An improved near-surface velocity climatology for the global ocean from drifter observations

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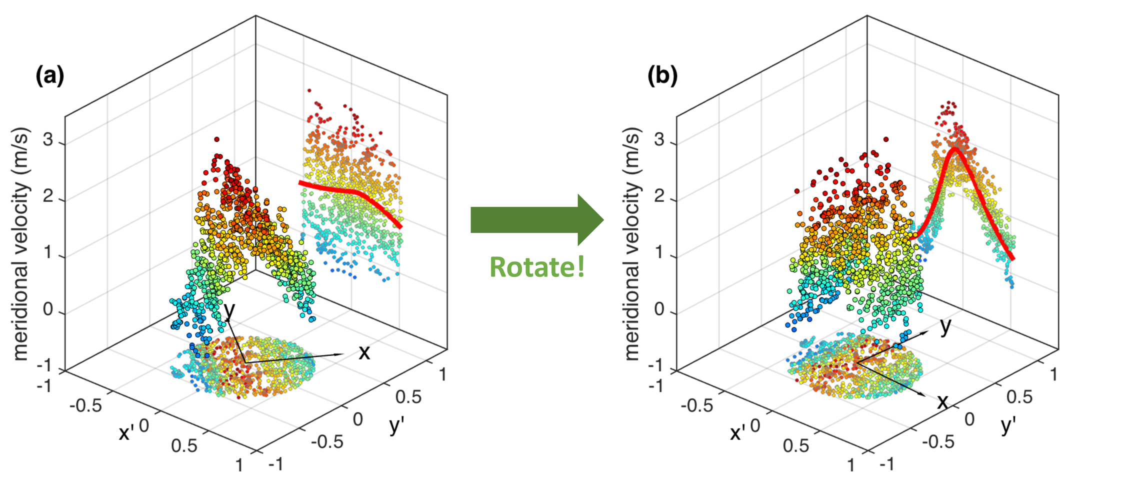
1. Introduction:

1. Global Drifter Program (GDP) drifters currently provide the most accurate observations of near-surface ocean velocities globally. Using data from 15-m drogued GDP drifters, Lumpkin and Johnson (2013) [1] produced a global near-surface velocity climatology using a new binning method that simultaneously models spatial and temporal variations.
2. To obtain statistically significant estimates homogeneously distributed throughout the oceans, [1] selected observations within relatively large bins [ellipses with areas of $A = \pi(2°)^2$], with the potential to smooth horizontal velocity gradients at scales smaller than the bin size.
3. Aiming to refine the drifter-derived climatology, this work [2] updates the methods of Lumpkin and Johnson (2013) by (a) incorporating data from undrogued drifters to the analysis, and (b) introducing a new estimation method designed to further reduce the smoothing of spatial gradients inherent in data binning methods.

2. Decomposition method:

- Previous studies modeled horizontal gradients within bins using 2-D functions, $U(x,y,t) = \langle U \rangle + \tilde{U}(x,y) + U'(x,y,t)$.
- Considering that time-mean ocean velocities are highly anisotropic, this work models $\tilde{U}(x,y)$ using 1-D functions, $\tilde{U}(\hat{x})$.
- $\hat{x}$ coordinates are found via the rotation of the Cartesian coordinate system, being defined at the angle that minimizes fitting error of the 1-D curve:



- Within a bin with N observations, $U_p(\hat{x},t)$, $p = 1, 2, 3, \ldots, N$:

$$U_p(\hat{x},t) = \underbrace{\sum_{i=0}^{n}[a_i(\hat{x})]^i}_{\text{Mean spatial structure: 1-D, } n^{th} \text{ degree polynomial}} + \underbrace{\sum_{j=1}^{m}\left[b_j \sin\left(\frac{\theta t}{j}\right) + c_j \cos\left(\frac{\theta t}{j}\right)\right]}_{\text{Seasonal fluctuations: Harmonical expansion with } \theta = 1 \text{ year}} + U_p'(\hat{x},t)$$

- In matrix form: $U = Az + U'$;
- Gauss-Markov Estimation (GME) solution for z is [1]:

$$z = R_z A^T (A R_z A^T + R_n)^{-1} U, \text{ where:}$$

- R_z: variance-covariance matrix of the coefficients in z,
- R_n: variance-covariance matrix of the eddy residuals, given by:

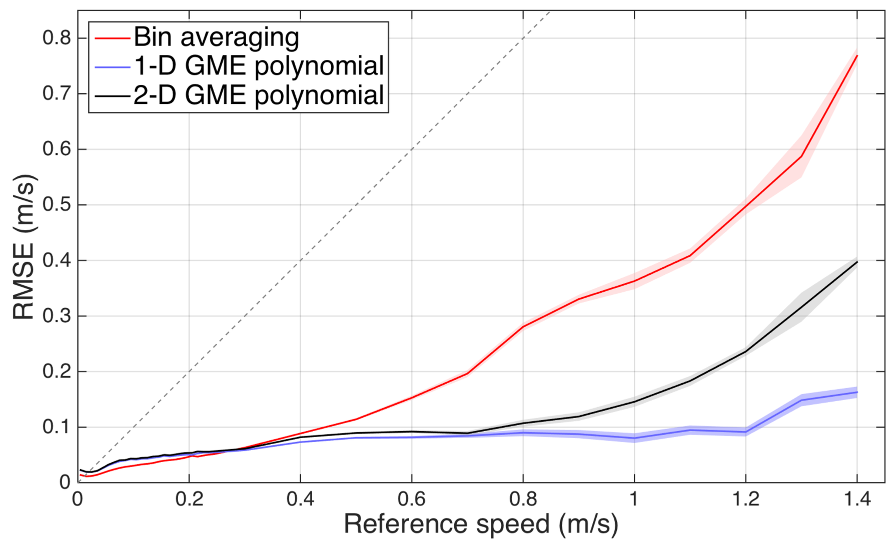
$$R_n = \sigma^2 \cos\left(\frac{\pi t}{2T_d}\right) \exp\left[-\left(\frac{\pi t}{2\sqrt{2}T_d}\right)\right], \text{ where}$$

- T_d: decorrelation time scale.
- Variance-covariance matrix of the standard errors (ε_{SE}) of z:

$$P_z = R_z - R_z A^T (A R_z A^T + R_n)^{-1} A R_z$$

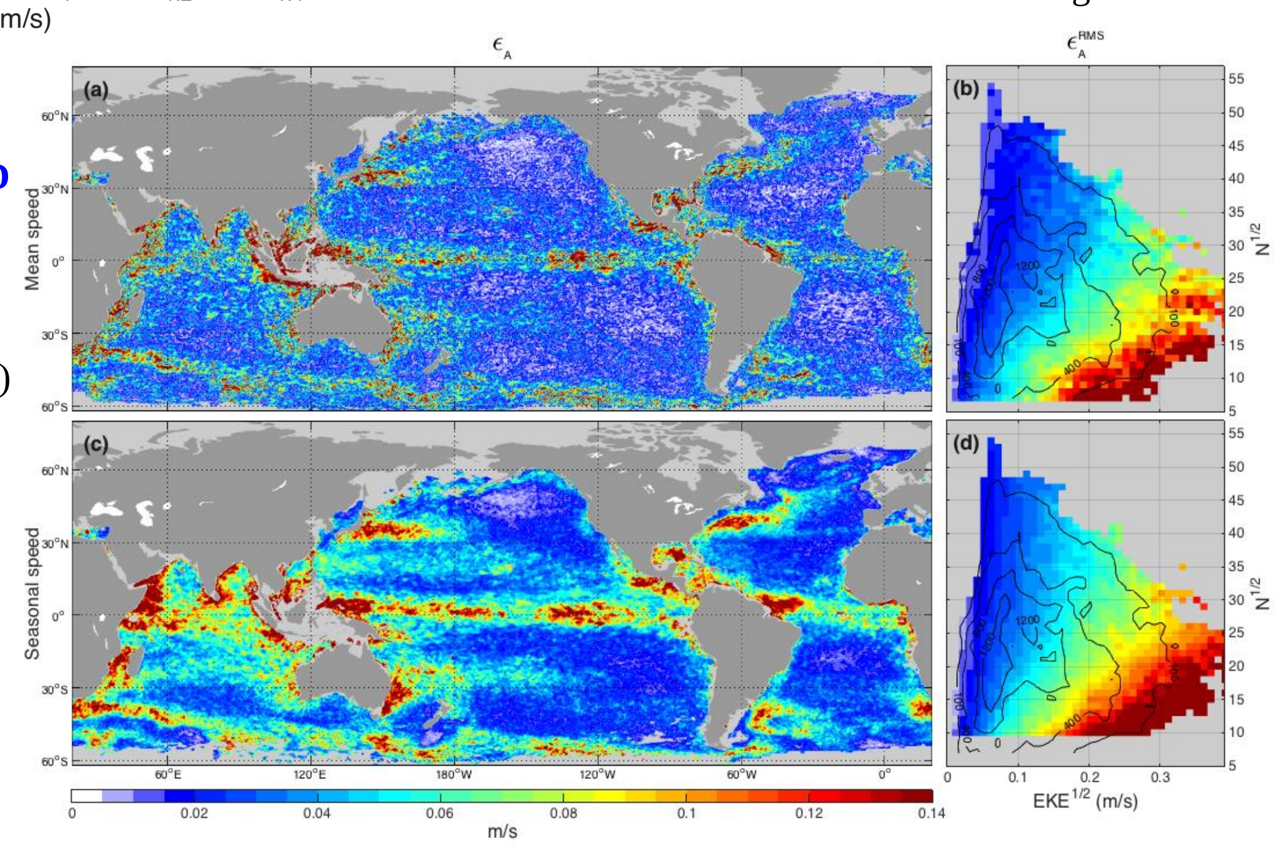
- Errors are propagated to modeled velocities via $P_n = A P_z A^T$

3. Method tuning and error analysis:



- Method is evaluated using Eulerian and pseudo-Eulerian statistics of a "toy" dataset, consisting of altimeter-derived geostrophic velocities (GV) subsampled at the GDP drifter locations, and the full GV fields.
- Absolute errors (ε_A) are defined as the magnitude of the difference between Eulerian and pseudo-Eulerian statistics.
- Sensitivity tests resulted in $n = 4$, $m = 2$, $T_d = 6.33$ days, and a ¼° × ¼° mapping resolution.
- 1° radius bins are chosen to balance smoothing and N.

- **Top:** ε_A of pseudo-Eulerian mean velocities obtained via **bin-averaging**, **2-D GME** [1], and **1-D GME**, as a function of the reference Eulerian values, for 1° radius bins.
- **Right:** ε_A map for (a) mean and (c) seasonal velocity estimates. (b) and (d) are diagrams of the RMS ε_A calculated as a function of EKE$^{1/2}$ and $N^{1/2}$ for each component.
- Absolute errors (ε_A) scale as a function of $(\sigma/N)^{1/2}$, however are about 2× larger than the standard errors (ε_{SE}) predicted by theory.



4. Correction of the slip bias of undrogued drifters:

- Slip is modeled as a simple downwind motion:

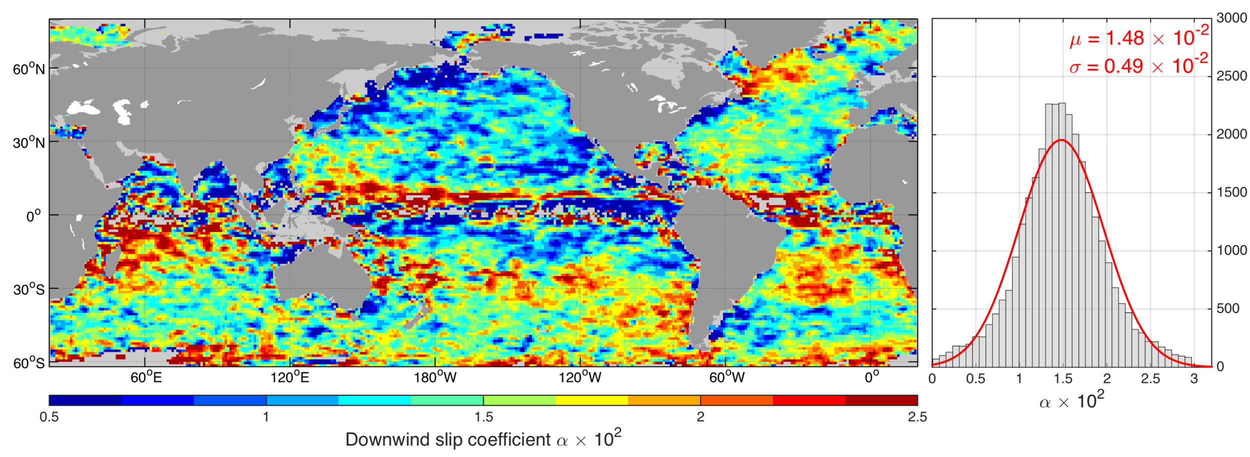
$$U_o^s = \alpha \times U_a$$

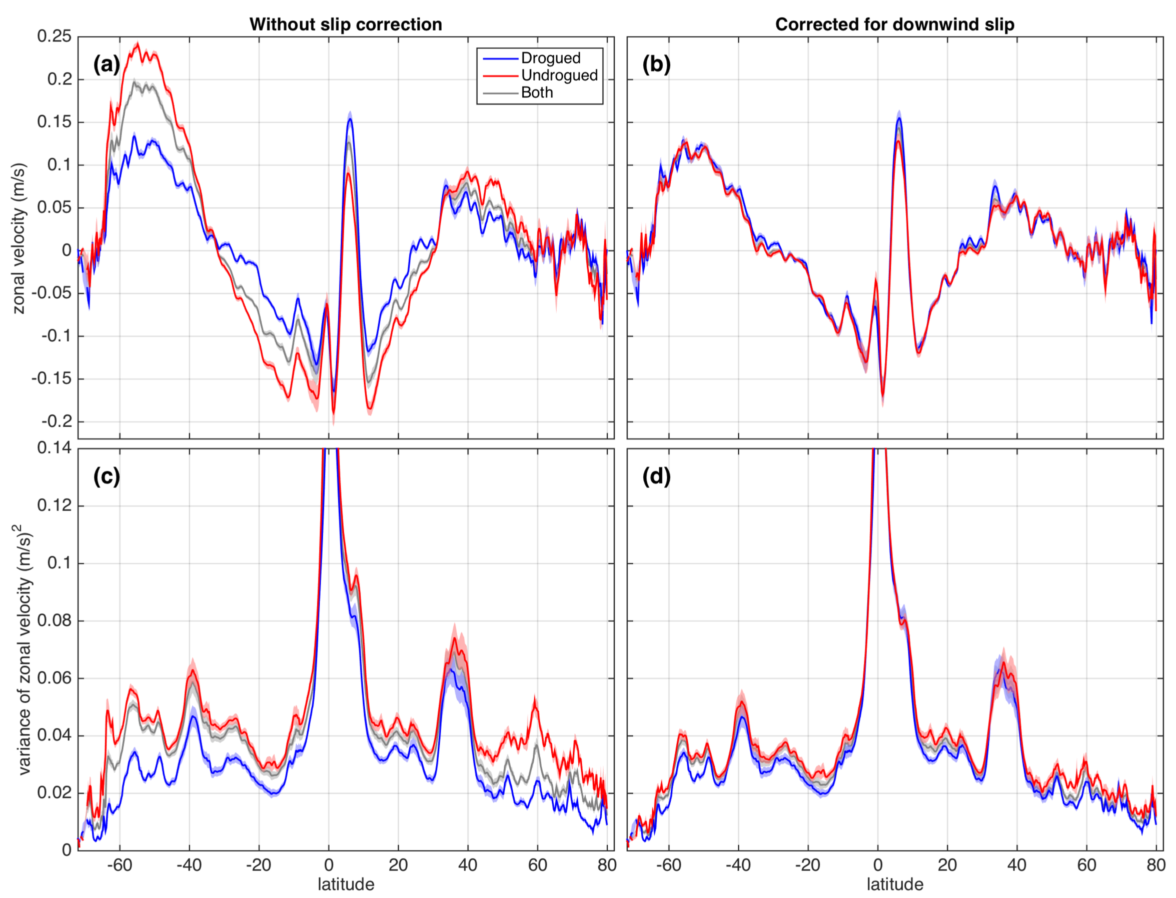
- where U_a: 10-m winds from the ECMWF ERA-Interim reanalysis
- For drogued drifters [3]:

$$\alpha_d = 7 \times 10^{-4}$$

- For undrogued [4]:

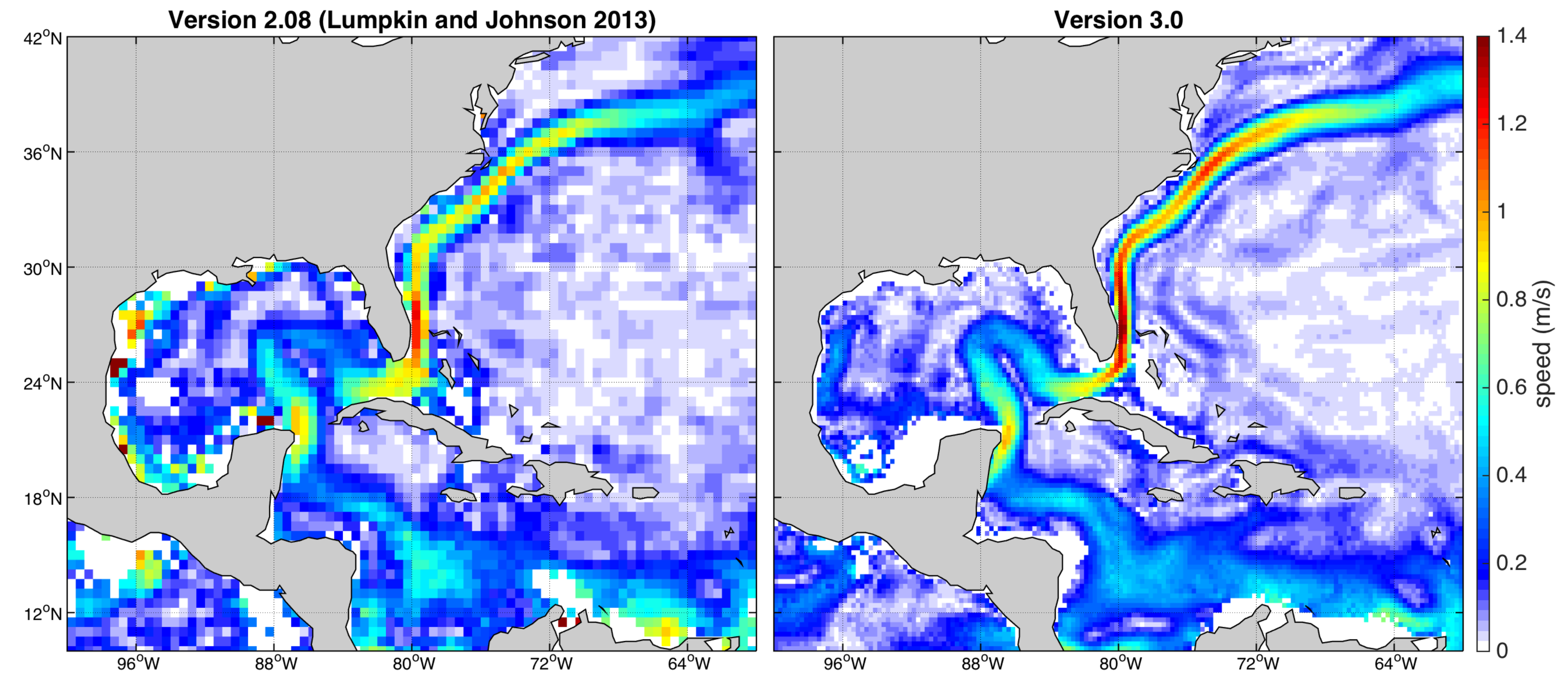
$$\alpha_u = \frac{\langle U_o^u \rangle - \langle U_o^d \rangle}{\langle U_a \rangle} + \alpha_d$$



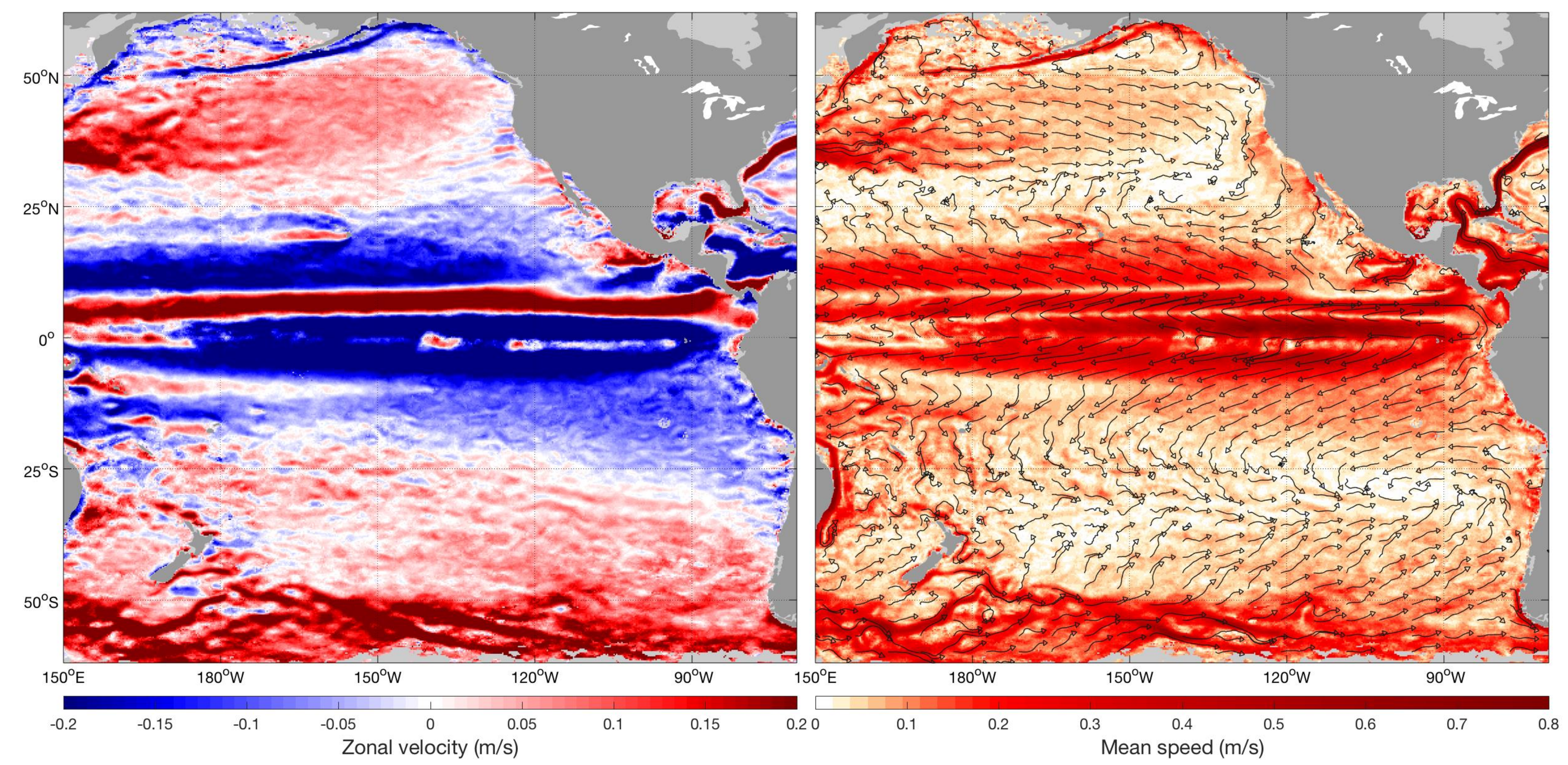


- **Top:** large-scale patterns of α_u suggests a geophysical forcing mechanism:
  - *Response to a spatially-varying surface gravity wave field?*
- The slip correction takes into account the spatial variations of α_u by interpolating the obtained values to drifter locations.
- **Left:** correction produces zonally-averaged pseudo-Eulerian mean velocities for drogued and undrogued data that are statistically similar across most latitudes, and reduces differences between their zonally-averaged variances.
- Remaining differences are largely caused by factors unrelated to the slip bias, e.g. method errors, biased sampling, and reduced N.

5. New Global Drifter Program climatological fields:



- Pseudo-Eulerian mean speed maps for the Gulf of Mexico and the western North Atlantic from GDP drifter data. **Left:** calculated as described in Lumpkin and Johnson (2013) [1]. **Right:** obtained using the updated procedure [2].
- The right panel shows core speeds for the Florida Current and Gulf Stream up to 50% larger, and includes a better resolved Antilles Current, recirculation cells, and circulation patterns in the basin's interior.



- **Left:** New pseudo-Eulerian mean zonal velocities for the Pacific Ocean, revealing numerous zonally-elongated striation patterns. **Right:** mean velocity magnitude (speed) overlaid with curly vectors (streamlines), to indicate the general direction of the large-scale circulation. Unlike in previous studies, the streamlines are calculated using unsmoothed mean velocity estimates.

6. Conclusions:

1) The proposed decomposition method reproduces pseudo-Eulerian mean velocities, their monthly variations, and formal error estimates better than other methods;
2) Standard errors underestimate the actual errors by about a factor of two;
3) The correction of drifter slip bias produces similar mean and variances for the drogued and undrogued drifter velocity datasets, allowing for a large increase in data density;
4) The new version of the climatology better resolves features such as the cross-stream structure of western boundary currents, recirculation cells, and zonally-elongated mid-ocean striations.

7. References:

[1] Lumpkin, R. and G. C. Johnson, 2013:. Global ocean surface velocities from drifters: mean, variance, ENSO response, and seasonal cycle. *J. Geophys. Res.*, **118**, 2992– 3006.

[2] Laurindo, L., A. Mariano, and R. Lumpkin, 2017: An improved near-surface velocity climatology for the global ocean from drifter observations. *Deep-Sea Res.*, accepted April 2017.

[3] Niiler, P. P., A. S. Sybrandy, B. Kenong, P. M. Poulain, and D. Bitterman, 1995:. Measurements of the water-following capability of holey-sock and tristar drifters. *Deep-Sea Res.* **42** (11/12), 1961–1964.

[4] Pazan, S. E. and P. P. Niiler, 2001:. Recovery of near-surface velocity from undrogued drifters. *J. Atmos. Oceanic Tech.*, **18**, 476–489.