# Surface ocean mixing inferred from different multisatellite altimetry measurements

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# Motivation

- AVISO distributes two gridded SLA records:
  - ▷ REF: measurements made using 2 altimeters with same ground-tracks; homogeneous sampling.
  - ▷ UPD: measurements made using *up to* 4 altimeters; improved sampling but heterogeneous.
- A number of works (Abraham and Bowen 2002; Waugh et al. 2006; Beron-Vera et al. 2008; d'Ovidio et al. 2008; Waugh and Abraham 2008; Rossi et al. 2009) support for the notion that mixing as sustained by UPD currents is largely heterogeneous, with the velocity field being largely spatially coherent and temporally regular on time scales over which Lagrangian motion is mainly irregular.
- Consistent with this notion, Shuckburgh et al. (2009) reported small sensitivity of effective diffusivity calculations to spatial smoothing of UPD currents.
- Suggests that the differences between UPD and REF currents should have a small effect on mixing, which we seek to investigate.

## Approach

Extract Lagrangian Coherent Structure (LCS)—skeletons of passive tracer patterns. Compute KE and tracer variance spectra—attempt using 2-d turbulence results. Construct Finite-Time Lyapunov Exponent (FTLE) statistics. Compare Eulerian and Lagrangian autocorrelations. Carry out explicit passive tracer advection experiments.

## Region and timespan

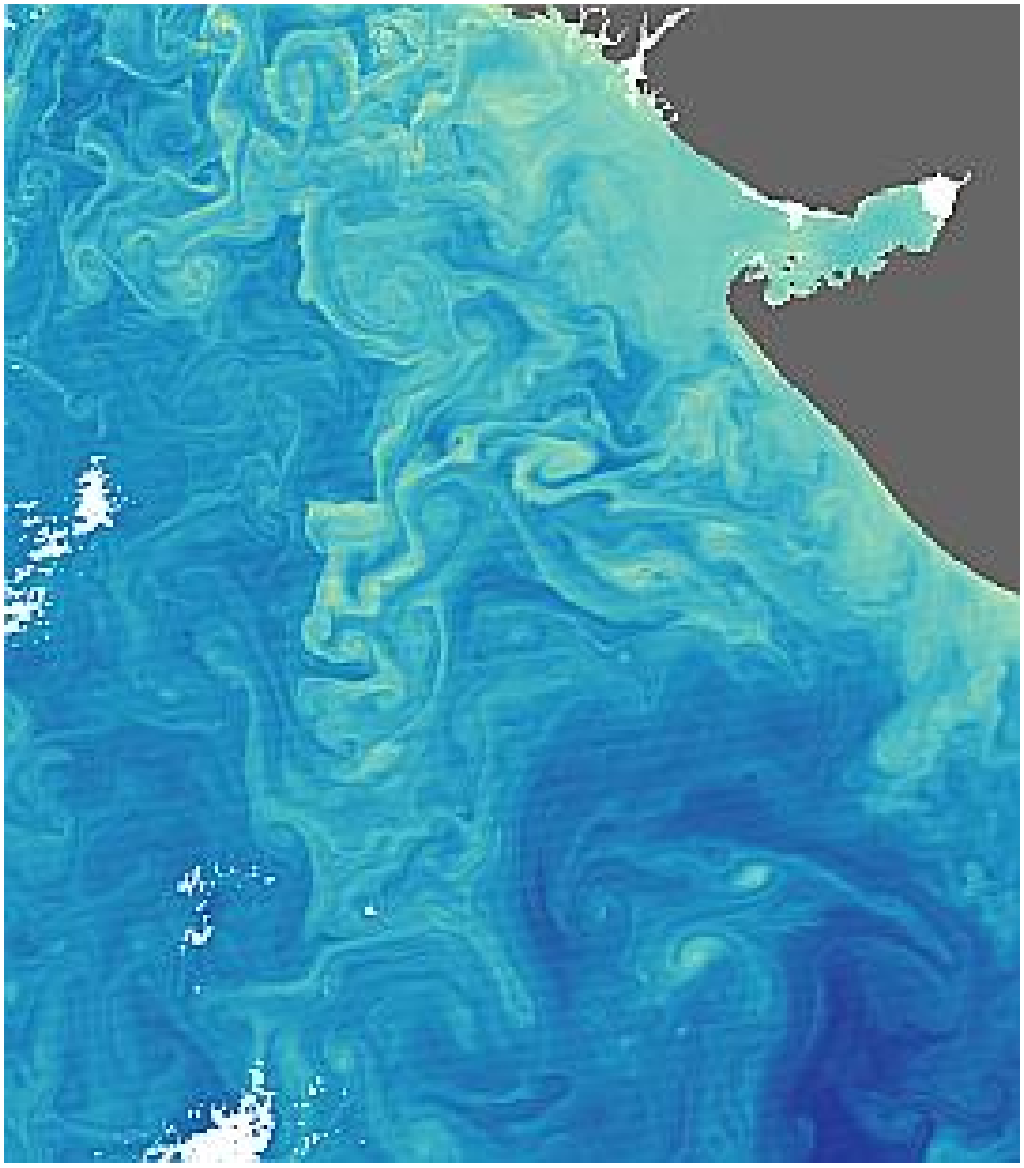
A domain in the western North Atlantic over 2003; UPD record includes measurements from 4 altimeters (T/P + Envisat + GFO + Jason-1); considered priorly by Pascual et al. (2006) with a focus on Eulerian aspects.

## References


Beron-Vera, F. J., M. J. Olascoaga and G. J. Goni (2010). *J. Phys. Oceanogr.*, doi:10.1175/2010JPO4458.1.

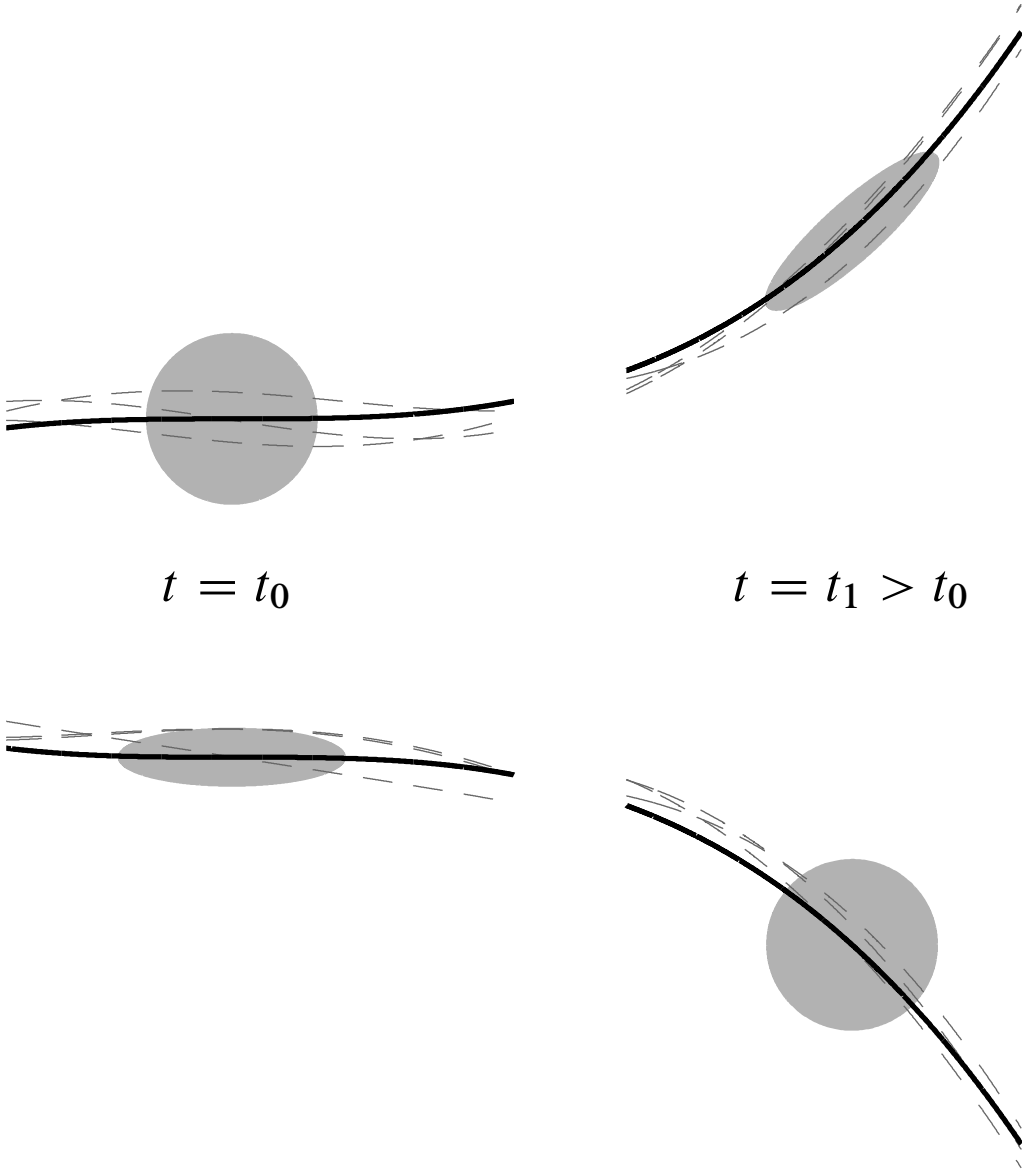
Beron-Vera, F. J. (2010). *J. Geophys. Res.*, 115, C10027, doi:10.1029/2009JC006006.

# Chlorophyll concentration from MODIS-Aqua satellite



We seek to identify the centerpieces of these patterns.

# Physical definition of LCS (Haller and Yuan 2000)




Locally strongest attracting or repelling material curve.

# Definition of FTLE

Let $\boldsymbol{x}(t)$ denote the position of a fluid particle at time $t$. The FTLE is given by

$$\sigma_t^\tau(\boldsymbol{x}) := \frac{1}{|\tau|} \ln \|\nabla \boldsymbol{\varphi}_t^{t+\tau}(\boldsymbol{x})\|$$

where

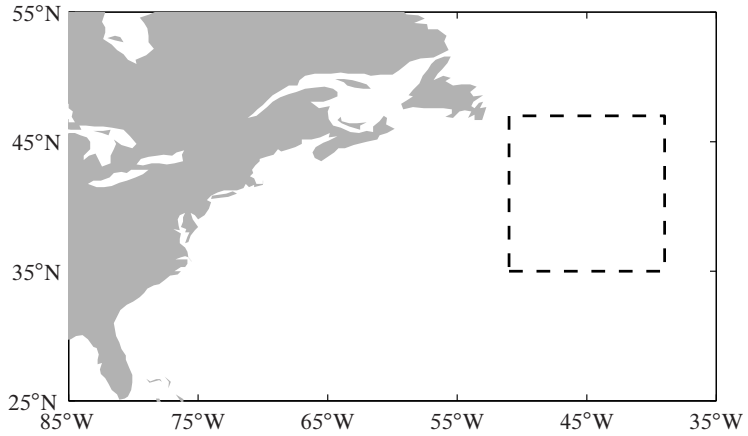
$$\boldsymbol{\varphi}_t^{t+\tau} : \boldsymbol{x}(t) \mapsto \boldsymbol{x}(t+\tau),$$

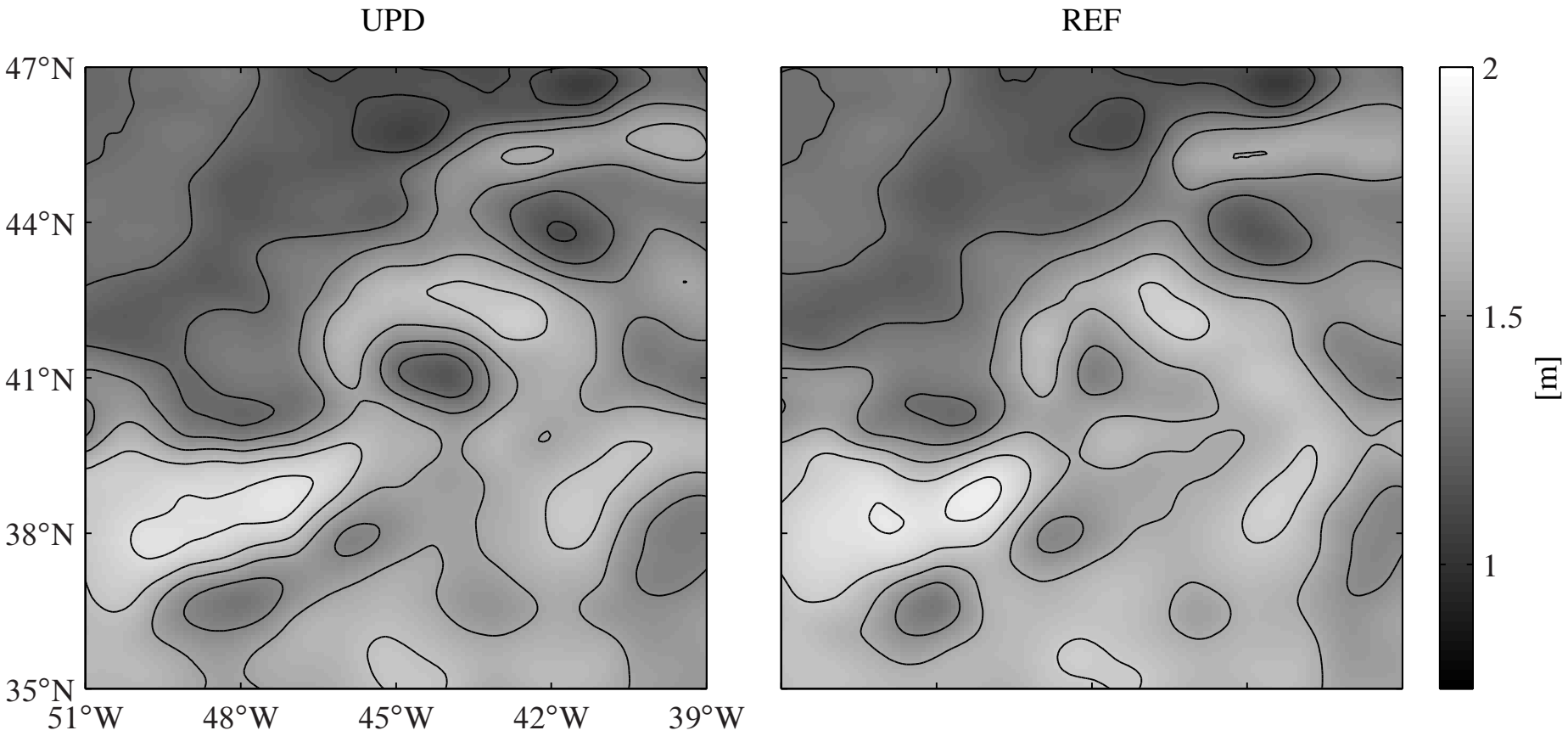
which is obtained by solving

$$\dot{\boldsymbol{x}} = \frac{g}{f(y)} \hat{\boldsymbol{z}} \times \nabla \eta(\boldsymbol{x}, t).$$

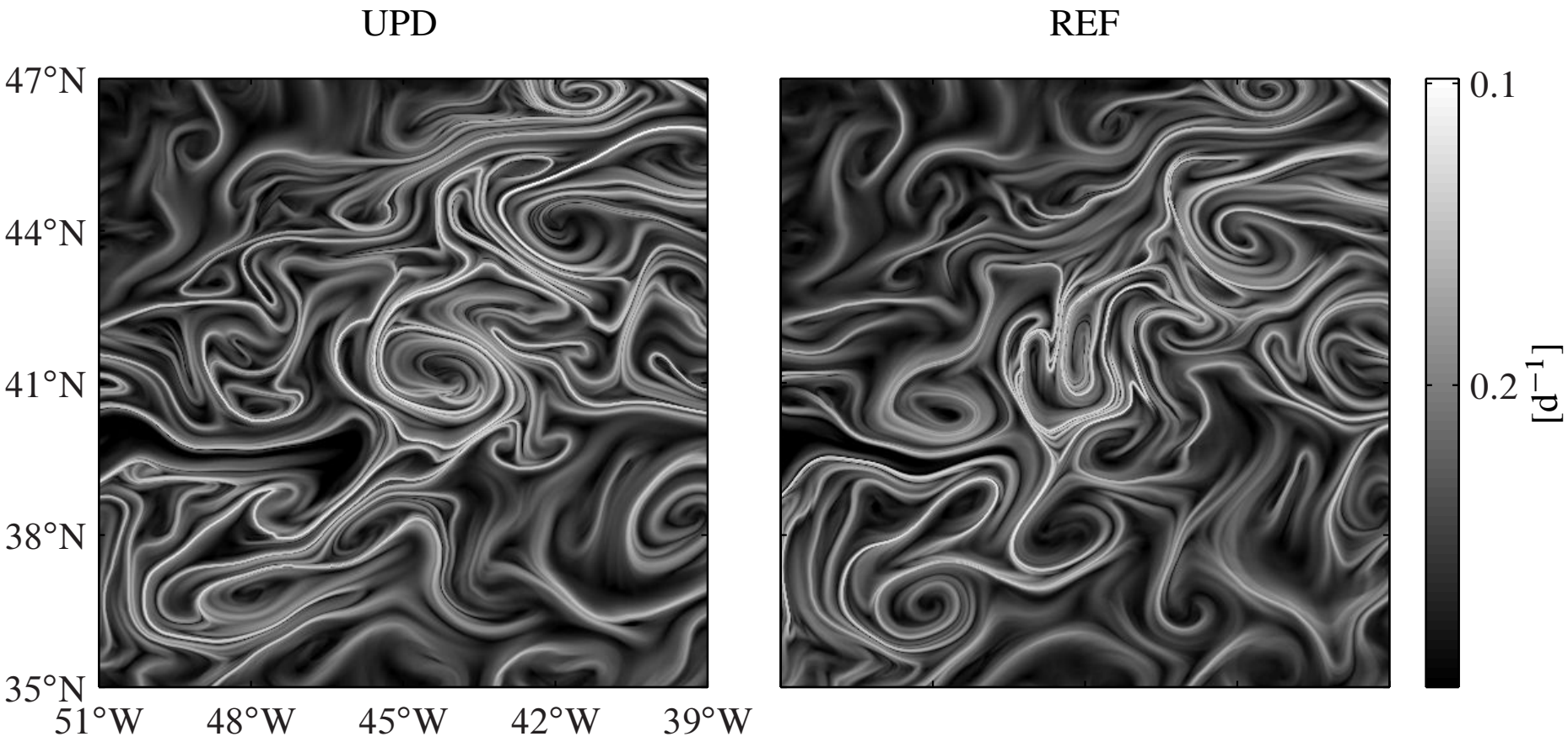
- Characterizes amount of stretching about fluid particle trajectories.
- LCS tend to produce local maximizing curves (ridges) of FTLE field (Haller 2001; 2002).
- Almost Lagrangian, i.e., $\dot{\sigma} = O(|\tau|^{-1})$ (Shadden et al. 2005).
- Commonly employed mixing diagnostic tool (e.g., Pierrehumbert 1991; Shepherd et al. 2000; Abraham and Bowen 2002).

# Domain and Rio05 MDT + SLA snapshot on 21-May-03



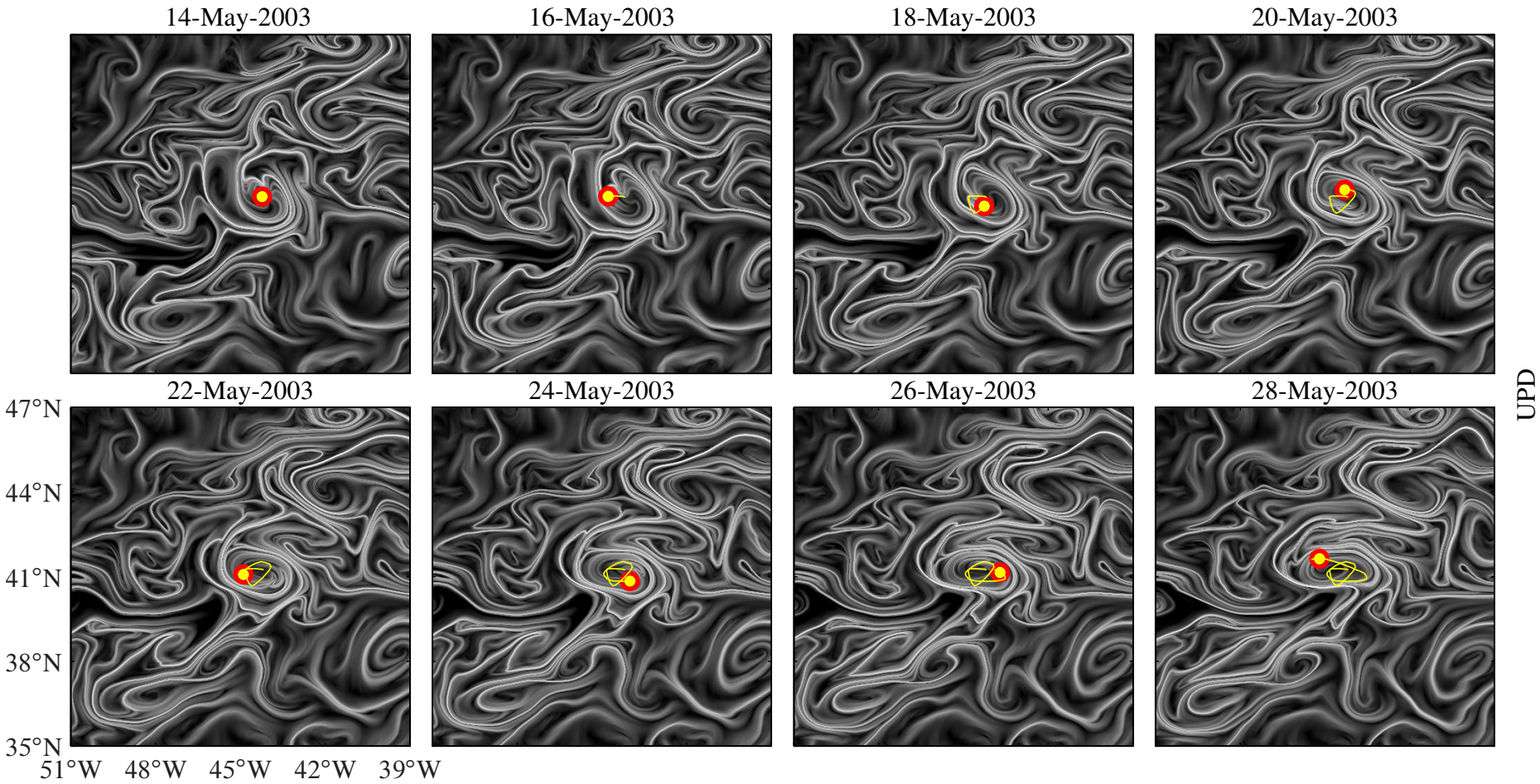



# Inspection of FTLE snapshot on 21-May-03



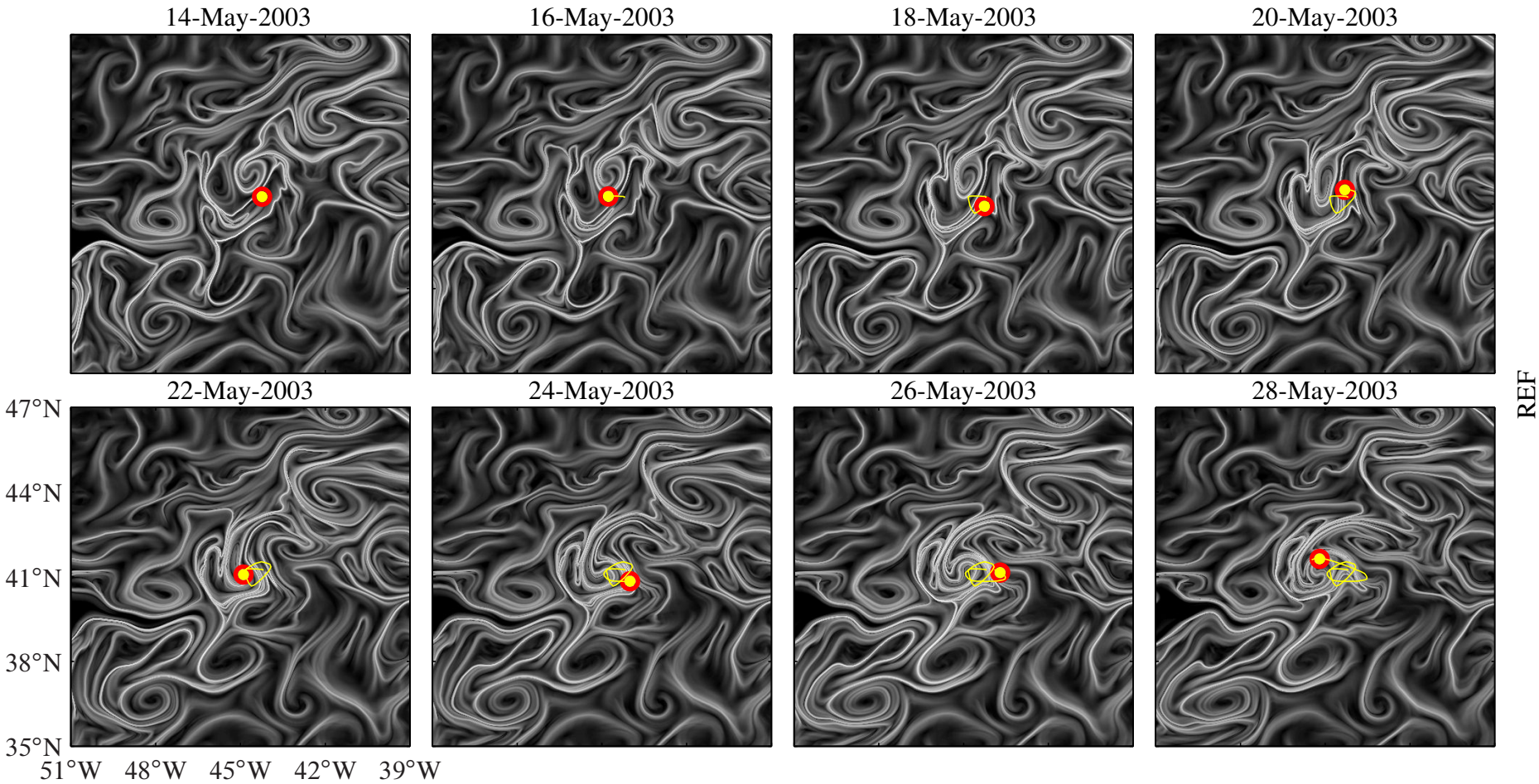

Convoluted narrow bands indicate LCS; fine texture suggests chaotic mixing; several common features.

# Comparison with drifter trajectory – UDP



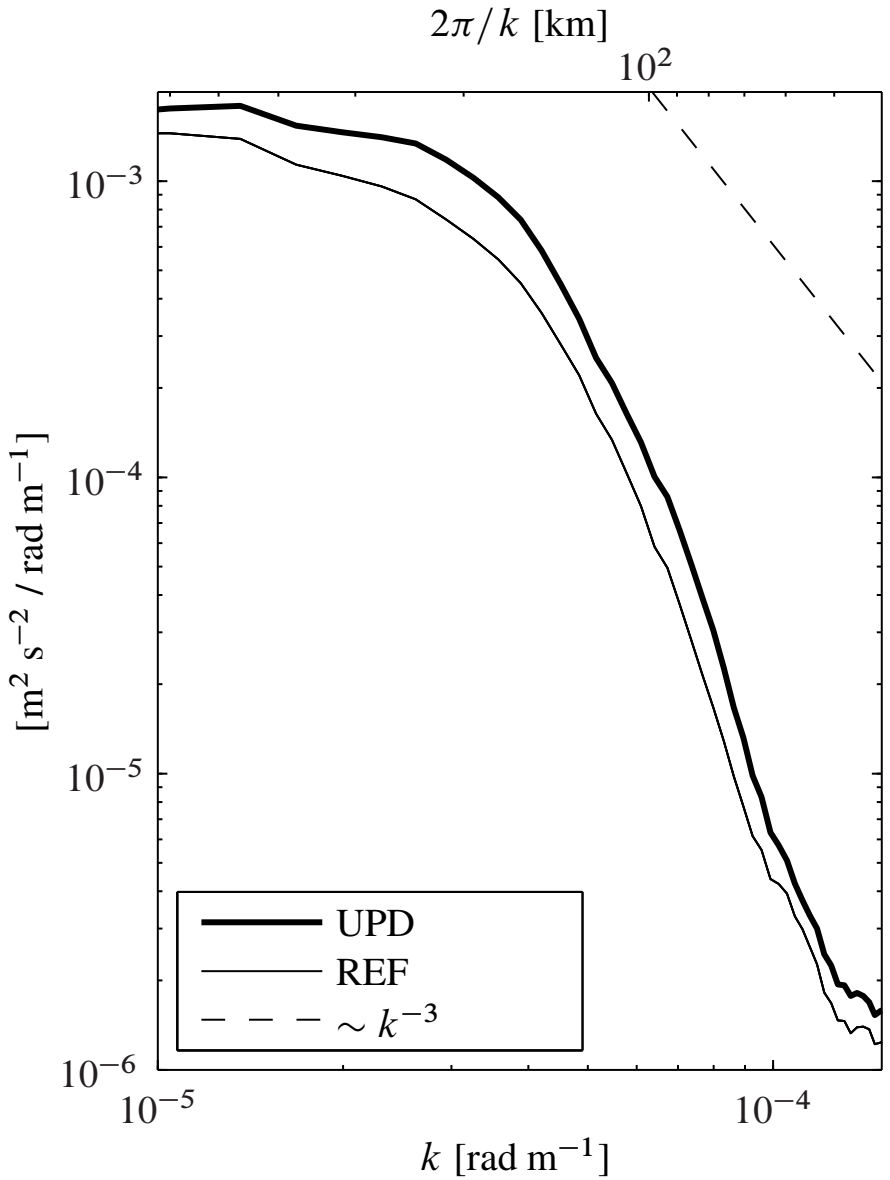

Drifter quite closely follows LCS evolution.

# Comparison with drifter trajectory – REF



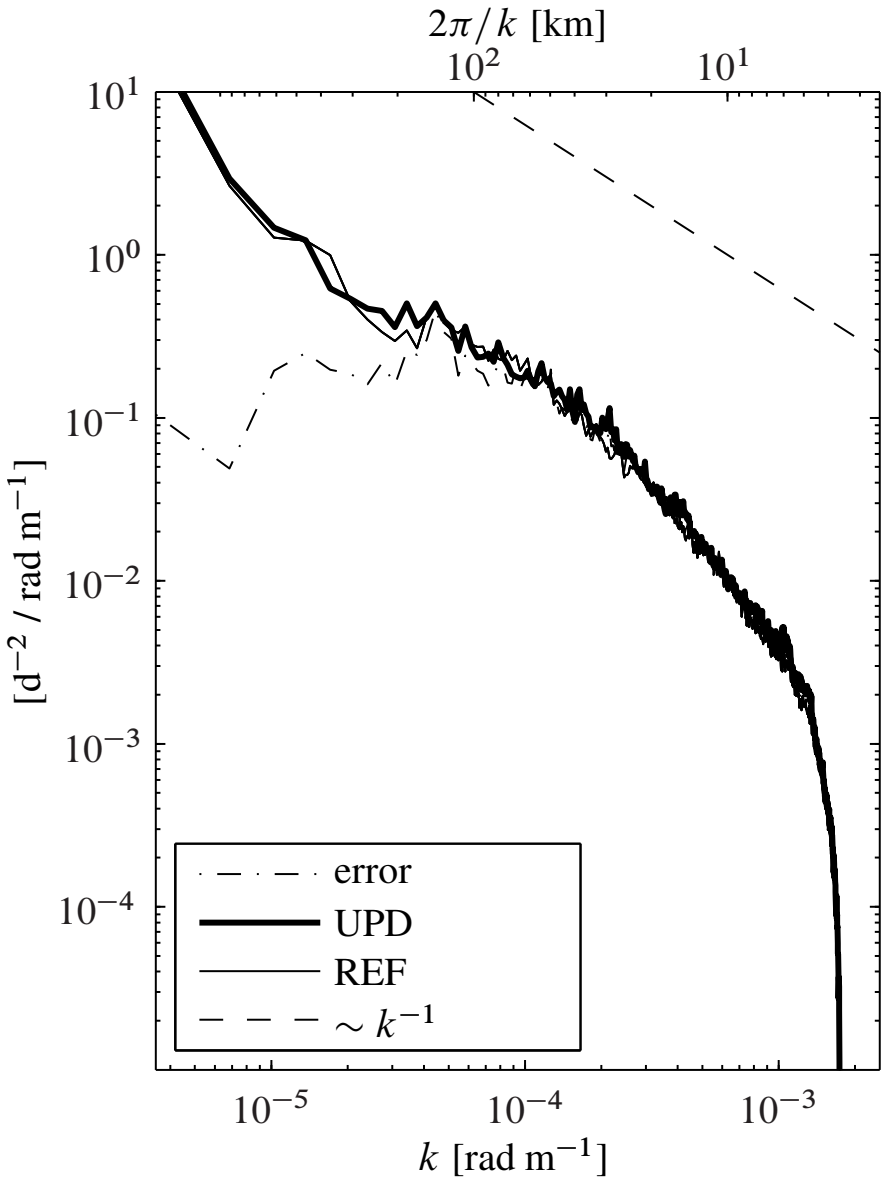

Agreement is not as good as in UPD case.

# KE spectra averaged over 2003



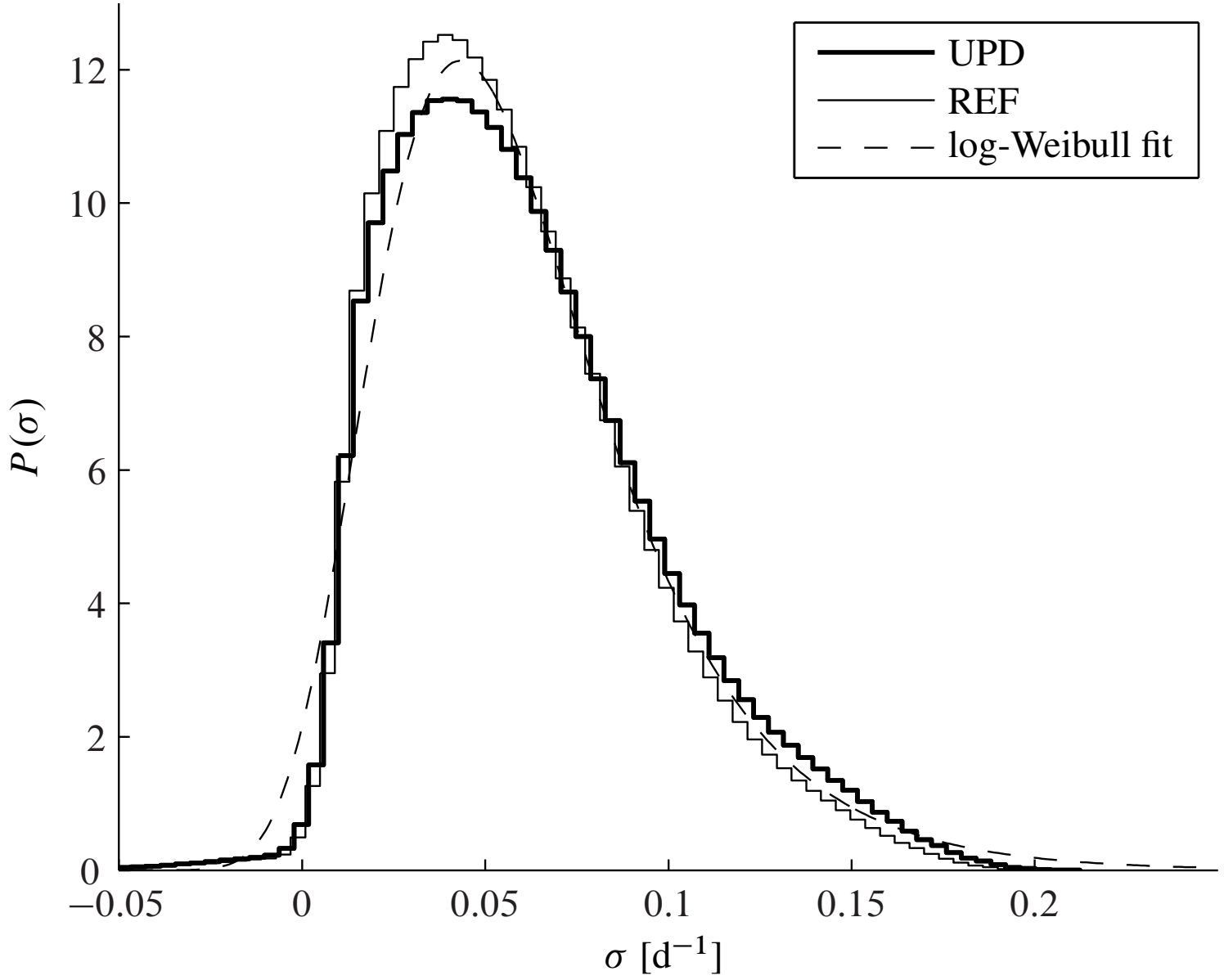

$$\tfrac{1}{2}\langle \boldsymbol{u}^2 \rangle =: \int E_{\boldsymbol{u}}(k)\,\mathrm{d}k,\ E_{\boldsymbol{u}}(k) \sim k^{-\alpha} \text{ with } \alpha < -3 \text{ (nonlocal dynamics)}$$

# FTLE (tracer) variance and error spectra on 21-May-03



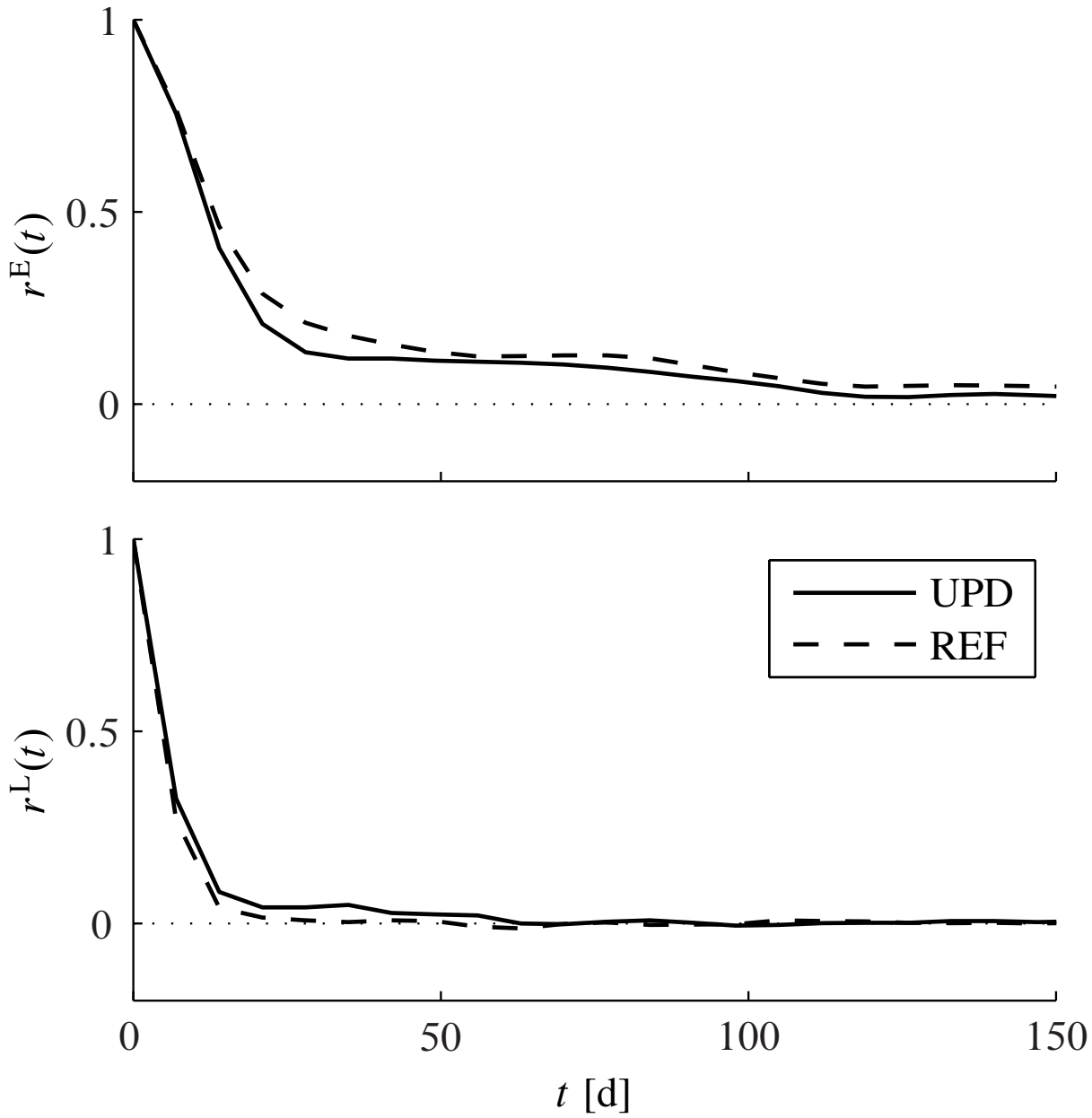

$$\tfrac{1}{4}\langle(\theta_1-\theta_2)^2\rangle =: \int E_{\delta\theta}(k)\,\mathrm{d}k,\ \langle\theta_1\theta_2\rangle = 0\ \&\ \langle\theta_1^2\rangle = \langle\theta_2^2\rangle : E_{\theta_n} = E_{\delta\theta}$$

# FTLE statistics



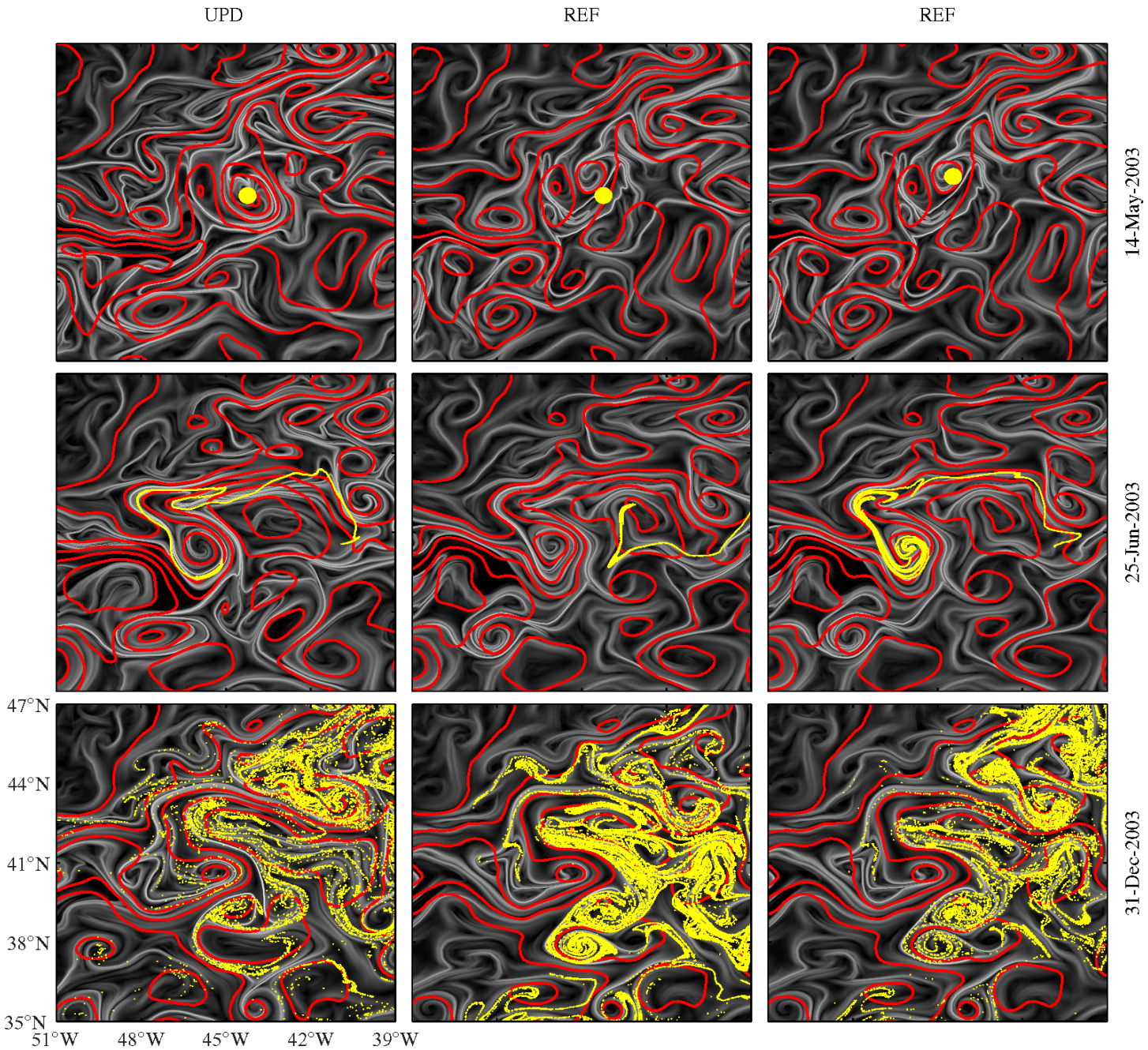

Broad, asymmetric PDF suggests heterogeneous mixing.

# Eulerian and Lagrangian correlations

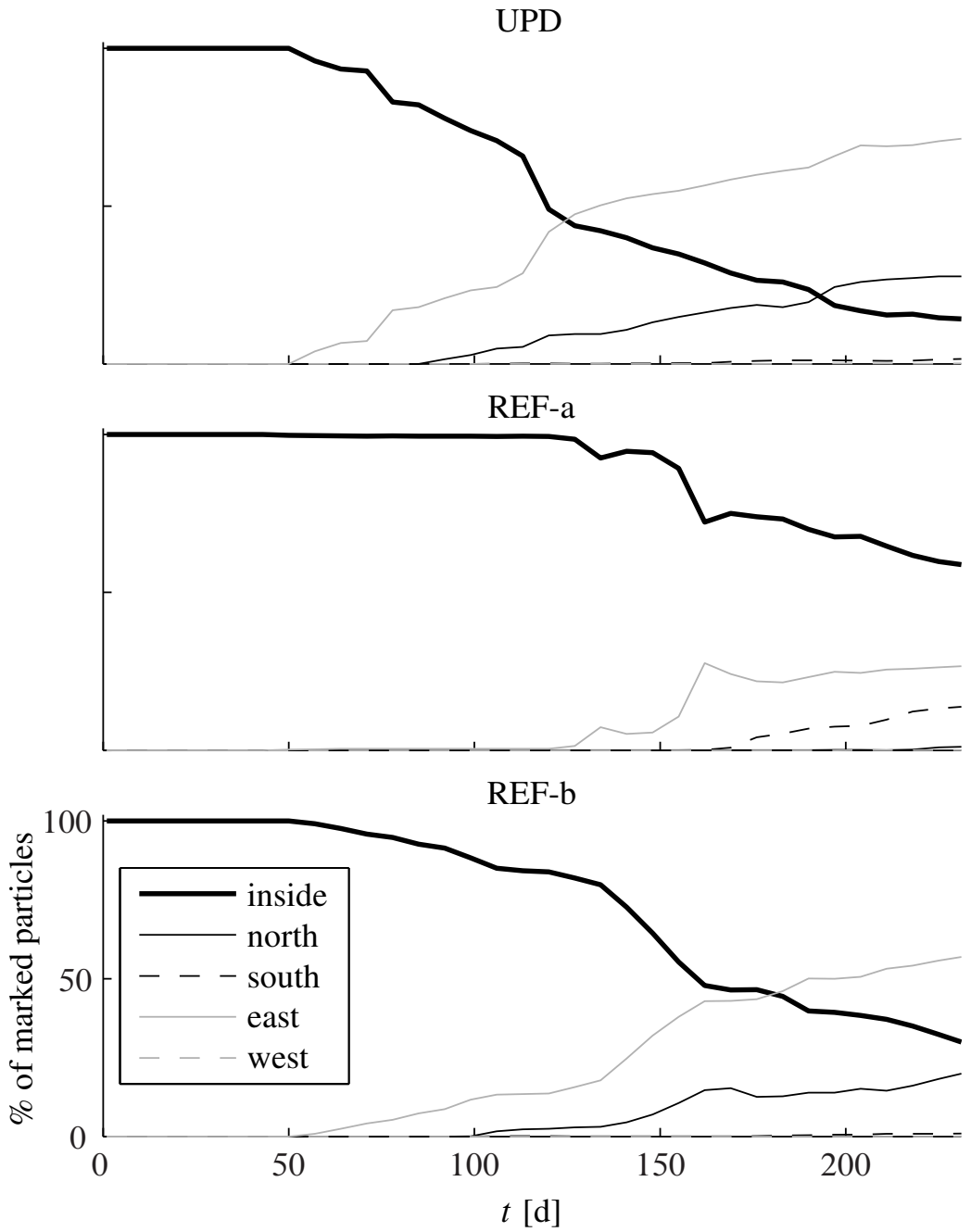



Lagrangian autocorrelation time is shorter than Eulerian.

# Explicit passive tracer advection



# Transport


UPD
REF-a
REF-b
% of marked particles
100
50
0
0
50
100
150
200
t [d]
inside
north
south
east
west

# Concluding remarks

- UPD currents support mixing with characteristics similar that sustained by REF currents.
- Follows from the fact that, being more easily characterized as chaotic than turbulent, mixing is not too resolution dependent.
- No attempt was made to make inferences about the effects of scales not resolved by UPD currents, except that extracted LCS showed consistency with drifter trajectory over a few weeks.
- Recent work (Beron-Vera 2010) based on analysis of OGCM suggests that surface ocean mixing may be more homogeneous than expected from altimetry:
  - ▷ consistent with recent studies on the effects of unresolved scales (e.g., Capet et al. 2008; Klein and Lapeyre 2009);
  - ▷ validation requires appropriate measurements, which may be supplied by SWOT.

# Thank you.