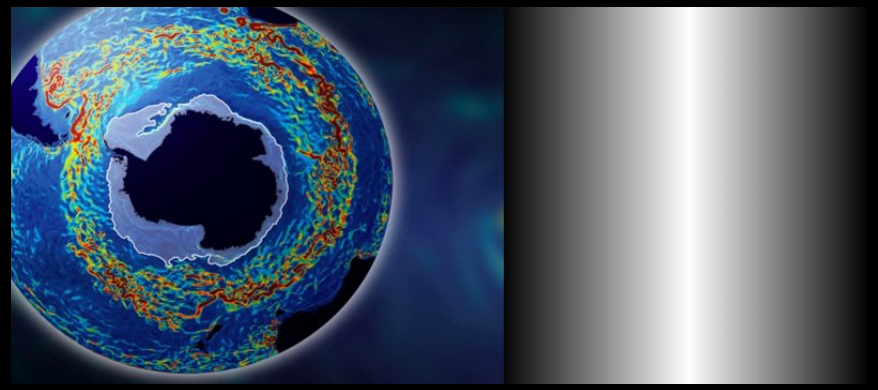


Nested regional state estimates @ ecco.ucsd.edu

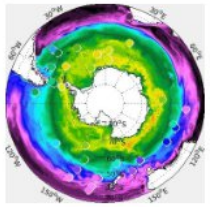
ECCO Annual Meeting, May 2026

Matt Mazloff, Bruce Cornuelle, Sarah Gille, Ganesh Gopalakrishnan, Angela Kuhn, Rui Sun, Ariane Verdy, ECCO, et al.

SCRIPPS INSTITUTION OF OCEANOGRAPHY

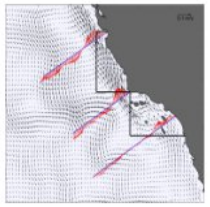
ecco.ucsd.edu

ECCO@Scripps: Our group contributes to the development and production of regional ocean state estimation using the methodology developed by the ECCO consortium (ecco.jpl.nasa.gov). The ECCO code is based on the MIT general circulation model (MITgcm) and employs automatic/algorithmic differentiation (AD) tools for generating tangent linear and adjoint code for ocean circulation and climate studies. The goal is to produce a model-observations synthesis, with consistent dynamics and closed budgets for all tracers, to be used for scientific analysis. We are currently working on:



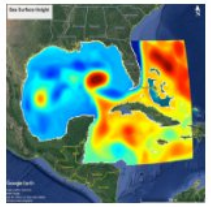
Southern Ocean State Estimate (SOSE)

The latest product, b-SOSE, is a physical-biogeochemical state estimate produced as part of the SOCCOM project.



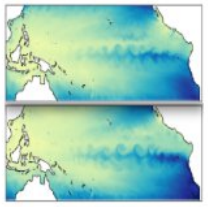
California Current System State Estimate (CASE)

Short- and long-term reanalyses synthesize observations of the California Current System.



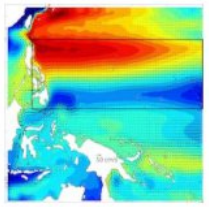
Gulf of Mexico State Estimate (GoM)

Estimation and prediction of the loop current and loop current eddy separation.



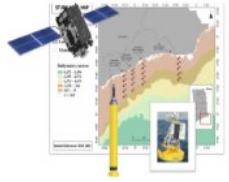
Tropical Pacific Ocean State Estimate (TPOSE)

Observations from the TPOS constrain 4-month state estimates.



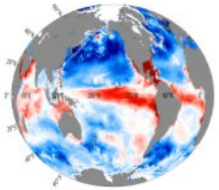
Northwest Pacific State Estimate (NWPac)

State estimation and prediction in the regions of Palau and Northern Philippine Sea.



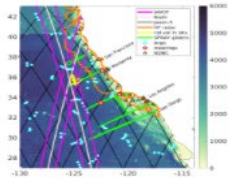
Gulf of Guinea Biogeochemical State Estimate (GG)

A modeling component of Ocean Margins Initiative



Biogeochemical Global Ocean State Estimate (BGOSE)

A quasi-global high resolution model with sea ice and ice shelves



California Current System Submesoscale State Estimate (CASSE)

SWOT data assimilation in a high-resolution coastal model.

At SIO we have been considering nested regional efforts targeting the mesoscale.

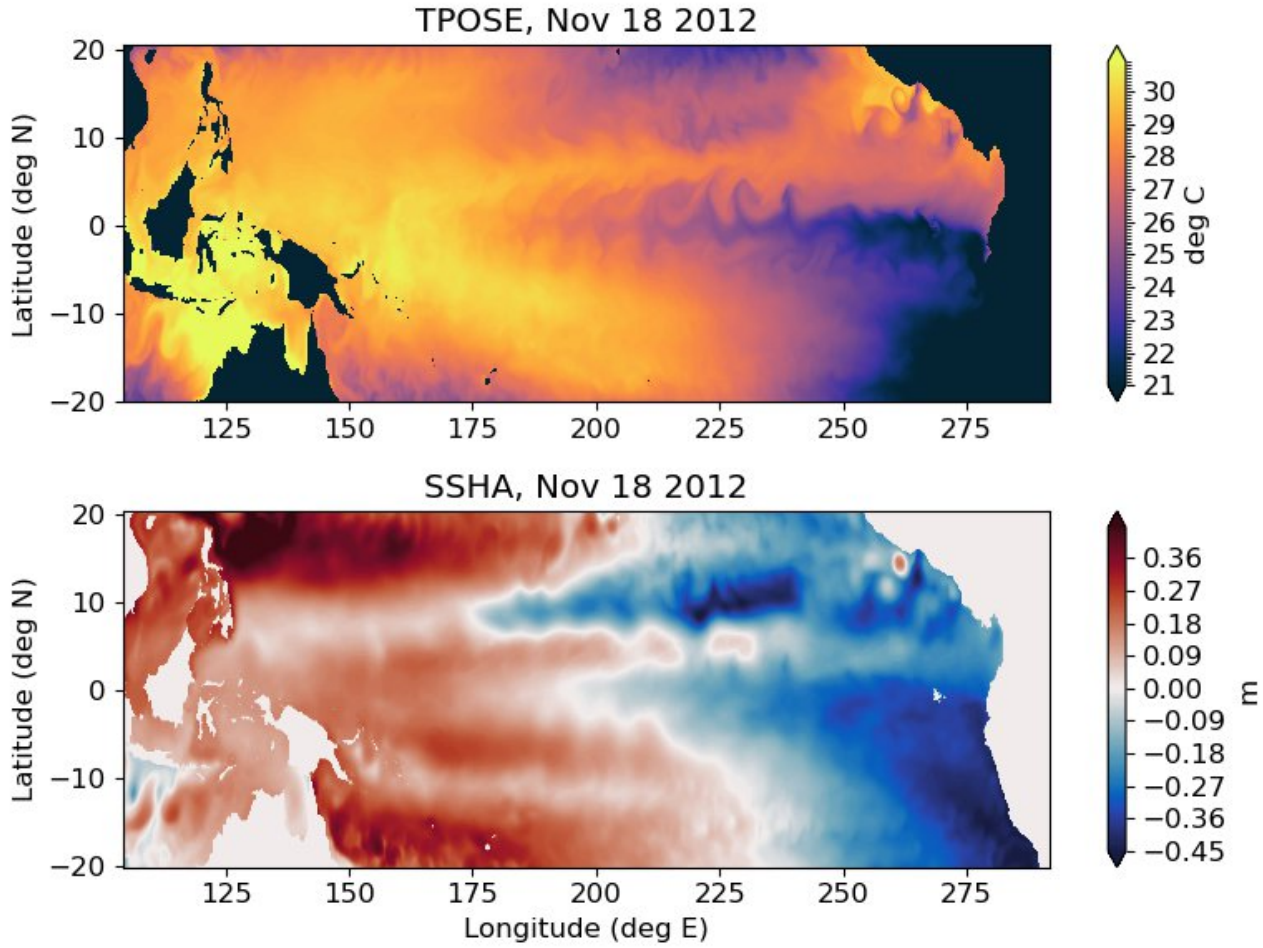
Hypothesis testing: Identifying model error (e.g. internal wave momentum fluxes not represented by KPP in the tropical Pacific)

Forecasting: Identifying timescales of controllability and predictability at ever shorter scales with SWOT (e.g. success assimilating dynamics down to 70 km with 31 day windows)

Observing system experiments: Identifying the value of observations (e.g. value in assimilating ADCP, SWOT, etc)

Tropical Pacific Ocean State Estimate (TPOSE)

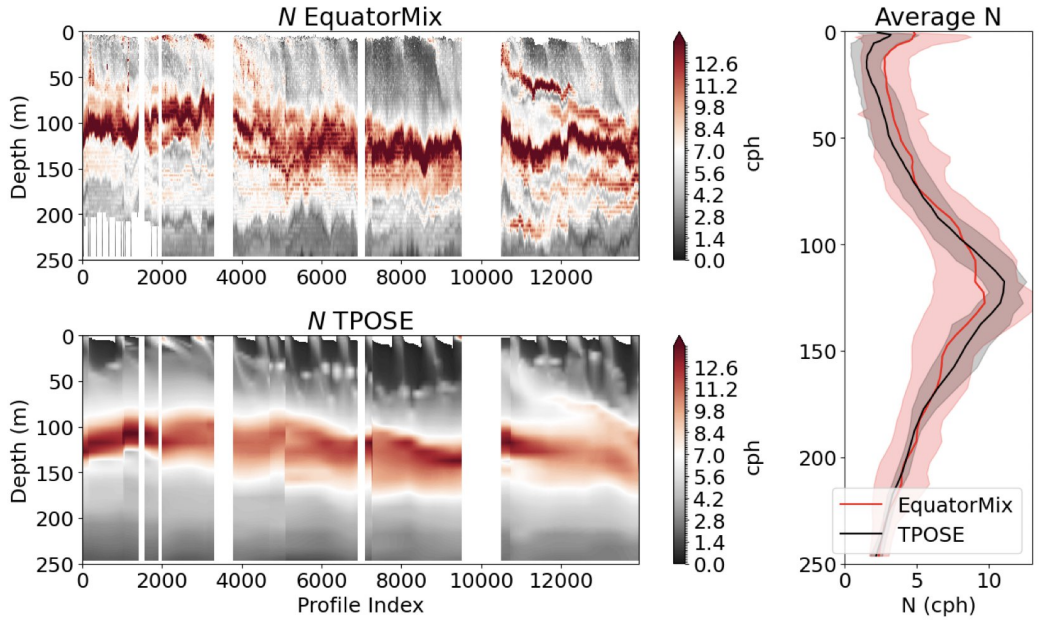
- MITgcm ocean model
- 66 vertical levels
- 2m resolution at the surface
- 1/6th degree horizontal resolution
- Assimilate SSH, SST, T and S profiles
- Ocean state dimension ~10^8
- Total dimension: ~10^{13}
- Observation: ~10^7
- **5 years of overlapping 4-month windows**



Tropical Pacific Ocean State Estimate (TPOSE)

Ellen, Ariane, Bruce, Matt

Buoyancy frequency



EquatorMix data vs. TPOSE

manuscript submitted to *JGR: Oceans*

Vertical Momentum Flux at 0°N, 140°W: Evidence for Unresolved Wave Contributions and Implications for Cold Tongue SST

E. H. Davenport[1], Ariane Verdy[1], Bruce D. Cornuelle[1], Matthew R. Mazloff[1], Robert Pinkel[1], Amy F. Waterhouse[1], Daniel B. Whitt[2]

[1]Scripps Institution of Oceanography, University of California, San Diego, La Jolla,CA, USA
[2]NASA Ames Research Center, Moffett Field, CA, USA

Key Points:

- A study at 0°N, 140°W suggests that vertical momentum flux in the Cold Tongue is driven by both turbulence and internal gravity waves.
- The K-Profile Parameterization reproduces observed vertical momentum flux but overestimates turbulent viscosity relative to measurements.
- Failure to separate momentum transport mechanisms in model parameterizations contributes to cold biases in sea surface temperature.

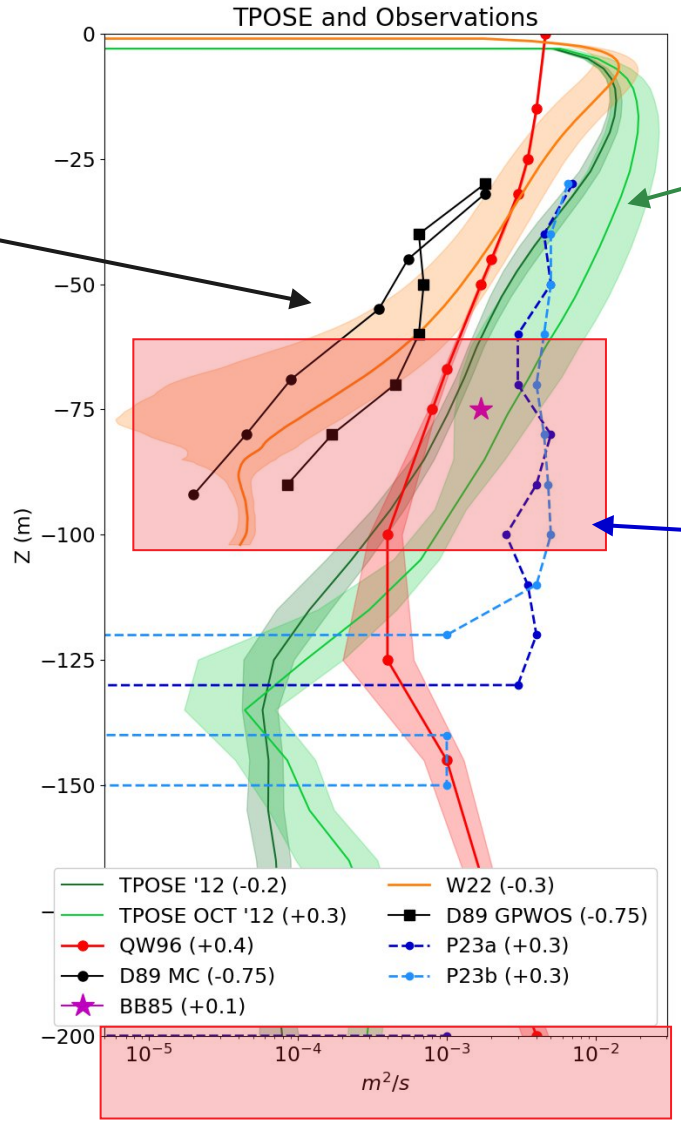
Hypothesis testing: Identifying model error
(e.g. internal wave momentum fluxes not represented by KPP in the tropical Pacific)

Mixing in TPOSE vs. Observations and LES

Turbulence

Dillon et al., (1989)
Whitt et al., (2022)

TPOSE and residuals

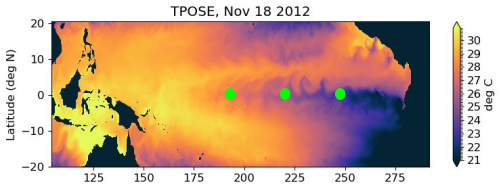


Internal Waves

Pinkel et al., (2023)

Given the same shear: 3 order of magnitude difference in momentum transport.

3 orders of magnitude!



TPOSE vs. Observed Velocity

Data

TPOSE

TAO Observations

TPOSE No TAO

Model-Data Difference

depth [m]

0N, 170W

0N, 140W

0N, 110W

Sep Oct Nov Dec 2013 Feb Mar Apr

U (m/s)

west

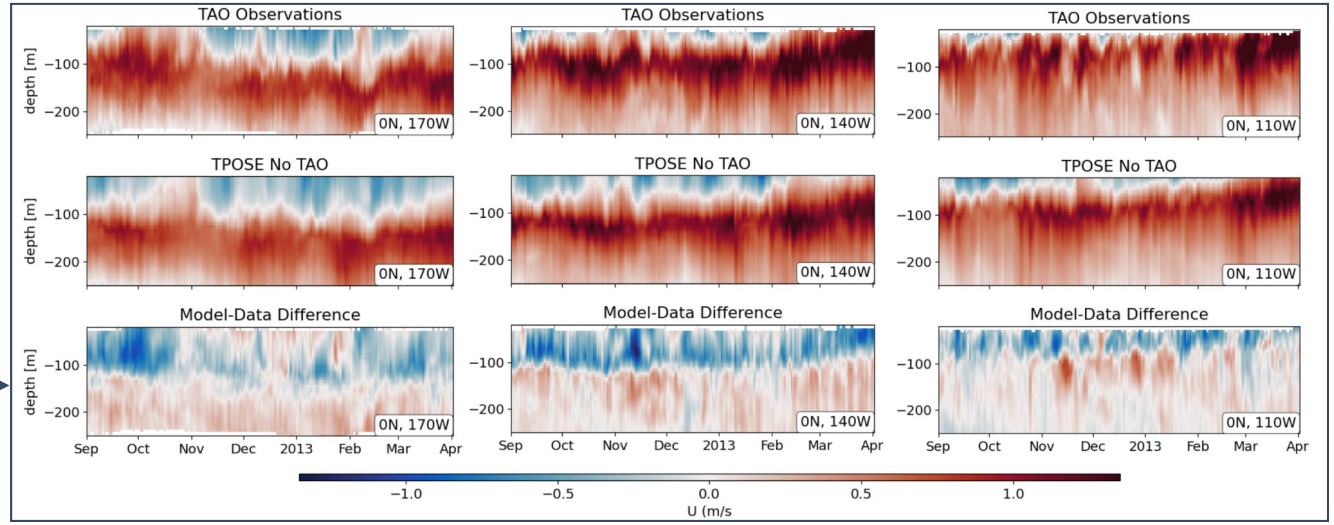
east

Velocity Assimilation Succeeds!

Data

Model

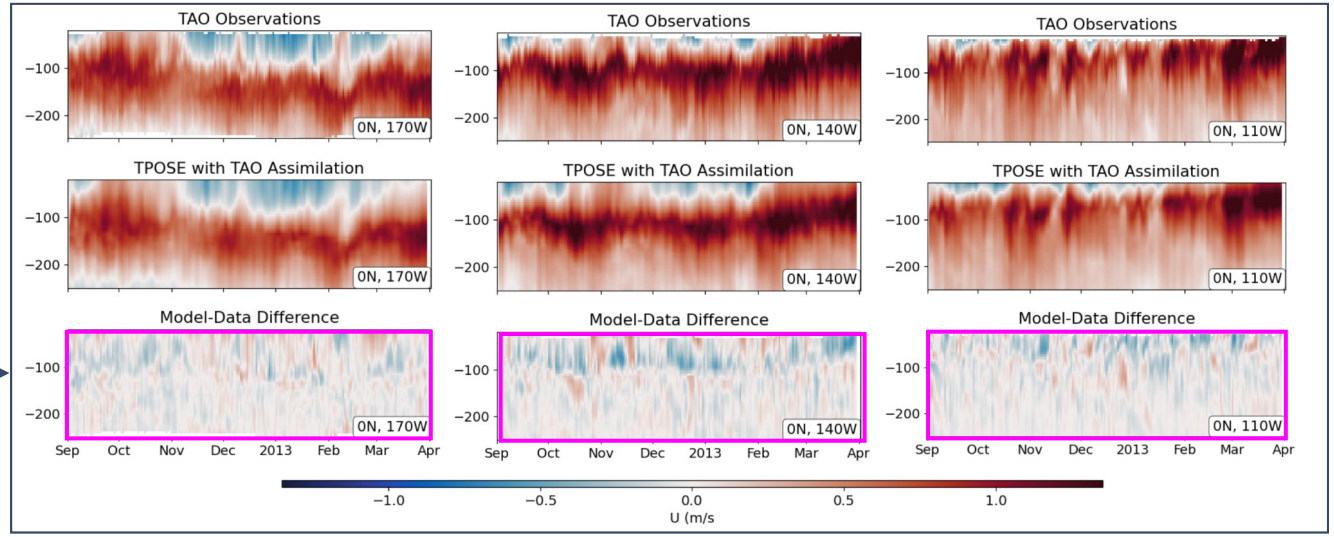
Assimilation *without* Velocity



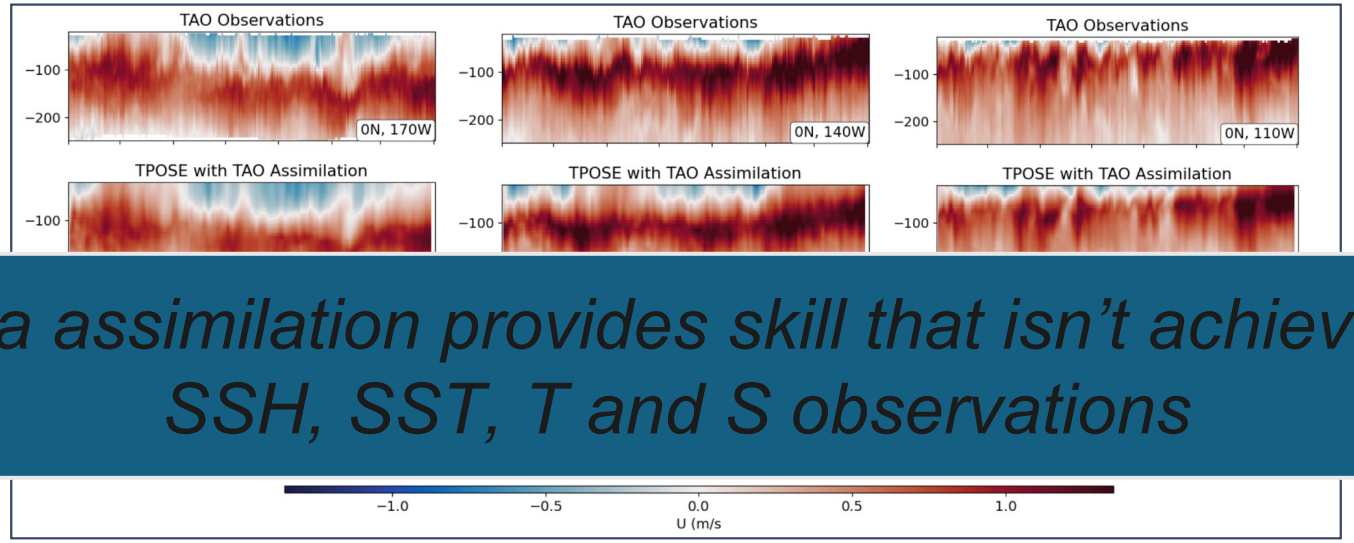
Data

Model

Assimilation *with* Velocity

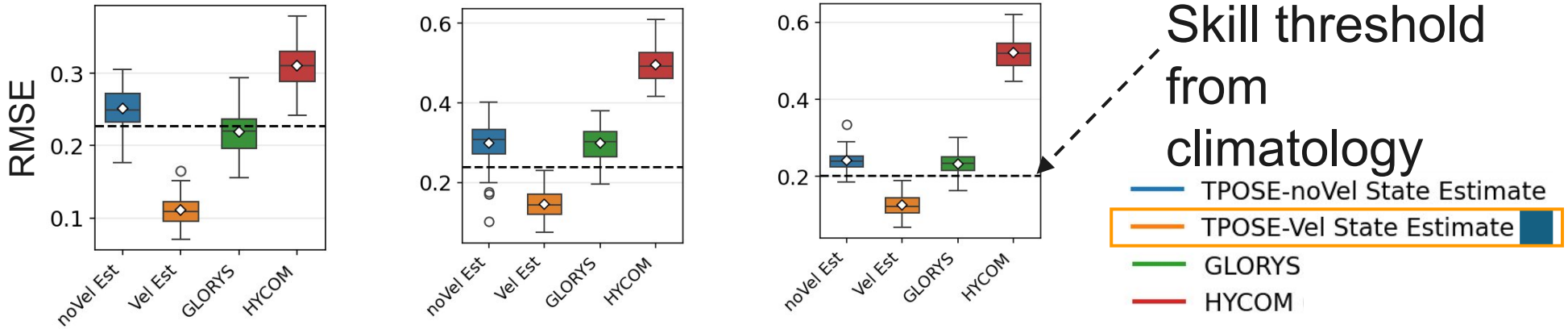


Velocity Assimilation Succeeds!

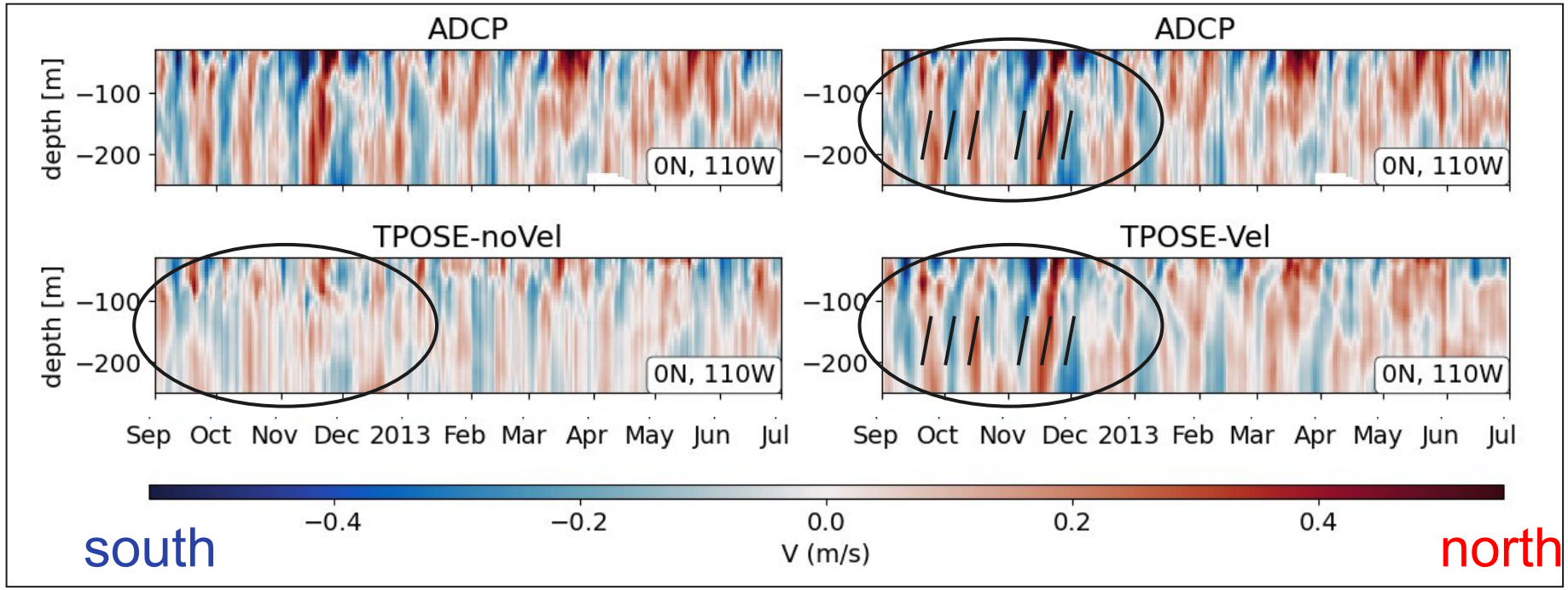


Velocity data assimilation provides skill that isn't achieved with only SSH, SST, T and S observations

More Skill

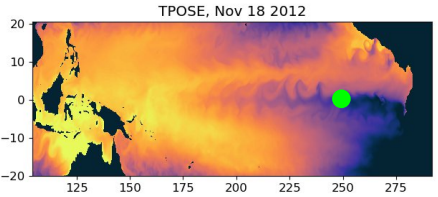


Assimilation Produces Equatorial Waves



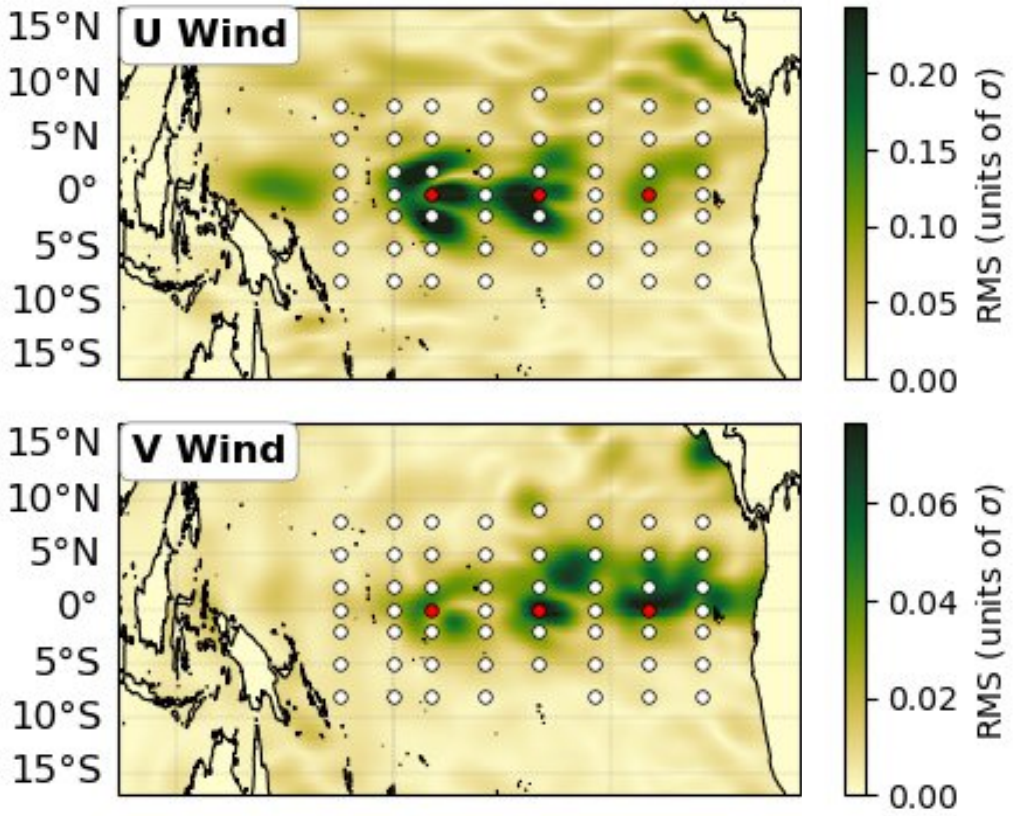
Assimilation *without* Velocity

Assimilation *with* Velocity



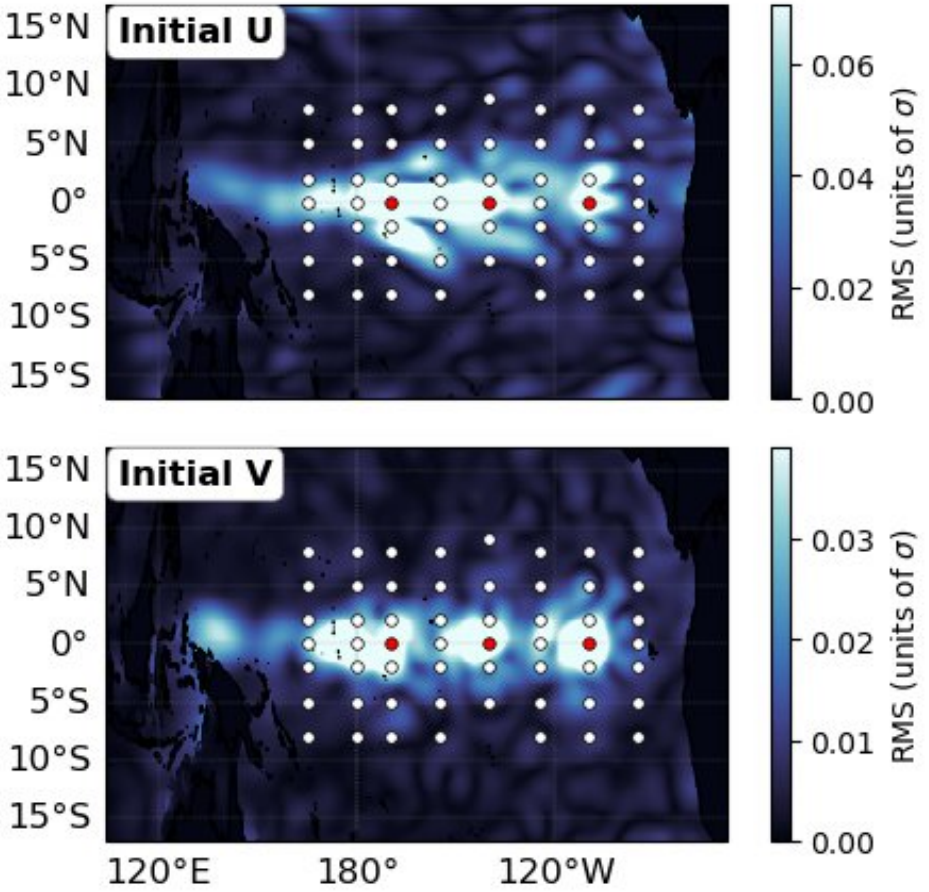
Changes to Wind Forcing

RMS adjustment to atmospheric winds over 4-months



Changes to Velocity Initial Conditions

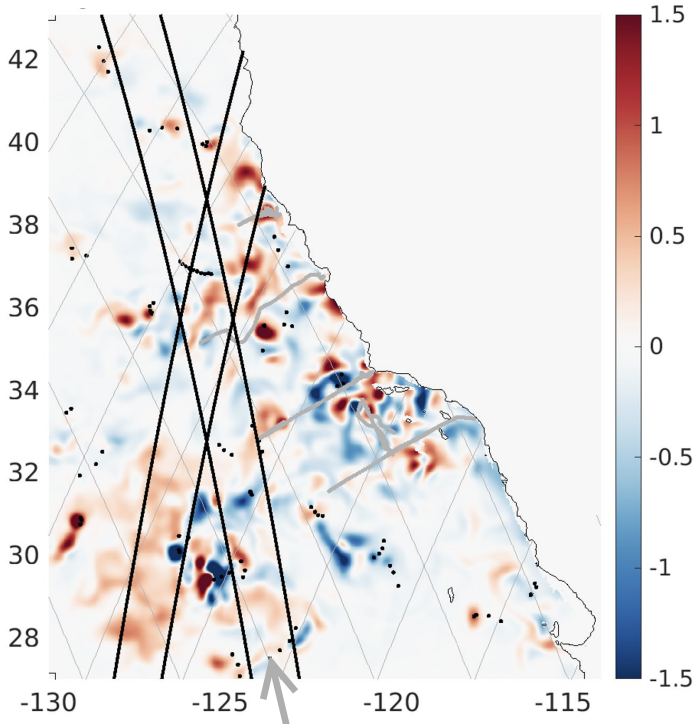
RMS adjustment to velocity initial conditions over 0-300m



Predictability: Identifying timescales of controllability success assimilating dynamics down to 70 km with 31 day windows

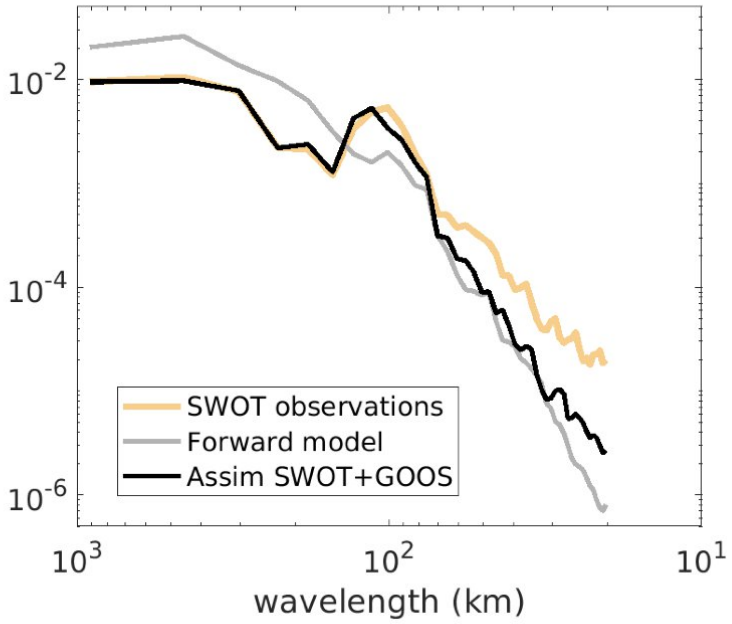
California Current System (CCS)

Adjustments to SST initial conditions



pass 026
Repeated daily in May 2023

Average spectrum (May 1-31, 2023) along SWOT pass 026



manuscript submitted to *Earth and Space Science*

SWOT Observations Constrain a 4D-Var State Estimate of the California Current System

erdy[1], S. T. Gille[1], B. D. Cornuelle[1], G. Gopalakrishnan[1], M. R. Mazloff[1]

[1]Scripps Institution of Oceanography, University of California San Diego

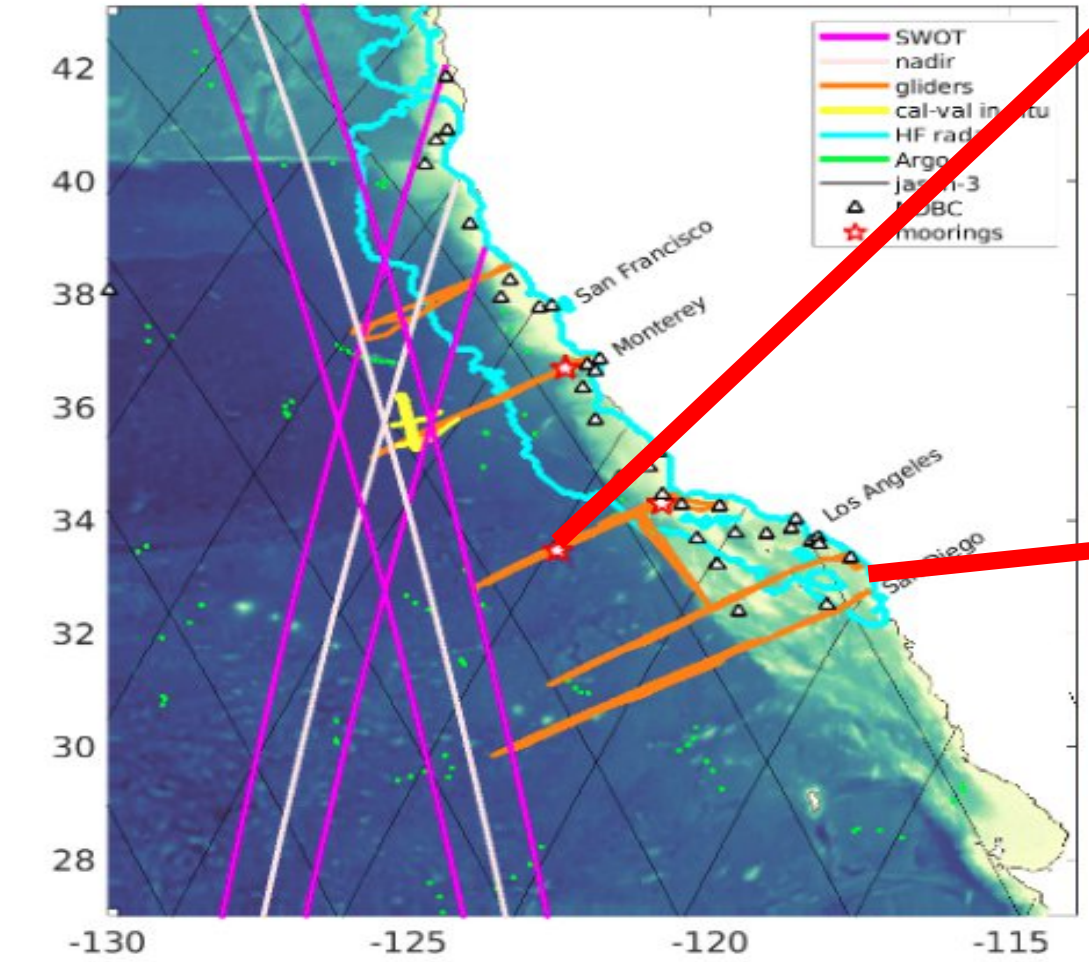
Key Points:

- Using 4D-Var, SWOT observations are assimilated into a regional ocean model targeting previously unconstrained scales of 50-100 km.
- Over the 31-day assimilation window, the state estimate fits SWOT data within the prescribed 2 cm uncertainty.
- SWOT sea surface height measurements lead to improved model agreement with independent *in situ* observations.

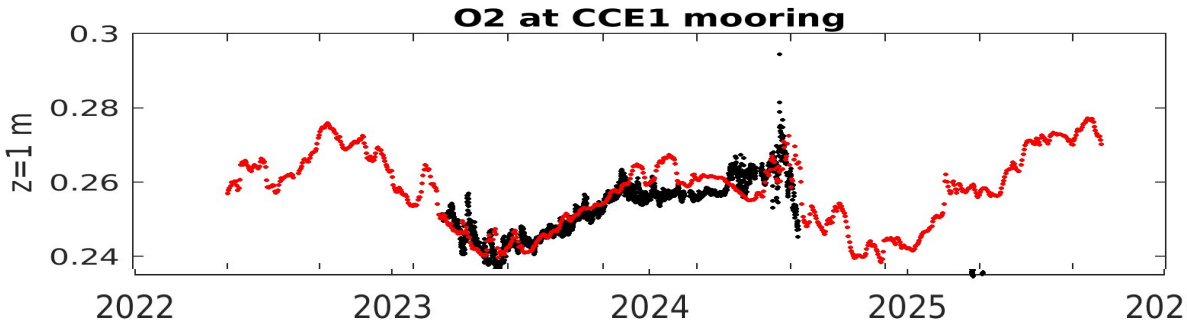
SWOT observations vs. state estimate (31-day assim. window) captures scales down to ~70 km

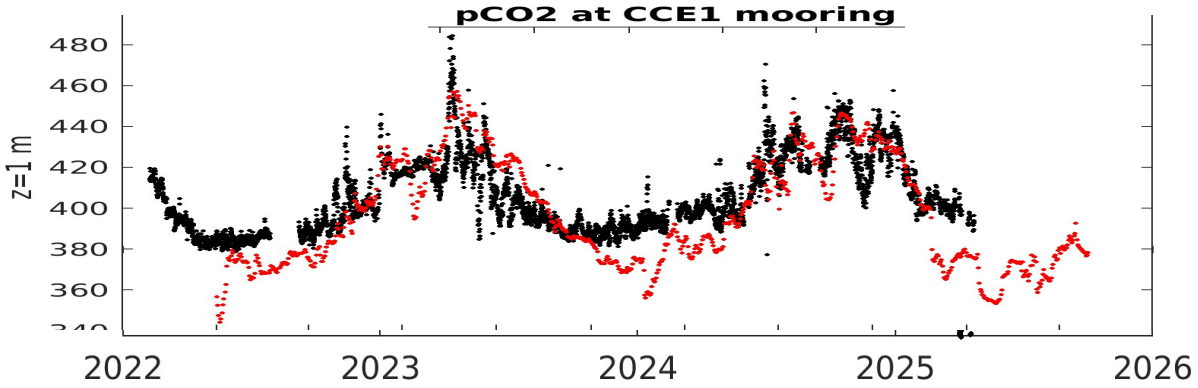
Push to the coast with BGC!

- 2-km grid spacing, 100 vertical levels
- 31-day assimilation windows constraining to Argo, Spray, SST, SSH including SWOT

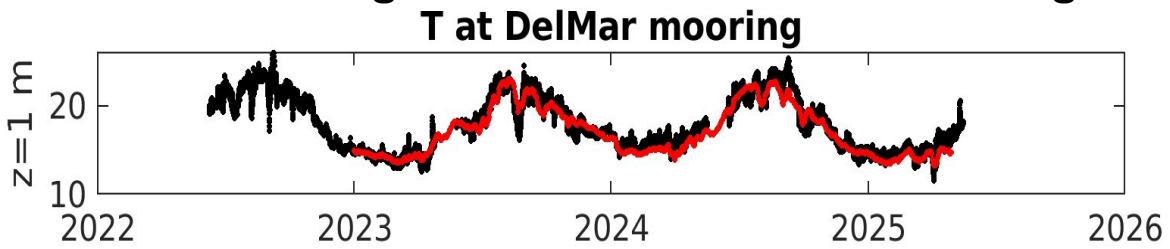


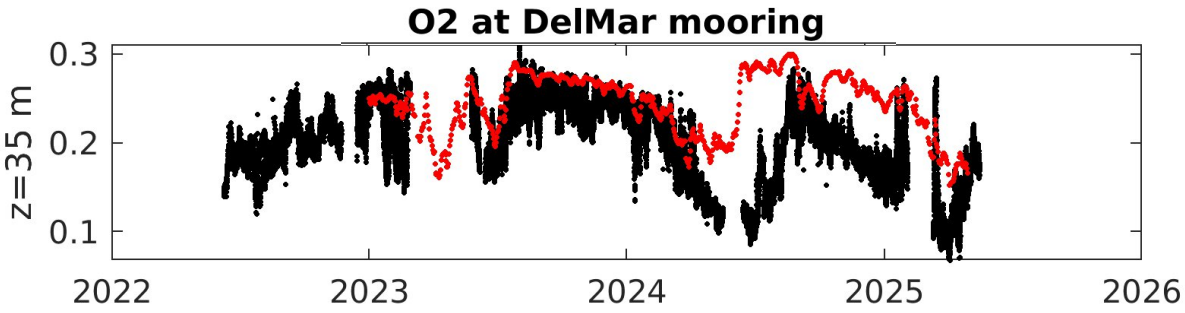
Validating with CCE1 mooring





Validating with Del Mar coastal mooring





SWOT Science Orbit Altimetry in the Gulf of Mexico

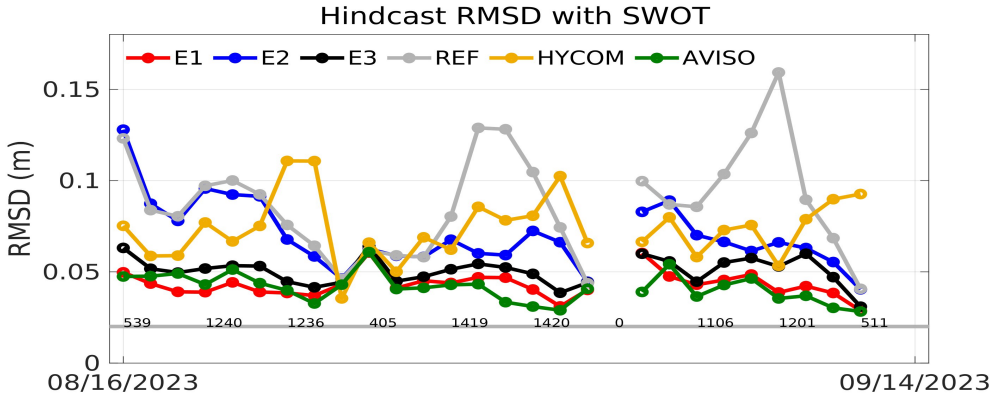
Resolution: $1/20^0$ (~ 5 km), 80 z-levels

Assimilation period:
08/16 – 09/14, 2023 (1 month) during an extreme event: Hurricane Idalia traversed GoM during 08/25 – 08/31 (landfall on 08/31 in Florida)

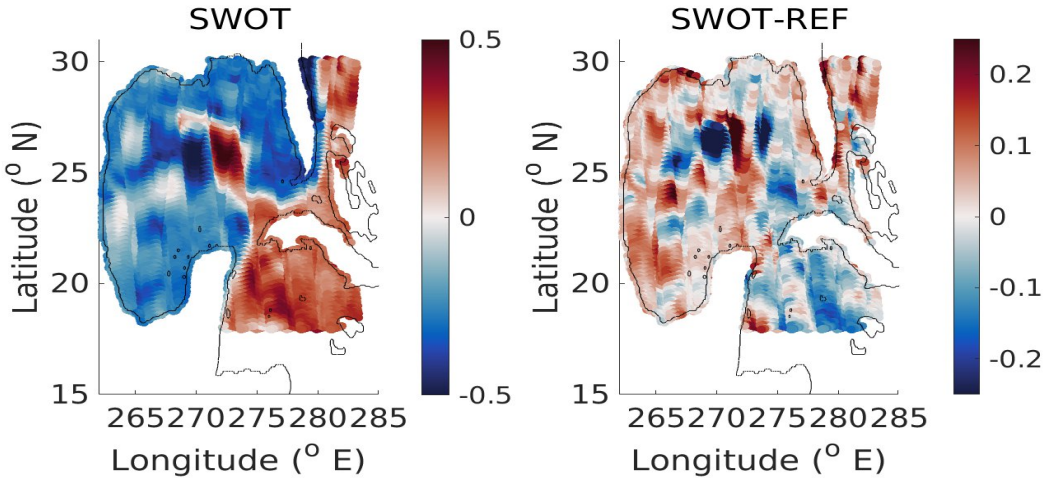
SWOT Observations

- Science orbit SWOT data from Level 3 low-resolution product (L3 LR SSH version 2.0.1) is used
- SWOT data were subsampled 10 km apart and are averaged in 10 km bins in the along-track direction
- SWOT data observation uncertainty is set to 2 cm

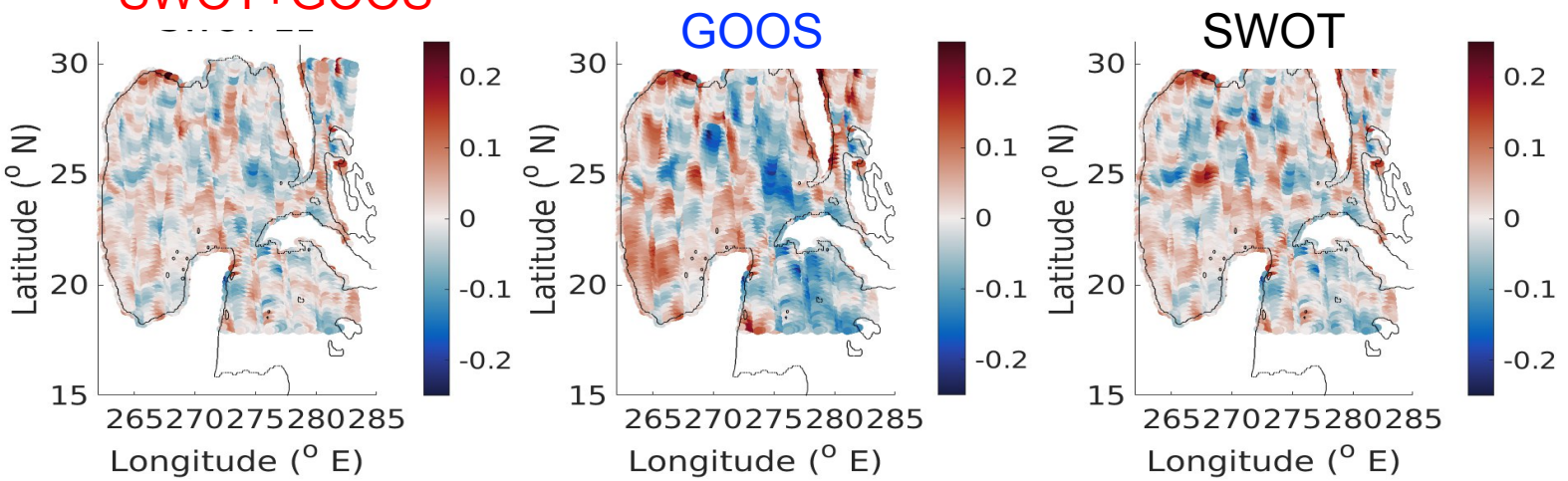
SSH RMSD against SWOT altimetry (SSH sampled along SWOT swaths)



SSH sampled along SWOT swaths overlaid for the 30-day assimilation.



SWOT+GOOS

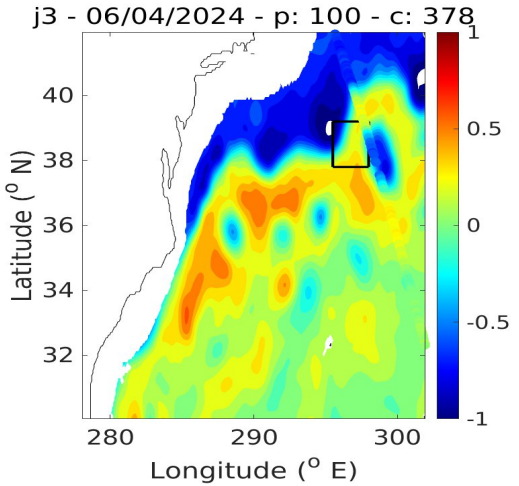


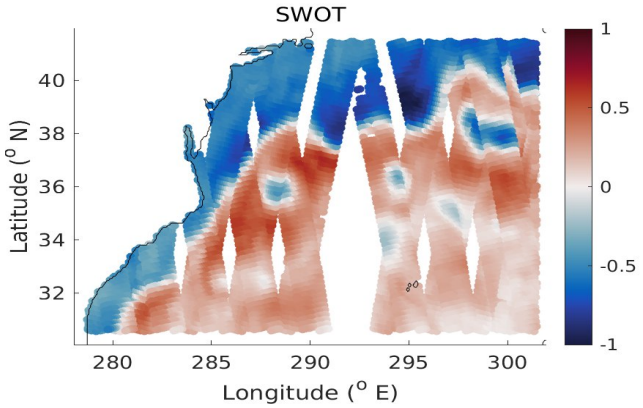
Using SWOT Science Orbit Altimetry in the Gulf Stream

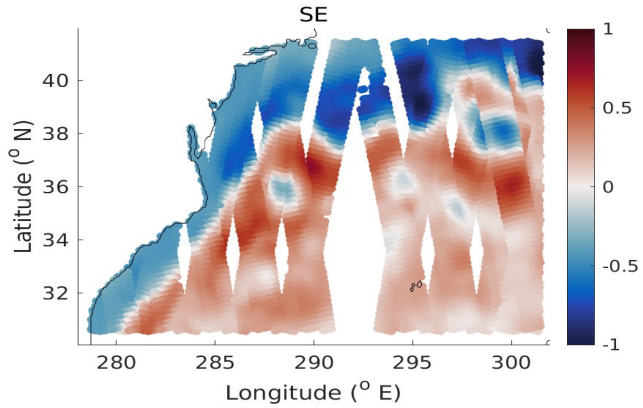
Resolution: 1/120 (~ 9 km), 50 z-levels

14-day assimilation with first-guess solution (initial conditions) initialized from HYCOM-ESPC global analysis

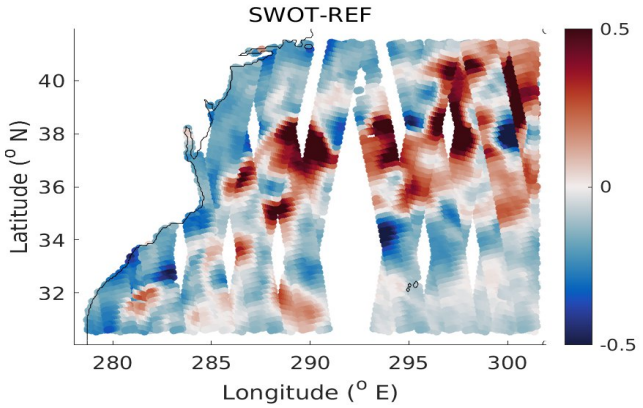
Assimilation period: June 1 - 14, 2024

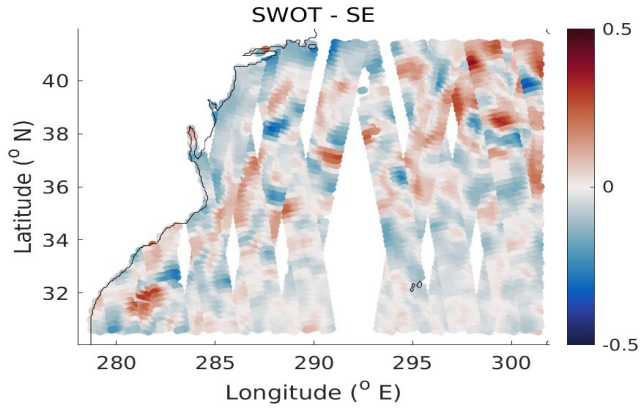


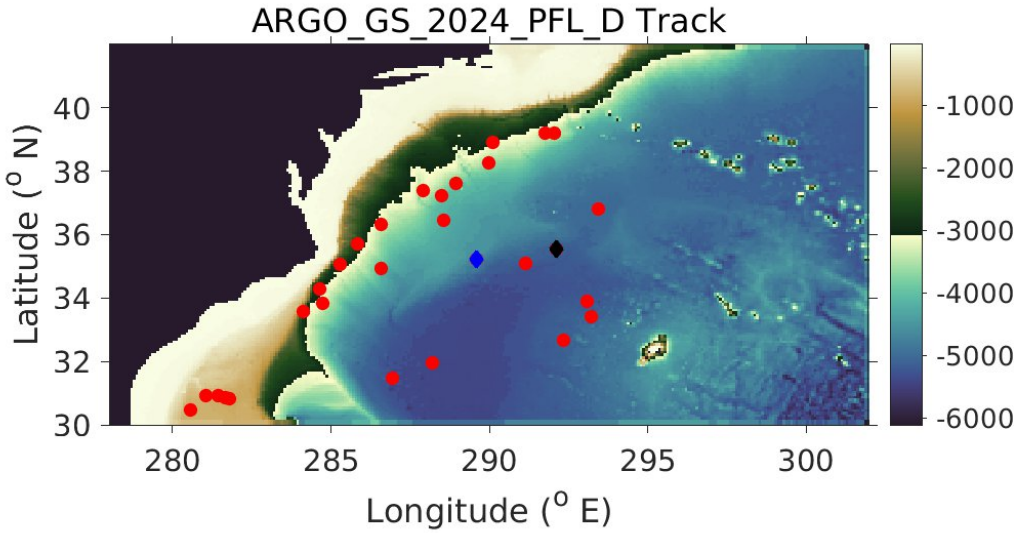


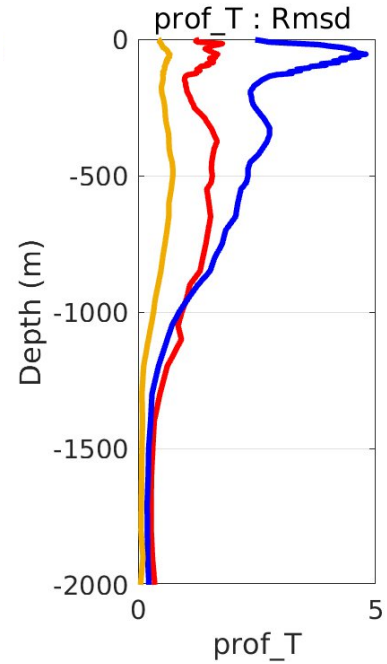


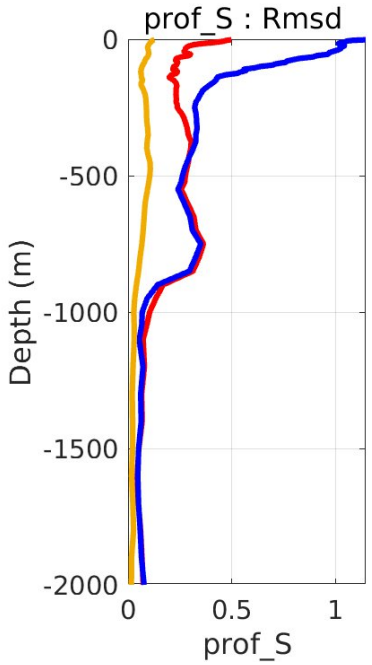
SSH comparison against SWOT (SSH fields sampled along SWOT tracks are overlaid over assimilation period)





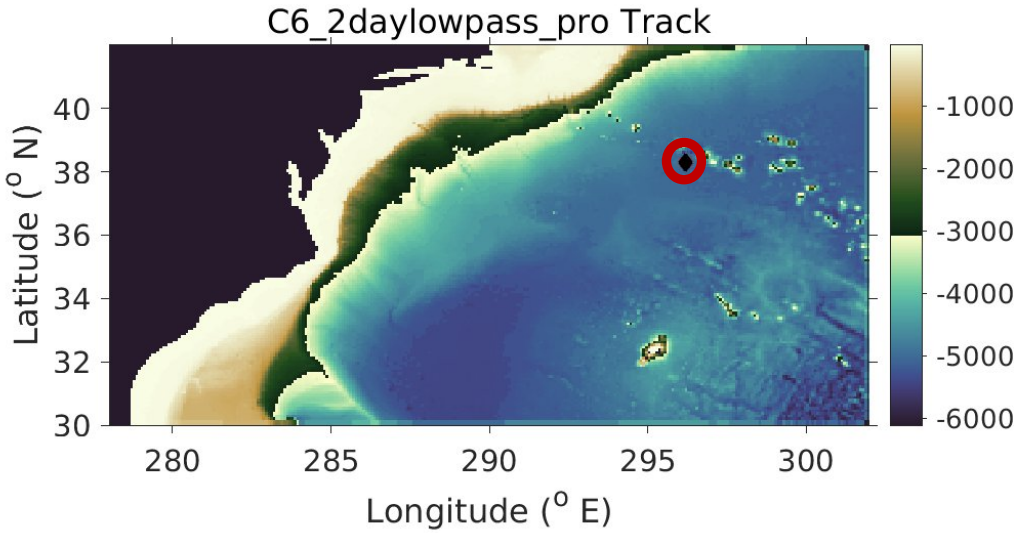


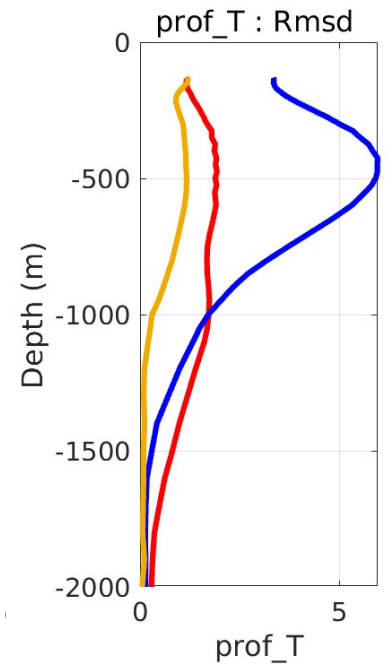


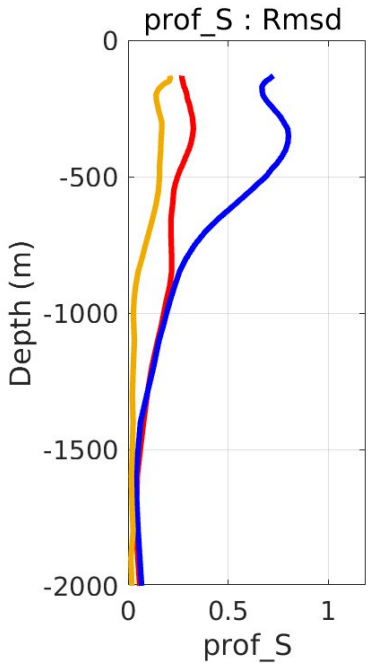


T & S comparison against Argo profiles (independent data comparison)

STATE
ESTIMATE
REFERENCE
STATE
PRIOR OBS
ERROR





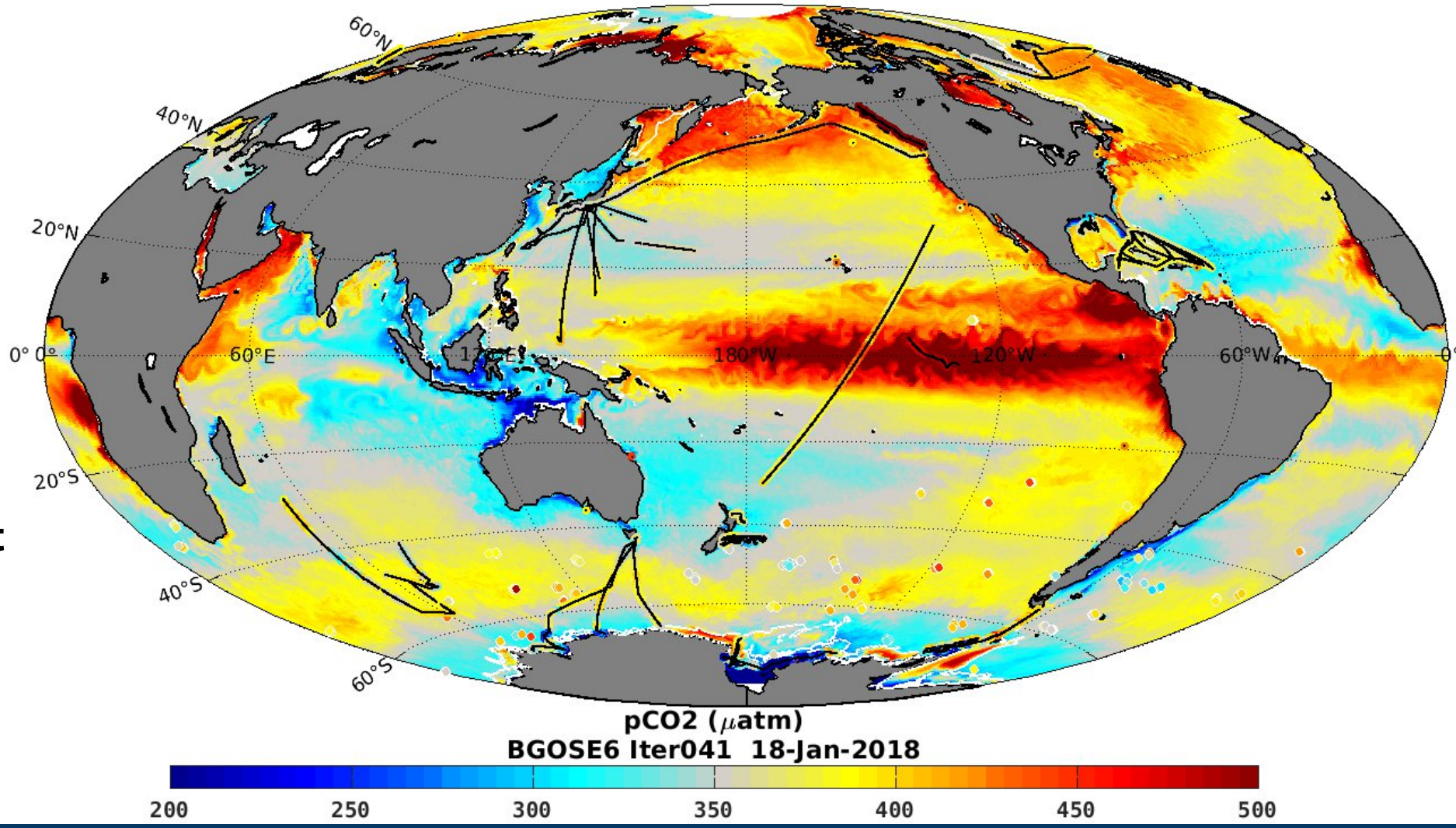


T & S comparison against CPIES C6 profiles (independent data)

SWOT assimilation improves subsurface T & S (in the upper 1000 m)

Biogeochemical global ocean state estimate (BGOSE)

- Expanded from BSOSE
- 83S to 86N
- Added Antarctic ice shelf cavities
- 52 vertical levels
- 1/6th degree horizontal resolution
- 2013 to 2025
- **sose.ucsd.edu/bgose.html**



Technical update time

- Data processing
- ObsFit
- AI/ML
- Coupled atmosphere-ocean-wave model, SKRIPS: WRF-MITgcm-WW3
  - DA with EnKF (DART), including with BGC
  - Consistent fluxes to atmosphere and ocean, including with sea ice!
  - Another system option for regional coupled downscaling within IMVI?

- Quick plug: SWOT data inversion and DA working group meets the 1st Monday of the month at 8 am PT. Contact Sarah Gille sgille@ucsd.edu to get on the email distribution list. Next presentation is June 1.

In Situ constraints processing

- **Argo** (directly from the DAC, not missing profiles anymore) 1997-2026
- **WOD**: CTD+OSD, XBT, GLD, MRB 1992-2026
- **ITP** (L2, L3) 2004-2023
- **MEOP** 2004-2024

ecco.ucsd.edu/assim.html

Ocean State Estimation at Scripps

SCRIPPS INSTITUTION OF OCEANOGRAPHY
UC San Diego

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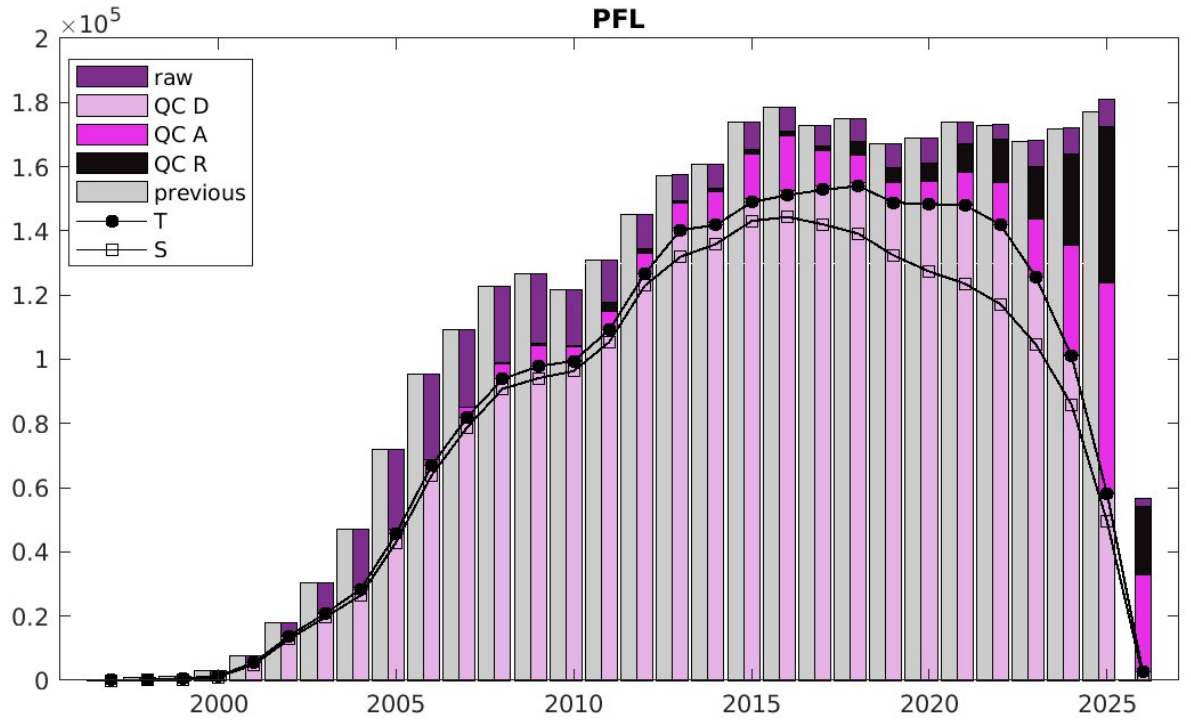
Constraints processed for MITgcm assimilation

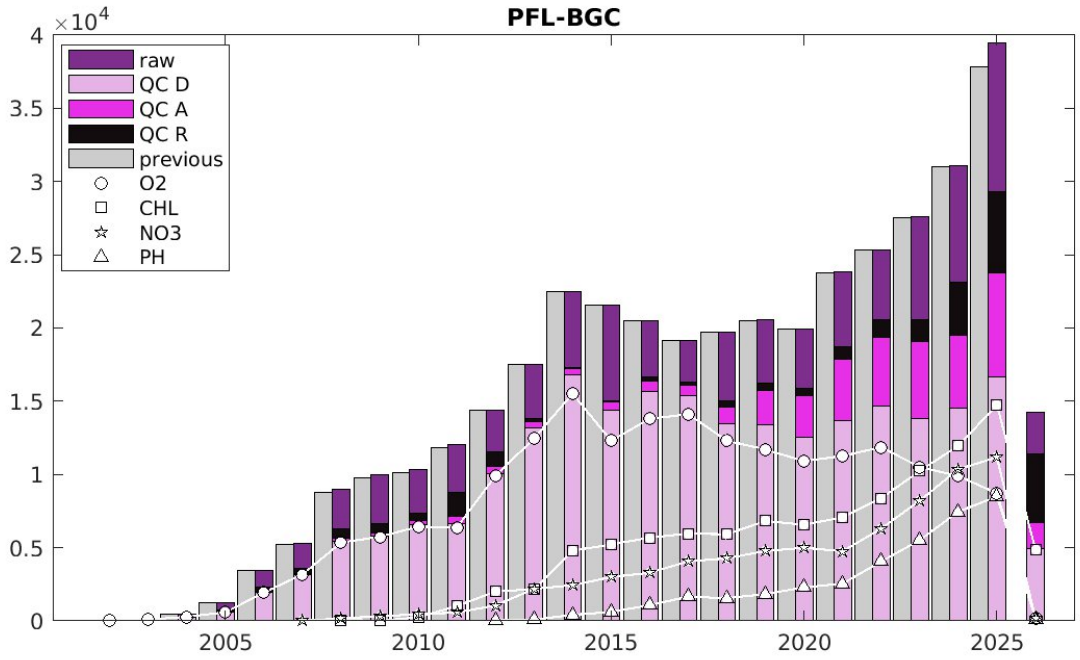
dataset	source	variables	years	last updated	notes
Argo (PFL)	Argo GDAC	T, S	1997-2026	May 2026	
BGC-Argo (PFLBGC)	Argo GDAC	O2, NO3, pH, chl	2005-2026	May 2026	
CTD	WOD	T, S, O2	1992-2026	May 2026	
XBT	WOD	T	1992-2024	May 2026	"noflag" = submitted without QC flag; processed separately
Gliders (GLD)	WOD	T, S, O2	2002-2025	May 2026	
Moorings (MRB)	WOD	T, S, O2	1991-2025	May 2026	97 and 36 depths
ITP	WHOI	T, S, O2	2004-2023	May 2025	L2 and L3; no data since 2023
Pinnipeds (APB)	MEOP	T, S	2004-2024	May 2024	no update since 2024



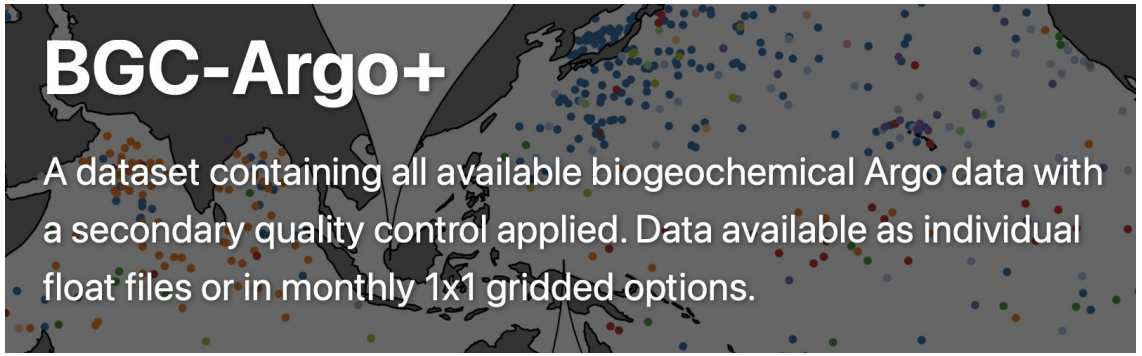
In Situ BGC constraints processing

- bgc-Argo 2005-2026
- WOD 1992-2026
- SOCATv2025 2012-2024
- GLODAPv2 1992-2021

ecco.ucsd.edu/assim.html



In progress:
Improved QC, BGC-Argo+ (Bushinski, Nashod)



pkg/ObsFit

Enabling technology for multi-model loss functions

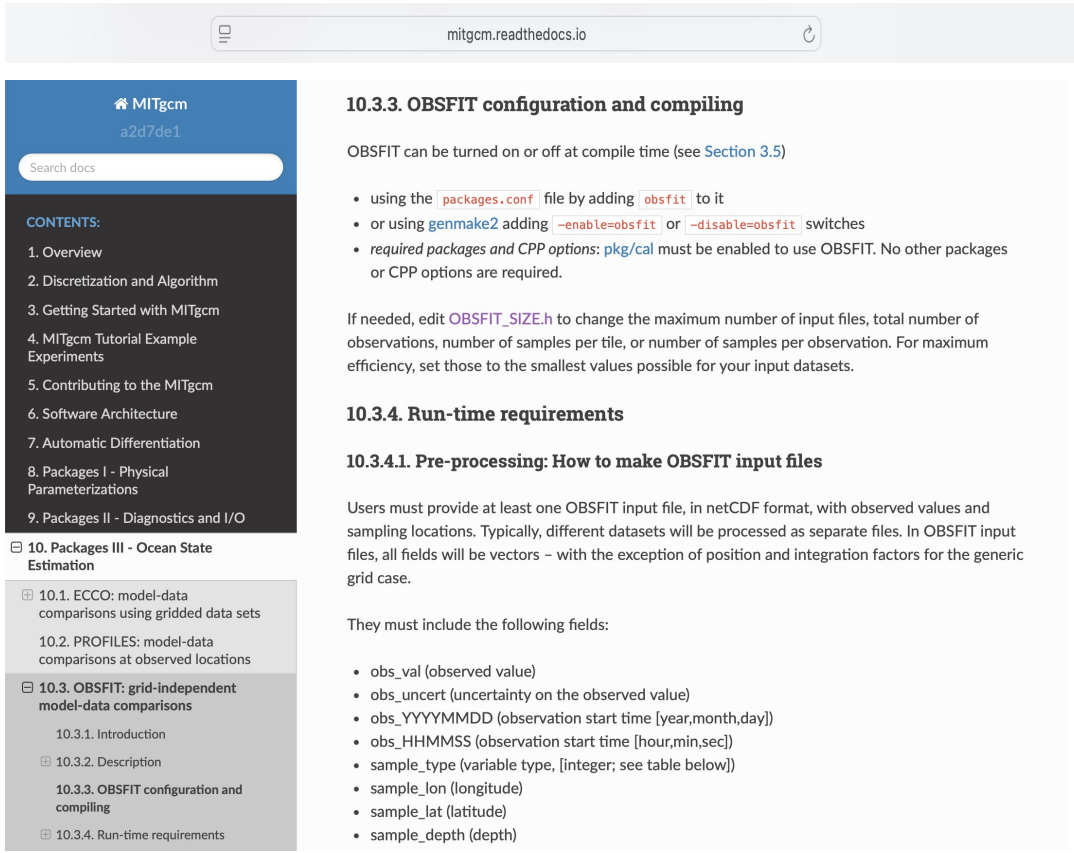
Data assimilation in observation space, not model space.

saves memory when sparse or irregular data (e.g. SWOT)

- Observations can be instantaneous or averaged/integrated in time
- Observations can be made of multiple sampled points (a weighted average of different variables or different locations)

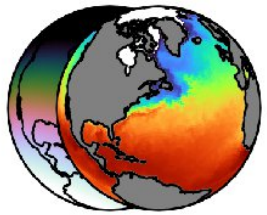
In progress: LLC grid compatibility?
Speed up cost calculations

https://github.com/MITgcm/MITgcm/tree/master/pkg/obsfit

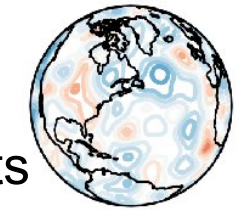


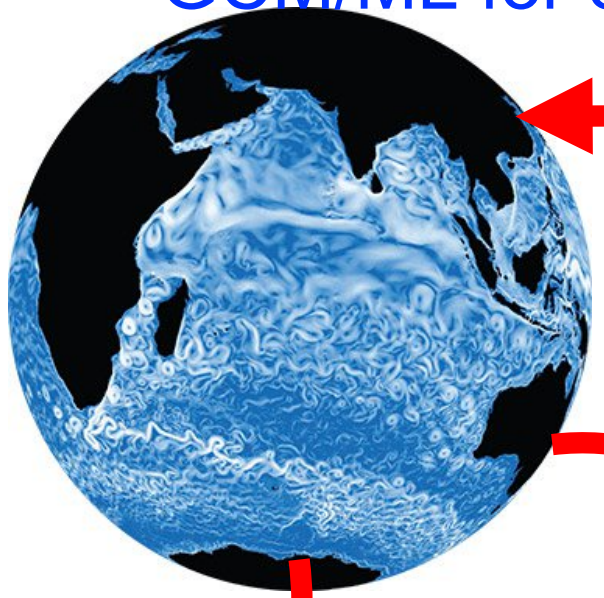
GCM/ML for ocean intelligence

Boundary and initial conditions



Parameter and input adjustments

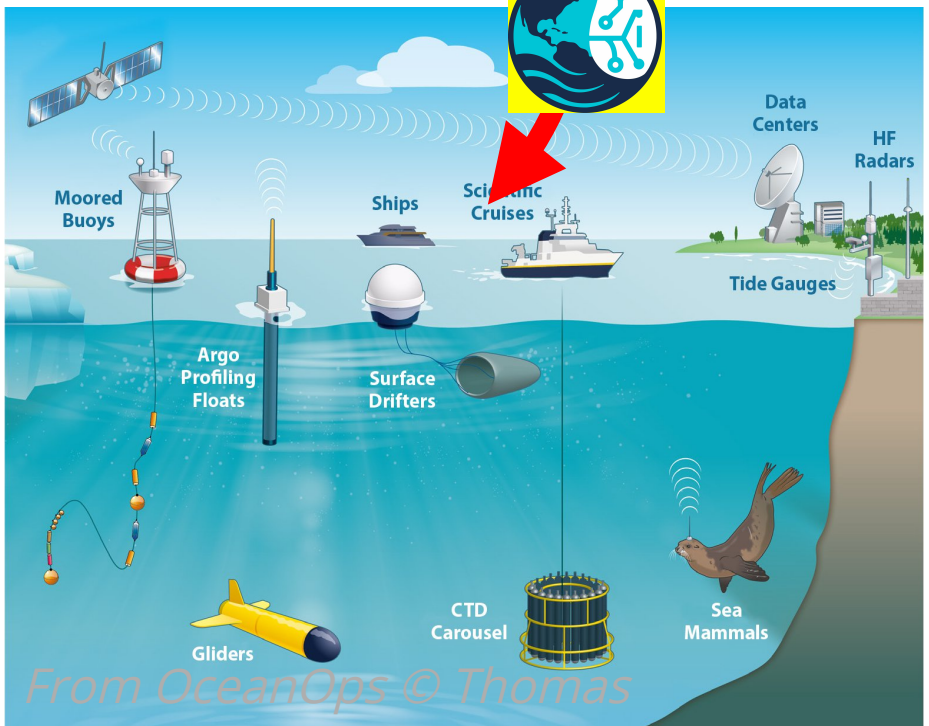




CONSERVATION LAWS
Mass Momentum
Energy Salt

Machine Learning can augment every component of this workflow

Ocean obs.



Stakeholders

ML for Ocean Boundary Layer Parameterization (KPP)

Yue (Luna) Bai, Schmidt AI in Science postdoc, SIO

- Parameterization of nonlinear subgrid processes is source of model error.

In the atmosphere:

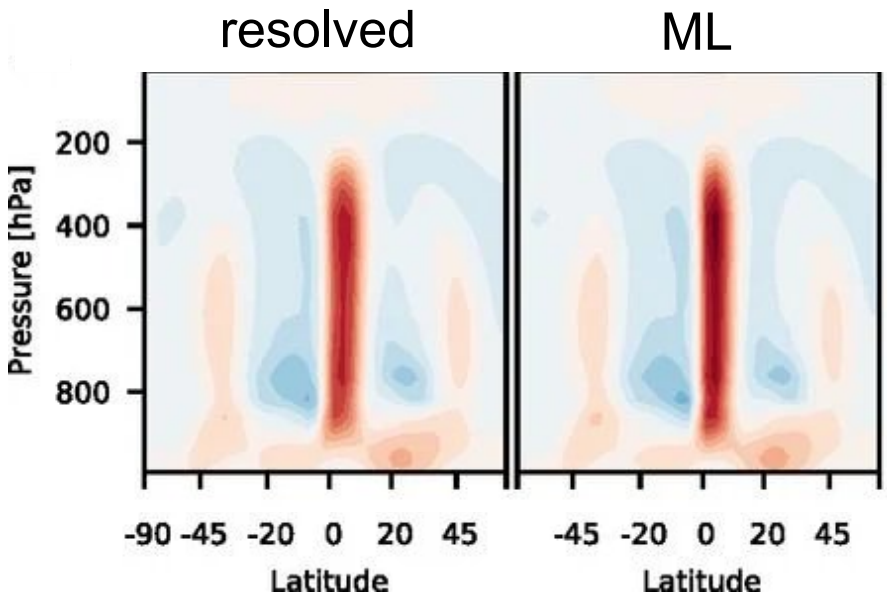
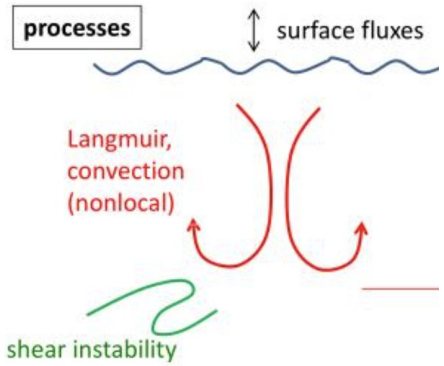


Figure from Rasp et al., 2018

In the ocean:



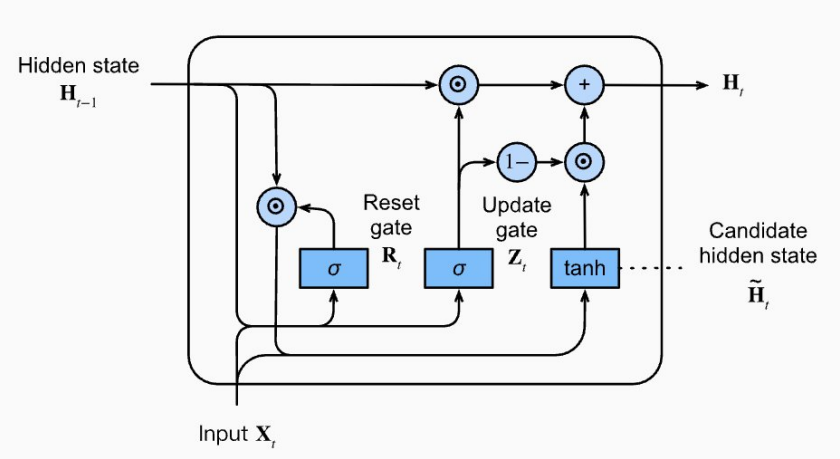
KPP: $\overline{w'\phi'} = -K_\phi \partial_z \Phi + NL_\phi$ (local diffusion; non-local transport)

Can we capture KPP using machine learning in ocean simulations?

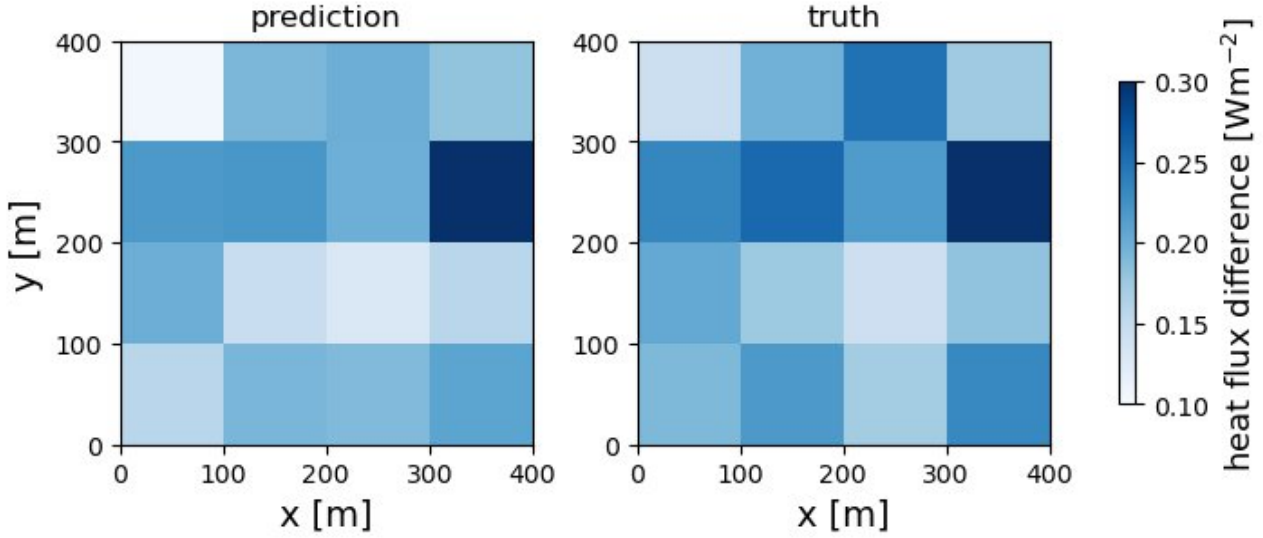
ML Captures KPP with High Skill

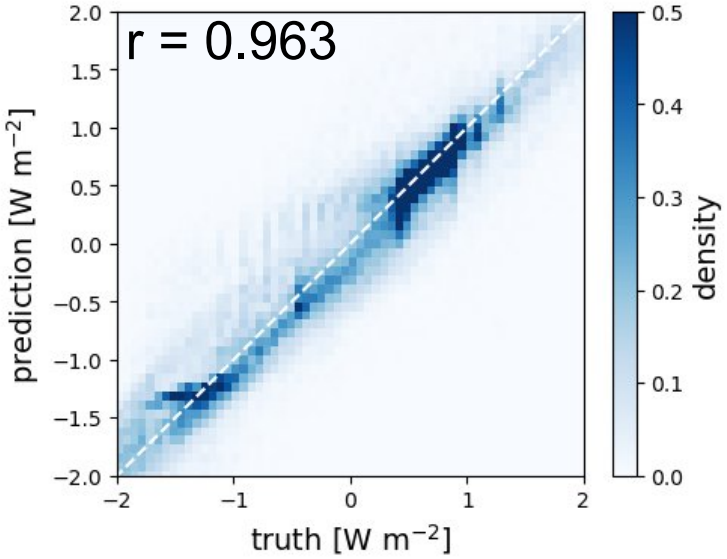
Yue (Luna) Bai, Schmidt AI in Science postdoc, SIO

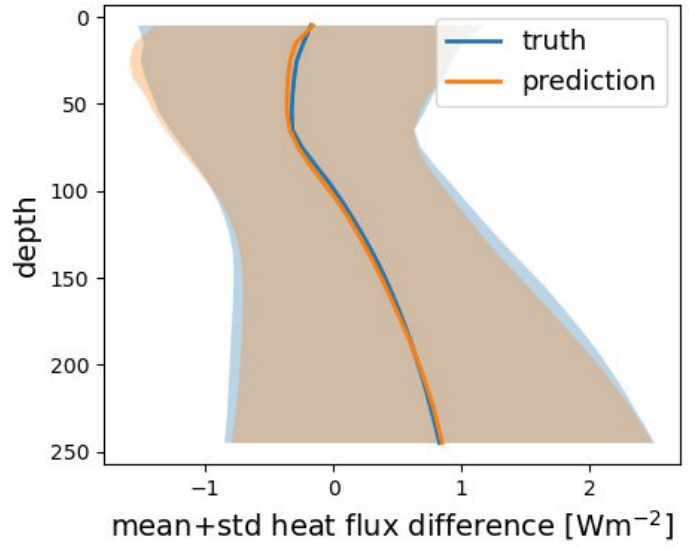
Gated Recurrent Unit (GRU)



- Input: variables from simulations w/o KPP
- Output: heat flux difference between w/ and w/o KPP
- Depth-wise training, ~51,600 sample grids
- Implemented into MITgcm with neural-fortran







Exploring air–sea interactions in a regional weakly coupled data assimilation system: An observing system experiment for the 2023 Indian Ocean monsoon and Cyclone Biparjoy

UCSD/SIO: Rui Sun, Matt Mazloff, Bruce Cornuelle, Art Miller, Ganesh Gopalakrishnan, Tien-Yiao Hsu
CU Boulder: Aneesh Subramanian and Lucy Recchia
KAUST: Ibrahim Hoteit and Sivareddy Sanikommu

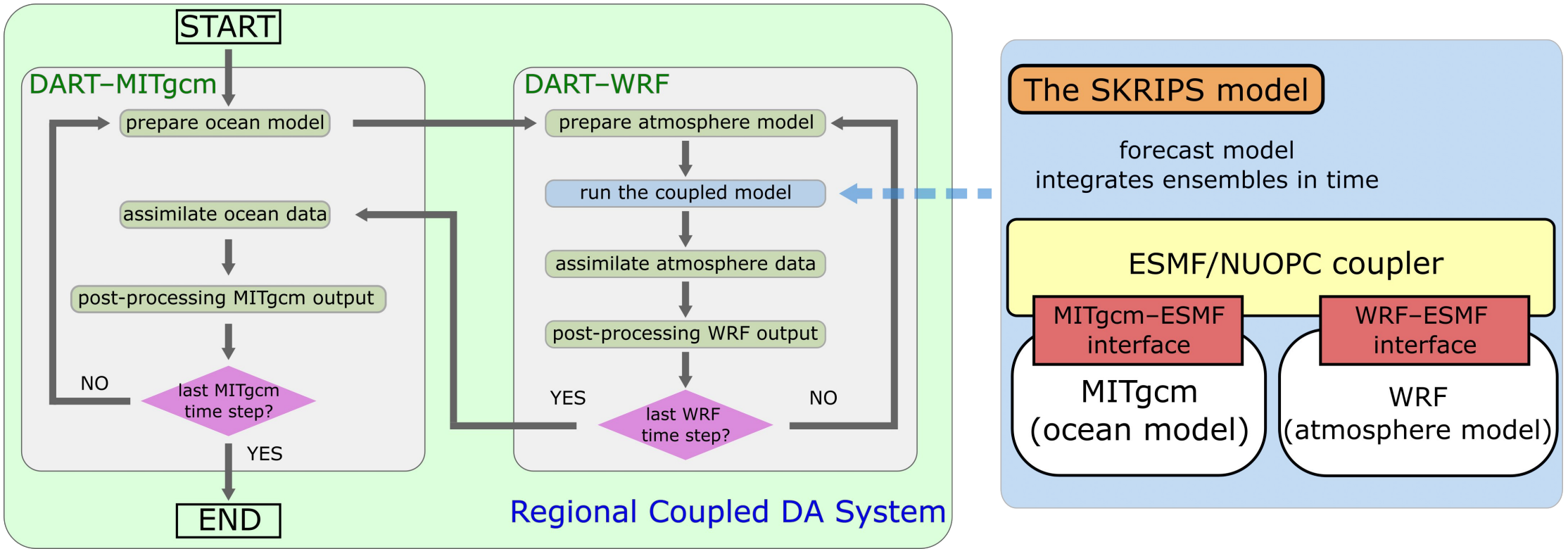
The forward model is the SKRIPS model.

Ocean component: MITgcm

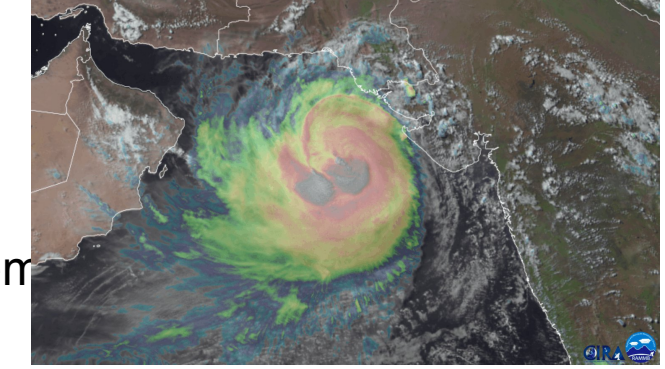
Atmosphere component: WRF

Coupler: ESMF

DART (Data Assimilation Research Testbed) is used to assimilate the observational data.



Coupled DA experiments



2023 Arabian Sea Monsoon + Cyclone Biparjoy.

We used the Ensemble Adjustment Kalman Filter (EAKF) with 50 mem

8 km MITgcm + 16 km WRF, initialised using HYCOM and ERA5 data.

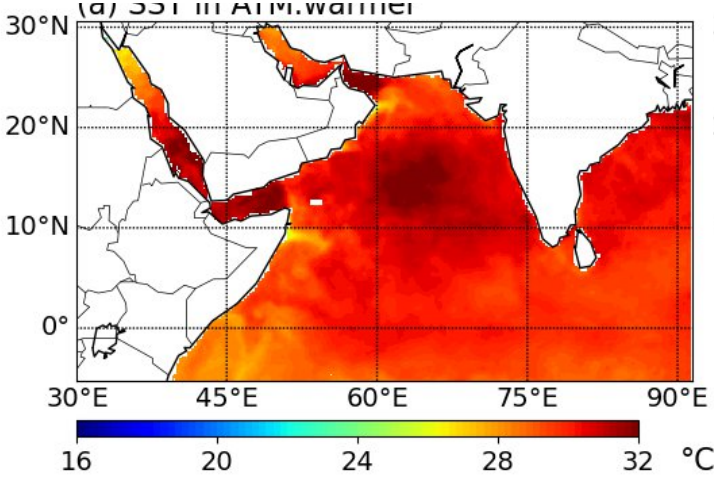
Ocean observation data: OSTIA SST, AVISO along-track SSH, EN4 T/S profiles.

Assimilated every 3 days.

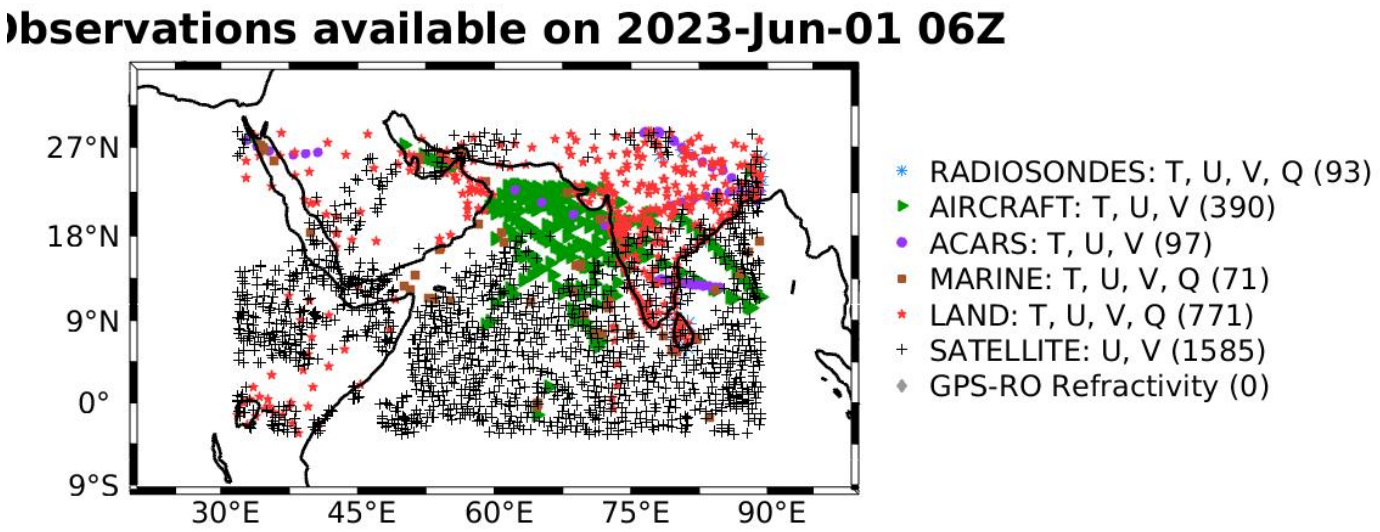
Atmosphere observation data: PrepBUFR

Assimilated every 6 hours.

Domain of the coupled system

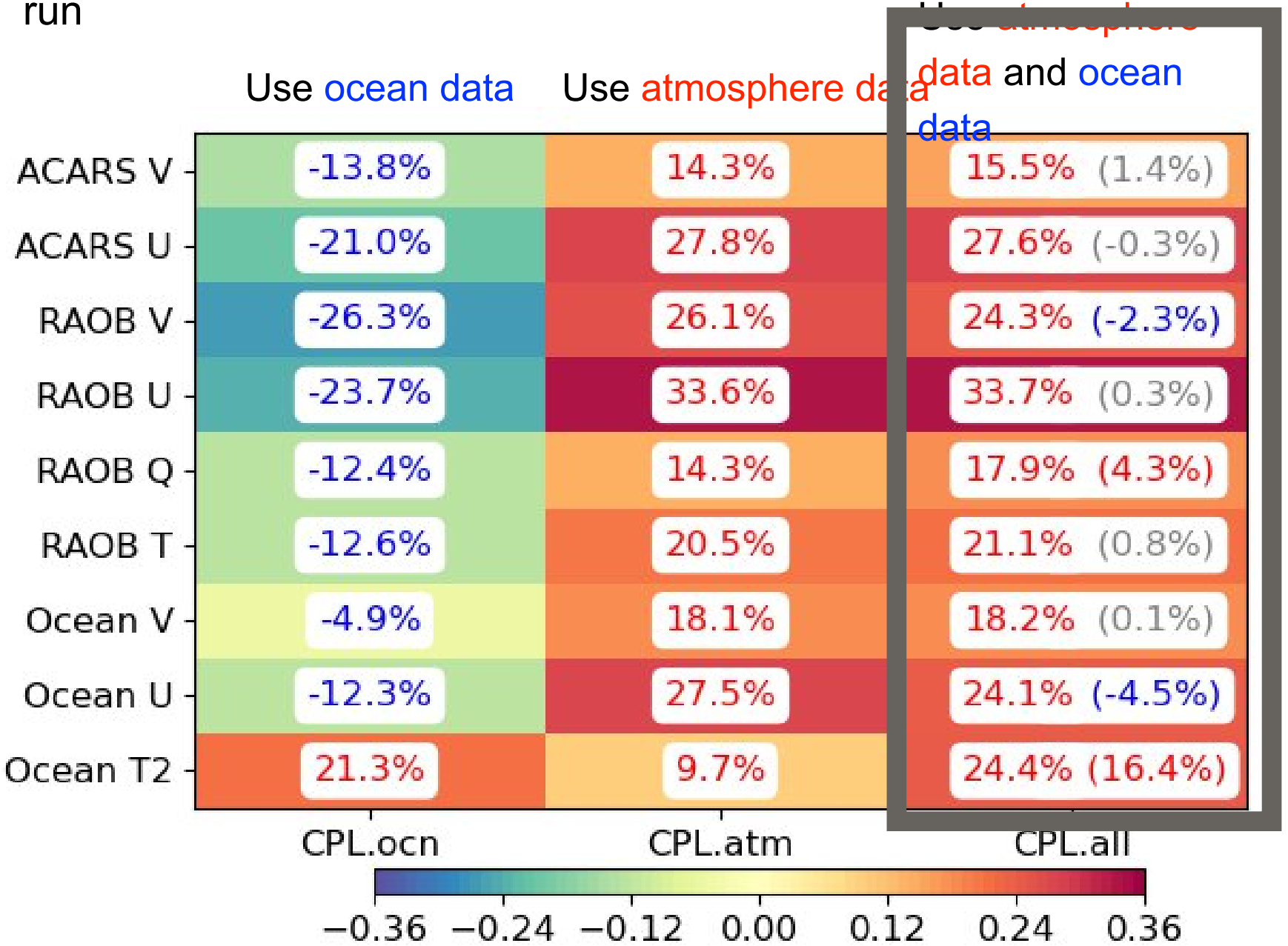


Atmosphere observation data



Preliminary results: forecasts of atmospheric states

Brier Skill Scores (BSS) compared with the free run

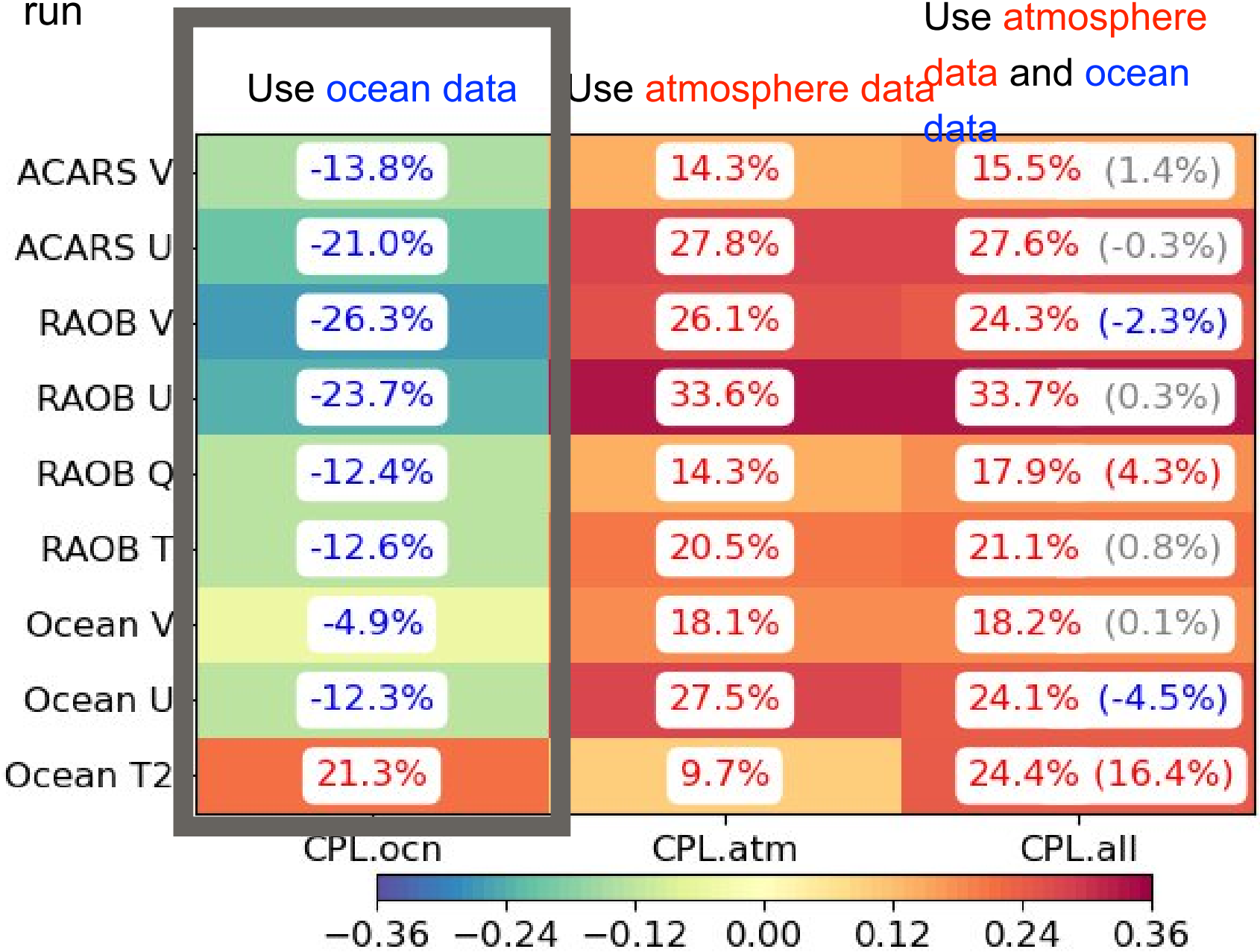


Forecasts are better if both data are used.

CPL.all is not significantly better than CPL.atm.

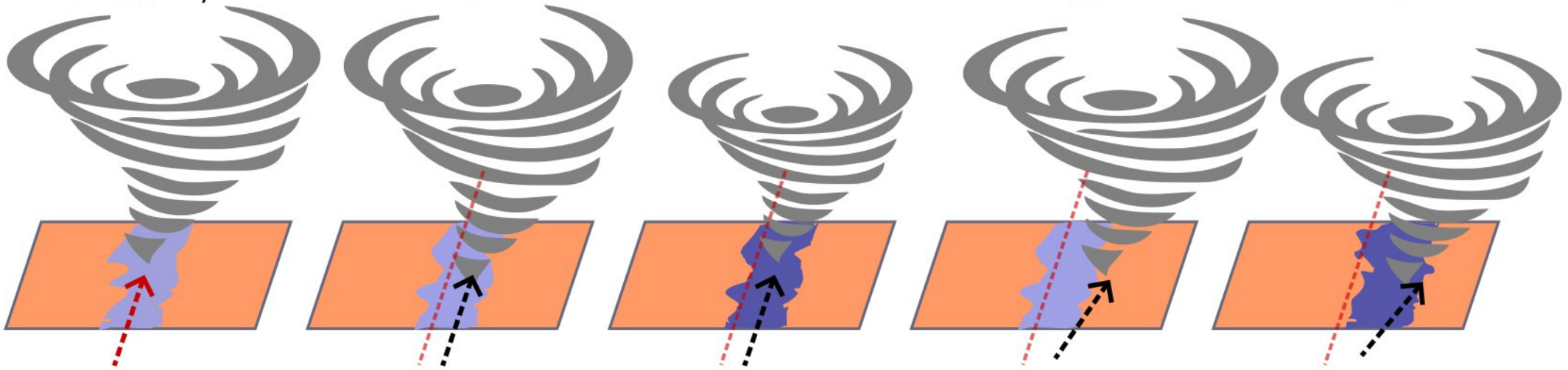
Preliminary results: forecasts of atmospheric states

Brier Skill Scores (BSS) compared with the free run



Forecasts are getting worse when only ocean data are used.

Impact of oceanic data on atmospheric forecasts

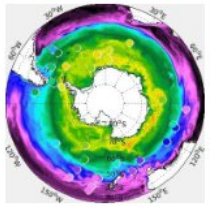


	(a) observation	(b) CPL.all	(c) CPL.atm	(d) CPL.ocn	(e) CPL.free
Initial SST:		30.9 degrees	30.3 degrees	30.9 degrees	30.2 degrees
Forecast SST cooling:		0.45 degrees	0.32 degrees	1.09 degrees	1.02 degrees
SST increments:		+0.01 degrees	N/A	+0.68 degrees	N/A
Heat loss:		147 W/m^2	70 W/m^2	263 W/m^2	218 W/m^2
		Use atmosphere data and ocean data	Use atmosphere data	Use ocean data	No data

Sun et al., Exploring air–sea interactions in a regional weakly coupled data assimilation system: An observing system experiment for the 2023 Indian Ocean monsoon and Cyclone Biparjoy. Submitted to JAMES.

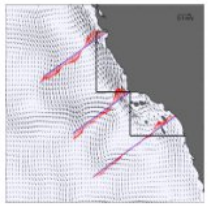
ecco.ucsd.edu

ECCO@Scripps: Our group contributes to the development and production of regional ocean state estimation using the methodology developed by the ECCO consortium (ecco.jpl.nasa.gov). The ECCO code is based on the MIT general circulation model (MITgcm) and employs automatic/algorithmic differentiation (AD) tools for generating tangent linear and adjoint code for ocean circulation and climate studies. The goal is to produce a model-observations synthesis, with consistent dynamics and closed budgets for all tracers, to be used for scientific analysis. We are currently working on:



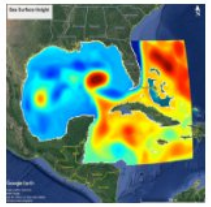
Southern Ocean State Estimate (SOSE)

The latest product, b-SOSE, is a physical-biogeochemical state estimate produced as part of the SOCCOM project.



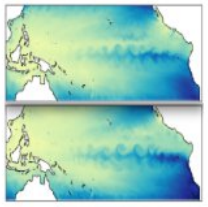
California Current System State Estimate (CASE)

Short- and long-term reanalyses synthesize observations of the California Current System.



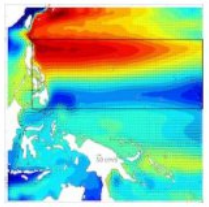
Gulf of Mexico State Estimate (GoM)

Estimation and prediction of the loop current and loop current eddy separation.



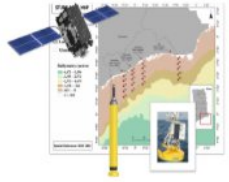
Tropical Pacific Ocean State Estimate (TPOSE)

Observations from the TPOS constrain 4-month state estimates.



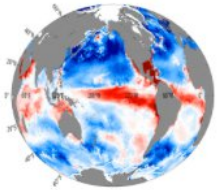
Northwest Pacific State Estimate (NWPac)

State estimation and prediction in the regions of Palau and Northern Philippine Sea.



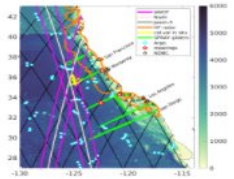
Gulf of Guinea Biogeochemical State Estimate (GG)

A modeling component of Ocean Margins Initiative



Biogeochemical Global Ocean State Estimate (BGOSE)

A quasi-global high resolution model with sea ice and ice shelves



California Current System Submesoscale State Estimate (CASSE)

SWOT data assimilation in a high-resolution coastal model.

At SIO we have been considering regional efforts targeting the mesoscale.

Hypothesis testing: Identifying model error (e.g. internal wave momentum fluxes not represented by KPP in the tropical Pacific)

Forecasting: Identifying timescales of controllability and predictability at ever shorter scales with SWOT (e.g. success assimilating dynamics down to 70 km with 31 day windows)

Observing system experiments: Identifying the value of observations (e.g. value in assimilating ADCP, SWOT, etc)