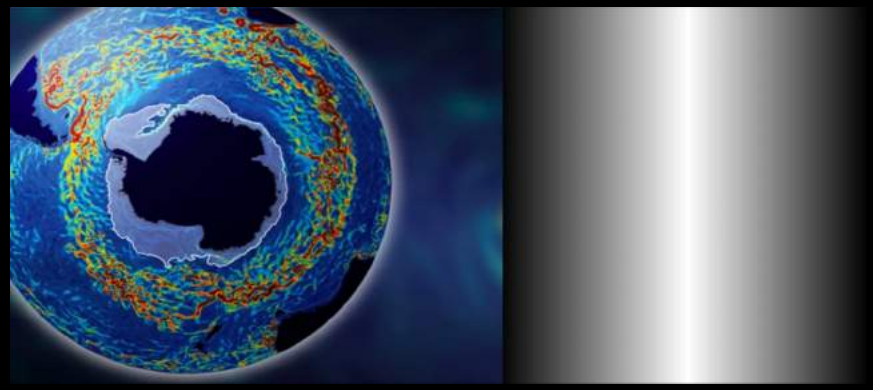

SIO activities in preparation for SWOT and the next generation observing system

ECCO Meeting 2018

Matt Mazloff, Paul Chamberlain, Teri Chereskin, Bruce Cornuelle, Ganesh Gopalakrishnan, Luke Kachelein, Heriberto Vazquez Peralta, Aneesh Subramanian, Rui Sun, Ariane Verdy, Bia Villas Bôas, Kasia Zaba

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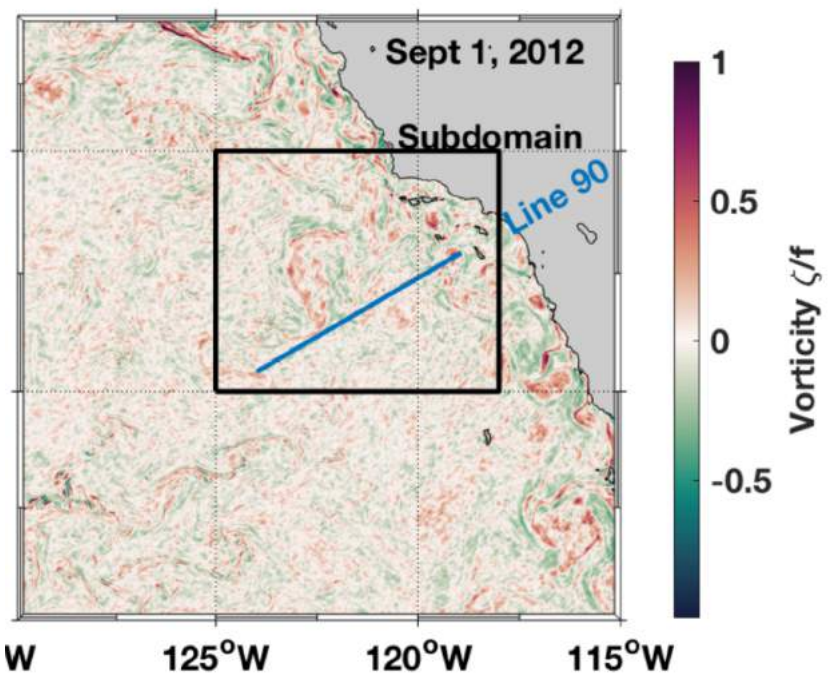
Assimilation for next generation observing system

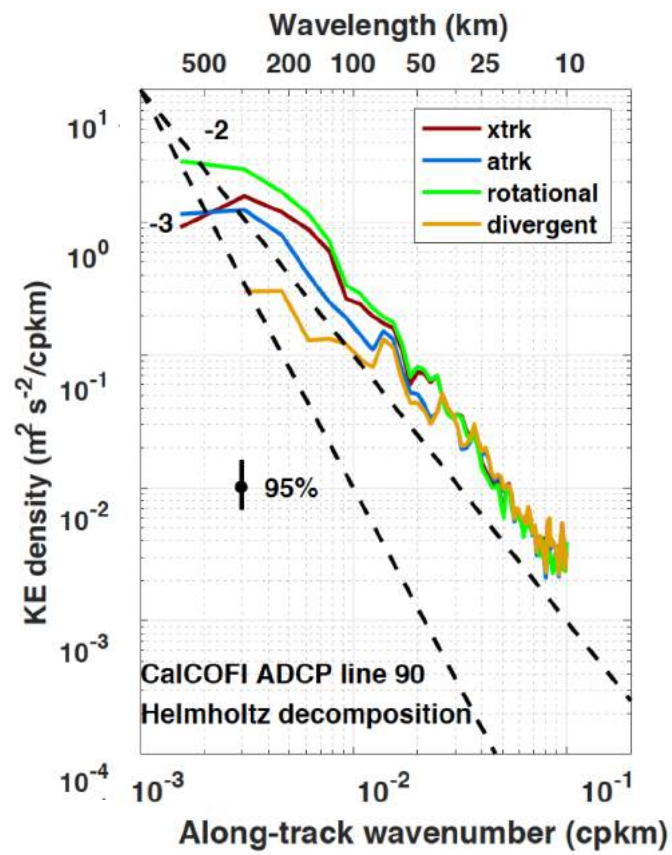
- Characterize physical scales and **develop tools** to map the state
- Hold model accountable to data. As data stream grows must also **semi-automate QC**: hold data accountable to model

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

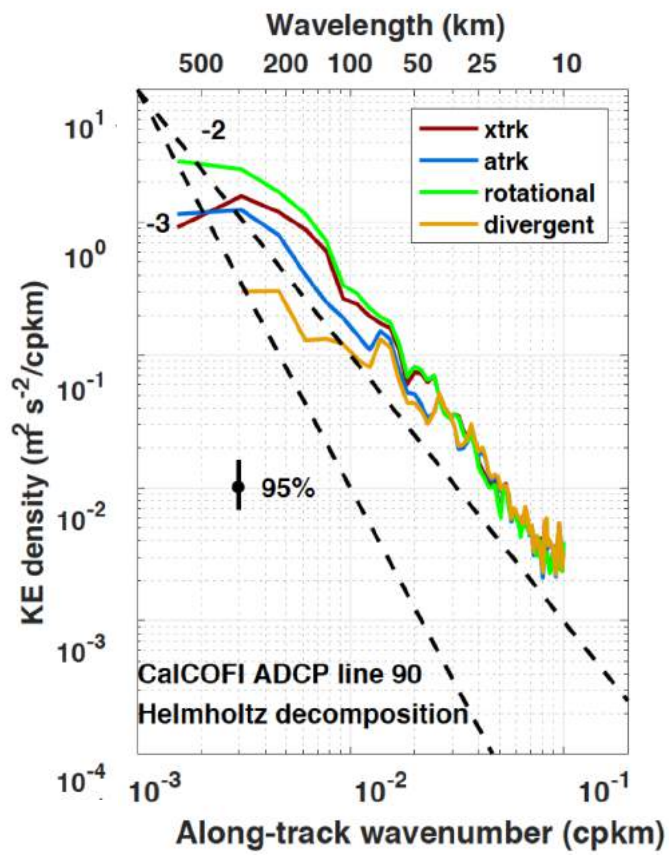
- Characterize physical scales and **develop tools** to map the state
- Hold model accountable to data. As data stream grows must also **semi-automate QC**: hold data accountable to model

Chereskin et al, submitted, JGR-Oceans,

Characterizing the California Current

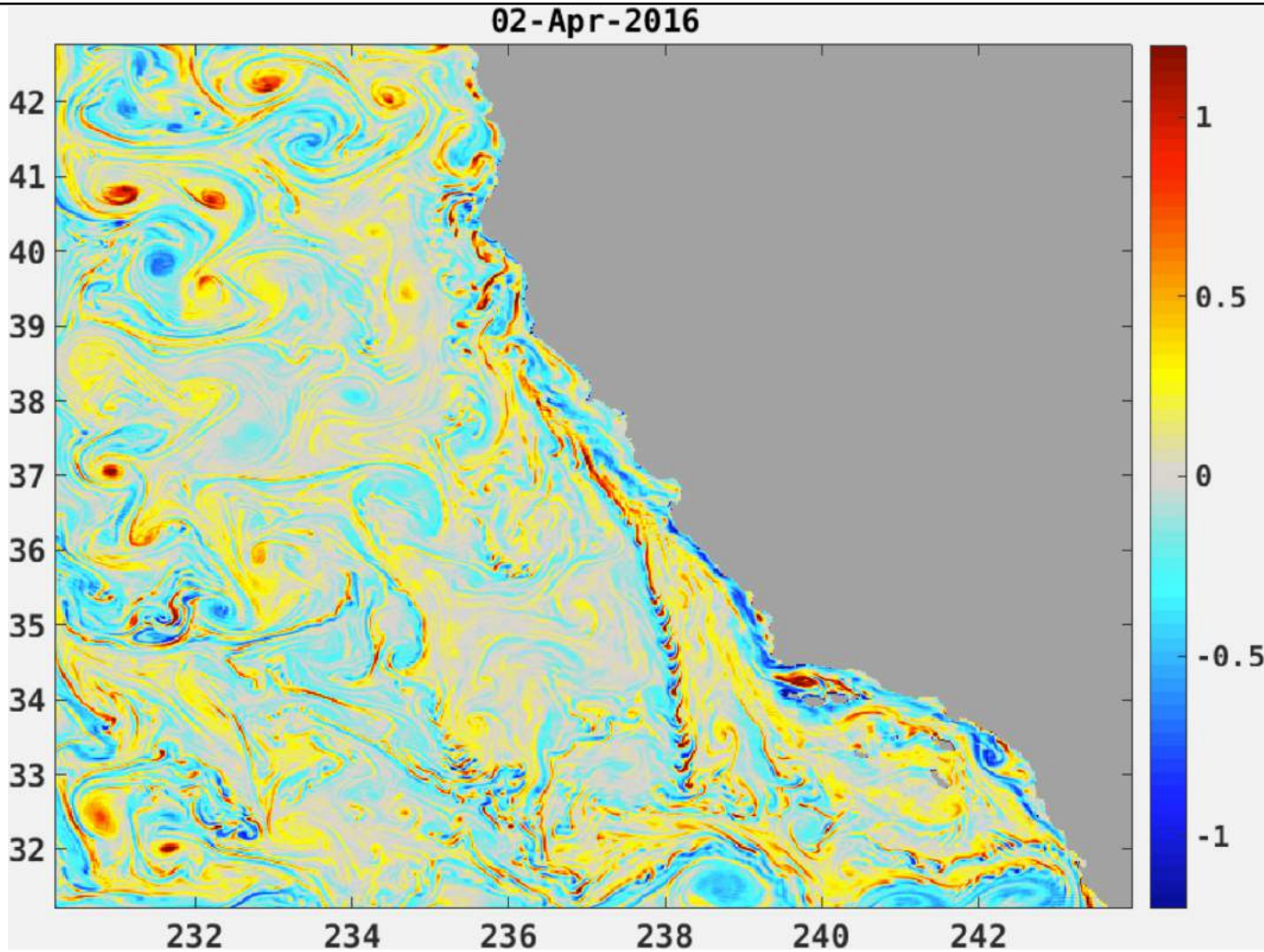
The challenge is to represent both the **rotational** (balanced, geostrophic) and **divergent** (ageostrophic) components of the flow.

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



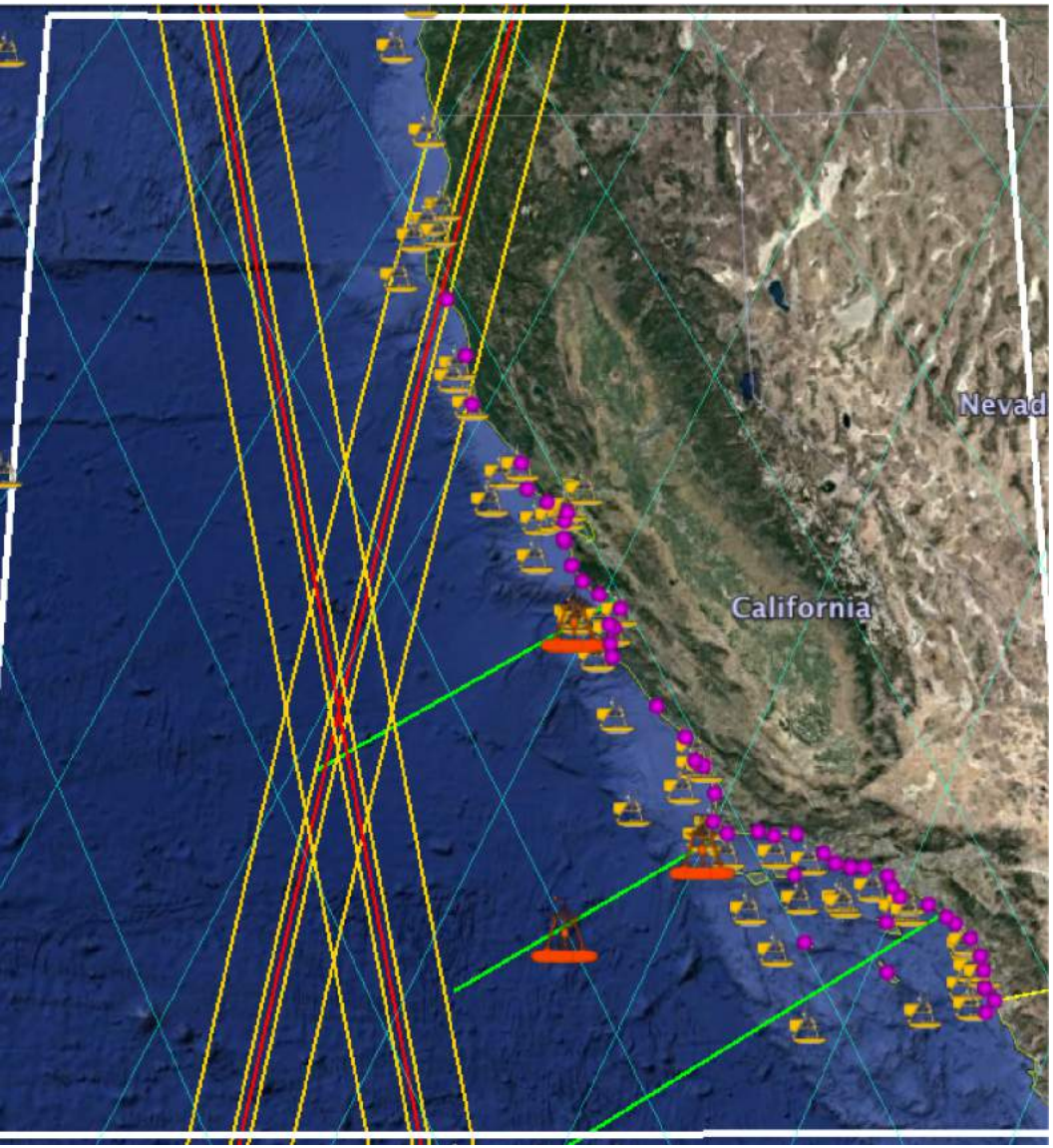
Mapping all parts of the signal

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

MITgcm: California Current test bed



MITgcm
- 2 km
- Numerics identical to LLC4320
- Inputs different

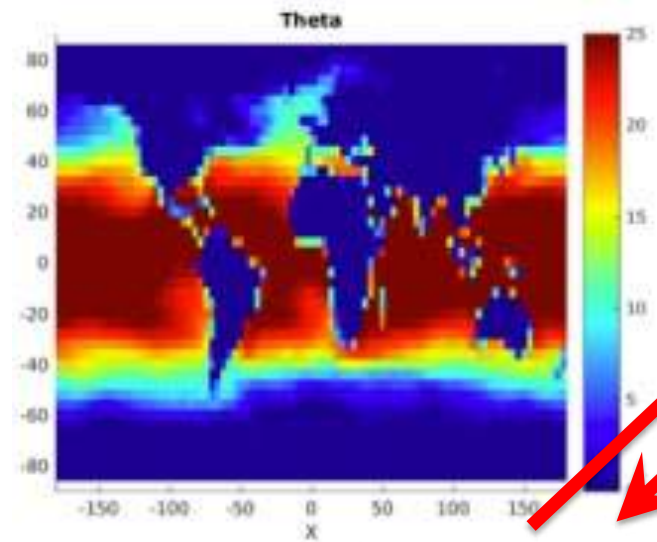
Assimilate:
- SWOT (yellow lines)
- Nadir altimetry (Jason in cyan)
- Moorings (red)
- HF radar (magenta)
- NDBC buoys (yellow)
- Glider lines (green)

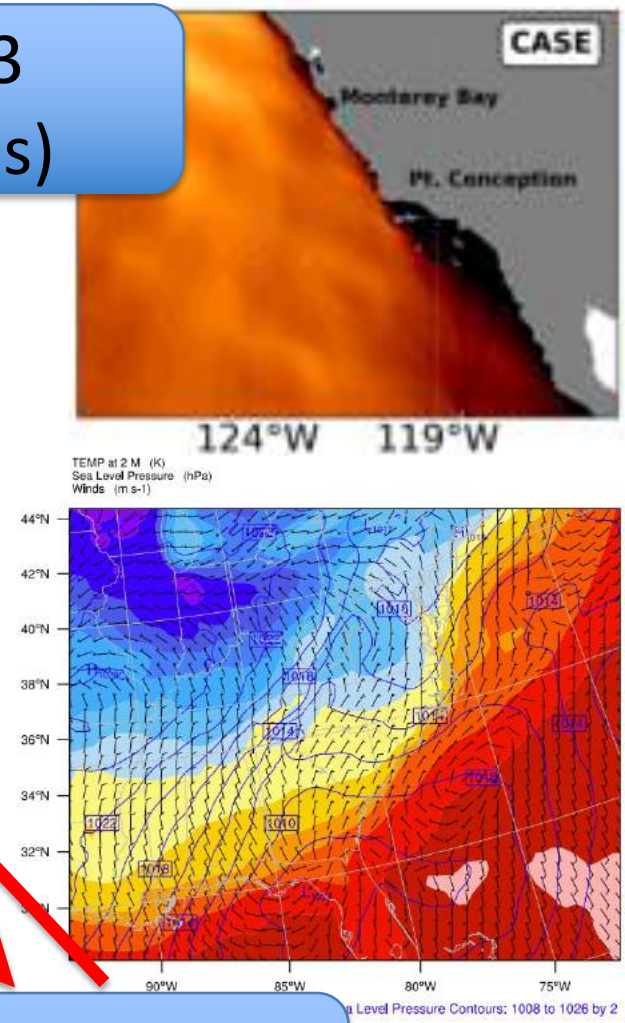
Developing a Regional Ocean-Atmosphere Coupled Model

- Rui Sun, A. Subramanian, M. Mazloff, B. Cornuelle, A. Miller, I. Hoteit, M. Ralph

Goals

- Developing a coupled atmosphere-ocean-wave model with assimilation capabilities.
- Developing a research tool for studying coupled interactions and extended range predictability.





WW3 (waves)

ESMF (driver)

WaveWatch III

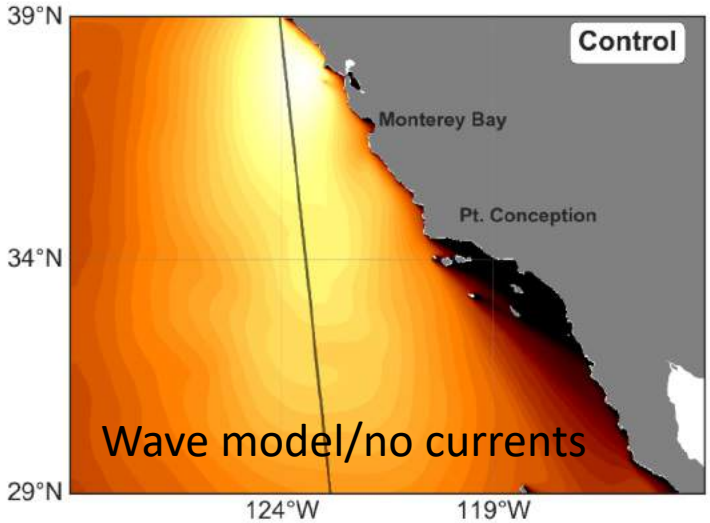
MITGCM (ocean)

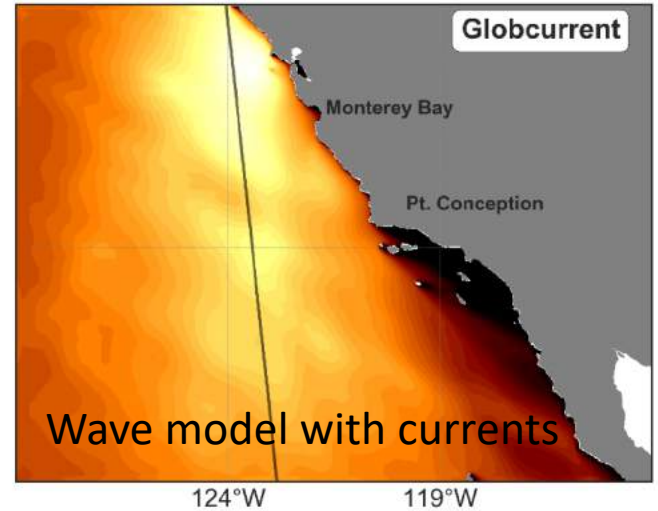
WRF (atmosphere)

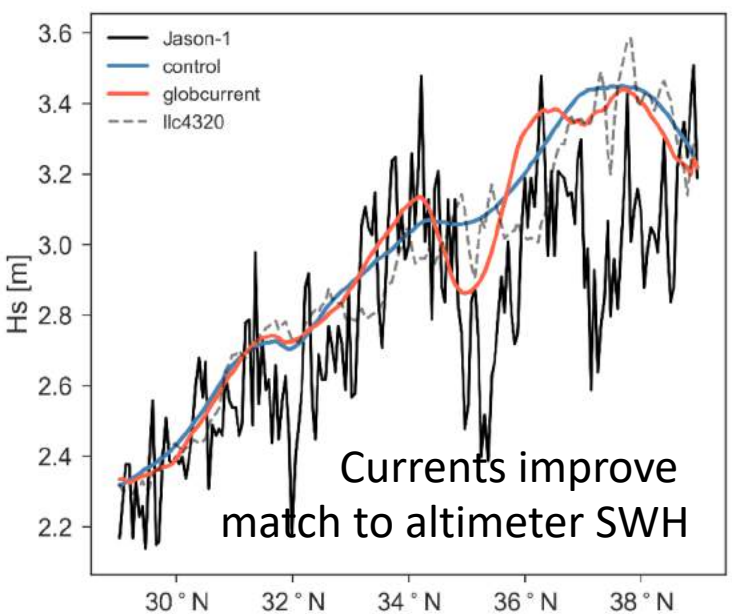
Bia Villas Boas: WaveWatch3

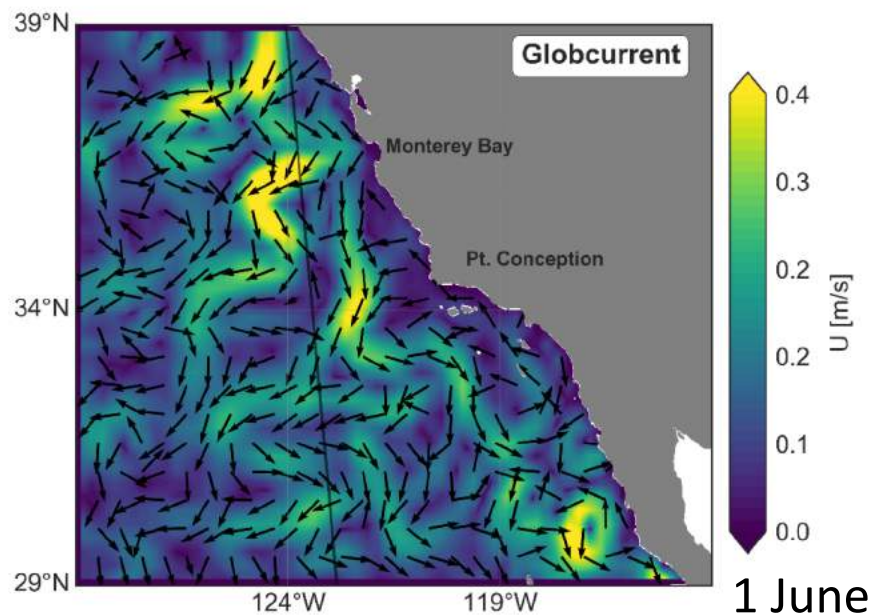
The eddy variability also affects the Surface wave field

One-way results: currents affect waves





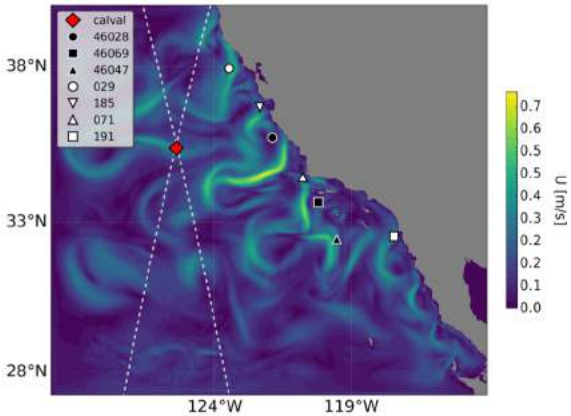




1 June 2012

Currents Drive Wave Field and Vice Versa

MITgcm
State Estimate



Surface Currents
+
Winds

WaveWatch III

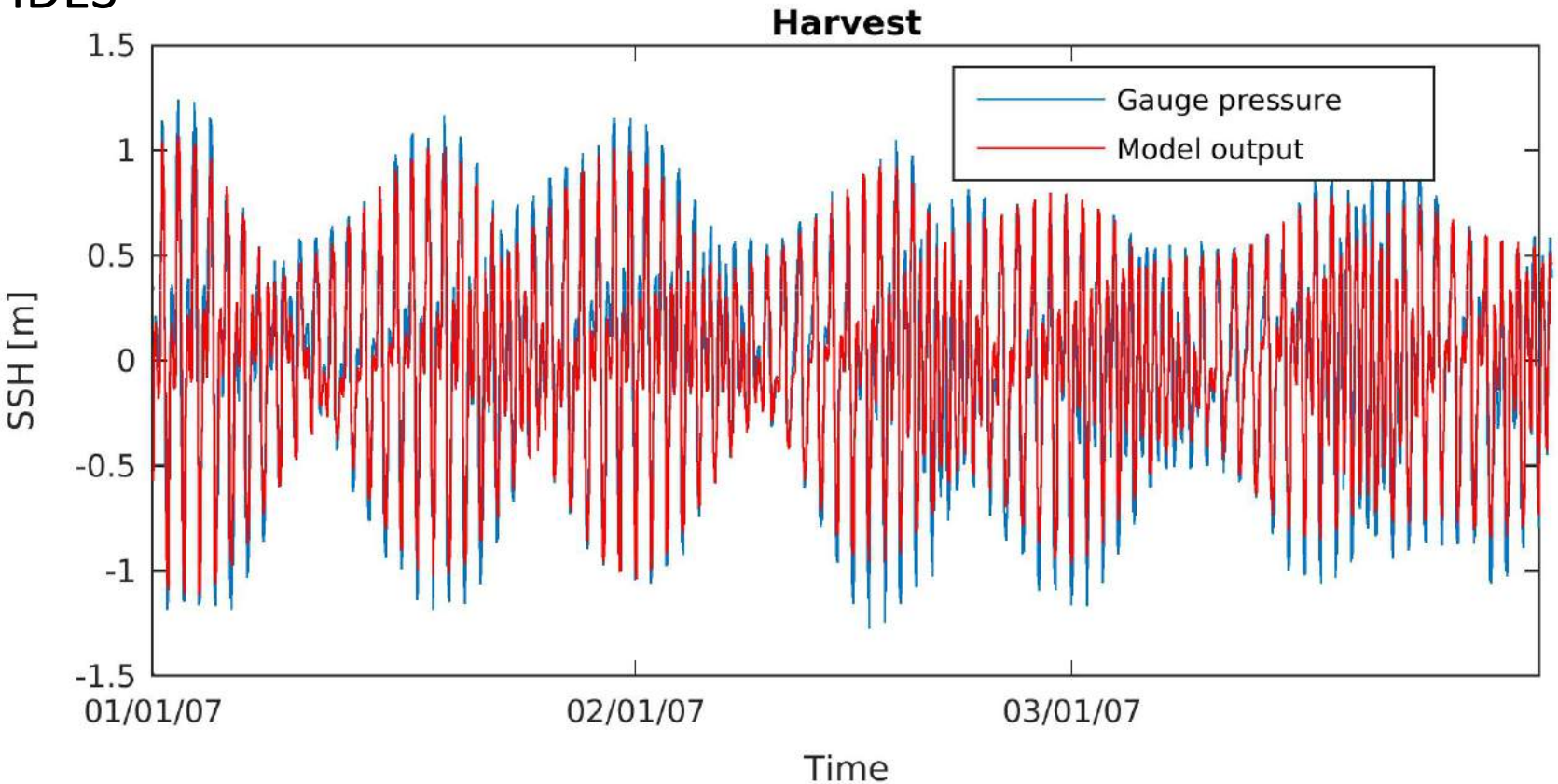
$$\frac{\partial N}{\partial t} + \nabla \cdot (\mathbf{c_g} N) = S_{in} + S_{nl} - S_{ds}$$

$$\mathbf{c_g} = \mathbf{c_g}' + \mathbf{U}$$

Two-way coupling now started via Earth System Modeling Framework

WRF (atmospheric model) also coupled

TIDES

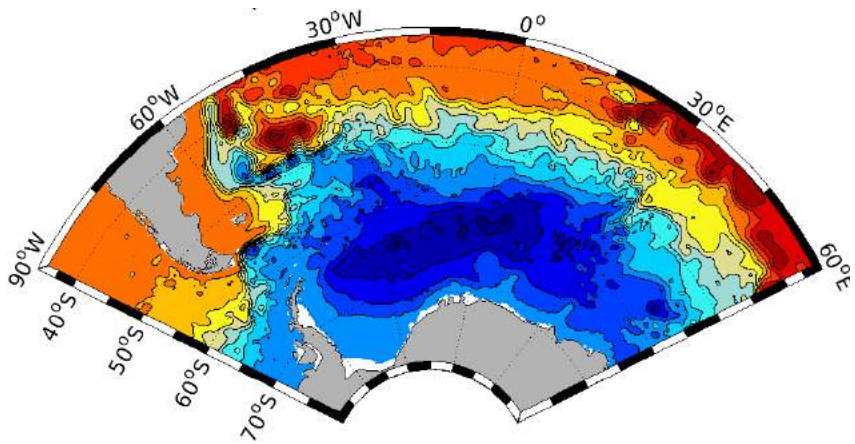


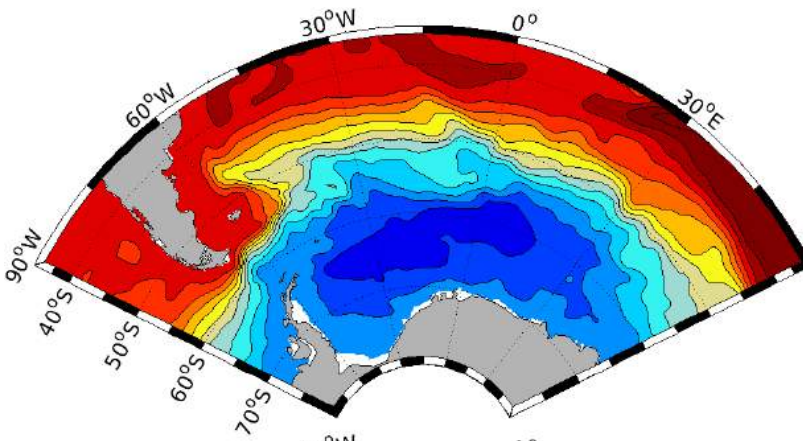
Tide model integrated into MITgcm

Assimilation for large-scale field; not for tides

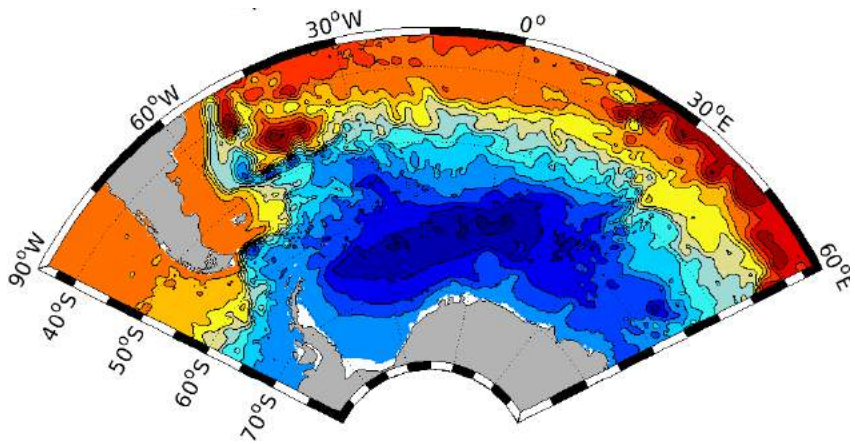
Good match to tide gauge data

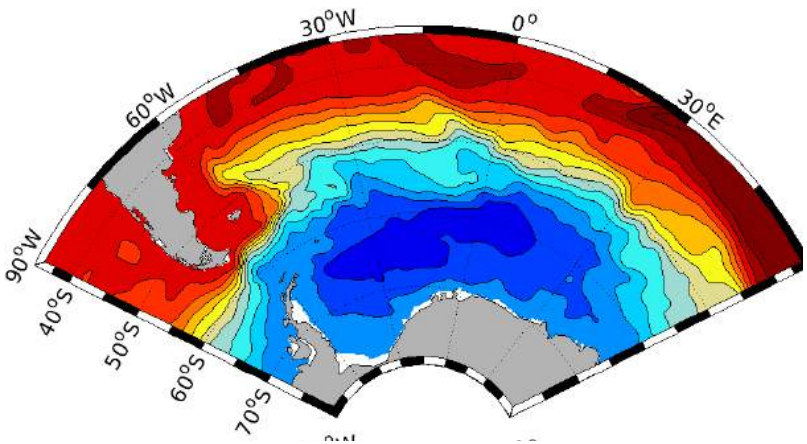
	AmpModel	PhaModel	AmpGauge	PhaGauge
M2	0.4283	173.0098	0.4586	162.4997
S2	0.1328	176.3363	0.1871	168.4910
N2	0.0986	146.7515	0.1063	147.6276
K1	0.3300	232.8317	0.3831	222.8095
O1	0.2181	207.2208	0.2564	200.7630
Q1	0.0411	199.7112	0.0507	197.0872





- **Multigrid 4D-Var stabilizes the adjoint**
  - 4D-Var optimization relies on the adjoint of the tangent linear model.
  - The adjoint is linear, it doesn't limit eddy-mean flow interaction – without feedback on mean flow sensitivity can grow without bound
  - Keeping adjoint model stable requires damping growing sensitivities.
  - Most trivial/common way to do this is with increased viscosity in the adjoint (e.g. factor of 10 or 100)
  - This mimics coarse resolution, so why run with the computational expense of the high-resolution forward model?





- **Other multigrid 4D-Var advantages**
  - Allows the forward simulation to use the best parameterizations and modeling schemes (may include tides, surface gravity waves, nonlinear advection and viscosity schemes, biogeochemistry)
  - Free to decide what observational information represented in optimization. (E.g. internal wave field can be treated as signal. If treated as noise the forward model can be used to help determine representation error on the fly)
  - Regardless of prescribed signal to noise, full cost function facilitates post-analysis validation of all scales. (Maps generated via 4d-var fit one set of scales & provide hypotheses on finer scales, informed and validated from SWOT)

Multi-grid 4D-Var is implemented in various architectures. Notably, it is part of the ECMWF operational methodology. Buehner et al., 2013 state that in February 2013 they were optimizing the 25 km resolution forward model solution using an adjoint run at 100 km resolution.

ECMWF Chapter 2: 4D variational assimilation

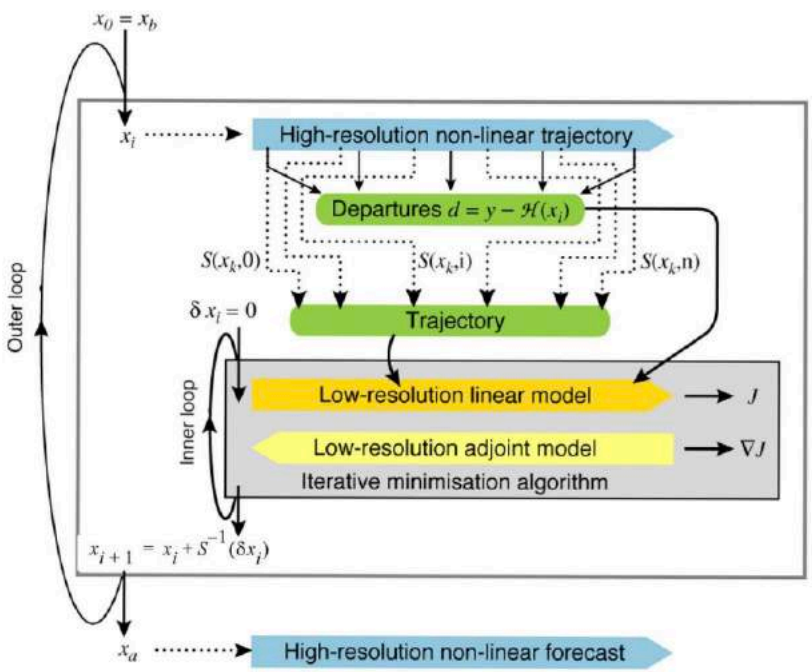


Figure 2.1 *Schematic of the revised 4D-Var solution algorithm implemented in January 2003 (Cy25r4). Outer loops are performed at high resolution (currently T1279) using the full non-linear model. Inner iterations are performed at lower resolution (first T159, then T255) using the tangent-linear forecast model, linearised around a 12-hour succession of model states ('the trajectory') obtained through interpolation from high resolution (S denotes the truncation operator, J the cost function and x the atmospheric state vector).*

IFS DOCUMENTATION – Cy40r1 Operational implementation (2013)

Multi-grid (or multi-resolution) 4D-Var is seamlessly integrated to ECCO via the adjoint model's *N*–level checkpointing algorithm

Reverse order integration (ii)

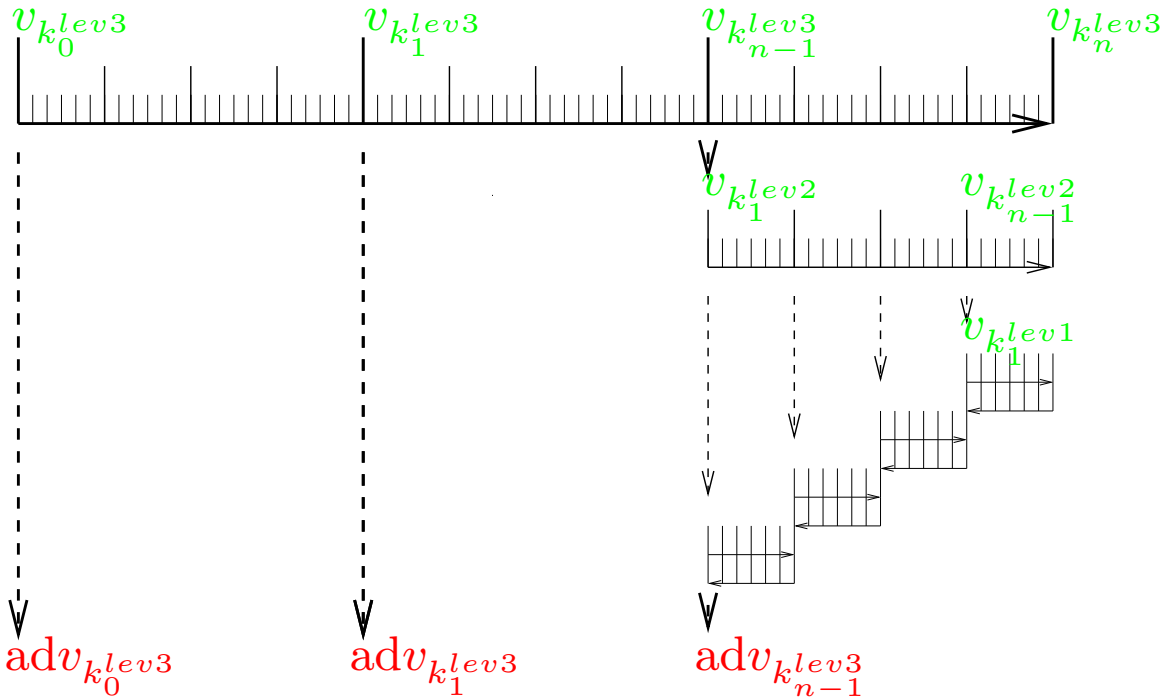
- *Adjoint = transpose of TLM*

  → evaluated in reverse order

  → model state at every time step required in reverse

  → all state stored or recomputed

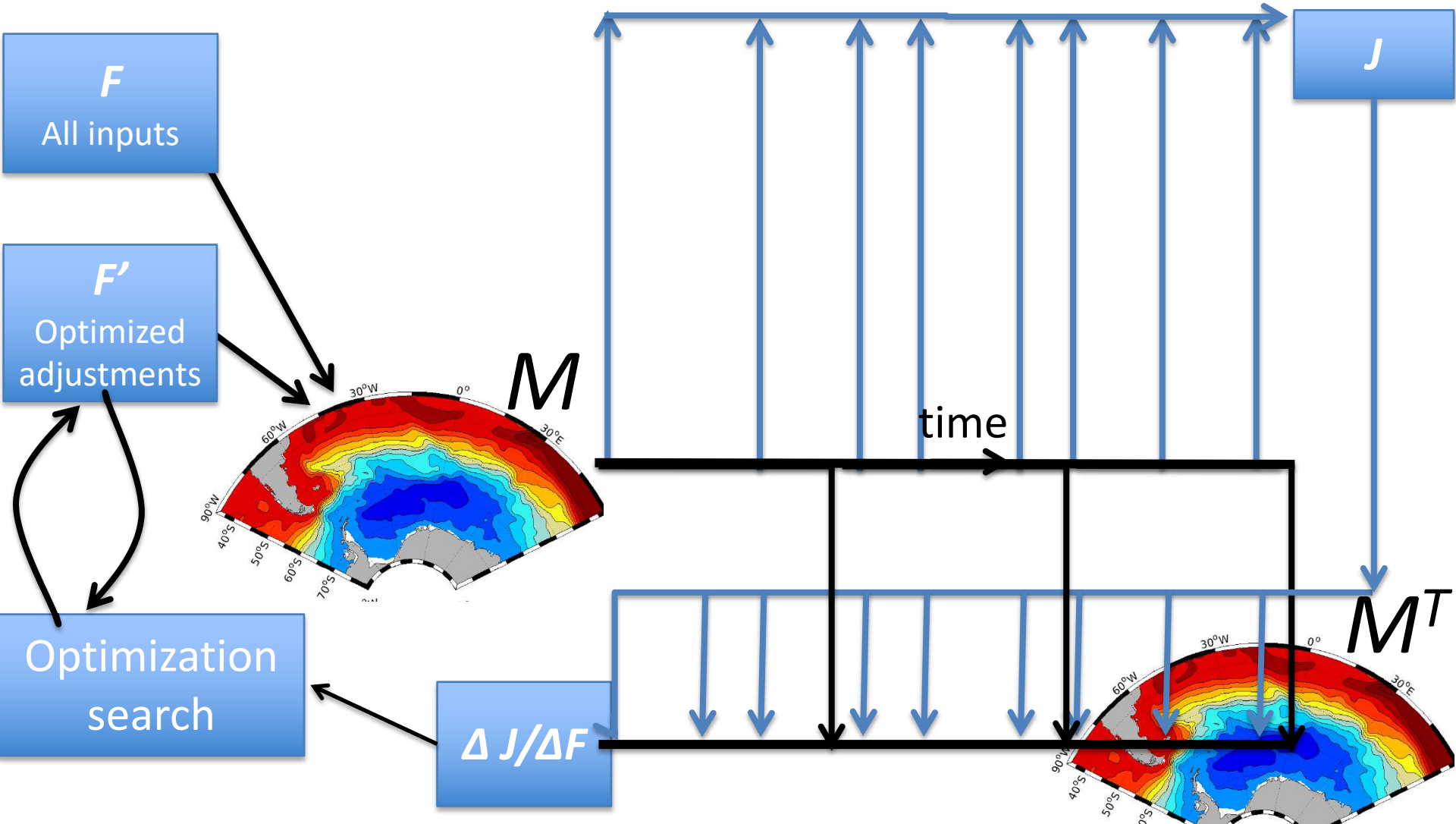
- *Solution: Checkpointing* (e.g. Griewank, 1992, Restrepo et al., 1998) balances storing vs. recomputation



Multi-grid coupling

A model, ***M***, and its adjoint, $\boldsymbol{M^T}$, are used to optimize input adjustments, **F'**, to the input forcing ***F***, such that $\boldsymbol{F_{opt} = F + F'}$

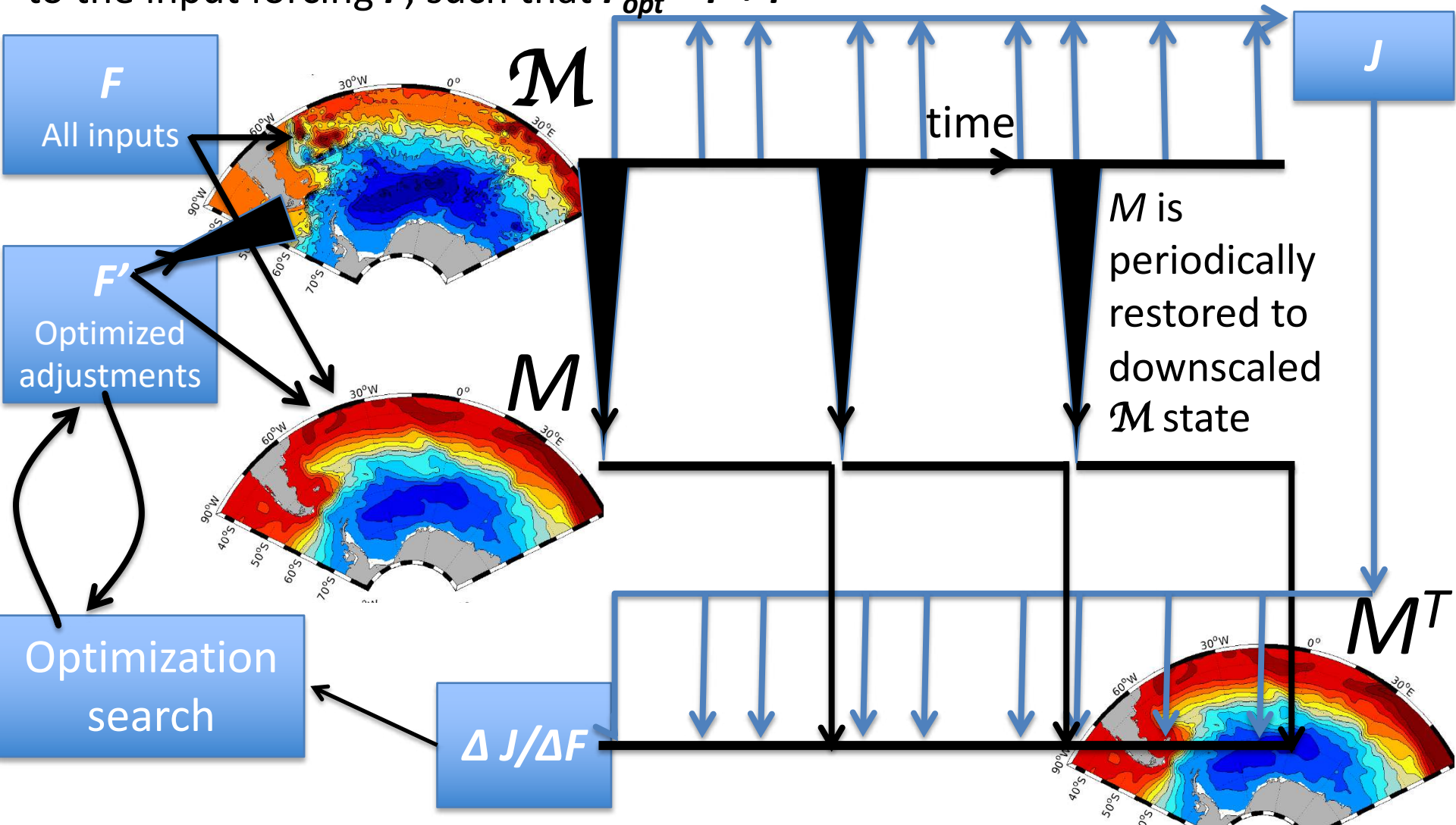
Cost function, ***J***, is calculated by sampling ***M***. It is stored in data and model space and forces $\boldsymbol{M^T}$



Multi-grid coupling

A state-of-the-art high-resolution model, $\mathcal{M}$, an upscaled model, ***M***, and its adjoint, $\boldsymbol{M^T}$, are used to optimize input adjustments, ***F'***, to the input forcing ***F***, such that $\boldsymbol{F_{opt} = F + F'}$

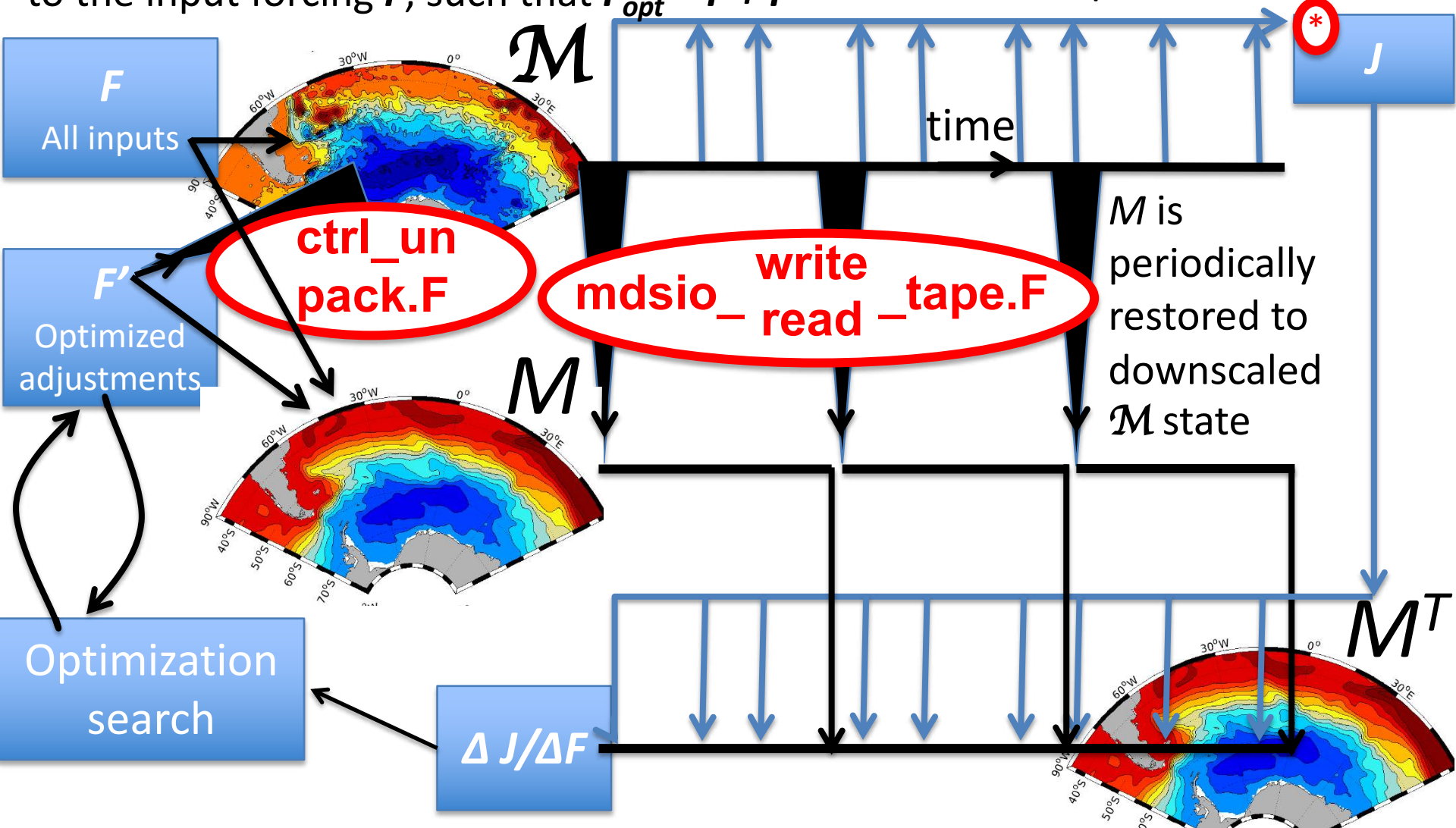
Cost function, ***J***, is calculated by sampling $\mathcal{M}$. It is stored in data space and forces $\boldsymbol{M^T}$



Multi-grid coupling

A state-of-the-art high-resolution model, $\mathcal{M}$, an upscaled model, $\boldsymbol{M}$, and its adjoint, $\boldsymbol{M}^T$, are used to optimize input adjustments, $\boldsymbol{F}'$, to the input forcing $\boldsymbol{F}$, such that $\boldsymbol{F}_{opt} = \boldsymbol{F} + \boldsymbol{F}'$

Cost function, $\boldsymbol{J}$, is calculated by sampling $\mathcal{M}$. It is stored in data space and forces $\boldsymbol{M}^T$

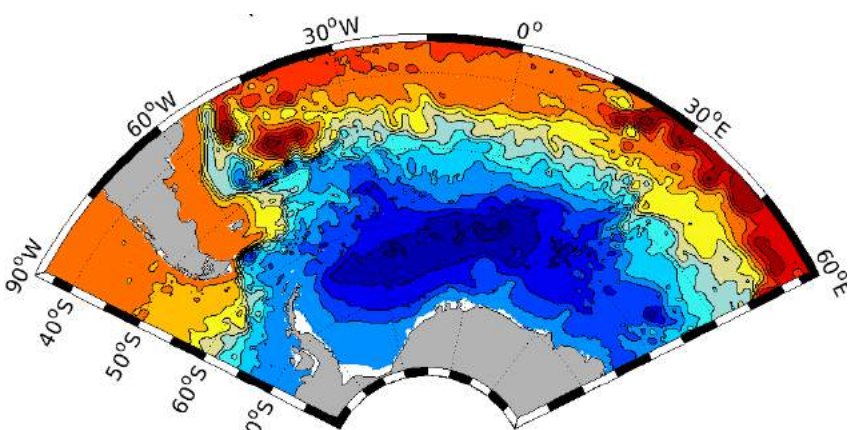


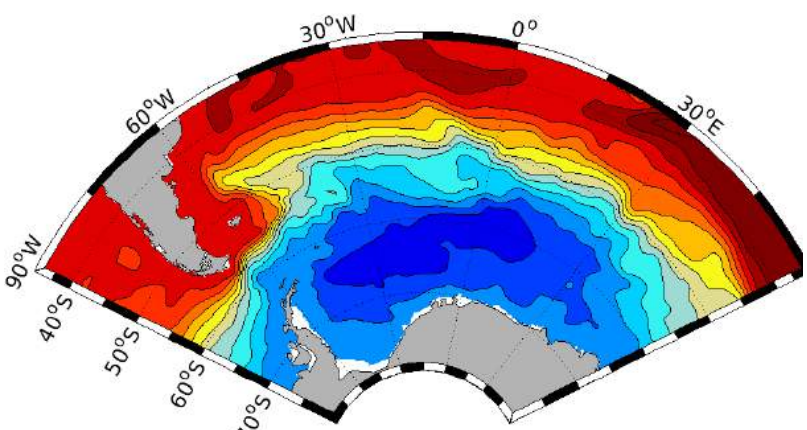
Computationally feasible to optimize at high resolution over large regions---even globally

34 day example: 1/6 forward, 1/3 back. 52 vertical levels

Two-level checkpointing.

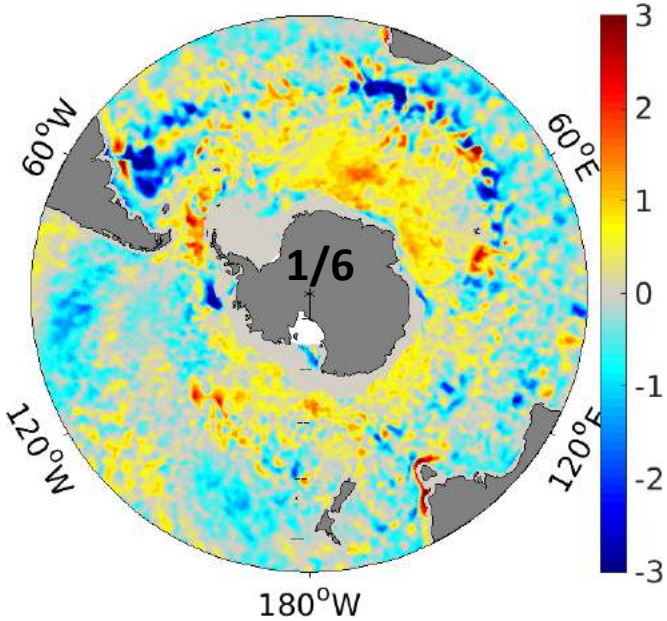
- 1/6 forward run, 30 minute time-step, 557 cores: **97 mins wallclock**
- The 1/3 adjoint run, 1 hour time-step, 229 cores: **25 mins wallclock**
- 1/6 adjoint run, 30 minute time-step, 557 cores: **189 mins wallclock**
- **One iteration of 4D-Var** (122 mins vs 286 mins = 2.3 times faster)
  - **With multigrid = ~22 hours per year of 1/6 optimization**
  - **Without multigrid = ~51 hours per year of 1/6 optimization**
  - **Adjoint model run ~4 times faster than forward run!**





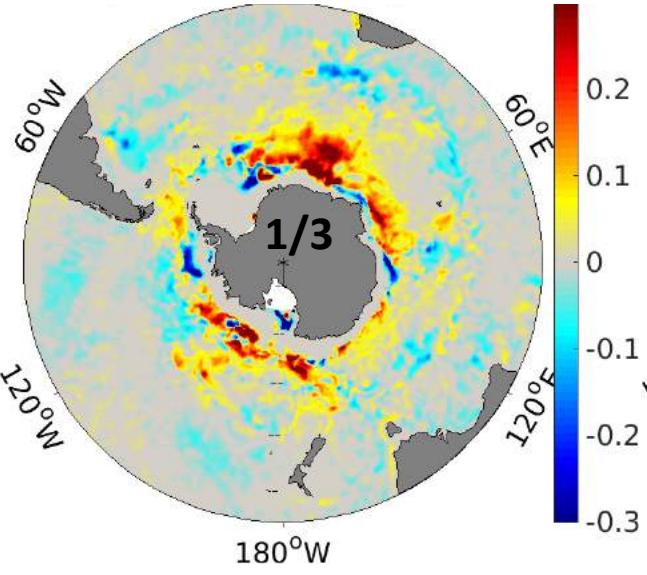
Mean SST misfit [^oC]

Example: 34 day run.
1/6° forward and 1/3° adjoint
Cost is misfit to sea surface temperature (SST).

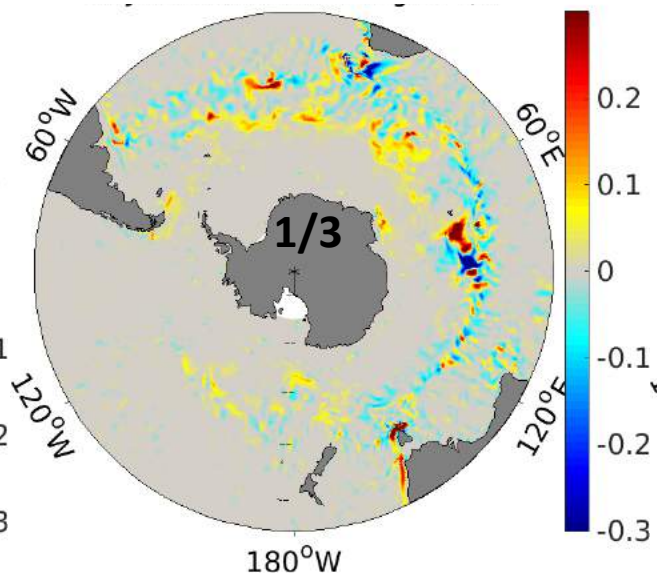


Normalized gradient with respect to initial conditions of temperature at

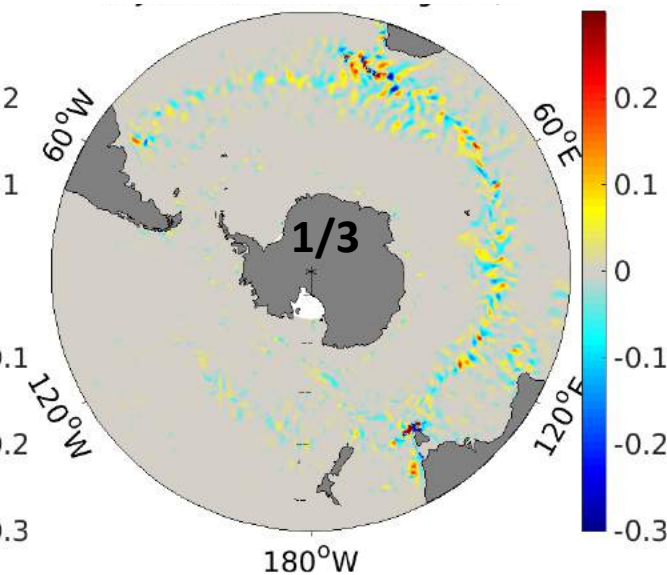
2.1 m



85 m

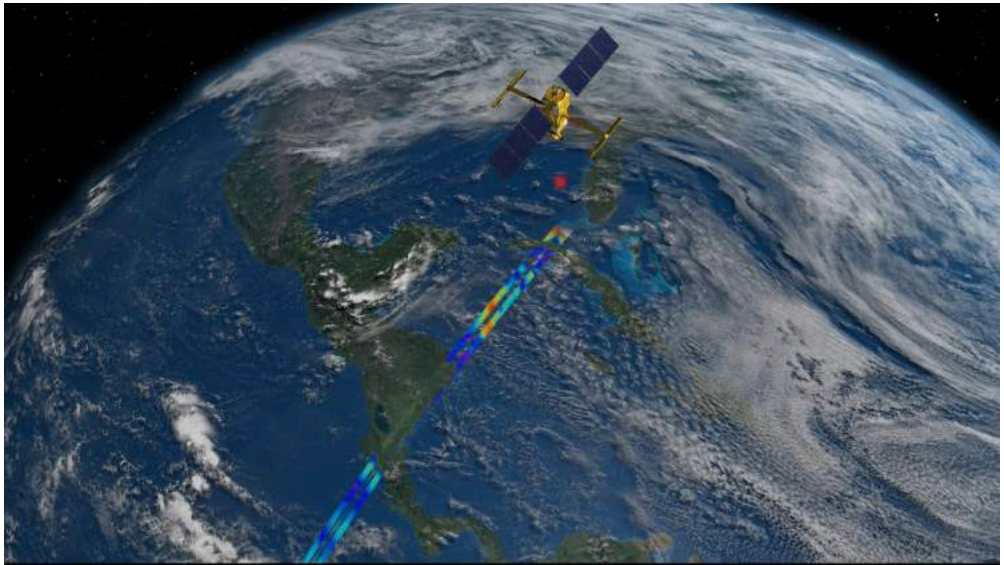


220 m



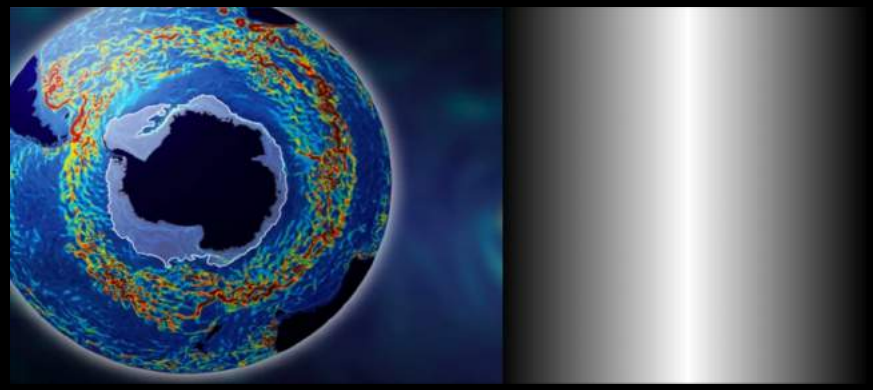
Assimilation for next generation observing system

- Characterize physical scales and **develop tools** to map the state
  - High-resolution implies high computational cost → regional domains, multi-grid assimilation
  - Surface waves → couple wave and ocean models
  - Tides → include tide model in ocean model
  - Internal waves → *exploring handling regional model open boundary forcing*
  - Errors → *ensemble approach or use gradient descent information from adjoint*
  - Evolved parameterizations and control vector → *informed from constraints*
- Hold model accountable to data. As data stream grows must **semi-automate QC**: holding the data accountable to model facilitated via state estimation



Surface Water Ocean Topography (SWOT) swath altimeter will measure SSH at 250 m resolution in two 50 km wide swaths on either side of its orbit. This is estimated to generate ~37 GB/day of data.

Image from swot.jpl.nasa.gov.



Why do regional models produce frequency spectra steeper than llc4320 and observations?

ECCO Meeting 2018

Matt Mazloff, Paul Chamberlain, Bruce Cornuelle, Ganesh Gopalakrishnan, Luke Kachelein, Heriberto Vazquez Peralta, Aneesh Subramanian, Rui Sun, Ariane Verdy, Bia Villas Bôas, Kasia Zaba

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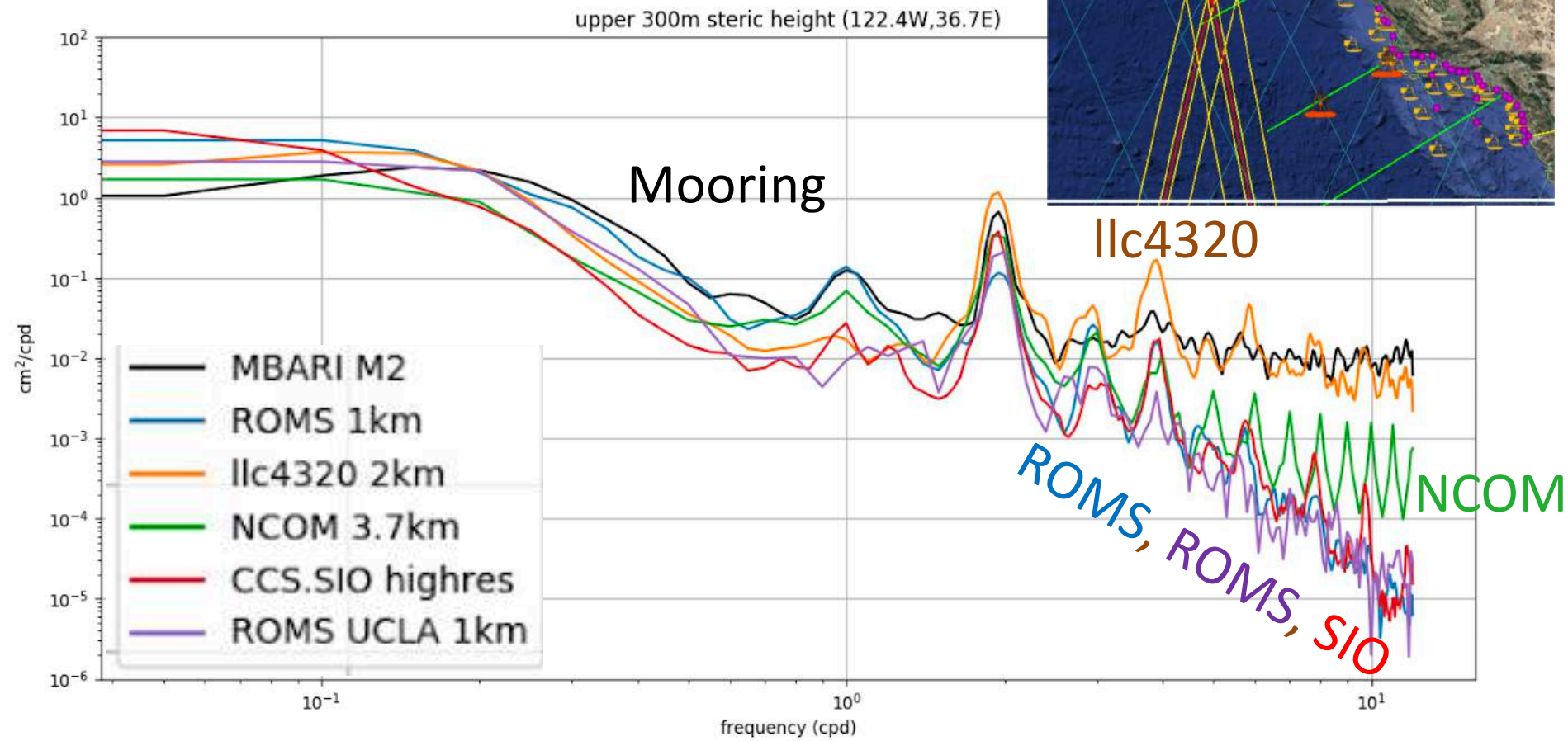
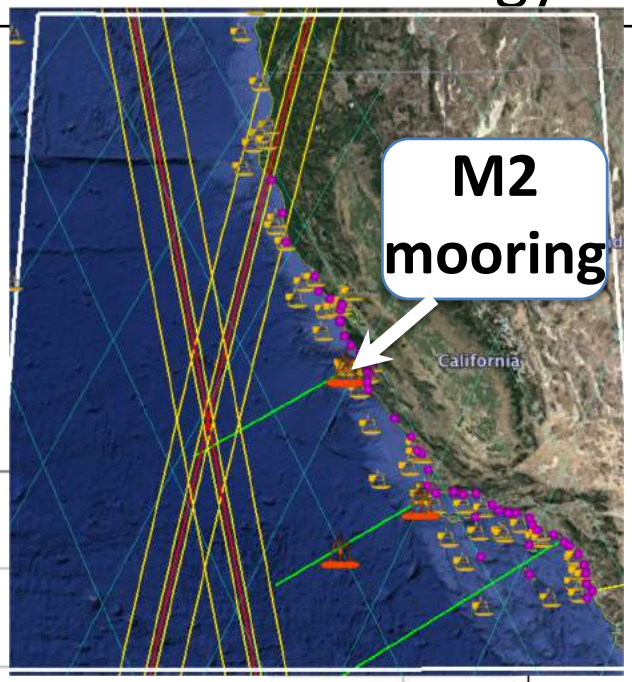
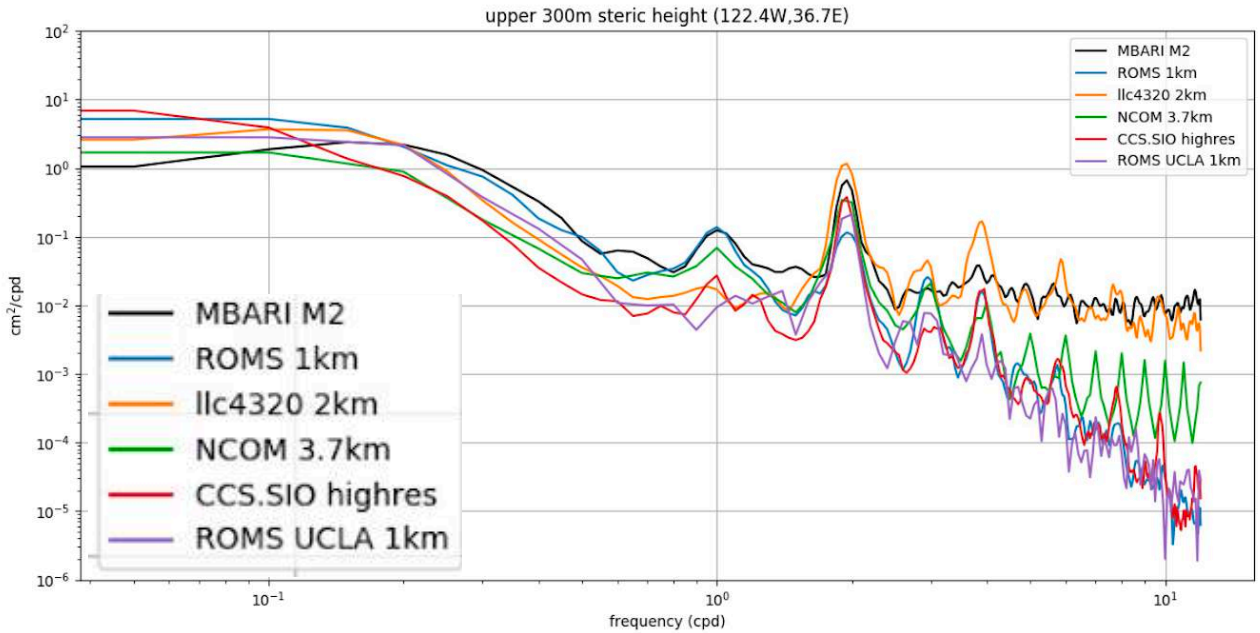
Can a regional model generate enough internal wave energy?

- 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





- 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:

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

Leading

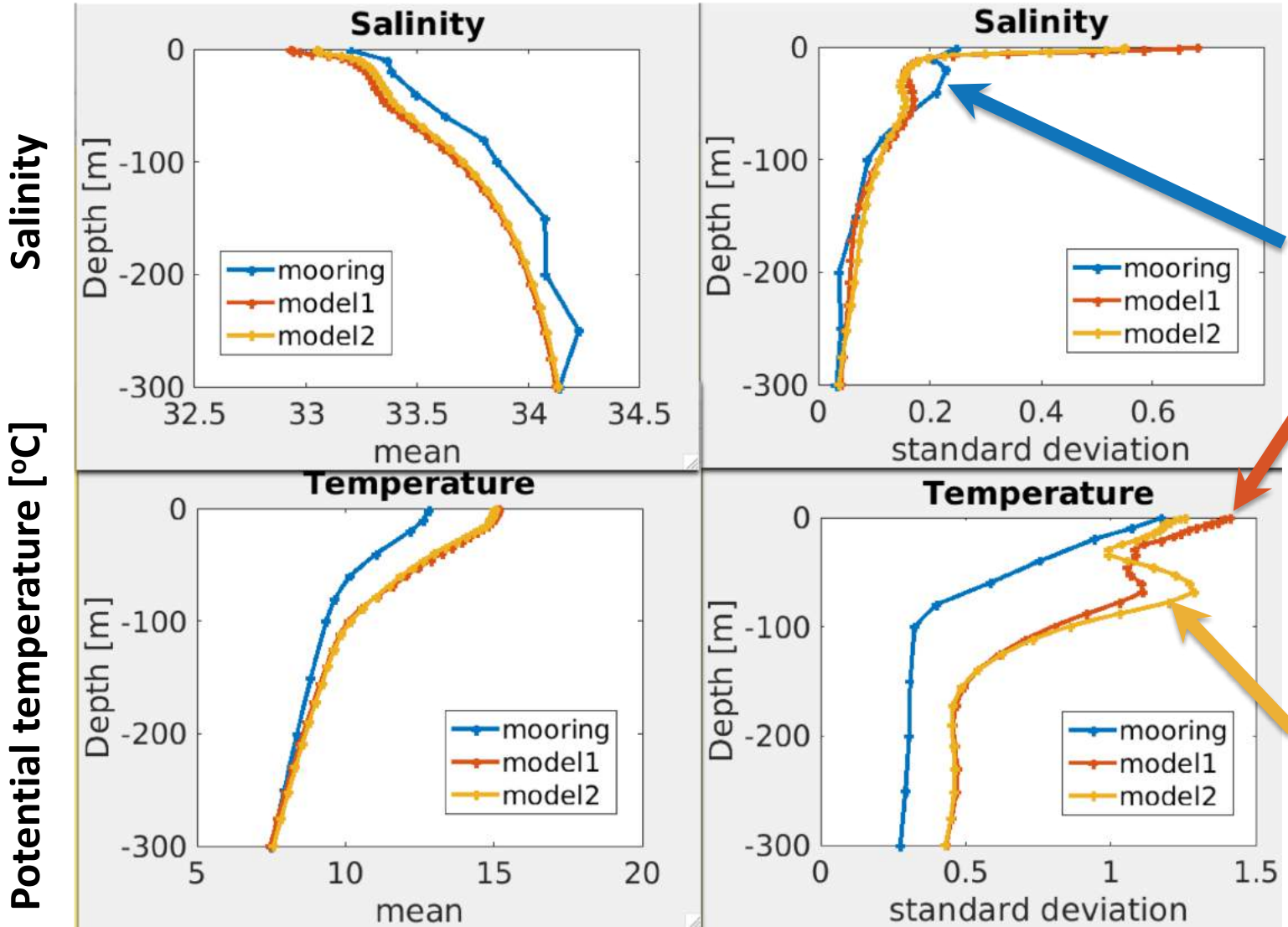
If the latter, solutions:

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

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

One year time-series

Mean | Standard Deviation



M2 Mooring

Model 1: without local tidal forcing.

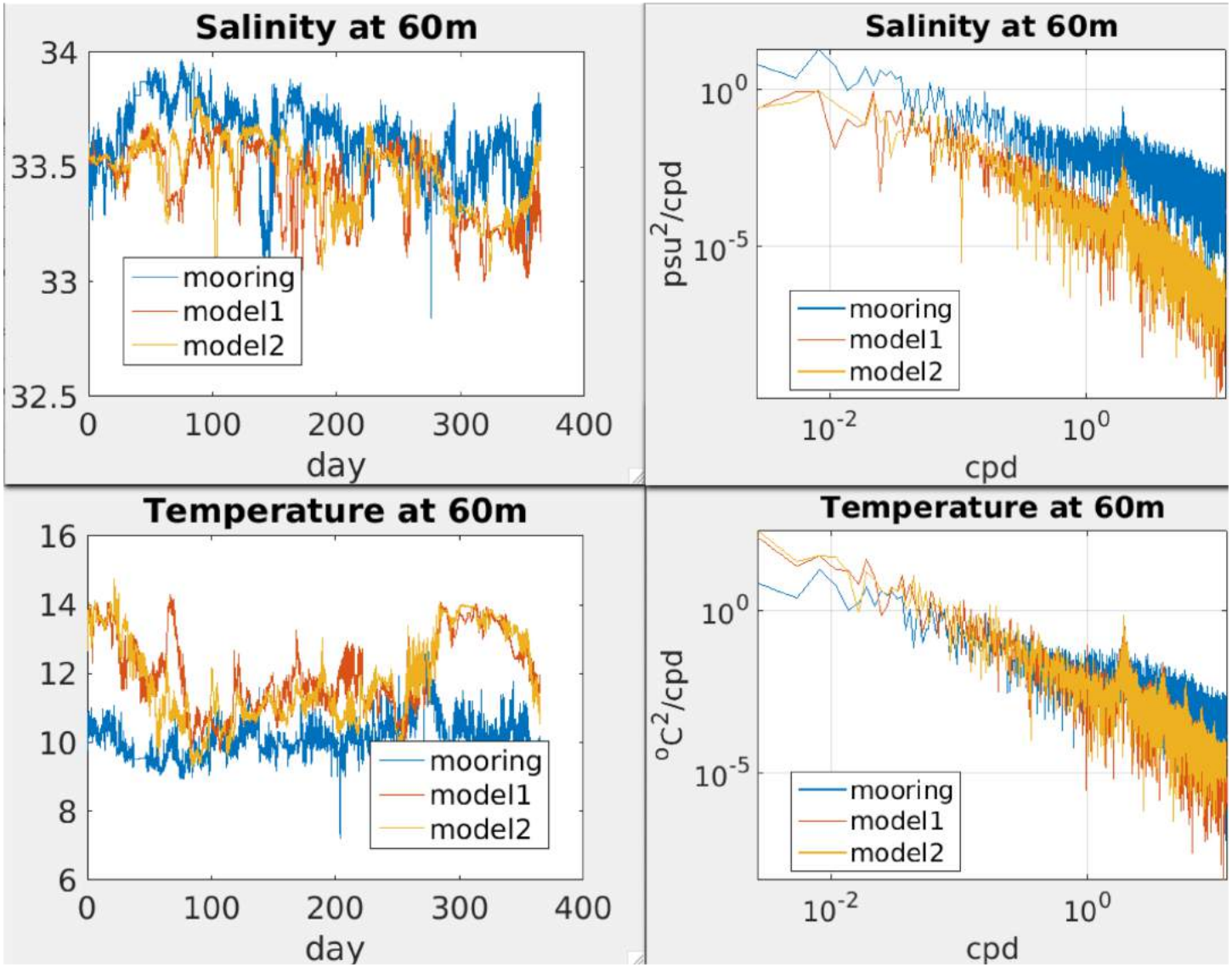
Model 2: with local tidal forcing

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

Time series | Frequency spectra

Salinity

Potential temperature [°C]



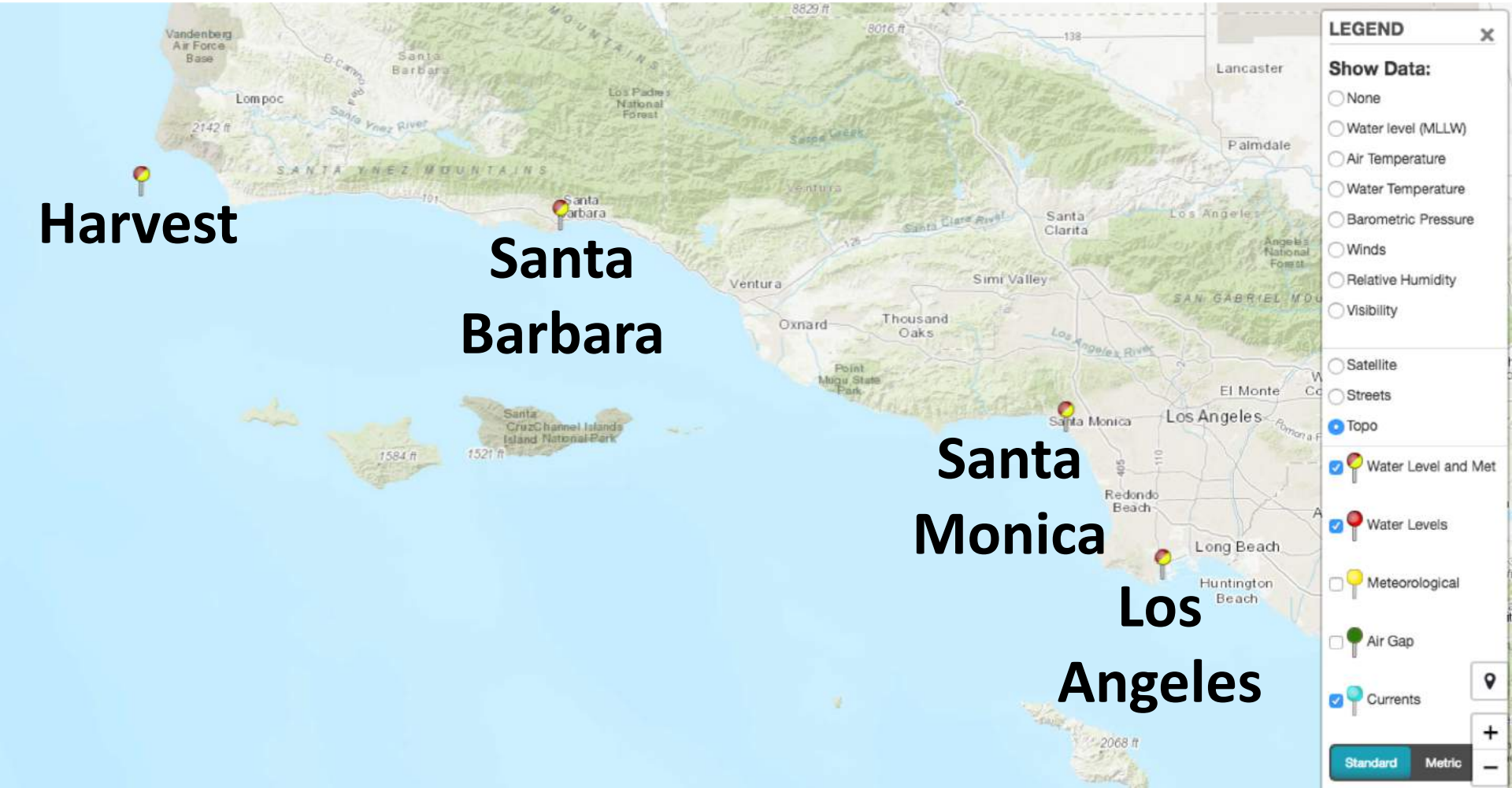
M2 Mooring

Model 1: without local tidal forcing.

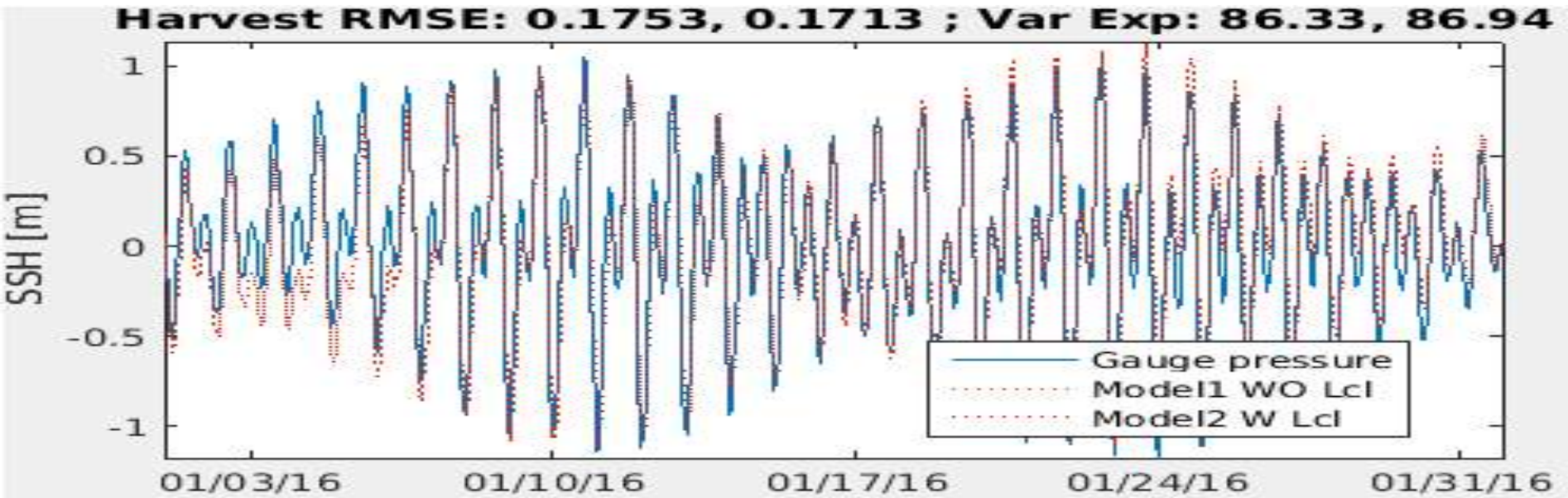
Model 2: with local tidal forcing

Implications of forcing with barotropic tides on boundaries vs barotropic tides on boundary and locally (via pressure loading)

Compare to tide gauge analysis. Data from https://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels



	% Variance explained		M2 amplitude			K1 amplitude		
Location	With-out	With local	Tide gauge	With-out	With local	Tide gauge	With-out	With local
Harvest	71.5%	74.0%	0.49	0.43	0.45	0.31	0.36	0.35
Santa Barbara	71.5%	73.4%	0.51	0.43	0.46	0.31	0.36	0.36
Santa Monica	70.0%	72.2%	0.52	0.41	0.44	0.30	0.36	0.35
Los Angeles	70.9%	73.1%	0/53	0.41	0.44	0.30	0.36	0.35



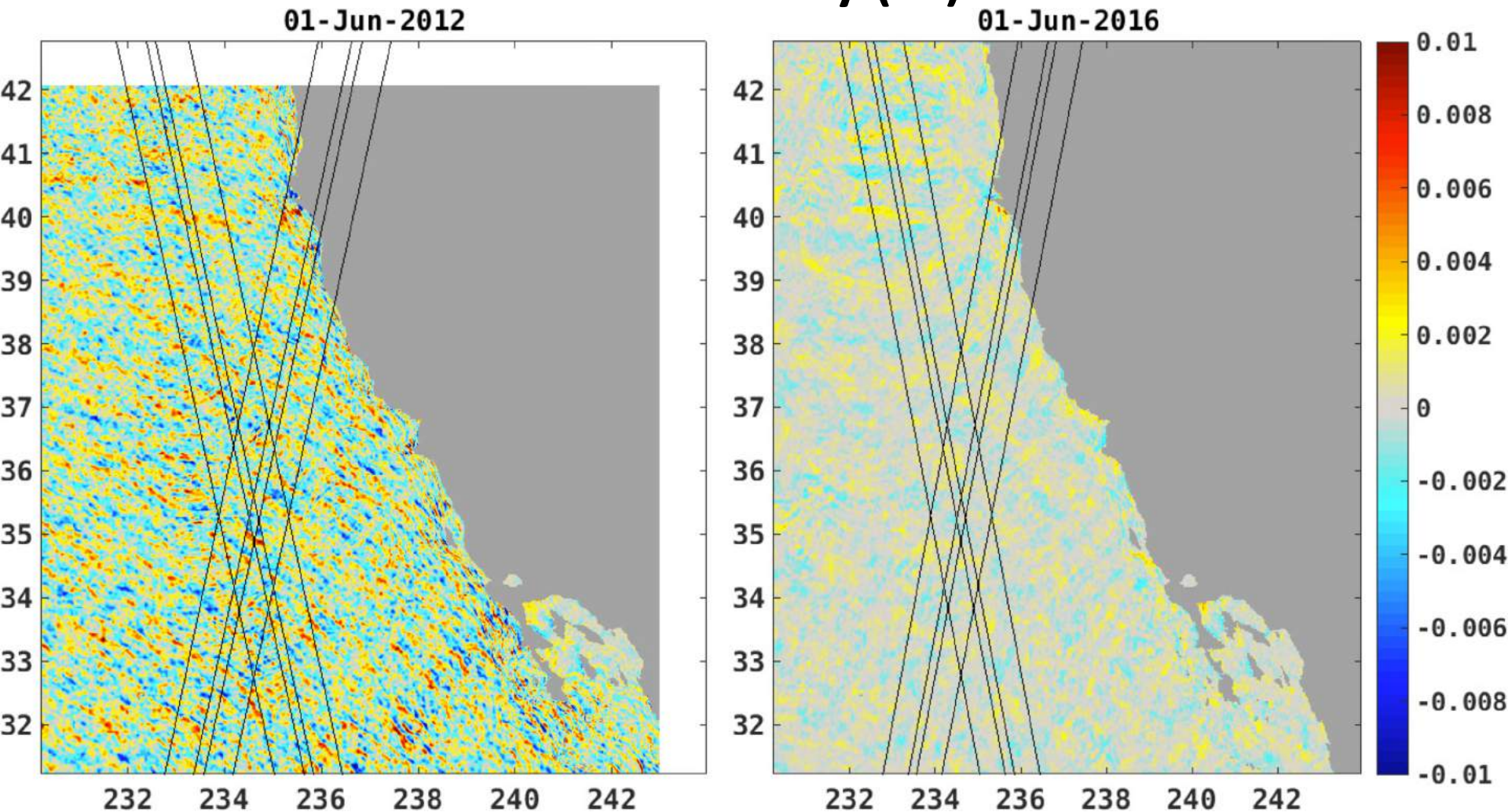
January 2016 shown above for clarity, analysis carried out for full 2016

Regional model analysis for 12 months

	% Variance explained		M2 amplitude			K1 amplitude		
Location	With-out	With local	Tide gauge	With-out	With local	Tide gauge	With-out	With local
Harvest	71.5%	74.0%	0.49	0.43	0.45	0.31	0.36	0.35
Santa Barbara	71.5%	73.4%	0.51	0.43	0.46	0.31	0.36	0.36
Santa Monica	70.0%	72.2%	0.52	0.41	0.44	0.30	0.36	0.35
Los Angeles	70.9%	73.1%	0.53	0.41	0.44	0.30	0.36	0.35
LLC4320 analyzed for 4 months (June to September 2012)								
Harvest					0.61			0.32
Santa Barbara					0.66			0.33
Santa Monica					0.70			0.32
Los Angeles								

Noise in LLC4320?

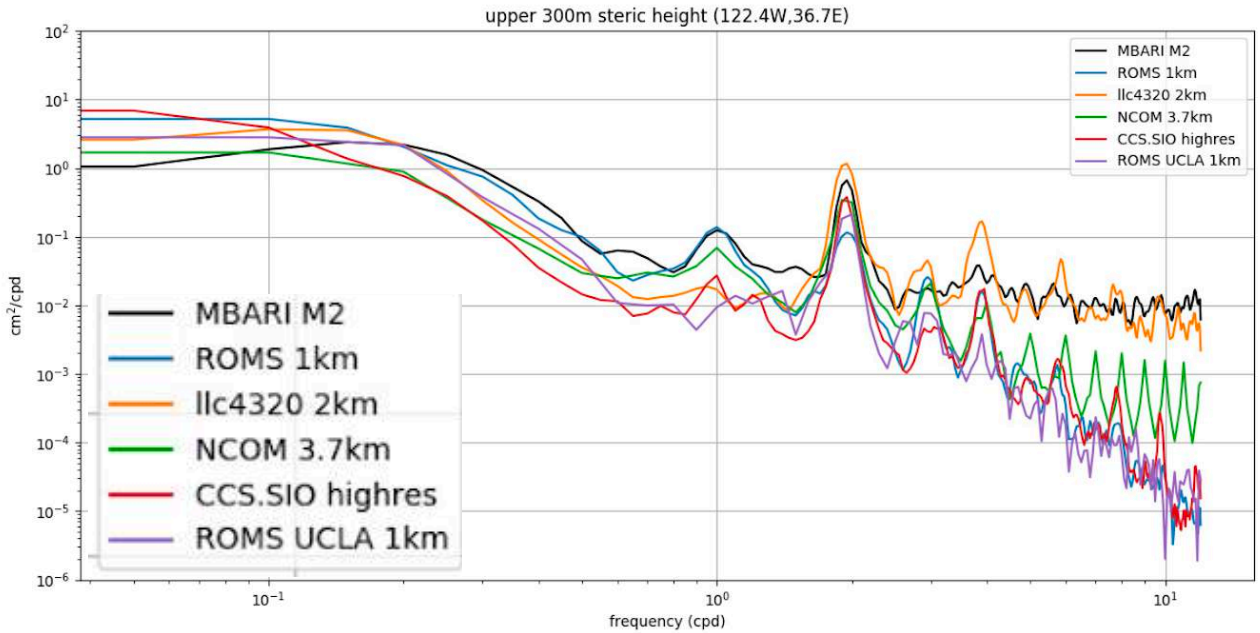
Vertical velocity (*W*) at 500 m



LLC4320 **MITgcm regional**

No, but note the difference in W magnitude!

- 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:

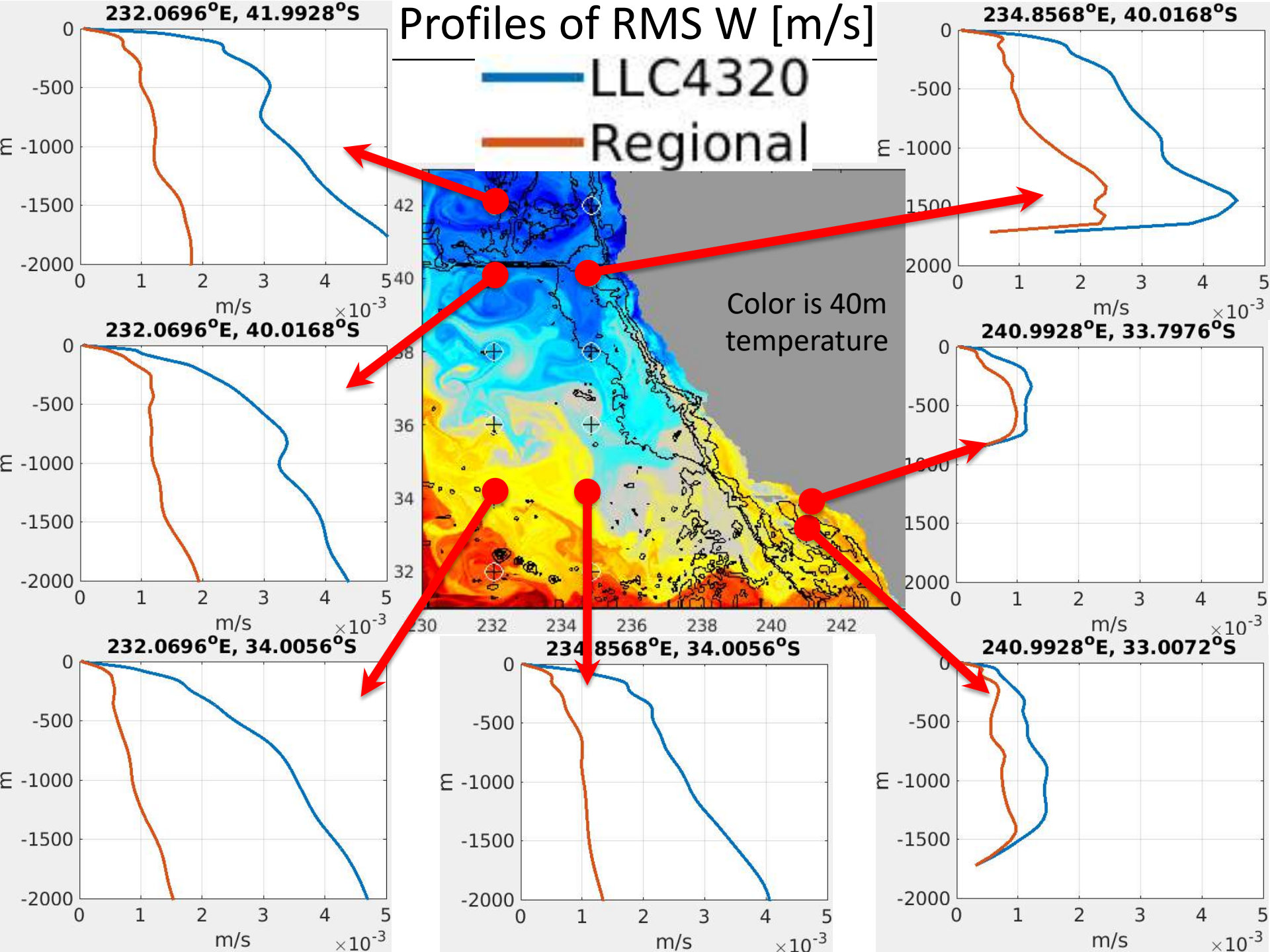
- Noise in LLC4320 and/or mooring meaning one or both is wrong.
- Representation of interaction with bottom topography
- How tides forced (i.e. as pressure loading) & their accuracy in LLC4320.
- Tidally generated internal waves do not have time to exchange energy and fill the (Garrett-Munk) spectrum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

Leading

If the latter, solutions:

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

Profiles of RMS W [m/s]



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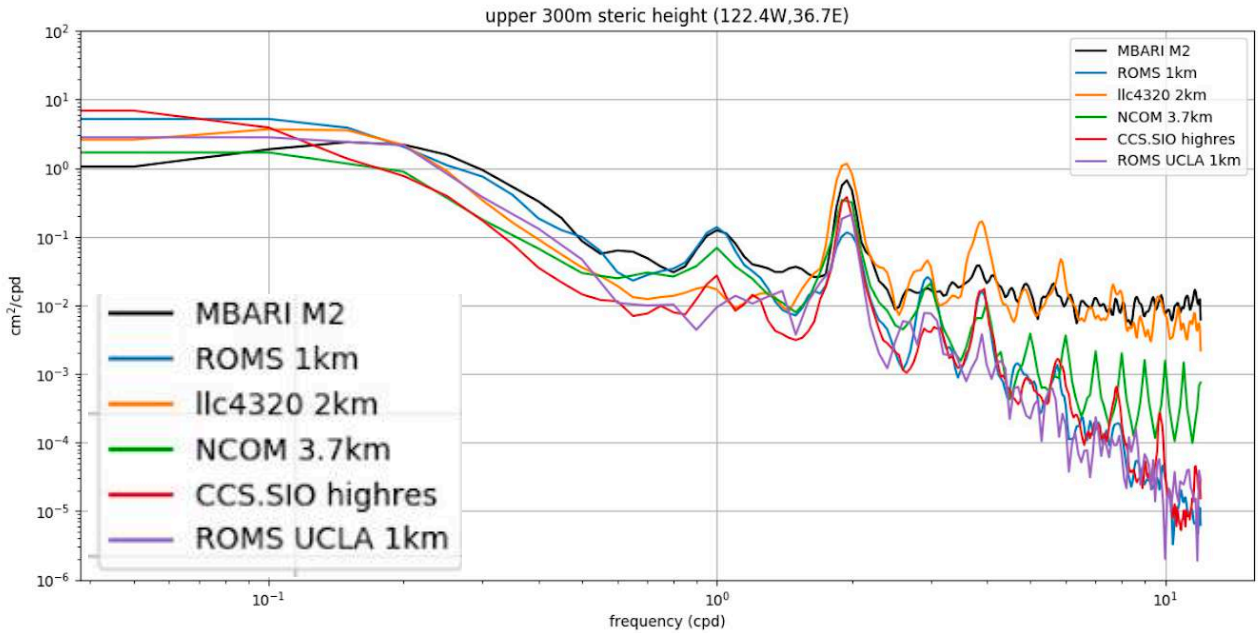

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