Modelling Early Earth Ocean Mixing Timescale: Implications on Oxygenation of Habitable Worlds

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Introduction

Ocean mixing timescales have a variety of biological and geochemical consequences on present-day Earth, but the role of ocean dynamics in shaping the evolution of our planet remains unexplored.

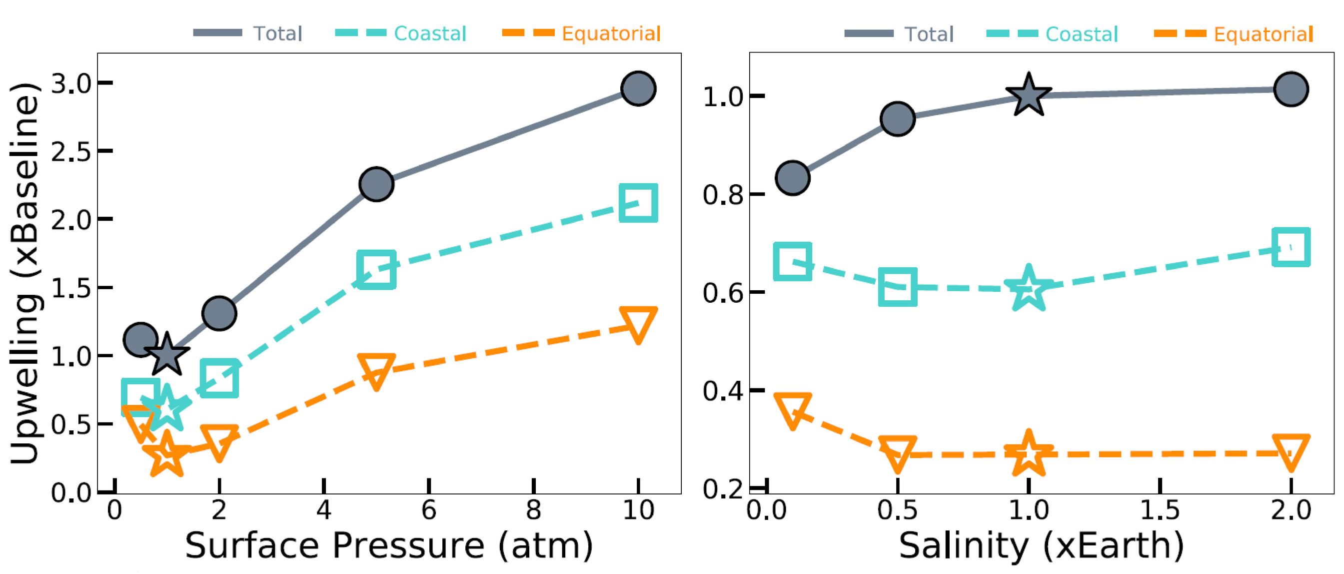

Fig. 1: Upwelling sensitivity to surface pressure and salinity on Earth-like exoplanets from ROCKE-3D output [1]. The strength of upwelling depends on wind stress, tidal influences, salinity and continental configuration—all of which are known to have changed in Earth's history.

The differences in ocean circulation pattern potentially impacted Earth's oxygenation trajectory by modulating the transport and availability of essential nutrients for photosynthetic oxygen production [1]. Moreover, early Earth ocean mixing timescales that differ from today may also undermine the reliability of some of the isotopic paleoredox proxies, such as uranium [2], that we use to reconstruct Earth's oxygenation history.

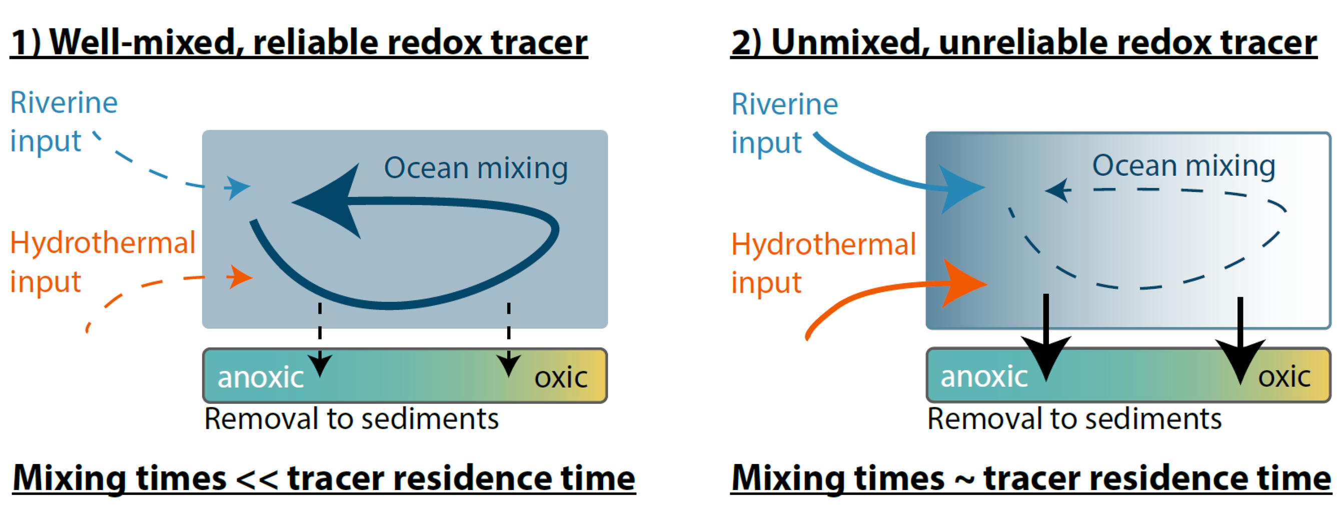

Fig. 2: Control of ocean mixing timescale on applicability of paleoredox proxies in marine sediments. An ocean mixing timescale comparable to the residence time of isotopic proxies, as shown in scenario 2, may only obtain geochemical records with local signal.

We explore these possibilities here by constraining Neoarchean mixing timescales. Our results will also have implications on habitable exoplanets with ocean whose dynamics are influenced by a wide variety of planetary conditions.

Methodology

Our experiments leverage the PLASIM-cGENIE intermediate complexity Atmosphere-Ocean General Circulation Model [3], which couples the 3-D atmosphere of PLASIM [4] to the 3-D ocean, sea-ice and land-surface components of cGENIE [5].

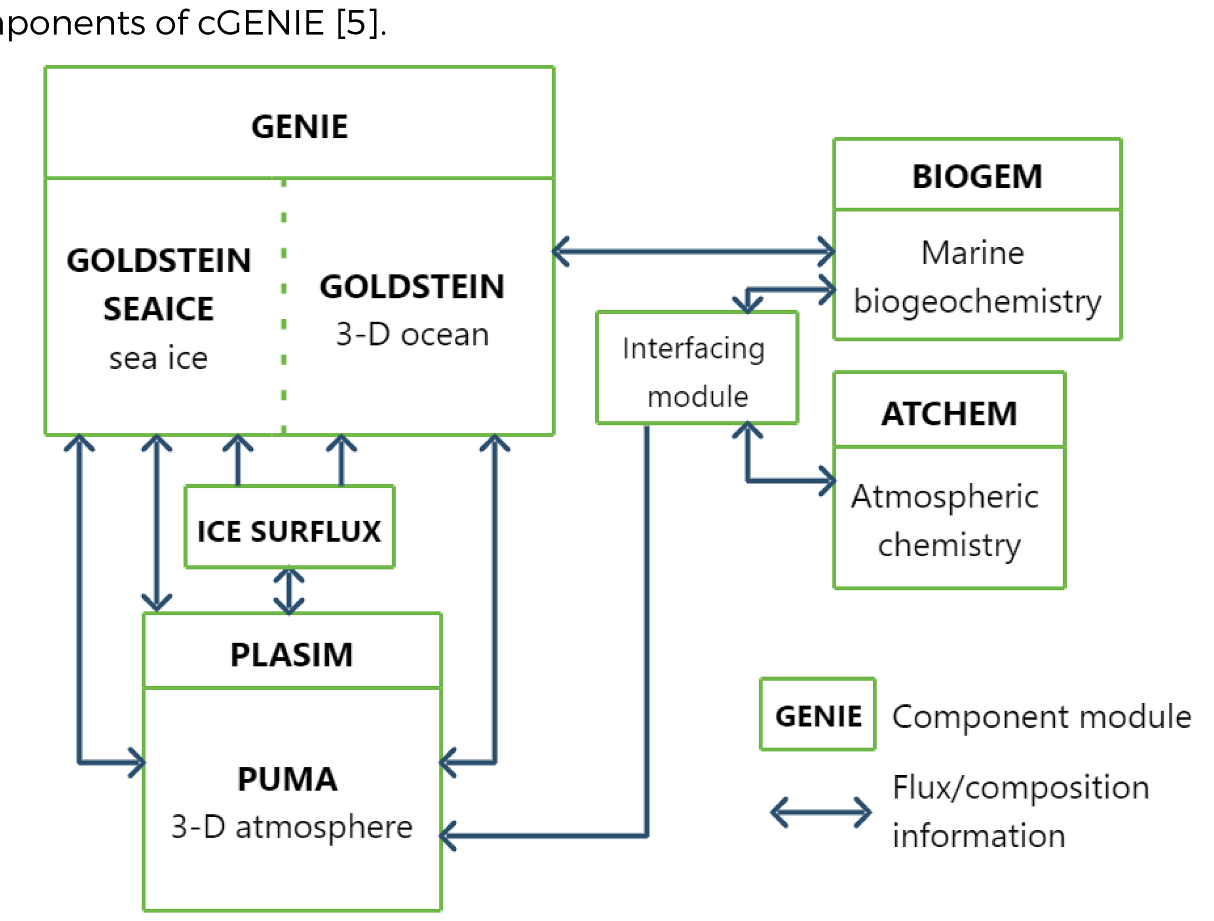

Fig. 3: Schematic of PLASIM-cGENIE coupling. PLASIM-cGENIE reproduces the main features of Earth's climate system with simpler parameterizations and lower spatial resolution than full-complexity models, allowing efficient exploration of a large parameter space for various paleoclimate questions [6].

Preliminary Results

We begin by testing the model for a sterile modern ocean with water mass age tracers that should reflect a residence time of deep ocean water close to modern value (~1 ka) when the system reaches equilibrium.

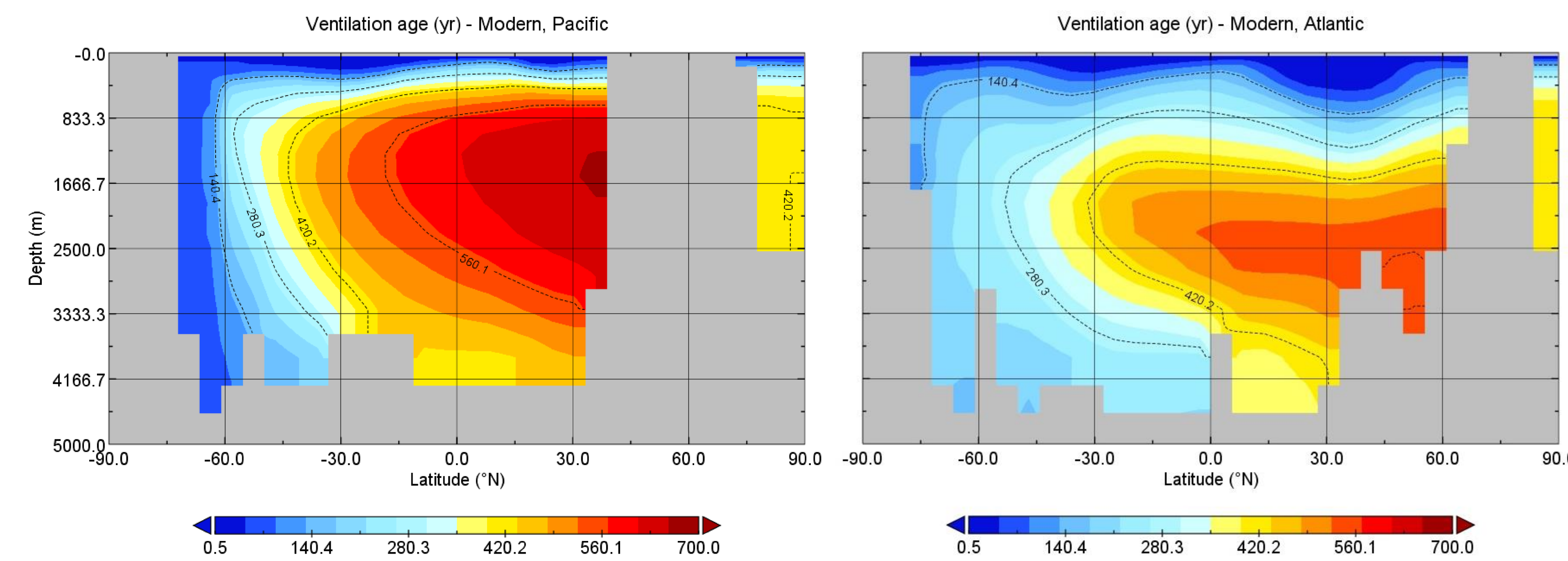

Fig. 4: Ventilation age as a function of depth and latitude, shown for modern Pacific (left) and Atlantic (right).

Day length (hr)	12, 15, 18, 21, 24*
Surface pressure (bar)	0.25, 0.5, 1*, 1.5, 2
Salinity (PSU)	20, 30, 35*, 40, 50
Diapycnal diffusivity	Default*, Archean, Proterozoic
Continentality	None, modern*, supercontinent

Table 1: Planned parameter space for sensitivity experiments under Neoarchean setting. We initially vary parameters in isolation and then strategically co-vary parameters to bracket the range of possibilities for Neoarchean Earth. Experiments initiated to date are highlighted in red.

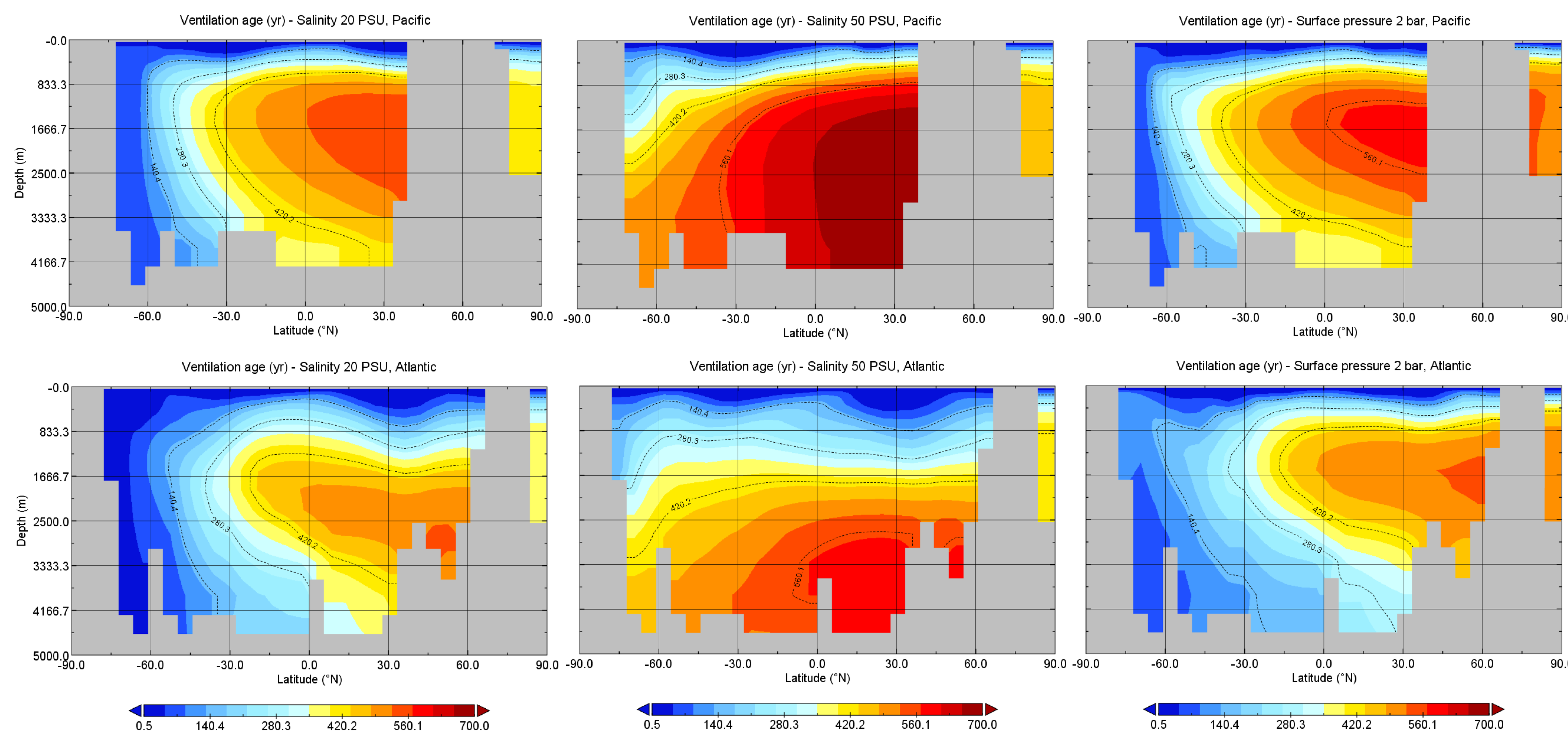

Fig. 5: Ventilation age as a function of depth and latitude, shown for modern Pacific (top row) and Atlantic (bottom row) but with global mean salinity set to 20 PSU (left column), 50 PSU (middle column) and with global mean surface pressure set to 2 bar (right column).

Sensitivity experiments	Deep ocean mixing timescale	
	Pacific	Atlantic
Modern	660 years	569 years
Salinity 20 PSU	559 years	532 years
Salinity 50 PSU	698 years	604 years
Surface pressure 2 bar	591 years	535 years

Table 2: Largest deep ocean mixing timescale of completed sensitivity experiments in which modelled ocean reached equilibrium.

Besides the modern run, only four of initial seven sensitivity experiments completed the 10,000-year spinning-up. For each of them, change in mixing timescales in Pacific and Atlantic goes in the same direction but is slightly greater in Pacific.

Saltier ocean has longer mixing time and fresher ocean mixes faster than modern ocean in our model, but the differences in deep water age compared to modelled modern ocean are not very significant. It's noteworthy that raising global mean salinity to 50 PSU evidently alters deep ocean circulation pattern while lowering salinity to the same extent does not exhibit such effect.

When global mean surface pressure was set to 0.5 bar, snowball Earth formed after about 1300 model years so that the distribution of deep water age was greatly interrupted. Interestingly, although the ocean went sea-ice free quickly when surface pressure was raised to 2 bar, its mixing timescale remained in reasonable range. Higher surface pressure leads to more efficient ocean mixing, but the sensitivity of the overall response of ocean circulation is similar with that to change in salinity.

Hypothesis

Our sensitivity experiments show that smaller salinity and higher surface pressure both slightly strengthen deep ocean mixing. Additionally, ocean circulation may be less efficient on planets that rotate faster, have less complex land distribution and smaller tidal energy dissipation [1]. We thus hypothesize that Neoarchean Earth may have had a longer mixing timescale [7-9], although additional factors, such as changes in tidally-driven turbulent mixing, remain to be explored. We expect the difference in timescale between our Neoarchean analog and modern Earth to be smaller than one order of magnitude. The differences may be biogeochemically significant, however, particularly if nutrient inventories were smaller or if paleoredox proxies had shorter residence times in Archean seawater.

References

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