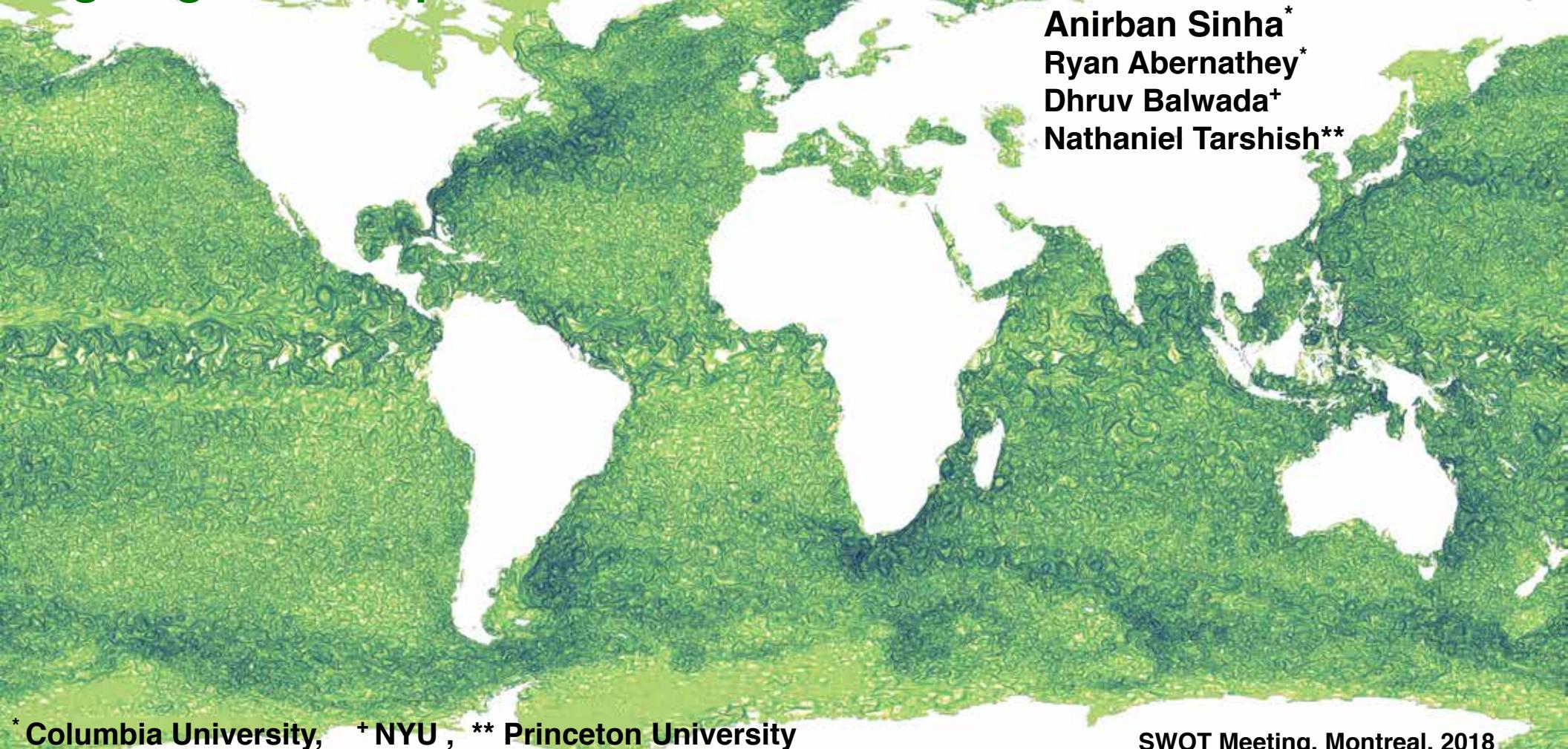


# Influence of Submesoscale Flows and Inertia-Gravity Waves on Lagrangian Transport Barriers

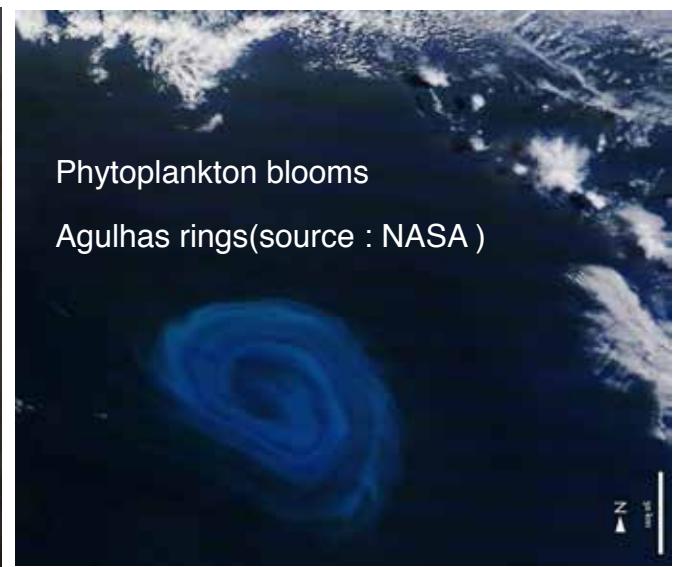
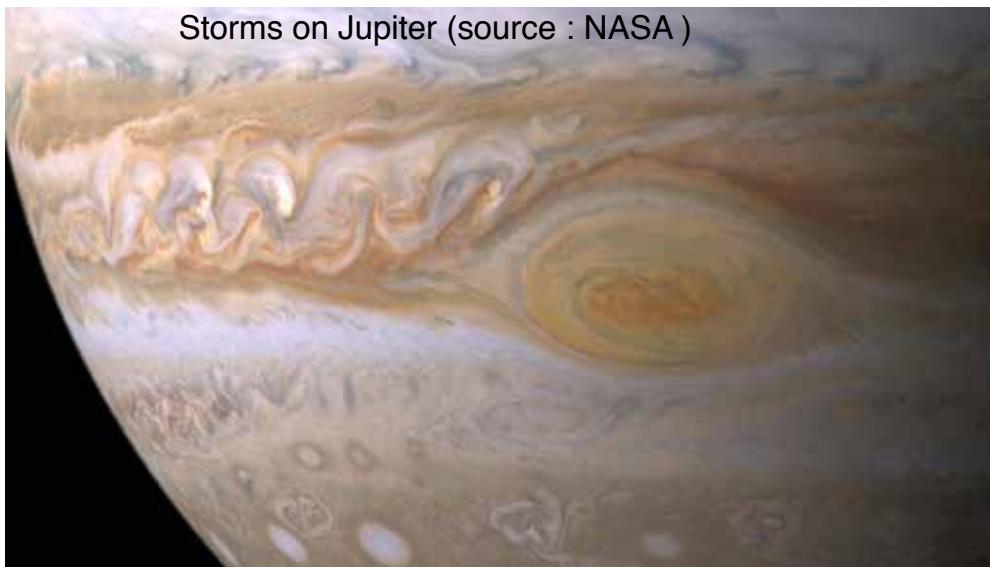
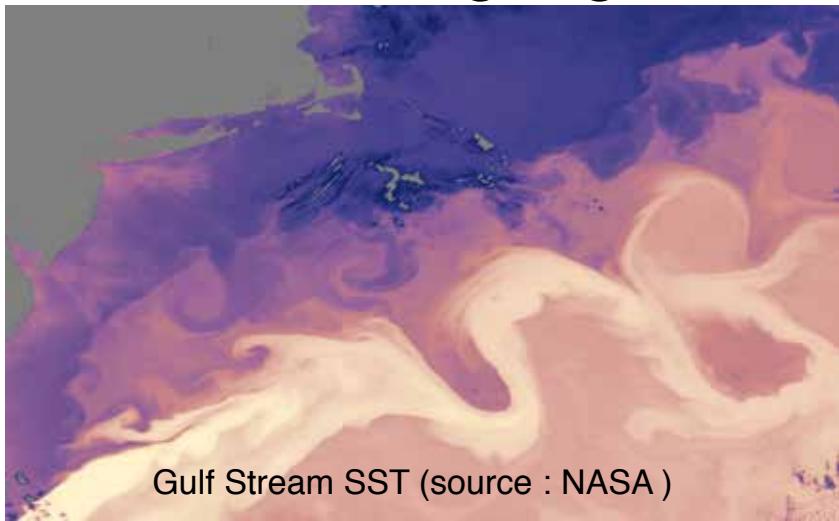


Anirban Sinha\*  
Ryan Abernathey\*  
Dhruv Balwada+  
Nathaniel Tarshish\*\*

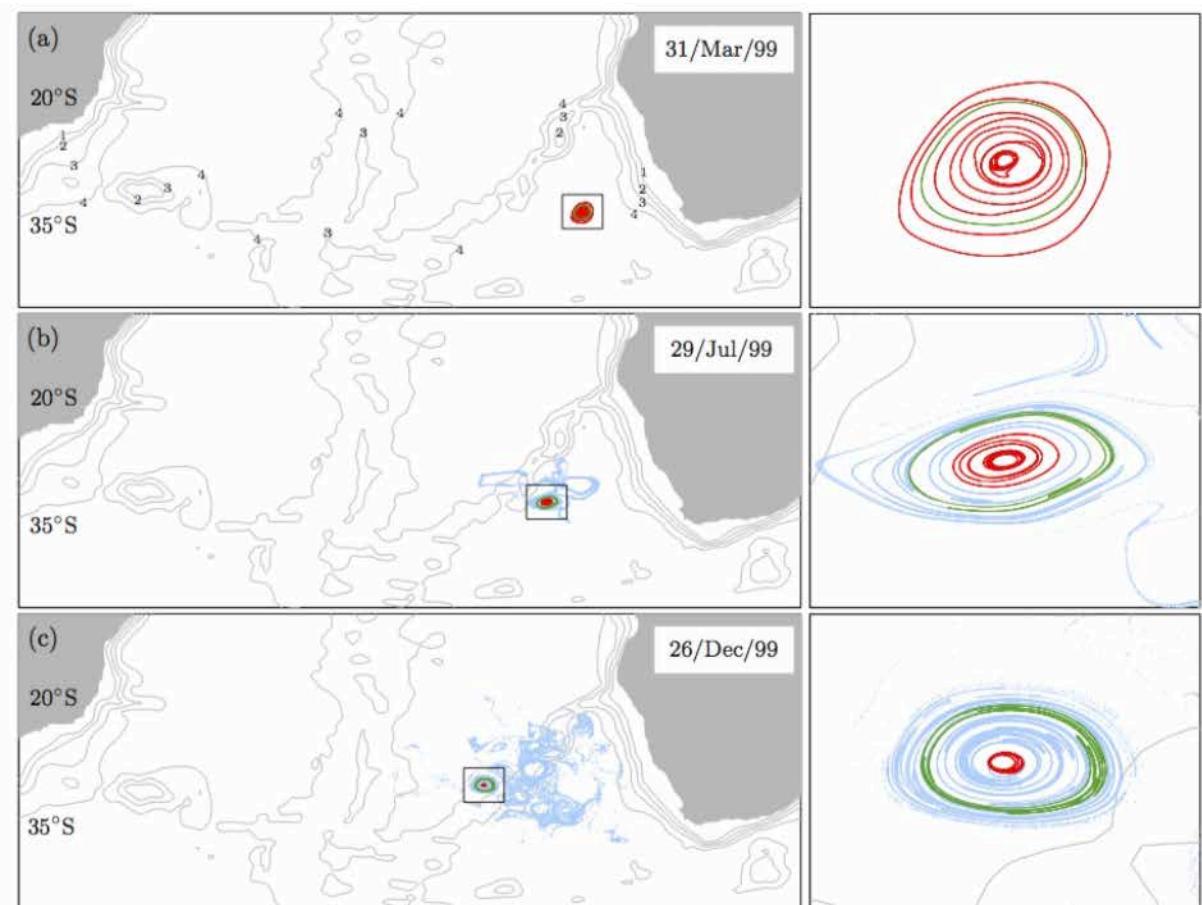
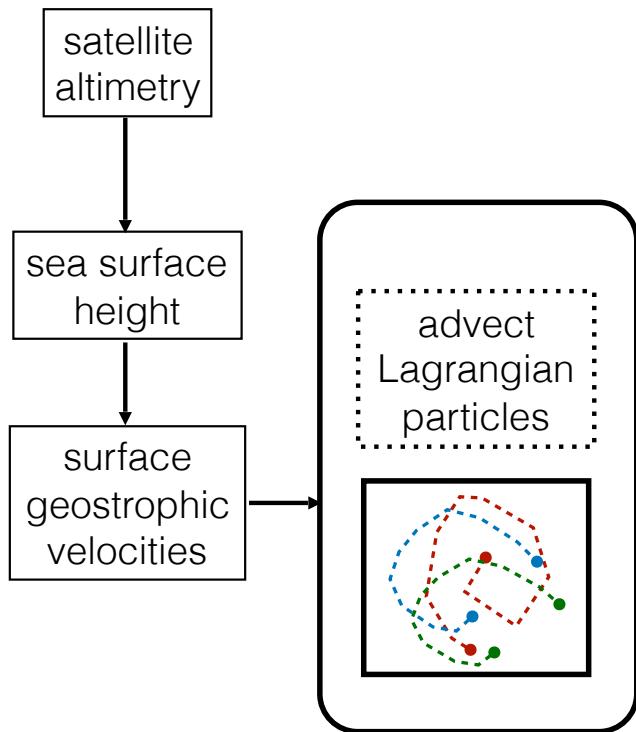
\* Columbia University, + NYU , \*\* Princeton University

SWOT Meeting, Montreal, 2018

## Lagrangian Coherent Structures



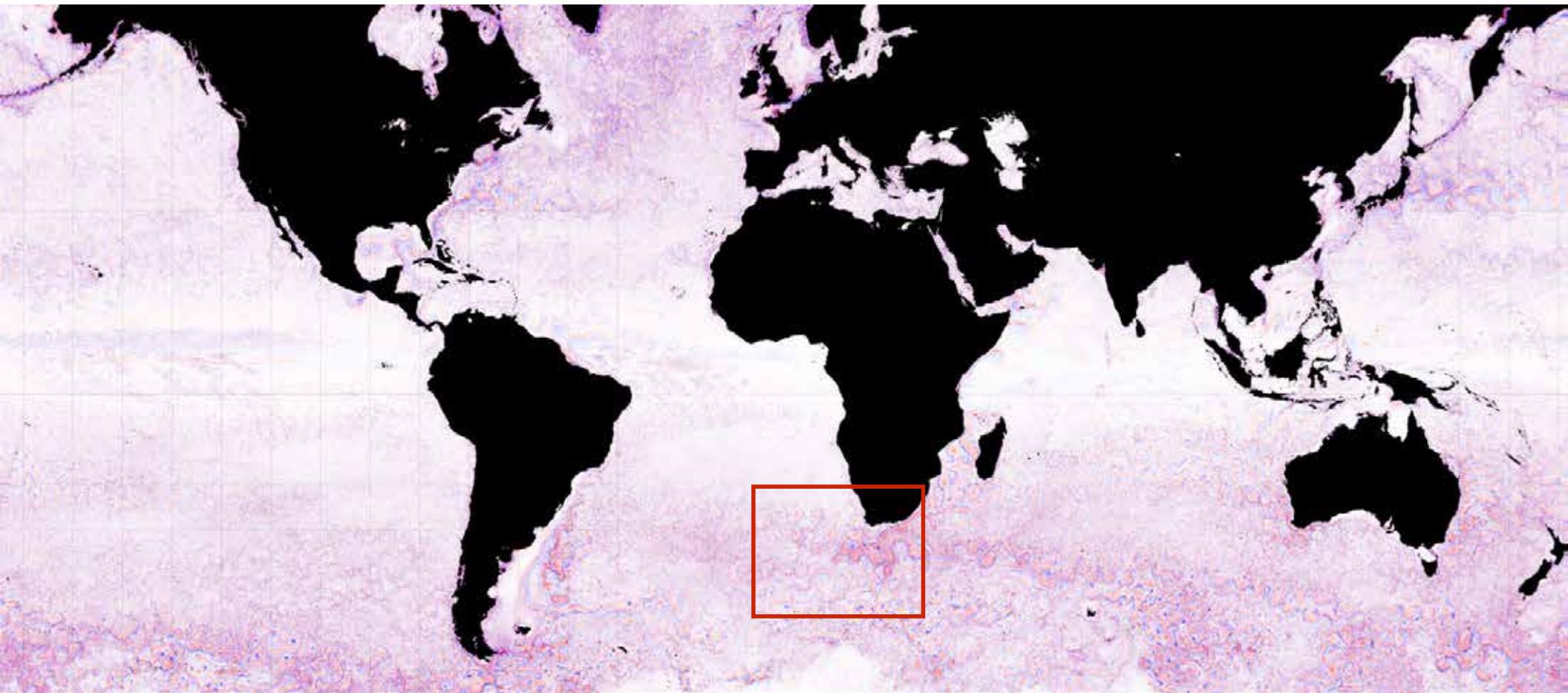
## Lagrangian coherence, Past Studies : Satellite Altimetry



*Wang et al., 2016 JGR*

# MITgcm LLC runs

llc\_4320 : global simulation on 1/48 ° lat-lon-cap grid, 90 vertical levels

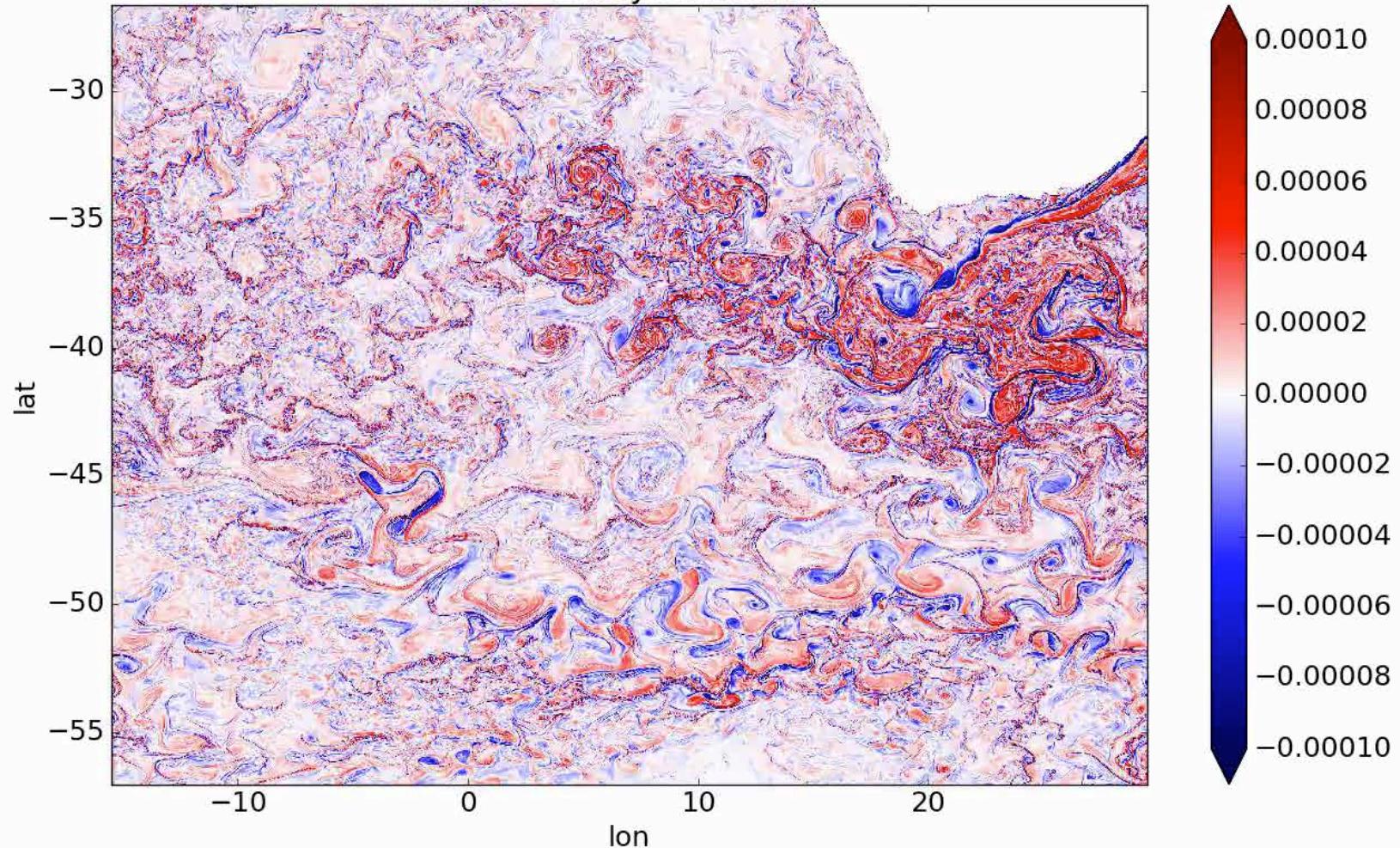


Agulhas region

hourly snapshots (1750 time steps (~ 73 days))

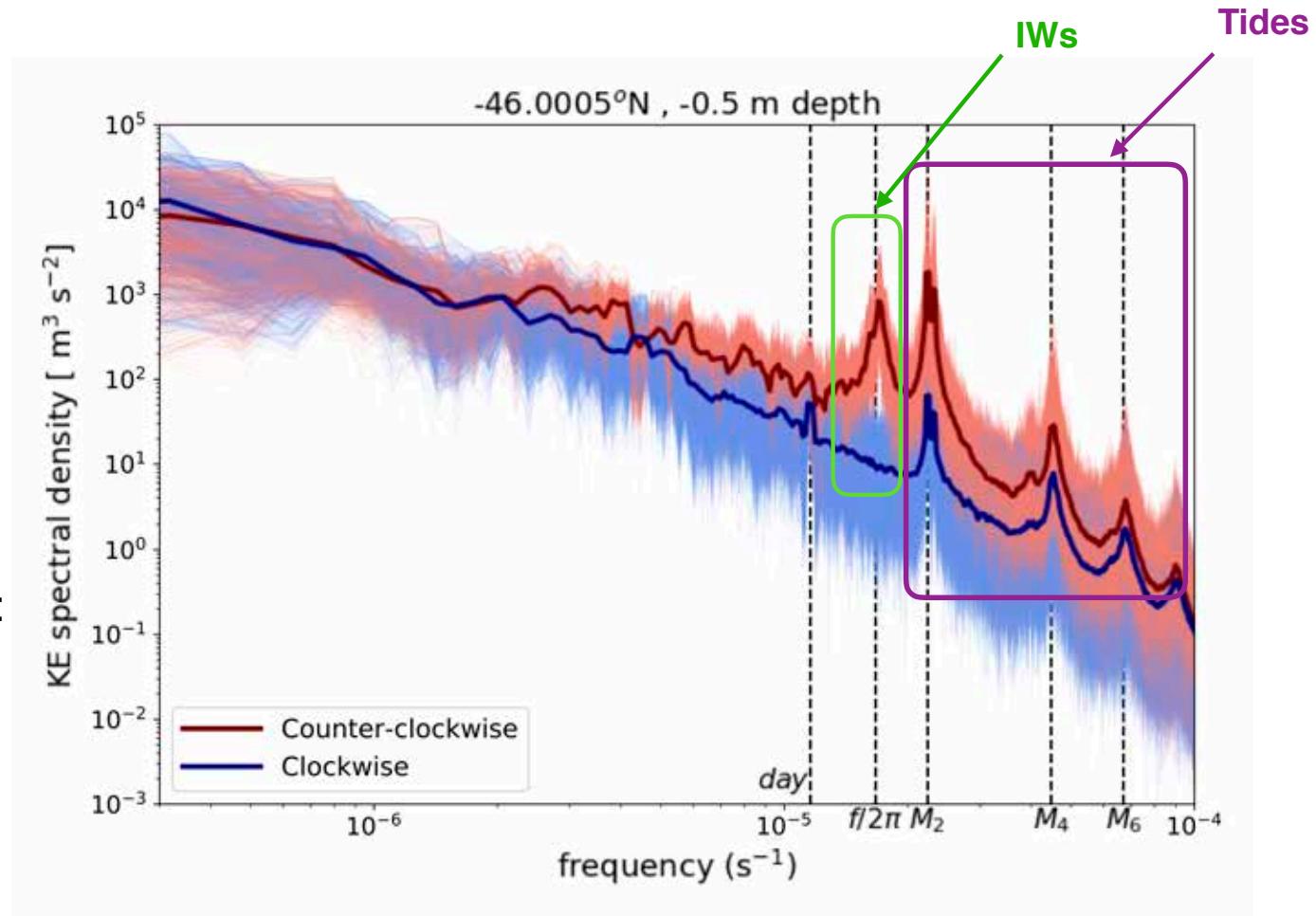
# Surface Vorticity in the Agulhas region

time = 3 days 00:00:00

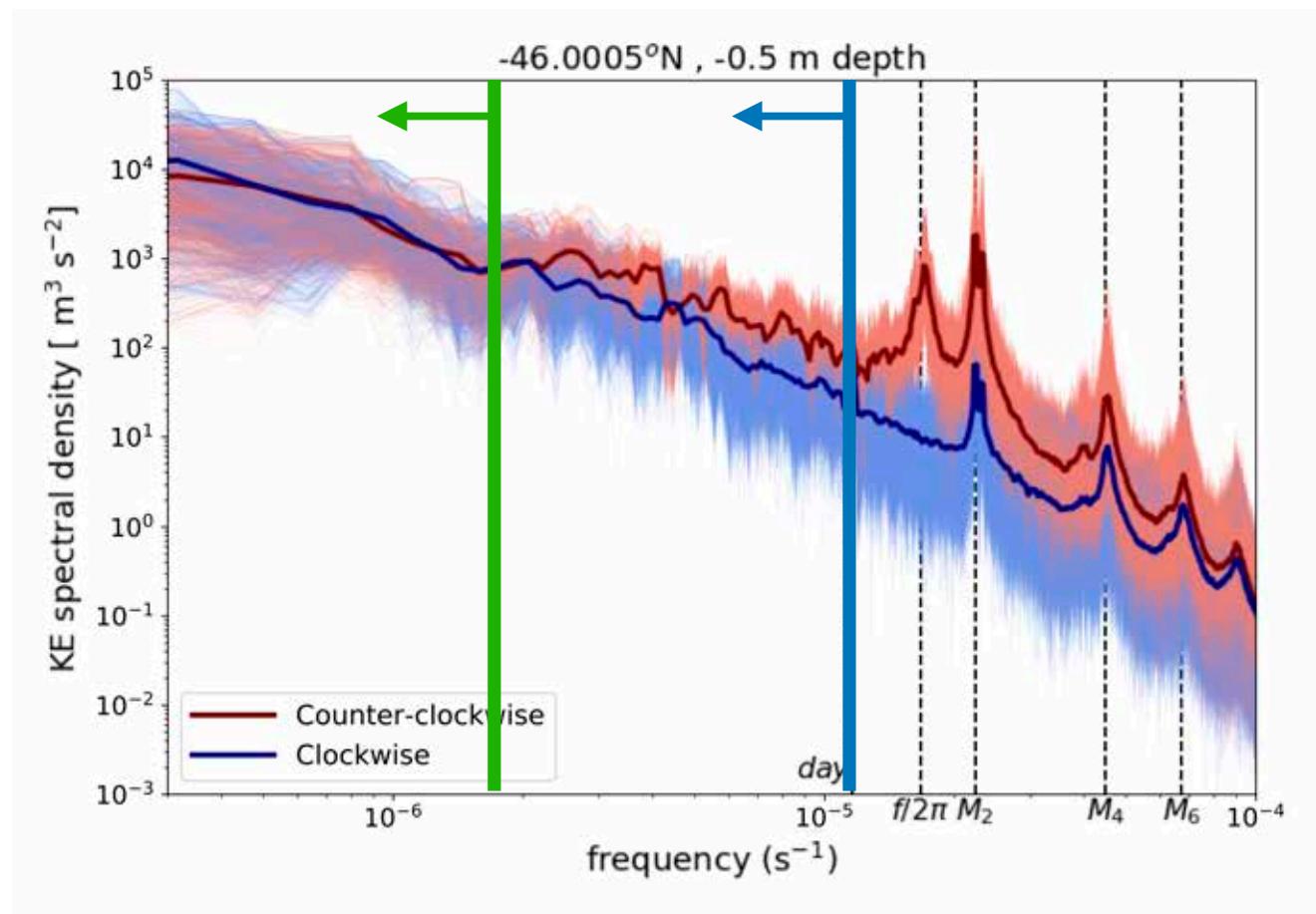
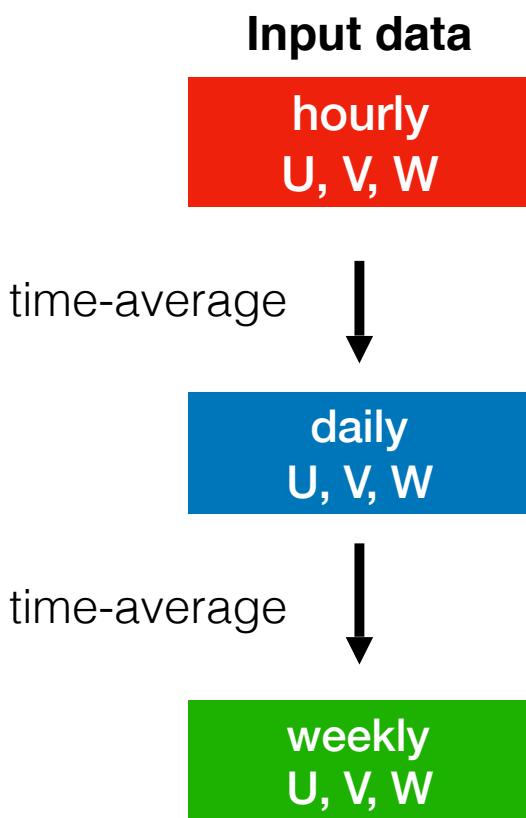


# Frequency Spectra (surface KE)

- What is the effect of **submesoscale flows, IGWs,tides** on Lagrangian coherence?
- How do small scale turbulent motions affect :
  - ◆ **material transport barriers**
  - ◆ **vertical subduction**
  - ◆ **lagrangian dispersion**



# Temporal Filter



# Wavenumber Spectra (surface KE)

**Input data**

hourly  
 $U, V, W$

time-average

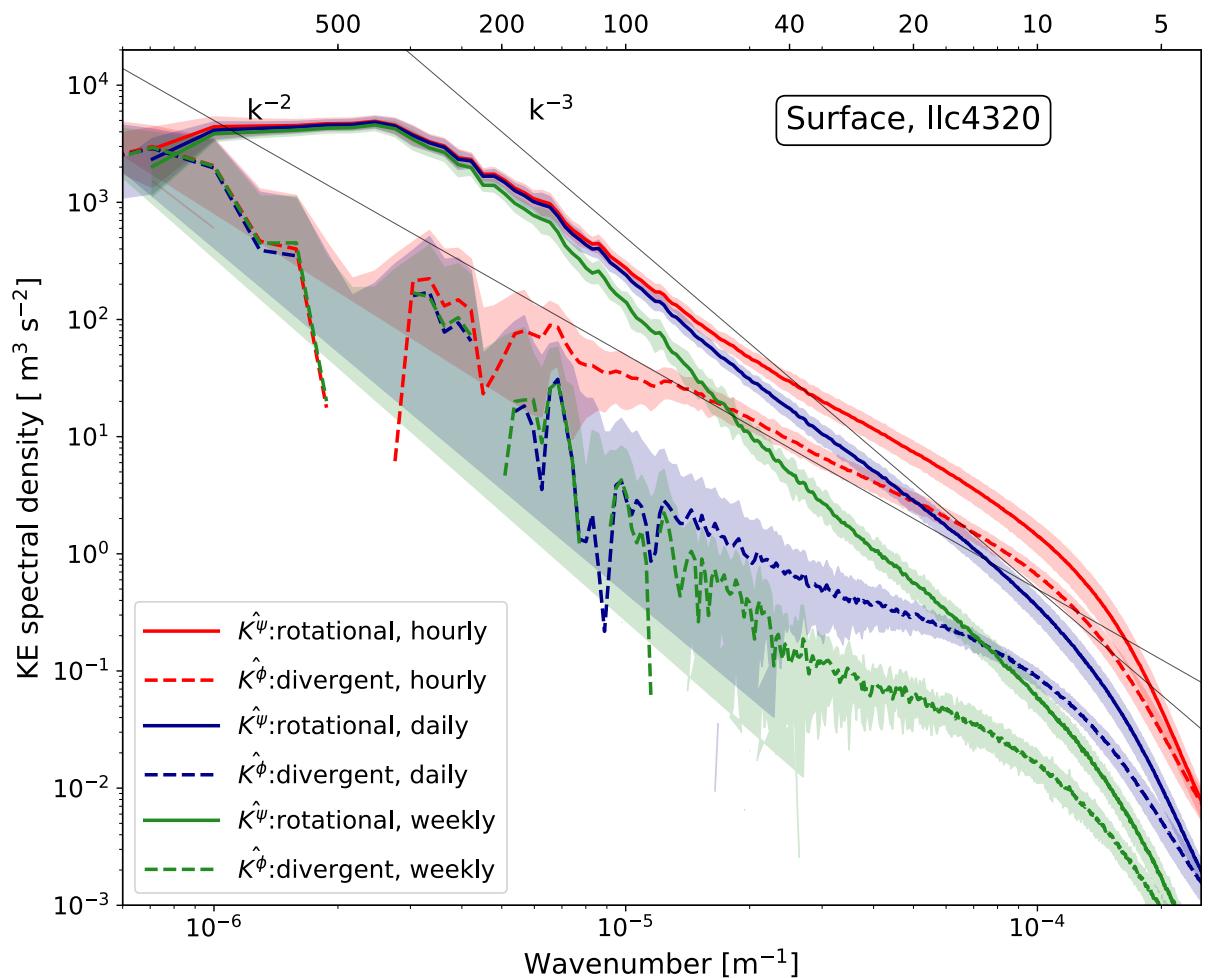
daily  
 $U, V, W$

time-average

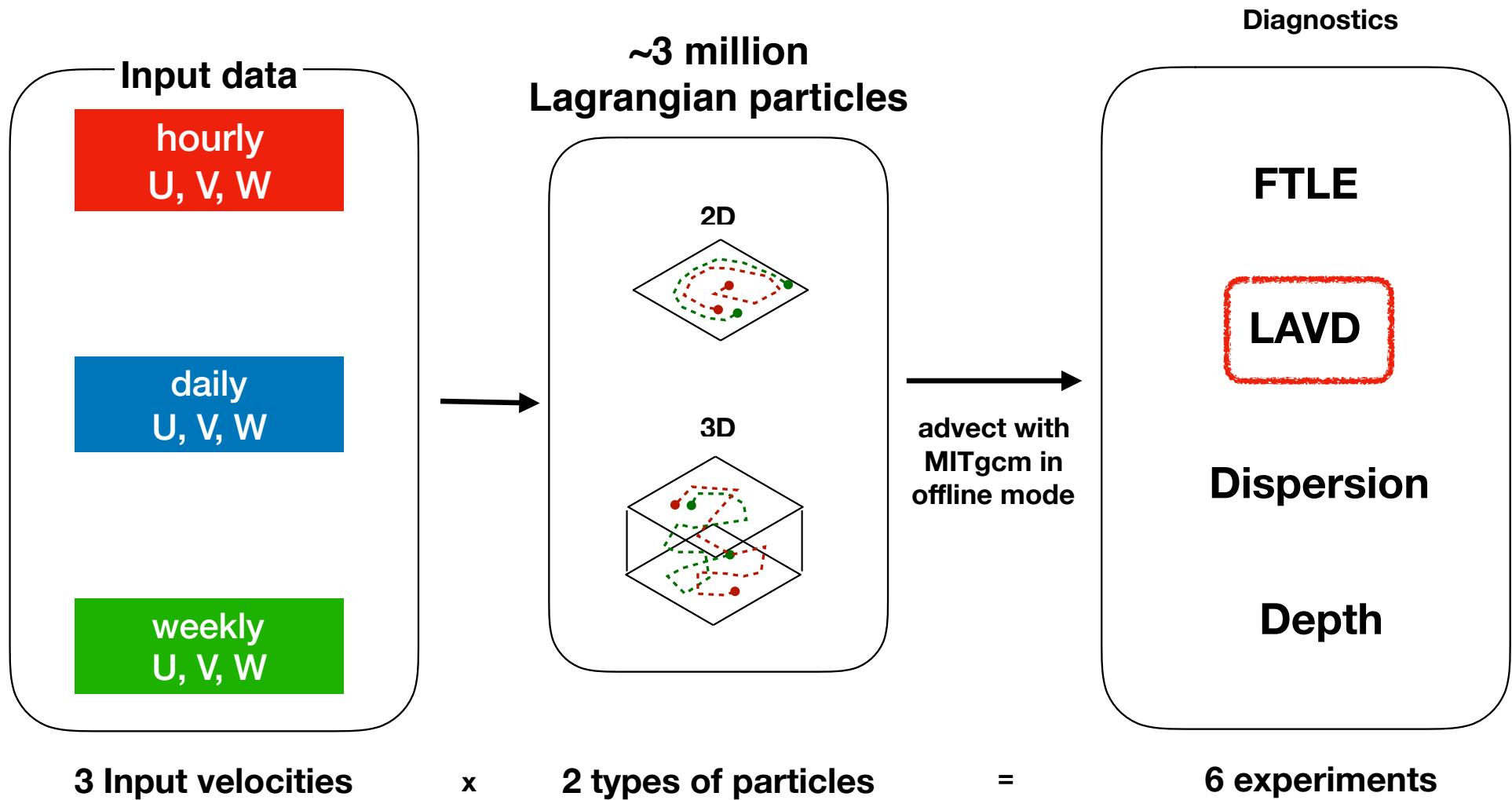
weekly  
 $U, V, W$



Helmholtz Decomposition: **rotational** and **divergent**  
(solid) (dashed)



# Experiments

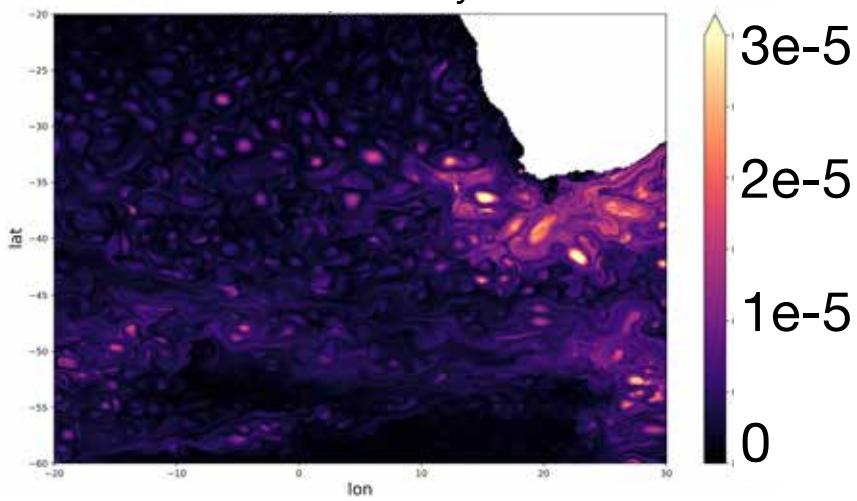


LAVD (Lagrangian averaged vorticity deviation)

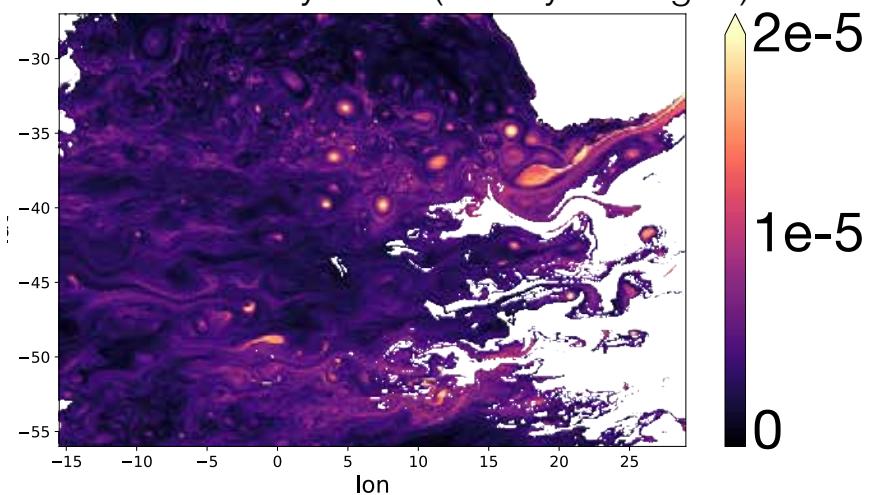
$$LAVD_{t_0}^t(x_0) := \int_{t_0}^t |\omega(x(s; x_0), s) - \bar{\omega}(s)| ds$$

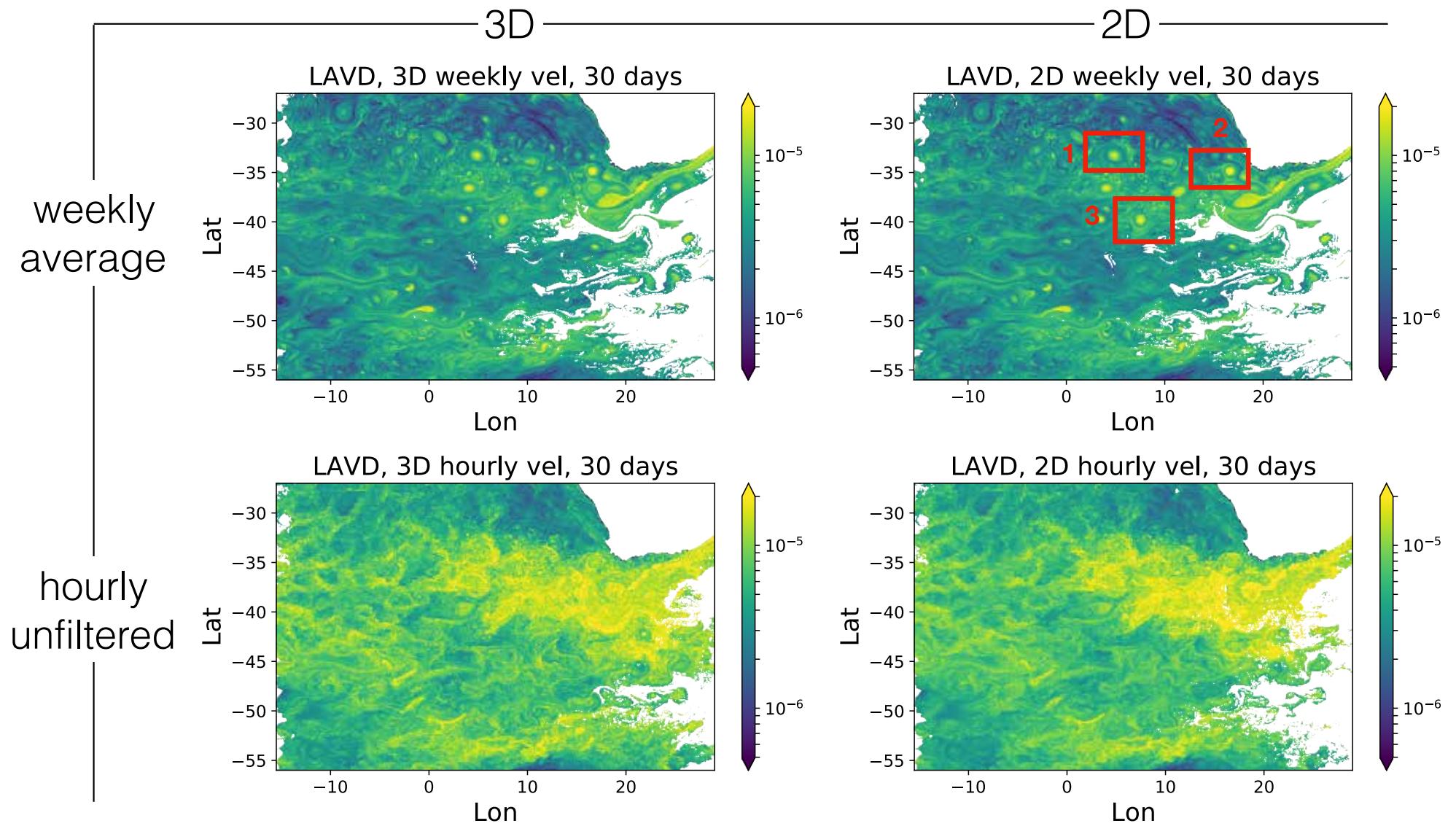
*Haller 2015 ARFM, Haller et al. 2016 JFM*

AVISO velocity fields



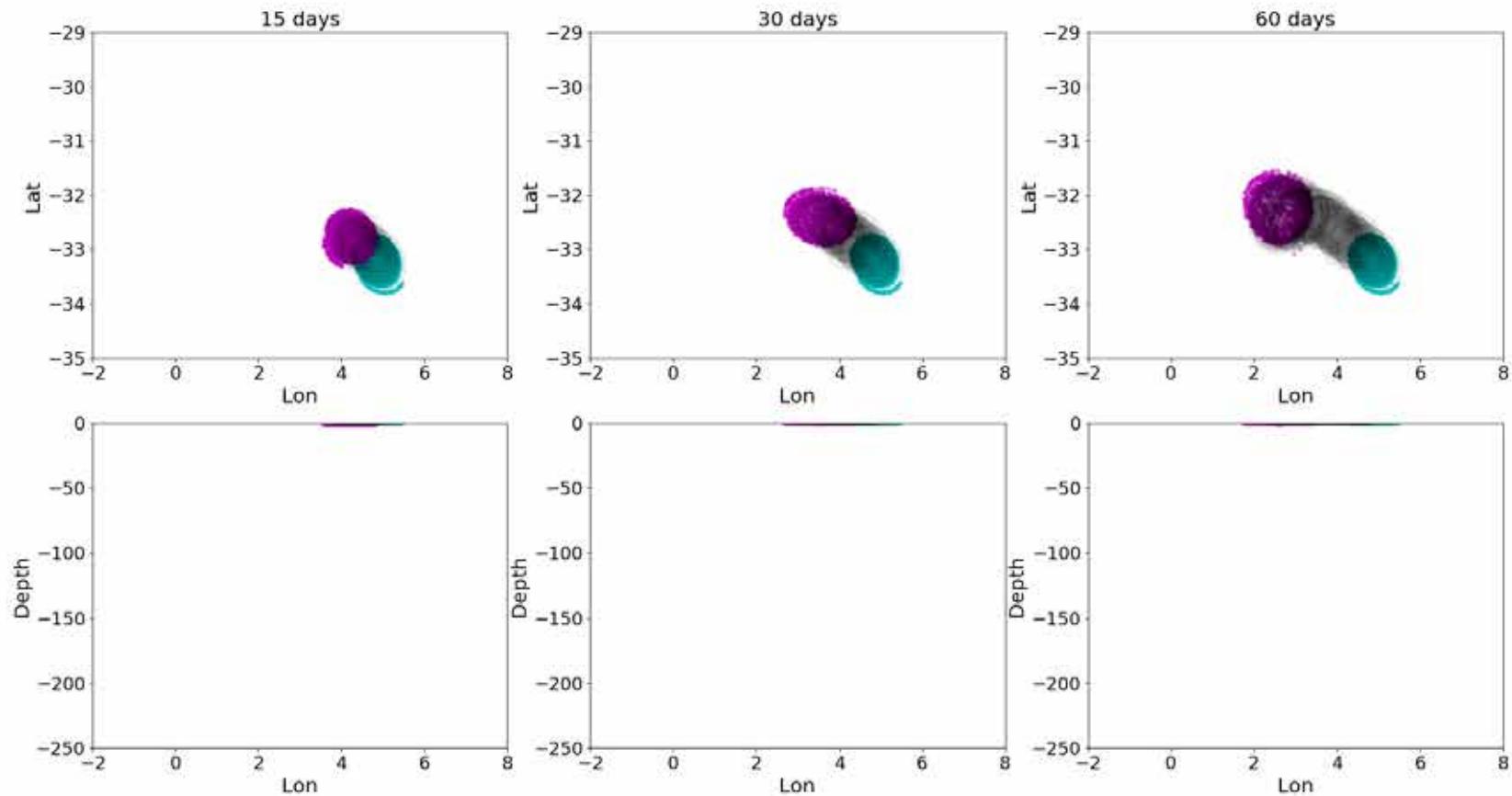
LLC velocity fields (weekly averaged)





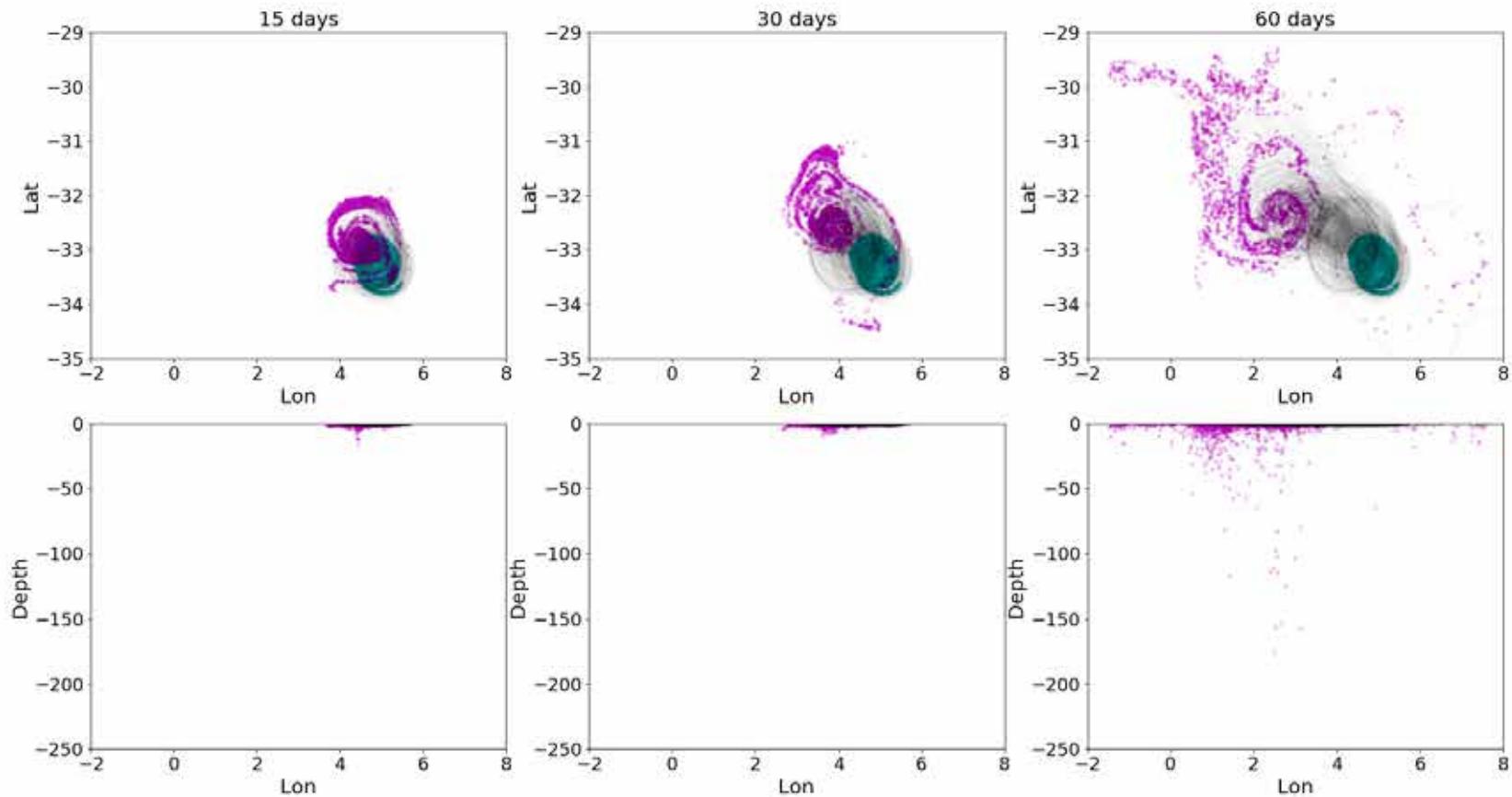
## Eddy I : An Area-preserving eddy

RCLV 1, 3D weekly



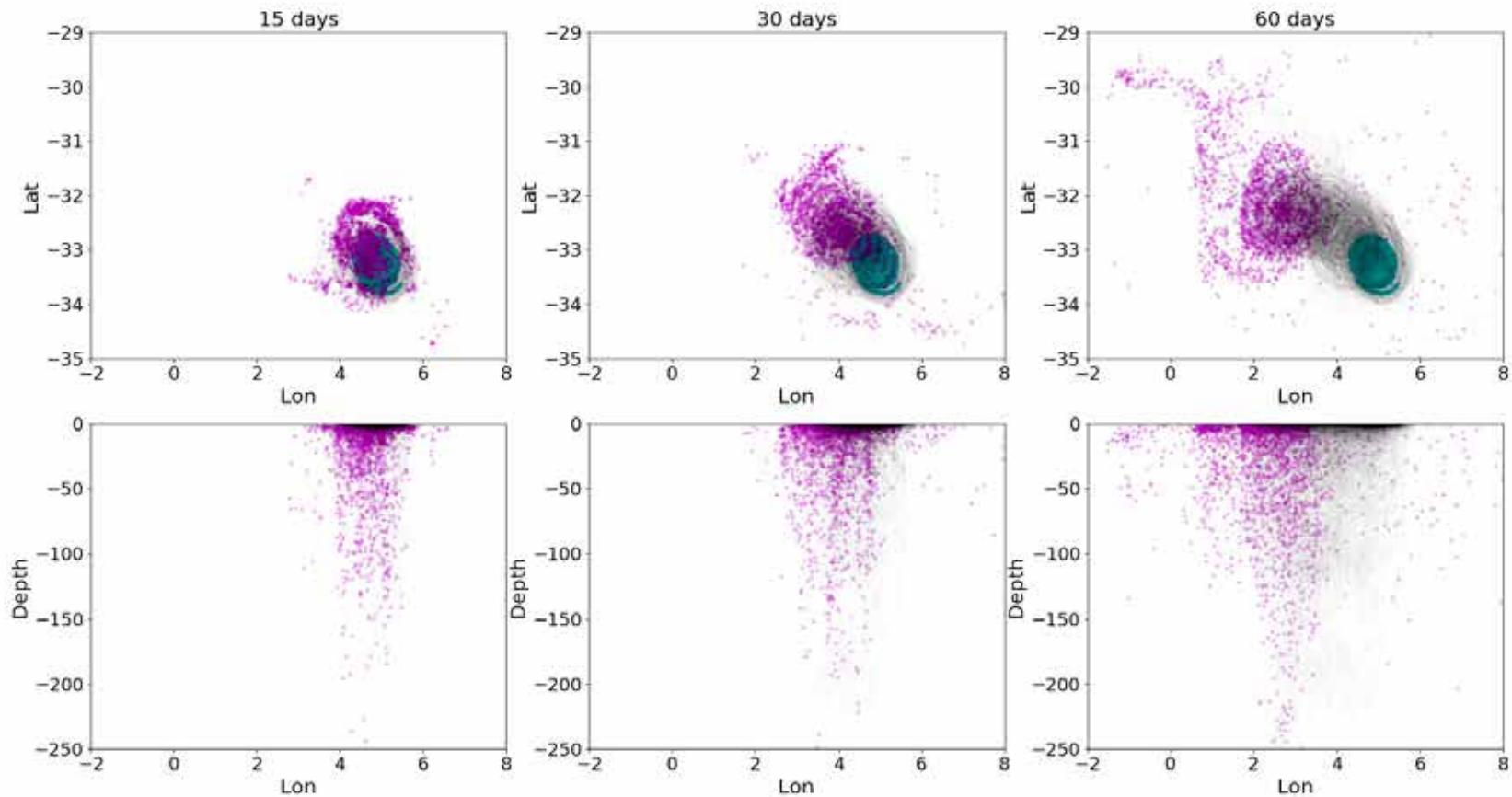
## Eddy I : An Area-preserving eddy

RCLV 1, 3D daily

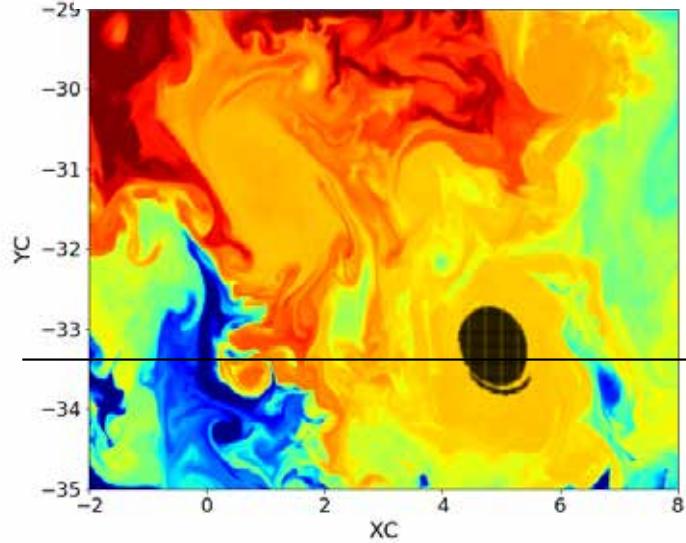


## Eddy I : An Area-preserving eddy

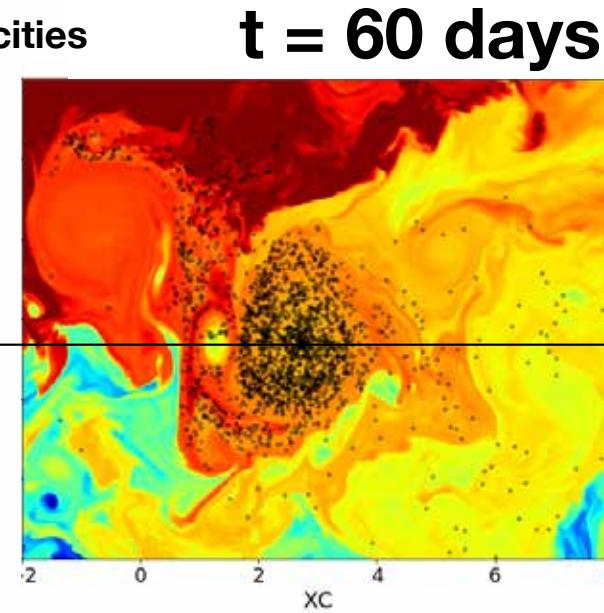
RCLV 1, 3D hourly



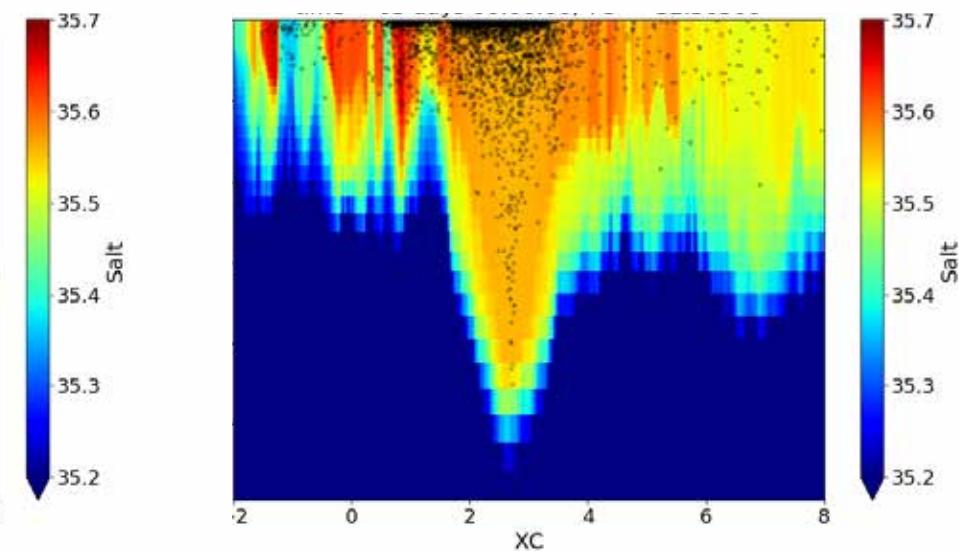
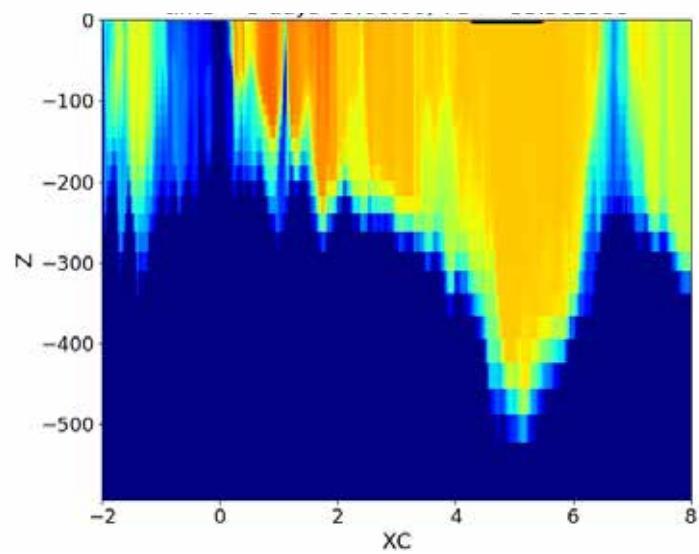
**$t = 0$**



**Hourly velocities**

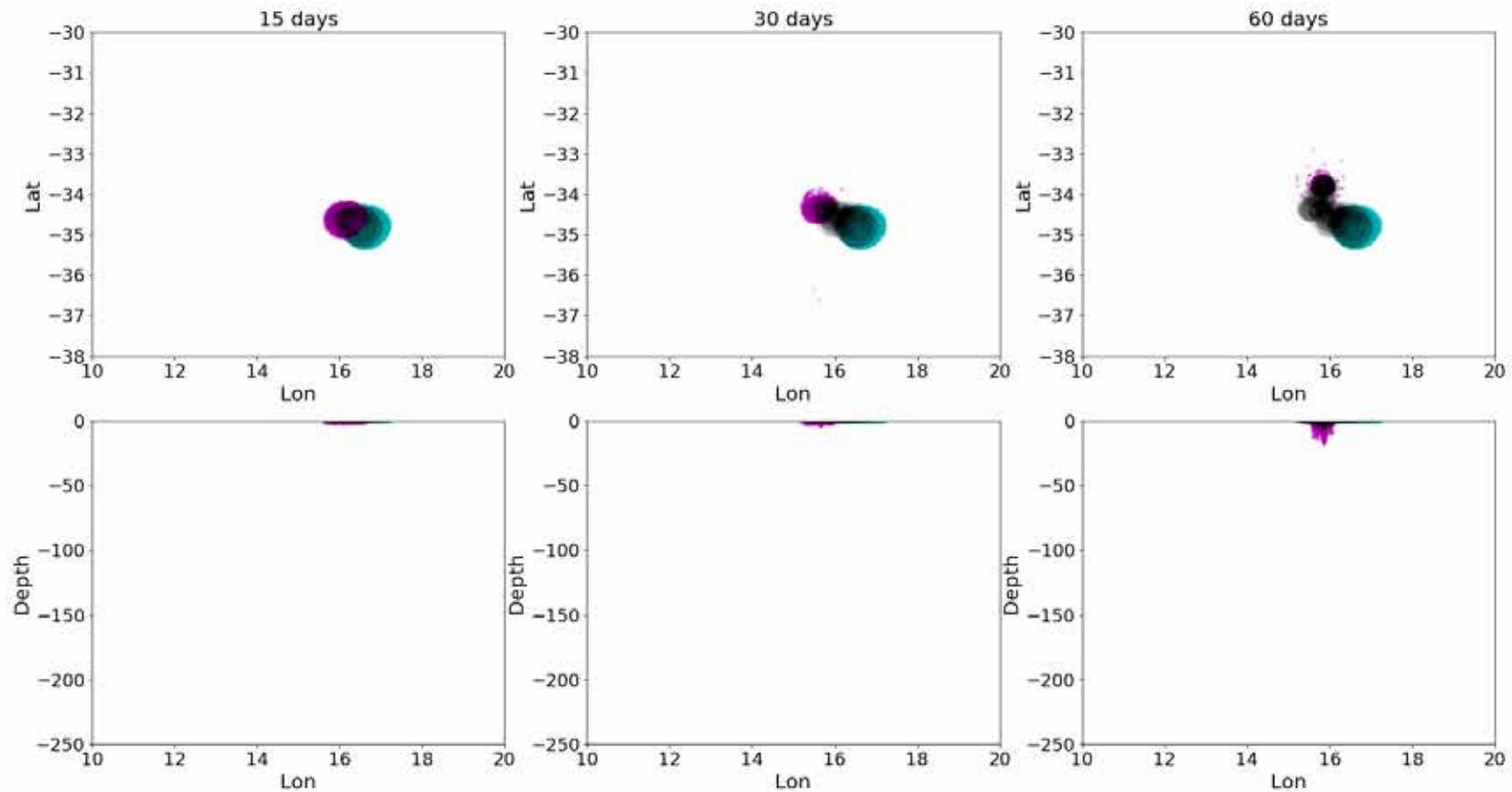


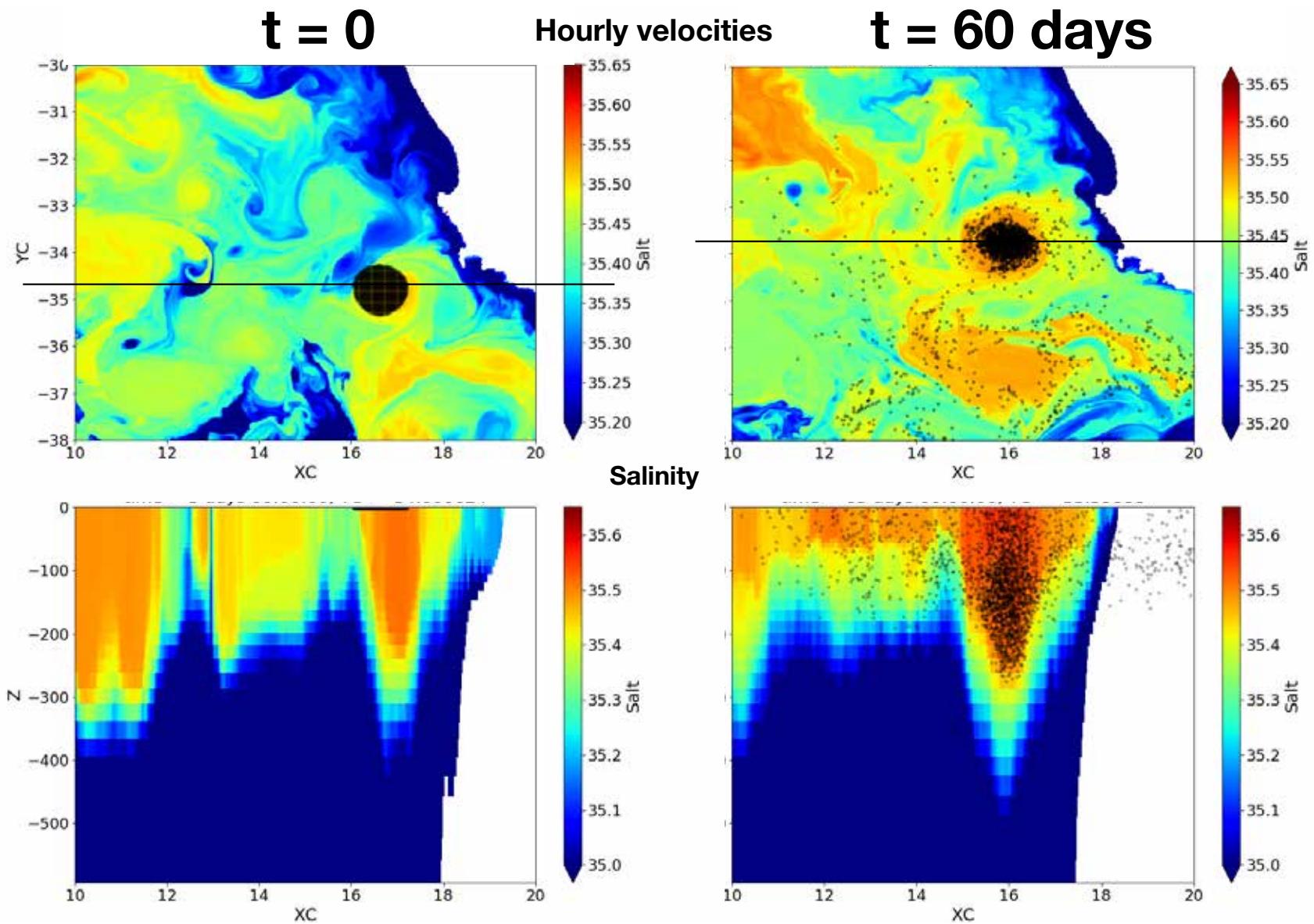
**$t = 60$  days**



## Eddy II : A shrinking eddy

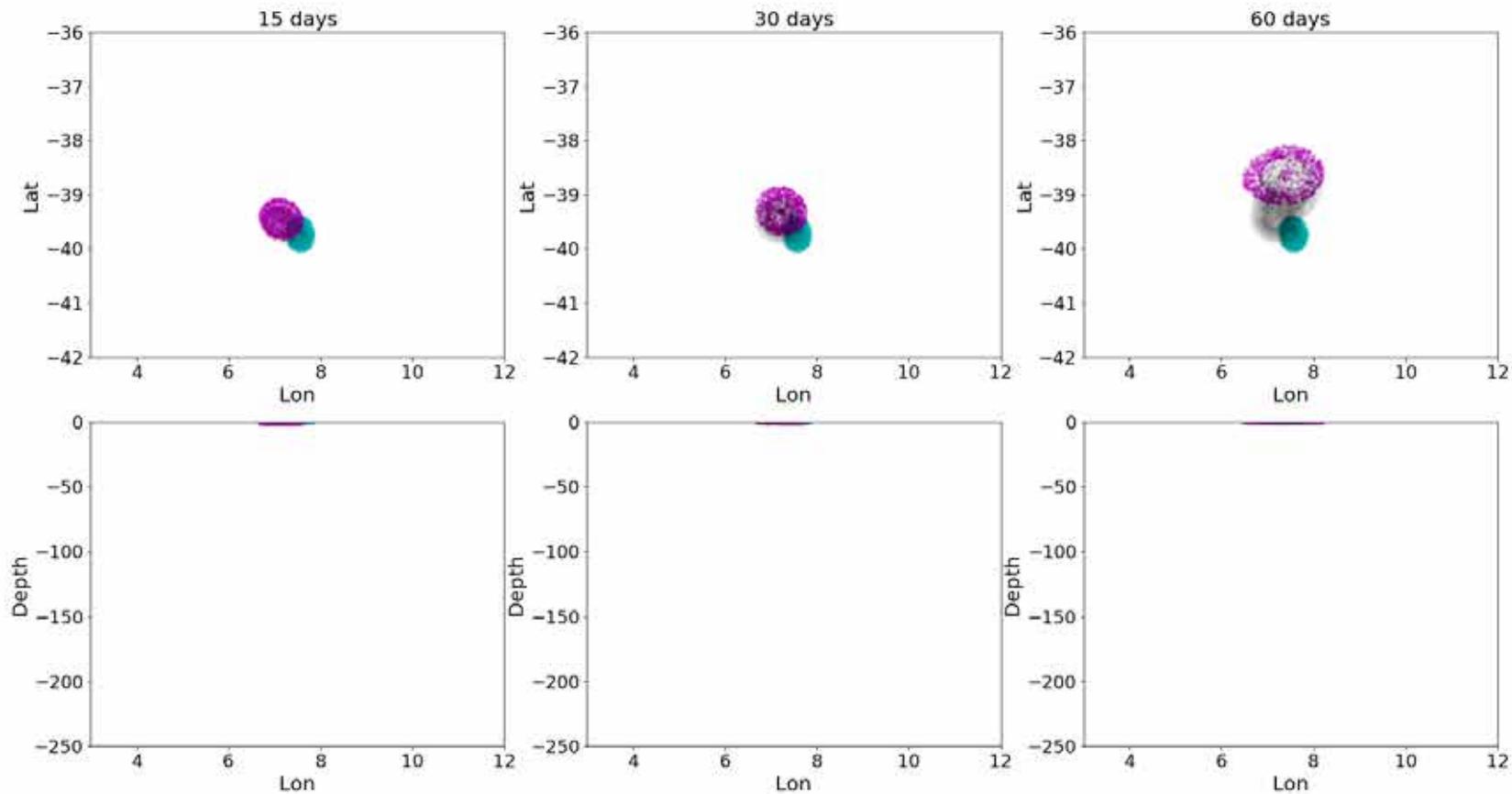
RCLV 2, 3D weekly

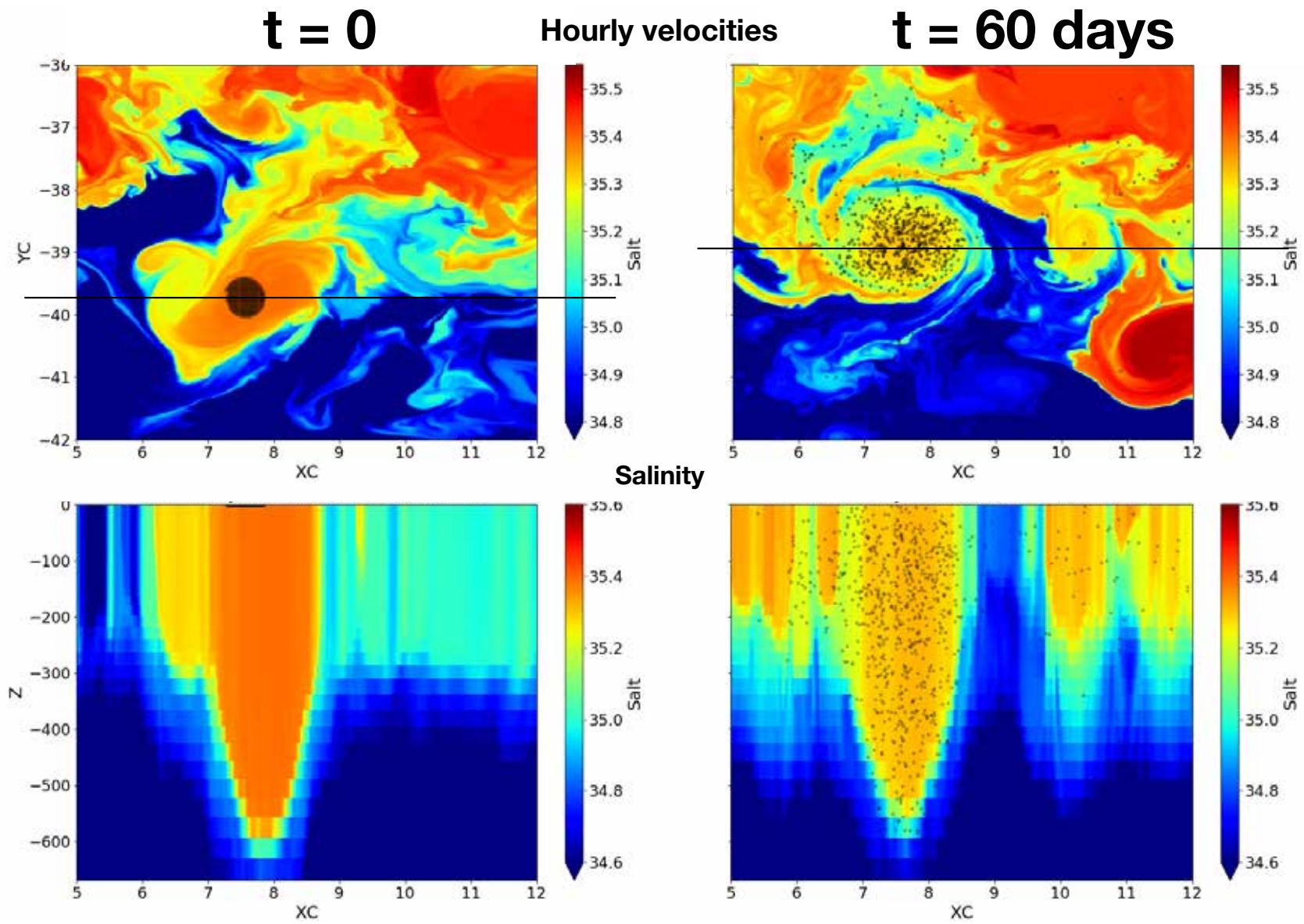




## Eddy III : An expanding eddy

RCLV 4, 3D weekly





# Summary

strong IGW / tides,  
submesoscale

KE spectra  
Divergent ~ Rotational

“leaky” / “blurry”  
no coherent structures

“Differently coherent”  
-Jim McWilliams

**enhanced** vertical motion  
upwelling/downwelling inside eddy cores

Temporal filter  
(avg.)

**affects**  
**Lagrangian coherence,**  
**small scale mixing,**  
**vertical subduction**

**doesn't affect**  
**large scale horiz. mixing**

filtered out IGW / tides,  
submesoscale

KE spectra  
Divergent < Rotational  
(mostly balanced flows)

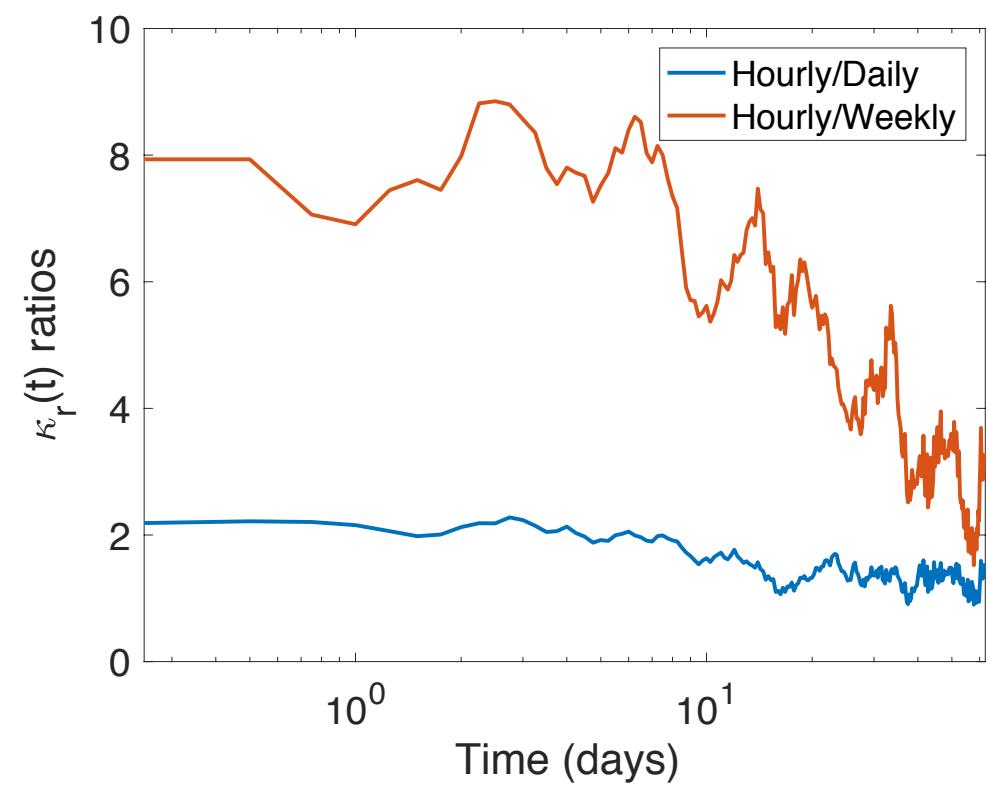
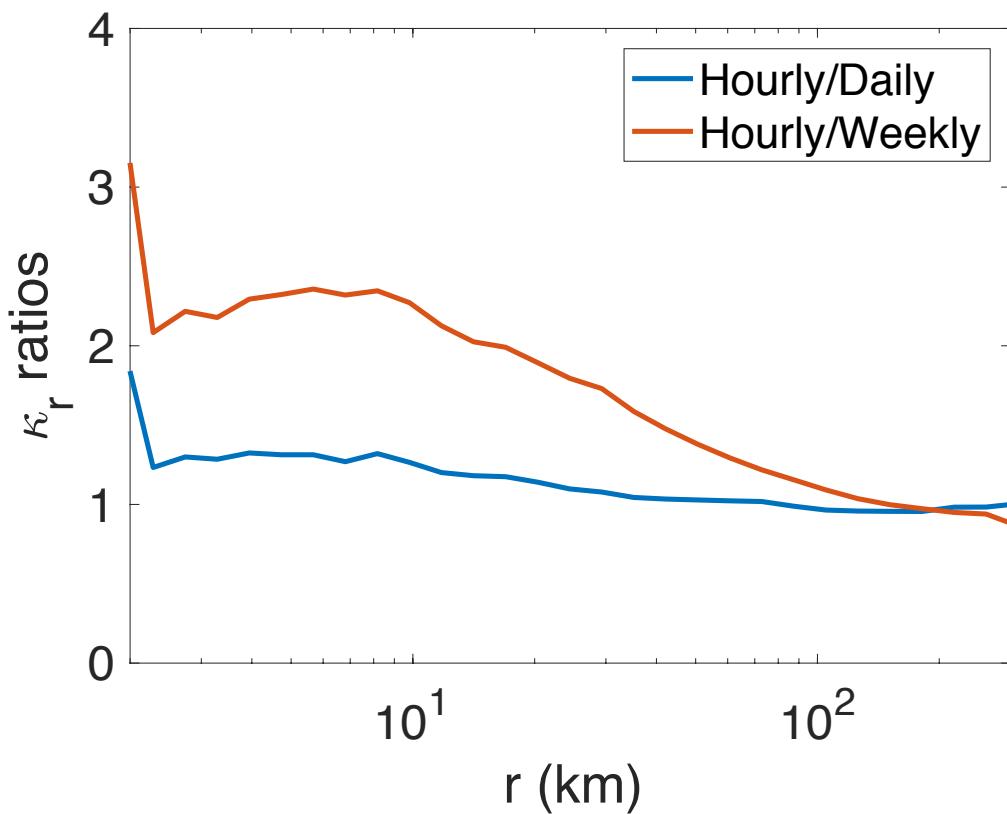
Coherent eddies, Sharp mat.  
transp. barriers

Vertical motion **suppressed**

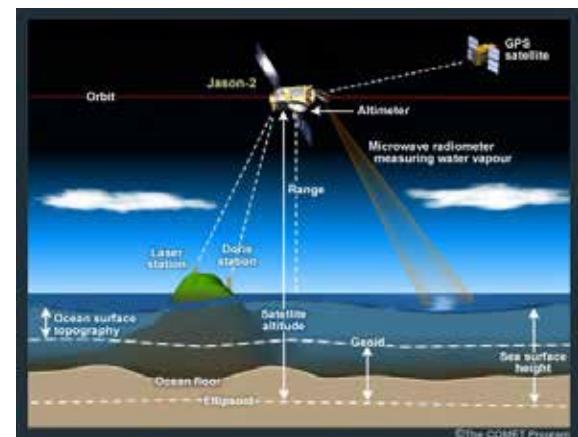
Thank you.

## Appendix

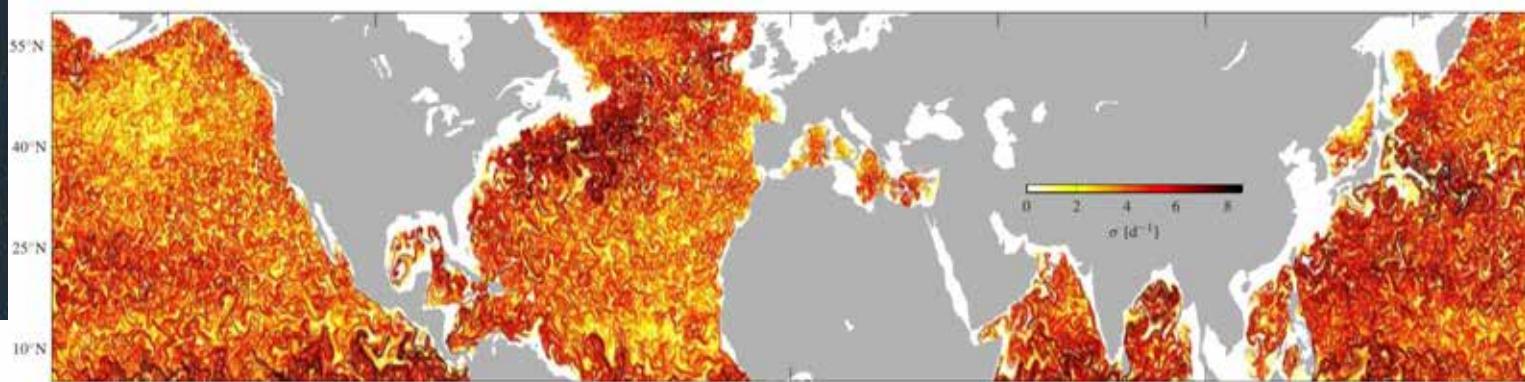
# Relative Diffusivity (Lagrangian)



## Past Studies : Satellite Altimetry



*Waugh et al. (2011, 2012; JPO),  
Rypina et al. (2012, JPO), Abernathey & Marshall (2013, JGR)*

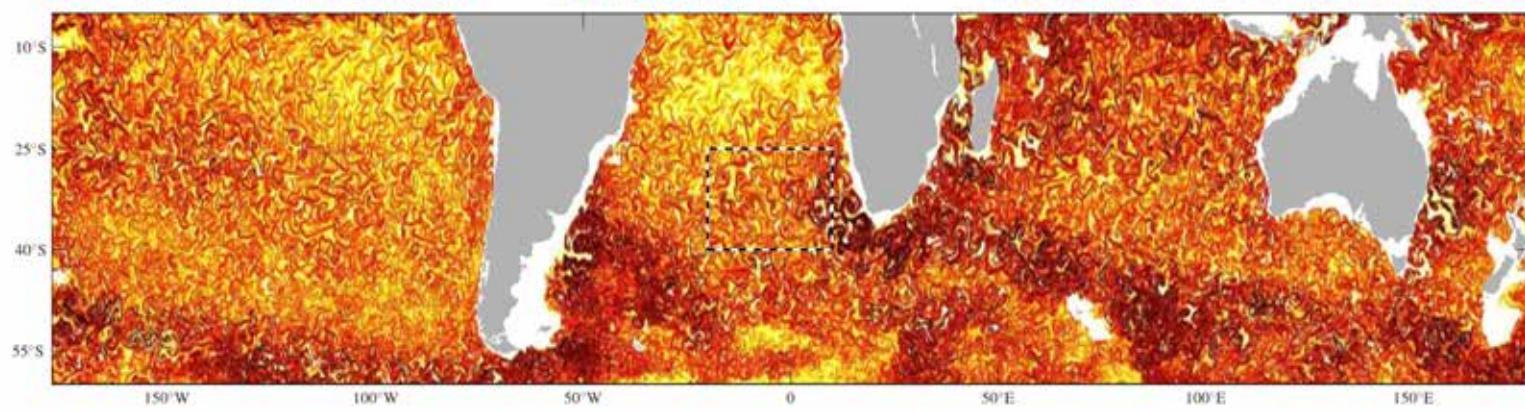


Lyapunov exponent,  
general idea:

$$|\delta z(t)| \approx e^{\Lambda t} |\delta z_0|$$

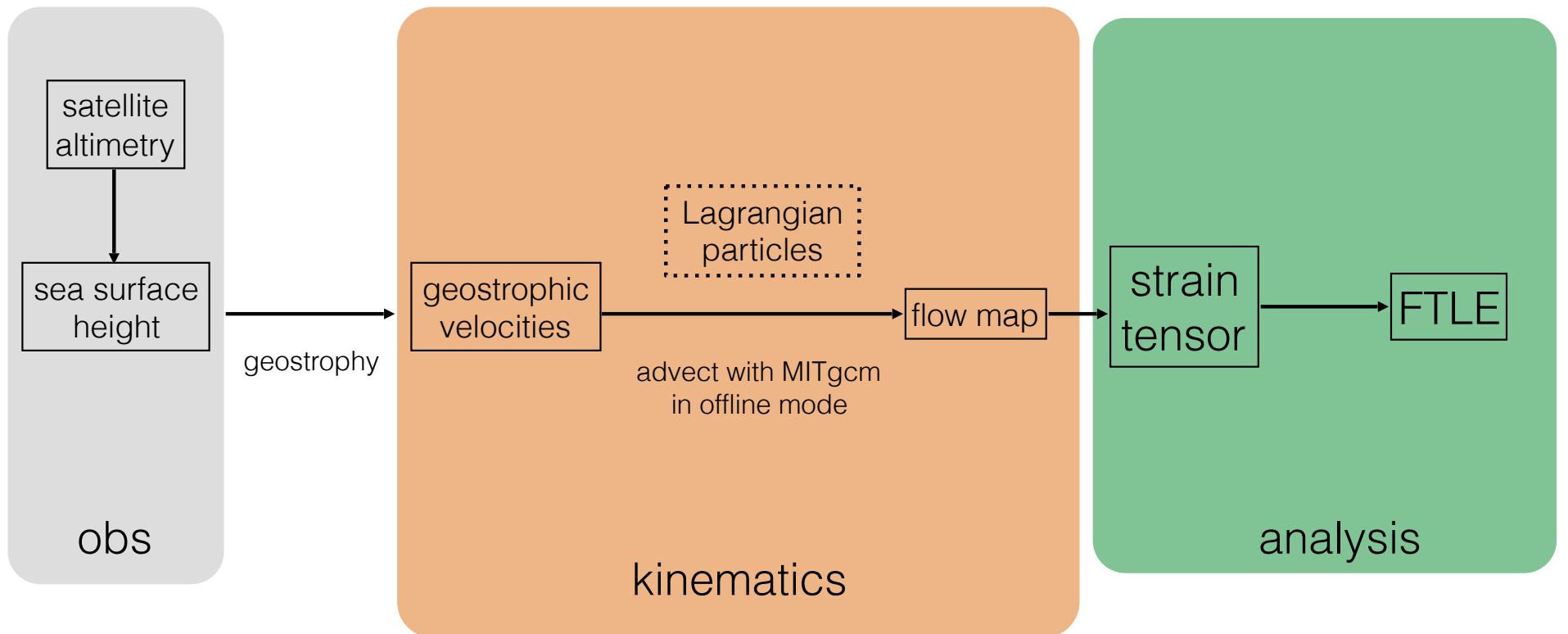
FTLE

$$\Lambda_{t_0}^t(\mathbf{x}_0) = \frac{1}{t - t_0} \log \sqrt{\lambda_2(\mathbf{x}_0)}$$



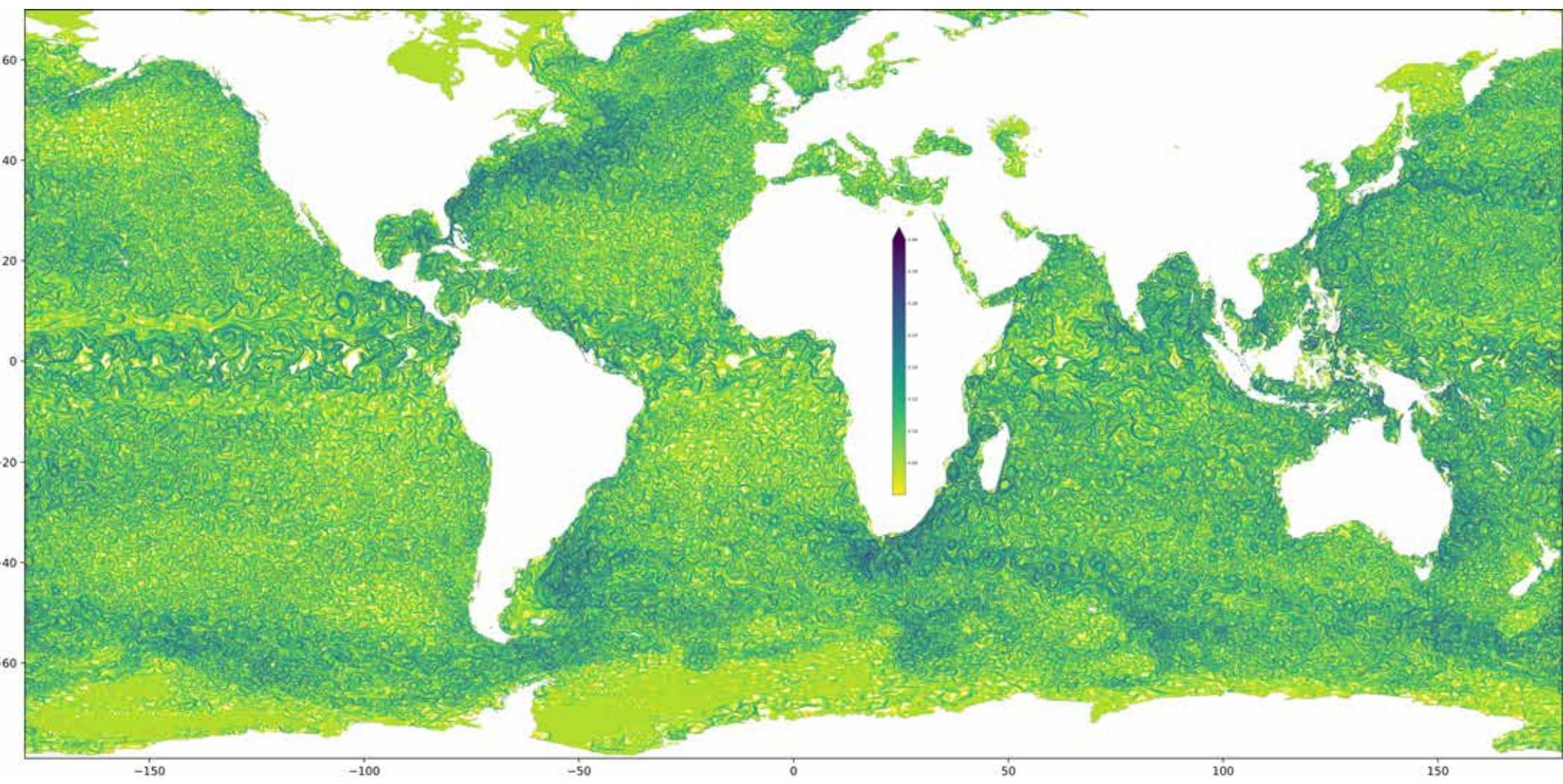
*Beron-Vera et al., 2008, GRL*

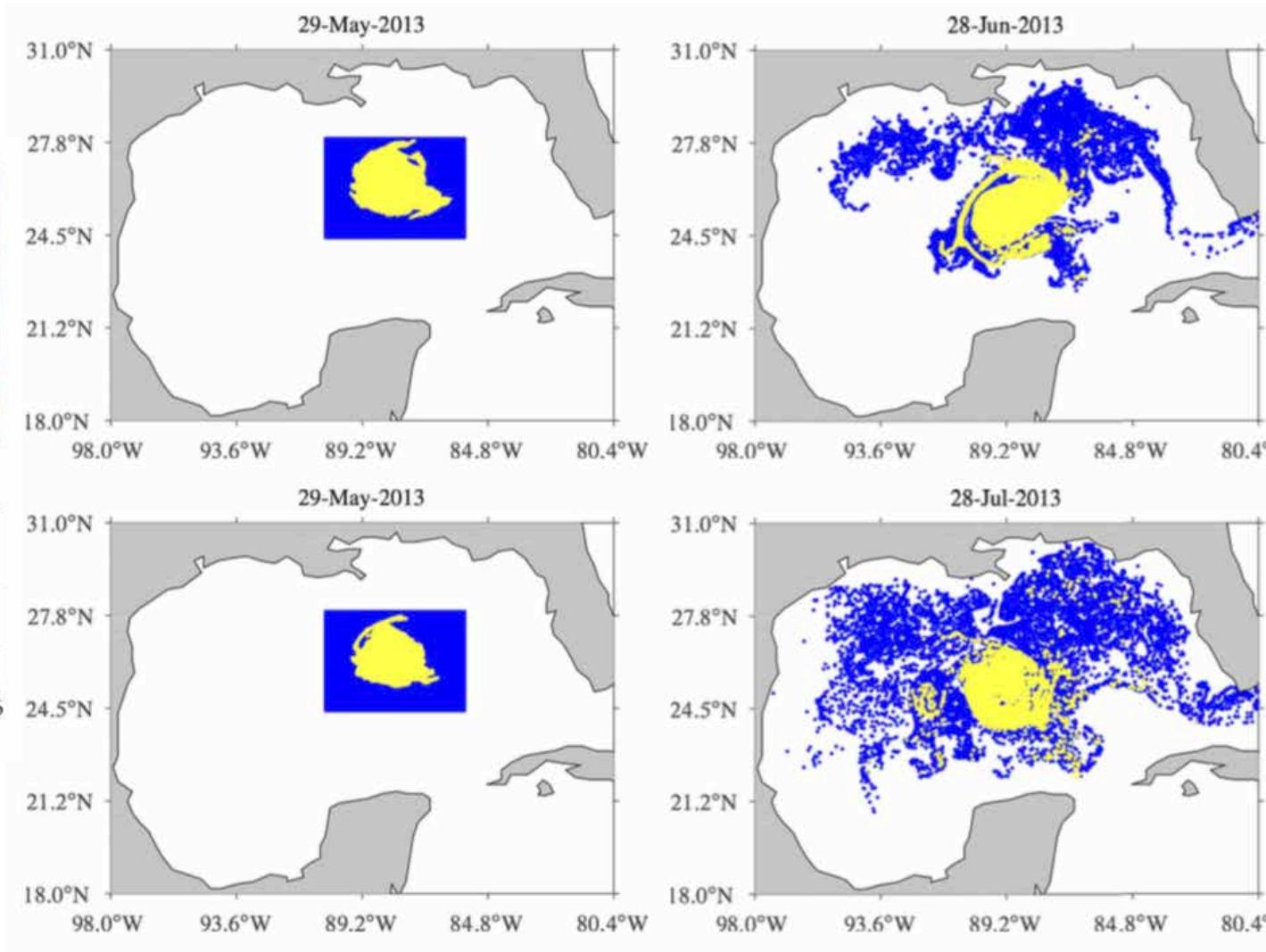
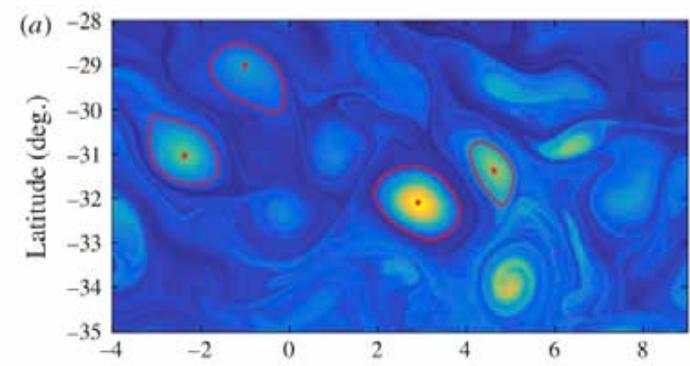
## MITgcm offline with AVISO stirring field



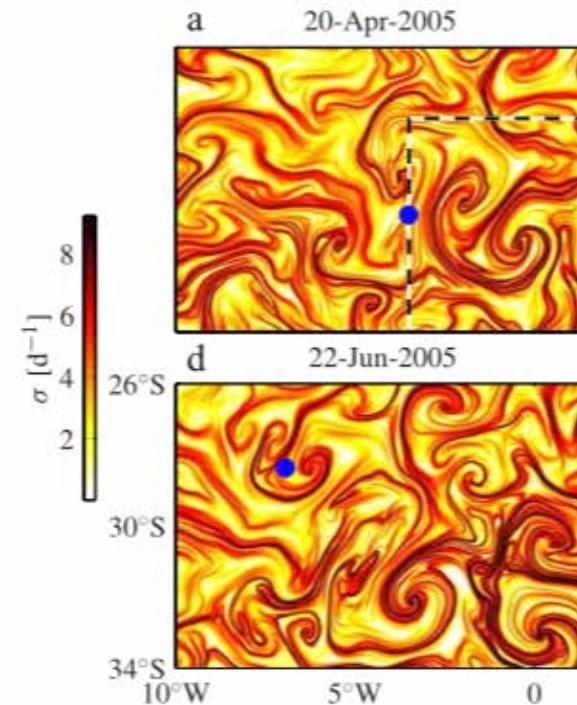
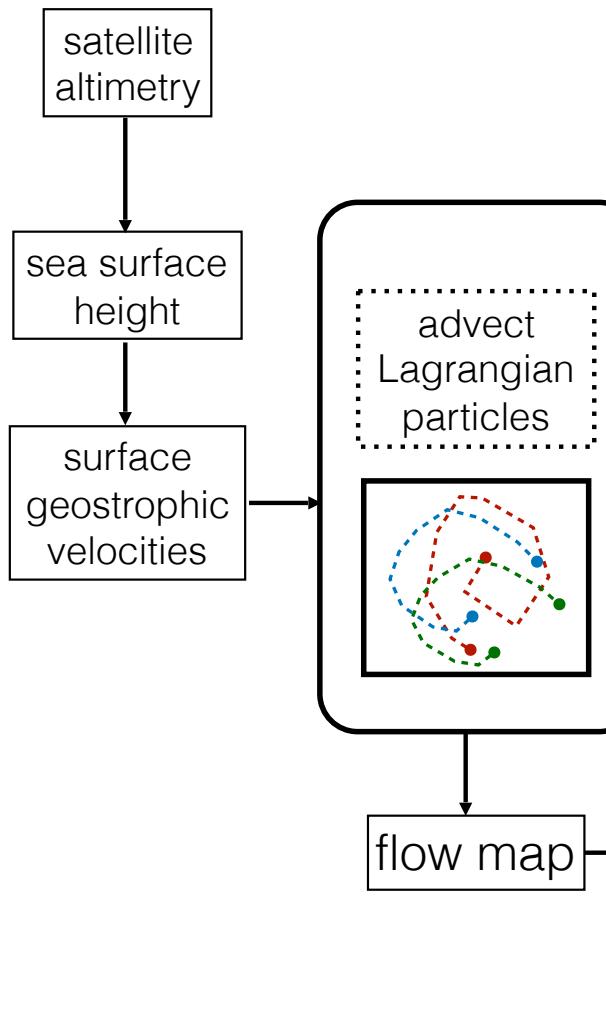
1/4 ° AVISO velocity (7 day interpolated to daily)  
interpolated to 1/10 ° model

1/32 ° particle grid, trajectories output daily

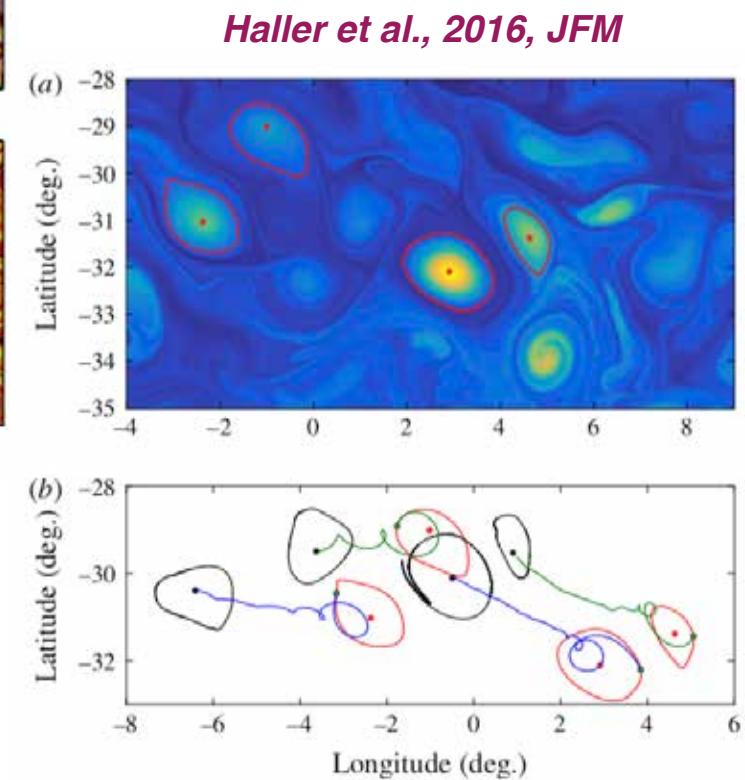




# Lagrangian coherence, Past Studies : Satellite Altimetry



**Beron-Vera et al., 2008, GRL**



**Haller et al., 2016, JFM**

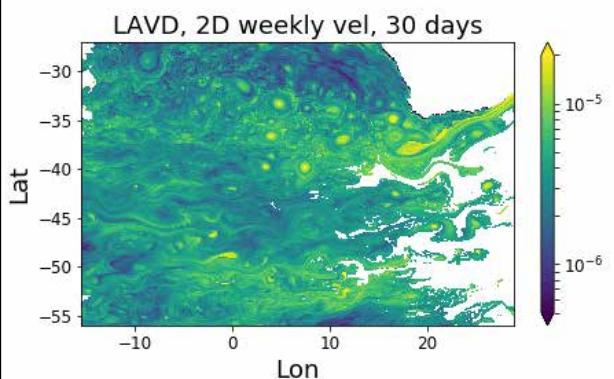
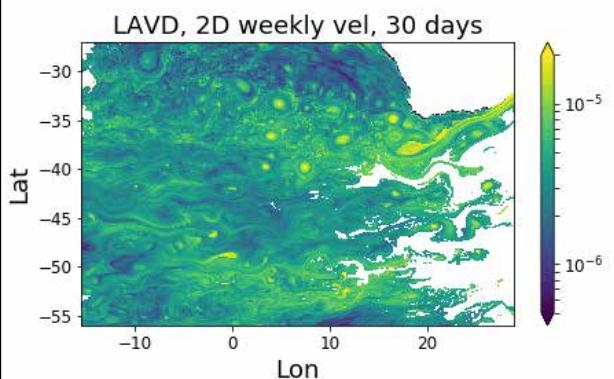
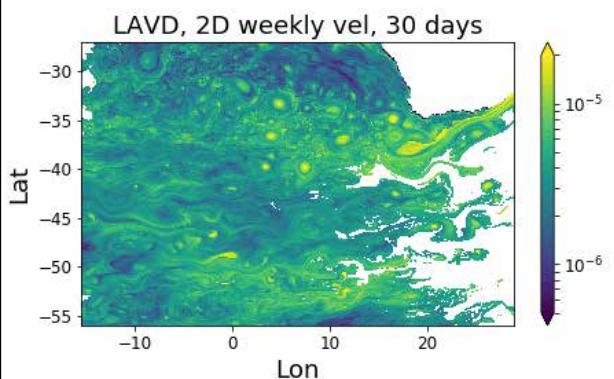
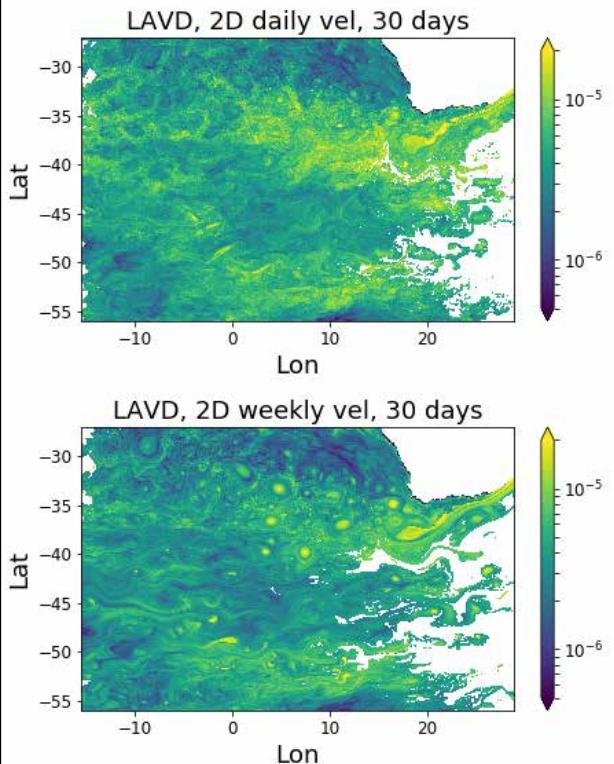
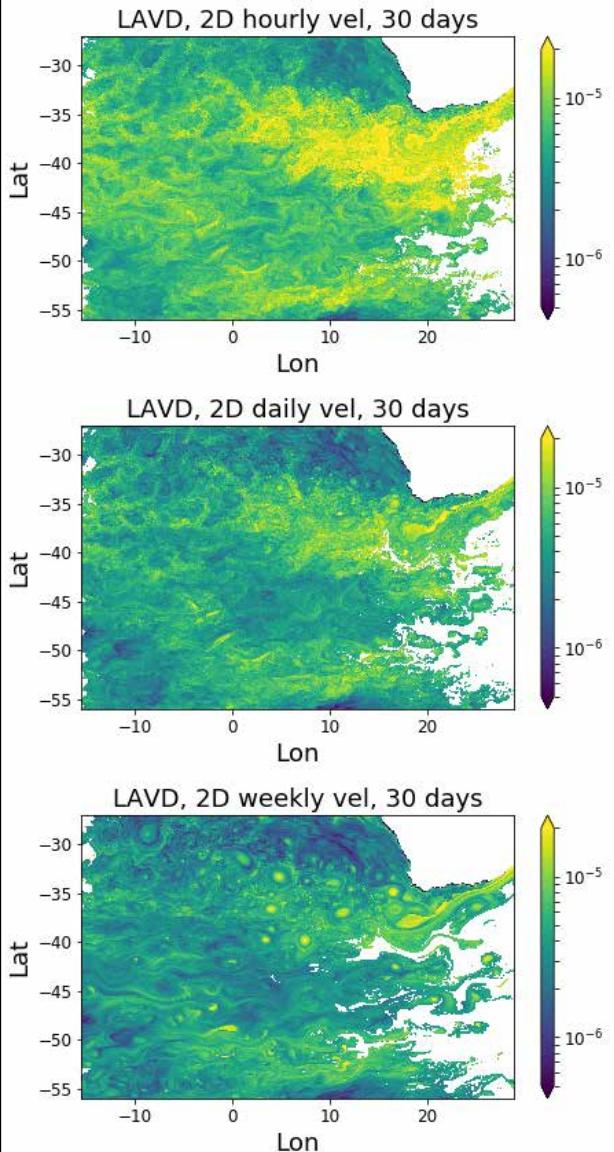
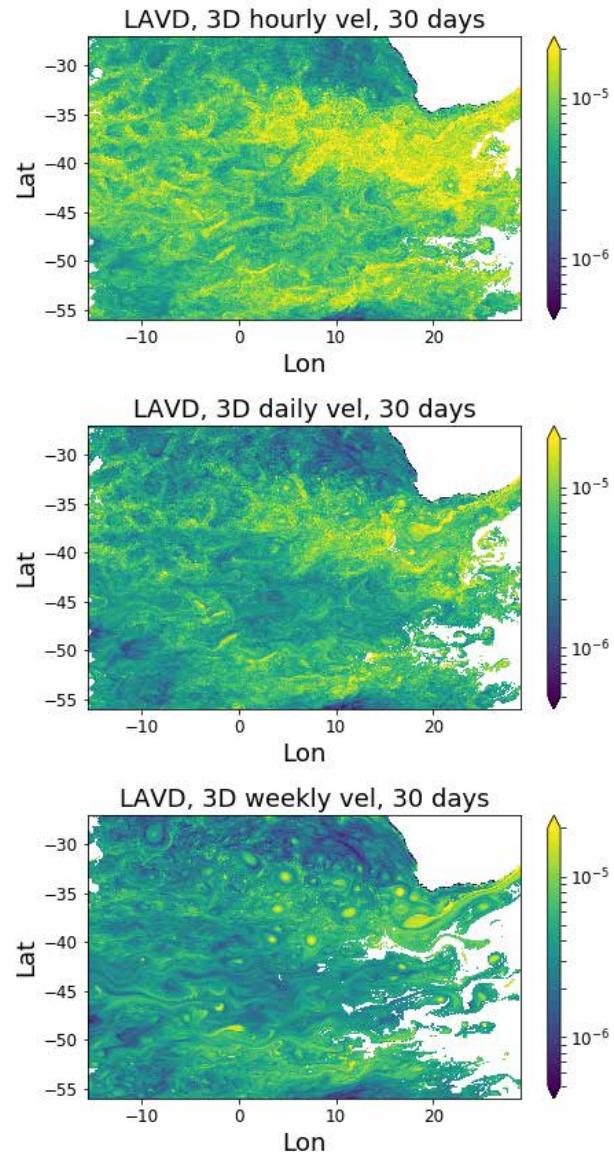
# 3D

HOURLY

High Res  
IGWs, Tides,  
submesoscale

DAILY

WEEKLY

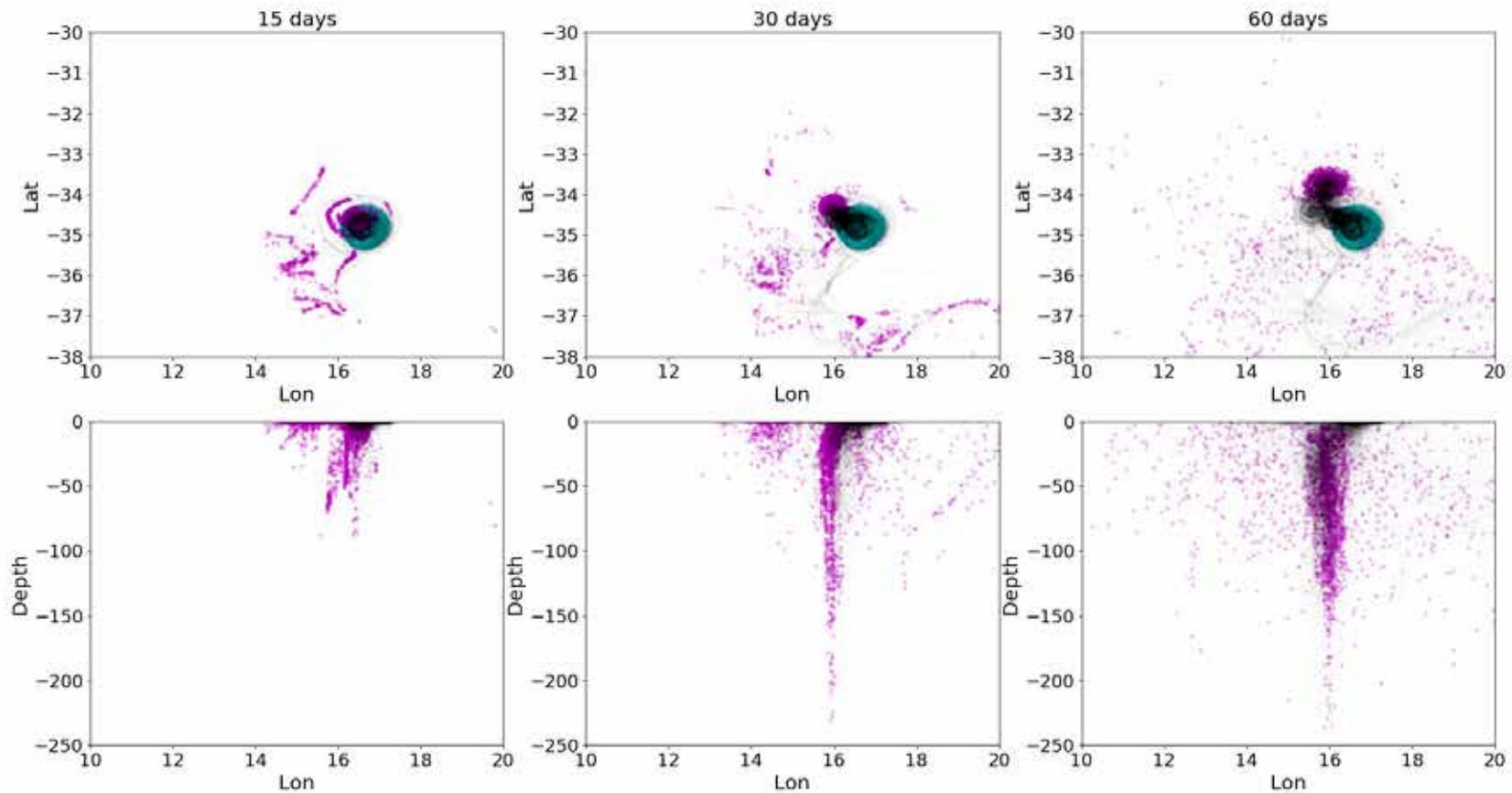


# 2D

Closest to  
Satellite Altimetry

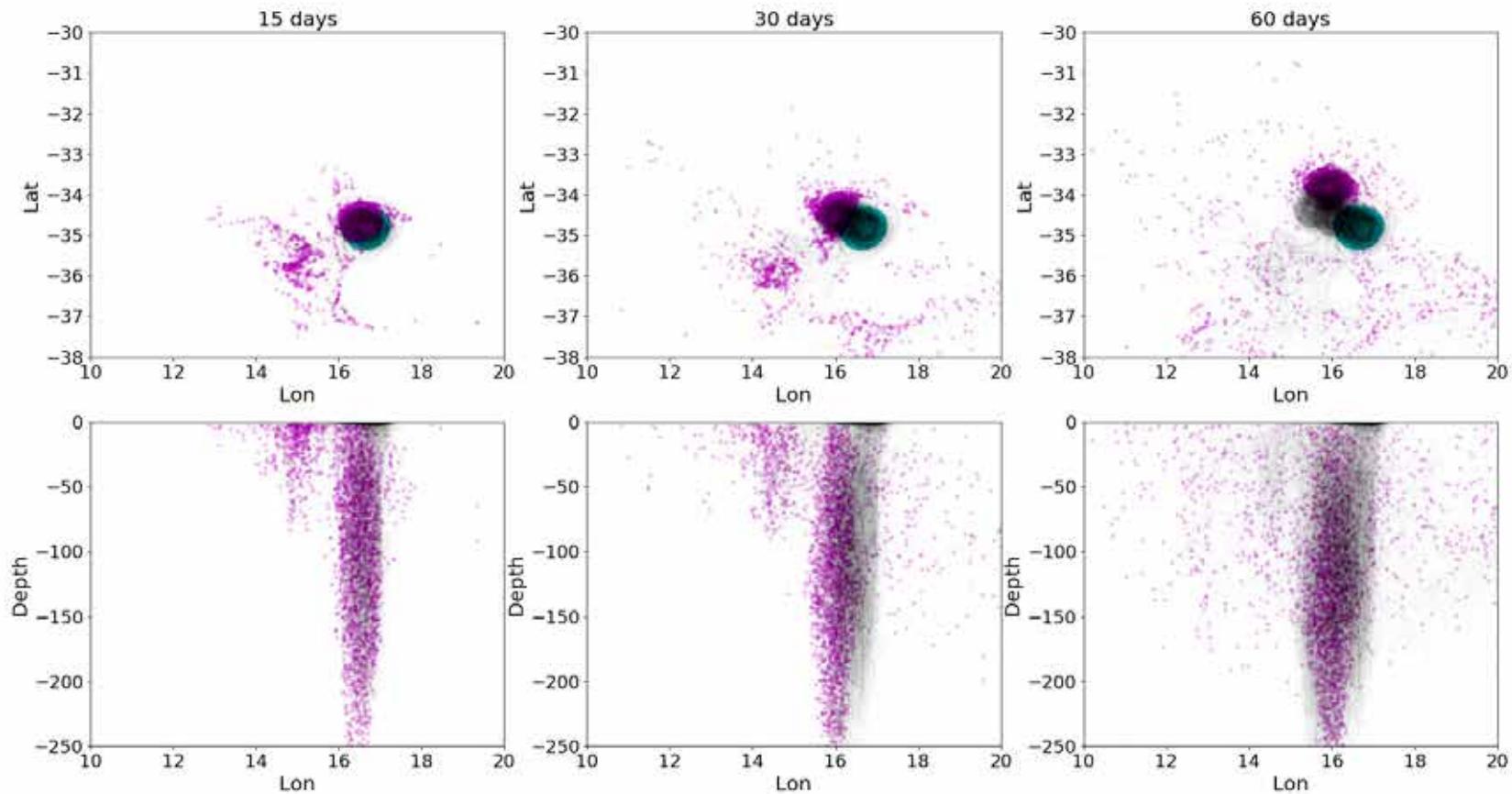
## Eddy II : A shrinking eddy

RCLV 2, 3D daily



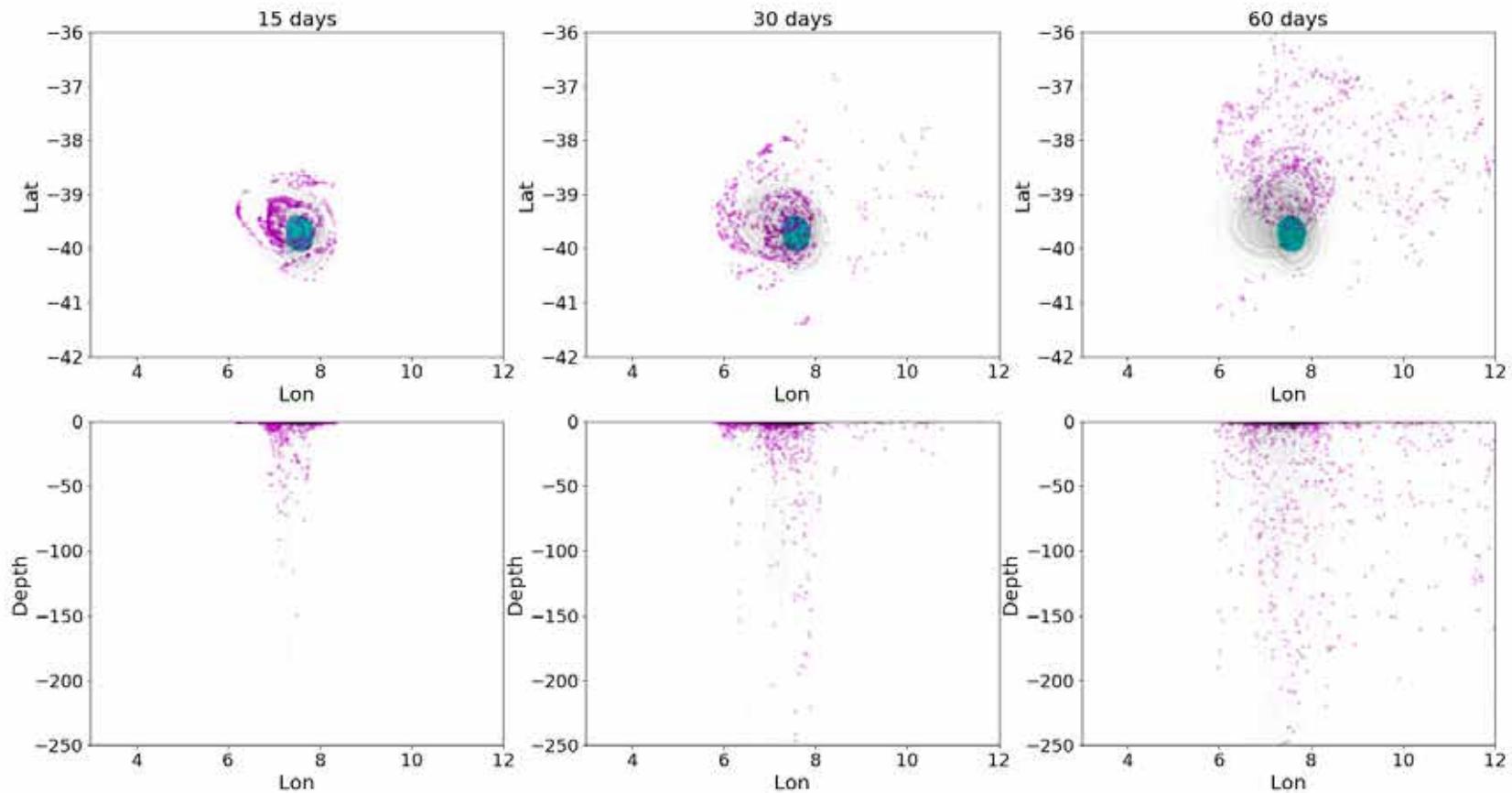
## Eddy II : A shrinking eddy

RCLV 2, 3D hourly



## Eddy III : An expanding eddy

RCLV 4, 3D daily



## Eddy III : An expanding eddy

RCLV 4, 3D hourly

