Modeling M_2 Internal Tide in Combination with Wind-Driven Circulation on the Oregon Shelf

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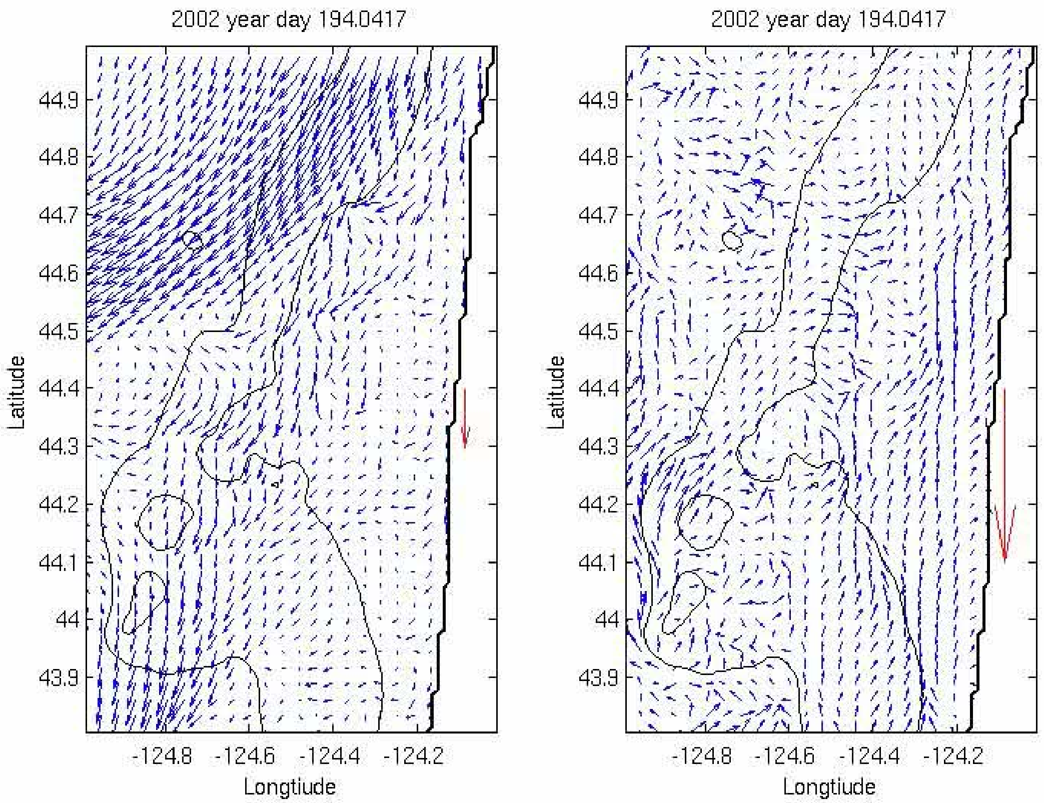
- Δt = 1 hour
- Red Arrows: 0.5 m s^{-1}
- Note periodic (i.e., tidal) variability!

Internal tide:

- Near surface: contributes to variability
- Near bottom: potential dominates variability

Model Surface Currents Model Bottom Currents

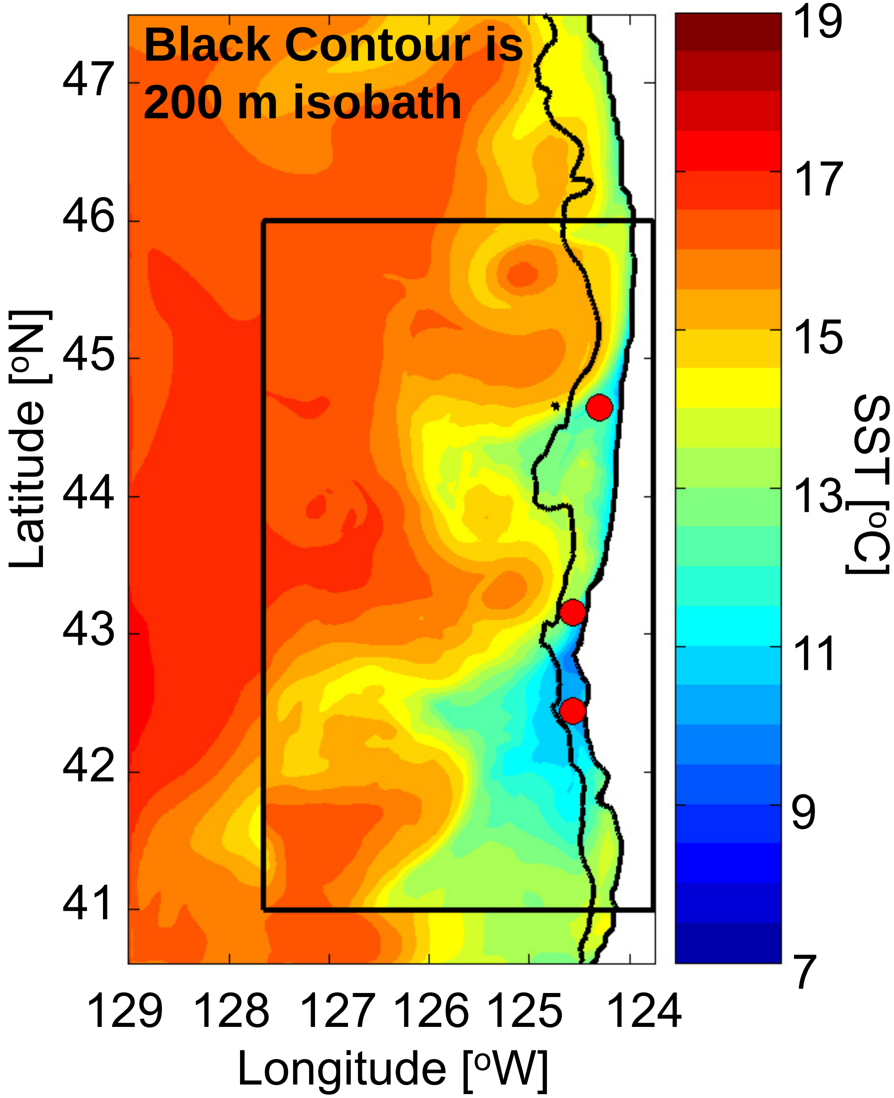


Objectives

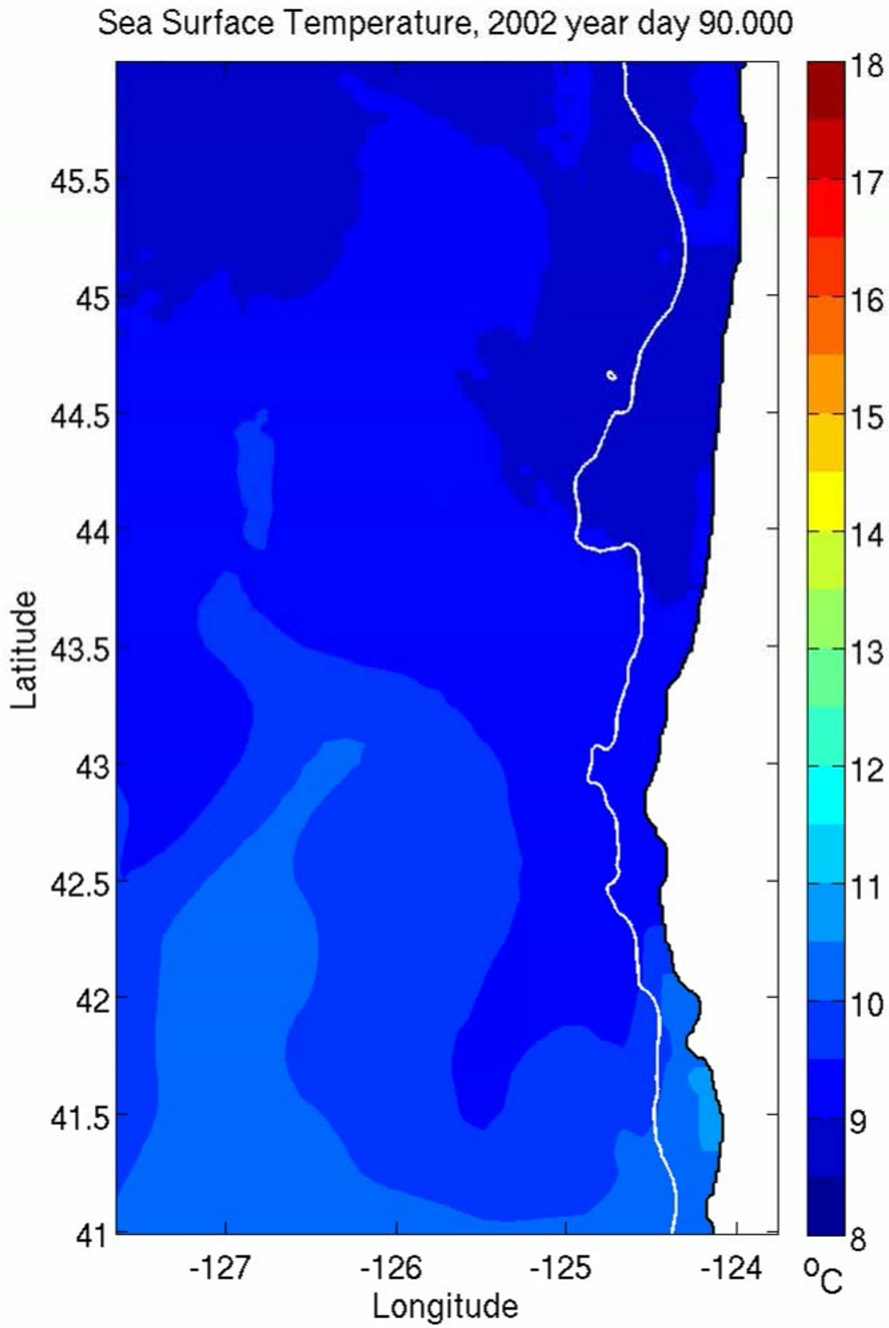
- Understand influences of wind-driven and tidally-driven currents on the Oregon shelf
- Identify and describe the generation, propagation, dissipation and intermittency of M_2 internal tide as affected by upwelling-induced changes in background hydrodynamic conditions
- Due to intermittency:
  - Internal tide is hard to sample
  - Modeling is the most promising approach

Model Setup

August Mean SST, 1 km nested in 3 km

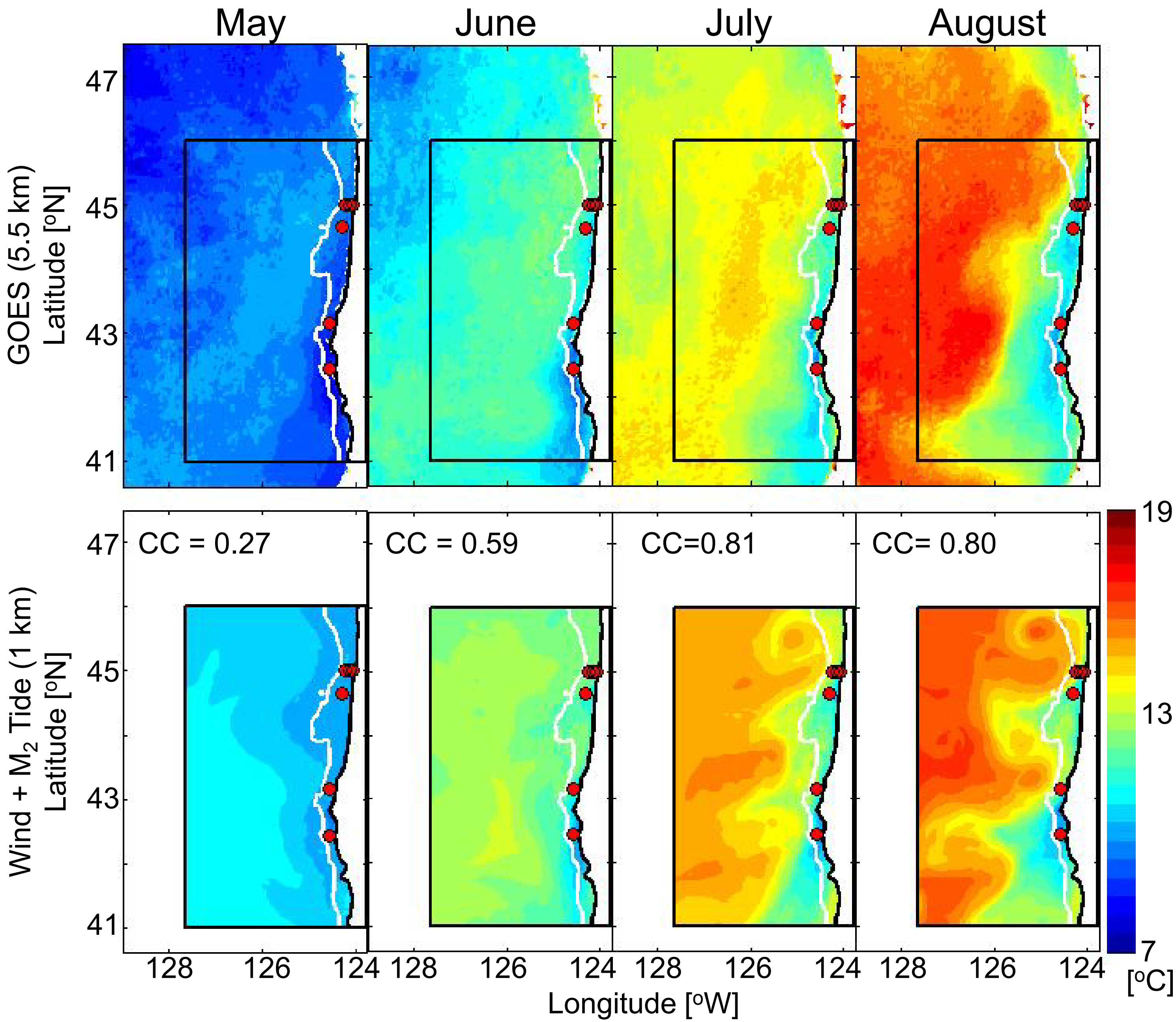


- ROMS
- Study Period: April - August 2002
- Resolution: 1 km, 40 σ-levels
- Initial Conditions: from 9-km NCOM-CCS (Shulman *et al*., NRL)
- Atmospheric Forcing: COAMPS (Winds), NCEP Reanalysis (Heat Flux Parameters)
- Boundary Conditions
  - Subtidal: 3-km ROMS (Koch *et al*., JGR 2010)
  - Barotropic Tide: TPXO 7.0 (Egbert *et al*., 1994)
    M_2 alone, or 8 constituents

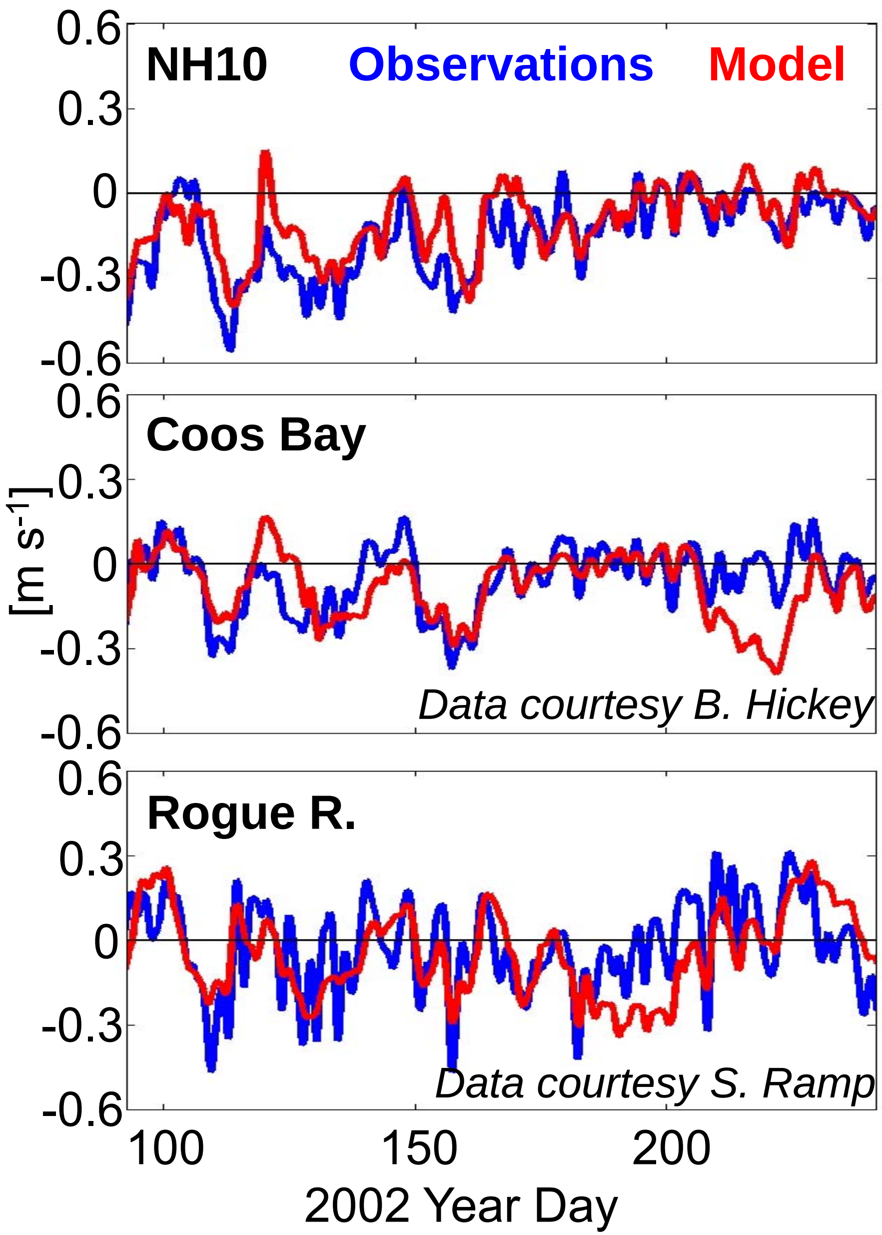


Sea Surface Temperature, 2002 year day 90.000
Latitude
45.5
45
44.5
44
43.5
43
42.5
42
41.5
41
-127
-126
-125
-124
Longitude
18
17
16
15
14
13
12
11
10
9
8
oC

Case Winds + M_2: Monthly-Ave. SST is Qualitatively Correct



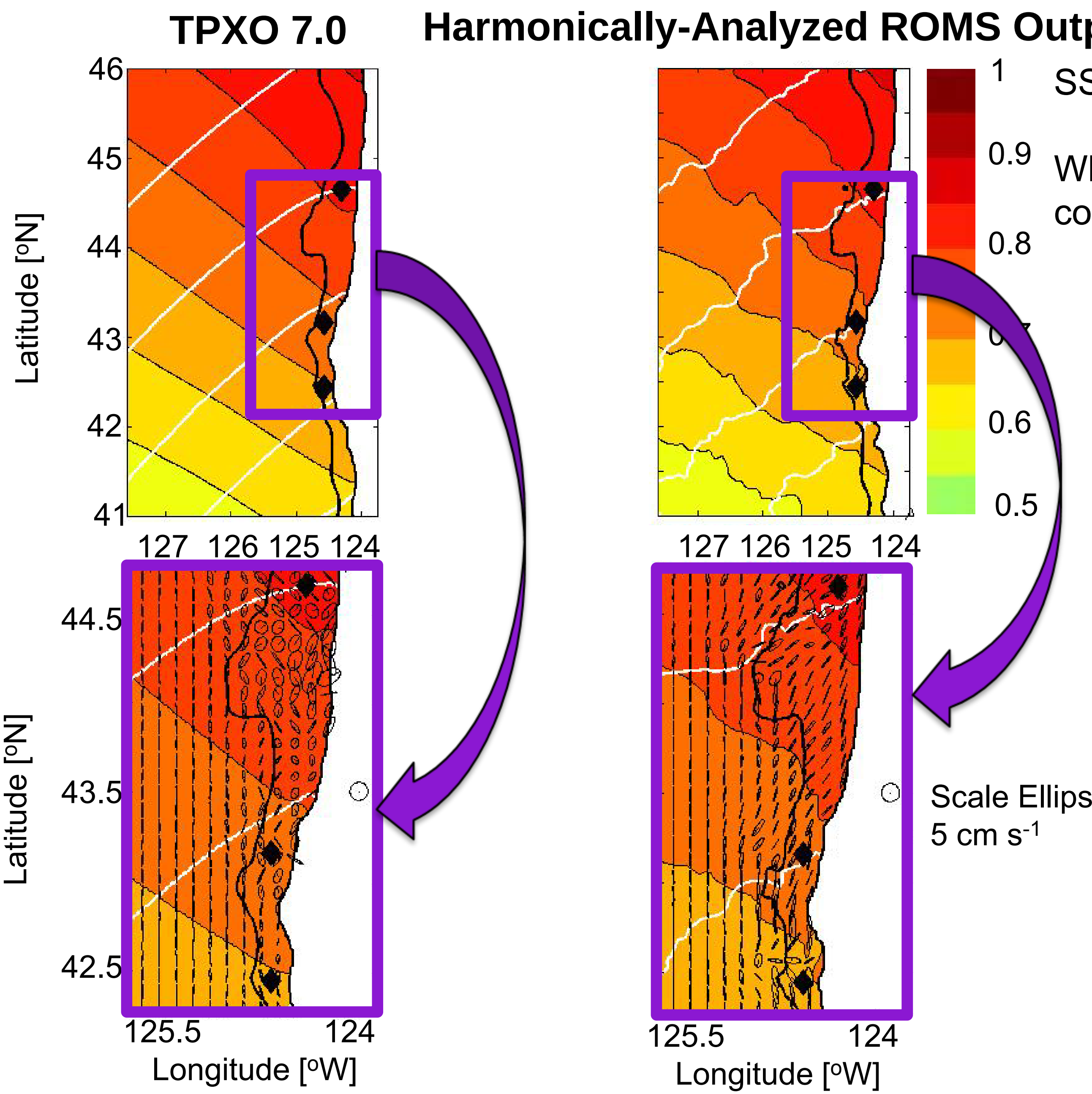
Subtidal Model Shelf Currents Agree With Obs.



- Meridional Currents
- 40 hr. Low-pass filtered
- Depth-averaged

Statistic	NH10	Coos Bay	Rogue R.
Complex Correlation	0.72	0.47	0.59
Complex Phase Angle	0.83^0	-3.28^0	10.53^0
RMS [m s^{-1}]	0.09	0.11	0.14

Barotropic Tide is Qualitatively Correct



Barotropic tide propagates northward along the Oregon coast as a Kelvin wave.

ROMS solution shows smaller scale variability in barotropic tide.

Modeled Internal Tide Variability is Qualitatively Correct

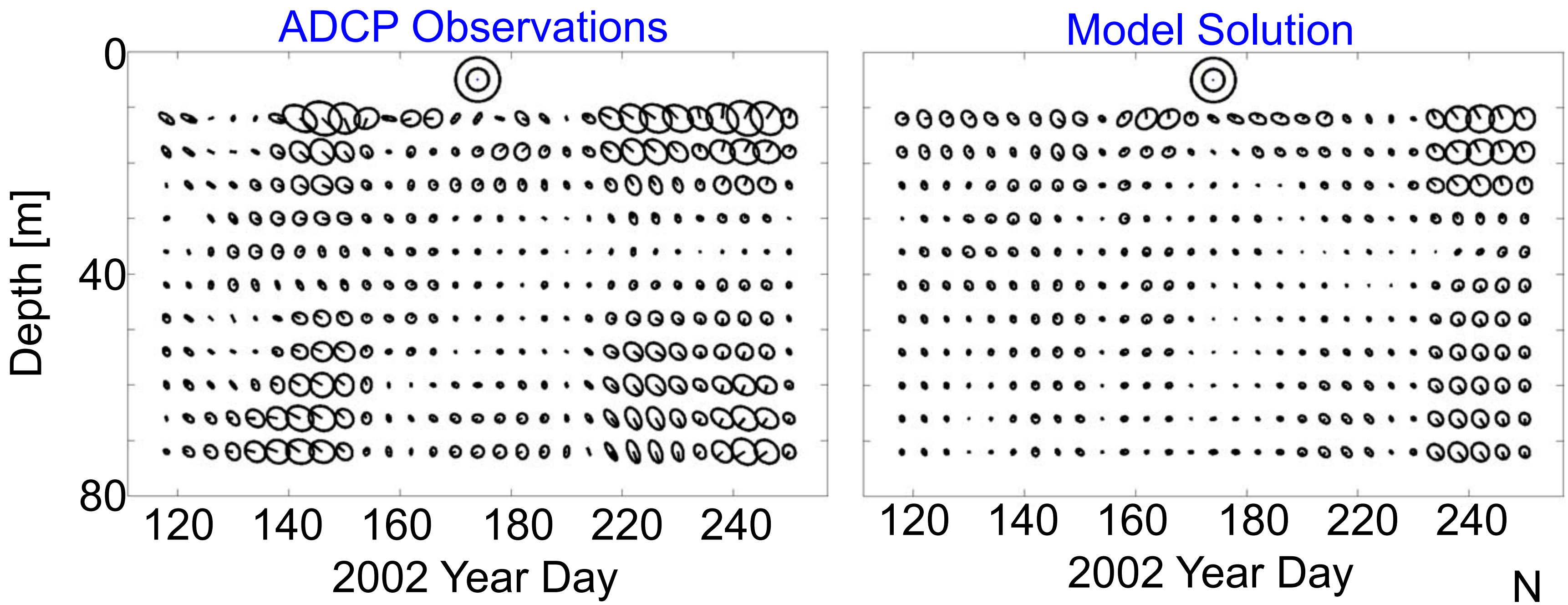
Baroclinic Tidal Ellipses: Horizontal Currents at NH10 Mooring

Method: 1. Subtract depth-averaged current $\overline{\mathbf{u}}(t)$ from total current $\mathbf{u}(z,t)$

2. High-pass filter

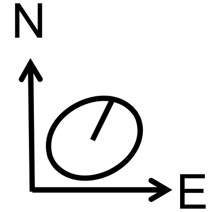
3. Harmonically analyze in a series of overlapping 14-day windows for tidal amplitudes (u, v, phase)

4. 14-day window is used to separate M_2 and S_2 frequencies in the observations

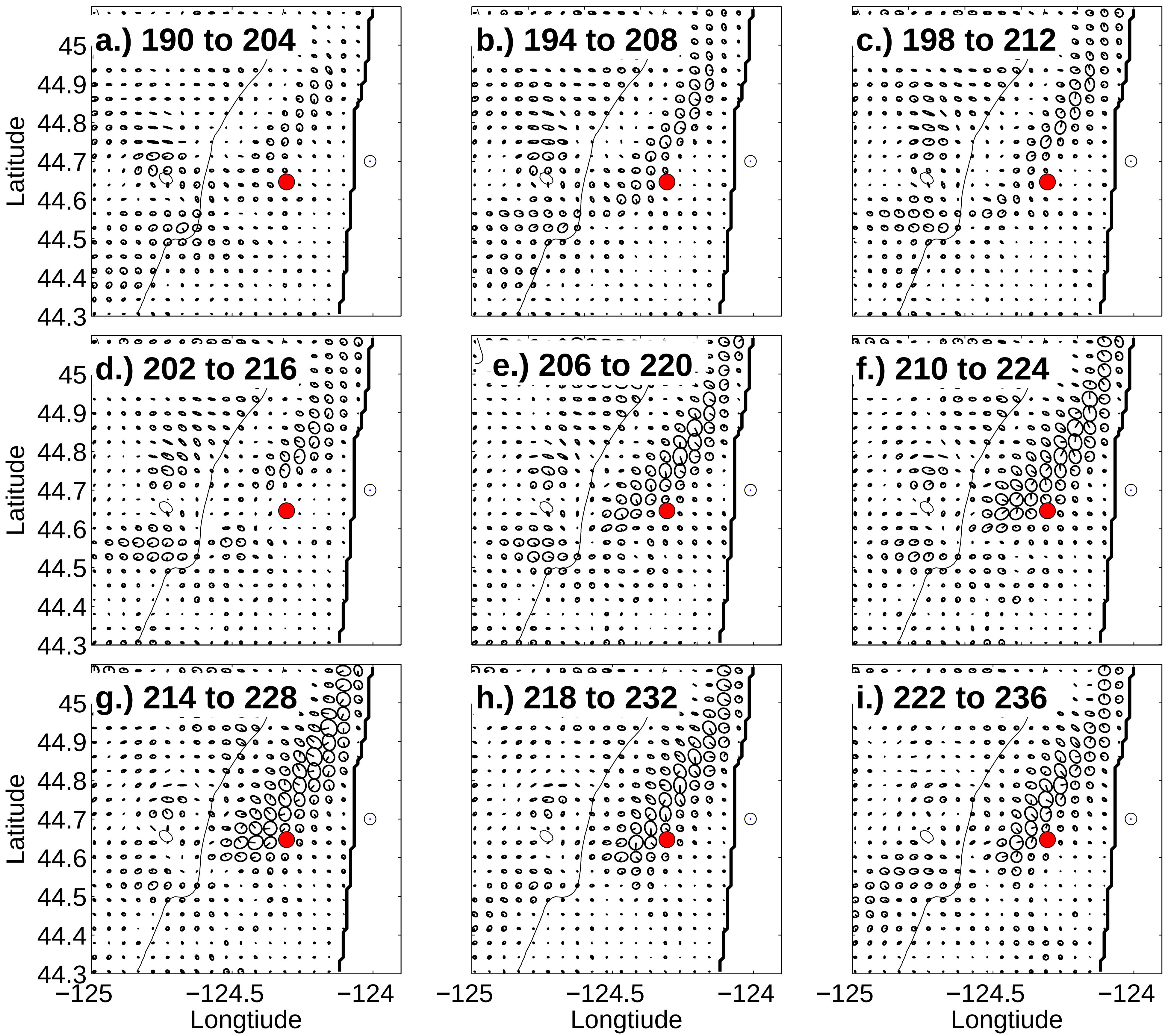


•Predominantly first mode behavior at both locations

•Variability is sensitive to background stratification and currents



Surface Baroclinic M_2 Tidal Ellipses Show Stronger Tide Near NH10



Tidally-Averaged, Depth-Integrated M_2 Baroclinic Tidal Energy Balance

Topographic Energy Conversion ≈ Energy Flux Divergence + Dissipation

(e.g., Kurapov *et al.*, 2003)

- Barotropic to Baroclinic Topographic Energy Conversion (TEC) $= \frac{1}{2} \times \underbrace{p_{\mathrm{BC}}(-h)}_{\text{Baroclinic pressure at the bottom}} \times \underbrace{\mathbf{u}^*_{\mathrm{BT}} \cdot \nabla(-h)}_{\text{Barotropic vertical velocity at the bottom}}$

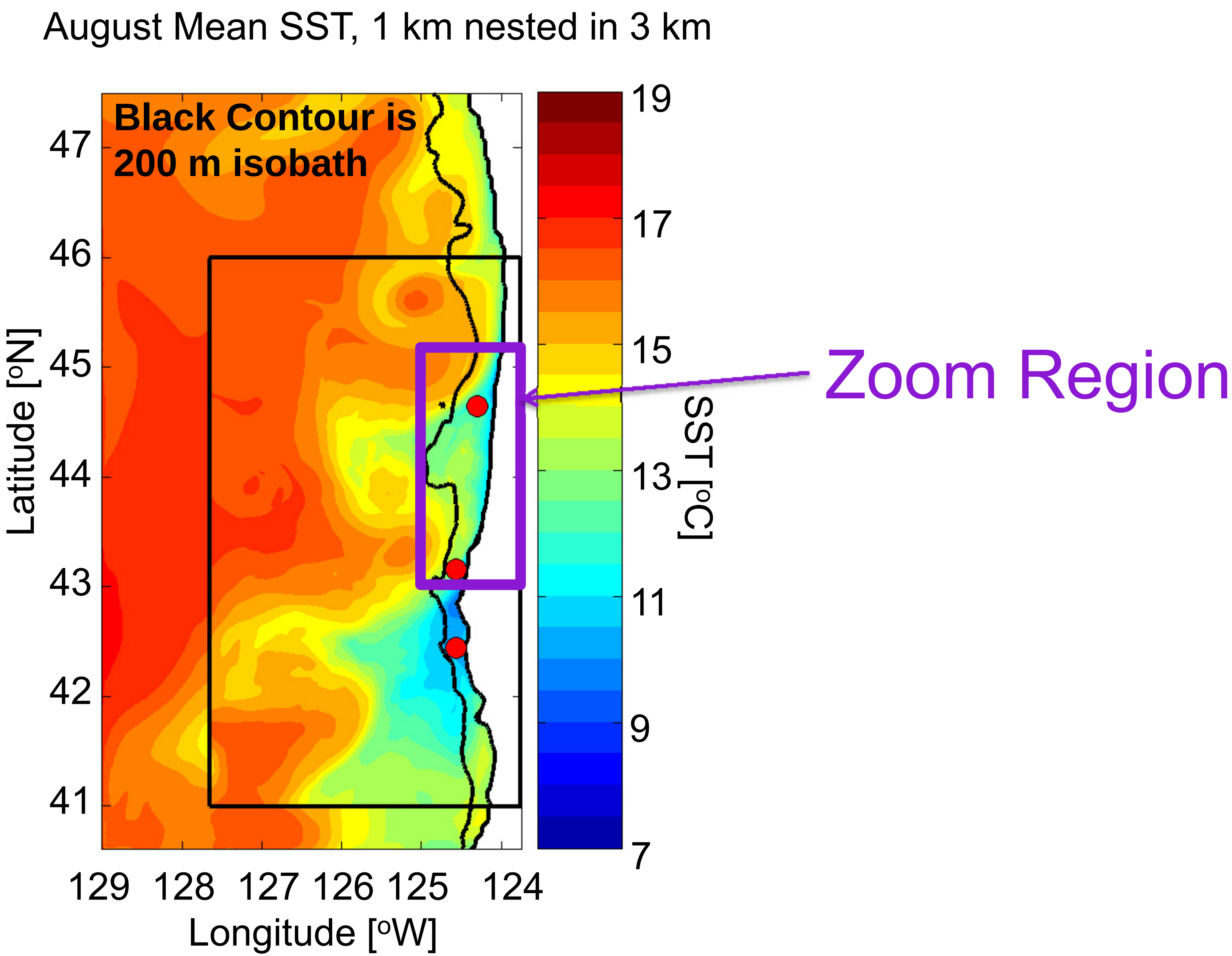
- M_2 Baroclinic Energy Flux (EF) $= \frac{1}{2} \int_{-h}^{0} \mathbf{u}_{\mathrm{BC}} \rho^*_{\mathrm{BT}} \, dz$

- Dissipation(DISS) is estimated as DISS ≈ TEC - $\nabla \cdot$ EF.

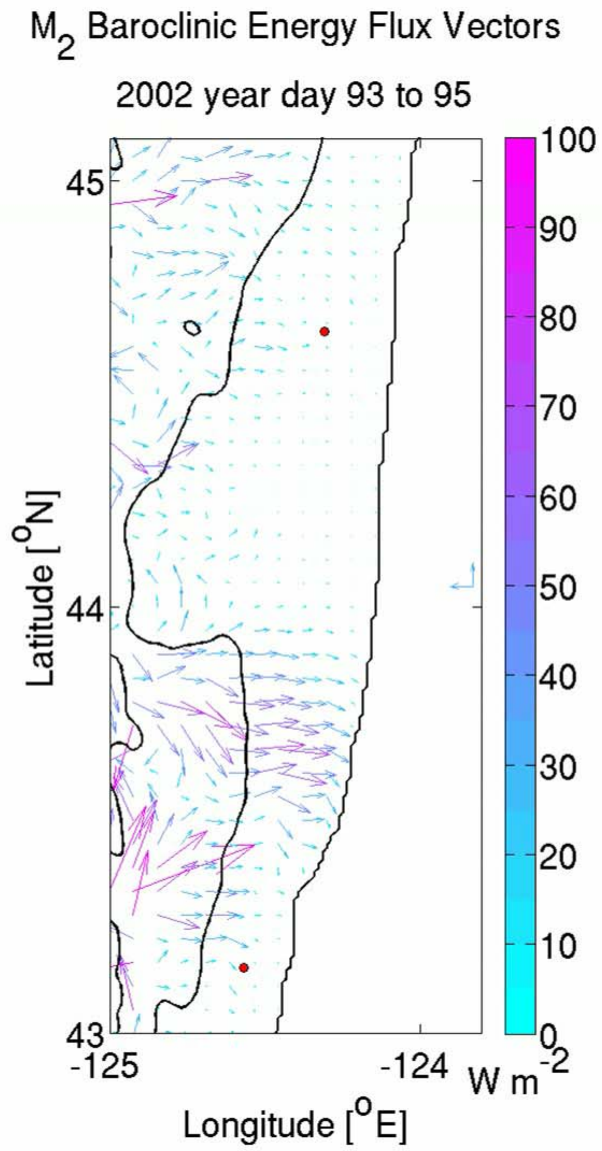
BT : Barotropic
BC : Baroclinic
$\mathbf{u}$, ρ, p : Complex tidal amplitudes
*: Complex conjugate

To compute TEC and EF, model output is harmonically analyzed in a series of 2-day time windows. This resolves intermittency of the internal tide on short time scales and enables calculations of seasonal means and standard deviations.

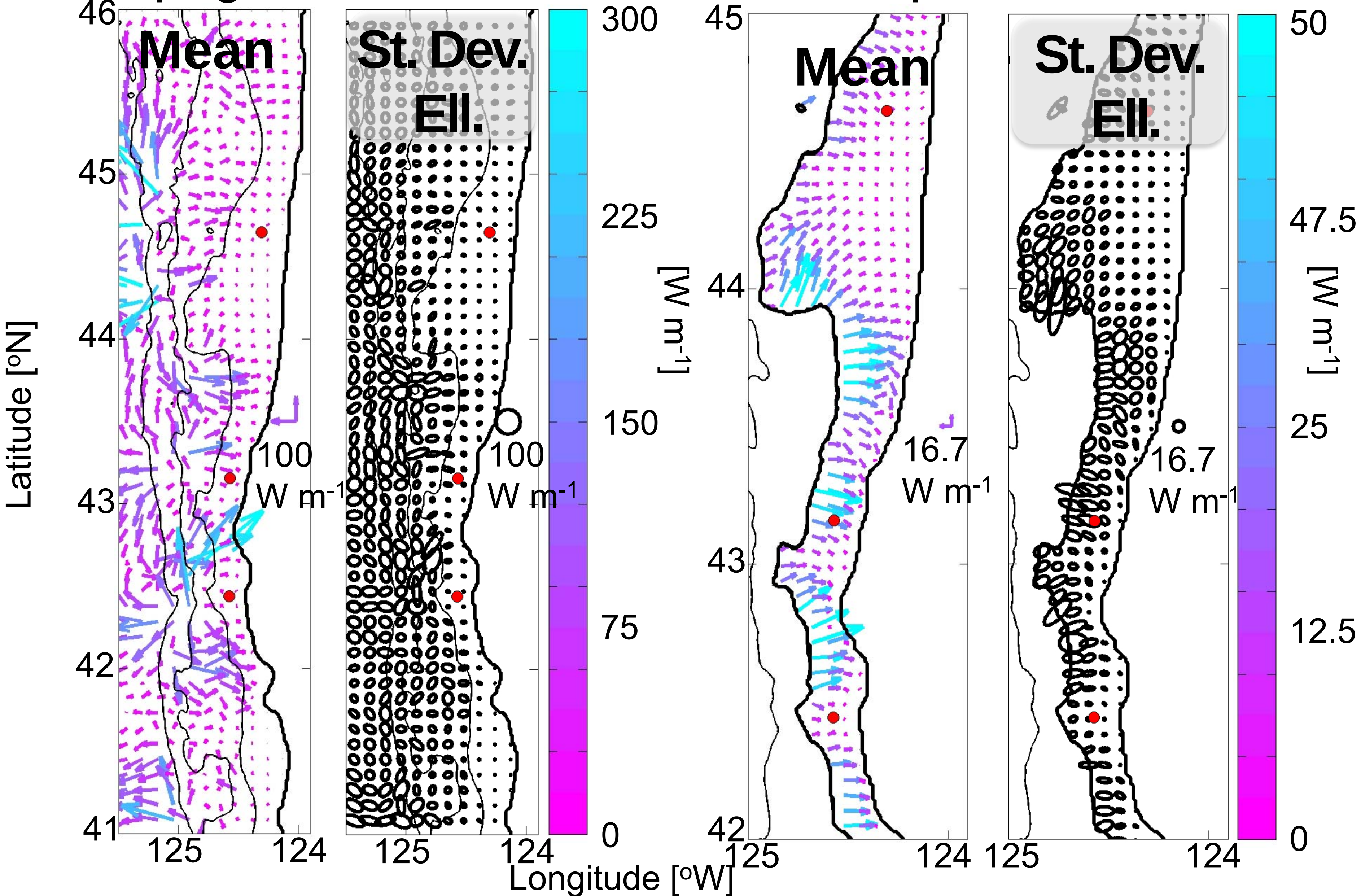
For energy balance analysis, we focus on the central Oregon shelf



Baroclinic Tidal Energy Flux Varies in Space and Time



Time-Averaged Baroclinic Tidal Energy Flux Propagates Both to the Ocean Deep and Onshore



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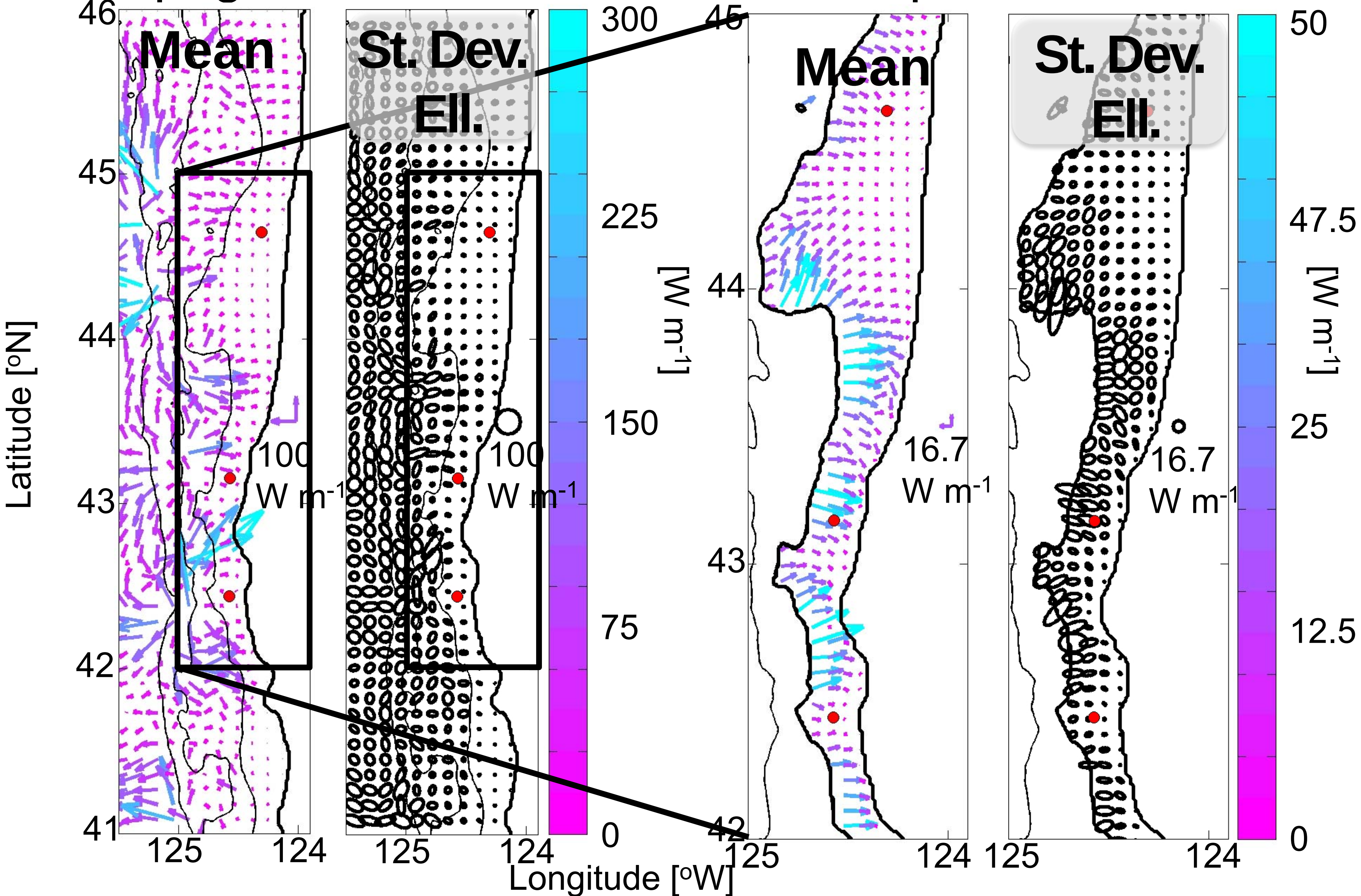
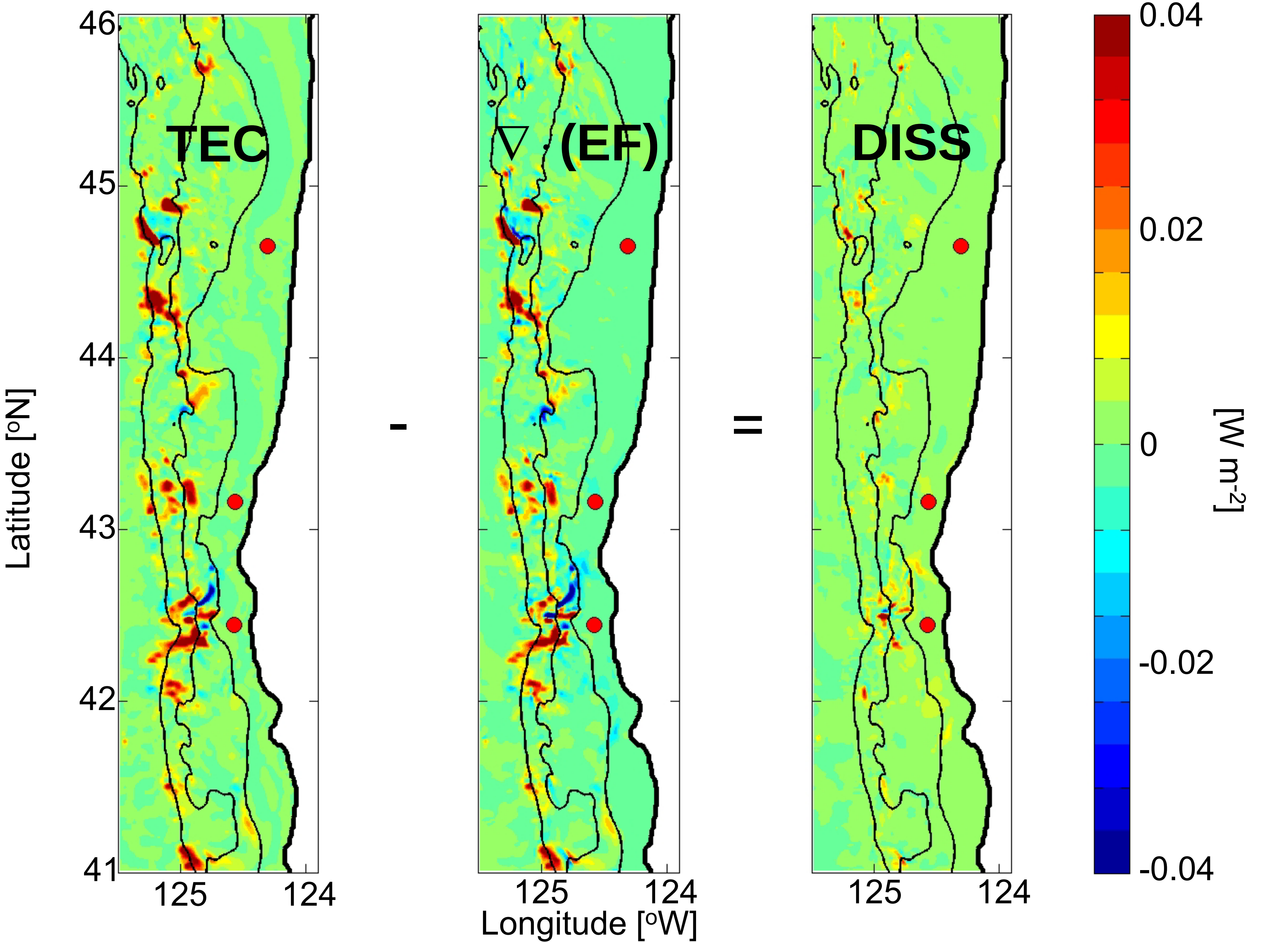
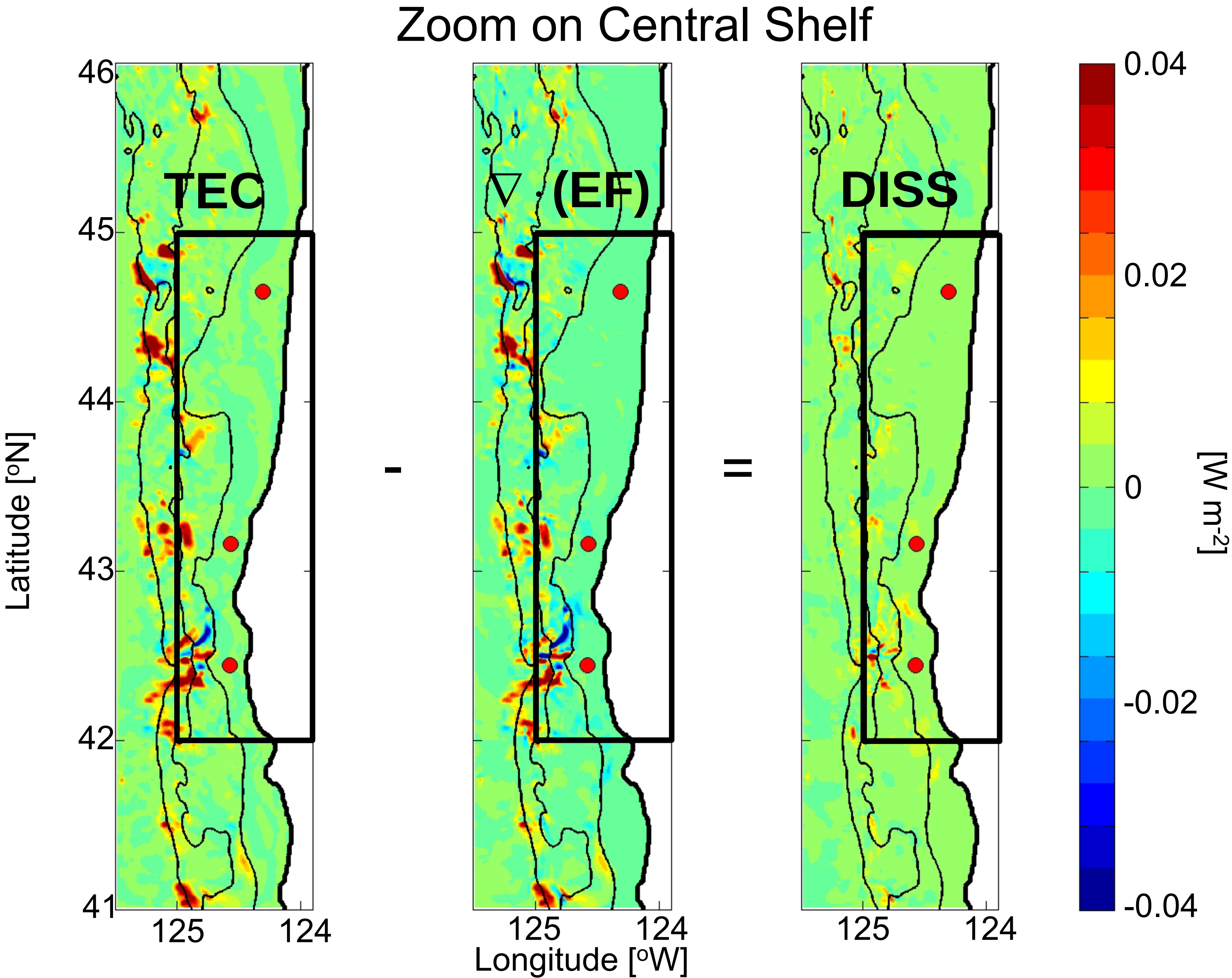


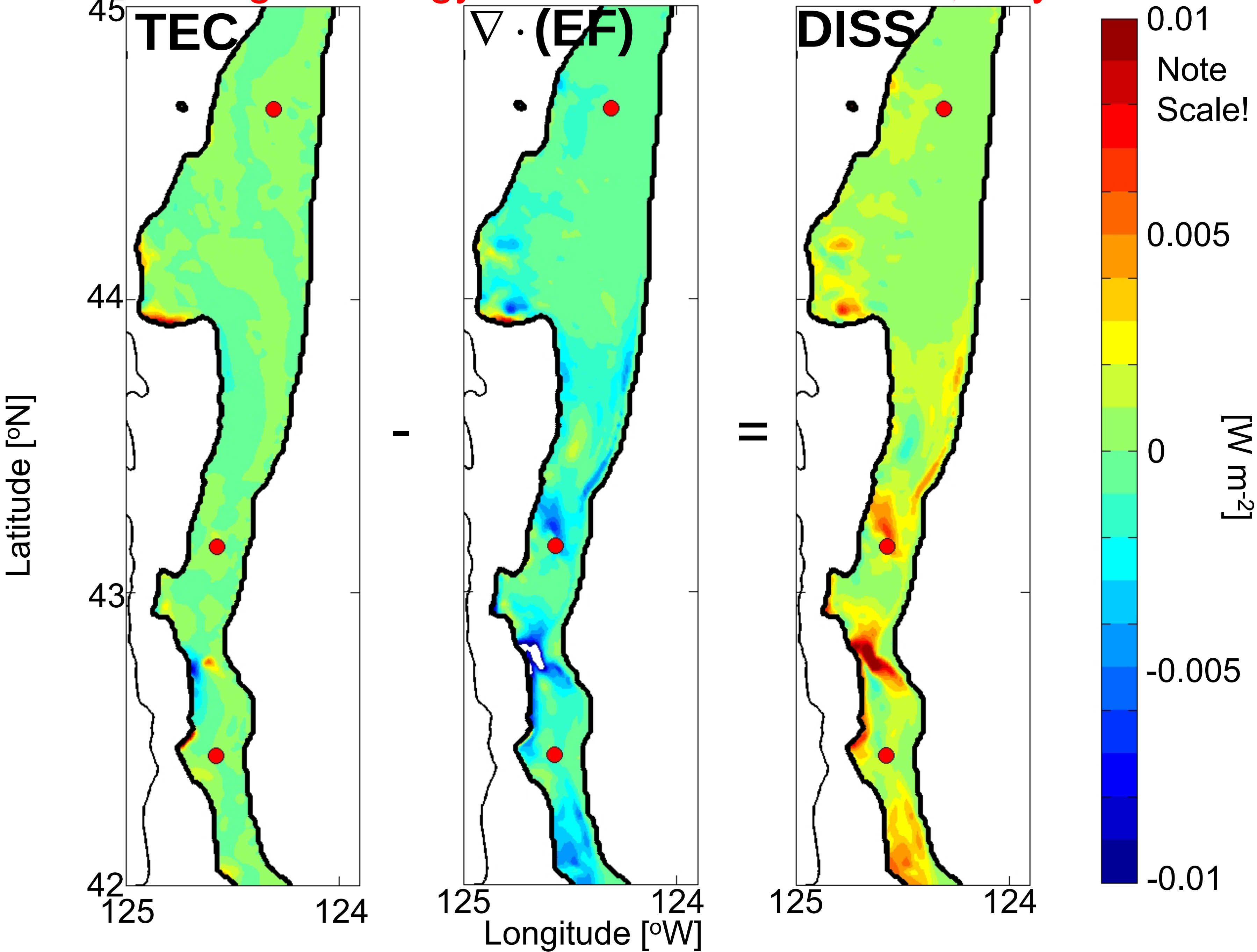
Time-Averaged Energy Balance Over the Slope, Days 93 to 241



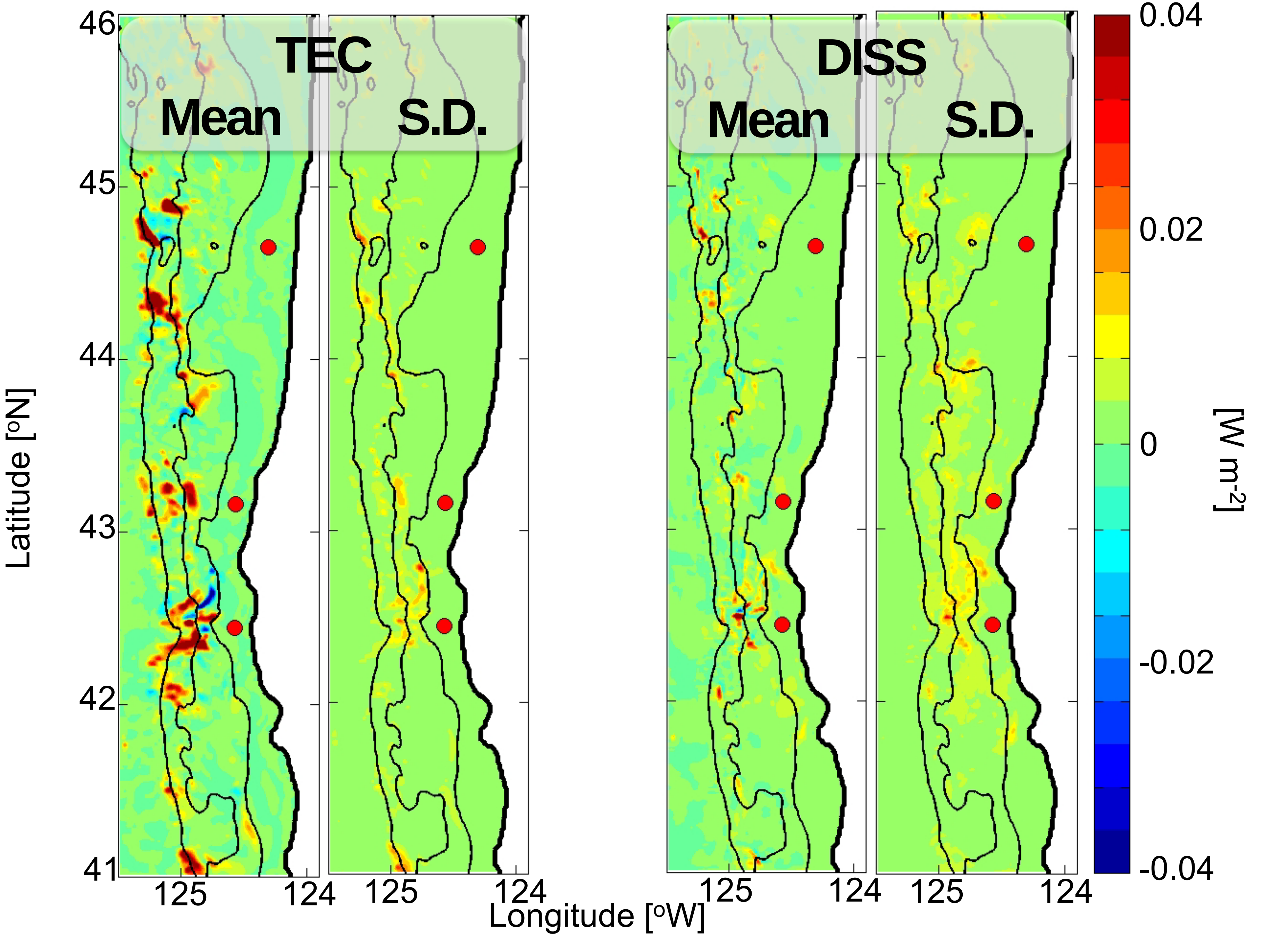


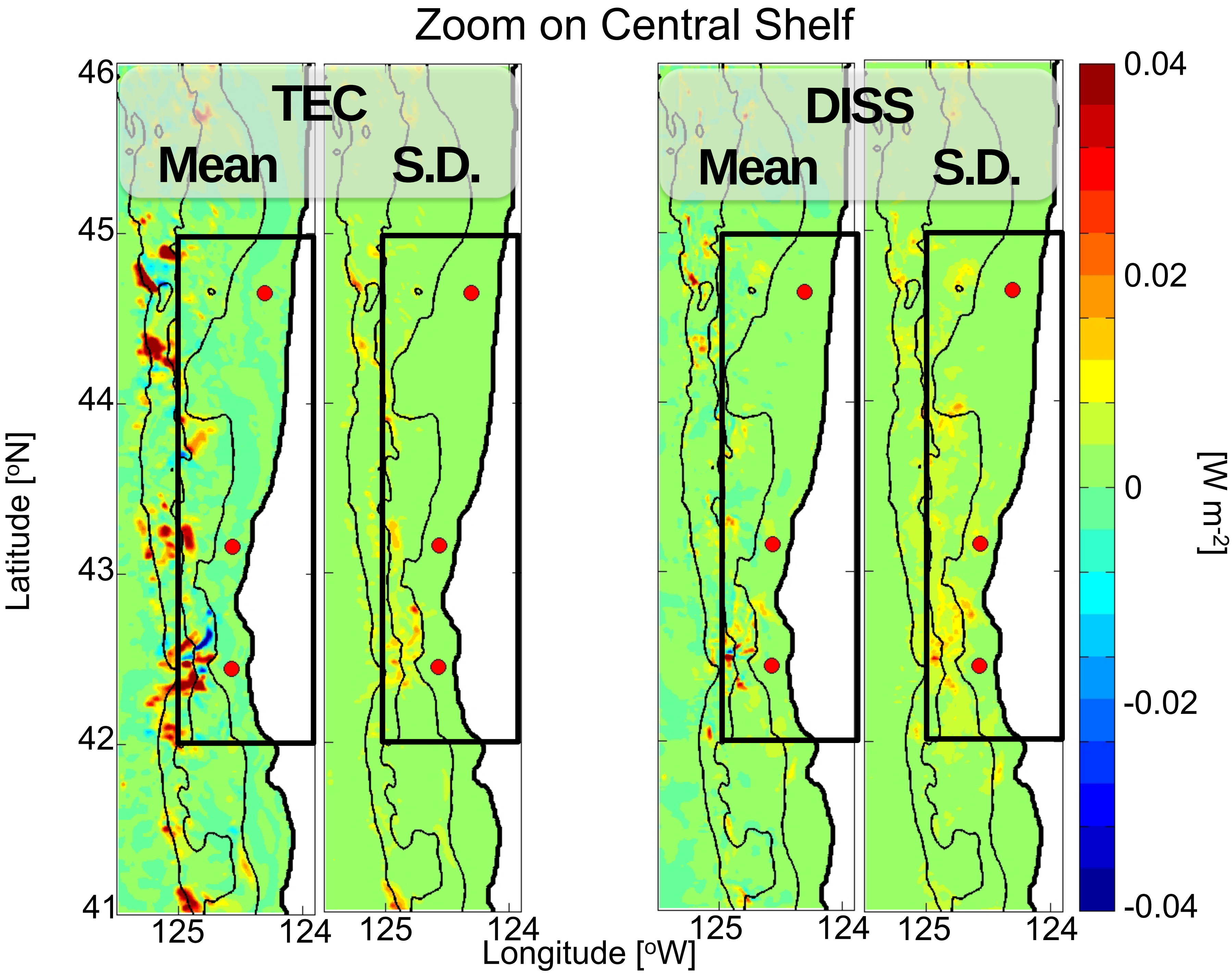
Zoom on Central Shelf
TEC
∇ · (EF)
DISS
-
=
46
45
44
43
42
41
Latitude [oN]
125
124
Longitude [oW]
0.04
0.02
0
-0.02
-0.04
[W m-2]

Time-Averaged Energy Balance Over the Shelf, Days 93 to 241



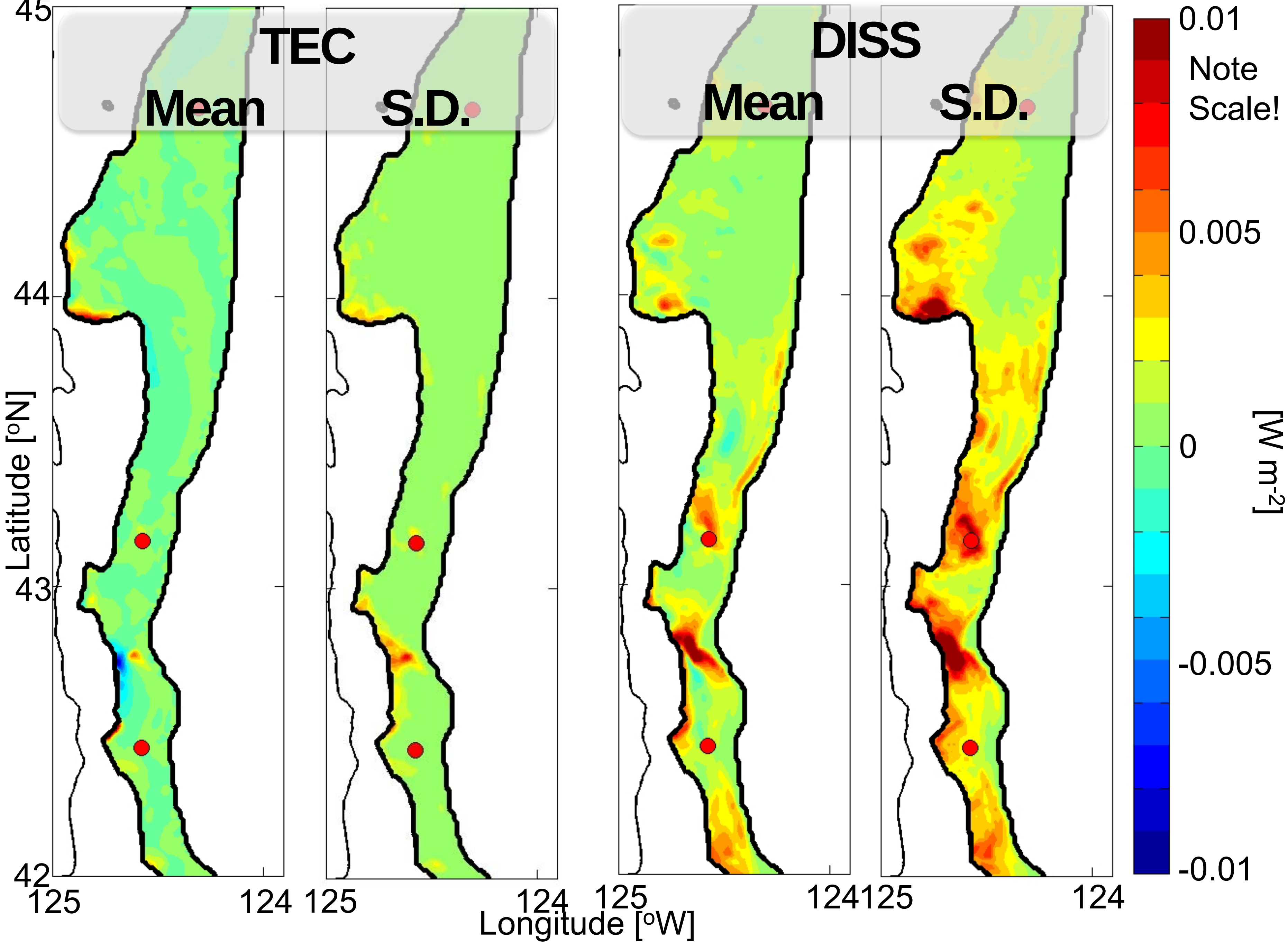
Large Mean Values Typically Associated With Large Standard Deviation



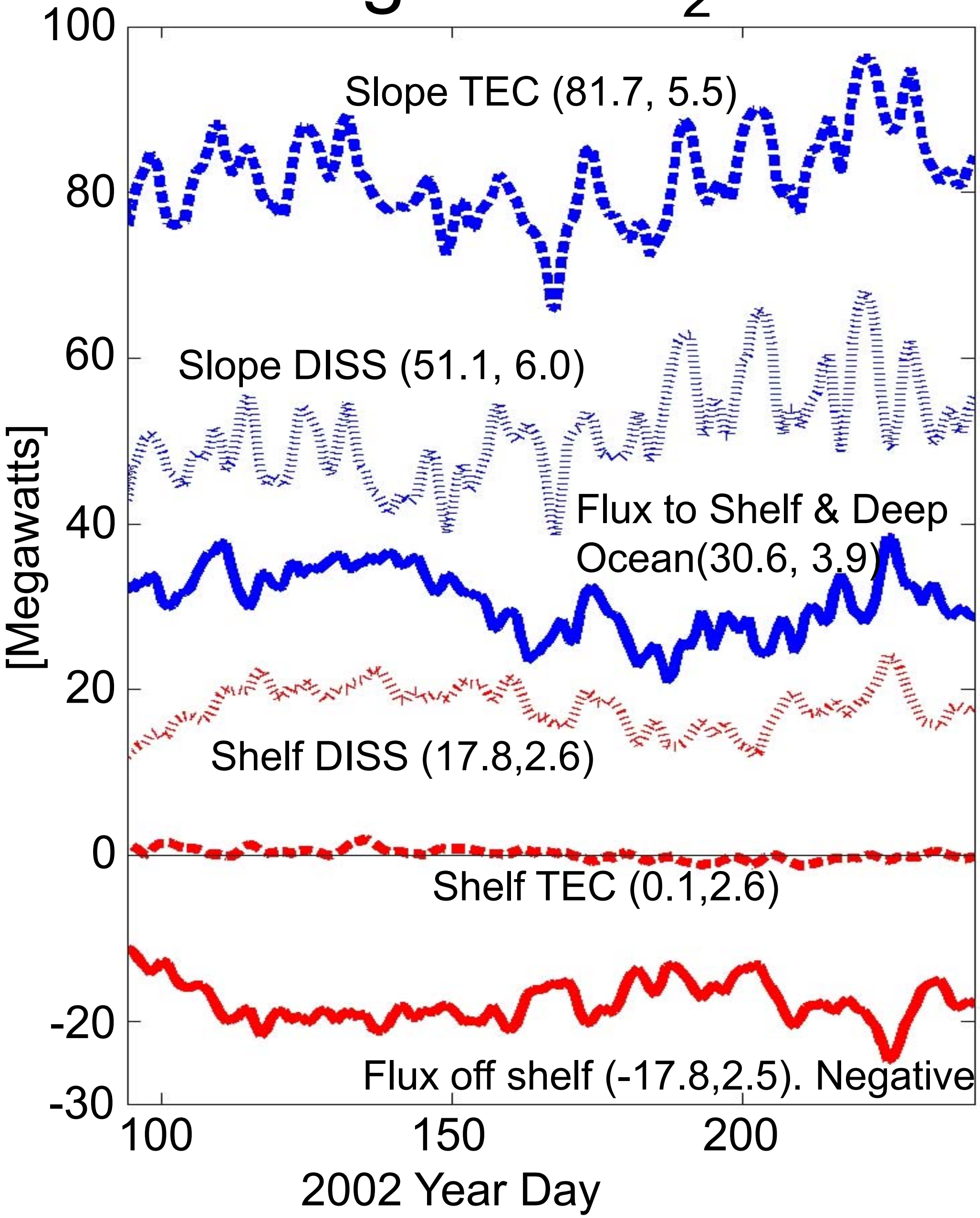


Zoom on Central Shelf
TEC
Mean
S.D.
DISS
Mean
S.D.
Latitude [oN]
46
45
44
43
42
41
125
124
Longitude [oW]
0.04
0.02
0
-0.02
-0.04
[W m-2]

Large Mean Values Typically Associated With Large Standard Deviation



Area- Integrated M_2 Internal Tide Energy Balance

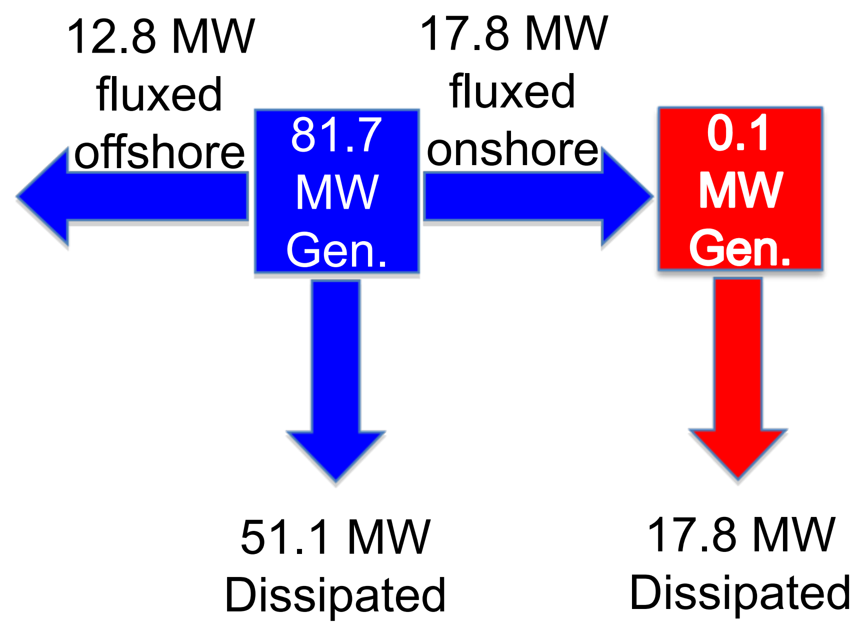


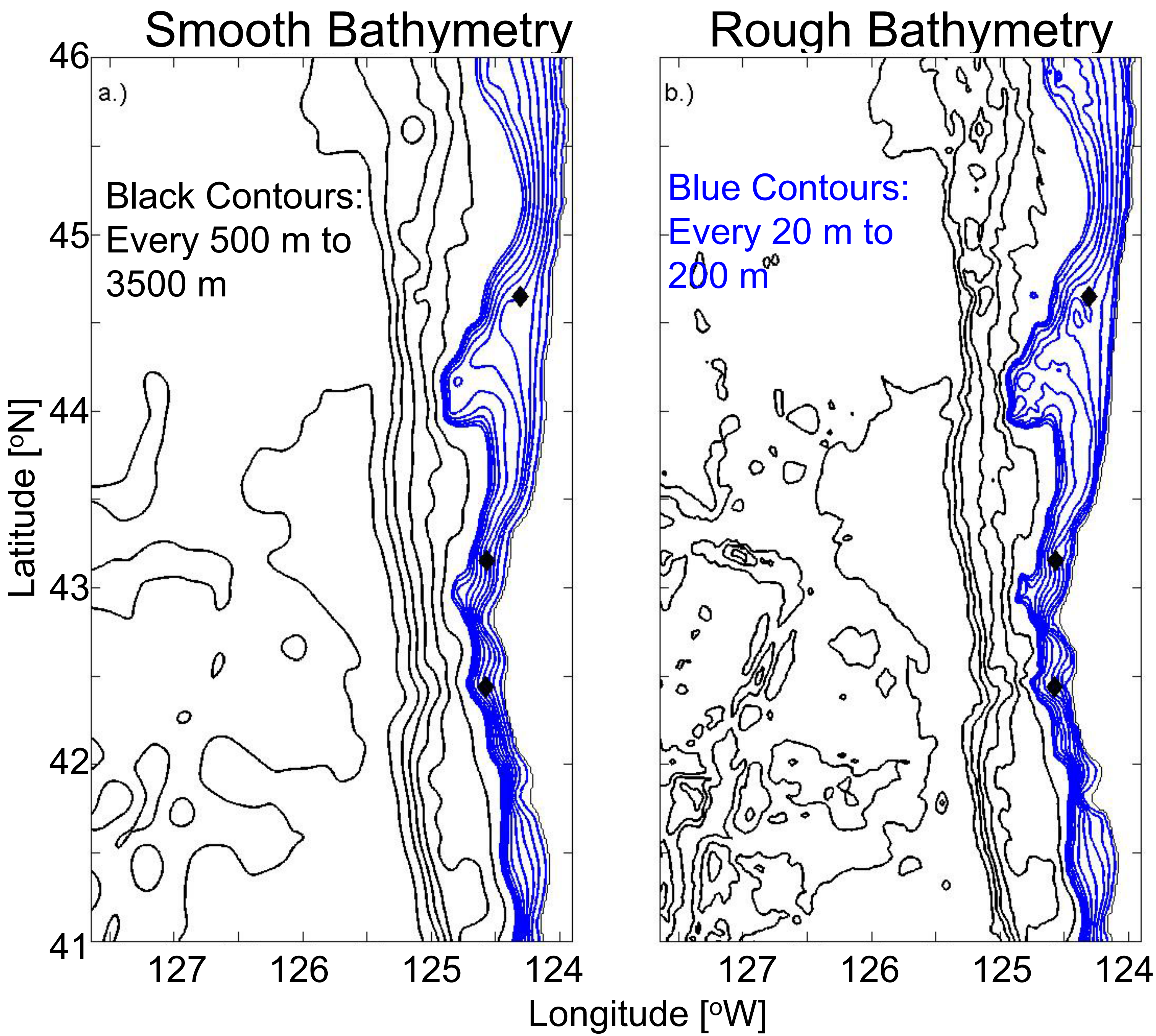
Key

•Property (Mean, Standard Deviation) [MW]

•Slope (200 m to 1800 m)

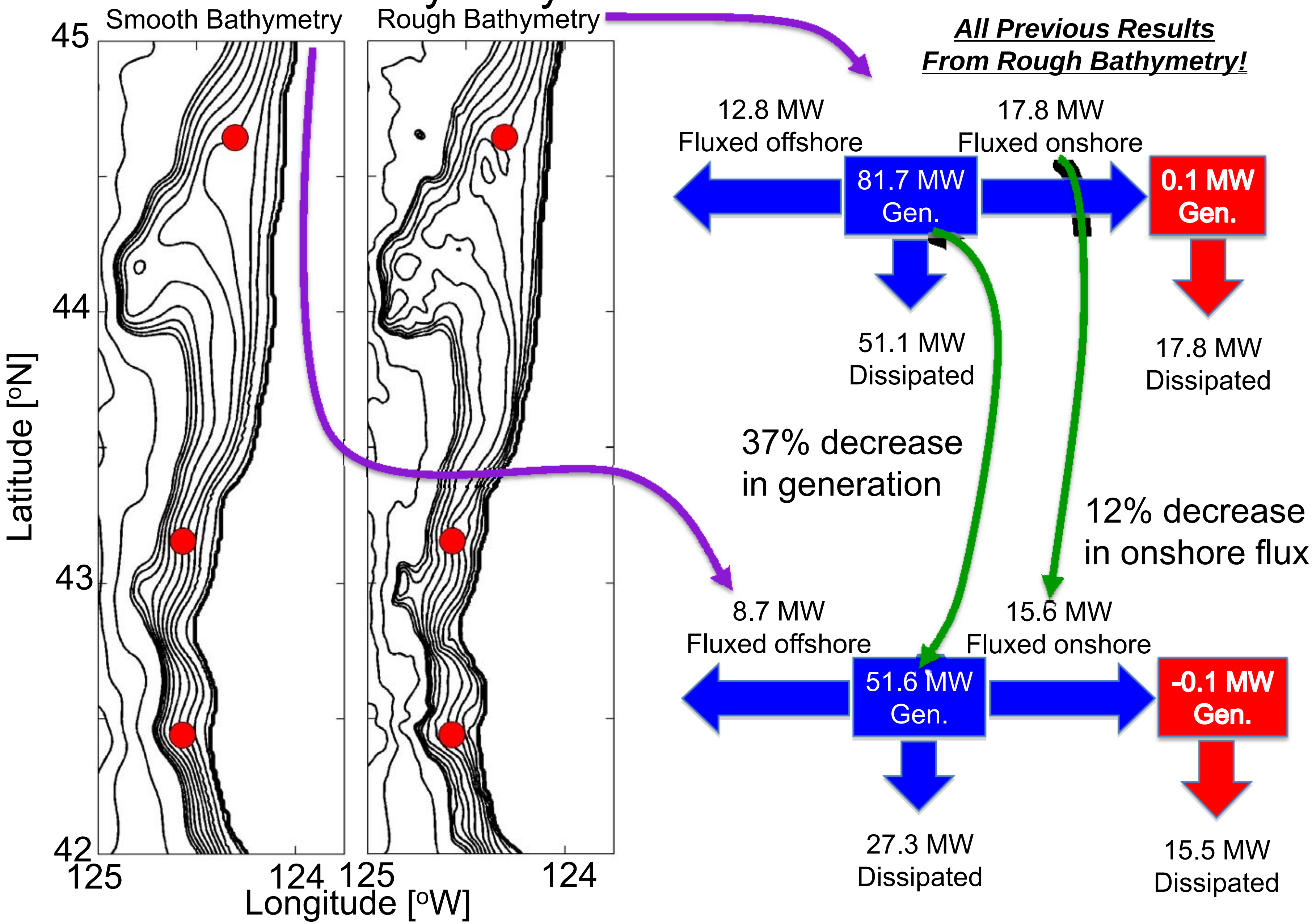
•Shelf (200 m to shore)

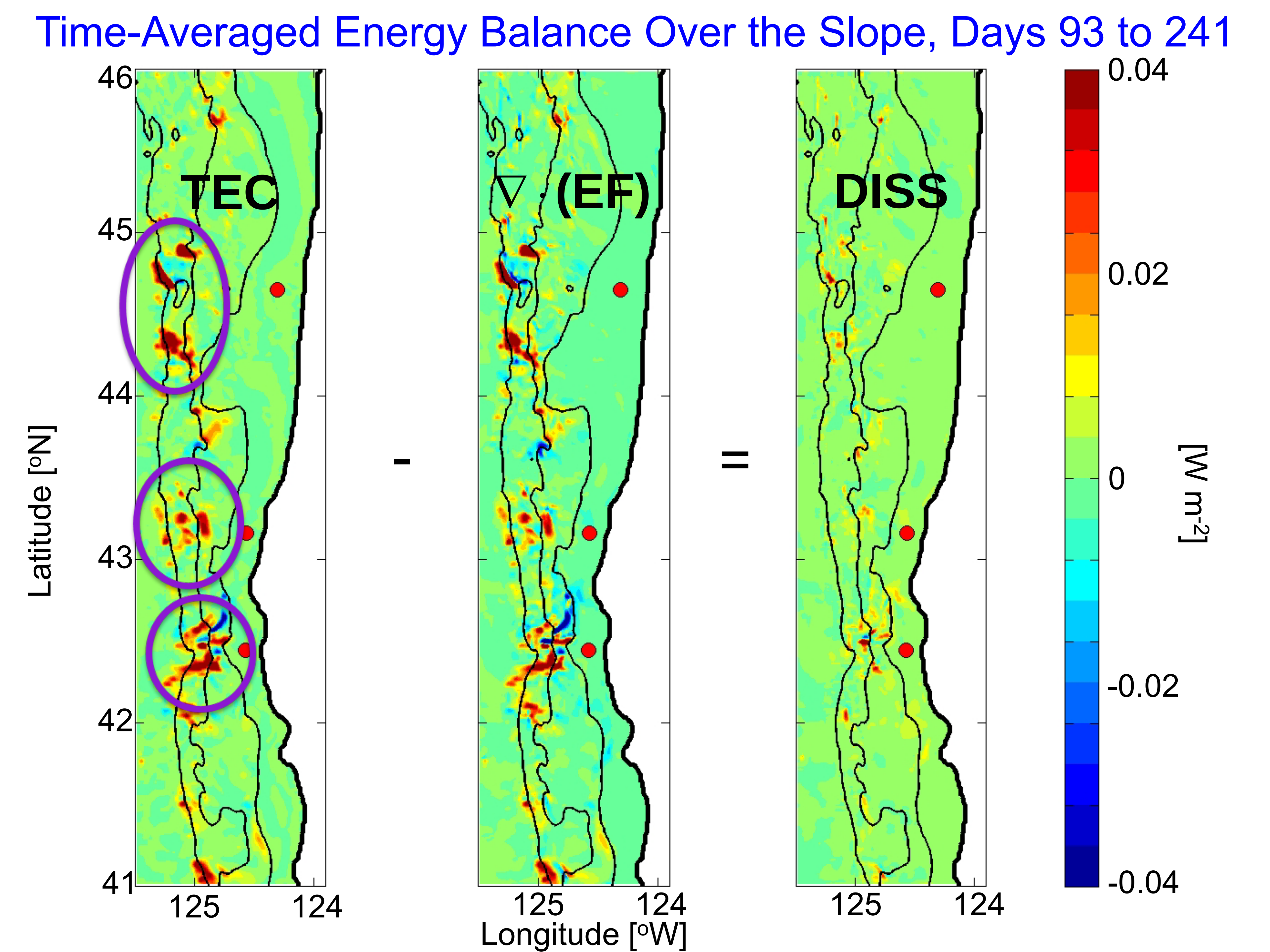




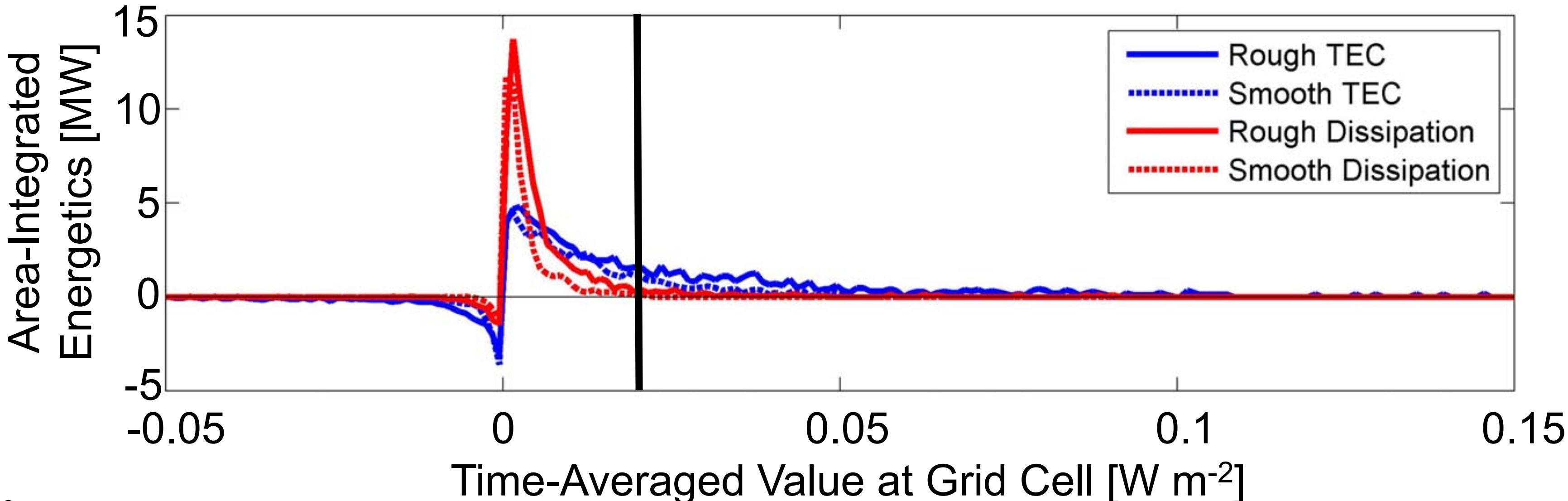
Smooth Bathymetry
Rough Bathymetry
a.)
b.)
Black Contours:
Every 500 m to
3500 m
Blue Contours:
Every 20 m to
200 m
Latitude [oN]
Longitude [oW]
46
45
44
43
42
41
127
126
125
124

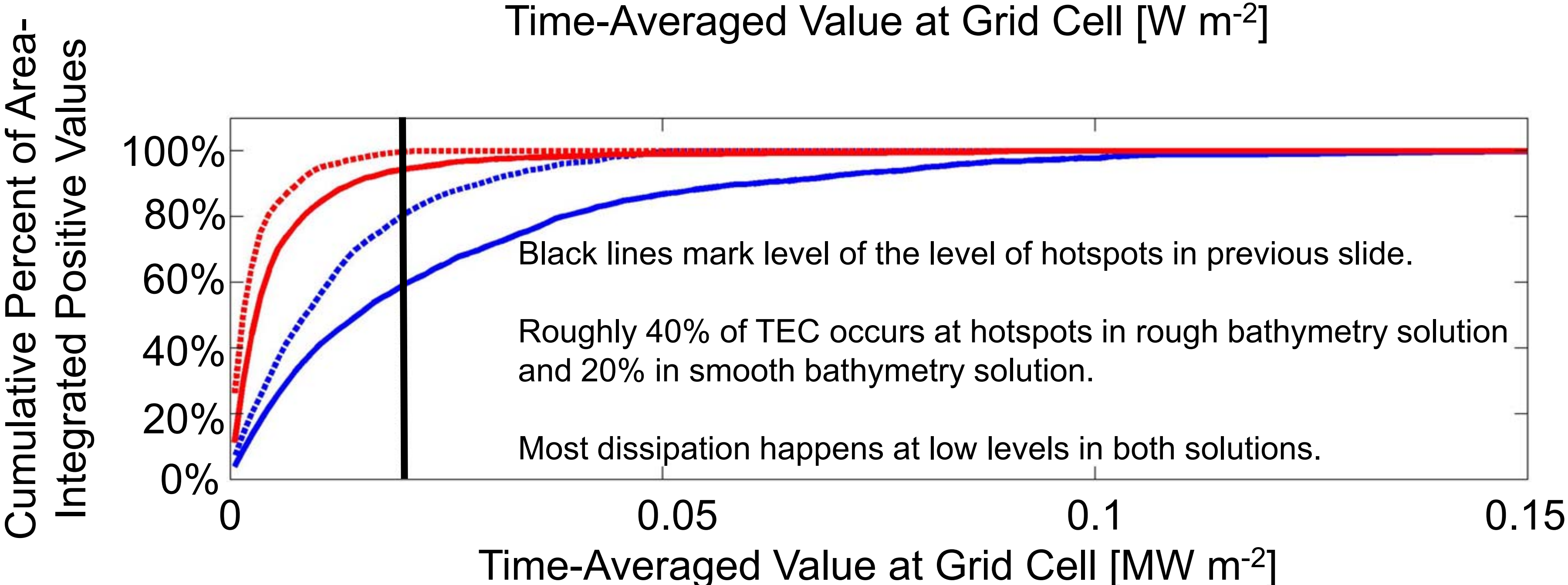
Area- Integrated M_2 Internal Tide Energy Balance: Smoother Bathymetry Yields Similar Onshore Flux



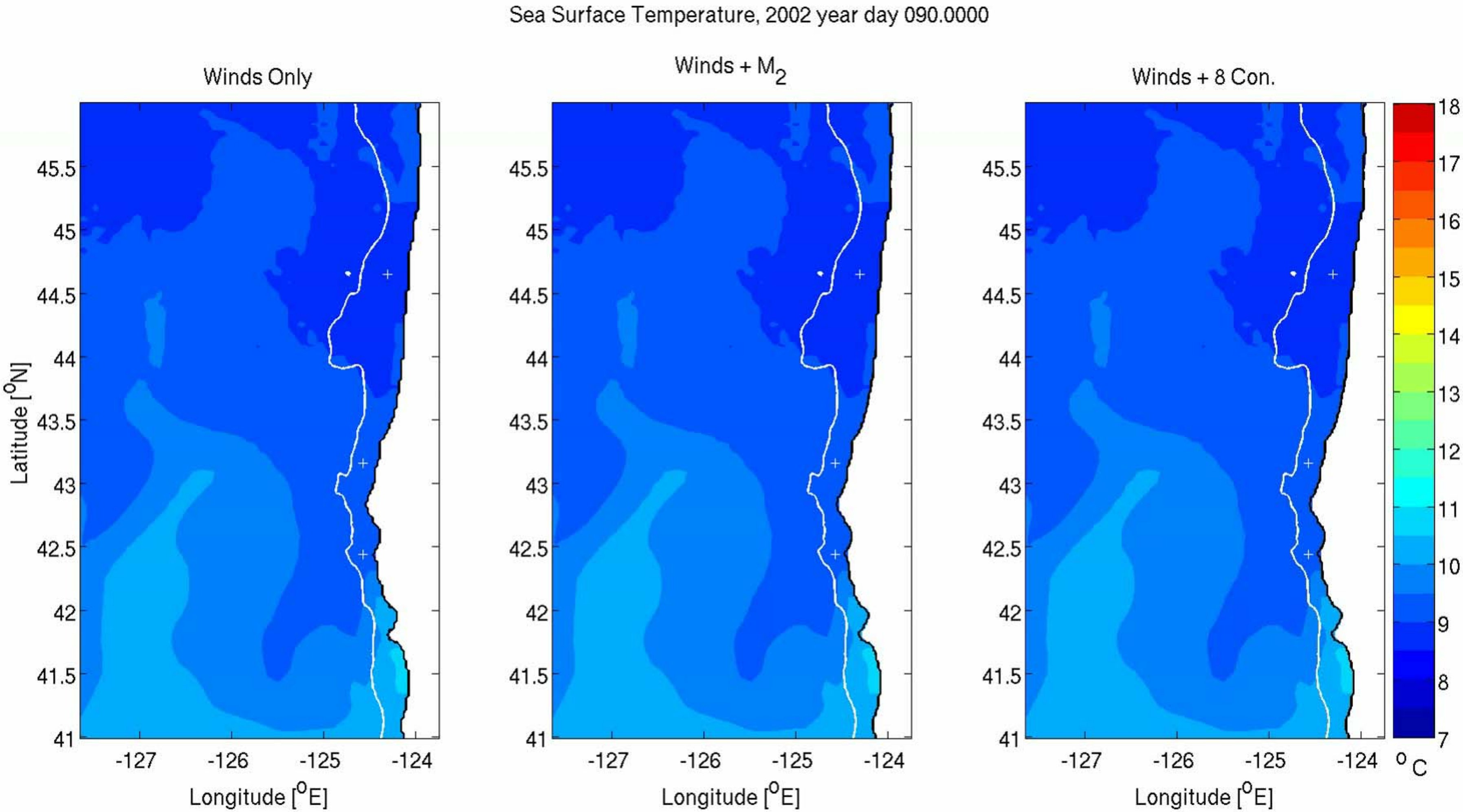

Time-Averaged Energy Balance Over the Slope, Days 93 to 241
TEC
∇ · (EF)
DISS
-
=
Latitude [oN]
Longitude [oW]
46
45
44
43
42
41
125
124
0.04
0.02
0
-0.02
-0.04
[W m-2]

Low TEC Level Zones Significantly Contribute to the Area-Integrated TEC





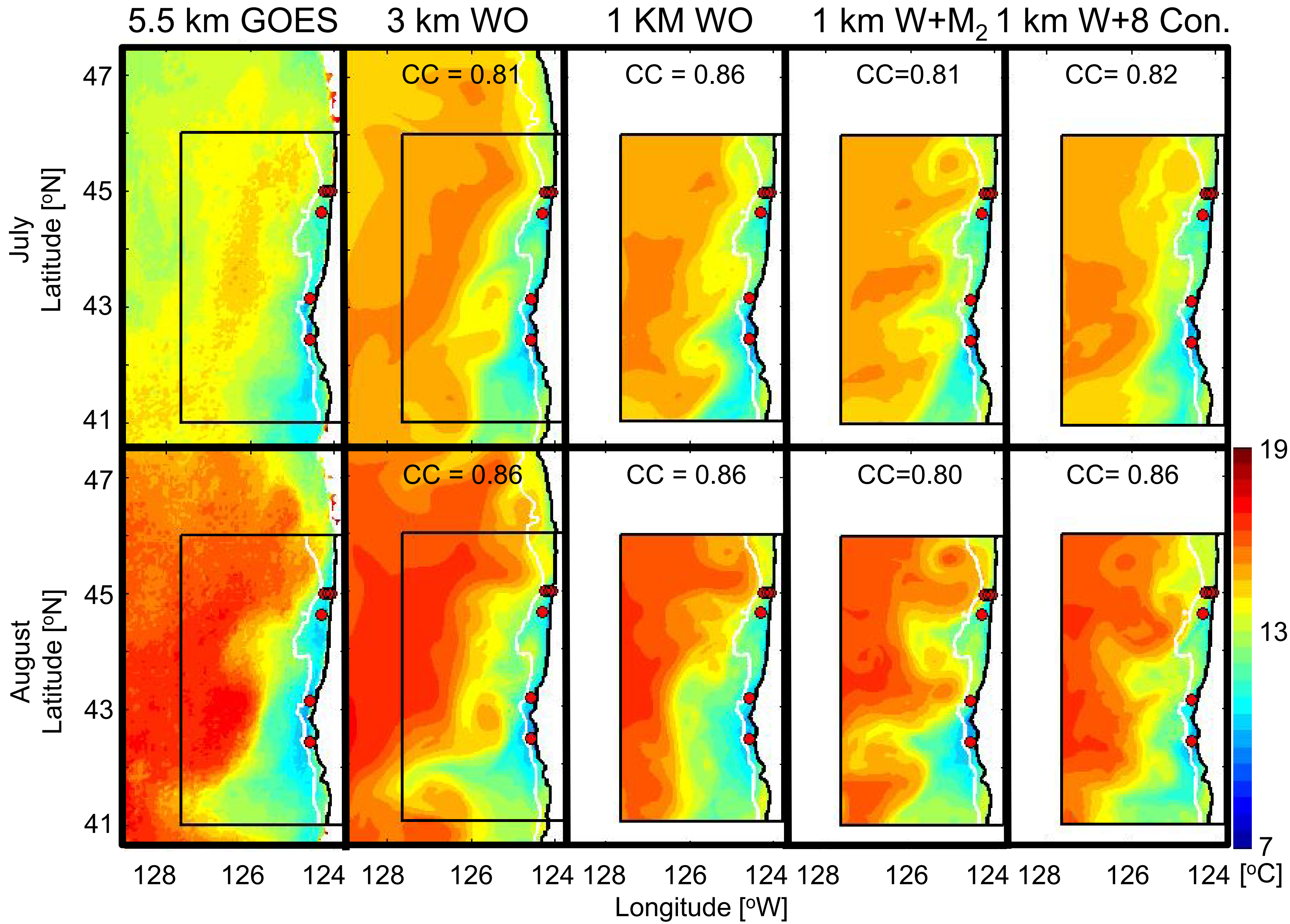
Cross-Shelf Transport: Winds-Only, Winds + M2 and Winds + 8 Constituents


Sea Surface Temperature, 2002 year day 090.0000
Winds Only
Winds + M_2
Winds + 8 Con.
Latitude [^oN]
45.5
45
44.5
44
43.5
43
42.5
42
41.5
41
-127
-126
-125
-124
Longitude [^oE]
18
17
16
15
14
13
12
11
10
9
8
7
^oC

Is this sensitivity to open boundary conditions (recall, the model based on hydrostatic equations is poorly-conditioned)?

Or, is it indeed the effect of the internal tide on horizontal turbulent heat flux?

Upwelling Qualitatively Varies Between Cases



Summary

- The nested 1-km ROMS application correctly reproduces both sub-tidal and tidal variability.
- Over the slope, internal tide generation hotspots are partially balanced by energy flux divergence with nearby dissipation.
- Over the shelf, there is a net onshore flux of baroclinic internal tide energy and low local production of internal tides.
- Zones of energy propagation and dissipation are mapped and are targets of for future analysis.
- Cross-shore transport is sensitive to model formulation. Do tides affect the shelf-open ocean exchange?