Regional assimilations and coupling efforts to inform model errors, predictability, and sensitivities.

Workshop: Improving climate models and projections using observation
MIT, 12-14 June 2023

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Motivations: improve forecasts and quantify their uncertainty.

- **Approach: identify and understand model errors using state estimation.**
  - Observations are compared to state estimates to generate realizations of errors.
  - Example: using assimilation to remove model parameterization biases

Adjoint-Based Estimation of Eddy-Induced Tracer Mixing Parameters in the Global Ocean. Liu, Köhl, Stammer. 2012

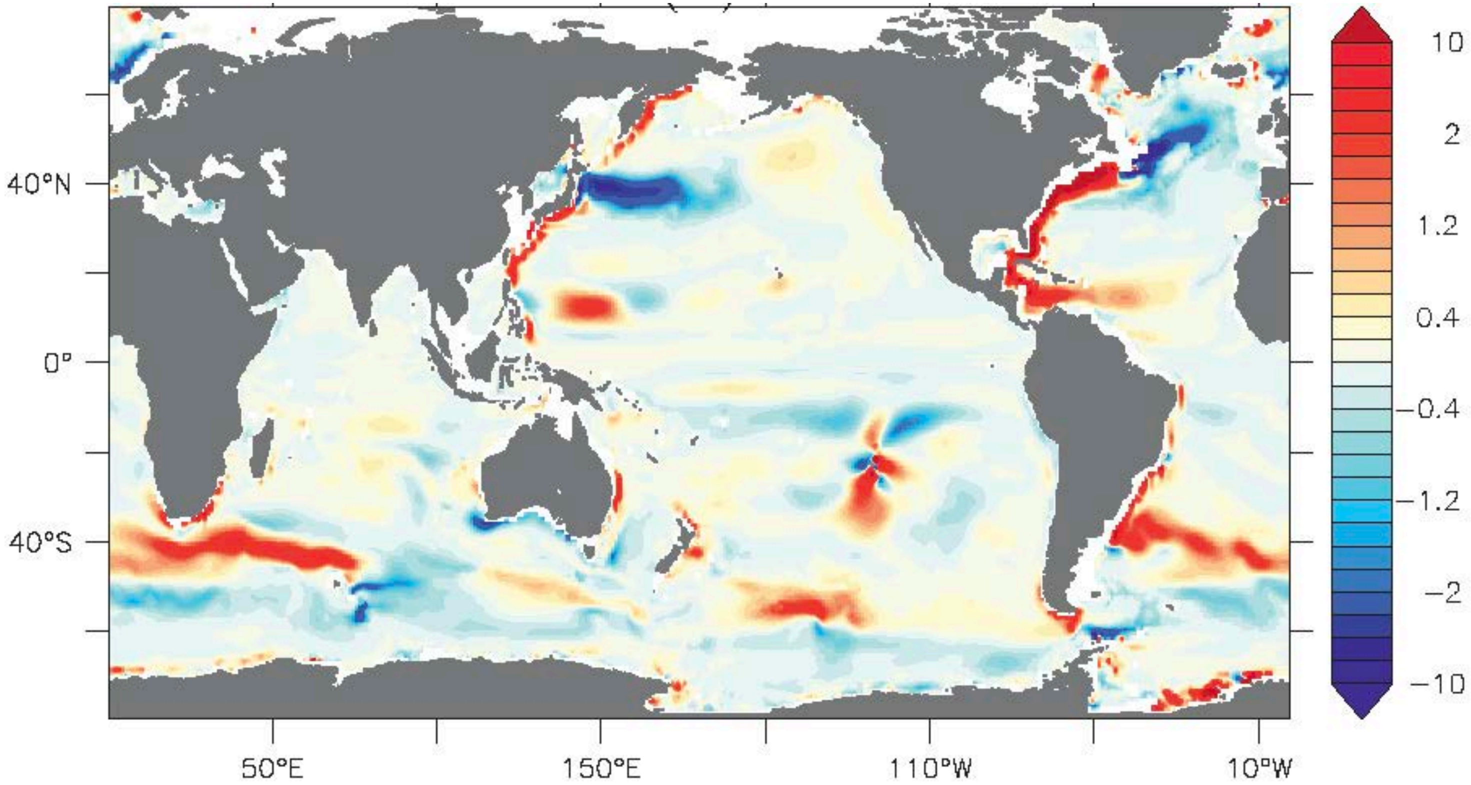


FIG. 1. Gradients of the total cost function with respect to k_{gm} (10^{-2} s m^{-2}) at 310 m from (a) the modified adjoint and (b) the original adjoint to the GM parameterization.

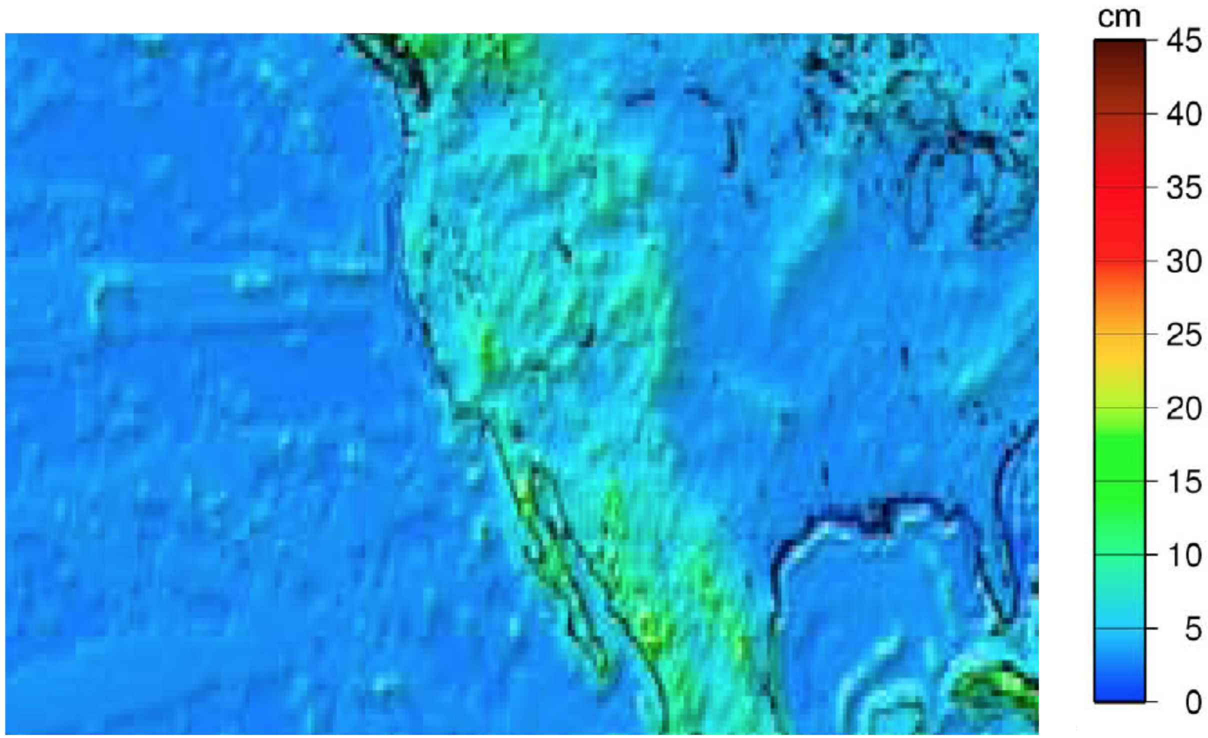
Error Identification

- Have incomplete observations
- Possible approach:
  - Guess the structure
  - Make a model for it with free parameters
  - Fit parameters using DA
  - Evaluate the fit
  - Discard or improve the model
  - Repeat

Error can be from:

- Initial condition errors due to observational/engineering/mapping
- Amplification of initial condition errors by flow instabilities
- Earth system model approximations and parameterizations

Example: using assimilation to remove bias in data



Geoid commission error on height anomalies [cm] implied by EGM2008 (Pavlis et al., 2012)

Example: using assimilation to remove bias in data
Regional state estimation to determine dynamic ocean topography (DOT)

Error can be from:

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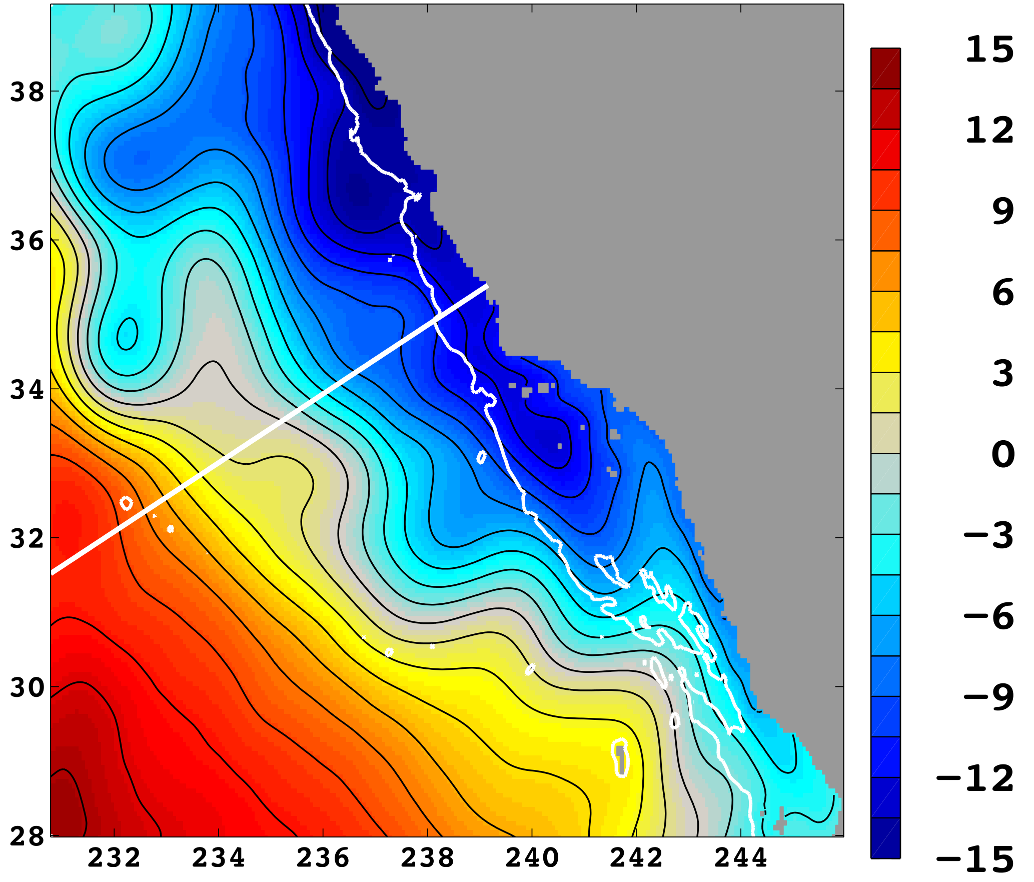
Hypothesis: we can solve for DOT and the geoid error simultaneously using the adjoint method to minimize
$J = (SSH - DOT - (geoid + F))^{-2}$

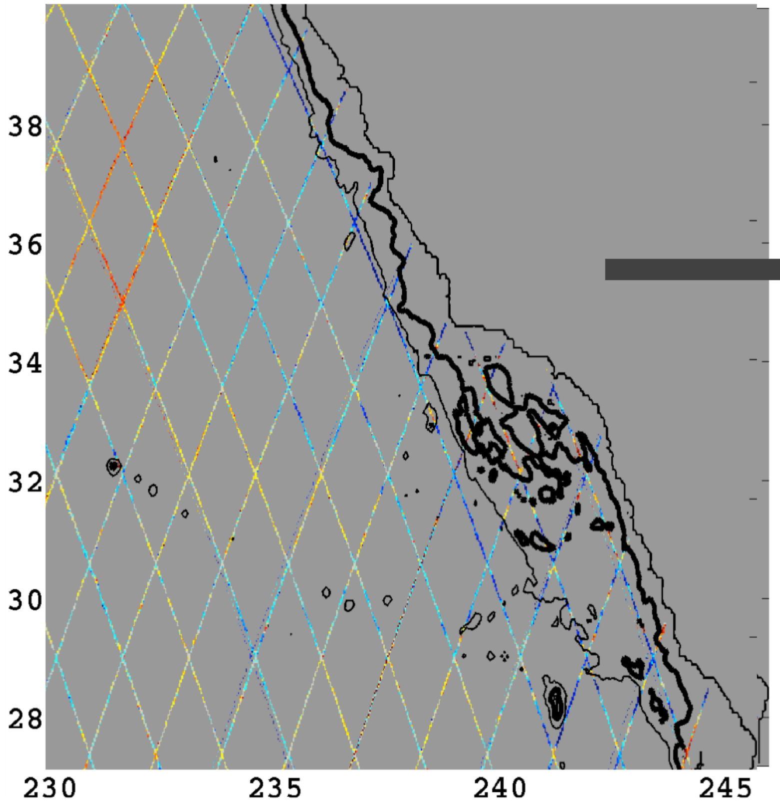
The California Current System state estimate (Iteration 186). It is available for 2007 – 2010 at http://sose.ucsd.edu/CASE. The 2000m bathymetric contour and CalCOFI line 75 in white.

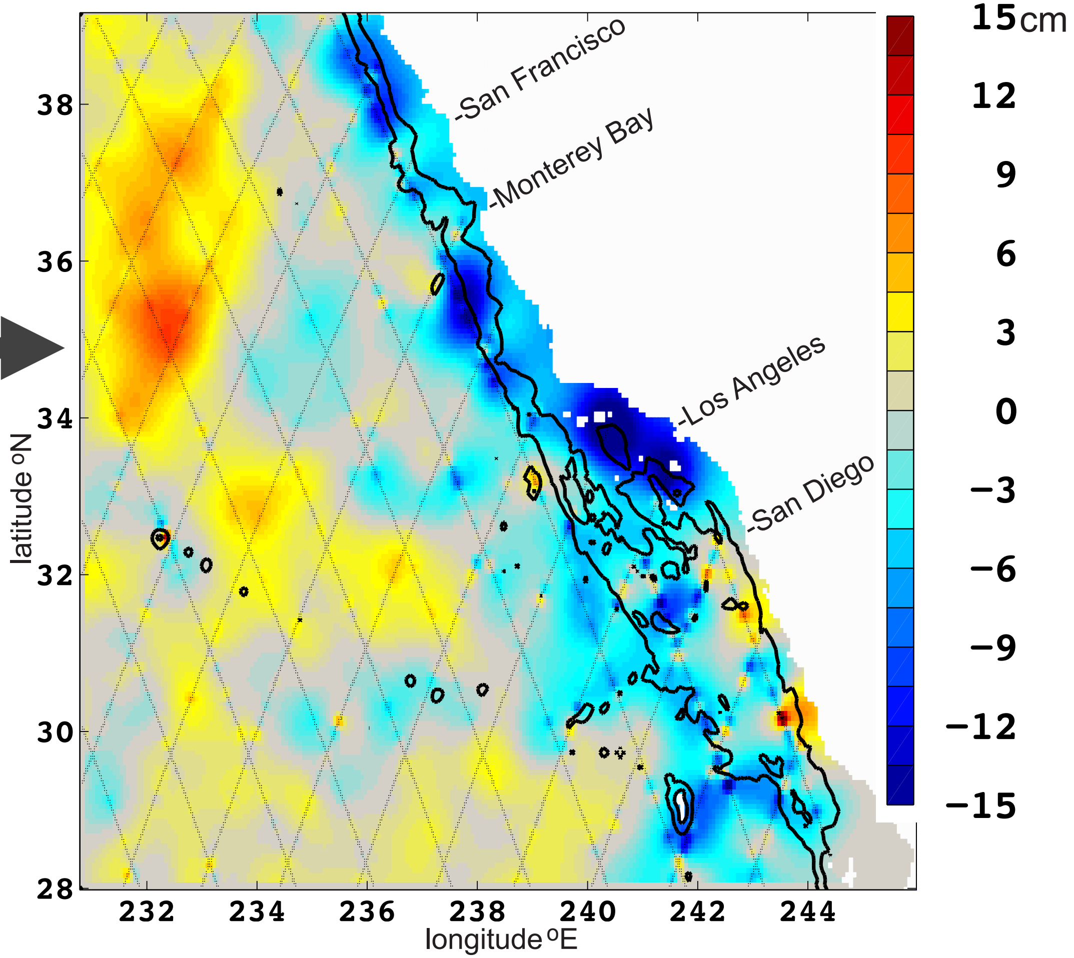


Objectively mapped geoid correction field in cm :

Time mean residual to Jason 1 & 2:

$$< r > = < SSH - DOT - EGM2008 >$$





Bathymetry is contoured in black with a 1000m contour interval.

Tested correction field:

- Cannot be explained by circulation errors (i.e. model errors)
- Reduced residual to AVISO (ie an alternative DOT estimate)
- Reduced residuals with independent altimeters and Jason at different times

Improving the geoid: Combining altimetry and mean dynamic topography in the California coastal ocean
Mazloff et al 2014

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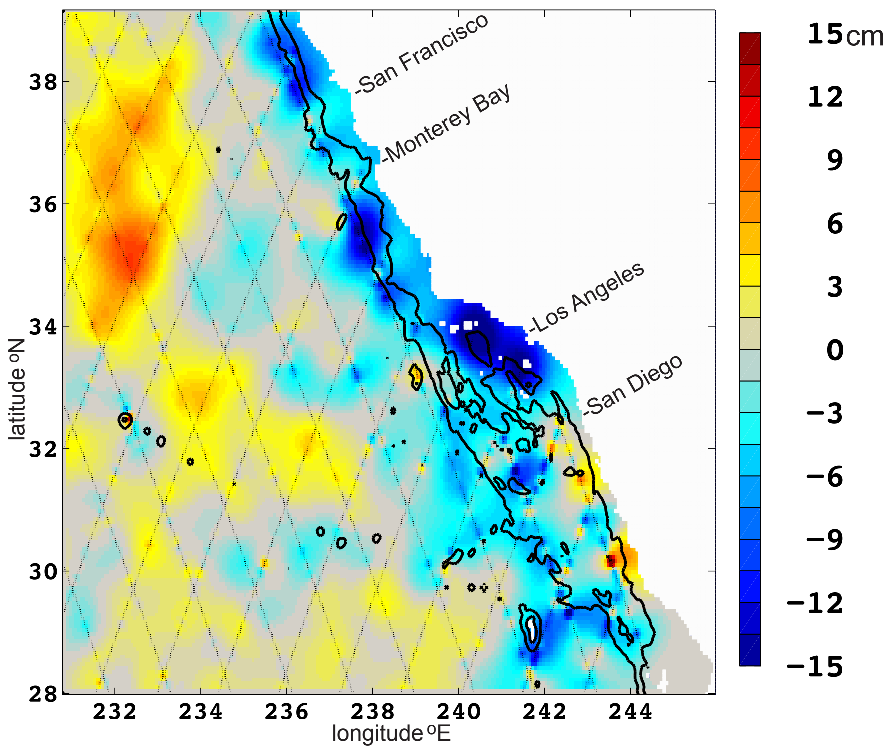
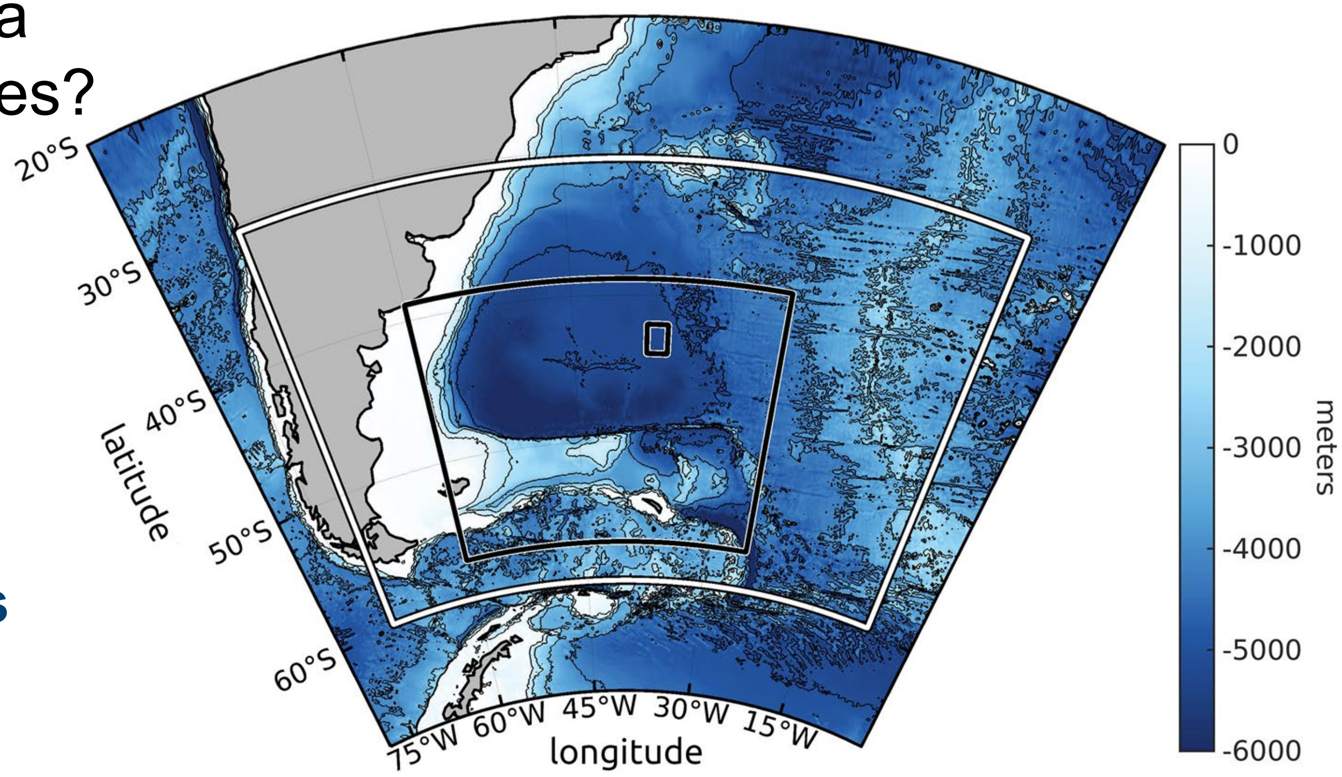


Assimilation can identify and remove bias in data

Sources of error

Forecast errors due to amplification of IC errors by flow instabilities.

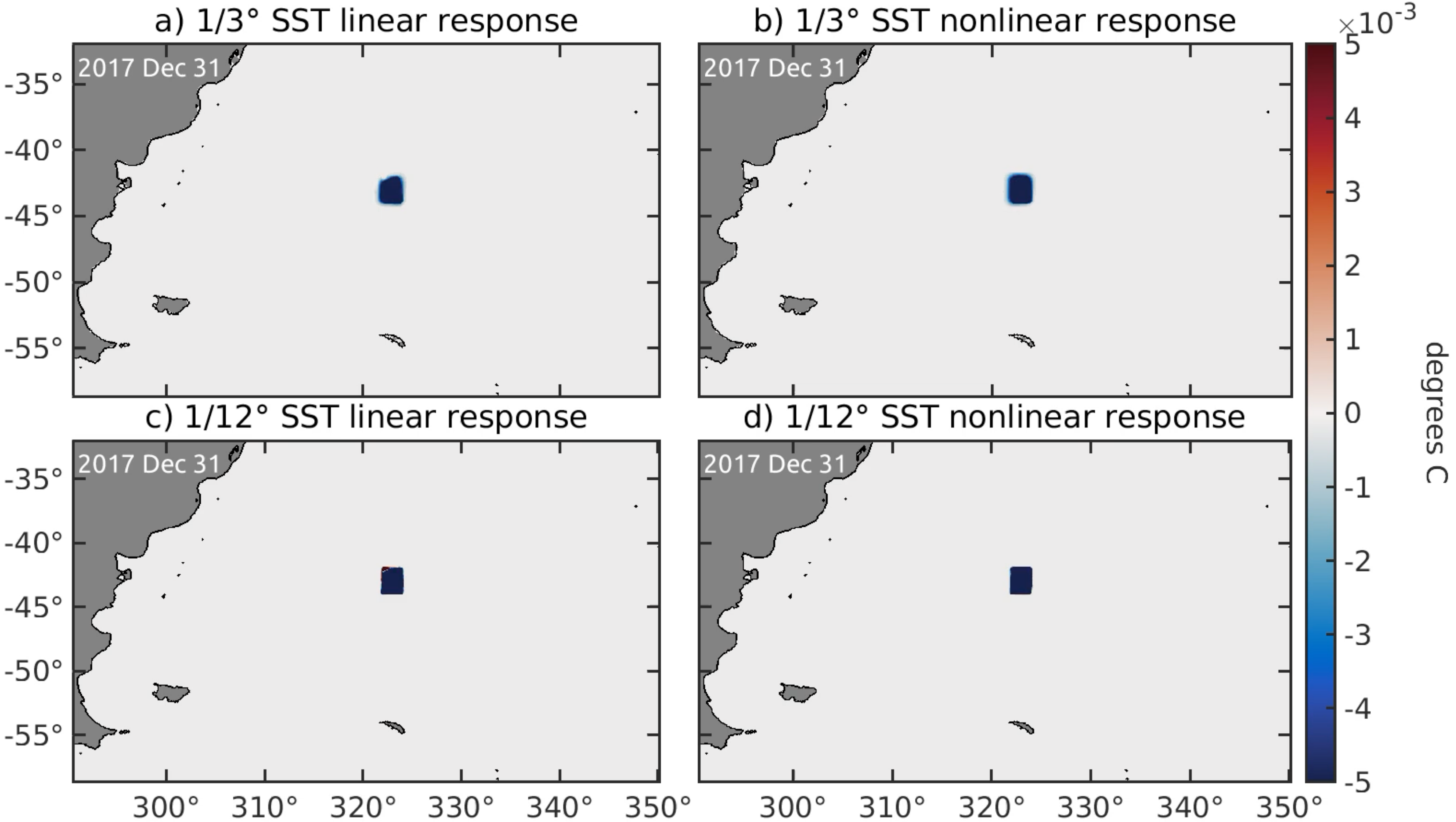
- What skill can be achieved for what lead times?
- May be addressed by increasing or reallocating observations, which requires understanding their structure. What and where to observe to maximize predictability?
- Can we control/damp the chaotic behavior and then parameterize the impact?
- Can we derive a nudging in the form of a parameterization of the chaotic processes?



Investigating Predictability of DIC and SST in the Argentine Basin Through Wind Stress Perturbation Experiments

Swierczek et al, 2021

Sources of error: Forecast errors due to amplification of IC errors by flow instabilities.



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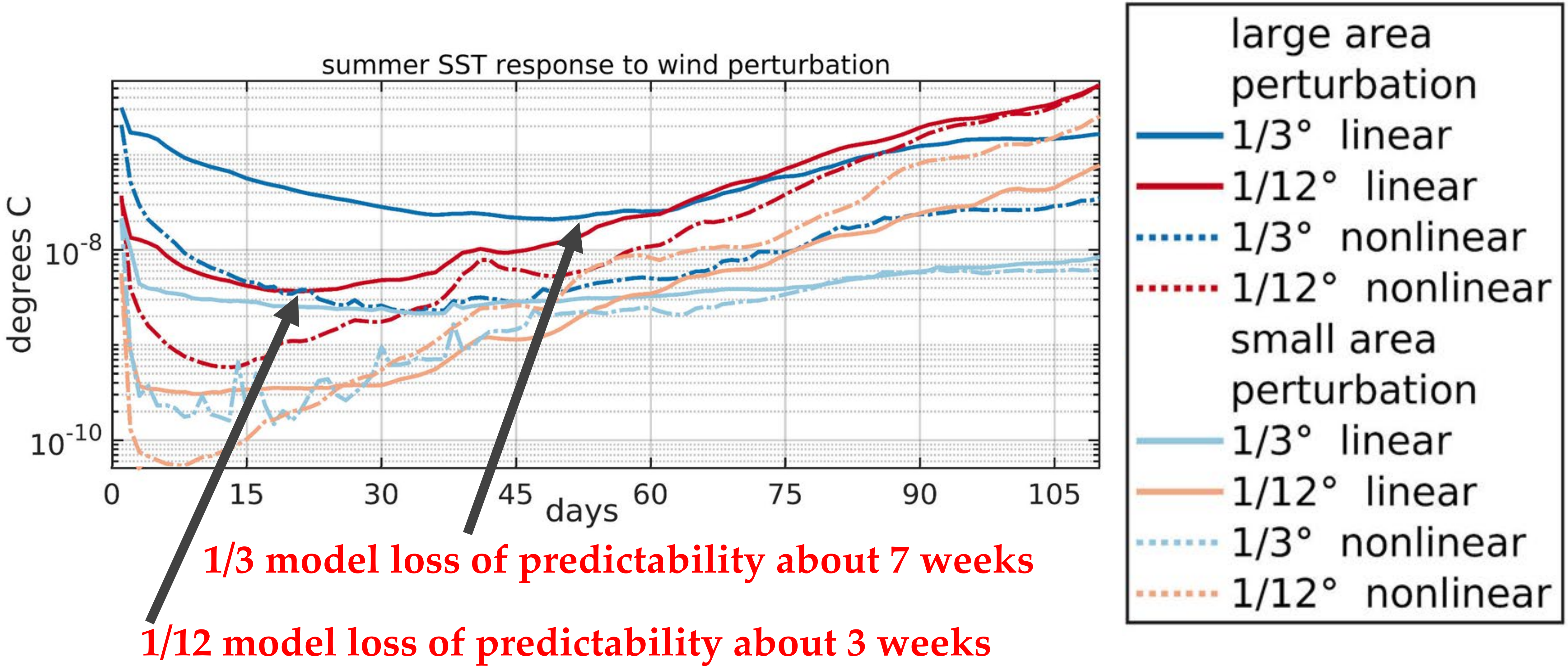
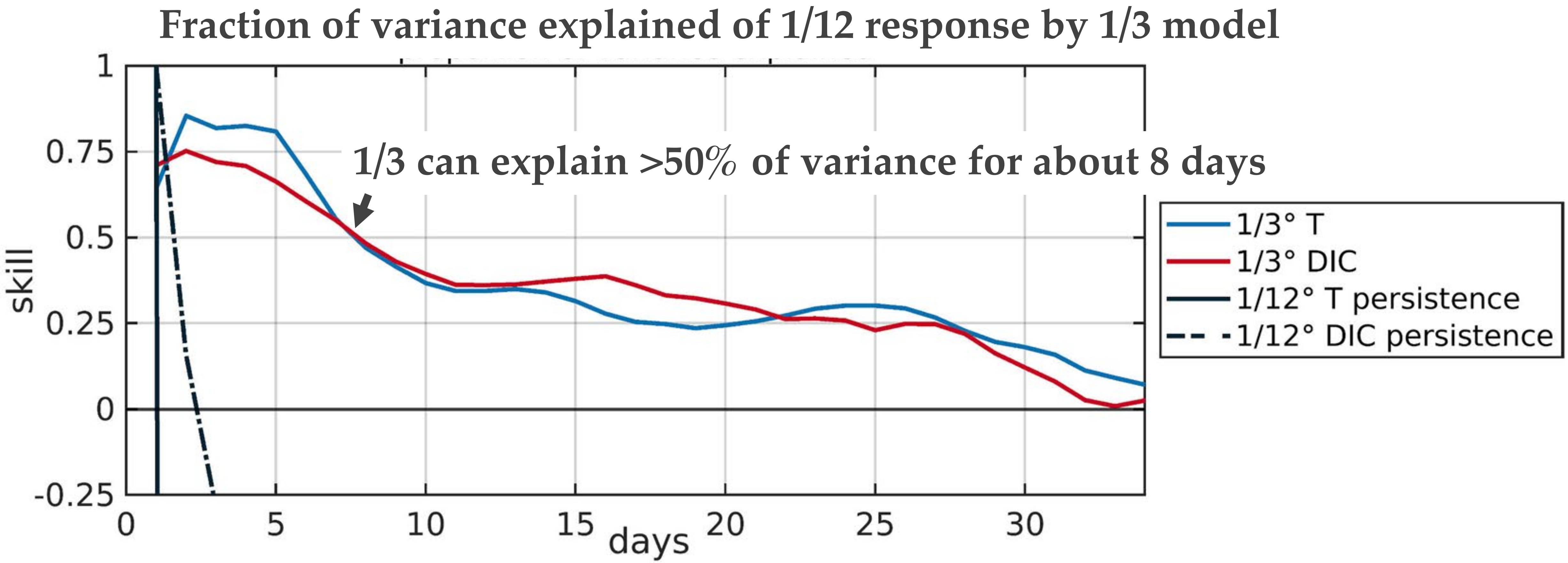


Sources of error: Forecast errors due to amplification of IC errors by flow instabilities.



- The 1/3 is more predictable.
- But the 1/3° model response is only consistent with the 1/12° model for about 8 days calling into question the potential predictive skill of the coarser model at longer lead times.

Can we derive a nudging in the form of a parameterization of the chaotic processes?

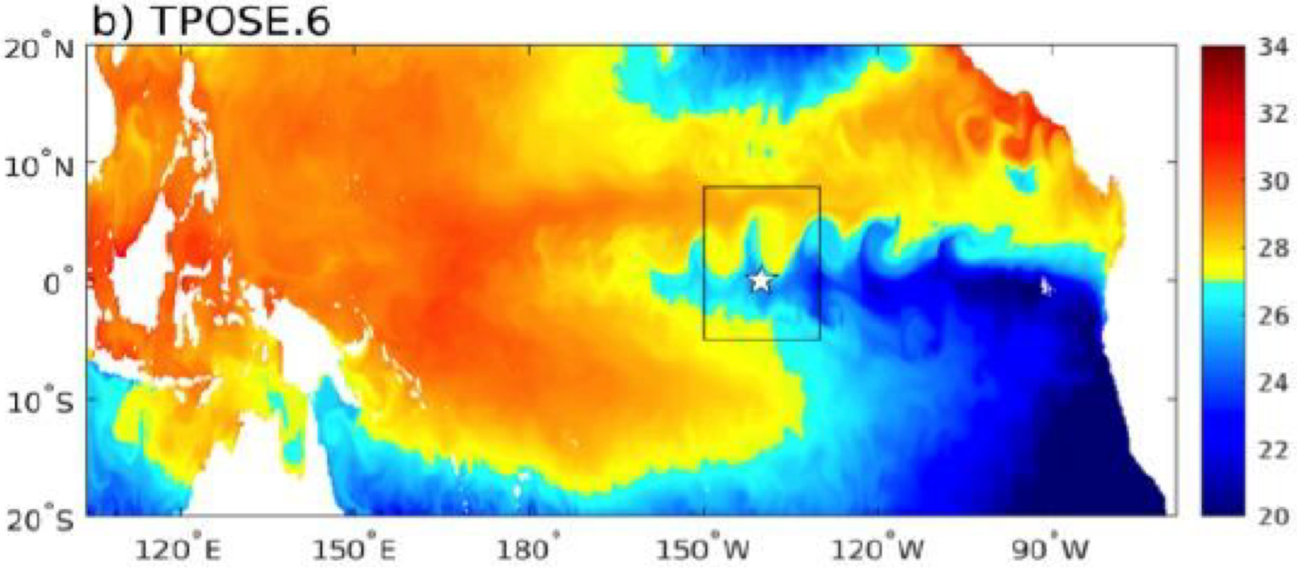
sources of error

- **Forecast errors due to model errors from approximations and parameterizations.**
  - We have an idea of where to look for these errors: boundary layers.
  - Located at fronts, topography, interfaces (especially air/sea/ice), other places?

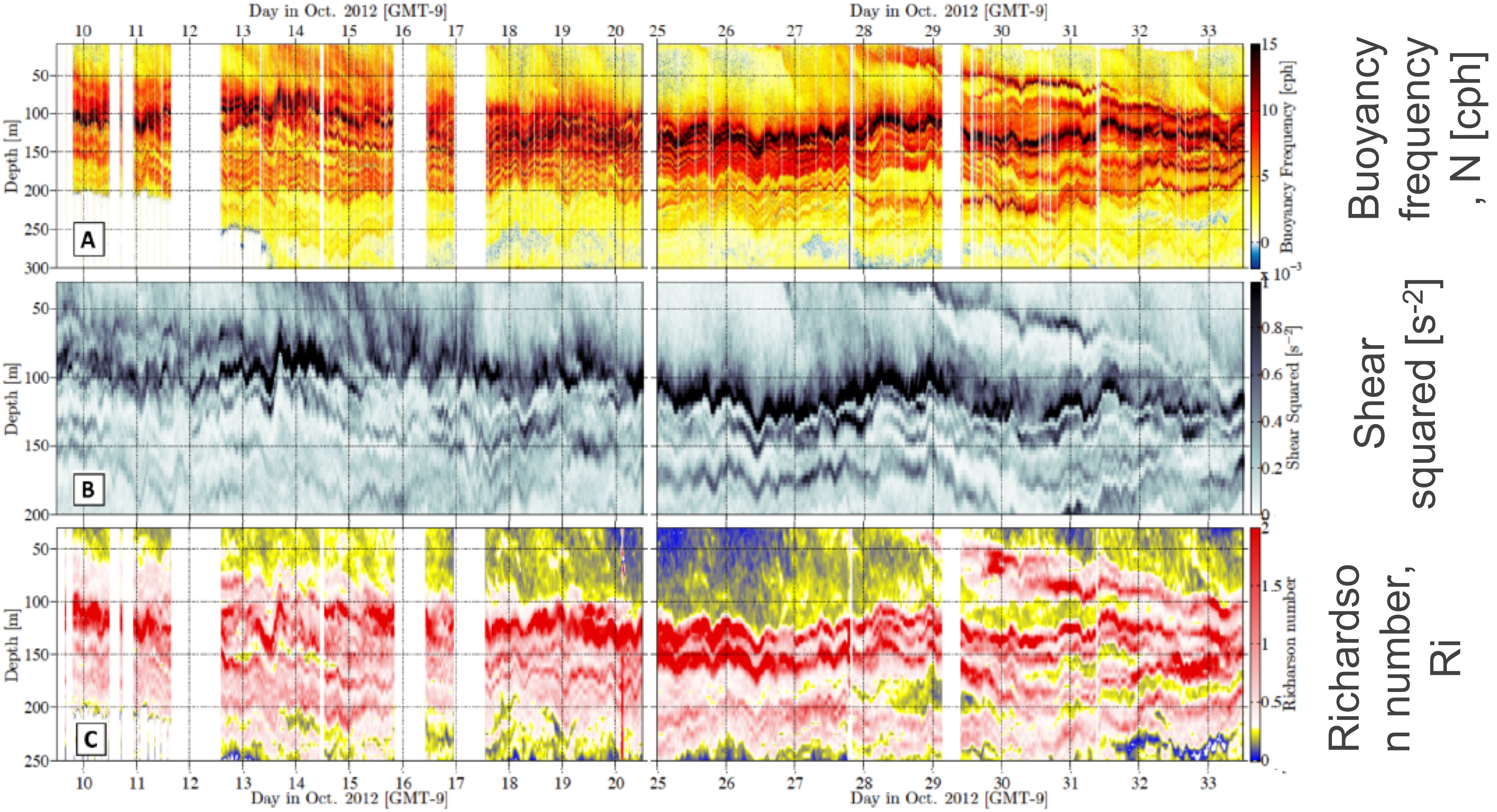
Example opportunity: The EquatorMix process study occurred Oct 6 to Nov 3, 2012 while a tropical instability wave past through.

Observations: Fast-CTD, Doppler Sonar, Extended meteorological sensors from UAVs

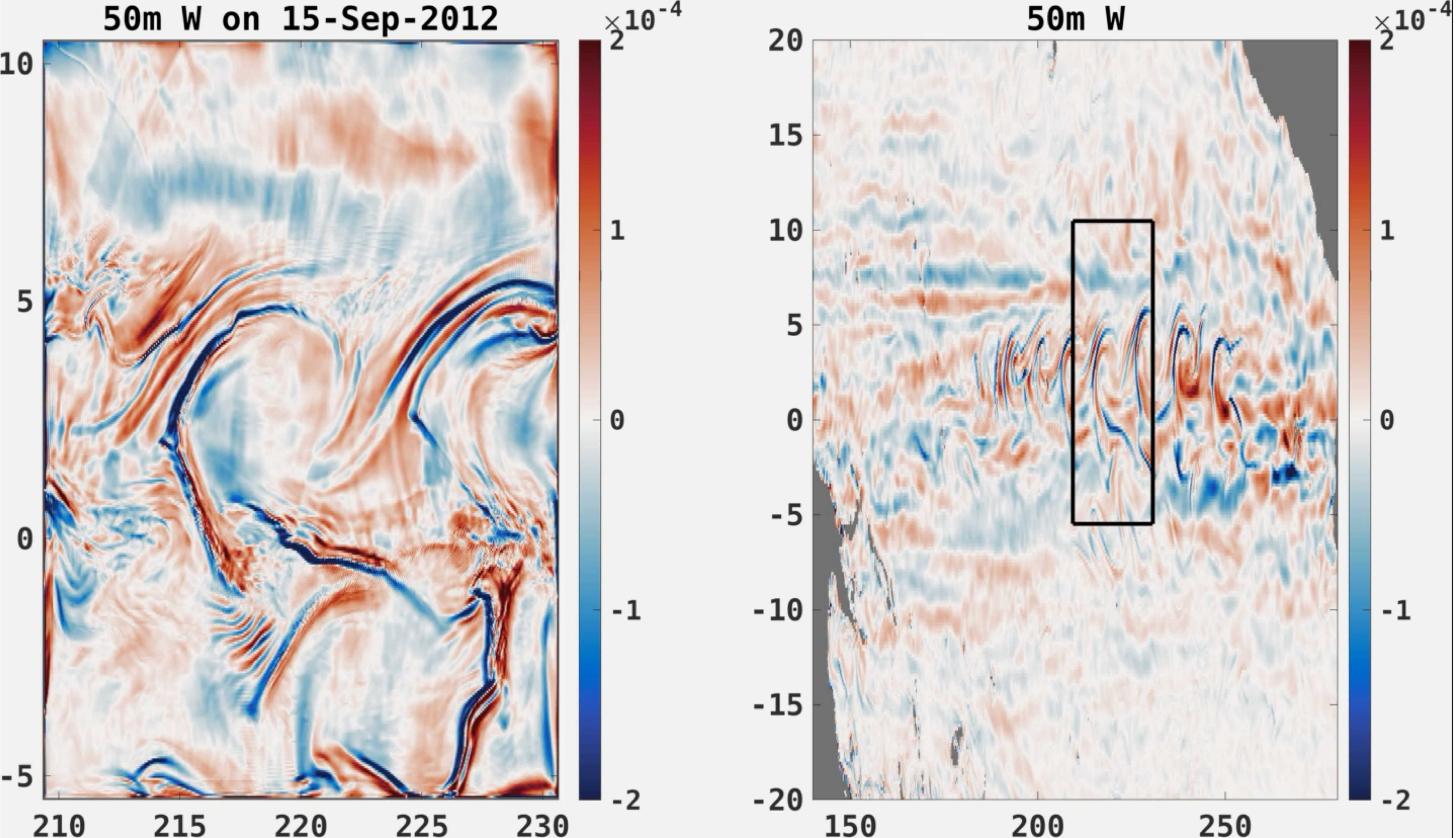
What are the processes important for upwelling and how well can we model them?



Can we reproduce the evolving T, S, and flux observations from EquatorMix?

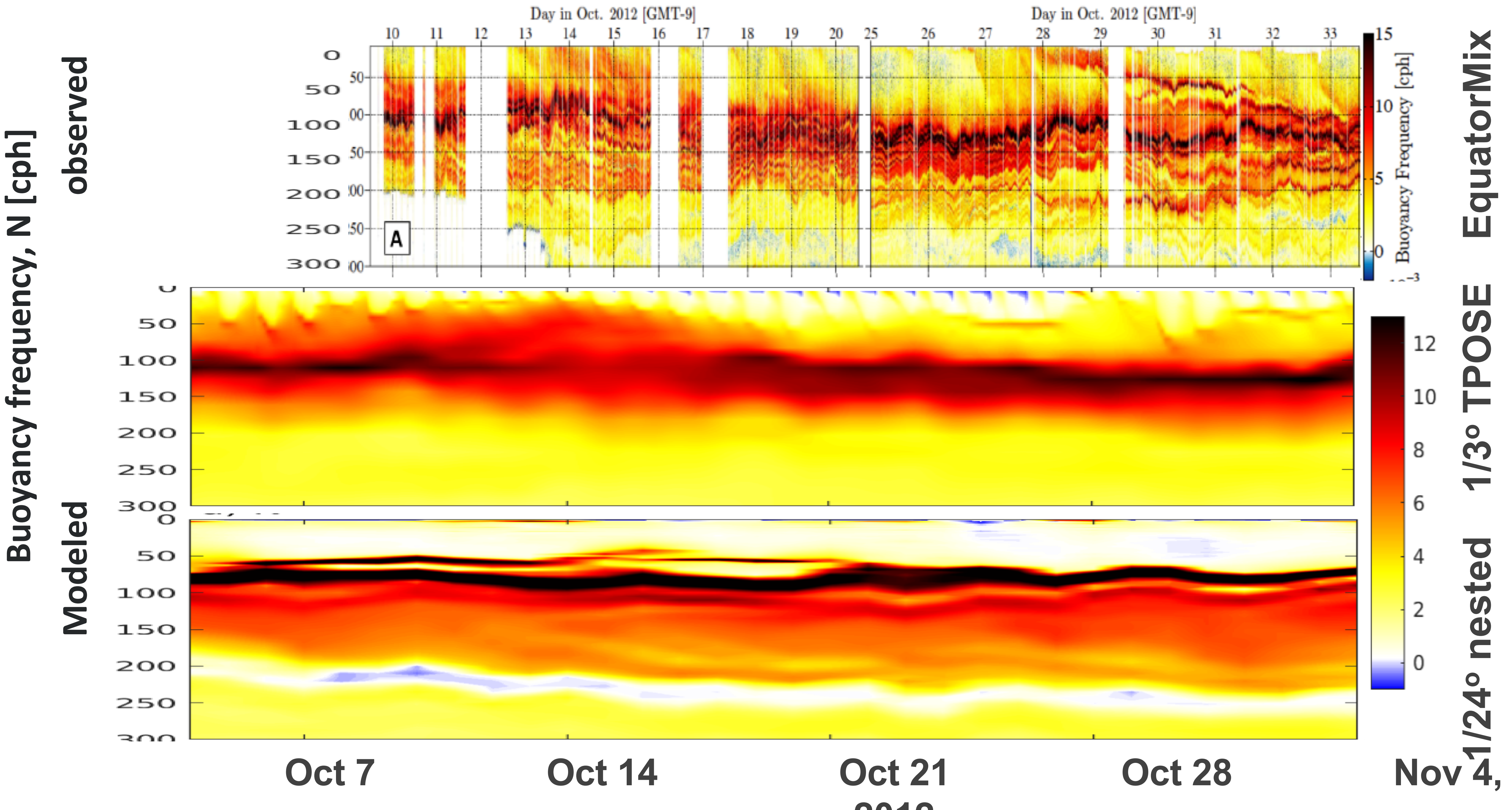


Workplan: assimilate these data in both a 1/6 large domain TPOSE, and in a nested 1/24 domain.



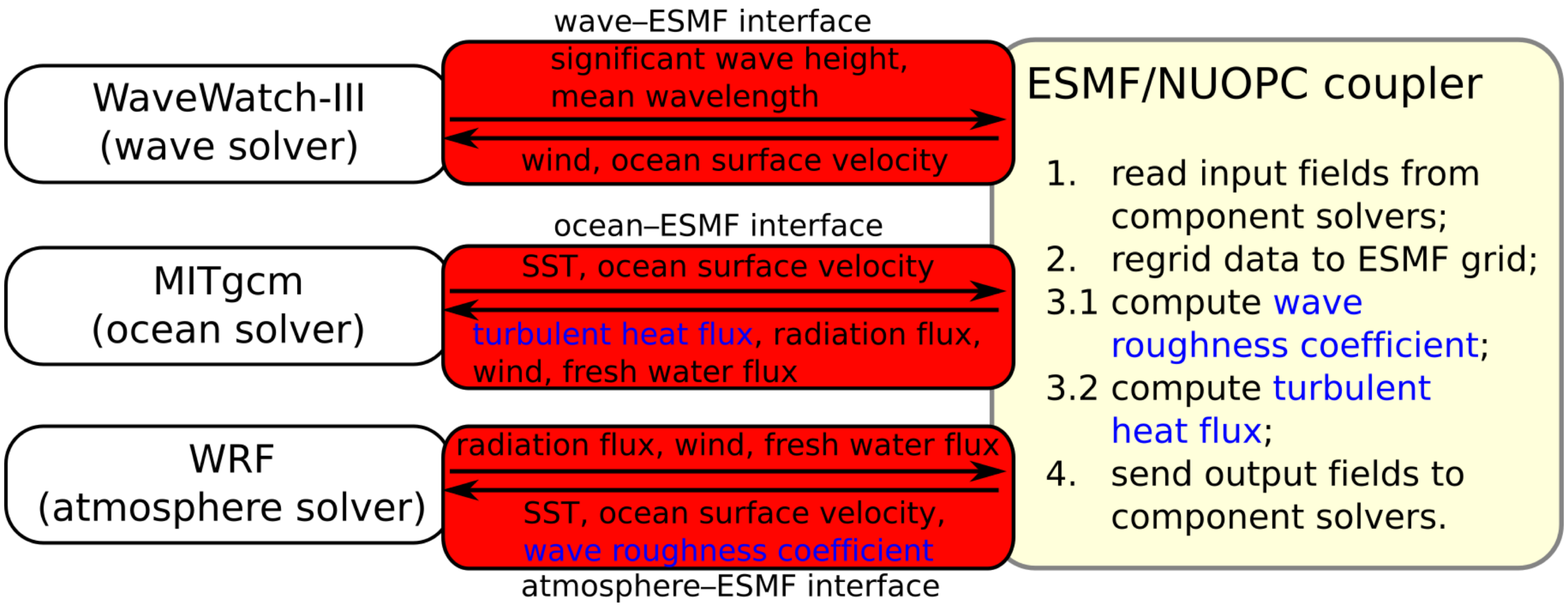
50m W on 15-Sep-2012
×10^-4
2
1
0
-1
-2
10
5
0
-5
210
215
220
225
230
50m W
×10^-4
20
15
10
5
0
-5
-10
-15
-20
150
200
250

Can we reproduce the evolving T, S, and flux observations from EquatorMix?



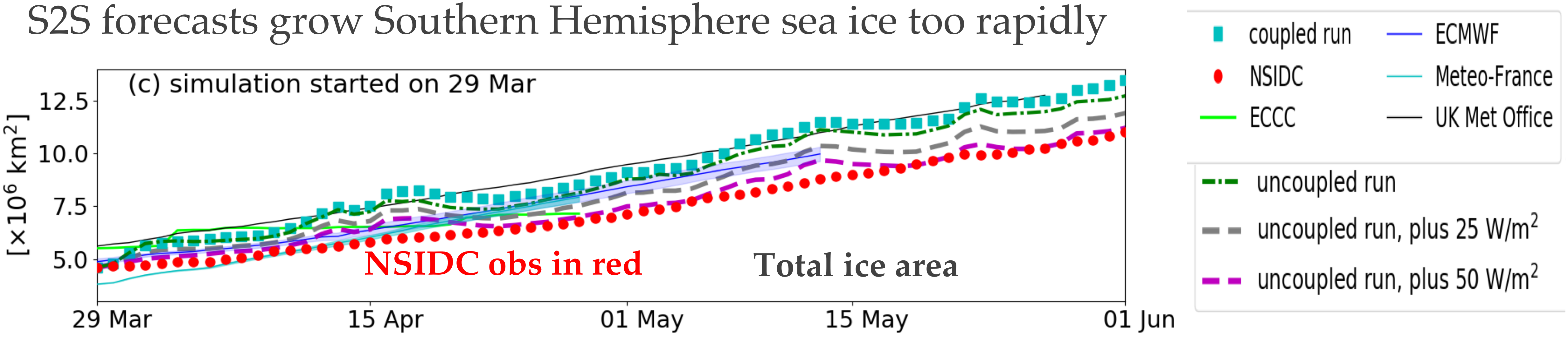
Regional MITgcm-WRF-WW3

- We are developing a regional coupled modeling and assimilation system that will include both strongly and weakly coupled ocean-atmosphere state estimation with EAKF and weakly coupled with 4DVar.
- Why develop a new model? Assimilation, process experiment needs, control over the development, a focus on processes (eg ocean surface wave effects.)



Power of coupled framework for validation

- Sea ice area is well observed and integrates fluxes
- S2S forecasts grow Southern Hemisphere sea ice too rapidly

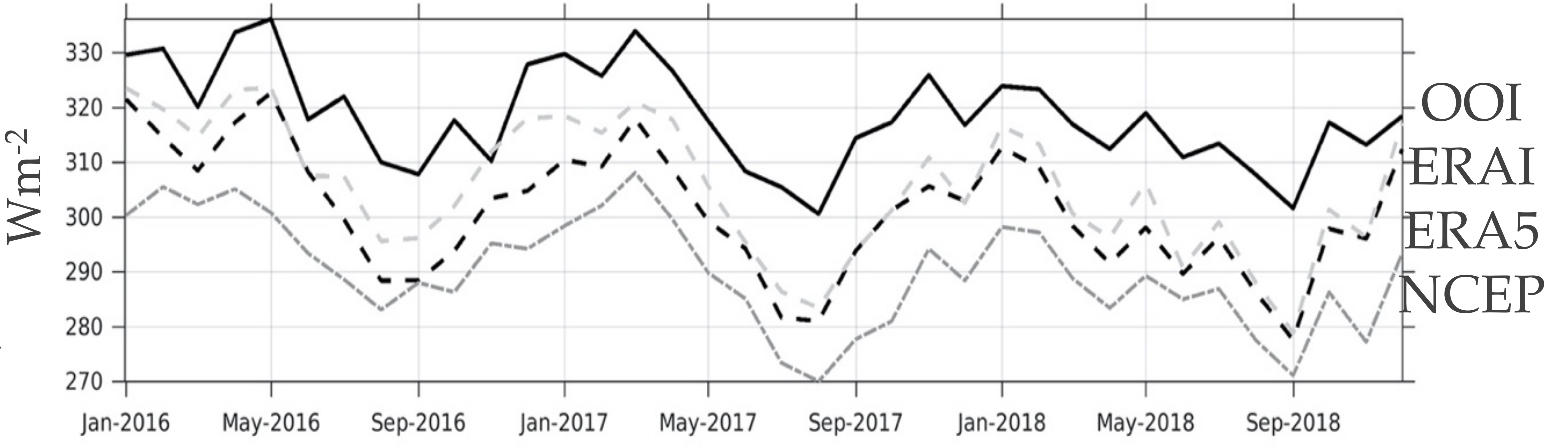


We tried *many* perturbation experiments in our coupled model. Two ways to bring sea ice growth rate into consistency with obs:

1. Change the bulk grid cell temperature when ice freezes
2. Increase downward longwave (DLW) radiation by ~50 Wm^{-2}

Obs can inform error causal mechanisms & show reanalysis do underestimate DLW

DLW at OOI Southern Ocean mooring

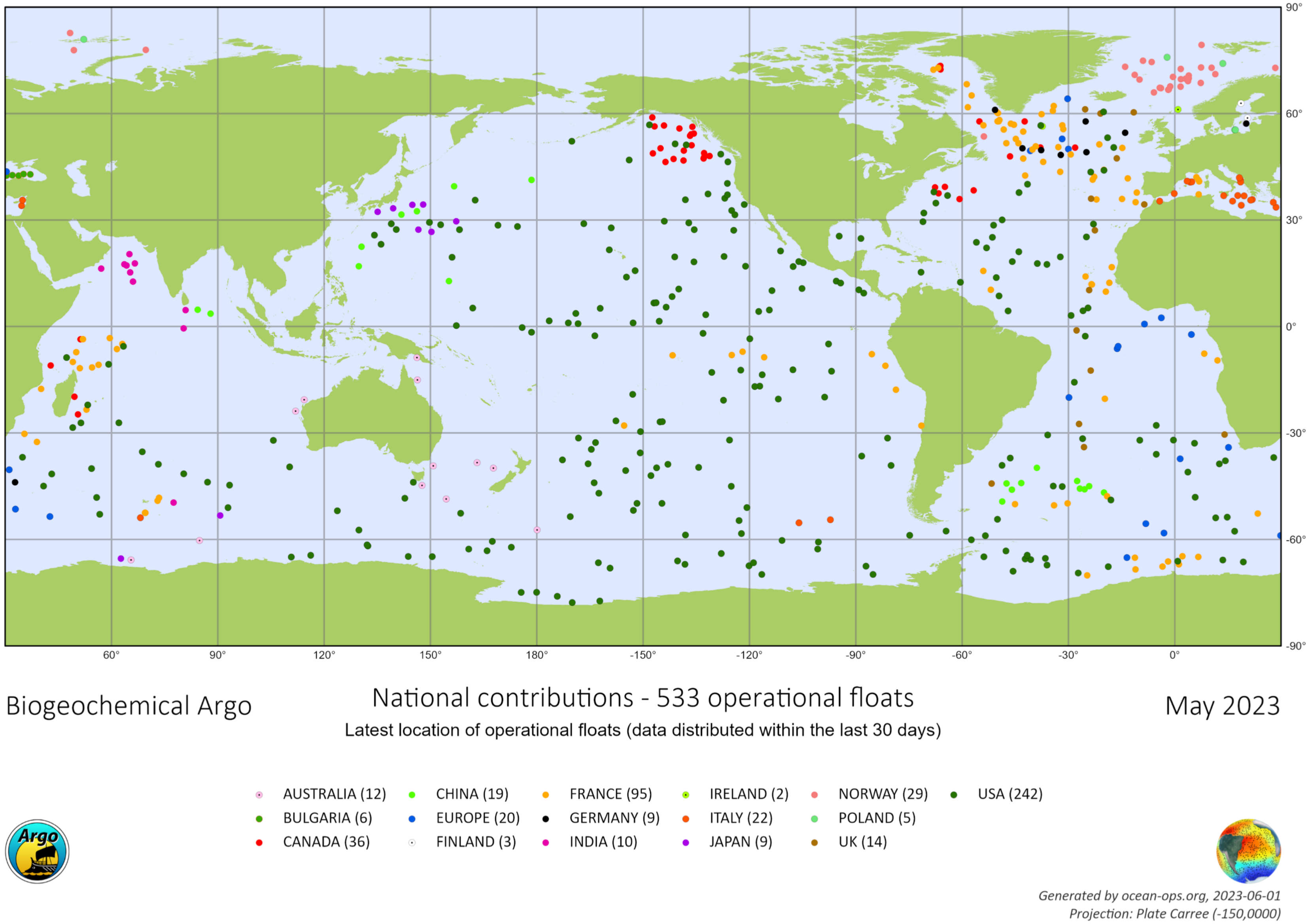


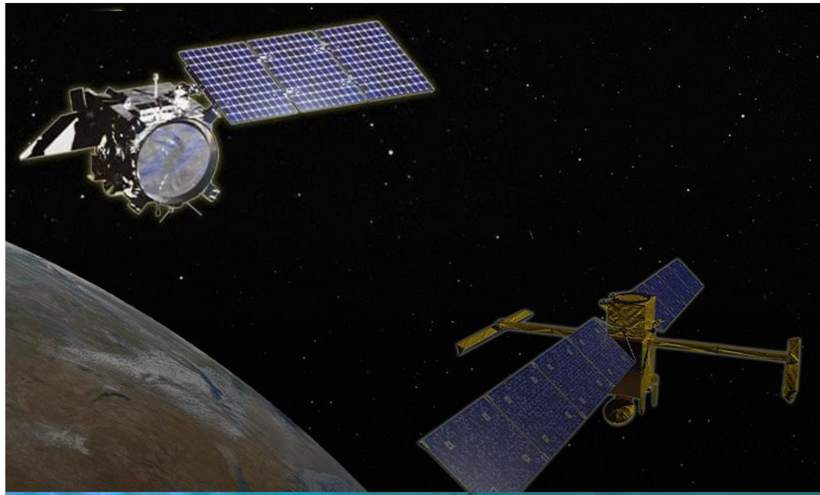
Cerovečki *et al* 2022 *ERL*

Papers using our regional SKRIPS model

- **Polar work:**
  - Conservation of heat and mass in P-SKRIPS version 1: the coupled atmosphere-ice-ocean model of the Ross Sea.
  - Impact of downward longwave radiative deficits on Antarctic sea-ice extent predictability during the sea ice growth period
- **Surface waves**:
  - Waves in SKRIPS: WaveWatch III coupling implementation and a case study of cyclone Mekunu
  - Focusing and defocusing of tropical cyclone generated waves by ocean current refraction
- **Coupled forecasting:**
  - The role of air–sea interactions in atmospheric rivers: Case studies using the SKRIPS regional coupled model
  - SKRIPS v1. 0: a regional coupled ocean–atmosphere modeling framework (MITgcm–WRF) using ESMF/NUOPC, description and preliminary results for the Red Sea
- **Assimilation papers in development, including BGC assimilation**

BGC-Argo is rapidly expanding, and beginning to provide sufficient coverage of in situ observations to justify a DA effort. The carbon observing system is becoming mature!

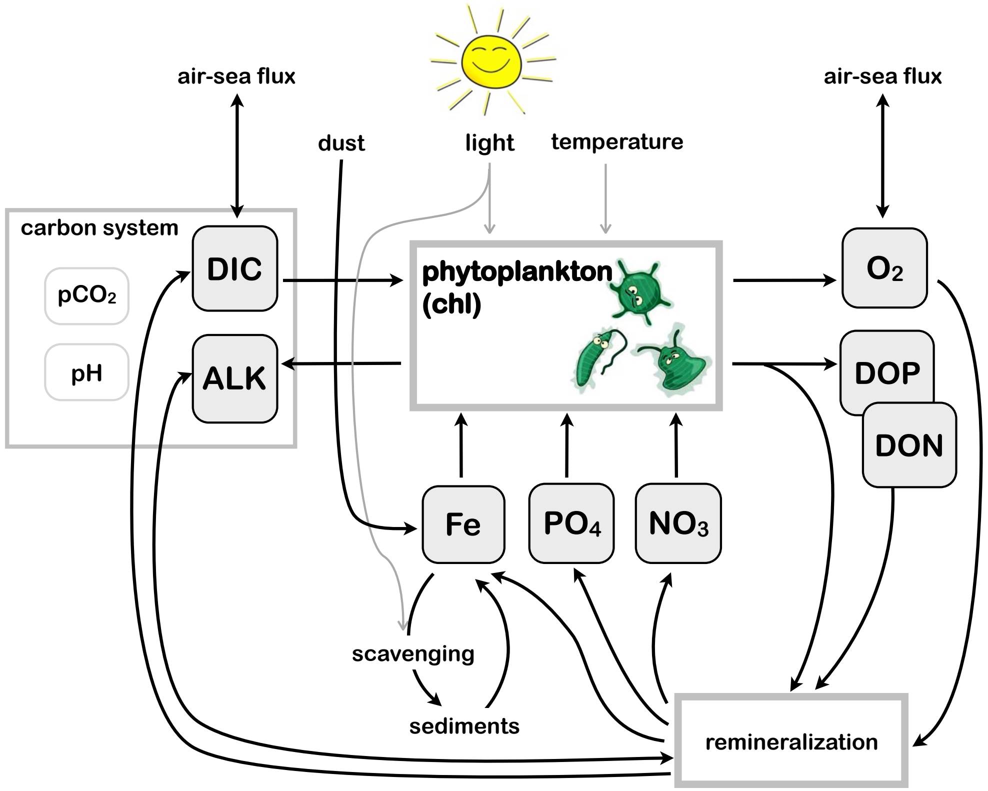




BGC model component is relatively computationally expensive

Adding N-BLING (evolved from Glabraith et al. 2010) adds 9 prognostic tracers

"N-bling"



B-SOSE
Biogeochemical Southern Ocean State Estimate

All prognostic and diagnostic variables are estimated. Can be constrained to observations, and this information can propagate through the system via DA

But there is great cause for optimism in BGC assimilation:

- **BGC DA works very well!** Minimal increase to the overall nonlinearity of the system.
- **BGC is a strong constraint on the physical system,** so great added value to ESM!

Discussion

- Errors come from model inputs (e.g. ICs), which may be be amplified by flow instabilities, and from the model approximations and parameterizations
- Assimilation should be a good way to find errors, but the model error covariance is the key problem hindering identification of error sources.
- Short-term regional assimilation allows high resolution and may be a useful tool for identifying errors and studying how to mitigate or resolve them.
- Regional process experiments can inform climate model parameterizations, and lead to new stochastic parameterizations based on the observed physics.
- We are working on regional process experiments using the DA as a data analysis tool for testing new ideas, formulating parameterizations and transport models and estimating the parameters.
- Can we control/damp the chaotic behavior and then parameterize the impact?