The motion of objects floating on the ocean surface

F. J. Beron-Vera

Department of Atmospheric Sciences
Rosesntiel School of Marine & Atmospheric Science
University of Miami

Joint work with:

M. J. Olascoaga (RSMAS) & R. Lumpkin (NOAA)

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fberon@rsmas.miami.edu

UNIVERSITY OF MIAMI
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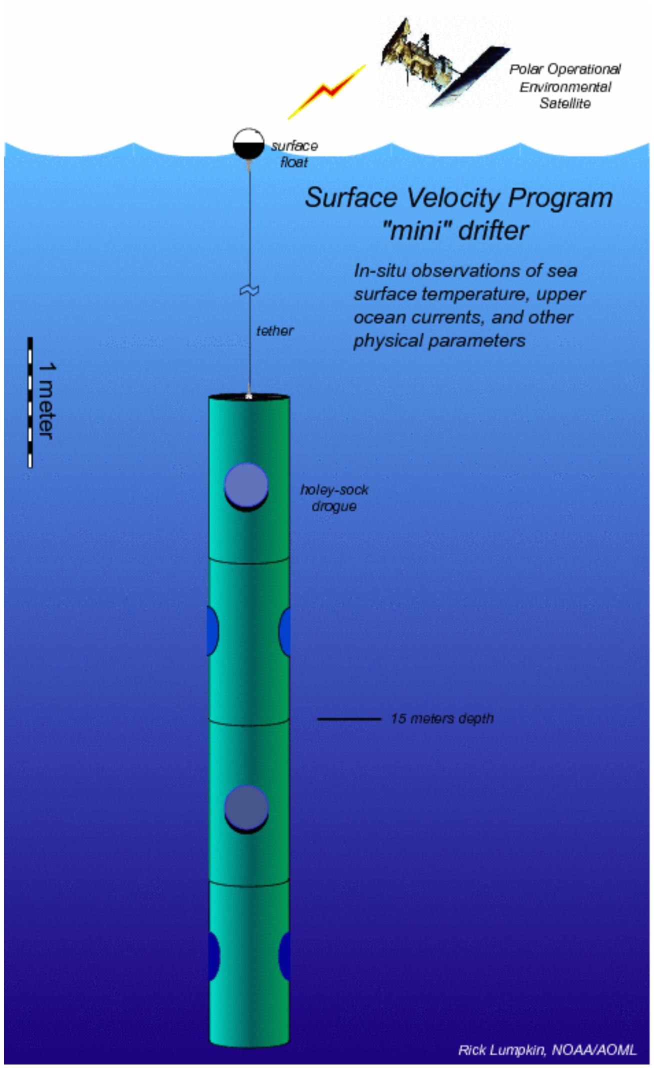
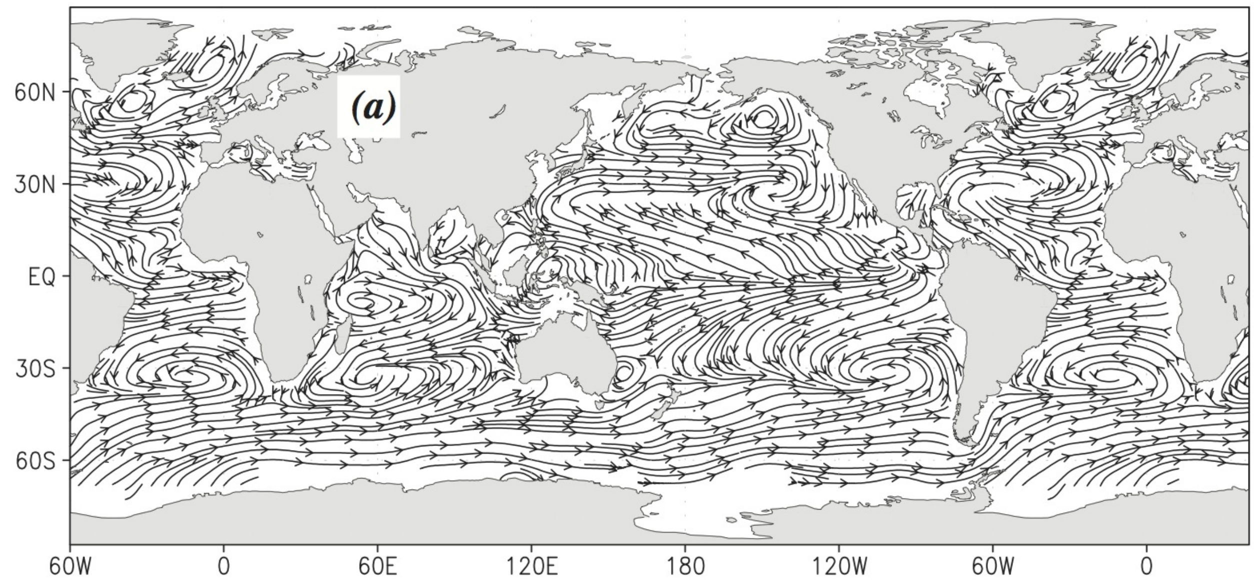
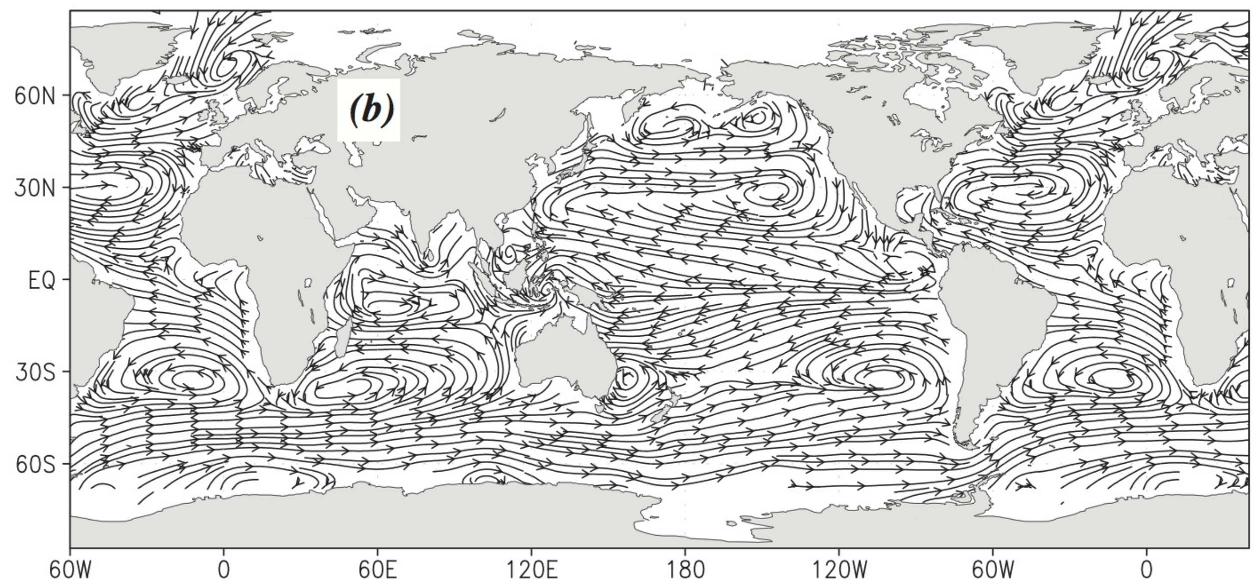
Surface drifting buoys from Global Drifter Program



Follow SVP design (Sybrandy & Niiler, 1992). About 5K over 1979–present. Tracked using satellites. GDP database maintained by NOAA (Lumpkin & Pazos, 2007).

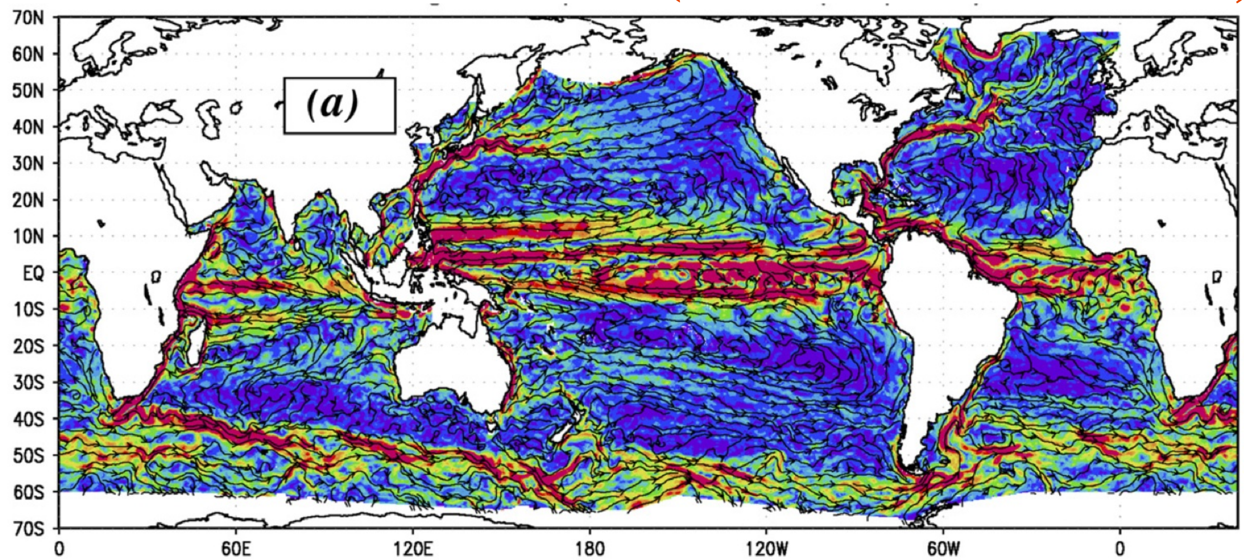
Converge in ocean gyres (Maximenko et al., 2012)

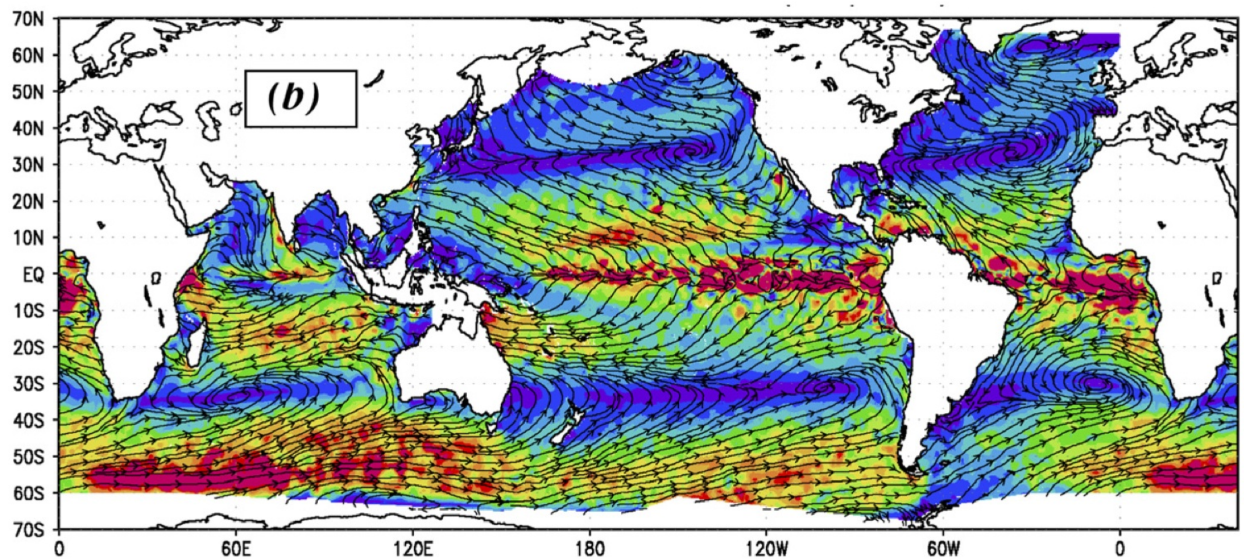




Both drogued (top) and *un*drogued (bottom) ensemble-mean (1979–2012) streamlines show sinks in the centers of the subtropical gyres.

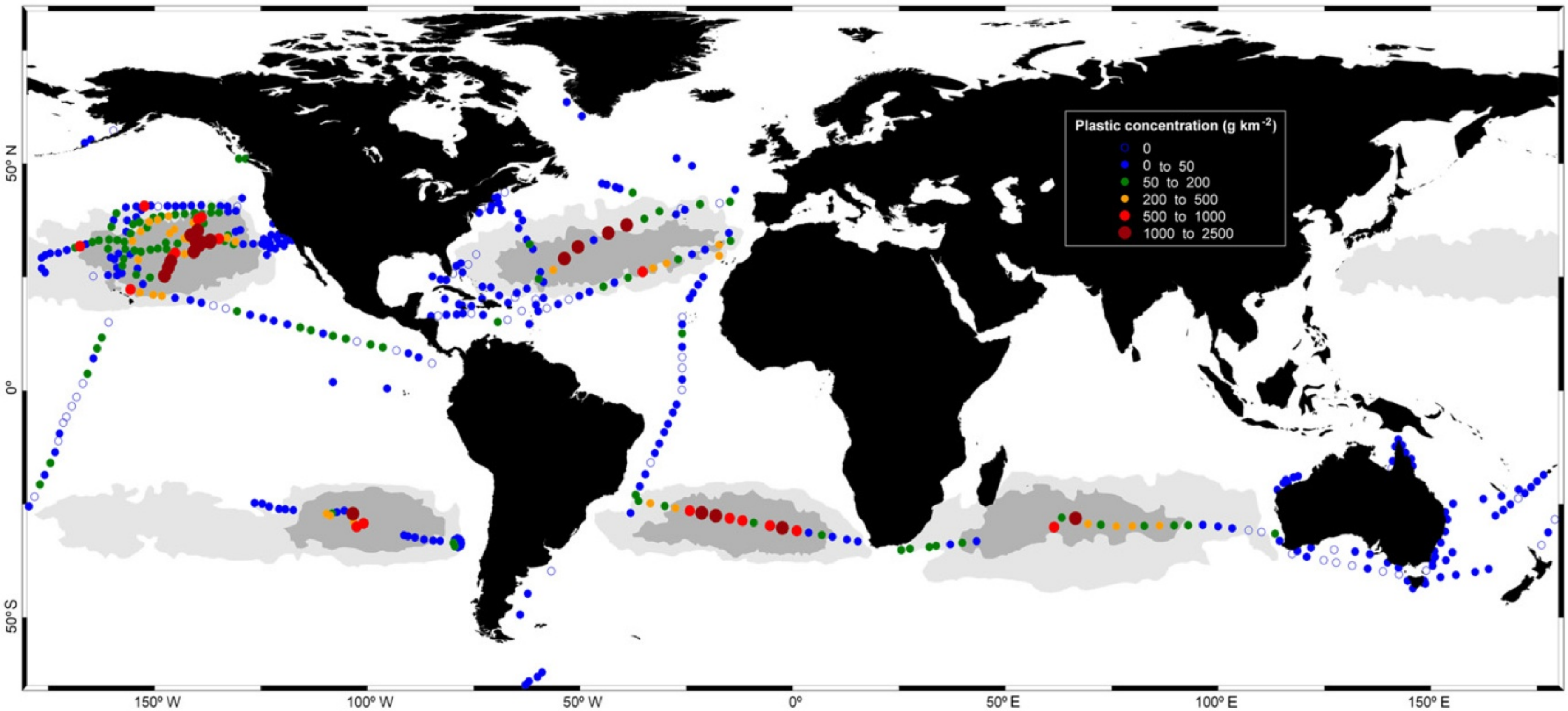
Attributed to Ekman drift (Maximenko et al., 2012)





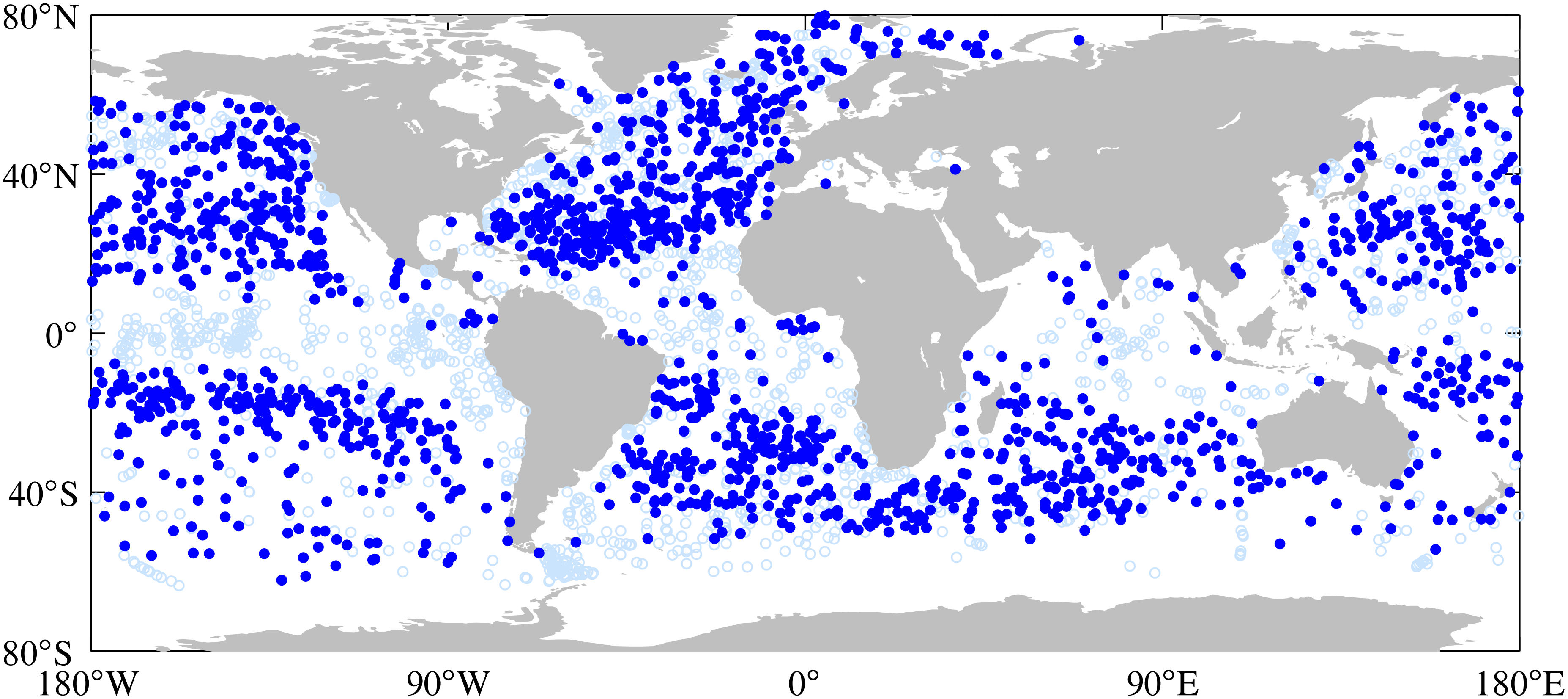
Mean geostrophic flow derived from altimetry ($g\nabla^{\perp}\eta/f$; top) does not show sinks. Wind-forced geostrophic flow ($g\nabla^{\perp}\eta/f - \sigma^{\perp}/Hf$; bottom) shows sinks *if parameters are chosen to match trajectories*.

Plastic debris accumulate in gyres too (Cozar et al., 2014)



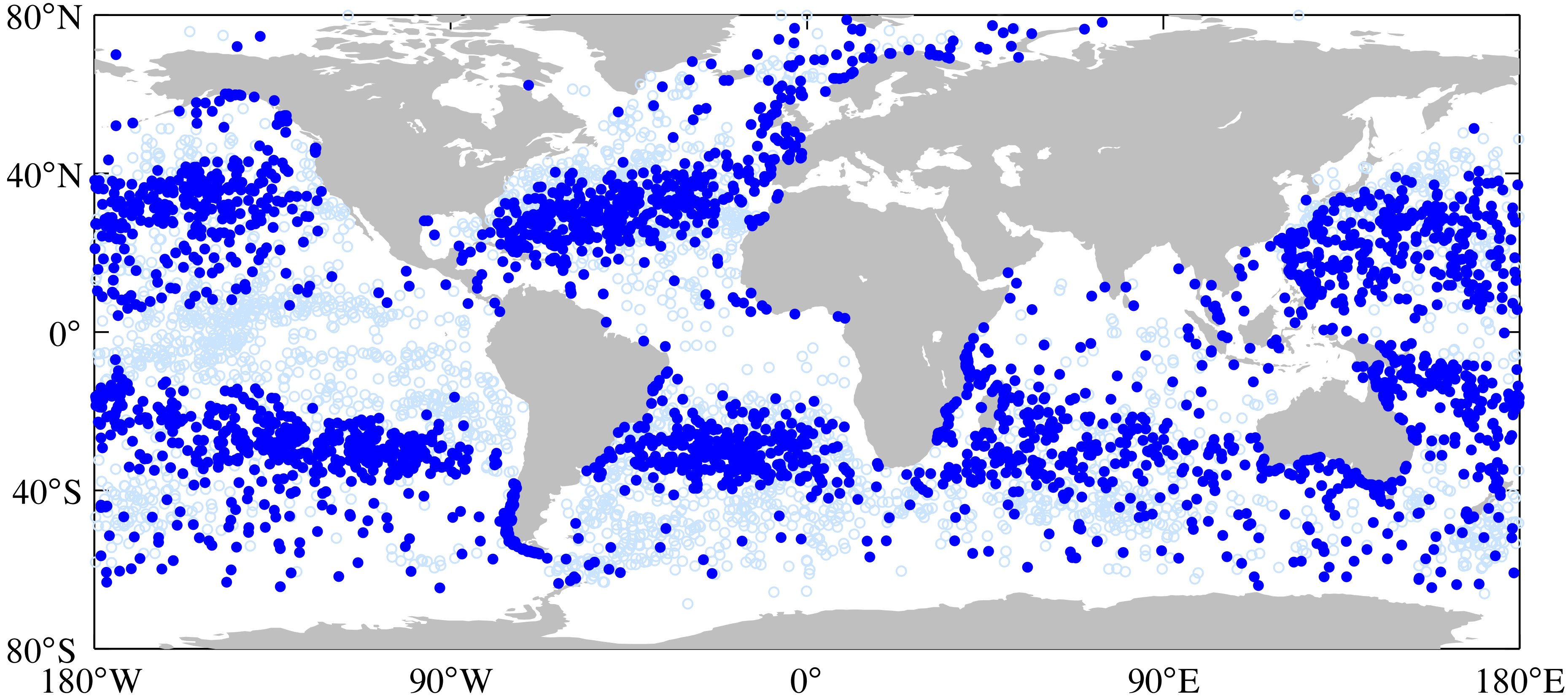
Consistent with Maximenko's et al. (2012) analysis but they were (apparently) unaware of issues with drogue presence verification (Lumpkin et al. 2012).

Drogued drifter distribution



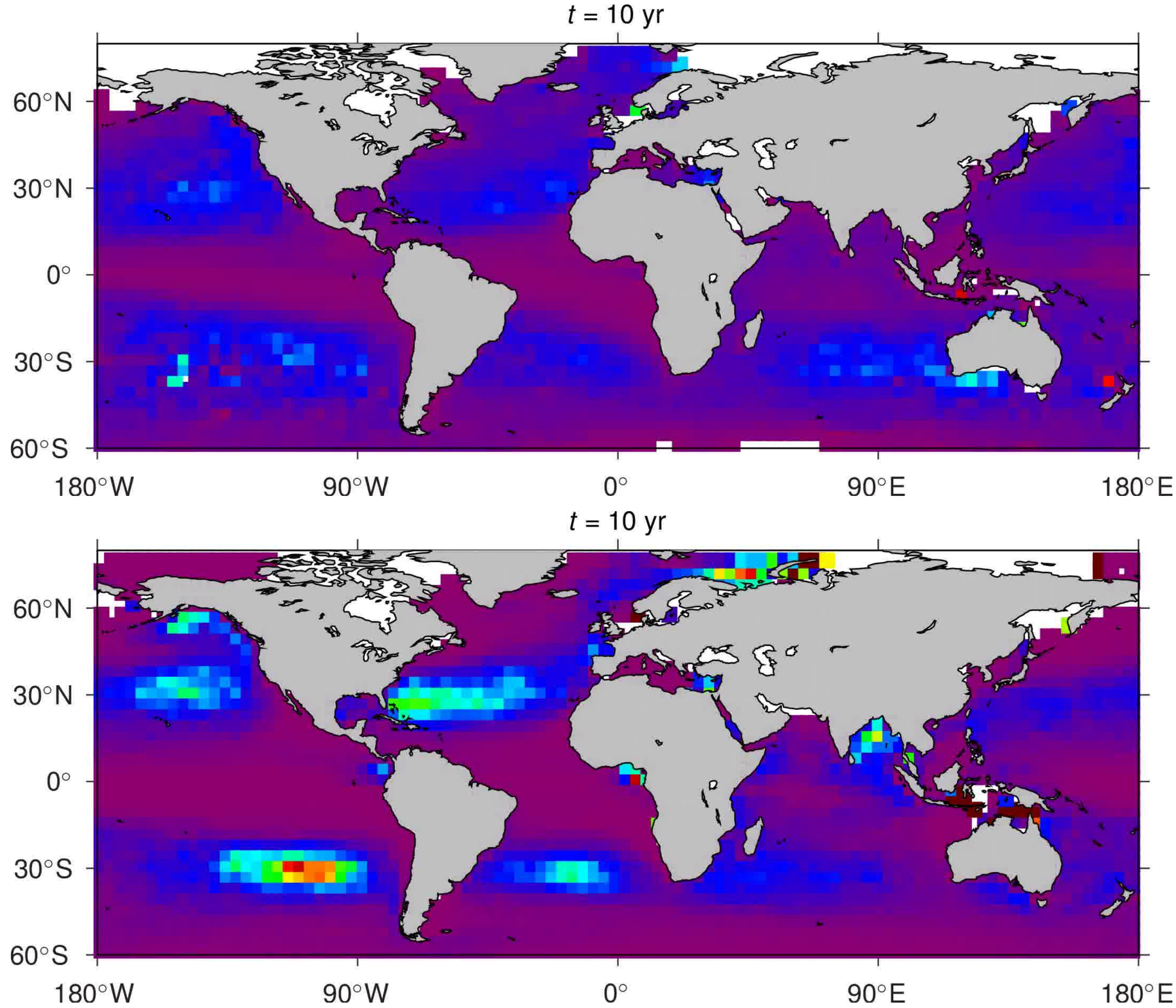
Light-blue circles are deployment sites over 1979–2015. Dark-blue dots are positions after 1.5 yr. Final positions are rather homogeneously distributed.

*Un*drogued drifter distribution



Light-blue circles indicate positions when drifters loss their drogues. Dark-blue dots are positions after 1.5 yr. Final positions are more concentrated in subtropical gyre centers. Suggests that inertial effects (i.e., of drifters' finite size and mass) are important.

Inertial effects accumulate over time



Uniform density pushed forward with transition matrix that uses 2-day-long trajectories regardless of starting time (Maximenko et al., 2012; van Sebille et al., 2012; Froyland et al., 2014). Work in progress.

New Maxey–Riley equation

$$\boxed{\ddot{x} + f\dot{x}^{\perp} = \dot{v} + fv^{\perp} - \frac{2\left(\gamma + \sqrt[3]{\delta - 1}\right)}{3\gamma\sqrt[3]{\delta}\tau}(\dot{x} - u)}$$

$$u := \frac{\gamma v + \sqrt[3]{\delta - 1}v_{\mathrm{a}}}{\gamma + \sqrt[3]{\delta - 1}}, \quad \delta := \frac{\rho}{\rho_{\mathrm{p}}} \geq 1, \quad \tau := \frac{2a^2}{9\nu\delta}, \quad \gamma := \frac{\nu\rho}{\nu_{\mathrm{a}}\rho_{\mathrm{a}}}$$

- Submerged (surfaced) particle piece is modeled as a sphere of the fractional volume that is submerged (surfaced), i.e.,

$$\sqrt[3]{\delta^{-1}}a\,\left(\sqrt[3]{1 - \delta^{-1}}a\right).$$

- Subspheres are advected together, forces are calculated at the same position, and added as if subspheres were decoupled.
- Basset history term and Faxen corrections ignored.

FJBV, M. J. Olascoaga & R. Lumpkin (2016). Inertia-induced accumulation of flotsam in the subtropical gyres. *Geophys. Res. Lett.* 43, 12228.

Reduced Maxey–Riley ("inertial") equation

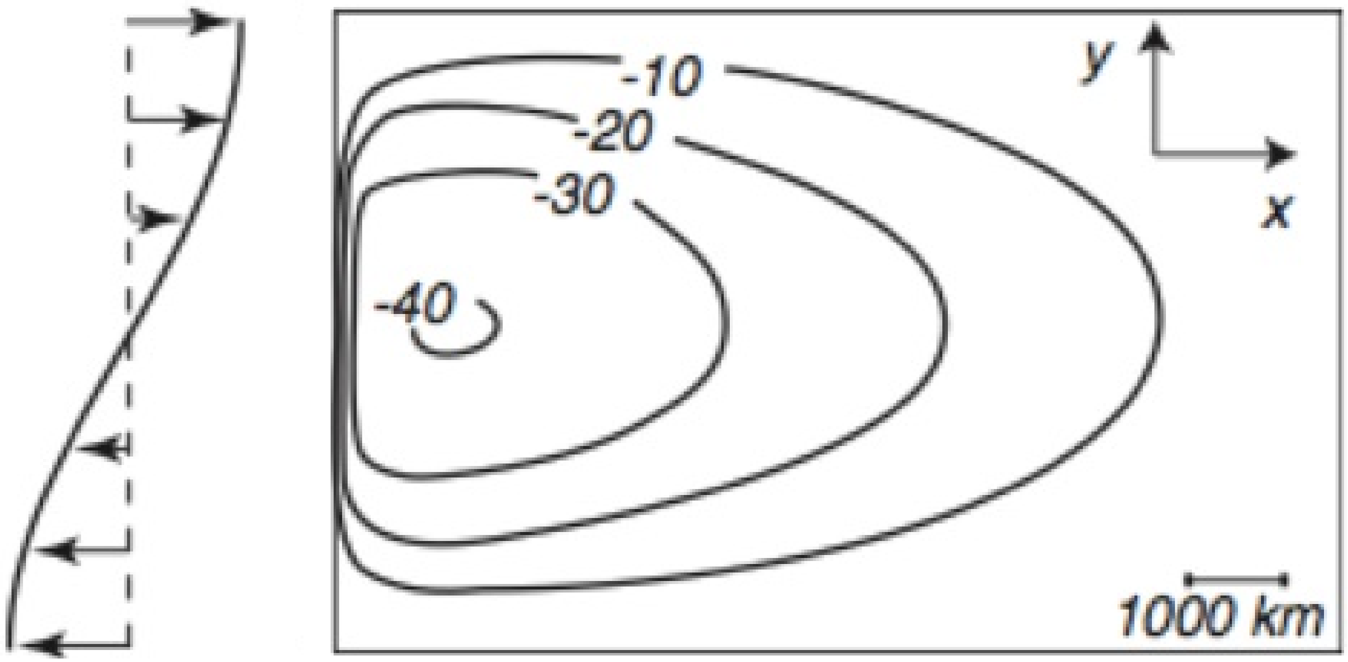
For infinitesimal particles ($\tau \to 0$):

$$\boxed{\dot{x} = v_{\mathrm{p}} = u + \frac{3\gamma\sqrt[3]{\delta}\tau}{2\big(\gamma + \sqrt[3]{\delta - 1}\big)}\big(\dot{v} - \dot{u} + f(v - u)^{\perp}\big)} + O(\tau^2).$$

Obtained by FJBV et al. (2016) following earlier work (Rubin et al., 1995; Haller & Sapsis, 2008; FJBV et al., 2015) that used Fenichel's (1979) singular perturbation approach.

- Sizeless ($\tau = 0$) but buoyant ($\delta > 1$) particles obey $\dot{x} = v_{\mathrm{p}} = u$.
- Infinitesimally-small ($\tau \to 0$) neutrally-buoyant ($\delta = 1$) behave as water particles because $u = v$.
- When a particle is completely exposed to the air ($\delta \to \infty$), the motion is driven by the air flow.
- When the air is sufficiently calm ($v_{\mathrm{a}} \approx 0$) and $\dot{v} \approx 0$ (geostrophic flow), $\operatorname{sign} \nabla \cdot v_{\mathrm{p}} = \operatorname{sign} f\omega$, so particles converge into (diverge from) cyclonic (anticyclonic) coherent Lagrangian eddies (FJBV et al., 2015; Haller et al., 2016).

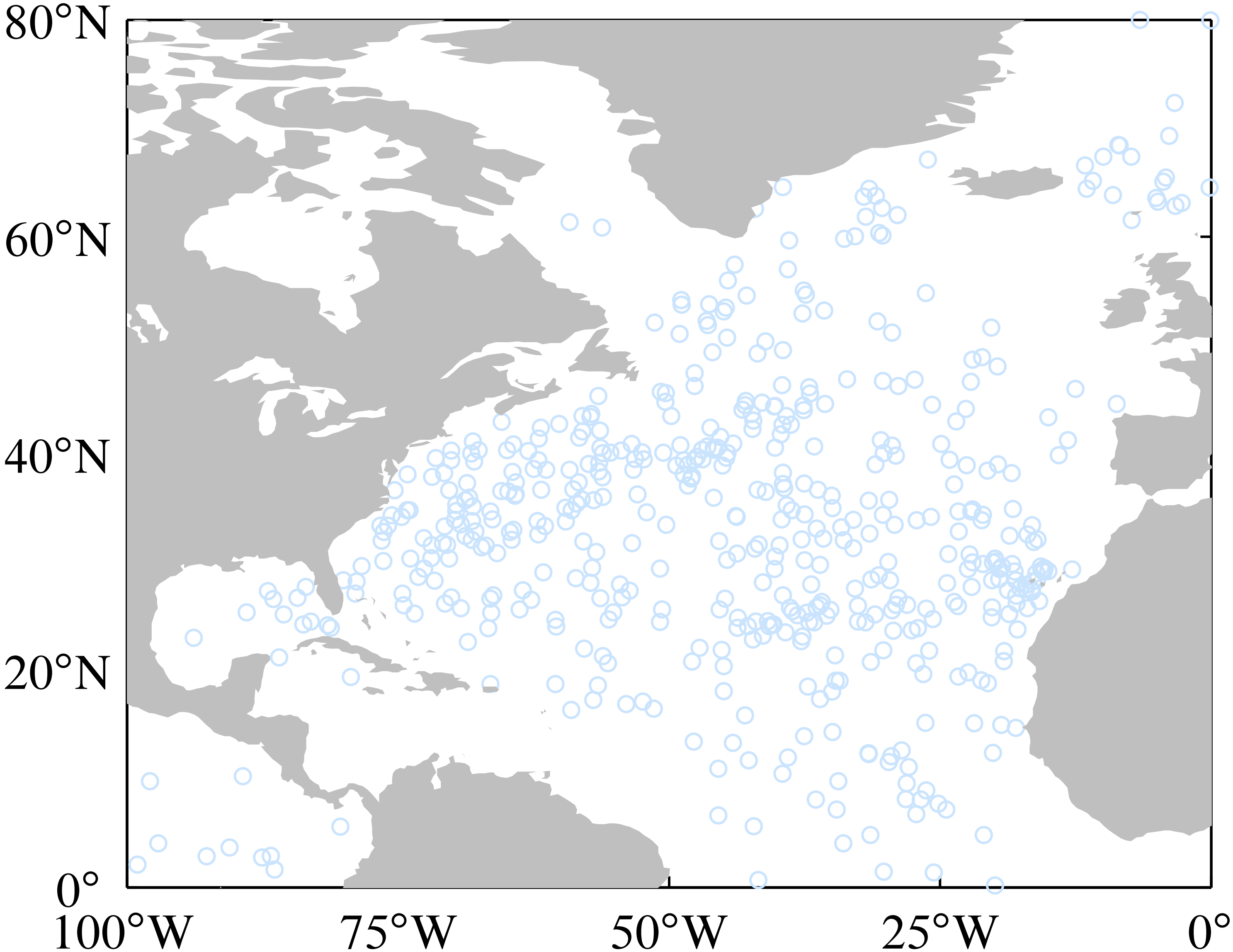
Can our proposed inertial equation ever work?



$$\partial_t v = 0, \quad v \cdot \nabla v \approx 0, \quad \nabla \cdot v = 0, \quad \nabla \cdot v_{\mathrm{a}} = 0 \quad \text{(Stommel, 1949)}$$

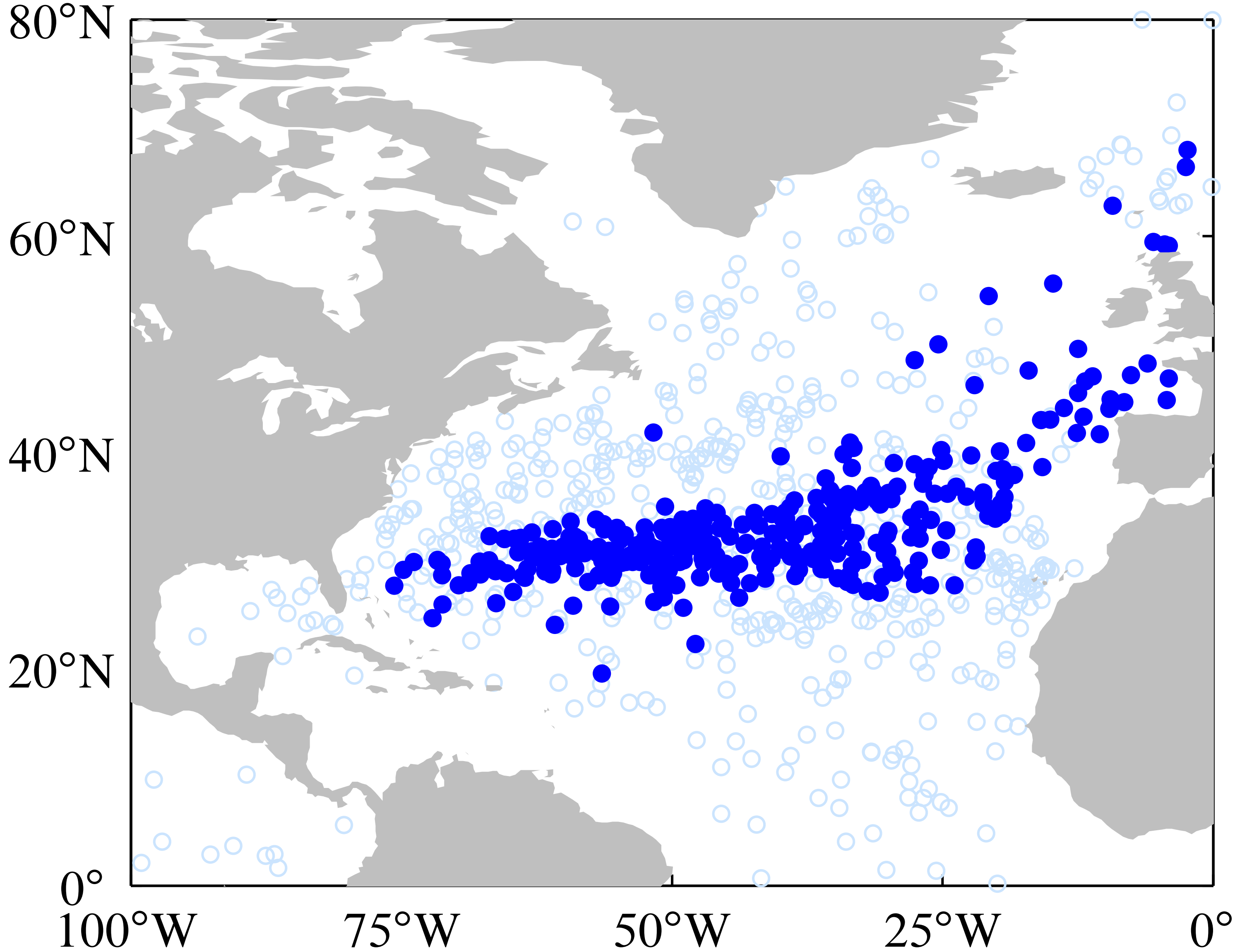
$$\nabla \cdot v_{\mathrm{p}} \approx \frac{3\gamma \sqrt[3]{\delta} \tau}{\underbrace{2\left(\gamma + \sqrt[3]{\delta - 1}\right)^2}_{>0}} \underbrace{\sqrt[3]{\delta - 1}}_{>0} \underbrace{f \omega_{\mathrm{a}}}_{<0} < 0$$

Start from undrogued drifter ICs



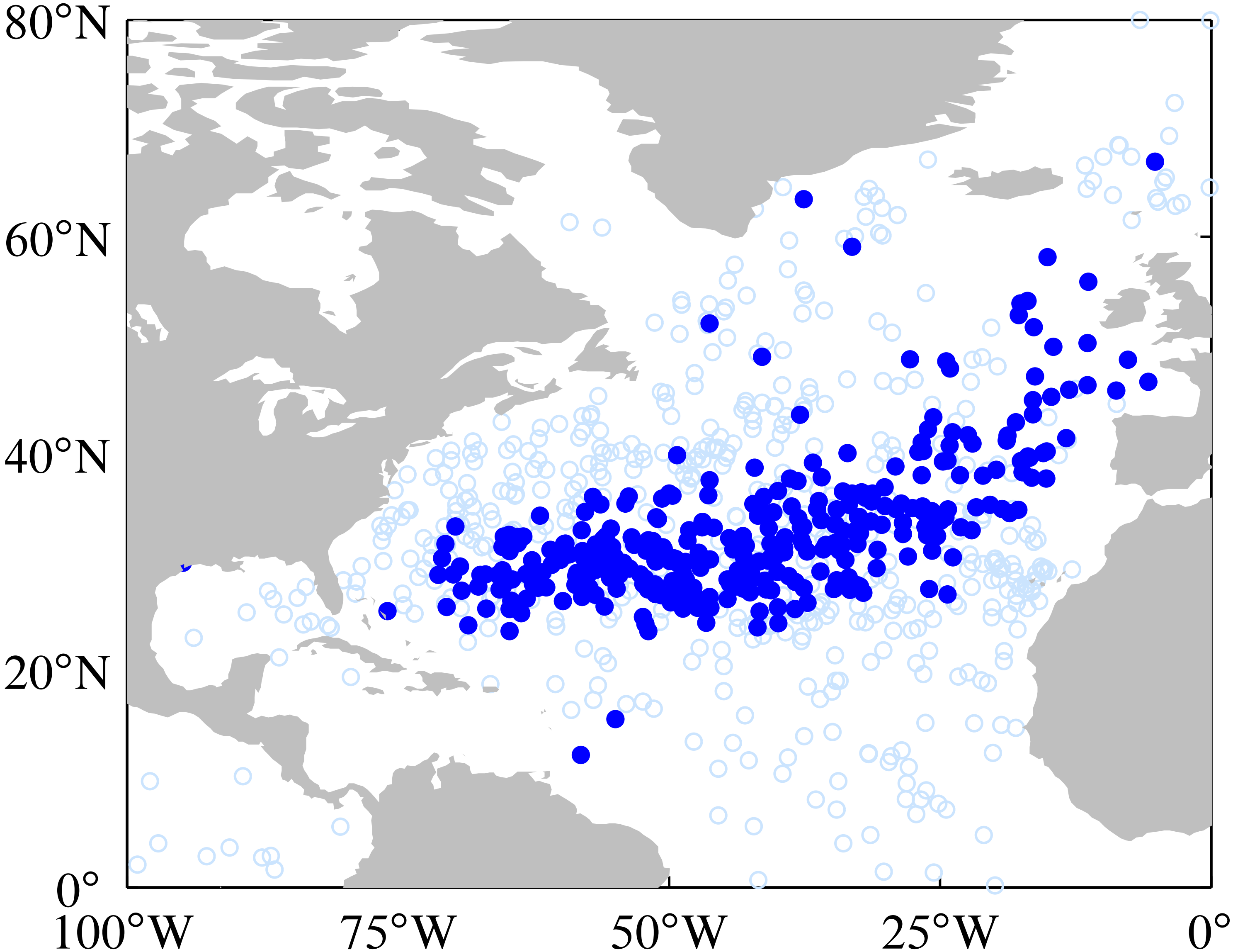
Take v from Global HYCOM Reanalysis and v_{a} from NCEP.

Inertial particles ($\dot{x} = u + \tau \cdots$) after 1.5 yr



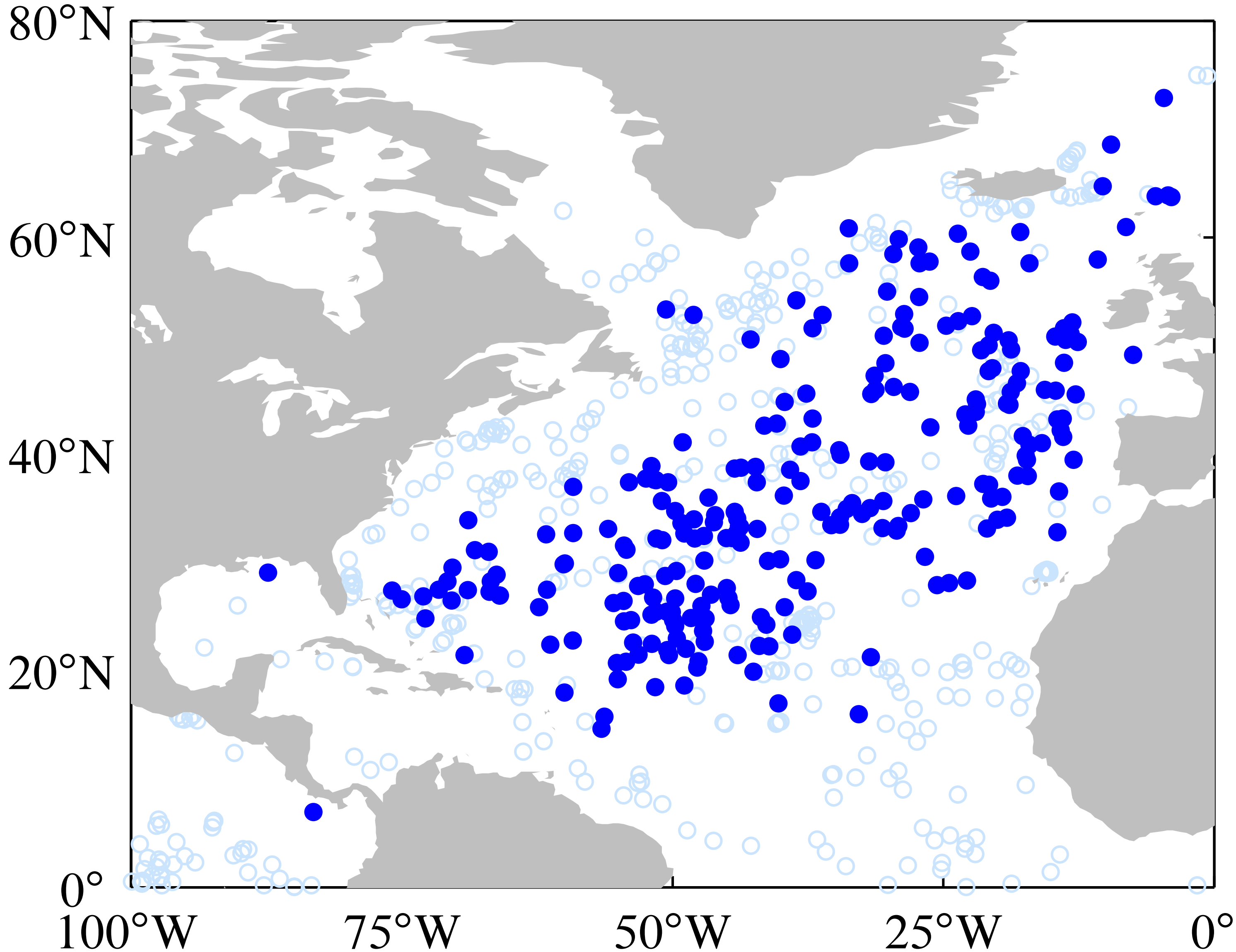
$\delta = 2, \gamma \approx 60, \tau \approx 0.05$ d

Full Maxey–Riley particles ($\ddot{x} + f\,\dot{x}^{\perp} = \cdots$)



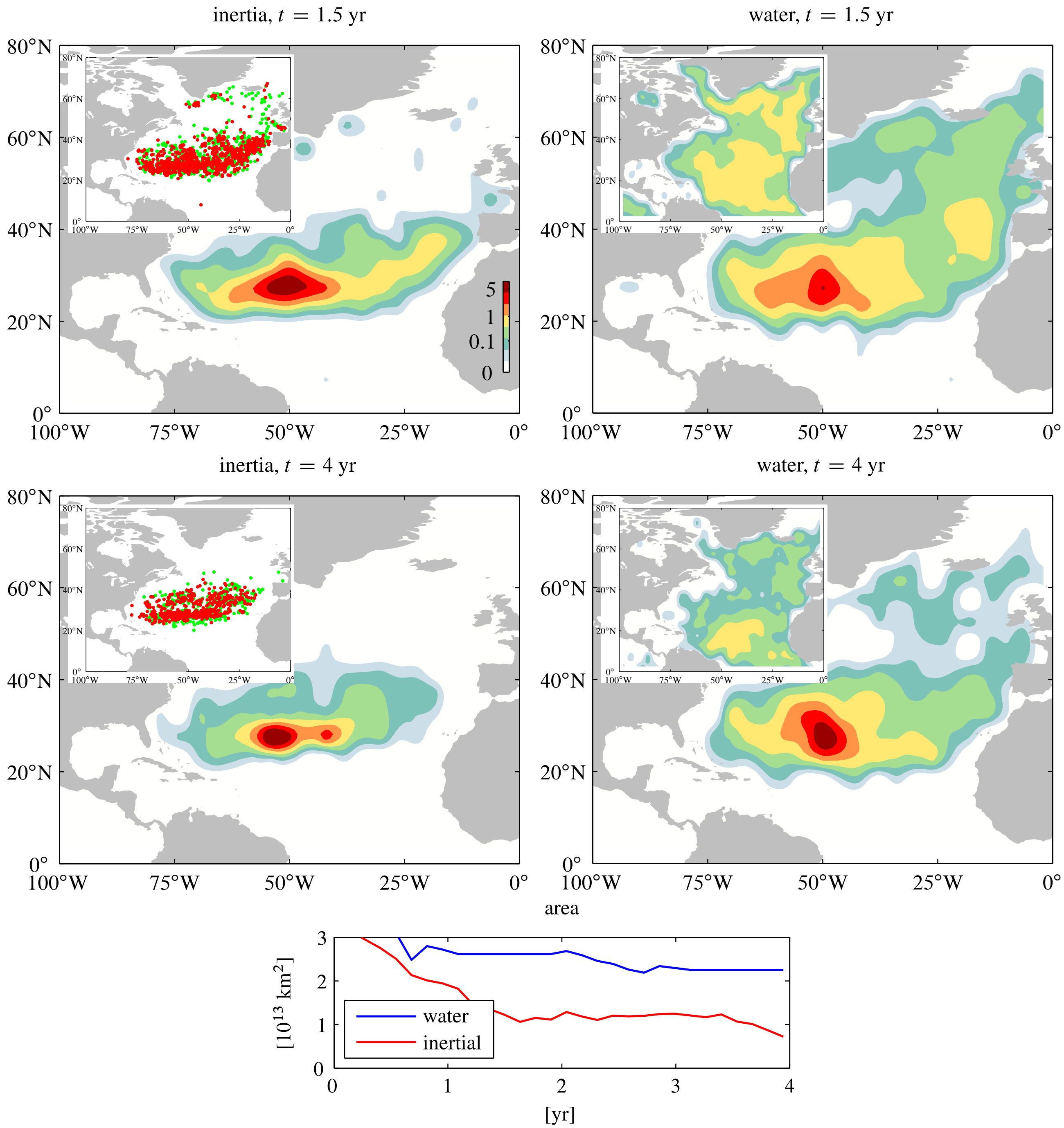
Initial velocities taken as inertial particle velocities.

Water particles ($\dot{x} = v$)

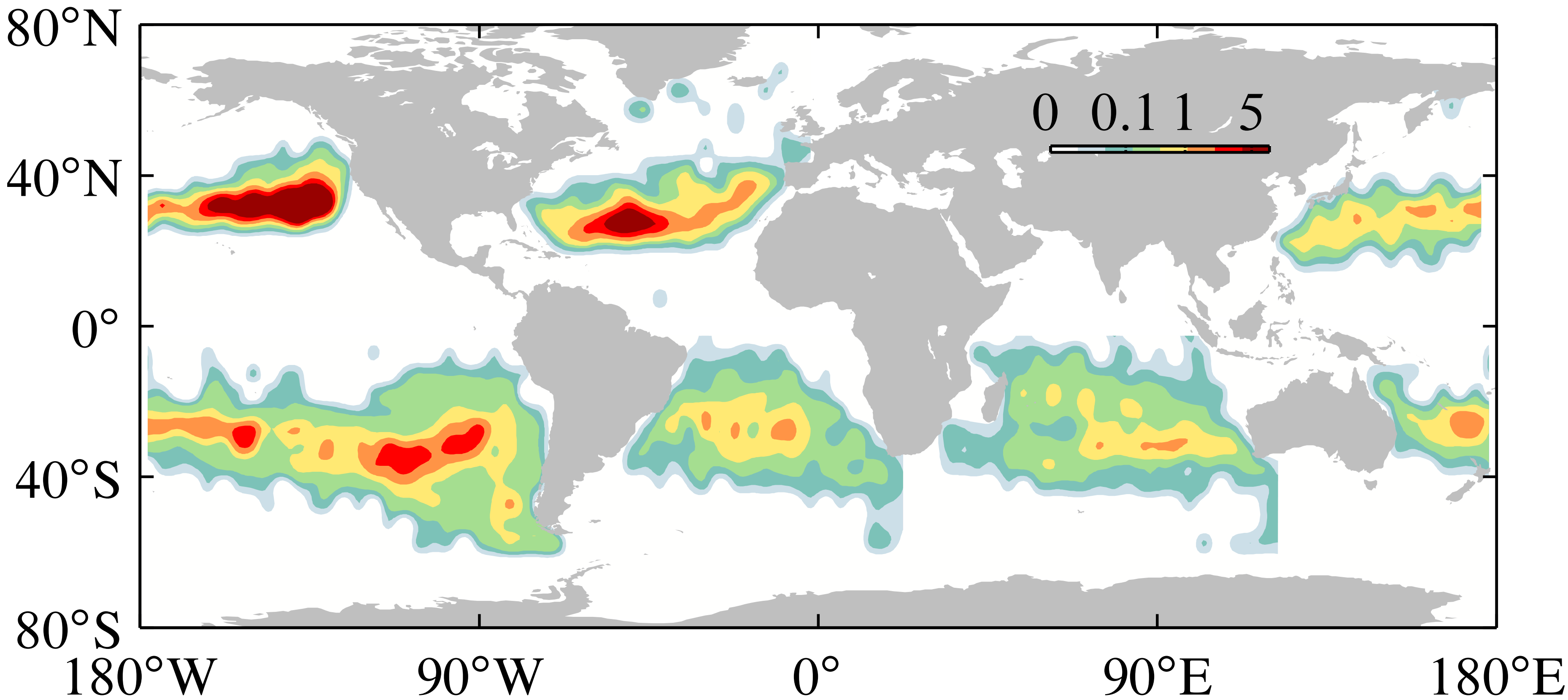


No noticeable signs of accumulation; need to wait longer.

Accumulation due to Ekman transport is a slower process

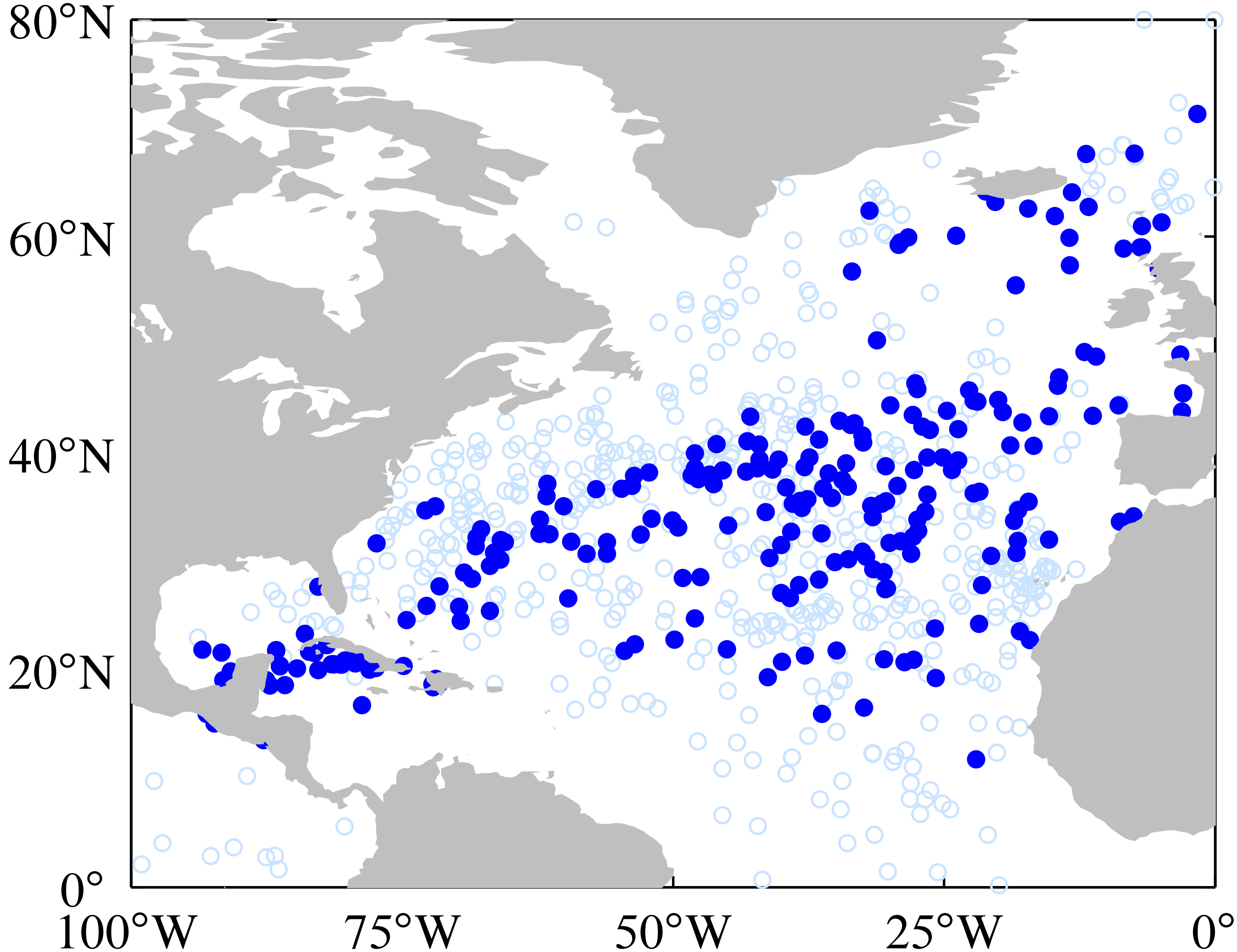


Global calculation



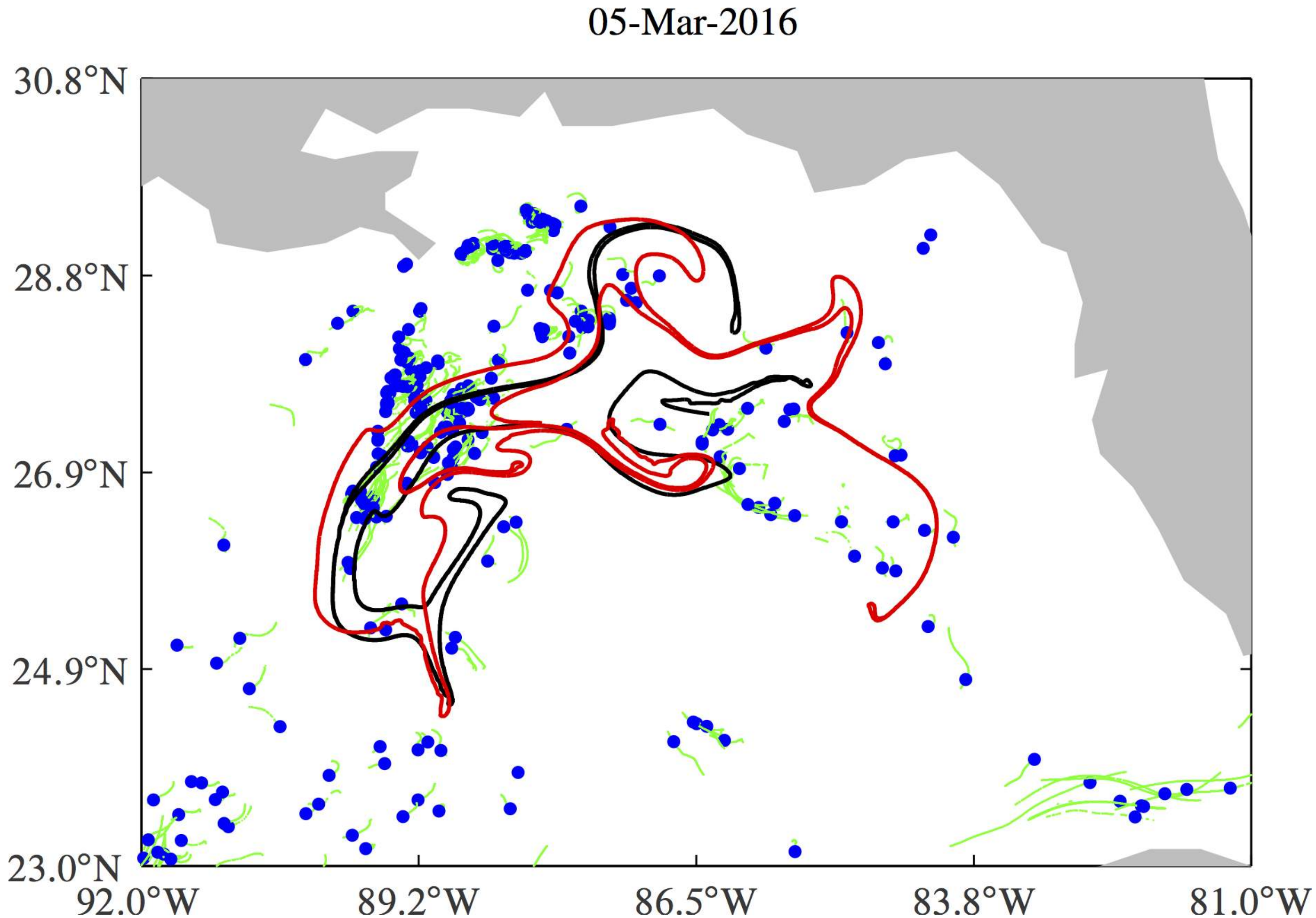
Reveals great garbage patches in the centers of the five ocean gyres.

Particles obeying $\dot{x} = v + 0.05v_a$



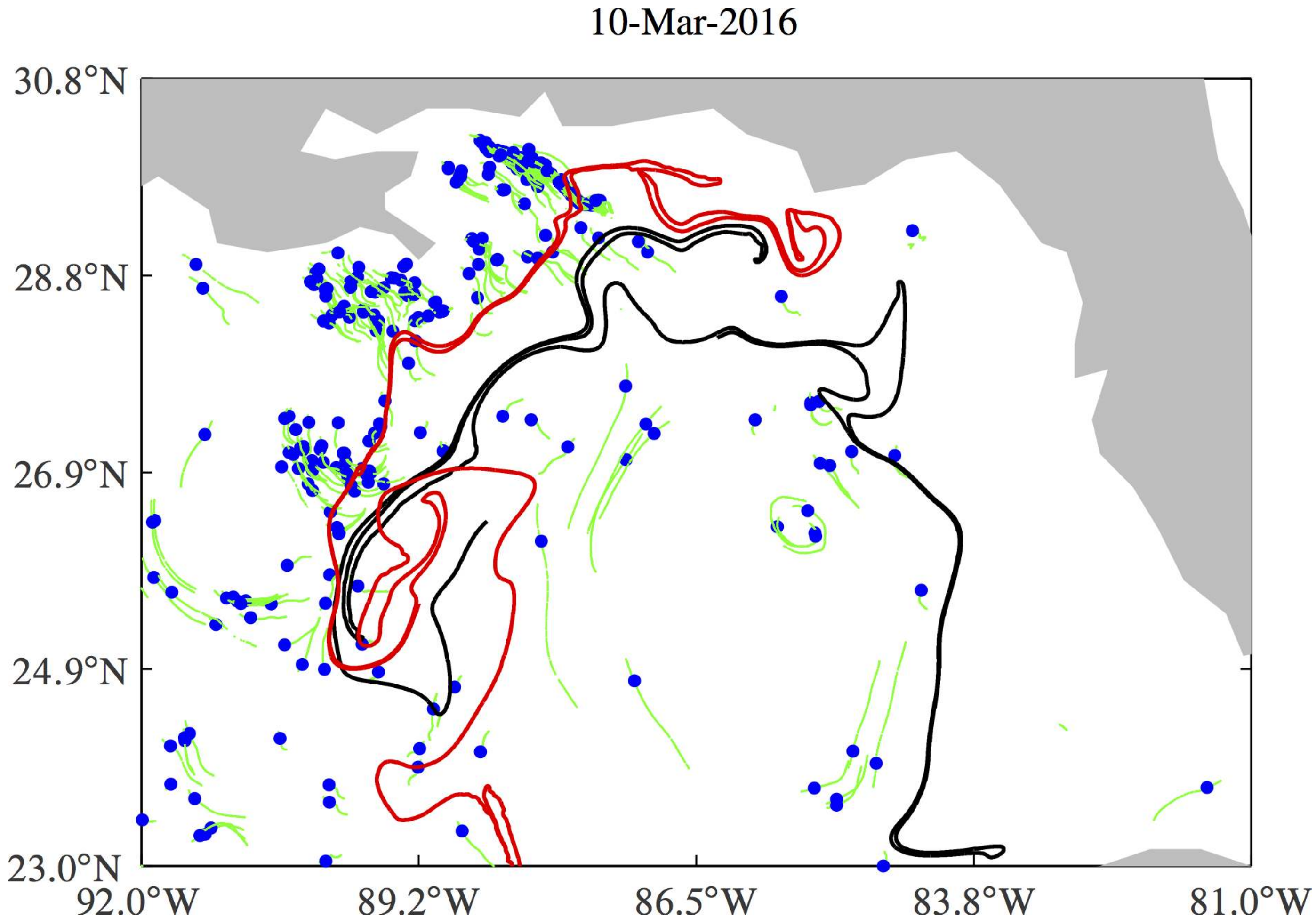
Note $u \approx v + 0.02v_a$ and recall $\dot{x} = u + \tau \cdots$ (size matters).

LCS vs iLCS



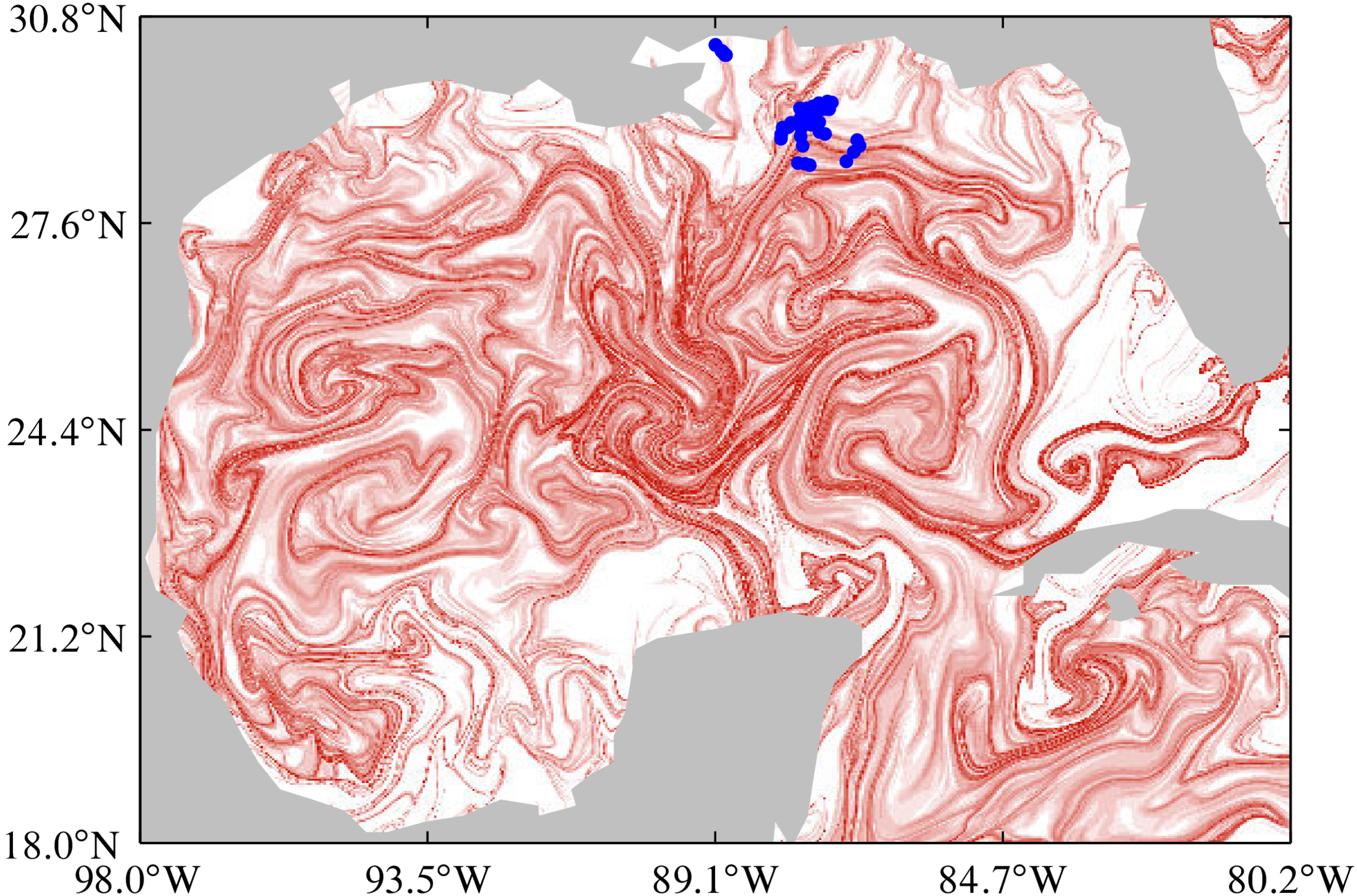
Drifters from the LAgrangian Submesoscale ExpeRiment (LASER) carried by GoMRI consortium CARTHE (T. Özgökmen, PI). Water velocities inferred from altimetry. LCS computed as fwd stretchlines using geodesic theory (Haller & FJBV, 2012; Farazmand et al., 2014).

LCS vs iLCS



iLCS (red) better flow drifter motion than LCS (black). Discrepancies attributed to uncertainty around water and air velocities.

22-Jan-2016



Concluding remarks

- Undrogued drifters are strongly influenced by inertial effects.
- We infer that plastic debris which accumulate in the same regions and flotsam in general are affected by inertial effects.
- Shipwreck and airplane debris tracking, pollution source identification, and search and rescue operations at sea are some applications that can benefit from the use of our inertial equation.
- Whether inaccuracies resulting from our heuristic derivation of this equation and omission of a number of potentially important processes (Stokes drift, infragravity waves, subgrid motions, etc.) or the quality of the velocity realizations will constrain more its success in such applications is a subject of ongoing research.

Thank you.