



# Detection timescales of environmental stressors in the interior ocean

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### OPEN **Early detection of anthropogenic climate change signals in the ocean interior**

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Robust detection of anthropogenic climate change is crucial to: (i) improve our understanding of Earth system responses to external forcing, (ii) reduce uncertainty in future climate projections, and (iii) develop efficient mitigation and adaptation plans. Here, we use Earth system model projections to establish the detection timescales of anthropogenic signals in the global ocean through analyzing

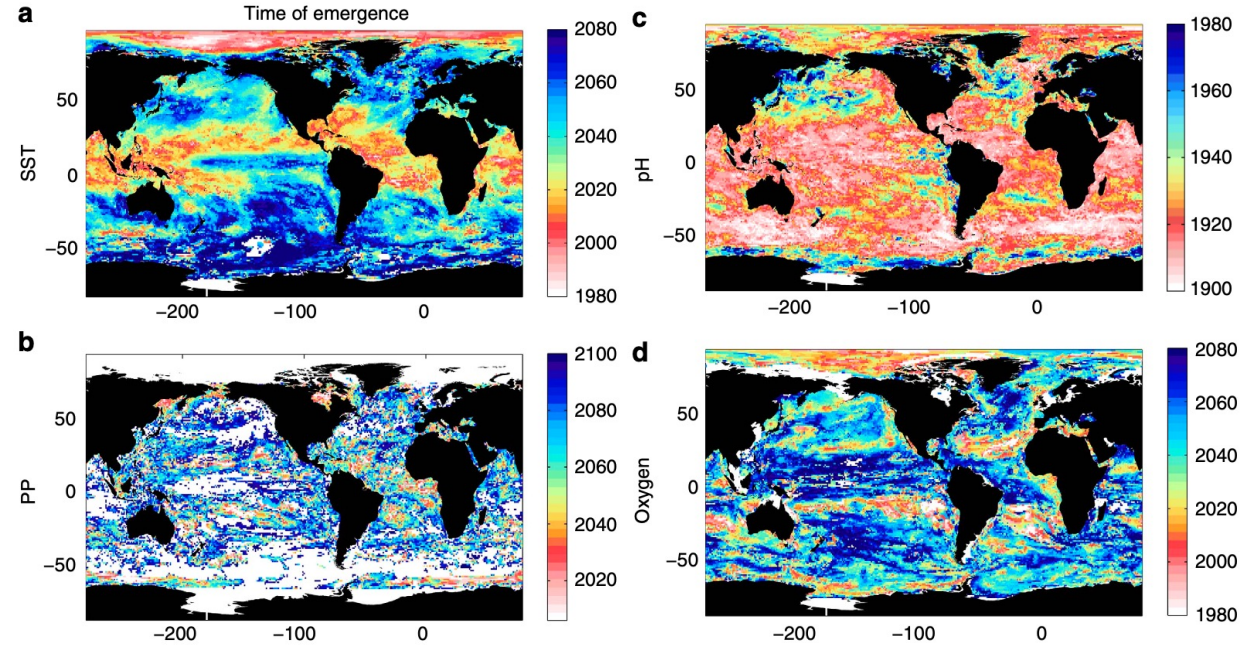
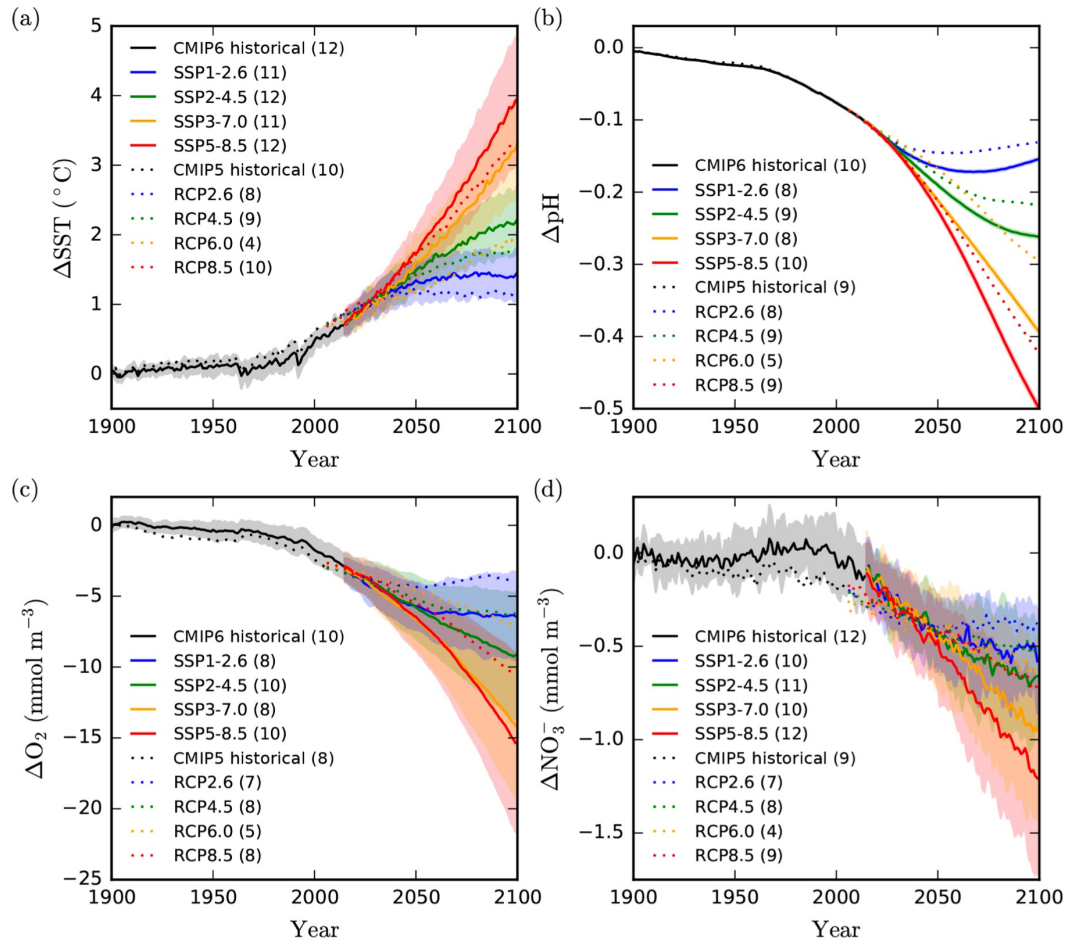


## Introduction

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- › Robust detection of anthropogenic climate change is important to:
  - Improve our understanding of Earth system responses to external forcing
  - Reduce uncertainty in future climate projections
  - Optimize monitoring strategy
  - Develop future efficient mitigation and adaptation plans
- › Determine the time of departure from surface to 2000 m depths for:
  - Temperature
  - Salinity
  - Oxygen
  - pH
- › Apply ensemble from 17 CMIP6 ESMs
- › Assess impact of climate mitigation on detection time scales (SSP2-4.5 vs SSP5-8.5)

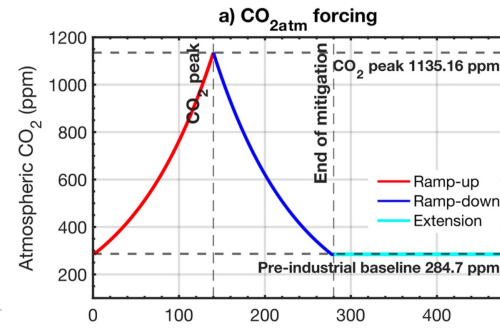
## Surface has been the main focus of past studies



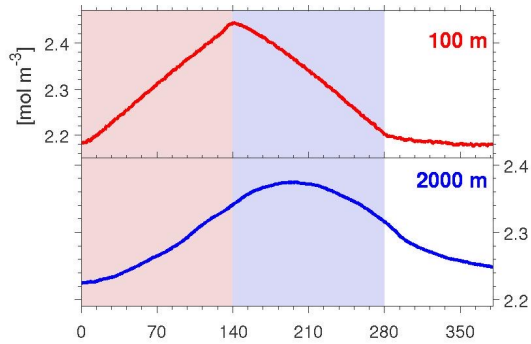
The lack of understanding of climate change-driven impacts on deep-sea increases the possibility of overlooking ecosystem vulnerabilities and risks (IPCC-AR6).

Kwiatkowski et al. (2020); Henson et al. (2017)

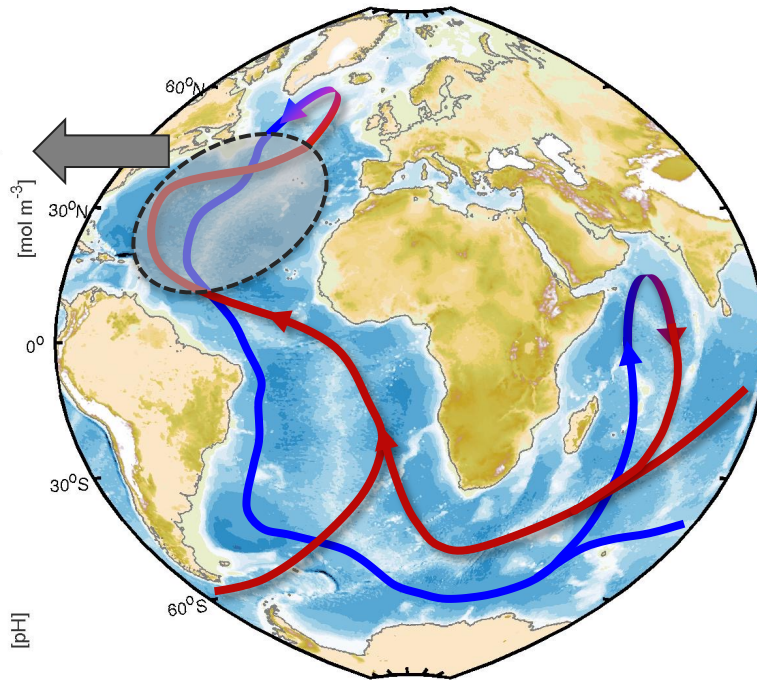
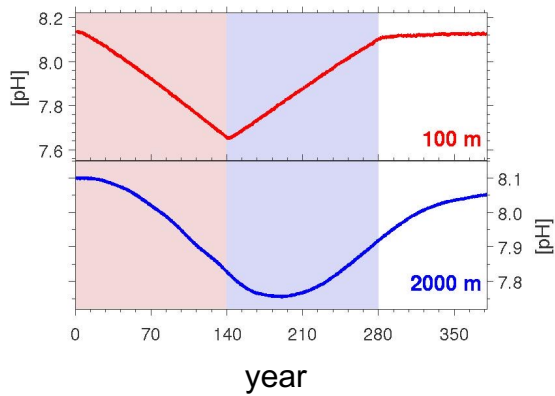
## Idealized emissions and mitigation scenario



N. Atlantic dissolved inorganic carbon



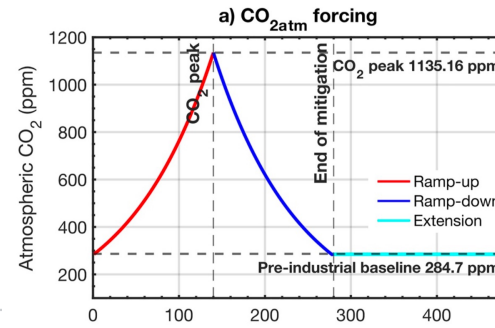
N. Atlantic pH



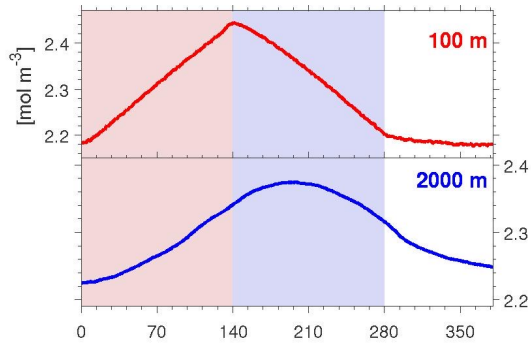
Surface flow  
Interior flow

Tjiputra et al. (2020; Nature); Bertini and Tjiputra (2022)

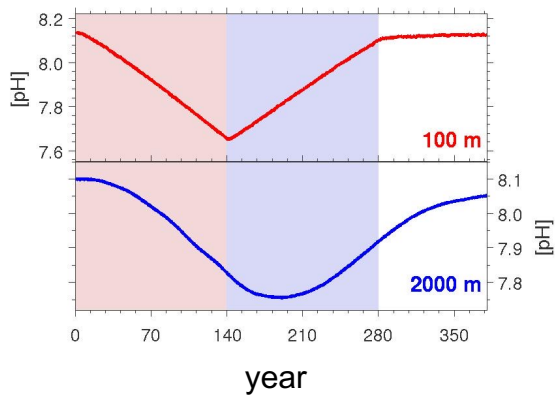
# Idealized emissions and mitigation scenario



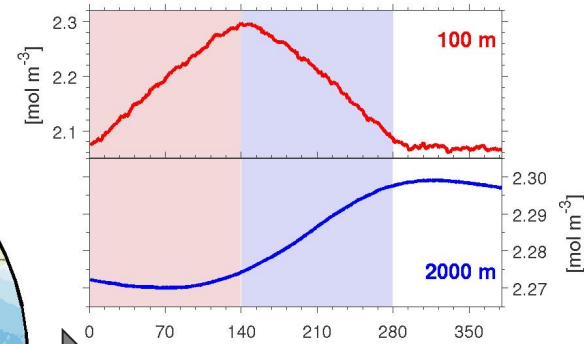
N. Atlantic dissolved inorganic carbon



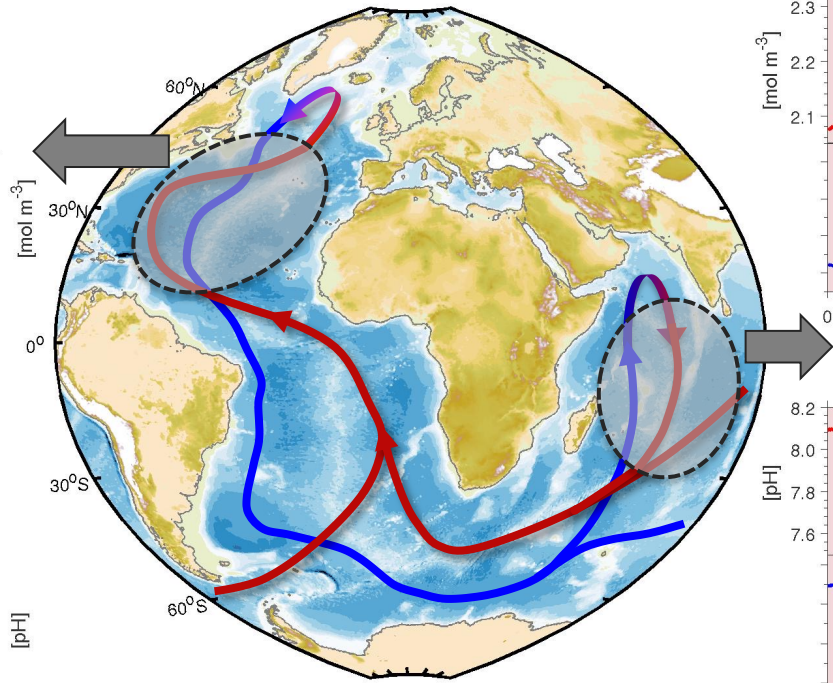
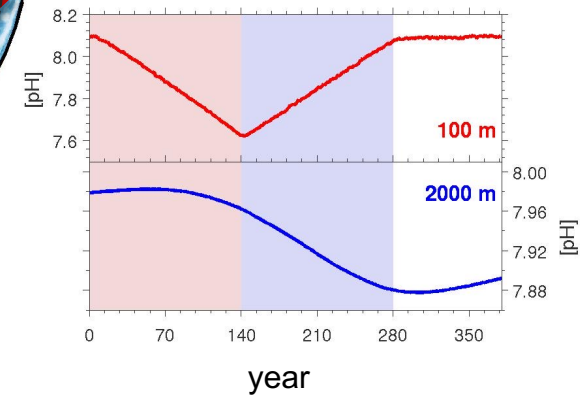
N. Atlantic pH



Indian Ocean dissolved inorganic carbon



Indian Ocean pH

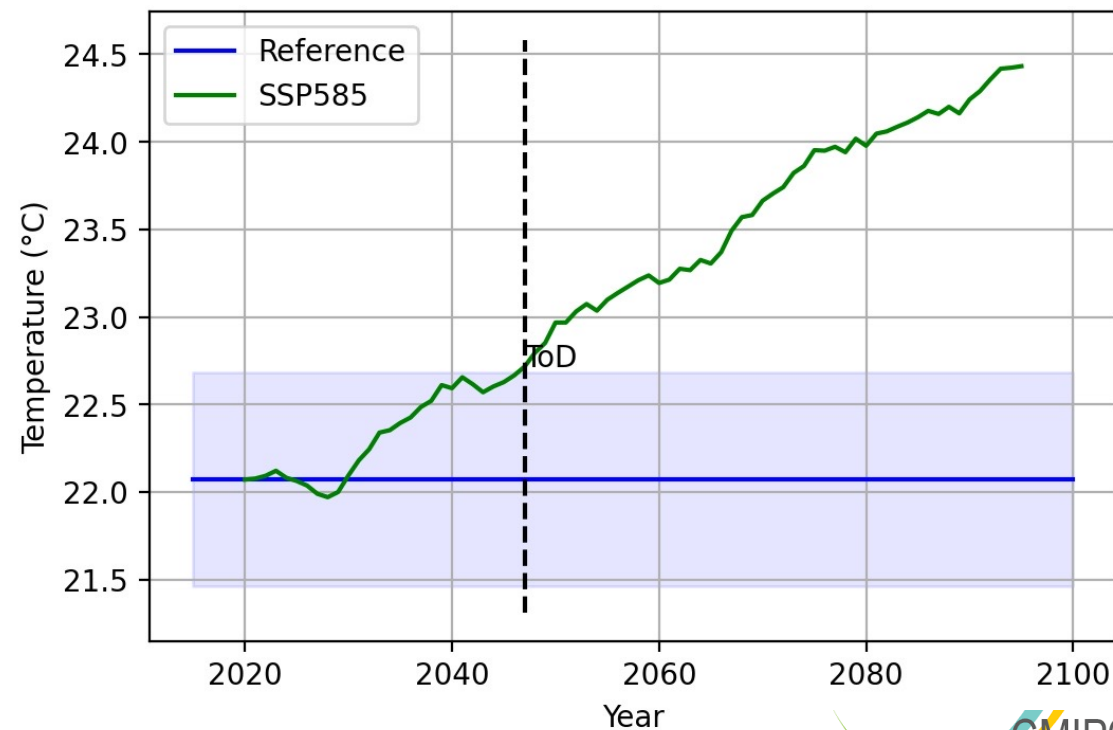


Surface flow  
Interior flow

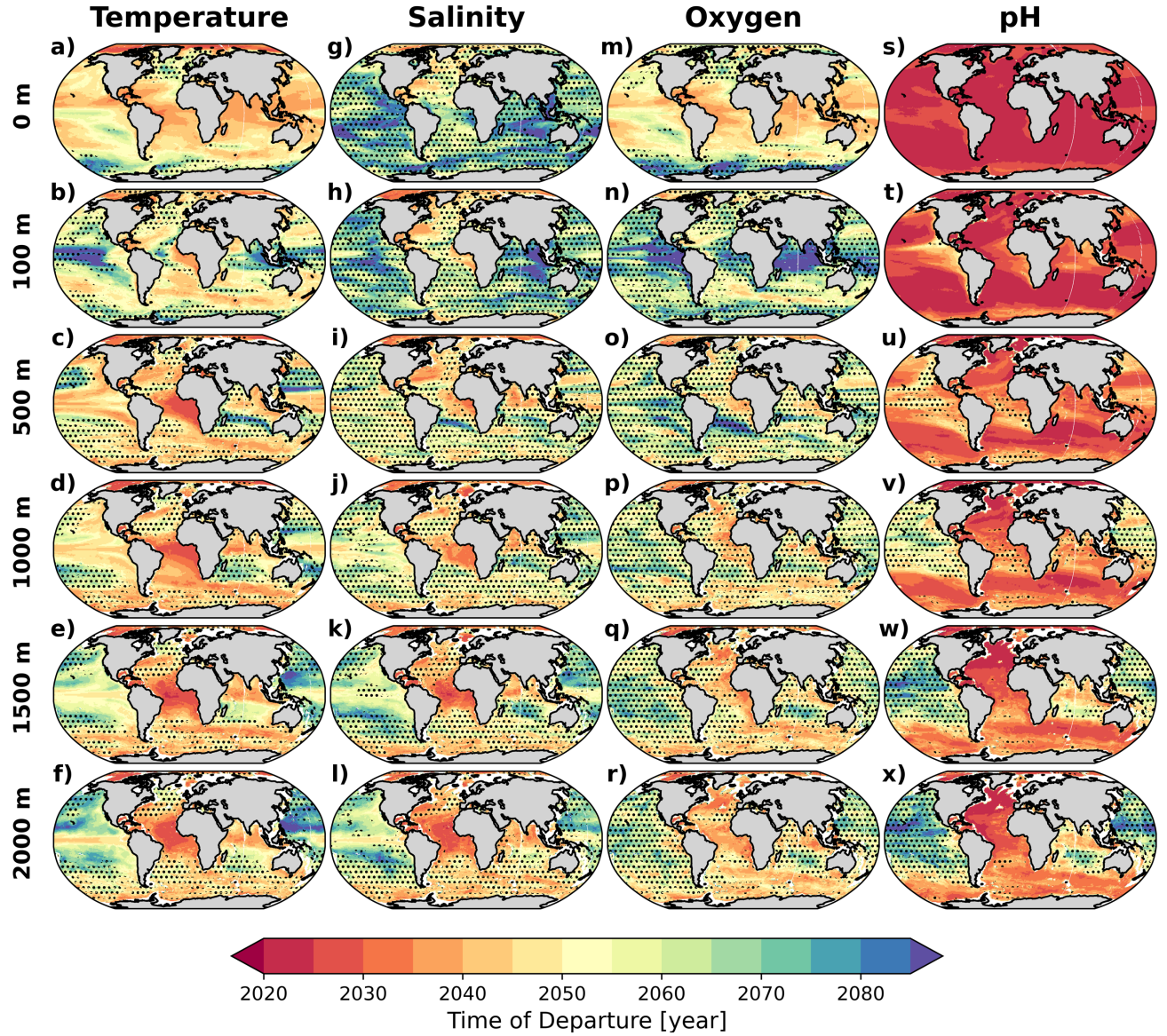
Tjiputra et al. (2020; Nature); Bertini and Tjiputra (2022)

## Time of departure/detection (ToD)

Model name	SSP2-4.5	SSP5-8.5	Spin-up	Resolution
ACCESS-ESM1-5	T, S, O2	T, S, O2	1000	1° × 1°
CanESM5	T, S, O2	T, S, O2	1000	1° × 1°
CanESM5-CanOE	T, S, O2, pH	T, S, O2, pH	1000	1° × 1°
CESM2	T, S	T, S	1200	1.125° × 0.53°
CESM2-WACCM	T, S, pH	T, S, pH	500	1.125° × 0.53°
CMCC-ESM2	T, S, O2, pH	T, S, O2, pH	1320	1° × 1°
CNRM-ESM2.1	T, S, O2, pH	T, S, O2, pH	2600	0.3°-1°
EC-Earth3-CC	T, S, O2, pH	T, S, O2, pH	1600	1° × 1°
GFDL-CM4	T, S, O2, pH	T, S, O2, pH	150	0.25° × 0.25°
GFDL-ESM4	T, S, O2, pH	T, S, O2, pH	400	0.5° × 0.5°
IPSL-CM6-LR	T, S, O2, pH	T, S, O2, pH	500	0.3°-1°
MPI-ESM1.2-HR	T, S, O2, pH	T, S, O2, pH	2000	0.4° × 0.4°
MPI-ESM1.2-LR	T, S, O2, pH	T, S, O2, pH	12000	1.5° × 1.5°
MRI-ESM2.0	T, S, O2, pH	T, S	2500	1° × (0.3–0.5)°
NorESM2-LM	T, S, O2, pH	T, S, O2, pH	1600	1° × 1°
NorESM2-MM	T, S, O2, pH	T, S, O2, pH	1200	1° × 1°
UKESM1.0-LL	T, S, O2, pH	T, S, O2, pH	500	1° × 1°

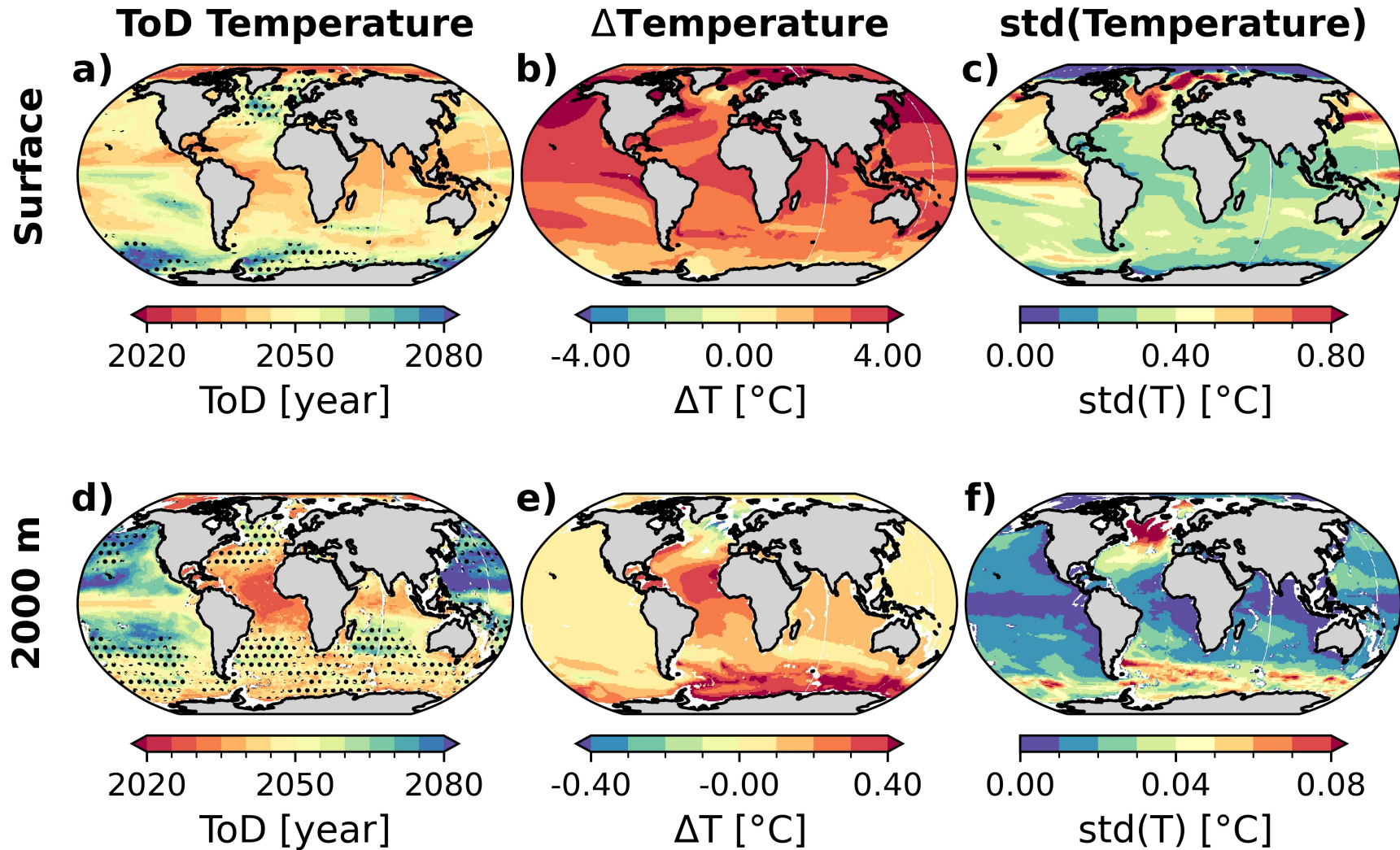


### Time of Departure under SSP5-8.5



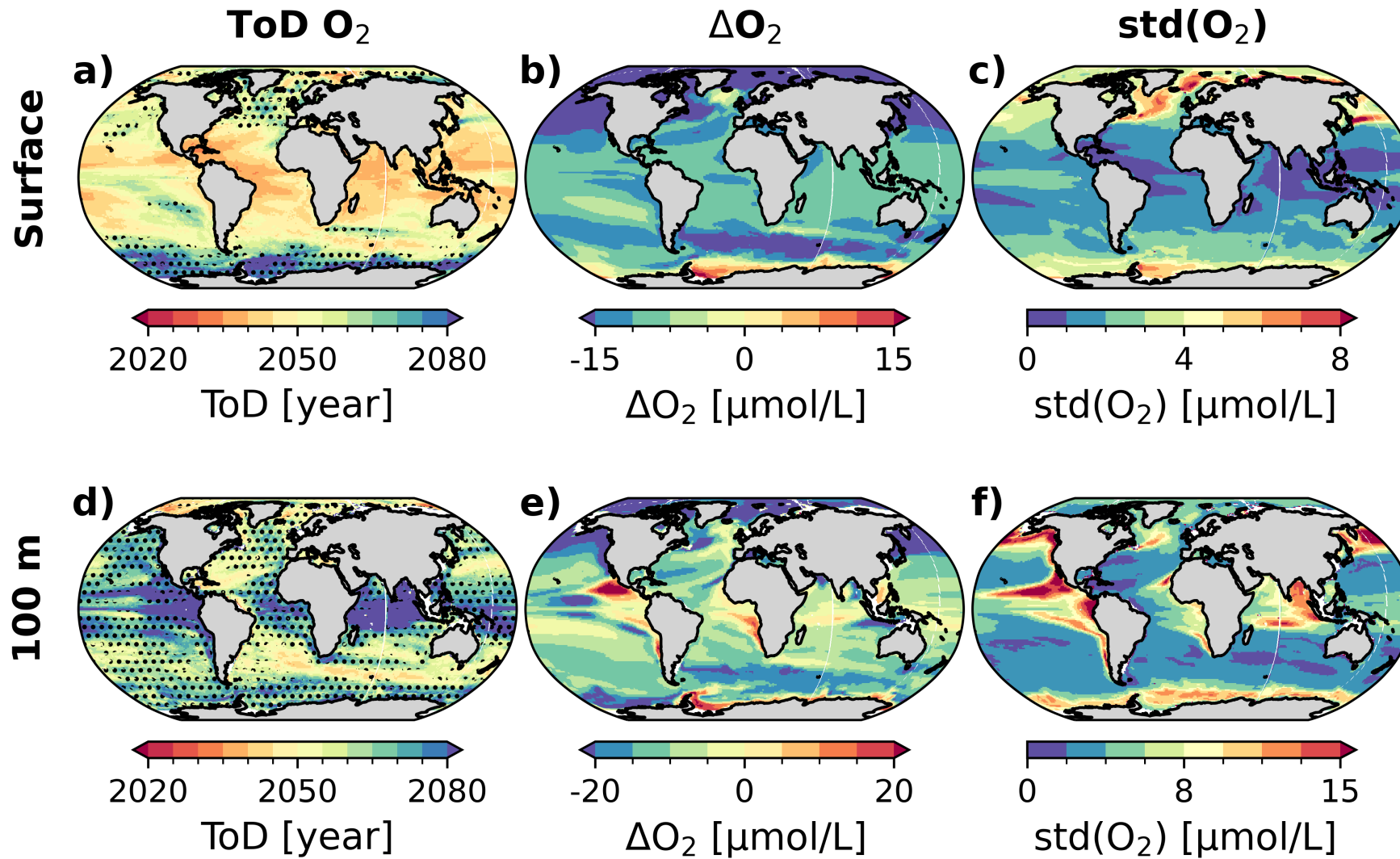


# Temperature surface and 2000 m



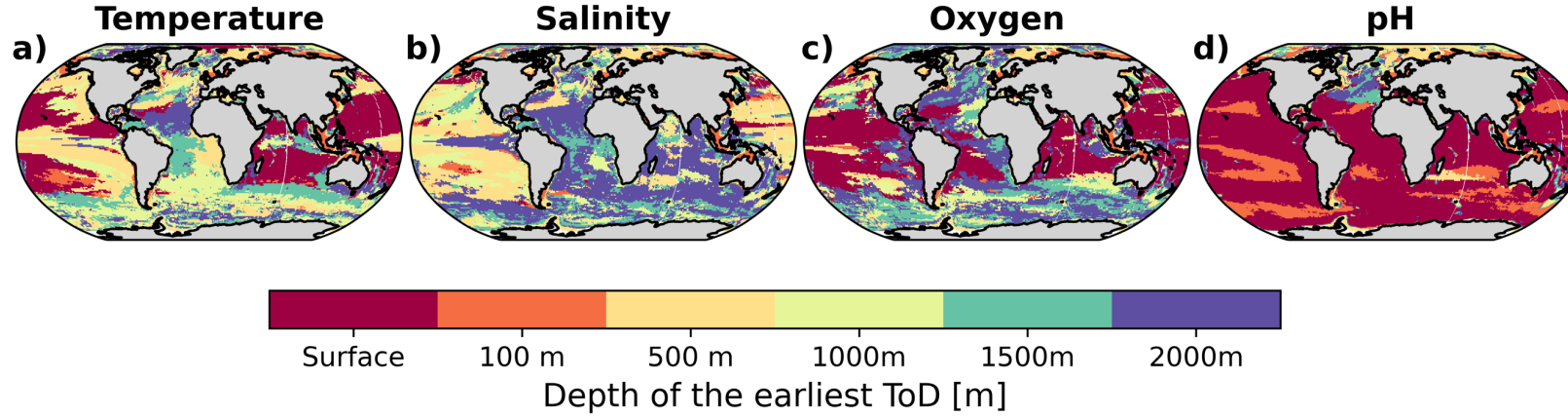


# Oxygen surface and 100 m

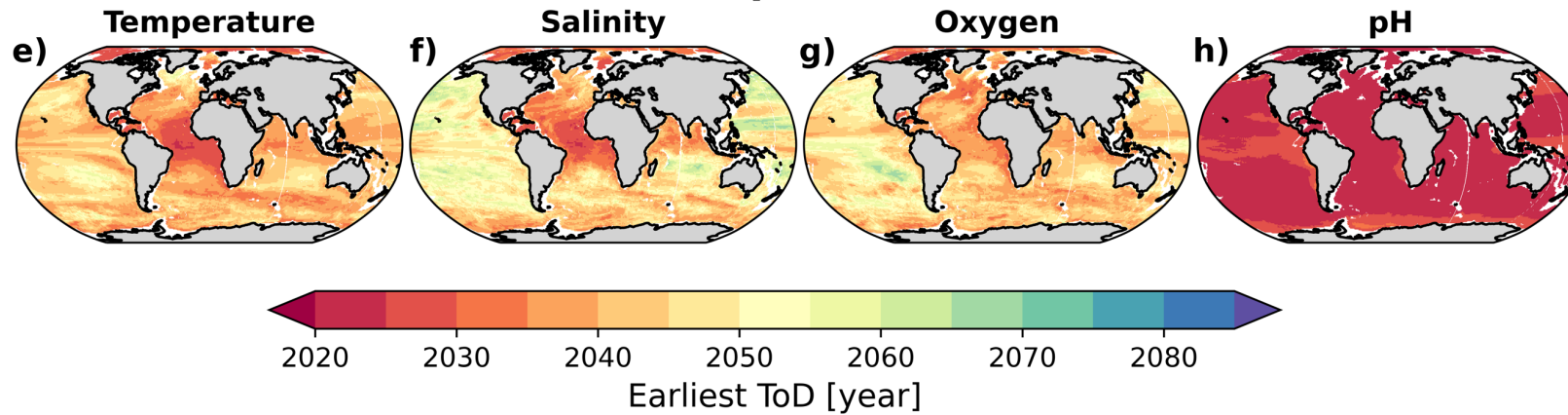




### Depth of the earliest Time of Departure under SSP5-8.5

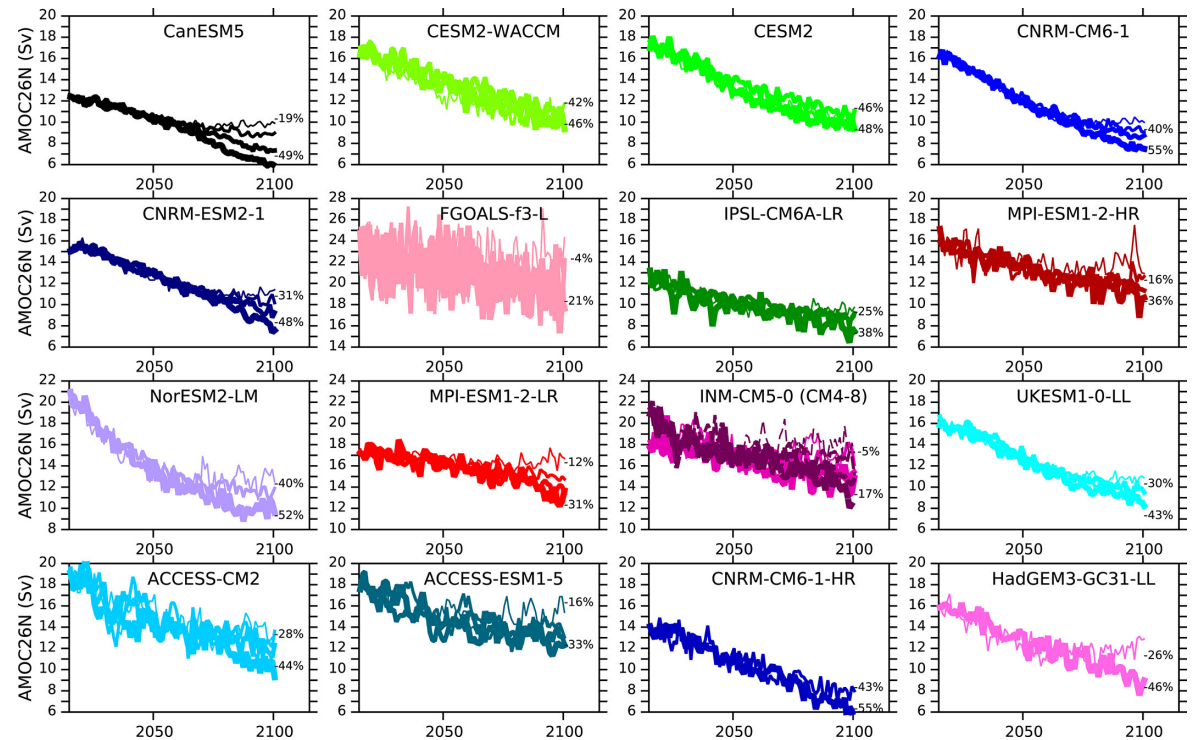
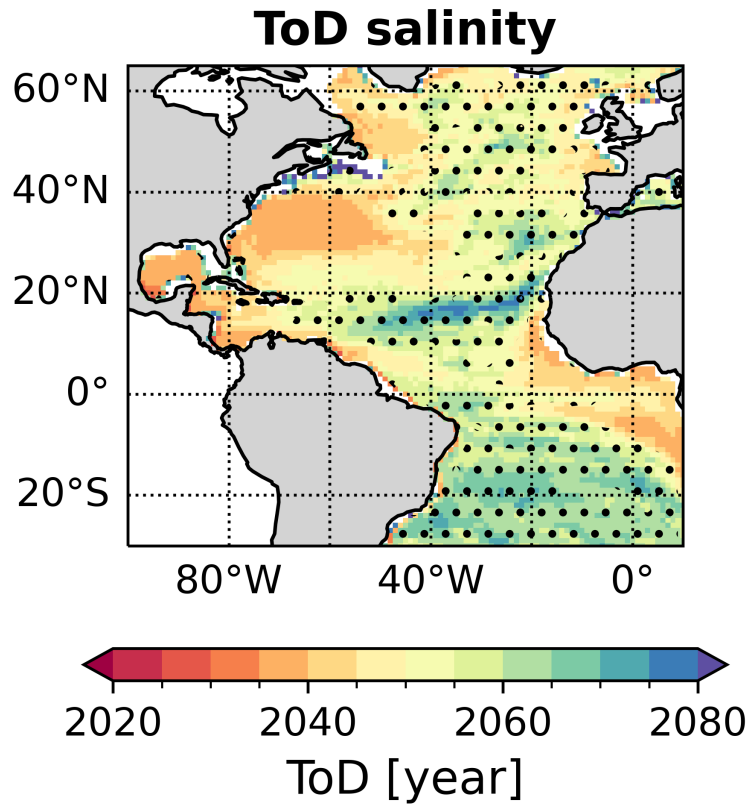


### Earliest Time of Departure under SSP5-8.5





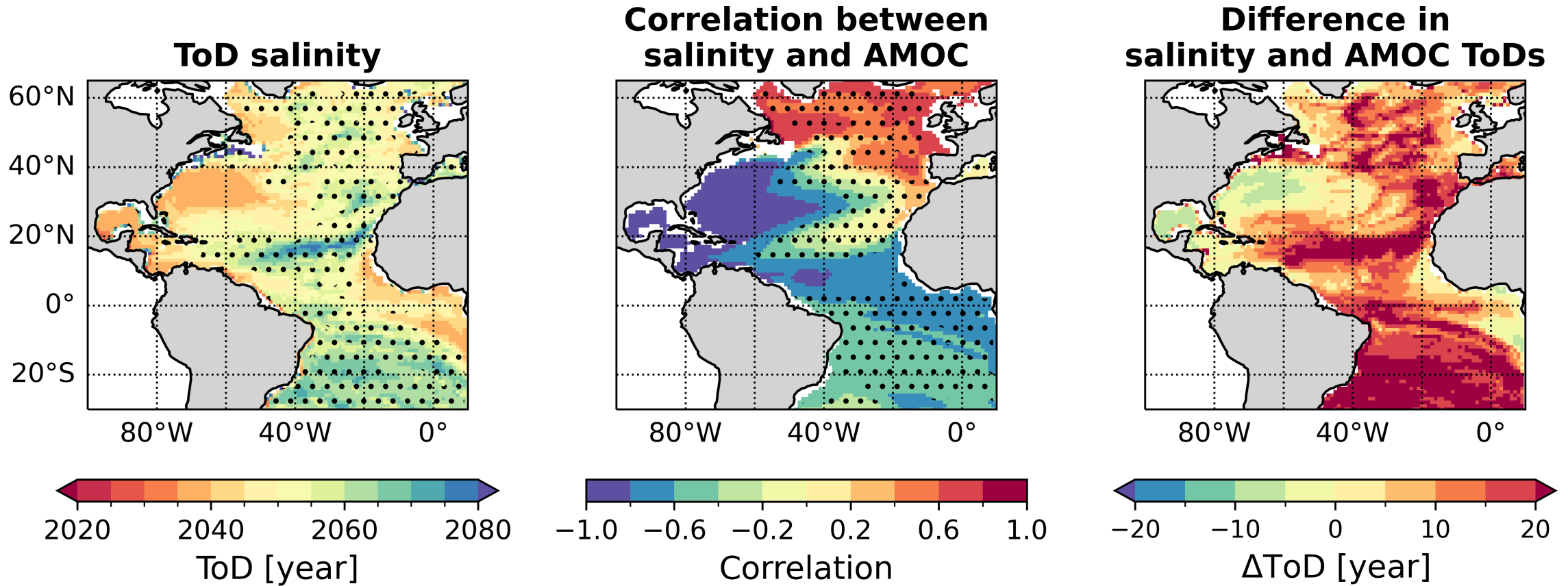
# Subsurface (100 m) salinity: a strong indicator for AMOC changes



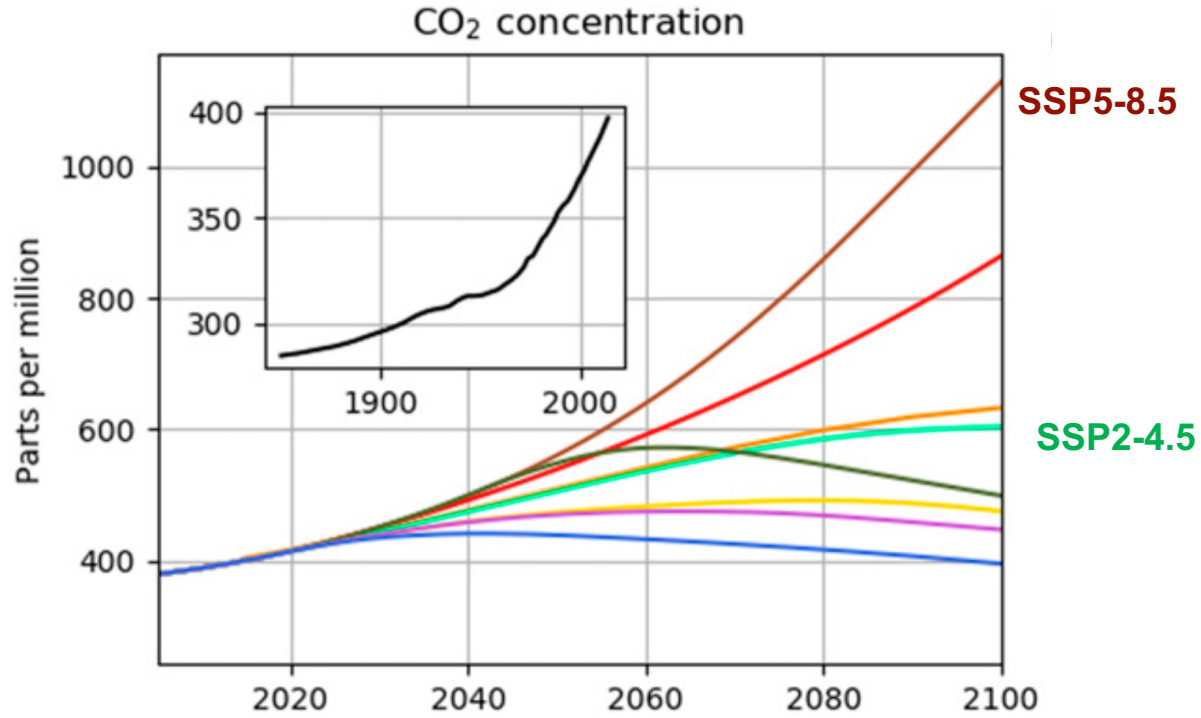
Weijer et al., (2020)



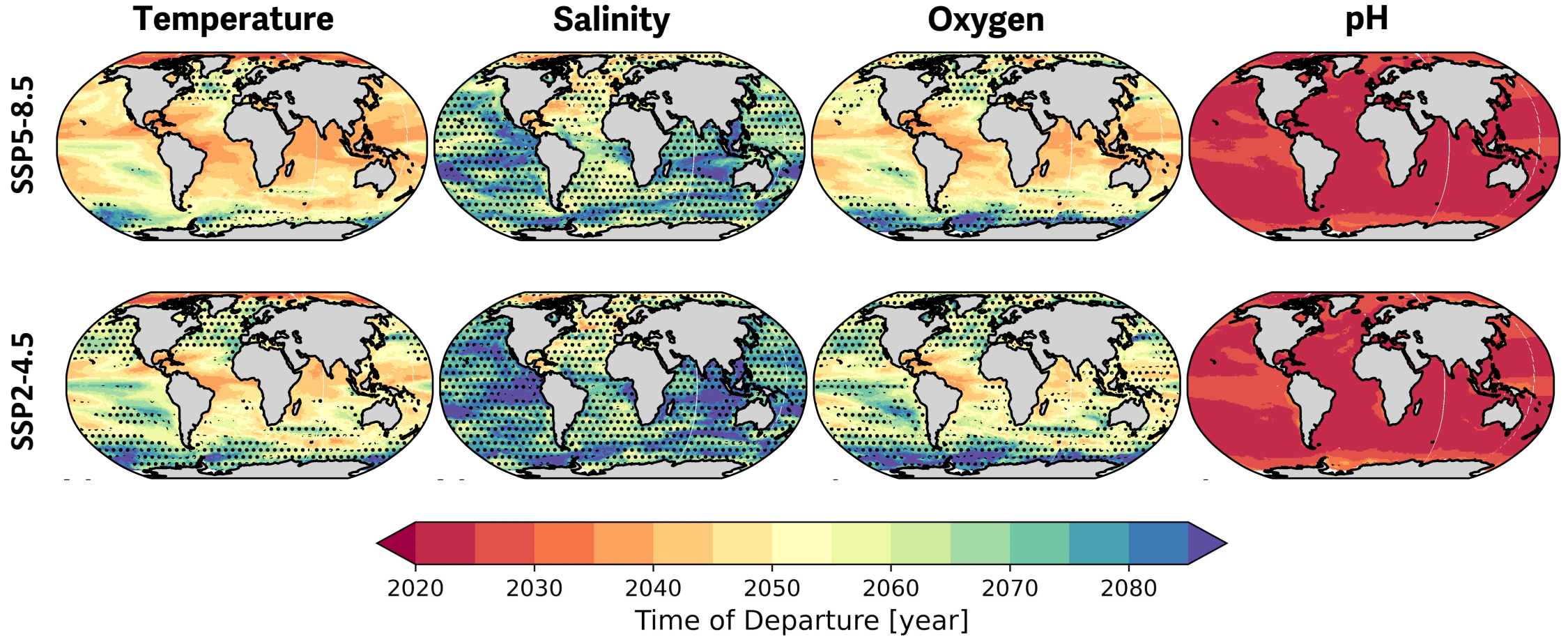
# Subsurface (100 m) salinity: a strong indicator for AMOC changes



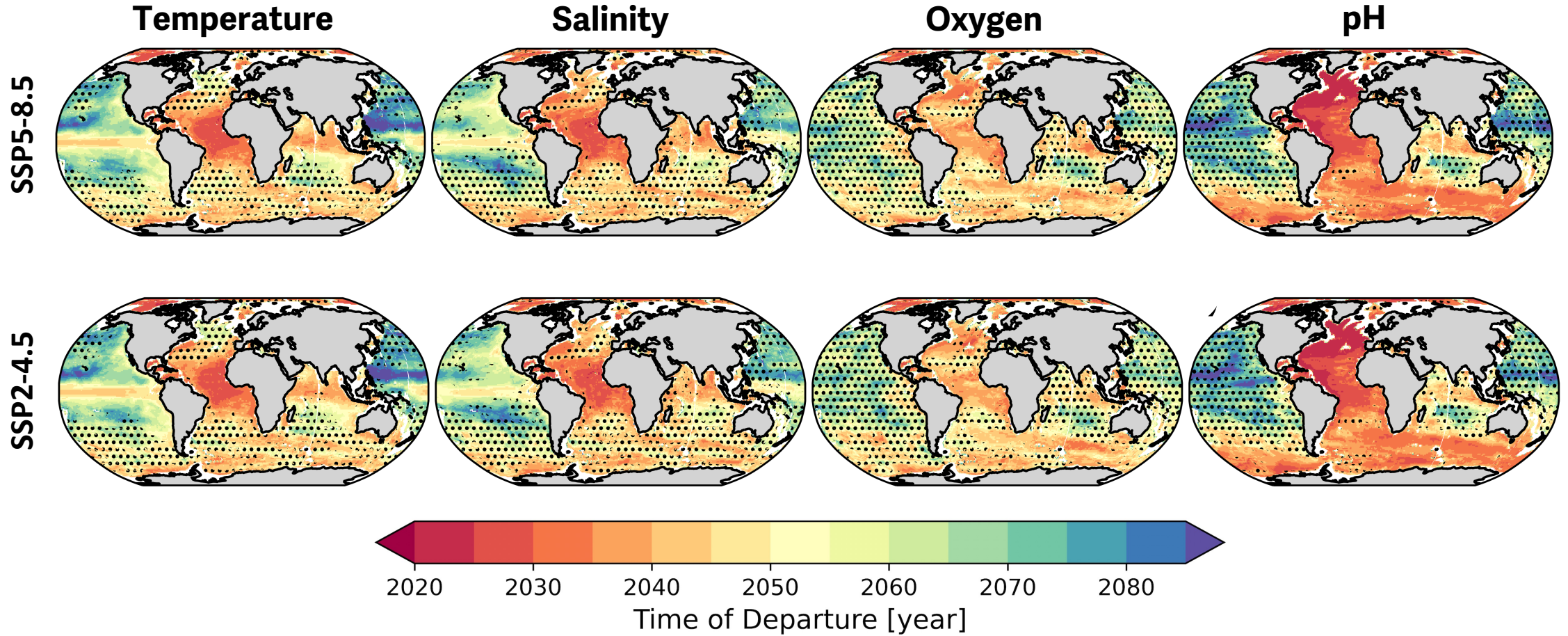
# Impact of significant emissions mitigation



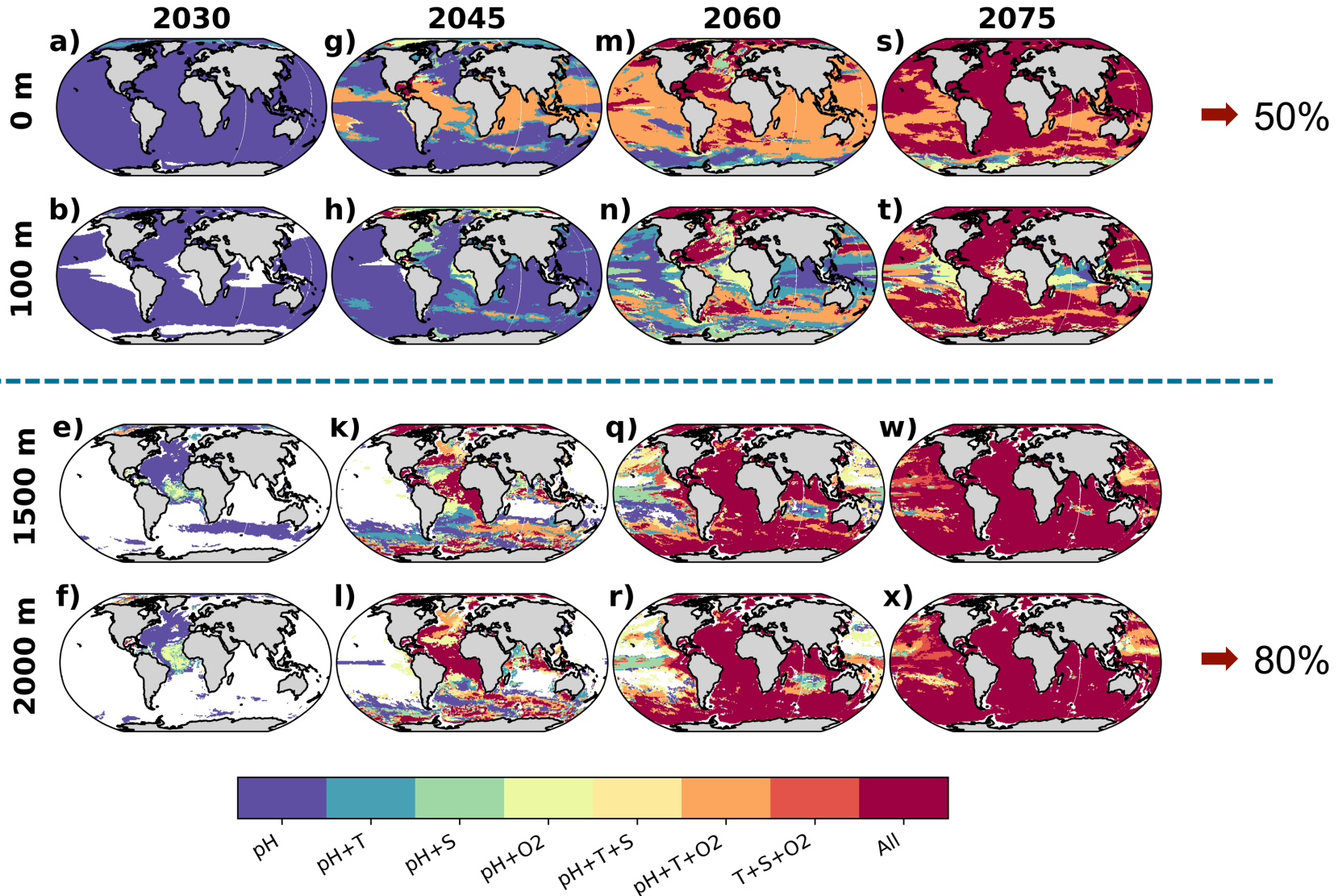
# Surface ToD (SSP5-8.5 vs SSP2-4.5)



# 2000 m ToD (SSP5-8.5 vs SSP2-4.5)



# Departure of multiple drivers (SSP5-8.5)

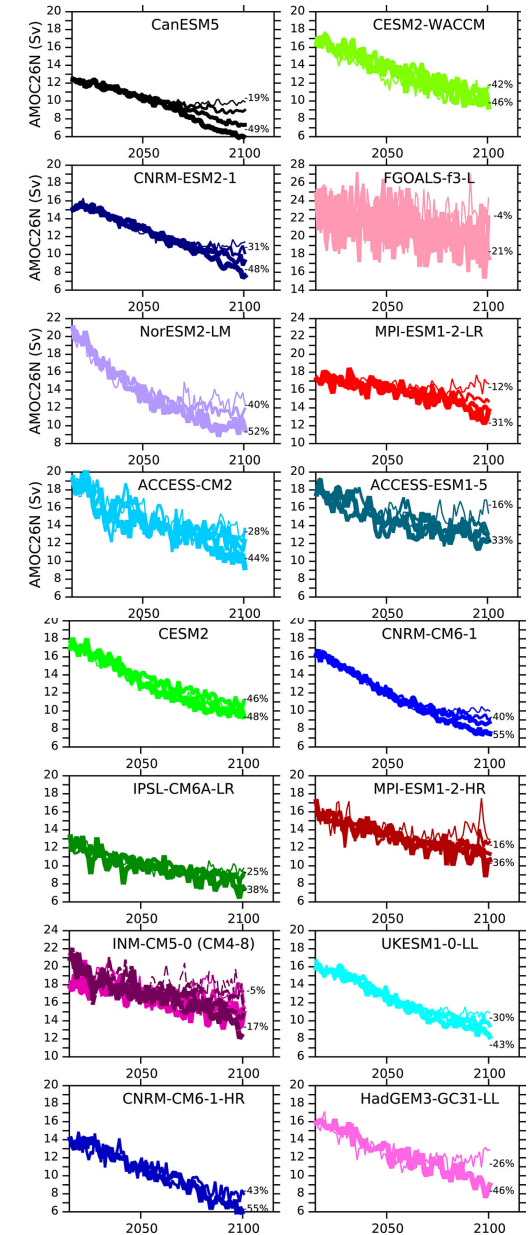
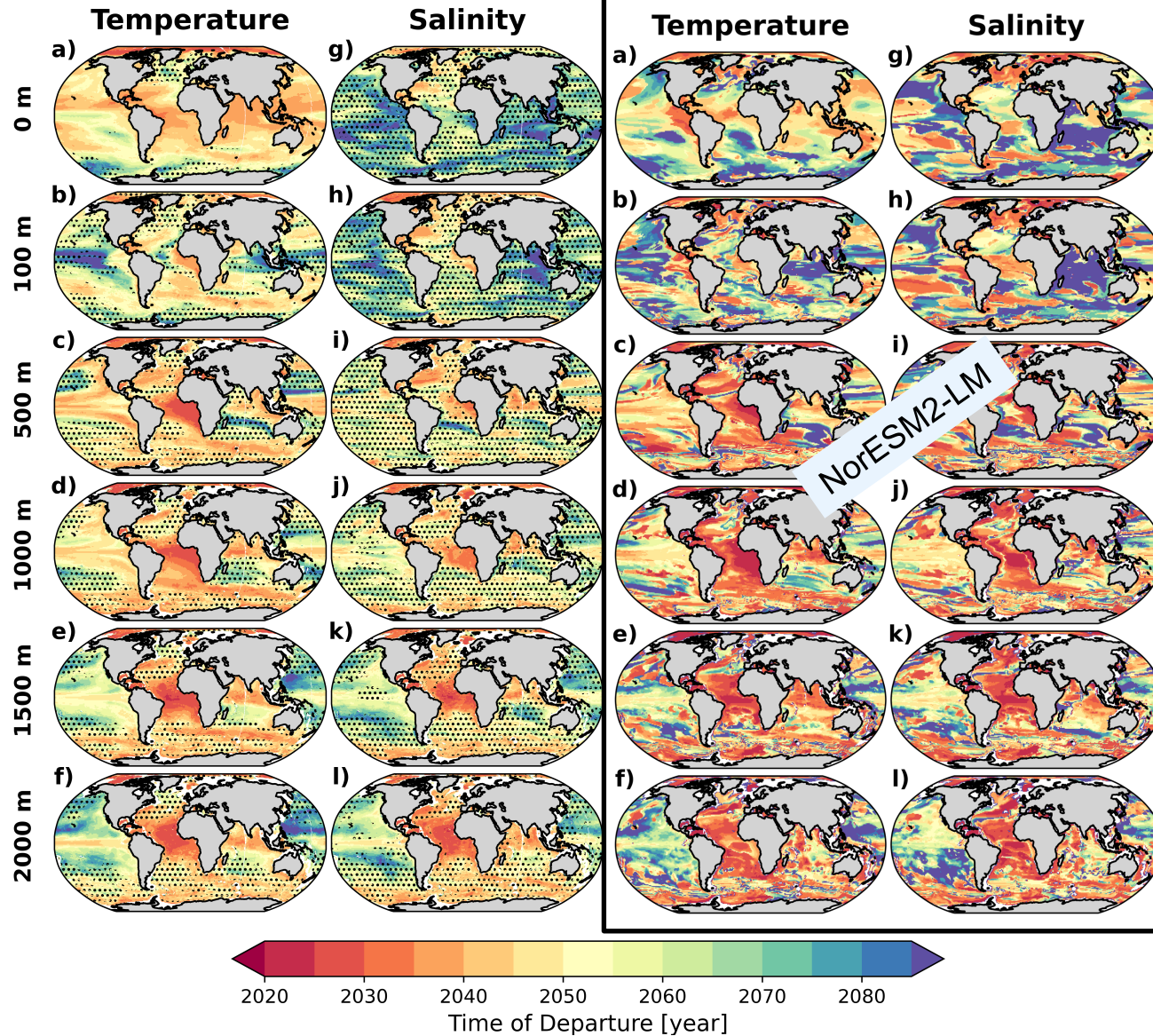




## Time of Departure under SSP5-8.5

How do NorESM2 compare to the ensemble mean?

Generally similar patterns but emerge earlier e.g., in the Atlantic.





## Summary

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- › Majority of anthropogenic changes (T, S, and O<sub>2</sub>) are detectable earlier in the interior rather than at the surface.
- › The low background variability of interior ocean makes it more vulnerable to future changes.
- › Acidification is detectable earliest, followed by warming and oxygen changes.
- › Temperature and salinity changes in the subsurface tropical and subtropical North Atlantic are early indicators for AMOC slowdown.
- › Substantial future changes in the interior ocean have been committed today => regardless of mitigation measures, interior ocean changes are projected to emerge within the next few decades.
- › Tropical+North Atlantic and the Southern Ocean are early emergence regions and would benefit from long-term monitoring system.

Tjiputra, et al. (2023), Early detection of anthropogenic climate change signals in the ocean interior, **Scientific Reports**, 13:3006, doi:10.1038/s41598-023-30159-0.