Massachusetts Institute of Technology

Estimating the Circulation and Climate of the Ocean

TEXAS
The University of Texas at Austin

Mode Water, a key pathway for Earth Energy Imbalance to deep ocean

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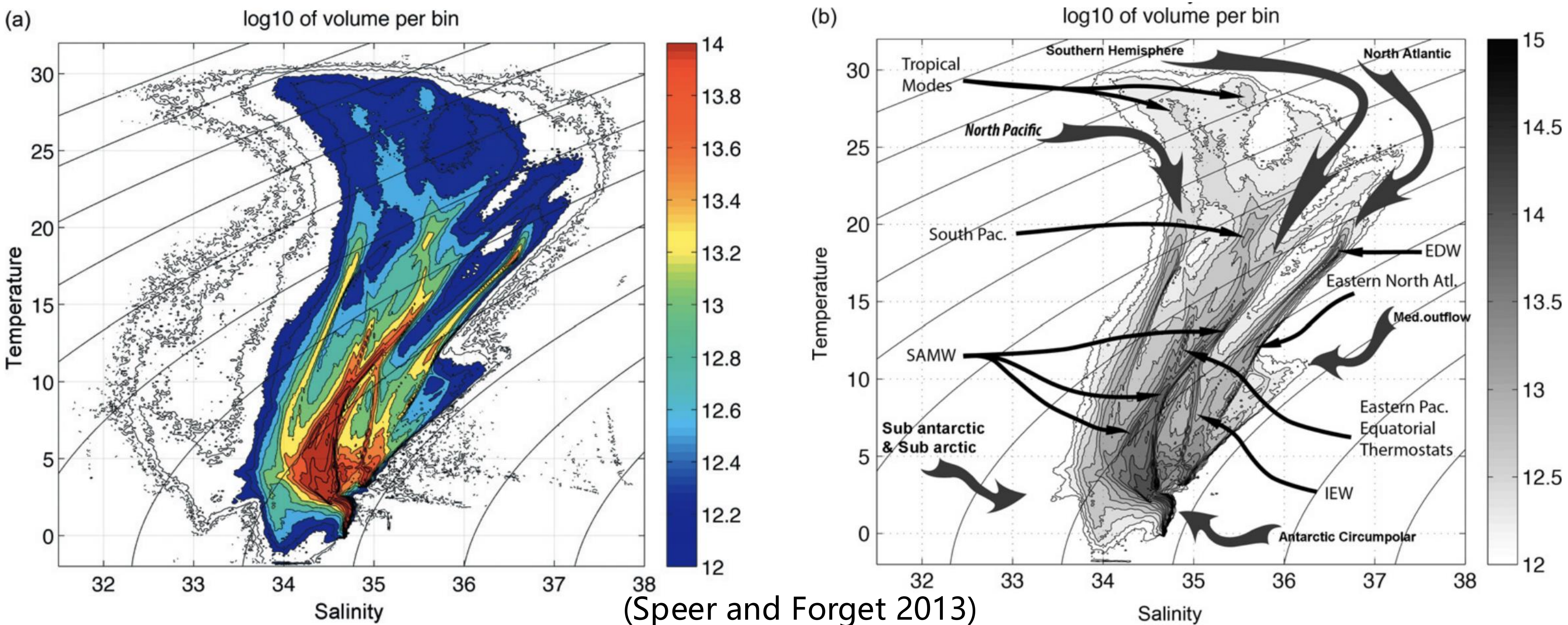
Background: What’ s Mode Water?

“Mode Water” is the name given to a layer of nearly vertically homogeneous water mass with **same temperature and salinity** found over **a large volume** in the upper ocean, immediately beneath the mixed layer (e.g. Hanawa and Talley 2001).

“mode” is a statistical concept, which means **the most frequently occurring value** in a dataset.

Volumetric census of global upper 2000 m ocean



(Speer and Forget 2013)

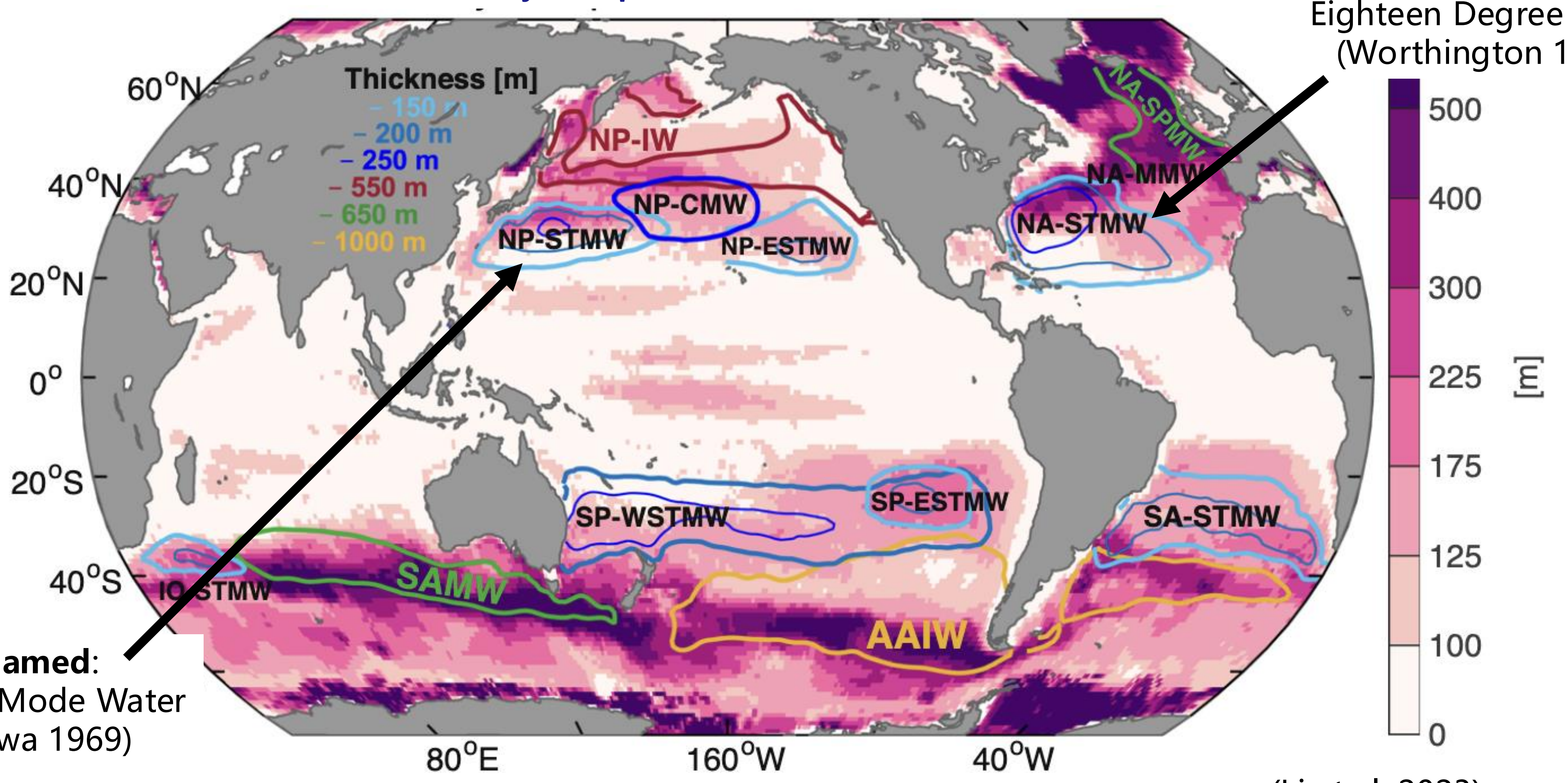
Background: Where’s Mode Water?

Horizontal distribution

Subtropical Mode Water (STMW) & Subpolar Mode Water (SPMW)

Mixed layer depth and water mass locations

First described:
Eighteen Degree Water
(Worthington 1959)

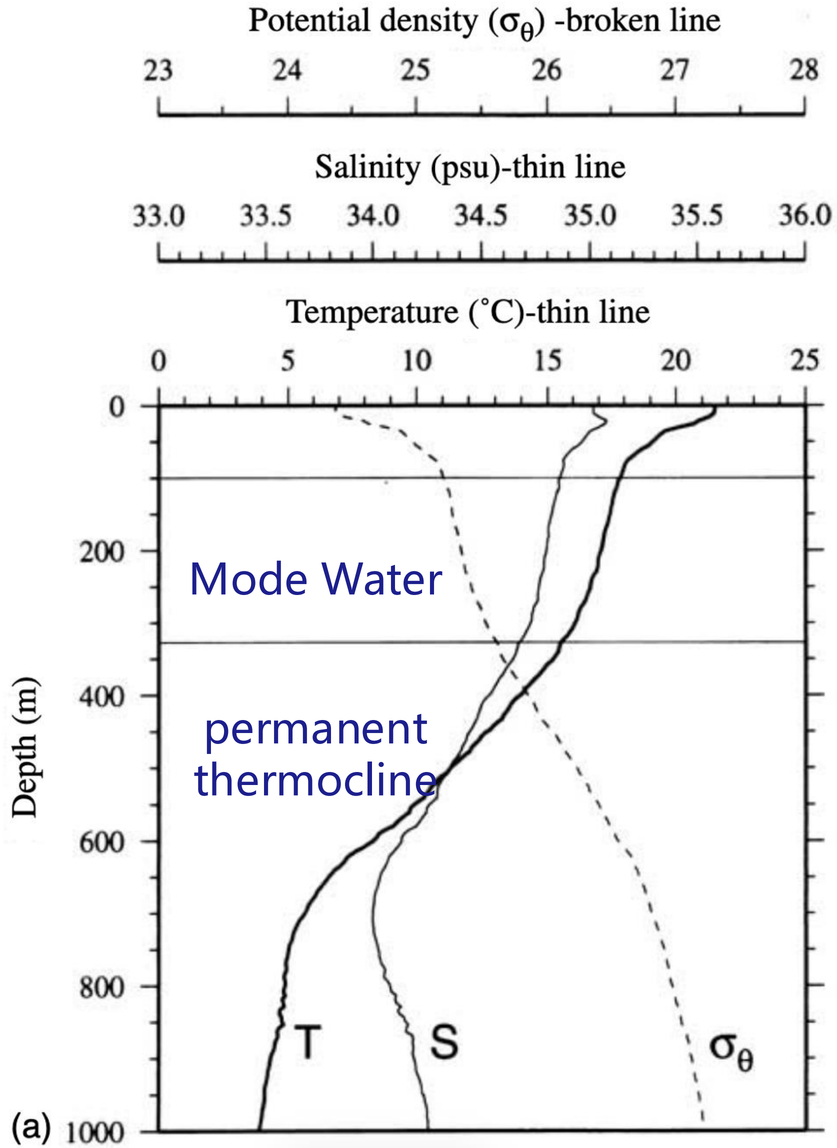


First named:
Subtropical Mode Water
(Masuzawa 1969)

(Li et al. 2023)

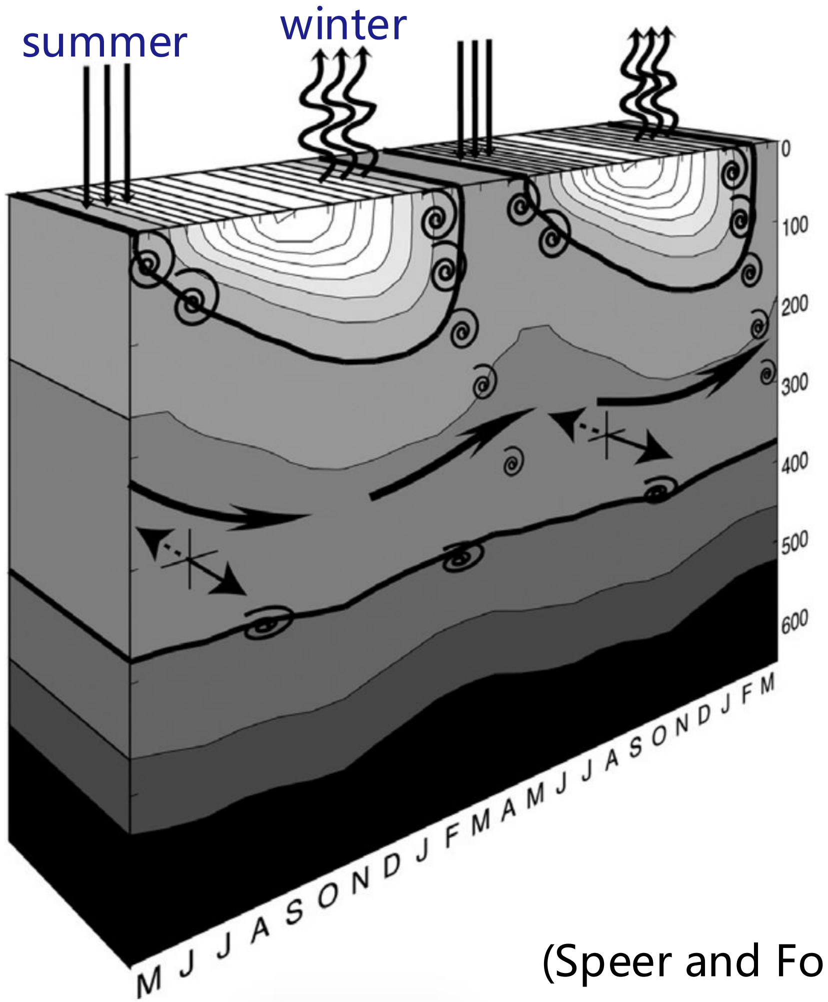
Background: Where’s Mode Water?

Vertical distribution



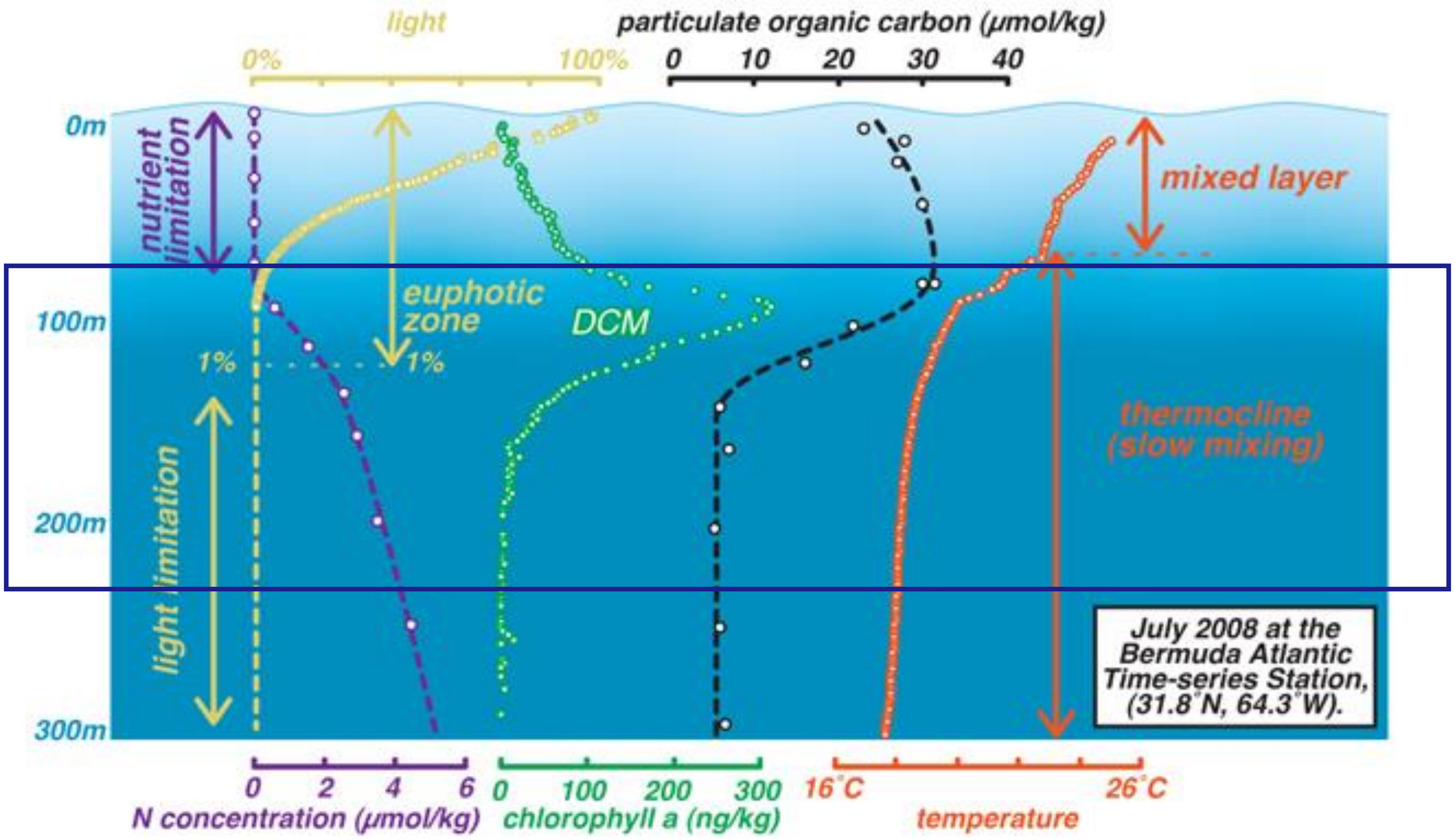
(Hanawa and Talley 2001)

- beneath the mixed layer
- above the permanent thermocline



(Speer and Forget 2013)

Background: Where's Mode Water?



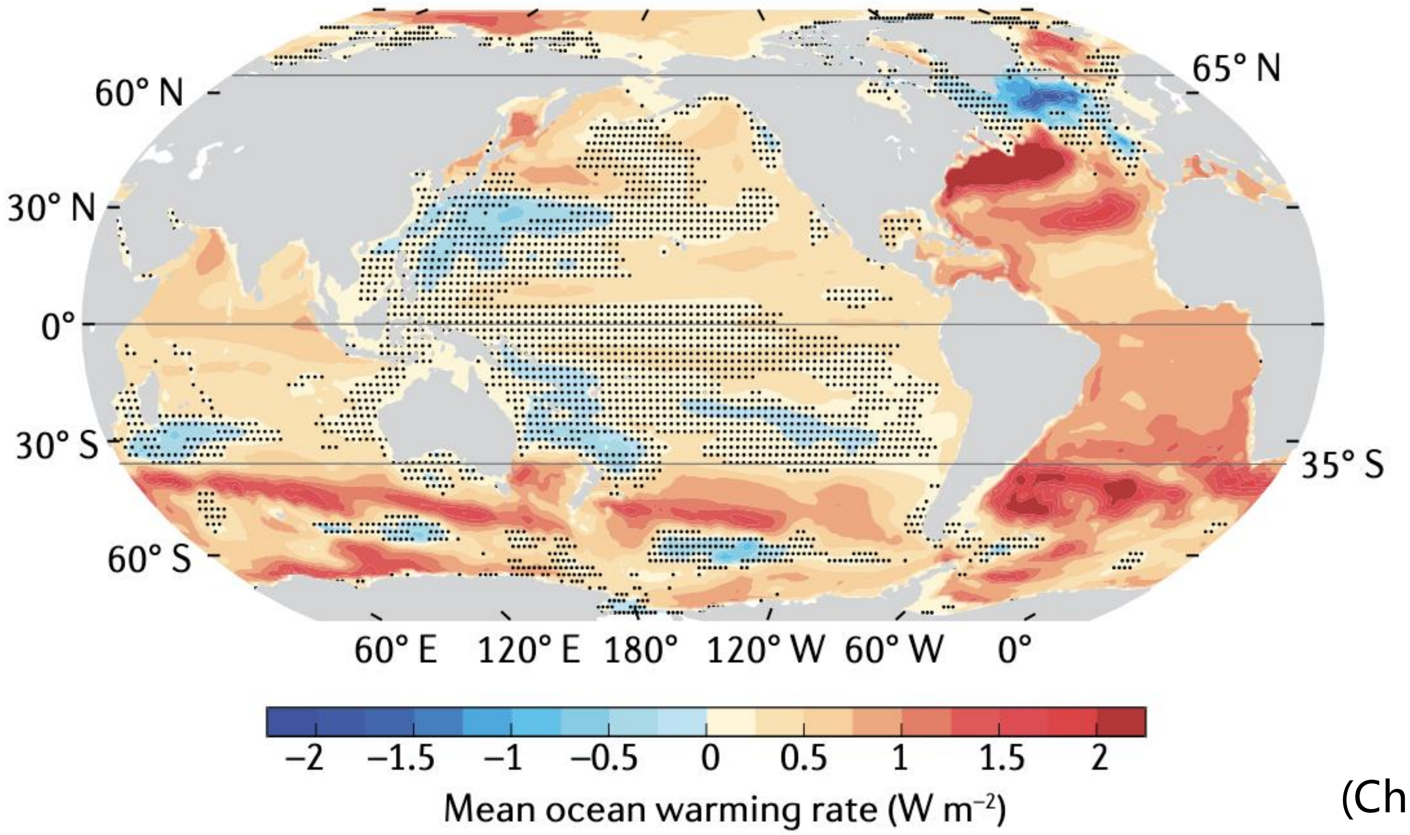
Background: Why does Mode Water matter in Earth Energy Imbalance?

Earth Energy balance → stable state (no significant warming/cooling)

Earth Energy Imbalance → excess heat → global warming

ocean (**98%**)

upper 2000 m (**70%**)

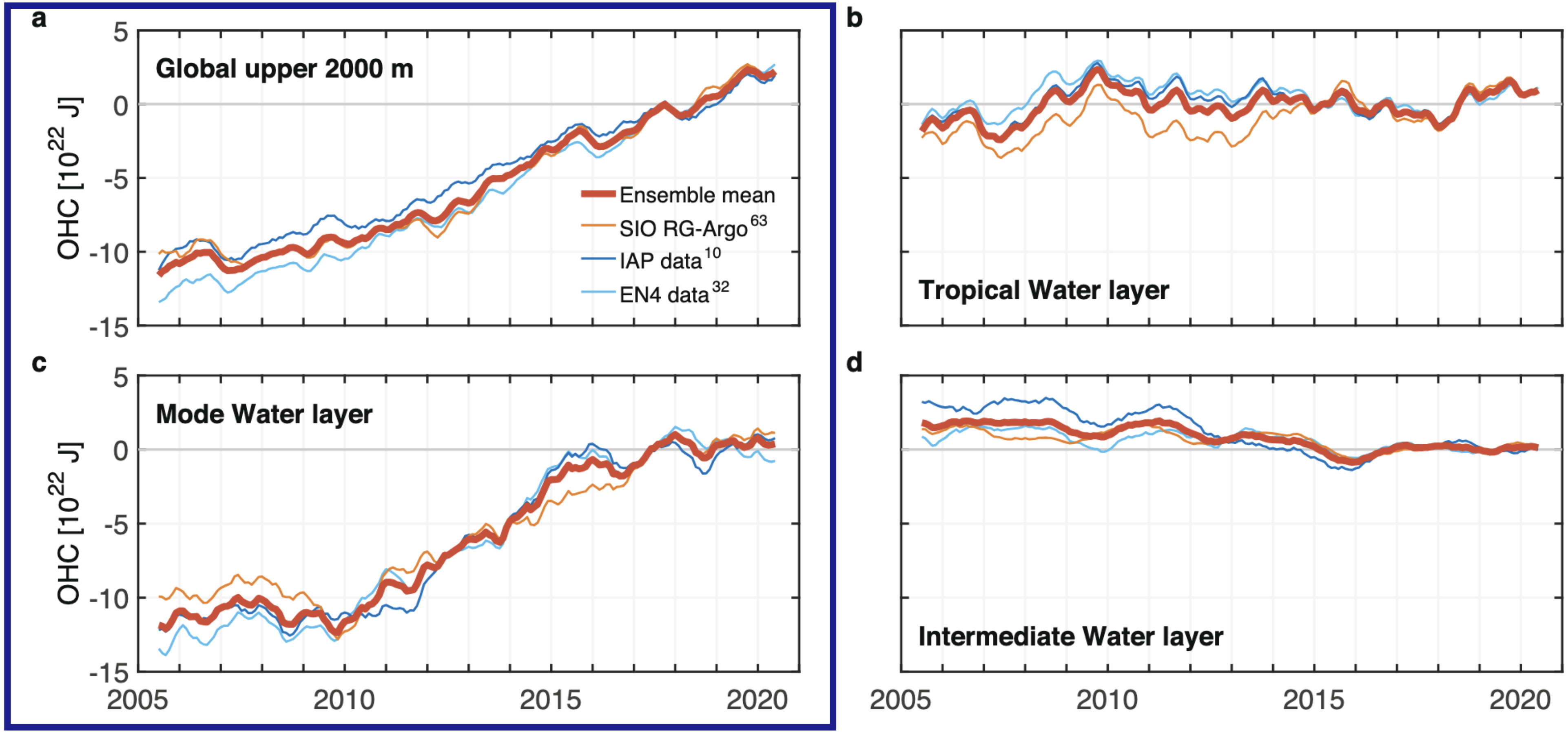


(Cheng et al. 2024)

Background: Why does Mode Water matter in Earth Energy Imbalance?

Mode Water account for almost the largest share of global ocean warming

Global upper 2000 m ocean heat content change during 2005-2020



(Li et al. 2023)

Scientific Questions

How does Mode Water temperature change in a longer period? E.g. 1980-2022?

Long linear trend vs. Internal variability?

What processes govern Mode Water temperature change?

Local processes vs. Remote factors?

Key Challenge: Observational ocean data is not reliable enough before Argo (2004).

Possible Solution

ECCO achieves **dynamical consistency**, which makes it particularly **well-suited** for diagnosing the underlying processes that drive ocean heat uptake and redistribution with closed heat budget.

ECCOv4R2 **1992-2011**

extend

- Inherite the **observational constraints** from the ECCOv4R2 adjoint optimization (satellite and in situ observations--Argo float profiles, CTD and XBT……)
- Take **optimized parameters** from ECCOv4R2, which largely reduce spurious mode drifts
- Forcing fields are created by starting from the **ERA5 reanalysis** (Hersbach et al. 2020) and adding a monthly climatology of the difference between ECCO4-R2 optimized forcing and ERA5.
- These adjustments are calculated over the period of overlap (1992–2011) and then applied to ERA5 every year from **1980 to 2022**.

OCCA2 **1980-2022**

(Forget et al. 2026?)

Longer period

closed heat budget

LLC90 grid

50 vertical levels

Data Comparison

IAPv4 is an observationally driven objective analysis product whose gridded fields are constructed through optimal interpolation of in situ data with covariances informed by climate model output (Cheng et al. 2024).

1º x 1º, 119 vertical levels, 1940-2026

- OCCA2 and IAPv4 differ fundamentally in their **construction methodology**.
- **Data-sparse regions** such as the Southern Ocean prior to the Argo era also contribute to discrepancies between the two products.

Definition of Mode Water

We define the perennial mode water source as a 100 m-thick layer spanning from 50 m above to 50 m below annual maximum mixded layer depth (MLD), given that mode waters are formed from the winter deep mixed layer and capped by the seasonal thermocline.

The MLD is defined as the depth where the potential density difference from the near-surface is larger than 0.03 kg/m^3 (de Boyer Mont´ egut et al. 2004).

A horizontal box is defined for each mode water based on the global map provided in Li et al. (2023).

Northern Hemisphere	Abbreviation	Southern Hemisphere	Abbreviation
North Atlantic STMW	NA-STMW	South Atlantic STMW	SA-STMW
North Atlantic Madeira MW	NA-MMW	South Pacific Western STMW	SP-WSTMW
North Atlantic SPMW	NA-SPMW	South Pacific Eastern STMW	SP-ESTMW
North Pacific STMW	NP-STMW	Subantarctic MW	SAMW
North Pacific Central MW	NP-CMW	Indian Ocean STMW	IO-STMW
North Pacific Eastern STMW	NP-ESTMW		

Definition of Mode Water

Aim: Provide a comprehensive insight of global mode water temperature change.

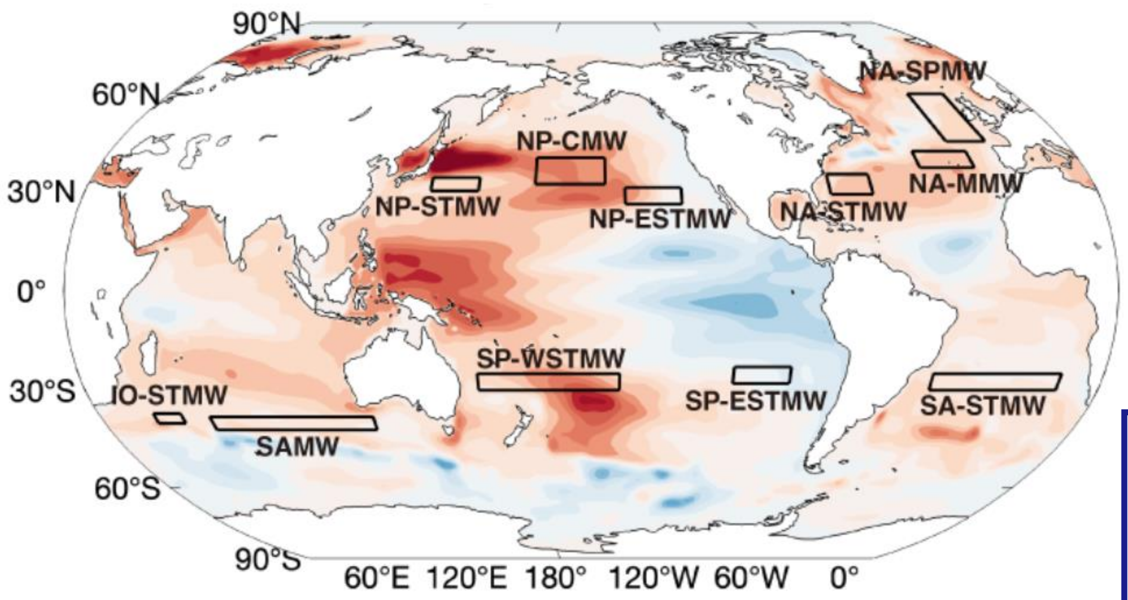


TABLE 1. Time-mean properties of mode waters.

Mode Water	Longitude Latitude	Depth (m)	MLD (m)	Density (kg/m^3)	Temperature (°C)	Salinity (psu)
NA-STMW	75°W-60°W 29°N-35°N	102-202	152	26.01-26.19	18.77-19.53	36.60-36.63
NA-MMW	40°W-20°W 37°N-42°N	98-198	148	26.60-26.69	14.68-15.36	36.03-36.12
NA-SPMW	10°W-25°W 45°N-60°N	204-304	254	26.98-27.05	3.48-3.51	35.40-35.43
NP-STMW	143°E-160°E 30°N-34°N	151-251	201	25.20-25.45	16.13-17.74	34.68-34.78
NP-CMW	180°-155°W 32°N-40°N	74-174	124	25.85-26.05	11.54-12.80	34.29-34.34
NP-ESTMW	148°W-128°W 26°N-31°N	51-151	101	24.85-25.53	13.54-18.18	34.18-34.66
SA-STMW	40°W-5°E 30°S-25°S	55-155	105	25.70-26.08	15.98-18.60	35.57-35.98
SP-WSTMW	160°E-150°W 30°S-25°S	42-142	92	25.30-25.68	17.65-19.42	35.56-35.63
SP-ESTMW	110°W-90°W 28°S-23°S	72-172	122	25.18-25.57	16.09-19.06	34.93-35.40
SAMW	60°E-120°E 42°S-38°S	311-411	361	26.55-26.63	10.51-11.24	34.84-34.94
IO-STMW	40°E-50°E 40°S-37°S	196-296	246	26.07-26.28	14.14-15.53	35.33-35.45

Closed heat budget in OCCA2

$$\frac{\partial T}{\partial t} = F_{adv} + F_{diff} + Q$$

adiabatic advection $F_{adv} = -\nabla \cdot (uT)$ ocean heat transport

diabatic

- diffusion $F_{diff} = \nabla \cdot (\kappa \nabla T)$ Along and cross isopycnal diffusion, mesoscale eddy parameterization
- forcing Q Reflects the parameterization of surface heat fluxes at the surface and shortwave radiation penetration largely confined to the upper 200 m.

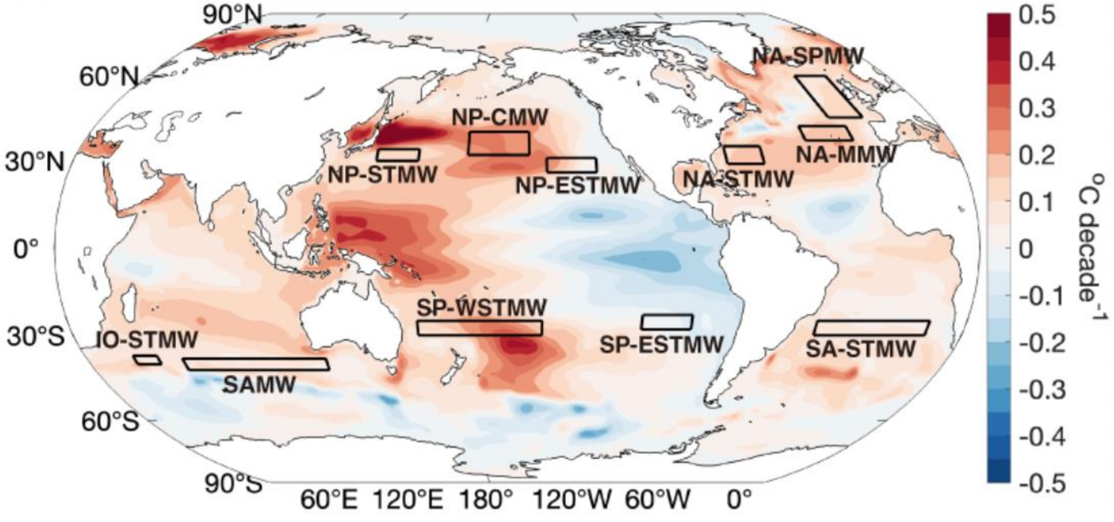
Separate Interannual and Decadal variability

Methods	Interannual	Decadal
temporal Lanczos filter (temperature)	10-year high pass on 1980-2022	10-year low pass on 1980-2022
bootstrapped cumulative analysis (heat budget terms)	cumulatively integrate heat budget anomalies within each of the 397 overlapping 10-year windows, followed by the bootstrap procedure	average each variable over the each 10-year window and subsequently applying the bootstrap

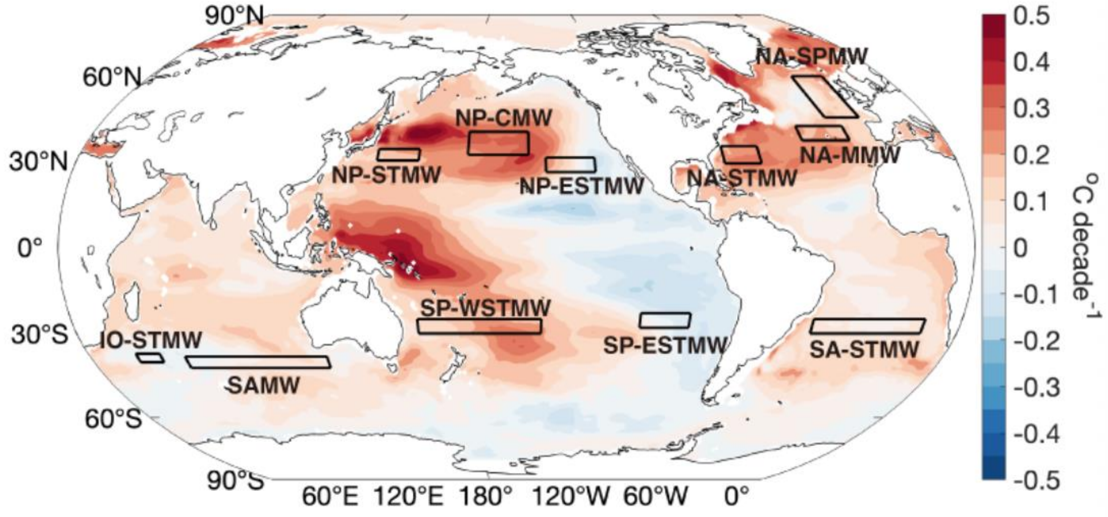
Results: Warm trend in mode waters

Linear trend of 0-200 m temperature during 1980-2022

(a) Linear trend of 0-200 m temperature (OCCA2)



(b) Linear trend of 0-200 m temperature (IAPv4)



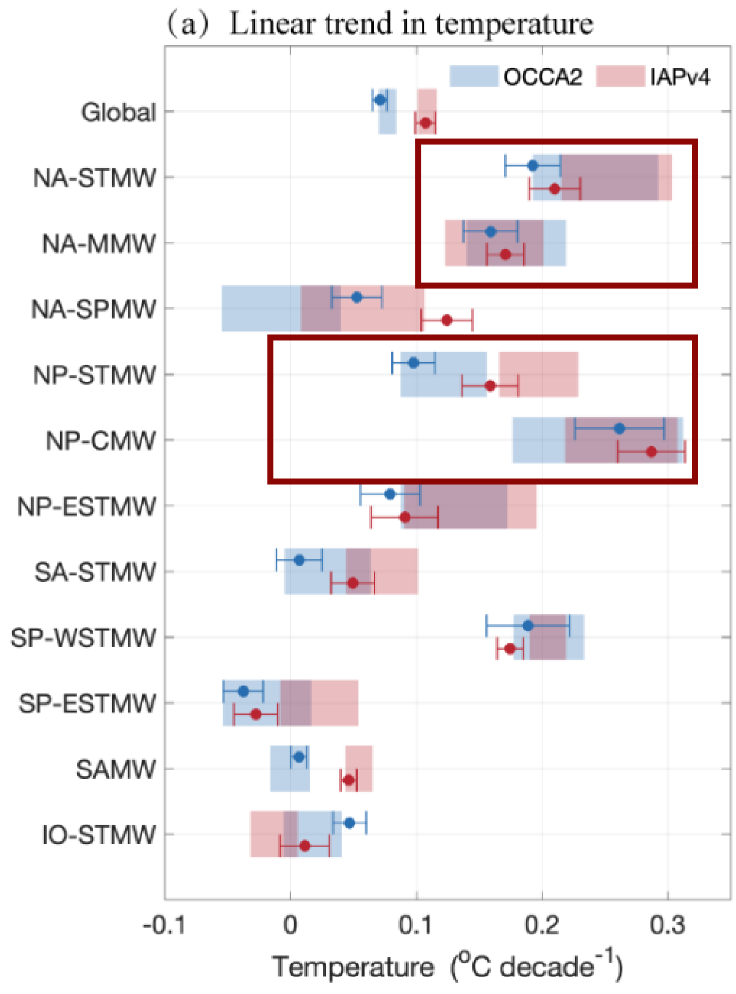
OCCA2 and IAPv4 are largely consistent in most regions.

Most mode water form regions, western current, show significant warming.

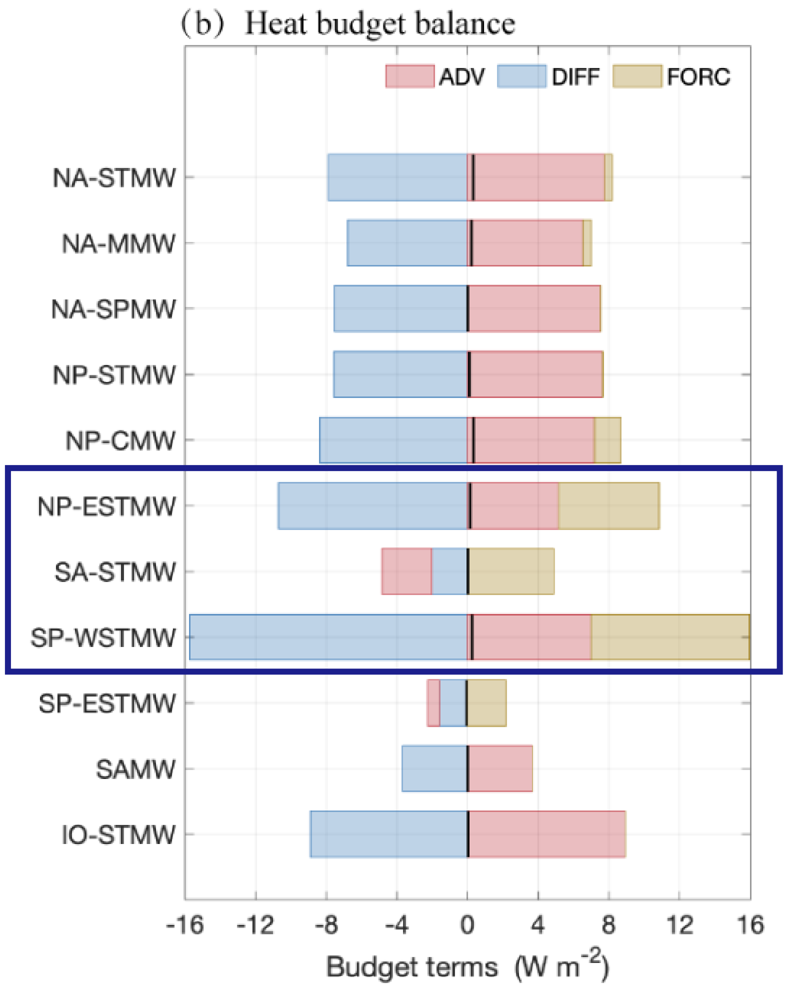
Results: Warm trend in mode waters

NA-STMW, NA-MMW, NP-STMW, and NP-CMW

Linear trend in mode water temperature

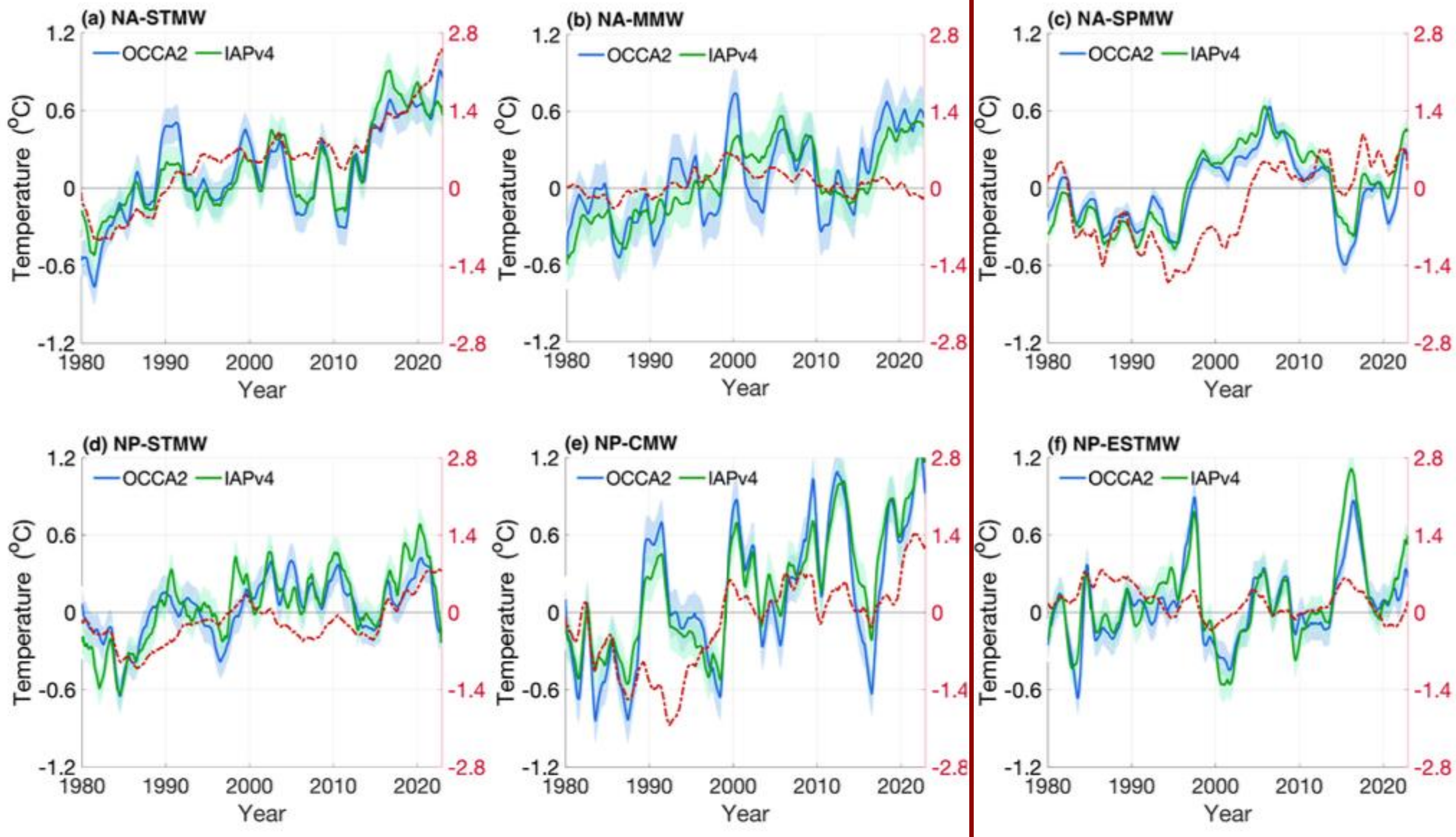


Heat budget balance



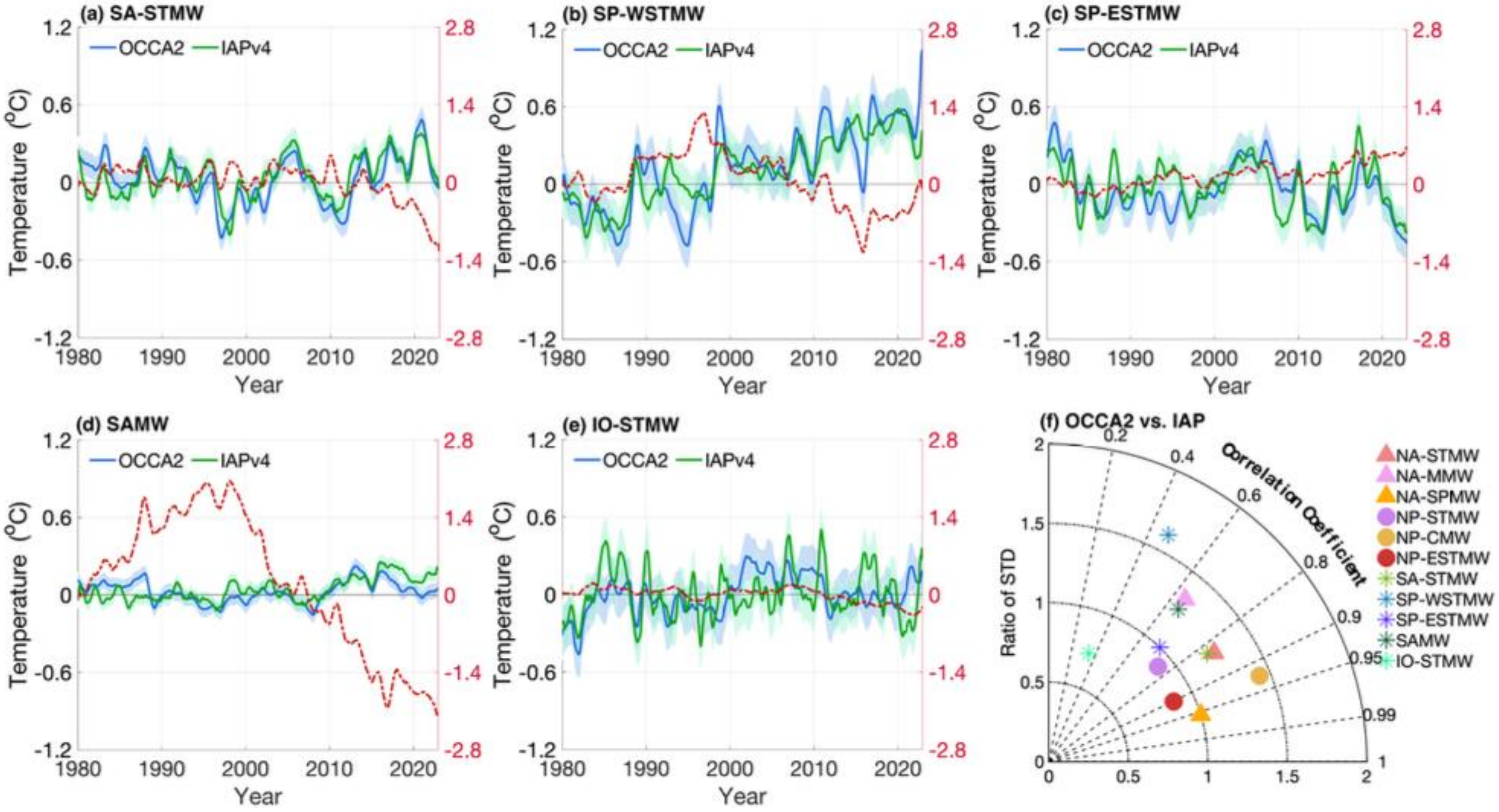
Results: Anomaly temperature time series

Northern Hemisphere Mode Waters

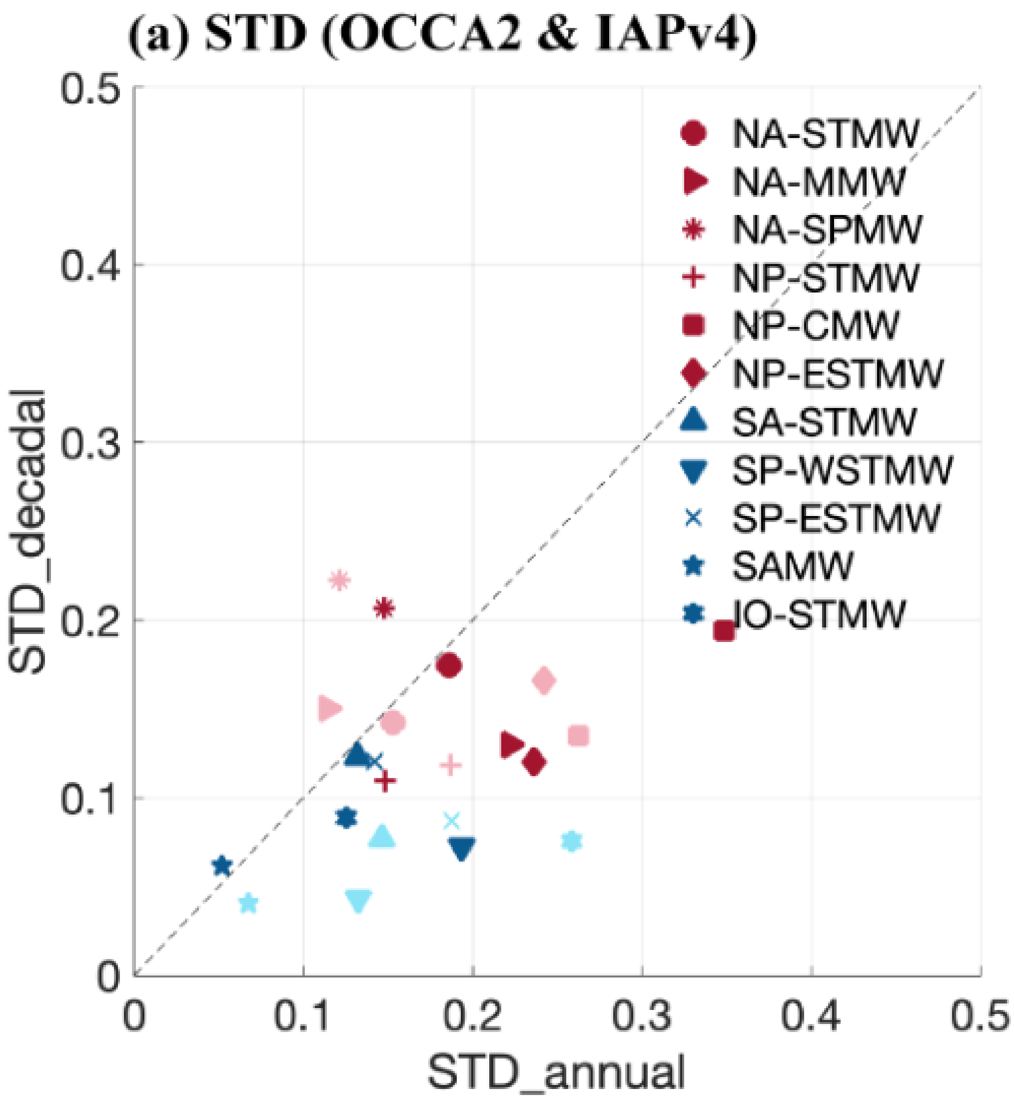


Results: Anomaly temperature time series

Southern Hemisphere Mode Waters



Results: Anomaly temperature time series

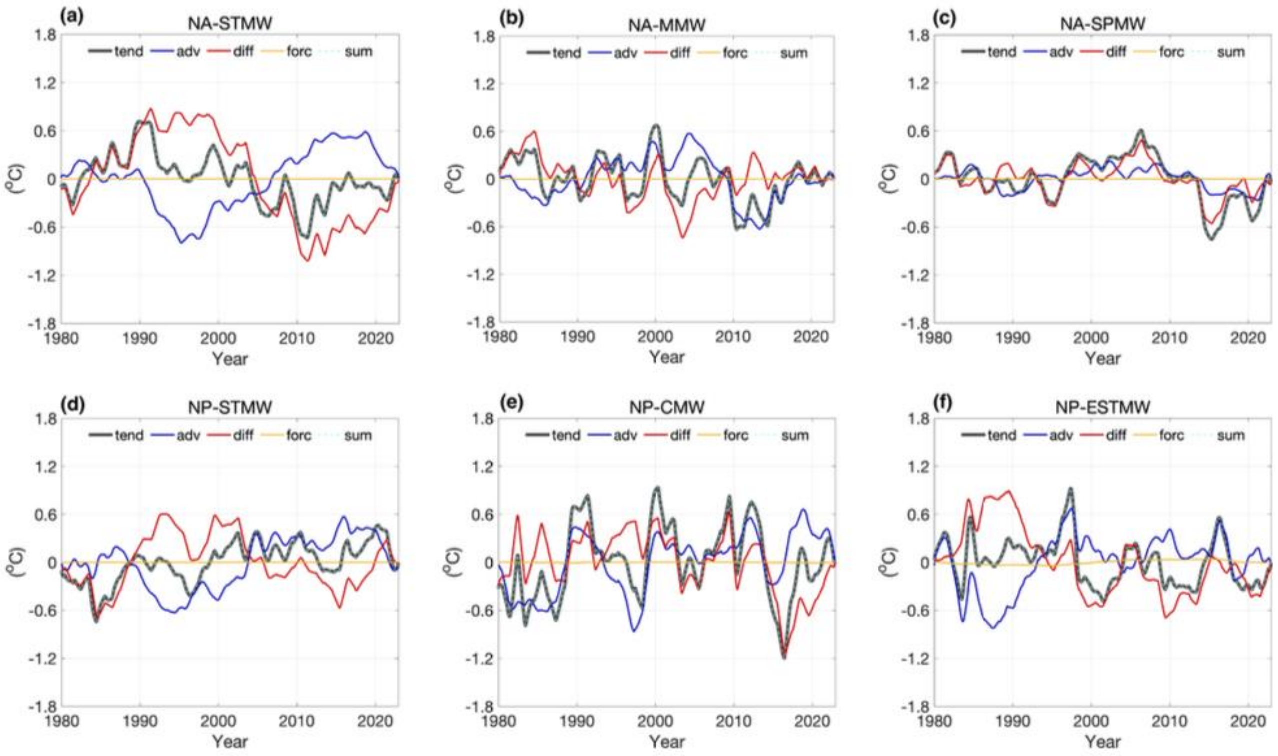


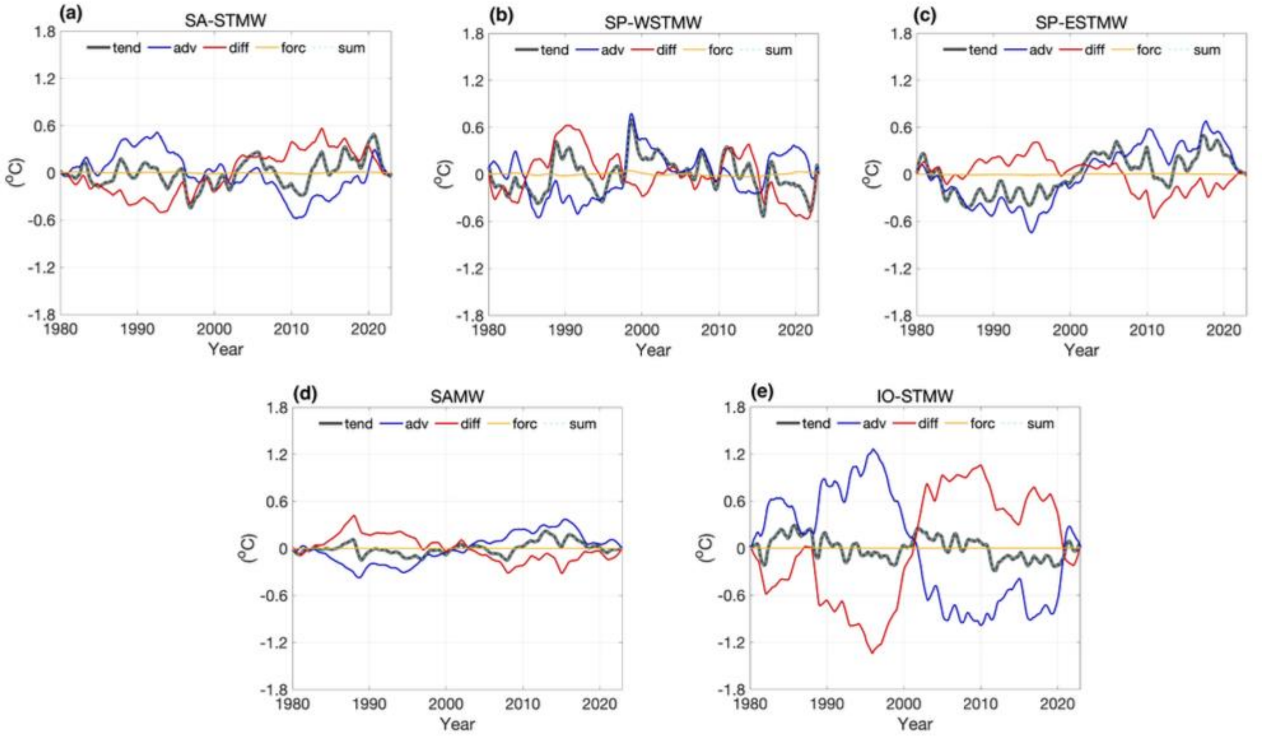
Northern hemisphere: more decadal

Southern hemisphere: more interannual

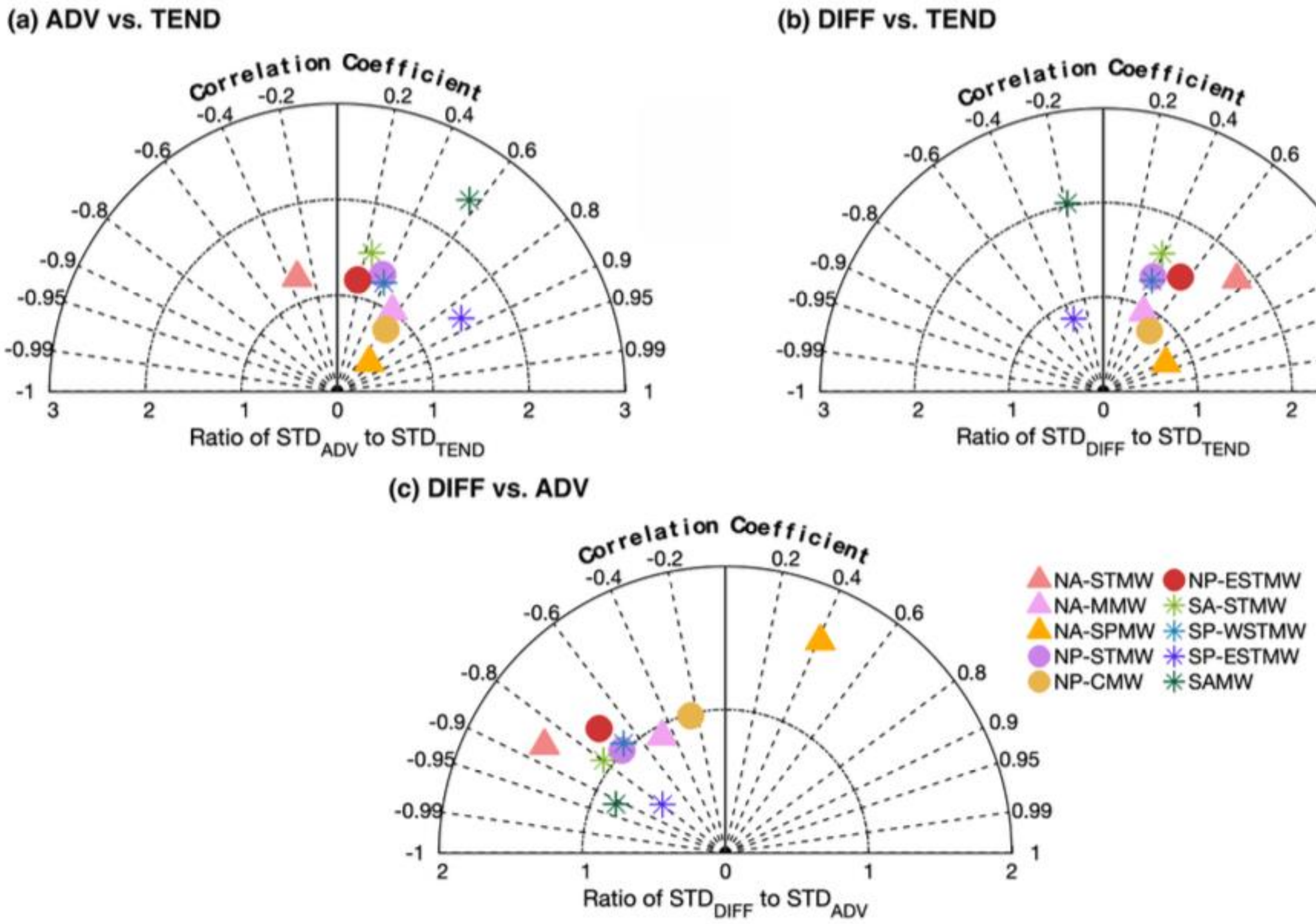
Results: Heat Budget

Cumulated detrended heat budget anomaly





Results: Heat Budget



Category 1: Advection dominates

- SP-ESTMW
- SAMW

Category 2: Diffusion dominates

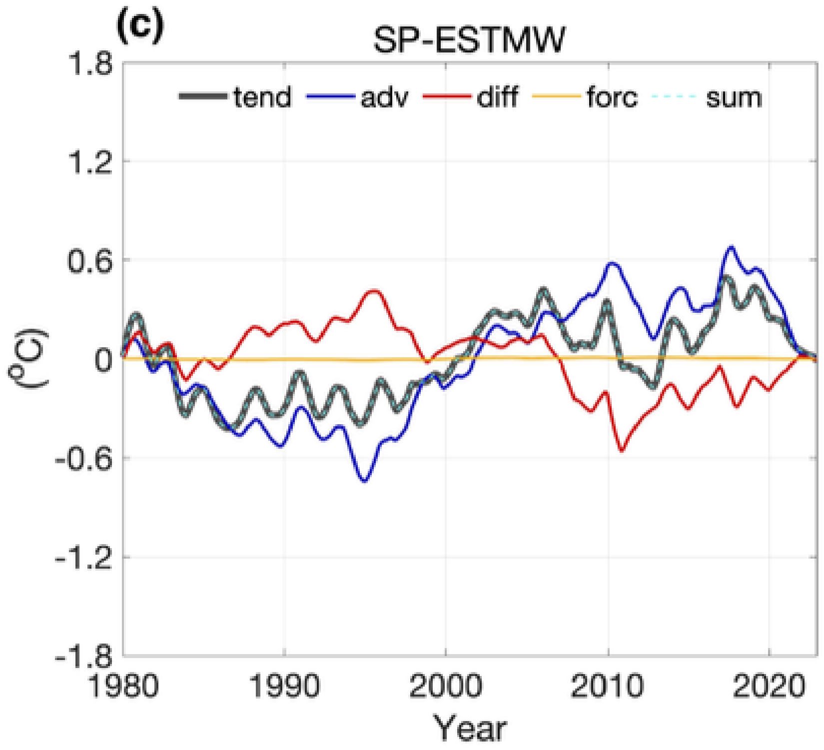
- NA-STMW
- NP-ESTMW
- SA-STMW

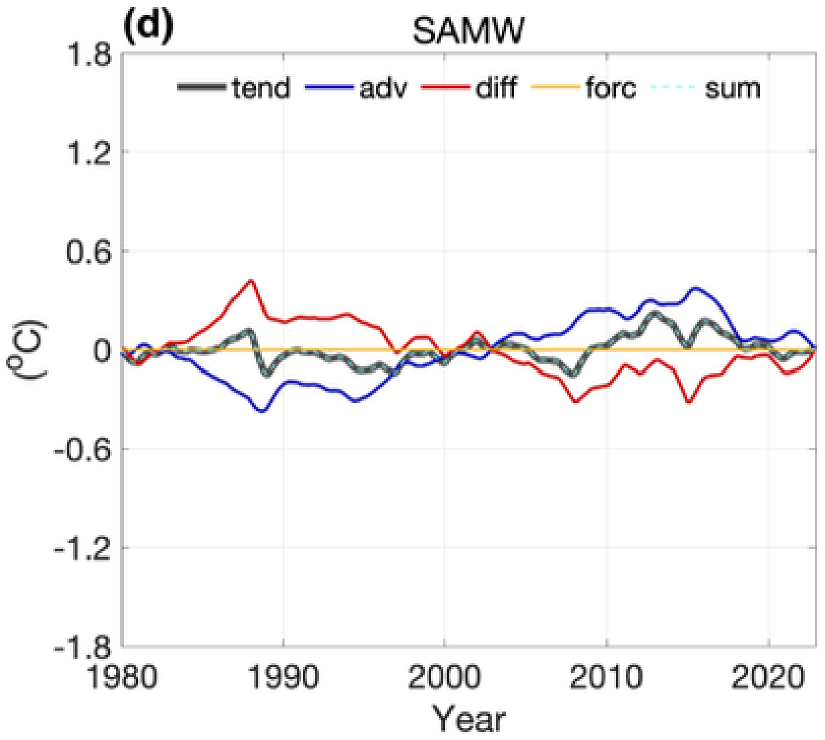
Category 3: Equal

- NP-STMW
- NA-MMW
- NA-SPMW
- NP-CMW

Results: Heat Budget

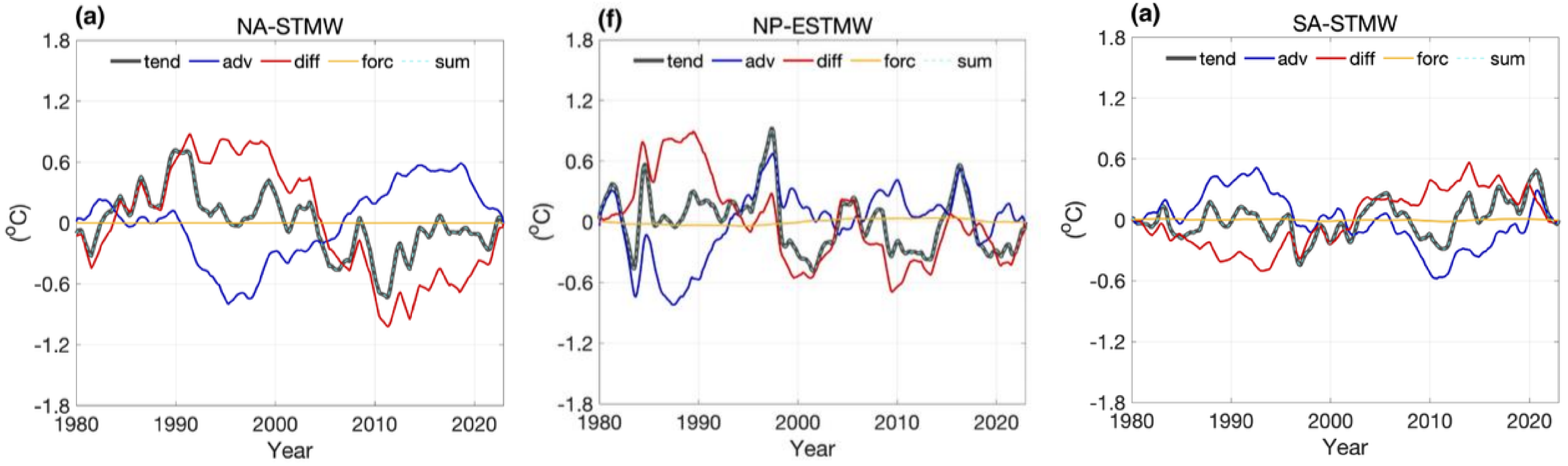
Category 1: Advection dominates





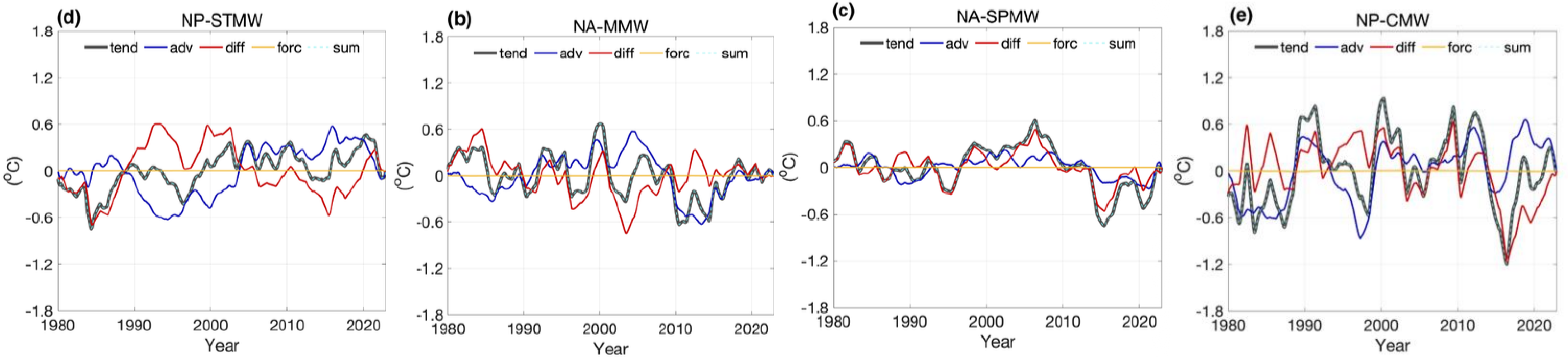
Results: Heat Budget

Category 2: Diffusion dominates



Results: Heat Budget

Category 3: Advection and Diffusion are equal.



Results: Indices of Interannual and Decadal variability

Correlation maps show consistency in OCCA2 and IAPv4.

NA-STMW & North Atlantic Oscillation (NAO)

NP-ESTMW & Interdecadal Pacific Oscillation (IPO)

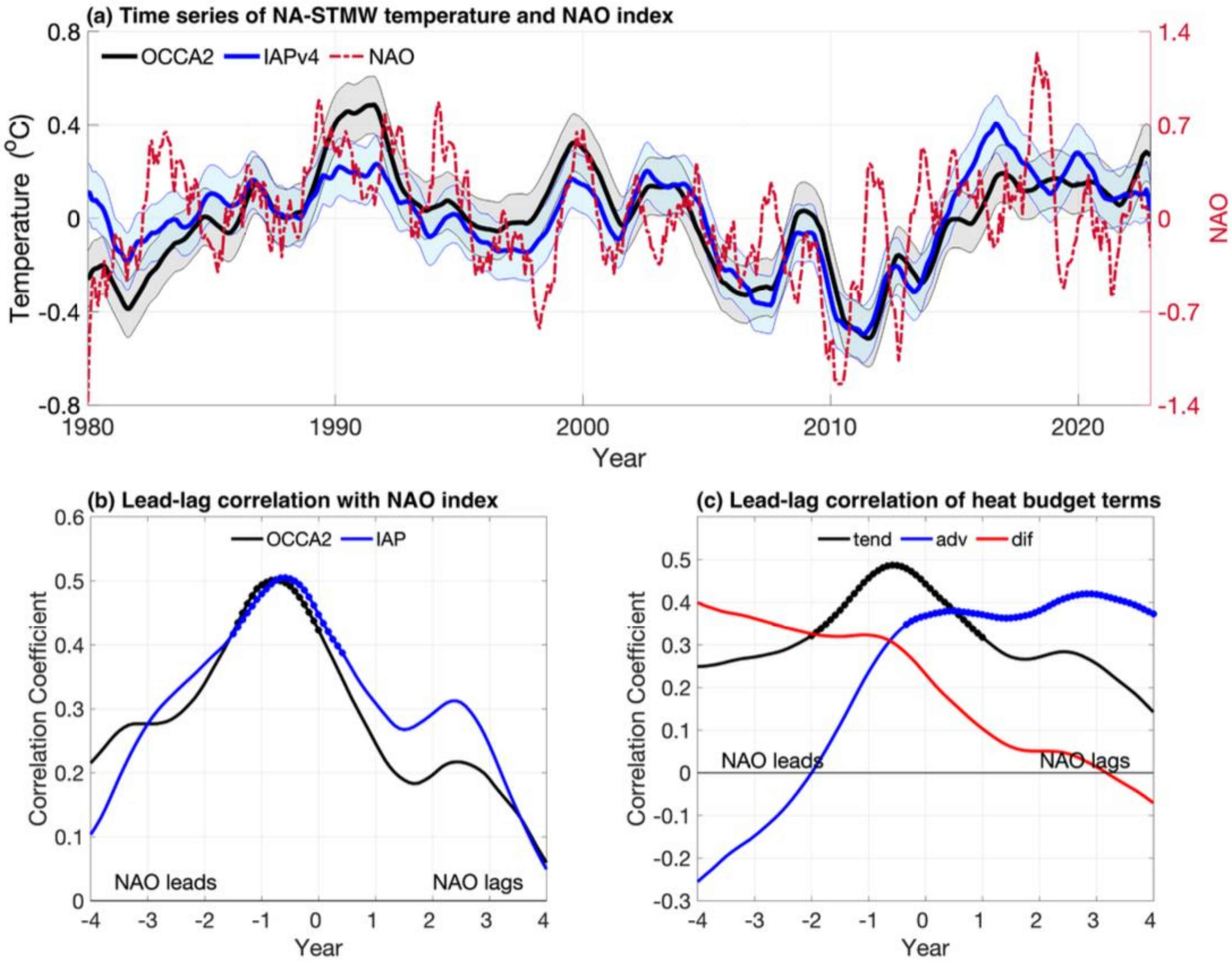
(a) Correlation with temperature (OCCA2)

	Nino3.4	NAO	SAM	IPO	AMO
NA-STMW	0.23	0.44	0.06	0.35	-0.36
NA-MMW	-0.20	-0.03	-0.01	-0.03	0.07
NA-SPMW	-0.24	-0.36	-0.09	-0.47	0.35
NP-STMW	0.03	0.02	-0.10	-0.40	0.27
NP-CMW	-0.27	0.23	-0.10	-0.32	-0.15
NP-ESTMW	0.21	0.11	0.16	0.56	-0.11
SA-STMW	0.16	0.24	-0.19	0.11	-0.12
SP-WSTMW	-0.25	0.11	0.02	-0.62	0.24
SP-ESTMW	0.30	0.02	-0.19	-0.43	0.57
SAMW	0.14	0.06	0.07	0.02	-0.07
IO-STMW	0.02	-0.03	0.08	-0.22	0.08

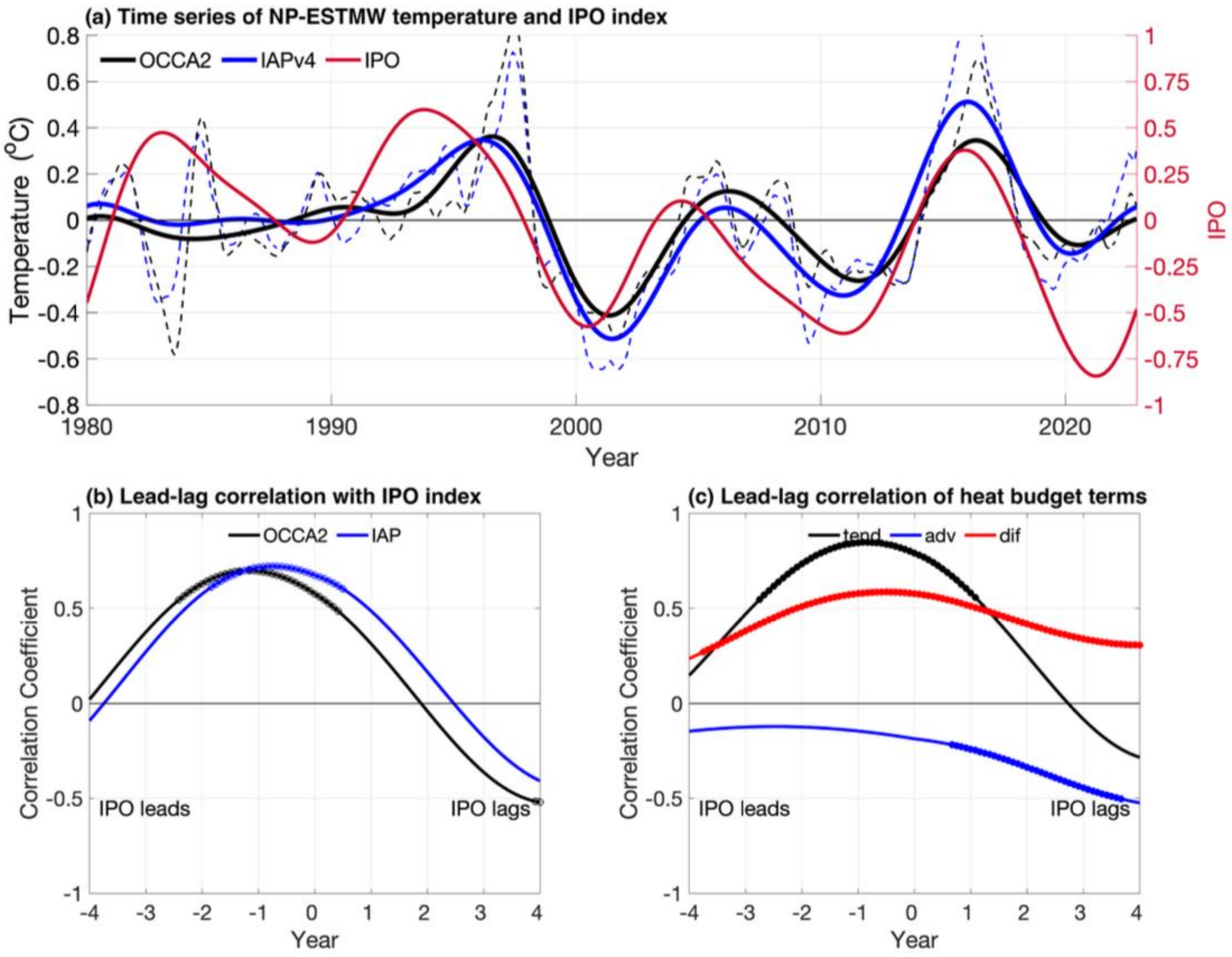
(b) Correlation with temperature (IAPv4)

	Nino3.4	NAO	SAM	IPO	AMO
NA-STMW	0.08	0.47	0.13	0.29	-0.19
NA-MMW	-0.18	0.23	0.11	-0.23	0.19
NA-SPMW	-0.26	-0.32	-0.11	-0.45	0.36
NP-STMW	0.05	-0.06	-0.15	-0.21	0.11
NP-CMW	-0.29	0.14	-0.11	-0.35	-0.18
NP-ESTMW	0.19	-0.02	0.06	0.64	-0.23
SA-STMW	0.09	0.21	-0.19	0.30	-0.09
SP-WSTMW	-0.52	-0.03	-0.01	-0.10	0.28
SP-ESTMW	0.13	-0.22	-0.27	0.07	0.37
SAMW	0.23	-0.01	-0.07	0.11	-0.07
IO-STMW	0.03	-0.07	0.01	0.05	-0.07

Results: Example of Interannual variability: NA-STMW & NAO



Results: Example of Decadal variability: NP-ESTMW & IPO



Takeaway

- OCCA2 provides a good solution to investigate temperature change in mode waters, with longer period (1980-2022) and closed heat budget.
- OCCA2 show most consistency with IAPv4. Some inconsistency in SP-ESTMW and IO-STMW needs caution.
- Northern hemisphere mode waters show more significant warming than southern hemisphere ones.
- Northern hemisphere shows more decadal variability, while southern hemisphere displays more interannual variability.
- Advection dominates SP-ESTMW and SAMW. Diffusion dominates in NA-STMW, NP-ESTMW, and SA-STMW. Advection and diffusion are almost equal in other mode waters.
- Correlations between NA-STMW and NAO, NP-ESTMW and IPO are robust, which are worth doing more detailed research.

Song and Forget, 2026 JC (under review)

Thank you for listening!

Open for jobs: Postdoc (Fellowship) / Research Scientist / Faculty

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What I'm done		Future Interests
ocean temperature change	Southern Ocean	SST bias in models Marine Heatwaves Ocean heat transport Machine learning ......
	Mode Water	
	Marine Heatwaves	
	ENSO ocean heat transport	
air temperature or precipitation change	Arctic sea ice impacts on Mid-latitude climate	

Bootstrapping technique

$$\chi(r) = \frac{1}{N}\sum_{k=1}^{N}\left(\frac{1}{M}\sum_{j=1}^{M} r_j^{*(k)}\right)$$

Bootstrap is a **non-parametric resampling** method that quantifies uncertainty from data. For each of the 397 overlapping 10-year windows from the 43-year monthly data, let r_i (i=1,2,...,397) denote the calculated coefficients from the 397 windows. These coefficients can be linear trends, cumulative sum, time-means, or correlation coefficients.

The result provides **a robust estimate of the mean coefficients and of the associated uncertainty.**