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On the cyclonic eddy generation in Panay Strait, Philippines

Charina Lyn A. Repollo[1], Xavier-Flores Vidal[2], **Pierre J Flament**[1], Cesar Villanoy[3]
[1]**University of Hawaii, Manoa, HI, USA**, [2]Universitad Autonoma de Baja California, Ensenada, Mexico, [3]Marine Science Institute, University of the Philippines, Diliman, Quezon City, Philippines,

Abstract

High Frequency Doppler Radar (HFDR), shallow pressure gauges (SPG), and Acoustic Doppler Current Profiler (ADCP) time-series observations during the Philippine Straits Dynamics Experiment (PhilEx) were analyzed to describe the mesoscale currents in Panay Strait, Philippines. Low frequency surface currents inferred from three HFDR (July 2008 to July 2009), revealed a clear seasonal signal in concurrent with the reversal of the Asian monsoon. The mesoscale cyclonic eddy west of Panay Island is generated during the winter northeast monsoon (NEM). This causes changes in the strength, depth and width of the intra-seasonal Panay coastal jet as its eastern limb. Winds from QuikSCAT satellite and from a nearby airport indicate that these flow structures correlate with the strength and direction of the prevailing local wind.

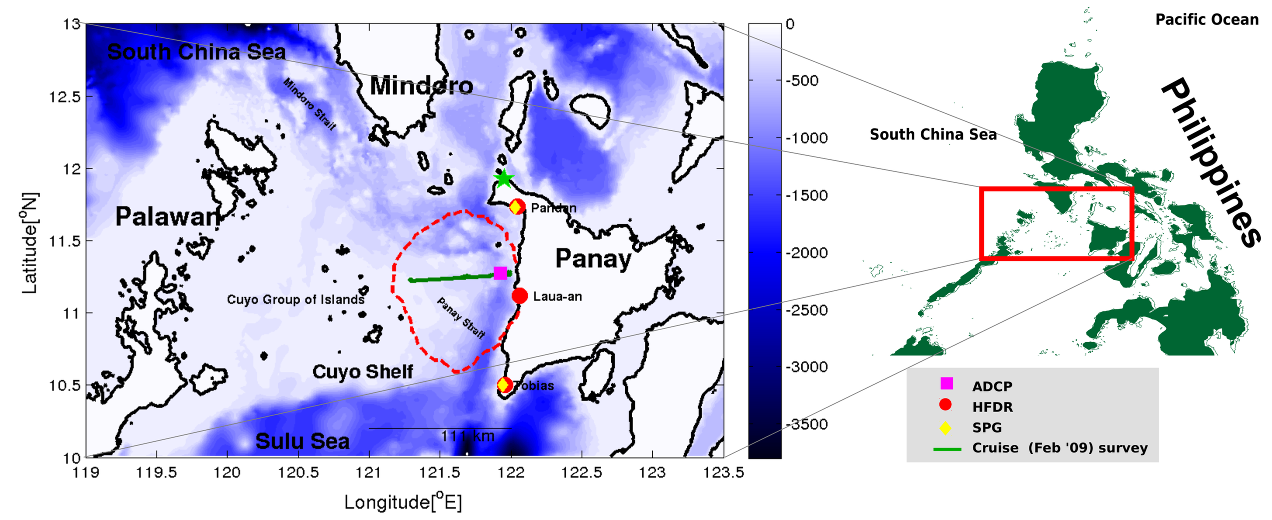
An intensive survey of the cyclonic eddy in February 8-9, 2009, obtaining a 24-hour successive cross-shore Conductivity-Temperature- Depth (CTD) sections in conjunction with shipboard ADCP measurements showed a well- developed cyclonic eddy characterized by near-surface velocities reaching 50 cm/s. This observation coincides with the intensification of the wind in between Mindoro and Panay islands generating a positive wind stress curl in the lee of Panay, which in turn induces divergent surface currents. Water column response from the mean transects showed a pronounced signal of upwelling, indicated by the doming of isotherms and isopycnals. A pressure gradient then was sets up, resulting in the spin-up of a cyclonic eddy in geostrophic balance. Evaluation of the surface vorticity balance equation suggests that the wind stress curl via Ekman pumping mechanism provides the necessary input in the formation and evolution of the cyclonic eddy. In particular, the cumulative effect of the wind stress curl plays a key role on the generation of the eddy. The Beta-effect on the other hand may led to propagation of the eddy westward.

I. Introduction

Surface wind forcing is particularly evident in the circulation patterns in and around the Philippine Archipelago. In Panay Strait, which is subject to pronounced Asian monsoon reversal, mean flow during the NEM (November 2008 - March 2009) is characterized by a jet-like northward flow, referred to here as the Panay coastal (PC) jet, and a southwestward return flow forming a cyclonic circulation. An intensive observation of the strait was carried out, using high-resolution (both in time and space) HFDR-inferred surface current in conjunction with time-series data from observations and satellites. In-situ data during the Philippine Straits Dynamics Experiment (PhilEX) regional Intensive Observational Period cruises in the winter of February 2009 (IOP-09) confirmed the mechanisms of the flow.

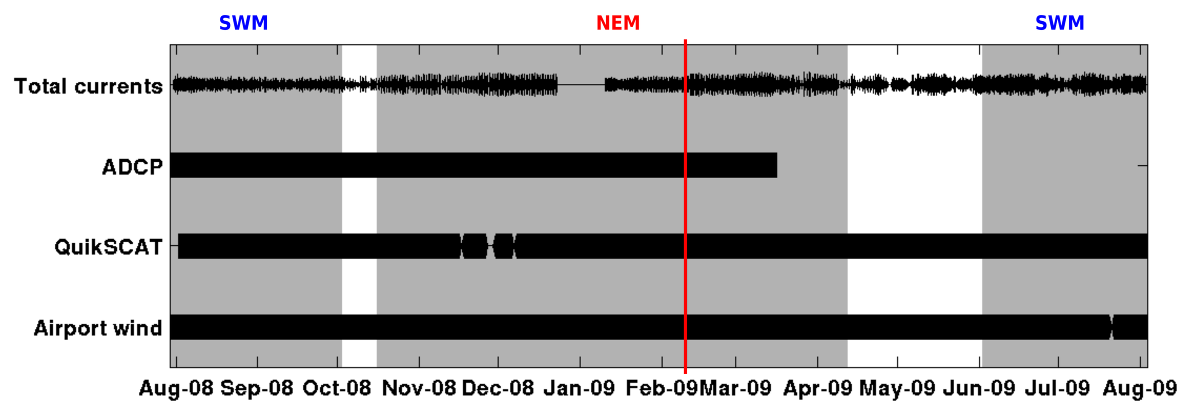
The Panay Strait (red inset) in Philippines serves as the major pathway of South China Sea water entering through Mindoro Strait into the deep Sulu Sea basin.

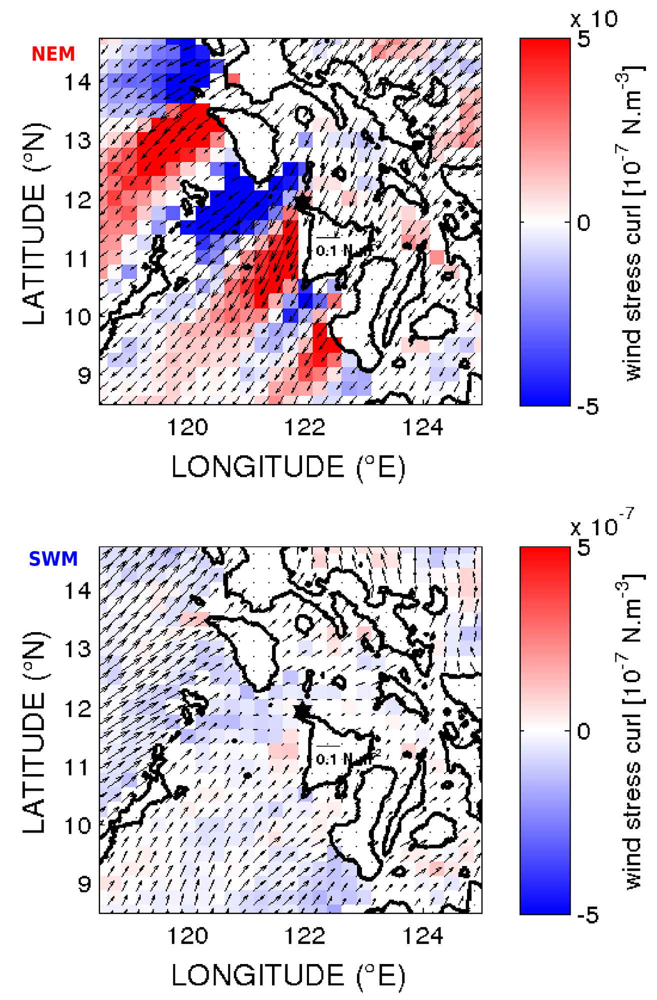
Marked are locations of instruments deployed. The red broken line indicate 75% coverage of HFDR. 24-hr successive cross-sections were surveyed during the PhilEx IOP-09 cruise.



II. Data

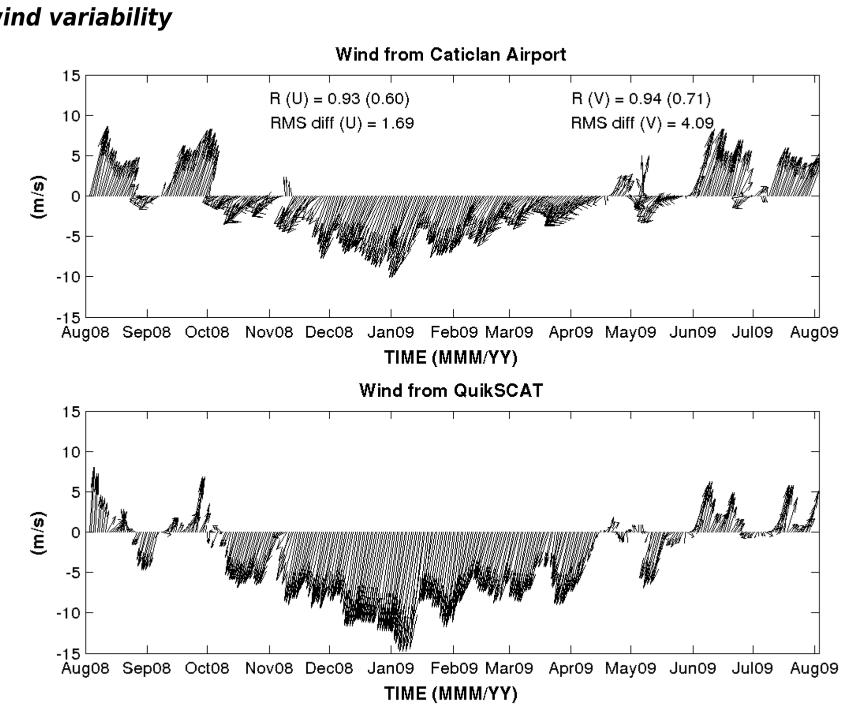
Temporal coverages of the data span over a year, covering the Asian monsoon reversal. All data were detided and subject to 6-day running median to obtain the low frequency signal. The thick red solid vertical line marked the IOP-09 cruise in February 2009





III. Observations

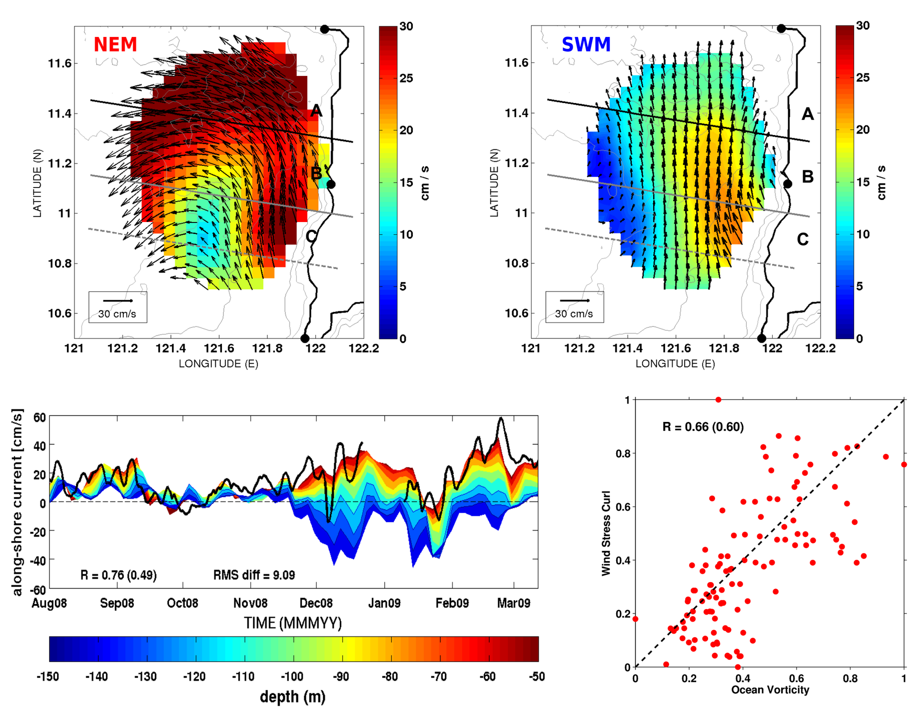
A. Local wind variability



Wind vectors from the nearby airport correspond well (correlation, *R*) with the QuikSCAT wind from the closest grid point. An abrupt reversal of the wind regime is marked by a well-defined transition period followed by the short phases of weakening. Persistent NEM winds occur from October to mid-April and southwesterly winds prevail from May to September, with pronounced sub-seasonal breaks.

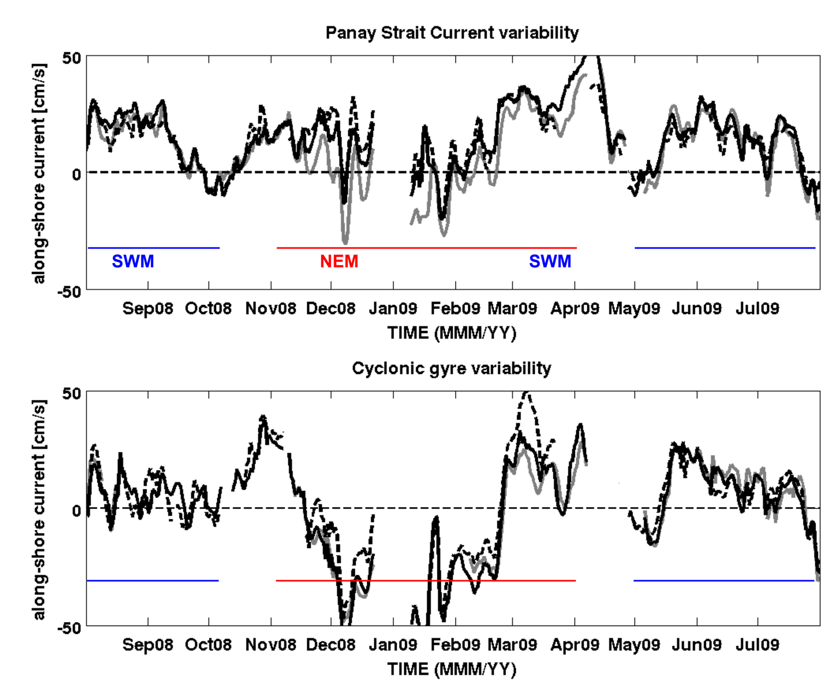
Wind stress curl contour overlaid by wind stress vectors from QuikSCAT. The wind field exhibits pronounced seasonal variations between the NEM and SWM periods. Northeasterly winds are stronger and more stable than southwesterly winds, producing wind jets in between islands generating a distinctive spatial pattern of alternating bands of positive curl on the left flank and negative curl on the right of Luzon, Mindoro, Panay and Negros Islands. Consequently, positive curl on the north flank of Panay is enhanced, dominating the lee and presenting a favorable condition for the formation of mesoscale eddies during NEM. These features are not evident during the SW monsoon period, which is characterized by weaker, highly variable winds.

B. Surface Current



NEM mean flow is characterized by a jet-like northward flow, referred to here as the PC jet, and a southwestward return flow forming a cyclonic circulation. In contrast, the SWM period is characterized by a relatively weak northward PC jet, with significant weakening and modification over the shallow Cuyo shelf.

During the NEM, variations of the PC jet are mainly influenced by the eddy. Contoured along-shore current profile from ADCP overlaid with along-shore surface current from the closest HFDR data (thick black line) show a generally northward PC jet with pronounced intensification when the cyclonic eddy is generated.

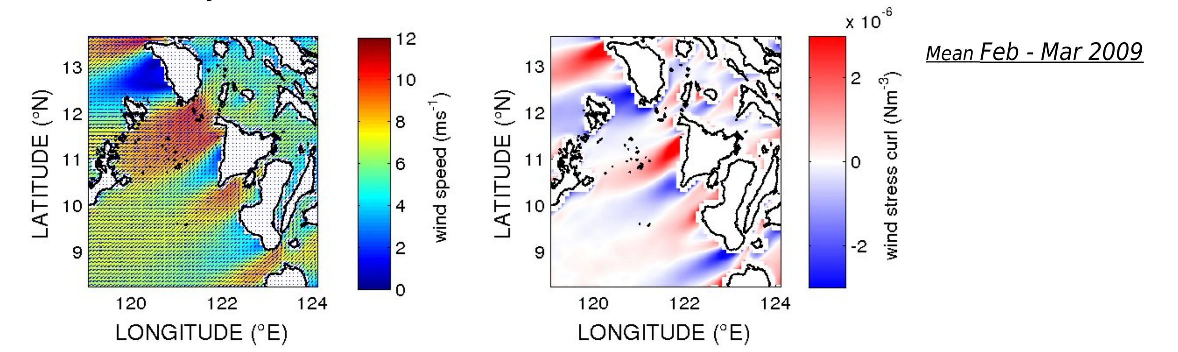


PC jet (top) defined as flow from the coast to the center of the gyre is intraseasonal while cyclonic gyre (bottom) defined as flow from the center of the gyre to the west, is highly seasonal. Positive values indicate flow towards the northwest.

IV. Evidence for a wind-induced cyclonic eddy formation mechanism

The seasonal evolution of the cyclonic eddy appears to be an oceanic response to the prevailing local wind.

a. Wind intensifies between Mindoro and Panay islands which generates positive wind stress curl in the lee of Panay Island.

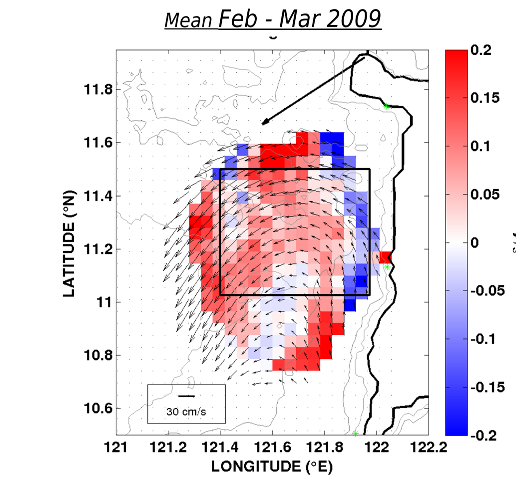


b. Positive curl of the wind stress causes Ekman flux divergence which in turn drives Ekman pumping. To conserve mass, a vertical velocity (w_E) results, which is [Gill, 1982];

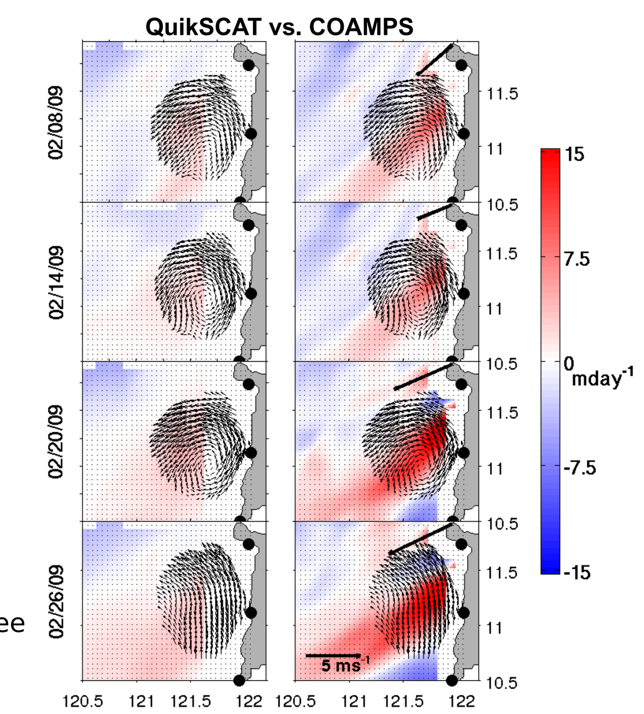
Ekman pumping velocity (w_E)

$$w_E = curl\frac{\tau}{\rho f}$$

Divergent surface currents from HFDR



QuikSCAT vs. COAMPS



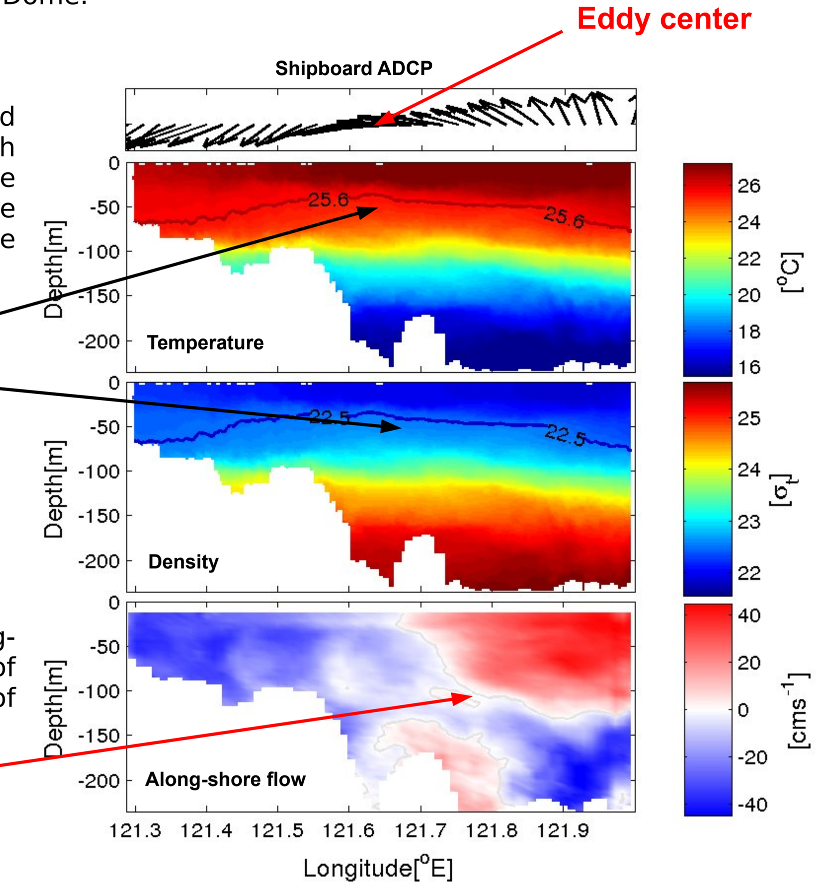
The instantaneous w_E indicate a wind-induced divergent Ekman transport which agrees with the mean divergence calculated from HFDR.

Largest curl-driven w_E over the Cuyo shelf is in the lee of Panay Island, indicating an upwelling zone.

c. As a result of surface divergence, the thermocline is lifted and the water column beneath is stretched, forming the Panay Dome.

The doming of isotherms and isopycnals corresponds well with the return flow in the near-surface along-shore current from the shipboard ADCP, indicating the center of the eddy.

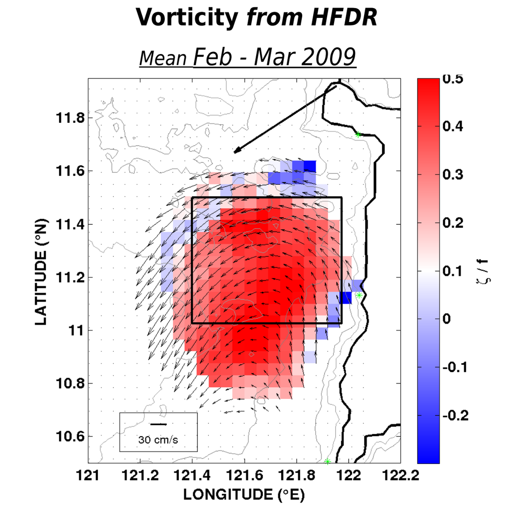
In the current profile the along-shore return flow reaches a depth of about 130m, indicating the depth of the eddy.



d. The uplift in the thermocline sets up a horizontal pressure gradient, which consequently spins up the geostrophic cyclonic eddy.

The eddy center coincides with the location of largest Ekman pumping and the doming.

Vorticity from HFDR



V. Vorticity balance

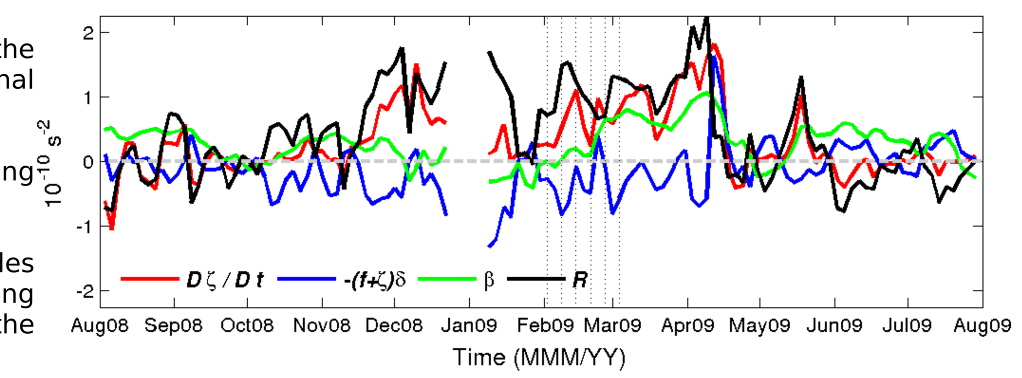
$$\underbrace{\frac{D\zeta}{Dt}}_{\text{Lagrangian rate of change}} = \underbrace{-(f+\zeta)\delta}_{\text{stretching}} \underbrace{-v\beta}_{\text{Beta-effect}} + \underbrace{R}_{\text{residual (noise, friction)}}$$

Evaluating all the terms of the surface vorticity balance equation (from the box in the divergence and vorticity plots) suggests that the wind stress curl via Ekman pumping mechanism provides the necessary input in the formation and evolution of the cyclonic eddy. The Beta-effect on the other hand may led to propagation of the eddy westward.

- evolution of the vorticity within the vortex core dominated by frictional processes, *R*.

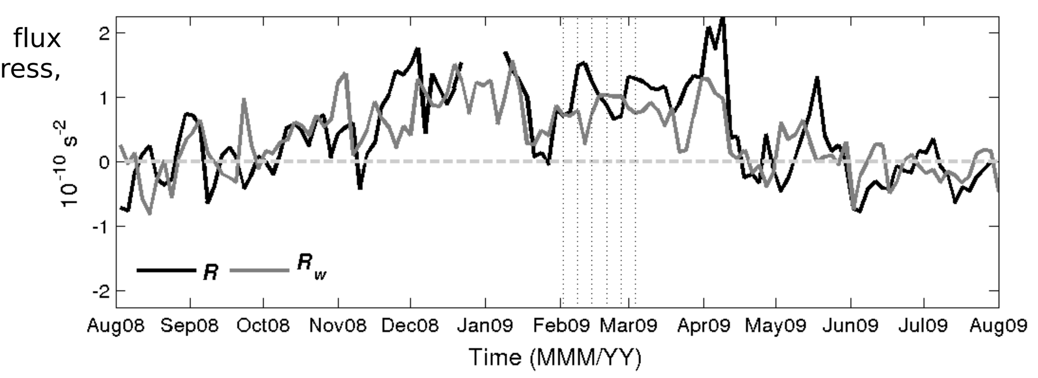
- signicant *R* lag of ~10 days in driving the cyclonic vorticity growth.

- westward shift of the eddy coincides with an increasing Beta term causing it to propagate westward in the manner of a Rossby wave.



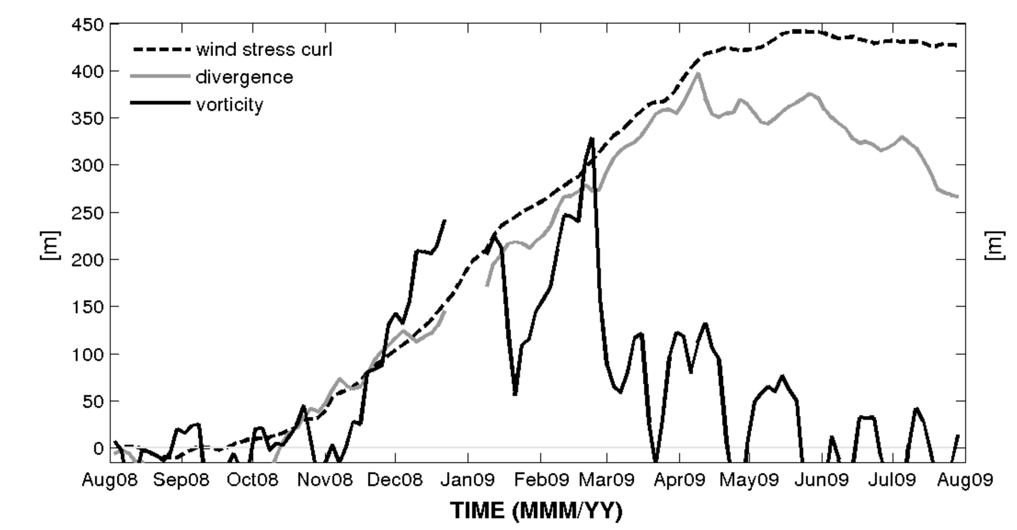
Assuming that the momentum flux from the surface is due to wind stress, its contribution to *R* is:

$$R_w = \frac{1}{\rho H_E} curl_z \tau$$



VI. Cumulative effect of wind stress curl

The time integrals of the Ekman pumping velocity and divergence from a reference time (July 28, 2008) represent their cumulative effect on the vorticity evolution, provided that internal and external drags are neglected.



- Ekman divergence is an instantaneous response to the positive wind stress curl forcing.
- convergence occurs during the SW monsoon period as the region is now dominated by the northward PC jet
- a time lag response in the vorticity field occurs a month after mid-November 2009
- ocean vorticity responds effectively to fluctuating local wind magnitude and direction where peaks and dips correspond with the strong and weak NEM wind, respectively.

VII. Summary and conclusion

- Observations show that the main generation mechanism of the cyclonic gyre is wind stress curl.
- Cumulative effect of the wind stress curl plays a key role on the generation of the cyclonic eddy, showing its robust mechanism to eddy kinetic energy.
- Unlike divergence, vorticity response to prevailing wind stress curl is not instantaneous causing a time-lag, which may help towards understanding the physical development of coastal upwelling due to Ekman pumping in the lee of the island

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