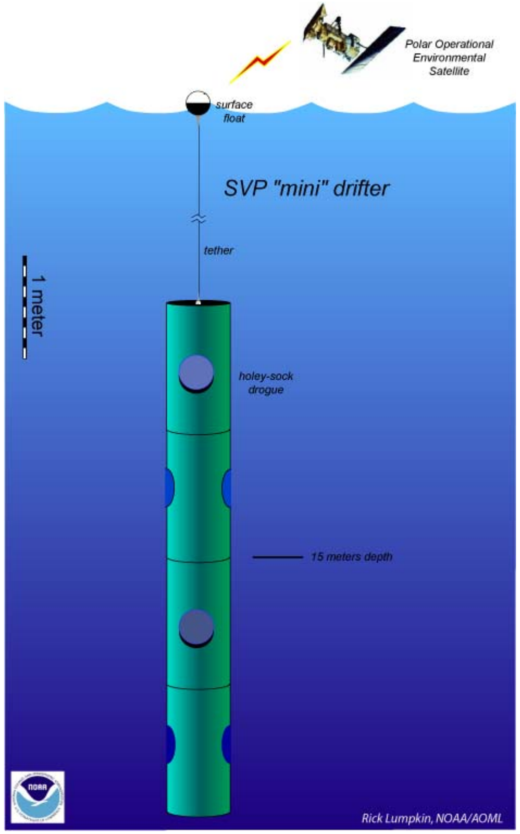
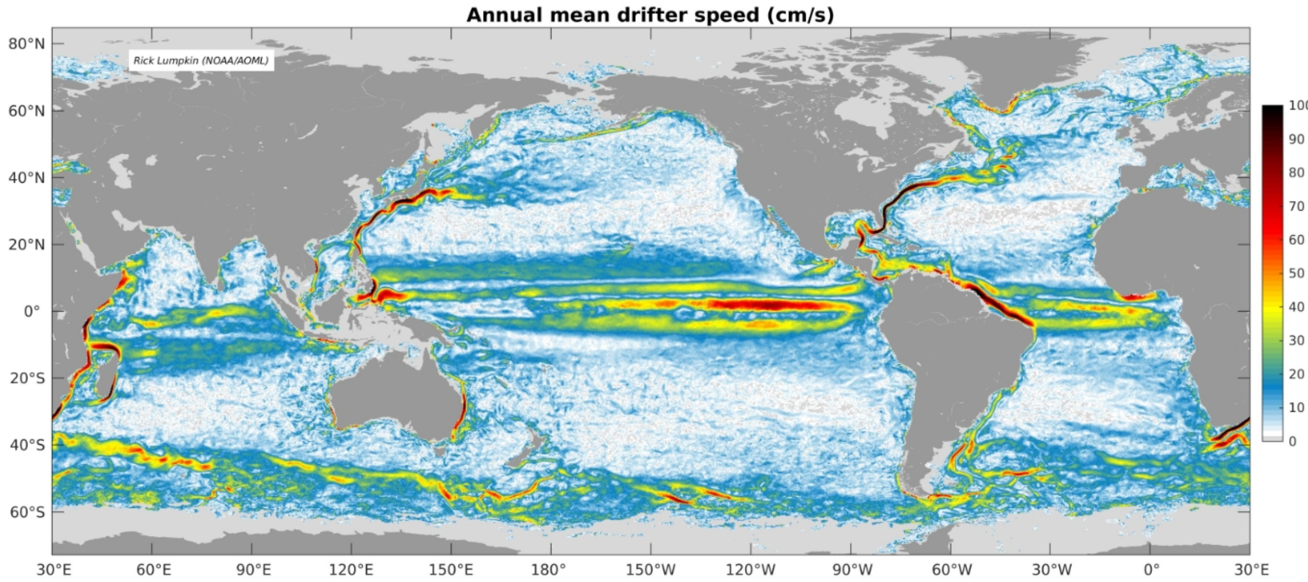
Recovering velocity information from undrogued buoys

Rick Lumpkin, NOAA/AOML

Work with Shaun Dolk (CIMAS/AOML), Luca Centurioni and Verena Hormann (SIO), Josefina Olascoaga (U Miami), Gustavo Goni (AOML), Joaquin Trinanes (Contractor/AOML), and Nathan Putman (LGL Research Assoc.)





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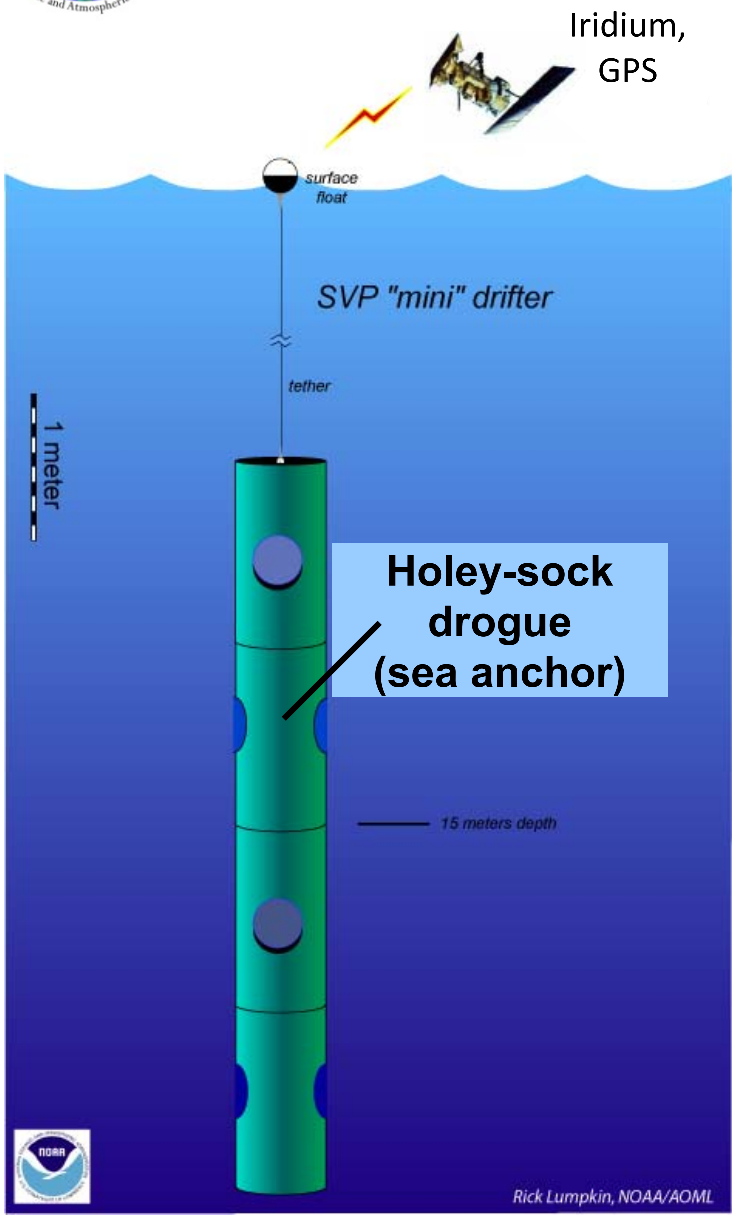
The satellite-tracked GDP drifter



Spherical surface float

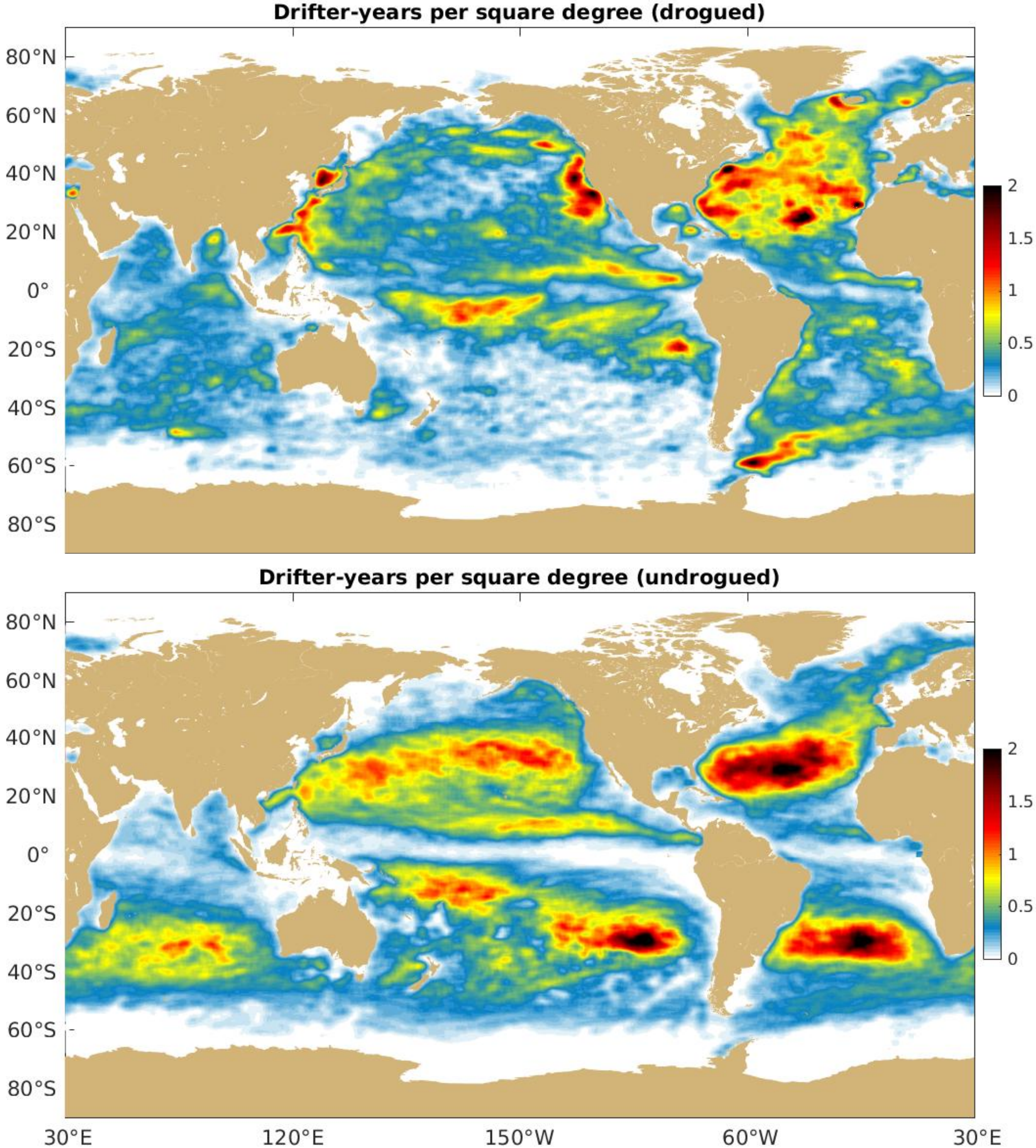
Polyurethane impregnated tether

Holey Sock nylon drogue centered at 15m depth

D-cell batteries inside the float

With drogue attached, slip with respect to flow at 15m is <1 cm/s per 10 m/s wind (Niiler et al., 1995).

Drogue lost: slip has been estimated at ~10 cm/s per 10 m/s wind (Pazan and Niiler, 2001).



Drifters lose their drogues after ~300 days on average, and can live much longer.

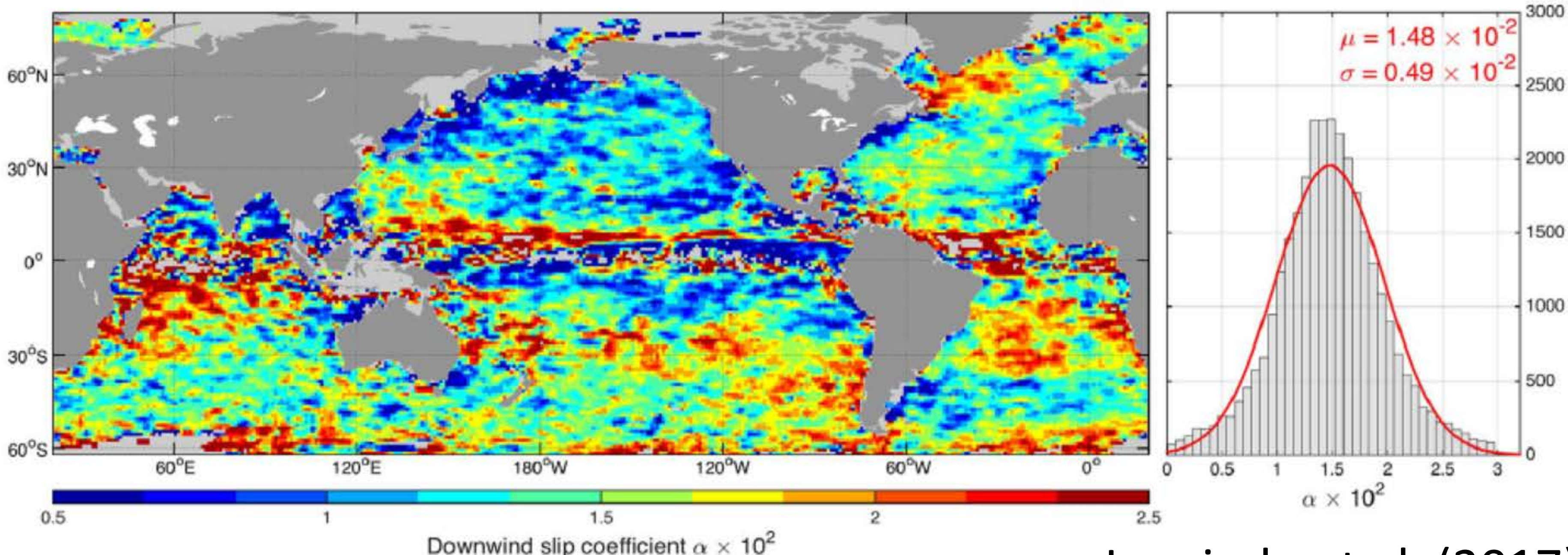
As a result, almost 54% of their locations are relayed by drifters with lost drogues. The locations of these observations include areas poorly sampled by drogued drifters.

Clearly, recovery of this velocity information is desirable.

Previous efforts to remove slip:

Pazan and Niiler (2001): slip can be removed by assuming it is a constant coefficient times wind speed, directed downwind. The globally-averaged value of this coefficient is 9.7 cm/s per 10 m/s wind (~1% of wind).

$$\overline{u_u} = \overline{u_d} + \alpha\overline{W}$$



Laurindo et al. (2017)

Obtaining cleaner estimates of slip

There are very few concurrent measurements of velocity from drogued and undrogued drifters.

Methods like Pazan and Niiler (2001) and Laurindo et al. (2017) rely on time averages in bins to reduce the impact of mesoscale and interannual variability.

Hypothesis: If we can estimate drogued velocities that are concurrent with the undrogued measurements, then the differences will allow significantly cleaner estimates of slip.

Gridded surface velocities tuned to match lowpassed drogued drifter observations

Let drifter observations $\vec{u} \equiv < \vec{U} > + \vec{u}'_{geo} + \vec{u}'_{Ek}$

< > is an ensemble average over 1993—2012 (AVISO reference period).

Unbiased time-mean

Geo. vel. anomalies

Wind-driven vel. anomalies

If $\overline{\cdot}$ is a bin average of inhomogeneous drifter observations, then taking $\overline{\cdot}$ of this equation gives:

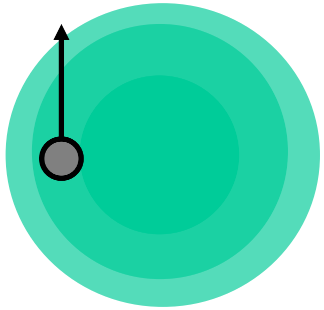
$$\overline{\vec{U}}_d = < \vec{U} > + \overline{\vec{u}'_{geo}} + \overline{\vec{u}'_{Ek}}$$

Bin-averaged drifter velocity

Unbiased mean

Average of fluctuations over inhomogeneous drifter observations (not necessarily = 0)

Including the centrifugal term



$$\boxed{\frac{v^2}{r} - fv = g\left|\frac{\partial h}{\partial x}\right|.}$$

Let $v = v_g + v_c,$ where $f v_g \equiv g\left|\frac{\partial h}{\partial x}\right|.$

Then $v_c = \frac{fr}{2} - v_g \pm \sqrt{\left(\frac{fr}{2} - v_g\right)^2 - {v_g}^2}.$ r=radius of curvature

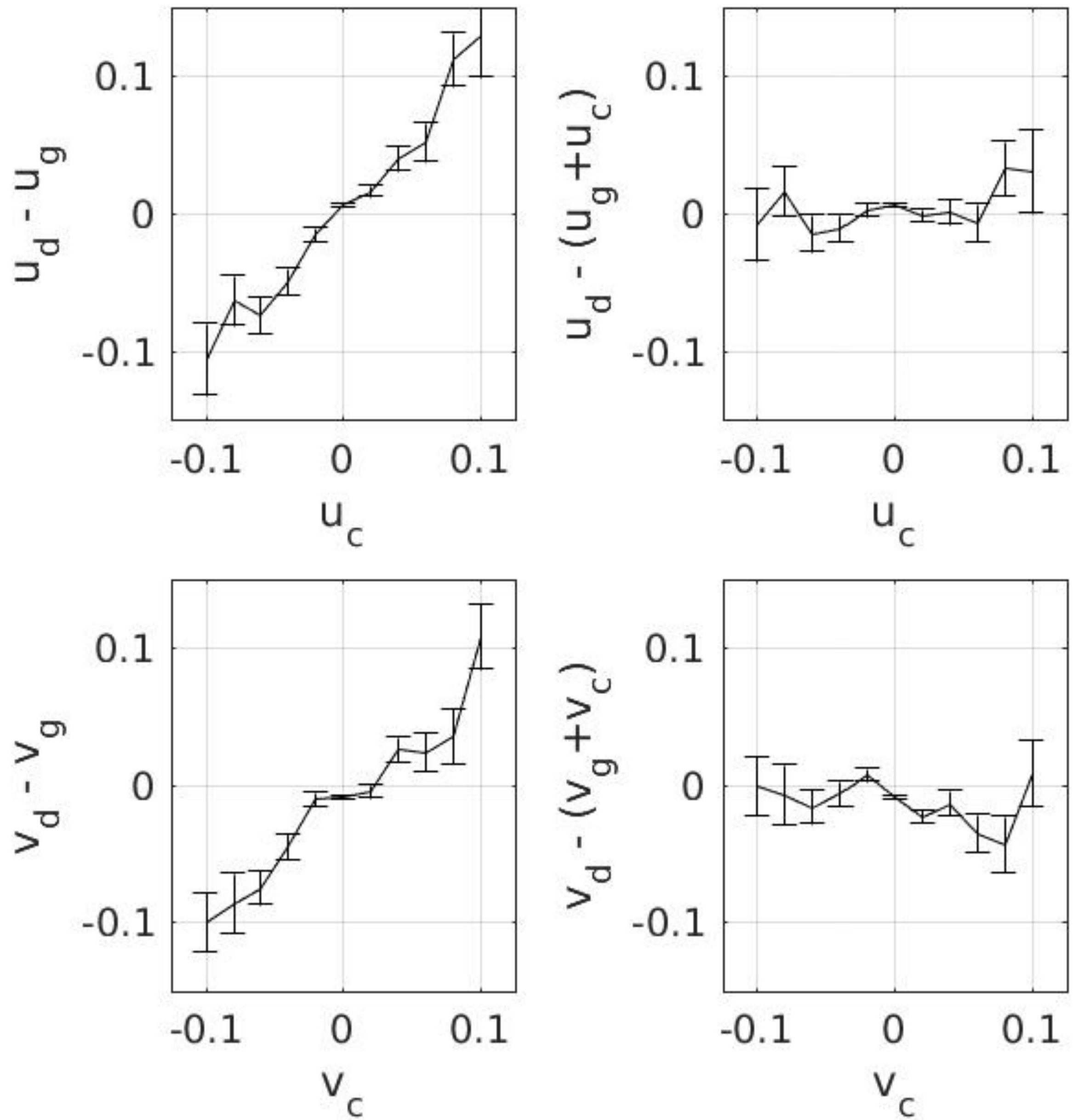
Mean curvature of a 2D surface:

$$\kappa = \left[\frac{\partial^2 h}{\partial x^2}\left(\frac{\partial h}{\partial y}\right)^2 - 2\frac{\partial^2 h}{\partial x \partial y}\frac{\partial h}{\partial x}\frac{\partial h}{\partial y} + \frac{\partial^2 h}{\partial y^2}\left(\frac{\partial h}{\partial x}\right)^2\right] \Big/ \left[\left(\frac{\partial h}{\partial x}\right)^2 + \left(\frac{\partial h}{\partial y}\right)^2\right]^{3/2}$$

$r = 1/\kappa.$

c.f. Penven et al. (2014)

$v = v_g + v_c$, 35—40°N, 50—70°W wind speed <10 m/s.



Gridded surface velocities tuned to match lowpassed drogued drifter observations

Assume geostrophic component of the form

$$u'_{geo} = (1 + A_u)u'_{av}, \qquad v'_{geo} = (1 + A_v)v'_{av}$$

Gain coefficient

Cyclogeostrophic velocity anomalies calculated from MDT and SLA (Lagerloef et al. 1999 near equator)

Assume wind component has magnitude $B\left|\vec{\tau}'\right|$ and is directed at angle θ to left of wind. Then

$$u'_{Ek} = b_1\tau'_x - b_2\tau'_y, \qquad v'_{Ek} = b_2\tau'_x + b_1\tau'_y,$$

where

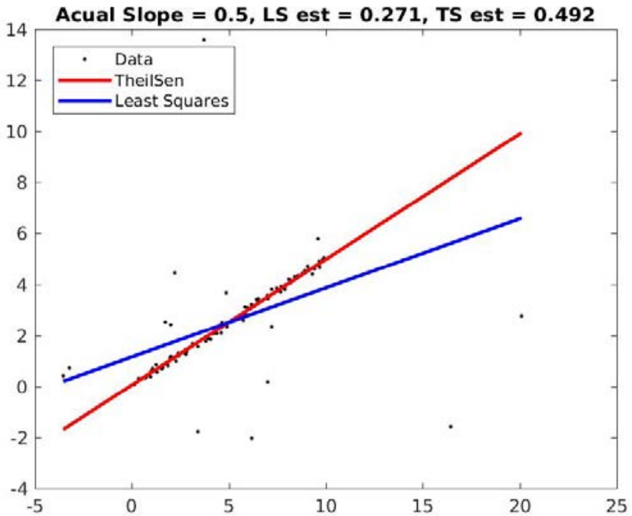
$$b_1 \equiv B\cos\theta,\ b_2 \equiv B\sin\theta,\ B = \sqrt{b_1^2 + b_2^2}\text{, and } \theta = \mathrm{atan}(b_2/b_1).$$

Putting it all together …

$$u - \overline{U}_d - u''_{av} = A_u u''_{av} + b_1 \tau''_x - b_2 \tau''_y, \qquad v - \overline{V}_d - v''_{av} = A_v v''_{av} + b_2 \tau''_x + b_1 \tau''_y.$$

$$x'' \equiv x' - \overline{x'}$$

Solve for the four unknowns A_u, A_v, b_1, b_2 in each bin, for each month with at least 20 drogued daily observations, using the Theil-Sen estimator.



Black dots: simulated data with outliers.
Blue: least squares fit. Red: Theil-Sen fit.

Gridded, daily, 1/4° surface velocities

Using daily cyclogeostrophic velocity anomalies derived from MDT-CNES-CLS18+AVISO SLA, daily ERA-15 winds, and fields of A_u, A_v, b_1, b_2, we can calculate gridded fields of velocity as:

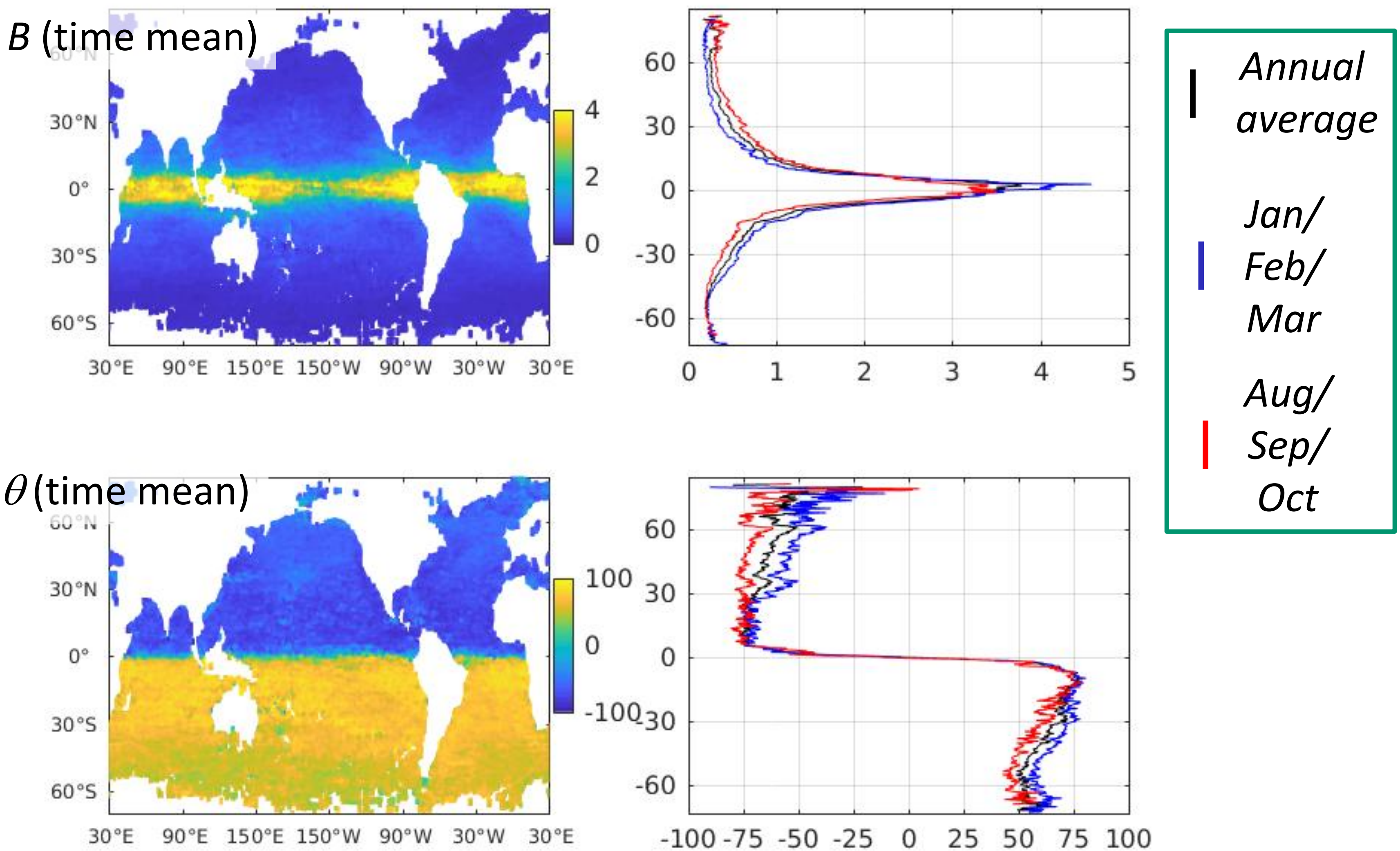
$$u^* = \left[\overline{U_d} - \overline{(1 + A_u)u'_{av}} - \overline{(b_1\,\tau'_x - b_2\,\tau'_y)}\right] + (1 + A_u)u'_{av} + b_1\,\tau'_x - b_2\,\tau'_y,$$

$$v^* = \left[\overline{V_d} - \overline{(1 + A_v)v'_{av}} - \overline{(b_2\,\tau'_x + b_1\,\tau'_y)}\right] + (1 + A_v)v'_{av} + b_2\,\tau'_x + b_1\,\tau'_y,$$

where the term in square brackets are the unbiased time-mean velocity for the period 1993—2012.

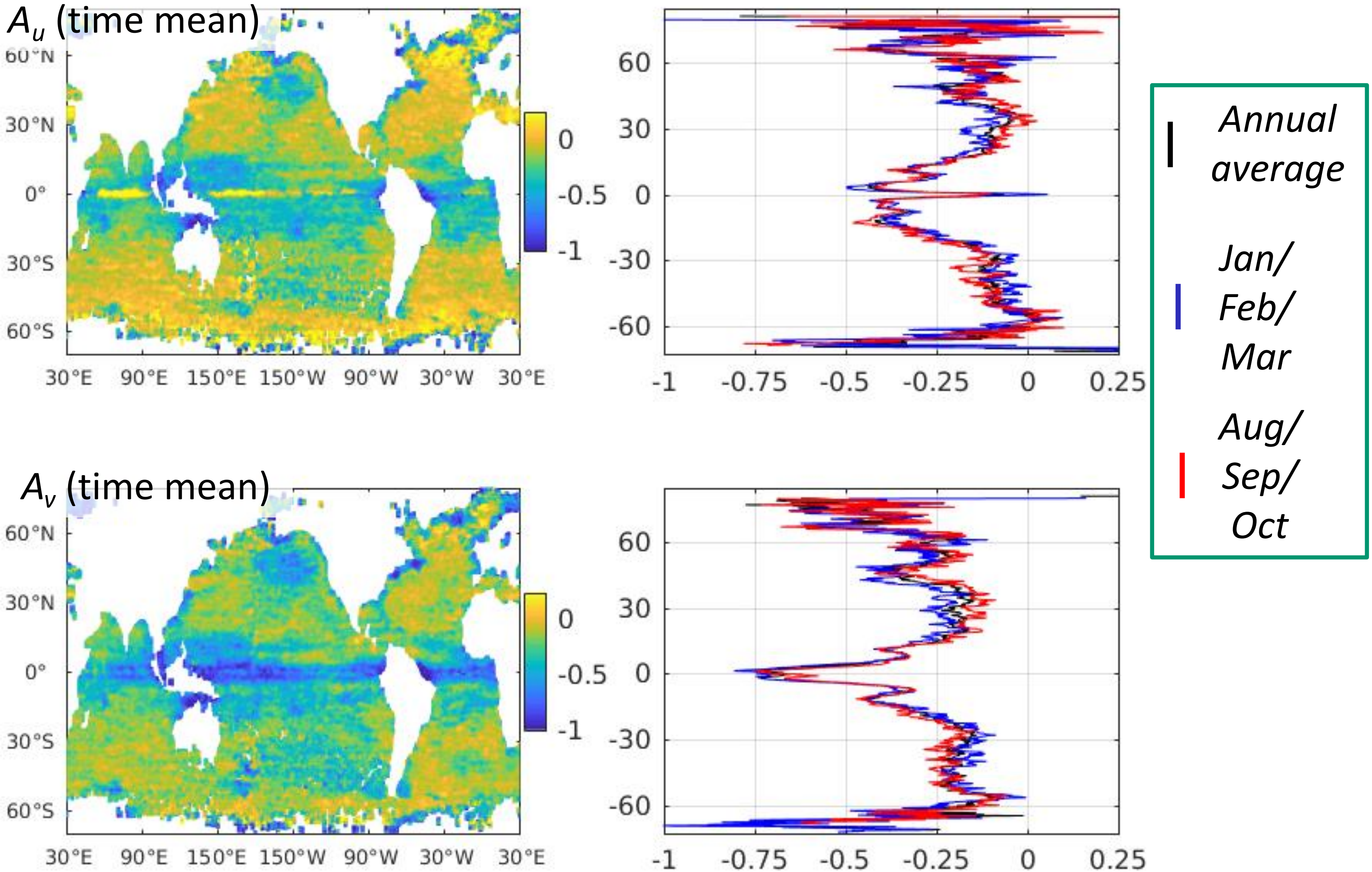
wind-driven coefficients

$$\vec{u}^{\,'}_{Ek} = B\left|\vec{\tau}^{\,'}\right|e^{i\theta}$$

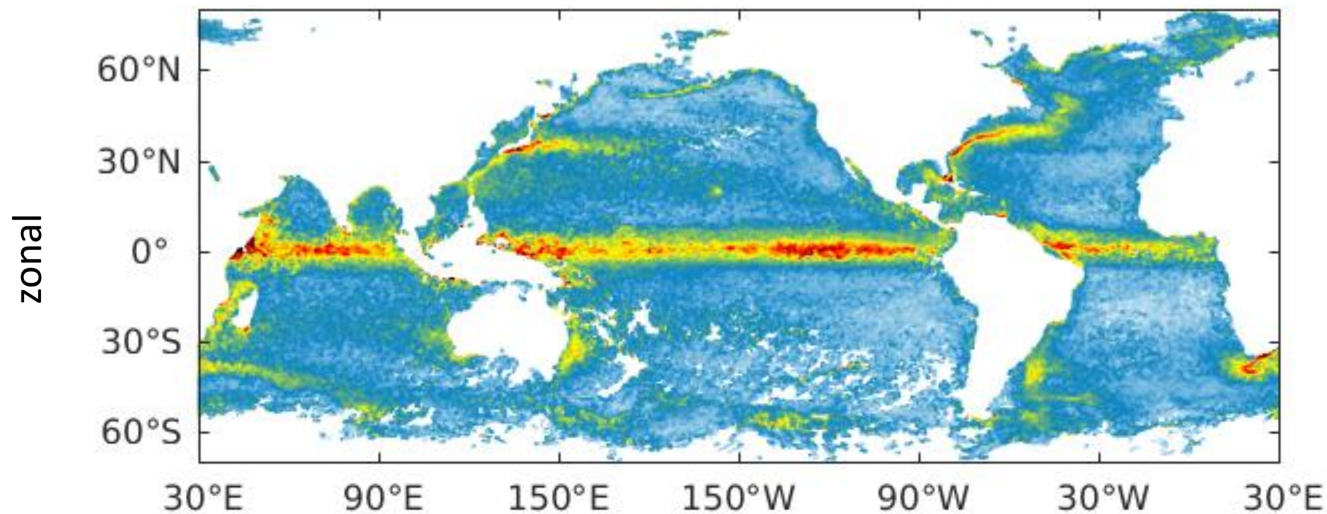


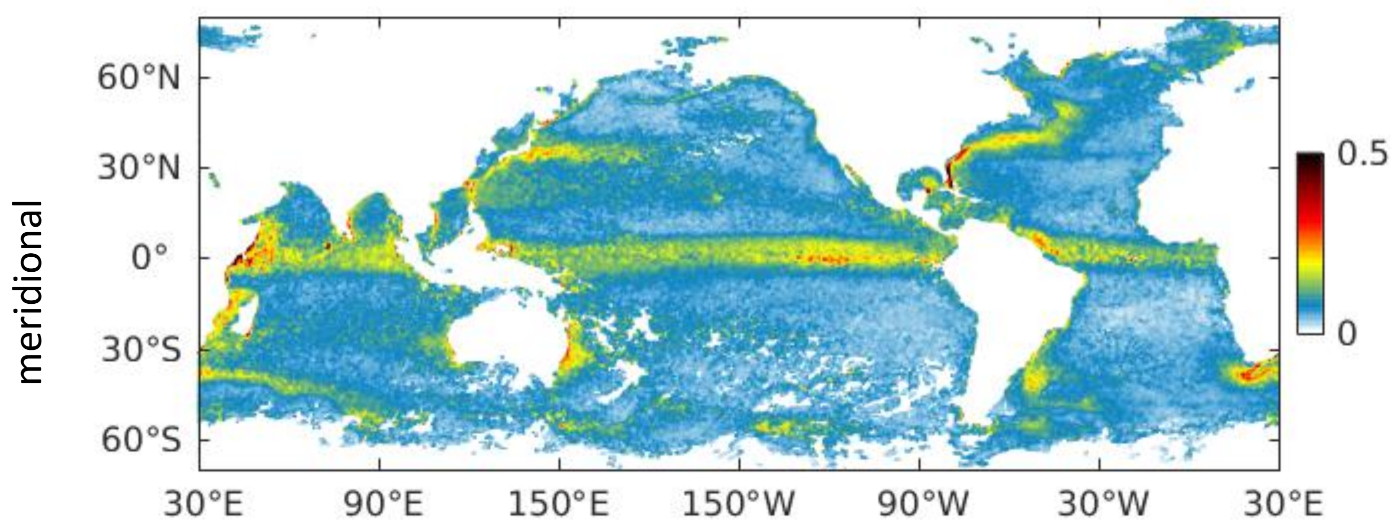
cyclogeostrophic coefficients

$$u'_{geo} = (1 + A_u)u'_{av}, \qquad v'_{geo} = (1 + A_v)v'_{av}$$



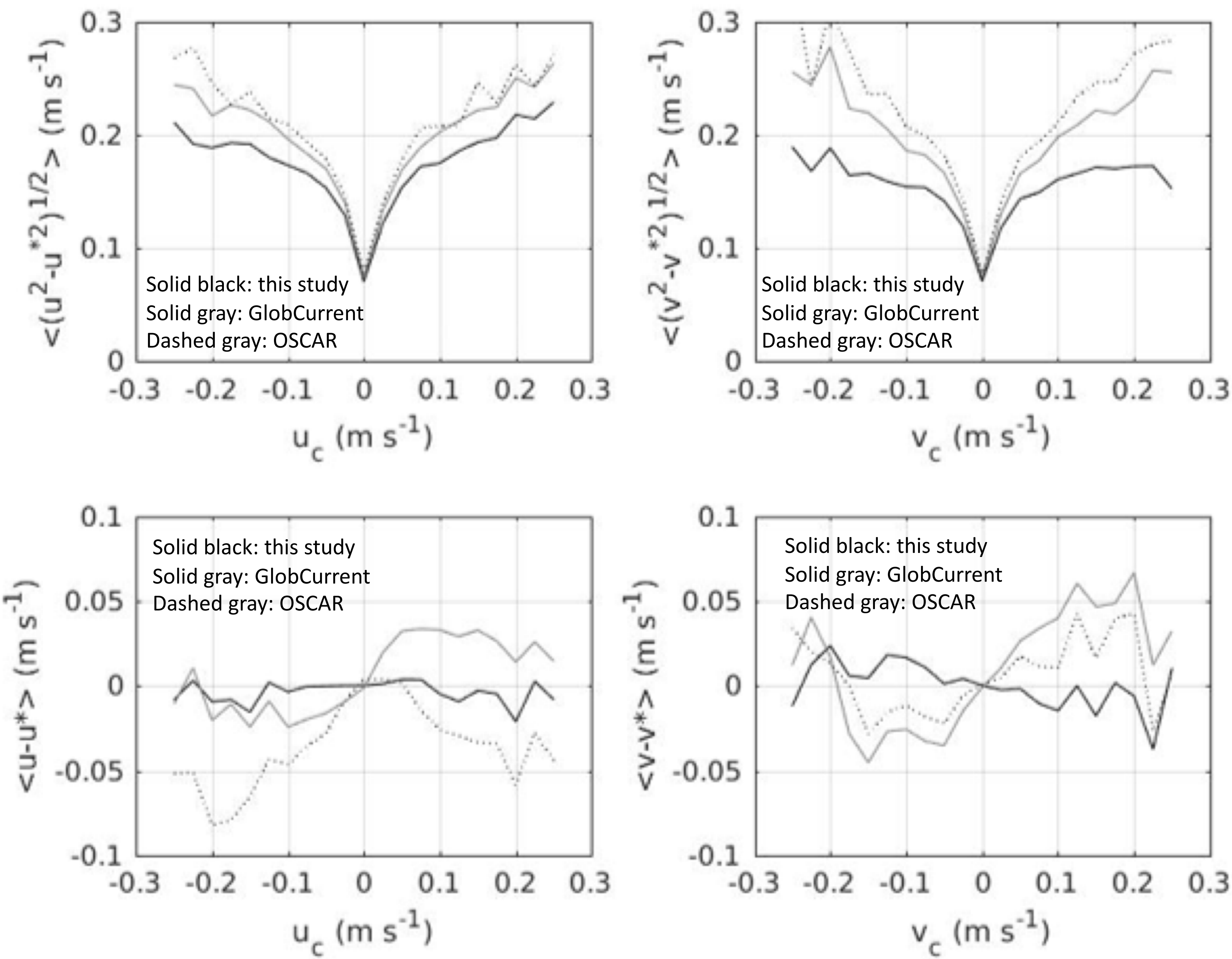
RMS differences between drogued drifter velocities and gridded velocities (this study) (m/s)





RMS differences with drogued drifters (cm/s)

	This study	GlobCurrent v3.0	OSCAR 1/3 degree
Global zonal	10.78±0.01	11.44±0.01	12.17±0.01
Global meridional	10.32±0.01	11.04±0.01	11.73±0.01
20°S—20°N zonal	12.48±0.02	13.78±0.02	14.22±0.03
20°S—20°N meridional	11.10±0.01	12.49±0.02	13.39±0.02
Poleward of 20°, zonal	9.48±0.01	9.66±0.01	10.59±0.01
Poleward of 20°, meridional	9.73±0.01	9.93±0.01	10.46±0.02



<(u²-u*²)^1/2> (m s⁻¹)
u_c (m s⁻¹)
Solid black: this study
Solid gray: GlobCurrent
Dashed gray: OSCAR
<(v²-v*²)^1/2> (m s⁻¹)
v_c (m s⁻¹)
Solid black: this study
Solid gray: GlobCurrent
Dashed gray: OSCAR
<u-u*> (m s⁻¹)
u_c (m s⁻¹)
Solid black: this study
Solid gray: GlobCurrent
Dashed gray: OSCAR
<v-v*> (m s⁻¹)
v_c (m s⁻¹)
Solid black: this study
Solid gray: GlobCurrent
Dashed gray: OSCAR

Using gridded velocities to correct slip

Downwind: $\overline{u_u} = (1-\alpha)\overline{u_d} + \alpha\overline{W}$

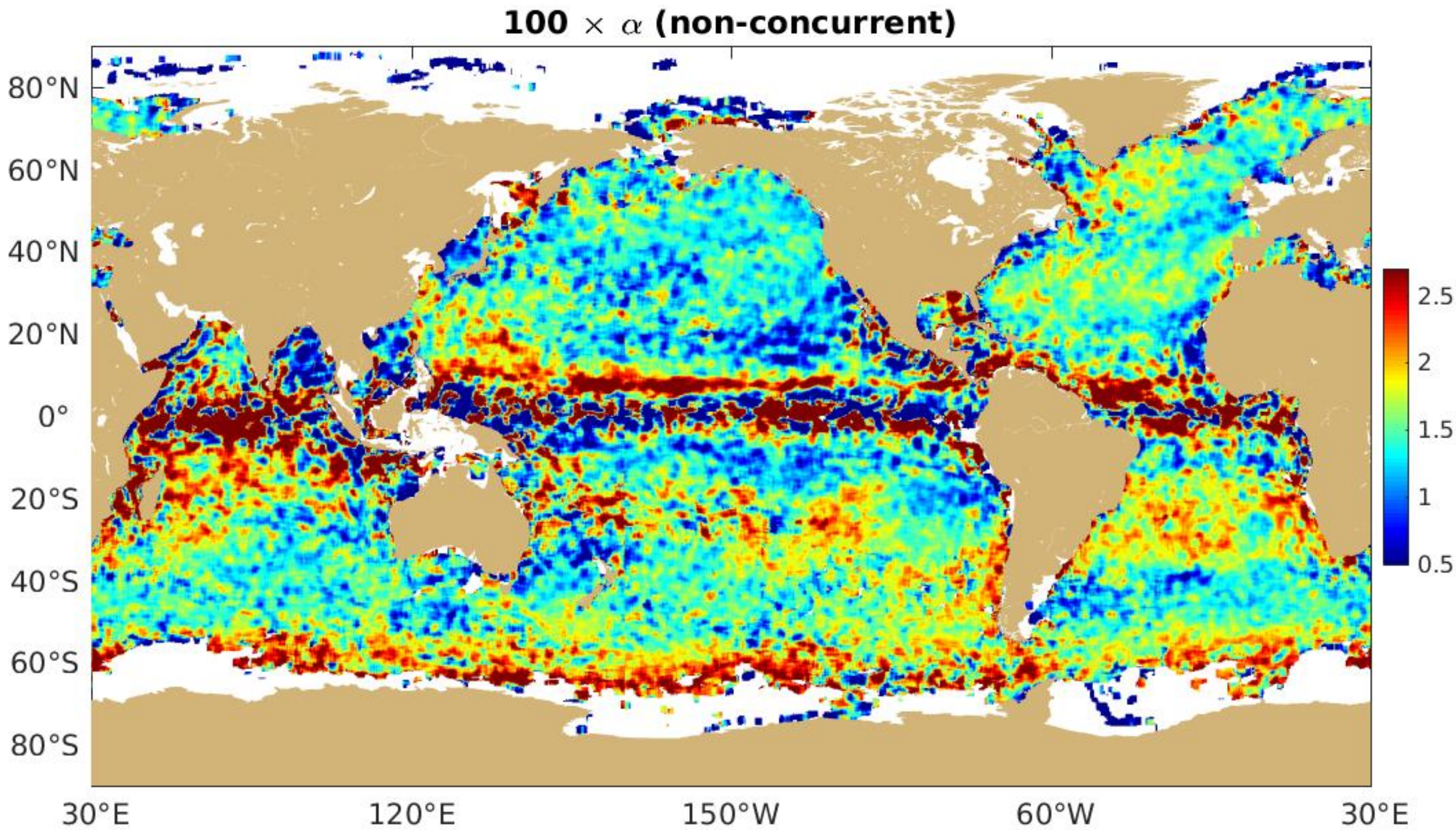
Left of wind: $\overline{v_u} = (1-\beta)\overline{v_d} + \beta\overline{W}$

Undrogued drifter velocity
(lowpassed at 1.5IP)

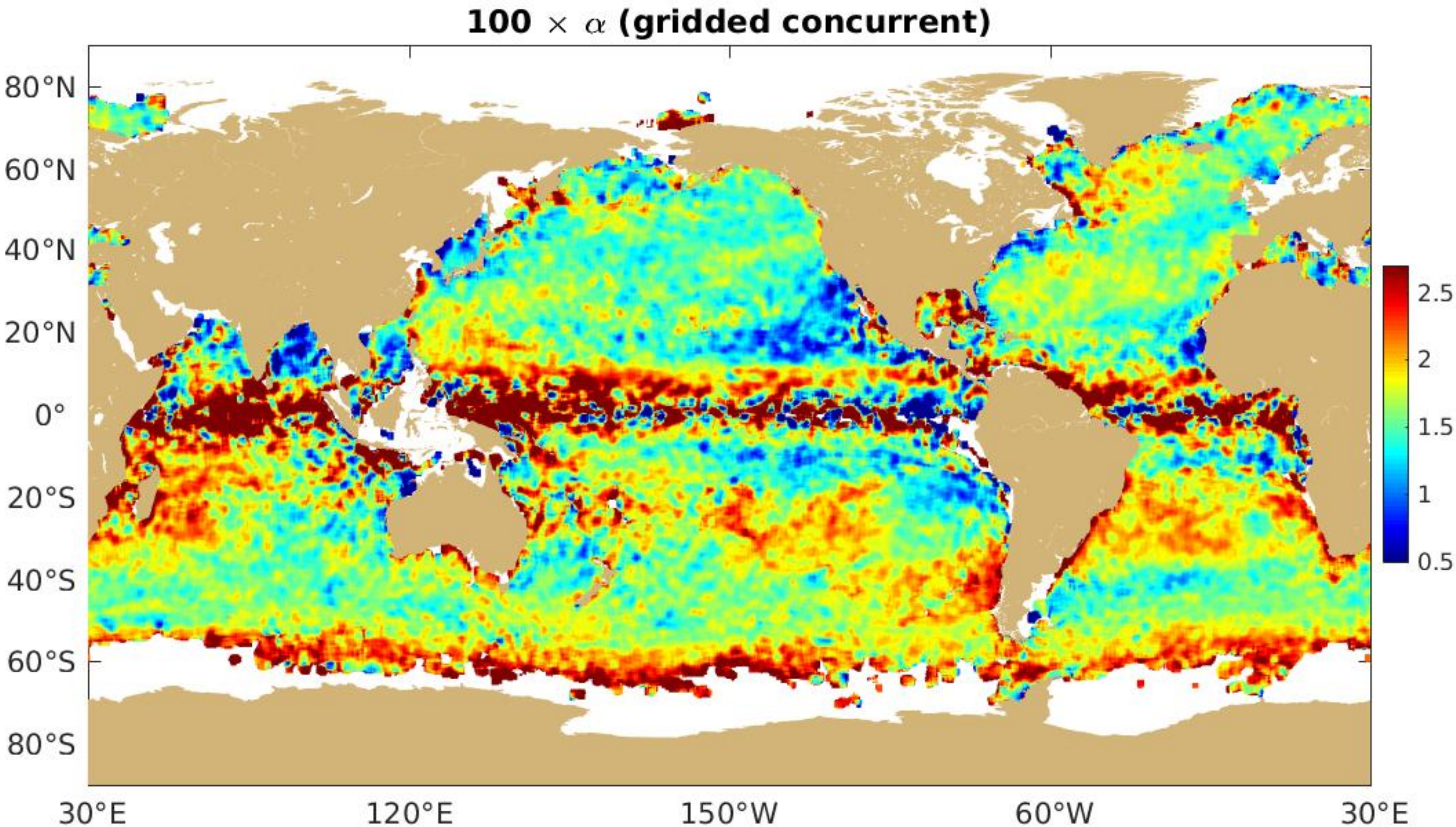
Gridded velocity interpolated to
time/location of undrogued
observations

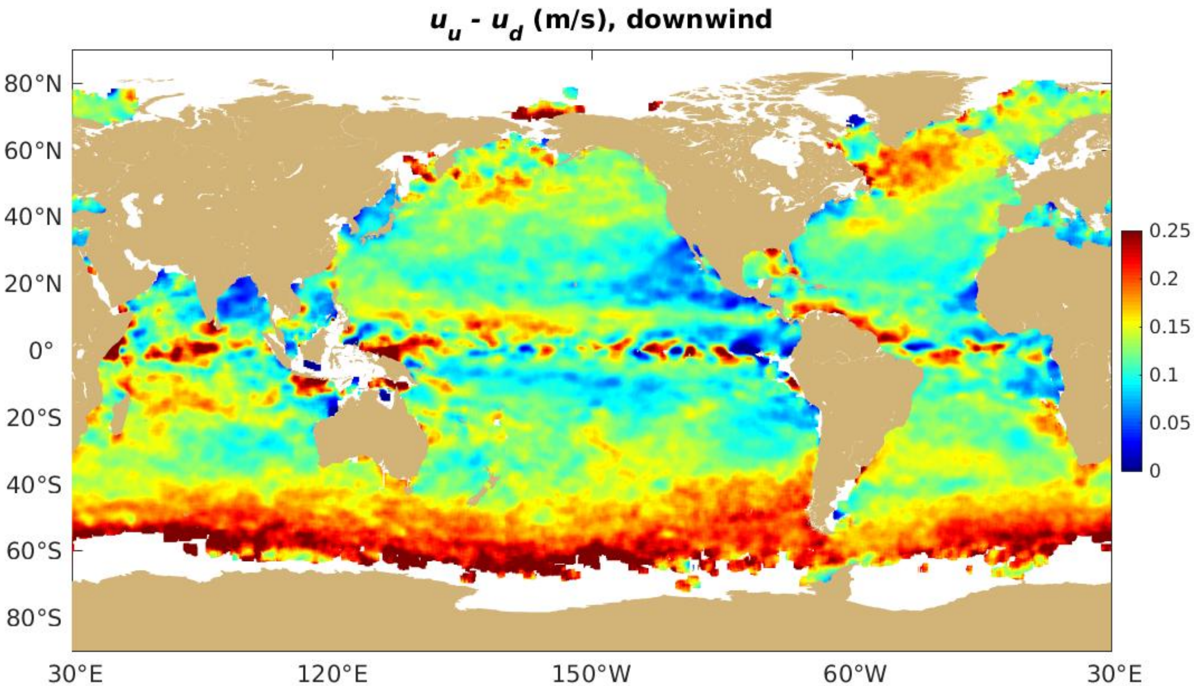
Wind speed
(lowpassed at
1.5IP)

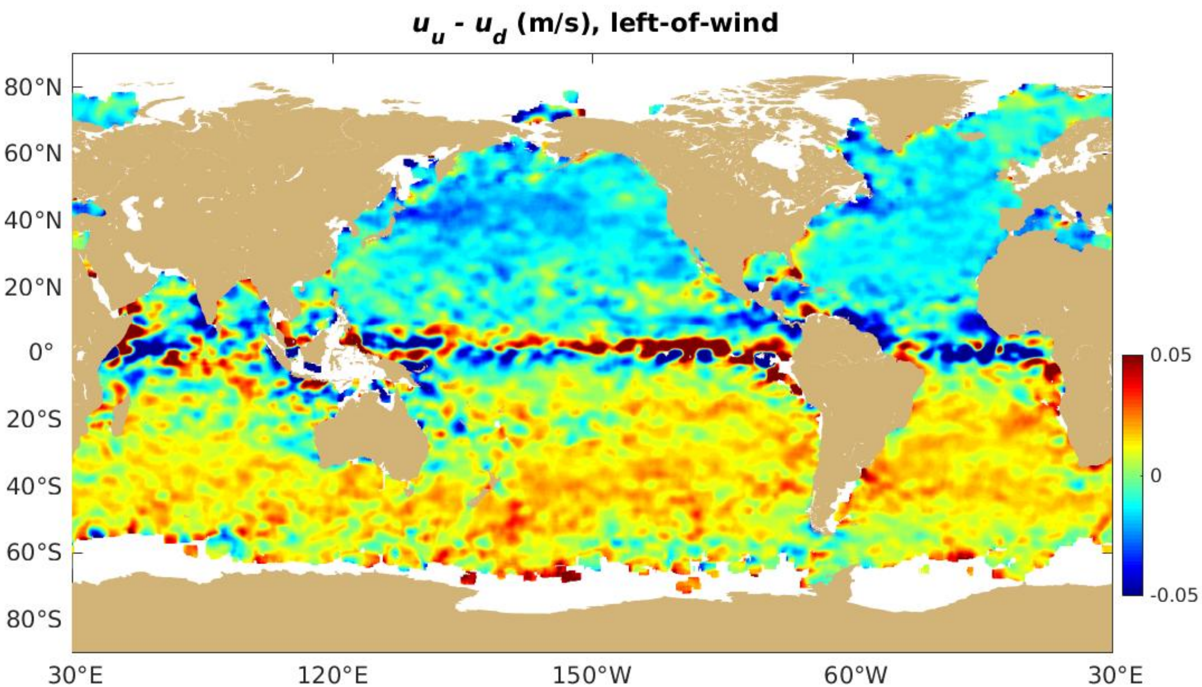
c.f. Olascoaga et al. (2020)

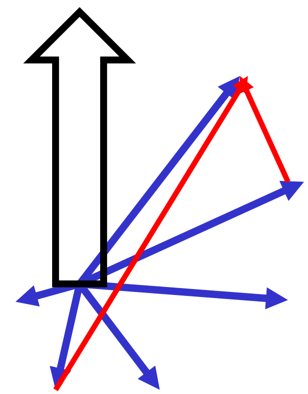


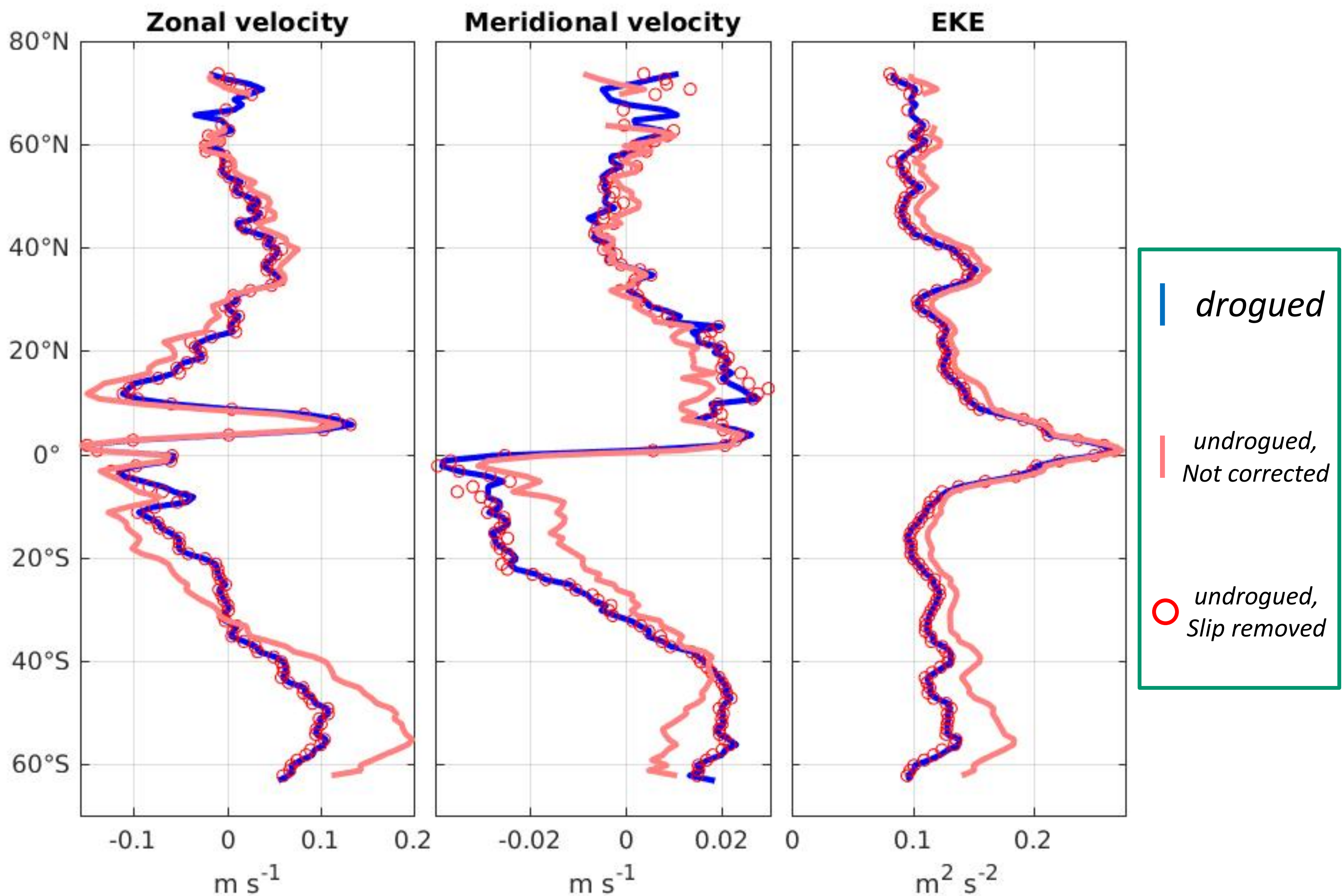
100 × α (non-concurrent)
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
30°E
120°E
150°W
60°W
30°E
2.5
2
1.5
1
0.5


100 × α (gridded concurrent)
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
30°E
120°E
150°W
60°W
30°E
2.5
2
1.5
1
0.5

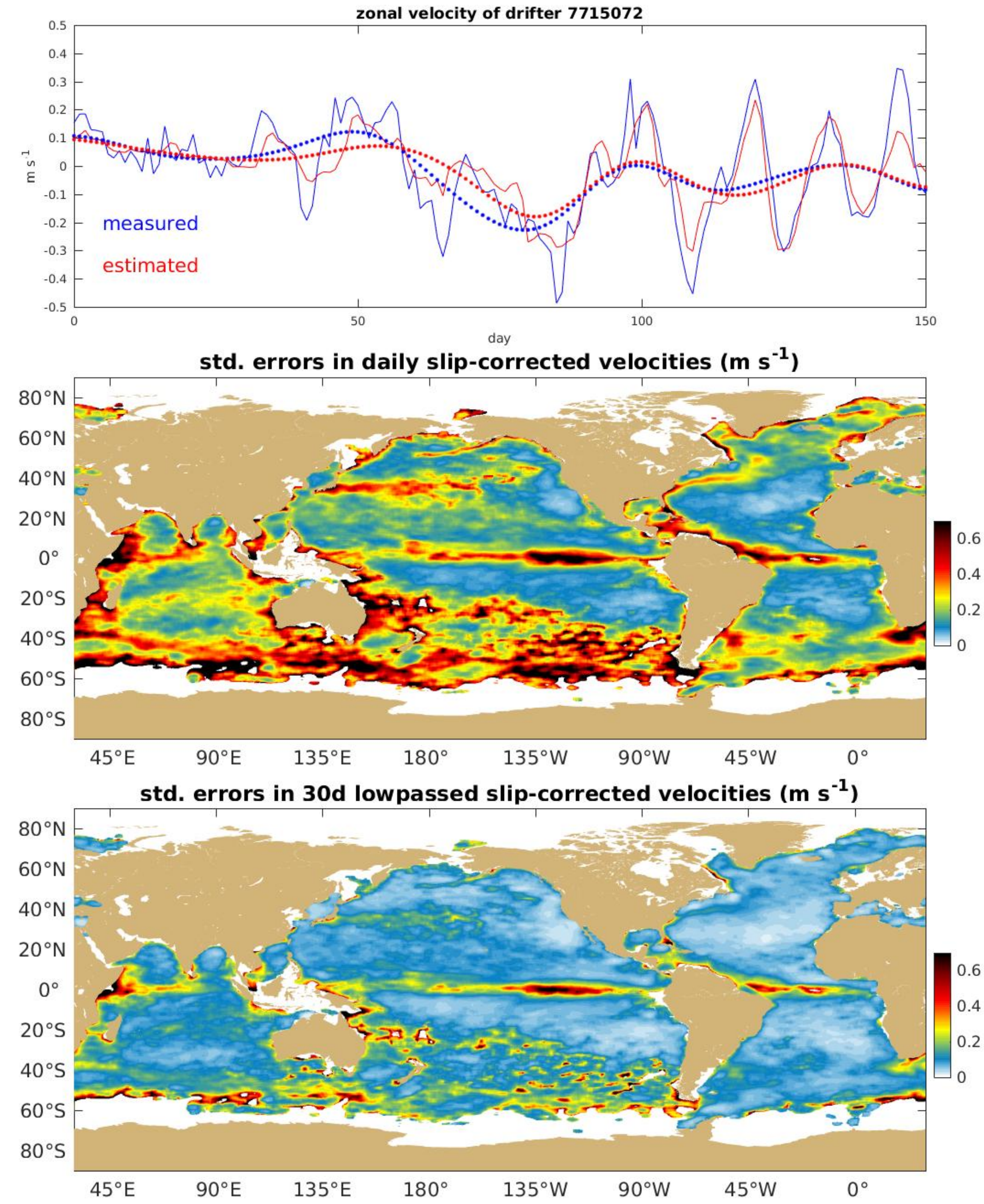

u_u - u_d (m/s), downwind
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
30°E
120°E
150°W
60°W
30°E
0.25
0.2
0.15
0.1
0.05
0


u_u - u_d (m/s), left-of-wind
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
30°E
120°E
150°W
60°W
30°E
0.05
0
-0.05





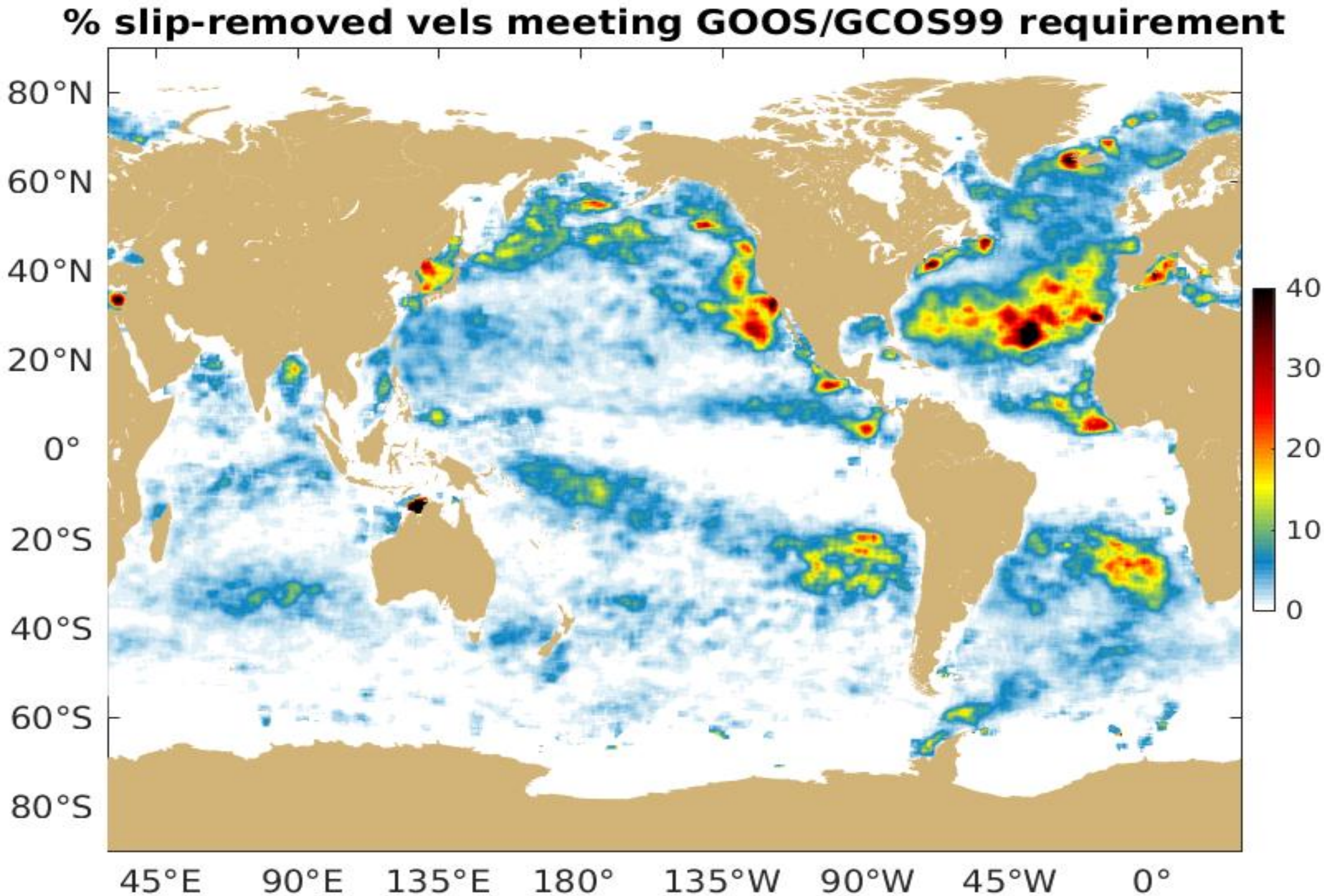
Zonal velocity
Meridional velocity
EKE
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
-0.1
0
0.1
0.2
m s-1
-0.02
0
0.02
m s-1
0
0.1
0.2
m2 s-2
drogued
undrogued, Not corrected
undrogued, Slip removed

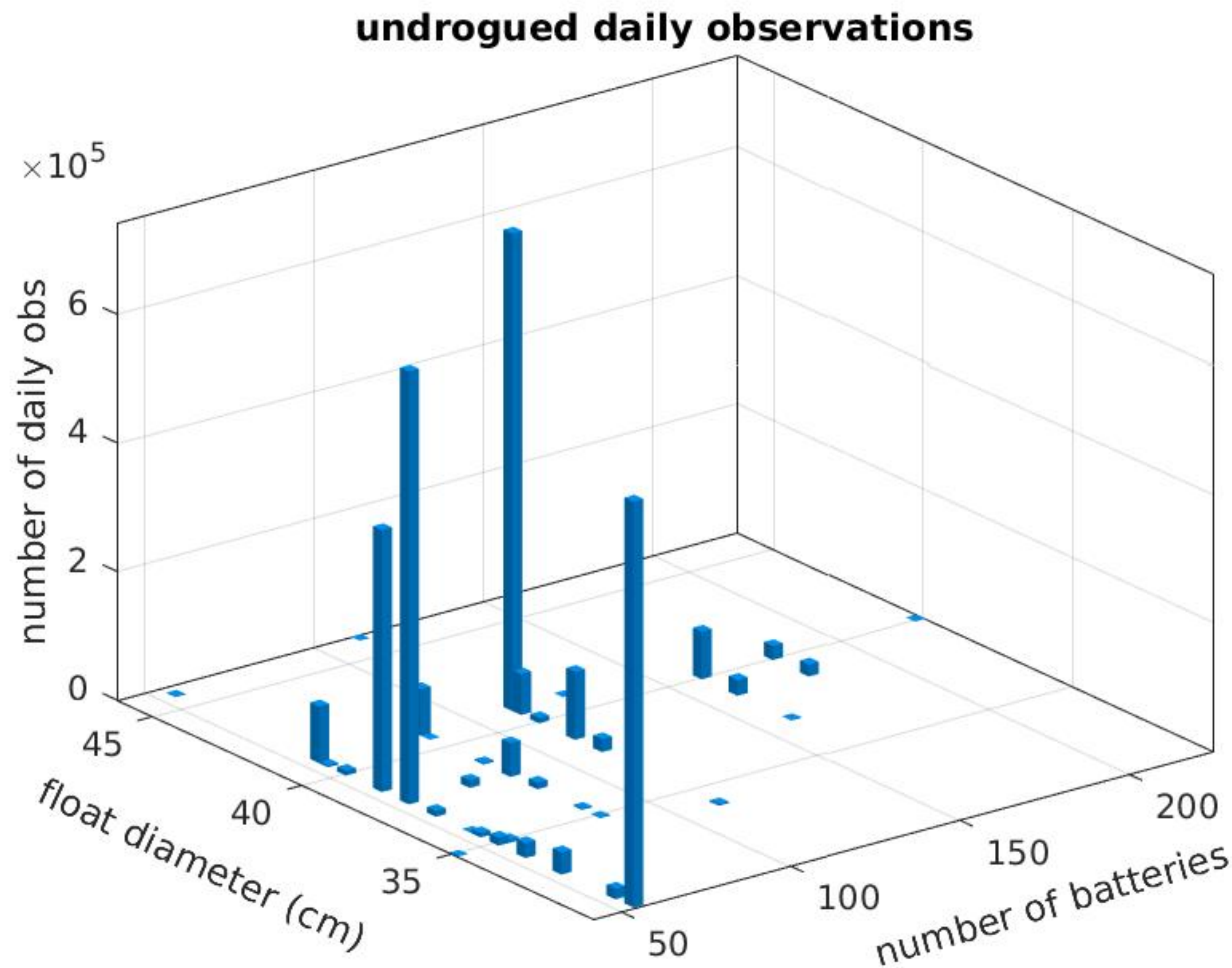


The GOOS/GCOS99 requirement for surface currents is one measurement per month, per 5°x5°, at an accuracy of 2 cm/s.

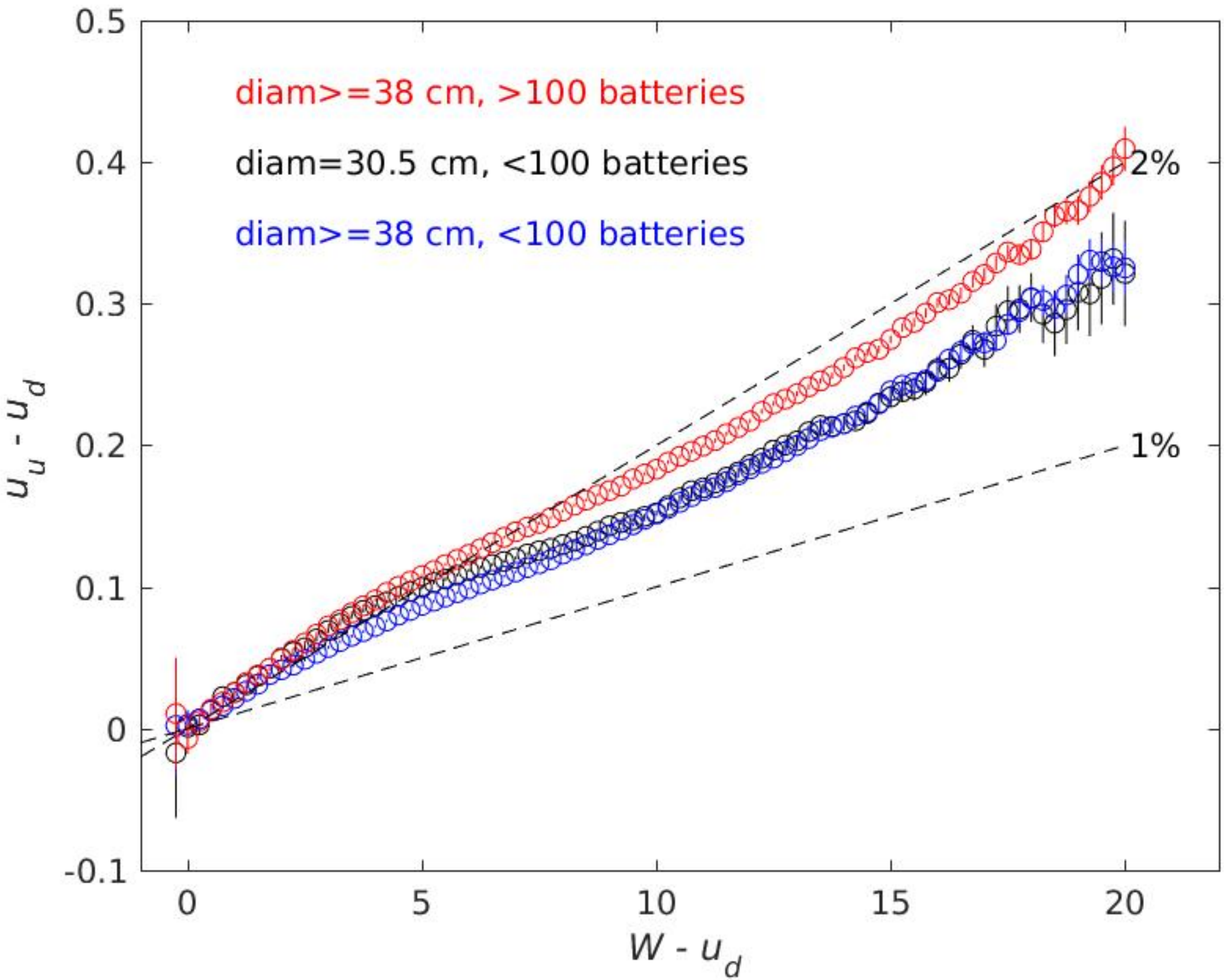
The ~daily slip-removed velocities from undrogued drifters has a global mean error of 35 cm/s.

30d lowpassed slip removed velocities: global mean error of 17 cm/s.


% slip-removed vels meeting GOOS/GCOS99 requirement
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
45°E
90°E
135°E
180°
135°W
90°W
45°W
0°
40
30
20
10
0



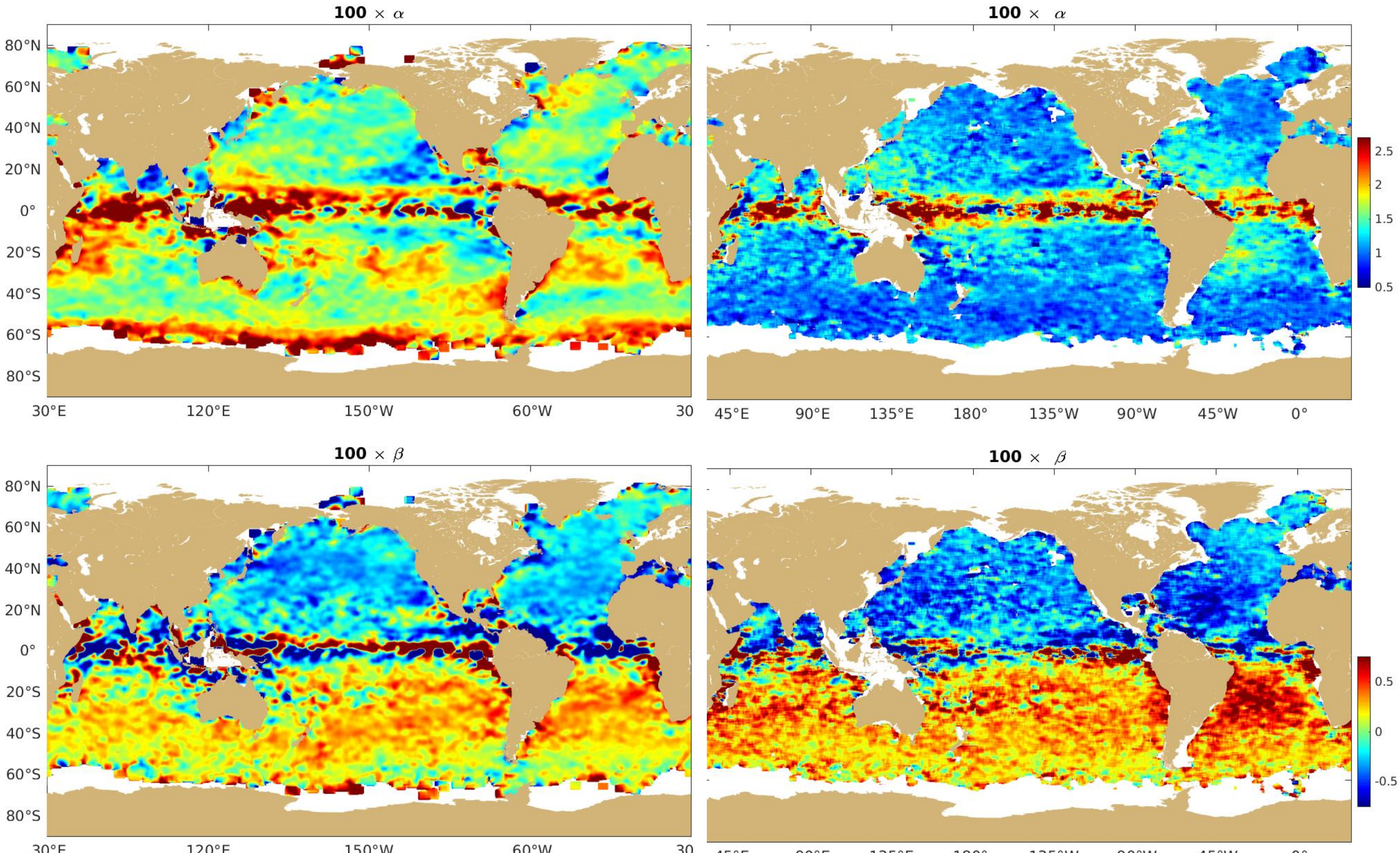
undrogued daily observations
×10^5
number of daily obs
0
2
4
6
45
40
35
float diameter (cm)
50
100
150
200
number of batteries



diam>=38 cm, >100 batteries
diam=30.5 cm, <100 batteries
diam>=38 cm, <100 batteries
2%
1%
$u_u - u_d$
$W - u_d$
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
5
10
15
20

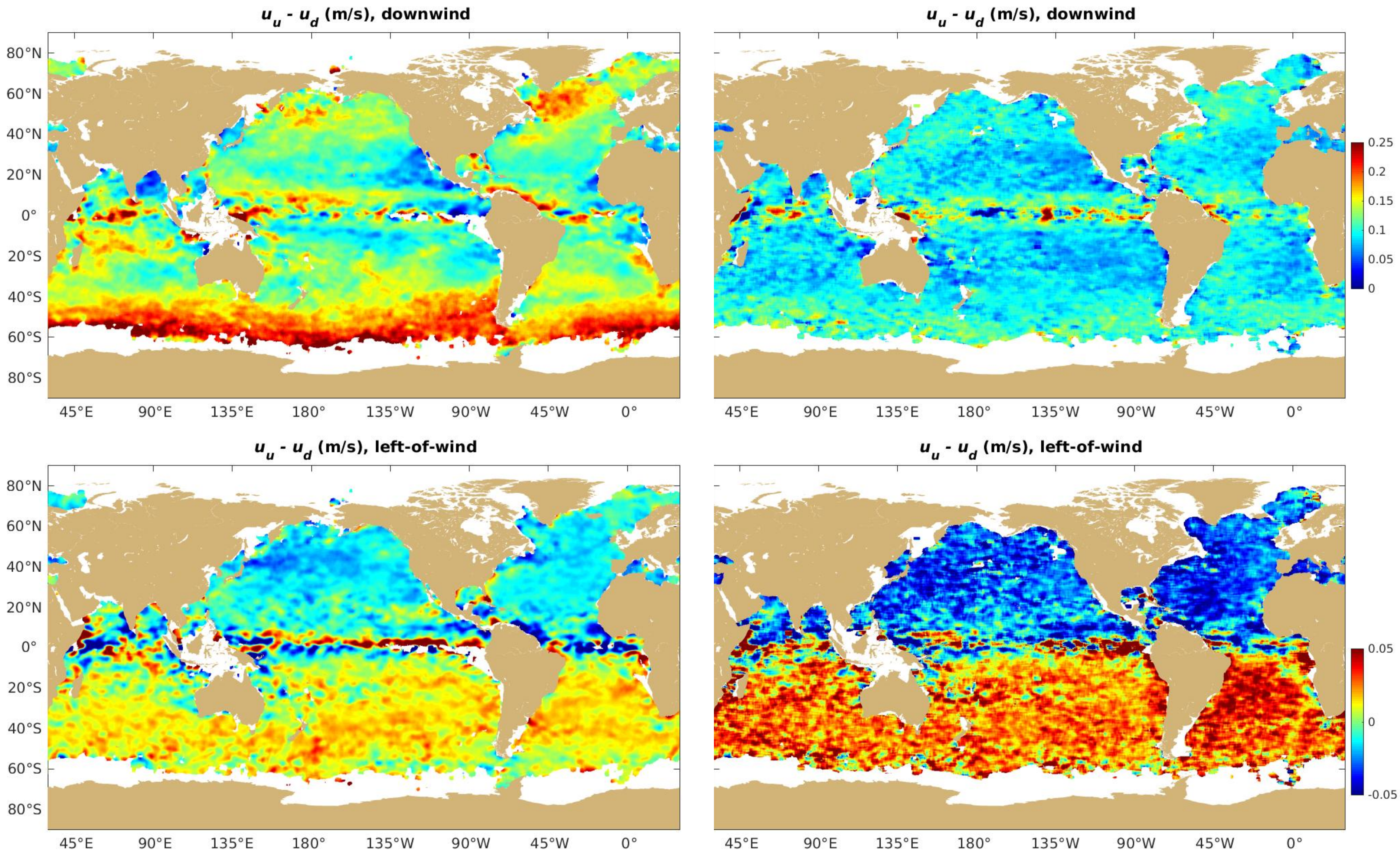
Undrogued drifters

Argo floats (YoMaHa)



Undrogued drifters

Argo floats (YoMaHa)



Summary

- Gridded, daily, ¼° resolution surface current fields can be derived from satellite observations and tuned to match drogued drifters. These could be useful for studies of upper ocean circulation, ship tracking, search operations, oil spill response, etc.

- By interpolating these fields onto undrogued drifter observations, less noisy estimates of the downwind and crosswind slip can be made.

- The difference between undrogued and drogued velocities indicates wave action and of vertical shear in the upper 15 meters of the ocean.

- Velocity information can be recovered from the undrogued drifters and used to improve estimates of ocean circulation. However, the error in most slip-corrected observations exceeds the GOOS/GCOS99 accuracy requirement.

Recovering velocity information from undrogued buoys

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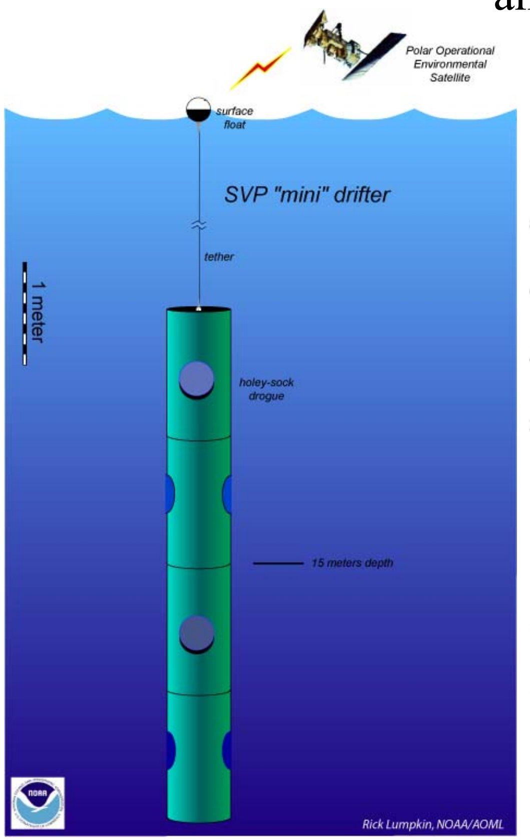
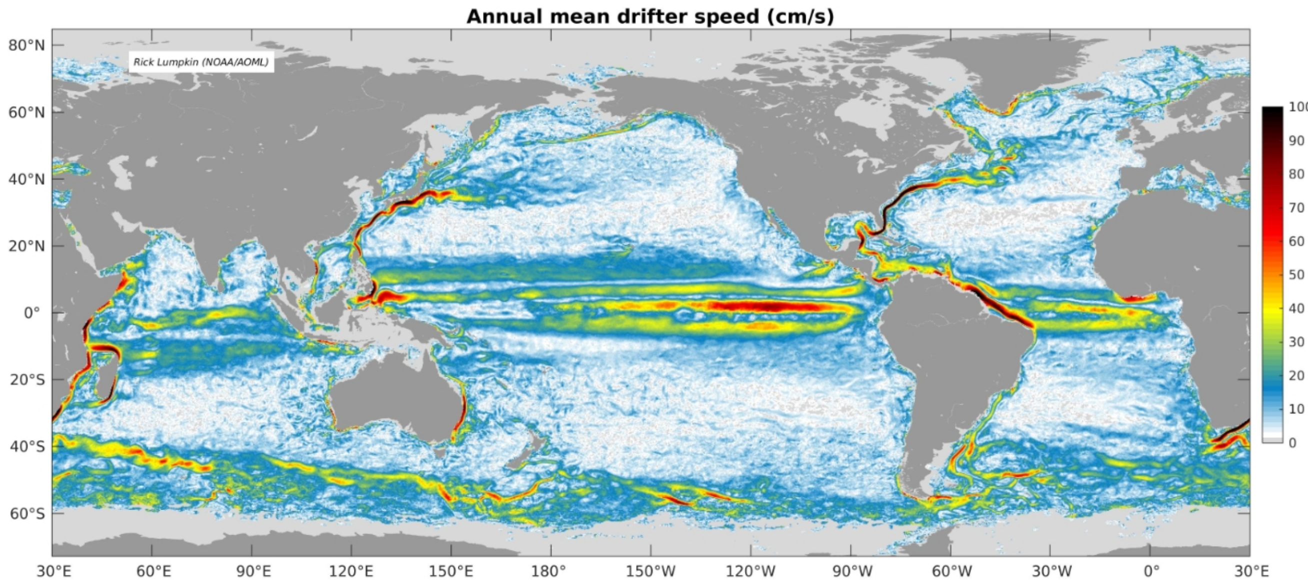
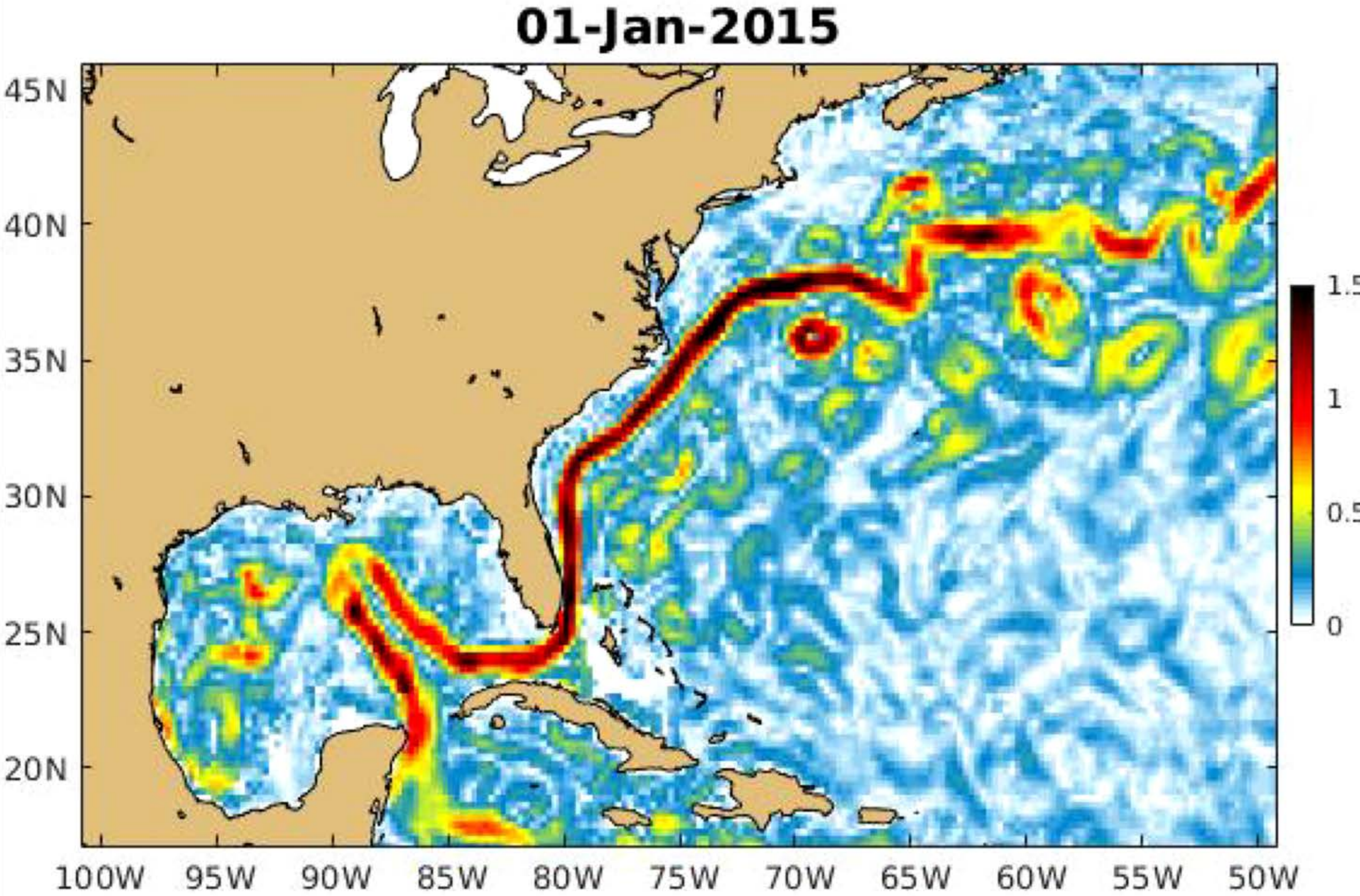
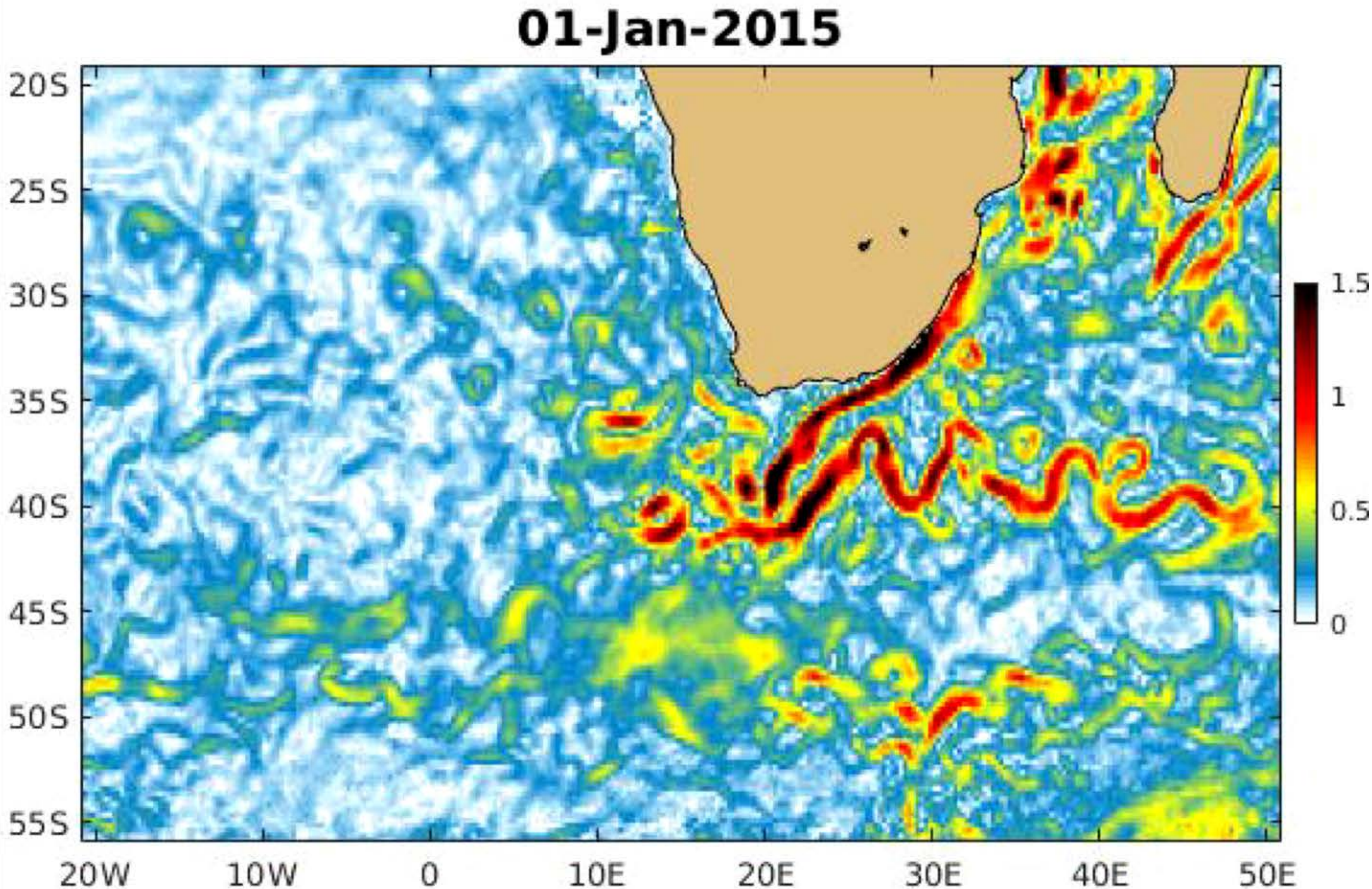


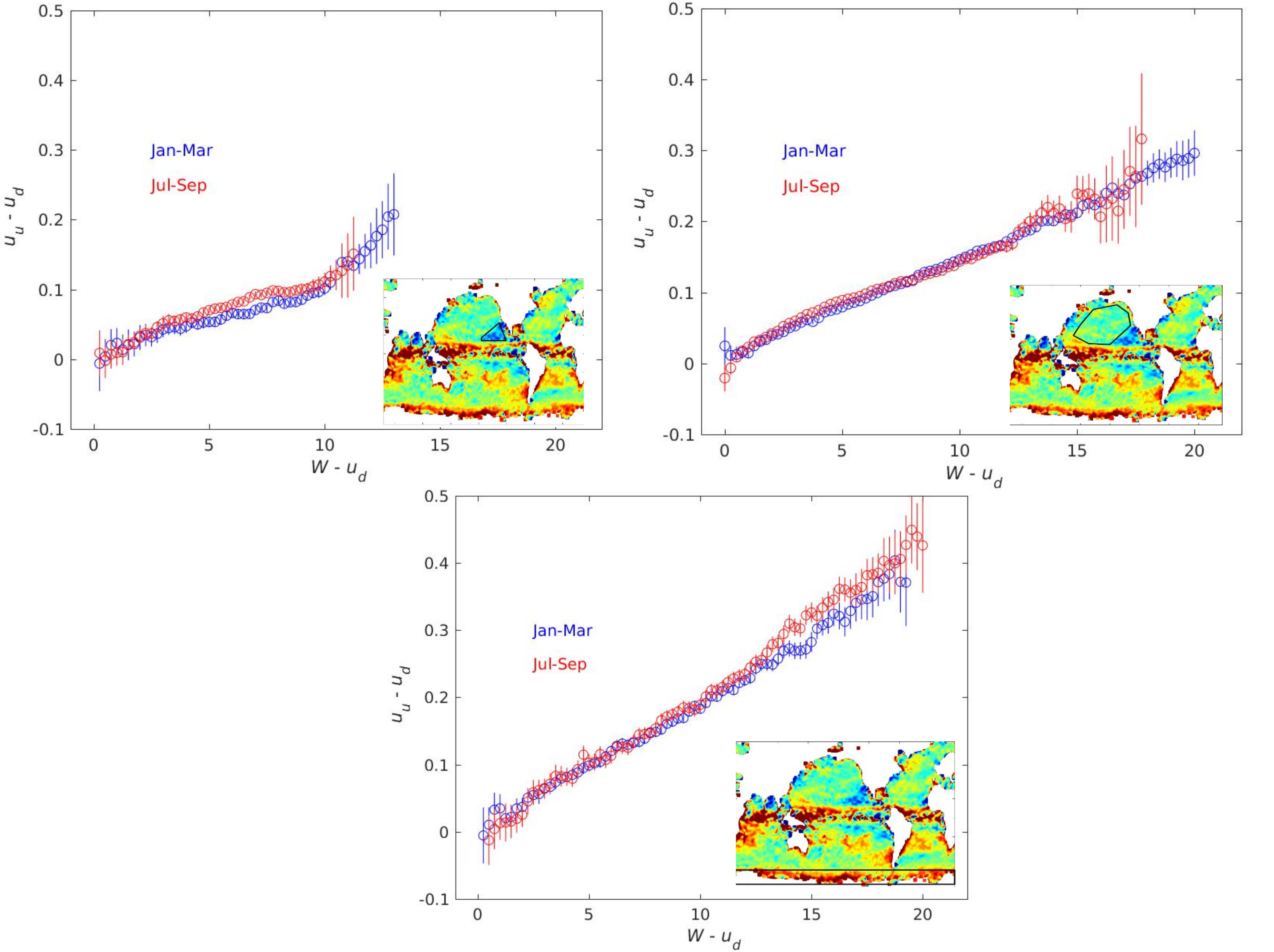


22 February 2020

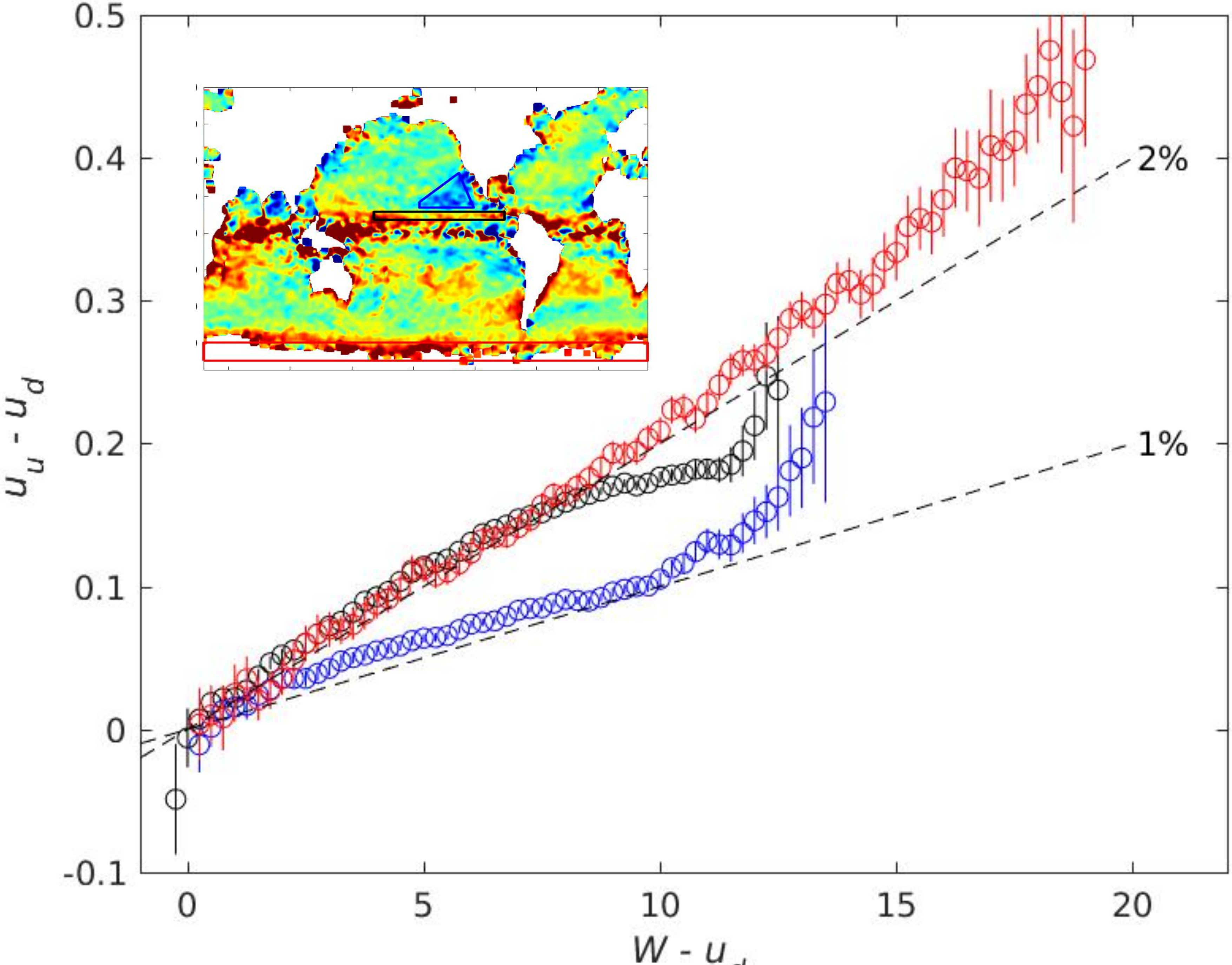

01-Jan-2015
45N
40N
35N
30N
25N
20N
100W
95W
90W
85W
80W
75W
70W
65W
60W
55W
50W
1.5
1
0.5
0



01-Jan-2015
20S
25S
30S
35S
40S
45S
50S
55S
20W
10W
0
10E
20E
30E
40E
50E
1.5
1
0.5
0

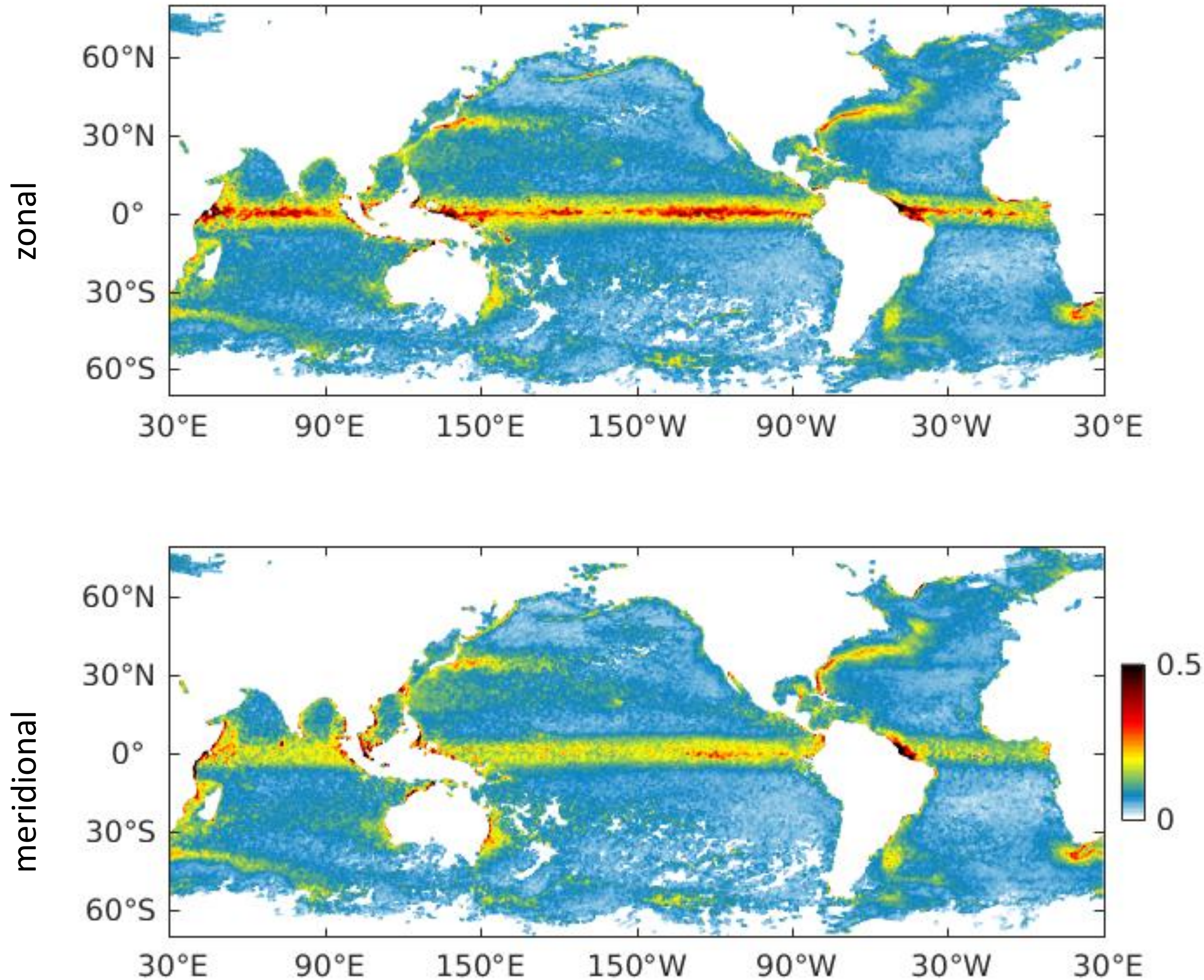


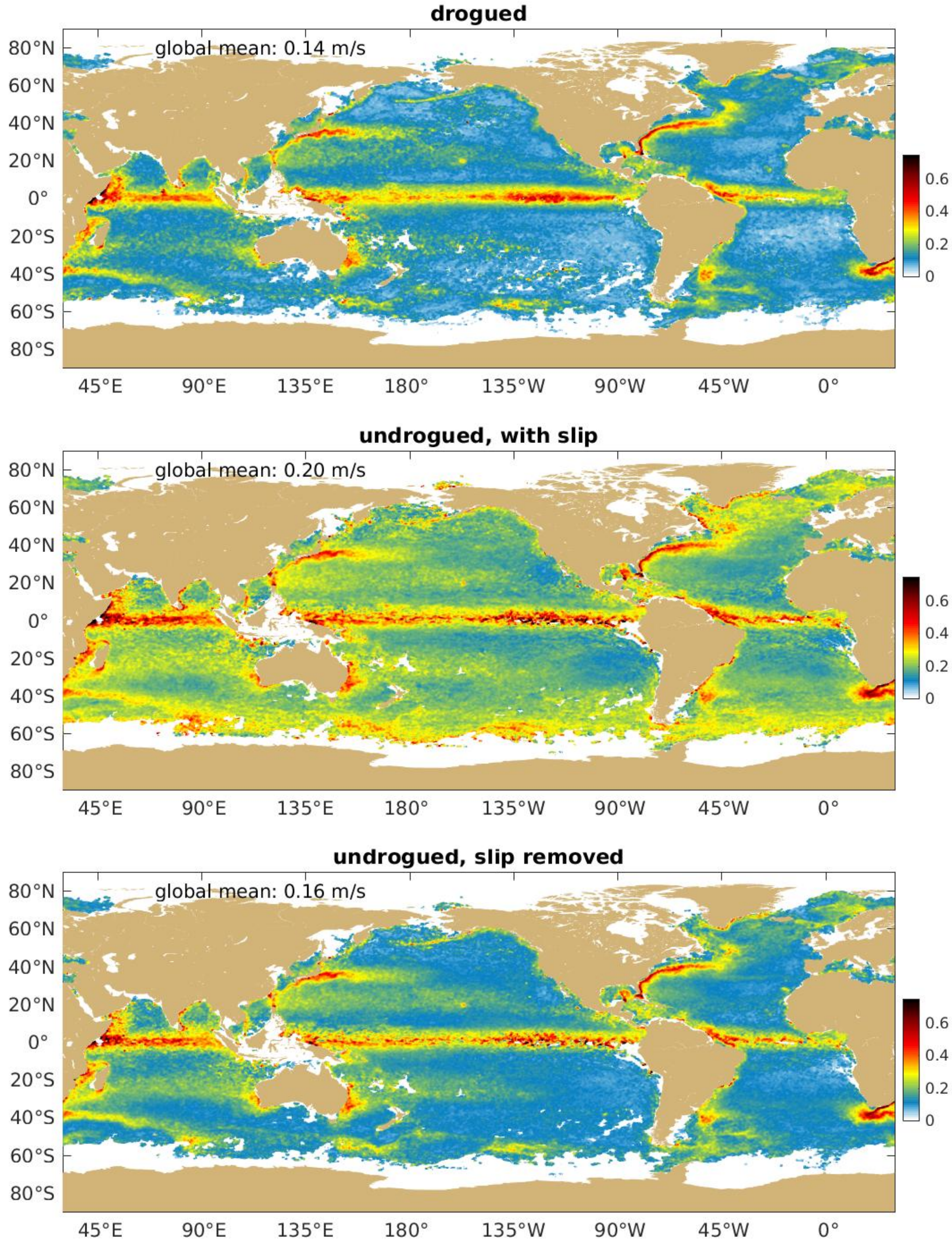
Jan-Mar
Jul-Sep
$u_u - u_d$
$W - u_d$
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
5
10
15
20



0.5
0.4
0.3
0.2
0.1
0
-0.1
$u_u - u_d$
0
5
10
15
20
$W - u_d$
2%
1%

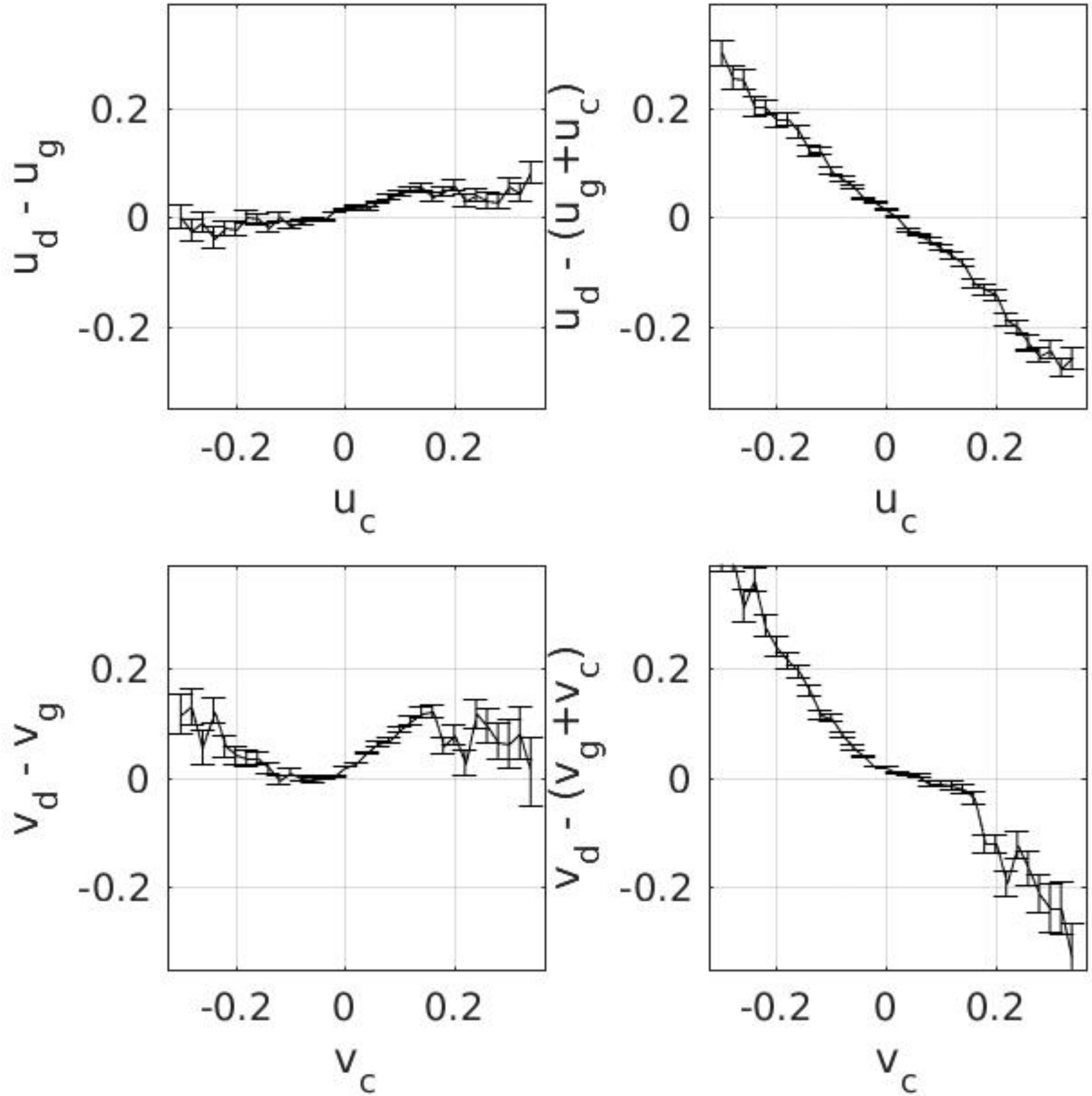
RMS differences between drogued drifter velocieis and GlobCurrent 6h velocities (m/s)

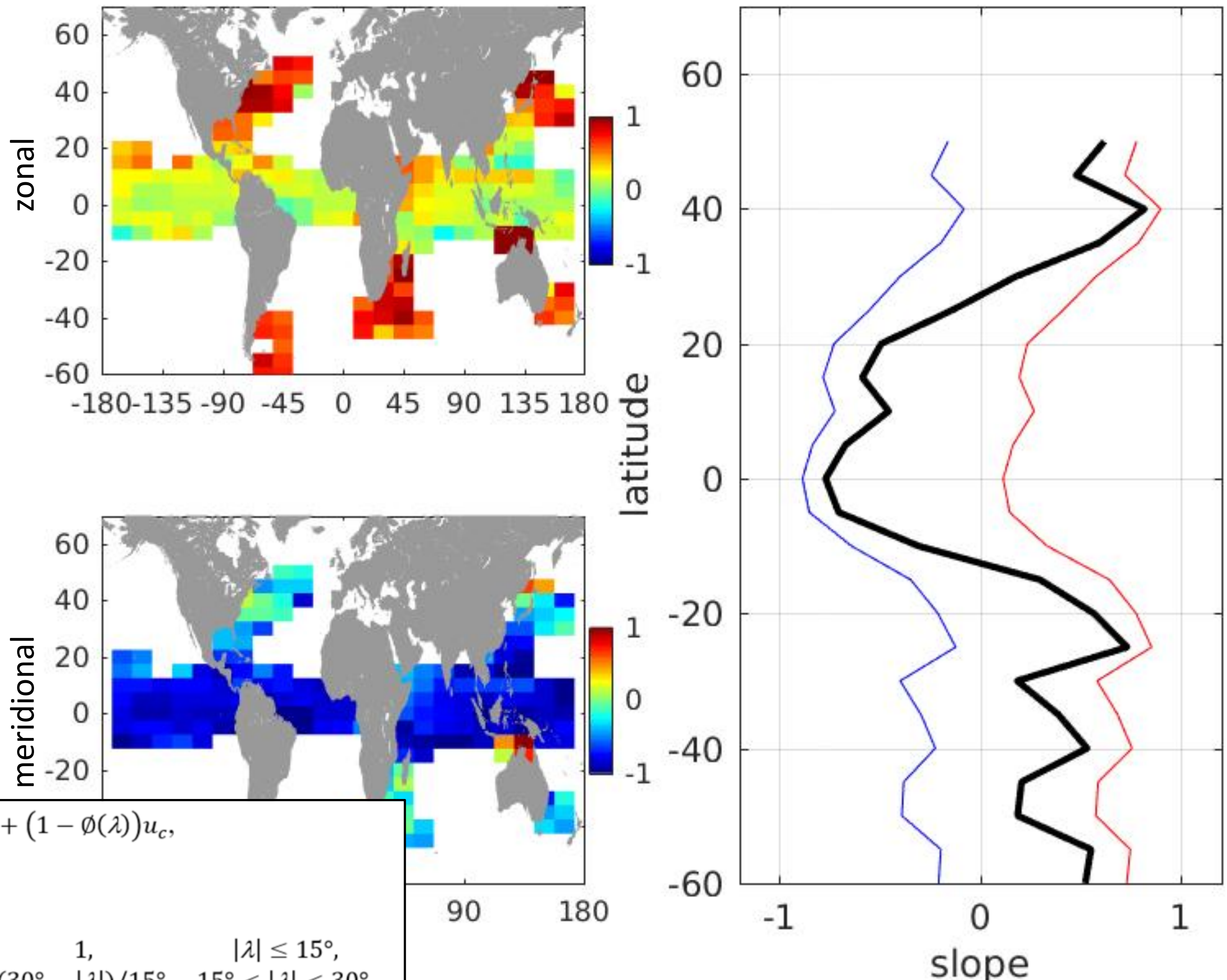




RMS differences between gridded velocity product and drifter velocities

Tropics



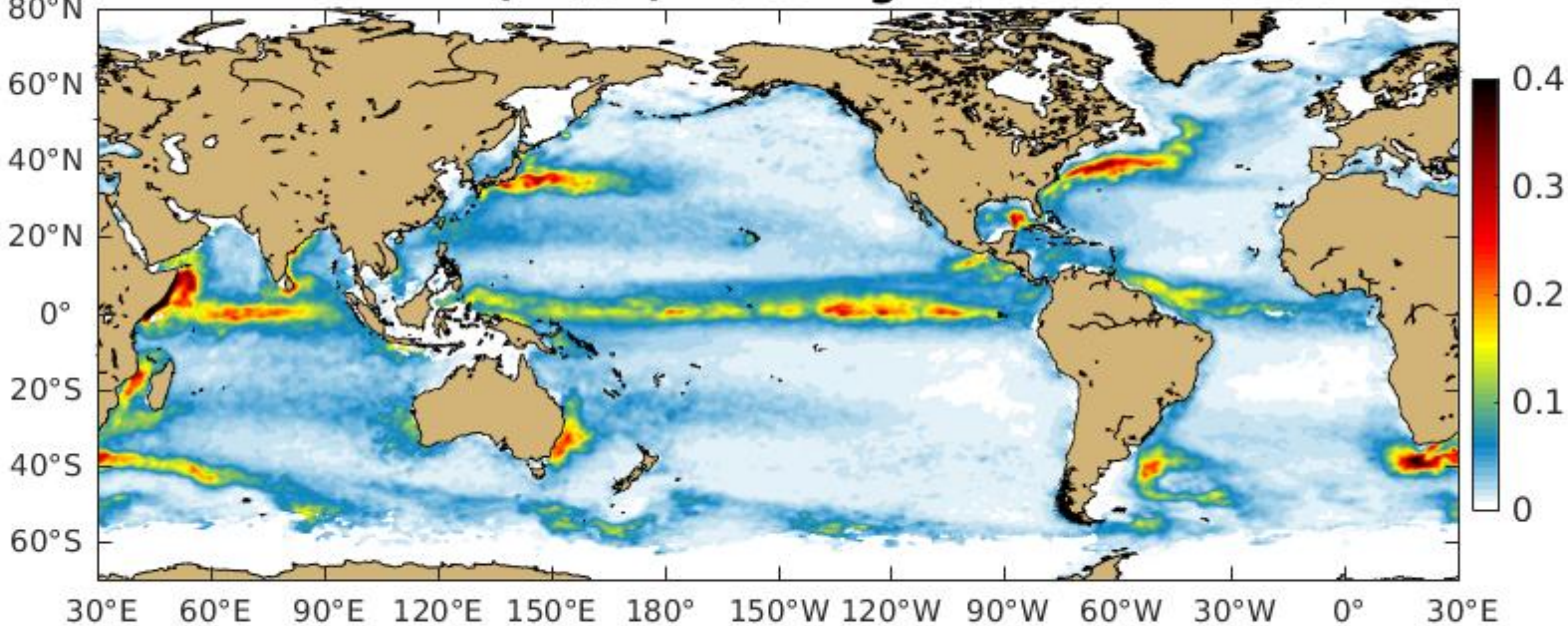


$$u_{av} = u_g + \big(1 - \emptyset(\lambda)\big)u_c,$$

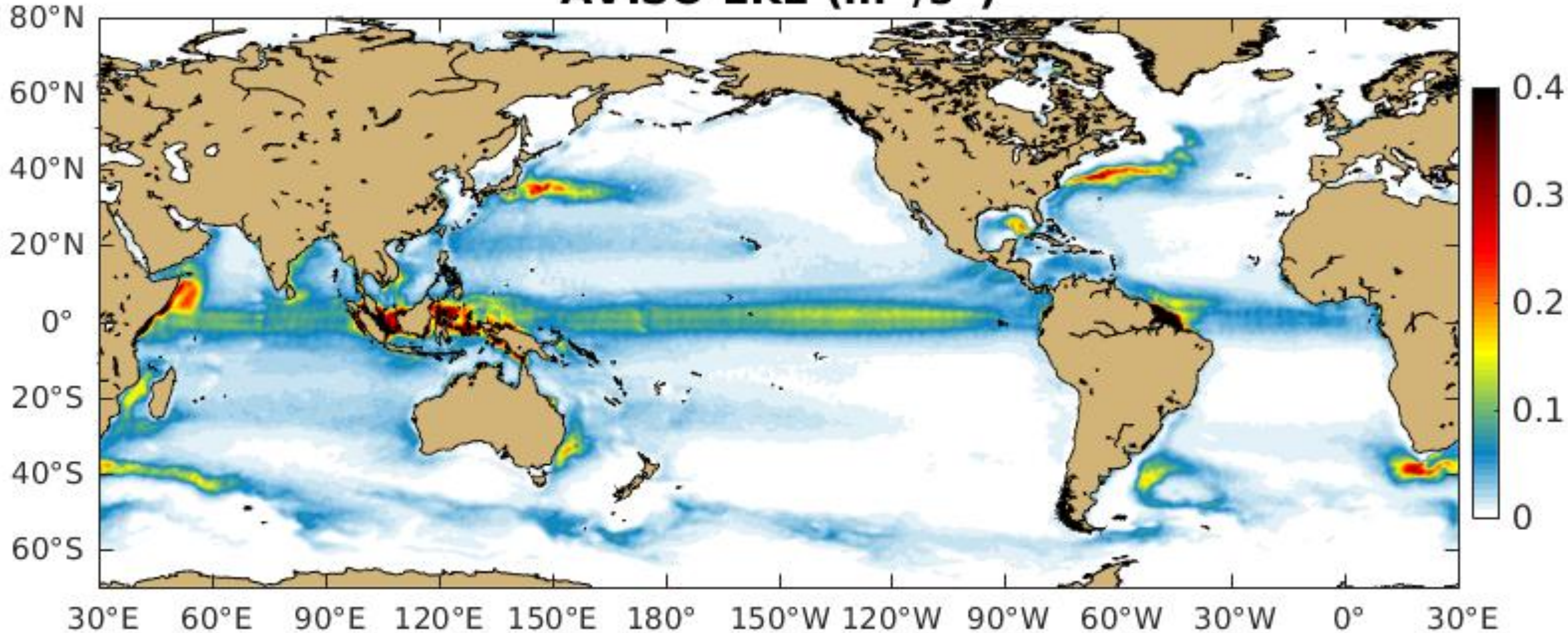
nd

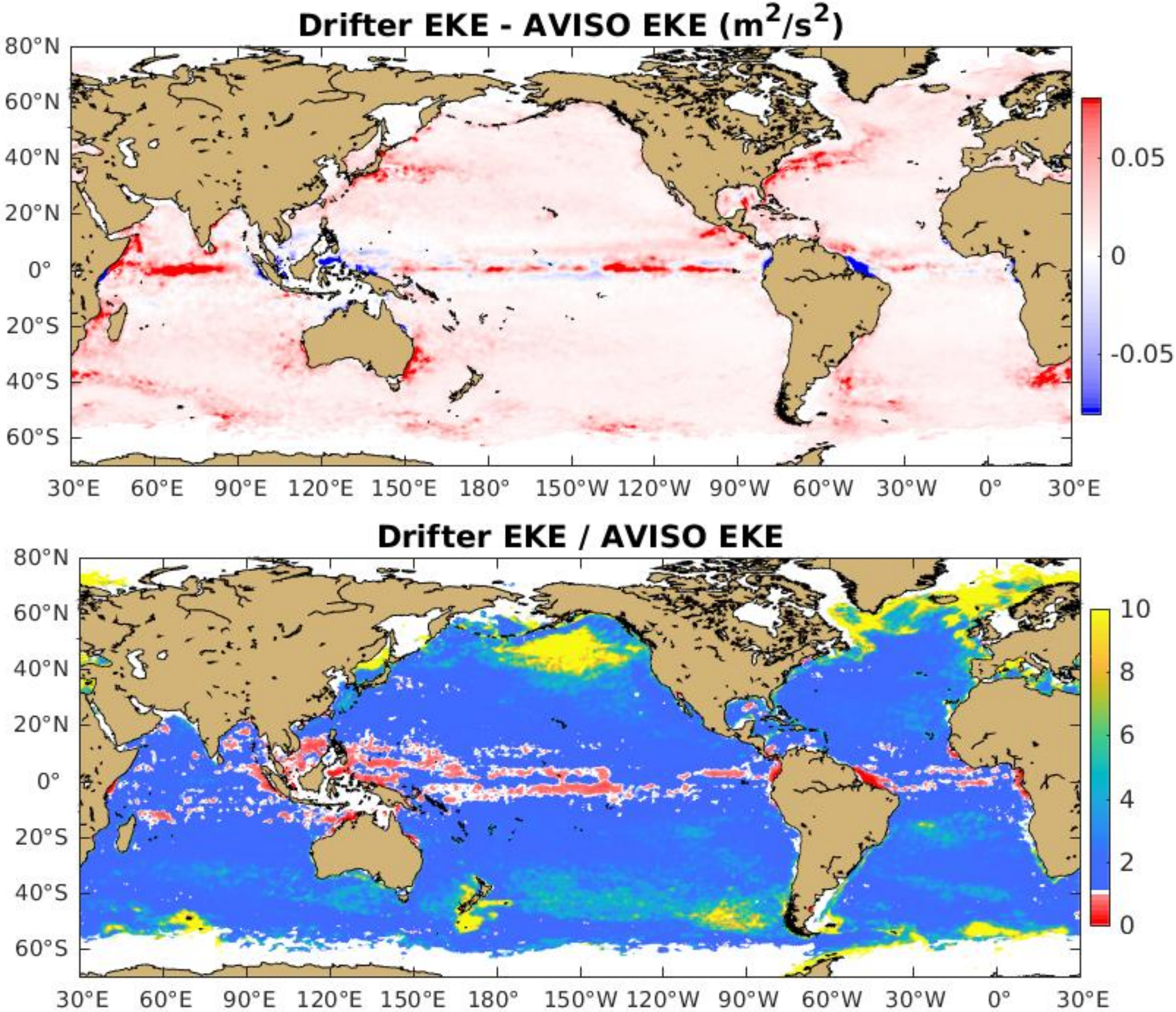
$$\emptyset(\lambda) = \begin{cases} 1, & |\lambda| \le 15°, \\ (30° - |\lambda|)/15°, & 15° < |\lambda| < 30°, \\ 0, & |\lambda| \ge 30°. \end{cases}$$

Drifter EKE (m^2/s^2) including seasonal variance

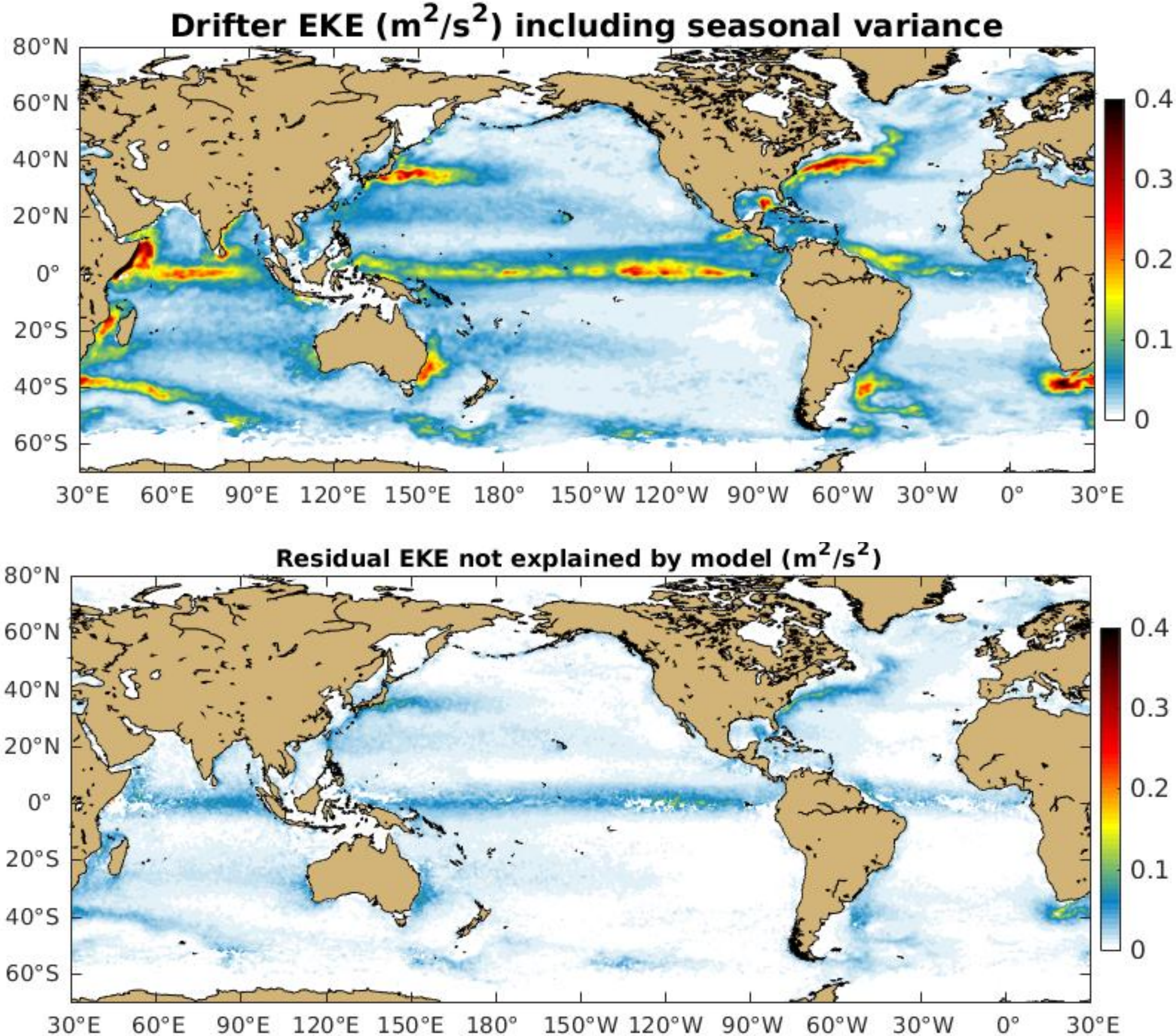


AVISO EKE (m^2/s^2)





Drifter EKE - AVISO EKE (m²/s²)
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
0°
30°E
0.05
0
-0.05
Drifter EKE / AVISO EKE
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
0°
30°E
10
8
6
4
2
0



Drifter EKE (m²/s²) including seasonal variance
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
0°
30°E
0.4
0.3
0.2
0.1
0
Residual EKE not explained by model (m²/s²)
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
0°
30°E
0.4
0.3
0.2
0.1
0