4D-Var Data Assimilation in a Nested Configuration of ROMS: Integrating Data from Observations across Scales

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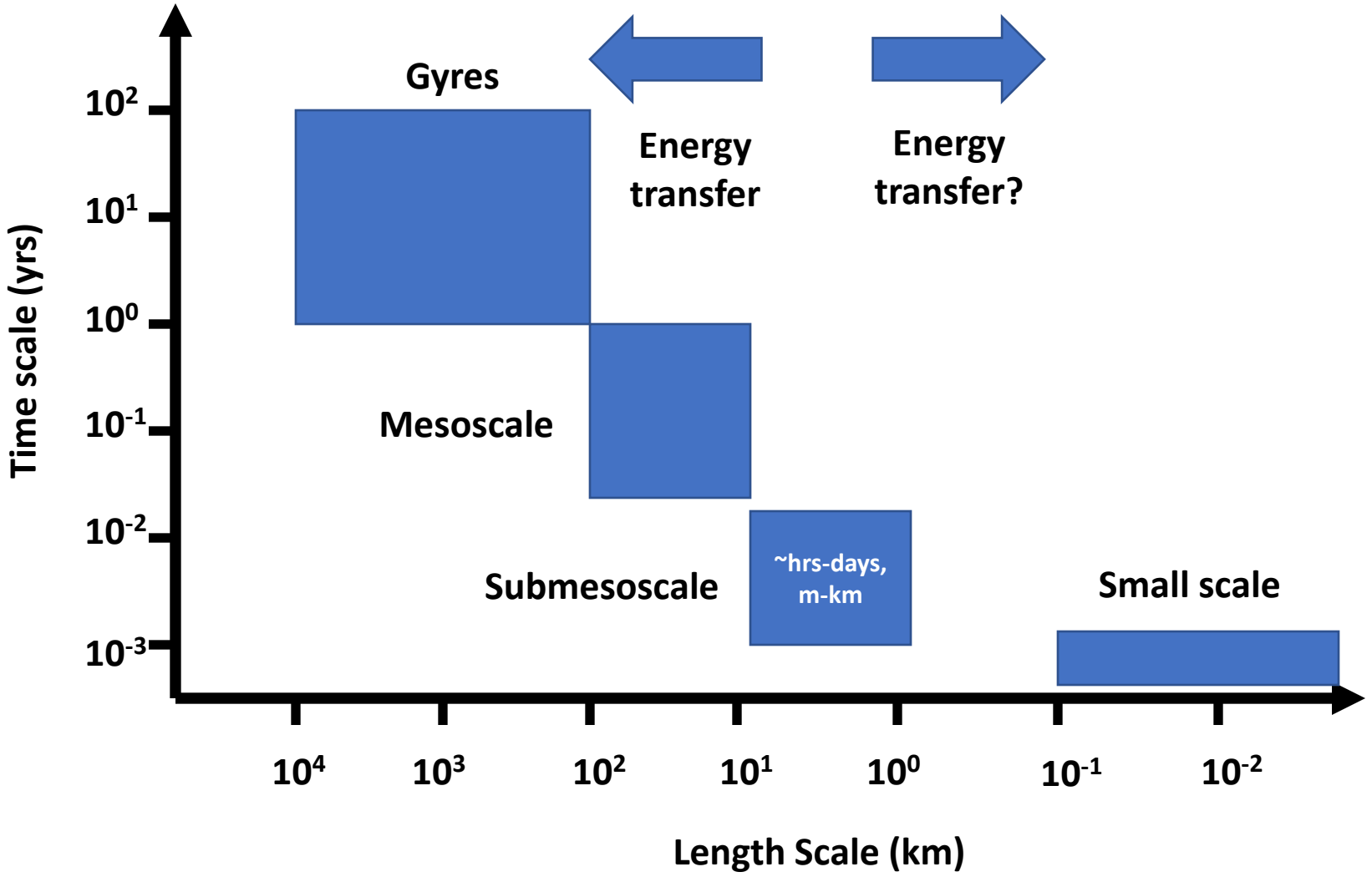
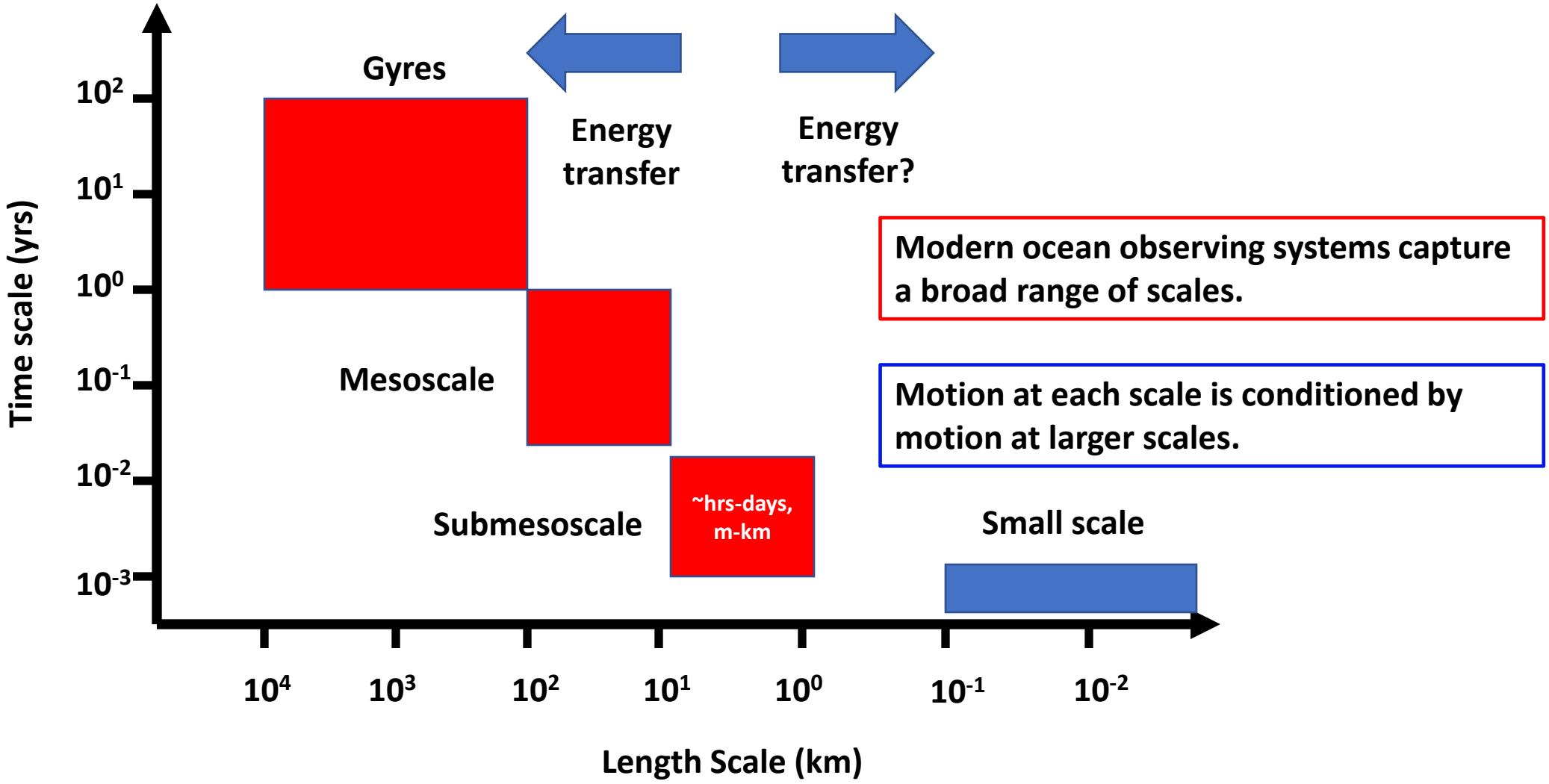
Motivation

Ocean Scales of Motion



Ocean Scales of Motion

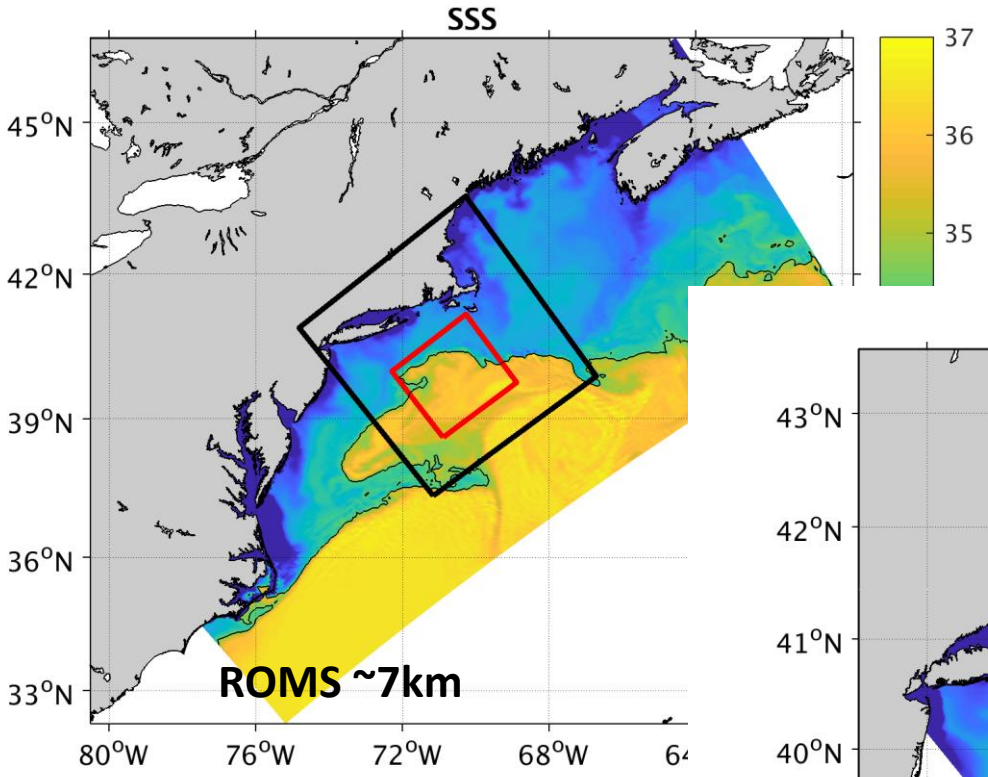


Modern ocean observing systems capture a broad range of scales.

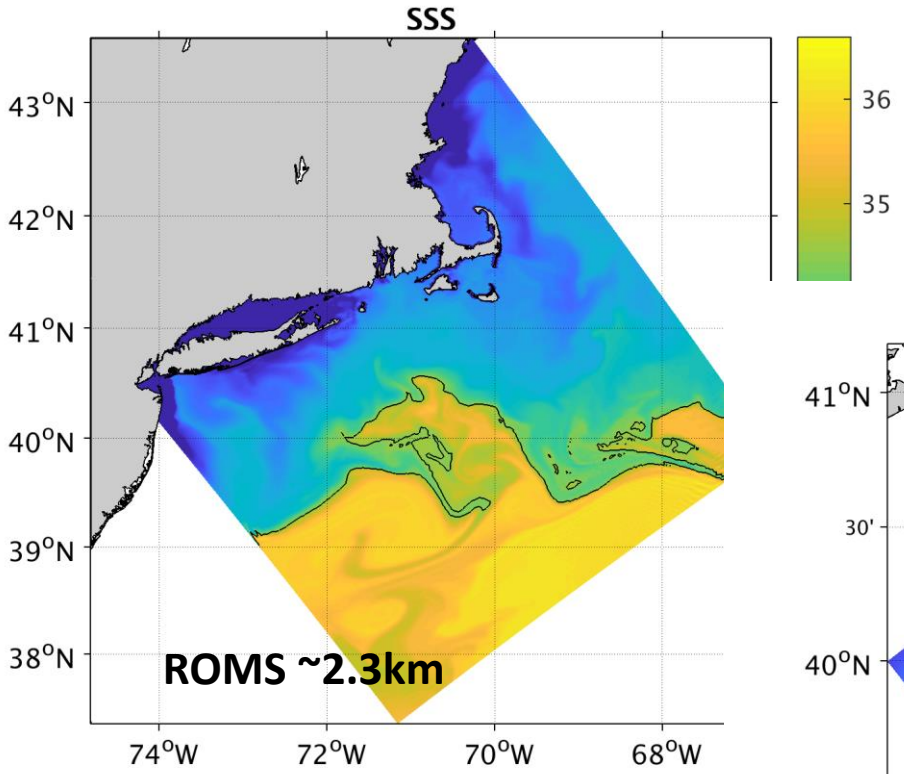
Motion at each scale is conditioned by motion at larger scales.

A Gulf Stream Ring Event

"Pinocchio's Nose Intrusions" (Zhang & Gawarkiewicz)

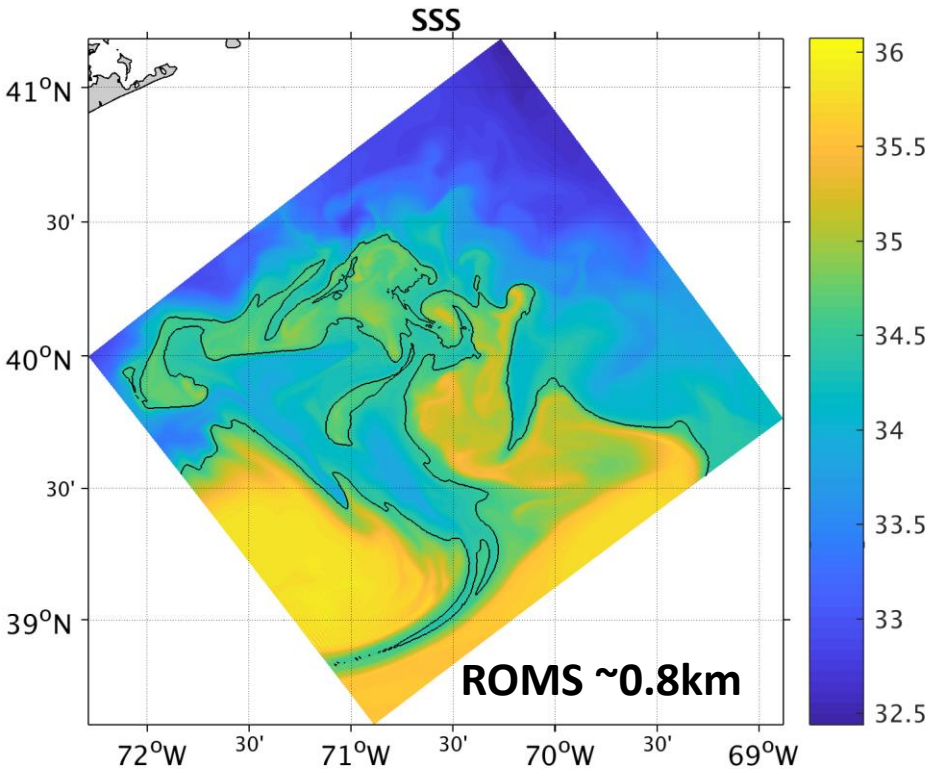


Quasigeostrophic & mesoscale



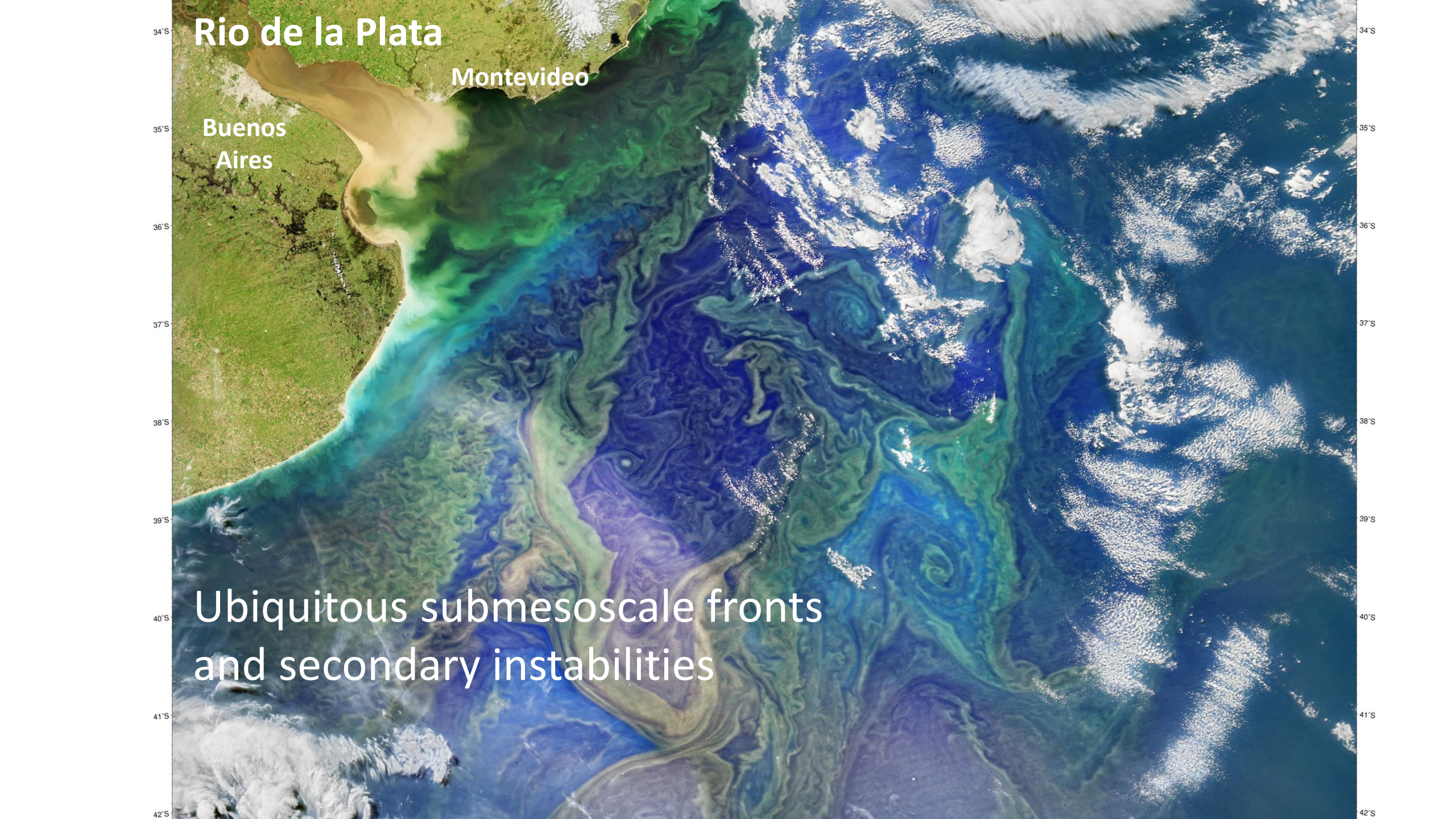
Mesoscale

Submesoscale



ROMS 4D-Var Analyses
16 May 2014
Sea Surface Salinity

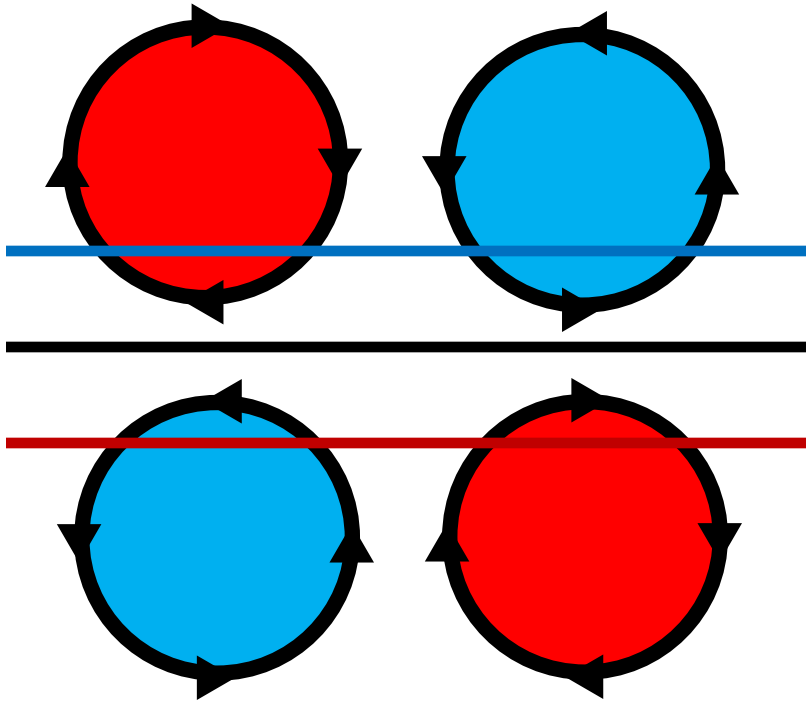
The Submesoscale

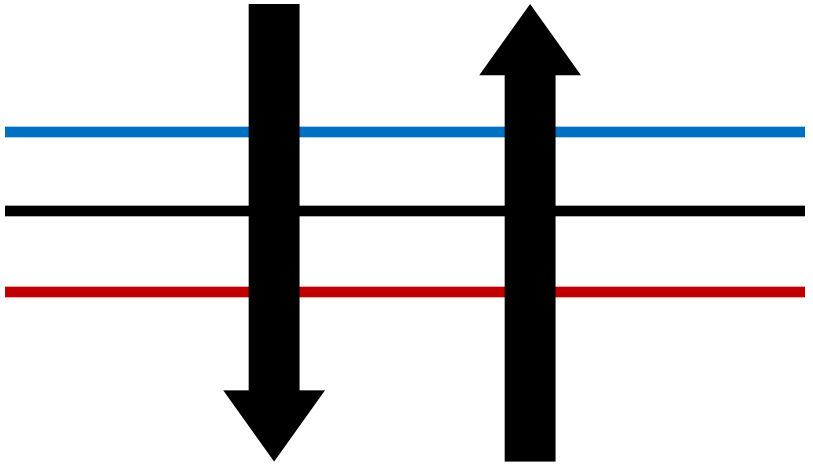

Rio de la Plata
Montevideo
Buenos Aires
34°S
35°S
36°S
37°S
38°S
39°S
40°S
41°S
42°S
Ubiquitous submesoscale fronts and secondary instabilities

Frontogenesis

Bergerson (1967); Hoskins (1982)

A field of mesoscale eddies





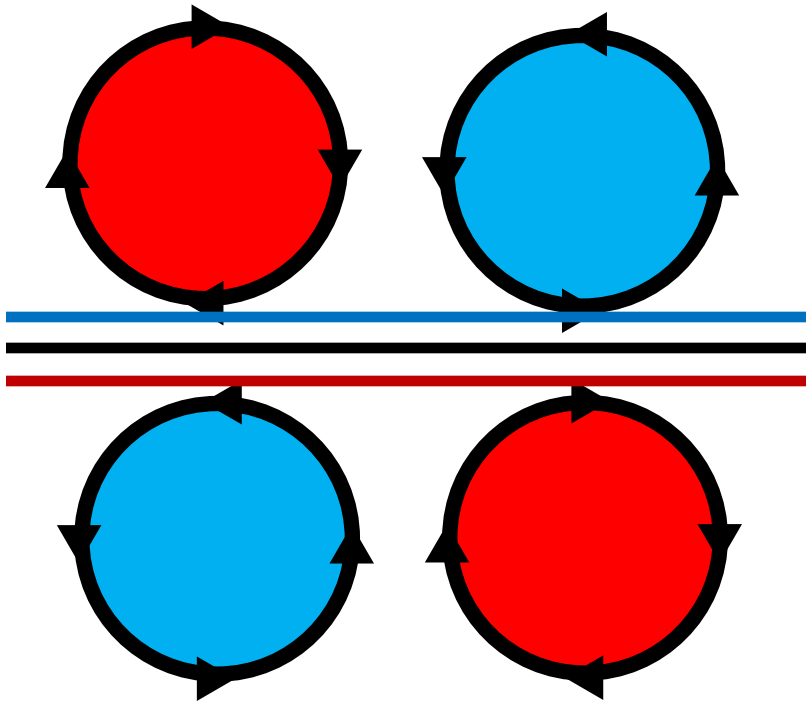
Strain-induced **Shear-induced**

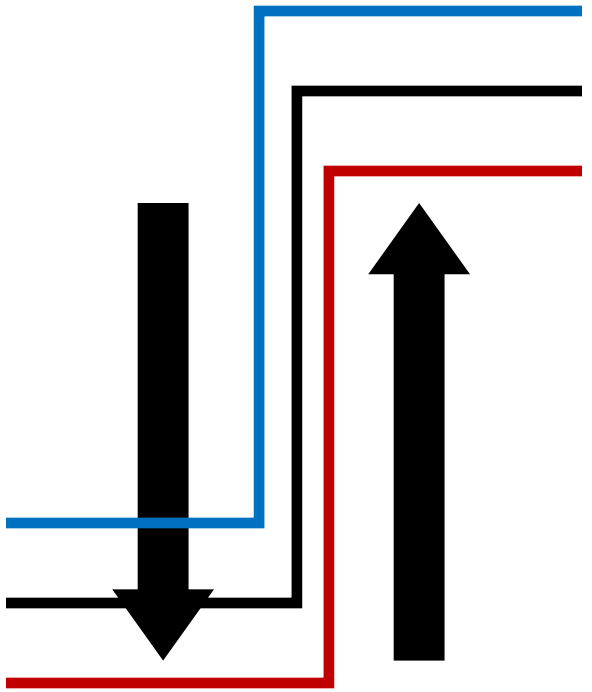
Conditioned by the mesoscale circulation

Frontogenesis

Bergerson (1967); Hoskins (1982)

A field of mesoscale eddies





Strain-induced **Shear-induced**

Conditioned by the mesoscale circulation

Evolution & Instability

Unforced

$$R_o \sim O(1)$$

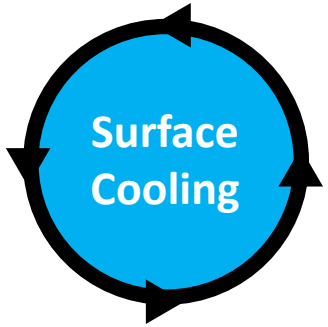
$$L \sim 1\ \mathrm{km}$$

$$U \sim 0.1\ \mathrm{m\ s^{-1}}$$

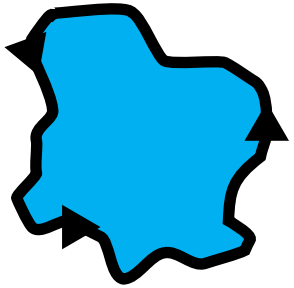
“Eady” instability

(eg. Molemaker et al, 2005)

Buoyancy Forced

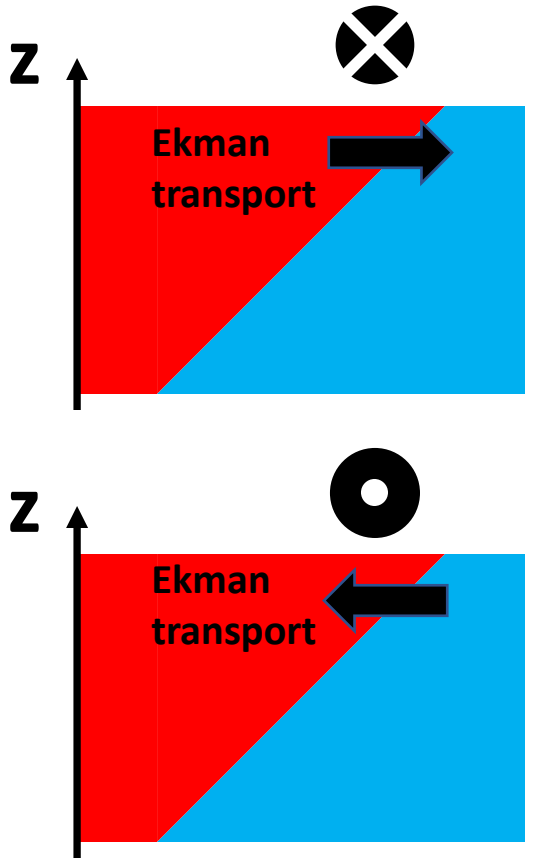


$$a = Nh_{ml} / f$$



(Legg et al.,1998)

Wind Forcing of Fronts



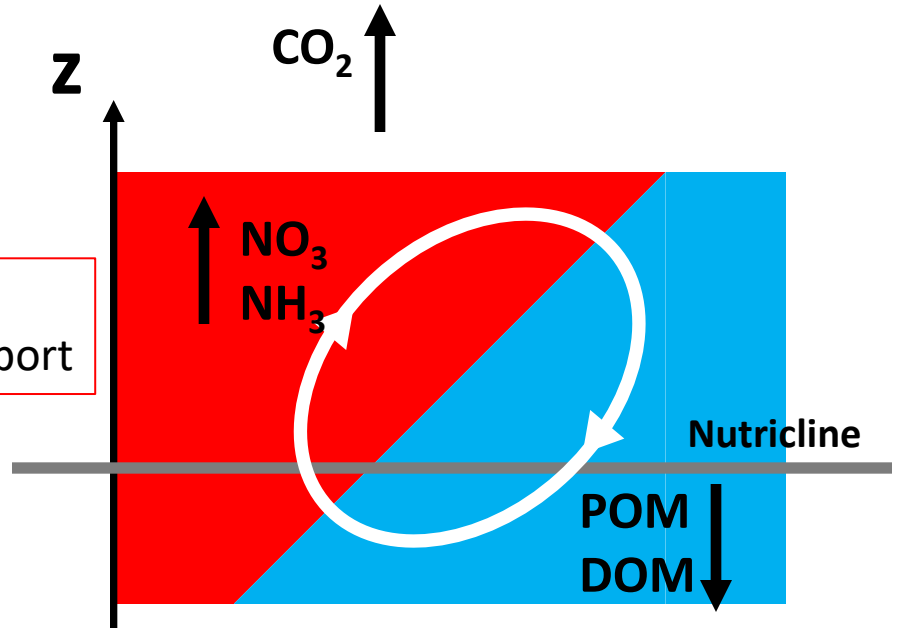
Along front winds can promote frontolysis, or…

…prolong the life of a front.

(Thomas and Lee, 2005)

Ocean Biogeochemistry

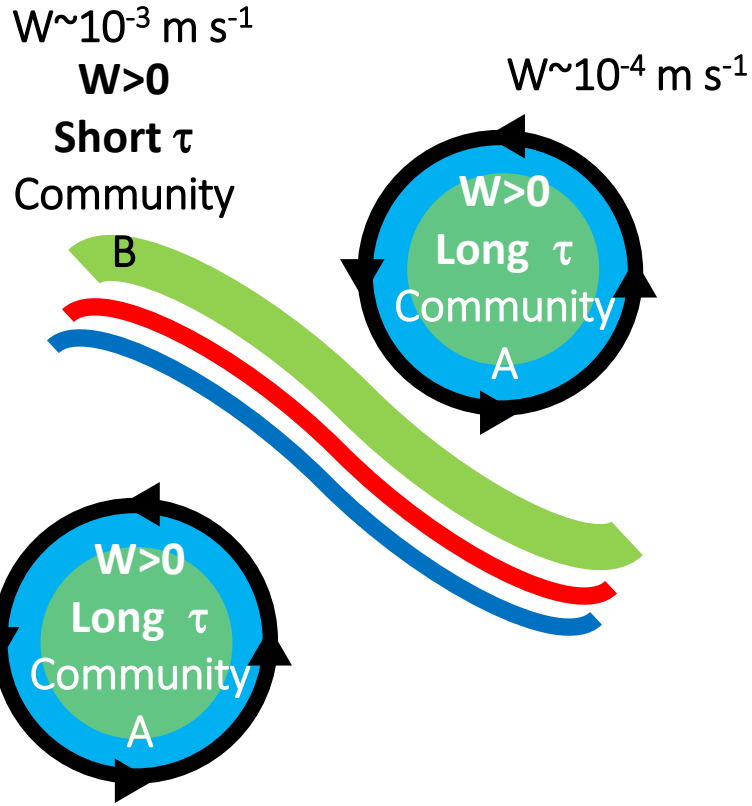
Lévy et al. (2012)



Enhanced nutrient fluxes & carbon export

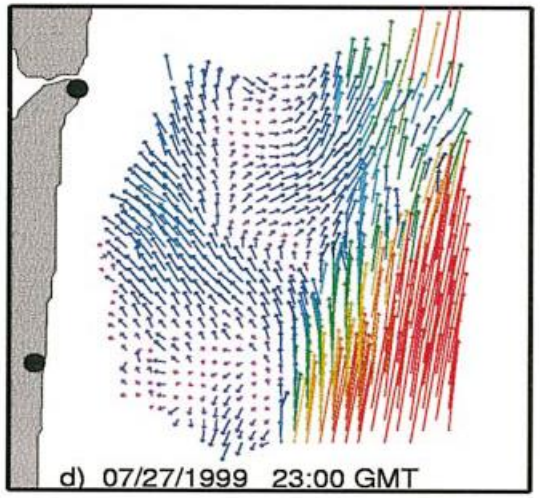
Upwelling and downwelling

Aggregation and Community Structure



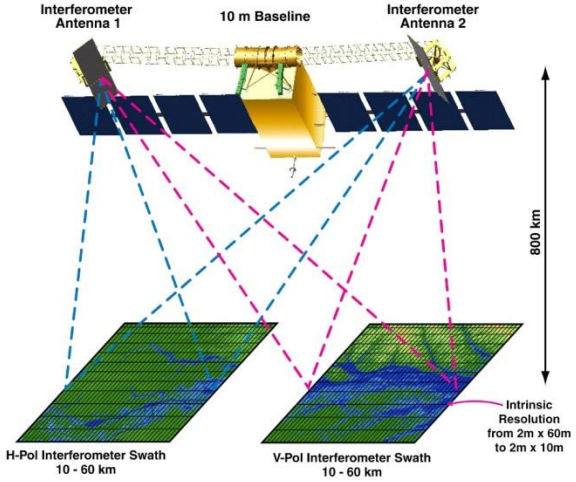
Phytoplankton (Lévy et al, 2012)
Zooplankton (Limouzy-Paris et al, 1997)
Birds (Tew Kai et al., 2009)
Cetaceans (Cotté et al., 2011)
"Great White Shark Café" (Thomas, 2022, pers. comm.)

Observing the Ocean Submesoscale



HF radar (Shay et al, 2003)

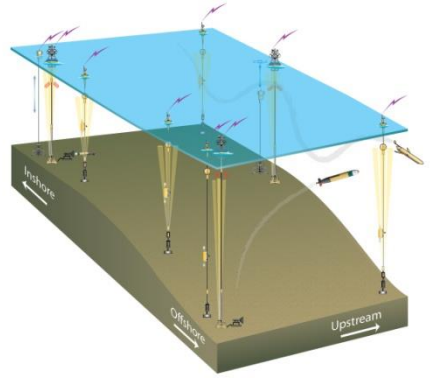
SAR (McWilliams et al, 2009)



SWOT (NASA, CNES, CSA, UKSA) (15 km)

Ocean gliders, AUVs & drifters

Aircraft (hyperspectral imagers, altimeters, lidar)



NSF OOI (endurance arrays)

(Challenging: short-lived small-scale)

$R_o \sim O(1)$
$L \sim 1km$
$U \sim 0.1\ ms^{-1}$

Challenges for Submesoscale Data Assimilation

- High resolution models
- Nested grids
- Complex non-linear circulations
- Inhomogeneous, anisotropic, flow dependent covariances
- Submesoscale time scales similar to IG waves (initialization?)
- Balance relations (SG, SQG?)

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- **Nested grids**
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Nested Data Assimilation

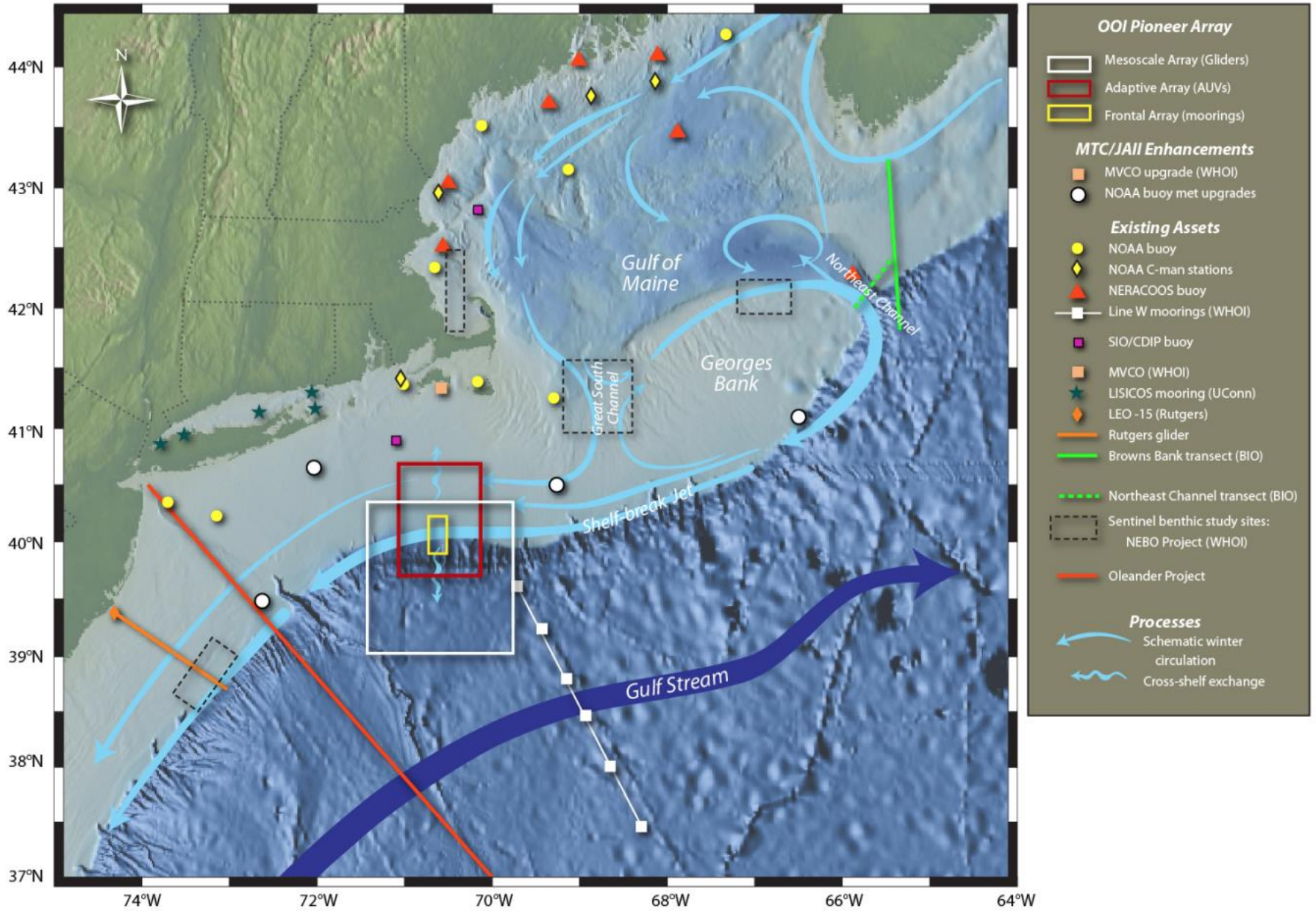
Data Assimilation in Nested Models

- Quite a long history in NWP:
  - nudging (e.g. Stauffer and Seaman,1994)
  - EnKF (e.g. Oigawa et al, 2018)
  - 3D-Var (e.g. Xiao et al, 2005)
  - 4D-Var (e.g. Huva et al, 2020)
  - WRF, COAMPS, ALADIN, HIRLAM, others…
- More recent in ocean applications:
  - EnKF (Vandebulke et al, 2006; Barth et al, 2007)
  - Var for tidal components (Logutov, 2008)
  - 4D-Var (Simon et al, 2011)

The Mid-Atlantic Bight & Gulf of Maine Circulation

Primary circulation features and major in situ observing systems.

A complex circulation comprising a western boundary current, and its interactions with a network of return flows on the continental shelf.



ROMS Triply Nested Configuration

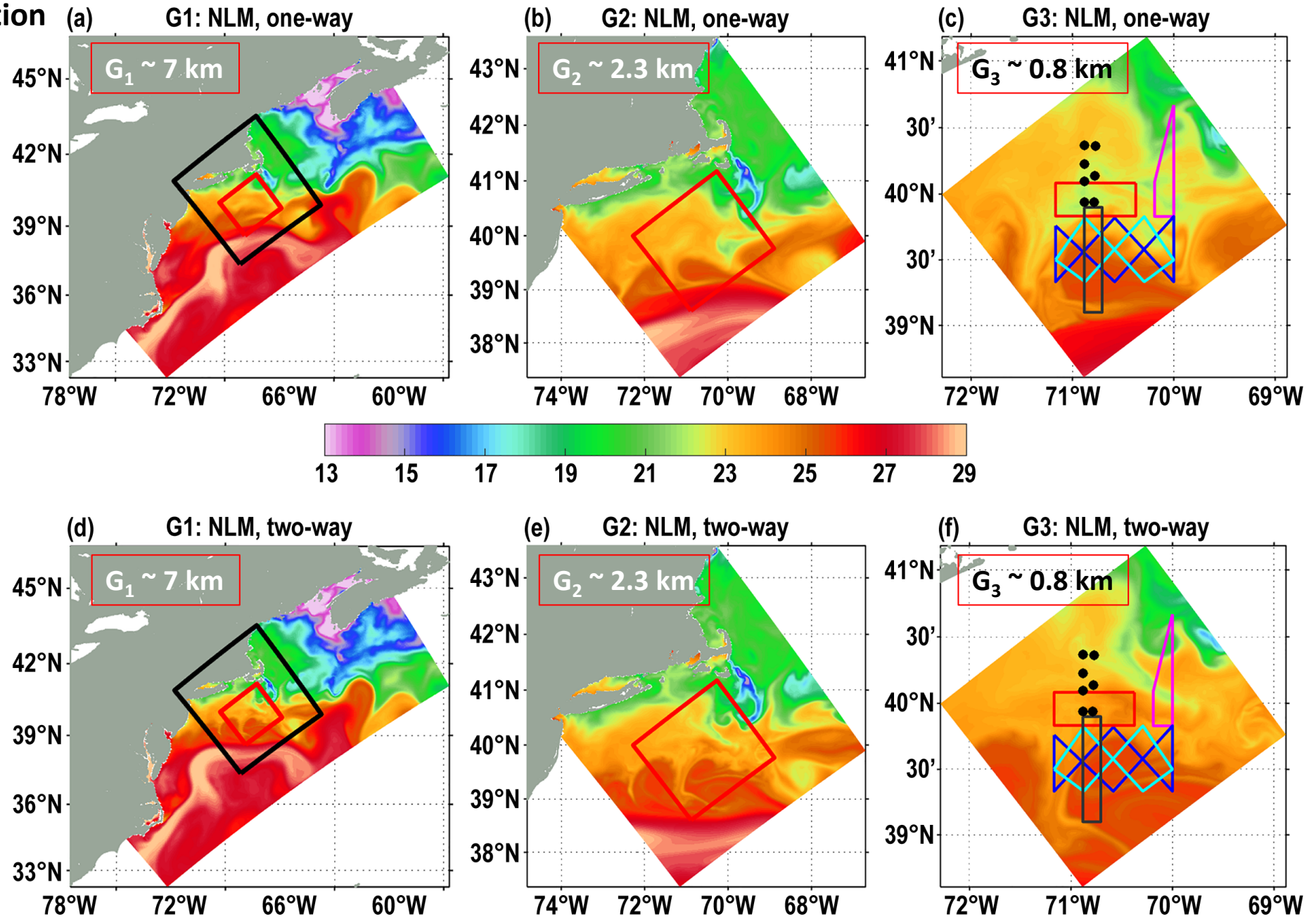
Forward Model SST (no DA)

25 July 2015

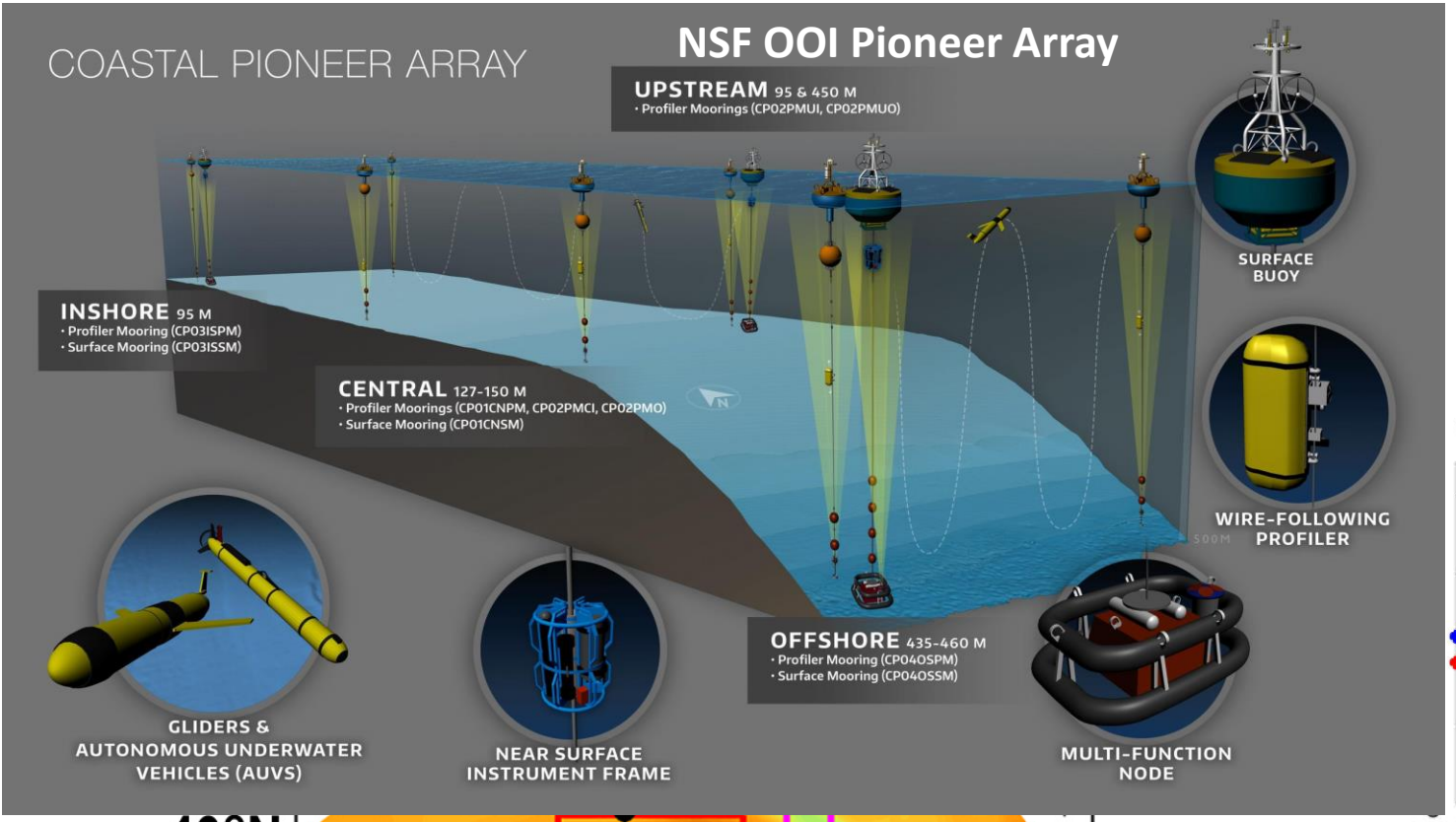
Model circulation spans the western boundary current (i.e. Gulf Stream), the energetic mesoscale eddy environment, and the complex submesoscale circulation

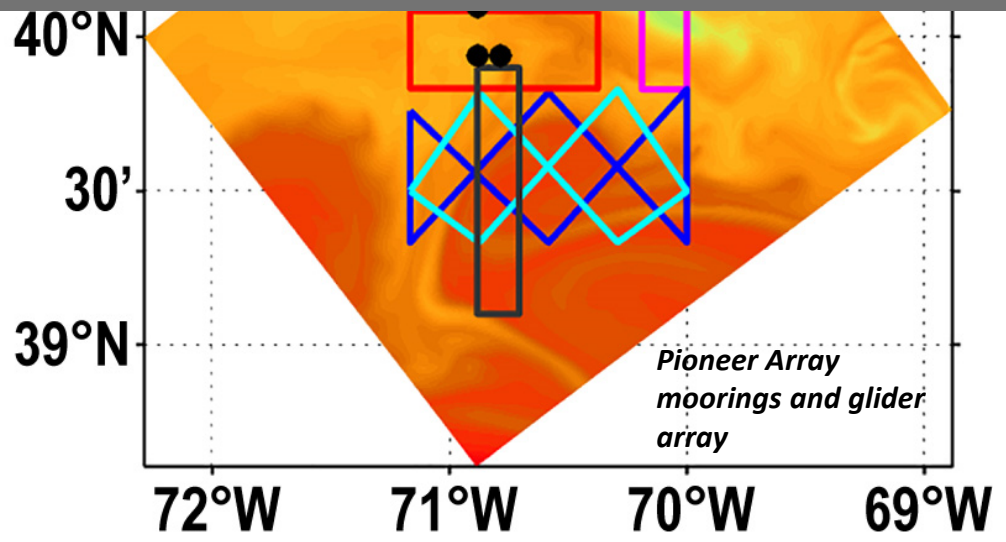
Period considered:
26 April – 3 August 2015

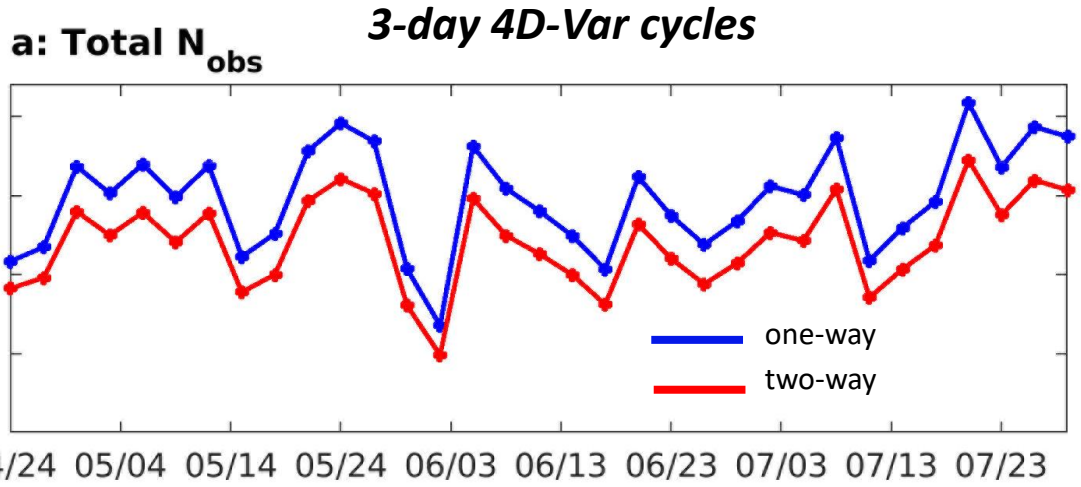
Model includes:
- tides
- rivers



Observations







Obs: SST (AVHRR, GOES, TRMM, AMSR2, WindSat)
SSH (Jason, AltiKa, CryoSat)
in situ T,S (NDBC buoys, Argo, XBT, drifters, gliders)
in situ u,v (moorings, HF radars)

one-way: obs in overlapping grid regions assimilated in each overlapping grid.

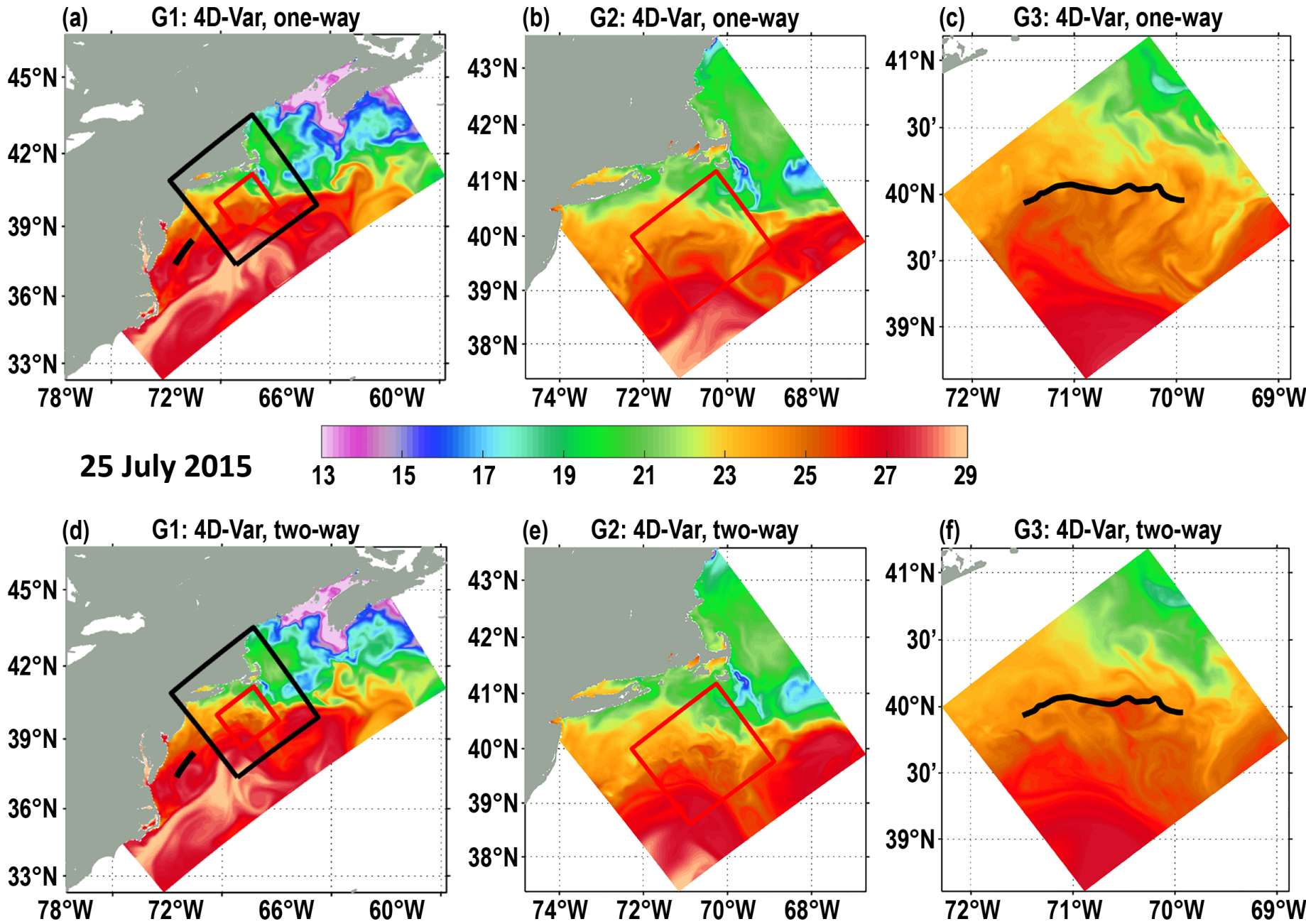
4D-Var SST Estimates

$$X_a = X_b + BH^T(HBH^T + R)^{-1}d$$

4D-Var DA
RBCG Lanczos
2 outer-loops
7 inner-loops
Background QC
***B* – diffusion operator**
***R* – diagonal**

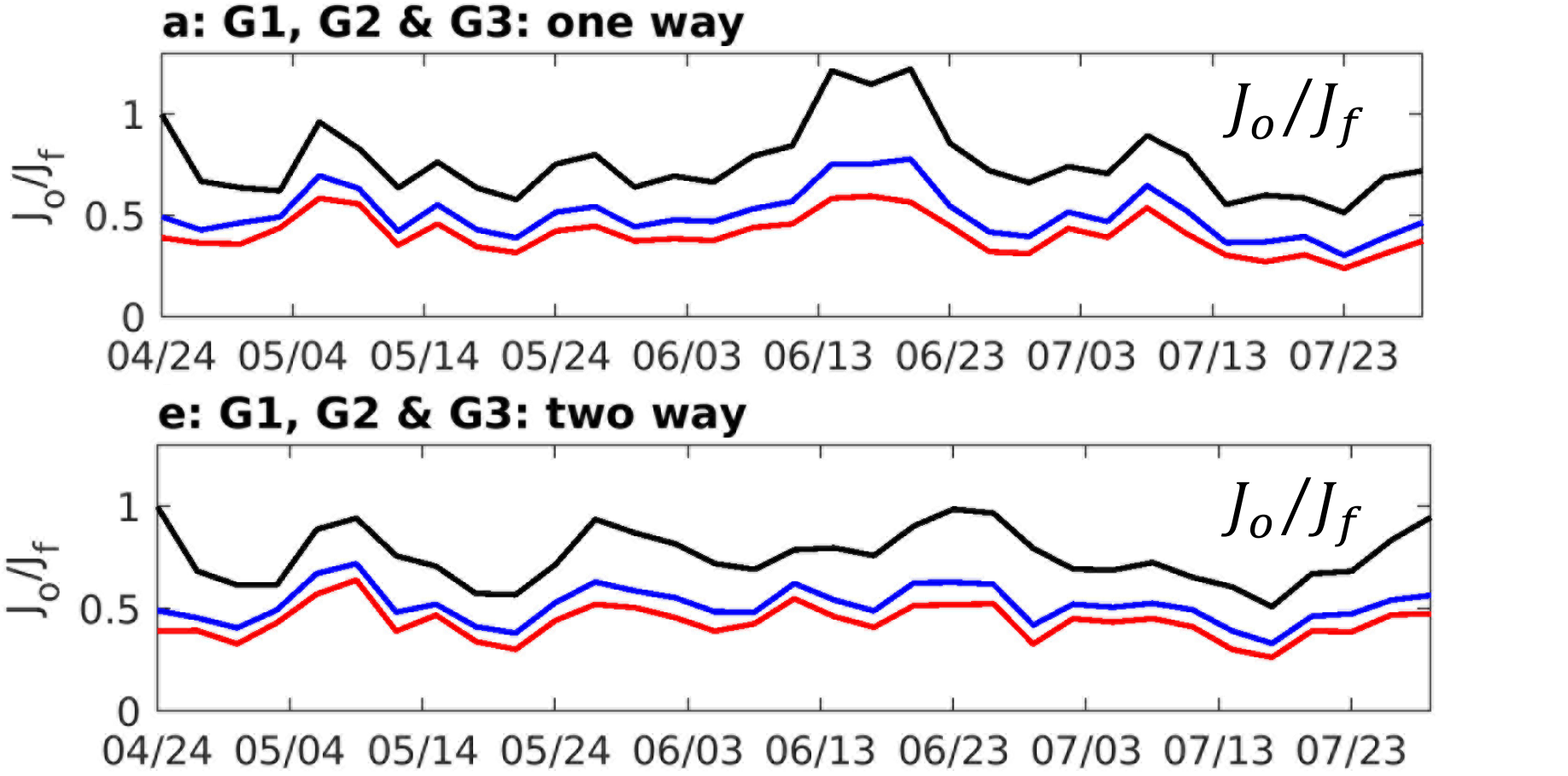
$$B = \begin{pmatrix} B_1 & 0 & 0 \\ 0 & B_2 & 0 \\ 0 & 0 & B_3 \end{pmatrix}$$

$$\mathrm{R} = \begin{pmatrix} R_1 & 0 & 0 \\ 0 & R_2 & 0 \\ 0 & 0 & R_3 \end{pmatrix}$$



RMS SST (2way-1way): 4DVar (free run) 0.9°C (0.8°C) 0.9°C (1.1°C) 0.9°C (1.4°C)

Model Fit to the Observations



background

outer-loop #1

outer-loop #2

Free run (no DA): $J_f = \left(\boldsymbol{y} - H(\boldsymbol{X}_f)\right)^T \boldsymbol{R}^{-1} \left(\boldsymbol{y} - H(\boldsymbol{X}_f)\right)$

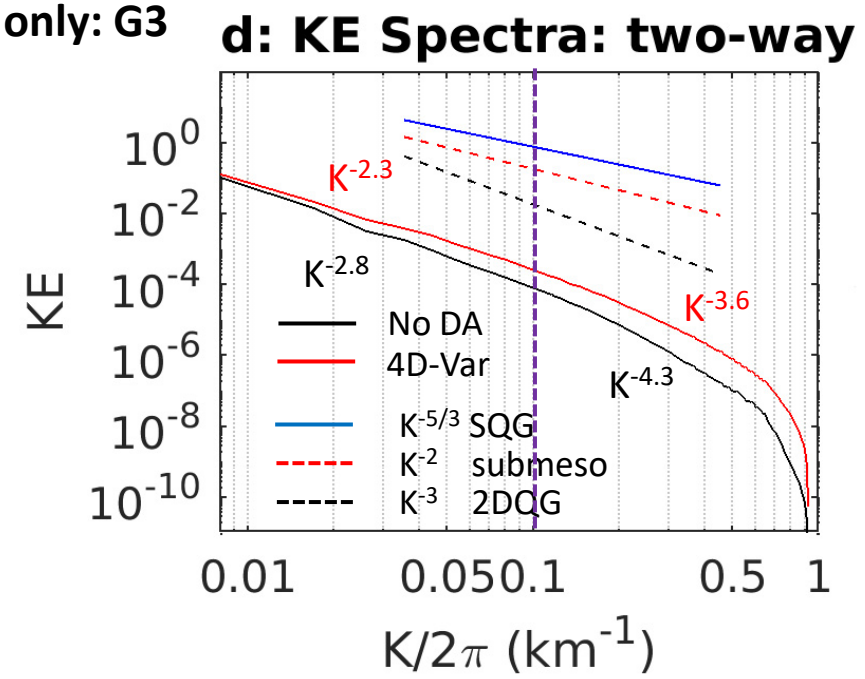
4D-Var: $J_o = \left(\boldsymbol{y} - H(\boldsymbol{X})\right)^T \boldsymbol{R}^{-1} \left(\boldsymbol{y} - H(\boldsymbol{X})\right)$

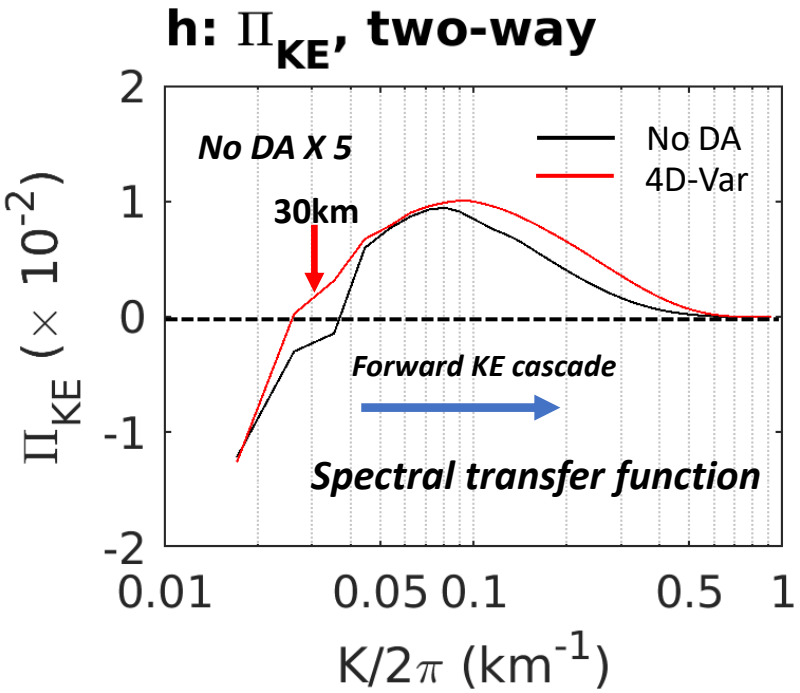
In general J_o/J_f<1

Energy Cascades
&
Predictability

Surface only: G3

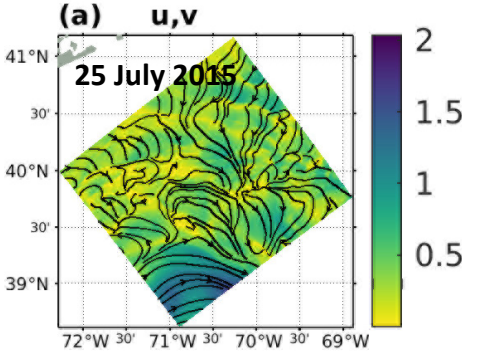
G3

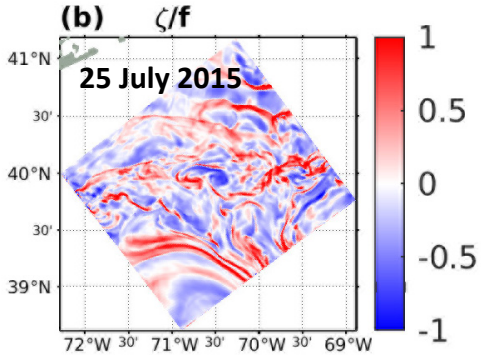


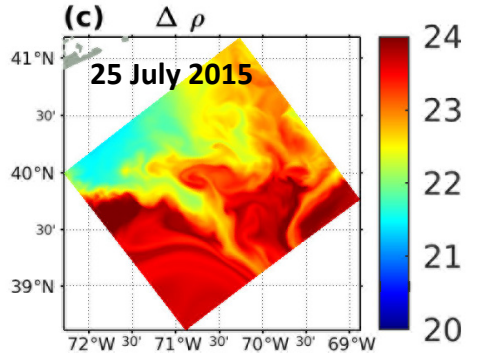


- **Data assimilation *energizes* the circulation at *all* scales**

- **Energy cascades to *smaller* scales at scales < ~ 30 km**
- **The cascade is not interrupted by data assimilation**
- **Contradicts the claims of Sandery & Sakov (2017)**







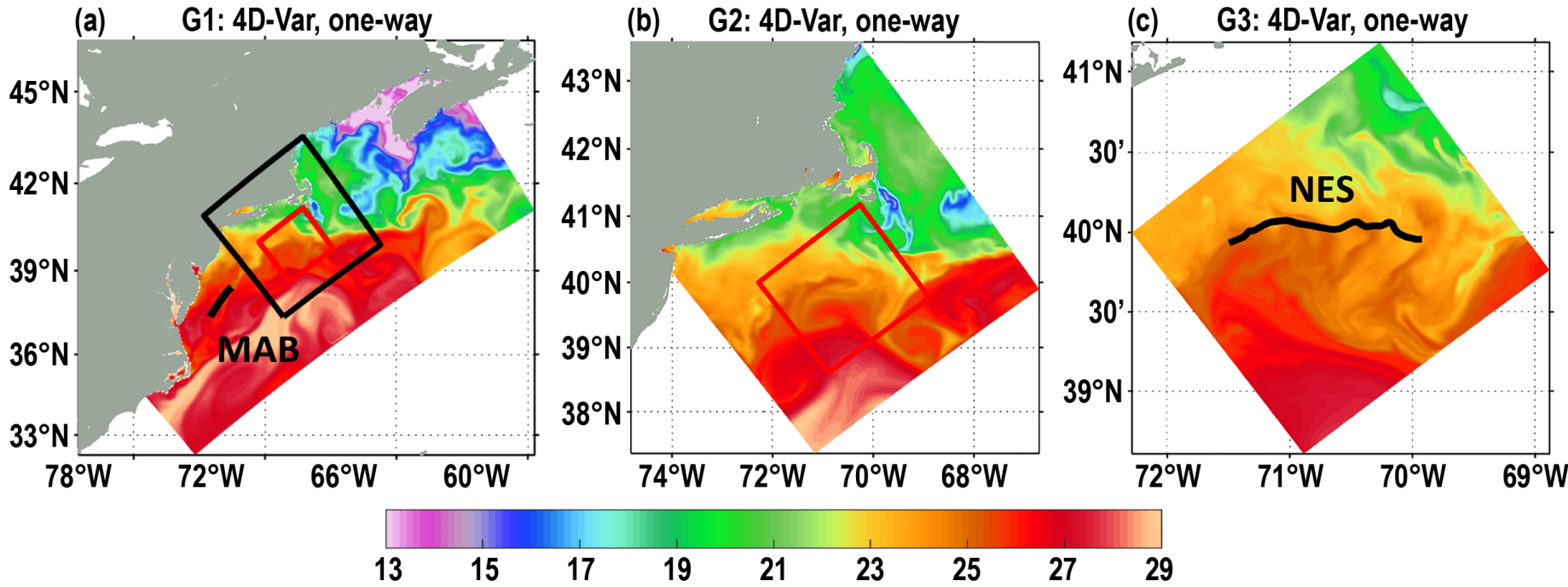
$$\Pi_{KE}(K) = -\int_{K}^{K_{max}} \hat{u}\left(u\widehat{\partial u/\partial x} + v\widehat{\partial u/\partial y}\right) + \hat{v}\left(u\widehat{\partial v/\partial x} + v\widehat{\partial v/\partial y}\right)dK \qquad w \ll (u,v)$$

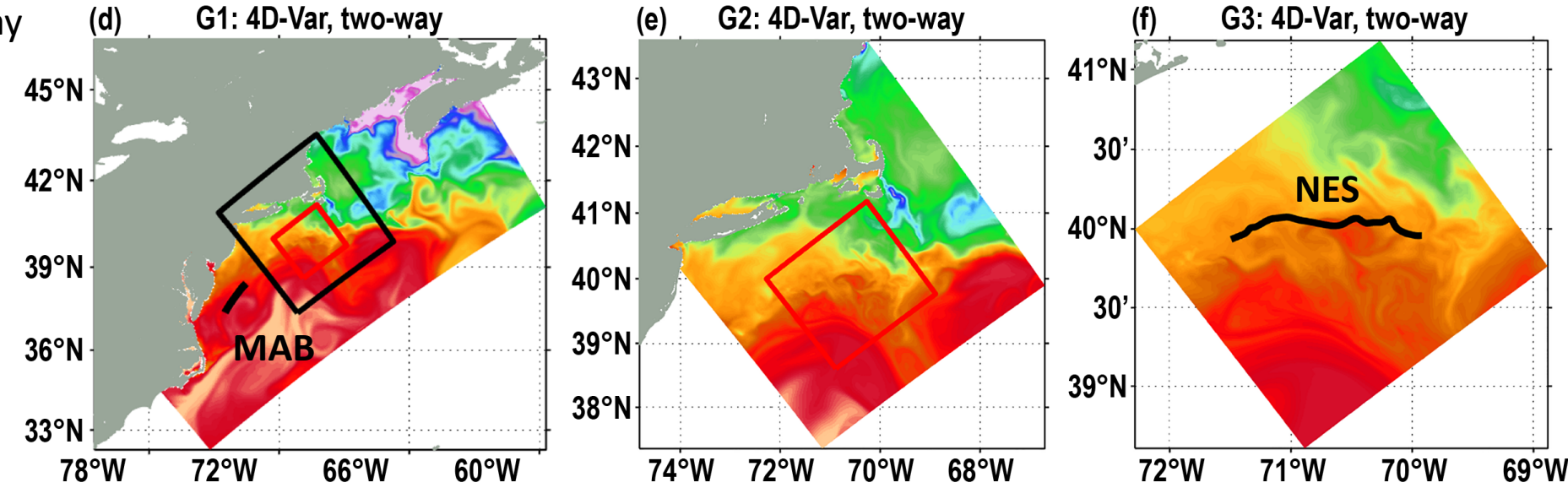
Downscaling & Upscaling

Downscaling & Upscaling

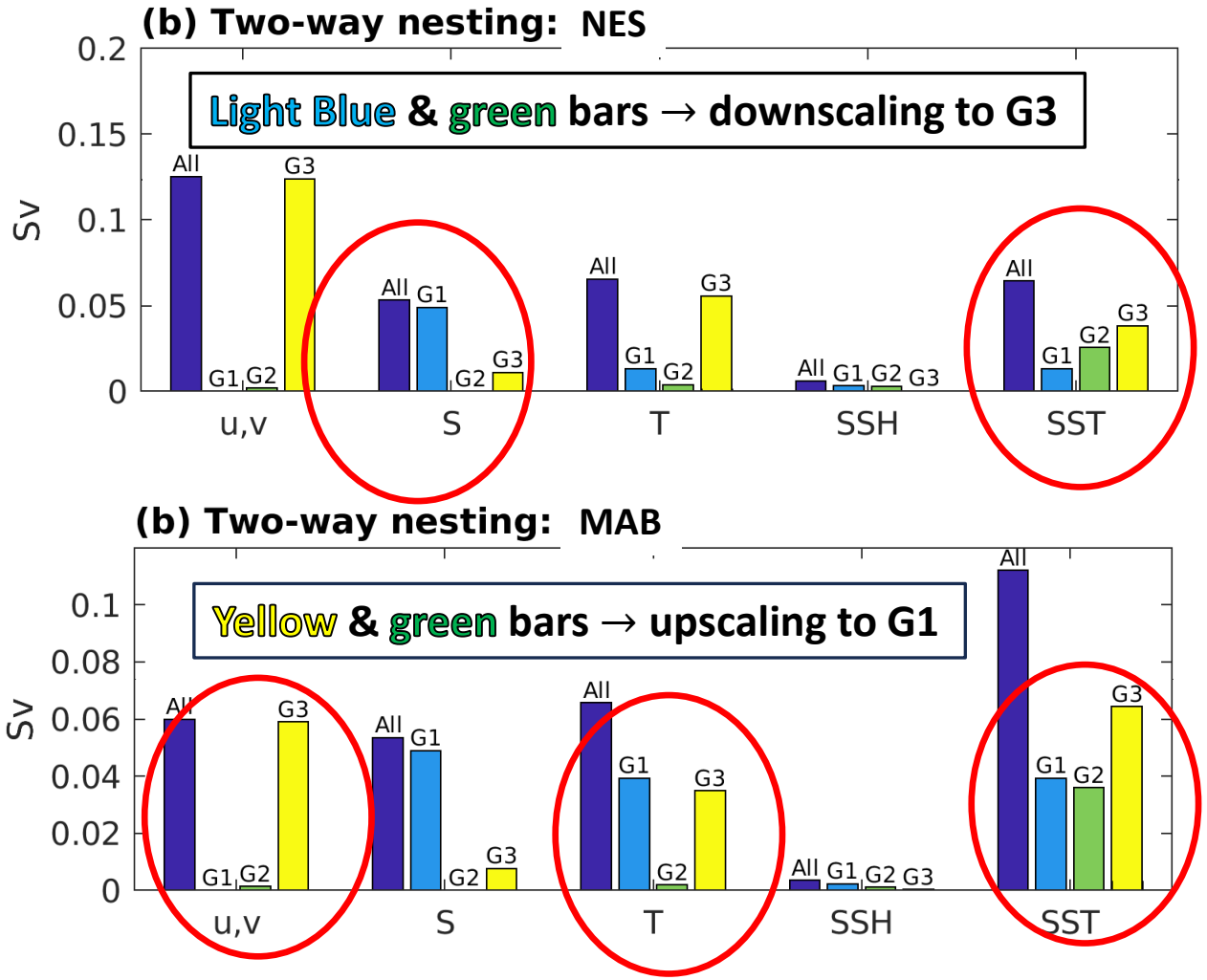
NES – prior site of Pioneer Array (2014-2022)

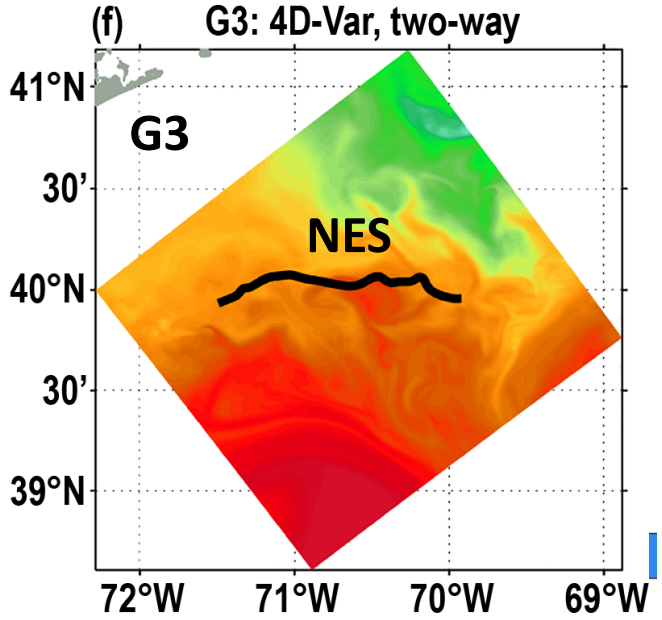
MAB – current site of Pioneer Array (2024-present)

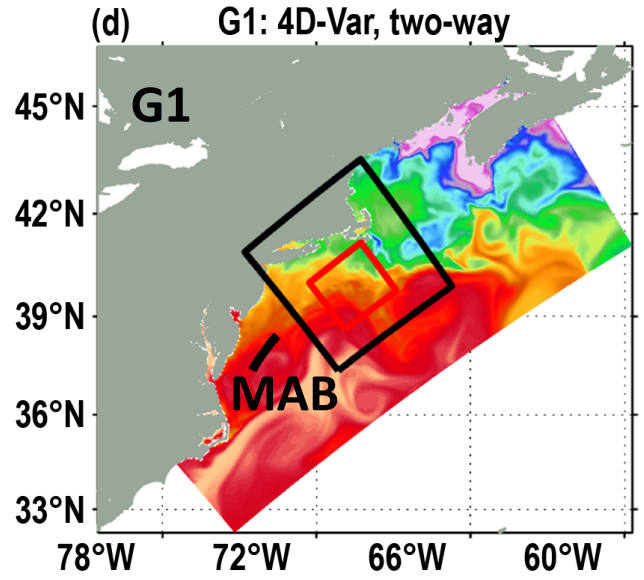




Observation Impacts on NES and MAB Cross-Shelf Transport







Summary & Conclusions

- **Nested 4D-Var is a useful tool and will soon be available in the ROMS community code release.**

- **All of the ROMS TL and AD tools apply seamlessly to the nested models:**
  - **FSOI**
  - **FSO**
  - **array modes**

- **Our results contradict previous arguments about the potential negative influence of submesoscale DA on the larger-scale circulation estimates. *In our case errors at the submesoscale will generally propagate to smaller scales and dissipate.***

- **Evidence of upscaling and downscaling of observational information.**