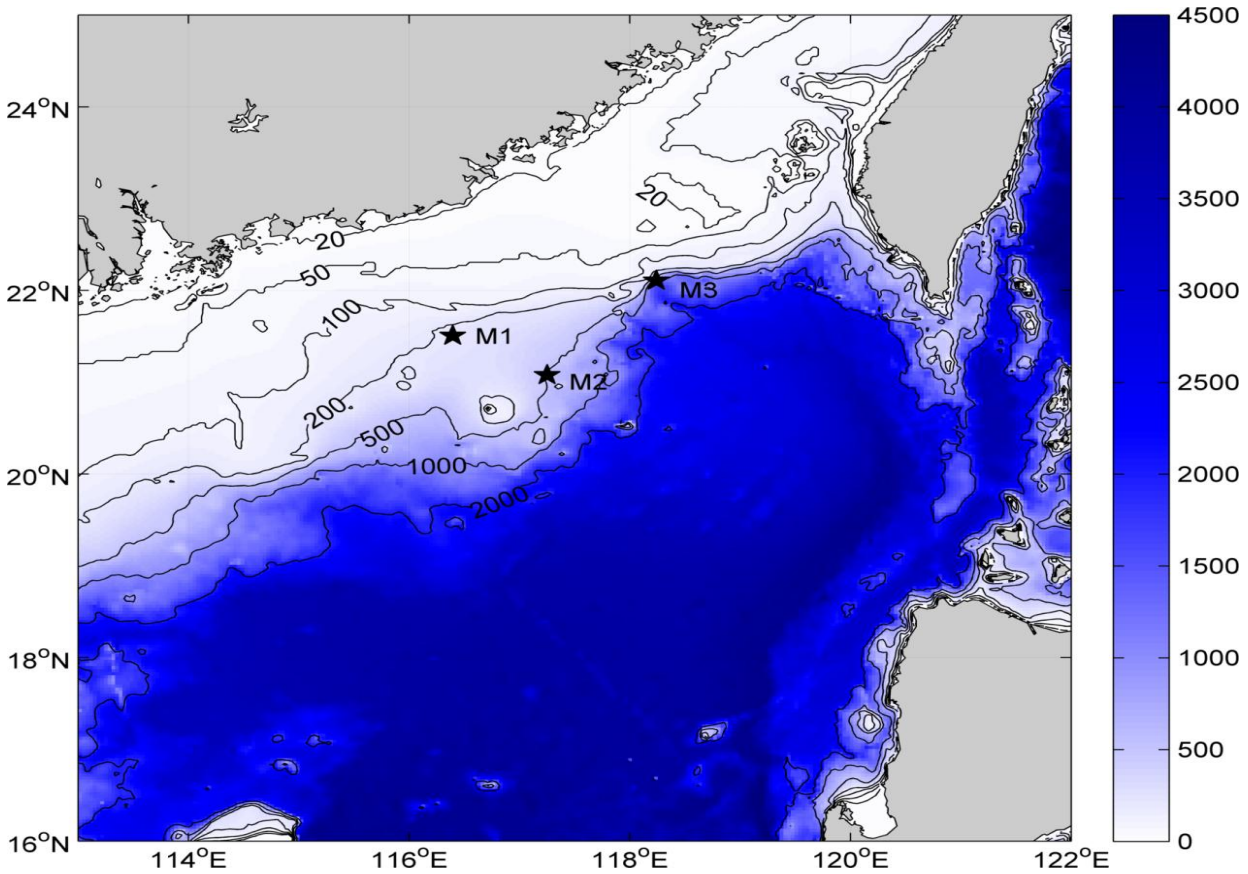
LLC4320--A Global Simulation of the Ocean at 2km Horizontal ~~Resolution~~ Grid Spacing

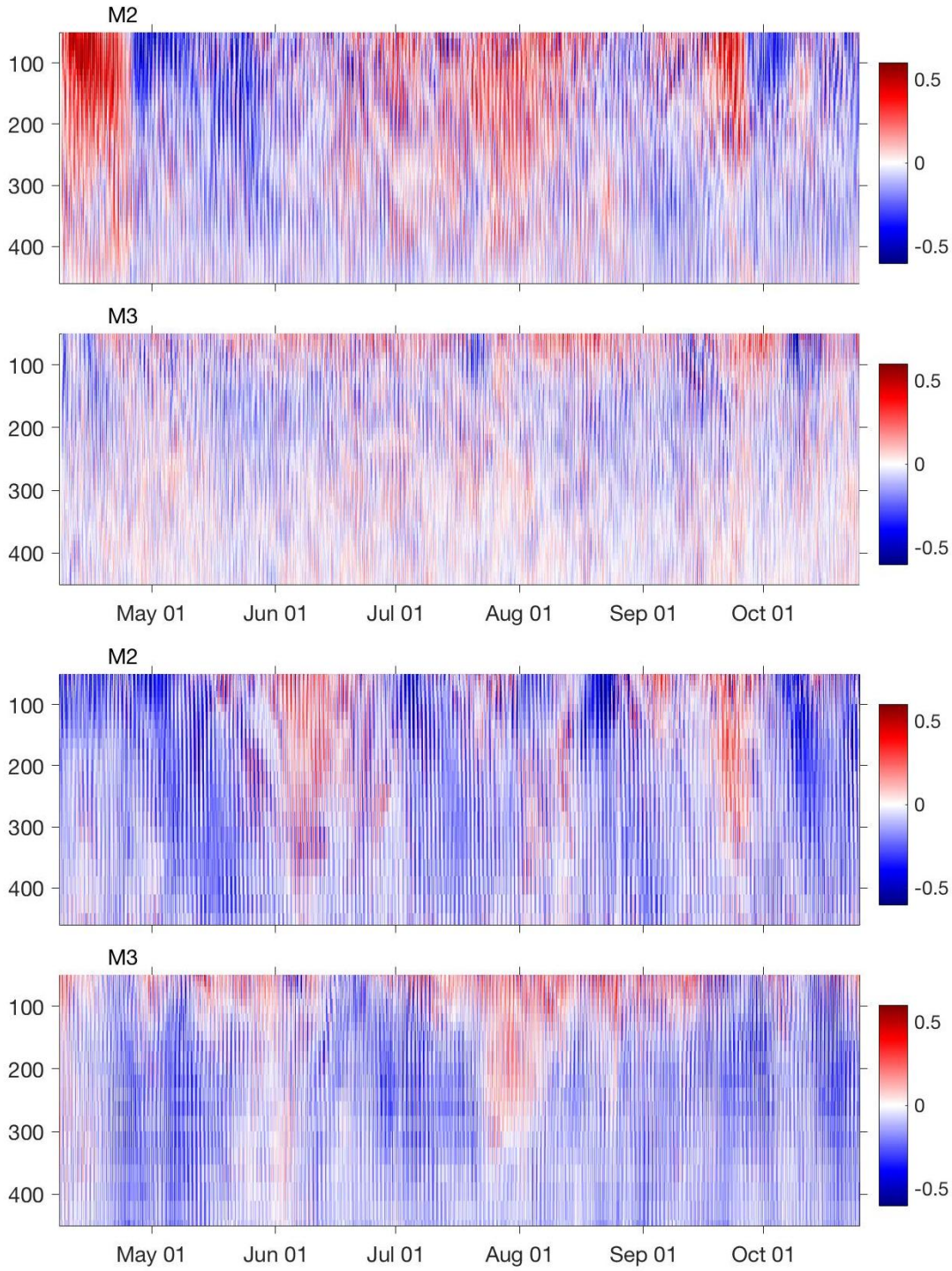
Dimitris Menemenlis (Jet Propulsion Laboratory).

Room: SMALL SEMINAR ROOM (1003A)
KITP [blayers18] Second Week. Time: 12 Apr 13:30 - 15:00

Dimitris will introduce how the (worst-named) global 2km MITgcm ocean simulations were set up and some of the interesting behaviors.

Observations from three moorings in the shelf break of the South China Sea in 2014





V-component (cm/s) from model (2012) and ADCP observations (2014).
Which is which?

(figures by Zhiyu Liu ~2 hours ago!)

ECCO slide from Ian Fenty,
Portland Ocean Sciences meeting:

ECCO WORKSHOP

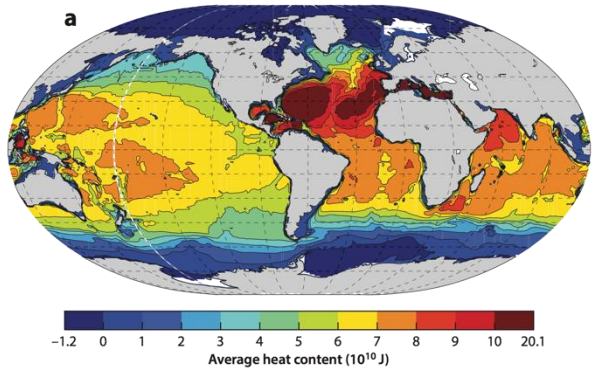
HOW TO USE THE LATEST ECCO OCEAN STATE ESTIMATE

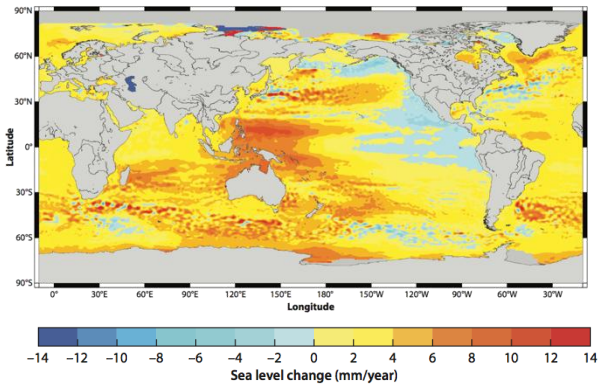
- *The "Estimating the Circulation and Climate of the Ocean" (ECCO) consortium is directed at making the best possible estimates of ocean circulation and its role in climate.*
- ***Solutions are obtained** by combining state-of-the-art ocean circulation models with nearly complete global ocean data sets in a physically and statistically consistent manner.*
- ***Products are being utilized** in studies on ocean variability, biological cycles, coastal physics, water cycle, ocean-cryosphere interactions, and geodesy, and are available for general applications.*

$$J = \sum_{t=0}^{t_f} (y_t - \Gamma_t x_t)' P_t (y_t - \Gamma_t x_t)$$

$$L = J(x_{[0,t_f]}) + \sum_{t=0}^{t_f-1} \lambda_t' \left(x_{t+1} - M(p_t, x_t)\right)$$

$$\lambda_0 = \sum_{t=1}^{t_f-1} \left\{A_1' A_2' \cdots A_t' G_{t+1}\right\} + G_1$$

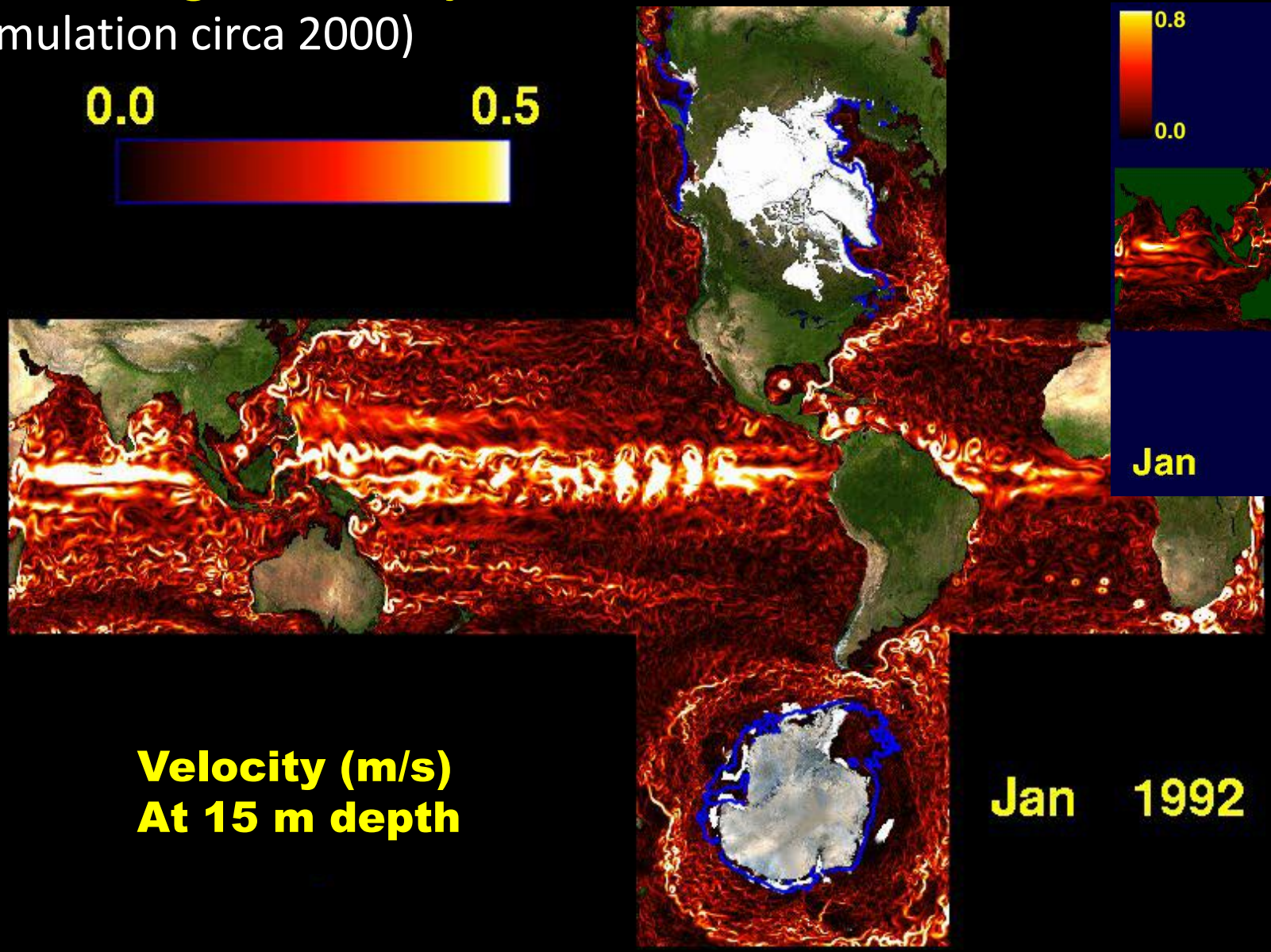


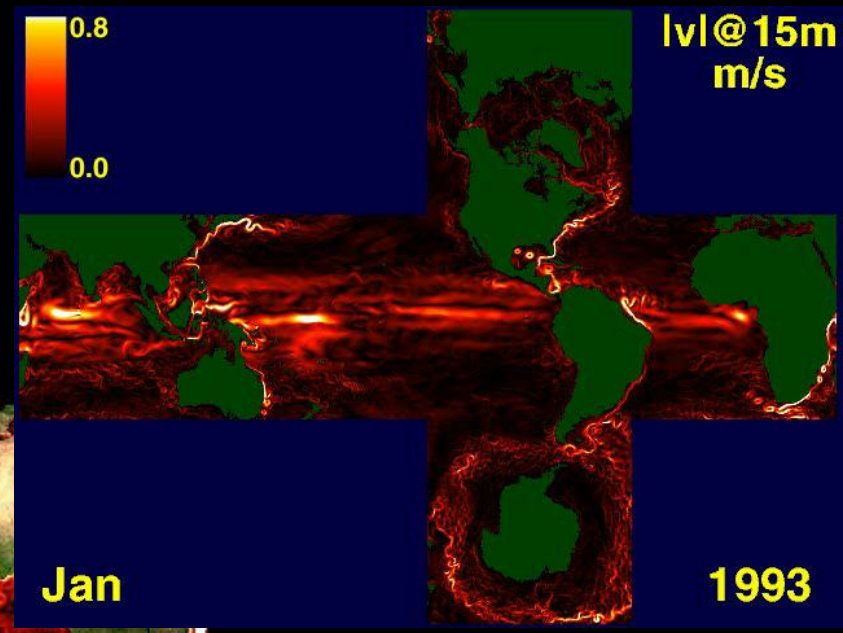


Towards a next-generation synthesis of ocean and sea-ice data

(hires simulation circa 2000)

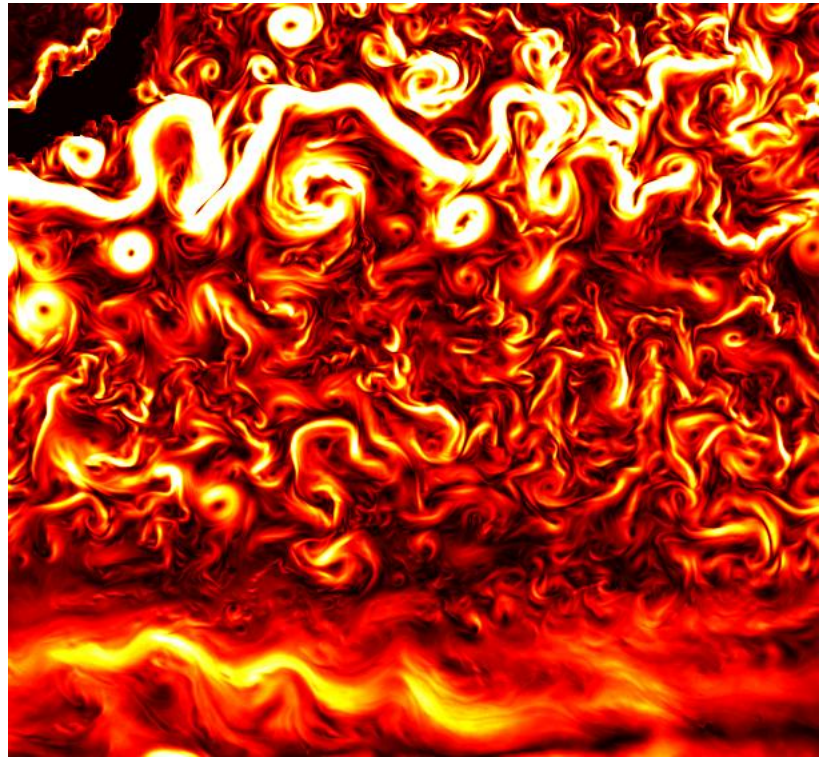
(Menemenlis, Hill, Adcroft, Campin, Cheng, Ciotti, Fukumori, Heimbach, Henze, Kohl, Lee, Stammer, Taft, and Zhang, 2005)



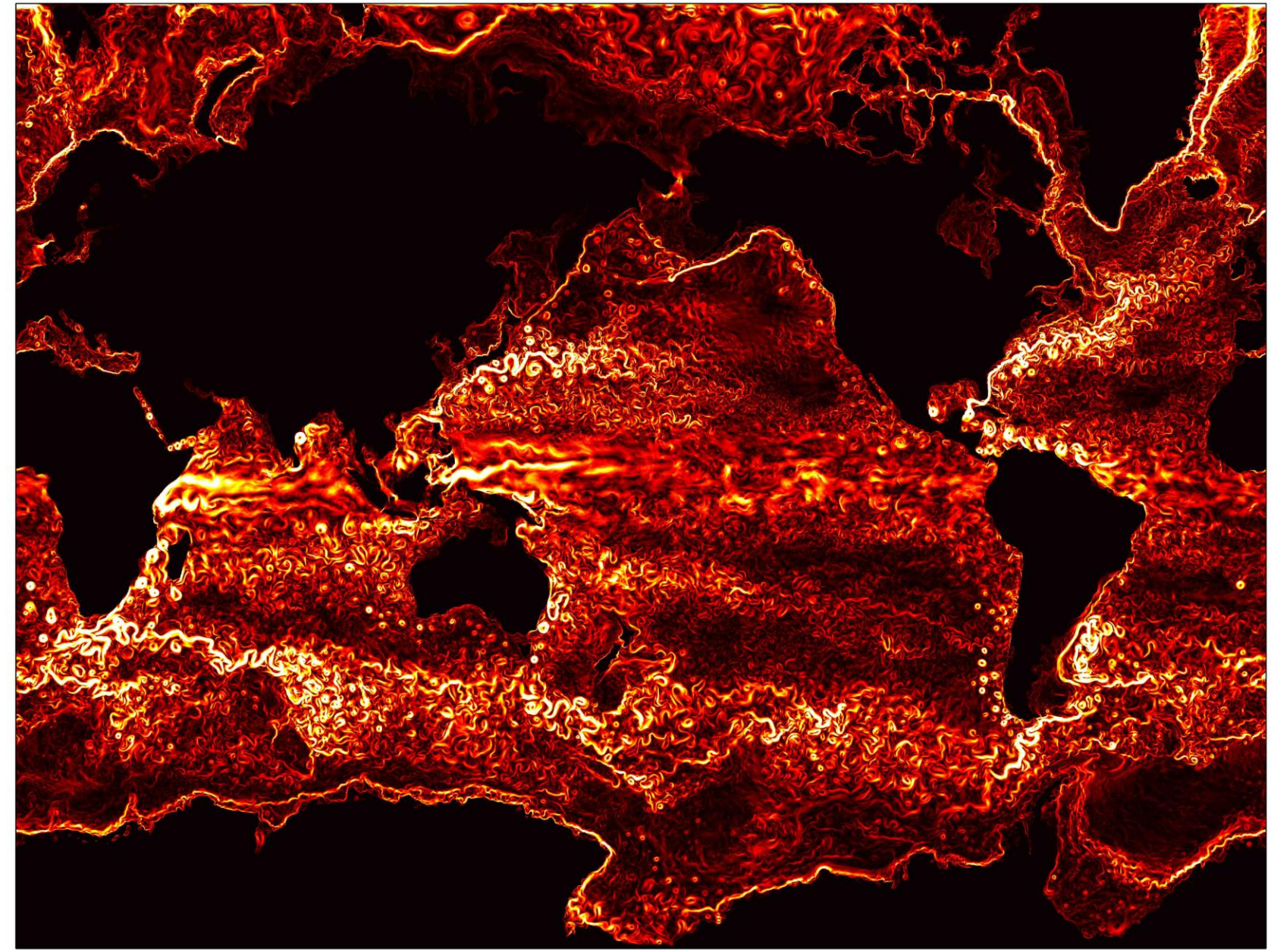


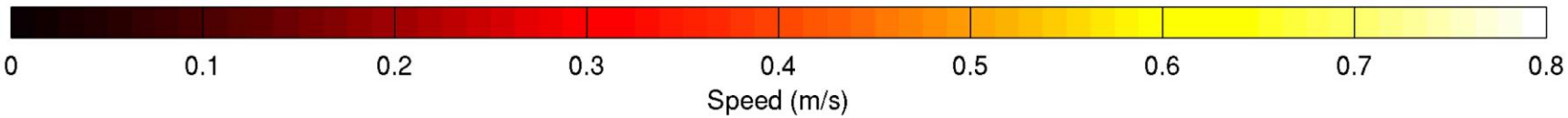
Objective: synthesis of global-ocean and sea-ice data that covers the full ocean depth and that permits eddies.
Motivation: quantify role of oceans in global carbon cycle, understand recent evolution of polar oceans, monitor time-evolving term balances within and between different components of Earth system, etc., etc.

Global 1/16-deg simulation circa 2005 (Hill et al., 2007)



Is the ocean really behaving like this? A question to be answered by SWOT. (Lee-Lueng Fu, 2009 ECCO meeting, Caltech)





~2014 presentation title

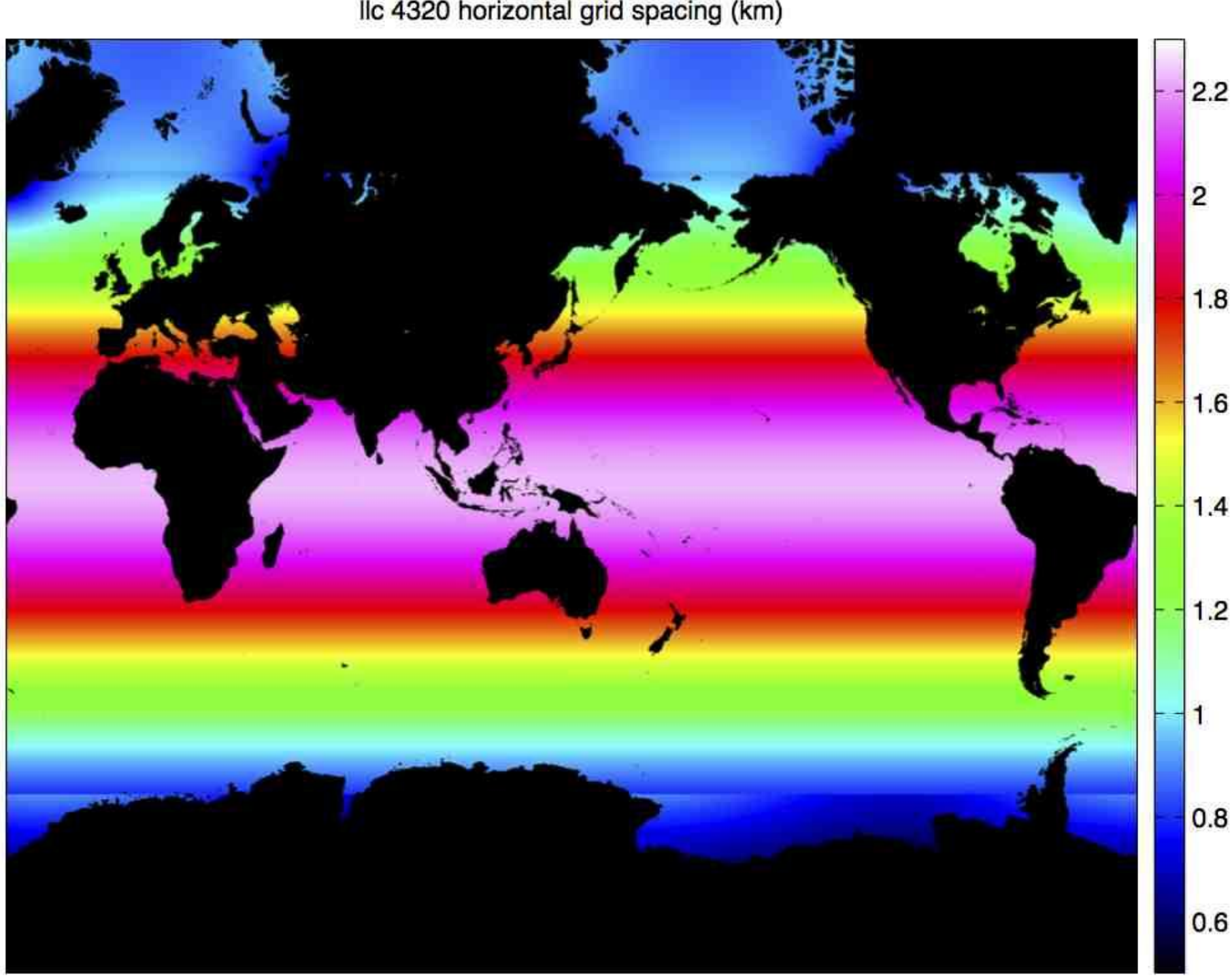
A global, highly instrumented, internal-tide-resolving numerical ocean and sea ice laboratory

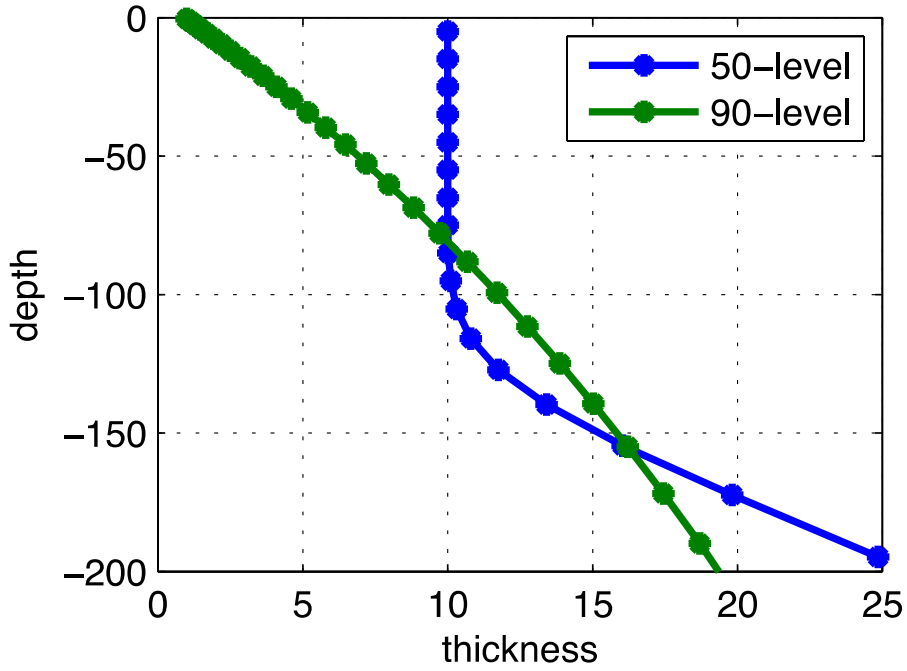
C. Hill and G. Forget (MIT)
C. Henze, B. Nelson, and B. Ciotti (Ames)
D. Menemenlis (JPL)
A. Chaudhuri (AER)
MITgcm developers and users
SGI and NAS computer scientists and engineers

MITgcm is the Massachusetts Institute of Technology general circulation model, which is the foundation of the Estimating the Circulation and Climate of the Ocean (ECCO) series of projects.

Comparison of 1/16 vs llcXXXX simulations

Simulation	Hill et al. (2007)	llcXXXX
Domain	80S – 80N	Global
Grid configuration	latitude/longitude	latitude/longitude/polar cap
Horizontal grid spacing	1/16 degree	1/12, 1/24, and 1/48 degree
Vertical levels	50	90
Surface level thickness	10 m	1 m
Atmospheric forcing	daily NCEP reanalysis 2.5-degree grid surface fluxes	6-hourly ECMWF analysis 0.14-degree grid bulk formulae/relative wind
Atmospheric load	No	Yes
Tides	No	Yes
Barotropic time stepping	Adams-Bashforth	Crank-Nicolson
Time step	120 s	90, 45, and 25 s
Dynamic sea ice	No	Yes
Output	Daily	Hourly


llc 4320 horizontal grid spacing (km)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6


50–level
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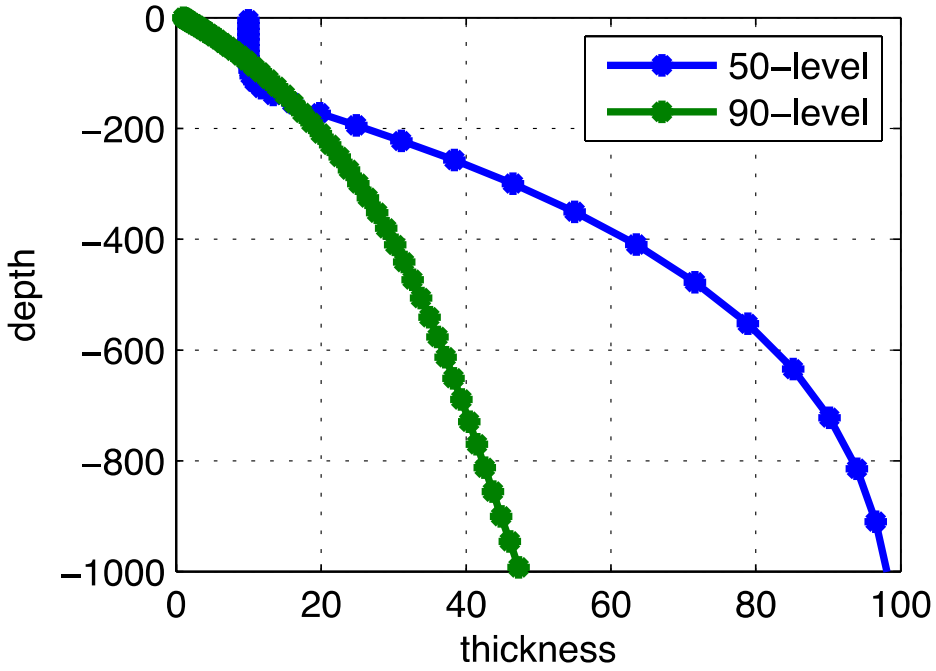
15
20
25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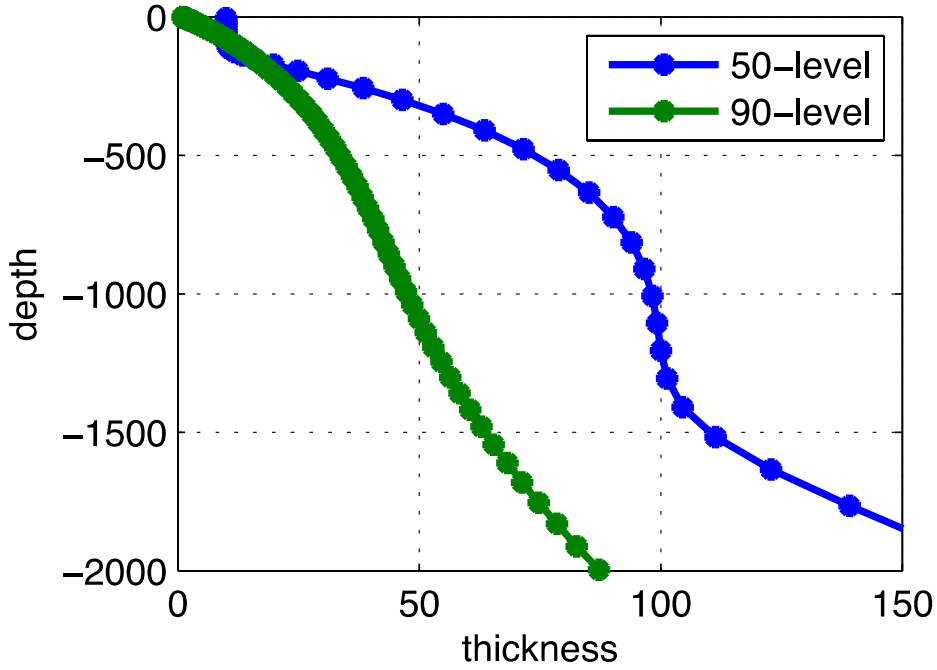
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−1000
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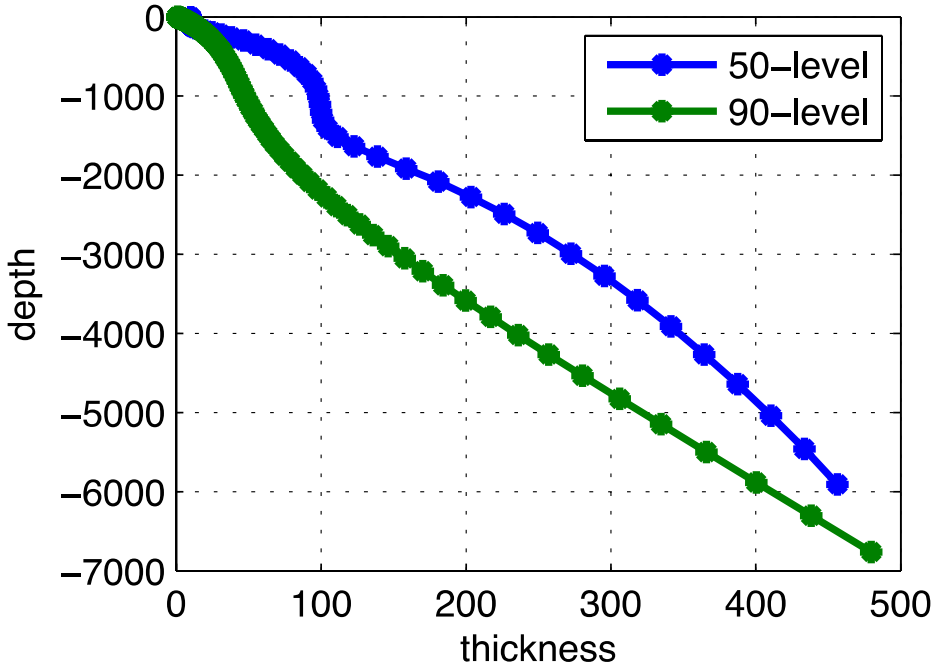
0
50
100
150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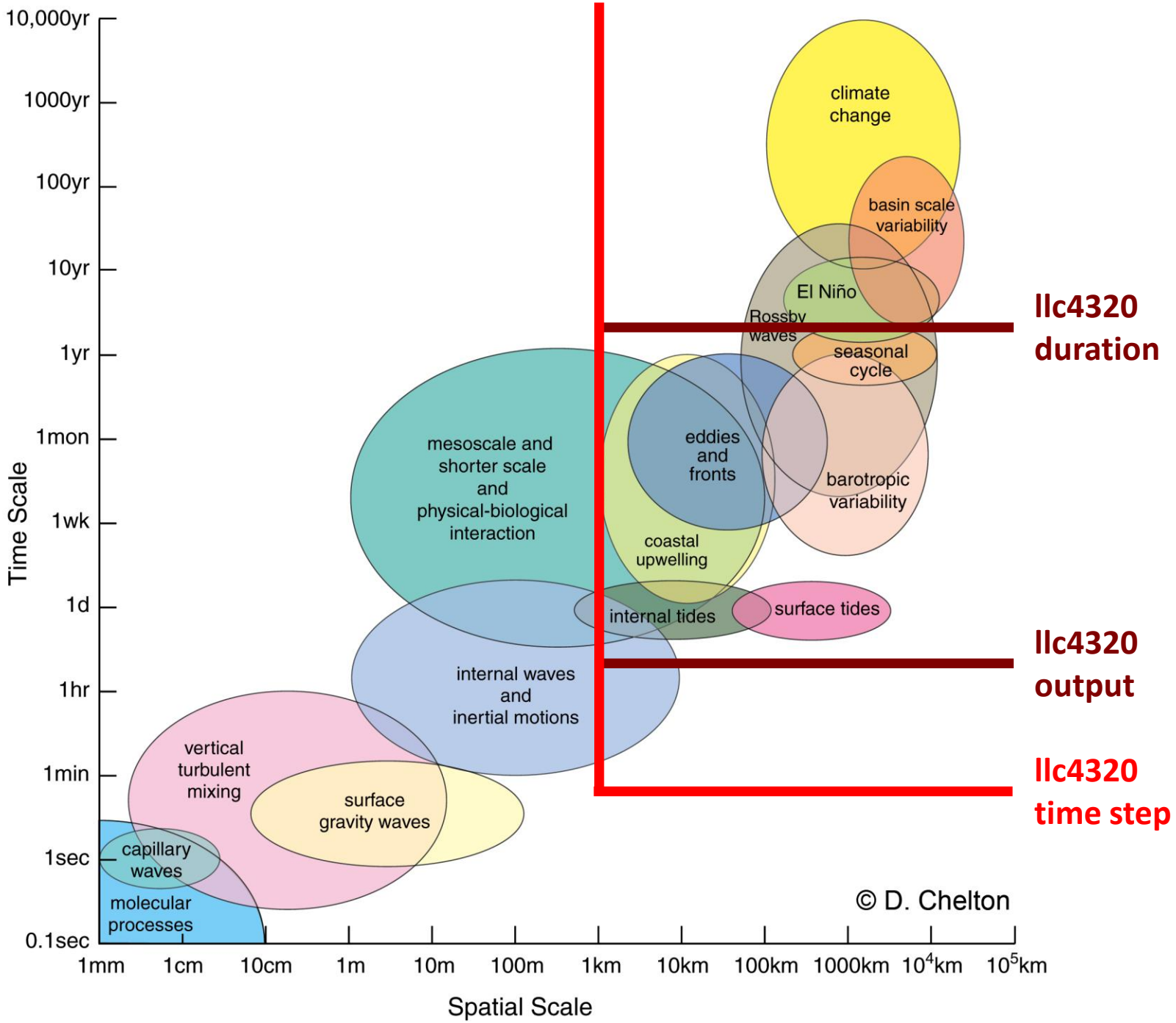
500


10,000yr
1000yr
100yr
10yr
1yr
1mon
1wk
1d
1hr
1min
1sec
0.1sec
Time Scale
1mm
1cm
10cm
1m
10m
100m
1km
10km
100km
1000km
10^4km
10^5km
Spatial Scale
climate change
basin scale variability
El Niño
Rossby waves
seasonal cycle
eddies and fronts
barotropic variability
mesoscale and shorter scale and physical-biological interaction
coastal upwelling
internal tides
surface tides
internal waves and inertial motions
vertical turbulent mixing
surface gravity waves
capillary waves
molecular processes
© D. Chelton
llc4320 duration
llc4320 output
llc4320 time step

llcXXXX spin-up and available output

llc1080
- start January 1, 2010 from 2009-2011 3-year CS510 adjoint-method estimate
- run for one year with ERA-interim, with corrected dlw
- add tides, atmospheric pressure, and 0.14-degree ECMWF on January 1, 2011
- output available to June 13, 2012 (896 days)

llc2160
- start January 14, 2011 from llc1080 simulation
- output available to April 22, 2013 (825 days)

llc4320
- start September 10, 2011 from llc2160 simulation
- output available to November 15, 2012 (15 months)

Integration times for llc4320:
120x120 tiles x 12,000 cores: 12 minutes of integration per hour of simulation
90x90 tiles x 20,400 cores: 7 minutes of integration per hour of simulation
72x72 tiles x 35,000 cores: 4 minutes of integration per hour of simulation
48x48 tiles x 70,000 cores: 3.5 minutes of integration per hour of simulation

CPU cycles are not so much an issue anymore, but storage and distribution is still problematic. The 14-month LLC4320 simulation produced ~5 PB (5000 TB) of model output:

```
bash-3.2$ ls -lh *0000138240.data
-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 Eta.0000138240.data
-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 KPPhbl.0000138240.data
-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 PhiBot.0000138240.data
-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 SIarea.0000138240.data
-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 SIheff.0000138240.data
-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 SIhsalt.0000138240.data
-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 SIhsnow.0000138240.data
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-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 SIvice.0000138240.data
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-rwxr----- 1 dmenemen g26209  82G Jan 21 10:55 Theta.0000138240.data
-rwxr----- 1 dmenemen g26209  82G Jan 21 10:55 U.0000138240.data
-rwxr----- 1 dmenemen g26209  82G Jan 21 10:55 V.0000138240.data
-rwxr----- 1 dmenemen g26209  82G Jan 21 10:55 W.0000138240.data
-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 oceFWflx.0000138240.data
-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 oceQnet.0000138240.data
-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 oceQsw.0000138240.data
-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 oceSflux.0000138240.data
-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 oceTAUX.0000138240.data
-rwxr----- 1 dmenemen g26209 926M Jan 21 10:55 oceTAUY.0000138240.data
-rwxr----- 1 dmenemen g26209 982G Jan 21 10:59 pickup_0000138240.data
-rwxr----- 1 dmenemen g26209  24G Jan 21 10:57 pickup_seaice_0000138240.data
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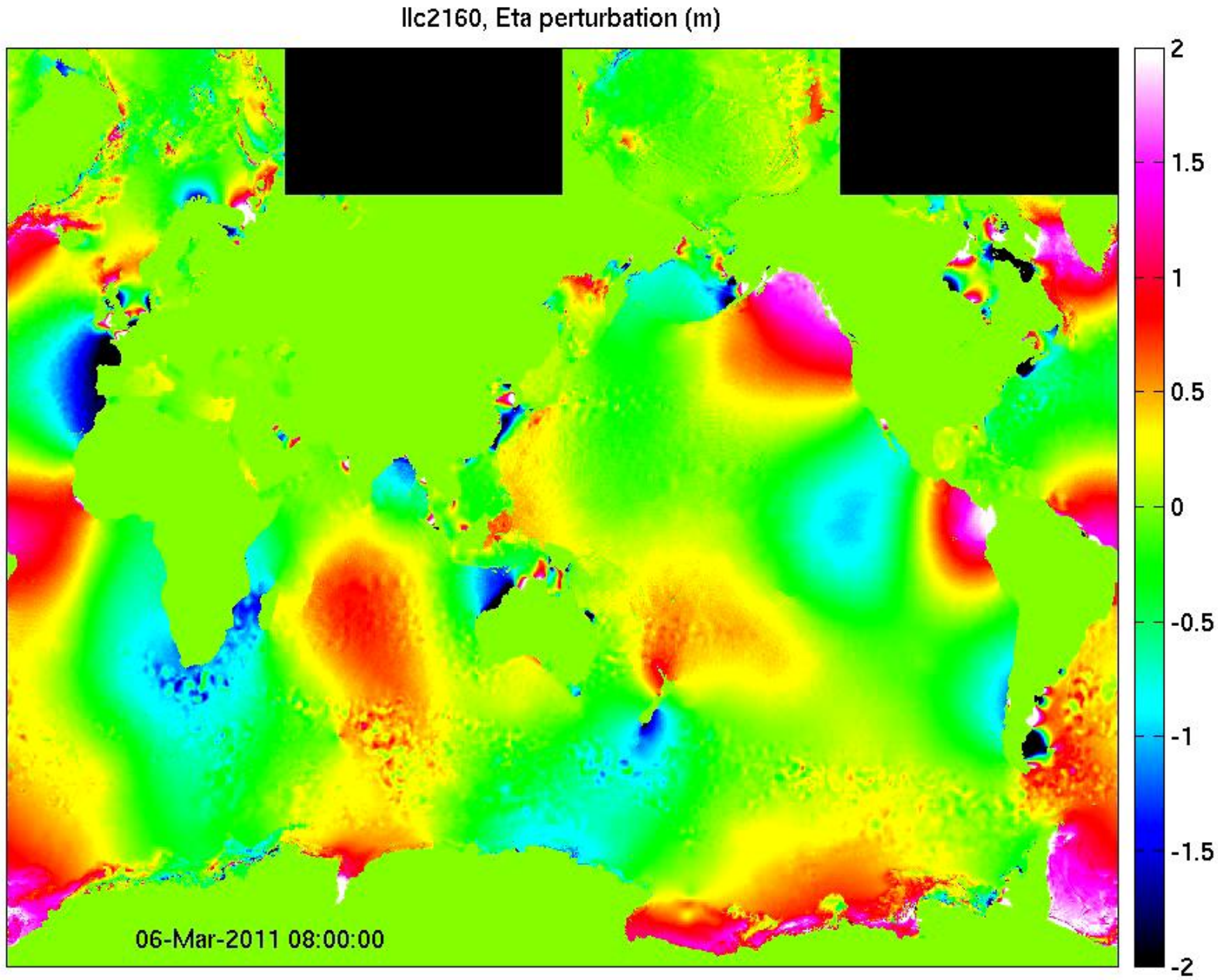
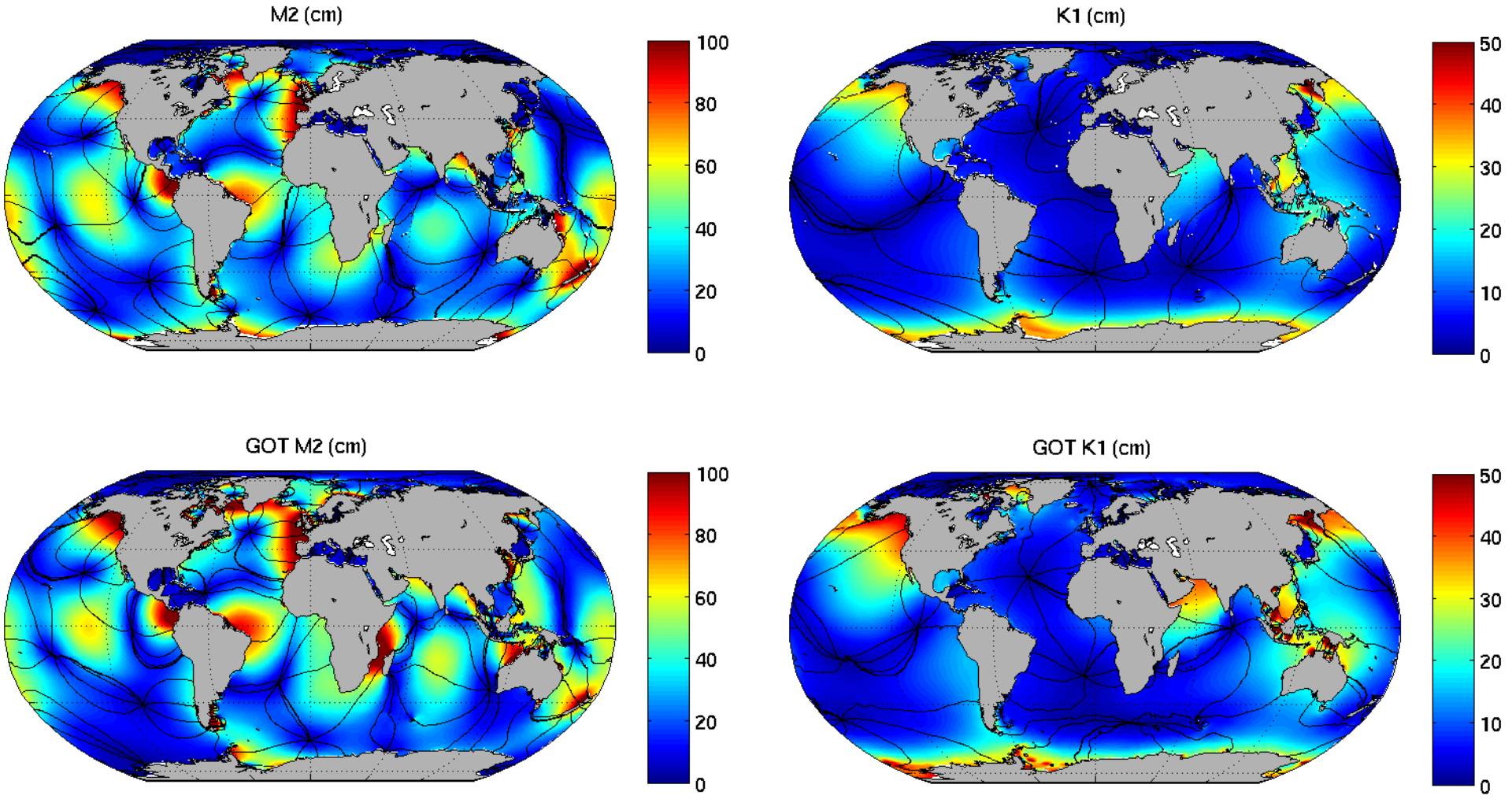
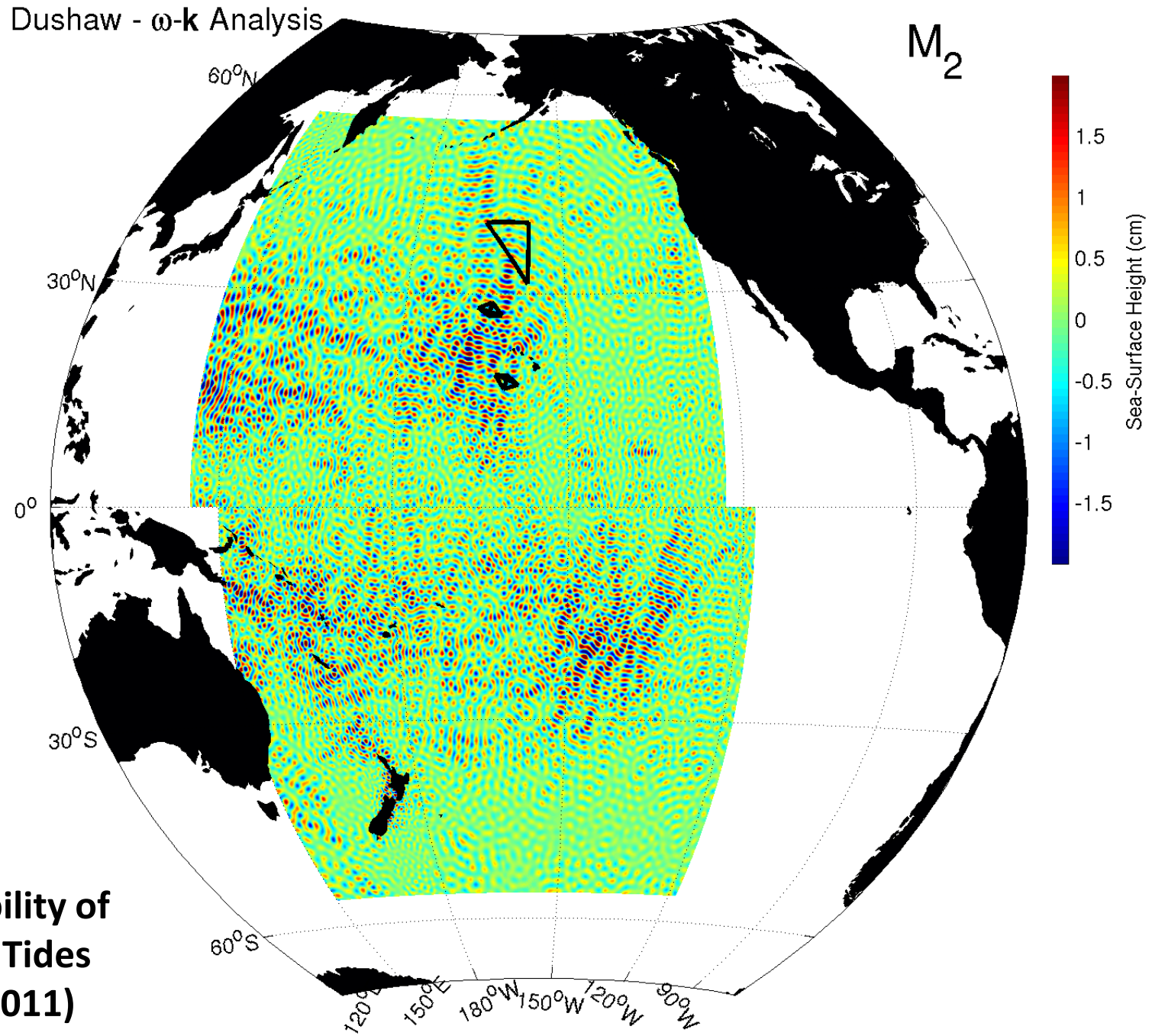

llc2160, Eta perturbation (m)
06-Mar-2011 08:00:00
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2

Barotropic tidal analysis of LLC2160 simulation (Ayan Chaudhuri)

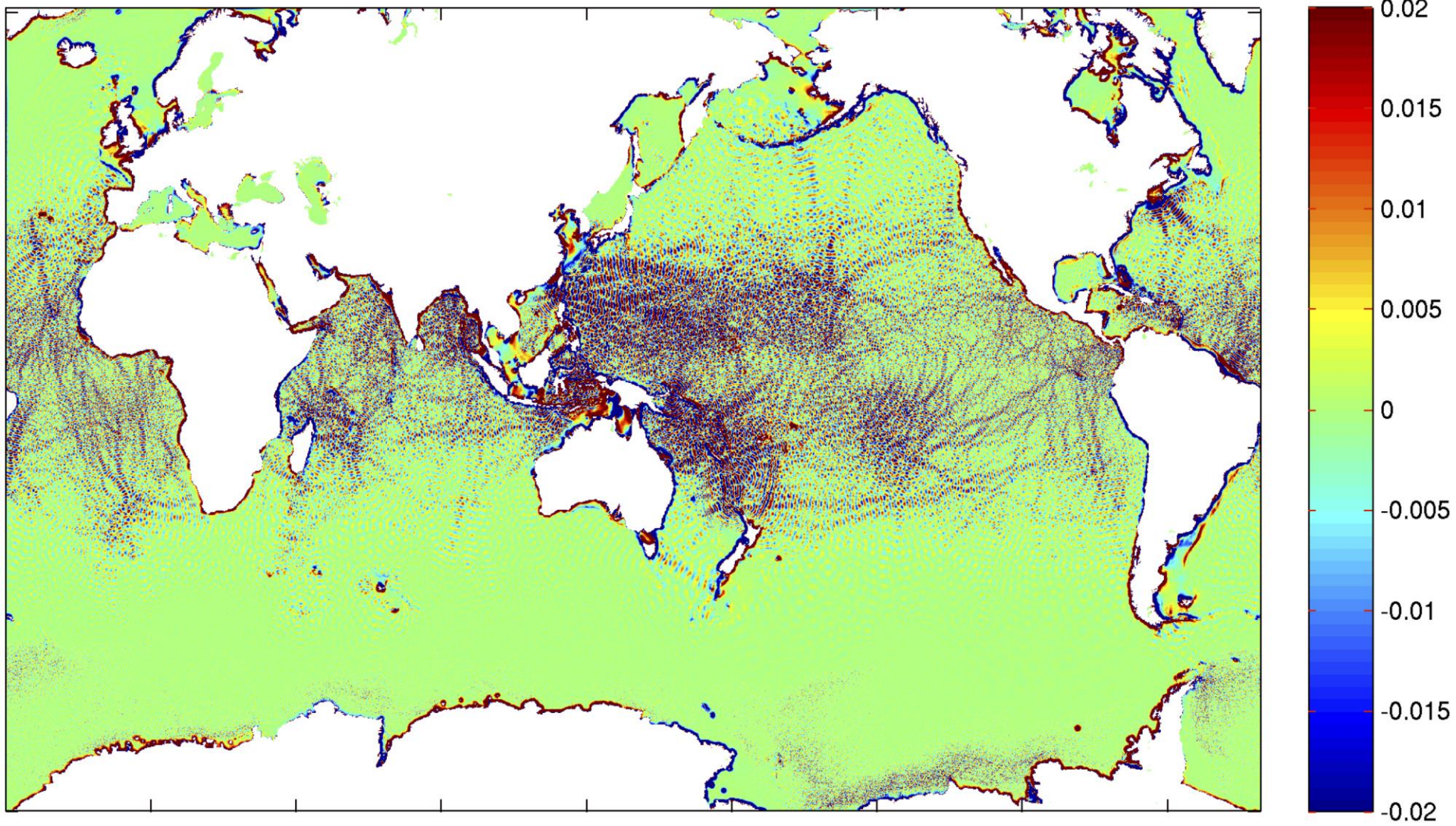


Constituent (Period)	Signal (S) GOT (cm)	Arbic et al. (D) cm 1-layer (% Var Explained)	Arbic et al. (D) cm 2-layer (% Var Explained)	MITgcm llc90 (D) cm (% Var Explained)	MITgcm llc2160 (D) cm (% Var Explained)
M2 (12.42)	26.29	7.76 (91.6)	7.26 (92.6)	5.26 (96.0)	5.35 (94.3)
S2 (12.00)	10.57	4.26 (83.8)	4.12 (84.8)	3.45 (89.3)	3.34 (90.0)
N2 (12.66)	5.65	1.51 (92.9)	1.37 (94.1)	0.95 (97.1)	0.8 (94.2)
K2 (11.97)	2.97	1.08 (86.8)	1.05 (87.6)	0.79 (93.0)	0.74 (93.8)
K1 (23.93)	9.54	2.45 (93.4)	1.88 (96.1)	2.15 (94.9)	2.84 (92.3)
O1 (25.82)	6.61	1.57 (94.4)	1.53 (94.7)	2.36 (87.2)	1.52 (94.7)
P1 (24.07)	3.13	0.77 (93.9)	0.64 (95.9)	0.71 (94.8)	0.71 (94.8)
Q1 (26.87)	1.39	0.36 (93.2)	0.38 (92.7)	0.45 (89.1)	0.36 (93.2)

Time- and area-averaged sea-surface height signals S calculated from GOT99.2 Third and fourth columns: Time- and area-averaged sea-surface height discrepancies D of 1/2_ multi-constituent one- and two-layer forward simulations with respect to GOT99.2 from Arbic et al., [2004]. Fifth column: Time- and area-averaged sea-surface height discrepancies D for MITgcm llc90. Sixth column: Time- and area-averaged sea-surface height discrepancies D for MITgcm llc2160. All quantities are computed in waters deeper than 1000m and equatorward of 66^{o}. Numbers in parentheses denote percentage of sea surface height variance captured in the model simulations. Variance explained = $100 * [1-(D/S)^2]$

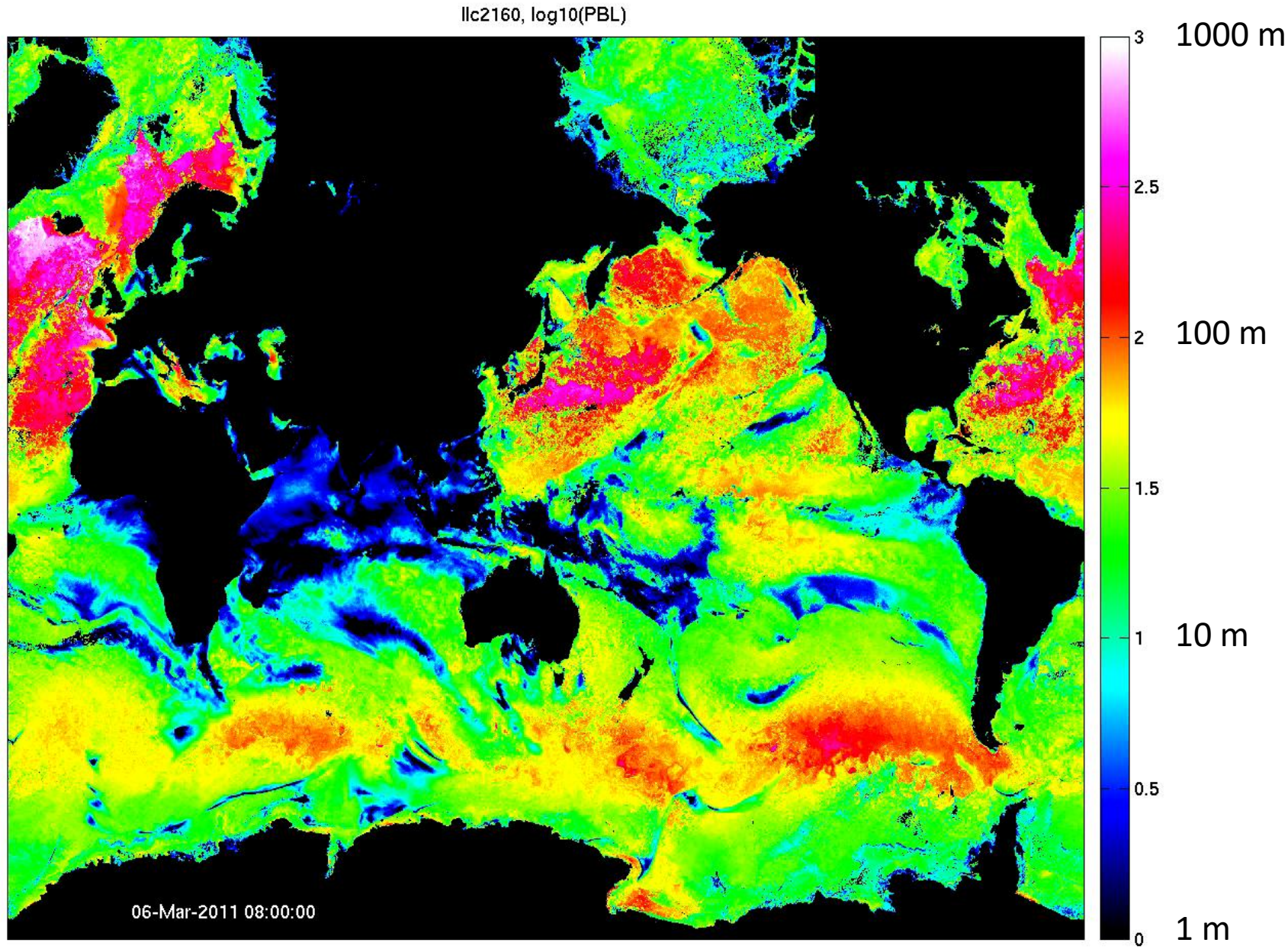


On the Predictability of Mode-1 Internal Tides (Dushaw et al., 2011)

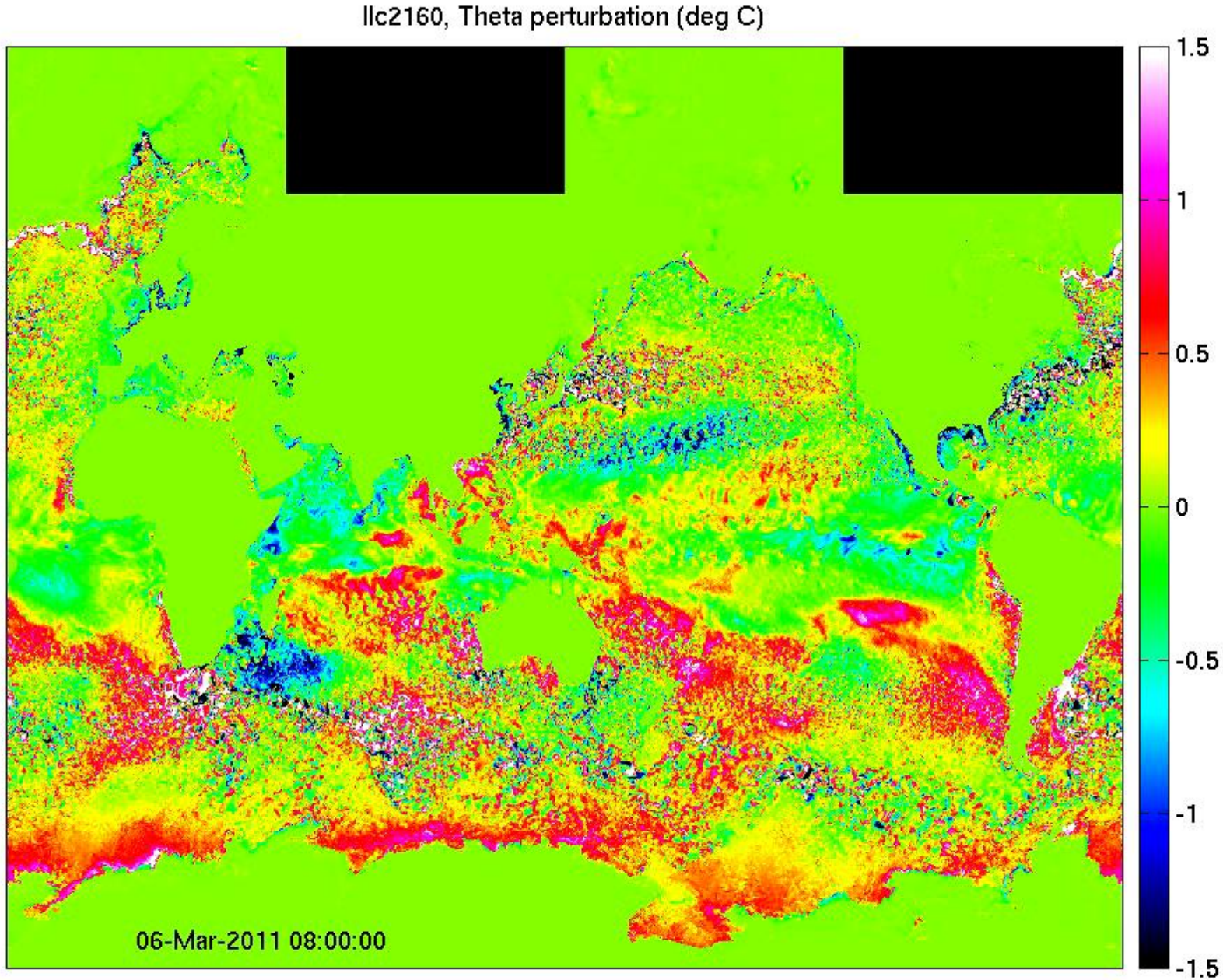


M2 internal tides on SSH in the 1/48 simulation. For each point in lat/lon, we have extracted the time series of hourly SSH over the 3 month run. We applied harmonic analysis with the 19 tide components present in the forcing of the run. We picked M2 here and applied spatial filters to amplitudes and phases to separate barotropic tides and internal tides. (C. Ubelmann)

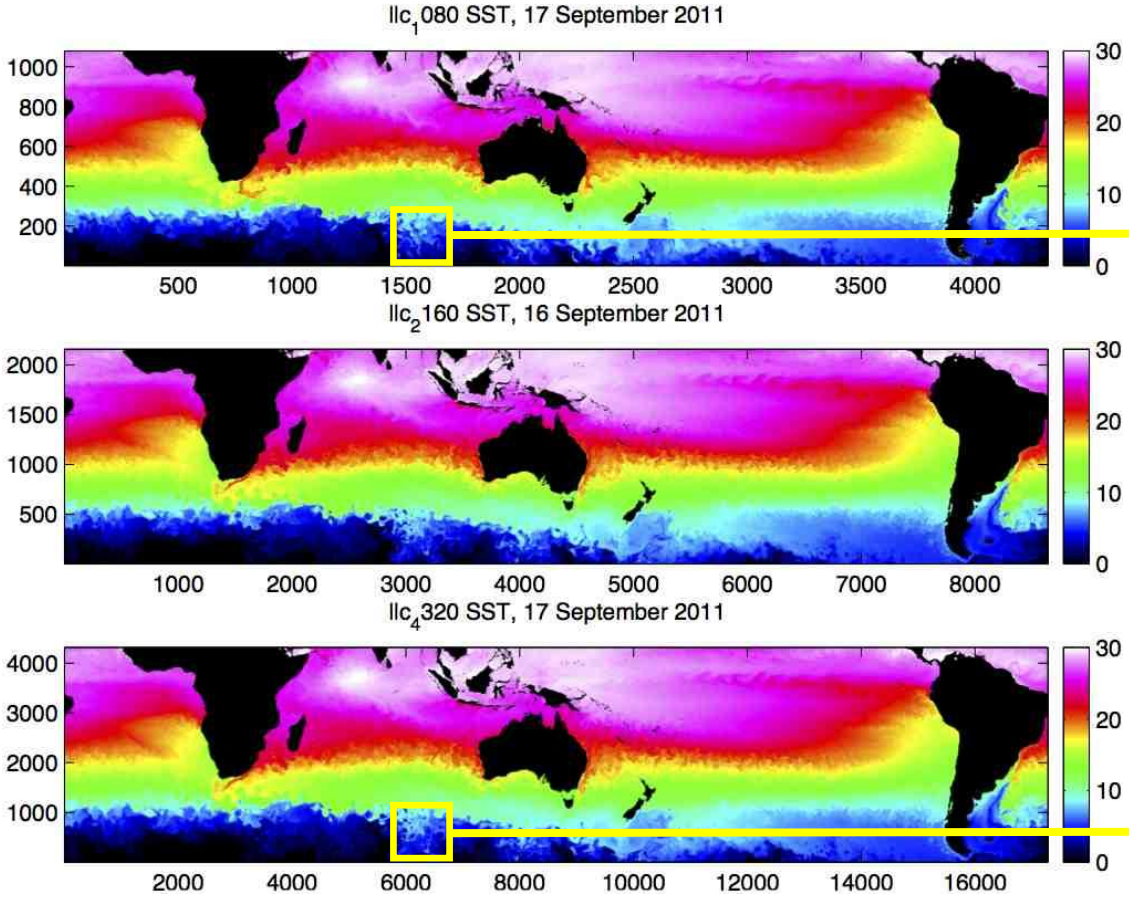
Oceanic planetary boundary layer depth

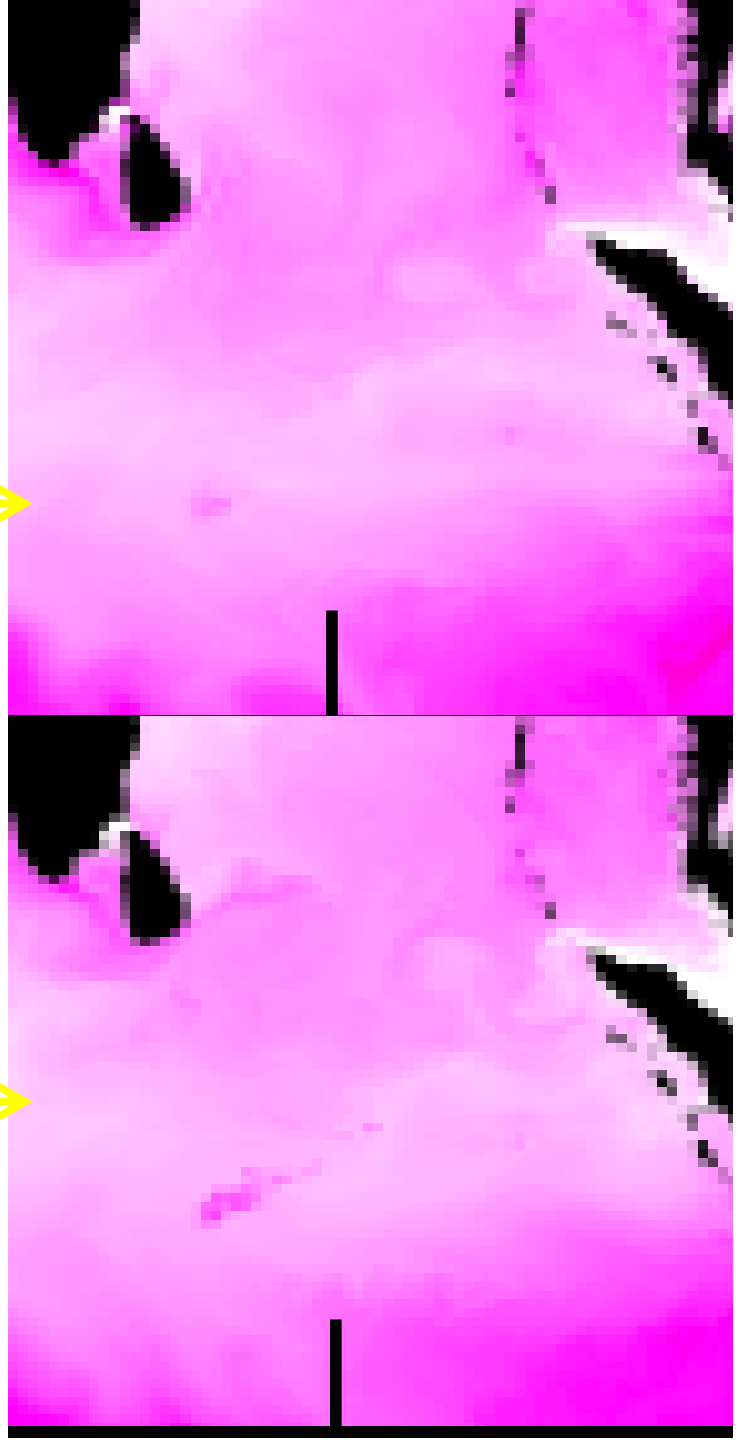


SST perturbation relative to monthly mean (deg C)

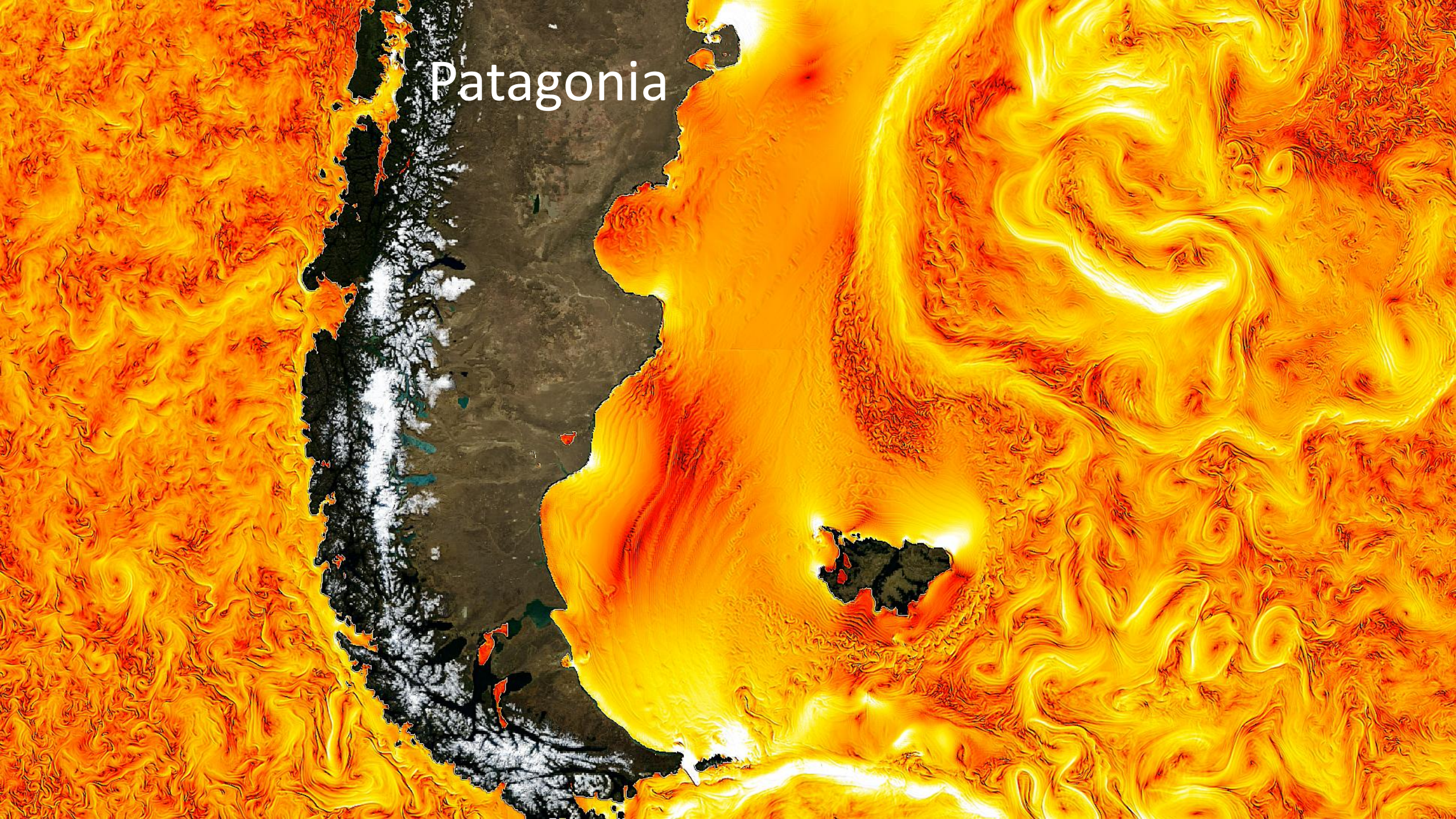


Simulated Sea Surface Temperature on September 17, 2011

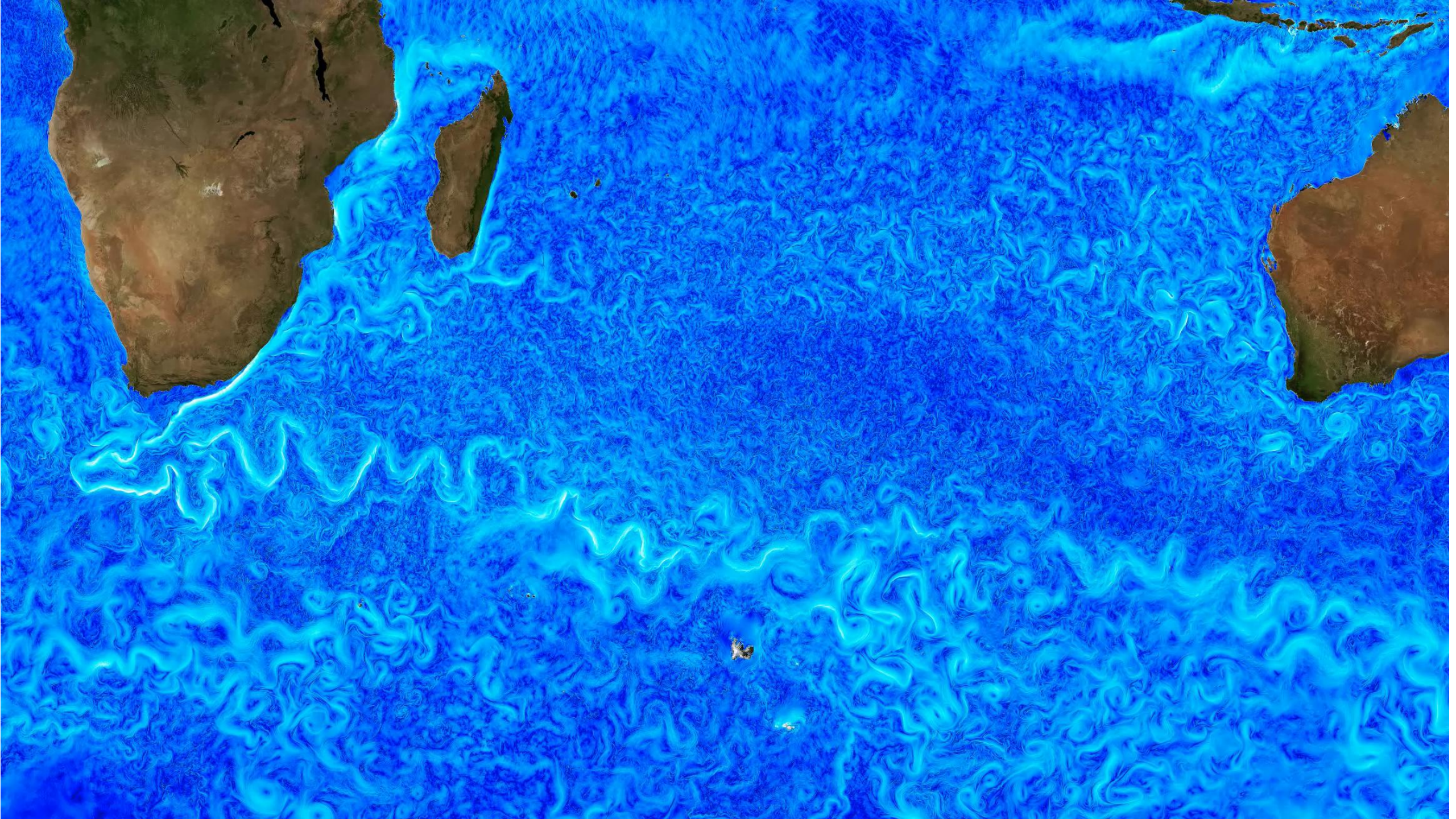


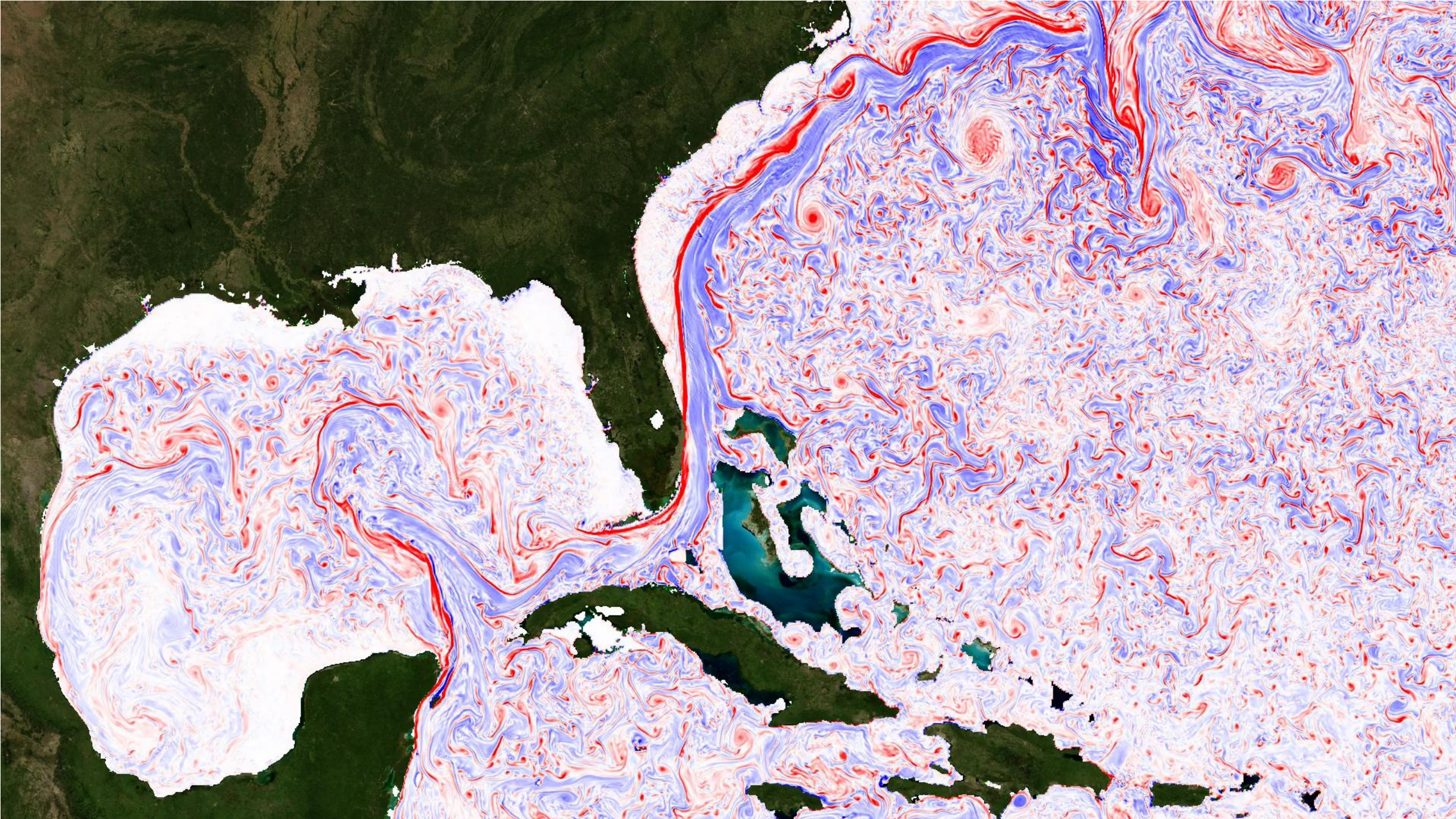



Aghulhas Rings


Patagonia


Bering Strait





Some recent updates on the LLC4320 simulation

(Paving the way for ECCO 2030–2035 global ocean state estimates)

- Nominal 1/48° horizontal grid spacing (750 m – 2.3 km – 1 km)
- 90 vertical levels: 1-m-thick near surface to 450-m-thick at 7 km
- Forced by 6-hourly 0.14° ECMWF analysis + 16 tidal components
- Spin-up from adjusted CS510 (1/6°) to LLC1080 (1/12°) to LLC2160 (1/24°)
- 14 months of hourly output (13 September 2011 – 15 November 2012)
- Also available: 26 months of LLC2160 and some LLC1080 hourly output

➢ **Lossless compression and efficient extraction tools**

➢ **Interactive visualization tools on NASA Ames hyperwall**

➢ **Some studies and model-data comparisons involving the LLC4320**

➢ **Regional set-ups forced by LLC4320 boundary conditions**

Lossless compression and efficient extraction tools

- Model output compressed by removing land points (5 → 2.5 Petabytes)
- Fast extraction tool written by Bron Nelson (NASA Ames)

usage: extract4320 [options] timesteps fieldNames 3DstartPoint 3Dextent
[options] are:
-d dir : data - root directory for the compressed timestep sub-directories
-m dir : mask - root directory for the three mask files
-o dir : output - output directory
-p : polar - extract from the polar (arctic) facet
-g : generateOnly - create commands for parallel execution
-l : little - little-endian output (default is big-endian)
-n : negate - reverse the sign of the output data
-s int : skip - bytes to skip in the output file (-1 means append)
-O file: Output - output file

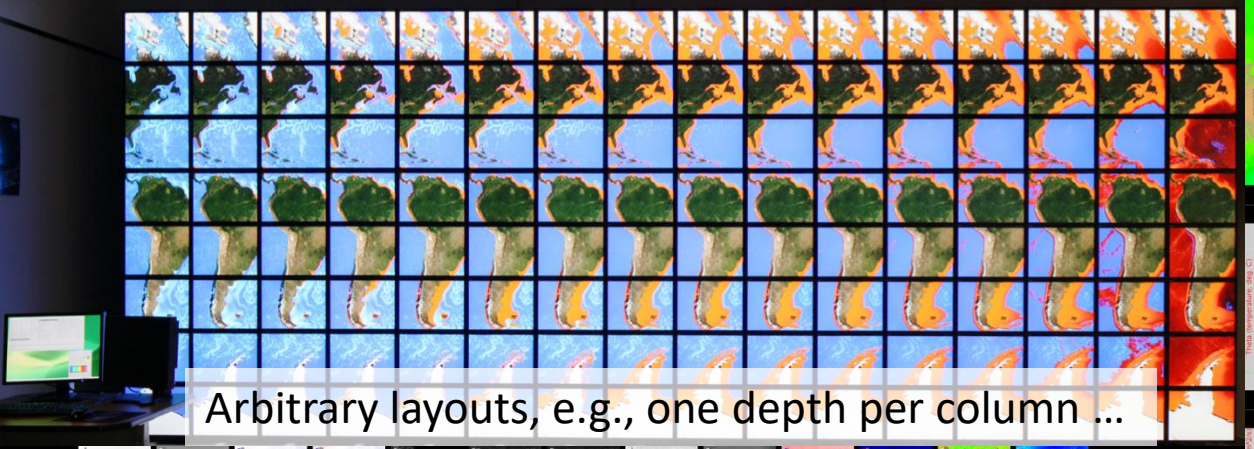
Interactive visualization tools on NASA Ames hyperwall

(David Ellsworth, Chris Henze, and Bron Nelson)

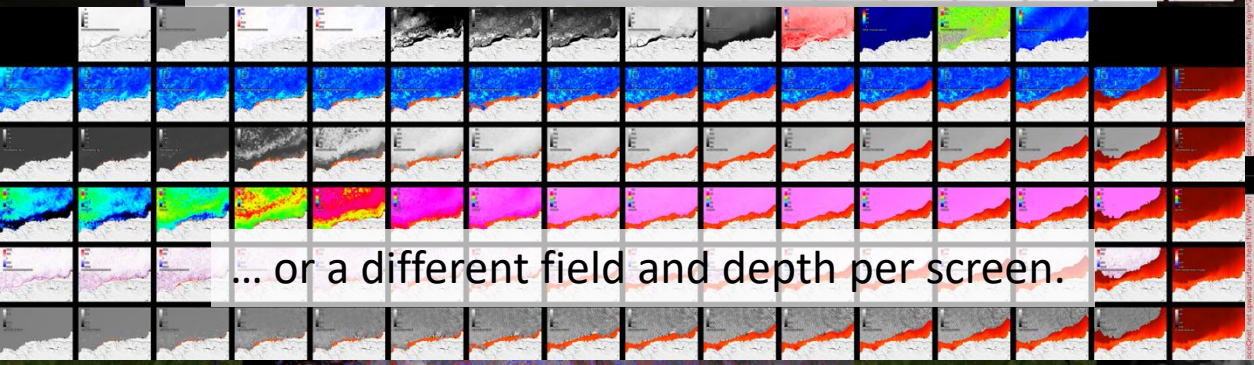
The hyperwall visualization system comprises 128 screens, each attached to a 20-core Intel Xeon Ivy Bridge node, for a peak overall processing power of 57 teraflops (1.5 times the original processing power of the Earth simulator).

Each node also has a 2 TB SSD. All the SSDs are aggregated together to form a fast, low latency 250 TB file system.

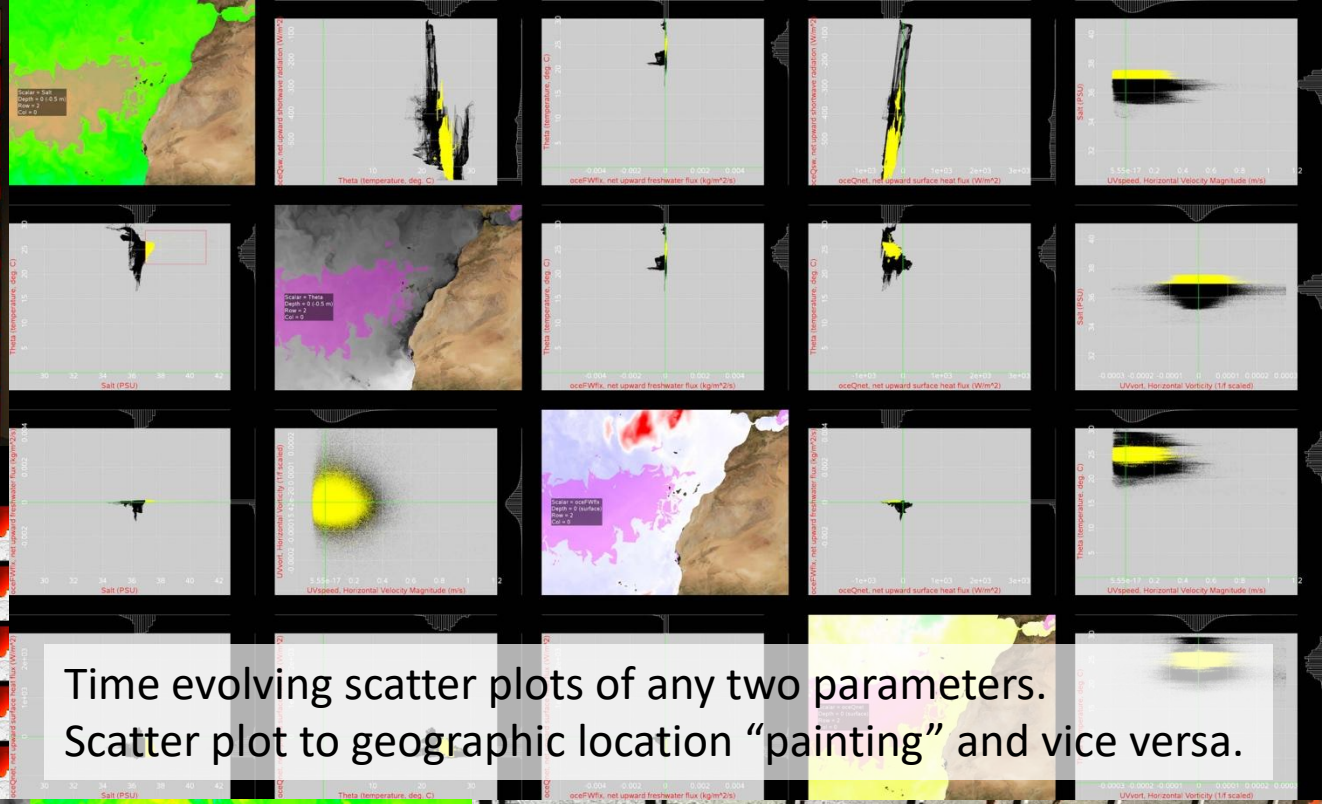
The LLC4320 simulation can be displayed at approximately one pixel per model horizontal grid cell, allowing simultaneous views of global and detailed regional views of the simulation variables.



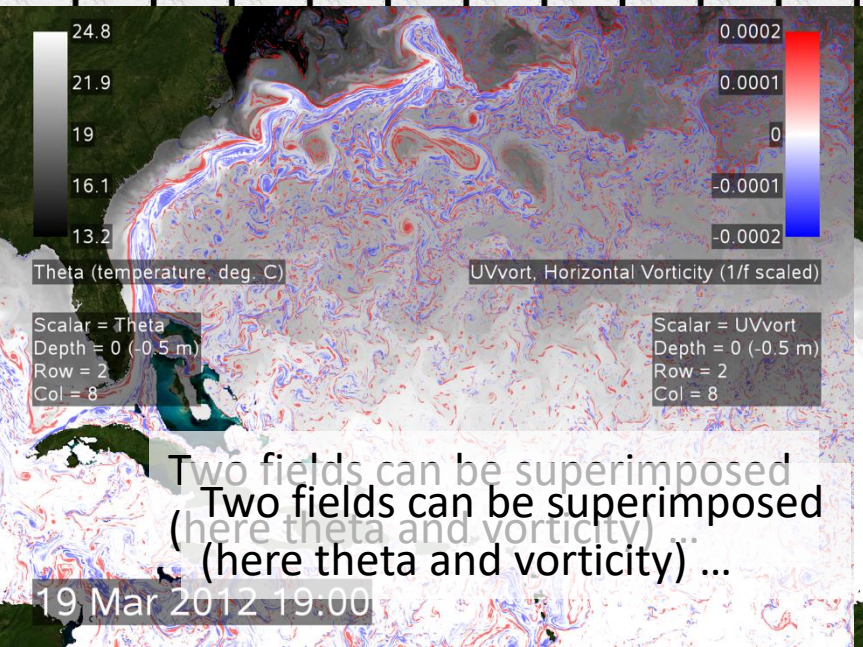
Arbitrary layouts, e.g., one depth per column …



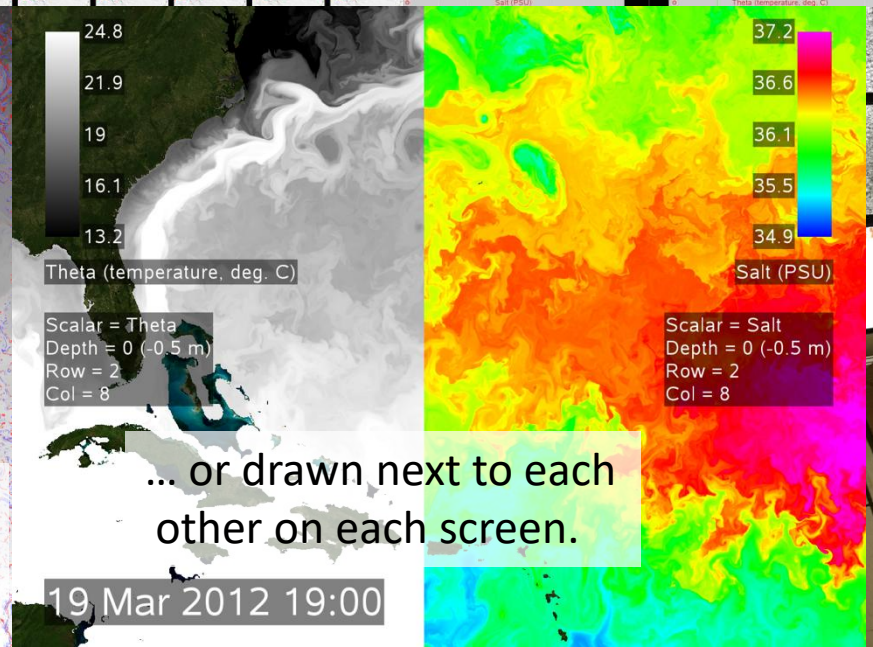
… or a different field and depth per screen.



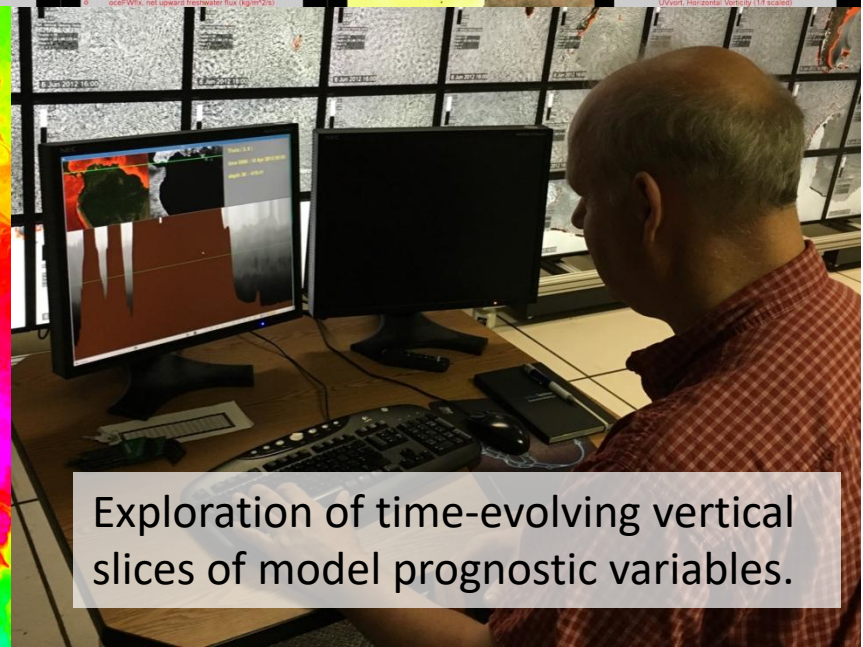
Time evolving scatter plots of any two parameters.
Scatter plot to geographic location “painting” and vice versa.



Two fields can be superimposed
(here theta and vorticity) …



… or drawn next to each other on each screen.



Exploration of time-evolving vertical slices of model prognostic variables.

Some studies and model-data comparisons involving the LLC4320

Carl's notes

Comparison of LLC4320 (dashed) with WHOI site D mooring (solid) in Western North Atlantic.

Results are comparable except for the presence of the tidal overtone peaks.

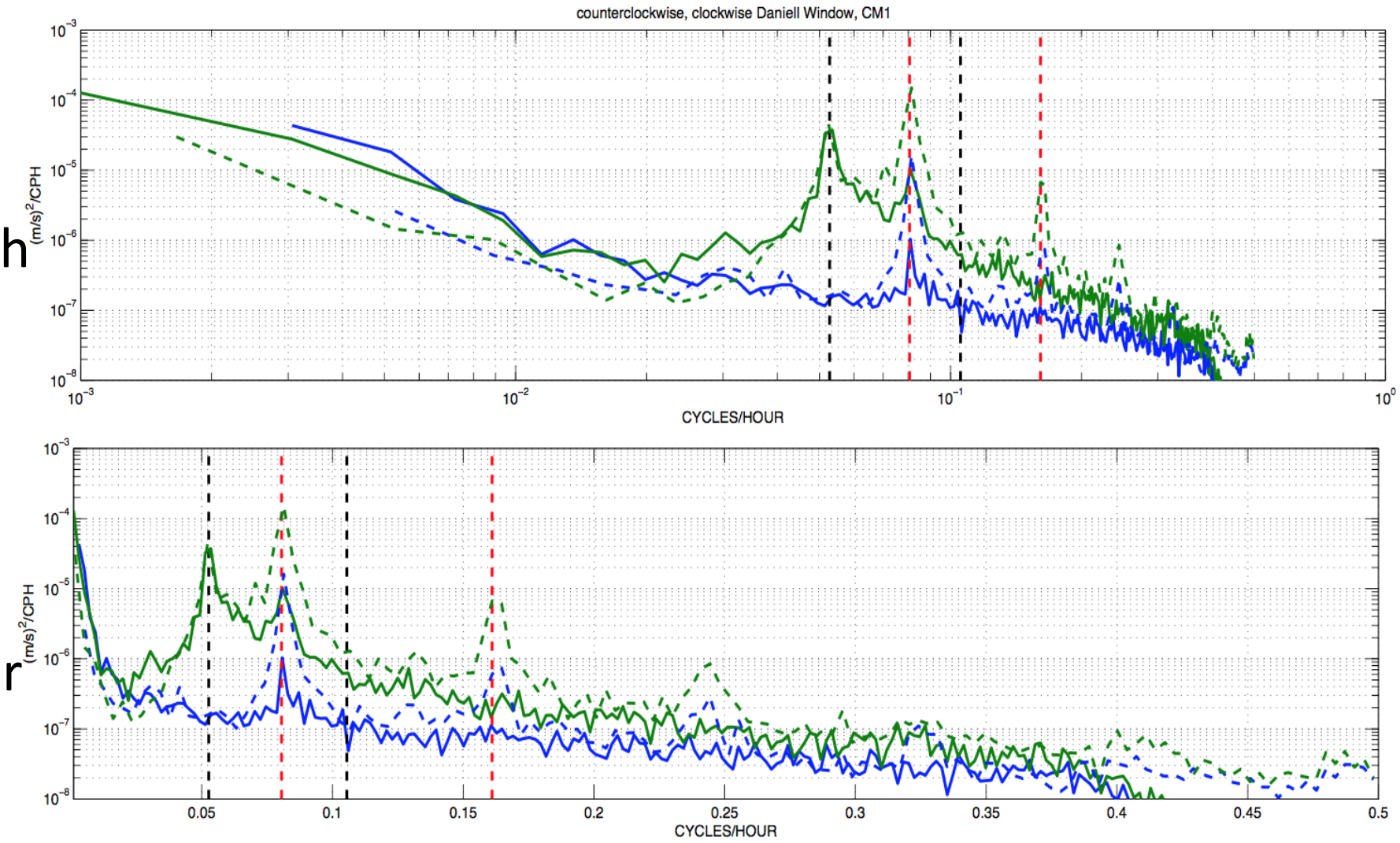
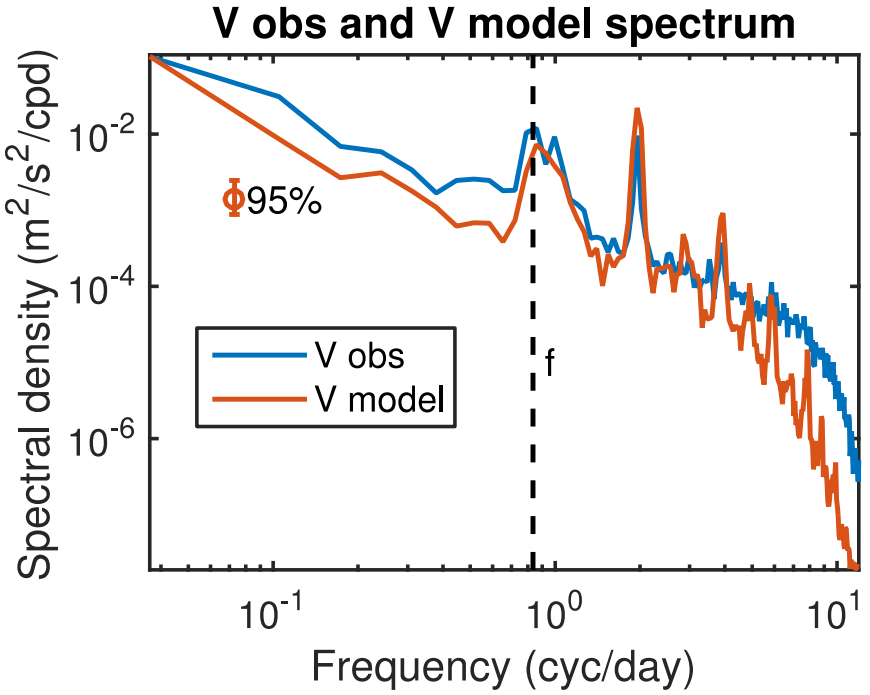
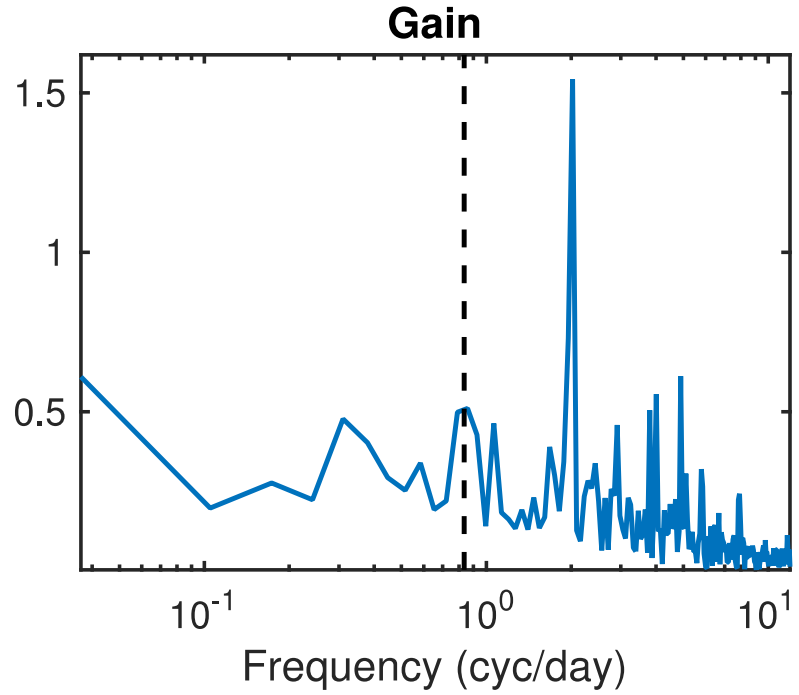
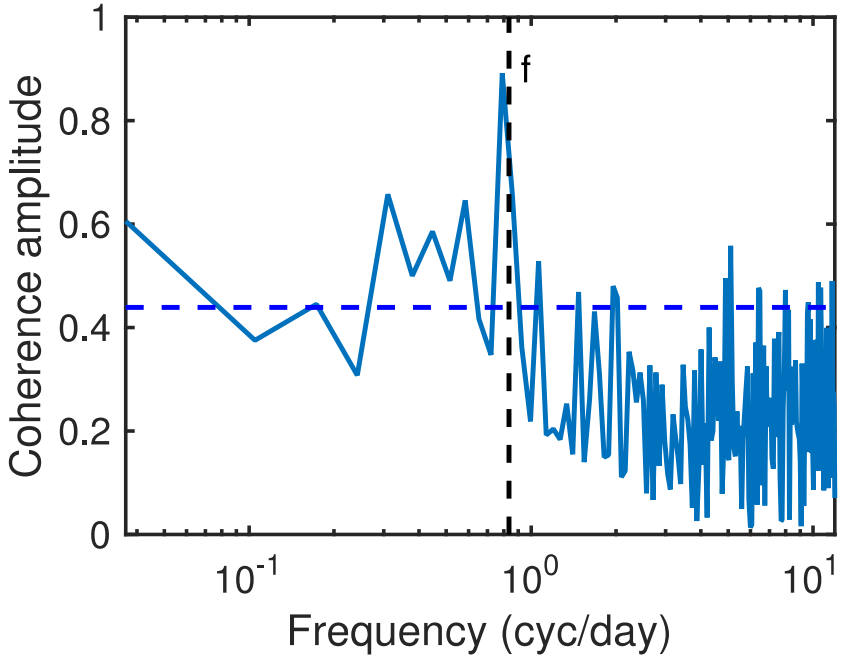


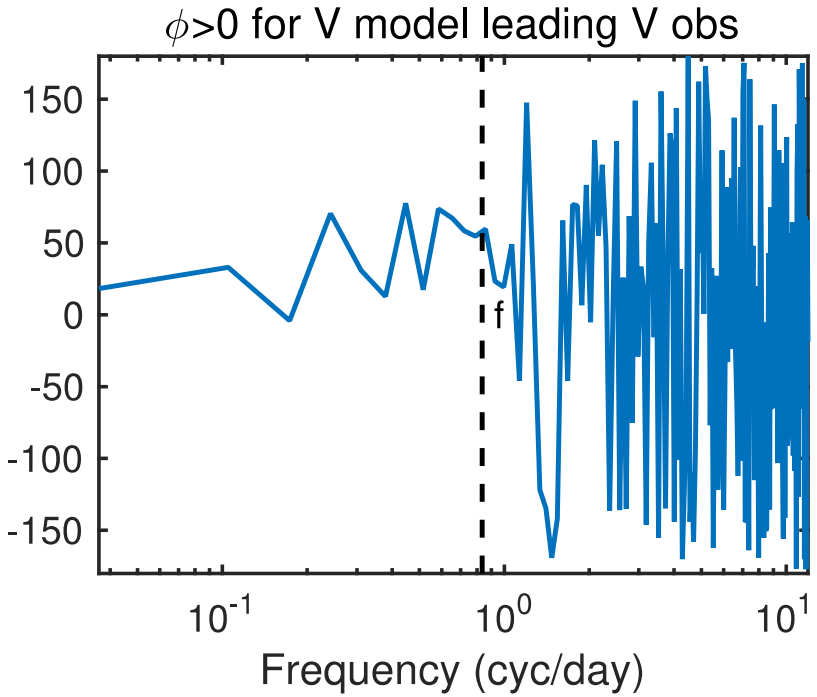
Figure 6: Rotary (clockwise, blue; counter-clockwise, green) spectra from the current meter and the model near 500m. Both logarithmic and linear displays are used. Results are comparable except, again, for the presence in the model of tidal overtone peaks and thus a generally more energetic negatively rotating spectrum.

SPURS (24.5 N, 38 W)
f ~ 28.7 h, z = 3.5 m







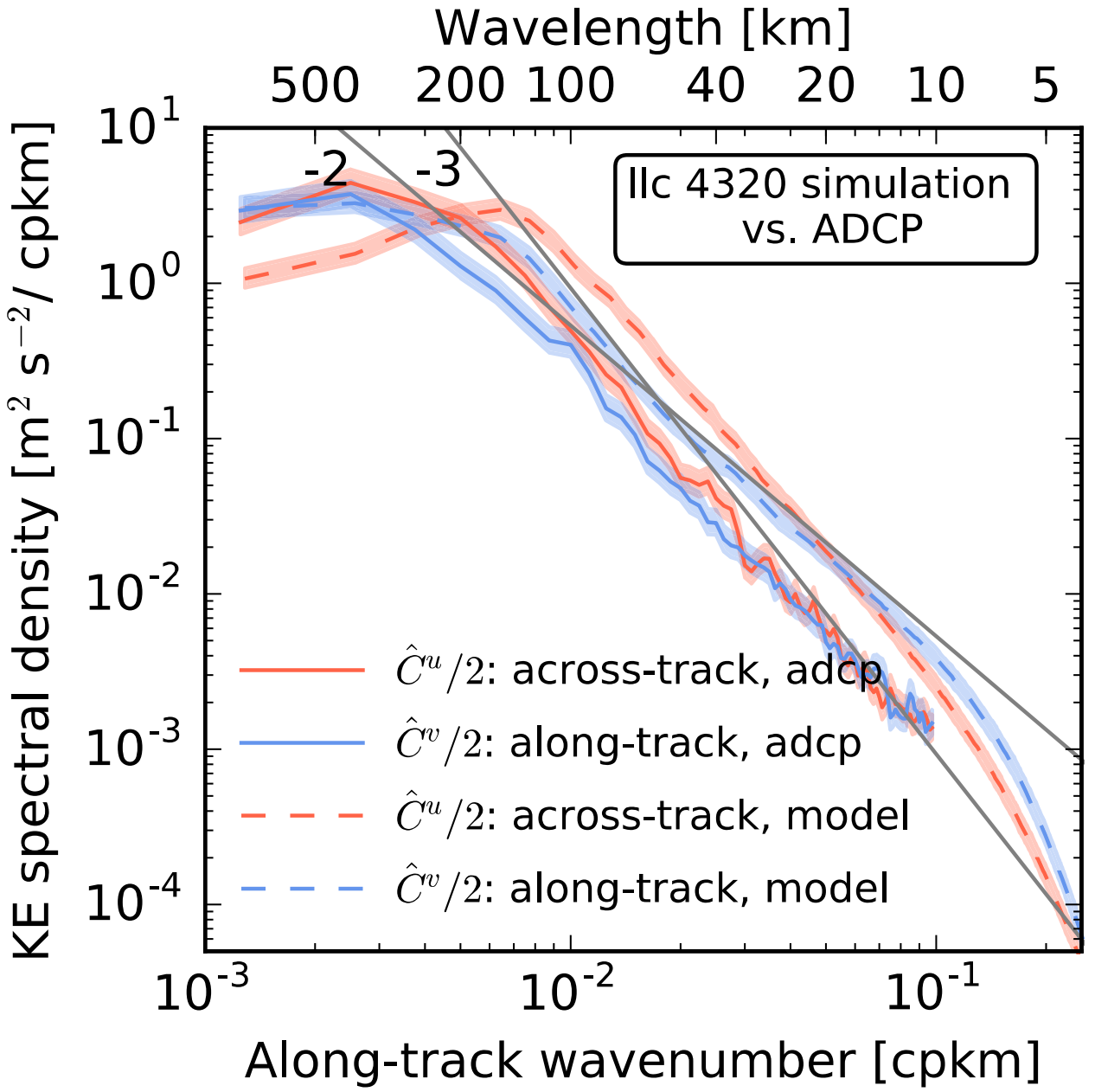


Tom Farrar

Mesoscale to Submesoscale Wavenumber Spectra in Drake Passage

(Rocha et al. 2016)

- The first three months of llc4320
- Inertia-gravity waves dominate scales <40km in SSH
- Compared llc4320 (dashed) with ADCP data (solid); gray lines are k^{-2} and k^{-3} curves.



Qiu et al. (2016)

- ADCP data cross western pacific
- Good model-data agreement of the zonal jets structure

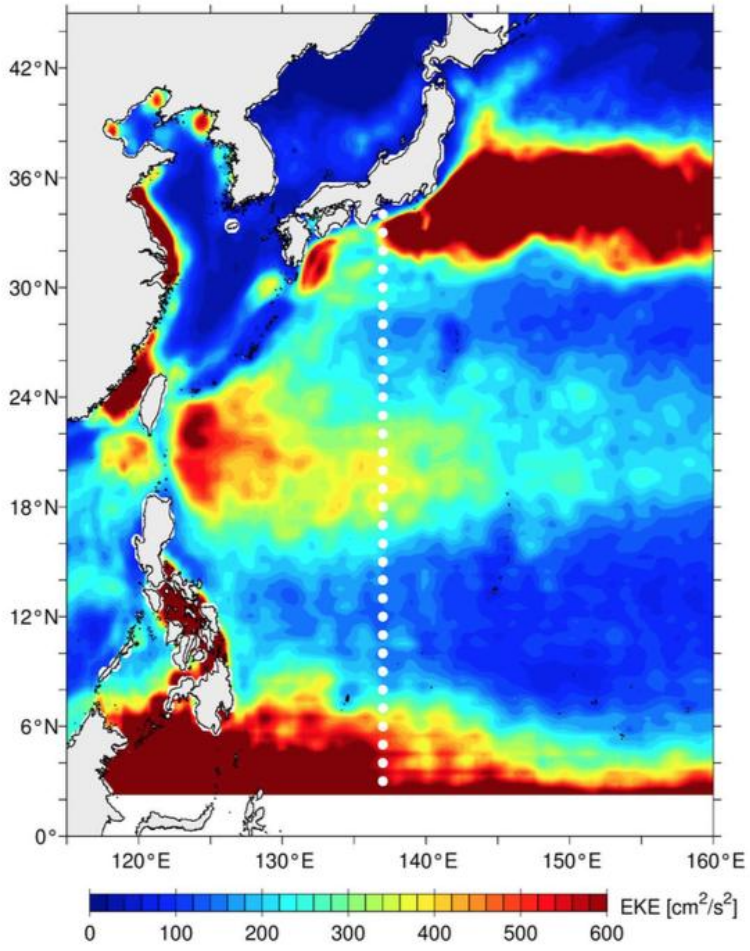


Figure 1: Surface eddy kinetic energy (EKE) distribution in the northwestern Pacific based on the weekly AVISO SSH anomaly data of 2004-2015. White dots along 137°E denote the transect of repeat ship-board ADCP measurements by Japan Meteorological Agency.

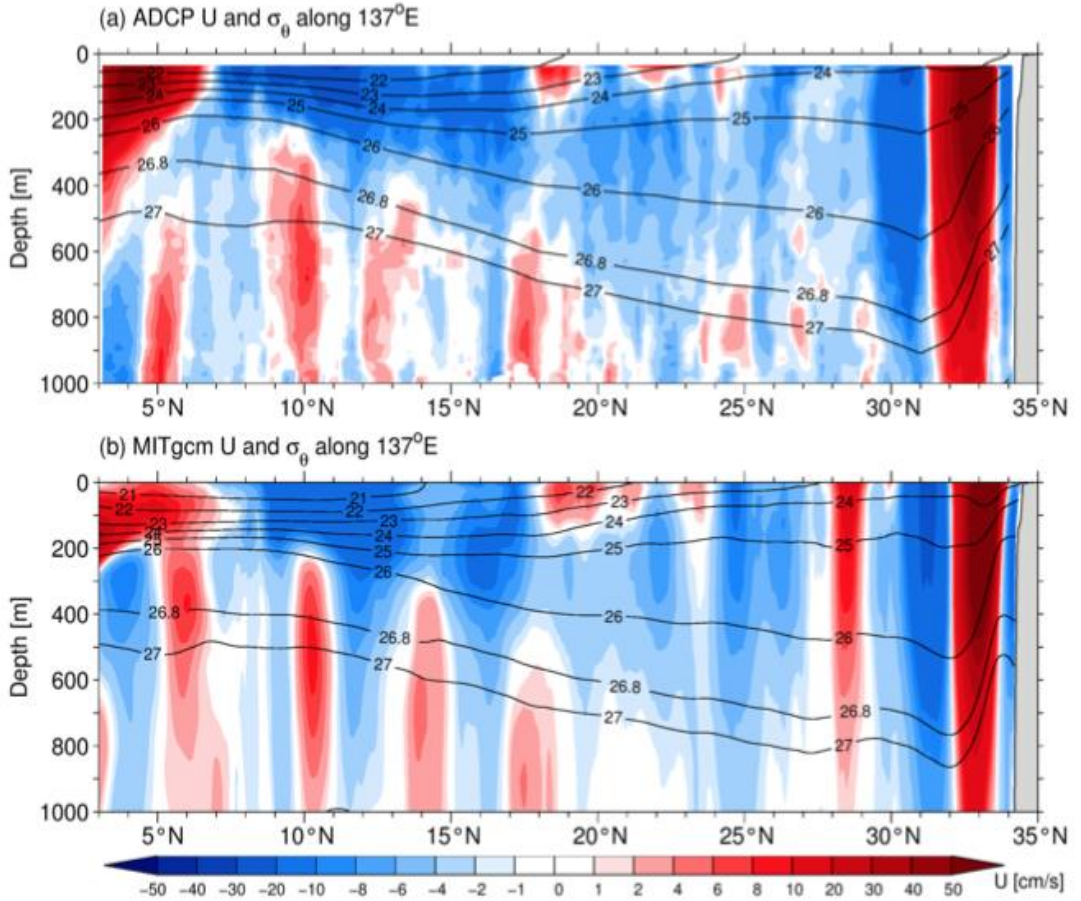
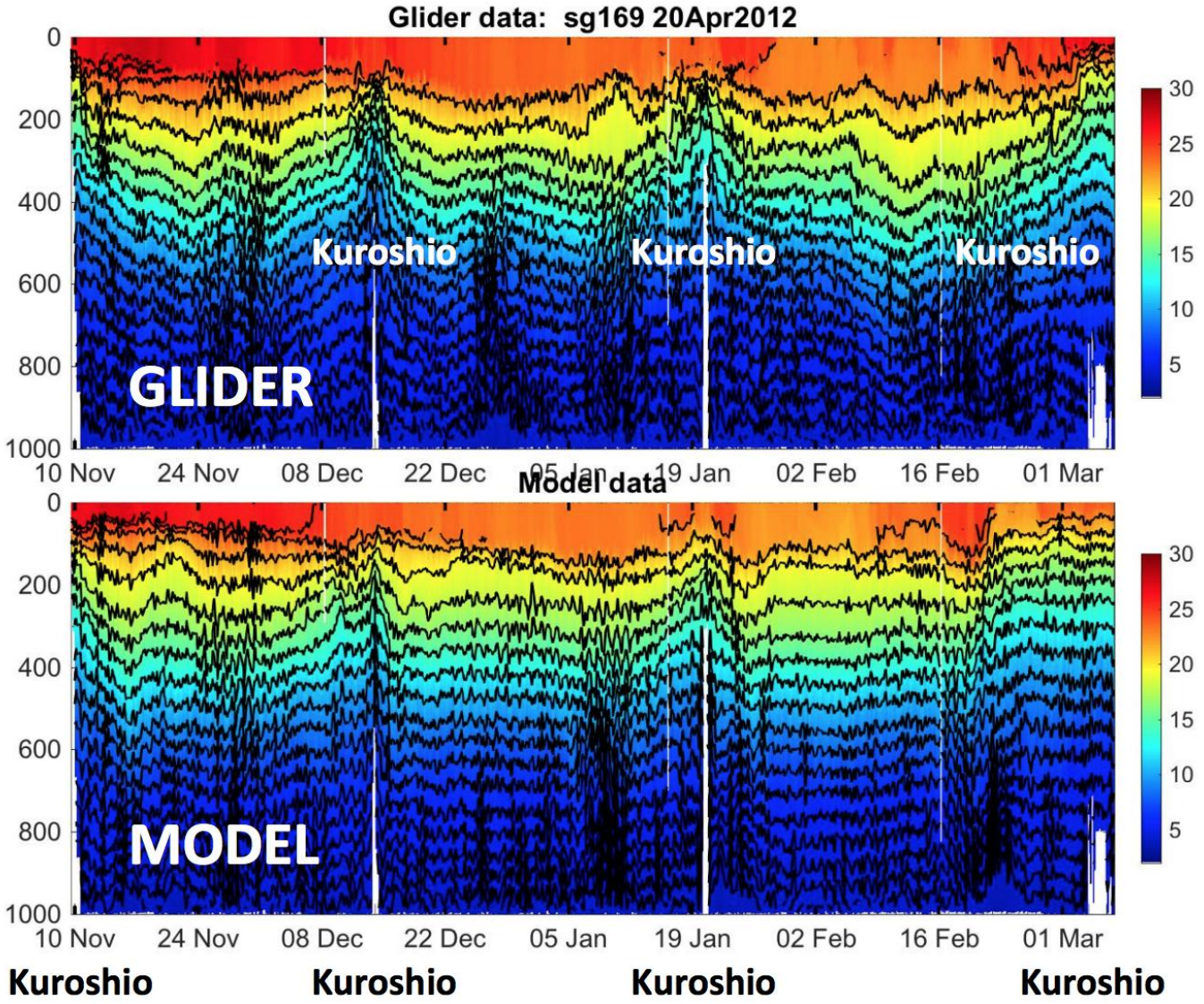
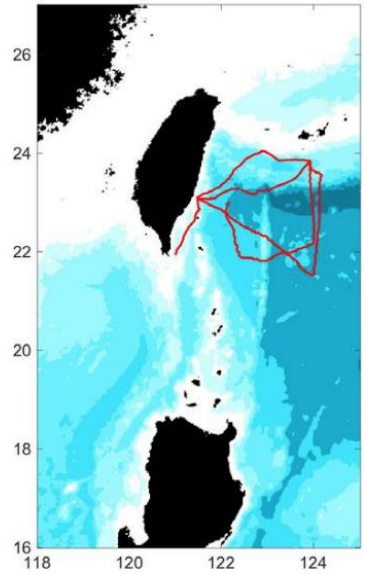


Figure 2: Latitude-depth sections of time-mean zonal velocity (colored contours) and density (black contours in σ_θ) along 137°E from (a) JMA repeat ADCP surveys of 2004-2016 and (b) MITgcm. Note that contour scales are nonlinear and red (blue) colors denote eastward (westward) flows.

High frequency motions in the western Pacific



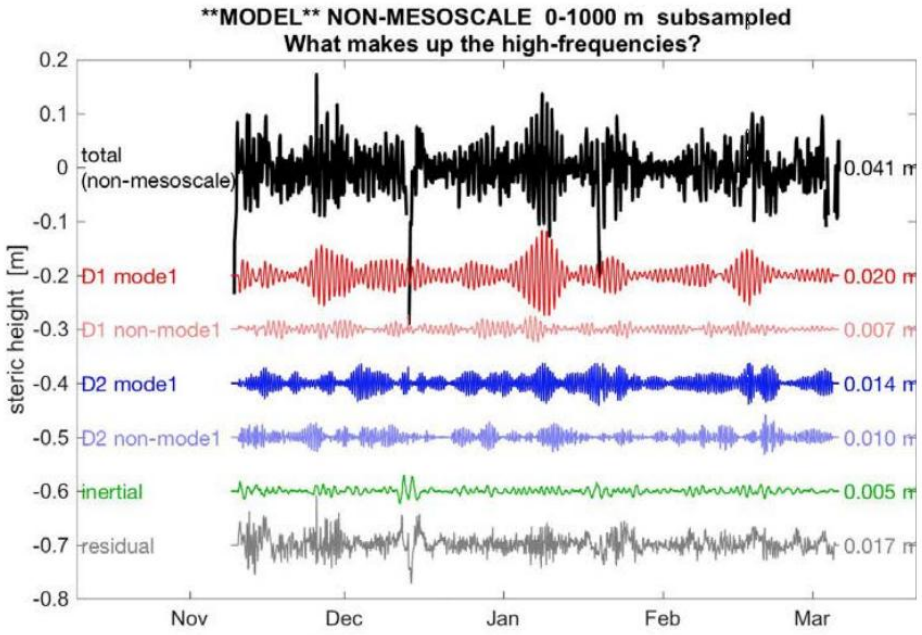


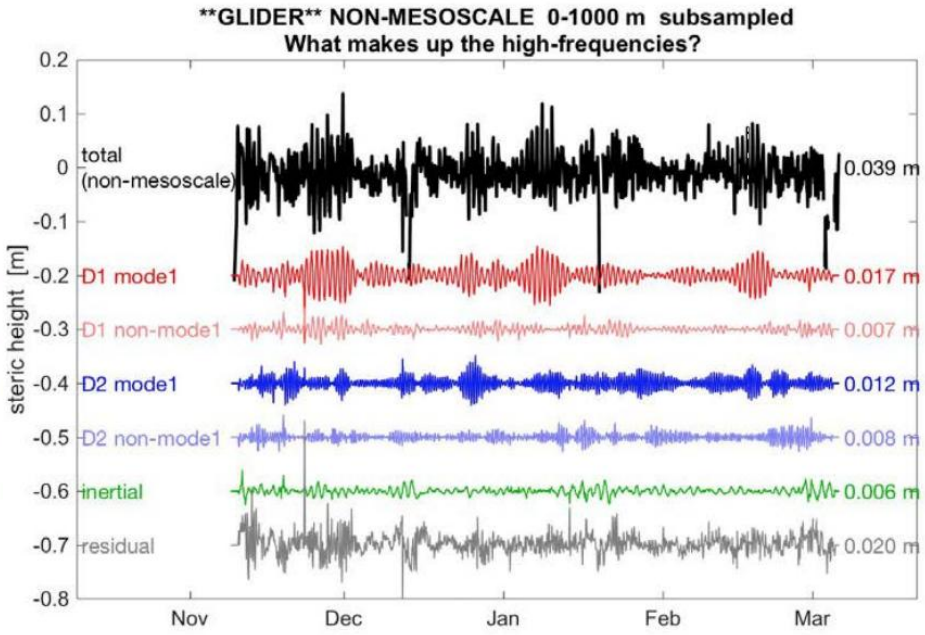
Drushka et al., 2016

Temperature, °C

High frequency motions in the western Pacific

Drushka et al., 2016





MODEL

Non-mesoscale steric height (4.1 cm)

- Diurnal, mode 1 (2.0 cm)
- Diurnal, non-mode1 (0.7 cm)
- Semidiurnal, mode 1 (1.4 cm)
- Semidiurnal, non-mode1 (1.0 cm)
- Inertial motions (0.5 cm)
- Residual (1.7 cm)

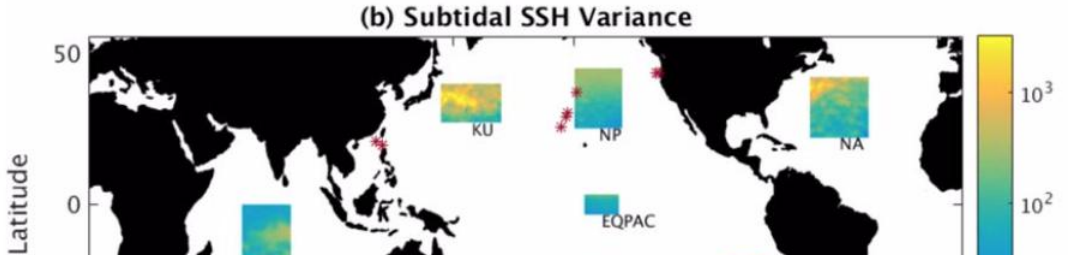
GLIDER

Non-mesoscale steric height (3.9 cm)

- Diurnal, mode 1 (1.7 cm)
- Diurnal, non-mode1 (0.7 cm)
- Semidiurnal, mode 1 (1.2 cm)
- Semidiurnal, non-mode1 (0.8 cm)
- Inertial motions (0.6 cm)
- Residual (2.0 cm)

High frequencies, Savage et al. 2017

LLC4320 is comparable to HYCOM25 at diurnal and semidiurnal but outperforms HYCOM25 at supertidal frequencies



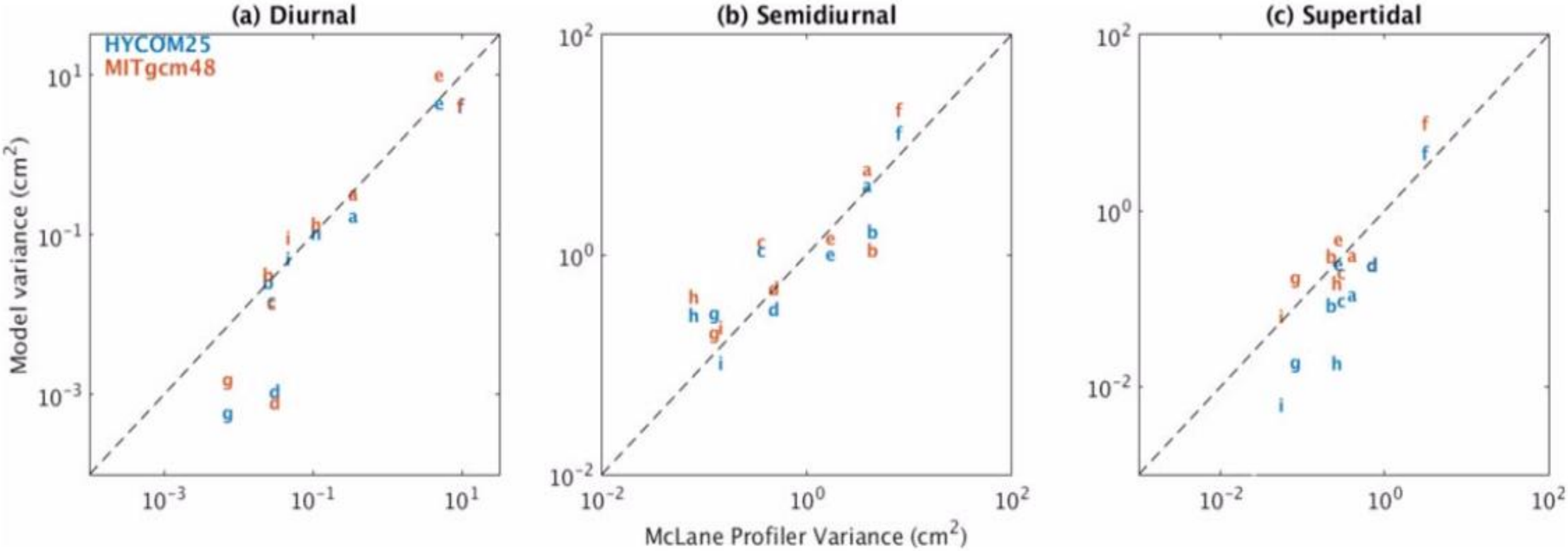
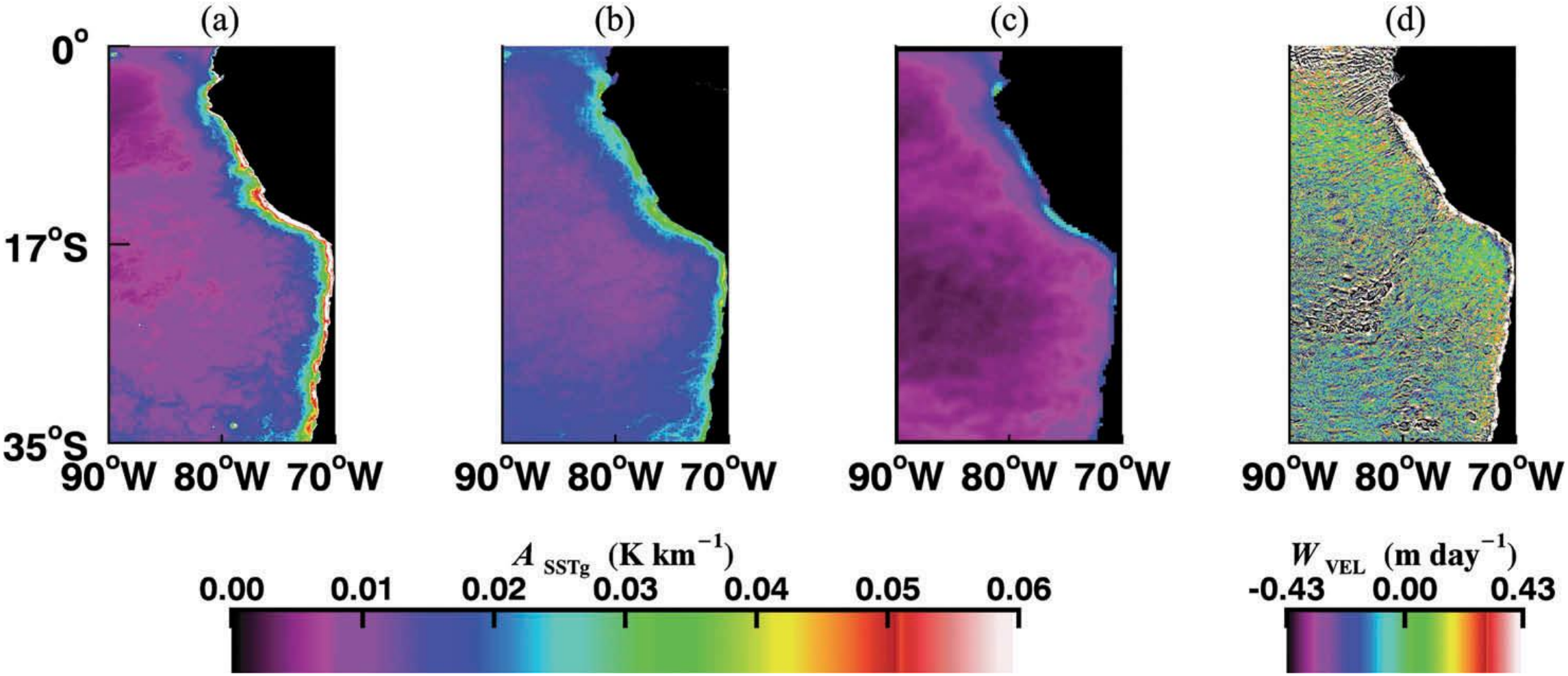


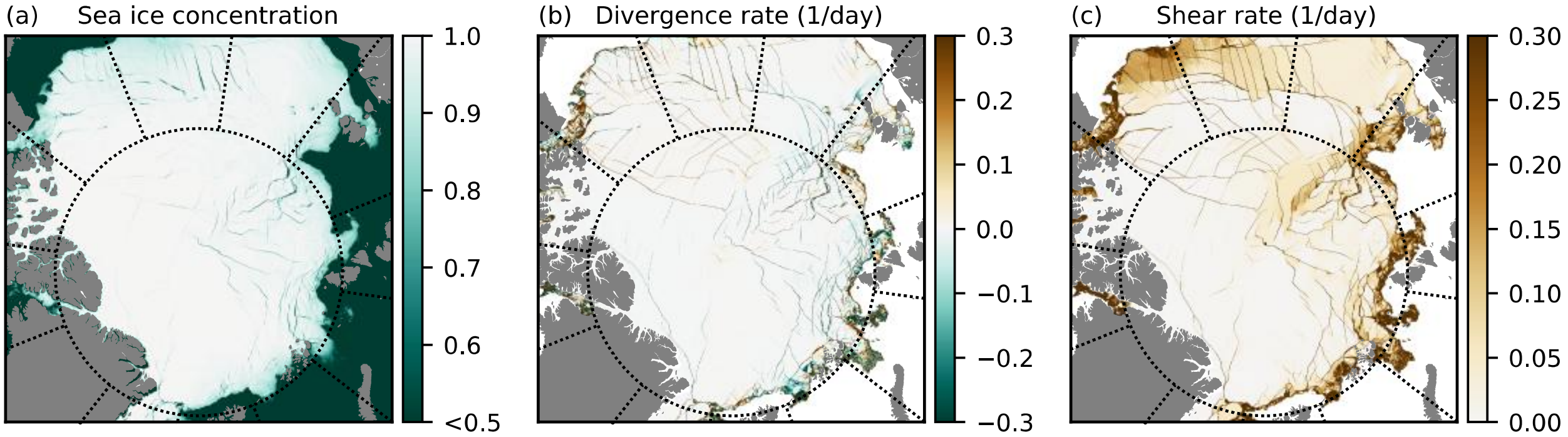
Figure 4. Scatterplots of band-integrated dynamic height variance vs. McLane profilers in 1/25° HYCOM and 1/48° MITgcm in (a) diurnal, (b) semidiurnal, and (c) supertidal frequency bands. Letters on scatterplots correspond to profiler locations listed in Table 1.

SST studies with LLC4320 (Jorge Vazquez)



Mean SST gradients from (a) LLC2160, (b) MUR (1 km grid), (c) NCEI (25 km grid), and (d) mean Wvel from LLC2160

Sea ice studies with LLC4320 (Nils Hutter and Martin Losch)

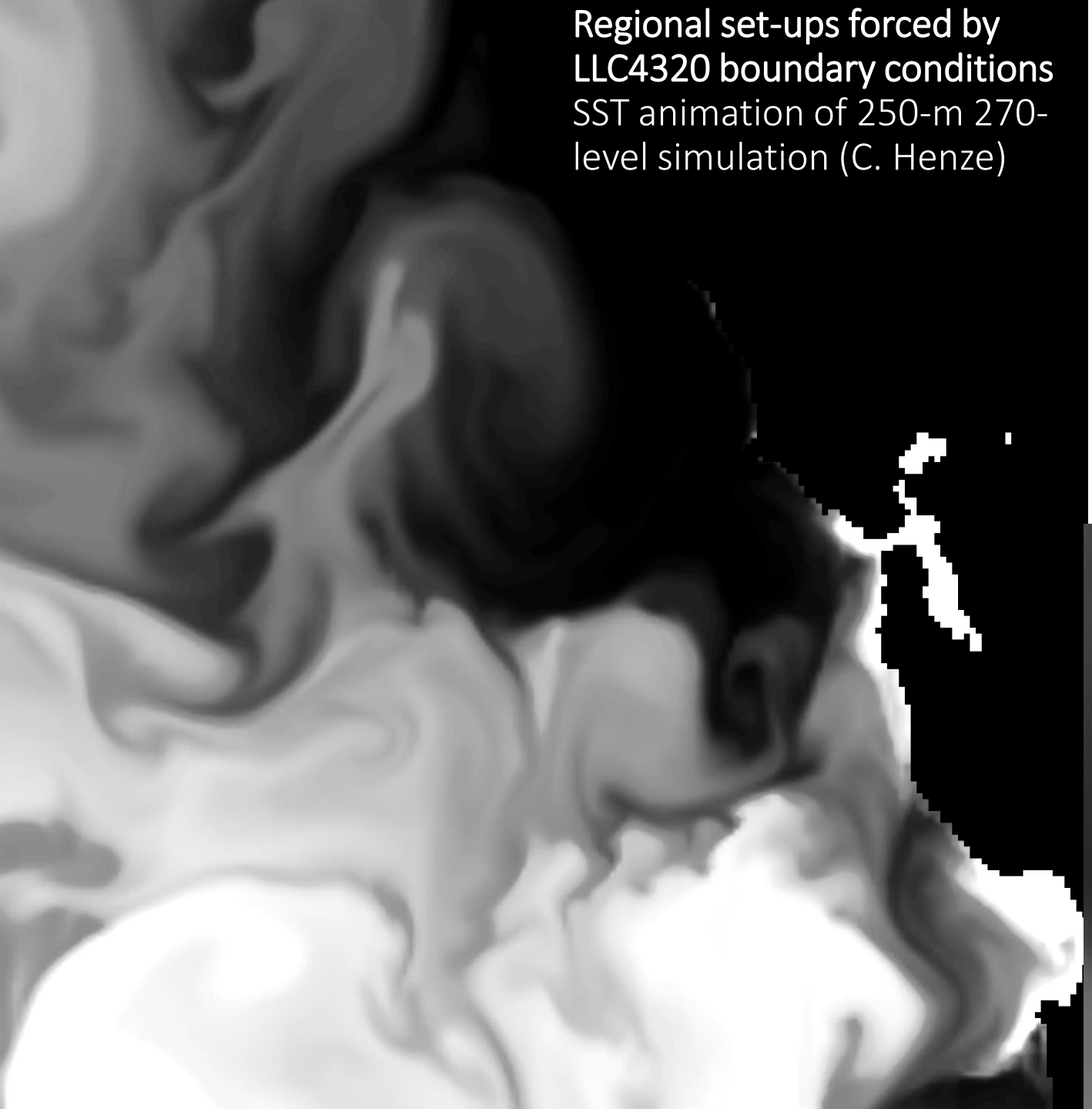


LLC4320 reproduces observed spatial scaling of linear kinematic features (LKFs), challenging earlier studies that concluded that Viscous-plastic (VP) rheology cannot realistically represent LKFs.

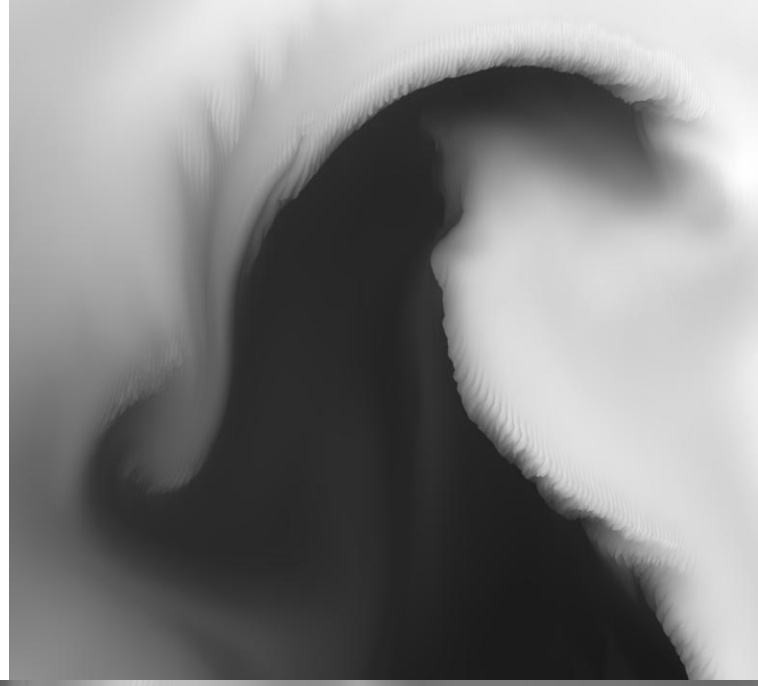
The temporal scaling analysis shows that the VP model, as configured in the LLC4320 simulation, does not fully resolve the intermittency of sea ice deformation that is observed in satellite data.

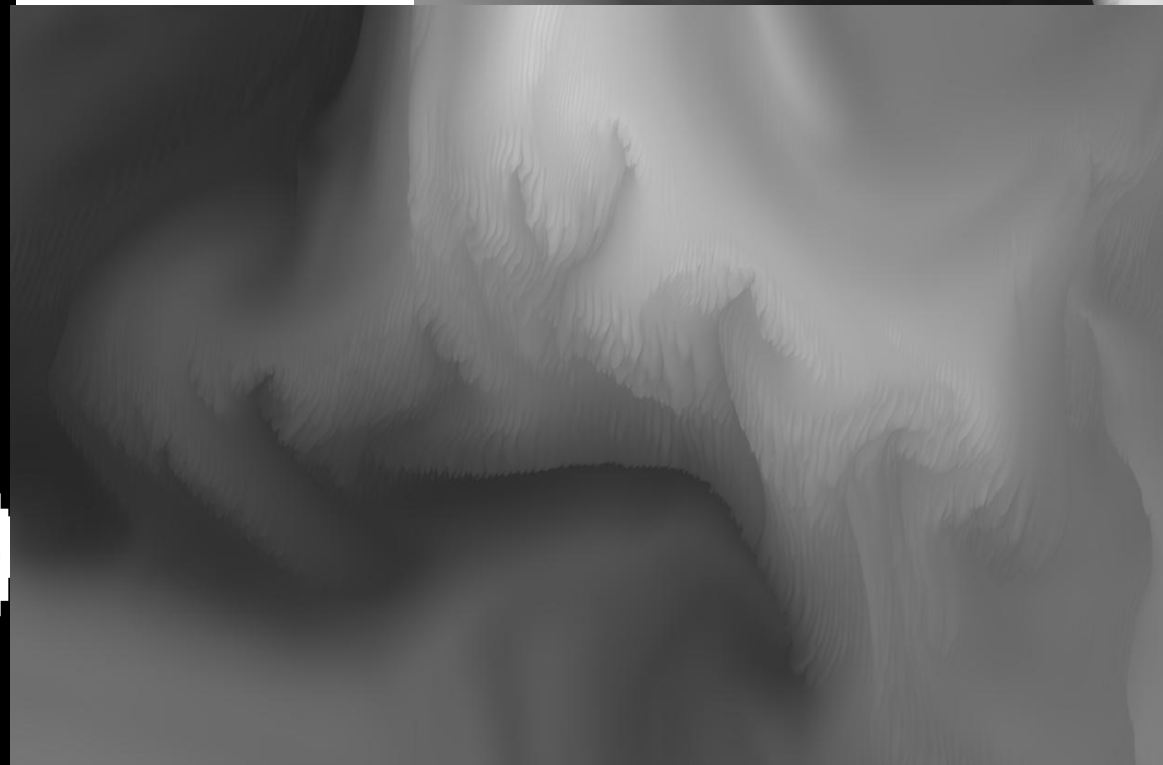
Regional set-ups forced by LLC4320 boundary conditions

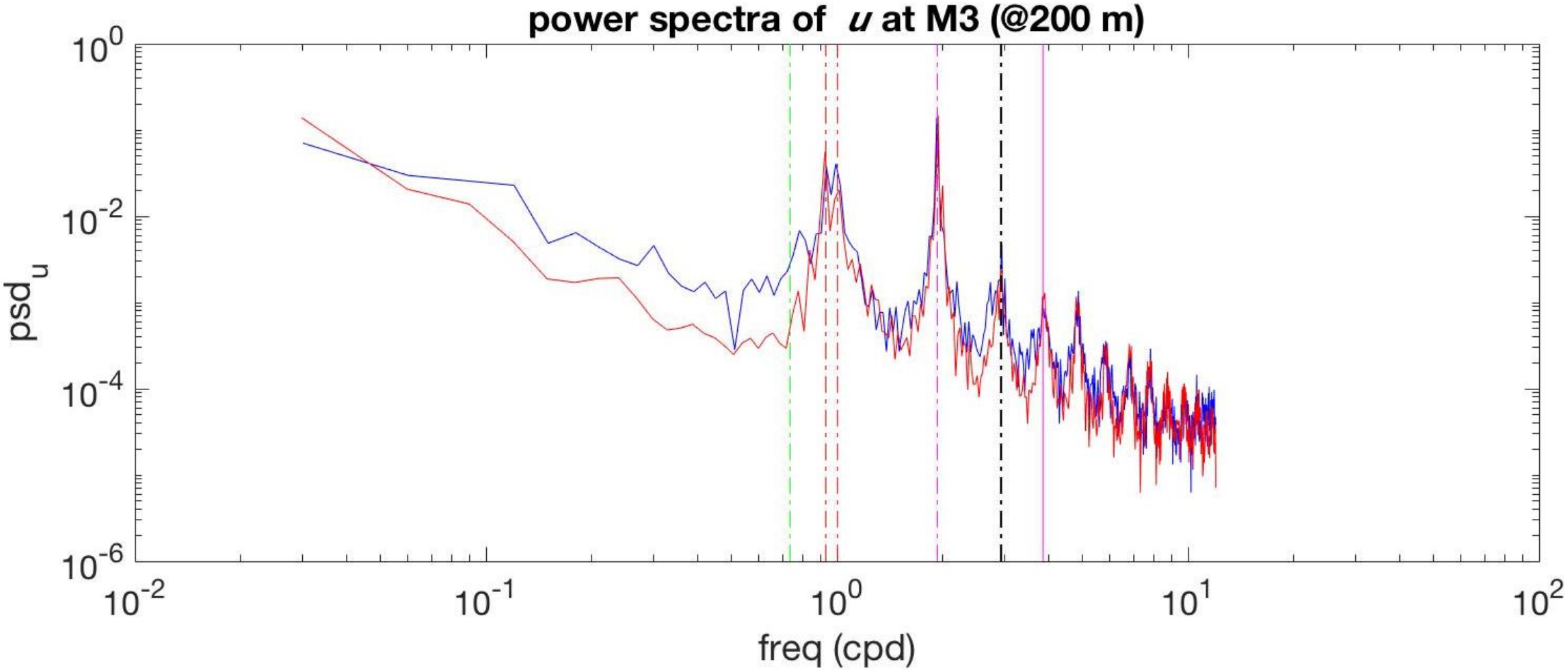
SST animation of 250-m 270-level simulation (C. Henze)



25-m grid details







(figure by Zhiyu Liu ~30 minutes ago!)