Scatterometer estimates of time-averaged surface wind divergence and vorticity in rain-free and all-weather conditions

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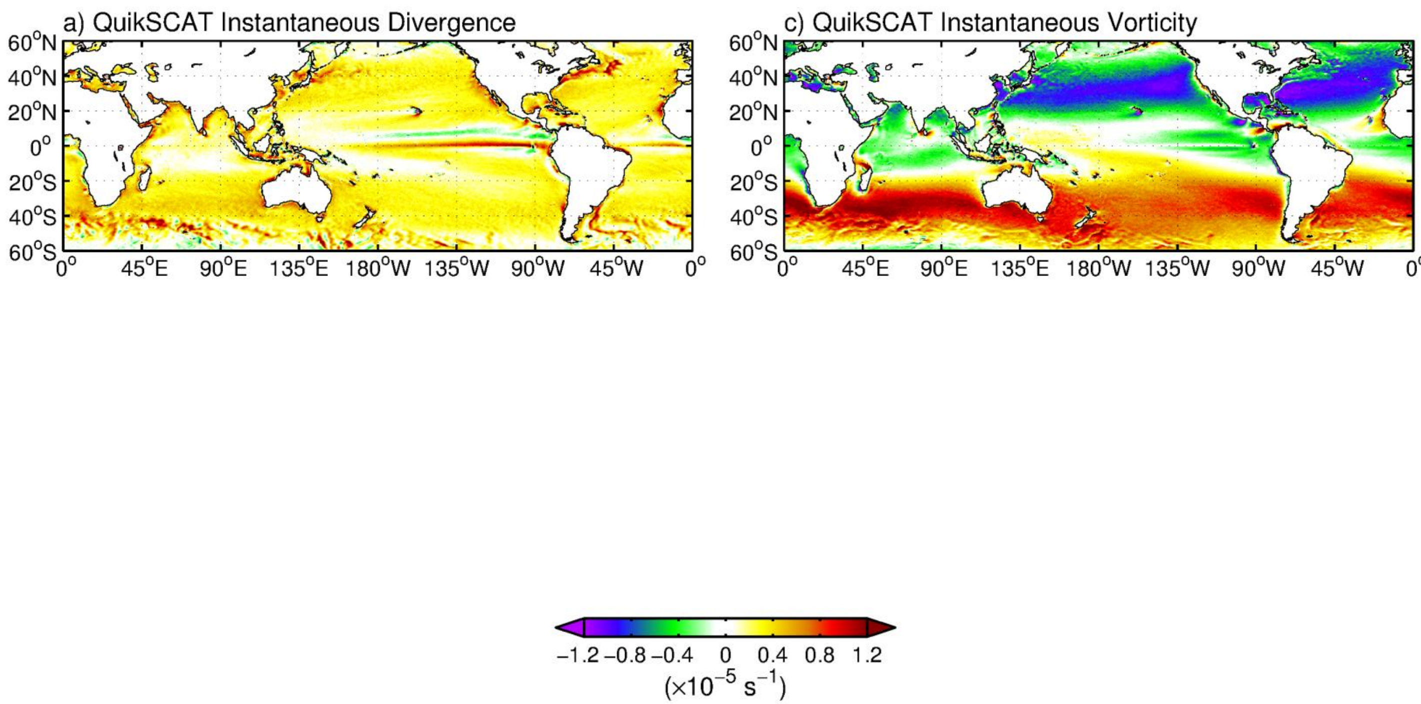
Overview:

1) Show how rain-flagging generates biases in scatterometer time-averaged surface divergence and vorticity, and how these are affected by the order of differentiation and time-averaging
2) Explain why the order of differentiation and time-averaging matter
3) Surface convergence field near the Gulf Stream from all-weather scatterometer wind fields

IOVWST Meeting, 2-4 June 2014, Brest, France

What happens when we switch order of spatial derivative and time-averaging operations applied to rain-flagged QuikSCAT winds?

Spatial derivative applied to (u_{rf}, v_{rf}) first, then time-average



Time- average (u_{rf}, v_{rf}) first, then compute spatial derivative

All spatial derivatives in this analysis computed using centered first differences

Two very different time-averaged divergence and vorticity fields for the very same rain-free winds

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Wind Stress Curl and Wind Stress Divergence Biases from Rain Effects on QSCAT Surface Wind Retrievals

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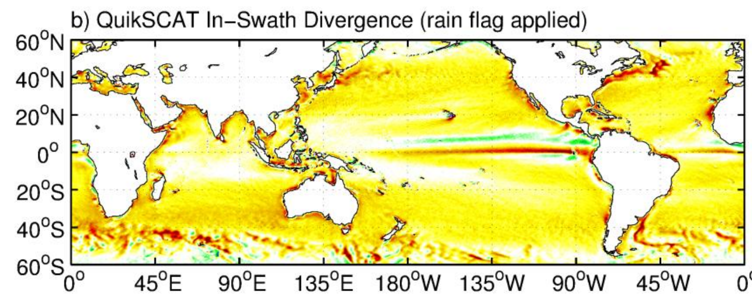
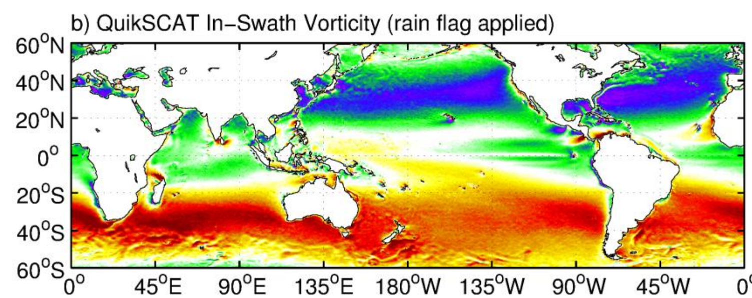
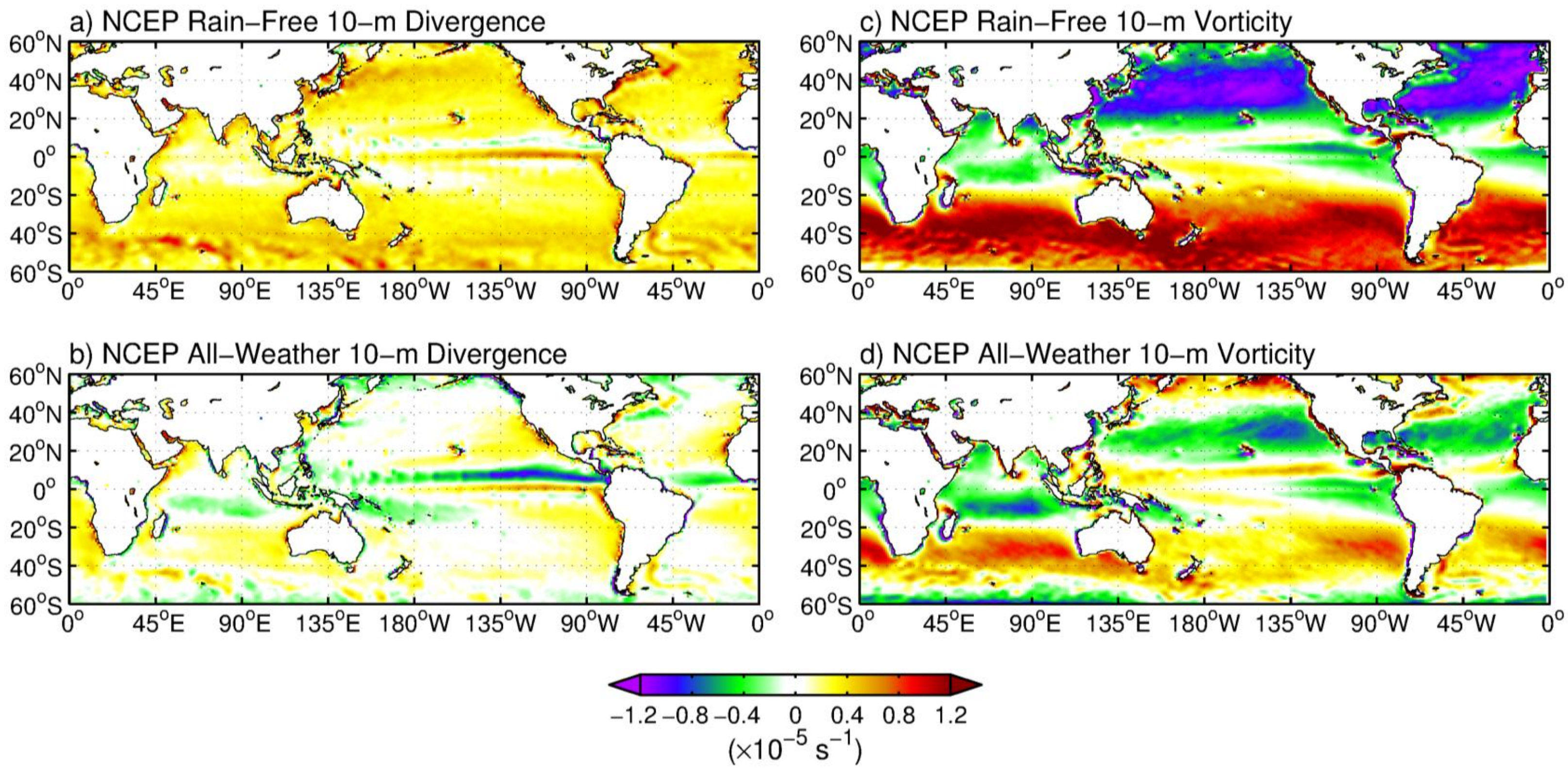
- Milliff et al. (2004) found that rain-flagging of QuikSCAT observations inherently produced divergent and anti-cyclonic sampling biases in the wind field since precipitation preferentially occurs in convergent, cyclonic conditions.
    - *Scatterometers conditionally sample non-precipitating conditions, and thus conditionally sample predominantly divergent, anti-cyclonic winds*



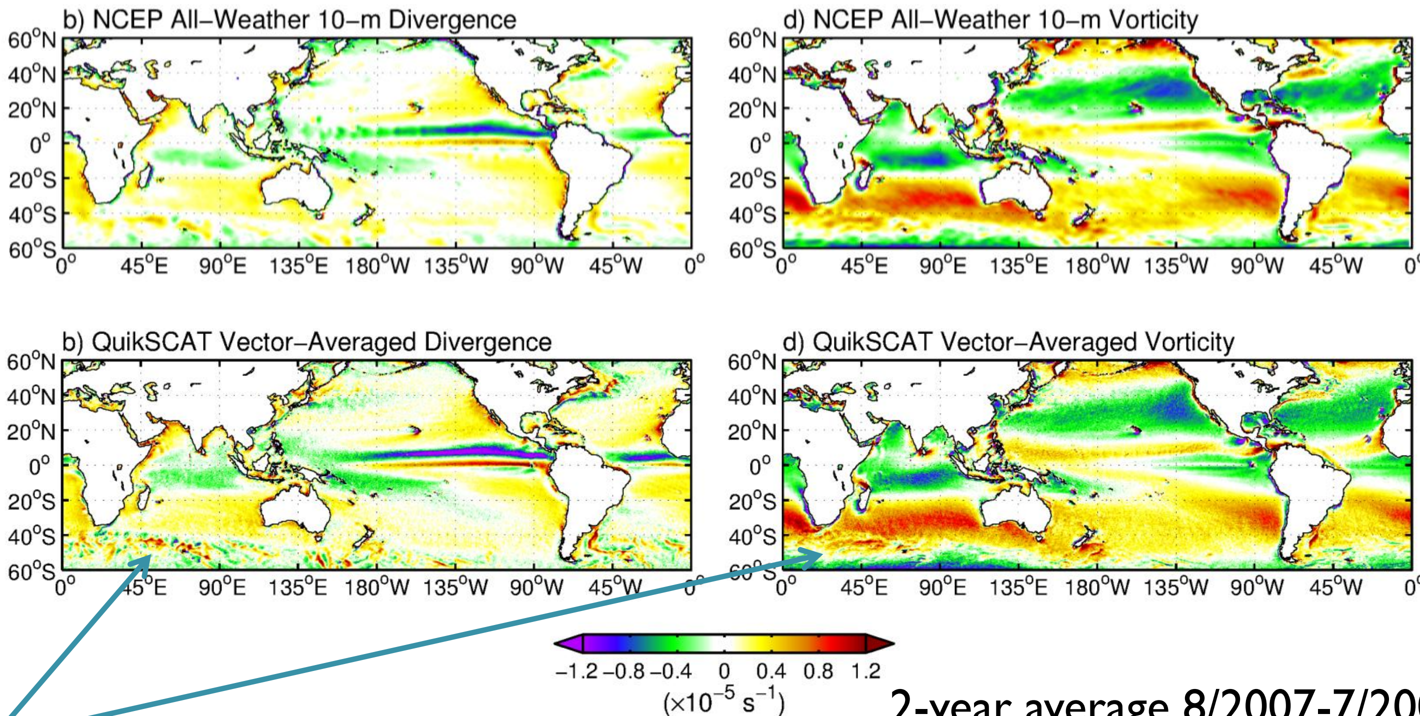


Large-scale mean divergence and vorticity fields from NCEP



3-yr average 1/2010-12/2012

Comparison of NCEP all-weather and QuikSCAT rain-free time-averaged divergence/vorticity

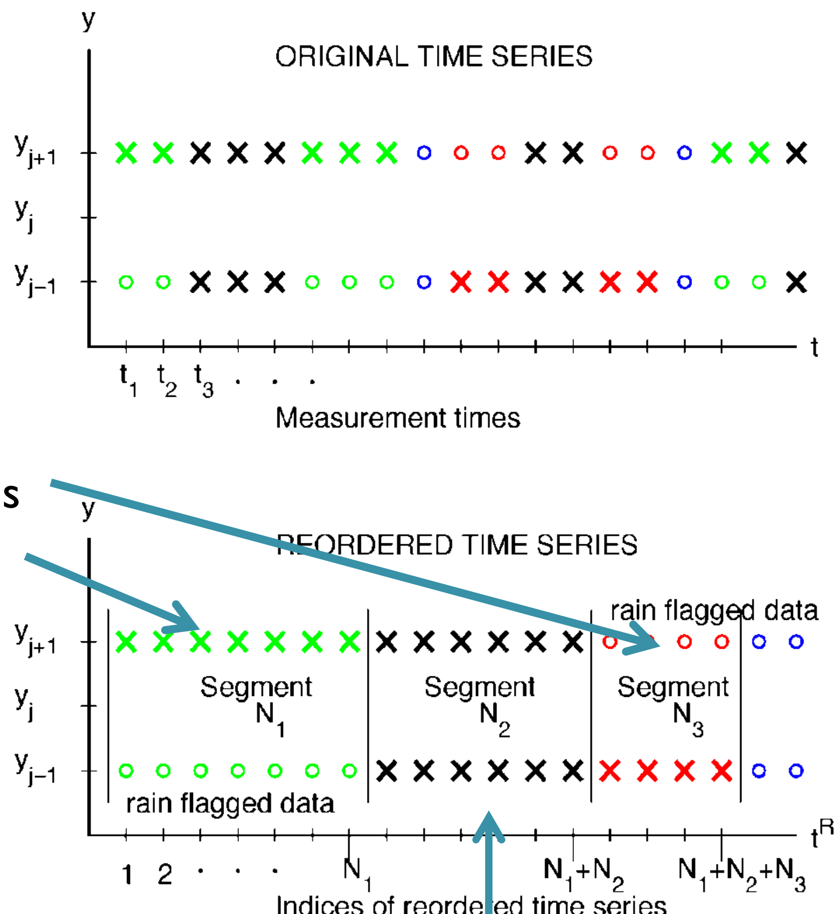


2-year average 8/2007-7/2009

These are the divergence and vorticty of the time-averaged rain-free QuikSCAT u,v winds!!!

Remarkably, the vector-averaged method applied to rain-free QuikSCAT winds accounts for the major large-scale features of the divergence and vorticity fields in the all-weather NCEP fields (which include rain).

Difference between time-averaged instantaneous and vector-averaged divergence and curl



Wind observations unpaired in time

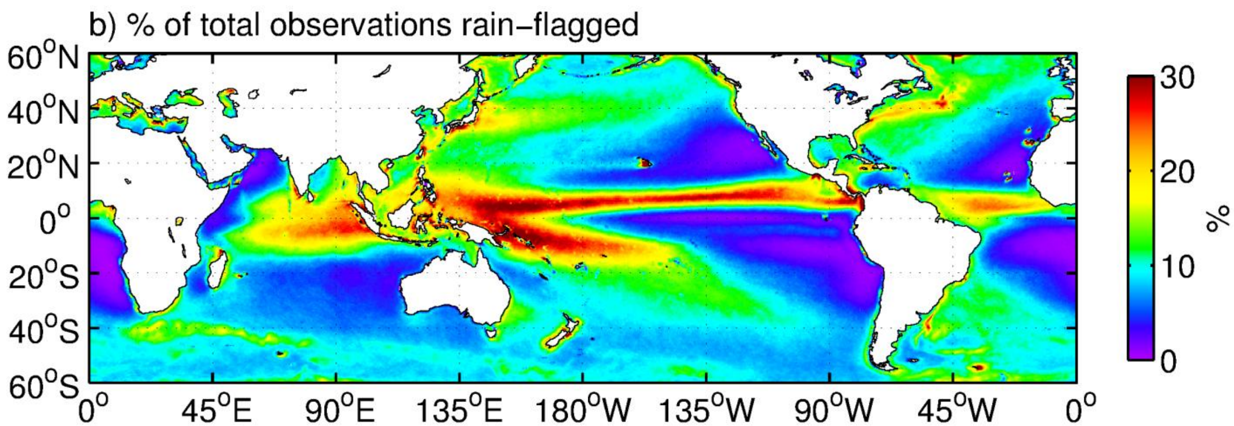
Wind observations paired in time

Difference between the two methods is the influence of *unpaired observations* in the vector-averaged method

Unpaired observations occur at the first non-rainflagged grid point bordering rain patches

The vector-averaged method thus contains more information than does the instantaneous averages

Frequency of rain-flagged occurrences in the 10-yr QuikSCAT data record



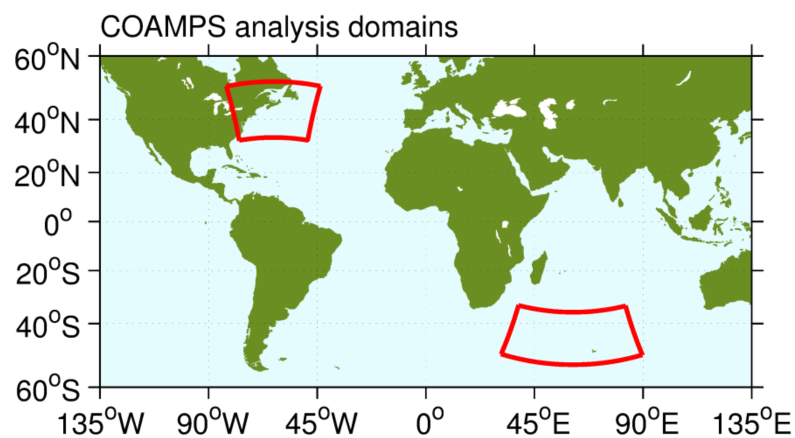
- Large spatial variability of frequency of rain frequency
- Oft-quoted global over-ocean average is 7.3%
    - This global average does not fully characterize regional variability

Questions raised by this analysis

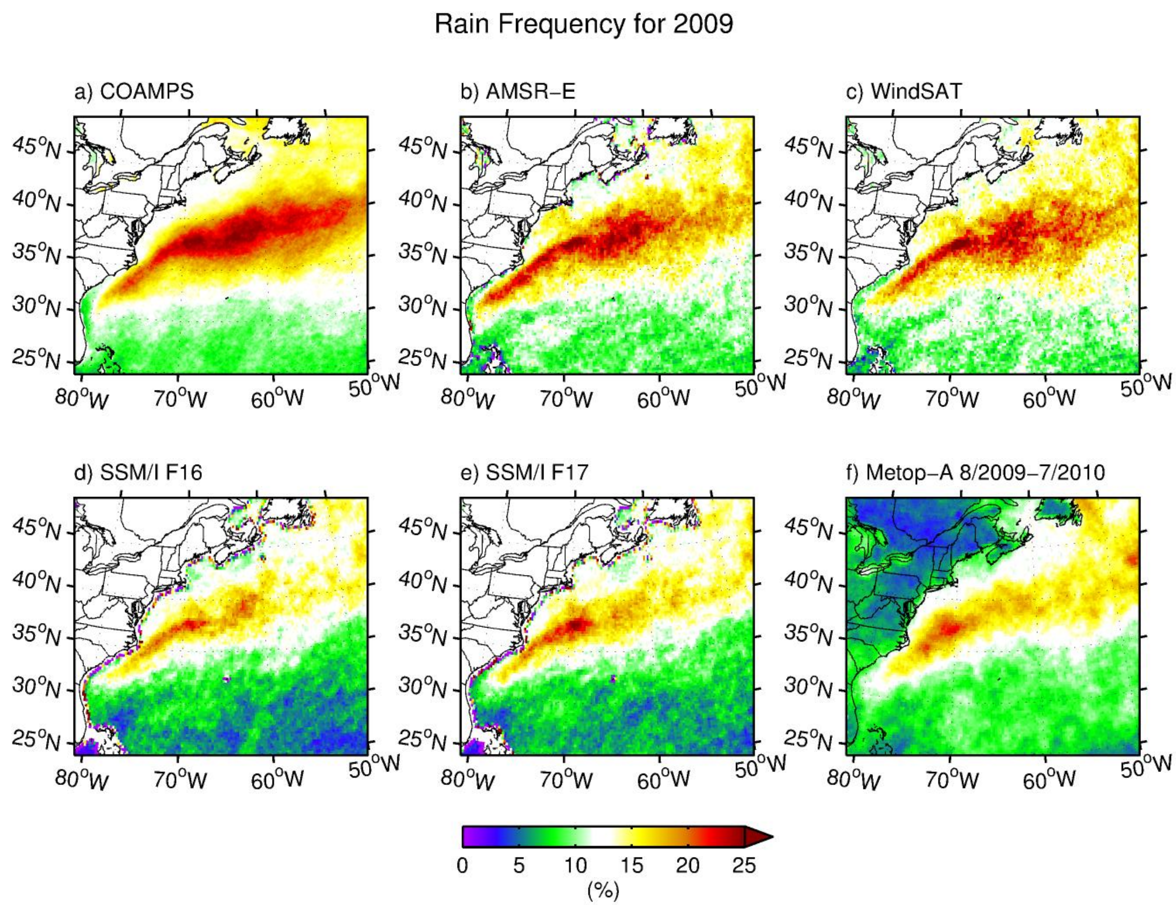
- The time-averaged divergence and vorticity from the vector-averaged method applied to rain-free winds resembles the time-means from the all-weather winds. Does this mean that…
    - … the link between rain and convergence and cyclonic vorticity is not true, weak, or more complicated than previously supposed?
    - … winds in rain are not necessary to get plausible estimates of the time-averaged all-weather divergence and vorticity?

Numerical simulation to evaluate vector-averaged method

- Diagnose why vector-averaged method applied to rain-free winds resembles time-averaged all-weather derivative wind fields.
- 1 year simulation using COAMPS mesoscale atmosphere model over the Northwest Atlantic
  - Realistic rain and wind variability/covariability
  - 9km grid resolution
  - Results here presented for 06Z and 18Z for year of 2009



Comparison of COAMPS Rain Frequency for 2009 with satellite estimates

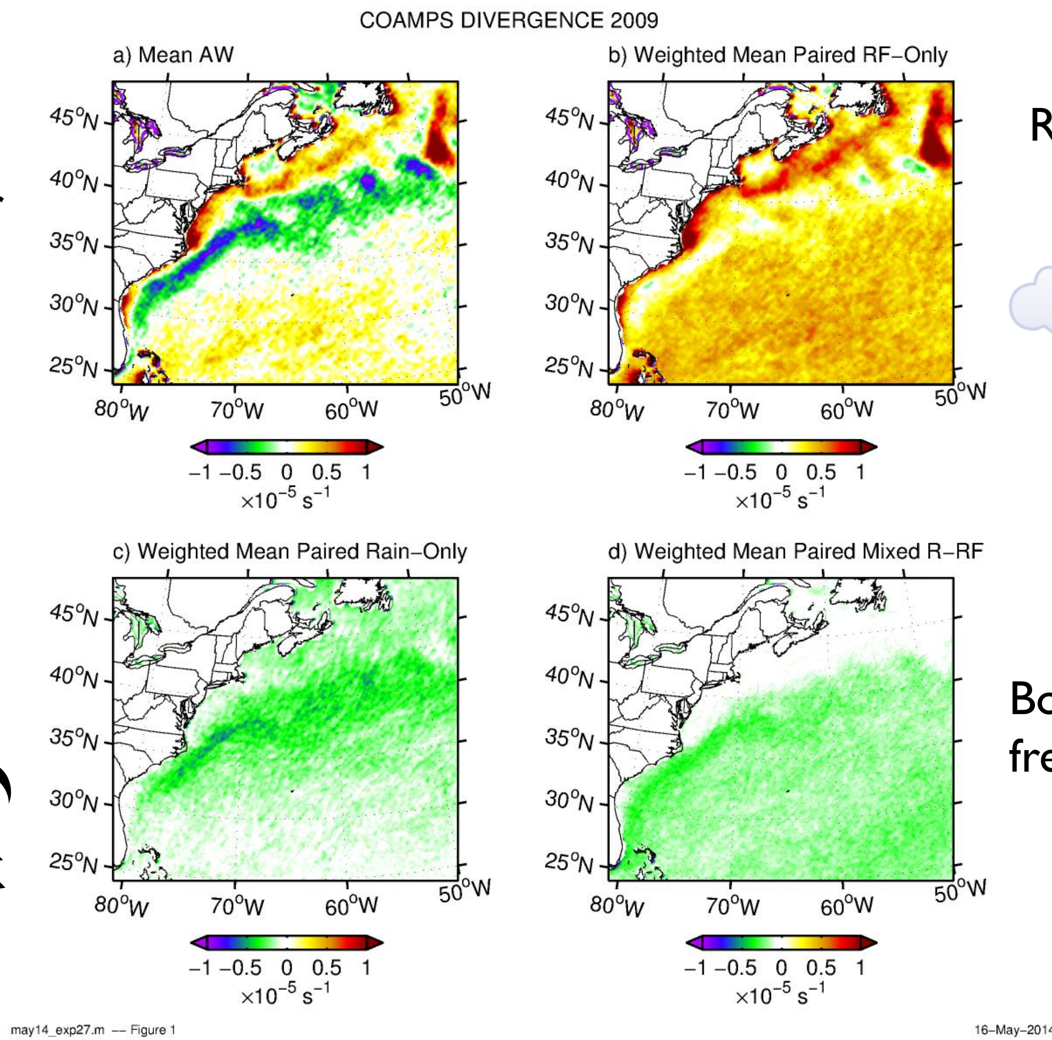


Spatial structure and magnitude of rain frequency well-represented in COAMPS, although it is a few percent higher compared to other satellite rain frequency estimates.

1-yr average surface divergence from COAMPS simulation

All-weather

Rain-free



Rain-only

Border of rain/rain-free regions

Analysis of divergence of vector-averaged u_{rf},v_{rf}

$$D_{i,j}^{VA} = \frac{1}{2\Delta x}\left[\frac{1}{N_{i+1,j}}\sum_{k=1}^{N_{i+1,j}} u_{i+1,j}(t_k) - \frac{1}{N_{i-1,j}}\sum_{l=1}^{N_{i-1,j}} u_{i-1,j}(t_l)\right] + \frac{1}{2\Delta y}\left[\frac{1}{N_{i,j+1}}\sum_{m=1}^{N_{i,j+1}} v_{i,j+1}(t_m) - \frac{1}{N_{i,j-1}}\sum_{n=1}^{N_{i,j-1}} v_{i,j-1}(t_n)\right].$$

$$\frac{1}{N_{i+1,j}}\sum_{k=1}^{N_{i+1,j}} u_{i+1,j}(t_k) = \frac{1}{N_{i+1,j}}\left(N^{p}_{i,j}\hat{\mu}^{p}_{u_{i+1,j}} + N^{up}_{i+1,j}\hat{\mu}^{up}_{u_{i+1,j}}\right),$$

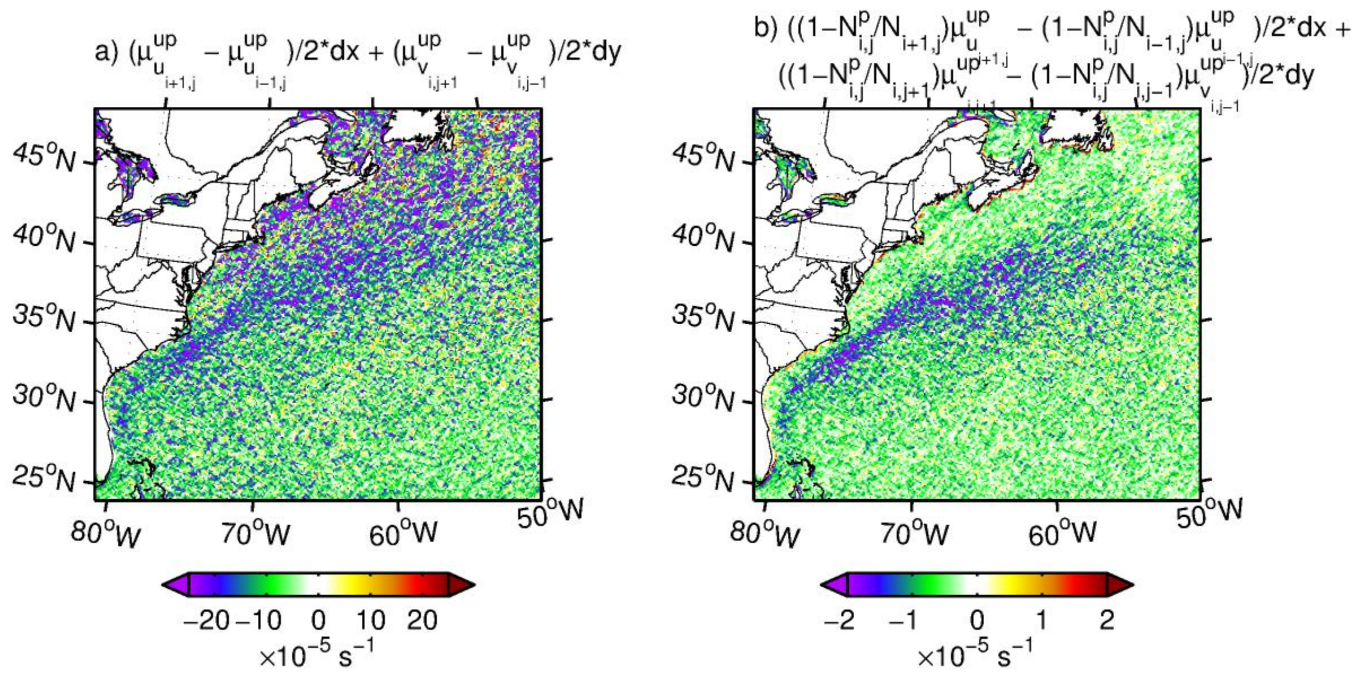
Split all four means into contributions from paired and unpaired winds…

$$D_{i,j}^{VA} = N^{p}_{i,j}\left[\frac{1}{2\Delta x}\left(\frac{\hat{\mu}^{p}_{u_{i+1,j}}}{N_{i+1,j}} - \frac{\hat{\mu}^{p}_{u_{i-1,j}}}{N_{i-1,j}}\right) + \frac{1}{2\Delta y}\left(\frac{\hat{\mu}^{p}_{v_{i,j+1}}}{N_{i,j+1}} - \frac{\hat{\mu}^{p}_{v_{i,j-1}}}{N_{i,j-1}}\right)\right] + \frac{1}{2\Delta x}\left[\left(1 - \frac{N^{p}_{i,j}}{N_{i+1,j}}\right)\hat{\mu}^{up}_{u_{i+1,j}} - \left(1 - \frac{N^{p}_{i,j}}{N_{i-1,j}}\right)\hat{\mu}^{up}_{u_{i-1,j}}\right] + \frac{1}{2\Delta y}\left[\left(1 - \frac{N^{p}_{i,j}}{N_{i,j+1}}\right)\hat{\mu}^{up}_{v_{i,j-1}} - \left(1 - \frac{N^{p}_{i,j}}{N_{i,j-1}}\right)\hat{\mu}^{up}_{v_{i,j-1}}\right].$$

Contribution from paired rain-free observations

Contribution from unpaired rain-free observations

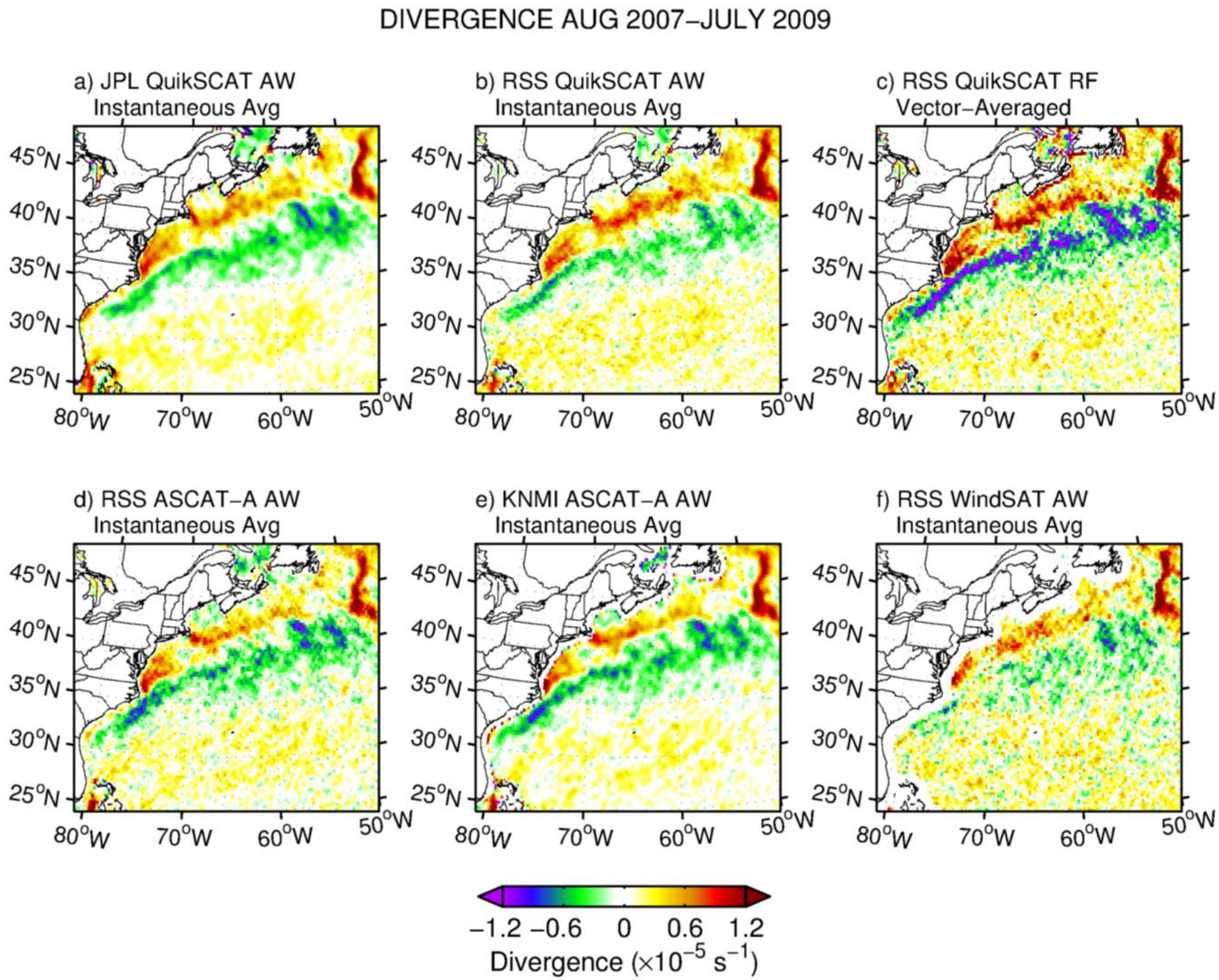
Contribution of unpaired winds to divergence of vector-averaged u_{rf},v_{rf} in model simulation



Unpaired winds partially sample the convergence in mixed rain/rain-free grid points, although it produces far too much convergence.

The spatial gradient in the number of rain-free data points focuses this convergence onto raining convergence zones.
=> This is why the vector-averaged method produces convergence and cyclonic vorticity in about the right geographical locations

Comparison of various time-averaged divergence estimates



Rain-rate induced wind speed biases in JPL QuikSCAT winds

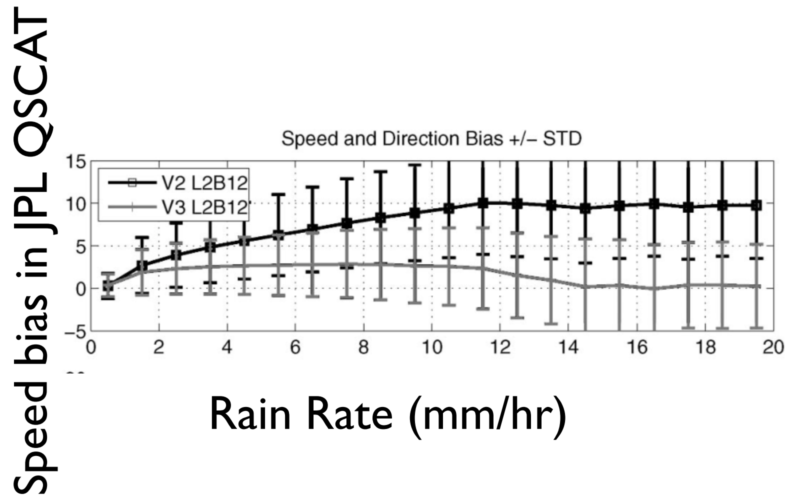


Figure 9, Fore et al. (2014)

Since there are strong rain-rate gradients in convergence zones, it is possible that all-weather scatterometer wind fields will contain rain-rate induced biases in divergence and vorticity

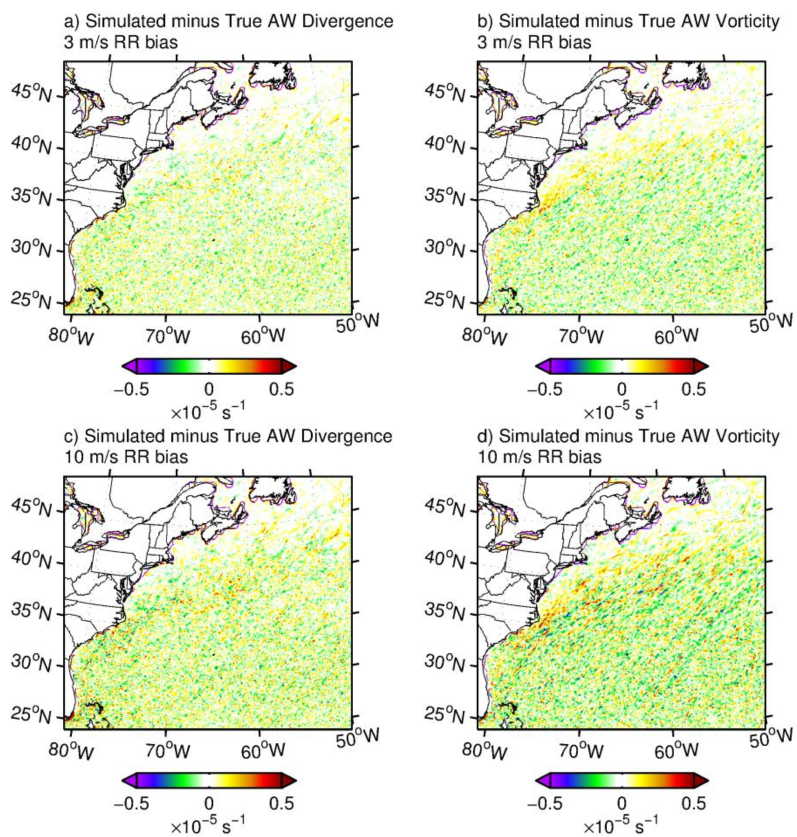
Simulate rain-rate induced divergence bias in all-weather QuikSCAT winds with COAMPS model winds

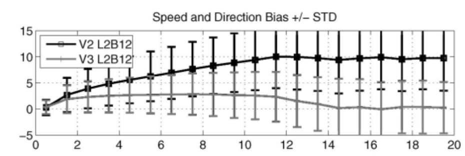
Difference between "true" all-weather COAMPS divergence and all-weather COAMPS divergence emulated to include QuikSCAT-like rain-rate induced wind speed bias

Emulated JPL QuikSCAT v3 bias

1-yr average

Emulated JPL QuikSCAT v2 bias

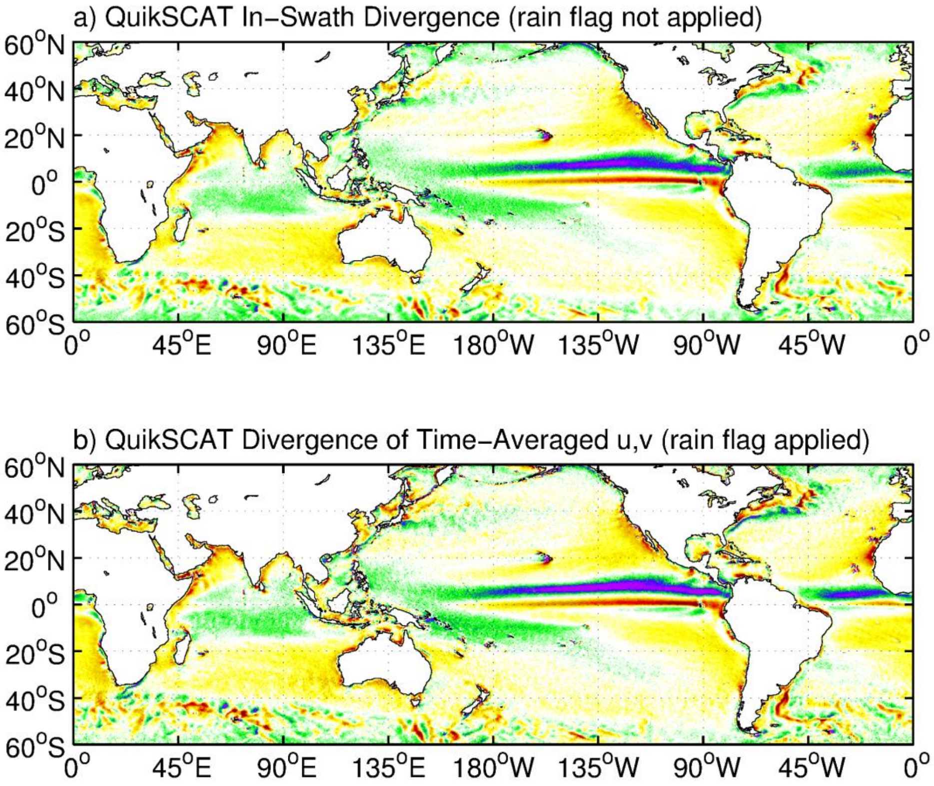


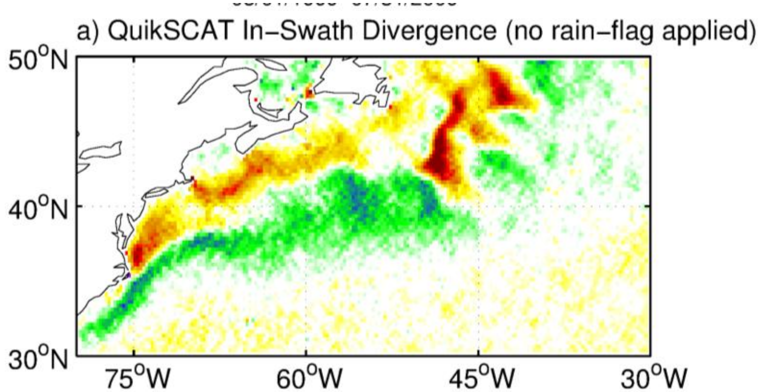


This suggests rain-rate induced biases in all-weather scatterometer winds are manageable in time-averages

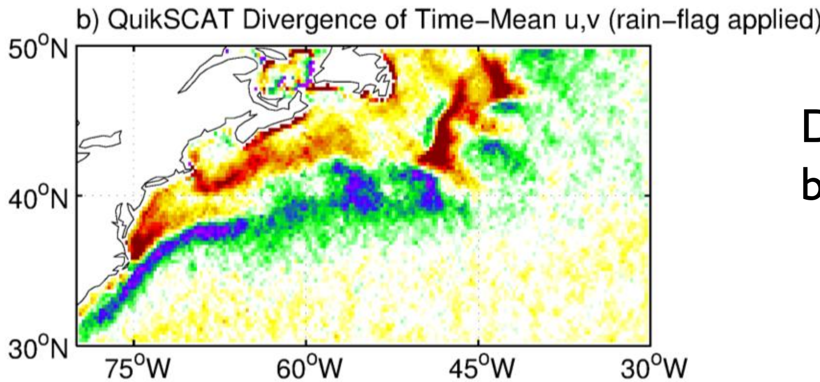
Summary

- Two methods of computing time-averaged divergence and vorticity
  - In-swath or Instantaneous
  - Vector-averaged
- When applied to rain-free winds, the vector-averaged method produces time-averaged div/crl fields that strikingly resemble the all-weather time-averaged div/crl
- Resemblance is due to:
  - Biased estimate of the time-mean mixed rain/rain-free div/crl introduced from wind observations unpaired in time, which occur on the borders of rain patches
  - Spatial gradients in the number of rain-free observations, which are strongest in raining convergence zones
- Vector-averaged method applied to rain-free winds should not be used.

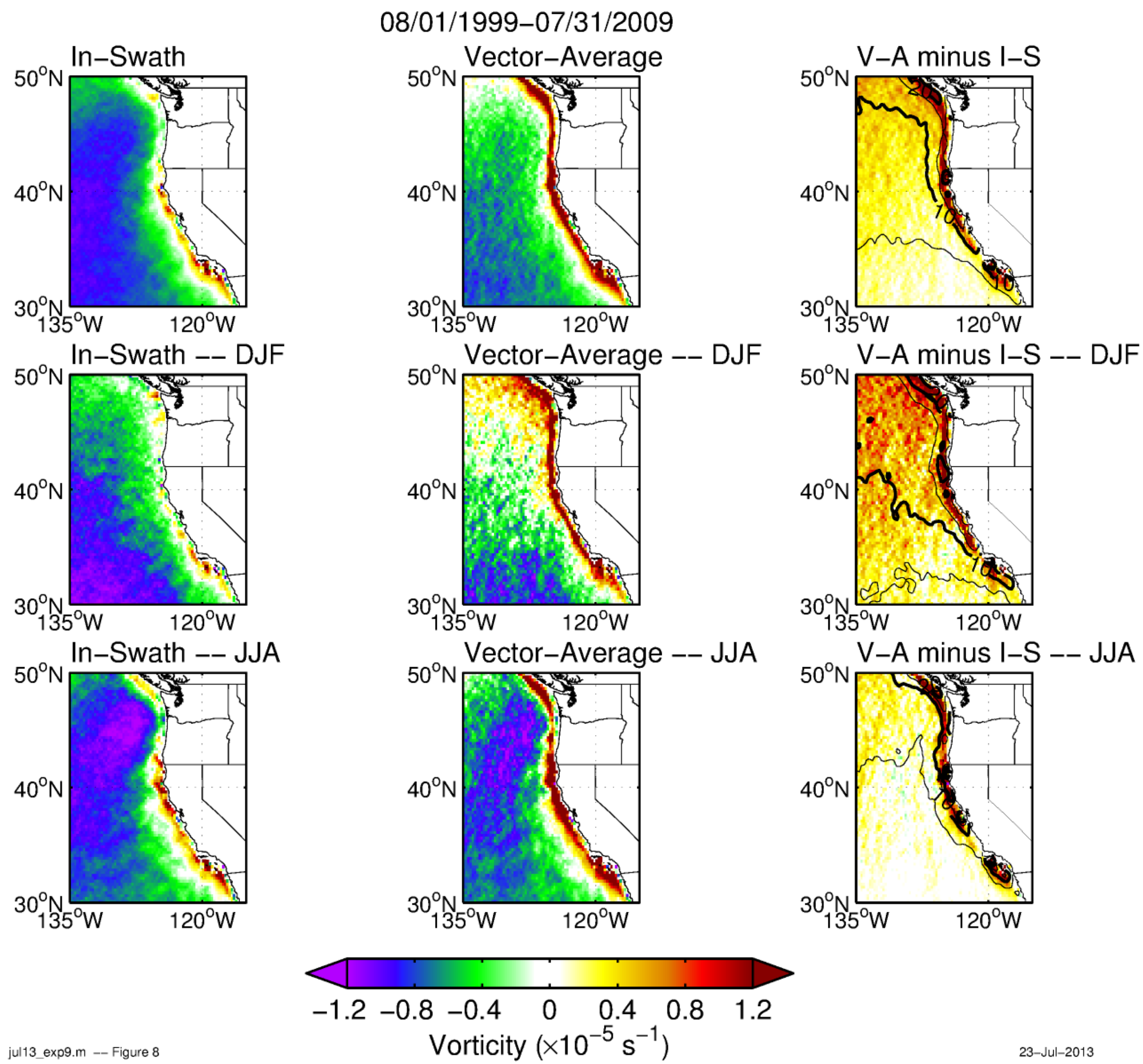

a) QuikSCAT In−Swath Divergence (rain flag not applied)
60°N
40°N
20°N
0°
20°S
40°S
60°S
0°
45°E
90°E
135°E
180°W
135°W
90°W
45°W
0°
b) QuikSCAT Divergence of Time−Averaged u,v (rain flag applied)
60°N
40°N
20°N
0°
20°S
40°S
60°S
0°
45°E
90°E
135°E
180°W
135°W
90°W
45°W
0°



QuikSCAT winds without applying the rain flag

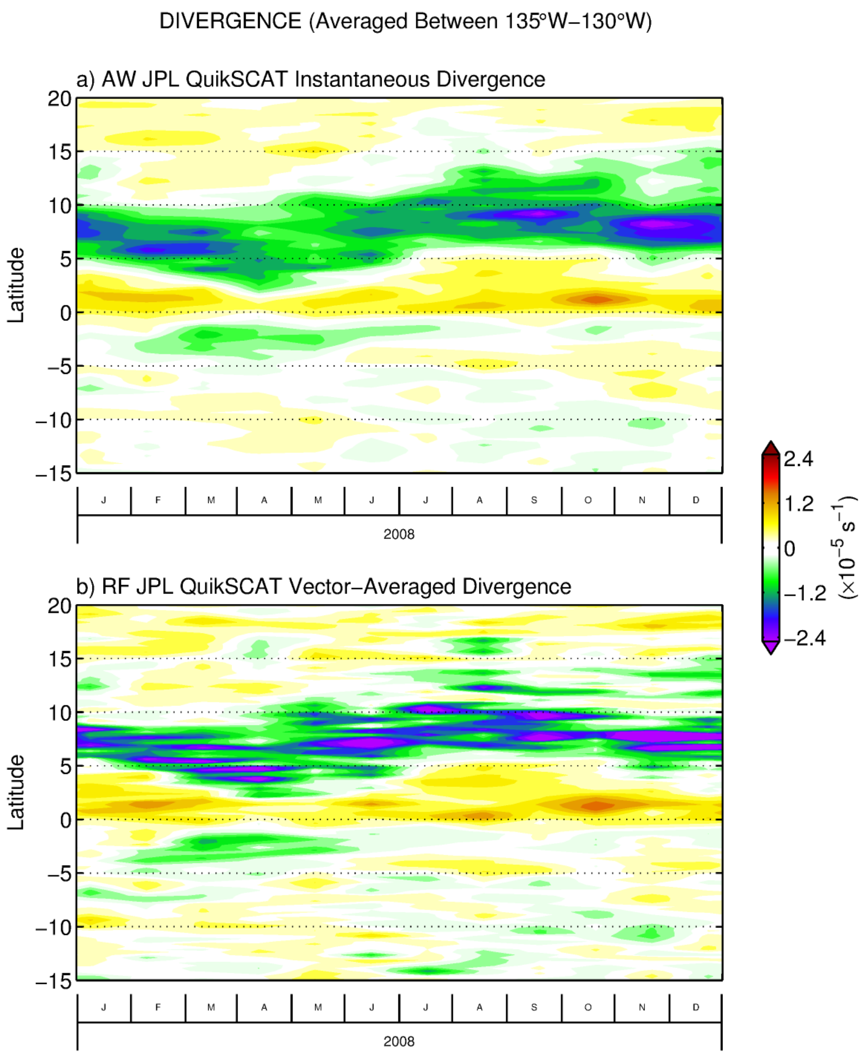


Divergence of time-averaged u,v that has been rain-flagged

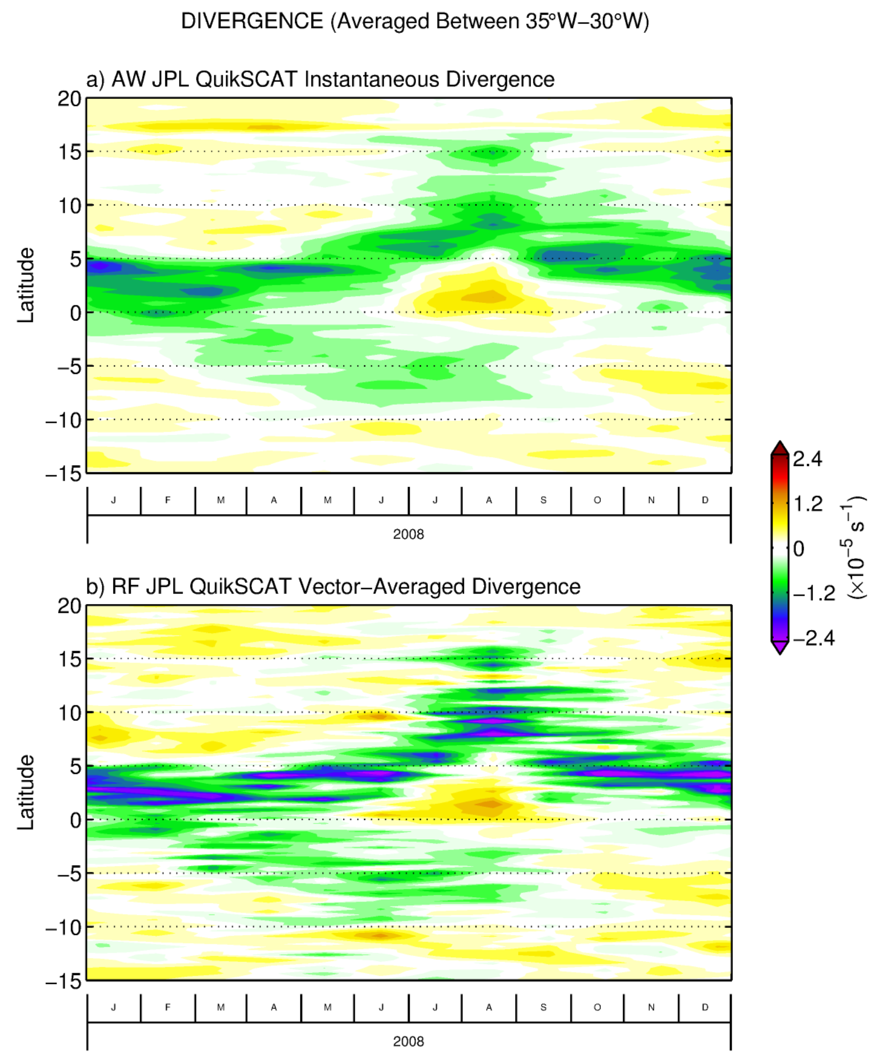


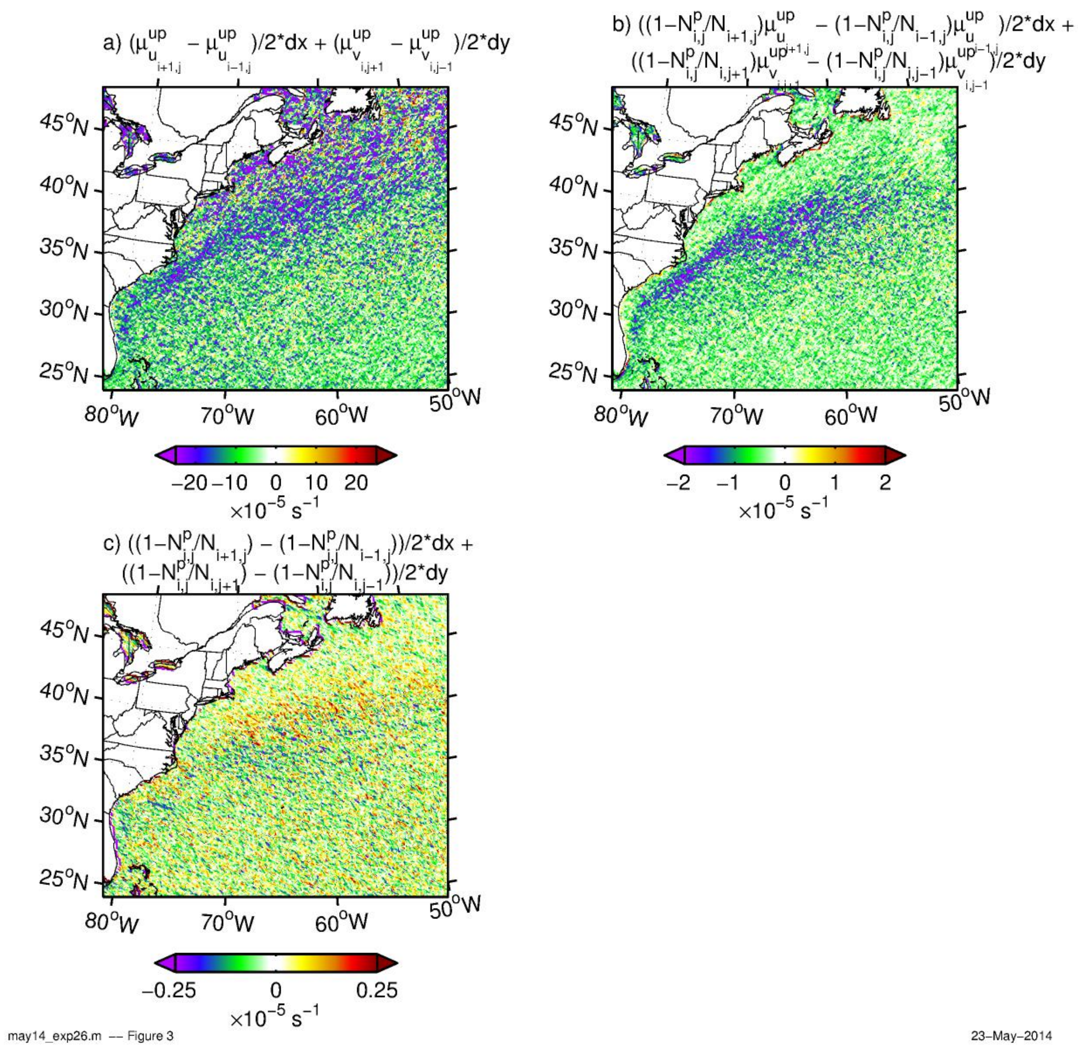
08/01/1999–07/31/2009
In–Swath
Vector–Average
V–A minus I–S
In–Swath –– DJF
Vector–Average –– DJF
V–A minus I–S –– DJF
In–Swath –– JJA
Vector–Average –– JJA
V–A minus I–S –– JJA
50°N
40°N
30°N
135°W
120°W
−1.2 −0.8 −0.4 0 0.4 0.8 1.2
Vorticity (×10^−5 s^−1)
jul13_exp9.m –– Figure 8
23–Jul–2013

Equatorial Pacific

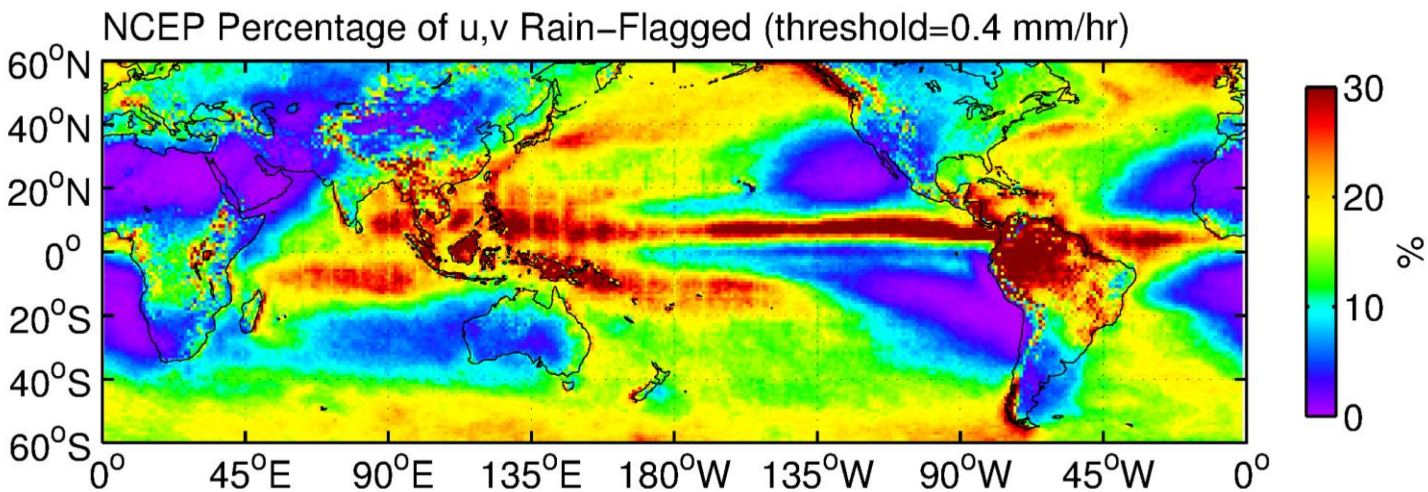


Equatorial Atlantic





a) (μ^up_u i+1,j − μ^up_u i−1,j)/2*dx + (μ^up_v i,j+1 − μ^up_v i,j−1)/2*dy
b) ((1−N^p_i,j/N_i+1,j)μ^up_u − (1−N^p_i,j/N_i−1,j)μ^up_u)/2*dx +
((1−N^p_i,j/N_i,j+1)μ^up_v − (1−N^p_i,j/N_i,j−1)μ^up_v)/2*dy
c) ((1−N^p_i,j/N_i+1,j) − (1−N^p_i,j/N_i−1,j))/2*dx +
((1−N^p_i,j/N_i,j+1) − (1−N^p_i,j/N_i,j−1))/2*dy
45°N
40°N
35°N
30°N
25°N
80°W
70°W
60°W
50°W
−20 −10 0 10 20
−2 −1 0 1 2
−0.25 0 0.25
×10^−5 s^−1
may14_exp26.m -- Figure 3
23–May–2014

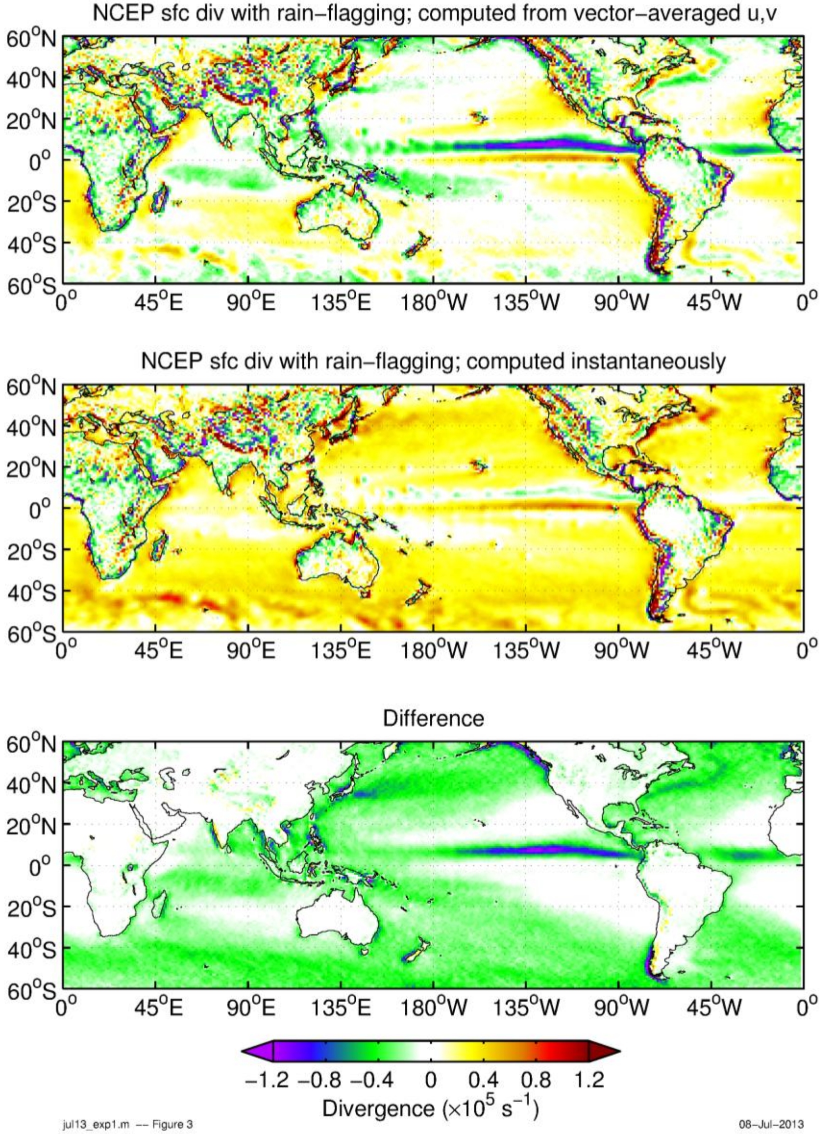


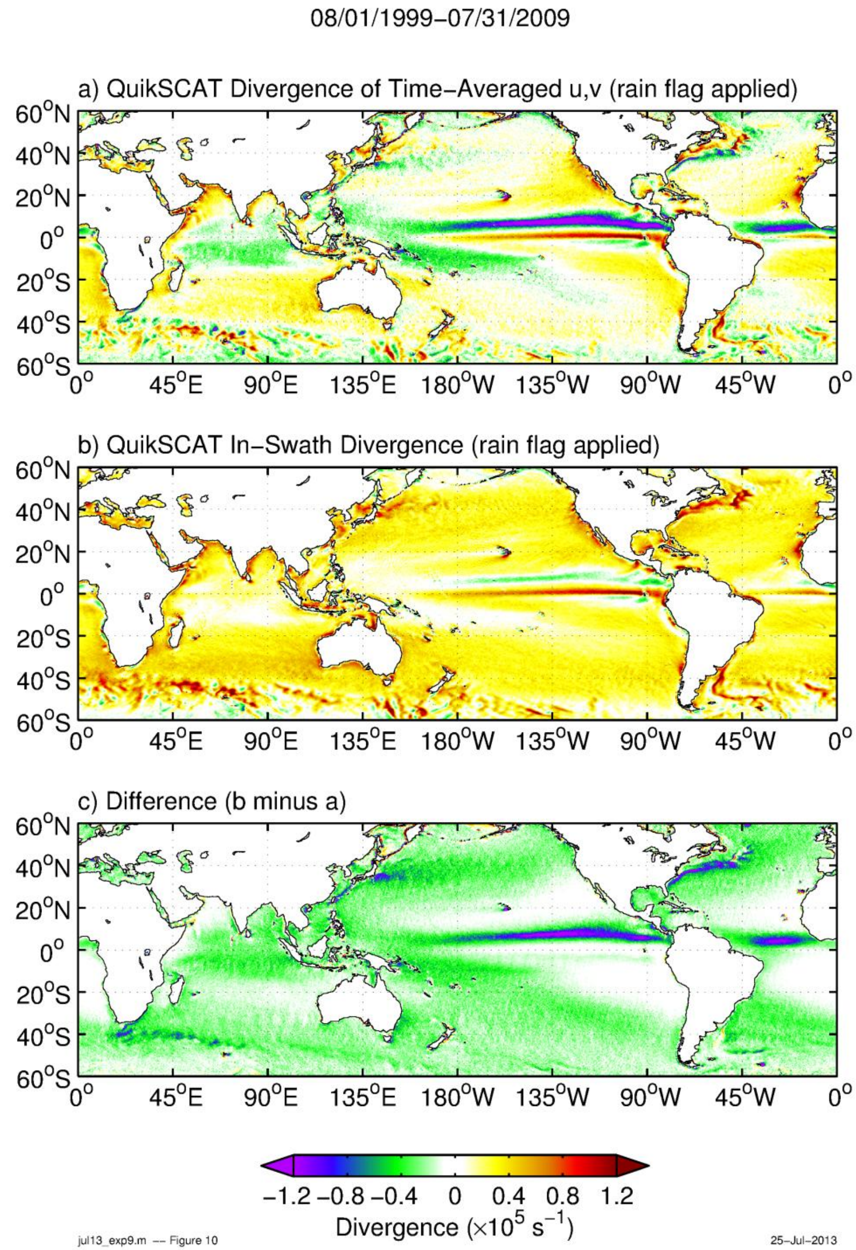
Create a rain flag for NCEP from precipitation rate (PRATE). Results not sensitive to a range of PRATE thresholds.

NCEP 1°x1°x6hr analyses 2010-2012

Divergence

QuikSCAT

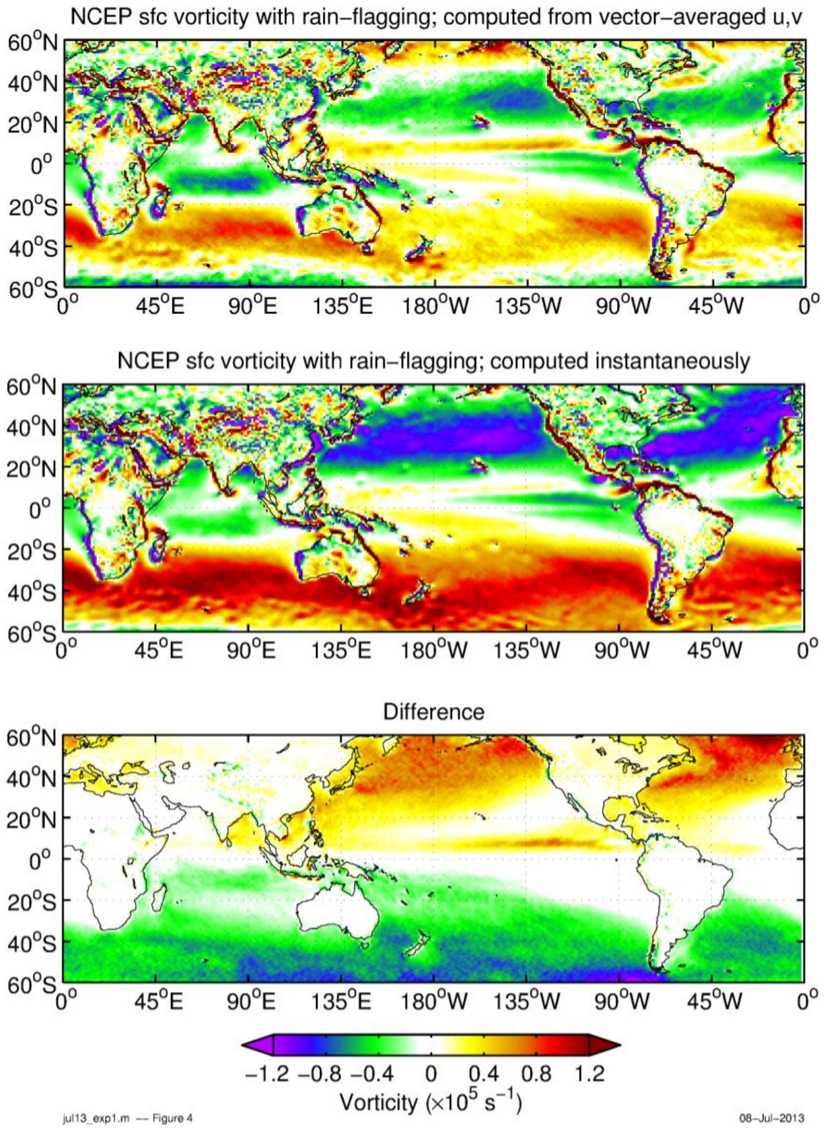


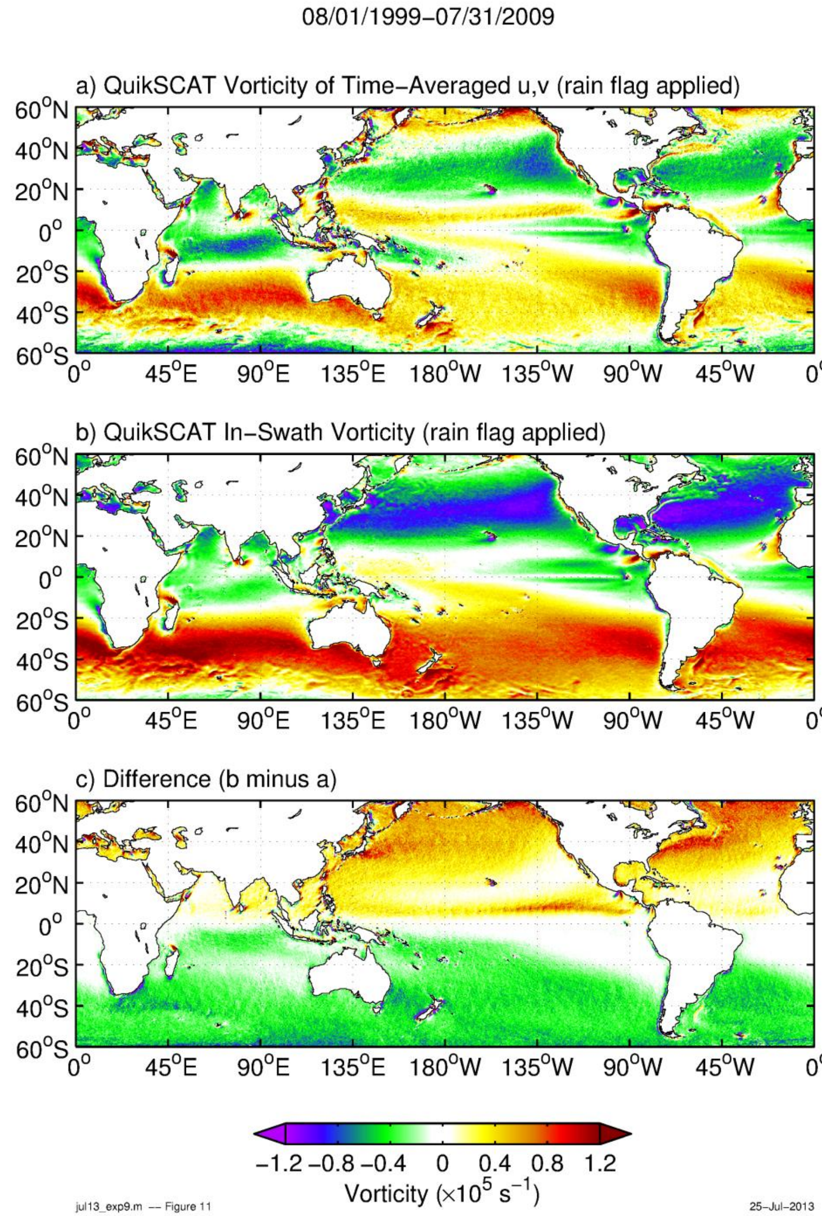


NCEP 1°x1°x6hr analyses 2010-2012

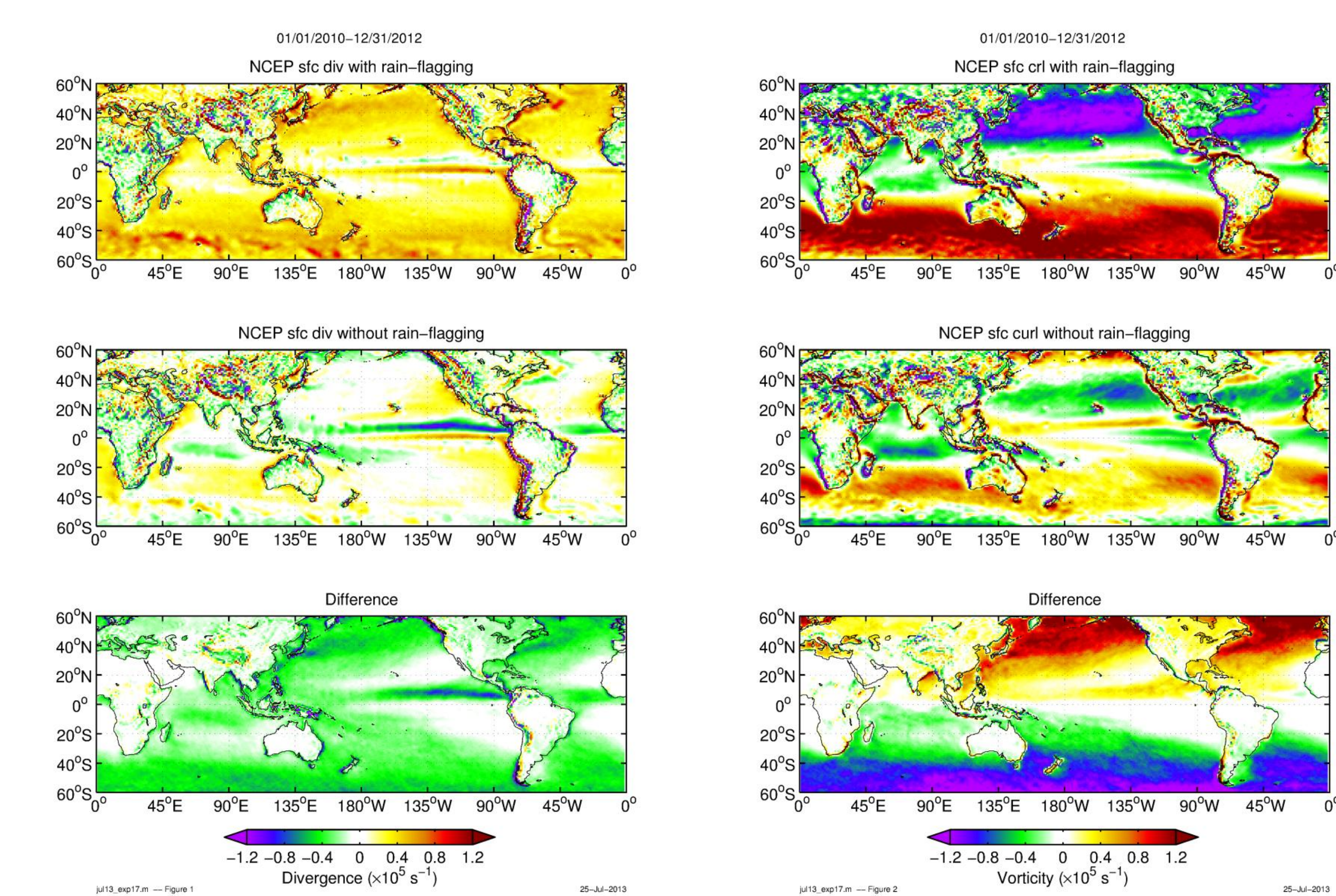
Vorticity

QuikSCAT

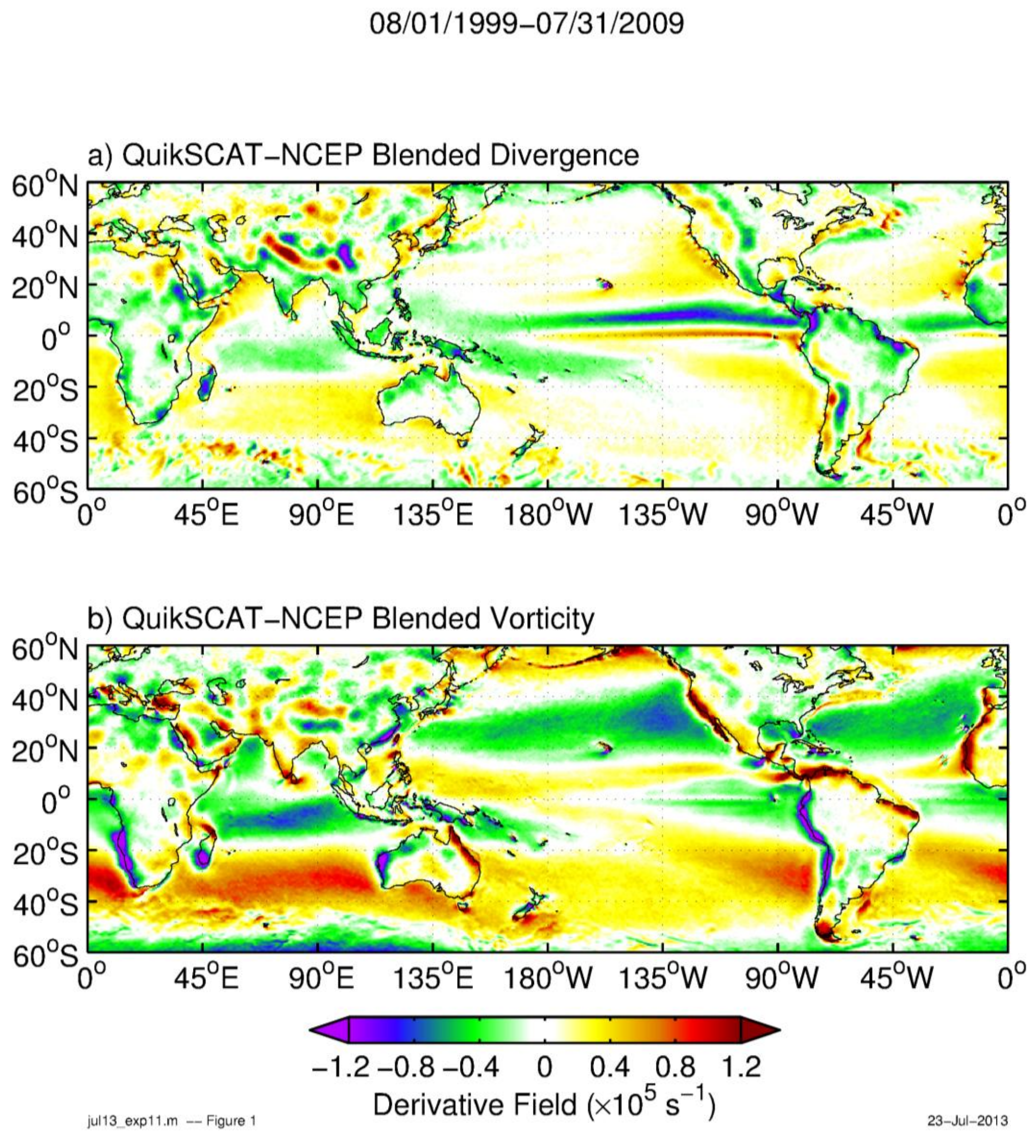




NCEP 10-m divergence and vorticity computed with and without rain-flagging (3-years 1/2010-12/2012)

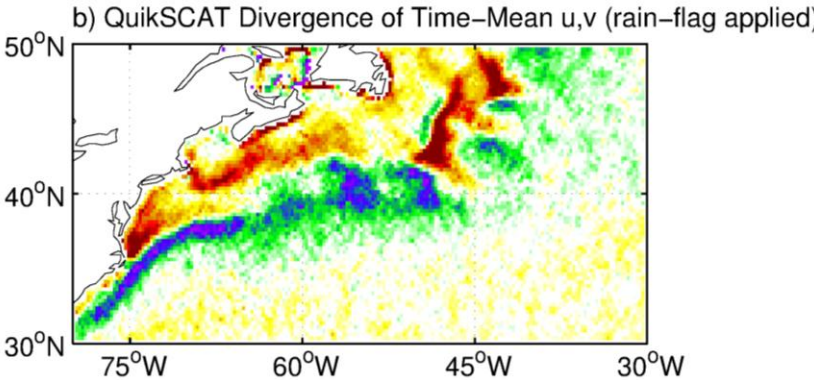


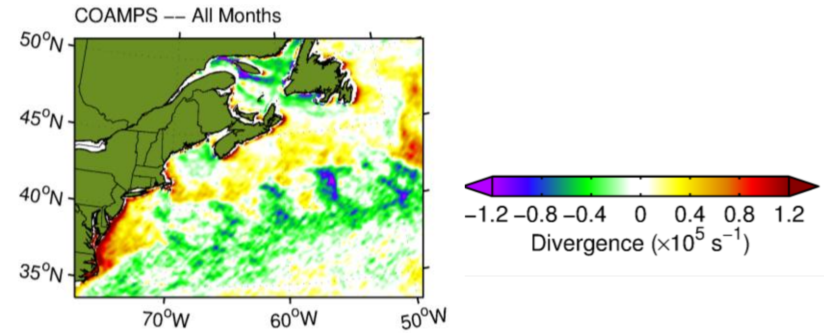
Blended QuikSCAT-NCEP dataset

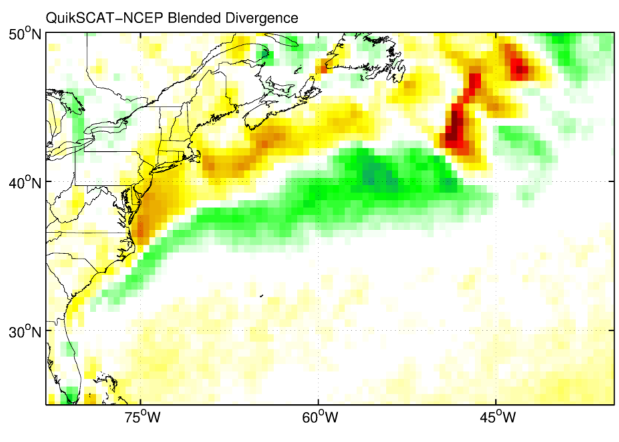


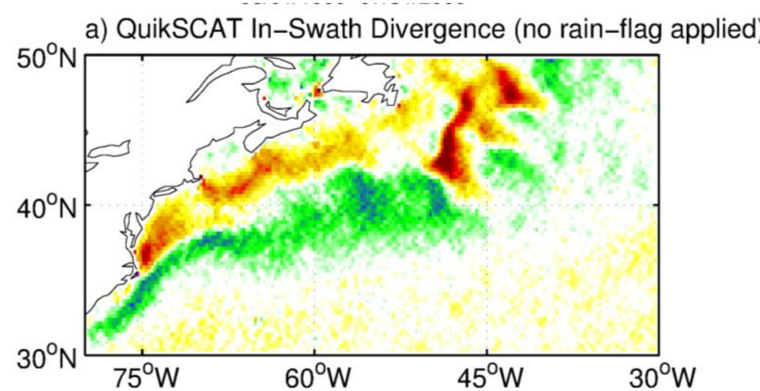
- Milliff et al. (2004) blended NCEP wind into QuikSCAT rain gaps
- Divergence and vorticity fields appear more realistic
    - Zero curl line is in a more realistic location
    - Divergence variability in the mid-ocean gyres is more realistic

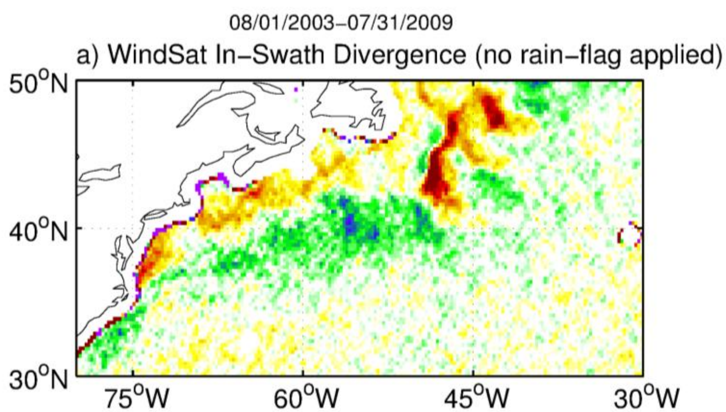
RDA dataset ds744.4

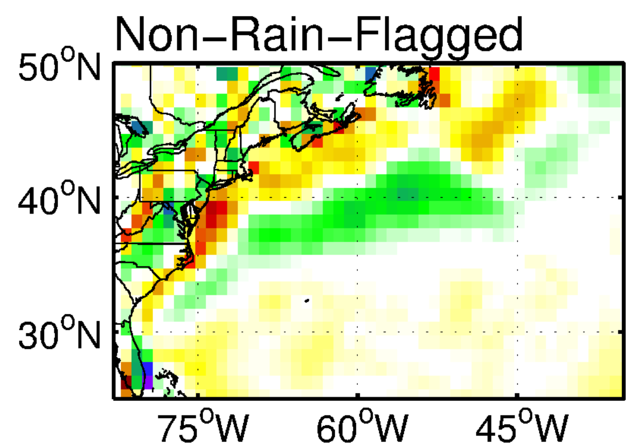












NCEP
1°x6hr
analyses

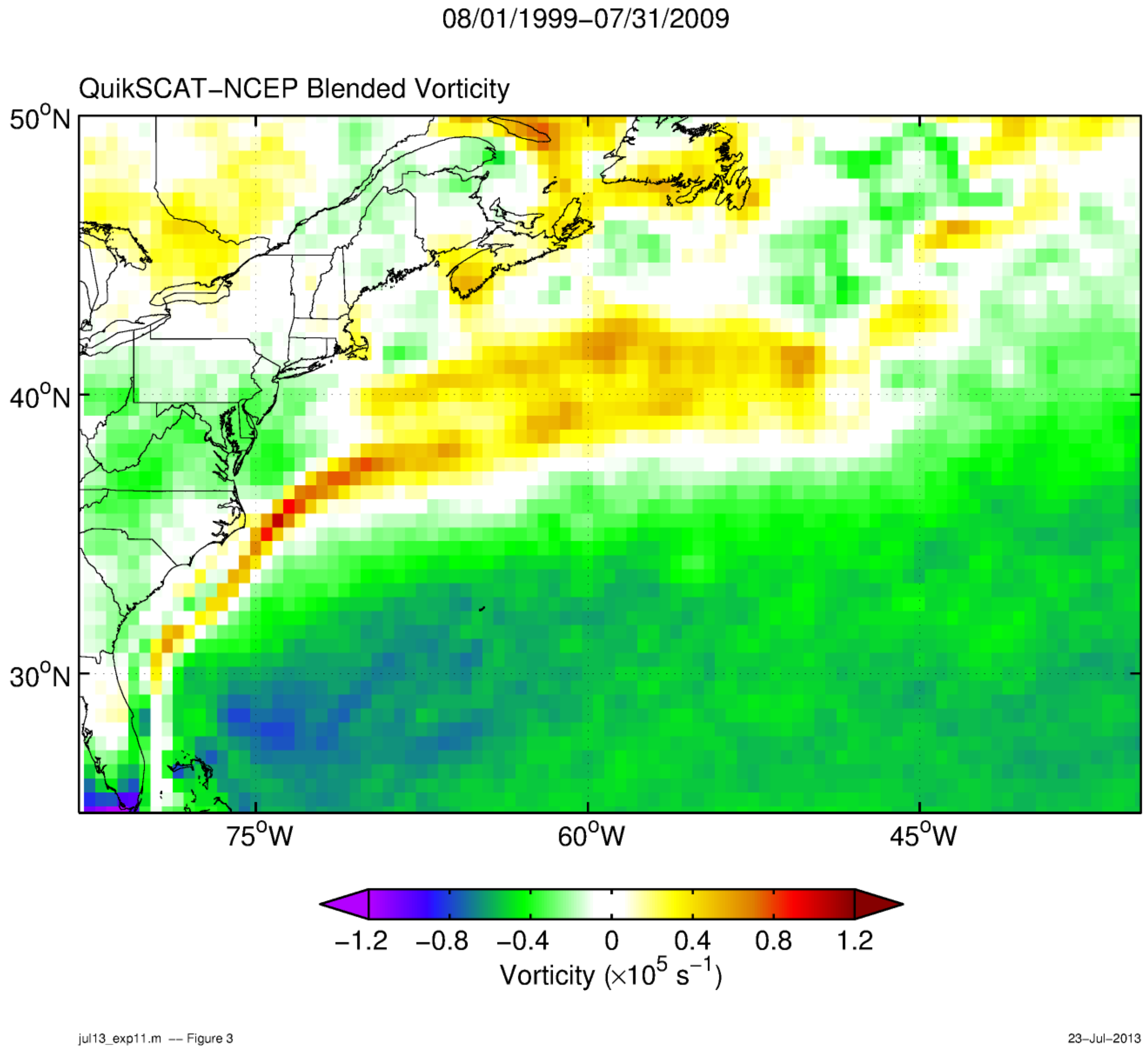
Summary

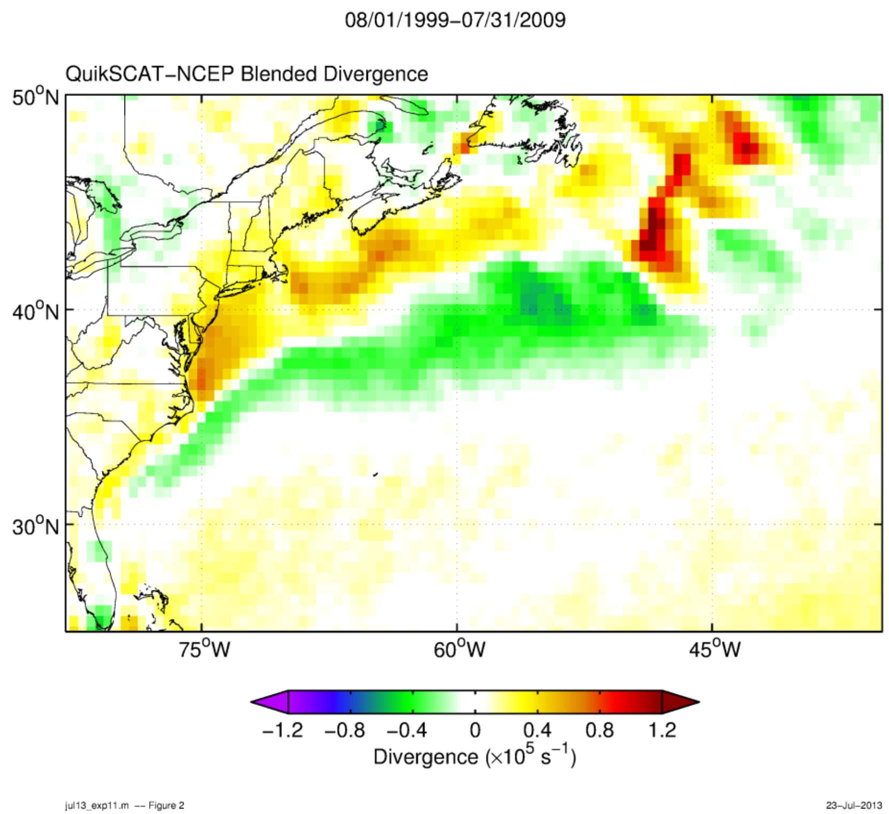
- Scatterometer wind fields contain divergent and anti-cyclonic biases due to conditional sampling of non-precipitating conditions, which typically occur in convergent and cyclonic conditions (e.g., Milliff et al. 2004)
- Computing the divergence and vorticity of the time-averaged u,v adds a second bias from incorrectly computing spatial derivatives from an average u,v field non-uniformly sampled in space and time
  - This bias acts against the divergent and anti-cyclonic biases inherent in rain-flagged scatterometer wind measurements
  - Produces time-averaged divergence and vorticity fields that resemble those expected when precipitation is included
    - Bias is stronger during winter and is associated with the time-averaged meridional wind structure to the south and east of rain bands
  - We are currently working on quantifying the relationship between these fields and the "true" divergence and vorticity fields including precipitation
- There is no physical reason why this second numerical bias should make the scatterometer derivative wind fields, not containing rain, equal to those containing rain
  - Issue is that spatial wind variability is not fully sampled on their natural time-scales – which in the case of rain, is synoptic

Mitigation and future work

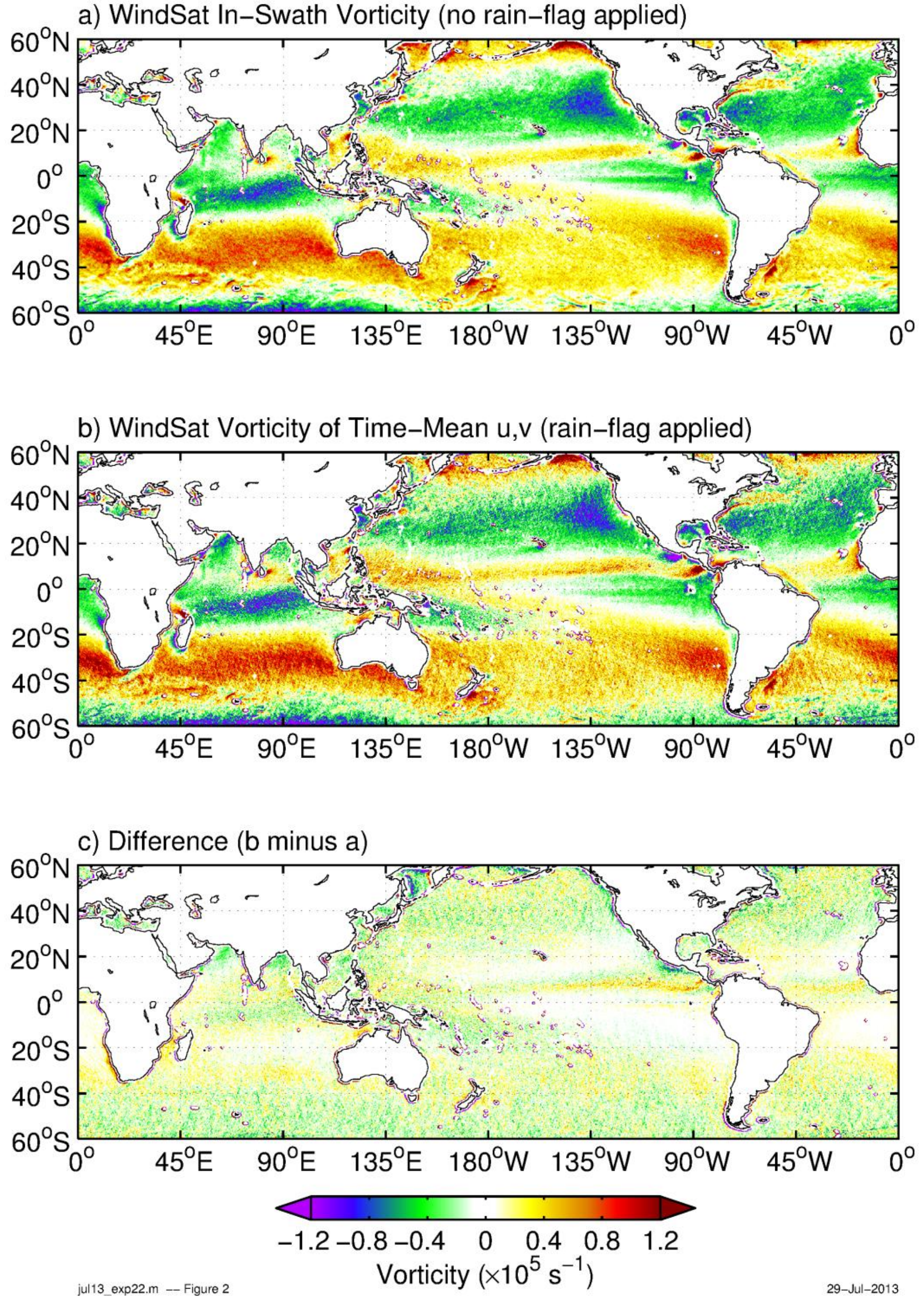
- Retrieving winds in rain has been an area of research for over 20 years, so the problem is to utilize the measured winds
- Estimate winds in rain-flagged regions
  - Milliff et al. (2004) filled rain holes with NCEP winds
  - Chelton et al. (2004) used smoothed wind estimates within 100 km of rain edges
  - Incorporate QuikSCAT winds in precipitating conditions into the derivative estimates
    - QuikSCAT wind retrievals in raining conditions have been done experimentally

QUIKSCAT-NCEP BLENDED


08/01/1999–07/31/2009
QuikSCAT–NCEP Blended Vorticity
50°N
40°N
30°N
75°W
60°W
45°W
–1.2
–0.8
–0.4
0
0.4
0.8
1.2
Vorticity (×10^{5} s^{-1})
jul13_exp11.m –– Figure 3
23–Jul–2013

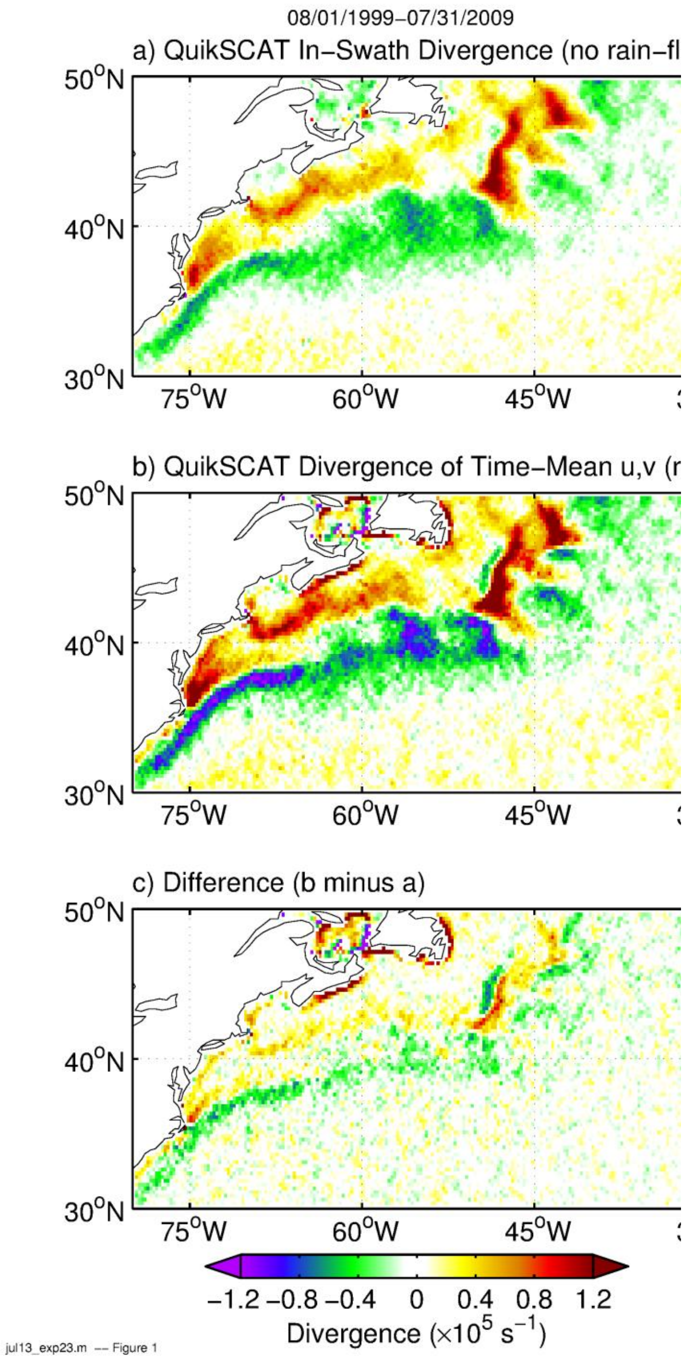

08/01/1999–07/31/2009
QuikSCAT–NCEP Blended Divergence
50°N
40°N
30°N
75°W
60°W
45°W
−1.2
−0.8
−0.4
0
0.4
0.8
1.2
Divergence (×10^5 s^−1)
jul13_exp11.m -- Figure 2
23–Jul–2013

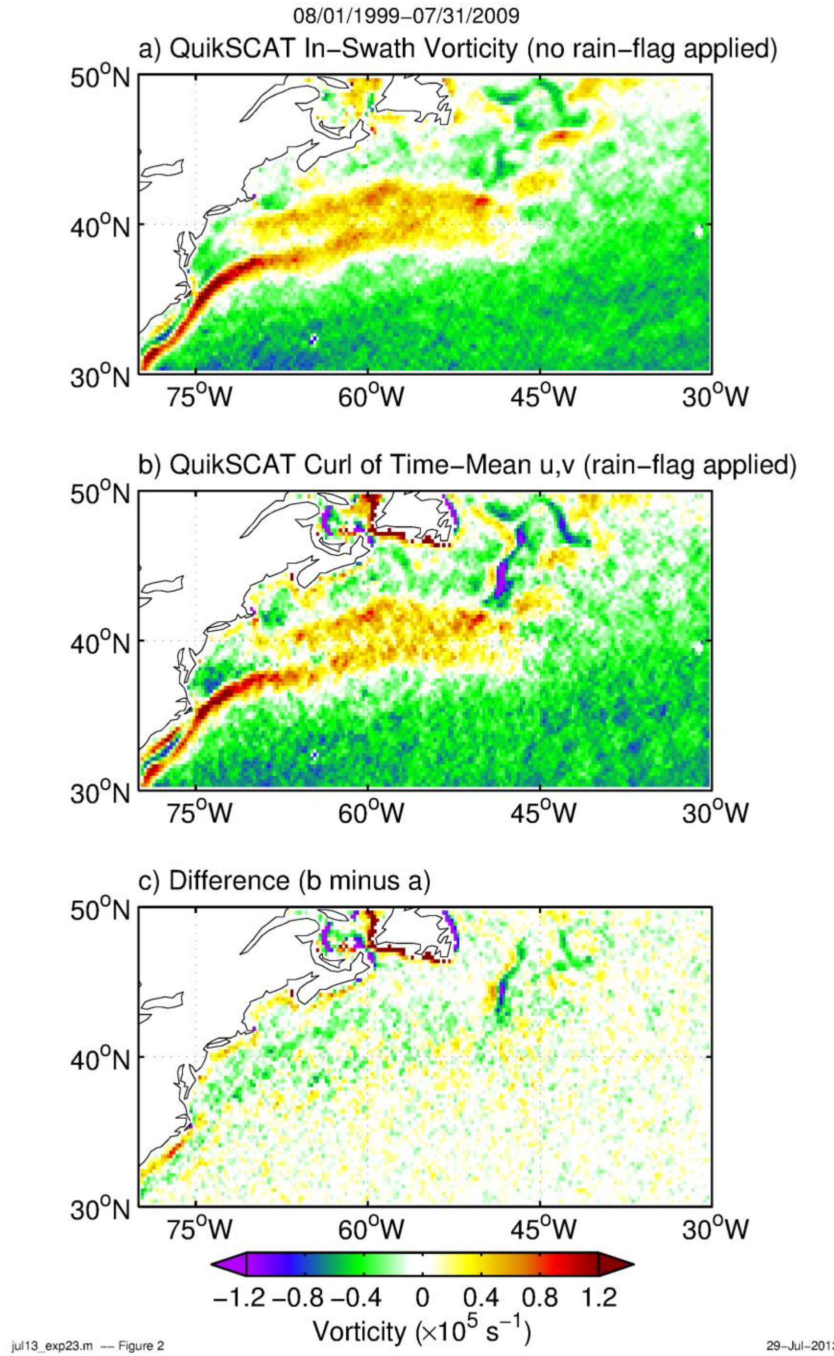
08/01/2003–07/31/2009

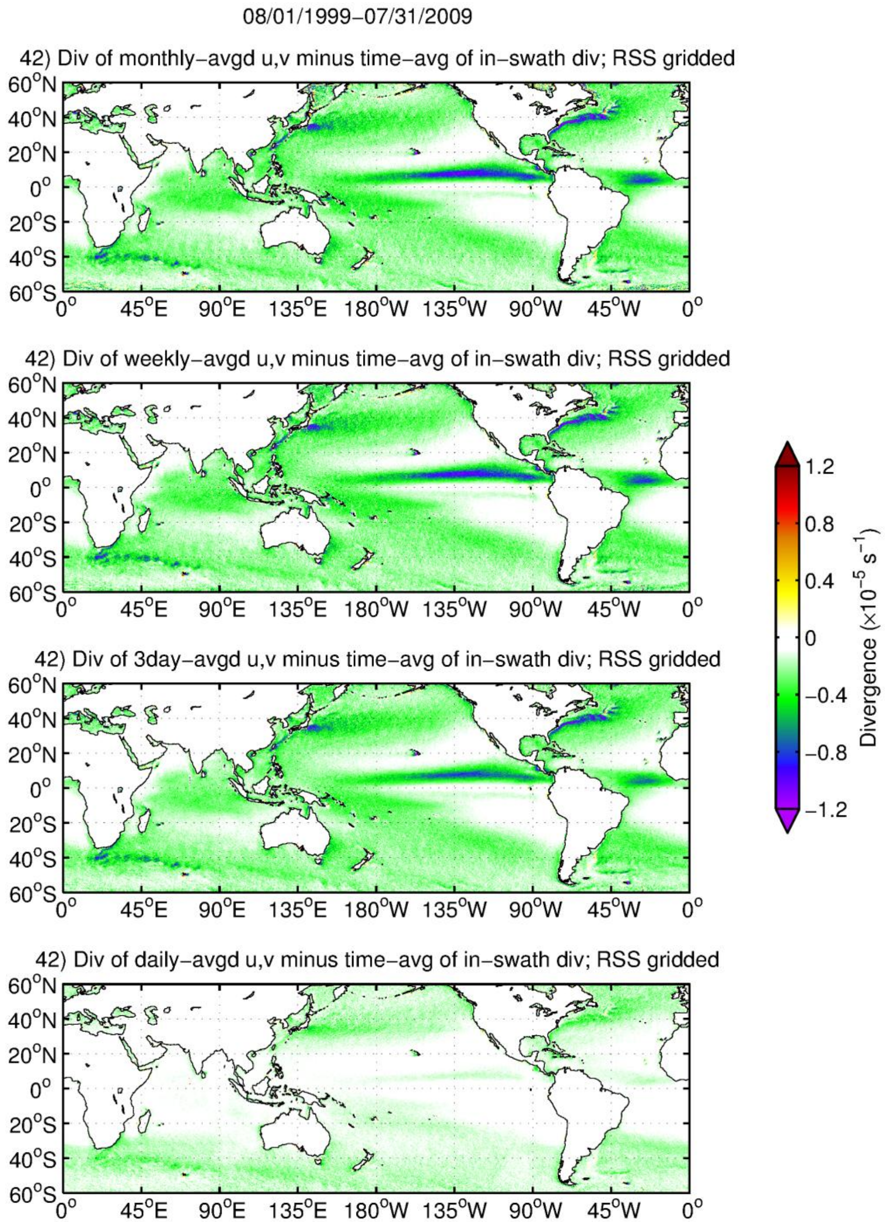


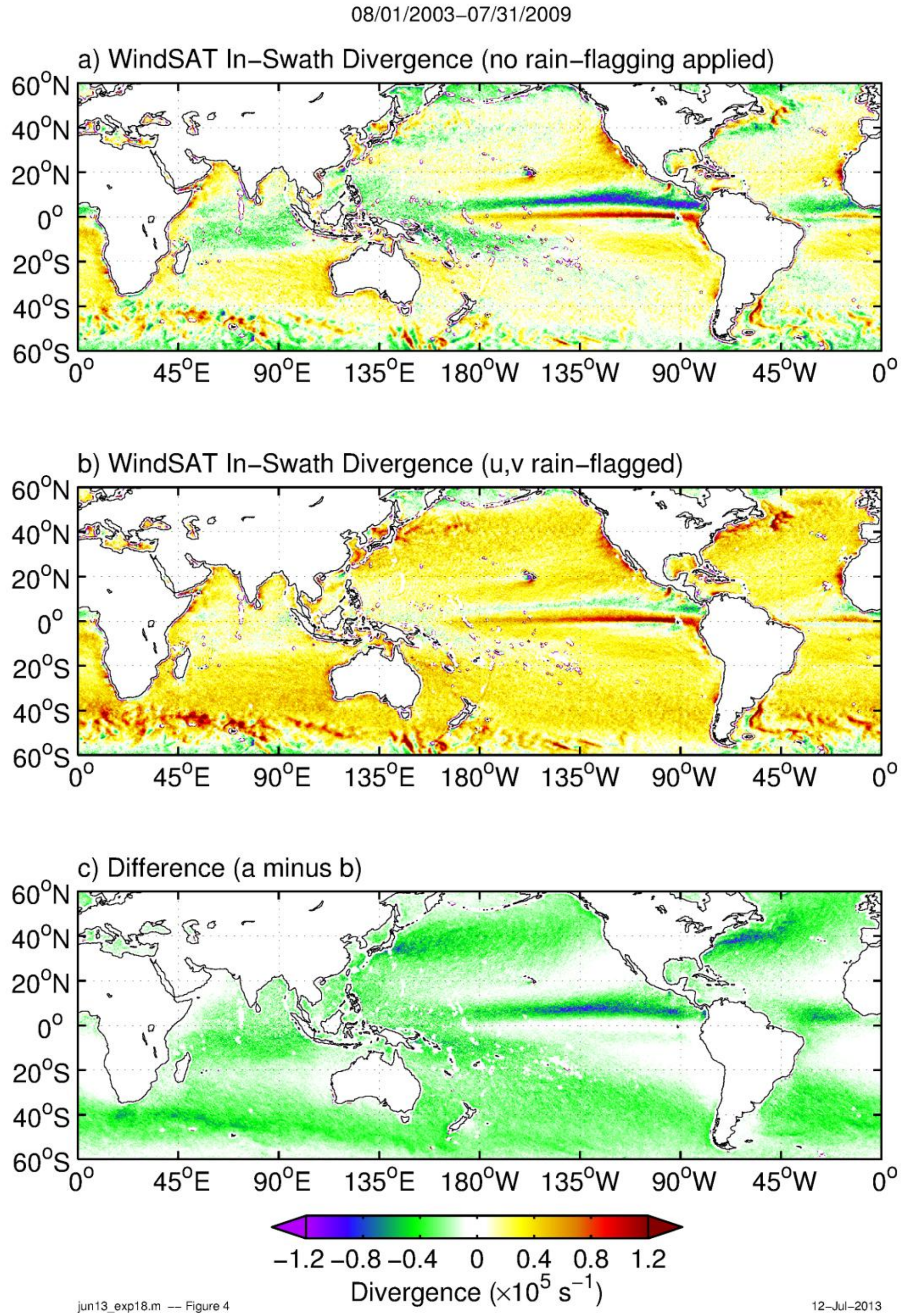
jul13_exp22.m -- Figure 2

29–Jul–2013

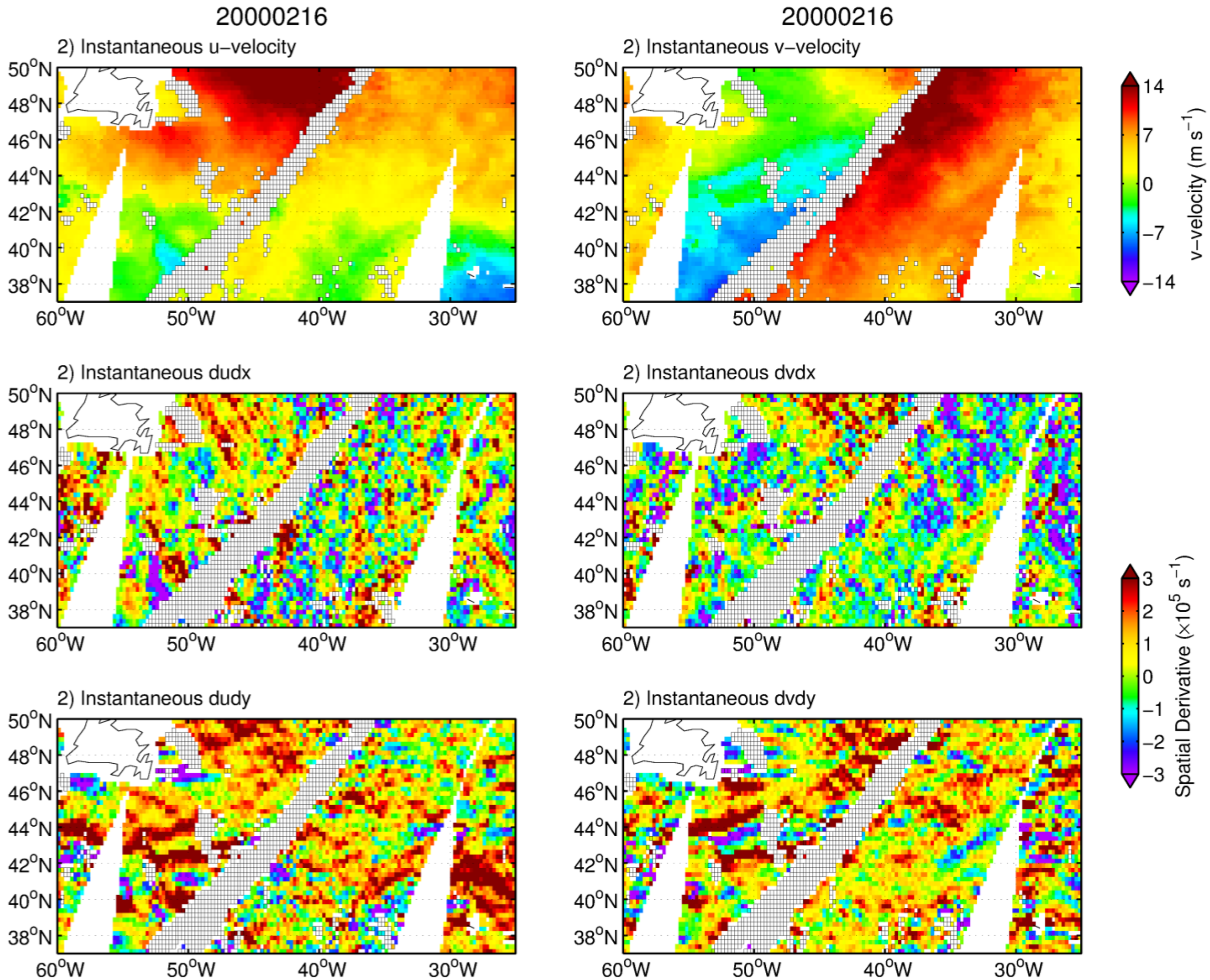

08/01/1999–07/31/2009
a) QuikSCAT In–Swath Divergence (no rain–fl
b) QuikSCAT Divergence of Time–Mean u,v (r
c) Difference (b minus a)
50°N
40°N
30°N
75°W
60°W
45°W
−1.2 −0.8 −0.4 0 0.4 0.8 1.2
Divergence (×10⁵ s⁻¹)
jul13_exp23.m –– Figure 1

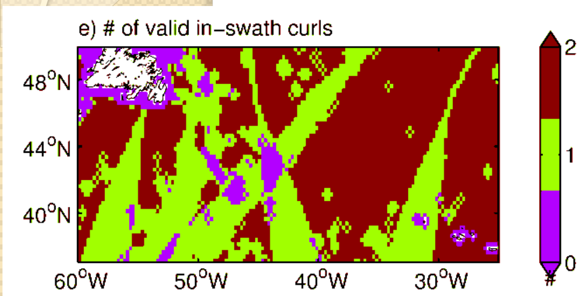

08/01/1999–07/31/2009
a) QuikSCAT In–Swath Vorticity (no rain–flag applied)
b) QuikSCAT Curl of Time–Mean u,v (rain–flag applied)
c) Difference (b minus a)
50°N
40°N
30°N
75°W
60°W
45°W
30°W
−1.2 −0.8 −0.4 0 0.4 0.8 1.2
Vorticity (×10⁵ s⁻¹)
jul13_exp23.m –– Figure 2
29–Jul–2013

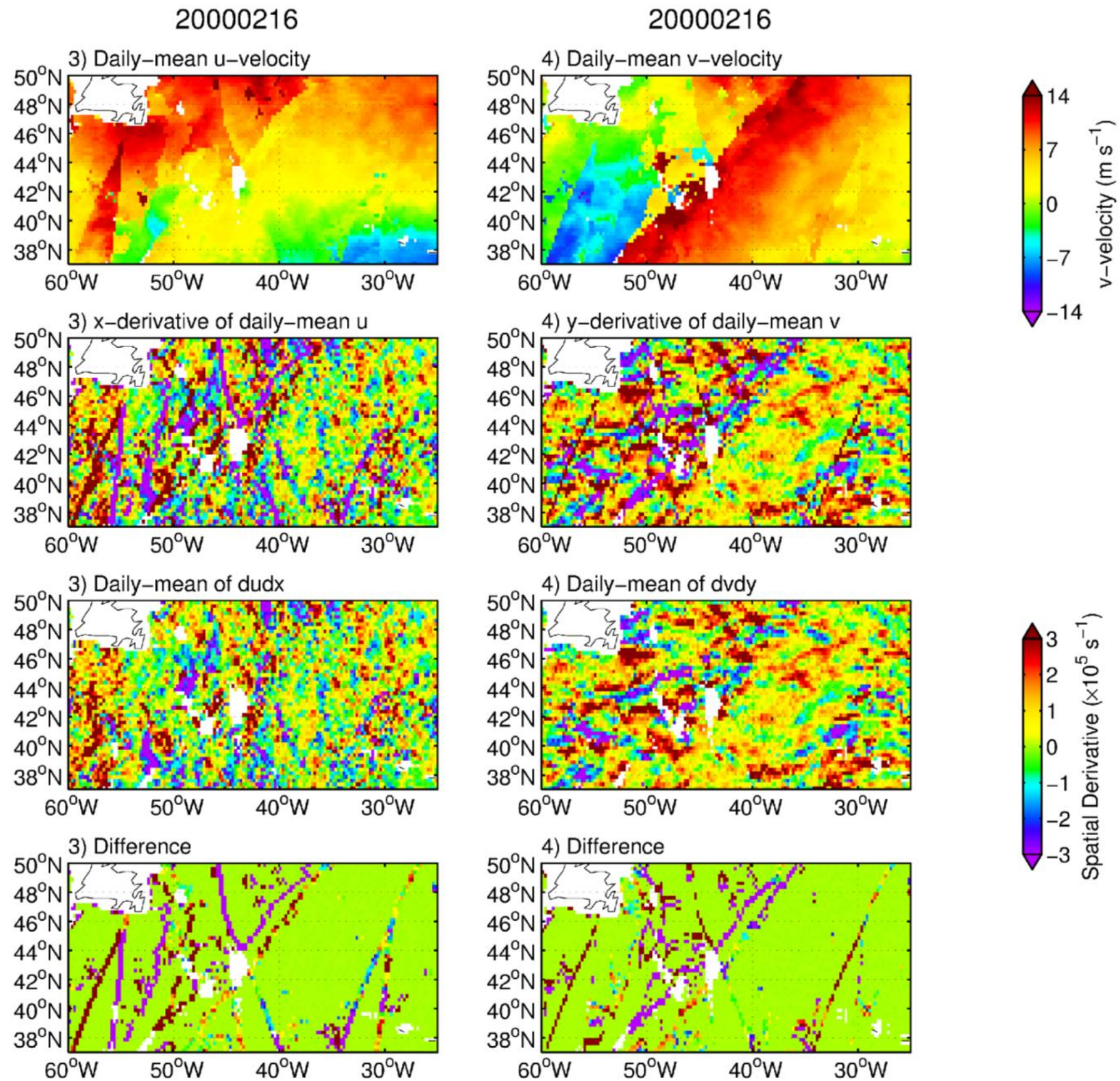

08/01/1999–07/31/2009
42) Div of monthly–avgd u,v minus time–avg of in–swath div; RSS gridded
42) Div of weekly–avgd u,v minus time–avg of in–swath div; RSS gridded
42) Div of 3day–avgd u,v minus time–avg of in–swath div; RSS gridded
42) Div of daily–avgd u,v minus time–avg of in–swath div; RSS gridded
60°N
40°N
20°N
0°
20°S
40°S
60°S
0°
45°E
90°E
135°E
180°W
135°W
90°W
45°W
0°
1.2
0.8
0.4
0
−0.4
−0.8
−1.2
Divergence (×10^{-5} s^{-1})


08/01/2003−07/31/2009
a) WindSAT In−Swath Divergence (no rain−flagging applied)
b) WindSAT In−Swath Divergence (u,v rain−flagged)
c) Difference (a minus b)
60°N 40°N 20°N 0° 20°S 40°S 60°S
0° 45°E 90°E 135°E 180°W 135°W 90°W 45°W 0°
−1.2 −0.8 −0.4 0 0.4 0.8 1.2
Divergence (×10^5 s^−1)
jun13_exp18.m -- Figure 4
12−Jul−2013

Instantaneous QuikSCAT u,v fields over the North Atlantic



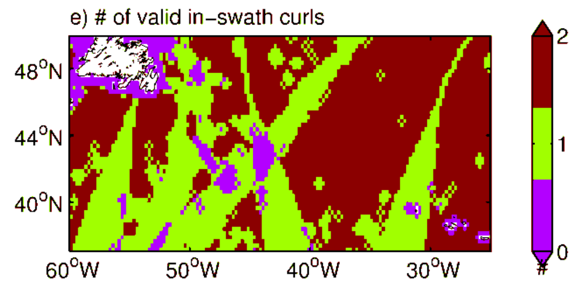


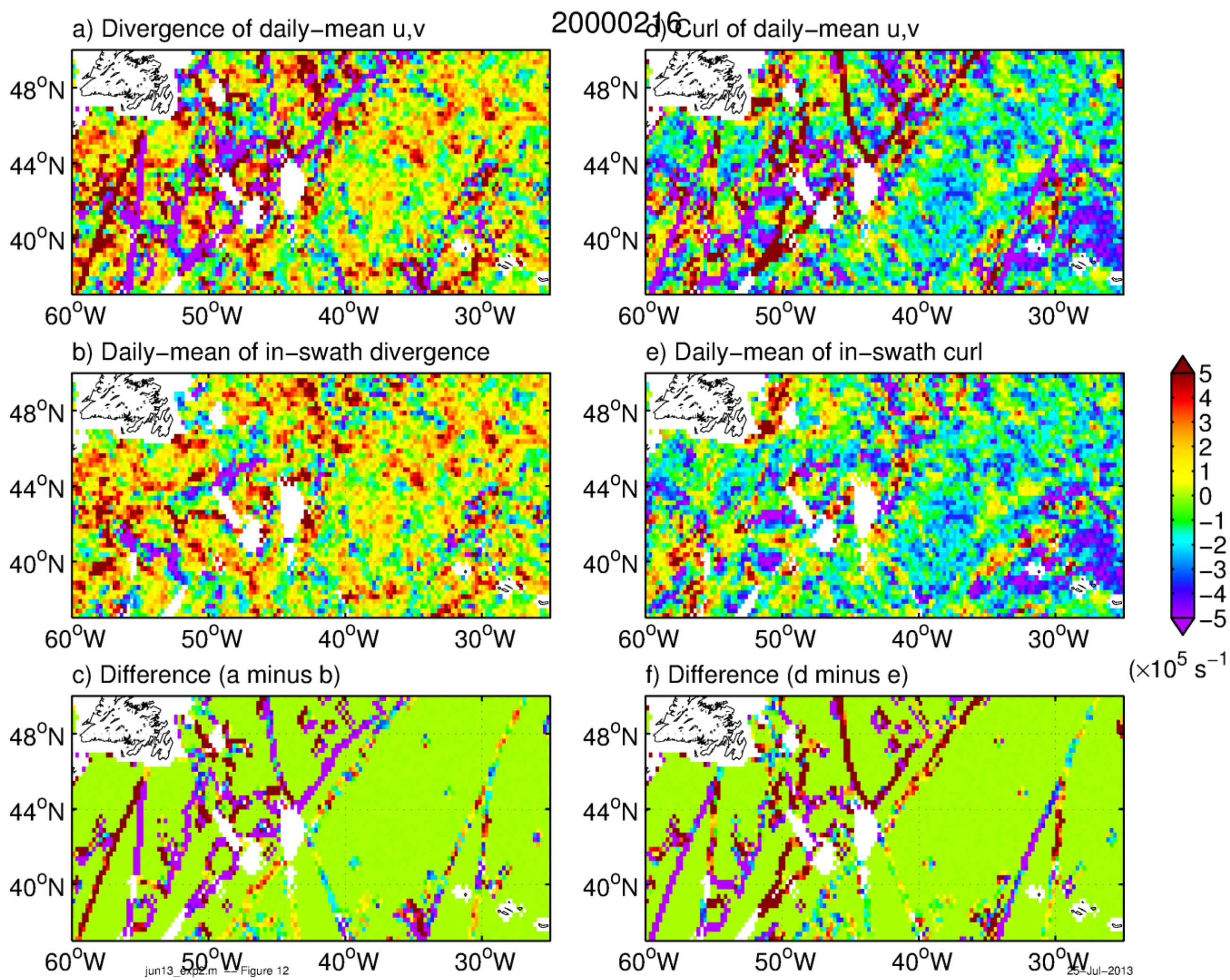


1) First, time-averaged u,v; then compute derivative

2) First take spatial derivative of u,v (which we call the "**in-swath**" or "**instantaneous**" derivative); then time-average

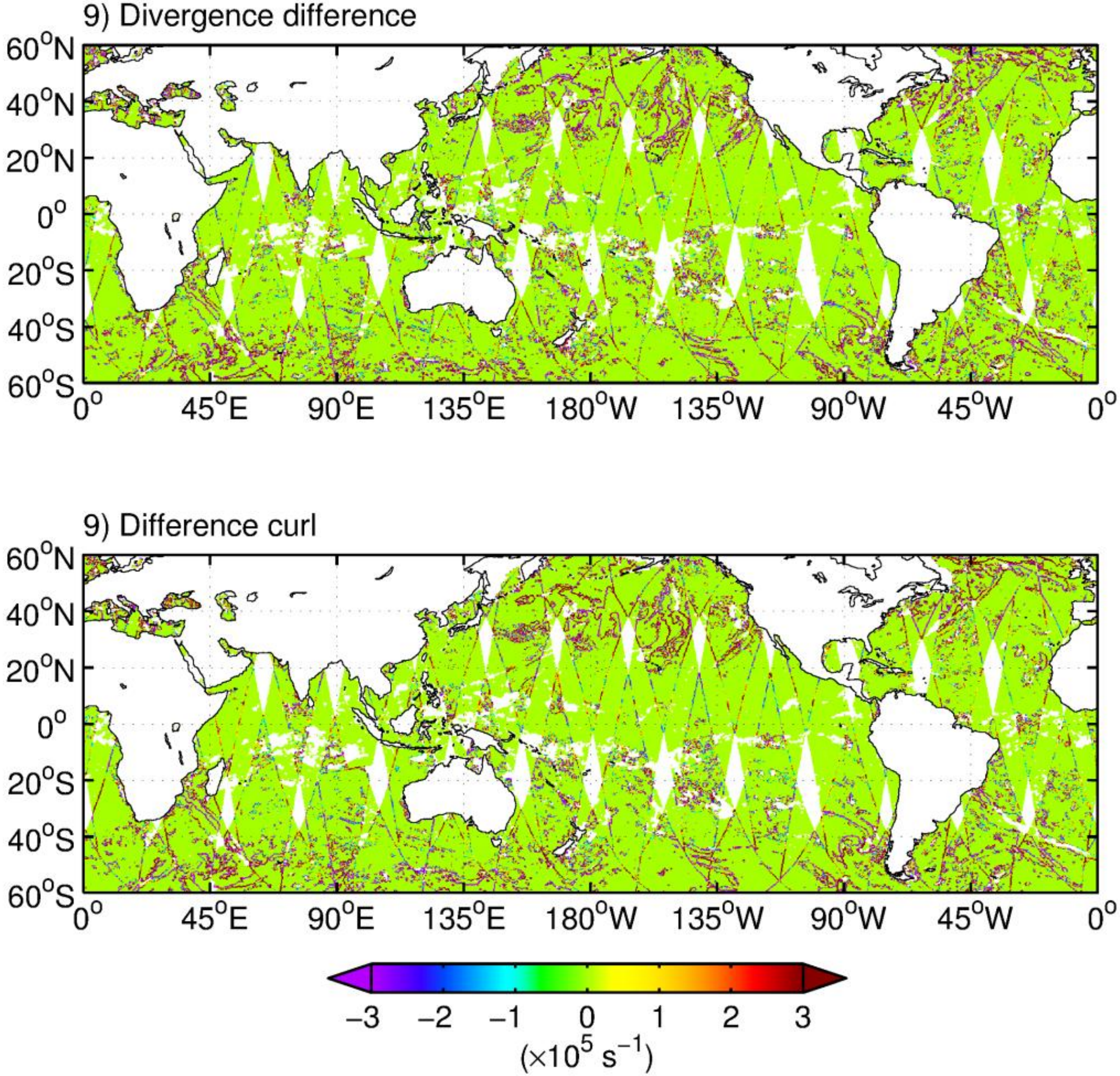
1-day example illustrating calculation differences in the divergence and vorticity



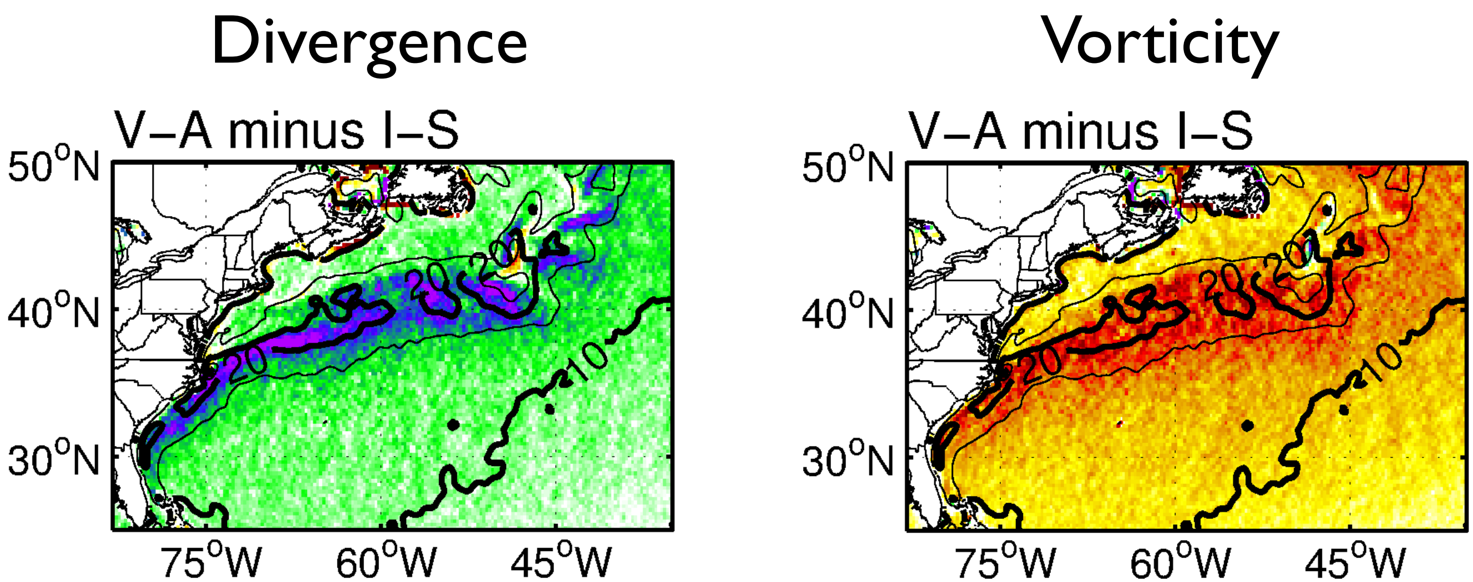


- Calculating spatial derivatives *before* time-averaging eliminates errors in derivative estimates from u,v measured at distinctly different times, such as along edges of overlapping swaths and rain bands.

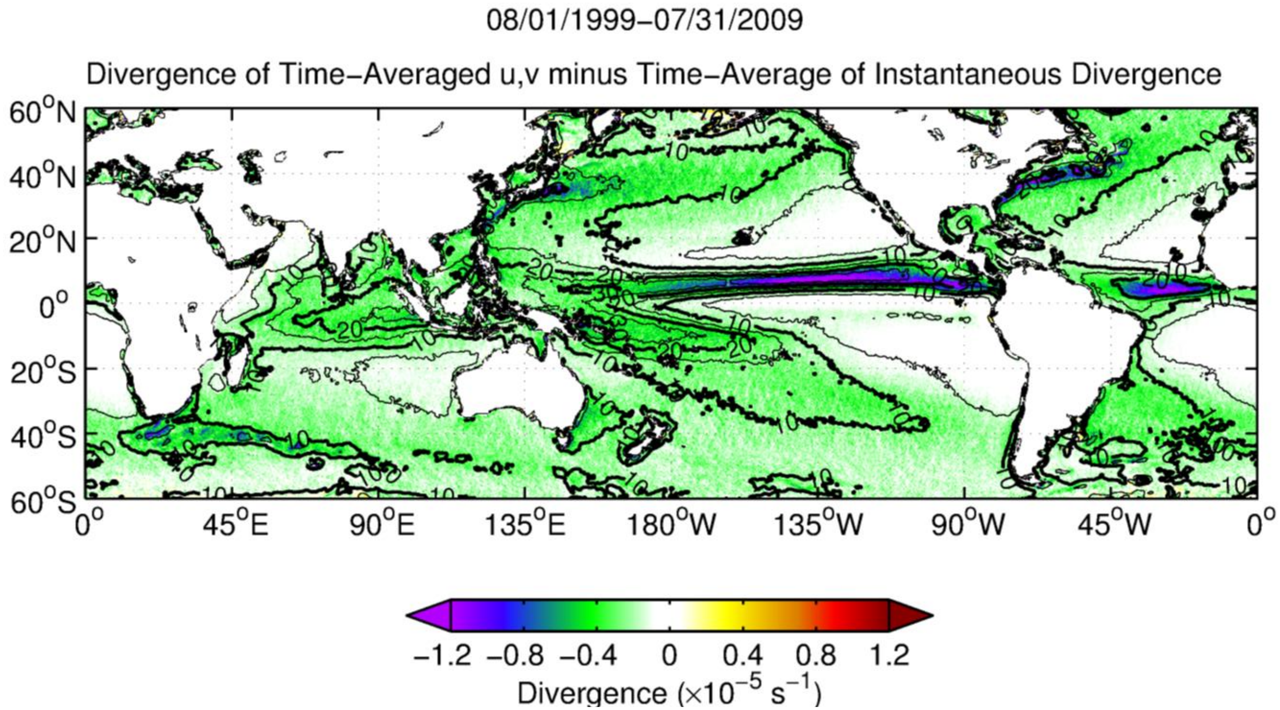
1-day average – 2/16/2000



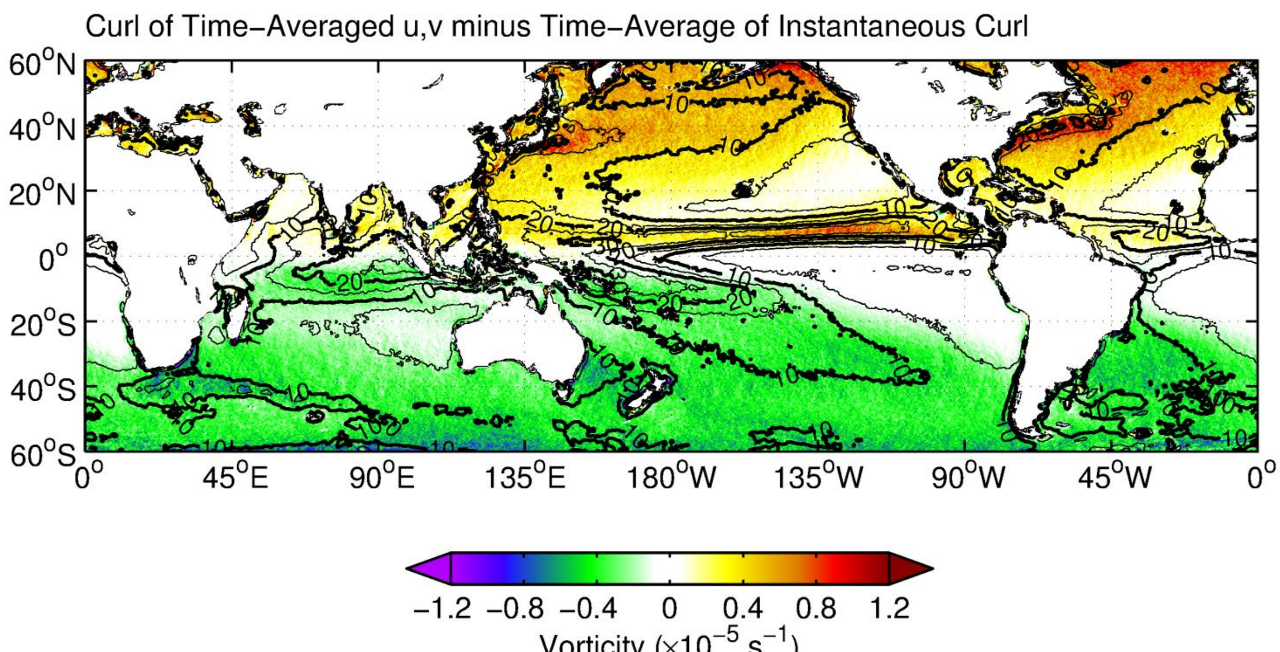
Sampling errors in rain-flagged QuikSCAT divergence and vorticity over the Northwest Atlantic



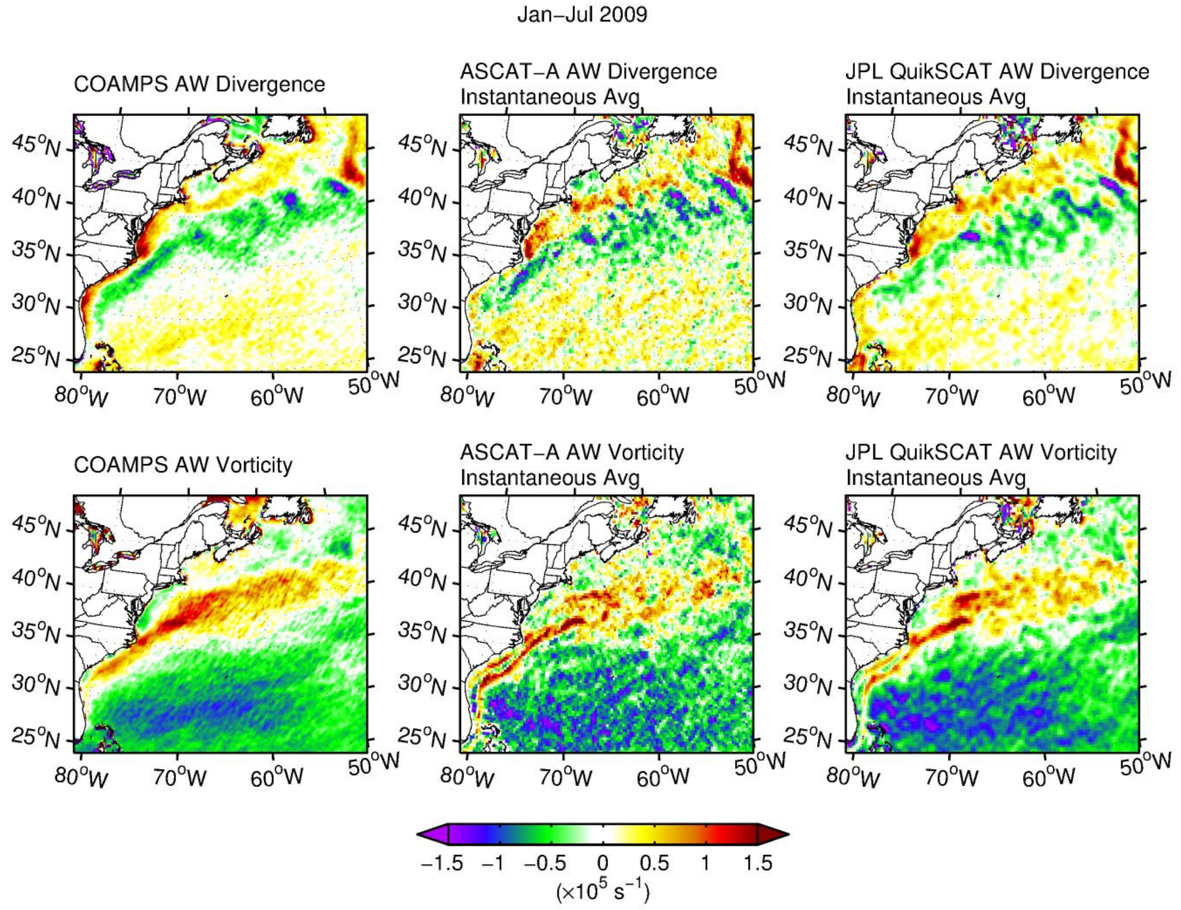
Contours are of the percent frequency of rain-flagged observations (c.i.=5%)



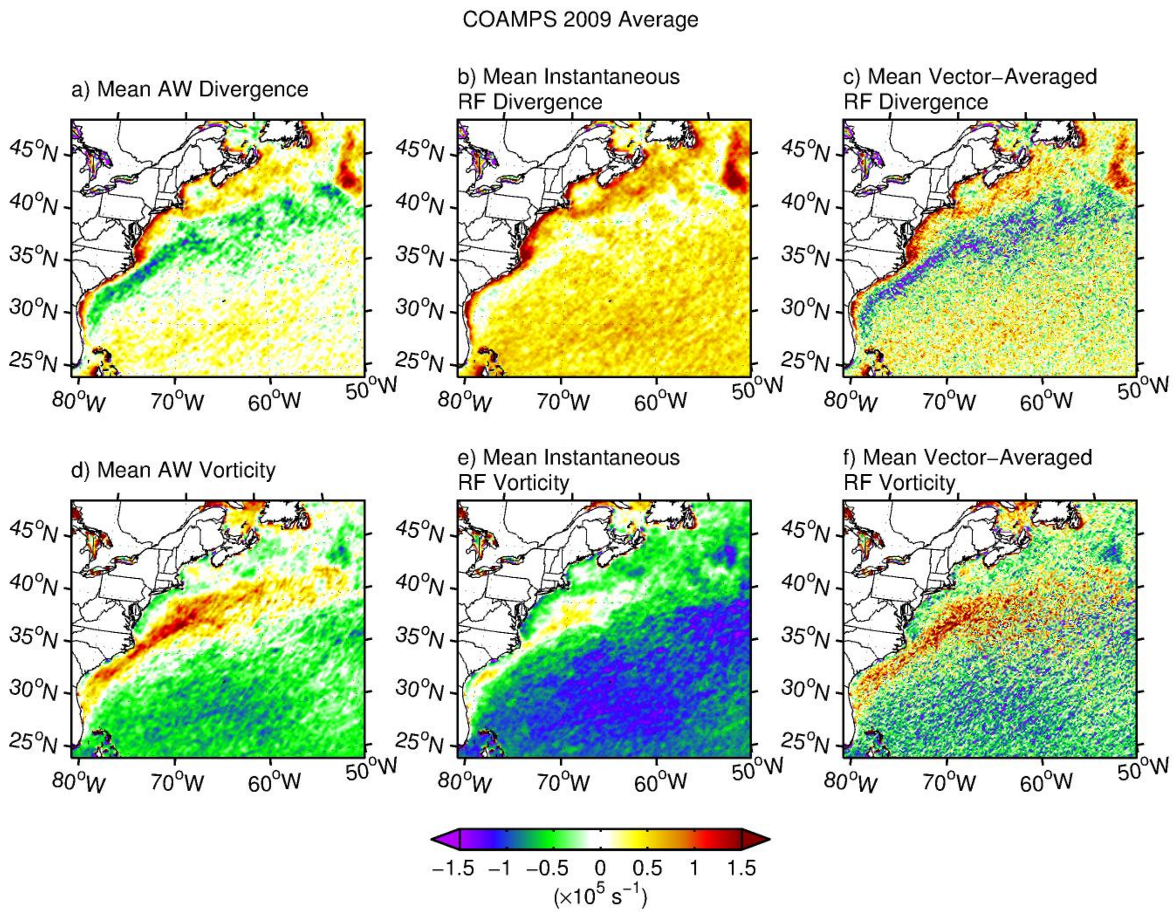
Contours of rain-flag frequency (c.i.=5%)

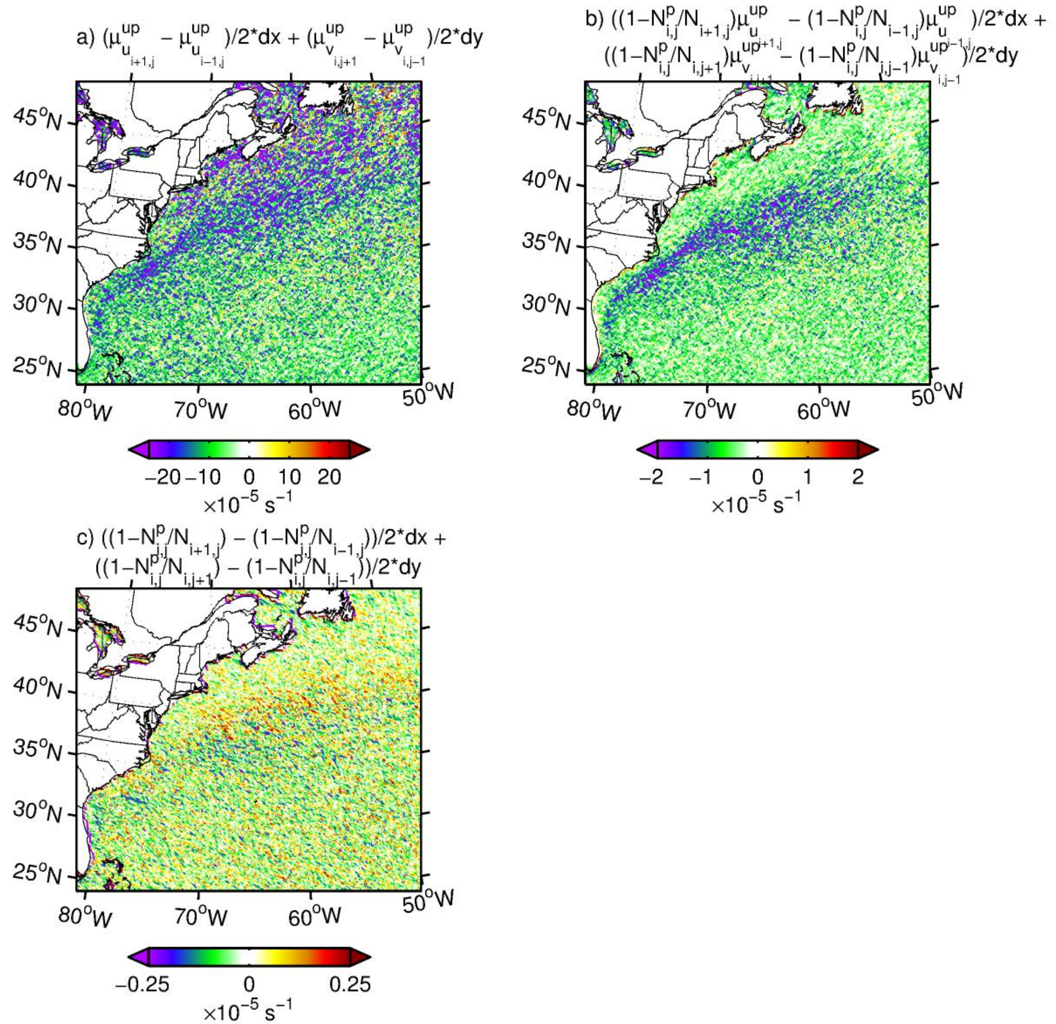


Difference between two calculation methods are highly correlated with the frequency of observations flagged for rain

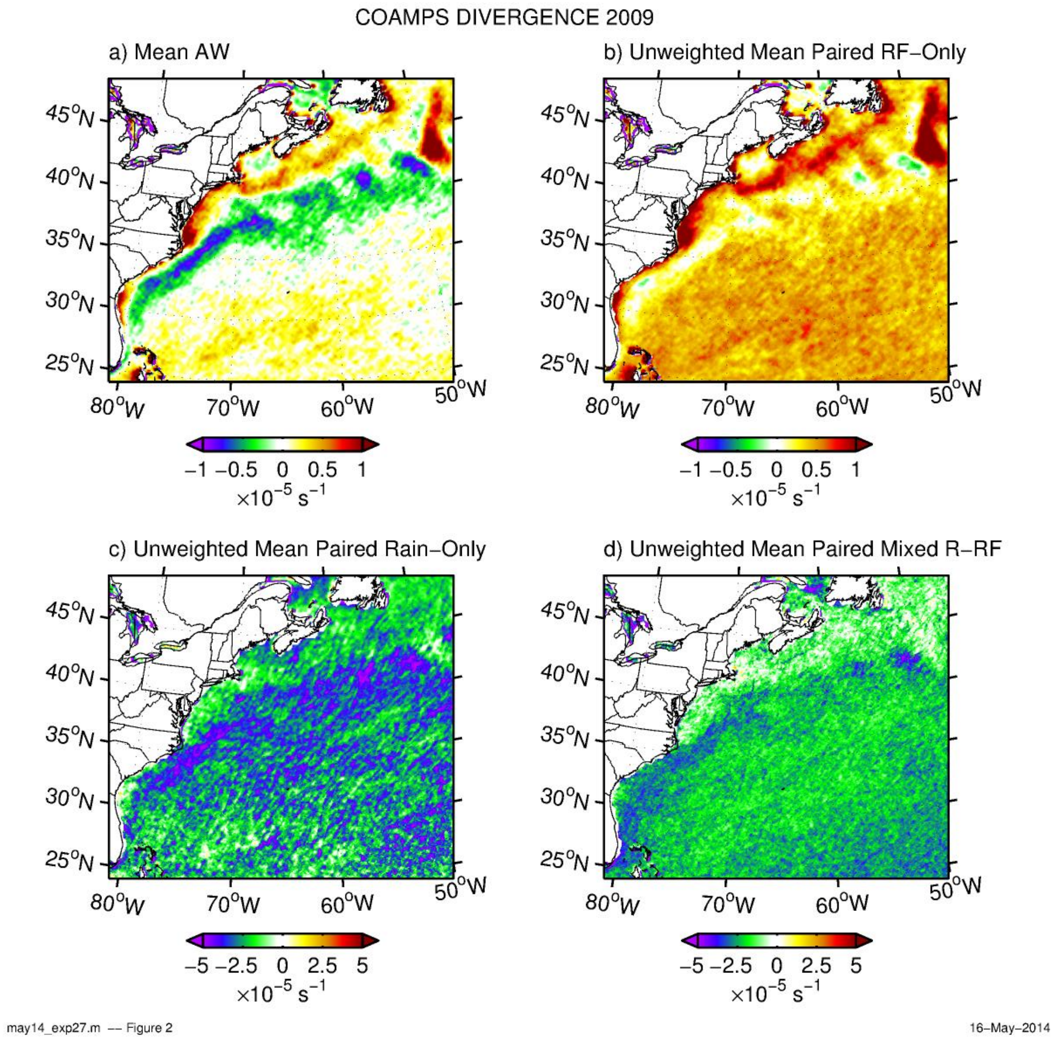

Jan–Jul 2009
COAMPS AW Divergence
ASCAT–A AW Divergence
Instantaneous Avg
JPL QuikSCAT AW Divergence
Instantaneous Avg
COAMPS AW Vorticity
ASCAT–A AW Vorticity
Instantaneous Avg
JPL QuikSCAT AW Vorticity
Instantaneous Avg
45°N
40°N
35°N
30°N
25°N
80°W
70°W
60°W
50°W
–1.5 –1 –0.5 0 0.5 1 1.5
(×10⁵ s⁻¹)

Large difference between two methods of computing time-averaged div/crl from rain-free winds is present in COAMPS simulations





a) $(\mu^{up}_{u_{i+1,j}} - \mu^{up}_{u_{i-1,j}})/2*dx + (\mu^{up}_{v_{i,j+1}} - \mu^{up}_{v_{i,j-1}})/2*dy$
b) $((1-N^p_{i,j}/N_{i+1,j})\mu^{up}_{u_{i+1,j}} - (1-N^p_{i,j}/N_{i-1,j})\mu^{up}_{u_{i-1,j}})/2*dx +$
$((1-N^p_{i,j}/N_{i,j+1})\mu^{up}_{v_{i,j+1}} - (1-N^p_{i,j}/N_{i,j-1})\mu^{up}_{v_{i,j-1}})/2*dy$
c) $((1-N^p_{i,j}/N_{i+1,j}) - (1-N^p_{i,j}/N_{i-1,j}))/2*dx +$
$((1-N^p_{i,j}/N_{i,j+1}) - (1-N^p_{i,j}/N_{i,j-1}))/2*dy$
45°N
40°N
35°N
30°N
25°N
80°W
70°W
60°W
50°W
−20 −10 0 10 20
−2 −1 0 1 2
−0.25 0 0.25
$\times 10^{-5}$ s^{-1}


COAMPS DIVERGENCE 2009
a) Mean AW
b) Unweighted Mean Paired RF−Only
c) Unweighted Mean Paired Rain−Only
d) Unweighted Mean Paired Mixed R−RF
45°N
40°N
35°N
30°N
25°N
80°W
70°W
60°W
50°W
−1 −0.5 0 0.5 1
×10^{-5} s^{-1}
−5 −2.5 0 2.5 5
×10^{-5} s^{-1}
may14_exp27.m --- Figure 2
16−May−2014

Two ways of computing the time-averaged divergence in the wild:

Vector-averaged method

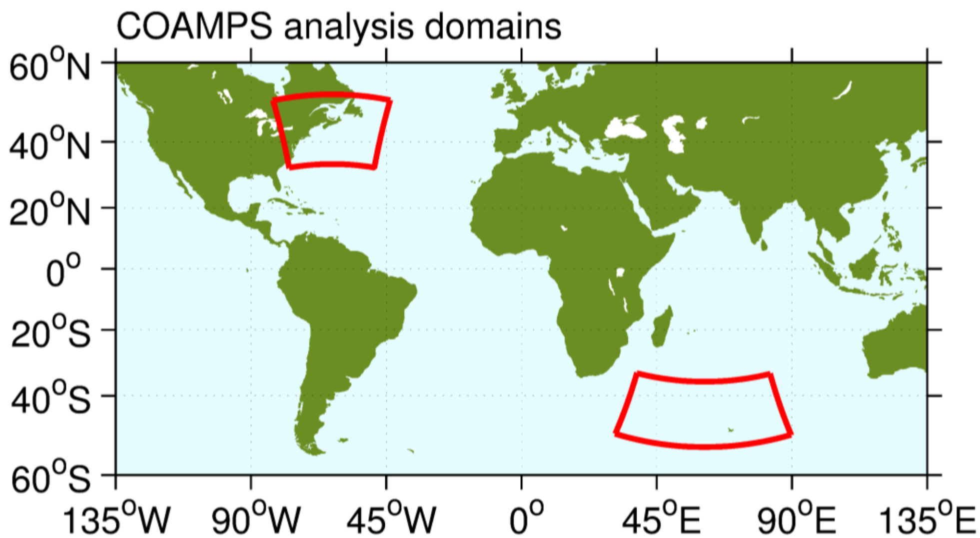
$$\left(\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{v}}{\partial y}\right)\Bigg|_{i,j} = \frac{1}{2\Delta x}\left(\frac{1}{N_{i+1,j}}\sum_{k=1}^{N_{i+1,j}} u_{i+1,j}(t_k) - \frac{1}{N_{i-1,j}}\sum_{l=1}^{N_{i-1,j}} u_{i-1,j}(t_l)\right) + \frac{1}{2\Delta y}\left(\frac{1}{N_{i,j+1}}\sum_{m=1}^{N_{i,j+1}} v_{i,j+1}(t_m) - \frac{1}{N_{i,j-1}}\sum_{n=1}^{N_{i,j-1}} v_{i,j-1}(t_n)\right),$$

Instantaneous method

$$\left(\overline{\frac{\partial u}{\partial x}} + \overline{\frac{\partial v}{\partial y}}\right)\Bigg|_{i,j} = \frac{1}{N}\sum_{k=1}^{N}\left[\frac{1}{2\Delta x}\Big(u_{i+1,j}(t_k) - u_{i-1,j}(t_k)\Big) + \frac{1}{2\Delta y}\Big(v_{i,j+1}(t_k) - v_{i,j-1}(t_k)\Big)\right],$$

(

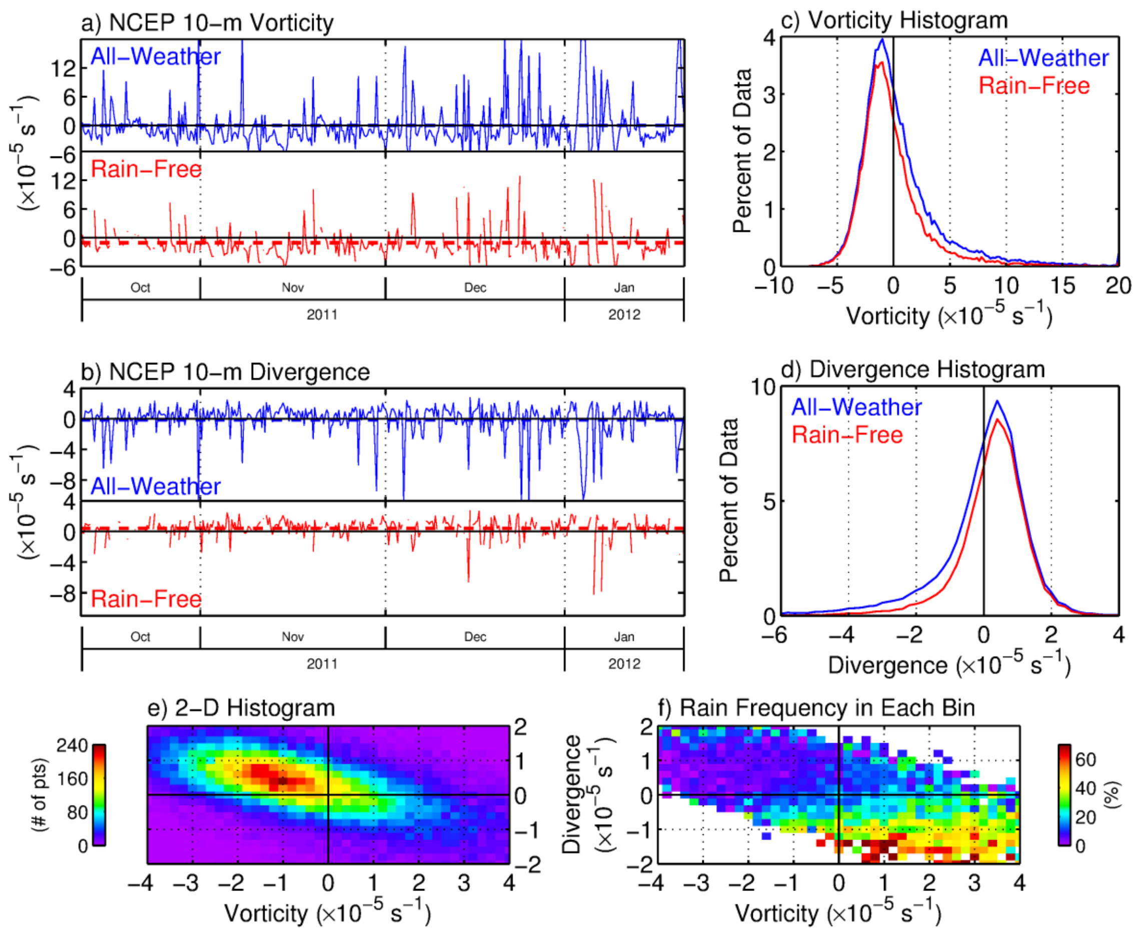
COAMPS atmospheric model simulation



Results are shown here from 1-year long simulation from the COAMPS model

- Entire year of 2009 shown here
- Atmosphere only simulation with prescribed SSTs (NCODA analyses)
- 50 vertical levels, with 20 below 1000-m
- Lowest grid point at 10 meter height above surface analyzed
- Doubly nested domain; inner nest analyzed; grid spacing of 9-km
- Non-hydrostatic
- 24 hour forecasts initialized every 12 hours; analyze forecast hours 06Z and 18Z
- Lateral boundaries forced with operational NOGAPS global analyses

Divergence and Vorticity variability in mid-latitudes



This is for a region in the North Pacific centered on 50N, 160W

$$D_{i,j}^{VA} = \frac{1}{2\Delta x}\left[\frac{1}{N_{i+1,j}}\sum_{k=1}^{N_{i+1,j}} u_{i+1,j}(t_k) - \frac{1}{N_{i-1,j}}\sum_{l=1}^{N_{i-1,j}} u_{i-1,j}(t_l)\right] + \frac{1}{2\Delta y}\left[\frac{1}{N_{i,j+1}}\sum_{m=1}^{N_{i,j+1}} v_{i,j+1}(t_m) - \frac{1}{N_{i,j-1}}\sum_{n=1}^{N_{i,j-1}} v_{i,j-1}(t_n)\right].$$

(5)

ous method

ncluded (cf.

tantaneous

paired and

nes $t_k, k =$

or example,

$$\frac{1}{N_{i+1,j}}\sum_{k=1}^{N_{i+1,j}} u_{i+1,j}(t_k) = \frac{1}{N_{i+1,j}}\left(N_{i,j}^{p}\hat{\mu}_{u_{i+1,j}}^{p} + N_{i+1,j}^{up}\hat{\mu}_{u_{i+1,j}}^{up}\right),$$

(6)

$(i+1,j)$,

ates of the

$_{-1,j}$ are the

$$D_{i,j}^{VA} = N_{i,j}^{p}\left[\frac{1}{2\Delta x}\left(\frac{\hat{\mu}_{u_{i+1,j}}^{p}}{N_{i+1,j}} - \frac{\hat{\mu}_{u_{i-1,j}}^{p}}{N_{i-1,j}}\right) + \frac{1}{2\Delta y}\left(\frac{\hat{\mu}_{v_{i,j+1}}^{p}}{N_{i,j+1}} - \frac{\hat{\mu}_{v_{i,j-1}}^{p}}{N_{i,j-1}}\right)\right] + \frac{1}{2\Delta x}\left[\left(1 - \frac{N_{i,j}^{p}}{N_{i+1,j}}\right)\hat{\mu}_{u_{i+1,j}}^{up} - \left(1 - \frac{N_{i,j}^{p}}{N_{i-1,j}}\right)\hat{\mu}_{u_{i-1,j}}^{up}\right] + \frac{1}{2\Delta y}\left[\left(1 - \frac{N_{i,j}^{p}}{N_{i,j+1}}\right)\hat{\mu}_{v_{i,j-1}}^{up} - \left(1 - \frac{N_{i,j}^{p}}{N_{i,j-1}}\right)\hat{\mu}_{v_{i,j-1}}^{up}\right].$$

$\hat{\mu}_{u_{i-1,j}}^{up})\Big] +$

$^{up}_{v_{i,j-1}})\Big].$

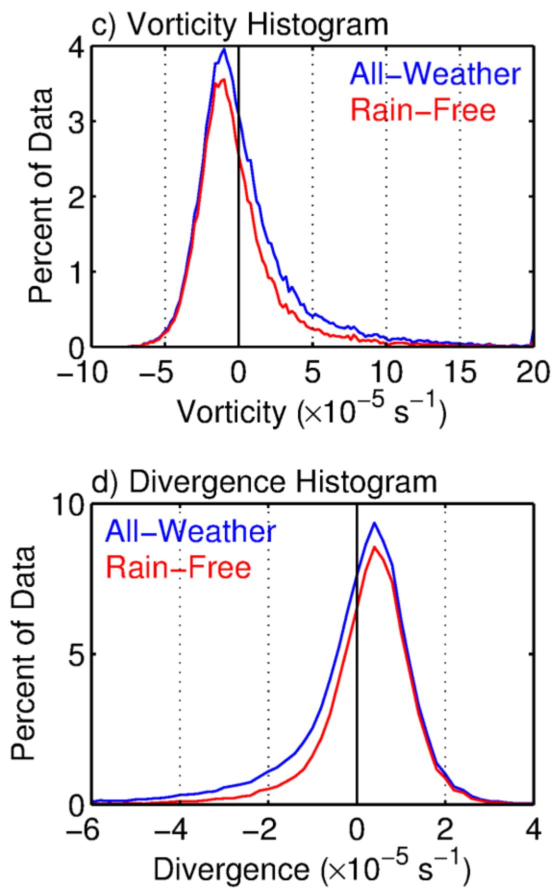
ields

(7)

$$\overline{D_{i,j}^{AW}} = \frac{1}{N_{i,j}} \sum_{k=1}^{N_{i,j}} \left[\frac{1}{2\Delta x} \Big(u_{i+1,j}(t_k) - u_{i-1,j}(t_k) \Big) + \frac{1}{2\Delta y} \Big(v_{i,j+1}(t_k) - v_{i,j-1}(t_k) \Big) \right].$$

$$\begin{aligned}
\overline{D_{i,j}^{RF}} &= \frac{1}{N_{i,j}^{RF}} \sum_{k=1}^{N_{i,j}^{RF}} \left[\frac{1}{2\Delta x} \Big(u_{i+1,j}(t_k^{RF}) - u_{i-1,j}(t_k^{RF}) \Big) + \frac{1}{2\Delta y} \Big(v_{i,j+1}(t_k^{RF}) - v_{i,j-1}(t_k^{RF}) \Big) \right] \\
\overline{D_{i,j}^{R}} &= \frac{1}{N_{i,j}^{R}} \sum_{l=1}^{N_{i,j}^{R}} \left[\frac{1}{2\Delta x} \Big(u_{i+1,j}(t_l^{R}) - u_{i-1,j}(t_l^{R}) \Big) + \frac{1}{2\Delta y} \Big(v_{i,j+1}(t_l^{R}) - v_{i,j-1}(t_l^{R}) \Big) \right] \\
\overline{D_{i,j}^{M}} &= \frac{1}{N_{i,j}^{M}} \sum_{m=1}^{N_{i,j}^{M}} \left[\frac{1}{2\Delta x} \Big(u_{i+1,j}(t_m^{M}) - u_{i-1,j}(t_m^{M}) \Big) + \frac{1}{2\Delta y} \Big(v_{i,j+1}(t_m^{M}) - v_{i,j-1}(t_m^{M}) \Big) \right],
\end{aligned}$$

Histograms of NCEP surface divergence and vorticity in rain-free and all-weather conditions



North Pacific Ocean

Conditional sampling of rain-free winds leads to divergent and anti-cyclonic sampling biases