Ekman Divergence from Shipboard Wind Measurements

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Introduction

From 27 January 2004 to 03 February 2004, the R/V Point Sur conducted several underway measurements of the atmosphere and ocean environment. This first portion of the cruise encompassed a box along the central California coast (fig. 1) starting from Moss Landing, CA on 27 January and ending at Port San Luis on 30 January. The geometry of the cruise track lends itself to studies that are based on mass conservation considerations. This project's subject of investigation is Ekman divergence as determined by shipboard measurements.

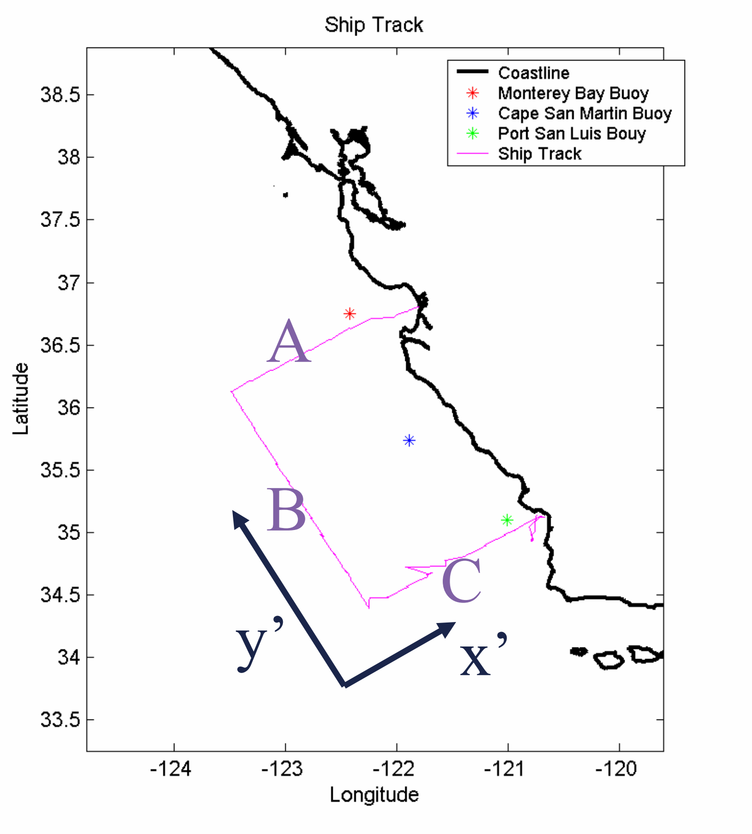

Figure 1. Ship track from 27 – 30 January 2004 and rotated coordinate system.

Ekman transport is a wind-driven circulation that occurs in the thin upper layer of the ocean known as the Ekman layer. This is the region where the wind imparts momentum to the ocean through frictional processes. The maximum speed of the Ekman layer current is at the surface.

The speeds diminish to zero through the column as depth increases. The direction of the currents is to the right of the wind direction in the Northern Hemisphere, thus the transport must also be to the right of the wind and has been shown to be 90 degrees to the right of the wind direction. Assuming a steady-state wind field and integrating the Ekman equations of motion from the bottom of the Ekman layer to the surface yields a solution that balances friction at the surface (wind stress) by the Coriolis force.

$$fM_{xE} = \tau_y \text{ and } fM_{yE} = -\tau_x \qquad (1)$$

where M_{xE} is transport in the x-direction,

M_{yE} is transport in the y-direction,

τ_x is wind-stress in the x-direction,

τ_y is wind-stress in the y-direction, and

f is the Coriolis parameter

These equations are for mass transport in the Ekman layer, which has units of kg/m/s. Volume transport is related to mass by the sea surface density and the width of the cross-section perpendicular to the transport (Pond and Pickard, 1983 and Stewart, 2003).

$$Q_{xE}=\rho^{-1} M_{xE}\, \Delta y \text{ and } Q_{yE}= \rho^{-1} M_{yE}\, \Delta x \qquad (2)$$

where Q_{xE} is volume transport in the x-direction,

Q_{yE} is transport in the y-direction,

ρ is the water density, and

Δx and Δy are the distances perpendicular to the transport

Measurements

Twenty second data from the Underway Data Acquisition System (UDAS) onboard the R/V Point Sur was used to calculate Ekman Transport from 27 to 30 January 2004. Wind direction and speed from the port and starboard anemometers were of

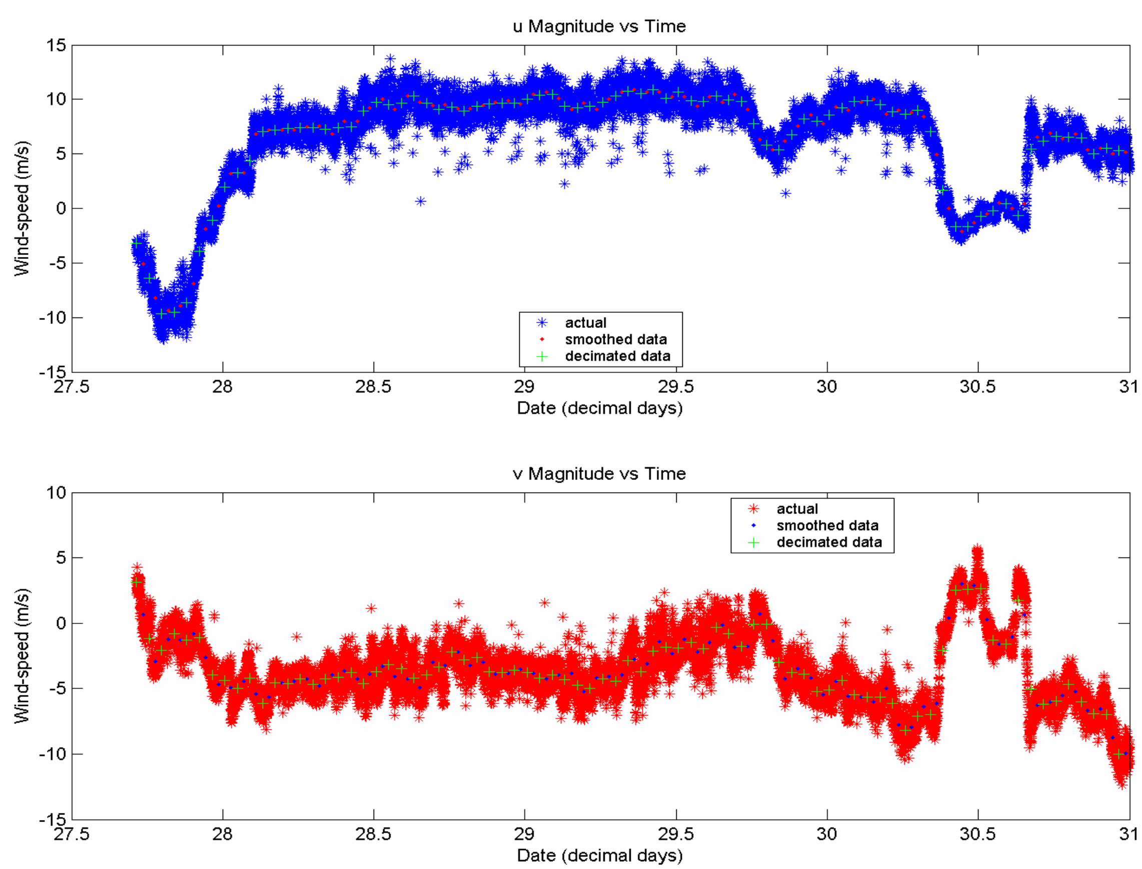

Figure 2a. u and v wind components (raw, smoothed, and decimated)

primary importance. The anemometers were located 16.8 meters above the sea surface on the R/V Point Sur's mast. Barometric pressure, humidity, air and sea temperatures, and position information were necessary to calculate wind stress at the sea surface. Additionally, surface layer density was calculated from the 1980 equation of state for sea water (Pond and Pickard, 1983) using sea surface temperature and salinity measurements collected by the UDAS. For comparison purposes, National Data Buoy Center (NDBC) buoy measurements from buoys 46028, 46042, and 46062 were retrieved.

Data Processing

One assumption of Ekman transport is that winds are steady state. Therefore, the wind measurements needed to be filtered and averaged to reduce the variability within the data set. The port and starboard measurements were decomposed into u and v components and then averaged to reduce the error in measurements induced by the fact that the instruments were at different locations on the ship's mast. The resulting values

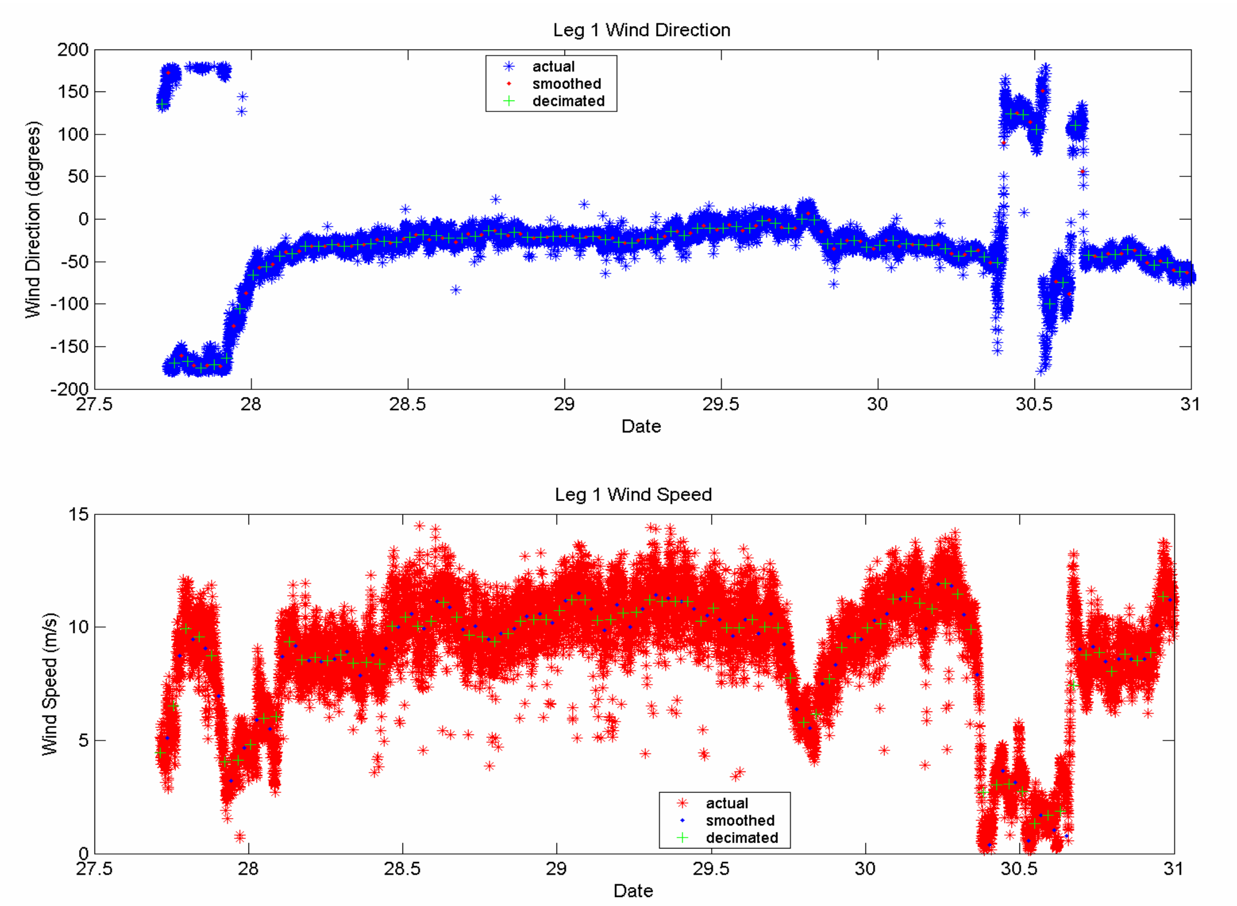

Figure 2b Wind speed and direction (raw, decimated, and smoothed).

were then filtered and resampled to one-hour measurements via two different methods. The first method was through a decimate function which uses a forward filter and resamples simultaneously. The second method was a forward-backward filter in conjunction with a Hanning window and then a value was chosen in the mid-range of each hour's measurements (figs. 2a,2b).

In order to calculate the wind stress at the sea surface, it was necessary to use a boundary layer model and routine to correct for instability in the marine boundary layer. Dr. Roland Garwood's MATLAB flux routine (Appendix A) , which is based on the Large and Pond 1982 flux model, was used to calculate the values of wind stress for each hourly averaged data point. The wind stress acts in the same direction as the wind (figs. 3a, 3b).

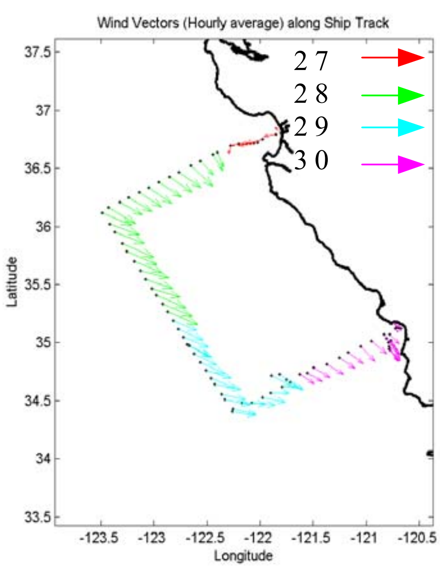

Figure 3a. Decimated winds along track.

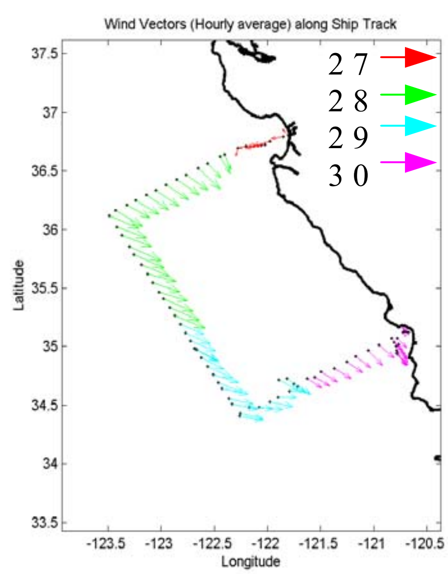

Figure 3b. Smoothed winds along track.

In order to calculate the components of Ekman mass transport (equation 1), the distance between data points was calculated and M_xE and M_yE were rotated into a new coordinate frame that is oriented along the box (fig.1). . M_xE is calculated along section B and M_yE

is calculated along sections A and C. Total Ekman volume transport (Q_E) is calculated by dividing the averaged Ekman mass transport between stations by an average surface density calculated from shipboard measurements of salinity and temperature and multiplying by the distance between the two corresponding stations (equation (2)). Finally, the values were integrated along the ship track.

Results

Wind measurements for the underway period indicate that the winds were generally from the northwest (figure 4), which leads one to believe that the assumption of steady-state flow is not a bad approximation. The two filtering methods showed little variation in the hourly values of wind speed and direction indicating that there should be little difference in Q_E values. For comparison, data were taken from the Monterey Bay buoy (46062), the Cape San Martin buoy (46048), and the Port San Luis buoy (46028)

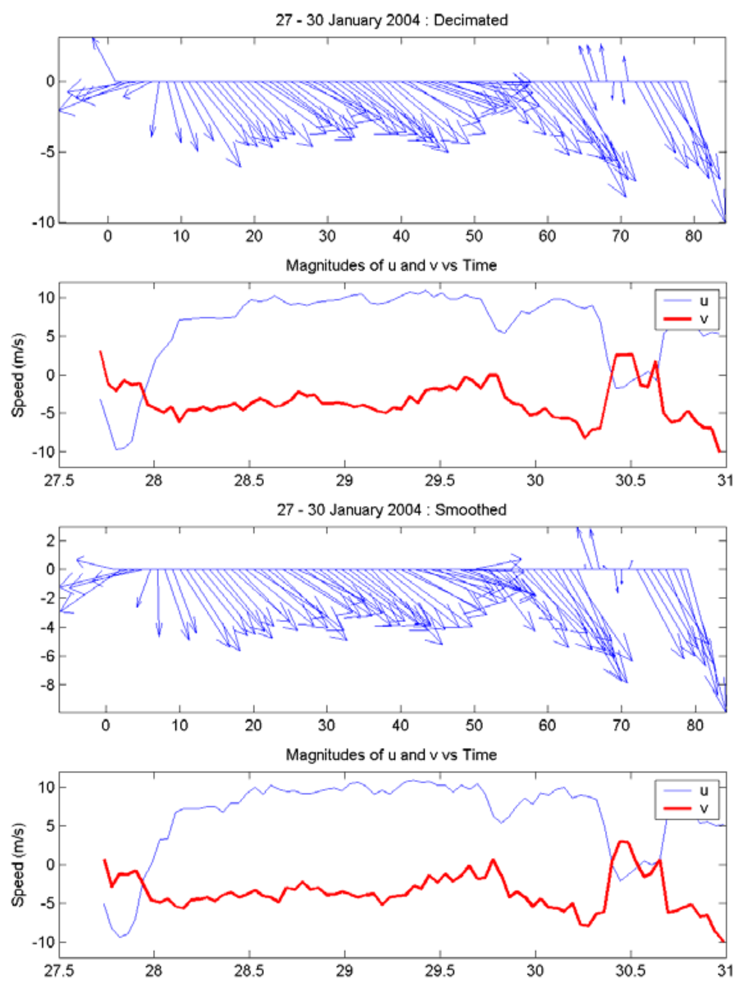

Figure 4. Wind measurement time series for 27 –30 January 2004

(figure 1). Buoy winds over the period were used to attempt to validate the steady-state assumption (figs. 5a, 5b, 5c). On the 28th all three coastal buoys report northwesterly winds and for the remainder of the period in question, leading to the conclusion that directionally, the steady-state assumption is valid to a first order approximation. Most of the wind speed changes are due to the diurnal variations along the coast.

Wind stress was calculated using a drag law relationship to calculate friction velocity at the surface, which was corrected for a stable or unstable boundary layer (Garwood, 1993). Wind stress values ranged from a minimum of 0.0019 N/m^2 to a maximum of 0.2213 N/m^2 for the decimated winds and a minimum of 0.00013 N/m^2 to a maximum of 0.2213 N/m^2 for the smoothed winds.

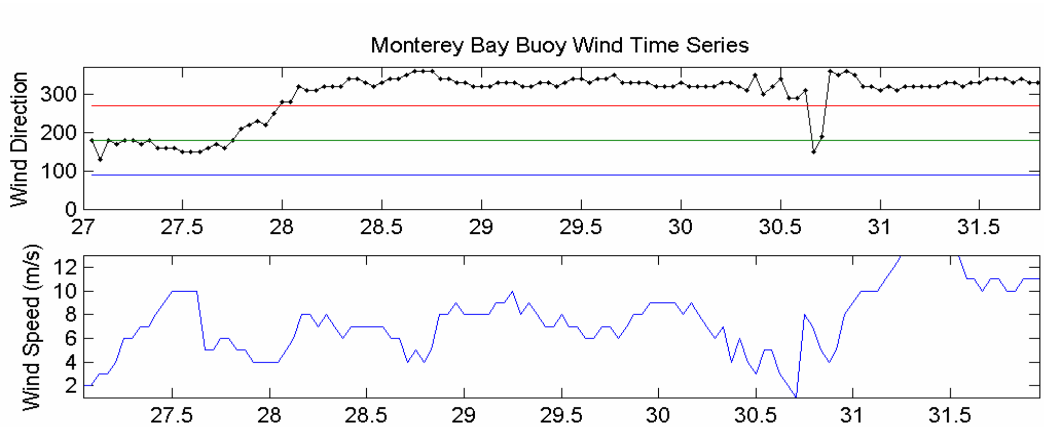

Figure 5a. Monterey Bay buoy time series in decimal day for January 2004.

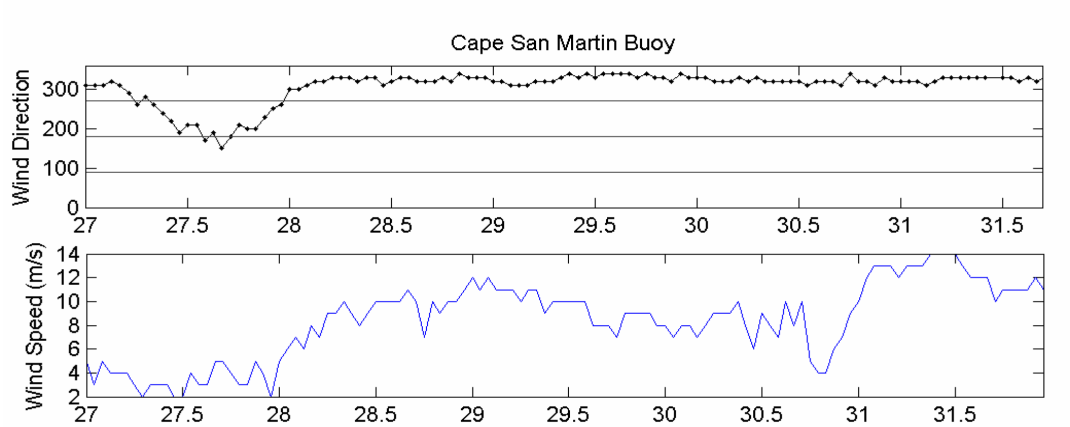

Figure 5b. Cape San Martin buoy time series in decimal day for January 2004.

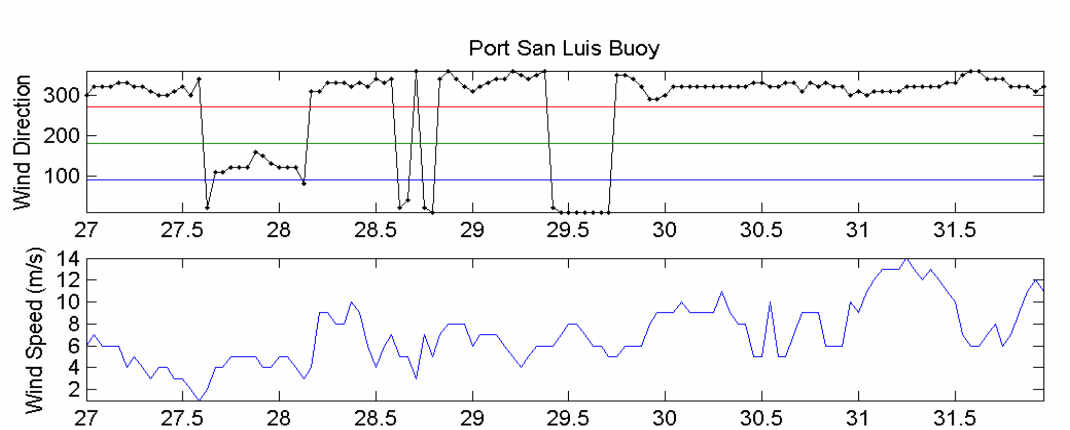

Figure 5c. Port San Luis buoy time series in decimal day for January 2004. Horizontal lines in above direction plots at 90˚, 180˚, 270˚

The wind stress values were decomposed into the x and y directions in order to calculate the components of mass transport. The mass transport components were then translated into the x',y' coordinate system (fig.1) by rotating the axes counter-clockwise by thirty degrees.

Surface layer density was calculated to translate mass transport into volume transport. Calculated densities ranged from a minimum of 1024.5 kg/m^3 to a maximum of 1025.2 kg/m^3. Ekman volume transport was calculated for each section of the leg that bounds the box on three sides (figs 6a, 6b, 6c). Since no mass can enter the box from the east where the coastline is, any transport into or out of the box will create mass convergence or divergence. Total Ekman volume transport was calculated to be –

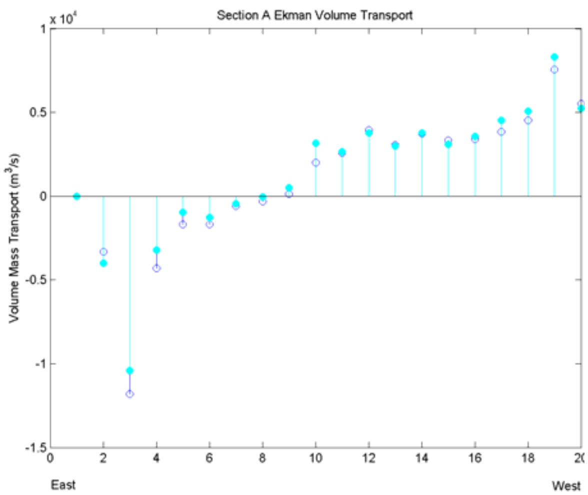

Figure 6a. Section A; Positive values indicate transport into the box in all cases.

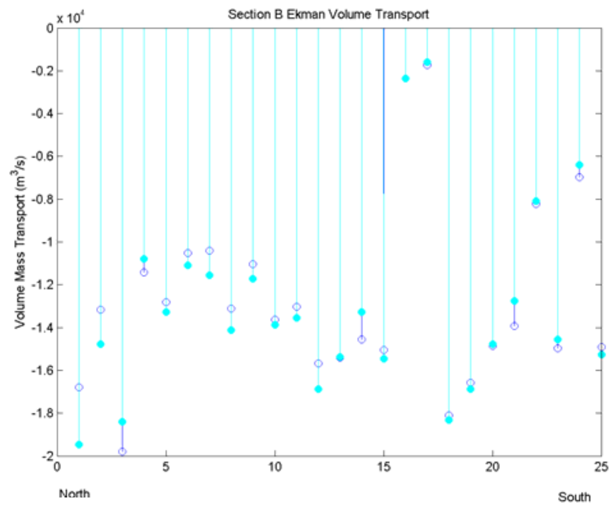

Figure 6b. Section B.

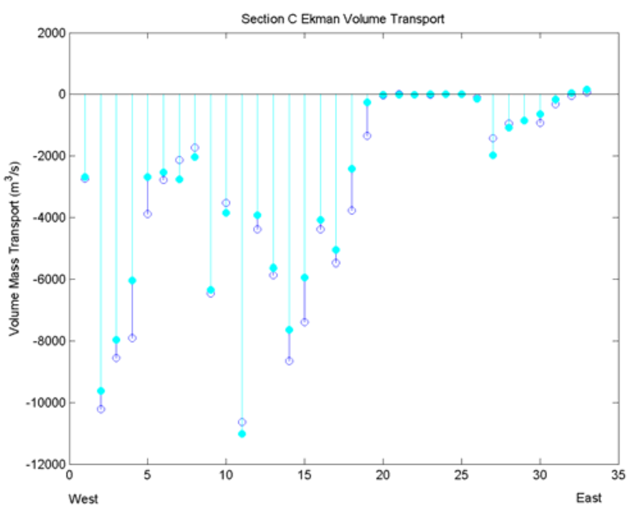

Figure 6c. Section C; filled (decimated values) , open (smoothed values).

0.40547 Sv in the decimated case and –0.39549 Sv in the smoothed case. The negative transport values suggest mass divergence in the Ekman layer within the area encompassed by the R/V Point Sur.

Conclusion

Ekman transport generates a phenomenon known as Ekman pumping. In regions of divergence, Ekman pumping brings water up from ocean depths, known as upwelling.

If this transport occurs over a long enough period, the bottom waters can reach the surface. In coastal regions, this is evidenced by nutrient rich waters that support increased biological activity as well as much cooler sea surface temperatures along the coast (Tomczak and Godfrey, 2003). This change in the water column can impact naval operations, particularly those operations affected by volumetric properties of the water column. Upwelling will change the sound speed profiles, significantly affecting acoustic propagation and subsequent detection or target acquisition. Additionally, upwelling can increase the presence of bioluminescence, which can significantly affect covert swimmer and submarine operations.

References

Pond, S. and G. L. Pickard (1983), Introductory Dynamical Oceanography 2nd Ed., Butterworth-Heinemen.

Stewart, R. H. Introduction to Physical Oceanography (2003), Open Source Text Book.

Tomczak, M. and J. S. Godfrey (2003) Regional Oceanography: an Introduction 2nd Ed., Pergamon Press

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