Pacific Northwest
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Contribution of Land to S2D Predictability Through Atmosphere-Land-Ocean Interactions

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US CLIVAR Summit: Earth System Predictability and Use of New Tools—AI/ML and High-Resolution Modeling

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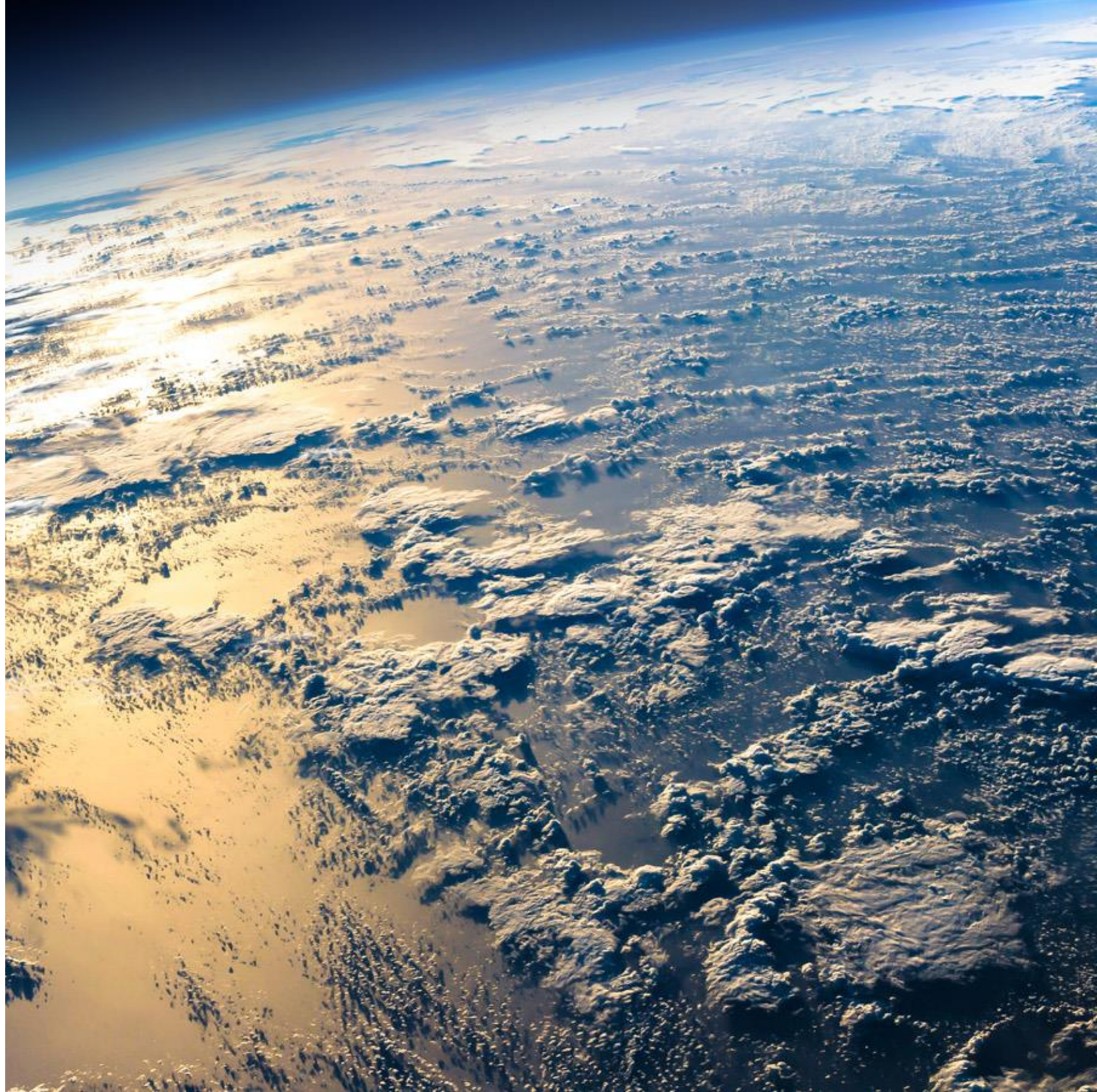
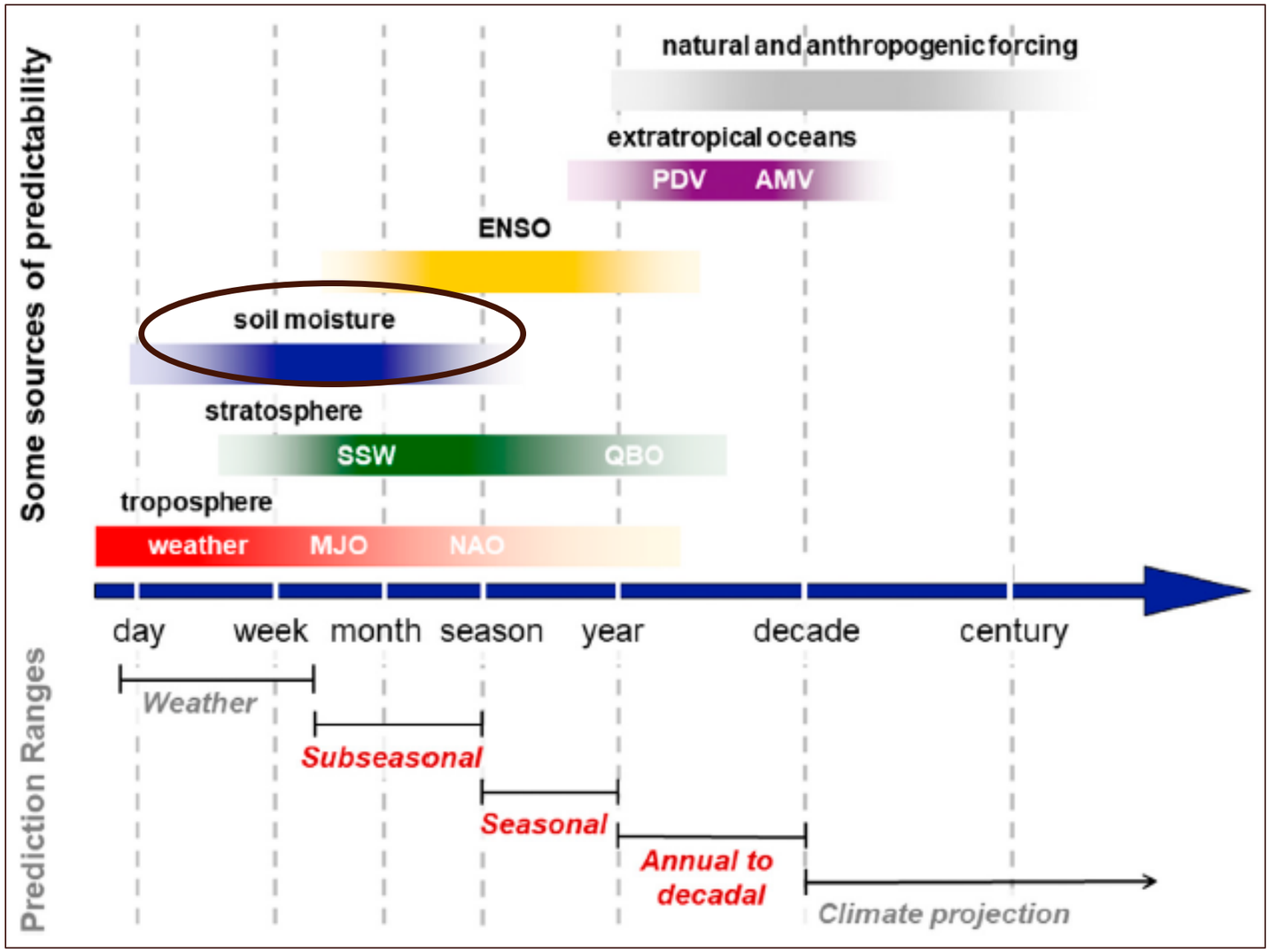
WACCEM
Water Cycle: Modeling of Circulation, Convection, and Earth System Mechanisms



Sources of predictability at different timescales



(Merryfield et al. 2020 BAMS)

Could soil moisture and temperature provide predictability at seasonal-to-decadal timescales through **longer memory land processes** and/or their **influence on oceans with longer memory**?

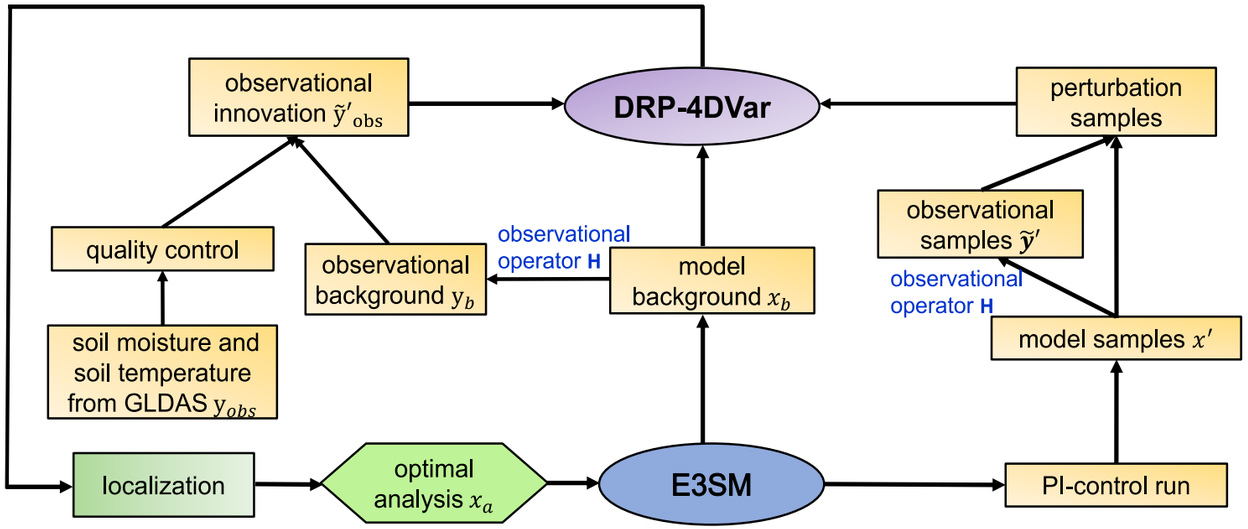
Land states are not initialized in decadal prediction experiments

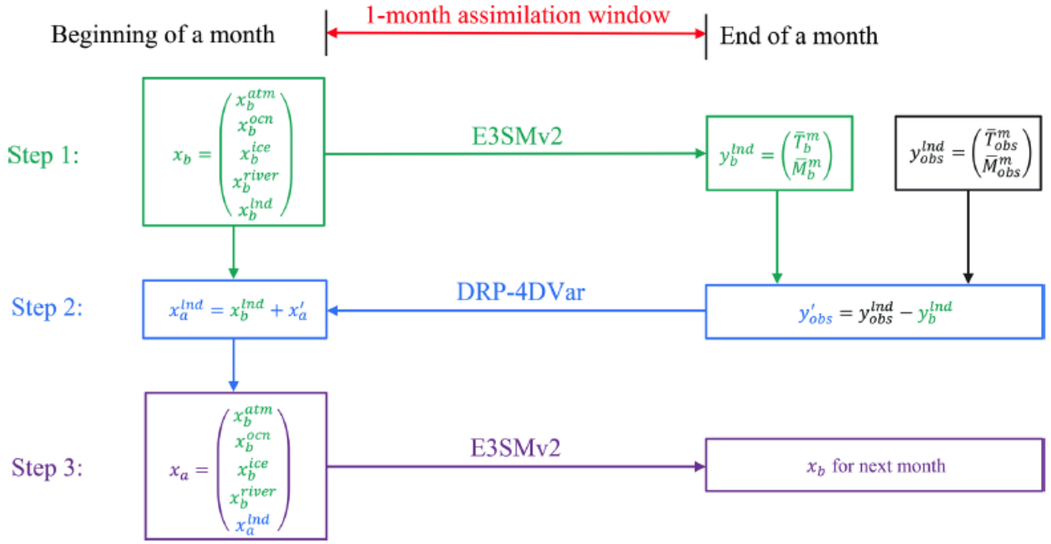
CMIP6 decadal climate prediction experiments

Project	Model	Initialization			Reference
		Atmosphere	Ocean	Land	
CMIP6	BCC-CSM2-MR	NO	Nudging	NO	Wu et al., 2019
	CanESM5	Nudging	Nudging	NO	Sospedra-Alfonso et al., 2021
	IPSL-CM6A-LR	NO	Nudging	NO	Boucher et al., 2020
	MPI-ESM1.2-HR	ERA40/Interim	ORAS4	NO	Bunzel et al.,2015
	NorCPM1	NO	EnKF	NO	Wang et al., 2017
	MIROC6	JRA55	IAU	NO	Tabete et al., 2012
	CMCC-CM2-SR5	NO	Nudging	NO	Huang et al., 2015
	EC-EARTH3	ERA40/Interim	Nudging	NO	Batte et al., 2015
	NorCPM1	No	EnKF	NO	Bethke et al., 2021

Land as a source of predictability at S2D timescale

A weakly coupled land data assimilation system based on 4DEnVar



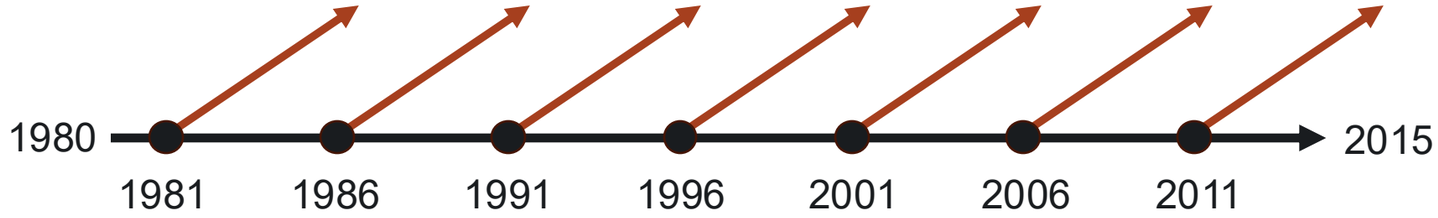


(Shi et al. 2021 Earth's Future; Shi et al. 2024 GMD; Shi et al. 2024 npj CAS)

Experiment design

ASSIM:

- A fully coupled E3SM simulation with atmosphere, land, ocean, and sea ice
- Monthly mean soil moisture and temperature from GLDAS are continuously assimilated in E3SM with a 1-month assimilation window
- Driven by historical forcing

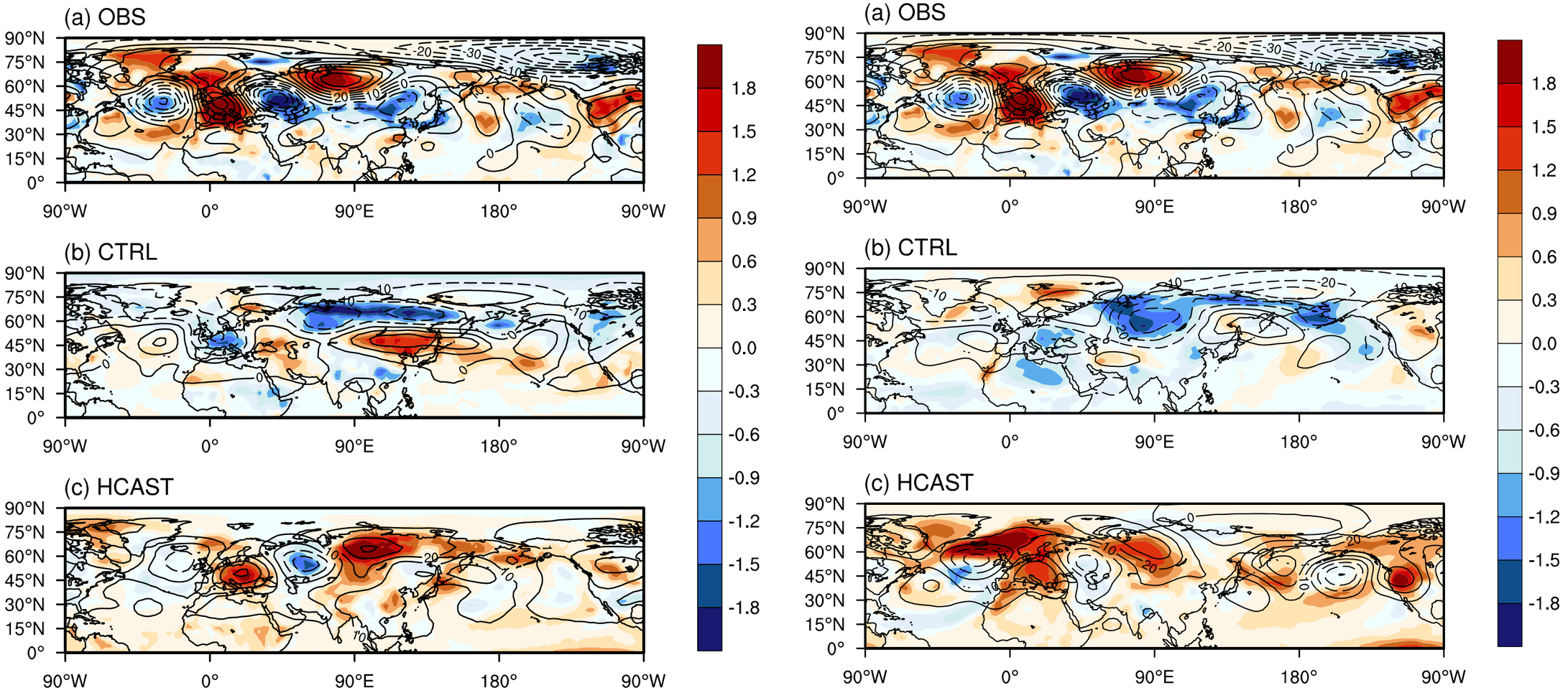


HCAST:

- Fully coupled E3SM ensemble hindcasts (10 members, 5-year long)
- Initialized using restart files from ASSIM with balanced atmosphere, land, and ocean states
- Driven by historical forcing

(Shi et al. 2024 npj CAS)

HCAST initialized in 2001 captures the 2003 European summer heatwave and associated Rossby wavetrains



Hindcast sensitivity experiments to isolate the sources of predictability

Pattern correlation of surface temperature over Europe in 2003

Experiment	Atmosphere	Land	Ocean	PCC
HCAST	ASSIM	ASSIM	ASSIM	**0.82**
SNS1	ASSIM	CTRL	ASSIM	-0.21
SNS2	ASSIM	ASSIM only over Tibetan Plateau	ASSIM	**0.80**
SNS3	CTRL	ASSIM only over Tibetan Plateau	CTRL	**0.56**
SNS4	CTRL	ASSIM only over Tibetan Plateau	ASSIM	**0.65**
SNS5	ASSIM	ASSIM only over Tibetan Plateau	CTRL	**0.55**
SNS6	CTRL	CTRL	ASSIM	-0.41

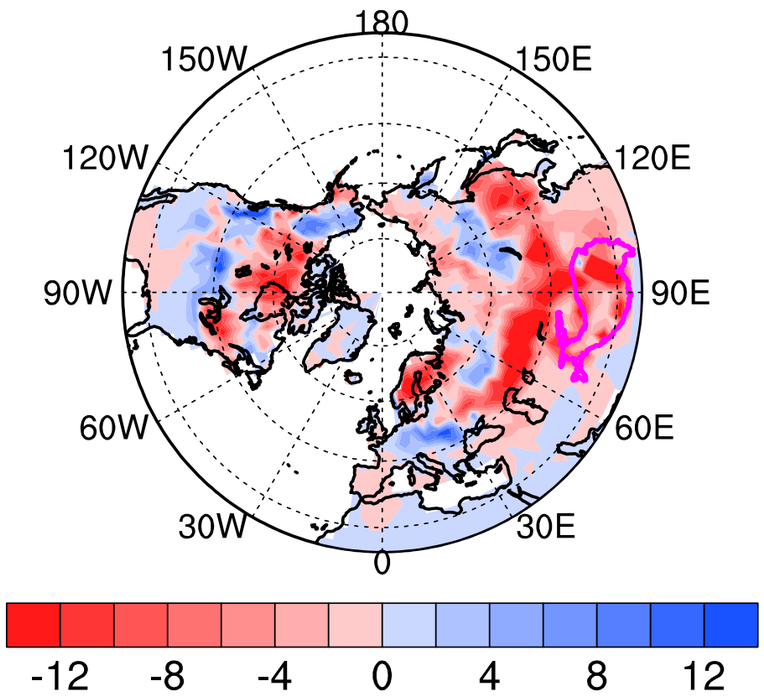
Impact of land

Impact of ocean

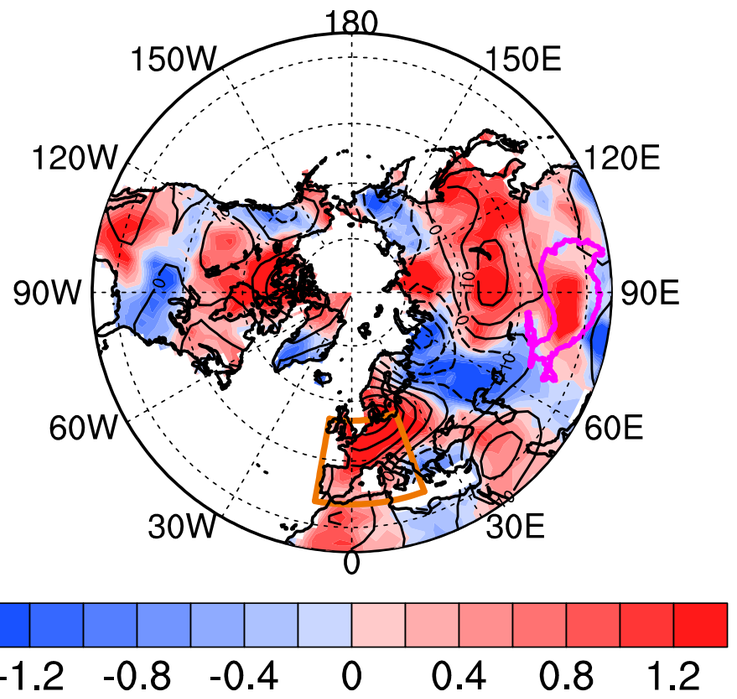
Large differences in snow cover and surface temperature in hindcasts initialized using land states from CTRL vs. ASSIM

Reduced snow cover and warmer surface temperature over the Tibetan Plateau in 2003 spring when initialized from ASSIM in 2001

(a) Snow Cover Fraction (shaded)

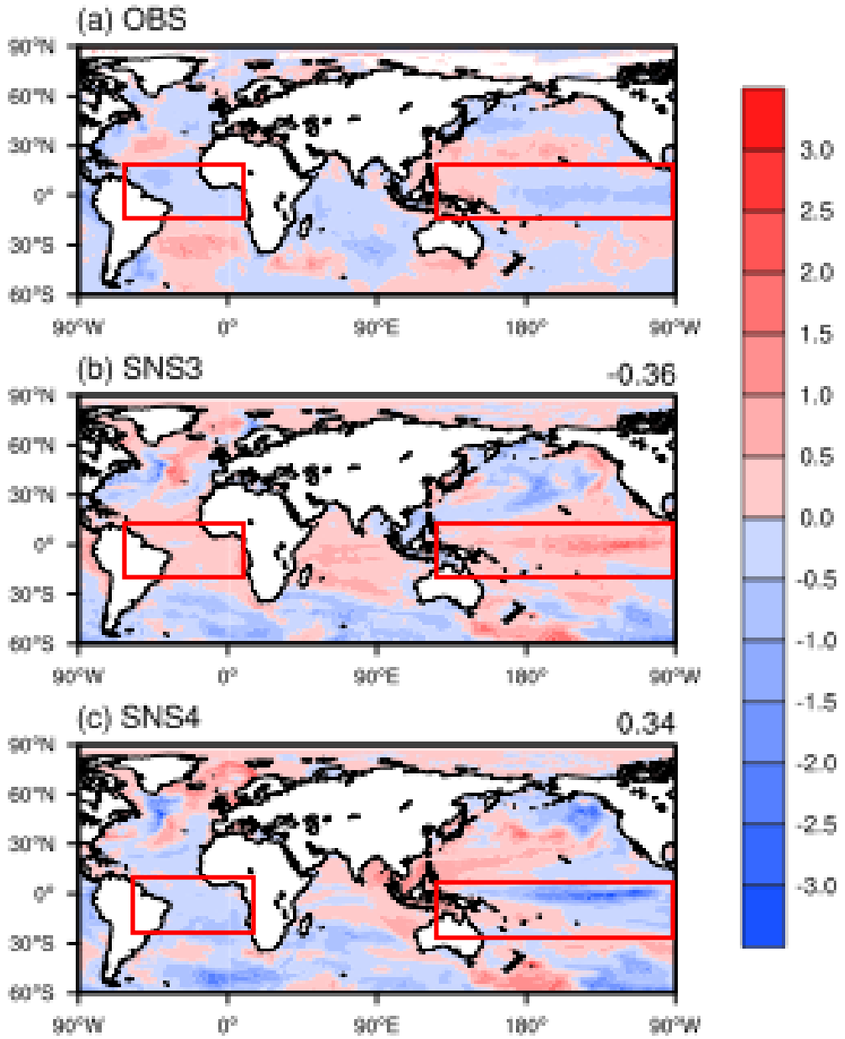


(b) T2m (shaded) & H500 (contour)



Large differences in the SST in hindcasts initialized using ocean states from CTRL vs. ASSIM in 2001 and persist through 2003

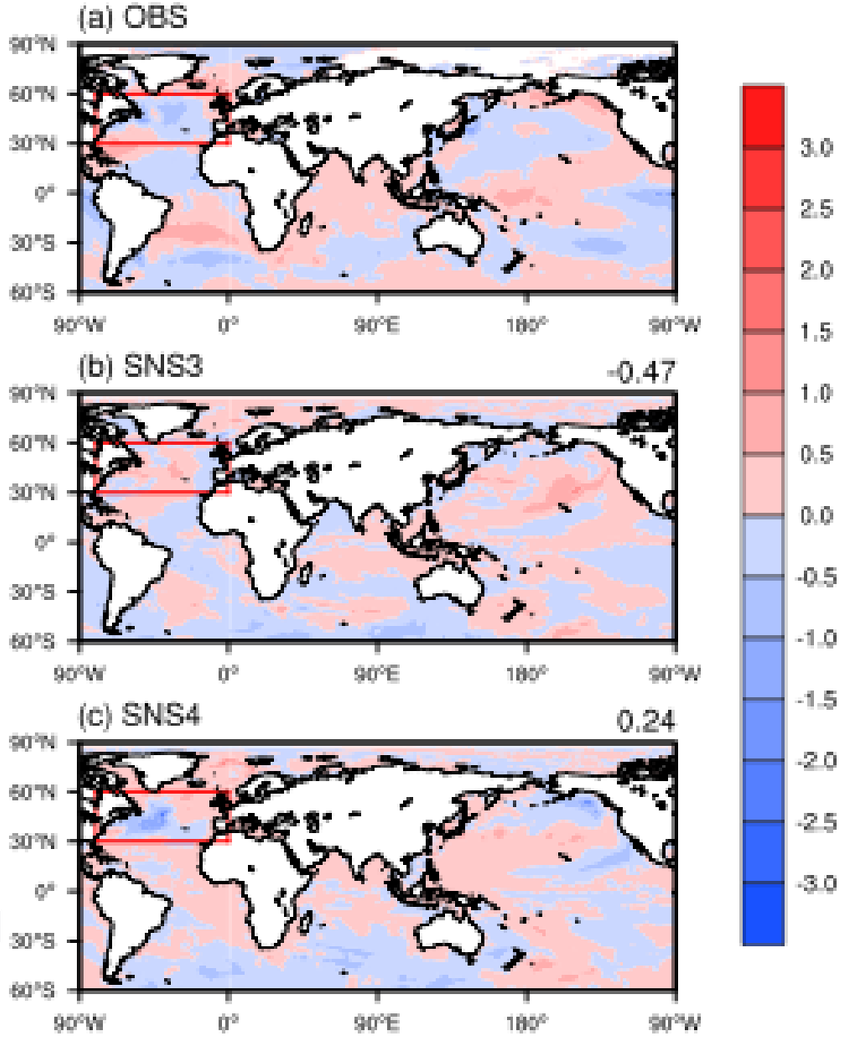
SST anomalies in January 2001



Ocean initialized from CTRL

Ocean initialized from ASSIM

SST anomalies in January 2003

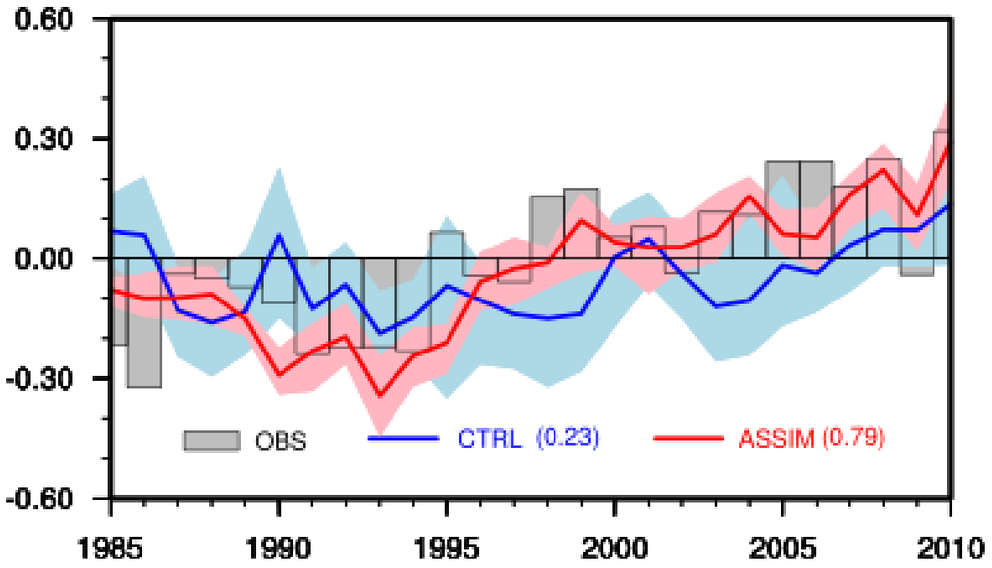


Ocean initialized from CTRL

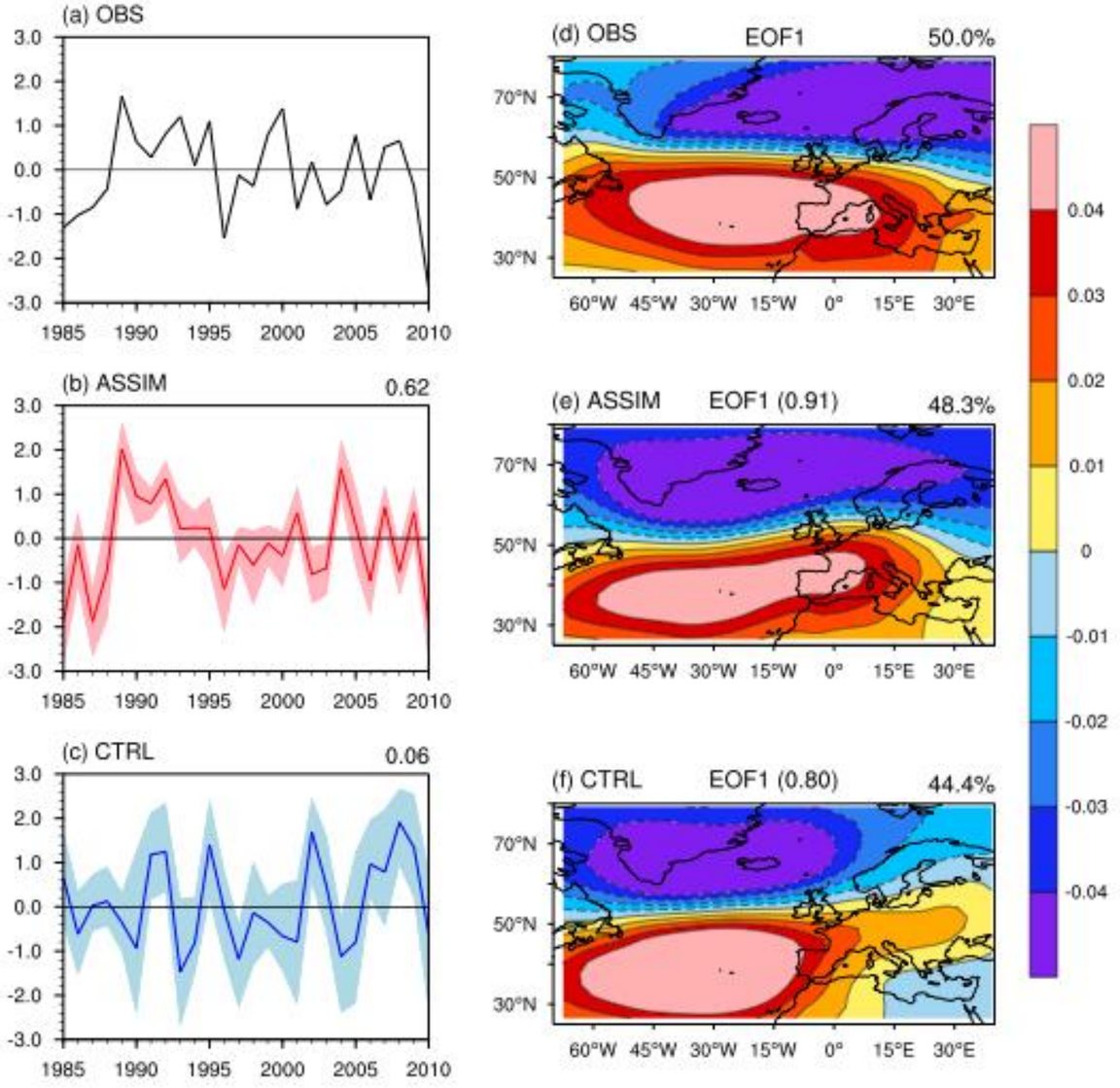
Ocean initialized from ASSIM

Assimilating soil moisture/temperature in ASSIM significantly constrains AMO and NAO

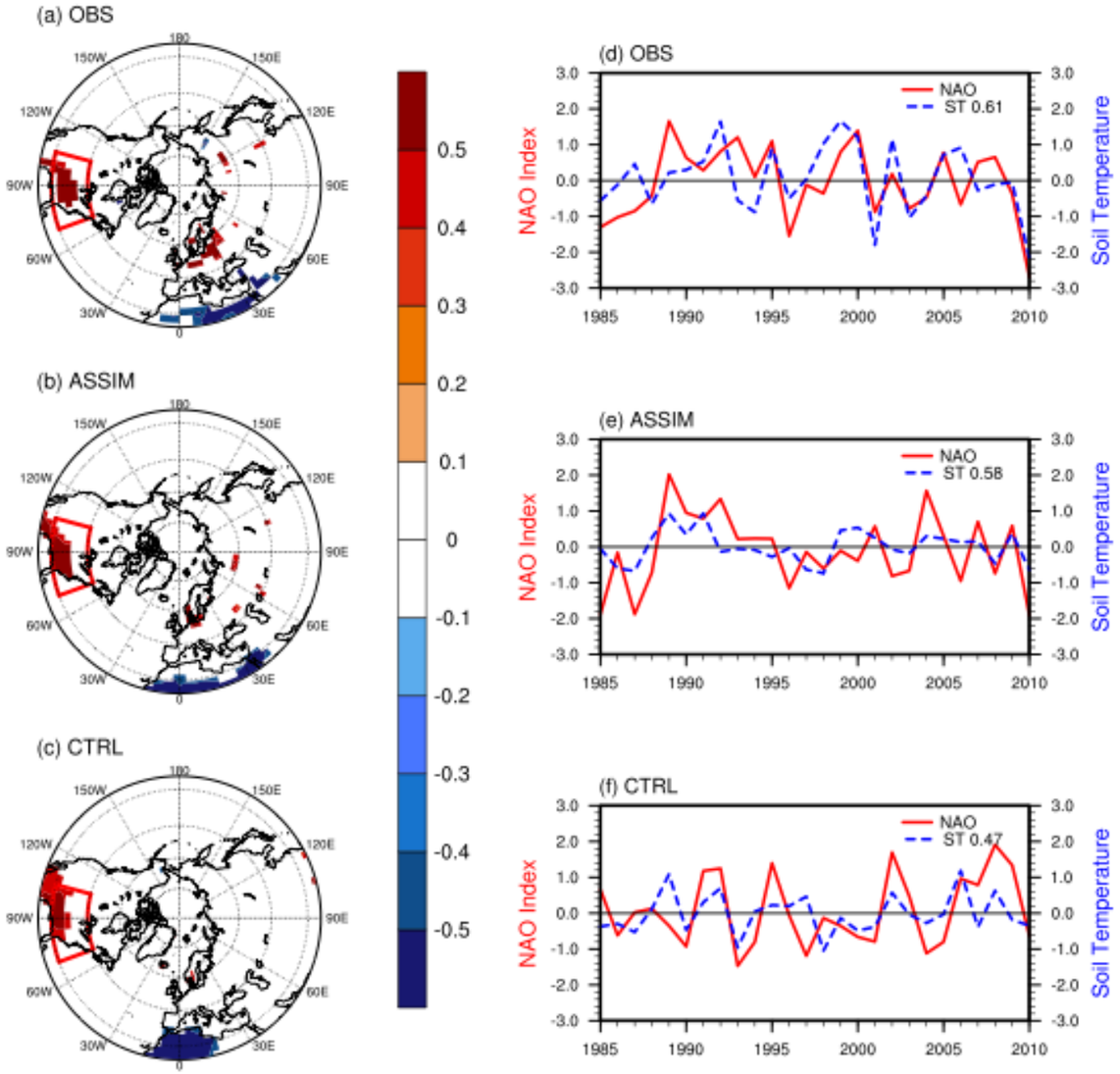
AMO index

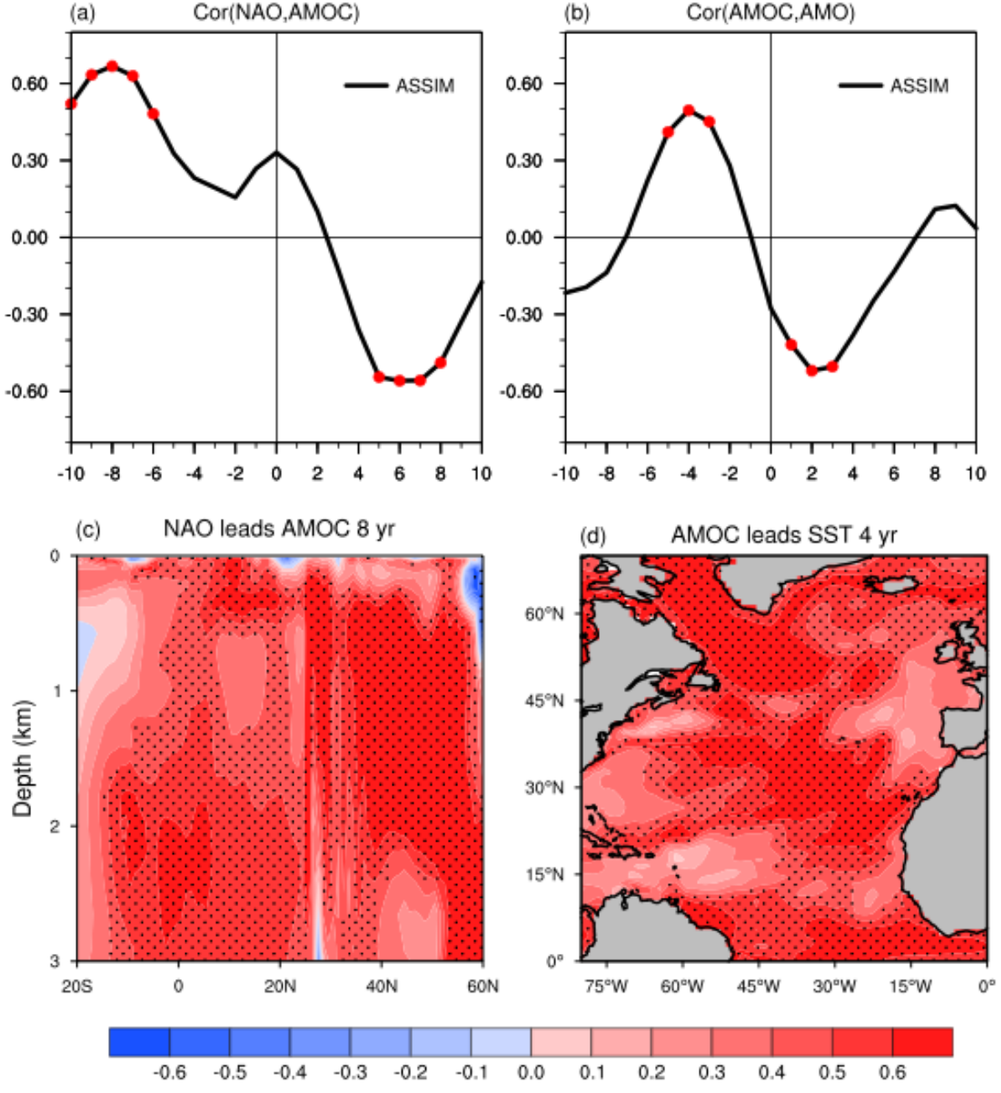


NAO index and EOF1



Connecting land states with AMO through NAO and AMOC





Summary and concluding thoughts

- Land states can provide important S2D predictability:
  - In high mountains such as the Tibetan Plateau and the Rocky Mountains, surface heating at high altitude can effectively induce Rossby waves and teleconnections to remote land and oceans
  - At low elevation, land states may induce teleconnections through changes in surface pressure gradients
- Elements to realize the predictability associated with land states:
  - Reducing initial shock through 4DEnVar
  - Reasonable model representation of atmosphere-land-ocean interactions
  - Future work: (1) use AI to isolate the relative contributions of land and ocean to S2D predictability; (2) use ML to emulate the innovations using training data from 4DEnVar; (3) evaluate the impacts of model resolution; (4) use both physical models and ML emulators for predictions

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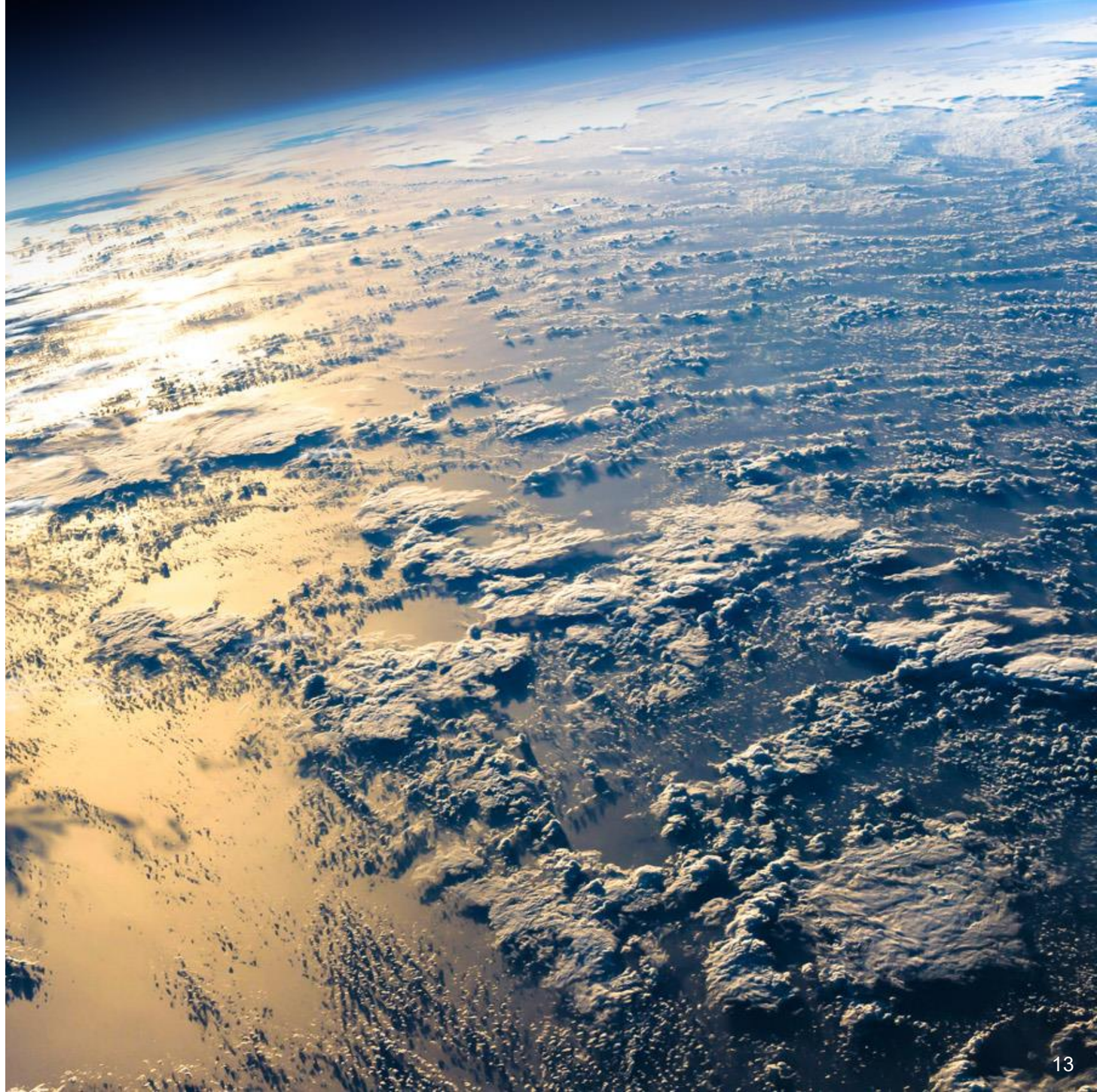
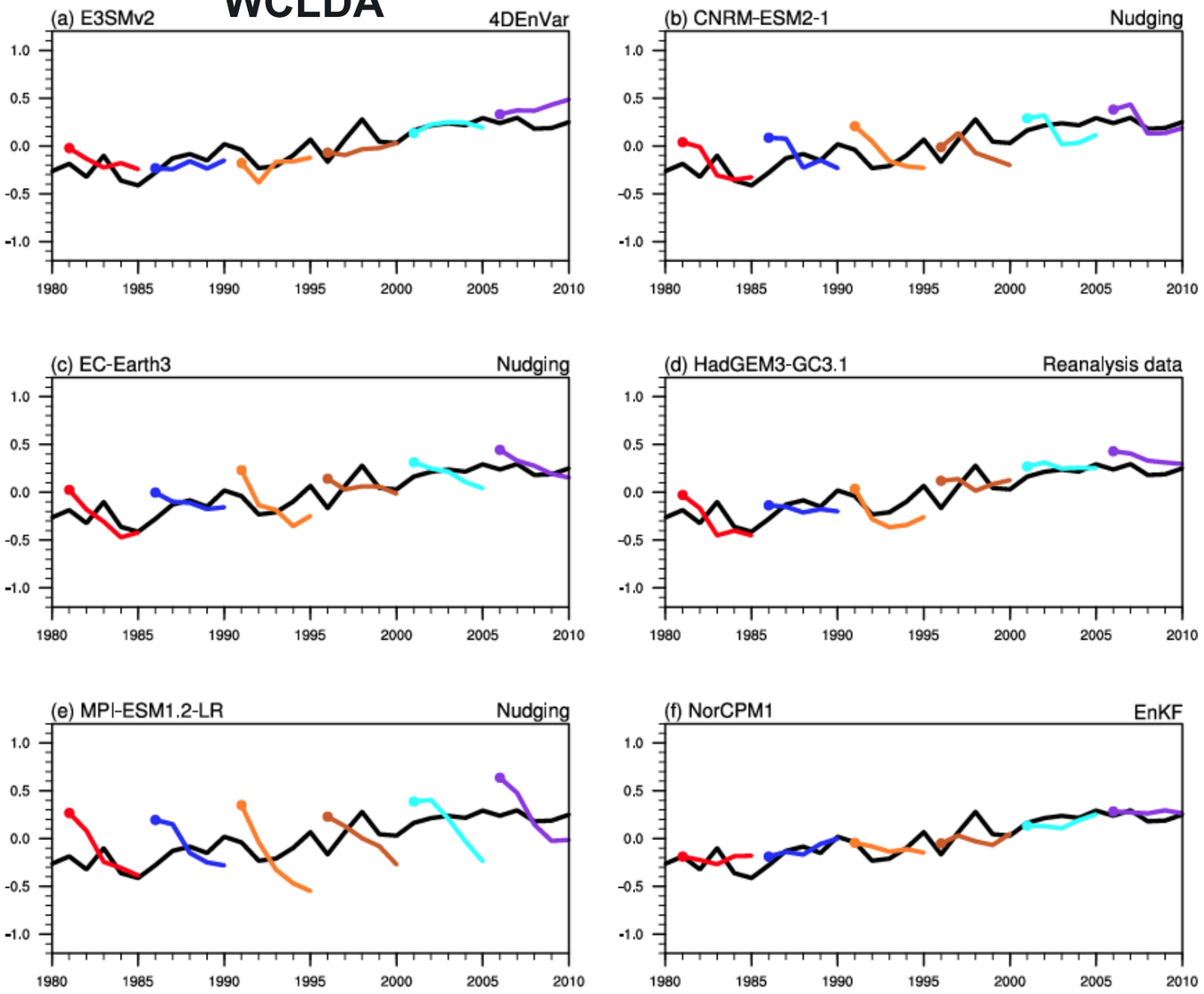
Thank you



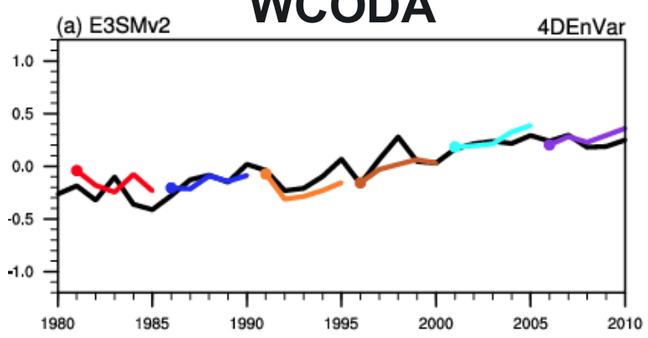
Model drift in hindcasts with data assimilation

Annual global mean surface air temperature anomalies

WCLDA



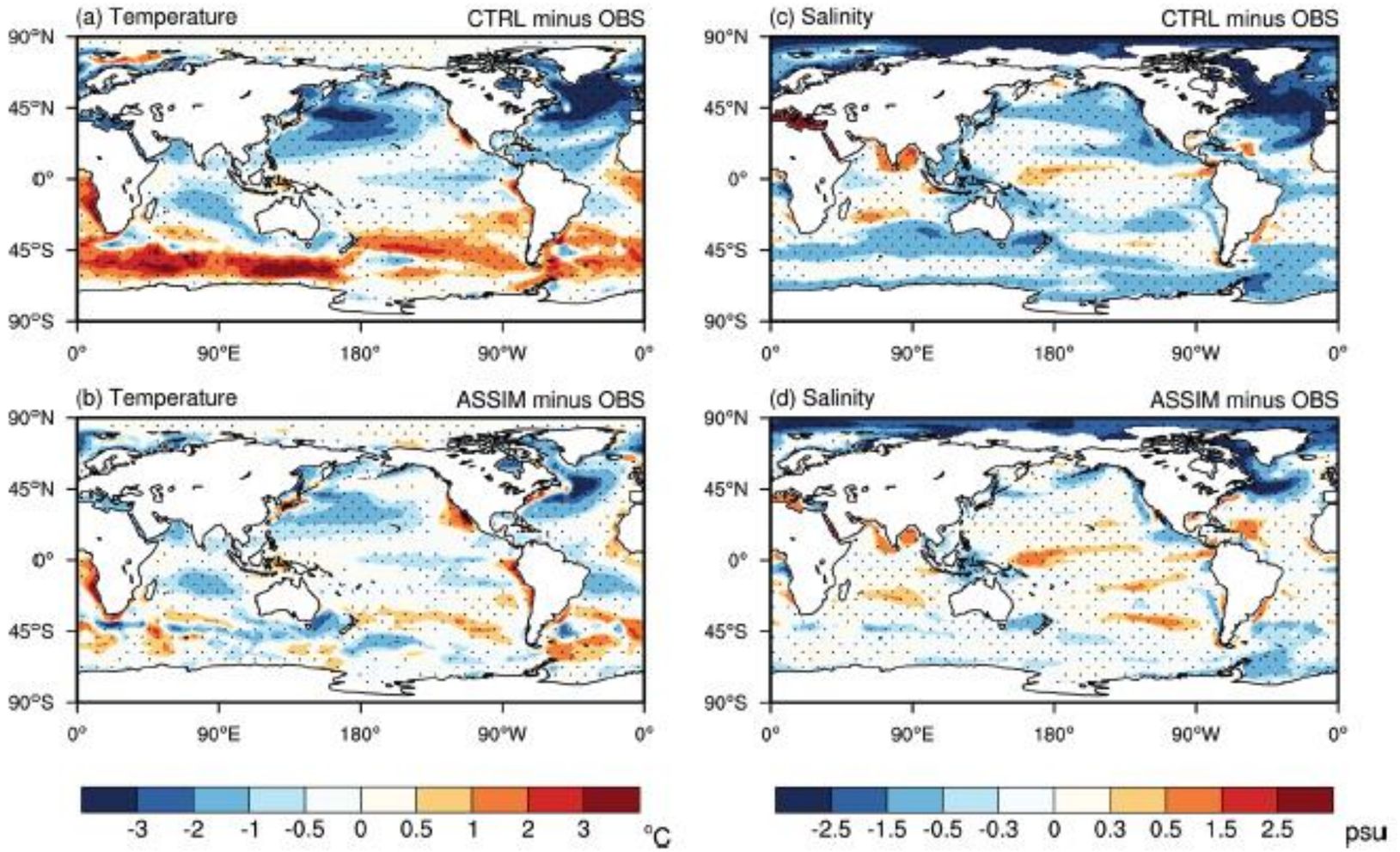
WCODA



Black: observations
Colored: mean of three hindcast members initialized on Sep, Nov, Jan of different start years

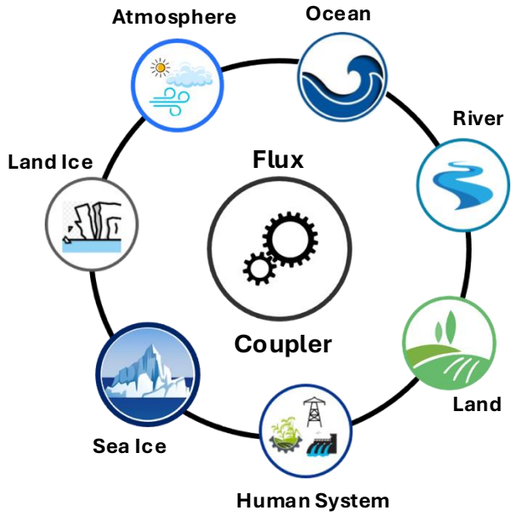
A weakly coupled ocean data assimilation system (WCODA) has also been implemented in E3SMv2

Ocean temperature and salinity from EN4.2.1 ocean reanalysis



(Shi et al. 2025 GMD)

E3SM modeling across components and scales



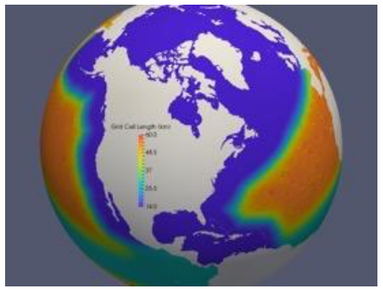
Three versions of E3SM have been developed since 2014

Model component	Lower resolution (LR)	High resolution (HR)	Cloud-resolving (SCREAM)	Regional refined model (RRM)
Atmosphere & Land	100 km	25 km	3 km	variable
Ocean & Ice	30-60 km	6-18 km	prescribed	variable
River	50 km	12 km	3 – 12 km	variable

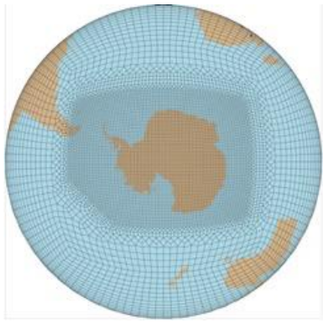
North America RRM

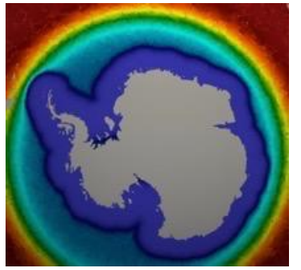
25 km → 100 km

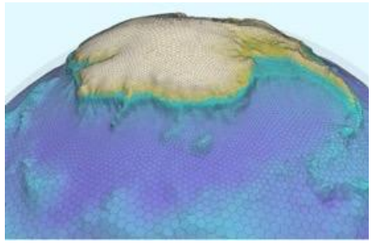
14 km → 60 km



Southern Ocean RRM



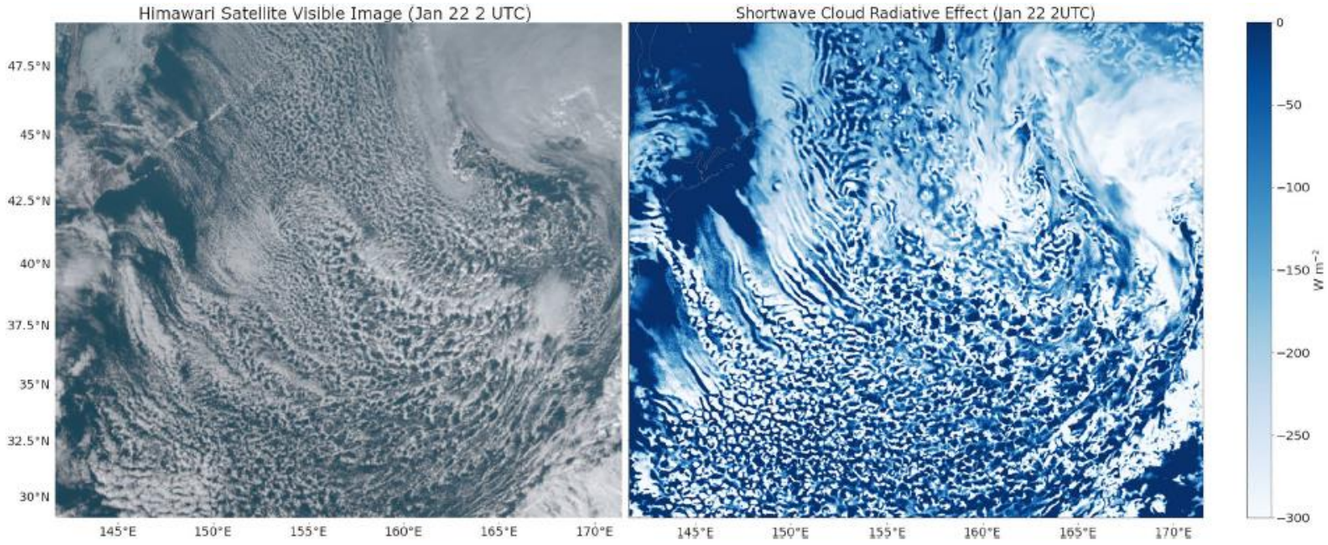




Global cloud-resolving modeling

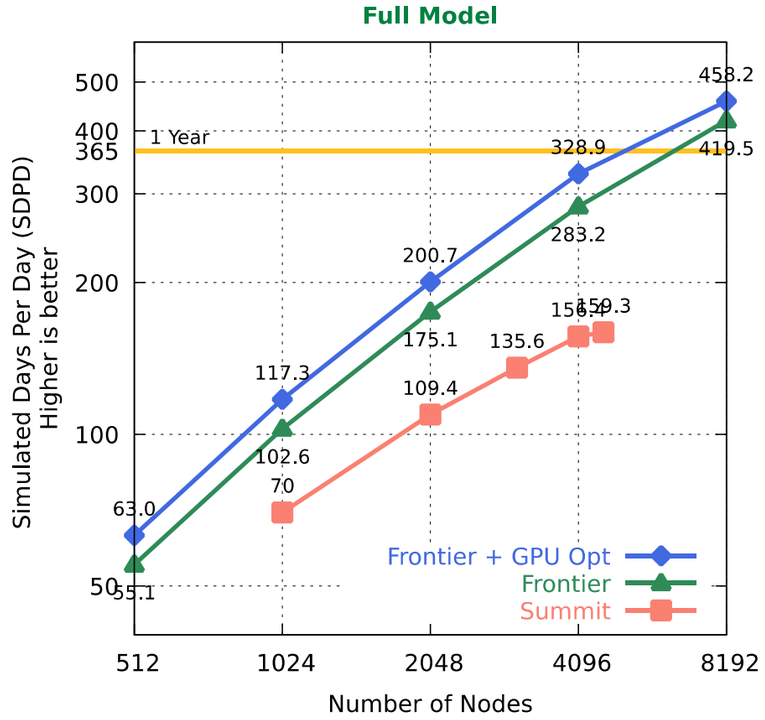
- The Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM) solves the fluid dynamics using a non-hydrostatic spectral element dynamical core (Taylor et al. 2020)
- The horizontal dynamical grid is a cubed sphere grid with 1024x1024 spectral elements (ne1024 ~ 3.25 km resolution) with 128 vertical levels and a model top at 40 km

Satellite image **SCREAM simulation**



(Caldwell et al. 2021 JAMES)

Throughput vs node count at Δx=3.25 km on Frontier (AMD GPUs) and Summit (NVIDIA GPUs)



(Taylor et al. 2023 SC 23)