Global Changes in Sea Surface Salinity and Freshwater Flux Based on Ocean Data Assimilation Products

Can ocean data assimilation help detect signals of global water-cycle changes?

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Changes in the Global Water Cycle

Global warming is intensifying the global water cycle

→ Changes in Evaporation minus Precipitation (E–P) IPCC AR3–AR6

What pattern?

DDWW: dry gets drier and wet gets wetter

How large?

Theoretical expectation: ~7 % K^{-1}

Climate models: ~3–4 % K^{-1}

What do observations tell us?

Changes in E–P are difficult to observe

Ocean **salinity** observations

+ Climate models

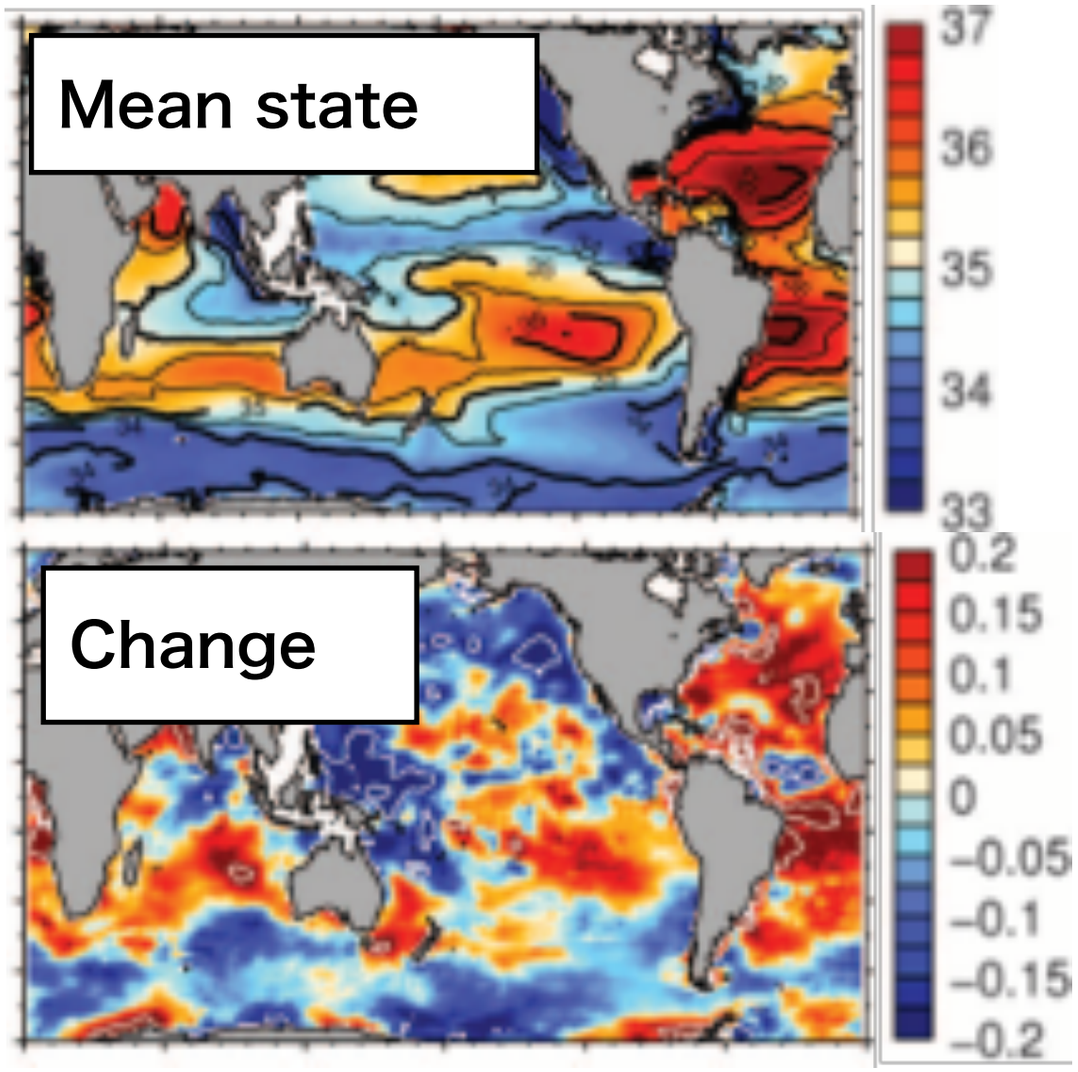


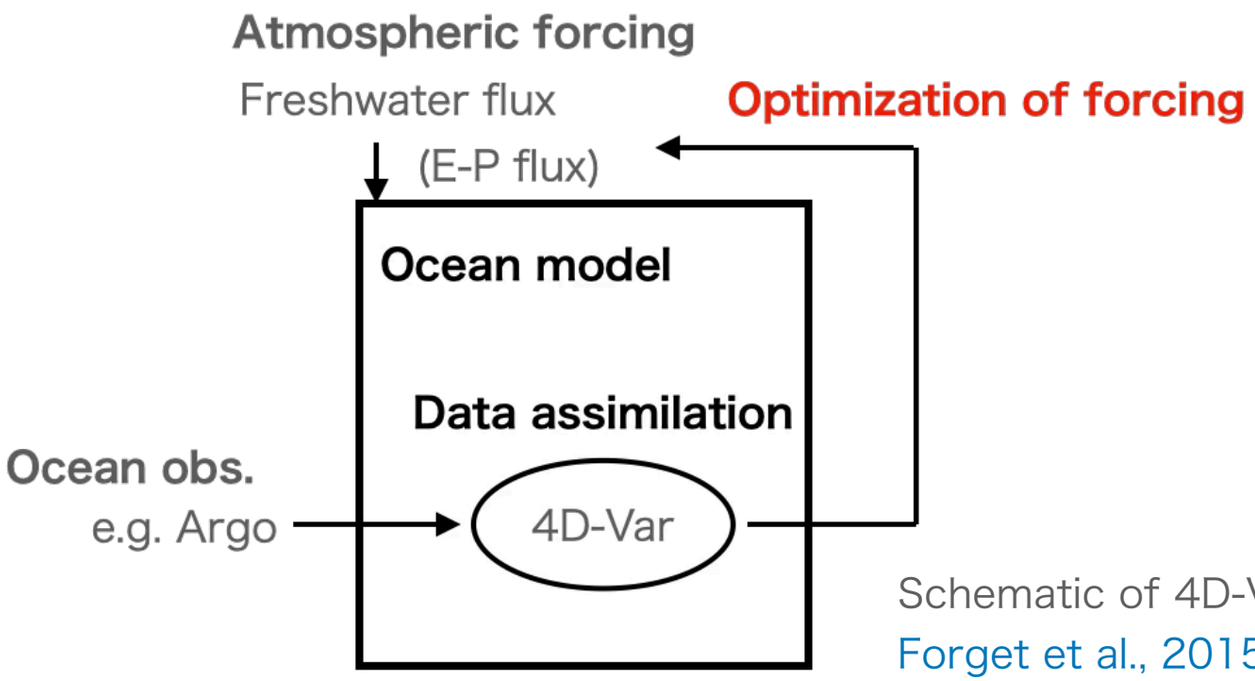
Fig. Global water-cycle changes inferred from ocean salinity observations (Durack et al. 2012)

Observational estimates remain highly uncertain

Motivation

Can ocean data assimilation help detect signals of global water-cycle changes?

- ✓ Changes in the global water cycle, particularly E–P (freshwater flux), are difficult to observe directly.
- ✓ In contrast, the ocean interior, especially temperature and salinity, is relatively well observed.
- ✓ Ocean data assimilation combines these ocean observations with numerical models, potentially allowing us to infer changes in E–P that are difficult to observe directly.



Schematic of 4D-Var ocean data assimilation (conceptually based on Forget et al., 2015; Masuda & Osafune, 2021).

Data: ocean data assimilation products

Product name	Data period	Forcing	DA	Spatial resolution	Ocean model
ESTOC (JAMSTEC)	1957-2014	**NCEP/NCAR reanalysis (NCEP1)**	4D-VAR	1°×1°	MOM3
GECCO2 (Univ Hamburg)	1948-2016				
GECCO3 (Univ Hamburg)	1948-2018				MIT
ECCO4 (NASA)	1992-2017	**ERA-Interim (ERA-I)**		0.5°×0.5°	
ORAS5 (ECMWF)	1992-2014		3D-VAR	0.25°×0.25°	NEMO v3.4

- **Purple: NCEP1-forced products**; **Green: ERA-I-forced products**
- Observational reference: World Ocean Atlas 2018 (**WOA**)
- Analysis period: 1992–2014 (common period for all products)

Data: atmospheric forcing data products

Product name	Data period	Data type	DA	Spatial resolution
NCEP/NCAR renanalysis (NCEP1)	1948-2016	Atmospheric reanalysis	3D-VAR	2°x2°
ECMWF reanalysis-Interim (ERA-I)	1979-2019	Atmospheric reanalysis	4D-VAR	1.125° x 1.125°
J-OFURO3	1988-2022	Satellite-based flux estimate	-	0.25°×0.25°

- **Purple: NCEP1-forced products**; **Green: ERA-I-forced products**
- Observational reference: World Ocean Atlas 2018 (**WOA**)
- Analysis period: 1992–2014 (common period for all products)

Quantifying Global Water-Cycle Changes: Pattern Amplification (PA)

PA quantifies the strength of amplification of the mean spatial pattern.

Calculation of PA

For both SSS and E–P, we calculate basin-mean pattern and changes for the Pacific, Atlantic, and Indian Oceans.

PA (%) is estimated from the regression slope between the mean state and its change.

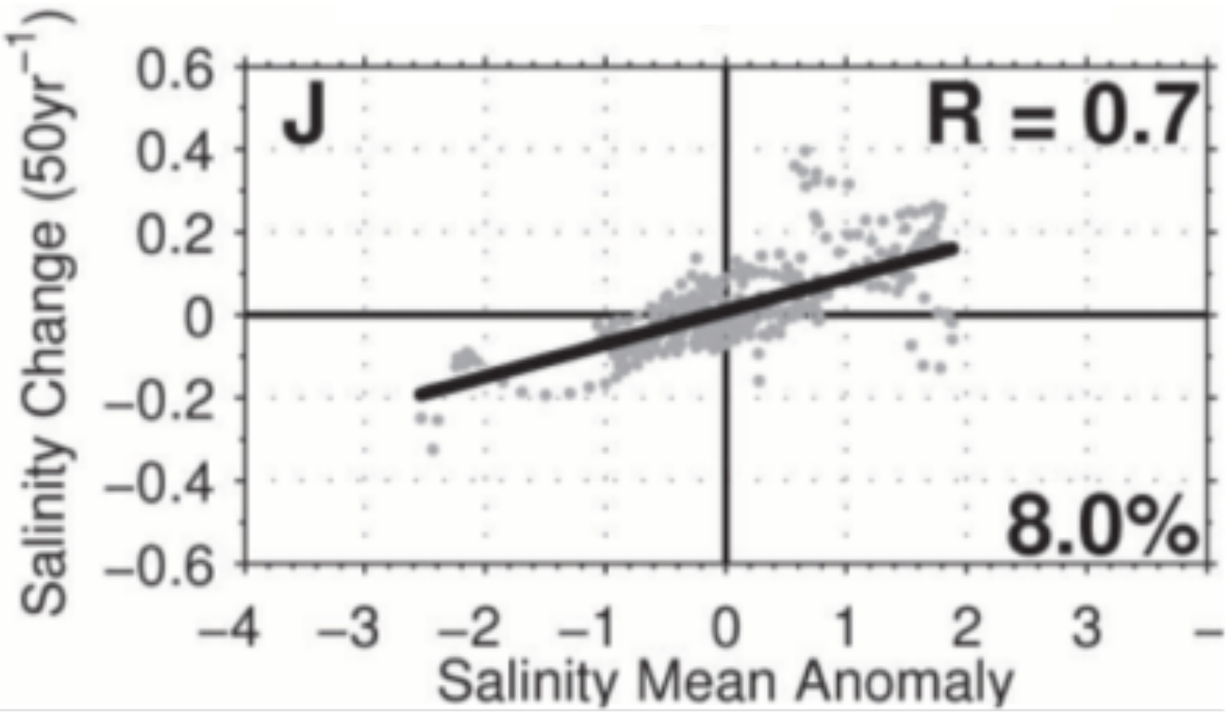


Figure. Example of PA estimation (Durack et al., 2012) x-axis: mean salinity anomaly; y-axis: salinity change. The regression slope gives PA (8.0% in this example).

Positive PA → “dry gets drier, wet gets wetter” (DDWW)

- Regions poleward of 60° and coastal regions were excluded to minimize the influence of sea ice and continental runoff on E–P.
- For SSS, the mean bias relative to WOA18 was removed before calculating PA.

Result ① Mean E–P Fields: Forcing vs. Ocean Data Assimilation Products

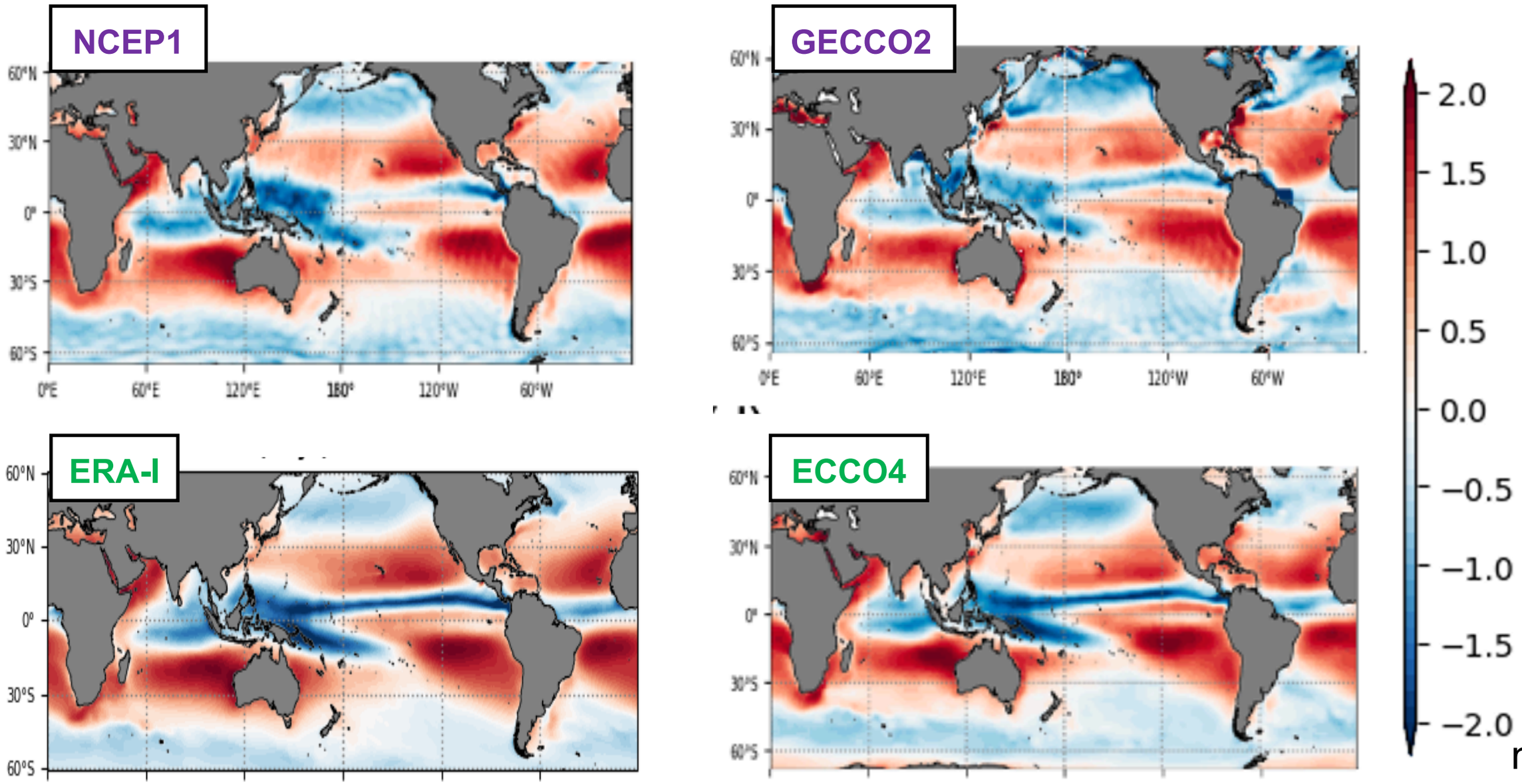
✓ **NCEP1** and **ERA-I** show substantial differences, particularly around the ITCZ.

✓ Despite the coarse-resolution NCEP1 forcing, GECCO2 reproduces a much more realistic spatial structure of E–P.

→ DA can substantially modify the E-P field from the original atmospheric forcing.

Atmospheric Forcing Data

Ocean Data Assimilation products



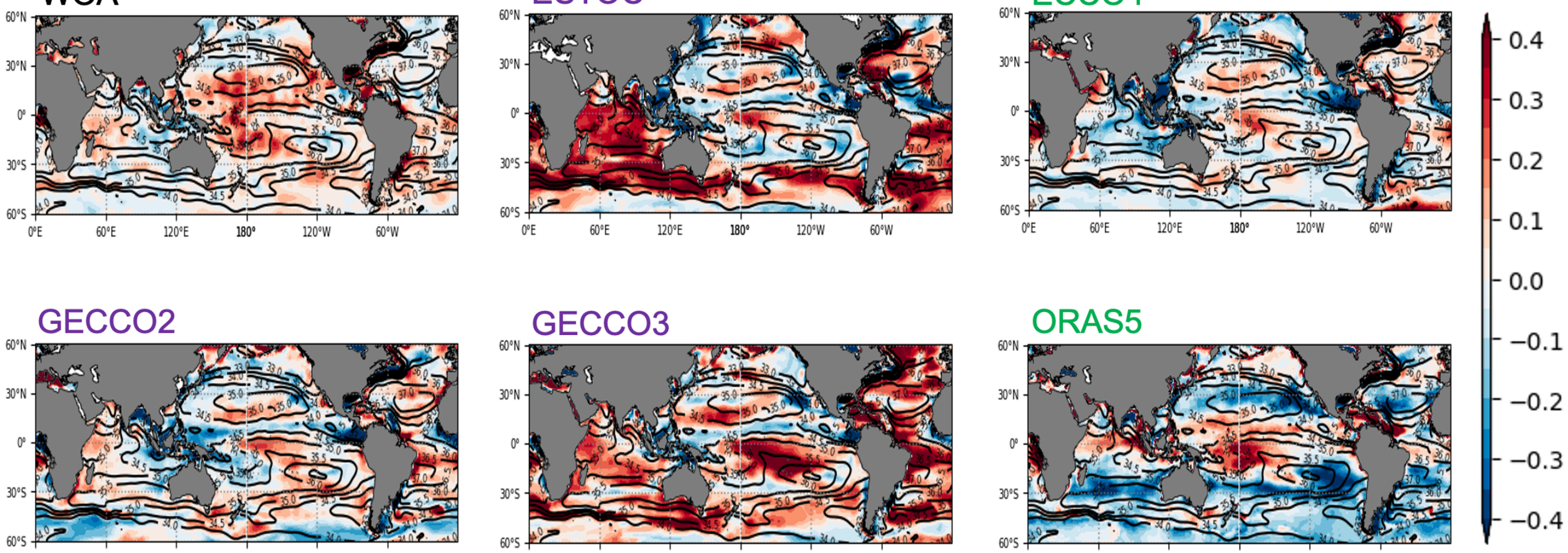
Result ② Changes in Sea Surface Salinity (SSS)

✓PA-like signal, with salty regions becoming saltier and fresh regions becoming fresher

✓There are substantial differences among data assimilation products.

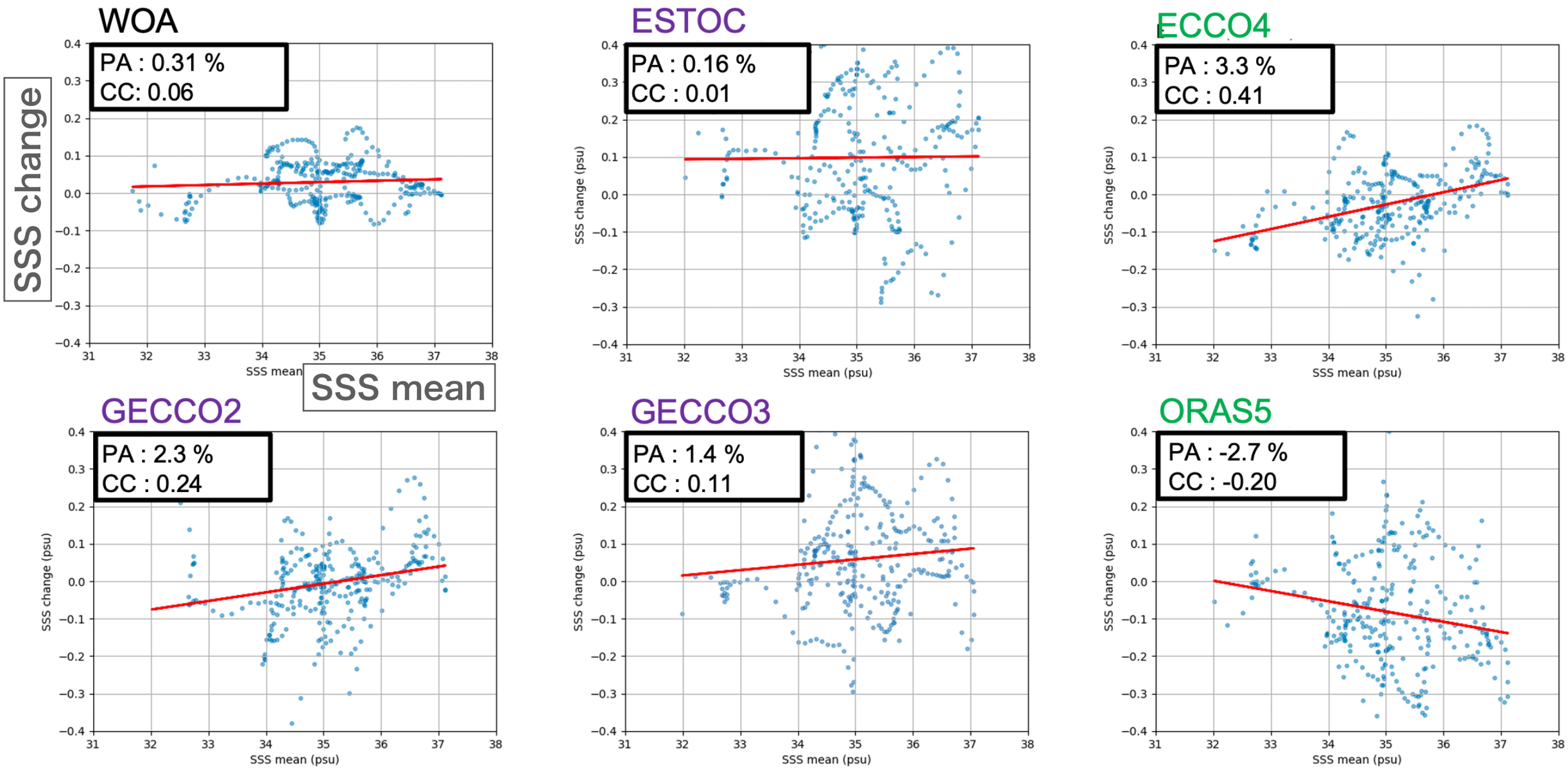
e.g., the magnitude of the changes varies considerably among the products

Figure. The mean fields in SSS (contour) and its long-term changes (shading) from observation (WOA) and each data assimilation product (1992–2014).



Result ② Pattern Amplification (PA) in SSS

- ✓PA was quantified for each ocean basin following Durack et al. (2012).
- ✓Positive PA signals are found in all products except ORAS5.
- ✓But their magnitudes vary considerably among the products.

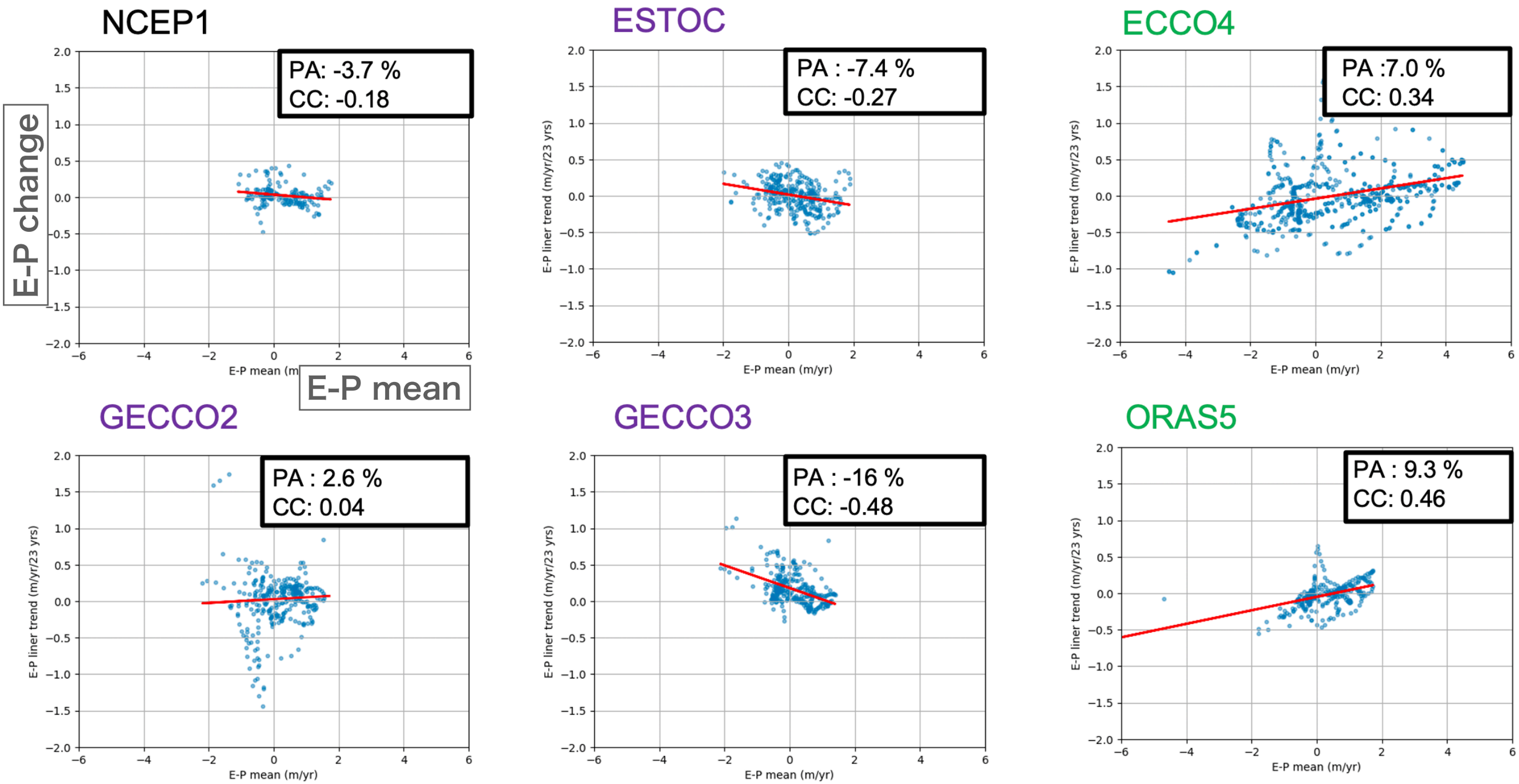


Result ③ Pattern Amplification (PA) in E-P

✓ Unlike SSS, NCEP1-forced products show weak or negative PA signals in E–P.

✓ ERA-I-forced products show clear positive PA signals (7.0–9.3%).

The quality of atmospheric forcing is particularly important for reproducing realistic long-term freshwater-flux changes



Result ④ Consistency between SSS and E–P Pattern Amplification

✓4D-Var products show a consistent positive relationship between PA in SSS and E–P (r = 0.59).

→ 4D-Var products consistently reproduce the expected E–P–SSS relationship

Table. Global Relationship between SSS and E–P PA.

Product	SSS PA (%/K)	E-P PA (%/K)
ESTOC	0.2	-8.9
GECCO2	2.8	3.1
GECCO3	1.7	-19.0
ECCO4	4.0	8.4
ORAS5	-3.3	11.0
NCEP1	0.4 (WOA)	-4.5
ERA-I		15.0
J-OFURO3		7.6

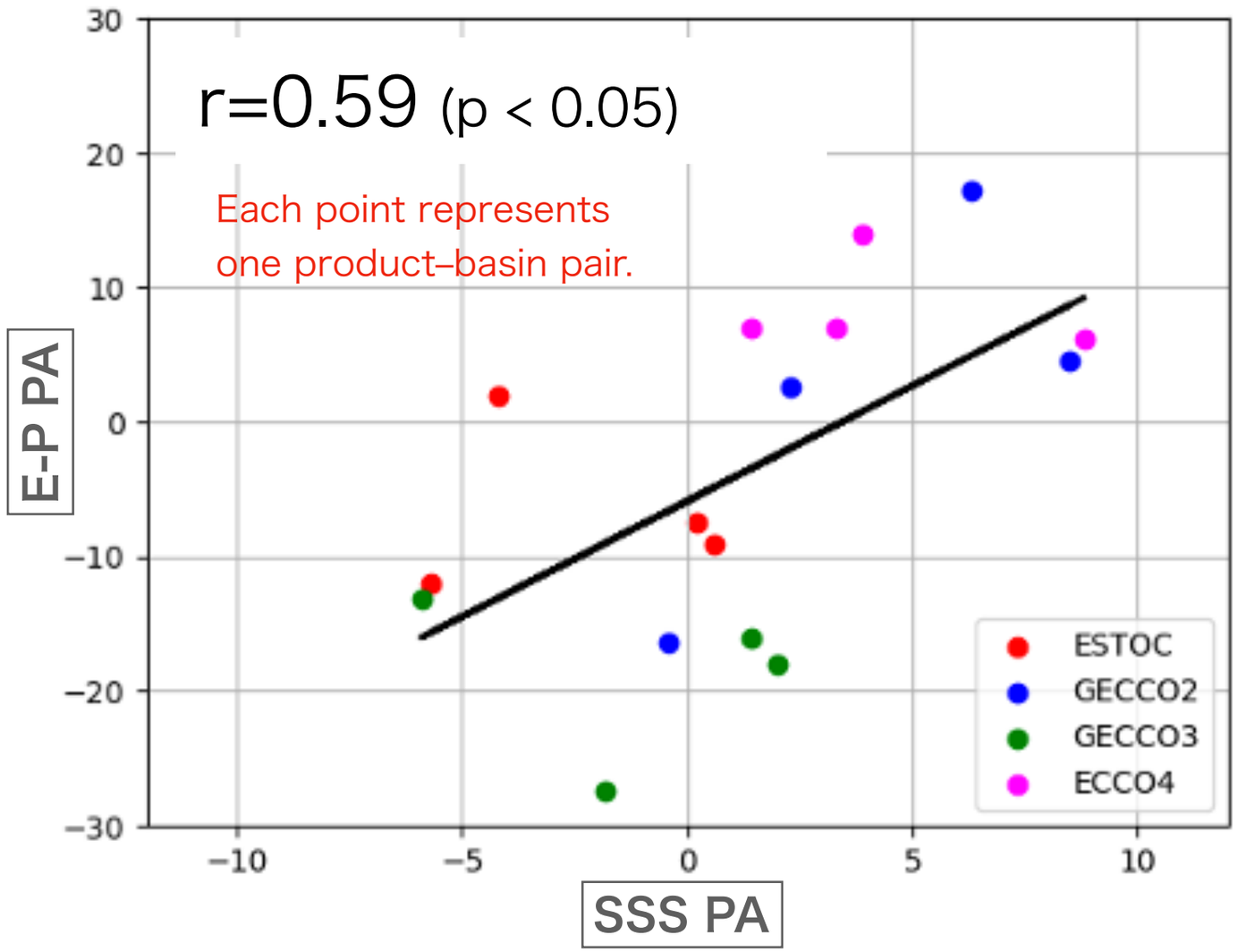


Figure. Relationship between SSS and E–P PA. Each point represents a basin-scale PA estimate from a 4D-Var ocean data assimilation product. ORAS5 (3D-Var) is excluded due to its negative SSS PA.

Summary

Can ocean data assimilation help detect signals of global water-cycle changes?

1. Ocean data assimilation works

   Ocean data assimilation can substantially improve E–P fields, even with low-resolution forcing.

2. Atmospheric forcing quality matters

   Better E–P forcing leads to more realistic freshwater-flux variability and changes.

3. Assimilation methodology matters

   With ERA-Interim forcing, **4D-Var provides the most realistic representation of long-term changes.**

Globally, ECCO4 (4D-Var) reproduces the most realistic water-cycle intensification, consistent with recent satellite-based estimates (J-OFURO3).