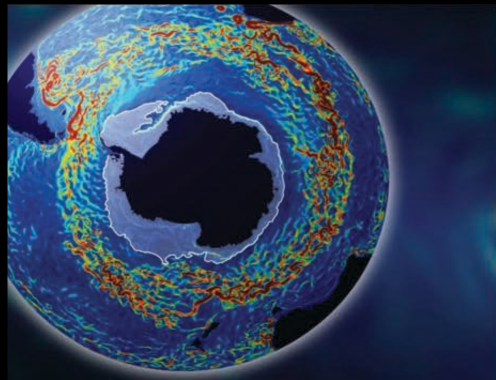


Regional state estimates

ECCO Summer School 2019

Matt Mazloff, Bruce Cornuelle, Ganesh Gopalakrishnan, Heriberto Vazquez Peralta, Ariane Verdy, Kasia Zaba

SCRIPPS INSTITUTION OF OCEANOGRAPHY

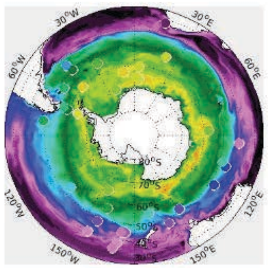
Ocean State Estimation at Scripps

SCRIPPS INSTITUTION OF OCEANOGRAPHY
UC San Diego

http://ecco.ucsd.edu/

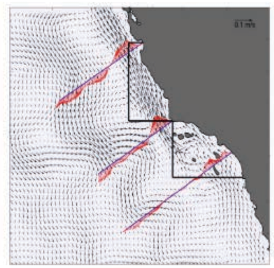
HOME PRODUCTS PEOPLE BIBLIOGRAPHY TERMS OF USE

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:



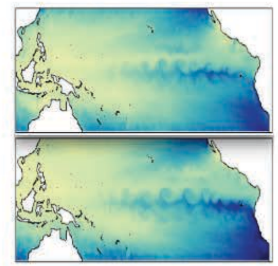
Southern Ocean State Estimate (SOSE)

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.

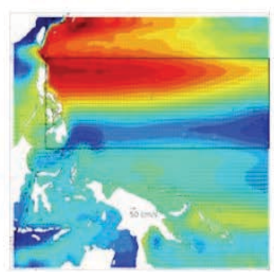


Tropical Pacific Ocean State Estimate (TPOSE)

Observations from the TPOS constrain 4-month state estimates.

Gulf of Mexico State Estimate (GoM)

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

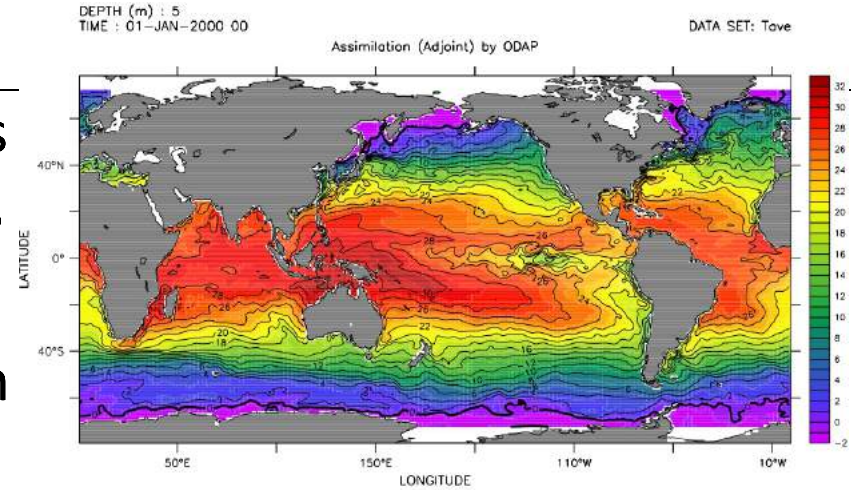


Northwest Pacific State Estimate (NWPac)

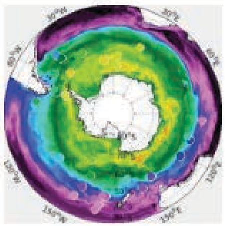
State estimation and prediction in the regions of Palau and Northern Philippine Sea.

ECCO software enables numerous applications

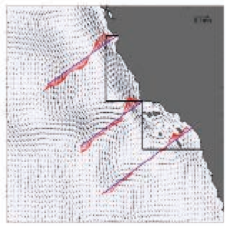
Flagship: 1992 to present production run



Temperature (Deg C)



Southern Ocean State Estimate (SOSE)



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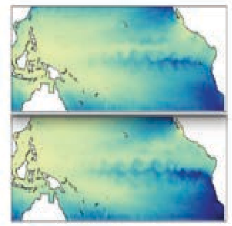
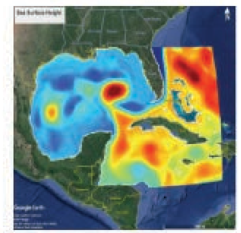
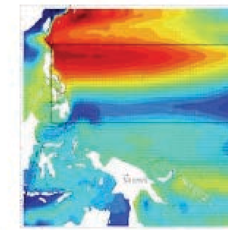


Tropical Pacific Ocean State Estimate (TPOSE)



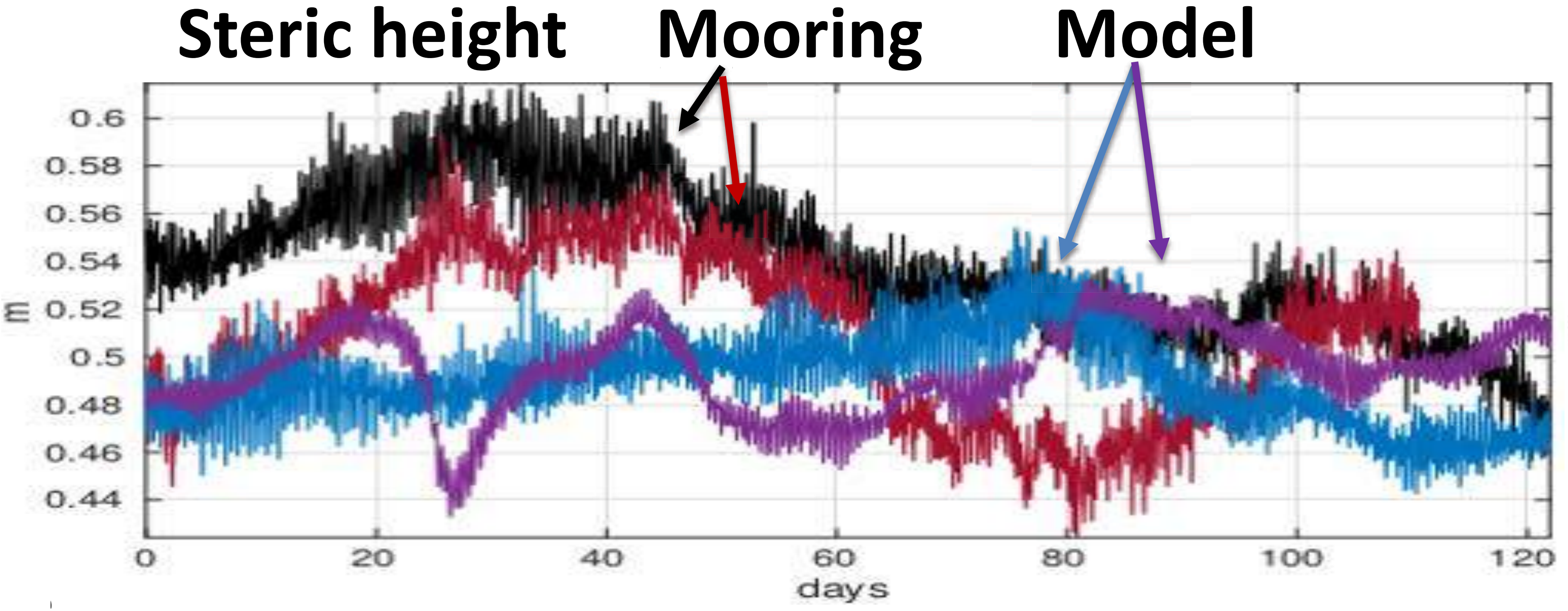
Gulf of Mexico State Estimate (GoM)



Northwest Pacific State Estimate (NWPac)

Targeted efforts can enable

- **Reproducing eddies: currently intrinsic eddies only controllable with initial conditions. Thus need assimilation windows less than ~4 months.**
- Consistency with specific system components (e.g. BGC, internal waves)
- Consistency in specific regions or times, or with specific obs platforms. Here the optimization problem can be framed to prioritize consistency
- Observing system design
- Forecasting: goal of state estimate is to provide forecast initialization



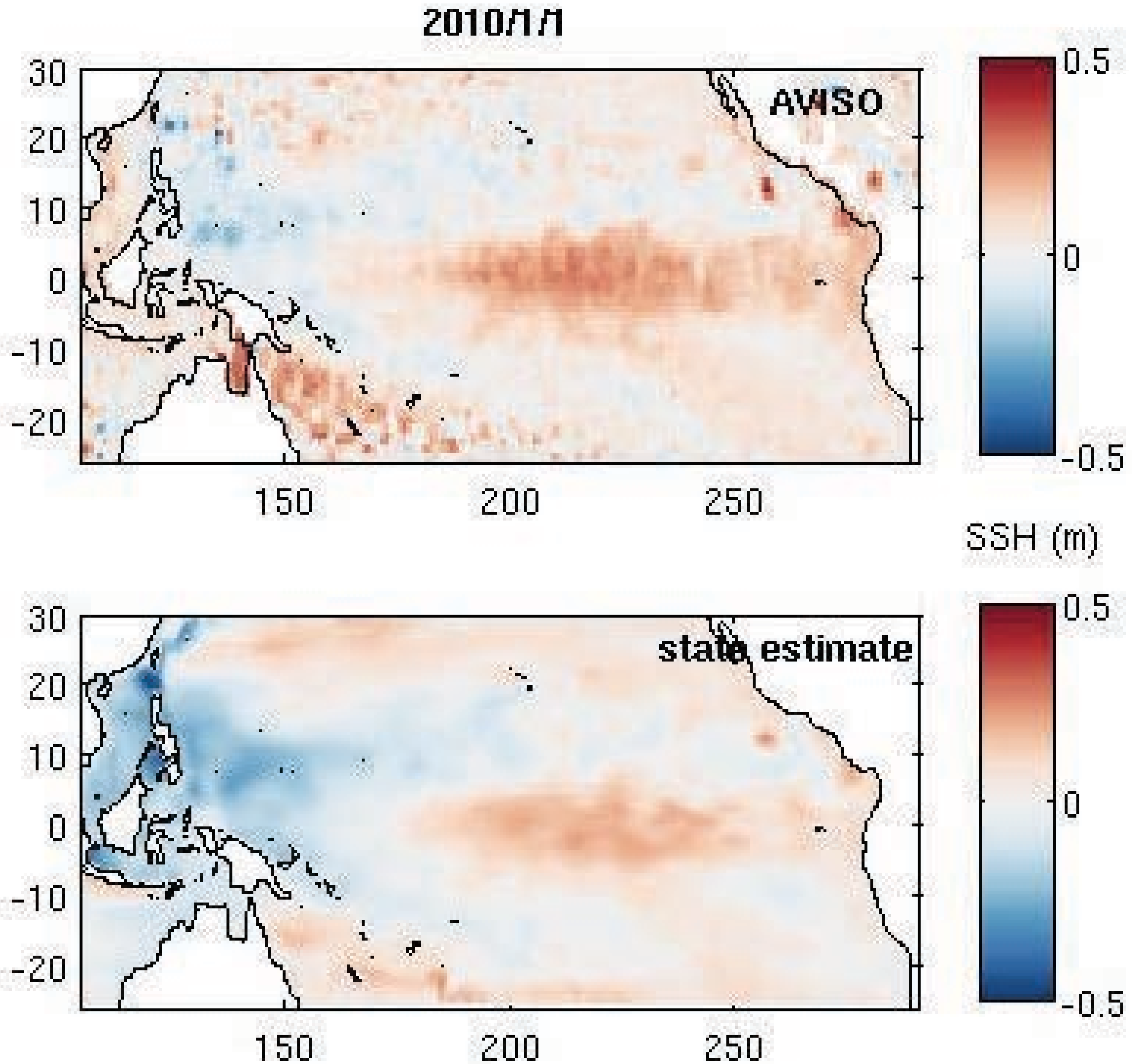
Targeted efforts can enable reproducing eddies

- Mapped products have formal mapping errors and representation error.
- **Formal mapping error** primarily from lack of info: sparse or noisy obs.
- **Representation error** comes from low resolution, missing physics, or errors in the model-data synthesis methodology.
- Mapping methods vary substantially, primarily with regards to how covariance estimates are determined and the level of physics included.
- **Representation error: must choose what scales are signal or noise.**

Tropical Pacific Ocean State Estimate (TPOSE)

A state estimate for **Jan 2010 - Dec 2017+** overlapping 4-month assimilation windows, 1/3° resolution.

Scientific focus on mass and heat budgets.
Also BGC and observing system design.

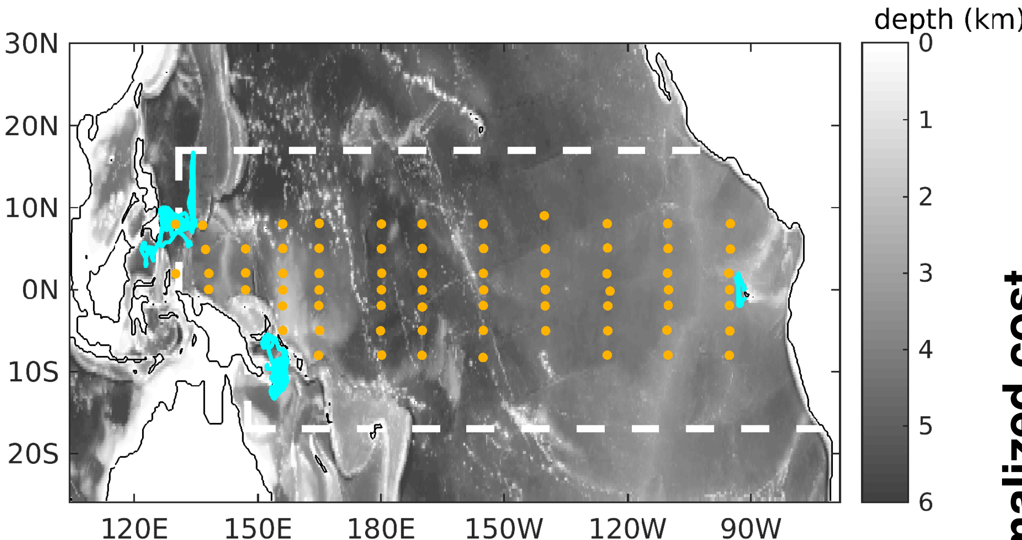


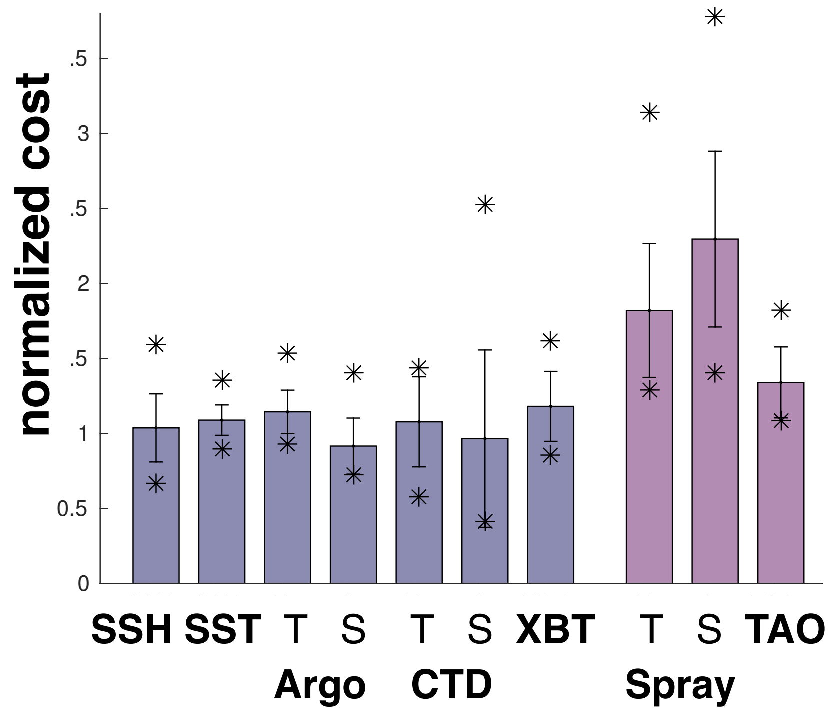
Switching from ERA-interim to ERA-5 reduced cost of initial forward runs

- for 11/13-2/14: SST is reduced by 18%, RADS by 2%, MDT by 4%
- JRA-55 gives similar results for SST & MDT but 5% increase in RADS cost.

Validates both new atmospheric reanalyses and MITgcm in targeted region

Tropical Pacific Ocean State Estimate

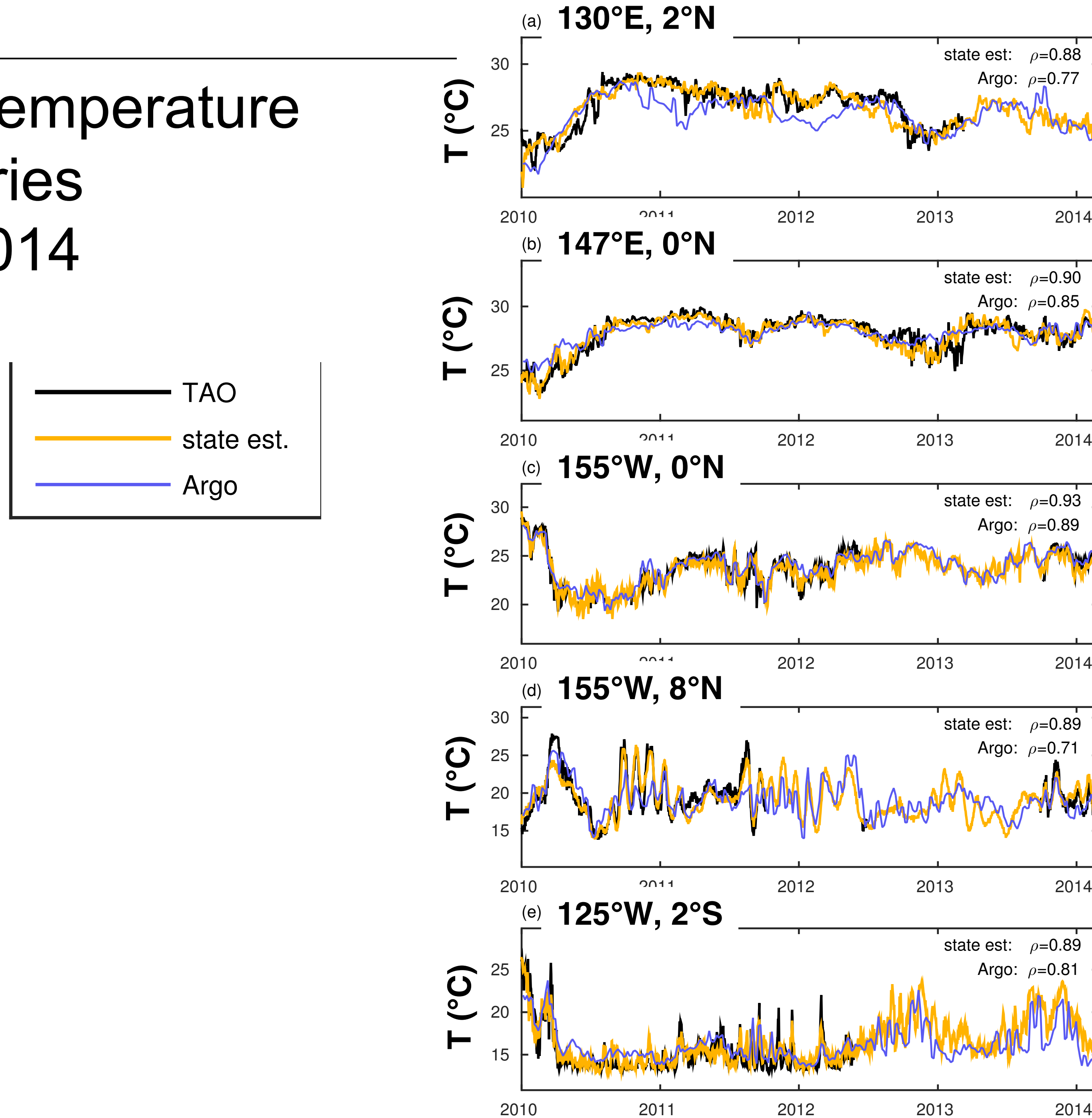




The state estimate has been produced for the period **Jan 2010 to Dec 2017+** with a 4-month assimilation window, 1/3° resolution.

Argo, CTD, XBT, altimetry, and **SST** are used as constraints. **TAO** and **Spray glider** data are used for independent validation.

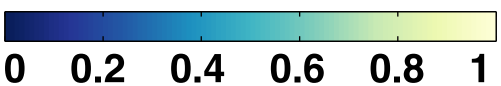
100 m temperature time series 2010-2014



100 m

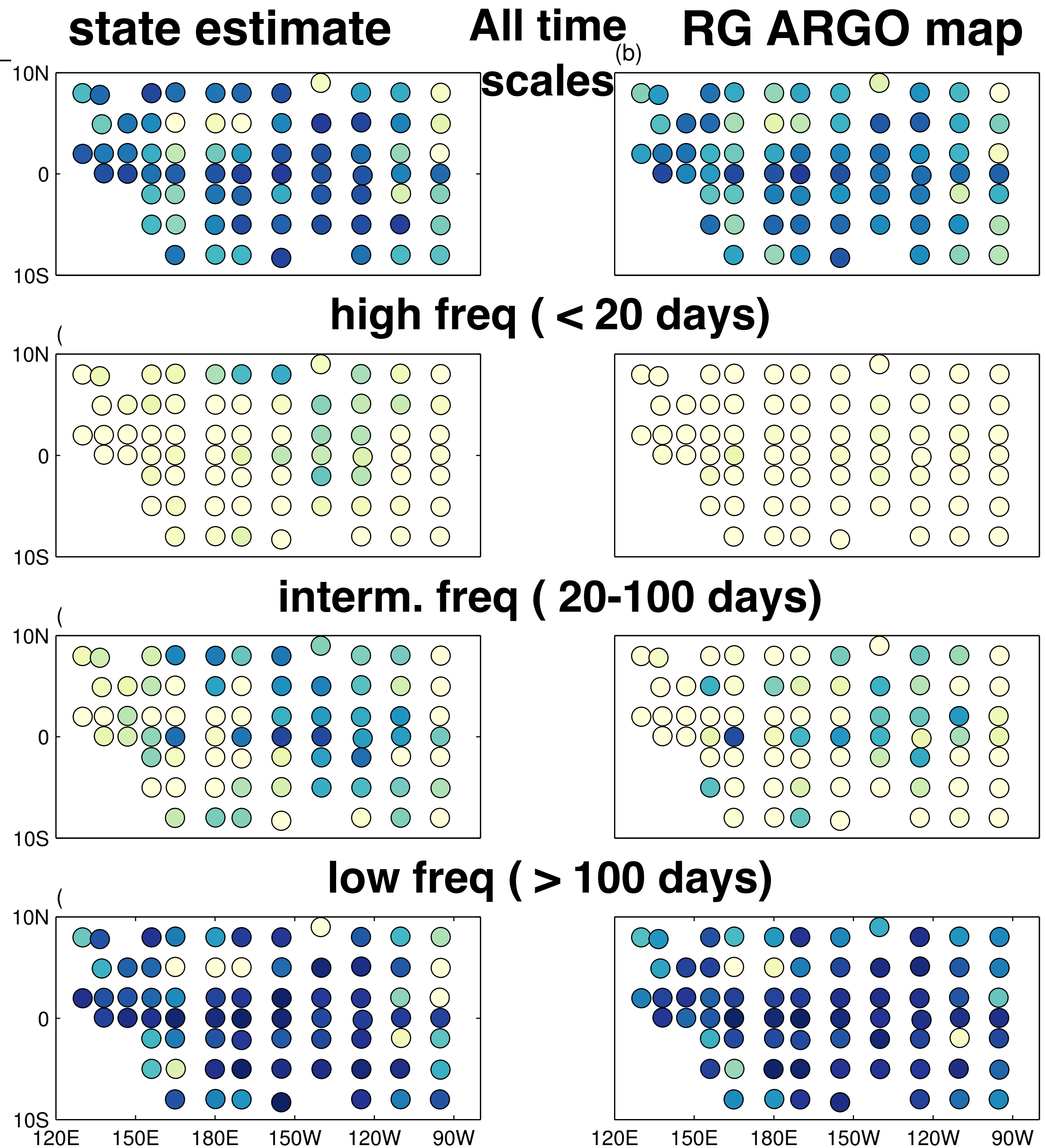
temperature at TAO moorings

fraction of variance error

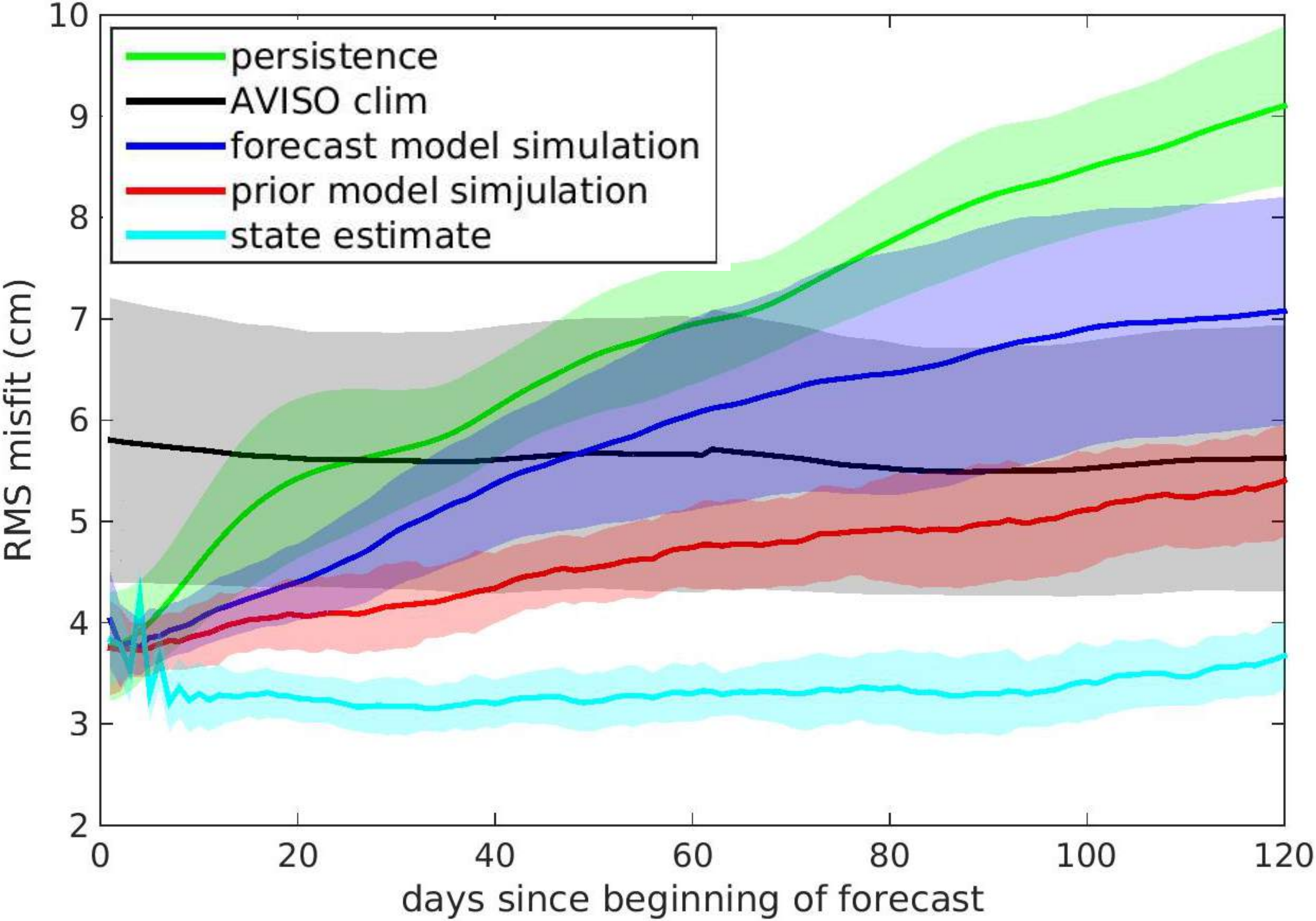


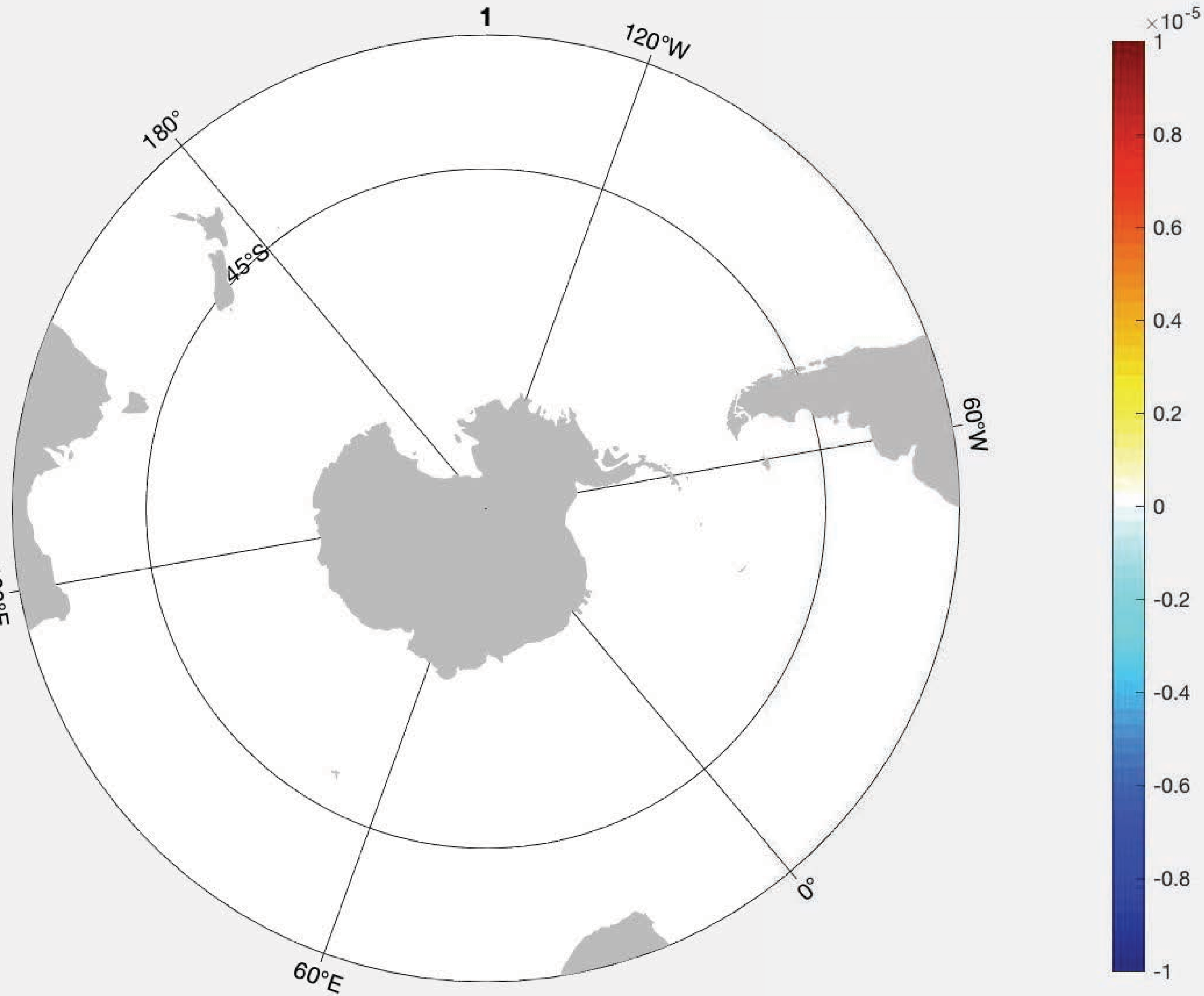
0 (blue) = good
1 (yellow) = bad

State estimation enables reduced model representation error and by propagating high-frequency dynamics with model physics.



TPOSE: forecasting



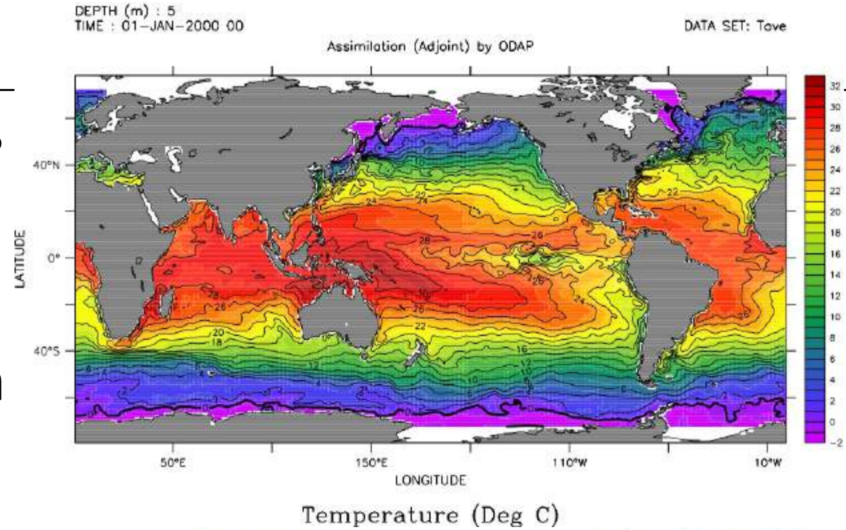

1
120°W
180°
45°S
60°W
120°E
0°
60°E
×10^-5
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1

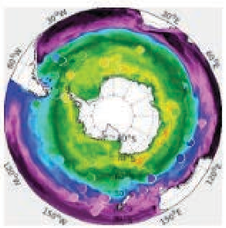
- Other movie here

Estimating the Circulation and Climate of the Ocean
ECCO
National Oceanographic Partnership Program

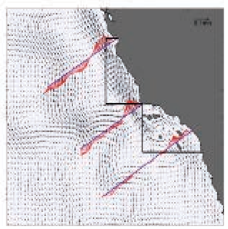
ECCO software enables numerous applications

Flagship: 1992 to present production run

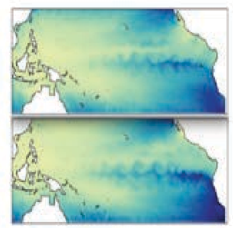




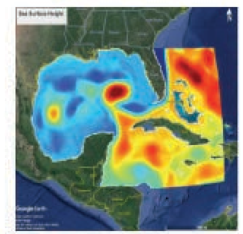
Southern Ocean State Estimate (SOSE)



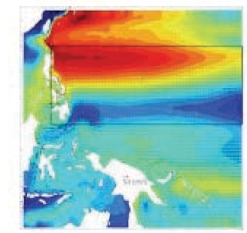
California Current System State Estimate (CASE)



Tropical Pacific Ocean State Estimate (TPOSE)



Gulf of Mexico State Estimate (GoM)



Northwest Pacific State Estimate (NWPac)

Targeted efforts can enable

- Reproducing eddies: currently intrinsic eddies only controllable with initial conditions. Thus need assimilation windows less than ~4 months.
- **Consistency with specific system components (e.g. BGC, internal waves)**
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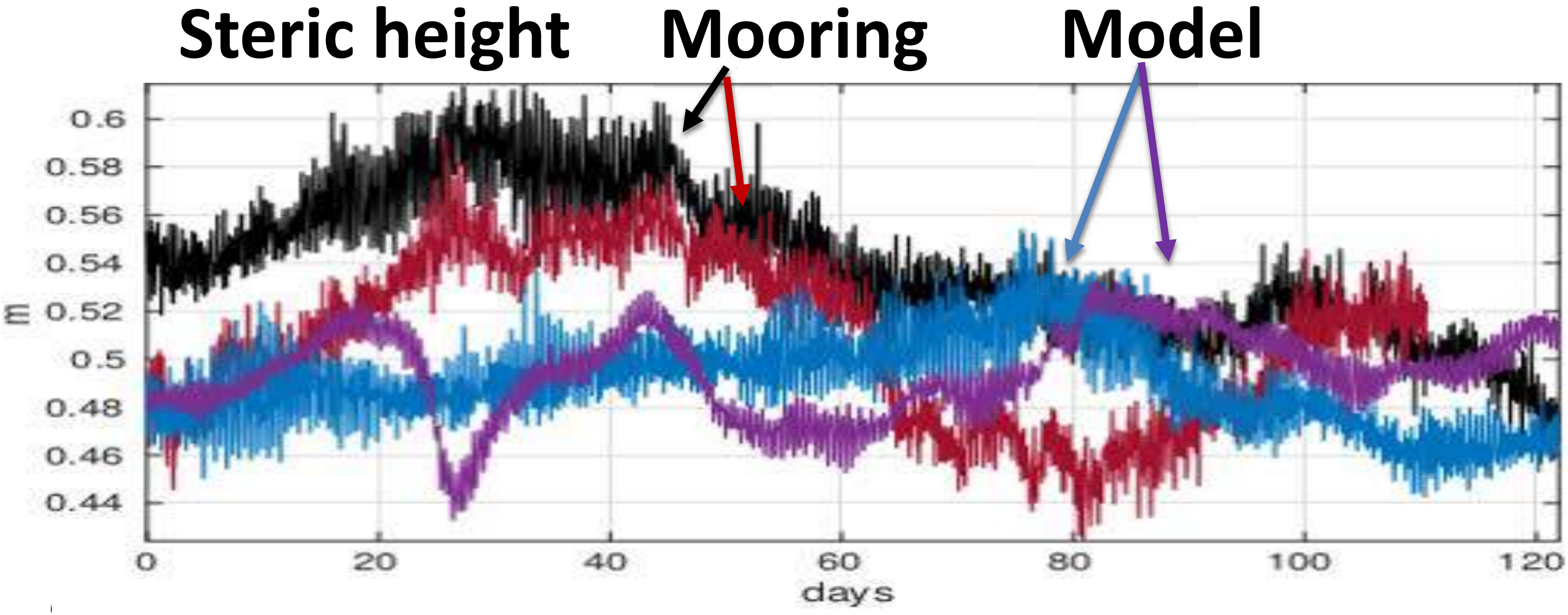


Assimilation window length

- **Shorter windows**
  - **more control** on the solution via optimization of ICs: fits data better
- **Longer windows**
  - More data in your window.
  - Greater manifestation of **model physics** (and model error)

Assessing 4D-VAR for dynamical mapping of coastal high-frequency radar in San Diego

I. Hoteit, B. Cornuelle, S.Y. Kim, G. Forget, A. Köhl, E. Terrill

Dynamics of Atmospheres and Oceans, 2009

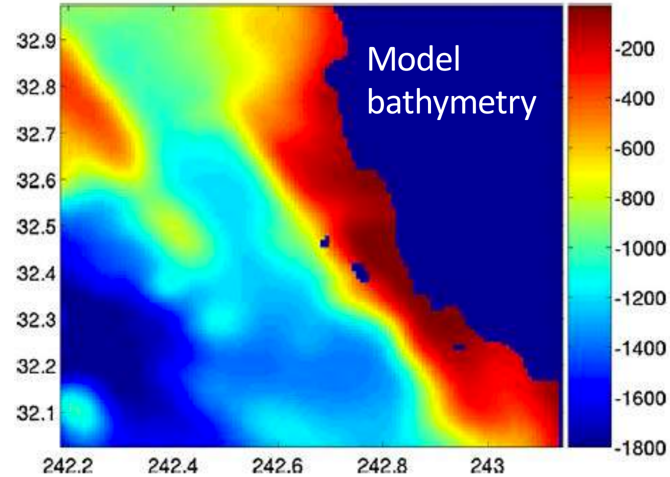
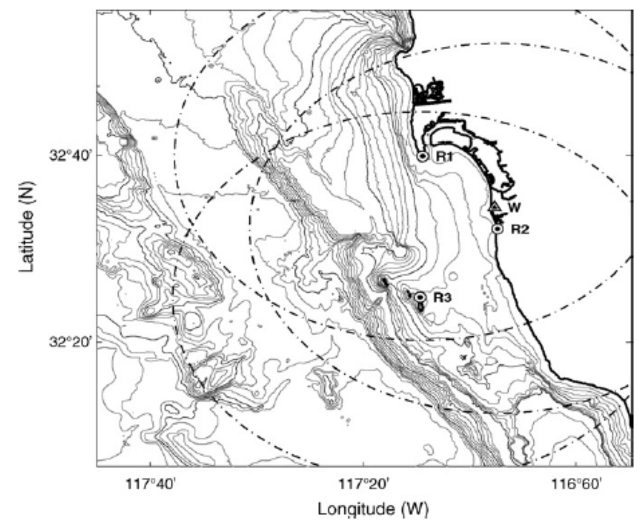


Fig. 2. Bathymetry of the model domain (m).



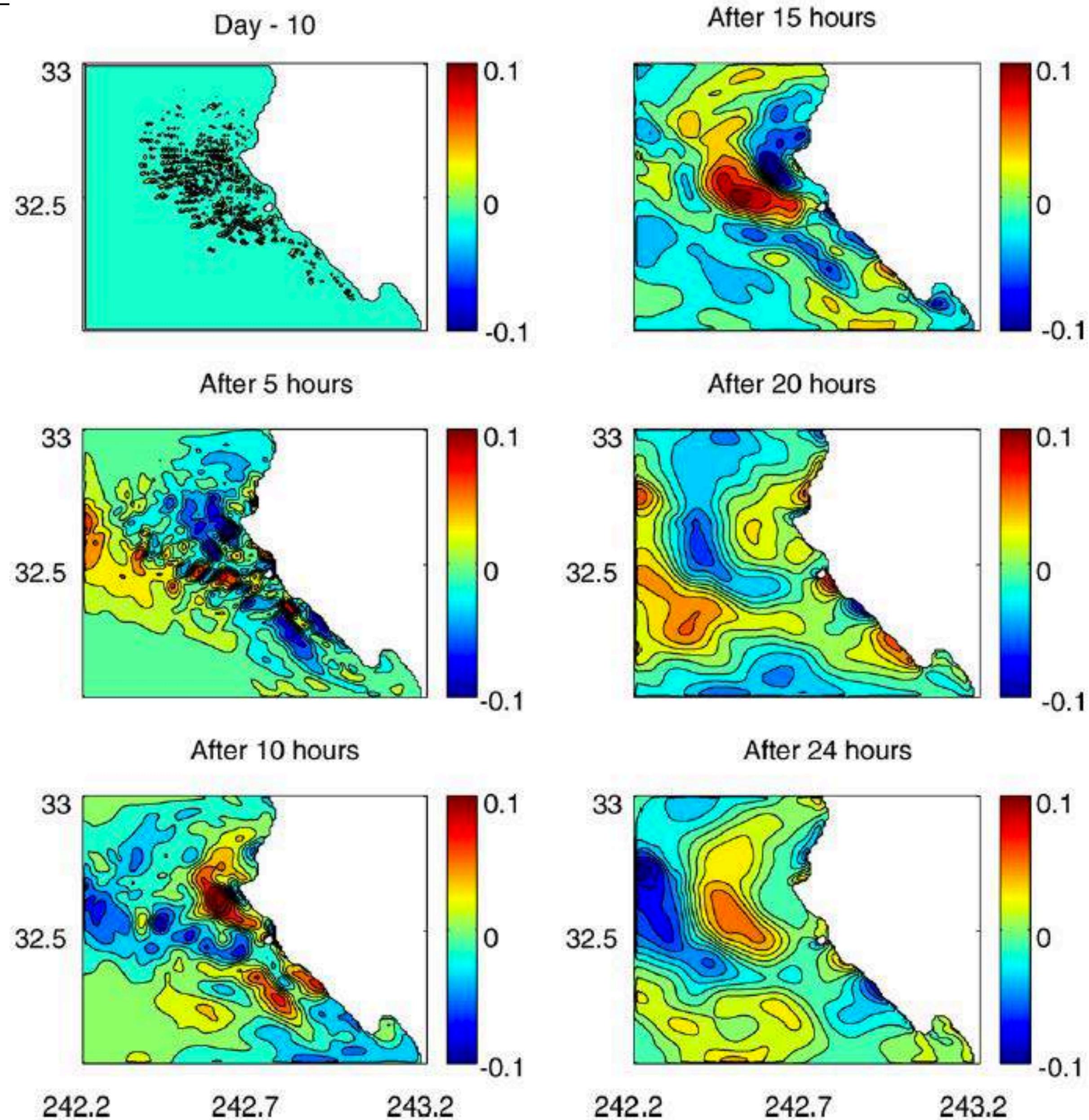
- MITgcm. 1 km resolution. 40 vertical layers.
- Initialized from single profile and forced by single shore station.
- Solve for ICs, open BCs of T, S, U, V, and surface fluxes to fit HF radar velocity observations

Results:

- The adjoint method can successfully be used in this setup over 10-day windows
- State estimates produced that are dynamically consistent and consistent with HF radar
- Forecast skill exceeds persistence for 20 hours

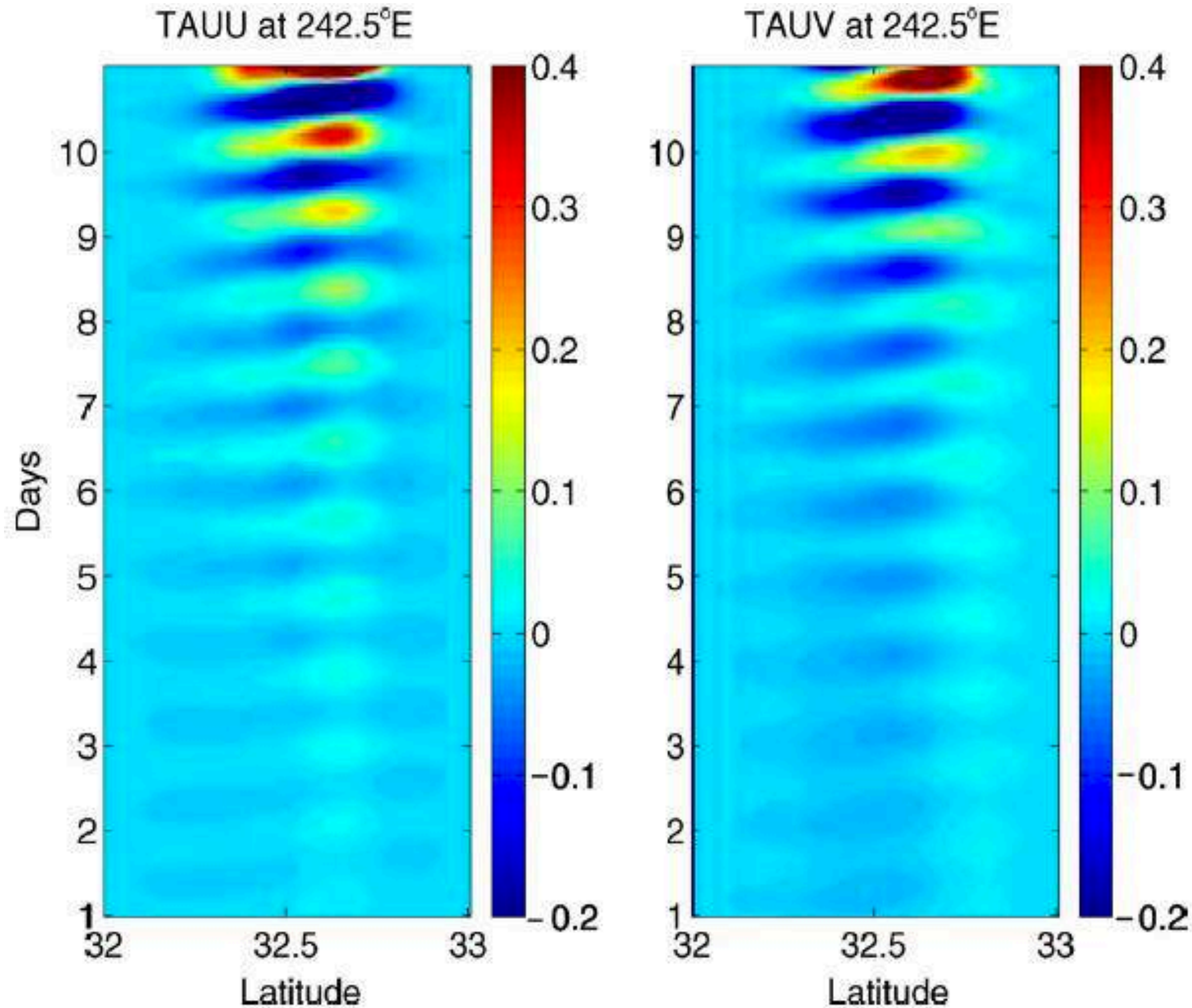
Sensitivity of misfit at end of assimilation window to temperature at 250 m =>

Sensitivity to state occurs immediately and over entire water column. Fit is sensitive to internal waves, Rossby waves, and topographically trapped waves

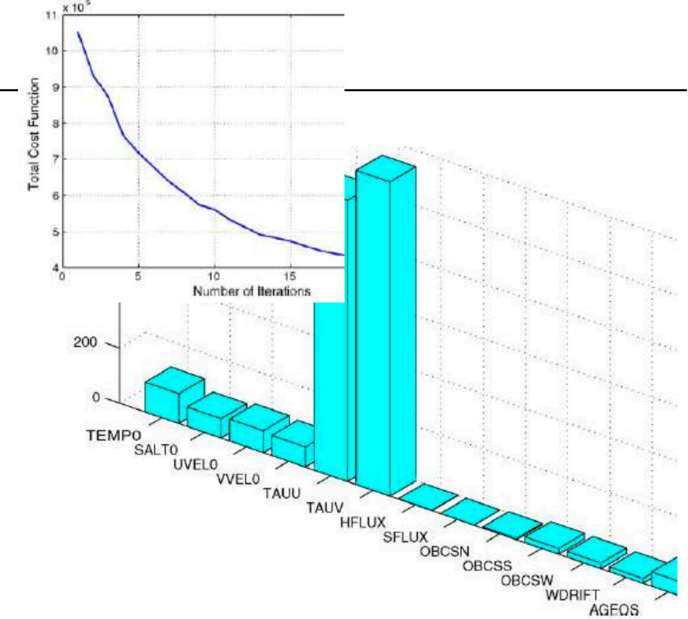


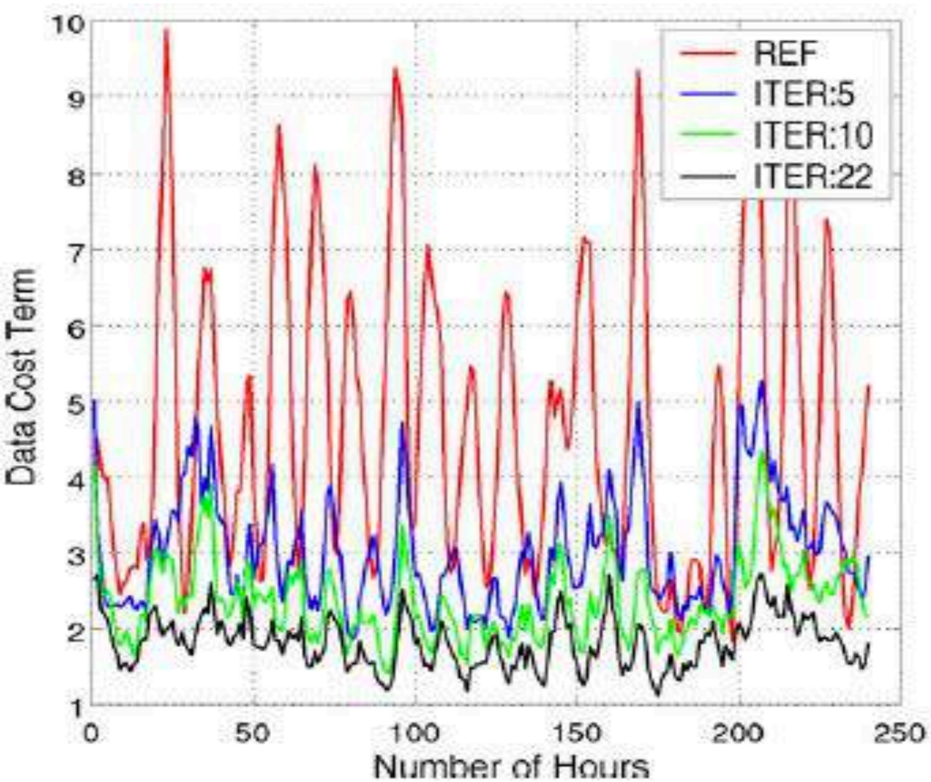
Sensitivity of misfit at end of assimilation window to wind stress at 242.5^{o}E =>

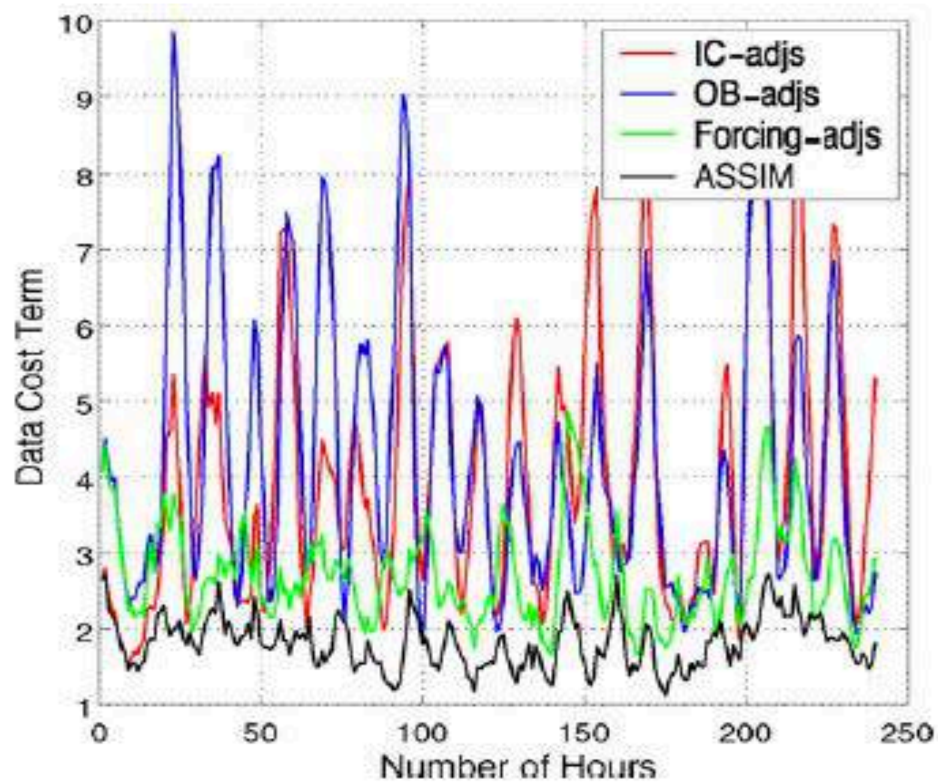
Sensitivity to wind stress dominated by inertial waves (period ~22.3 hours at 32.5^{o}N), and damps after a few days.



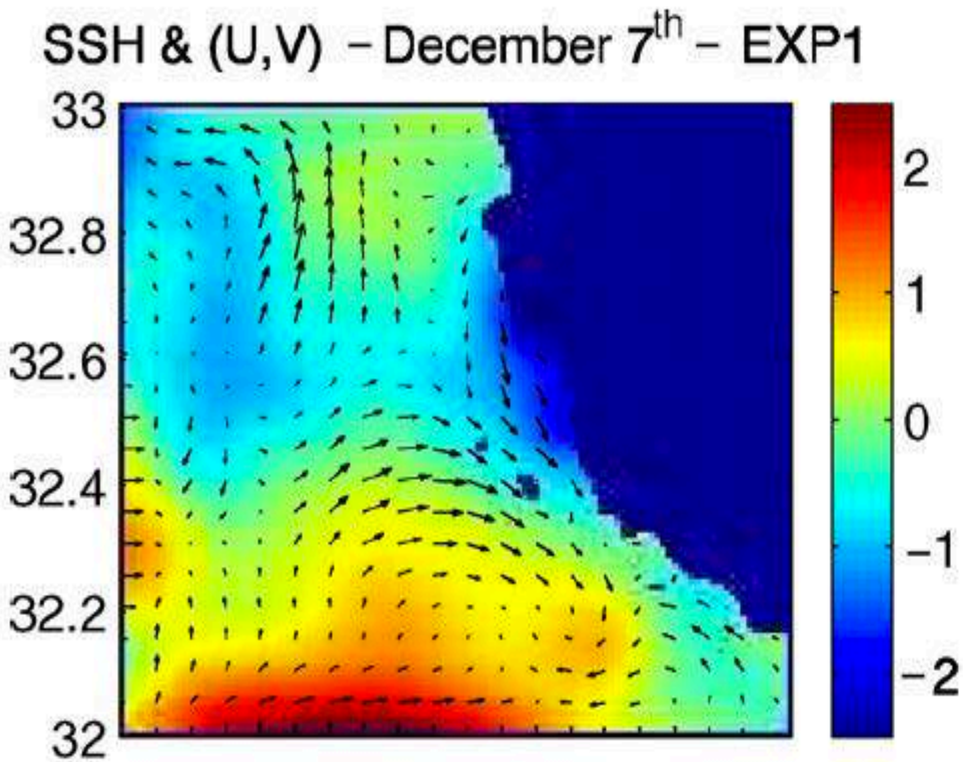
- Misfit reduction efficient. System is controllable
- Optimization brings misfit to about 6 cm s^{-1}
- Initial model error variance shows strong peaks near the semi-diurnal period.
- **IC controls matter for ~18 hours.** Then mostly wind stress, but fluxes and OBCs do contribute

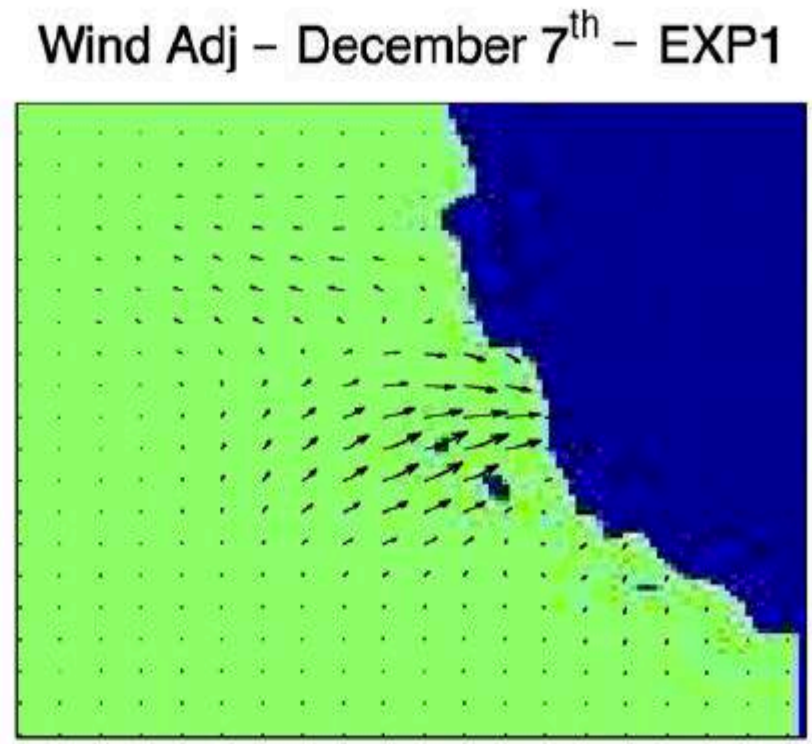






SSH (cm) and sea surface velocities (cm s^{-1}) Wind stress adjustments





Solution on 7 December 2003 for window starting on 1 December 2003

- The assimilation was able to solve for a dynamically consistent solution.
- SSH signal is +/- 2 cm!

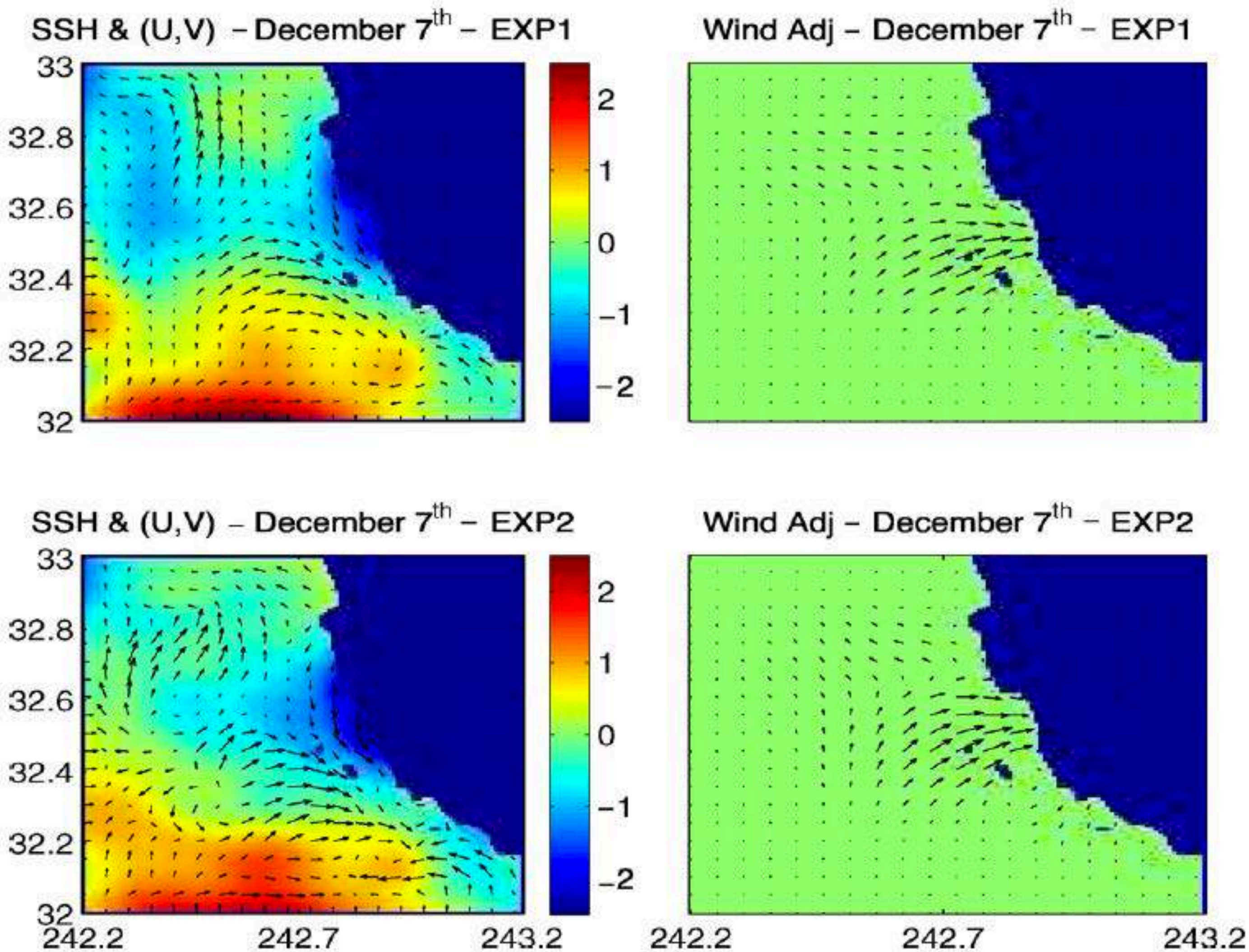
Solution on 7 December 2003

Top: assimilation starting 1 Dec. 2003

(i.e. state 6 days from IC)

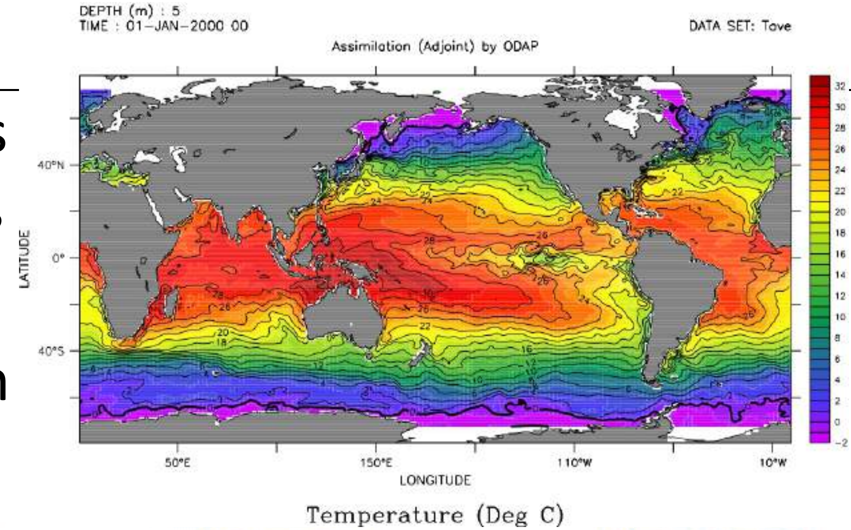
Bottom: assimilation starting 6 Dec. 2003

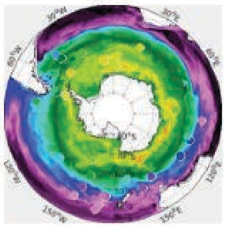
(i.e. state is 1 day from IC)



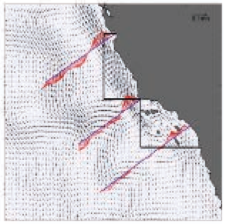
ECCO software enables numerous applications

Flagship: 1992 to present production run





Southern Ocean State Estimate (SOSE)



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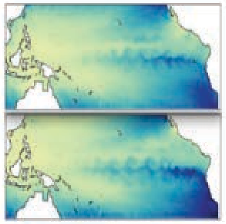

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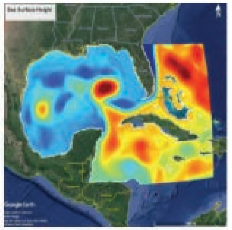
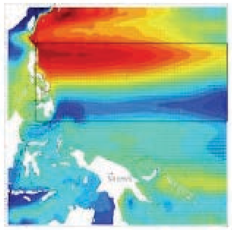


Gulf of Mexico State Estimate (GoM)



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- Forecasting: goal of state estimate is to provide forecast initialization

Gulf of Mexico

Goals

- State estimation and prediction of the loop current and its separation
- Synthesize deep gulf observations 2009-2011 to facilitate understanding of deep circulation and topographic interaction

Setup

- $1/20^{\circ}$ (~5km) in the deep gulf telescoping to $1/10^{\circ}$ near the boundary
- 80 vertical levels (~2.5m near surface)
- NCEP1 atmospheric state. Monthly runoff climatology
- HYCOM+NCODA global $1/12^{\circ}$ analysis initial and boundary conditions
- Controls: atmospheric state. U,V,T,S initial and open boundary conditions
- 1 to 2 month assimilation window

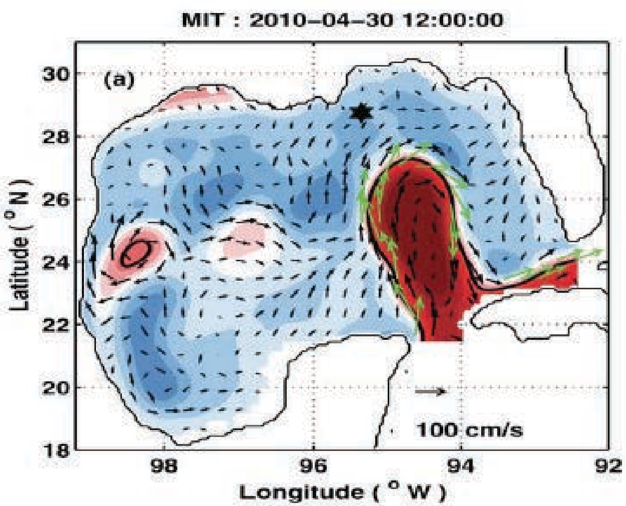
Forecasting the loop current

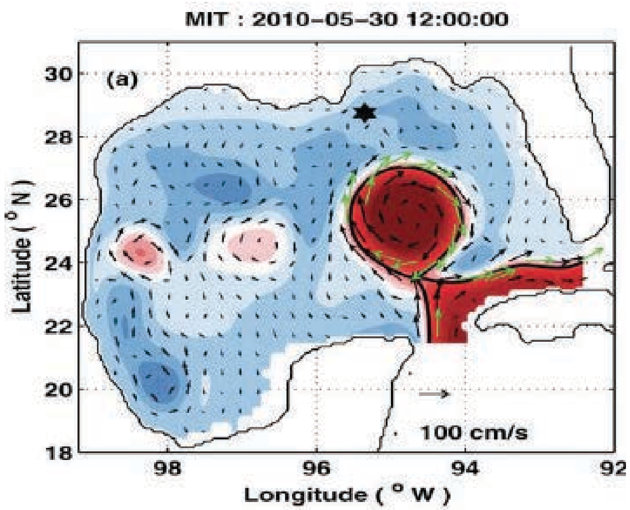
Gopalakrishnan et al 2013

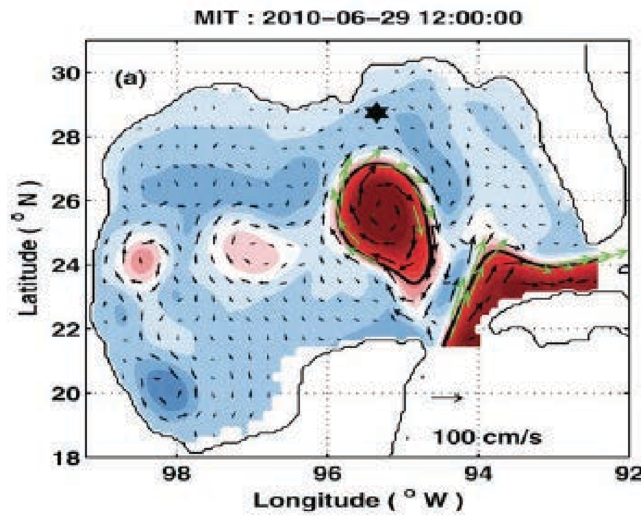
End of 2 month state estimate

Forecast at 1 month

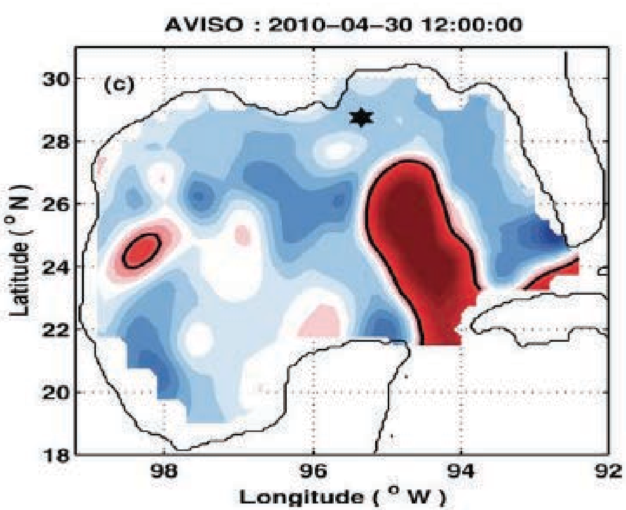
Forecast at 2 months

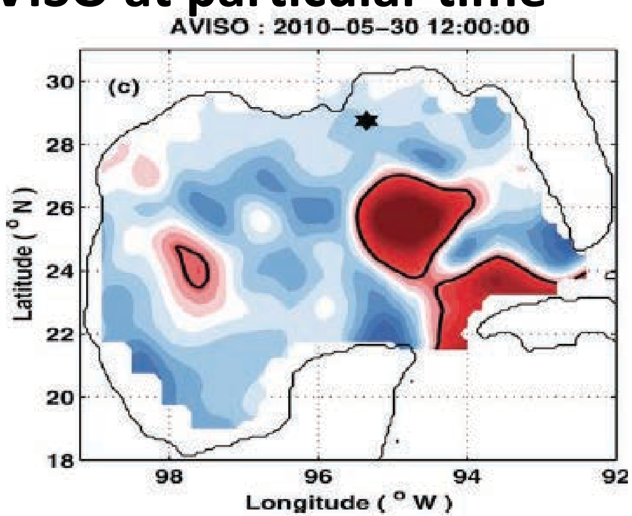


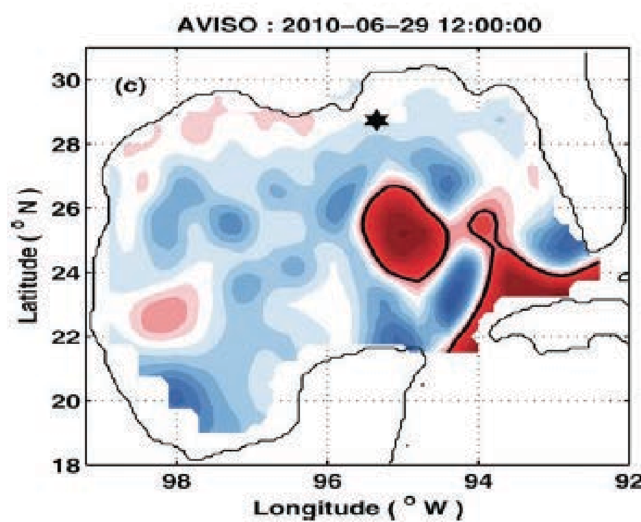




AVISO at particular time







SSH r.m.s. difference with AVISO

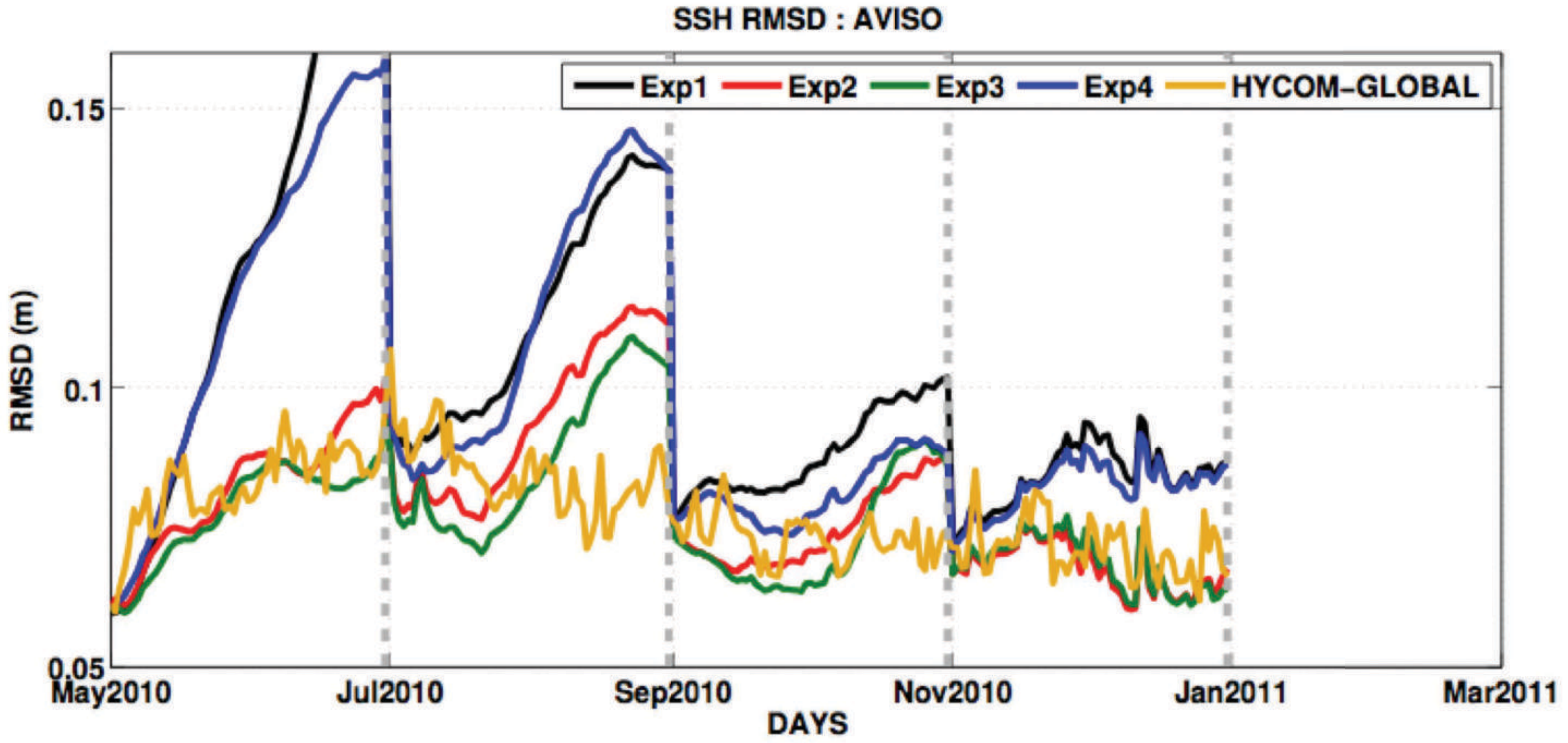
Ref. no assimilation

Assimilation only satellite

Assimilation only mooring

Assimilation both

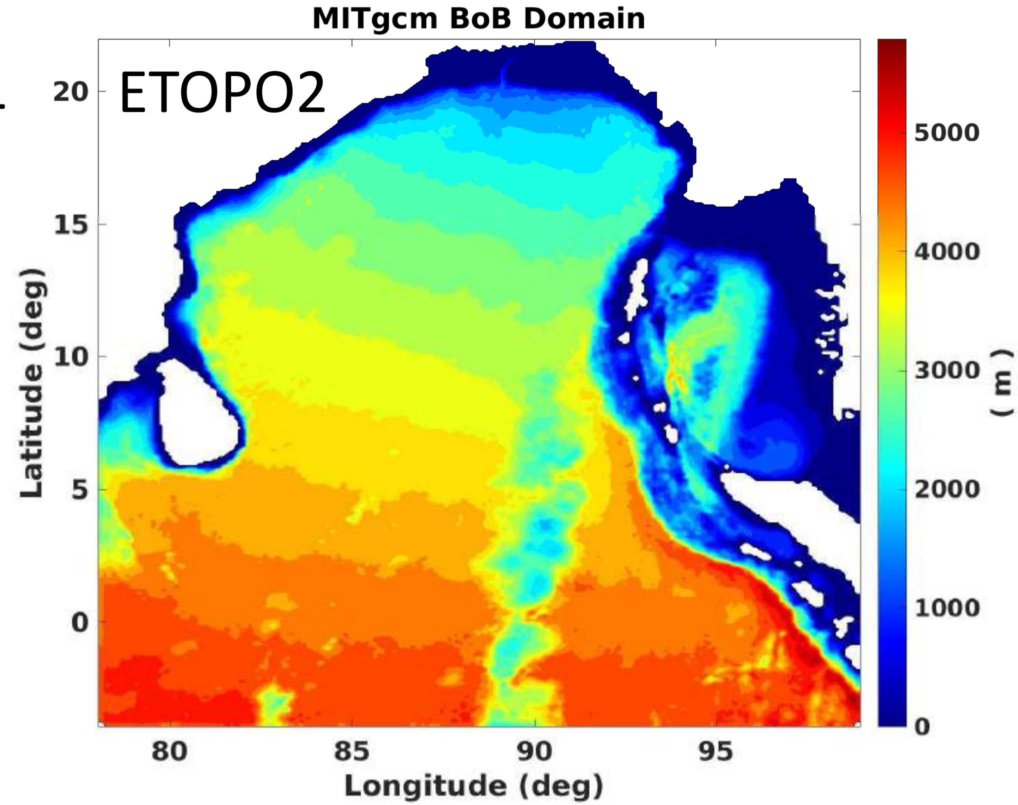
HYCOM



Bay of Bengal

Goals

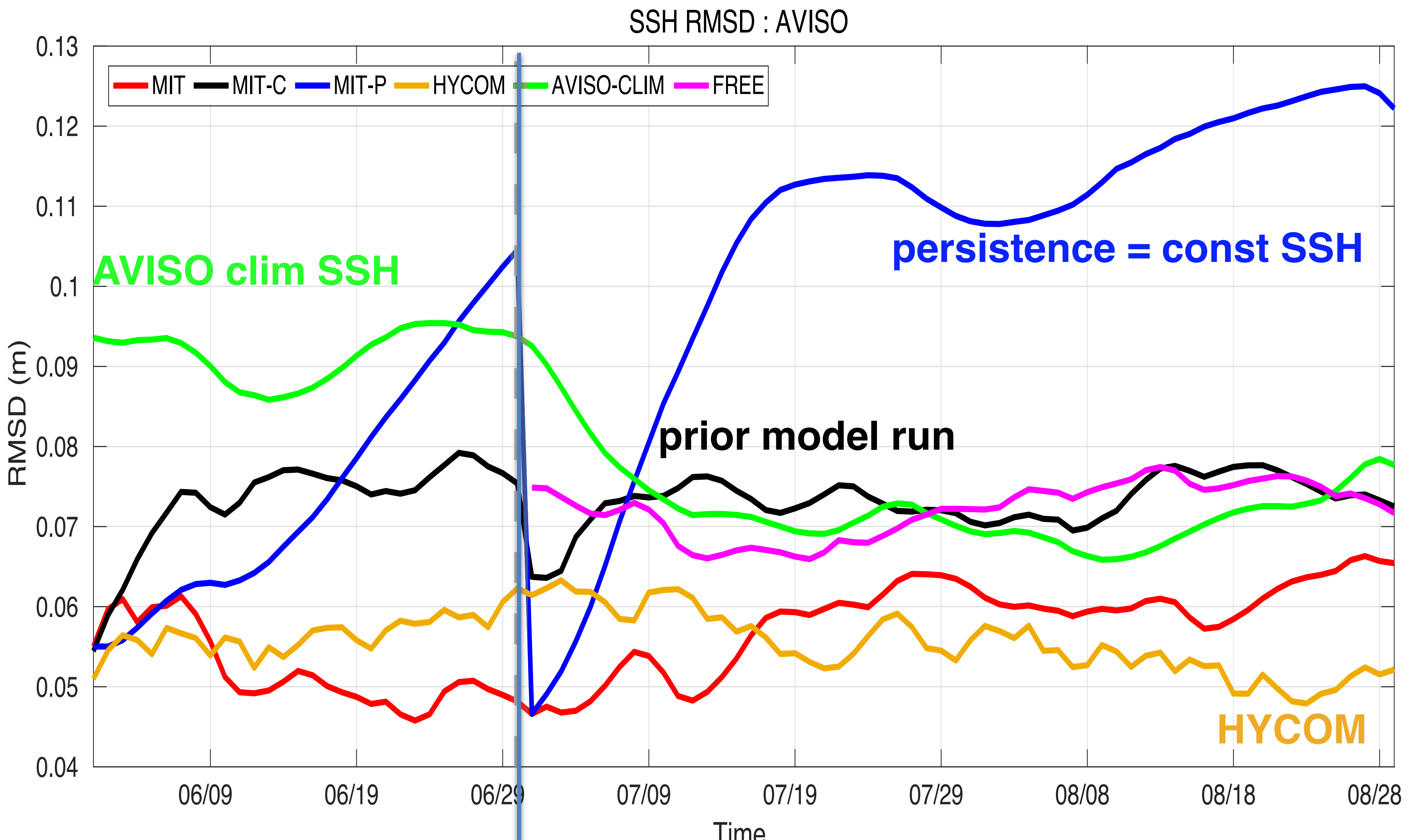
- Determine predictability of SST
- Determine atmospheric-ocean coupling, and SST feedback on the atmospheric state
- Understanding and prediction of the monsoon rainfall



Setup

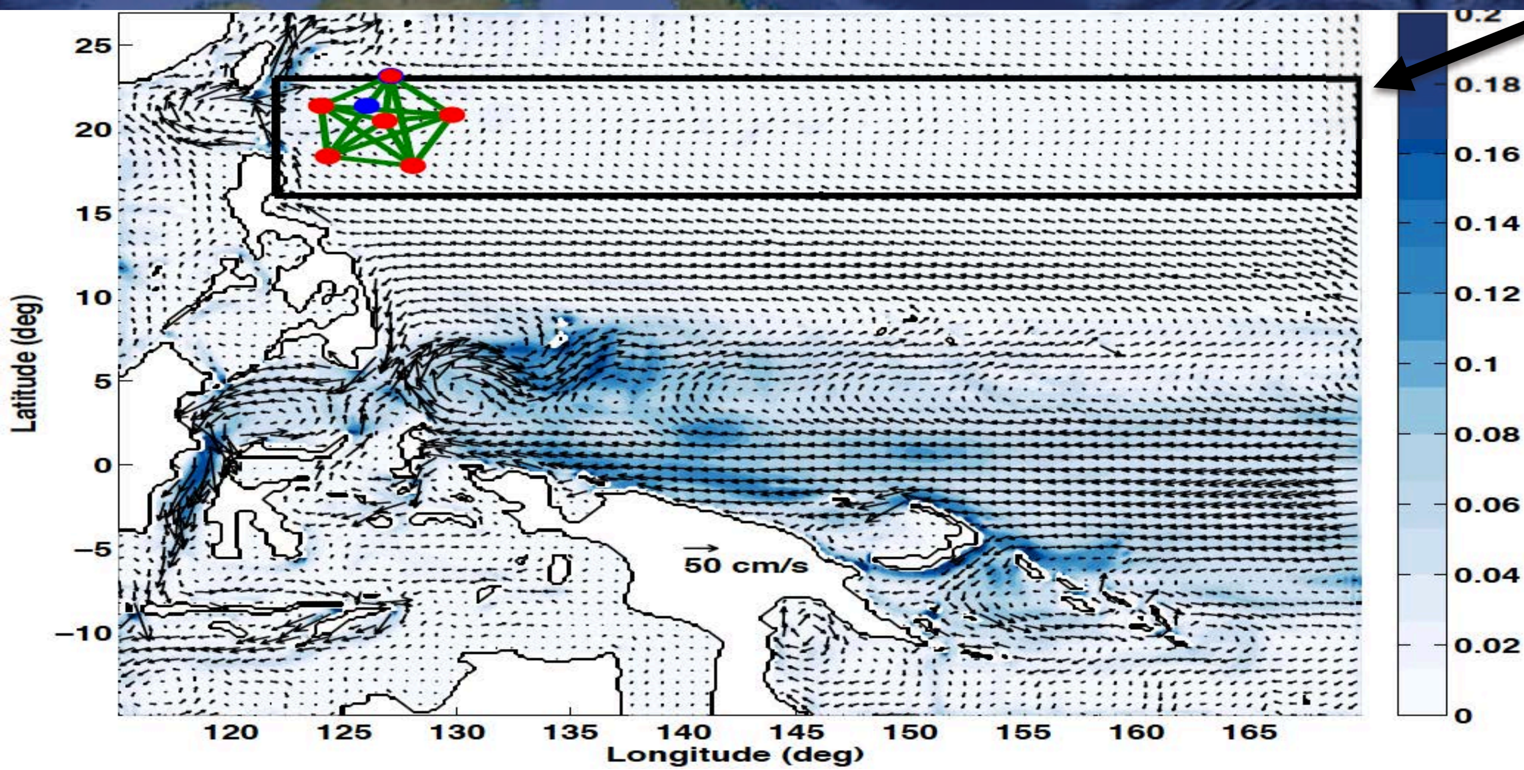
- 1/12° (~8km) with 50 vertical levels (~2.5m near surface)
- JRA-55 atmospheric state. Monthly runoff climatology
- HYCOM+NCODA global 1/12° analysis initial and boundary conditions
- Controls: atmospheric state. U,V,T,S initial and open boundary conditions
- 1 to 2 month assimilation window

SSH *rmsd* for June - August 2016



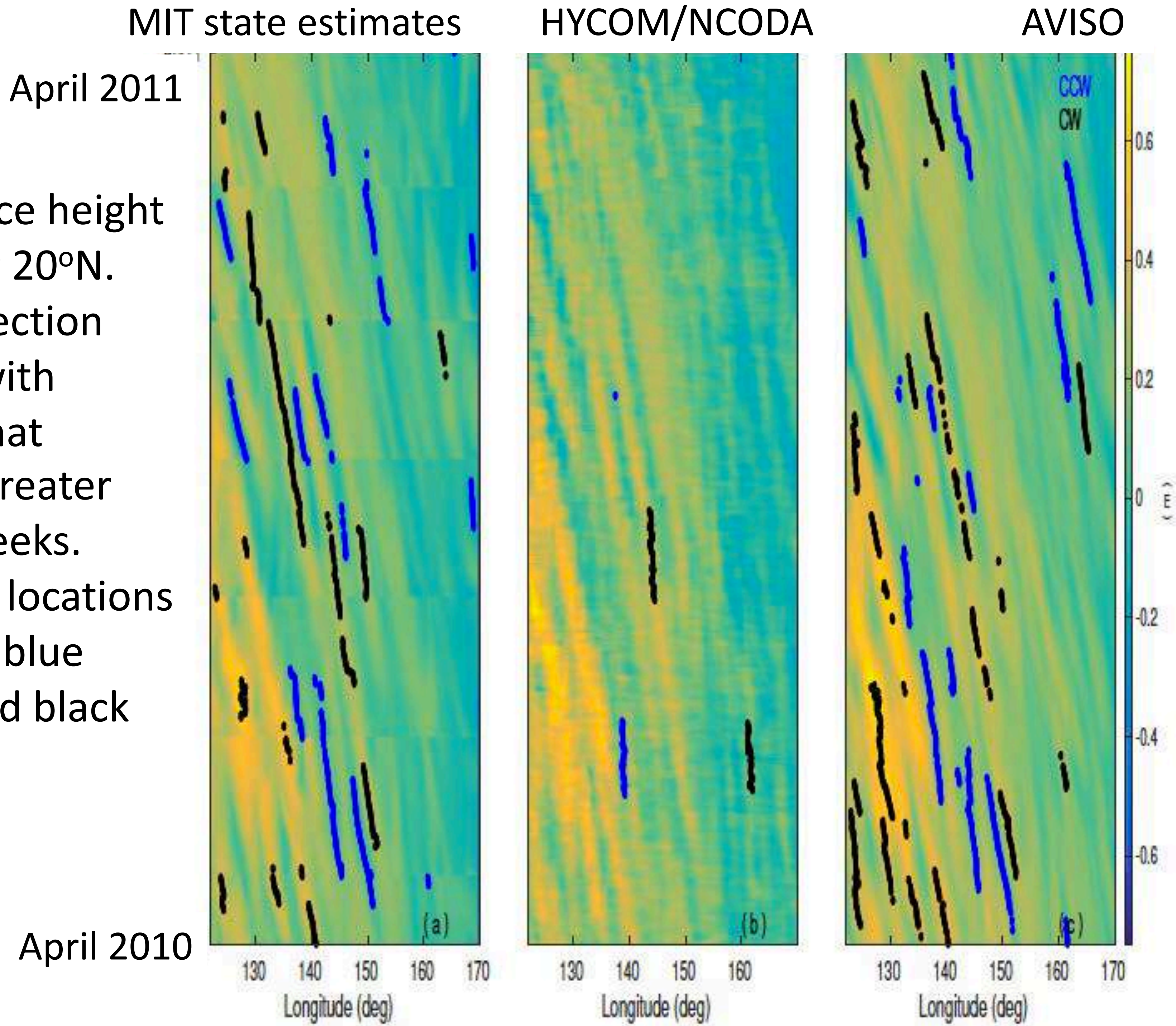
state estimate for June and then forecast for July & August

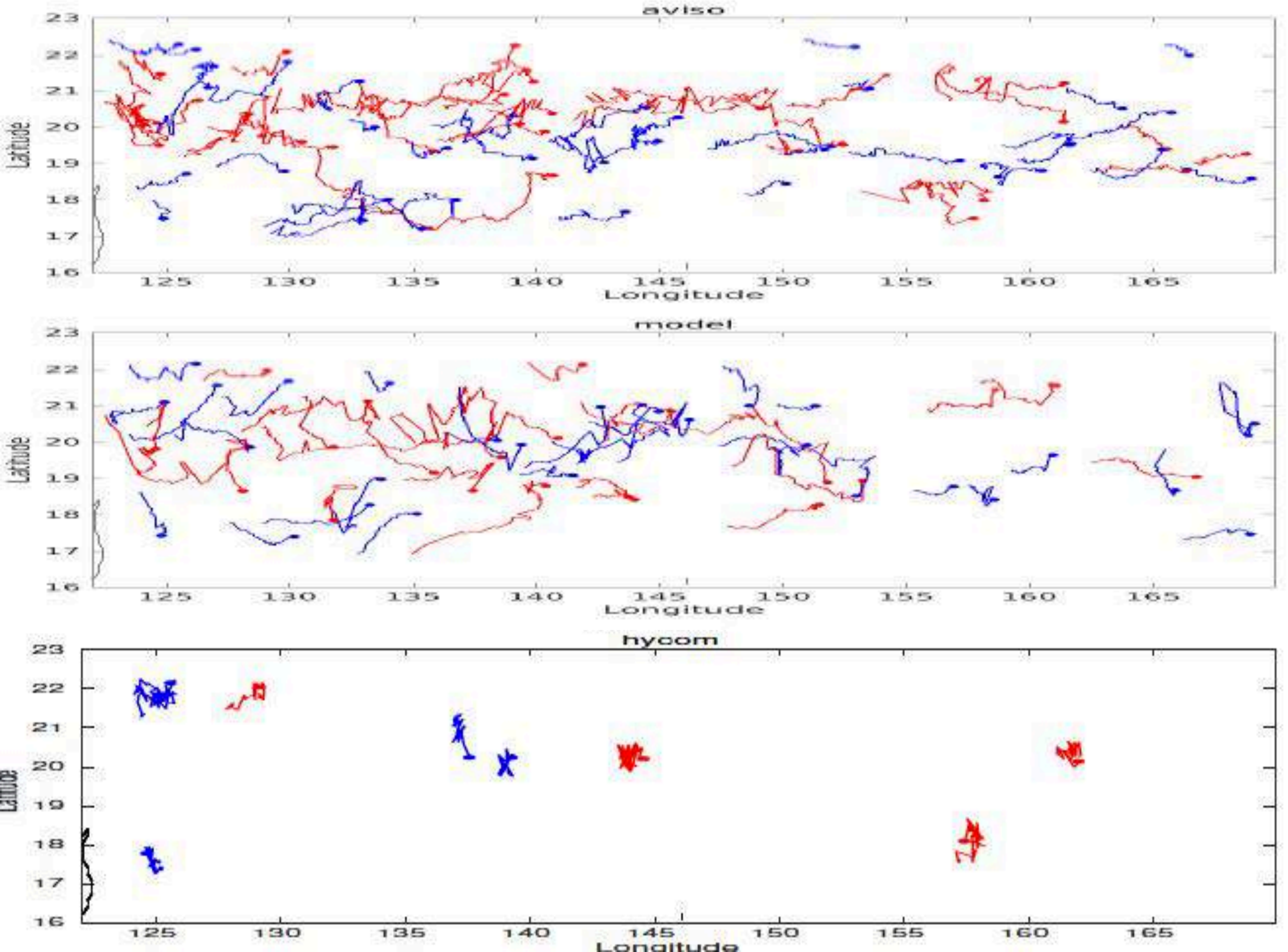
Philippine Sea State Estimate

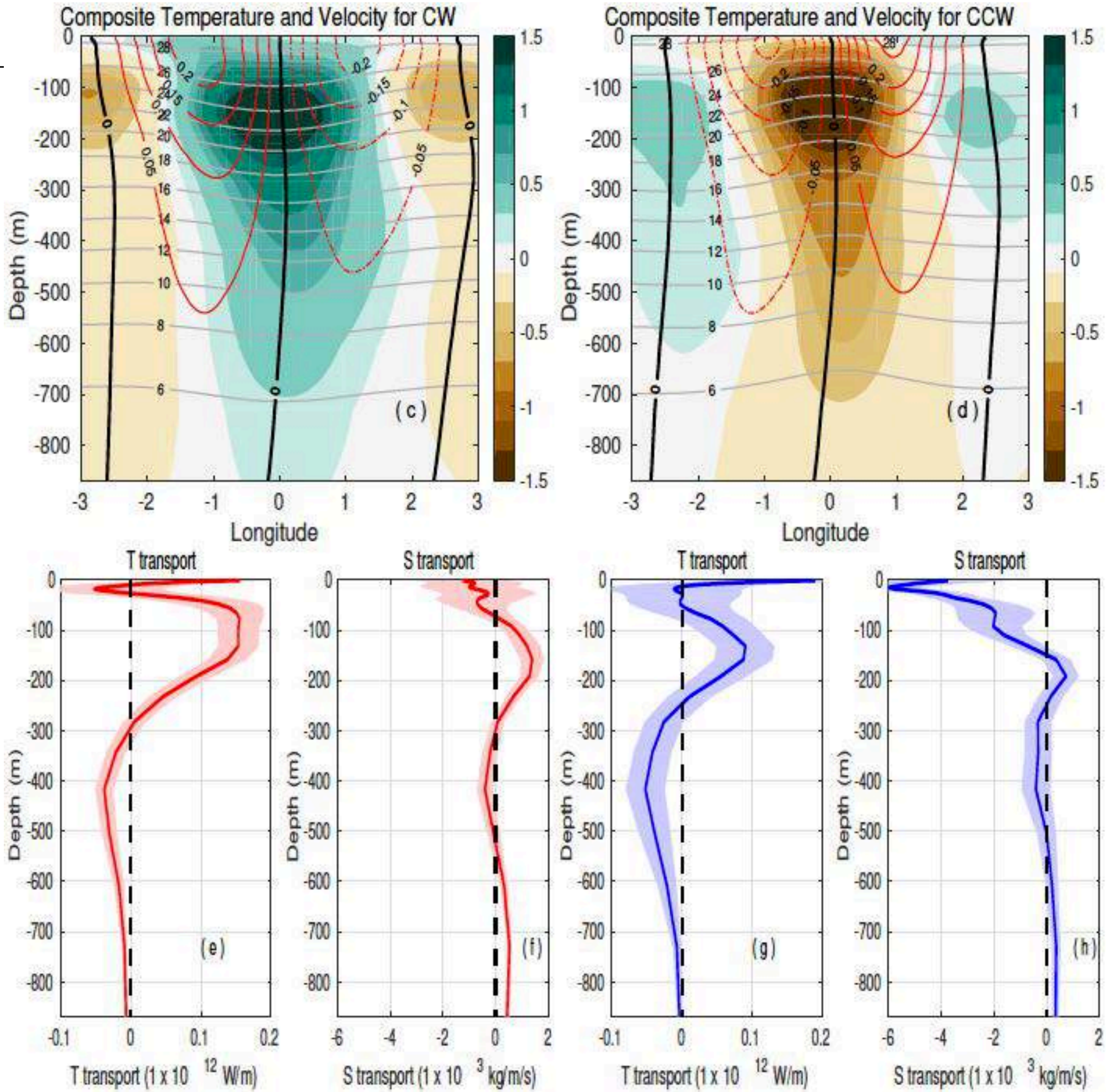


Eddies drive transport across box. Nonlinear dynamics dominate, but eddies persist for many months. Can we estimate eddy fluxes?

Sea surface height (m) along 20ºN. Eddy detection applied with criteria that lifetime greater than 4 weeks. The eddy locations shown in blue (CCW) and black (CW)




aviso
model
hycom
Latitude
Longitude

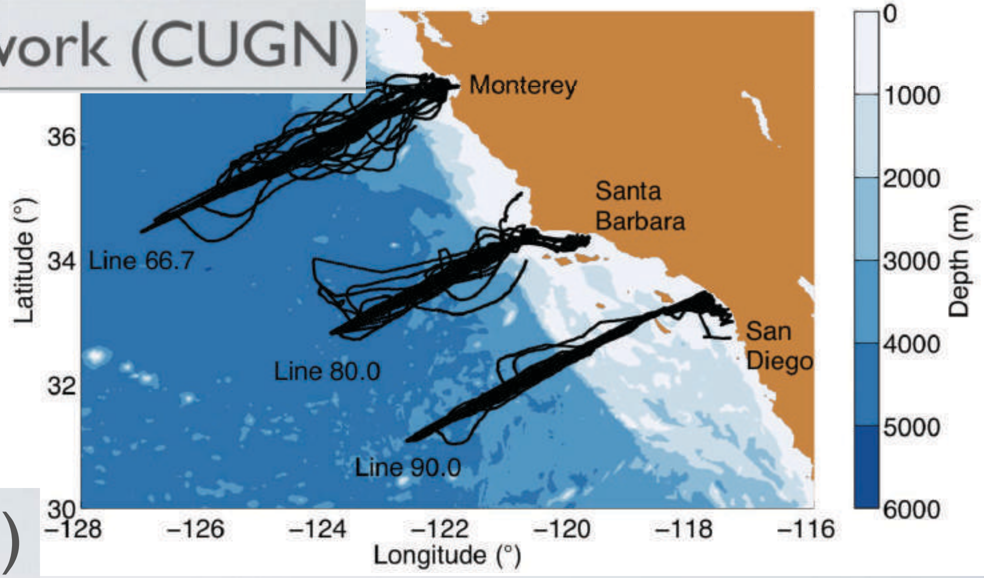


Composite Temperature and Velocity for CW
Composite Temperature and Velocity for CCW
Depth (m)
Longitude
(c)
(d)
T transport
S transport
(e)
(f)
(g)
(h)
T transport (1 x 10 12 W/m)
S transport (1 x 10 3 kg/m/s)

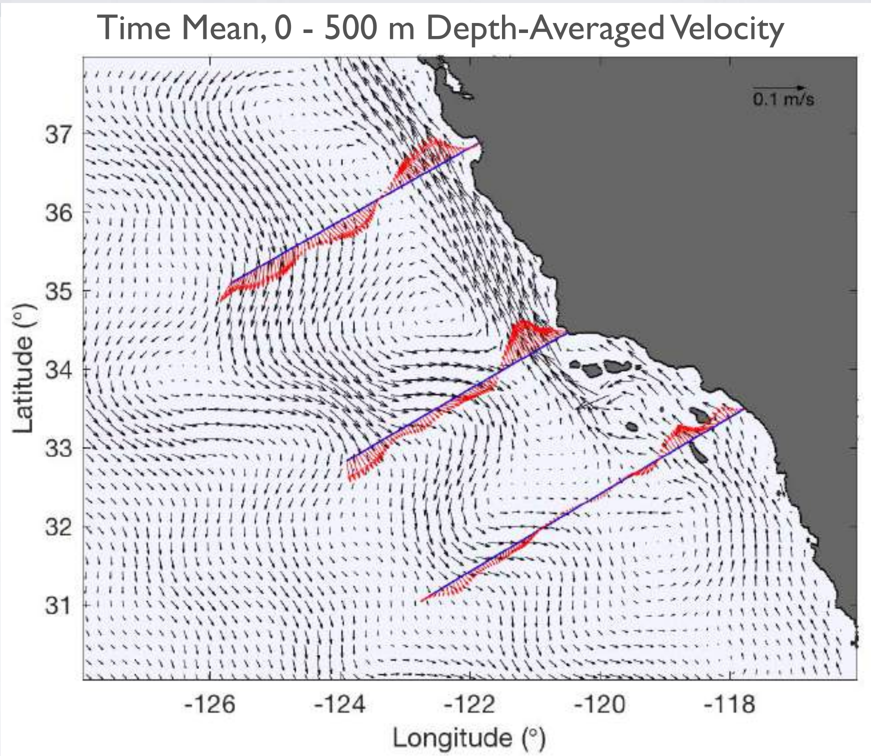
California Underwater Glider Network (CUGN)

Established in 2006: continuous surveillance along CalCOFI lines 66.7, 80, 90

Longest sustained glider timeseries



California State Estimate (CASE)

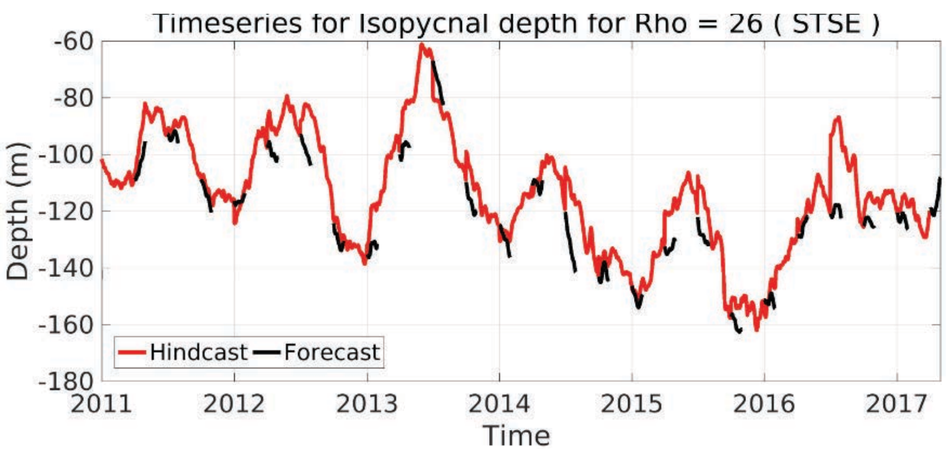


Zaba et al. (2018) under review

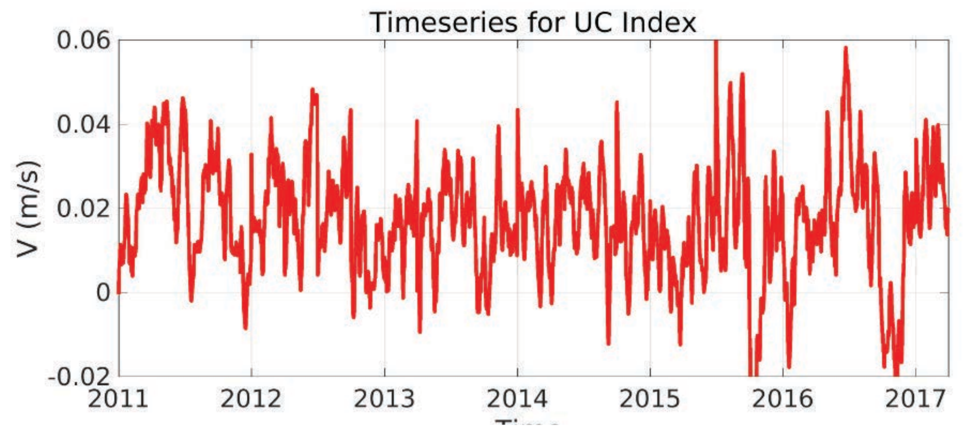
- Regional version of **MITgcm**
  - $^1/_{16}$ degree (~7km) resolution
- 4-dimensional variational (**4D-Var**) **assimilation**
  - Consistent with model dynamics over 3 month assimilation windows
  - Optimized to fit SSH, SST, glider, Argo, XBT observations
- **4D solutions** for Jan 2007 - Mar 2017

CCS Upwelling indices state estimate

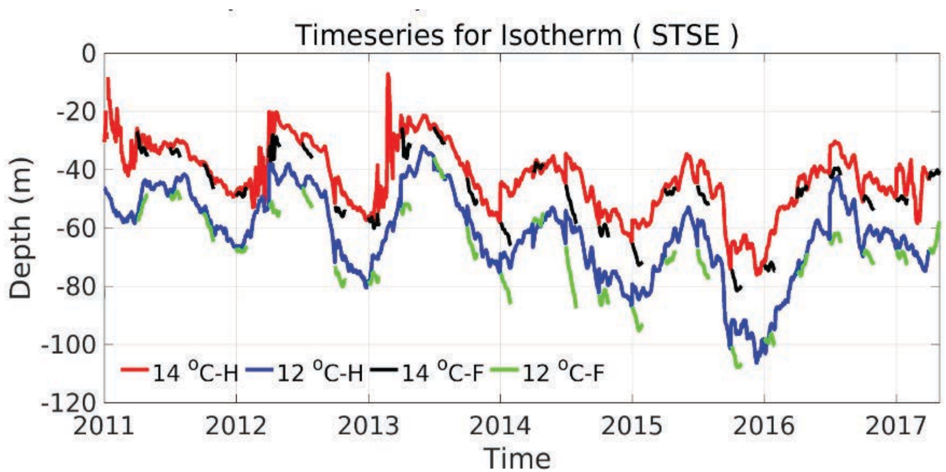
Depth of $\rho = 26$ isopycnal



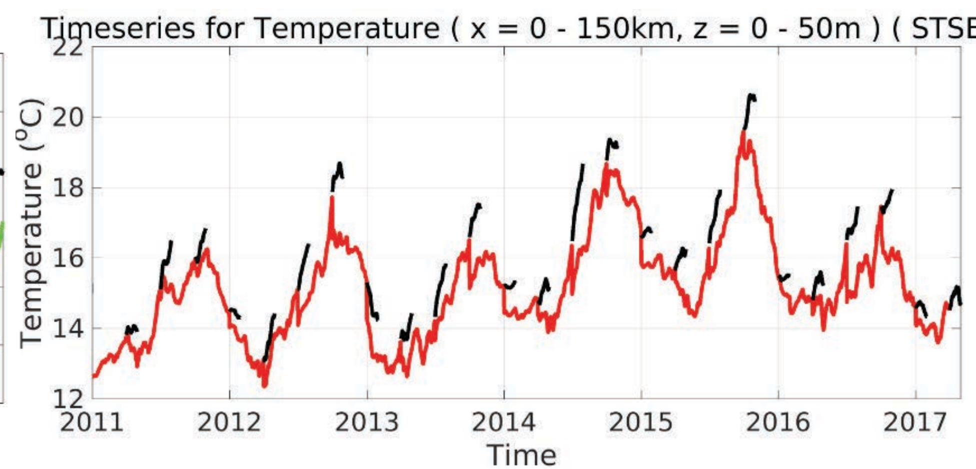
Undercurrent index



Depth of *12°C & 14°C* isotherm



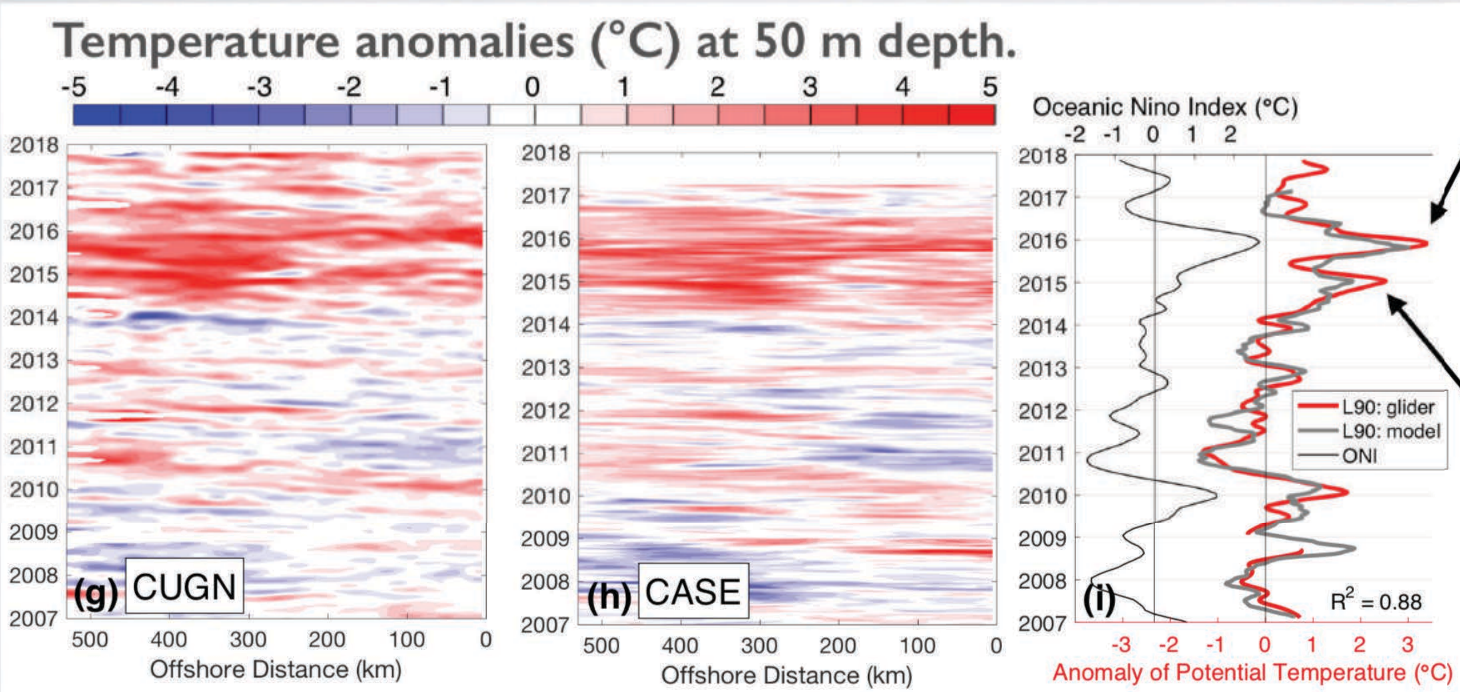
Mean temperature in an upwelling location



http://ecco.ucsd.edu/case_stse_results2.html

Global SST Anomalies

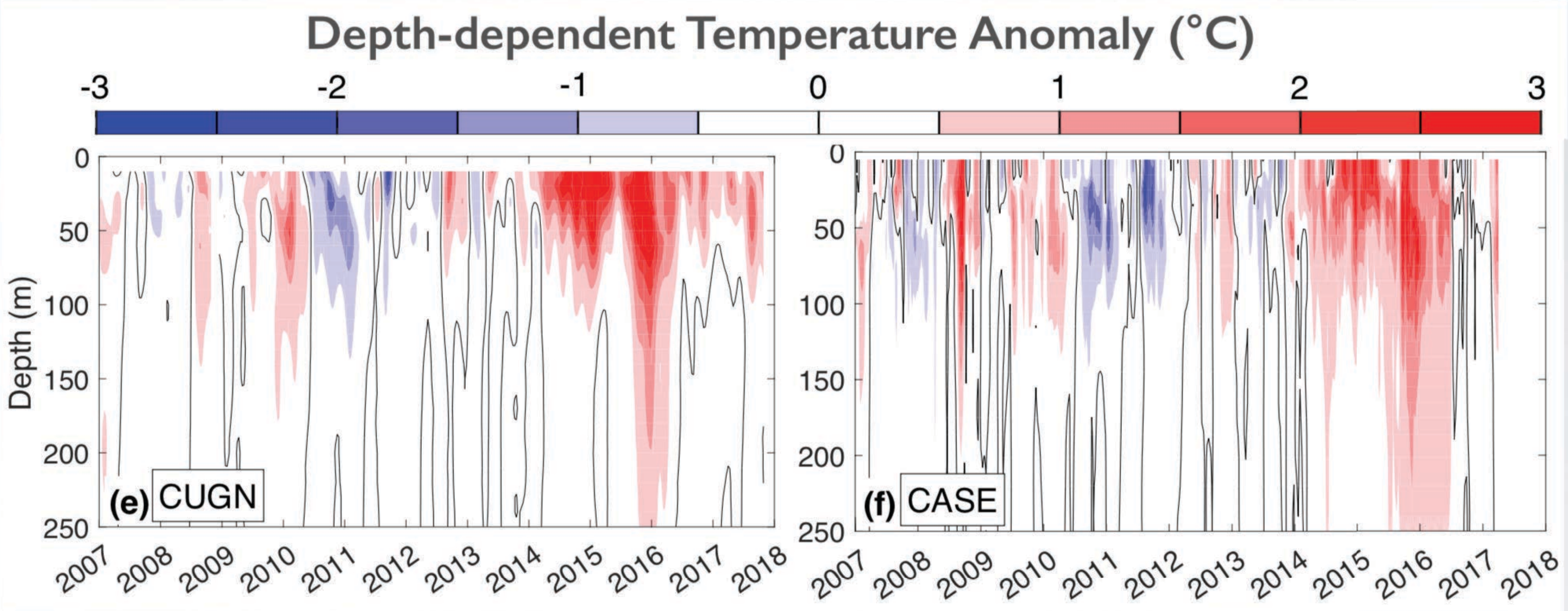
Warm Temperatures along Line 90



El Niño warming peaks at turn of year 2015-16

MHW warming peaks at turn of year 2014-15

Warm Temperatures along Line 90

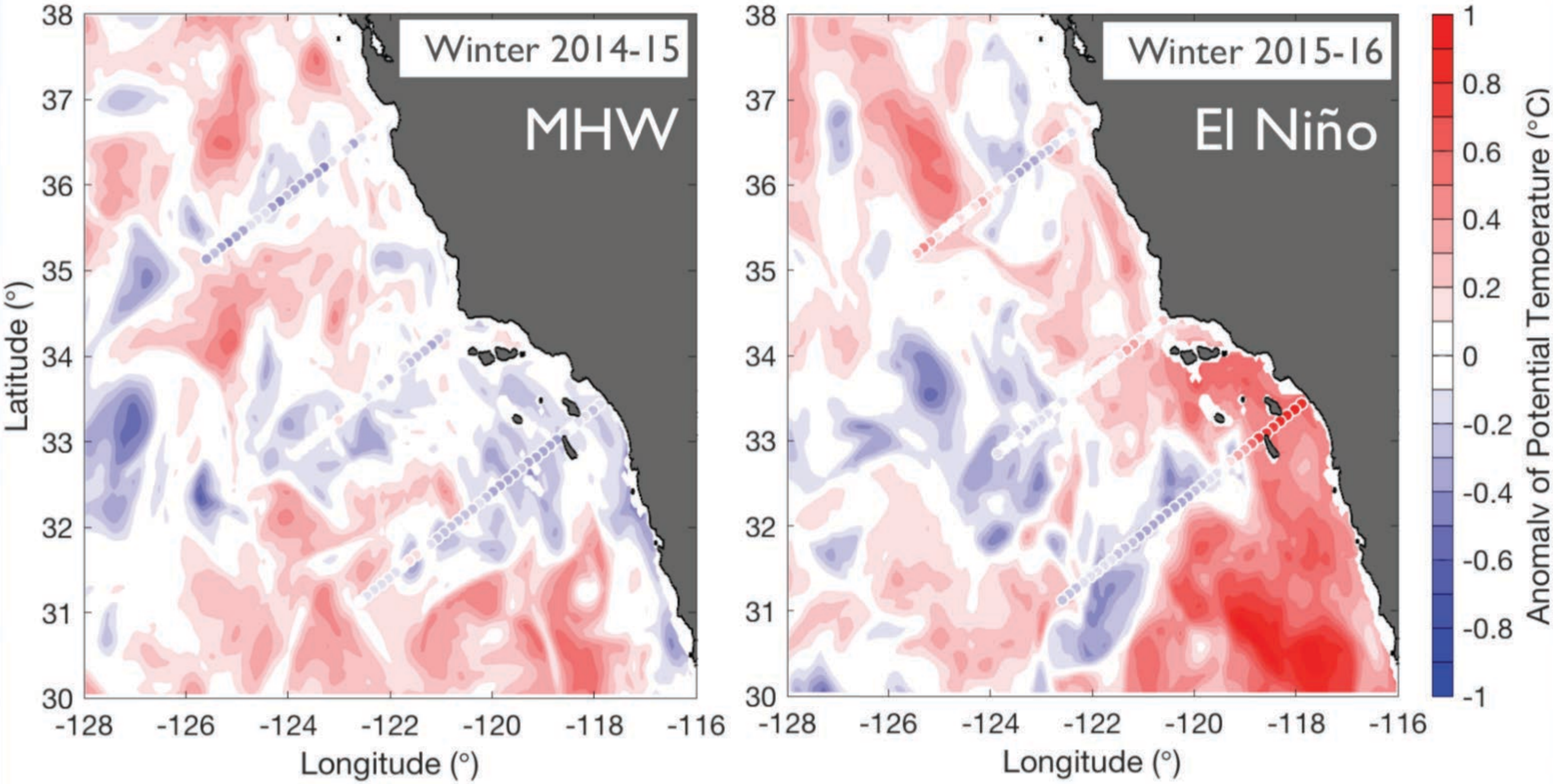


MHW warming is shallow and surface-intensified.

El Niño warming penetrates deeper.

Positive Heat Advection Subsurface (50 - 150 m)

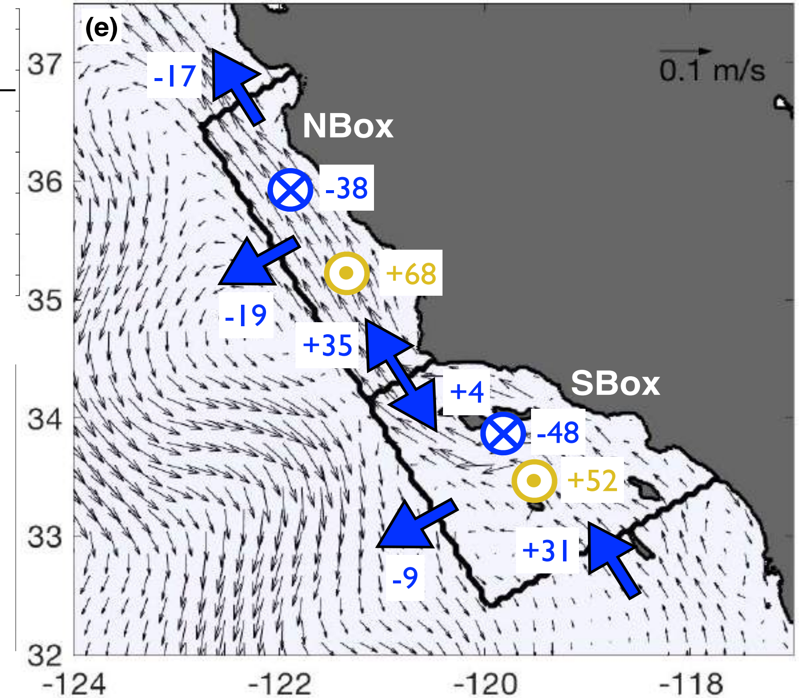
Temperature anomalies along 26.0 kg/m³ isopycnal.

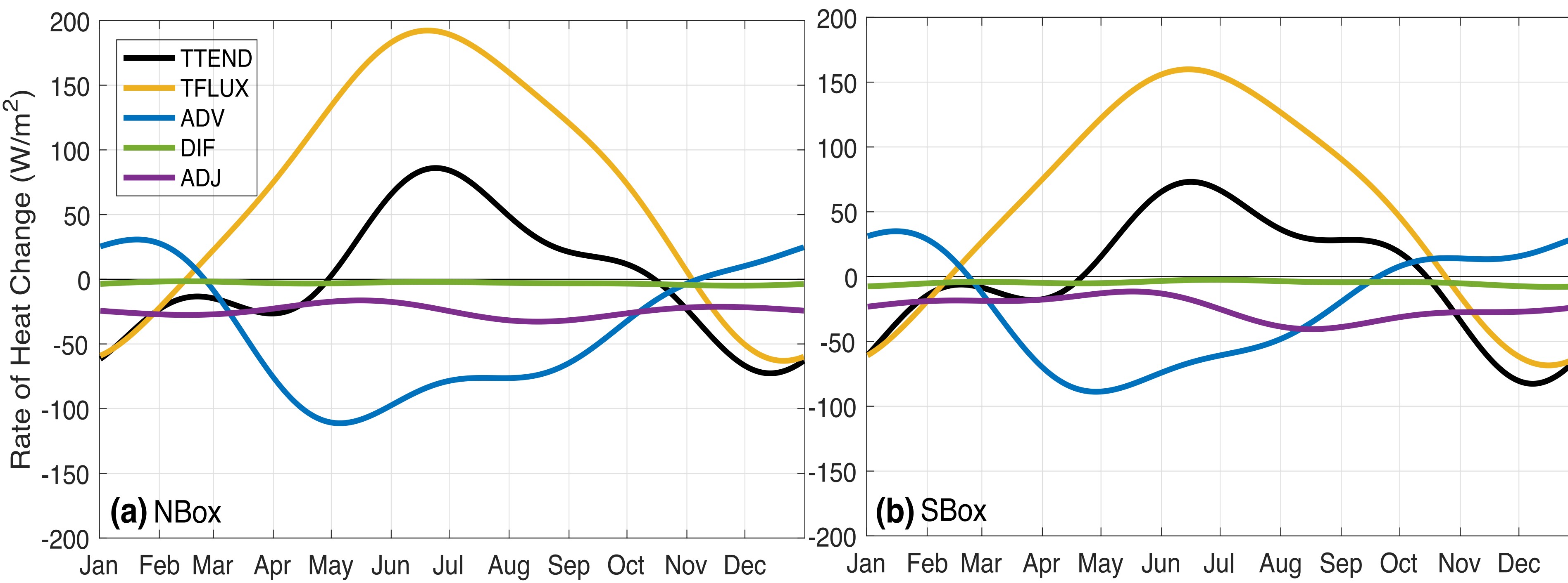


Anomalous **poleward advection** during peak El Niño.

Assess heat budget in control volumes.

Due to excessive short wave heating estimates in reanalysis there are large adjustments to temperature initial conditions. For budgets this adjustment must be accounted for

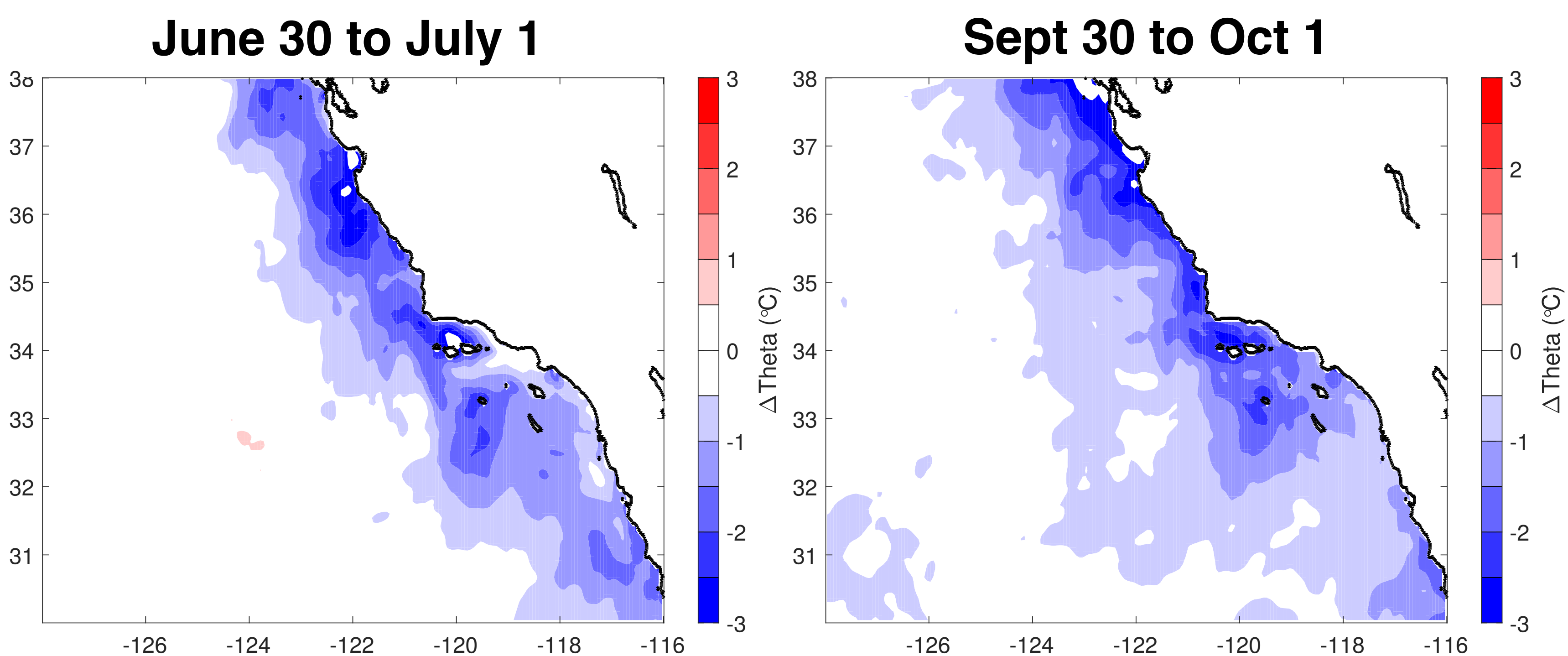




Shortwave heat flux is too strong because weather model does not capture clouds near the coast

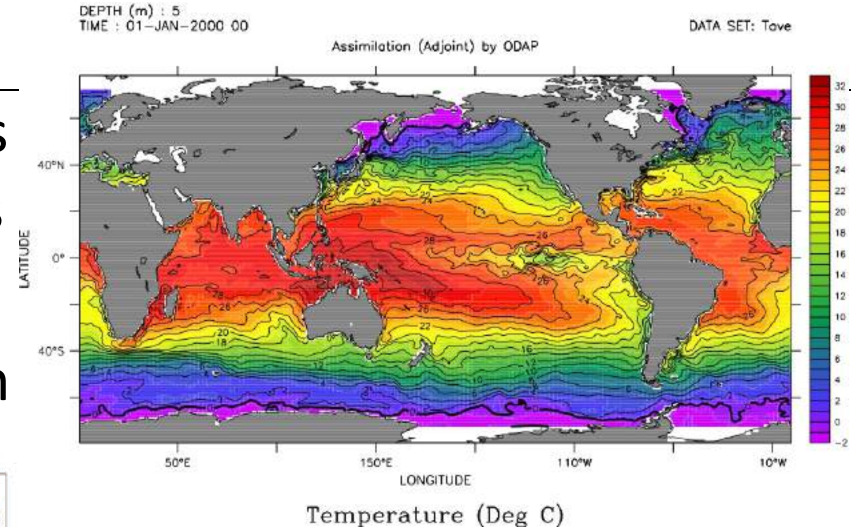
Optimization corrects by reducing T initial conditions (every 3 months)

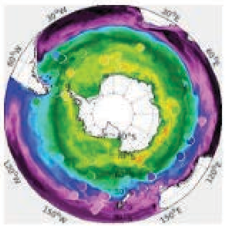
Mean surface temperature increment



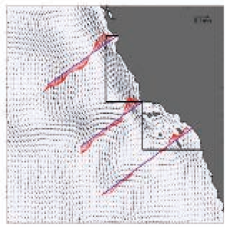
ECCO software enables numerous applications

Flagship: 1992 to present production run

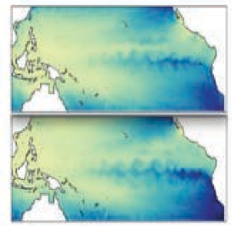




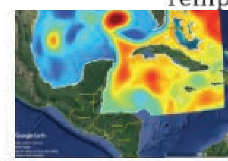
Southern Ocean State Estimate (SOSE)



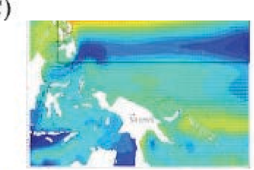
California Current System State Estimate (CASE)



Tropical Pacific Ocean State Estimate (TPOSE)



Gulf of Mexico State Estimate (GoM)



Northwest Pacific State Estimate (NWPac)

Targeted efforts can enable

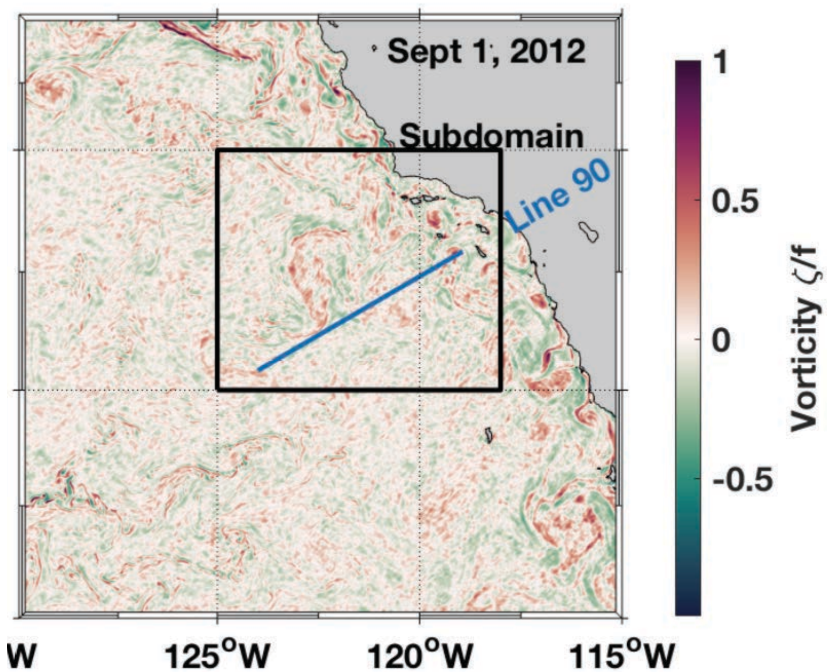
- Reproducing eddies: currently intrinsic eddies only controllable with initial conditions. Thus need assimilation windows less than ~4 months.
- Consistency with specific system components (e.g. BGC, internal waves)
- Consistency in specific regions or times, or with specific obs platforms. Here the optimization problem can be framed to prioritize consistency
- Observing system design
- Forecasting: goal of state estimate is to provide forecast initialization
- **Development!**

Assimilation for next generation observing system

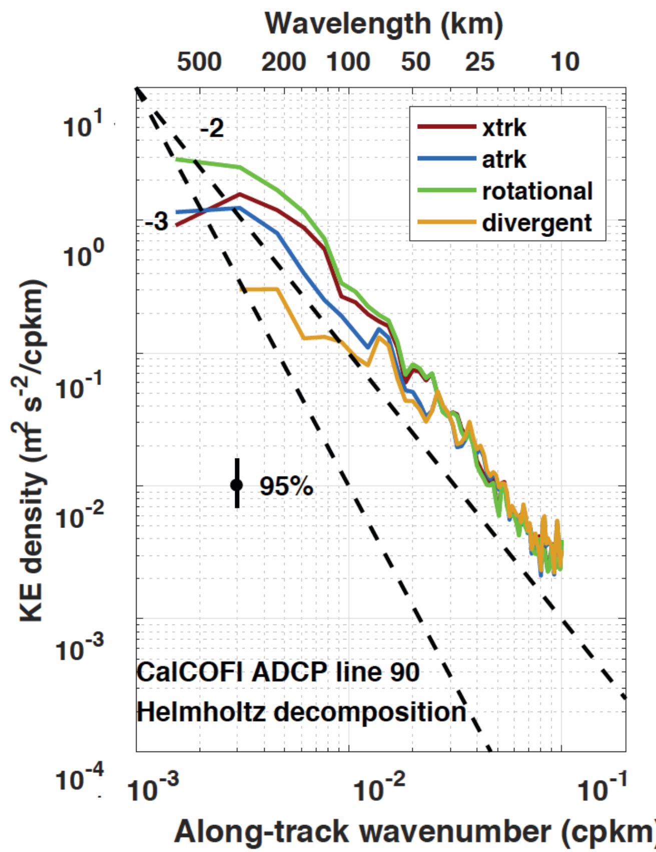
- Characterize physical scales and **develop tools** to map the state
- Hold model accountable to data. As data stream grows must also **semi-automate QC**: hold data accountable to model

Characterizing the California Current

Chereskin et al, submitted, JGR-Oceans,



Helmholtz decomposition to separate rotational and divergent components



Acoustic Doppler Current Profiler data: 1993-2004, 39 cruises

Assimilation for next generation observing system

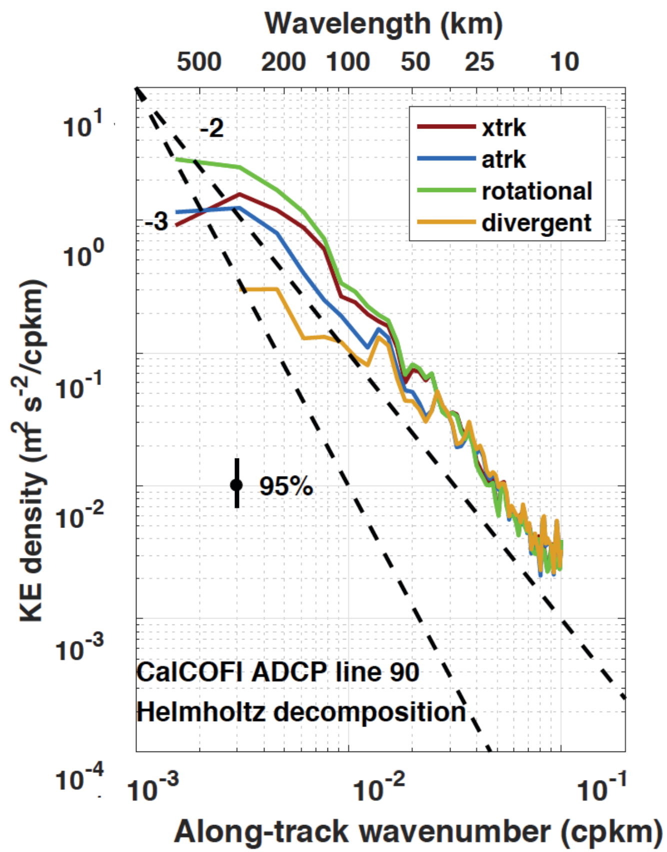
- Characterize physical scales and **develop tools** to map the state
- Hold model accountable to data. As data stream grows must also **semi-automate QC**: hold data accountable to model

Chereskin et al, submitted, JGR-Oceans,

Characterizing the California Current

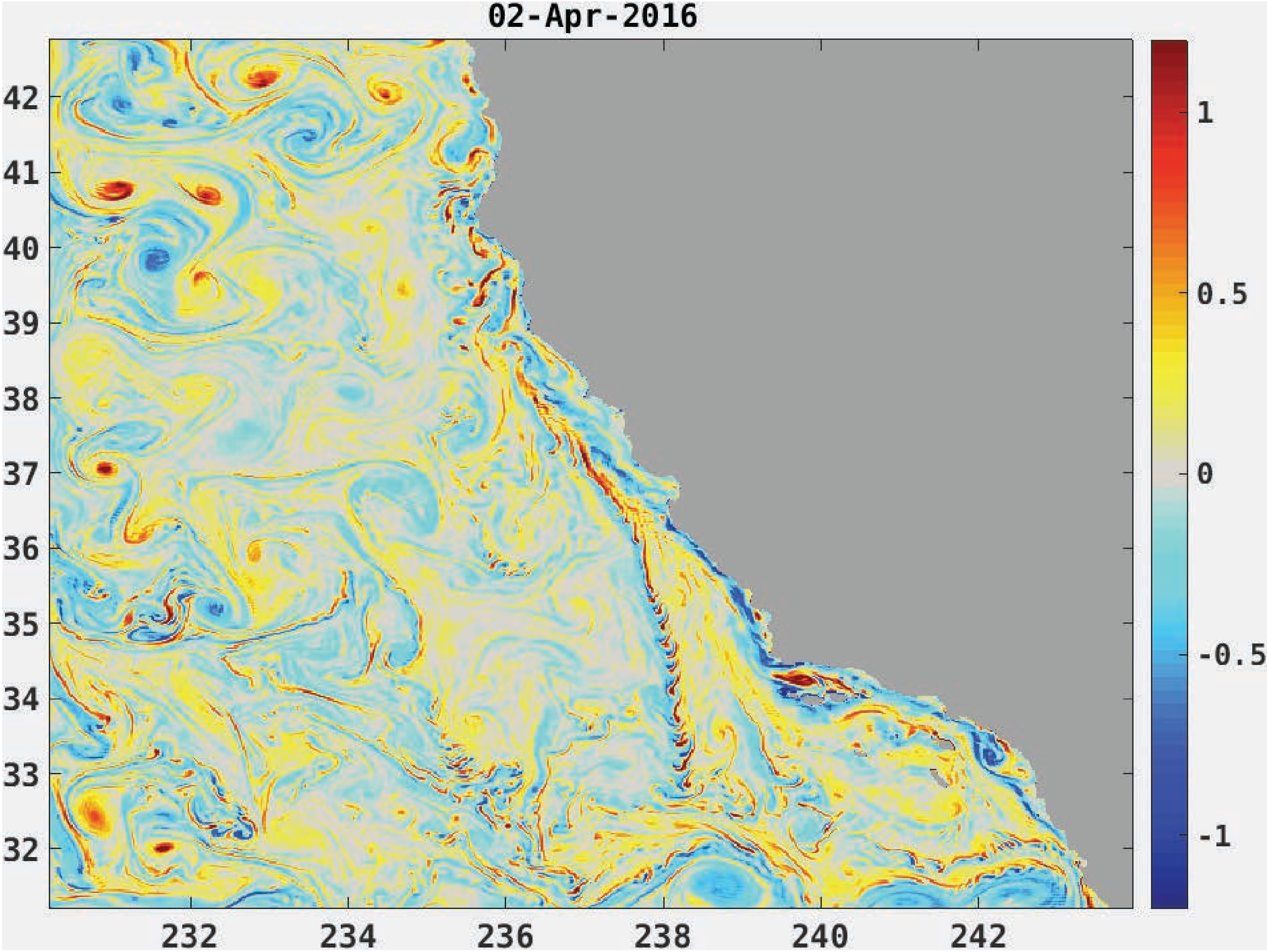
The challenge is to represent both the **rotational** (balanced, geostrophic) and **divergent** (ageostrophic) components of the flow.

In the CCS, the energy in these components converge at 70 km



Mapping all parts of the signal

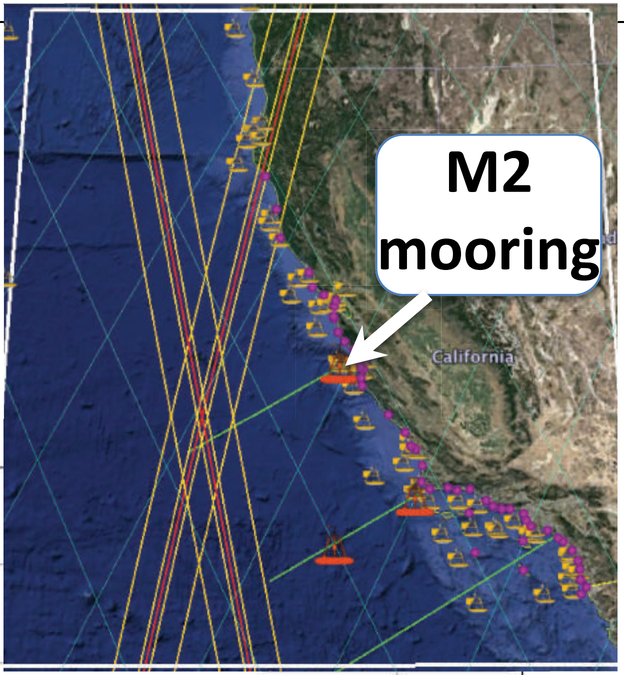
Normalized relative vorticity, *ζ/f*, at 13m

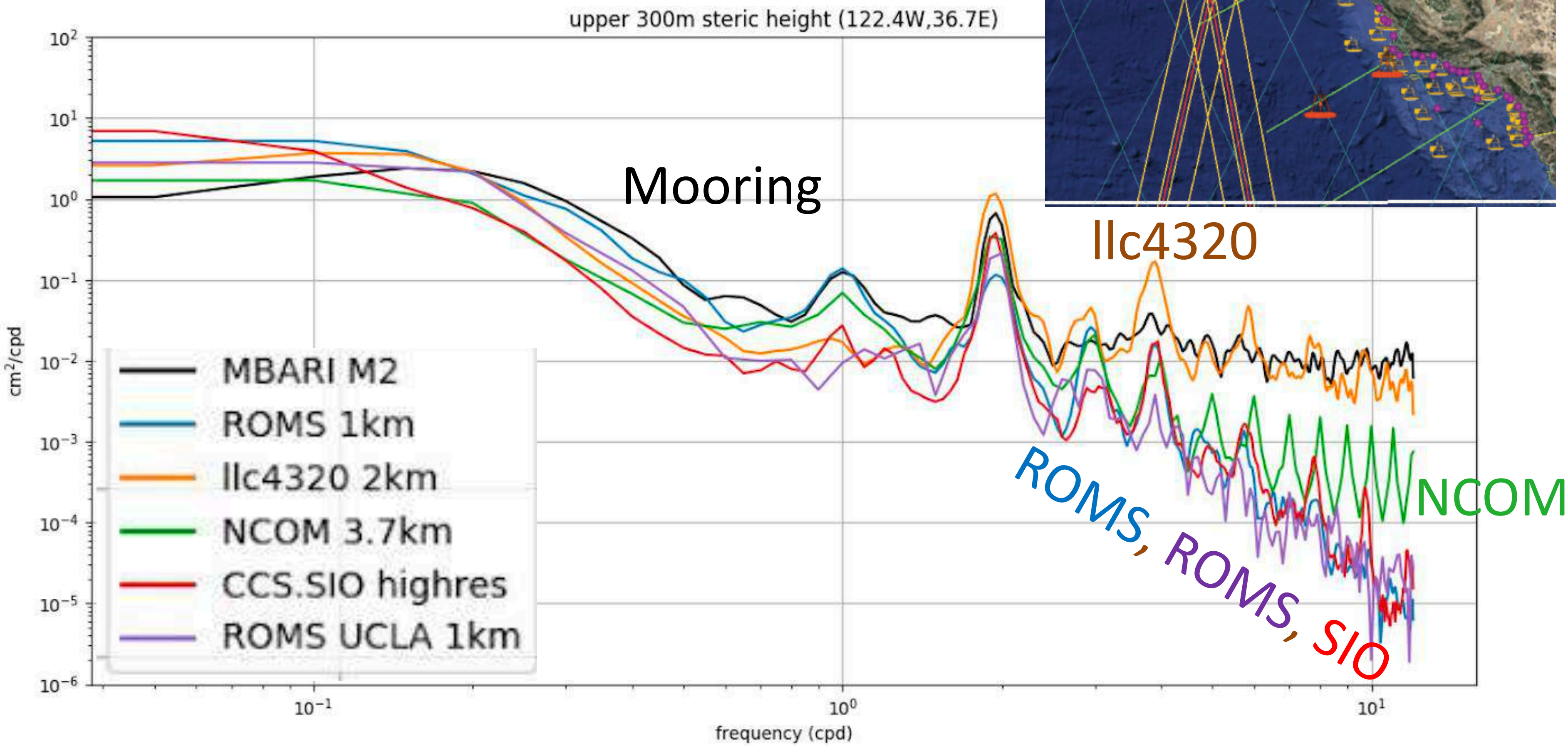


- Surface waves
- Tides
- Internal waves
- Mixing
- Errors
- High-resolution implies high computational cost regional model and multi-grid assimilation

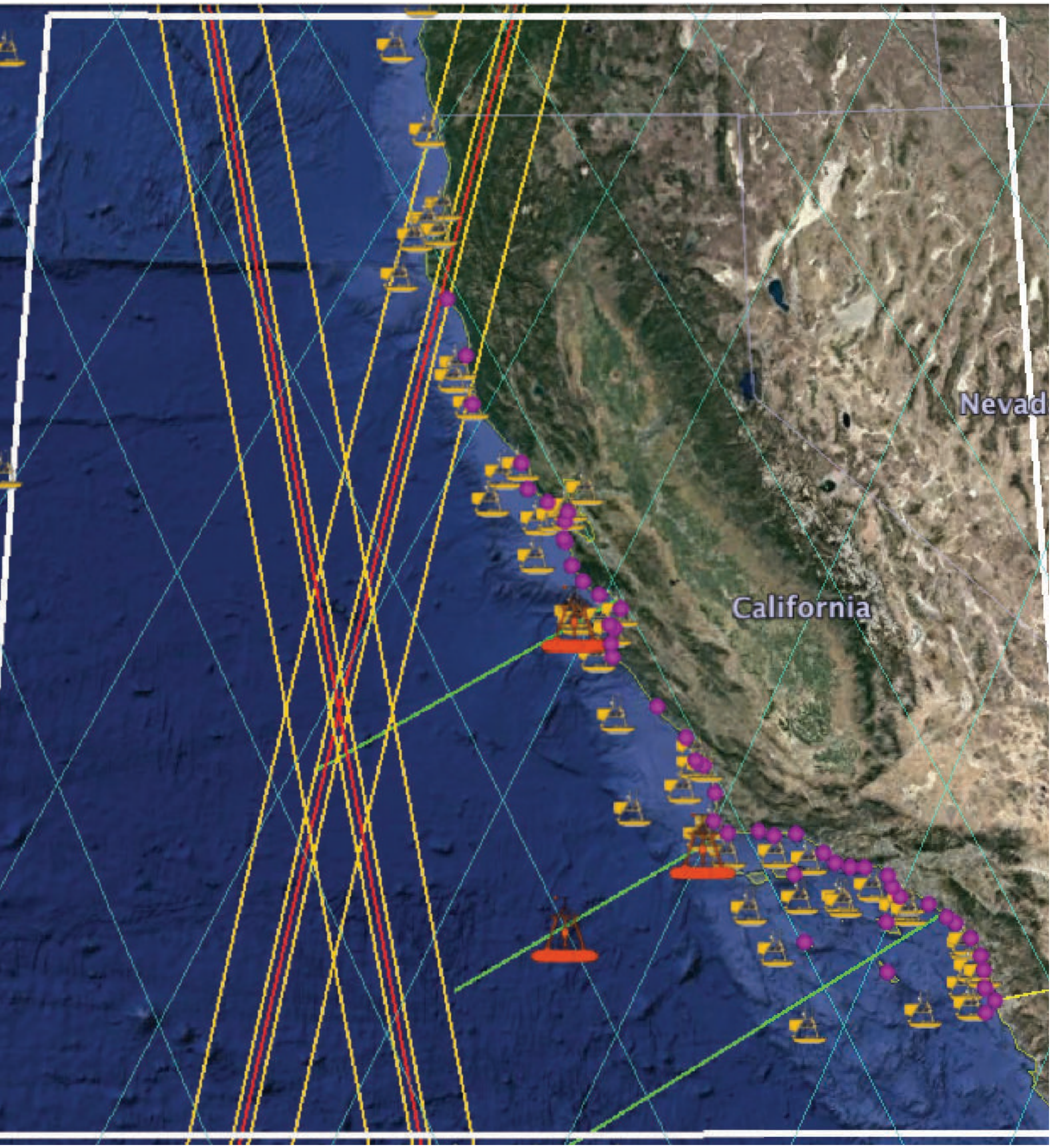
Regional model problems

- Mooring has high-frequency energy
- **Global** Llc4320 (2km) replicates mooring energy
- **Regional** ROMS (1km), MITgcm (2km), and NCOM (3.7km) are missing high-frequency energy





MITgcm: California Current test bed



MITgcm

- 2 km
- Numerics identical to LLC4320
- Inputs similar

- Mooring and **global** Llc4320 (2km) have high-frequency energy
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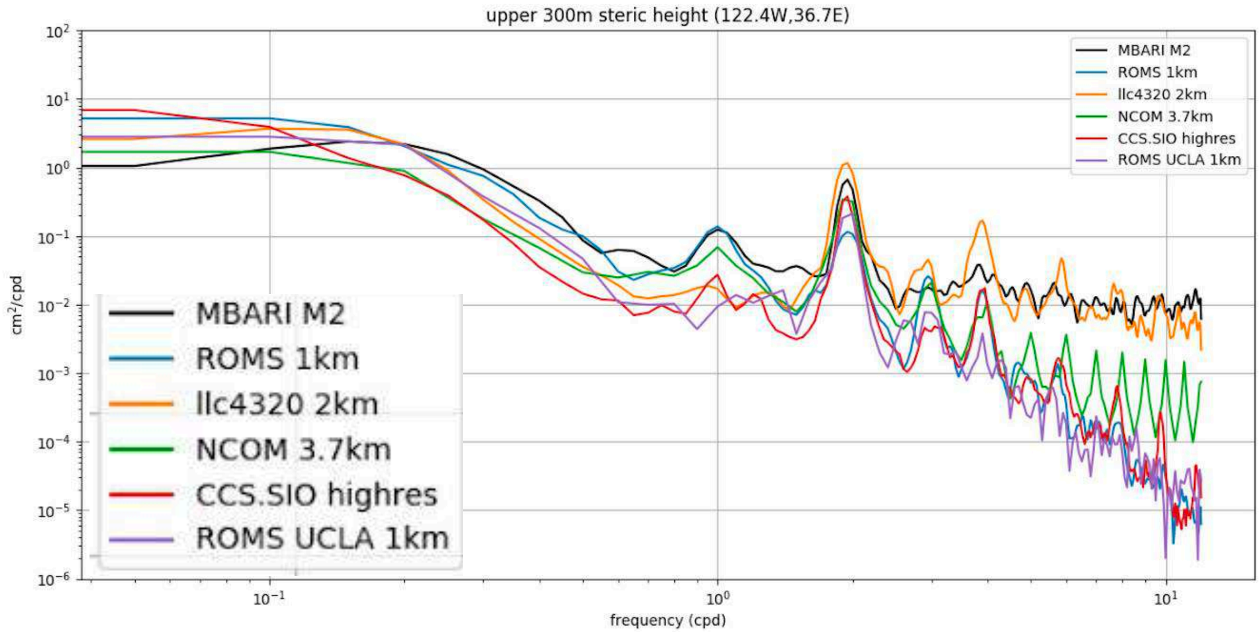
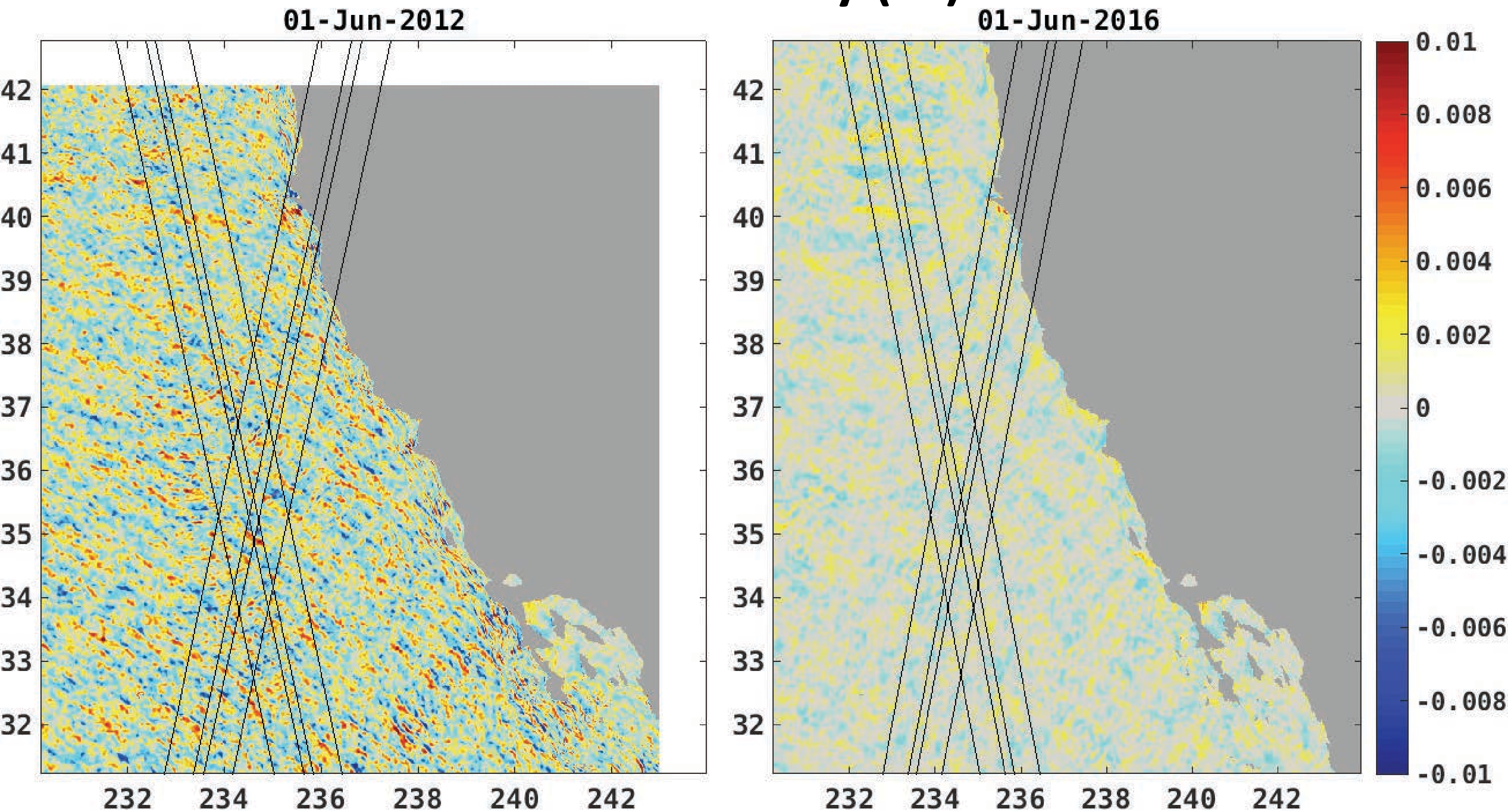


Hypotheses:

1. Representation of interaction with bottom topography
2. Noise in LLC4320 and/or mooring meaning one or both is wrong.
3. Tidally generated internal waves do not have time to exchange energy and fill the (Garrett-Munk) spectrum in a regional domain.
4. How tides forced (i.e. as pressure loading) & their accuracy in LLC4320.

Vertical velocity (*W*) at 500 m



LLC4320 **MITgcm regional**

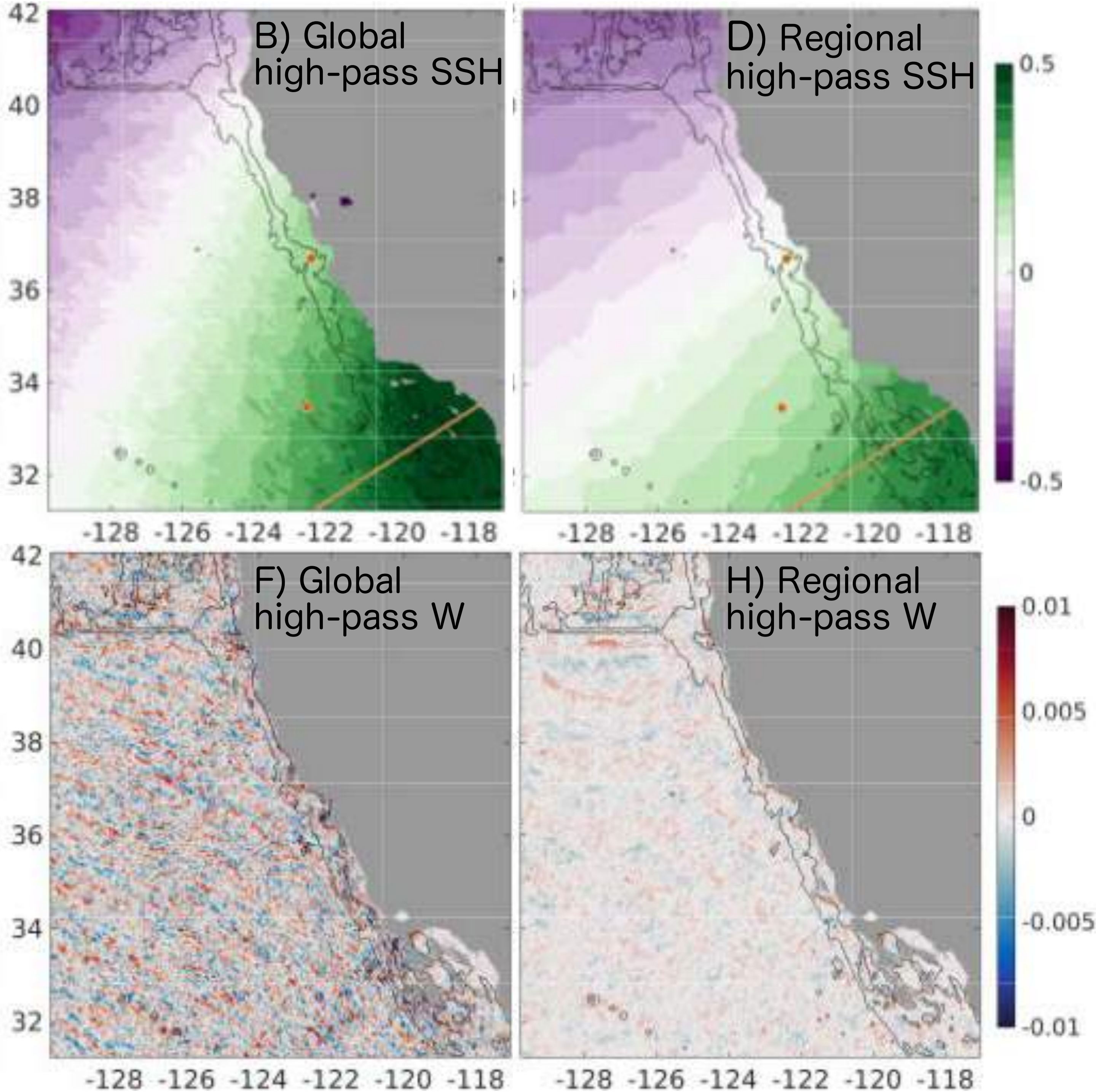
High-pass SSH

Global LLC4320 (left)

vs

a regional version with same numerics (right)

High-pass vertical velocity



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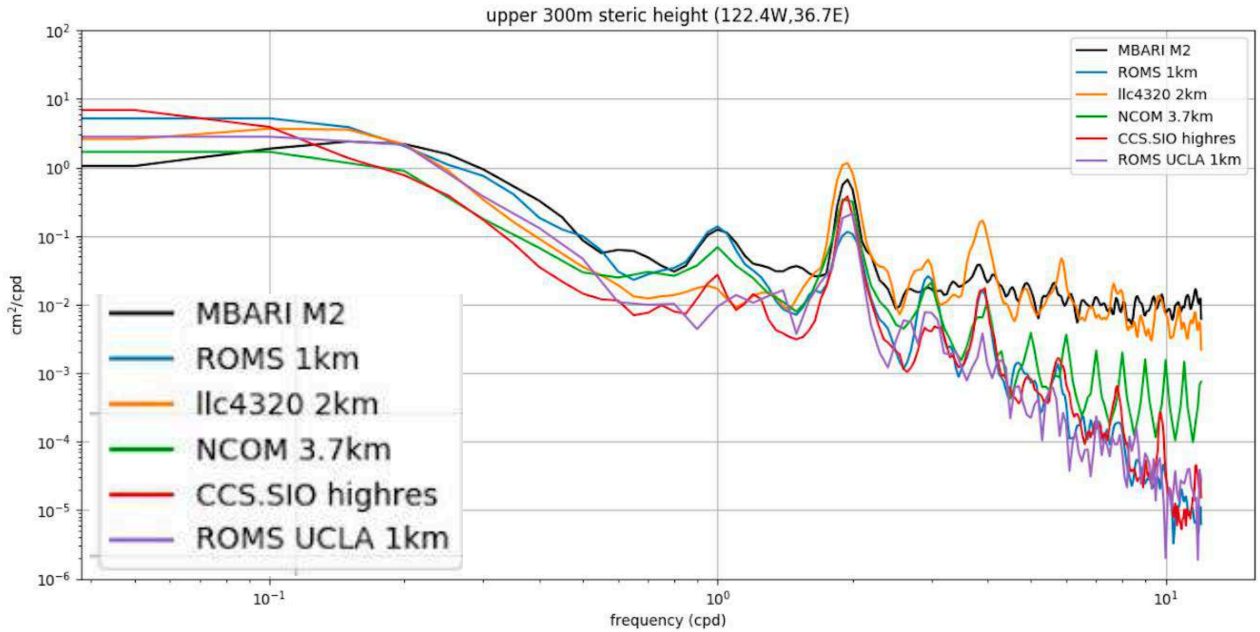

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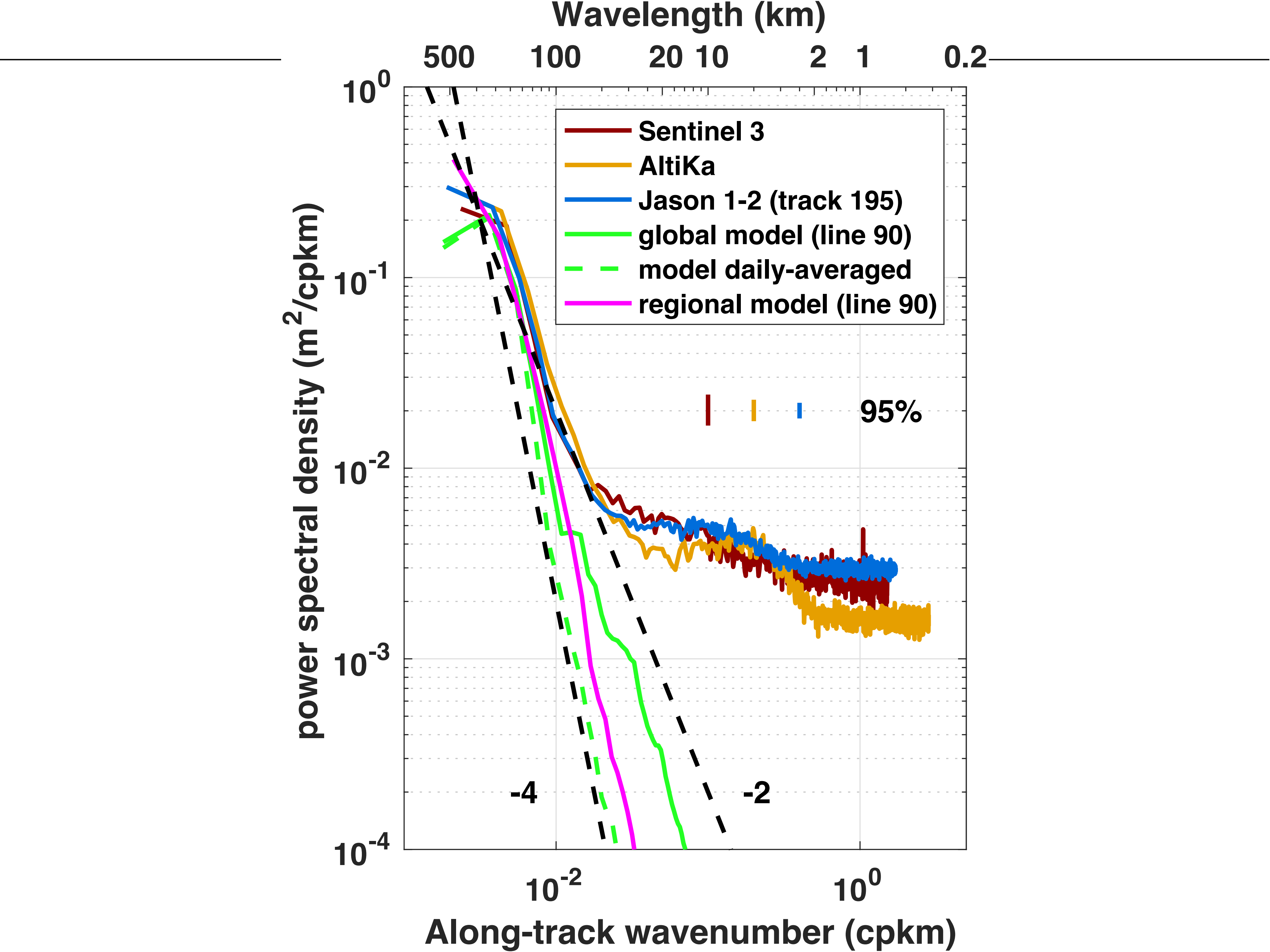
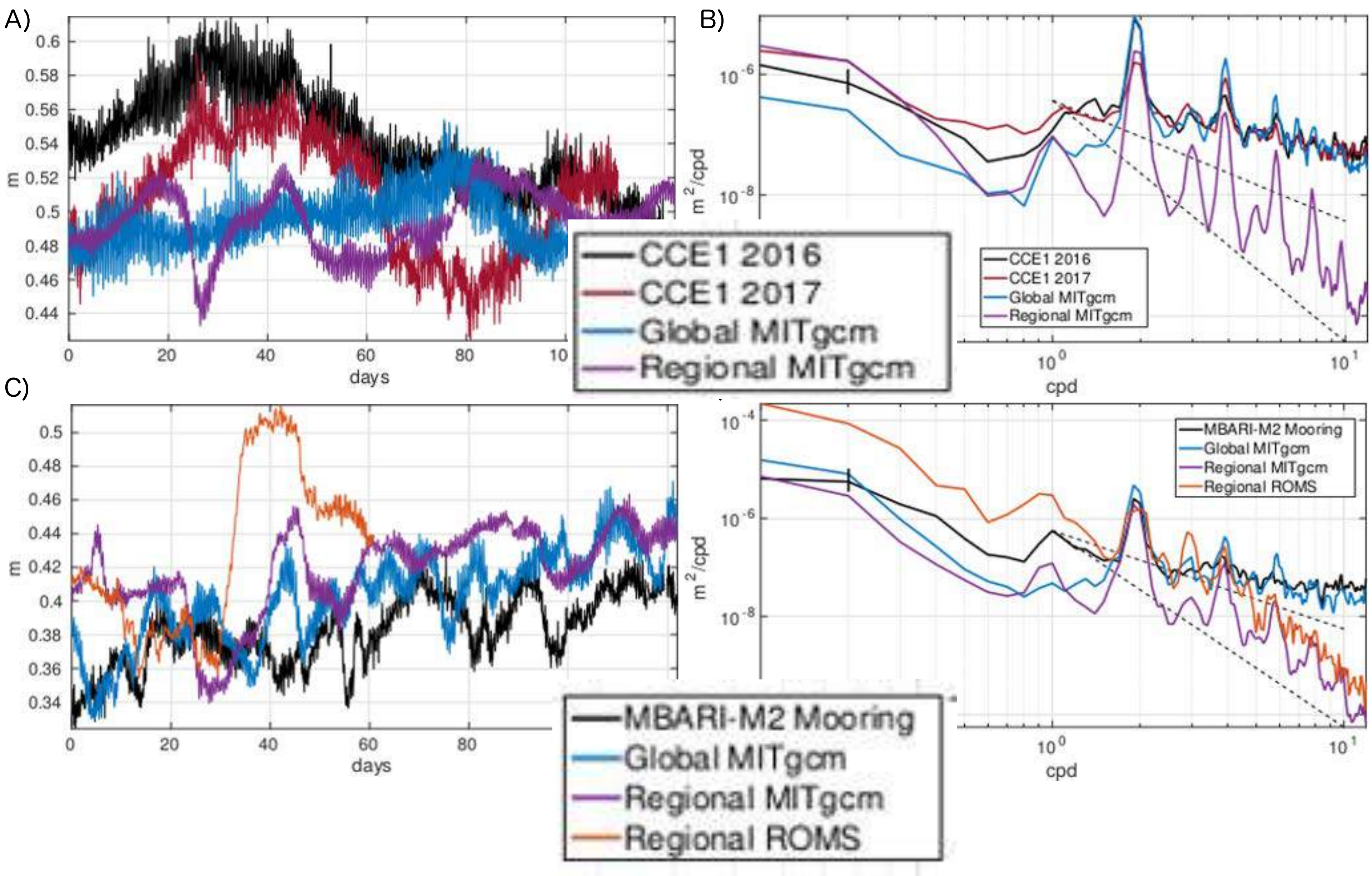


Wavelength (km)
500
100
20
10
2
1
0.2
Sentinel 3
AltiKa
Jason 1-2 (track 195)
global model (line 90)
model daily-averaged
regional model (line 90)
95%
-4
-2
power spectral density (m²/cpkm)
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
Along-track wavenumber (cpkm)

Steric height

time series

power spectra density



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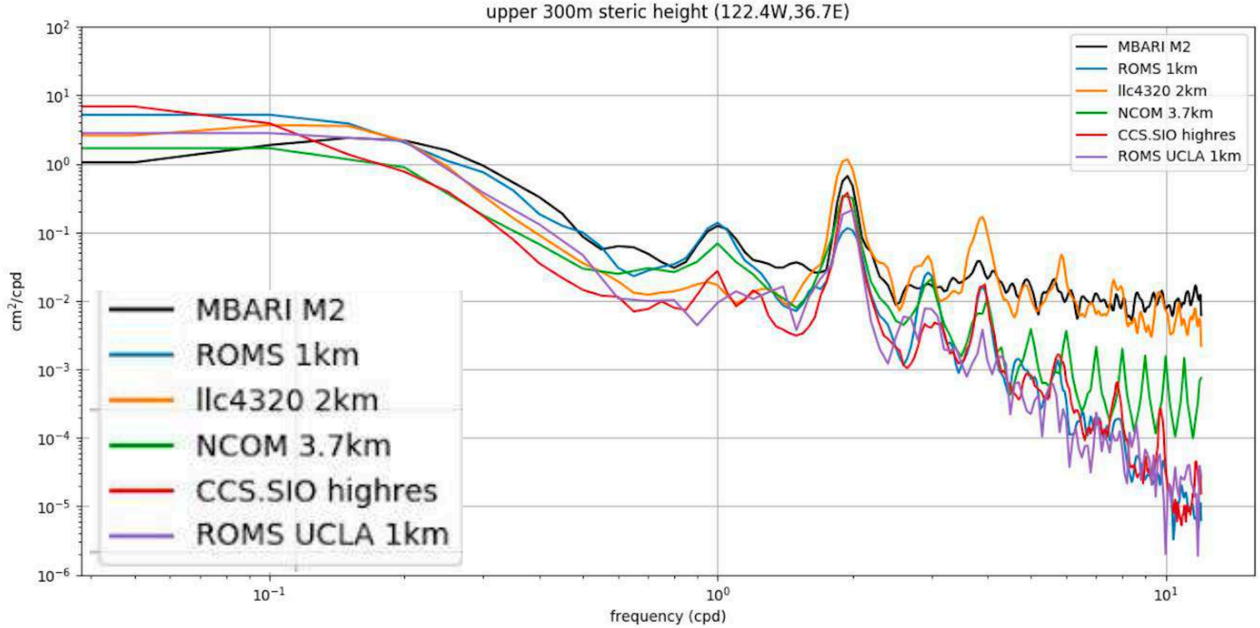

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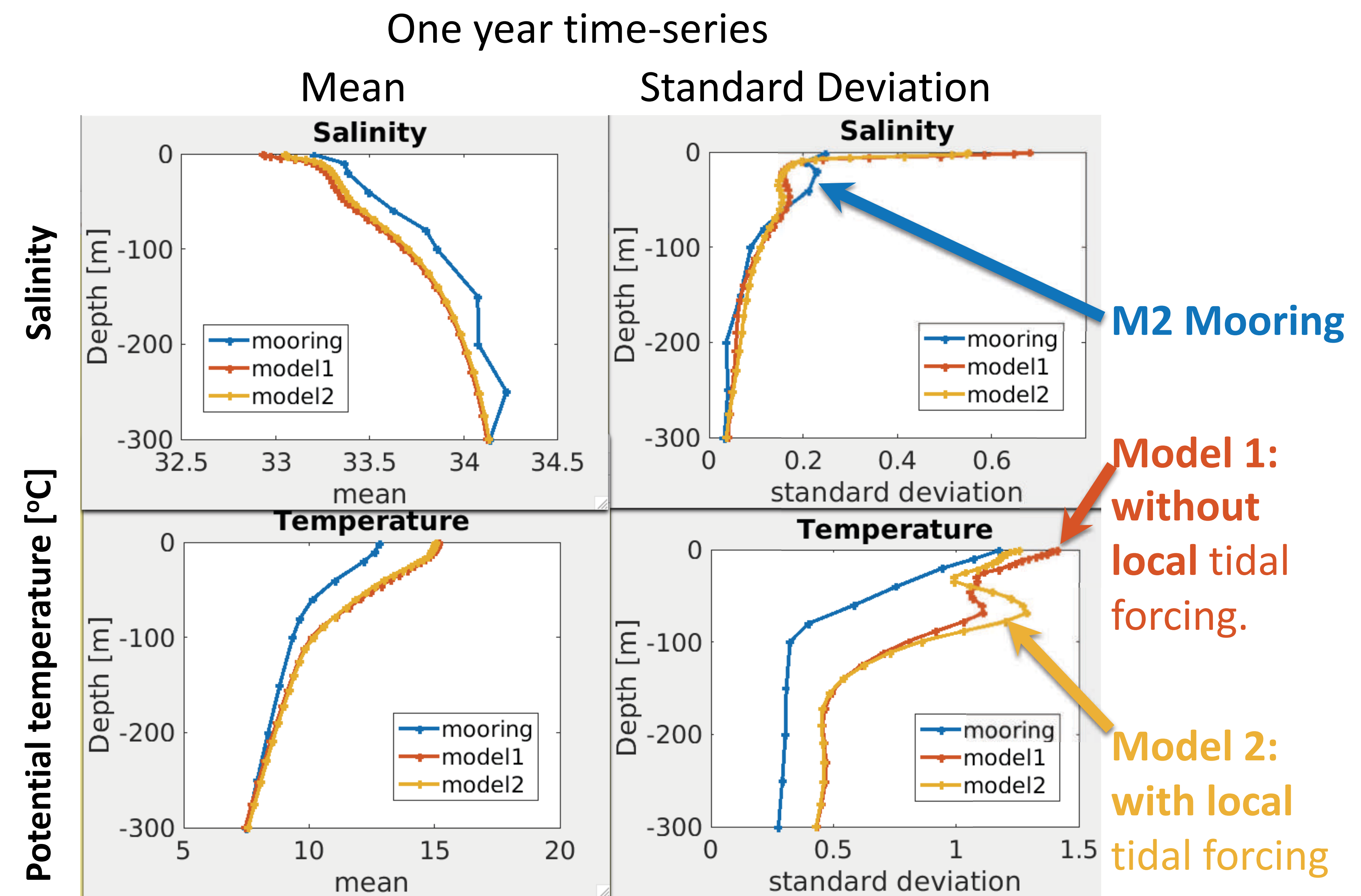
What is impact of local barotropic tidal forcing (imposed as a pressure loading) on the regional setup?



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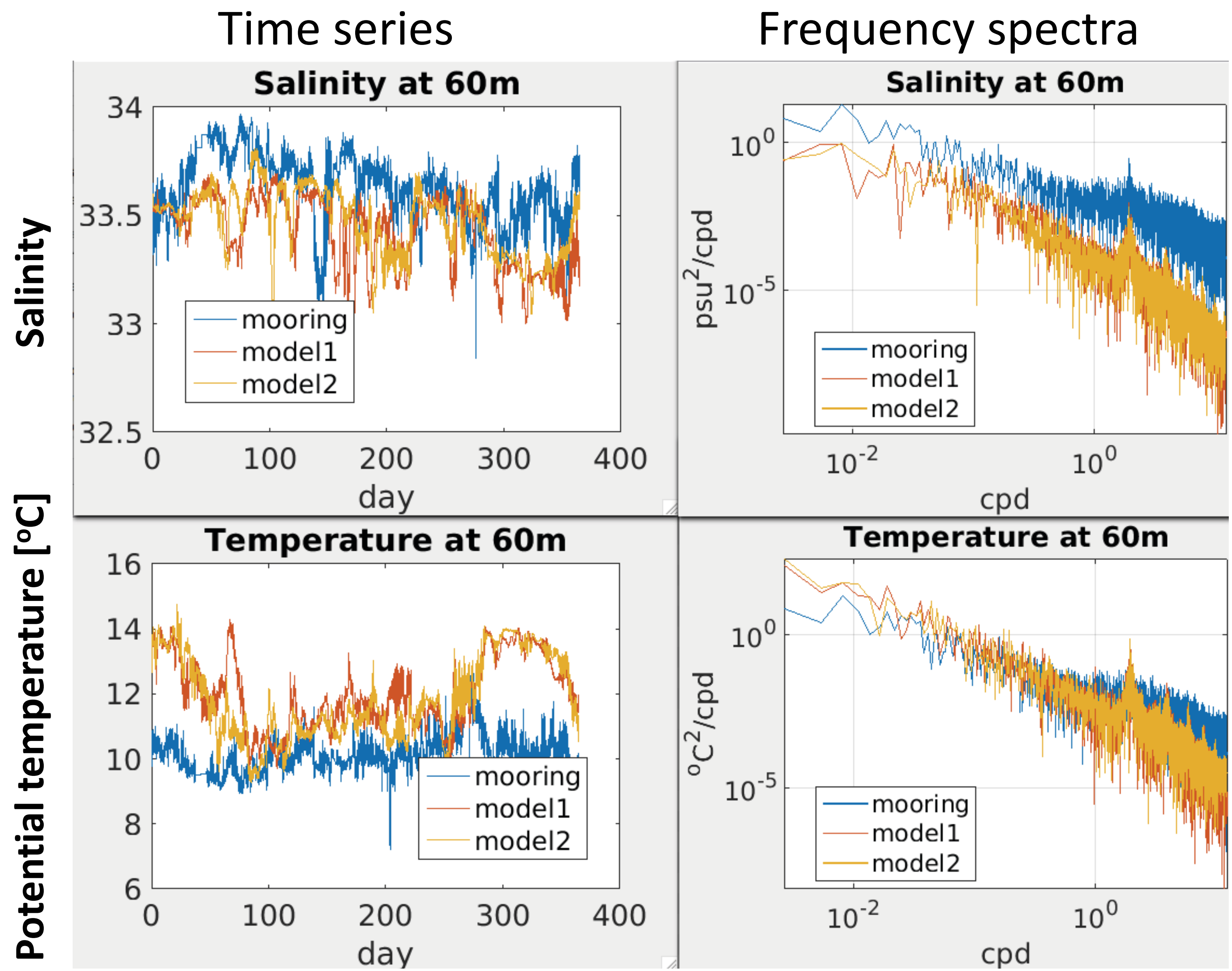


M2 Mooring

Model 1: without local tidal forcing.

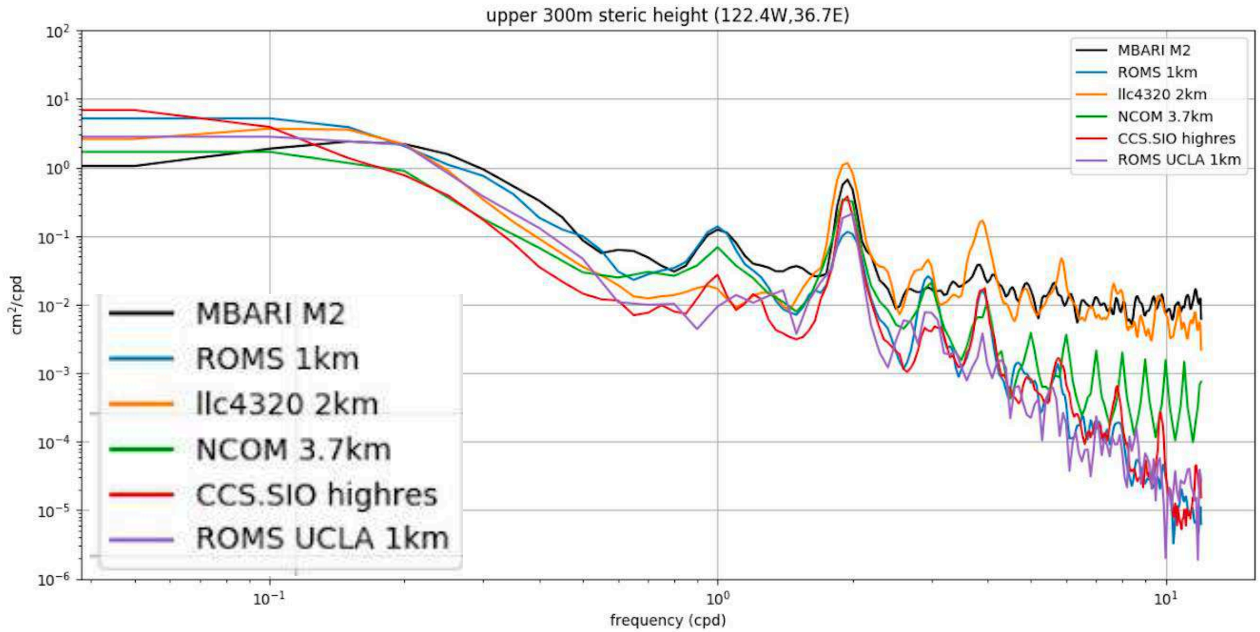
Model 2: with local tidal forcing

Compare to tide gauge analysis.

Both regional and global MITgcm setups have reasonable representations of the tides, with discrepancies less than 35%. However the global model M2 amplitude averages 0.657 m for the three tide gauge locations, while the regional amplitude mean is 31% lower at 0.451 m.

https://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels

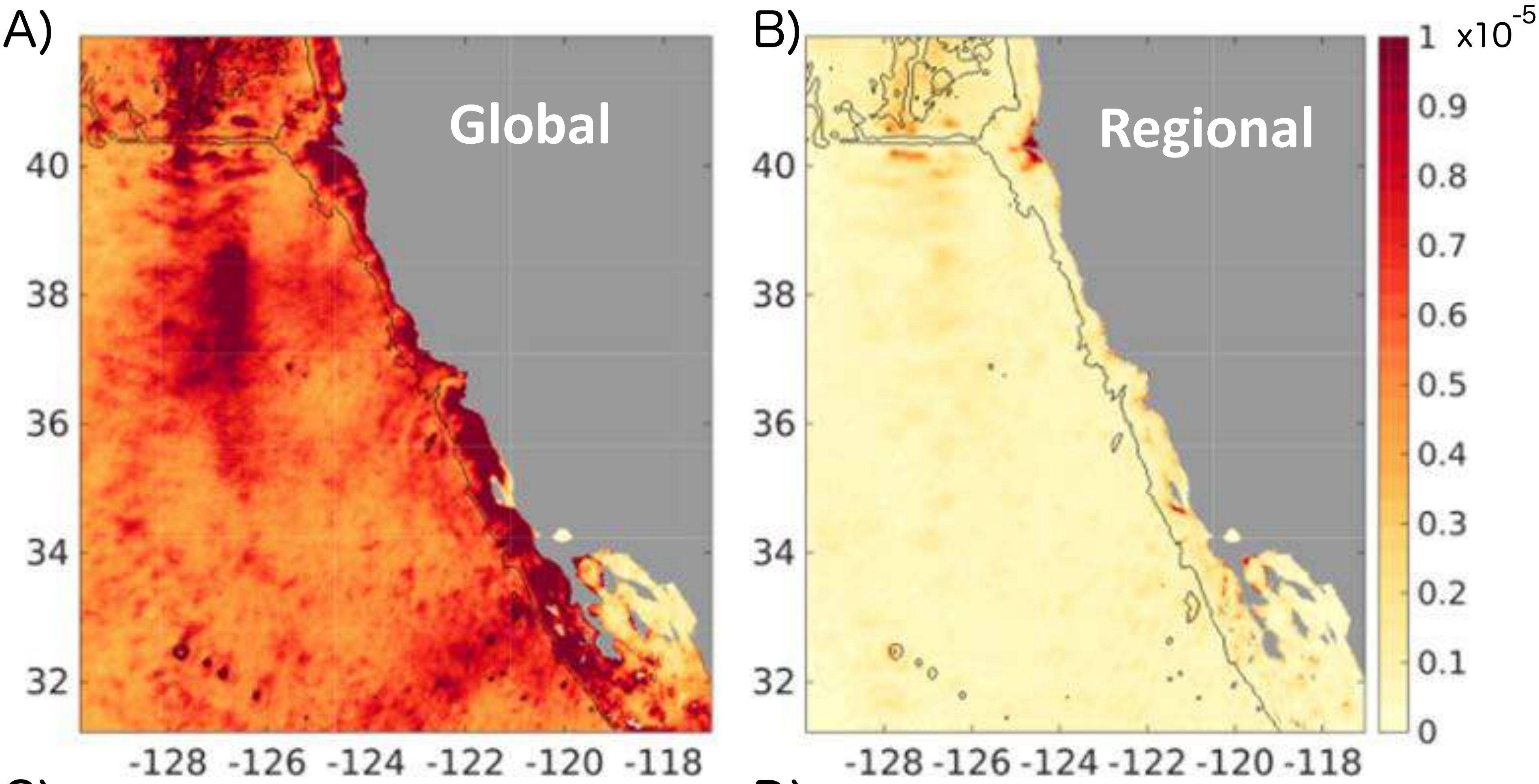
- Mooring and **global** Llc4320 (2km) have high-frequency energy
- **Regional** ROMS (1km), MITgcm (2km), and NCOM (3.7km) are all missing high-frequency energy



Hypotheses:

- ~~Representation of interaction with bottom topography~~
- ~~How tides forced (i.e. as pressure loading) & their accuracy in LLC4320.~~
- ~~Noise in LLC4320 and/or mooring meaning one or both is wrong.~~
- Tidally generated internal waves do not have time to exchange energy and fill the (Garrett-Munk) spectrum in a regional domain.

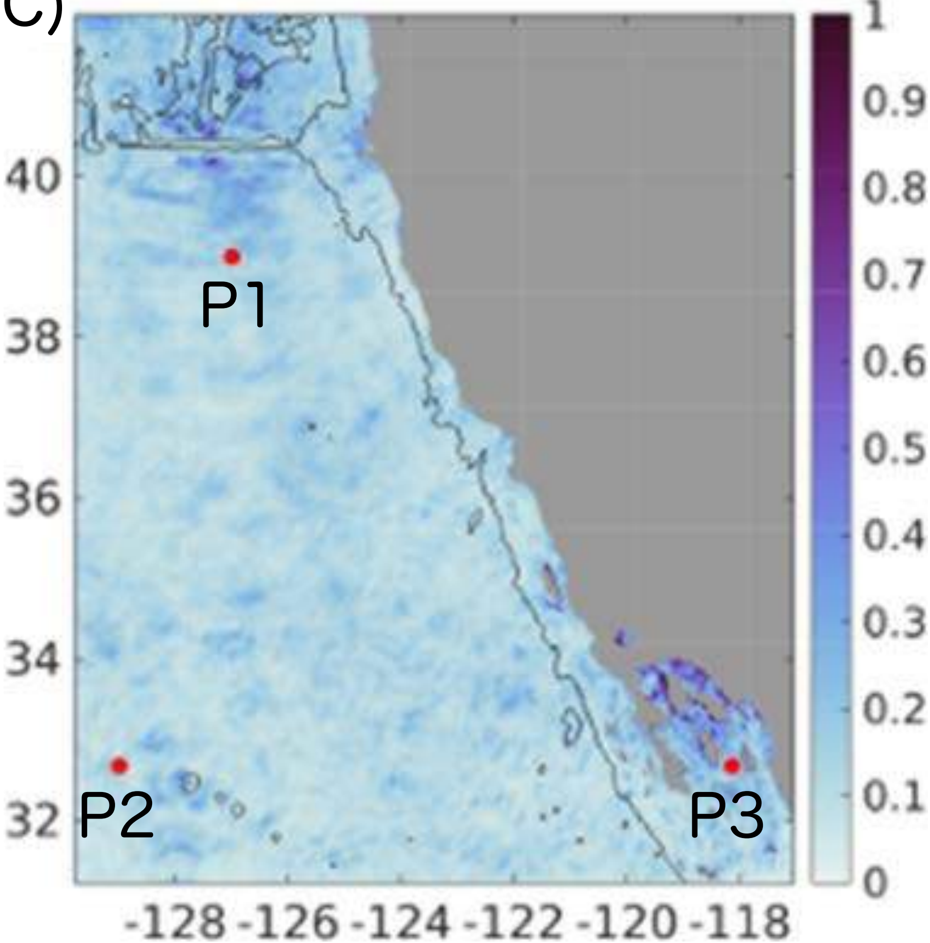
Variance of vertical velocity, w, at 500. The 3000 m bathymetry contour in black.



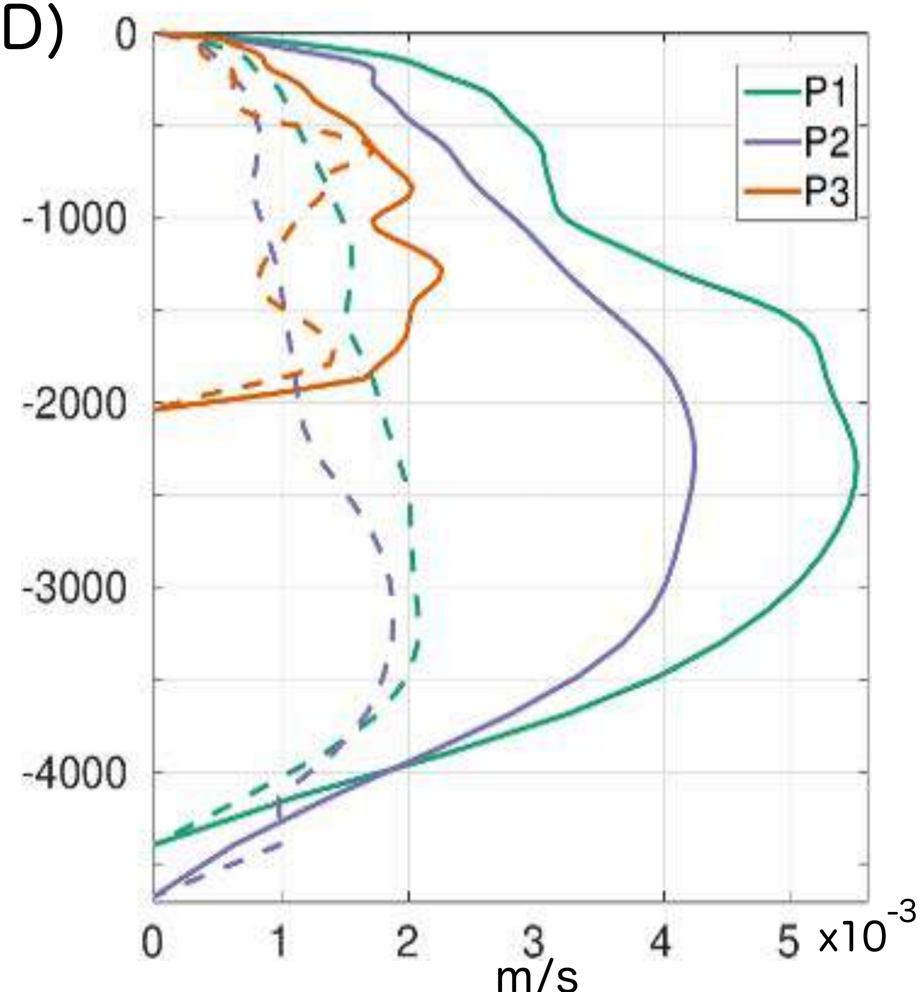
Ratio of w variance at 500 m: Regional divided by global. Three points: P1 near the Mendocino Ridge, P2 in the analysis domain southwest corner, P3 inside the Southern California Bight.

Vertical profiles of vertical velocity, w, standard deviation at **P1**, **P2**, **P3** for the global (solid lines) and regional (dashed lines) models.

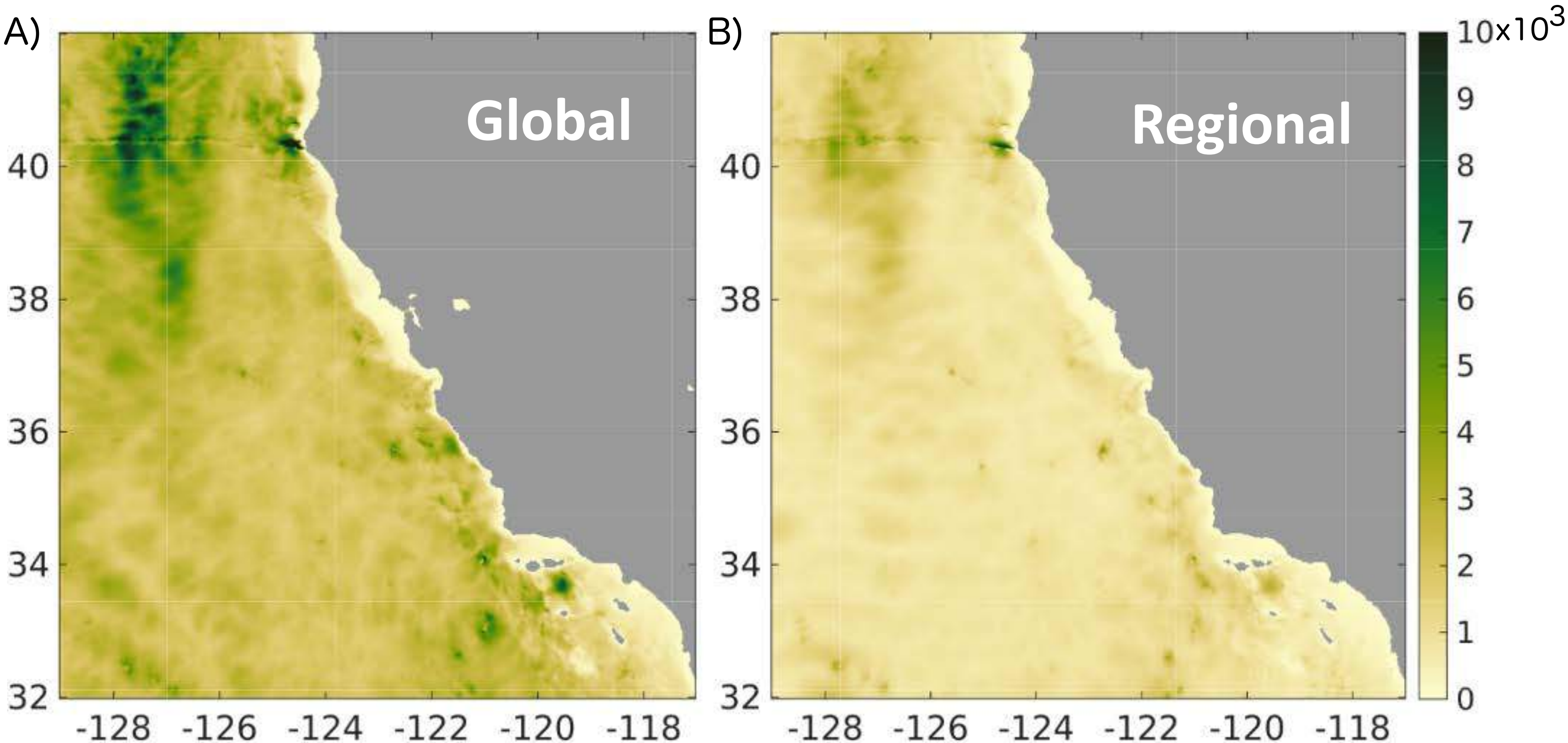
C)

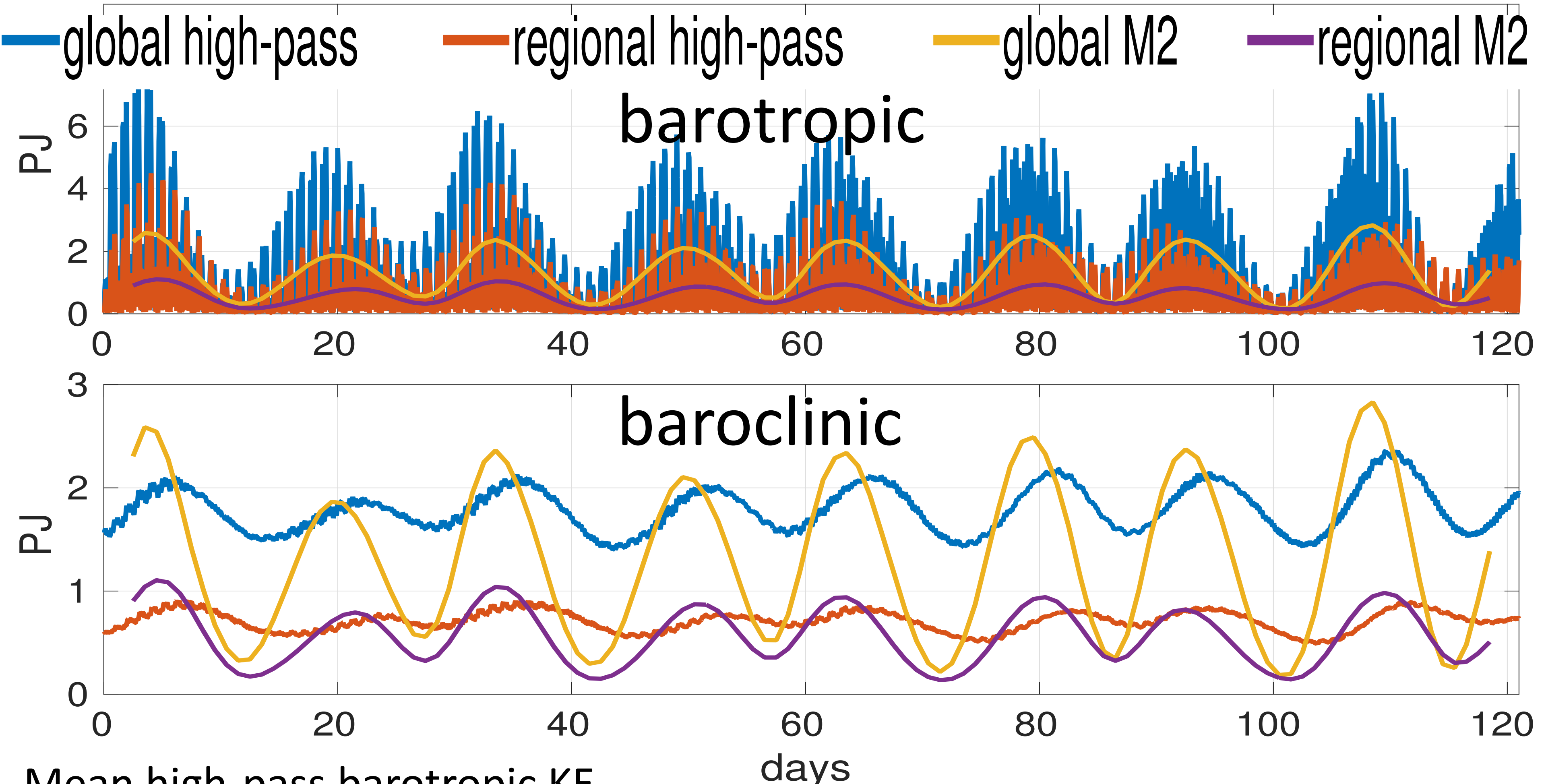


D)



Vertically integrated high-pass baroclinic kinetic energy [J m].
The total high-pass baroclinic energy in the domain is
1.79 PJ for the global model and 0.71 PJ for the regional model.





Mean high-pass barotropic KE

Global: 1.40 PJ Regional: 0.71 PJ

Barotropic KE at the M2 frequency

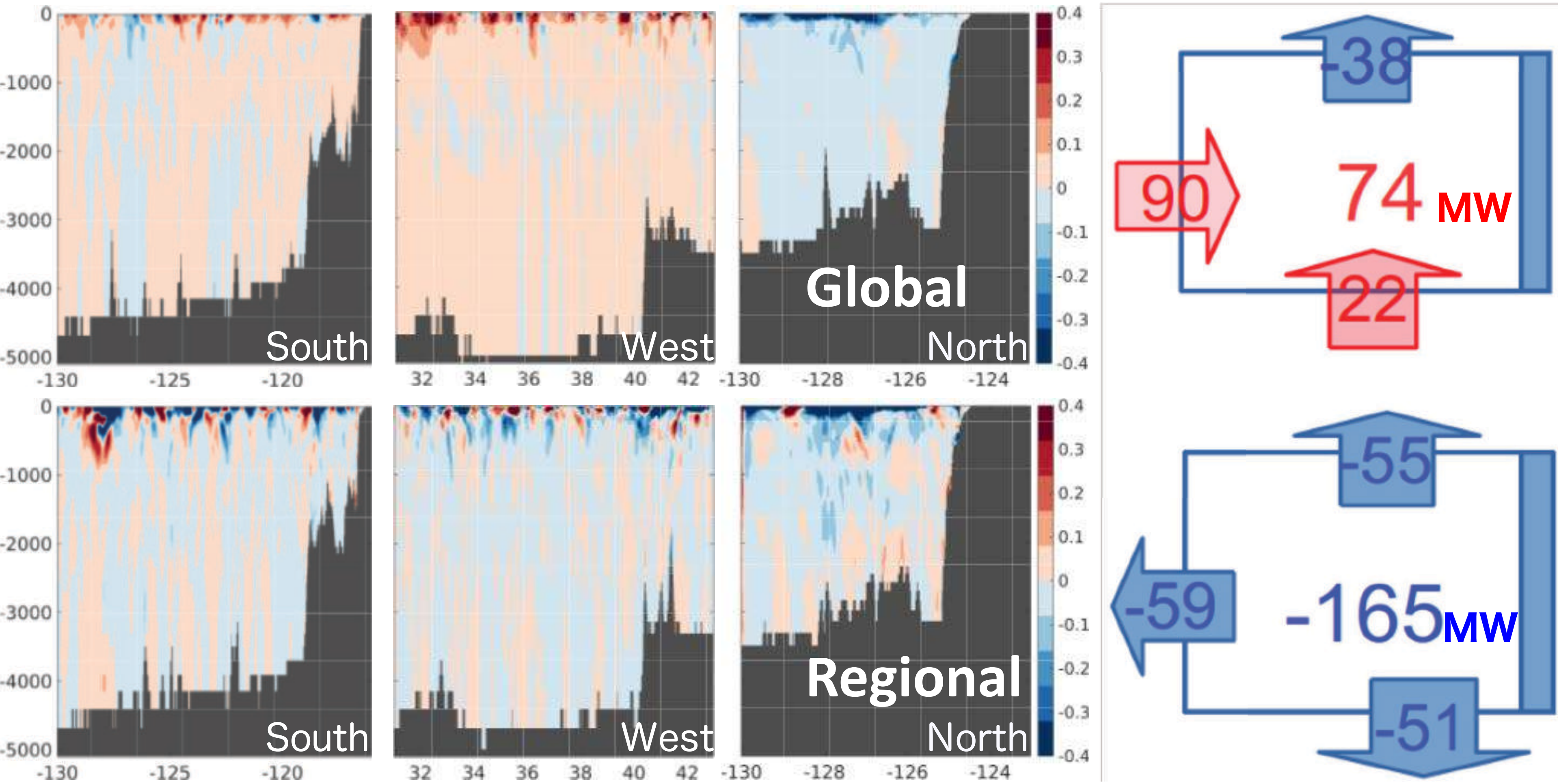
Global: 1.33 PJ Regional: 0.57 PJ

The mean high-pass baroclinic KE

Global: 1.79 PJ Regional: 0.71 PJ

Global has a baroclinic KE 0.39 PJ greater than barotropic.

Global has a baroclinic KE 0.39 PJ greater than barotropic.

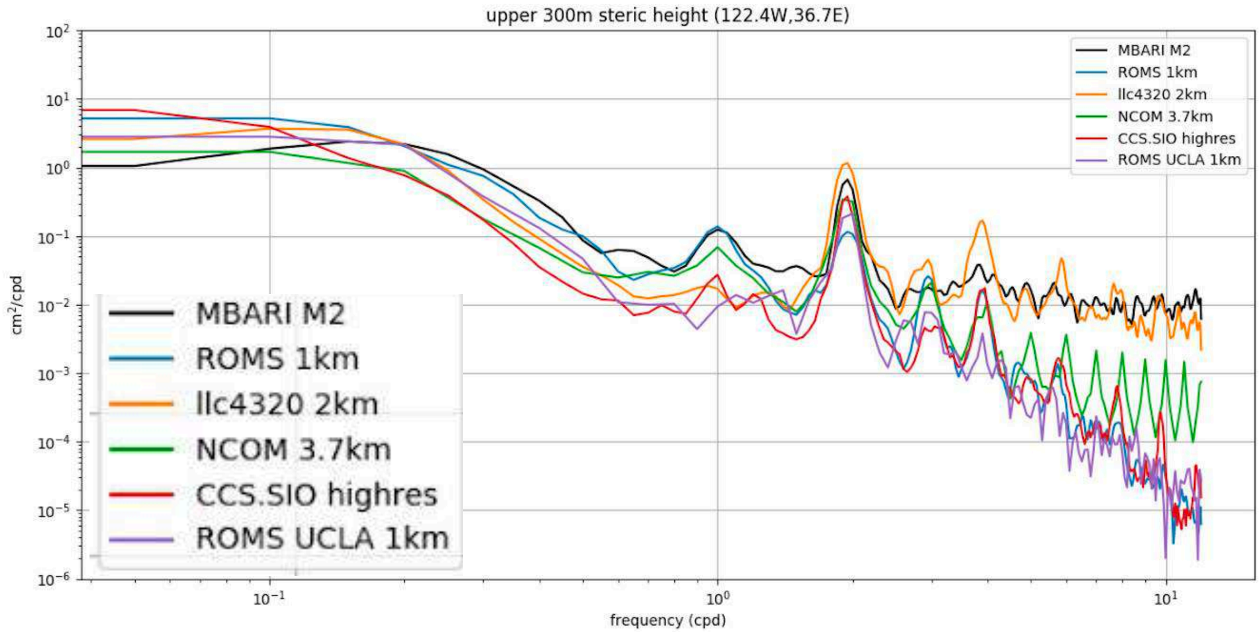


Internal wave energy flux along the analysis domain boundaries.
Red is flux into the domain. Blue is out of the domain.

Integrated boundary energy fluxes **Global: +74 MW** **Regional: -165 MW**

To reconcile the excess 0.39 PJ with a boundary flux discrepancy of 239 MW implies a baroclinic wave energy residence time in the domain of 18.9 days.

- Mooring and **global** Llc4320 (2km) have high-frequency energy
- **Regional** ROMS (1km), MITgcm (2km), and NCOM (3.7km) are all missing high-frequency energy



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- ~~Noise in LLC4320 and/or mooring meaning one or both is wrong.~~
- Tidally generated internal waves do not have time to exchange energy and fill the (Garrett-Munk) spectrum in a regional domain.

Solutions:

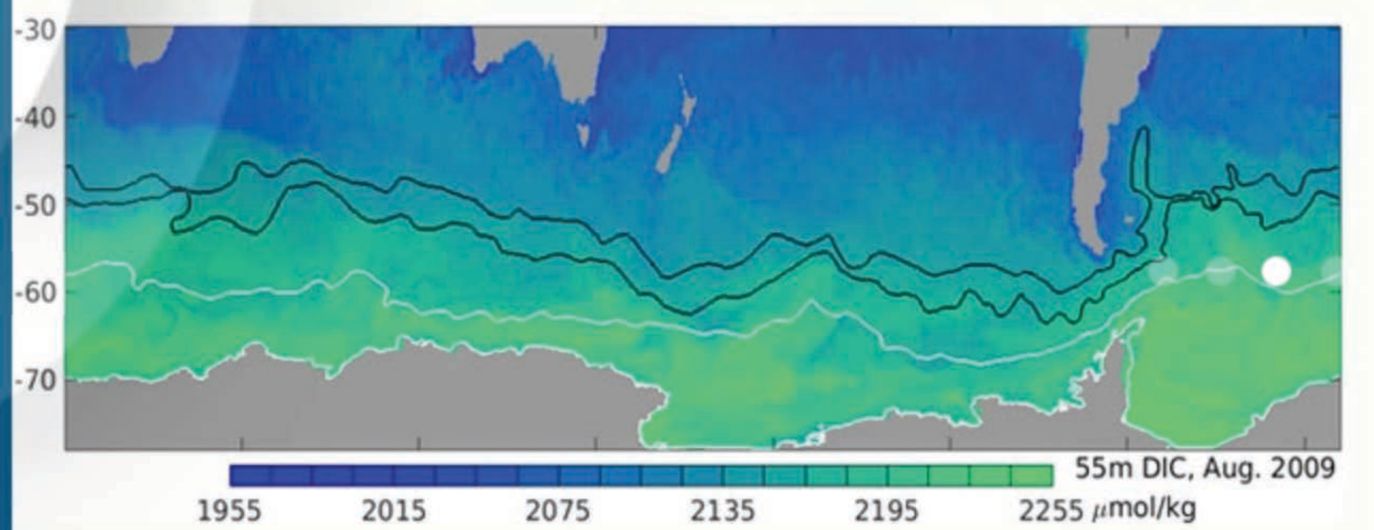
1. Make domain large enough to allow internal waves to transform
2. Prescribe internal wave flux into the domain at the open boundaries

SOCCOM

Unlocking the mysteries of the Southern Ocean

Biogeochemical SOSE Solution Now Available

Access our 3-D estimate of Southern Ocean biogeochemistry



B-SOSE

Biogeochemical Southern Ocean State Estimate

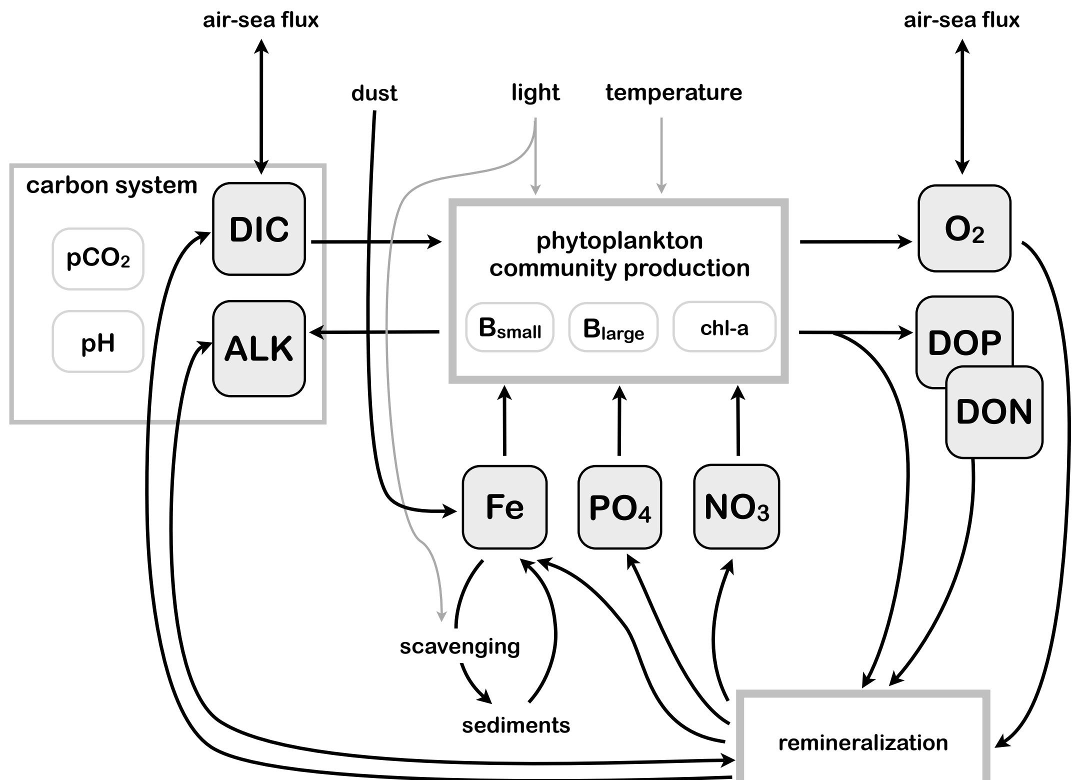
B-SOSE

Biogeochemical Southern Ocean State Estimate

Biogeochemical – ice – ocean Southern Hemisphere model Mercator projection poleward of 30ºS with 1/6º & 52 levels, then telescopes to equator.

Biogeochemistry with Light, Iron, Nutrients and Gases (BLING) version 2.

State estimate is being derived with MITgcm-ECCO machinery: **Closed budgets!**



Budget diagnostic software and examples

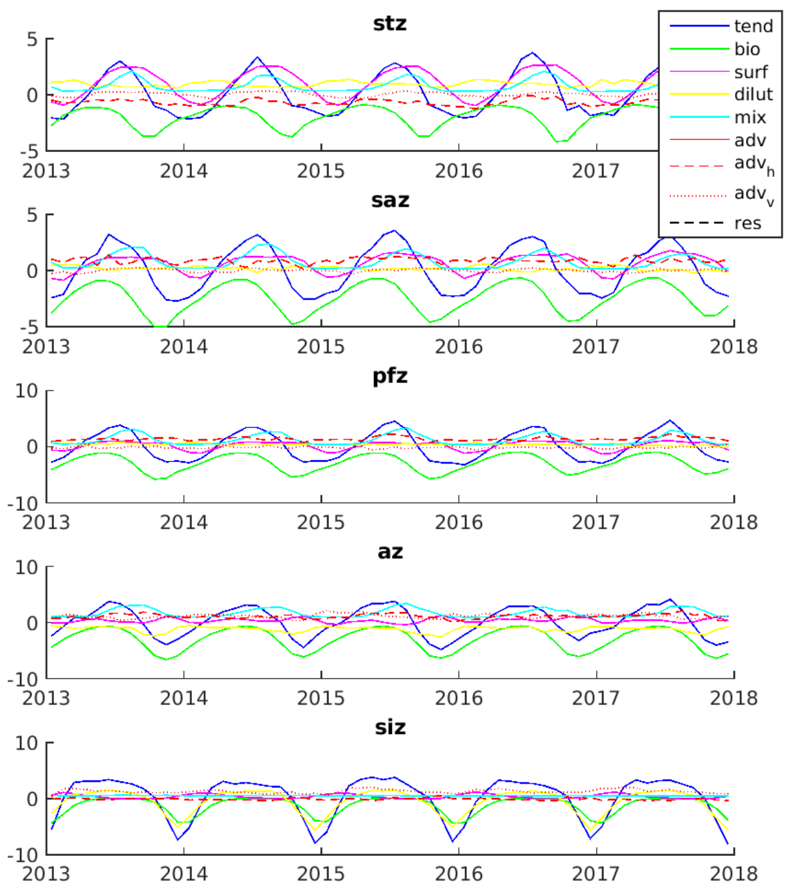
http://sose.ucsd.edu/budgets/

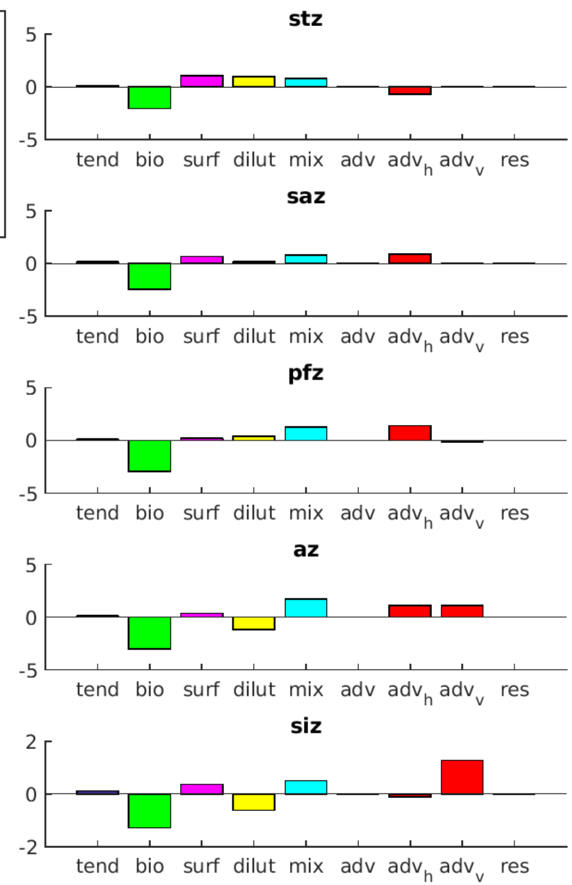
BGC budgets being presented for BSOSE iteration 105 (2008-2012)

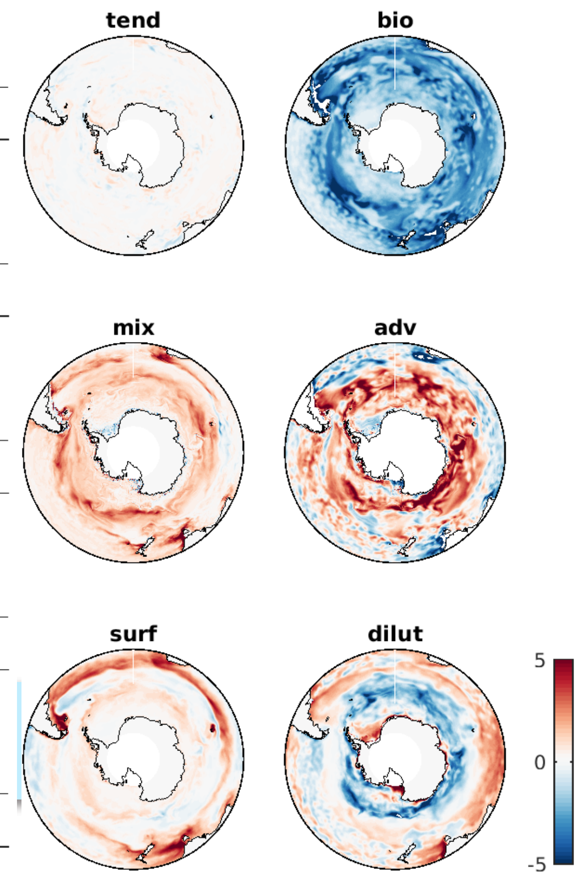
In development. Currently has: DIC, O2, NO3, and FE for top 150m and top 650m

For five regions of the Southern Ocean we present:

Time series (bins), mean (bins) , mean







Regional models are great for targeted efforts

- Reproducing small scales
- Consistency with specific system components, regions, times, obs platforms
- Observing system design
- Forecasting
- Development

But beware the open boundaries!!!