Self-Induced Ekman Pumping overOceanic Mesoscale Eddies

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- Two mechanisms for eddy self-induced Ekman pumping:
  1. From air-sea interaction as winds blow over eddy-induced perturbations of SST.
     - *First shown for Gulf Stream rings by Park & Cornillon (2002) and Park et al. (2006).*
     - *The feedback effects of this SST-induced Ekman pumping on the ocean disrupt the coherent evolution of the mesoscale eddy field (Jin et al., 2009).*
  2. From the influence of eddy surface currents on the relative wind, and therefore on the wind stress
     - *The potential importance of the feedback effects of this surface current induced Ekman pumping on the evolution of mesoscale eddies was first noted by Dewar & Flierl (1987).*
     - *First shown for Gulf Stream rings by Cornillon & Park (2001) and Park et al. (2006).*
- Both mechanisms tend to attenuate eddies.
- The surface current effects generate upwelling within anticyclonies and downwelling within cyclones (Martin and Richards, 2001; McGillicuddy et al., 2007).

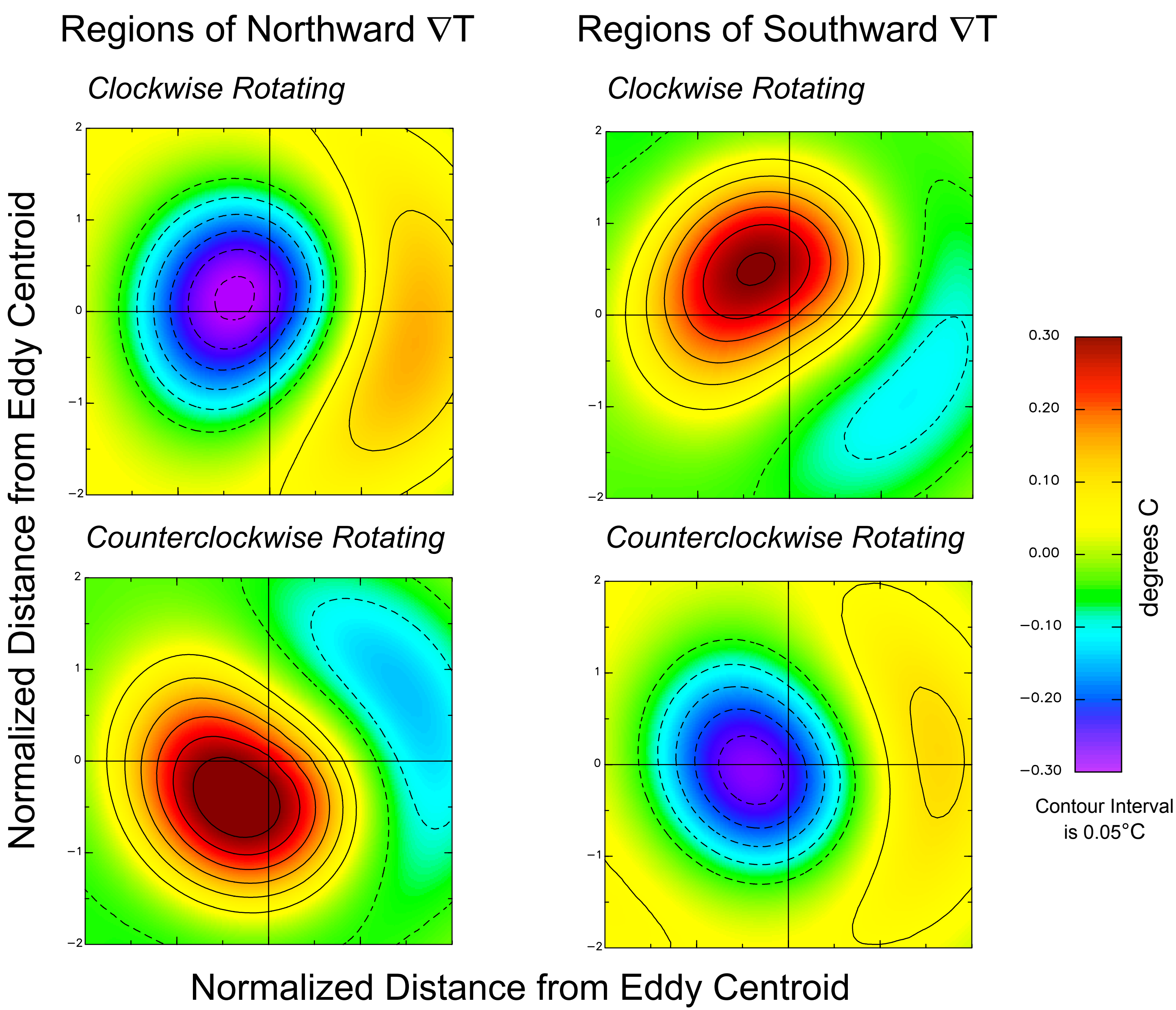
* The results presented here are part of the PhD thesis by Peter Gaube

Procedure for Composite Averaging SST, Wind Speed and Wind Stress Curl in Eddy-Centric Coordinates: *Synergy Between 4 Complimentary Satellite Datasets*

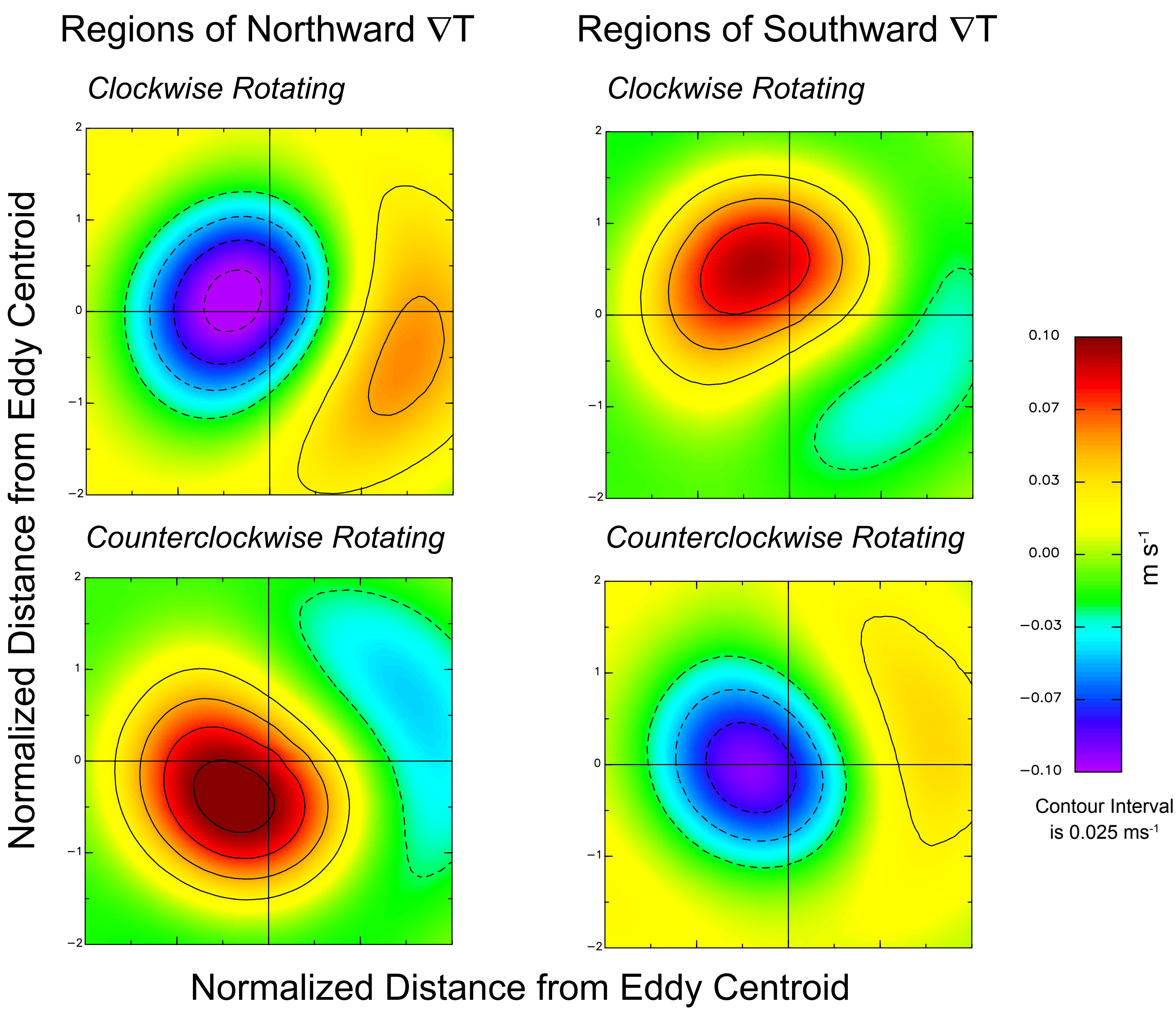
- Identify mesoscale eddies by altimetry from their SSH signatures.
- Composite average the other satellite datasets in an "eddy-centric" translating reference frame with $(\Delta x, \Delta y)$ coordinates relative to the eddy centroid normalized by the radius L_s of maximum rotational speed at each location along its trajectory.
  - *AMSR+AVHRR measurements of SST (Reynolds OI2 analyses).*
  - *QuikSCAT measurements of wind speed and wind stress.*
  - *SeaWiFS estimates of oceanic chlorophyll.*
- Because the dominant mechanism for eddy-induced SST variability is horizontal advection by the rotational velocity of the eddy, SST and wind speed must be composite averaged in a coordinate system that is rotated by an amount determined from the large-scale background SST gradient.

1. Eddy Influence on SST and Wind Speed

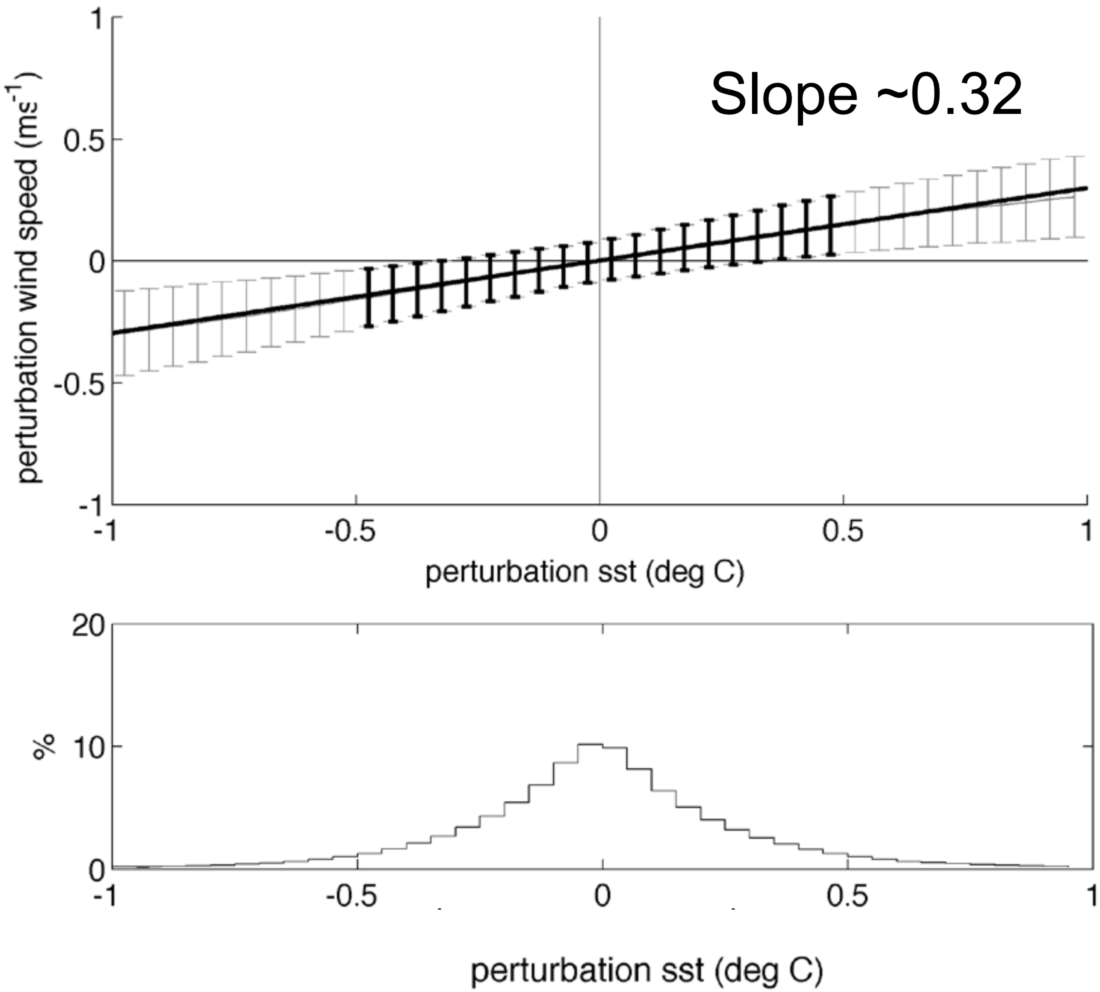
Global Composite Averages of SST in Eddy-Centric Coordinates



Global Composite Averages of Wind Speed in Eddy-Centric Coordinates



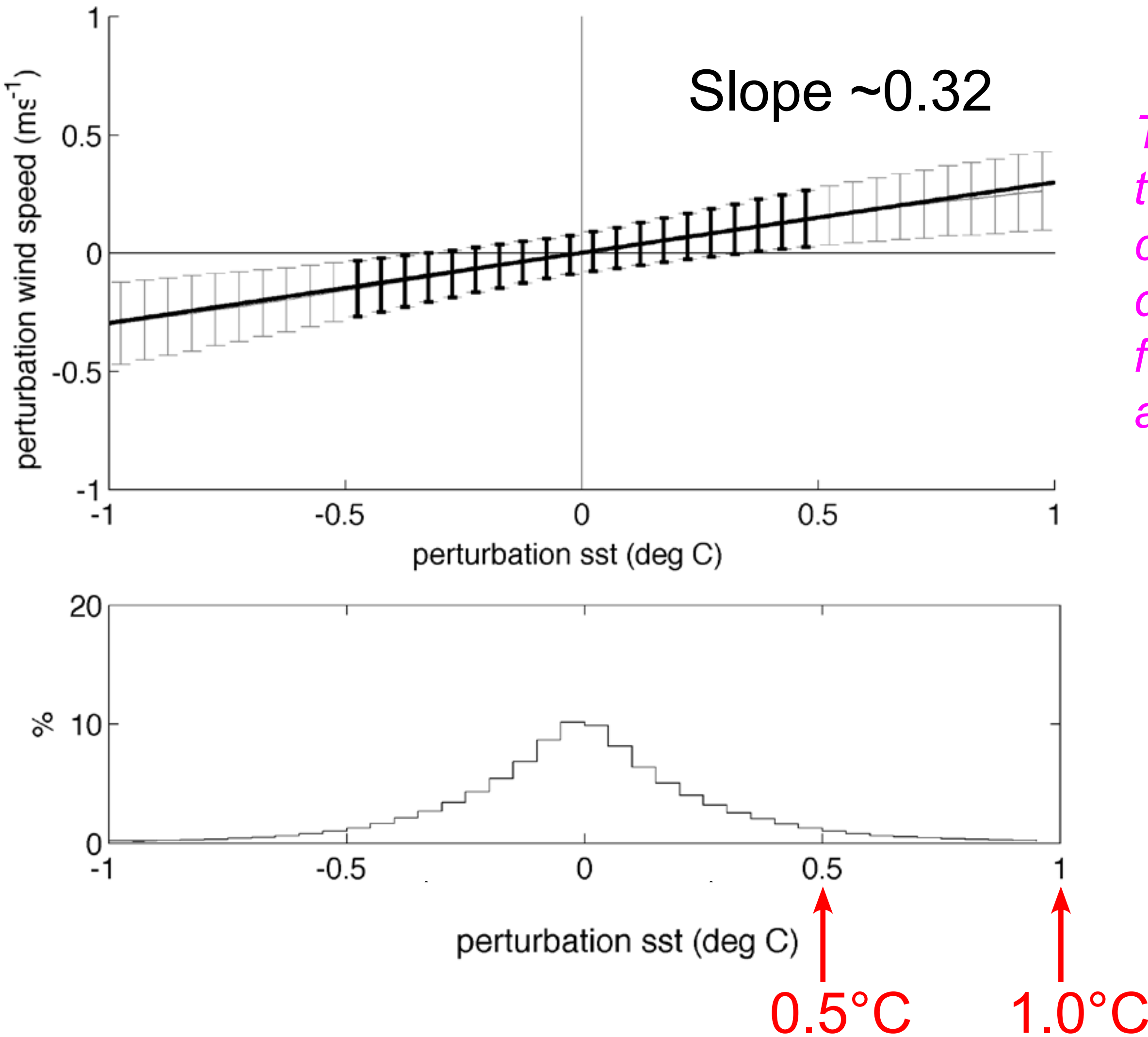
Coupling Coefficient Between Wind Speed and SST over Globally Distributed Mesoscale Eddies



This wind speed response to SST over eddies is consistent with the coupling deduced previously over frontal regions by O'Neill et al. (2010; 2012)

2. Ekman Pumping from Eddy-Related SST Influence on Wind Speed

Coupling Coefficient Between Wind Speed and SST over Globally Distributed Mesoscale Eddies

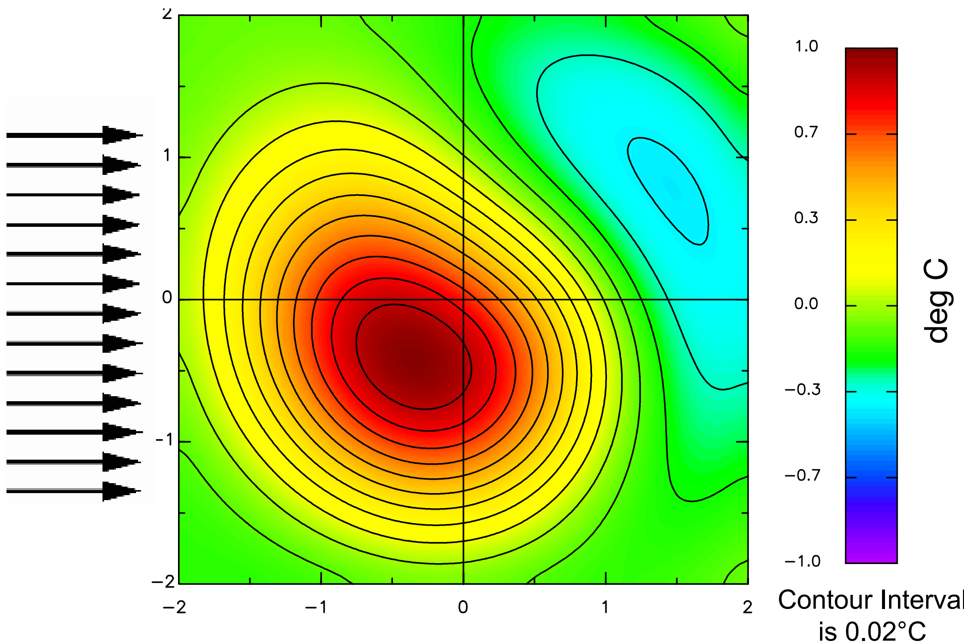


This wind speed response to SST over eddies is consistent with the coupling deduced previously over frontal regions by O'Neill et al. (2010; 2012)

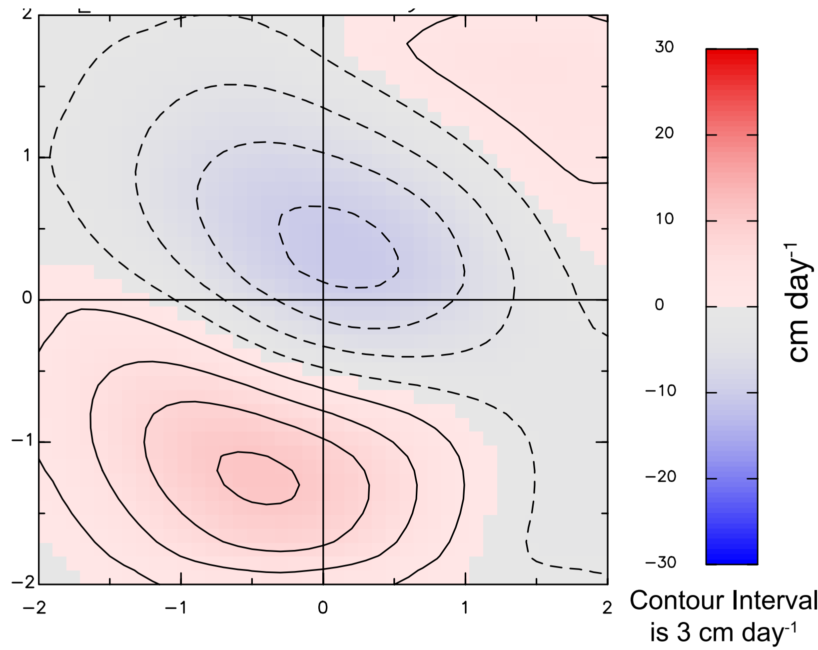
Ekman Pumping from Eddy Perturbations of SST

for Westerly Winds Over a 1.0°C SST Anomaly at 30°S

Composite SST Structure



Ekman Pumping Velocity



- 30°S
- 20 cm anticyclone
- 10 ms^{-1} wind speed
- 1° SST perturbation

$$U'_{wind} = \alpha\ SST'$$

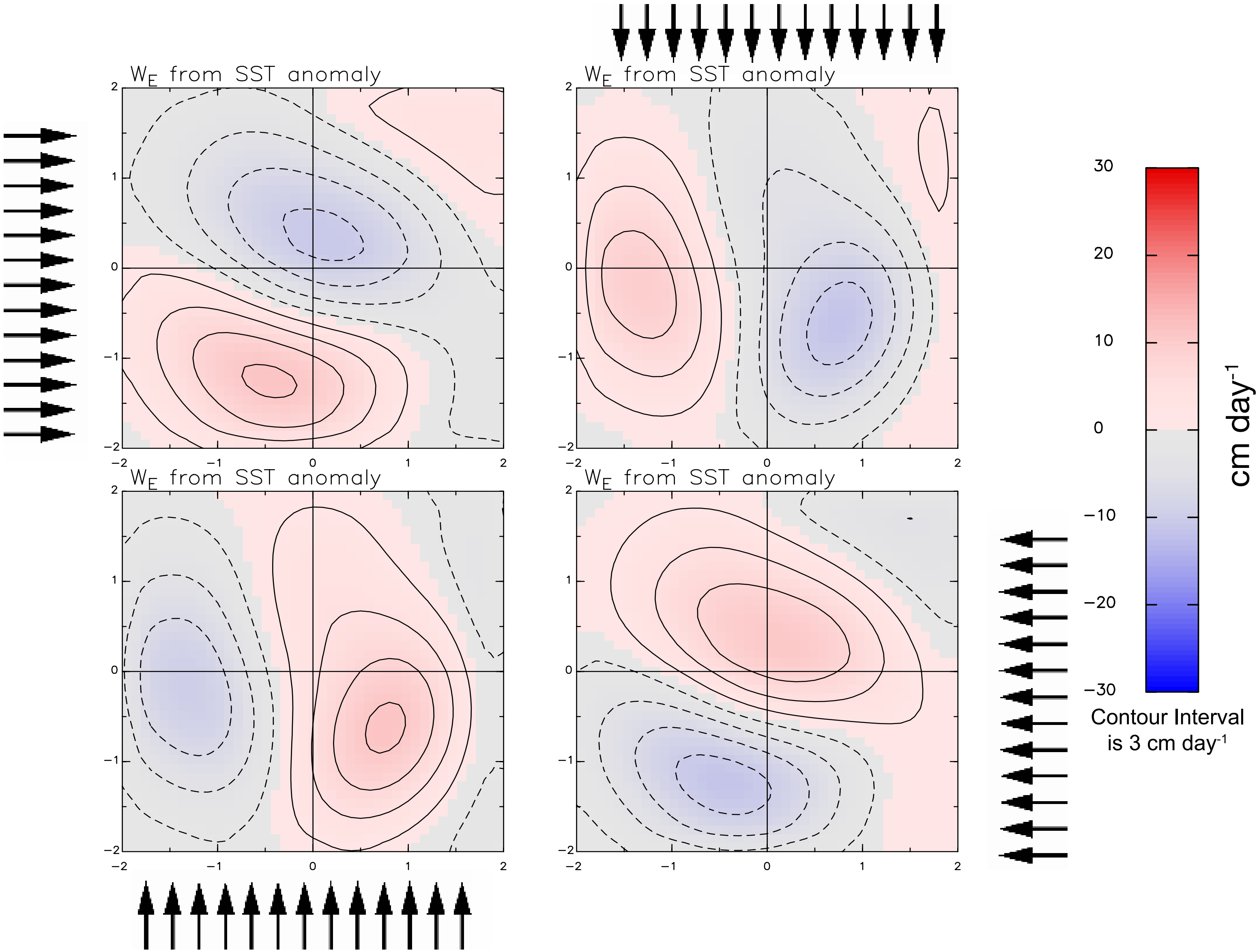
$$\alpha = 0.32$$

$$\overrightarrow{\tau} = \rho\ C_D\,|\overrightarrow{u}|\,\overrightarrow{u}$$

$$W_E = \frac{1}{\rho f}\nabla \times \overrightarrow{\tau}$$

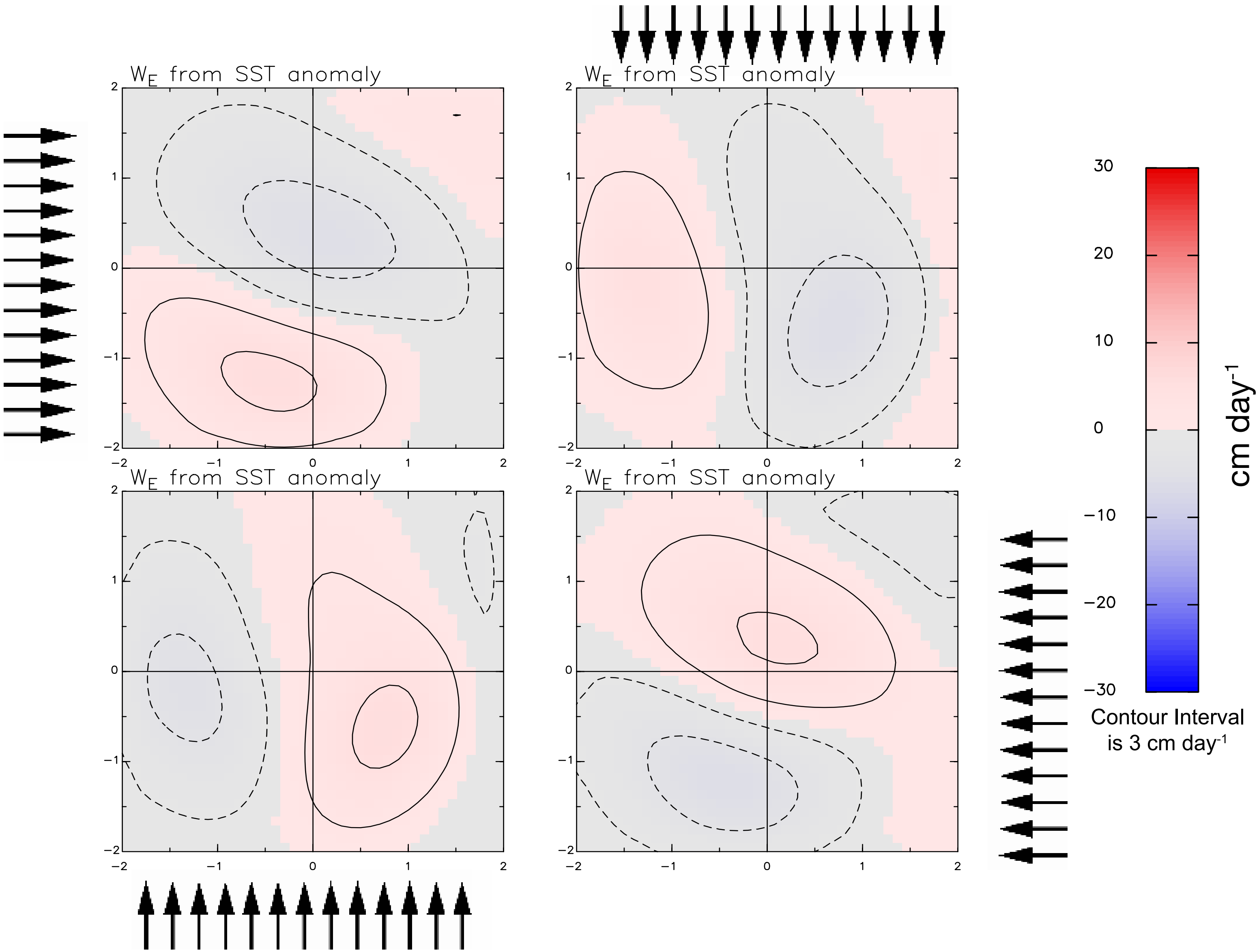
Ekman Pumping from Eddy Perturbations of SST

for Winds from Various Directions Over a 1.0°C SST Anomaly at 30°S



Ekman Pumping from Eddy Perturbations of SST

for Winds from Various Directions Over a 0.5°C SST Anomaly at 30°S

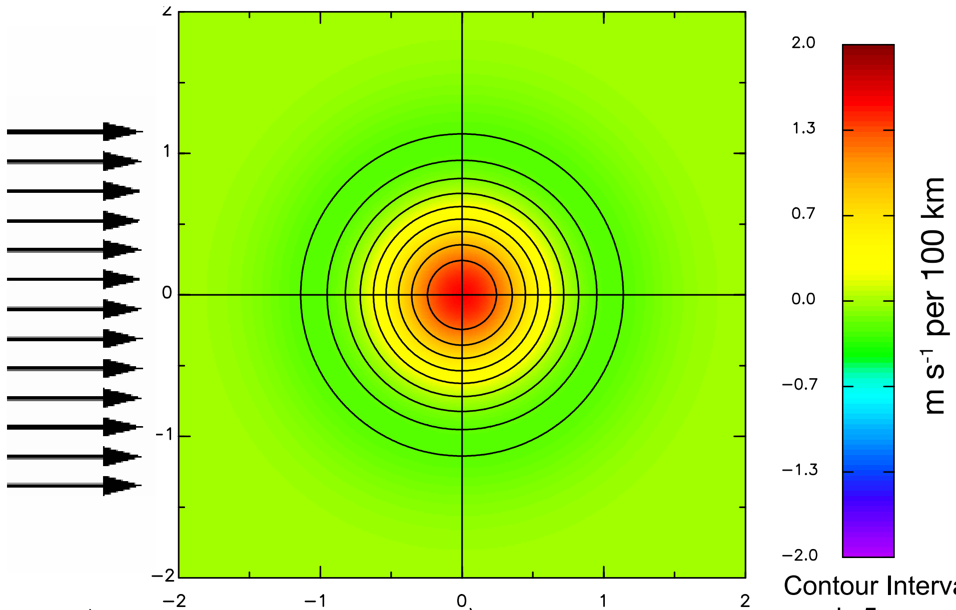


3. Ekman Pumping from Eddy Surface Currents for an Idealized Gaussian Eddy

Ekman Pumping from Eddy Surface Currents

for an Idealized Anticyclonic Gaussian Eddy and Westerly Winds at 30°S

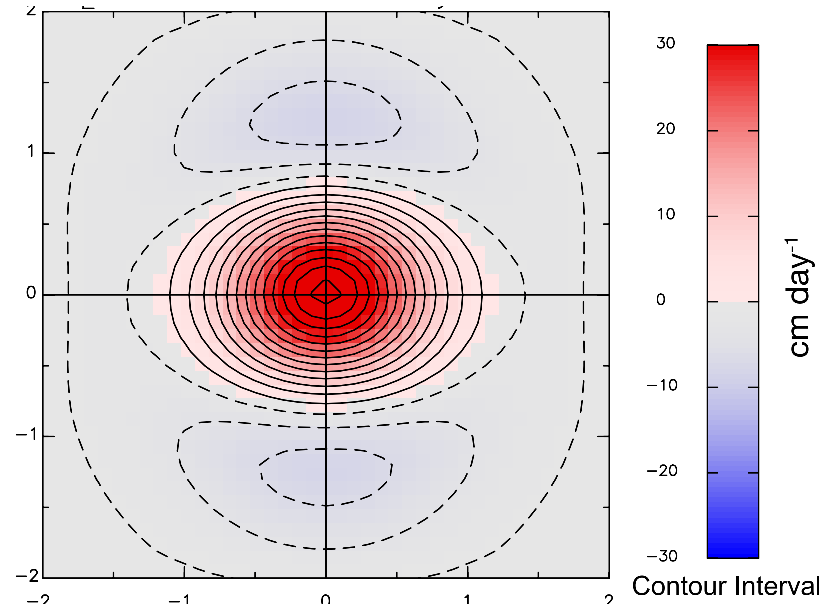
SSH Structure of Idealized Gaussian Eddy



Contour Interval is 5 cm

$\overrightarrow{u}_a$ $\overrightarrow{u}_o$

Ekman Pumping Velocity



Contour Interval is 3 cm day^{-1}

$$\overrightarrow{\tau} = \rho C_D |u_{rel}| \overrightarrow{u}_{rel}$$

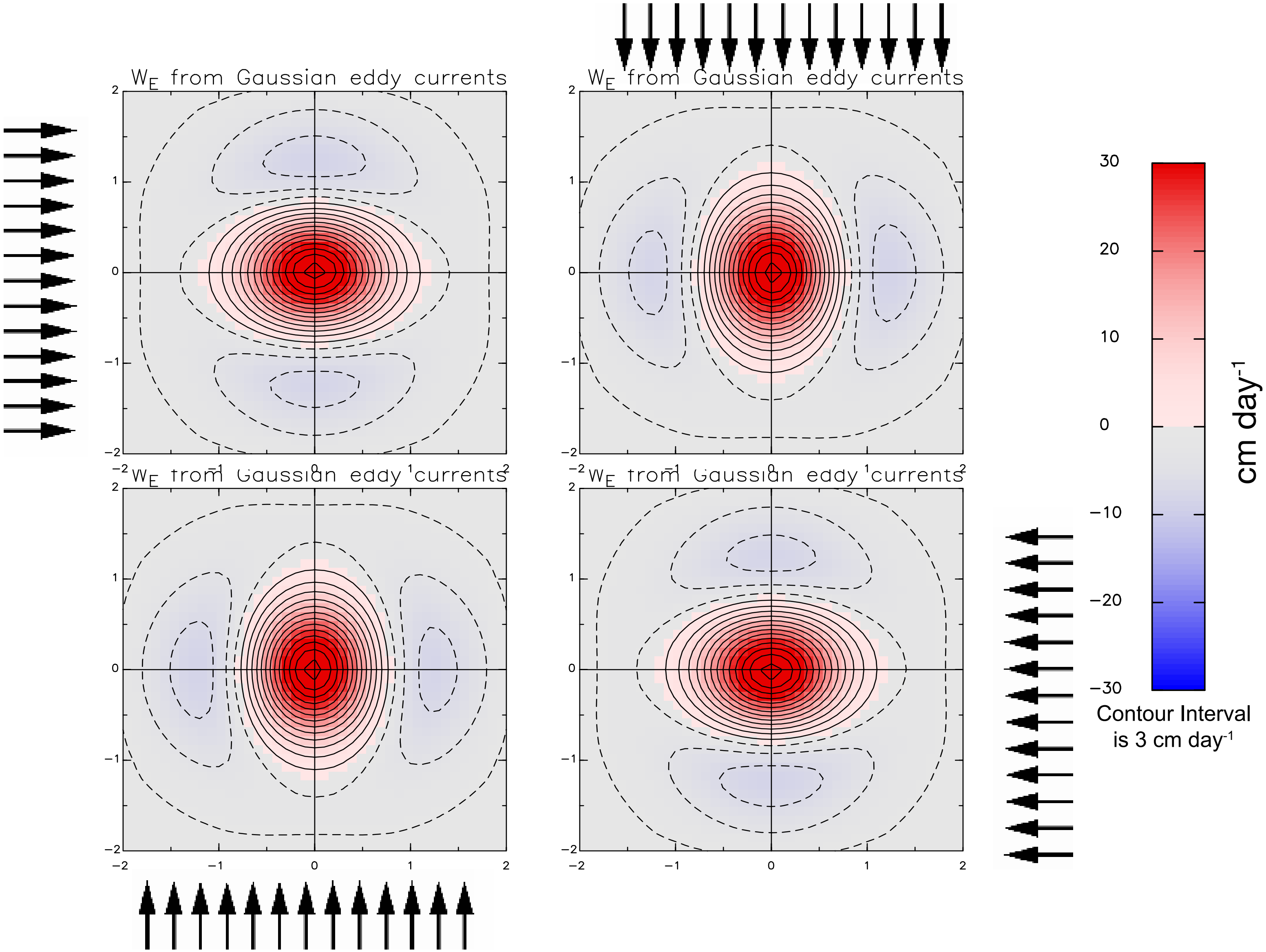
$$\overrightarrow{u}_{rel} = \overrightarrow{u}_a - \overrightarrow{u}_o$$

- 30°S
- 20 cm amp.
- 10 ms^{-1} wind
- Max current 40 cm s^{-1}

$$W_E = \frac{1}{\rho f} \nabla \times \overrightarrow{\tau}$$

Ekman Pumping from Eddy Surface Currents

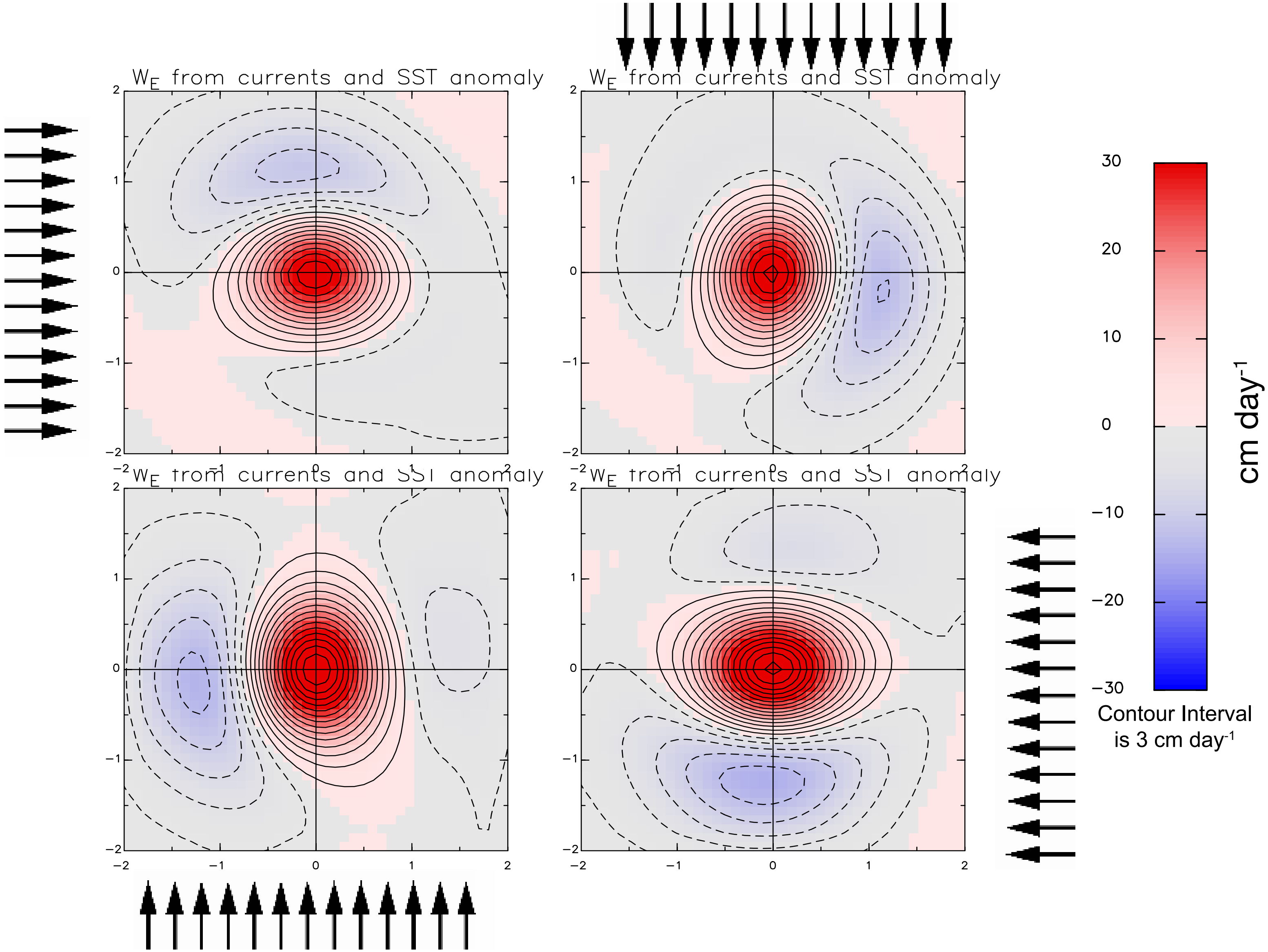
for an Idealized <u>Anticyclonic</u> Gaussian Eddy and Winds from Various Directions at 30°S



4. Ekman Pumping from the Combined Effects of SST Influence and Eddy Surface Currents for an Idealized Gaussian Eddy

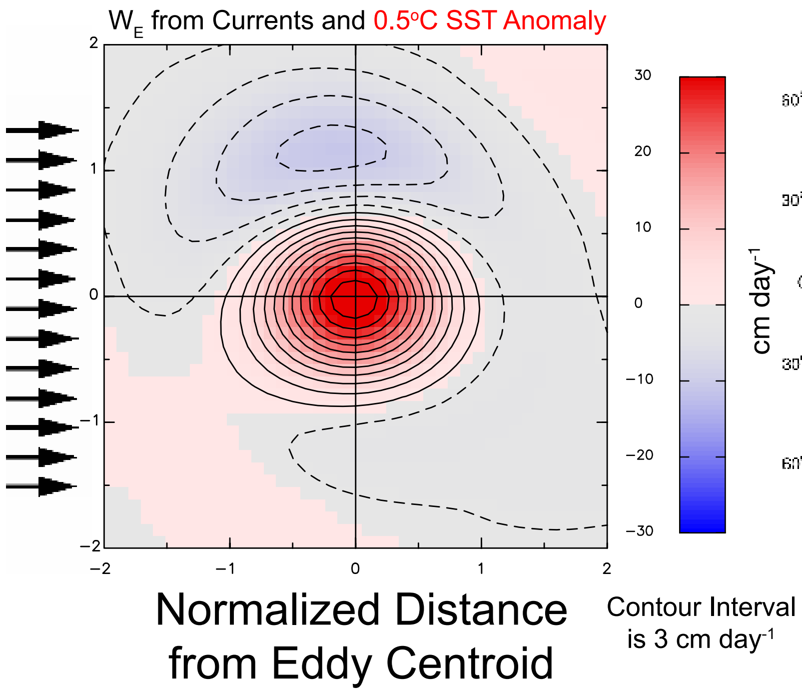
Ekman Pumping from Eddy Surface Currents and SST Combined

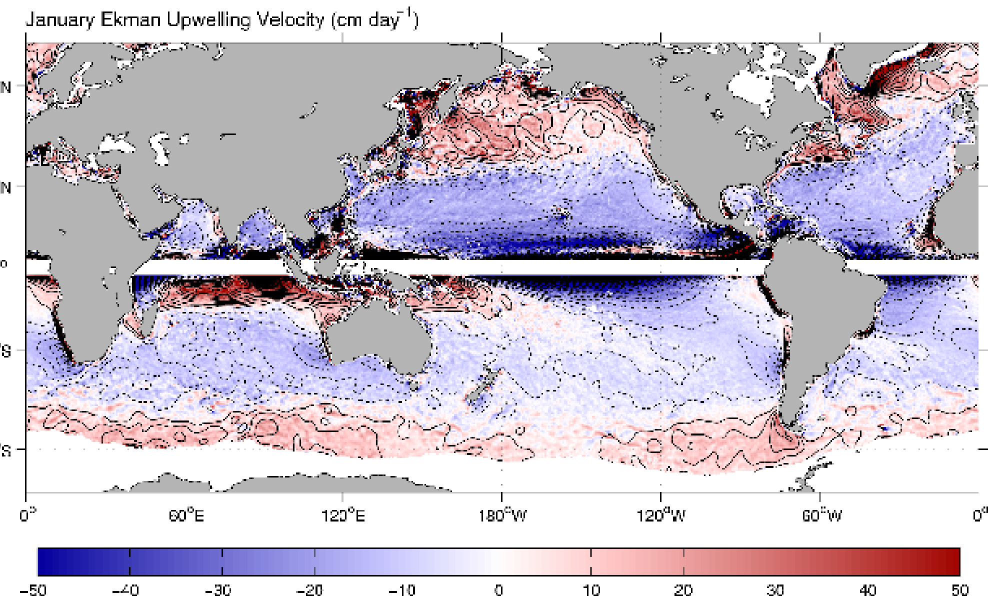
for an Idealized Anticyclonic Gaussian Eddy and Winds from Various Directions over a 0.5°C SST Anomaly at 30°S



How does this eddy-induced Ekman pumping compare with Ekman pumping associated with the large-scale wind field?

$$W_E = \frac{1}{\rho f} \nabla \times \overrightarrow{\tau}$$





Risien and Chelton, 2008

Eddy-induced Ekman pumping is an Order-1 Perturbation of the Ekman pumping associated with the large-scale wind field.

5. Is the previous Ekman pumping for an idealized Gaussian eddy observed in the QuikSCAT data?

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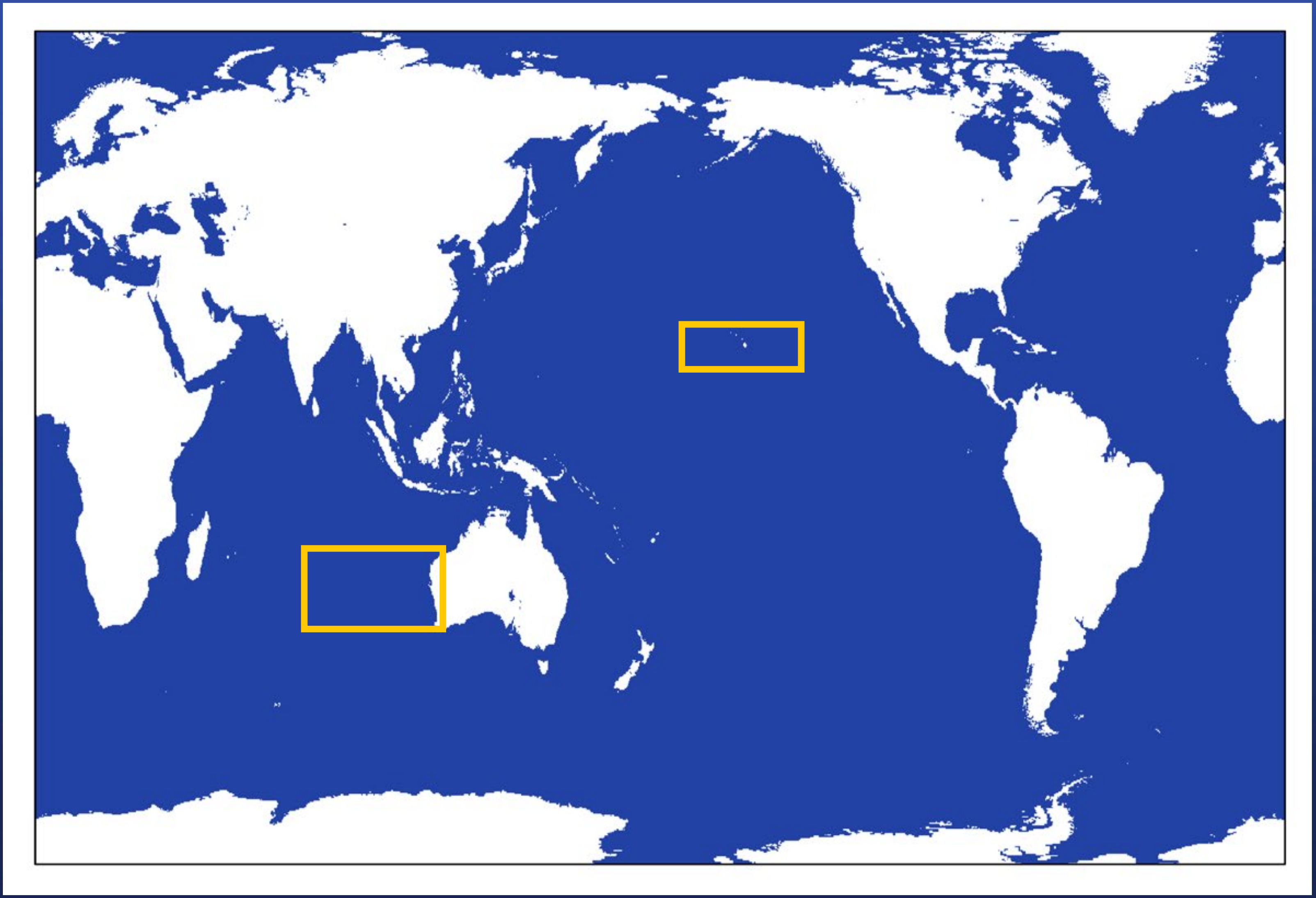
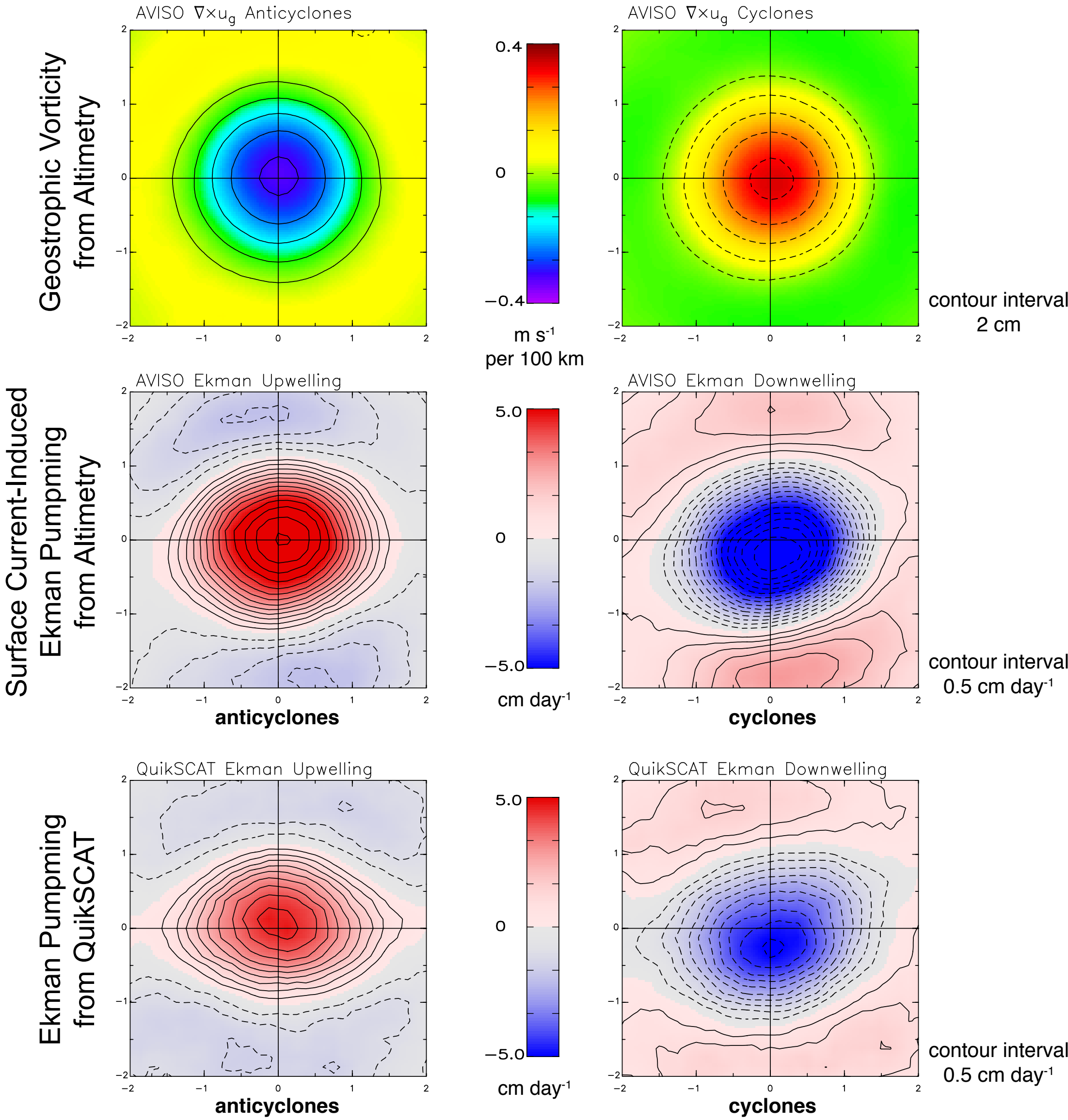
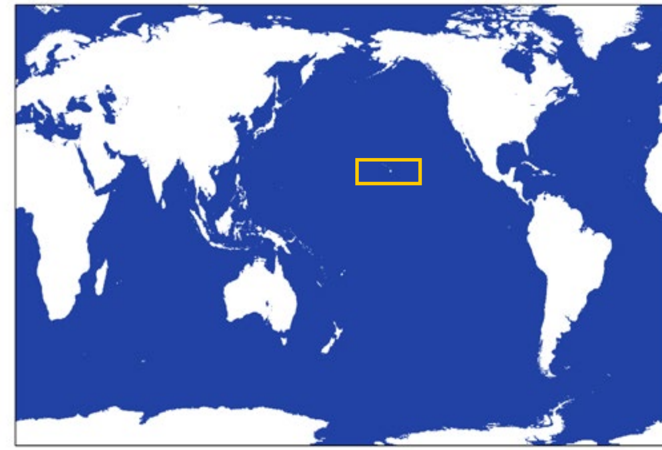


Composite Averages of Eddy-Induced Vorticity and Ekman Pumping Velocity in the Hawaiian Island Region

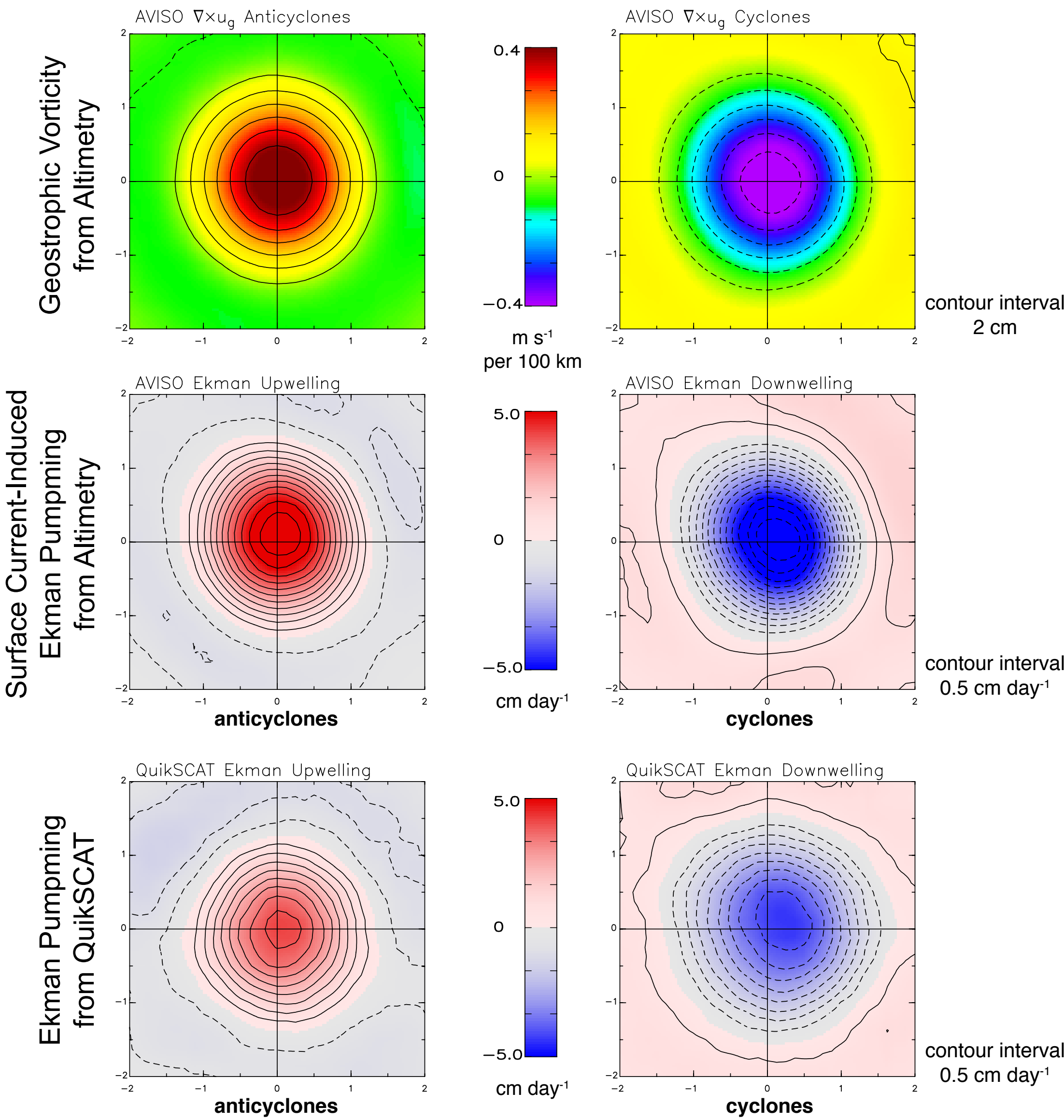


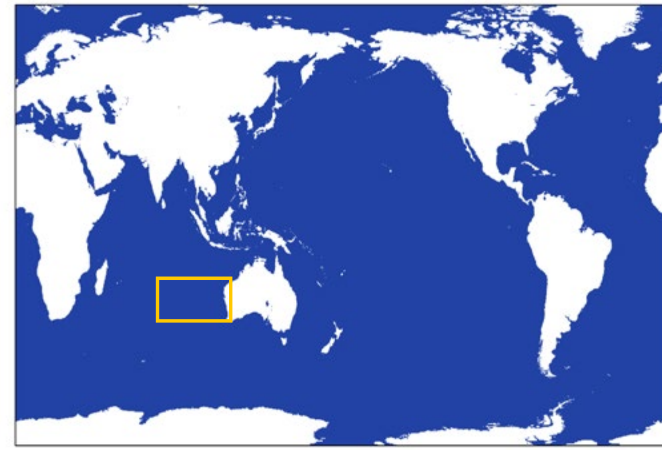


The regions of strong upwelling and downwelling are zonally elongated because the winds are predominantly nearly zonal (easterly) in this region.

The somewhat weaker upwelling velocities in the QuikSCAT composites are consistent with small mislocations of the eddy centroids because of noise in the altimeter SSH fields.

Composite Averages of Eddy-Induced Vorticity and Ekman Pumping Velocity in the South Indian Ocean





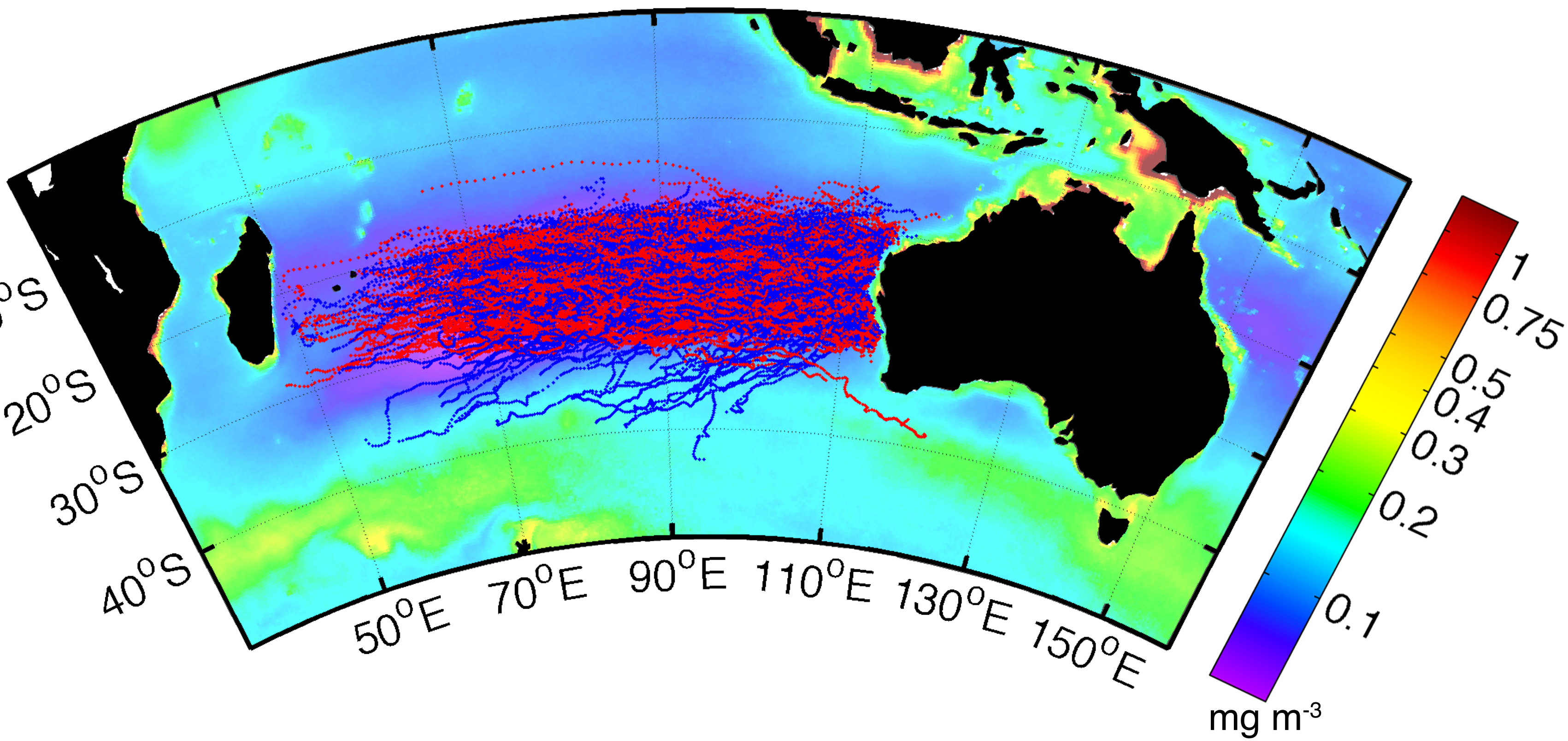
The nearly circular regions of strong upwelling and downwelling are indicative of highly variable direction of the wind stress.

The somewhat weaker upwelling velocities in the QuikSCAT composites are again consistent with small mislocations of the eddy centroids because of noise in the altimeter SSH fields.

6. Influence of Ekman Pumping on Oceanic Biology

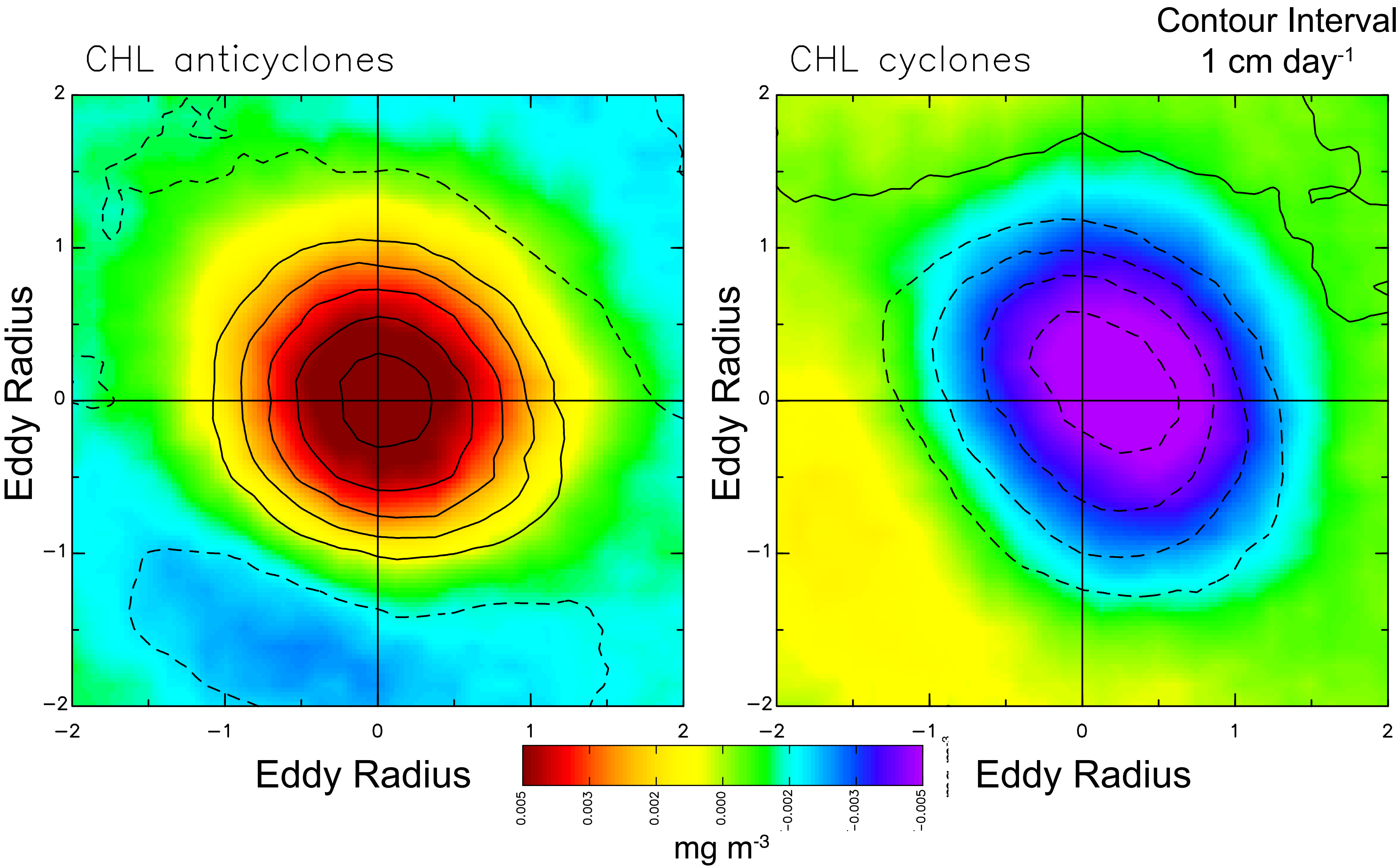
Eddies Spawned from the Leeuwin Current

a total of 734 anticyclonic and 818 cyclonic long-lived eddies were tracked from 2000-2008



Eddy-Induced Ekman Pumping Can Sustain Phytoplankton Blooms

Filtered wintertime SeaWiFS chlorophyll with contours of QuiksCAT Ekman pumping



- Seasonally (May - September), we observed enhanced CHL at the cores of anticyclonic eddies.
- Negative CHL anomalies are a persistent feature of cyclonic eddies in this region.

Conclusions

1) *Eddy-induced SST variability consists of horizontal advection by the azimuthal velocity of the eddies that is consistent with the coupling found previously between SST and wind speed along meandering SST fronts.*

2) *The Ekman pumping associated with these SST anomalies over the eddy interiors is usually secondary to the Ekman pumping associated with eddy surface currents.*
   - *This Ekman pumping is clearly evident in the surface winds measured by QuikSCAT.*
   - *The small differences between the Ekman pumping velocity deduced from QuikSCAT data and the geostrophic velocity computed from altimeter data are consistent with noise in the SSH fields that results in small mislocations of the eddy centroids and hence misalignment of the Ekman pumping velocity fields.*

3) *Ekman pumping over anticyclones appears to sustain blooms of phytoplankton within the cores of eddies in the South Indian Ocean during wintertime.*
   - *The reason that this is limited to wintertime is thought to be that the mixed layer is sufficiently deep to reach the nutricline, thus allowing the injection of nutrients ino the eddy interior where they can be utilized by phytoplankton trapped in the cores of anticyclones.*