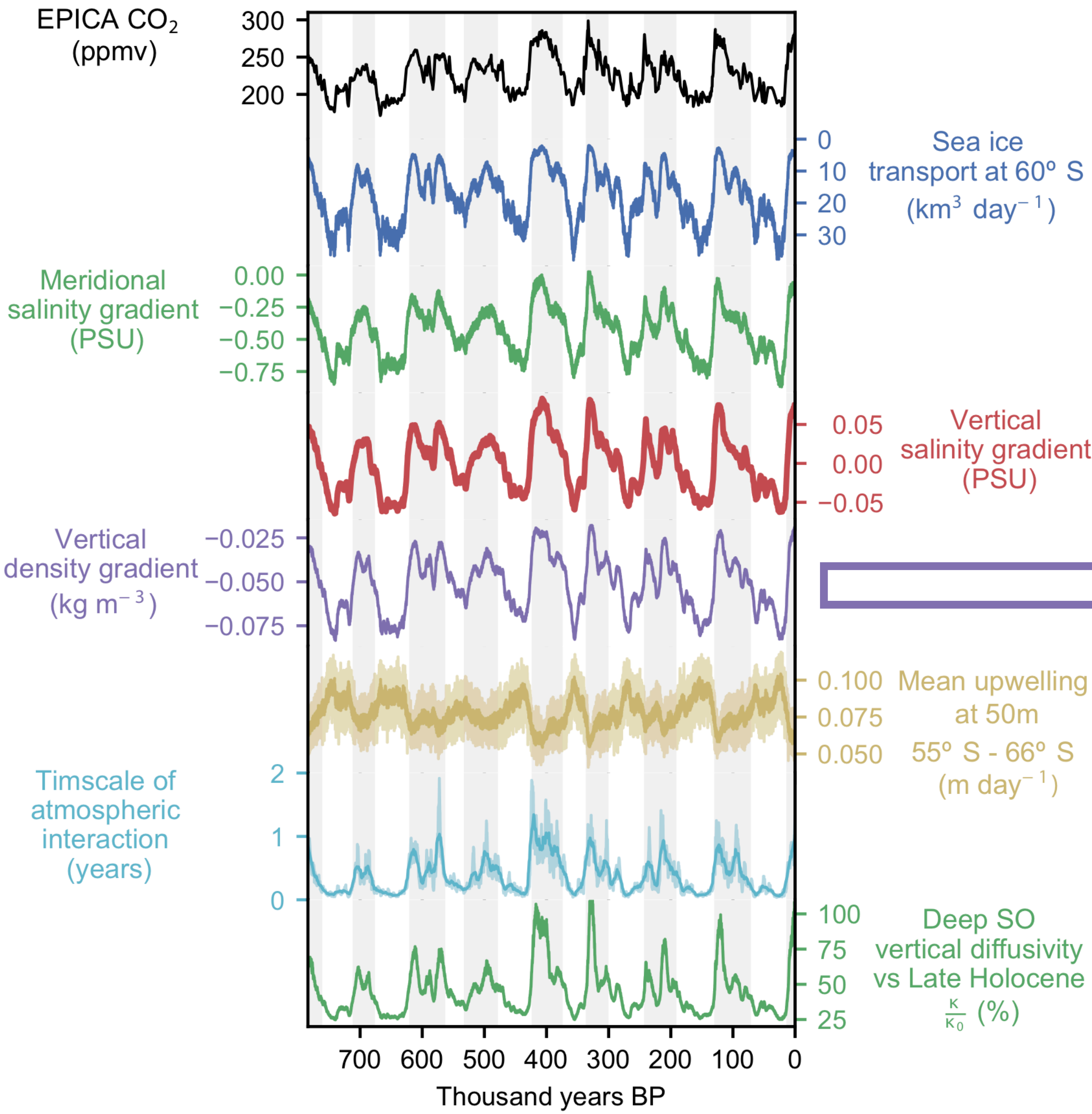


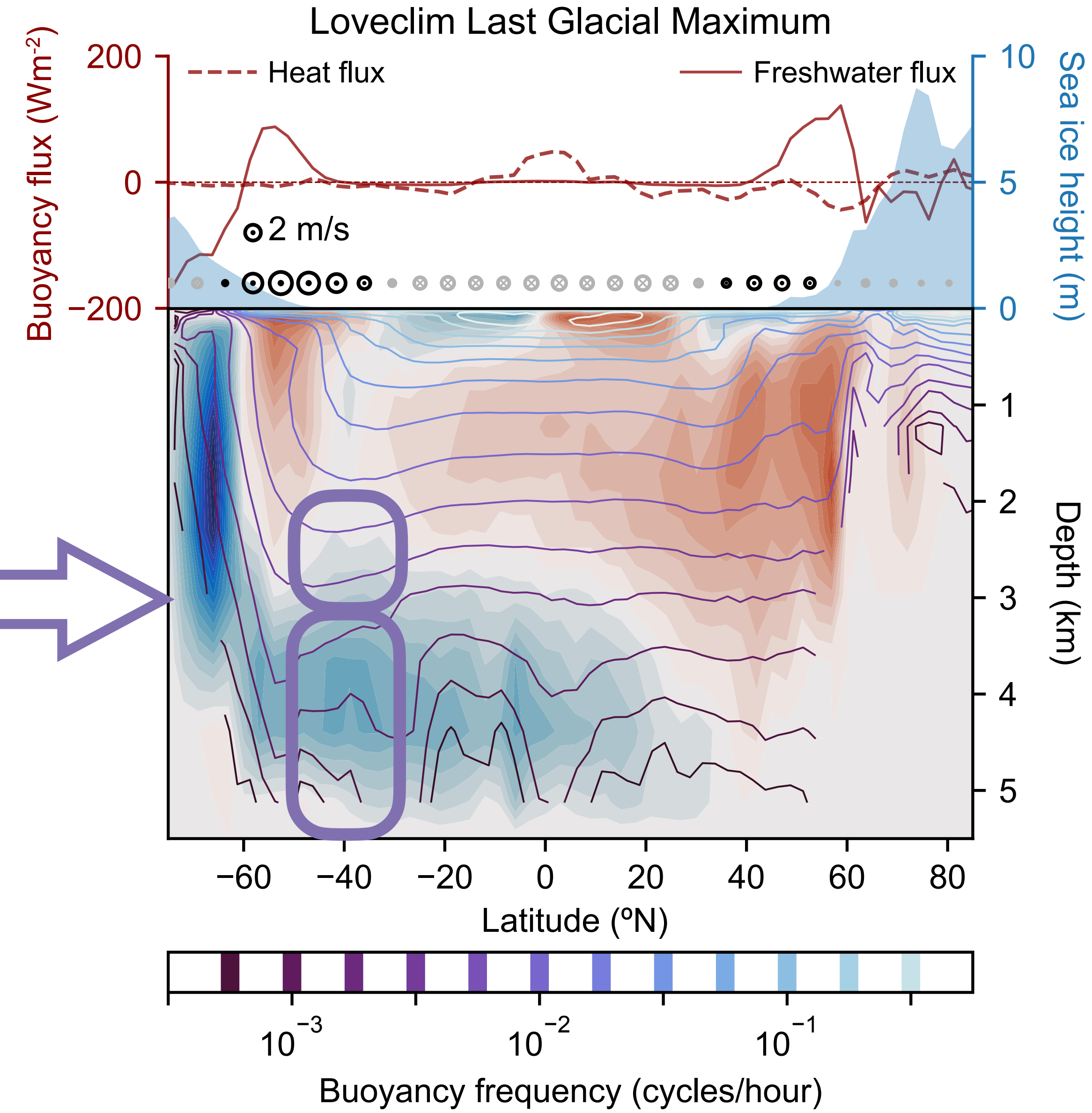
Timescale of atmospheric interaction





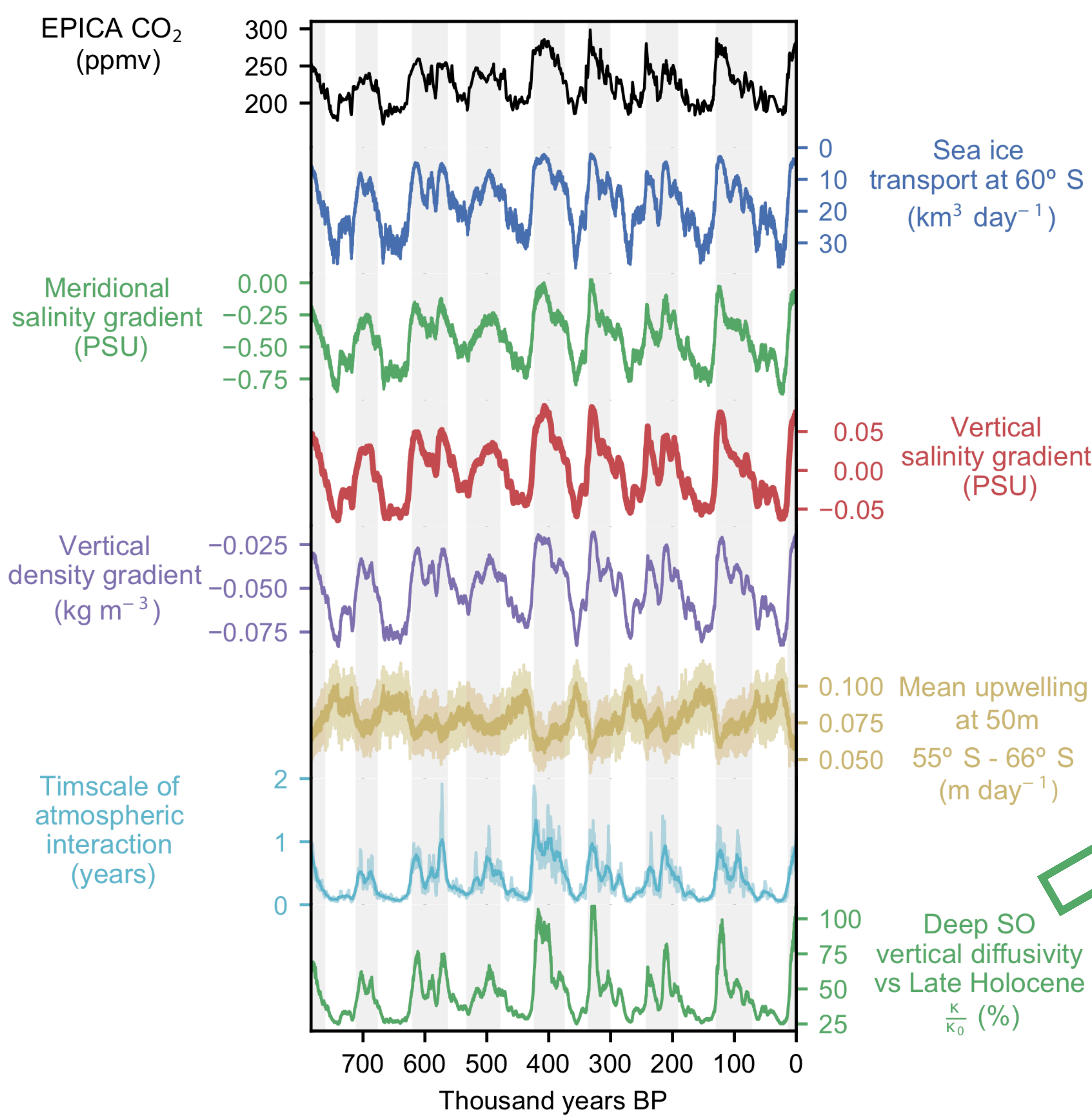
Deep ocean stratification

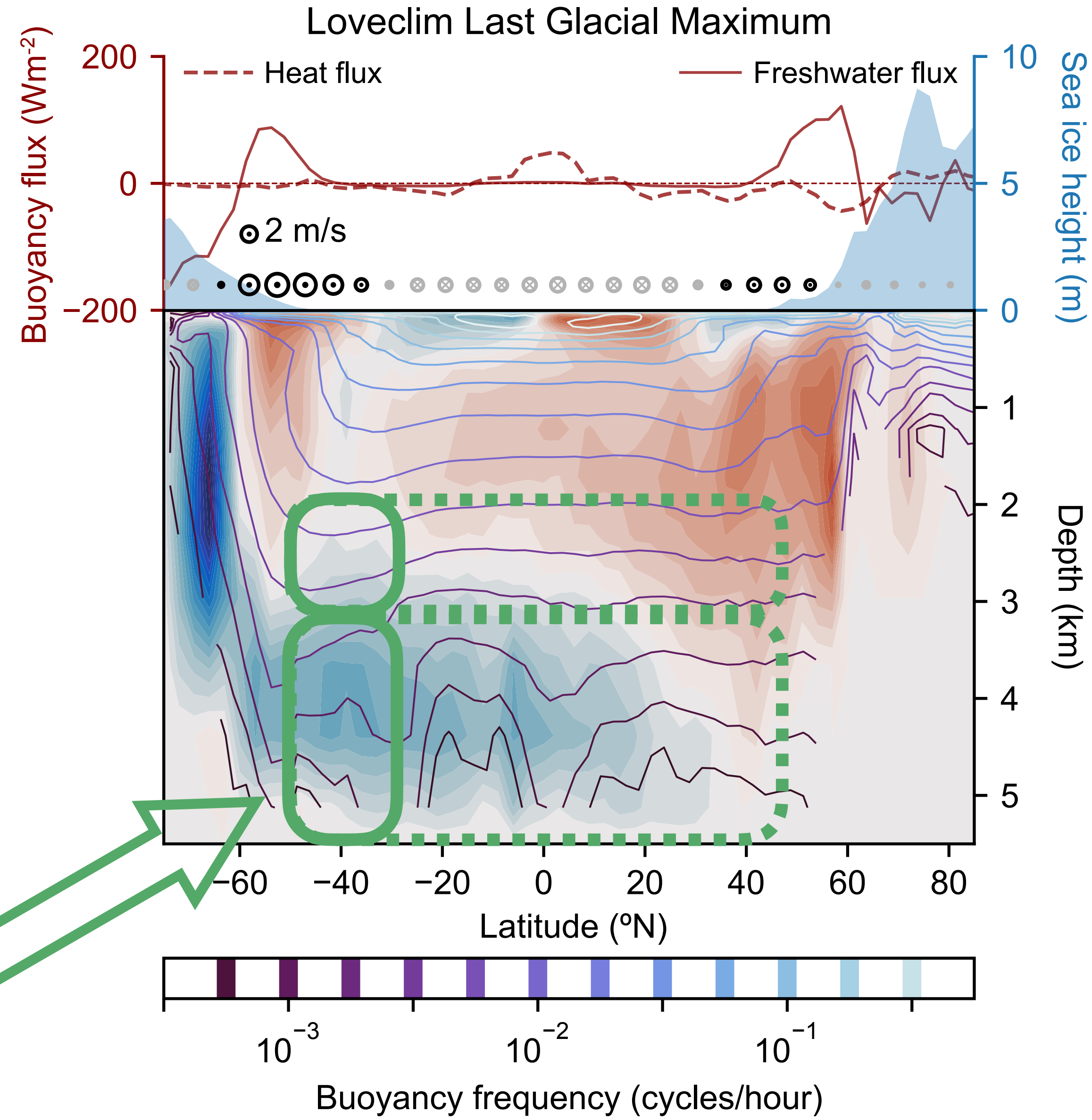




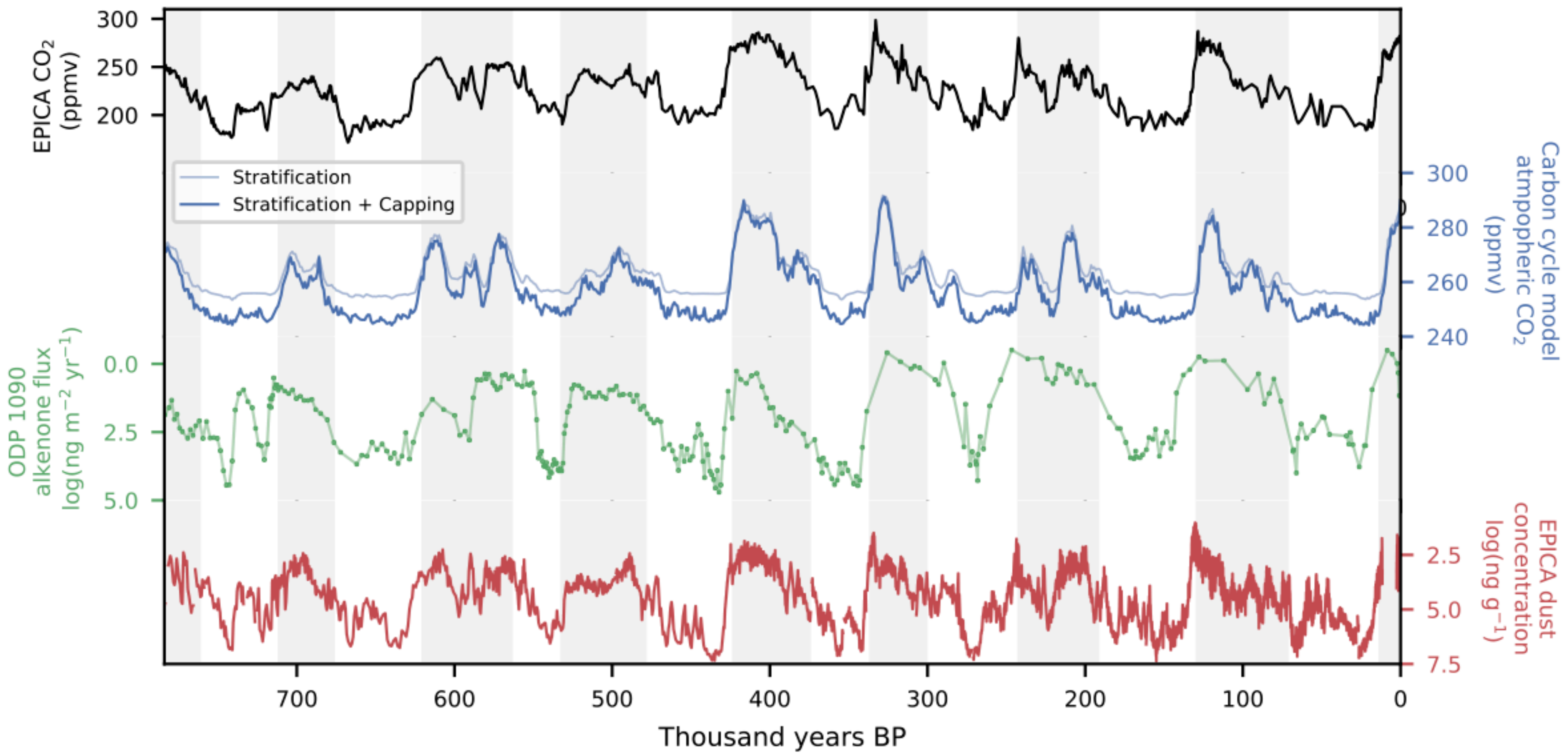
Deep ocean stratification

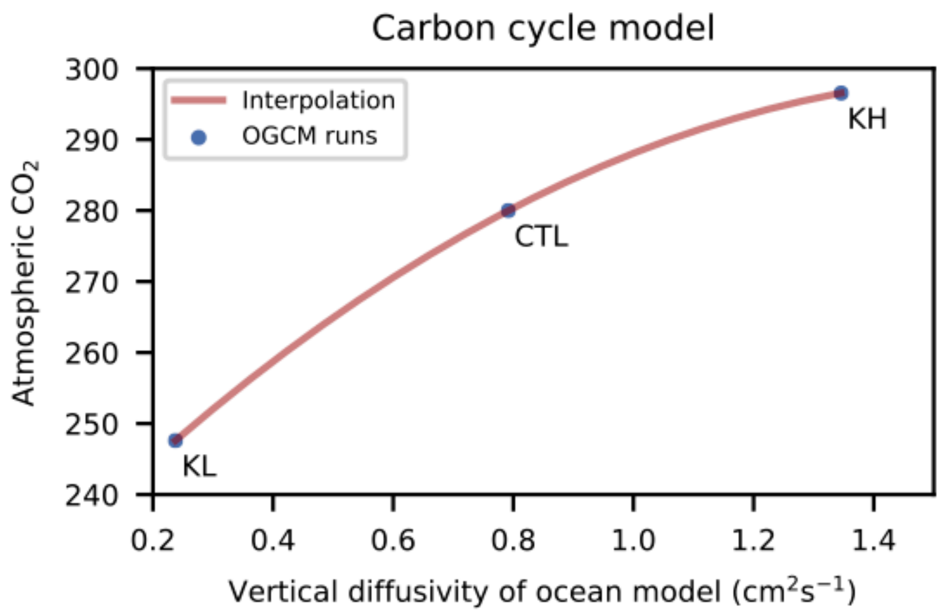
$$\kappa = \kappa_0 \left(\frac{N}{N_0} \right)^{-\alpha}$$

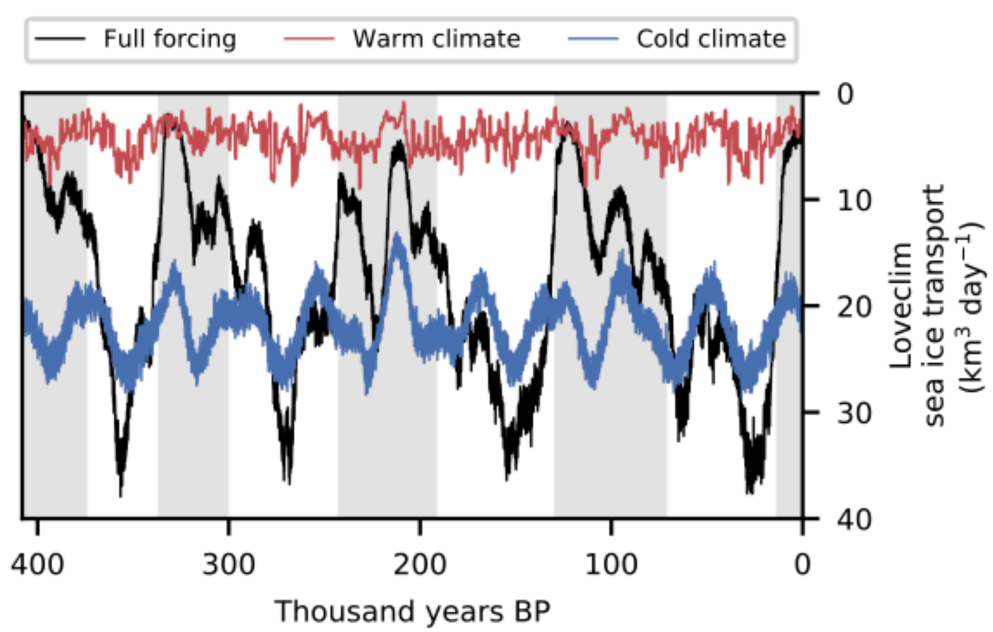




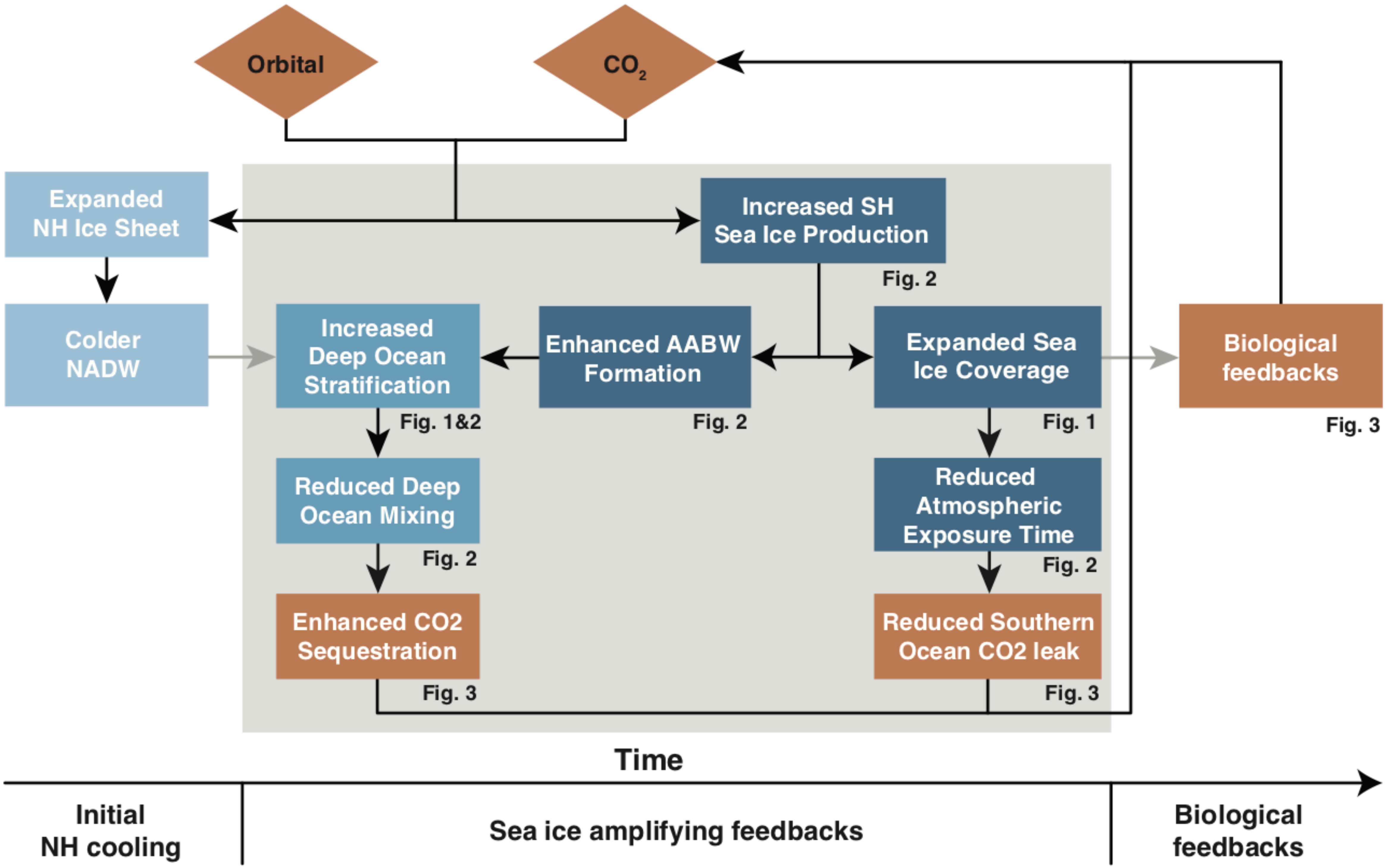
Results from carbon cycle model







Summary schematic



Summary

- Sea ice can decrease deep ocean ventilation during cold climates through “capping” of upwelled waters and by increasing stratification in the deep ocean.

- Carbon cycle model estimates a 40 ppm drawdown of atmospheric CO2, 10ppm through “capping” and 30ppm due to stratification.

- Increased AABW formation by increased sea ice production can stratify the deep ocean early within a glacial cycle, providing a strong and quick feedback to the carbon cycle.

- Orbital only experiments indicate that sea ice variations due to insolation changes are too weak to initiate glaciation, so the “trigger” resides elsewhere.