Ekman Divergence from Shipboard Wind Measurements

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Introduction

From August 4, 2004 to August 7, 2004 I participated in the OC3570 field trip on board R/V Point Sur, which conducted several measurements of the atmosphere and ocean environment. This first portion of the cruise followed the track shown at figure 1, along the central California coast, starting from Moss Landing and ending at Port San Luis. The subject of my project, already investigated by other students in past cruises, is Ekman divergence as determined by shipboard wind measurements. Upwelling is partially caused by this divergence and obviously has important economic, scientific or even military applications

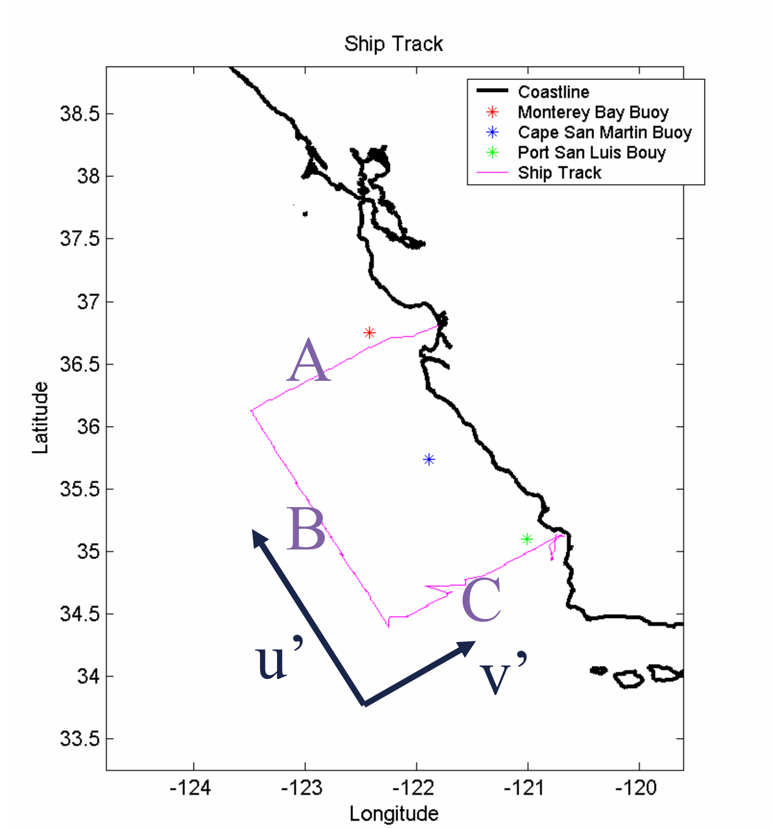


Figure 1. Ship track from August 4, 2004 to August 7, 2004 and the rotated coordinate system used.

Ekman transport is a wind-driven circulation that occurs in the thin upper layer of the ocean (~100 [m]) known as the Ekman layer. This is the region where the wind imparts momentum to the ocean through frictional processes. Actually, the wind interacts with the sea surface, starts to "move" it, but its path is altered due to Coriolis deflection, as shown to Figure 2. Hence, in the North Hemisphere, the surface currents flow deflects 45 degrees to the right of the surface winds. However, due to frictional loss with depth the total mass Ekman transport is 90 degrees from the true surface wind directions. The depth at which the affects of the Ekman transport are felt depend on a variety of parameters, like the latitude and the surface wind. The maximum speed of the Ekman layer current is at the surface. The speeds decrease to zero through the column as depth increases, due to friction.

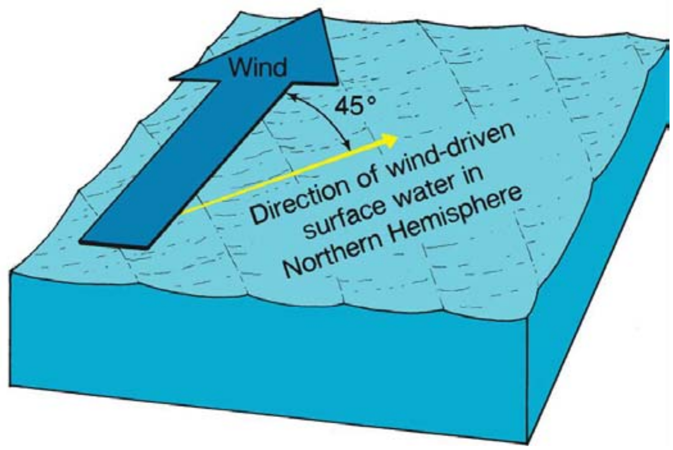


Figure 2. Ekman Transport in the North Hemisphere. (Sverdrup et al., *Introduction to the World's Oceans*)

This underwater movement is called Ekman "Spiral" and is shown in figure 3. Assuming a steady-state wind field, an infinitely deep ocean with no boundaries, homogeneous sea water and by making the f-plane approximation, we integrate the Ekman equations of motion from the bottom of the Ekman layer to the surface and we get a solution that balances friction at the surface (wind stress) by the Coriolis force.

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

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 [kgr/m/sec]. 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).

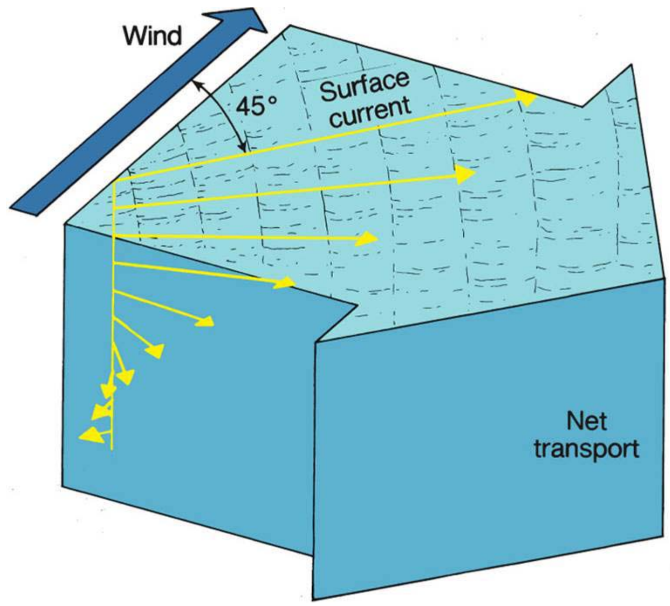


Figure 3. Ekman Spiral in the North Hemisphere. (Sverdrup et al., *Introduction to the World's Oceans*)

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

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 [show units for all variables]

Measurements

All the data used were taken every twenty seconds from the Underway Data Acquisition System (UDAS) onboard the R/V Point Sur from 4 to 12 August 2004 (Legs 1 and 2, in which I did not participate). Especially the wind direction and speed from the starboard anemometer was used. The anemometer was recently calibrated and was located 16.8 meters above the sea surface on the R/V Point Sur 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.

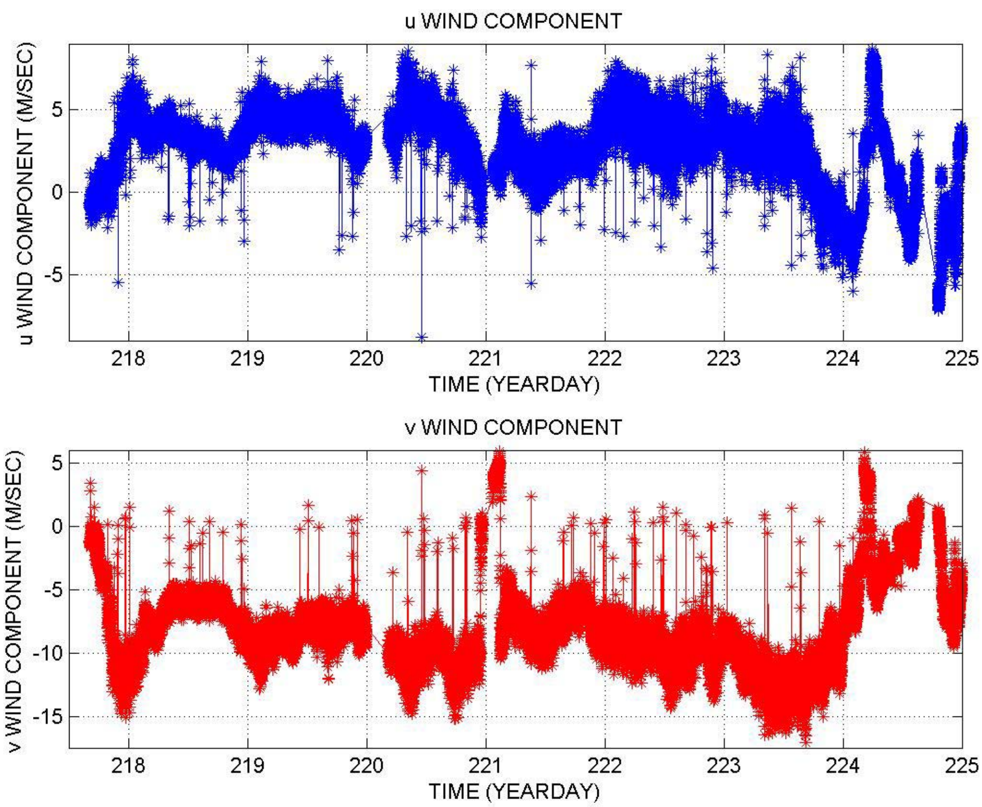


Figure 4. Decomposed raw wind speed

Data Processing

In order to comply with the assumption of Ekman transport that winds are steady state, the wind measurements needed to be filtered and averaged to reduce the variability within the data set. Firstly the measurements were decomposed into u and v components as shown in figure. 4. The resulting values were filtered with a Hanning [Hamming or Hanning?] window with the results shown in figure 5 and through a forward filter. Then they were averaged with the results shown at figure 6. The last filtering and averaging result is shown in figure 7.

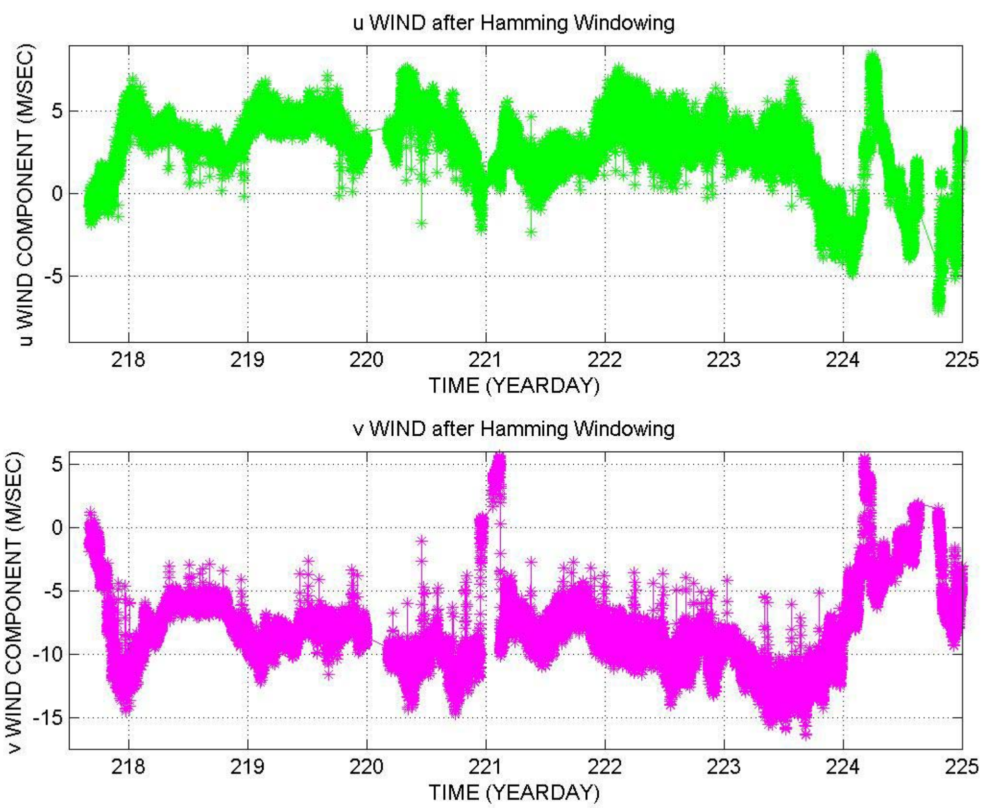


Figure 5. Wind data filtered through Hamming window

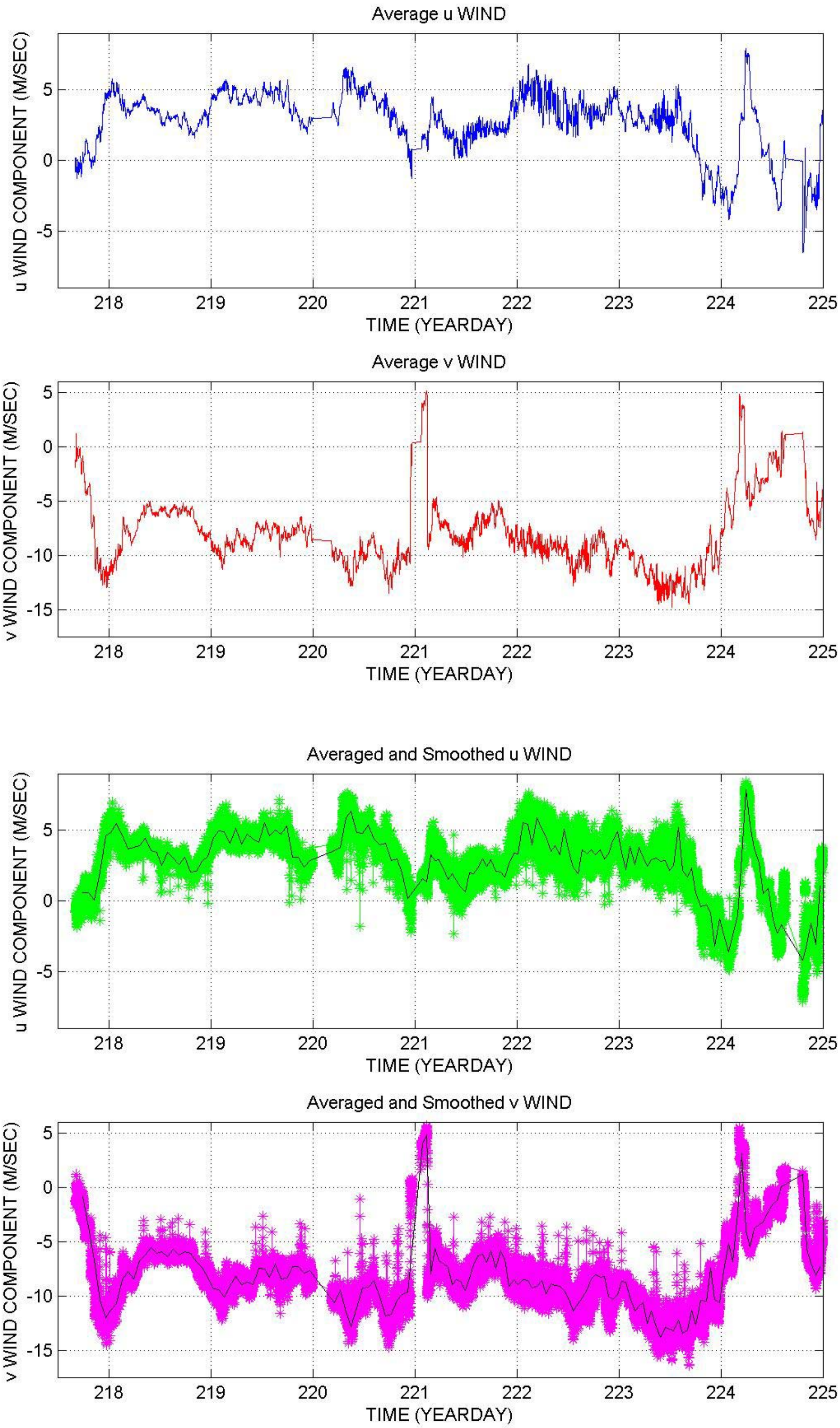
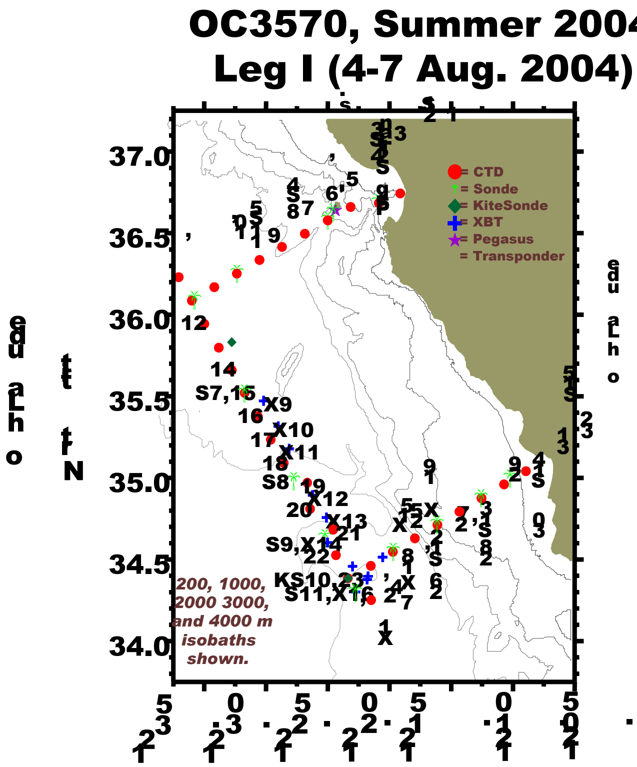


Figure 6. Wind data averaged and smoothed (re-filtered)

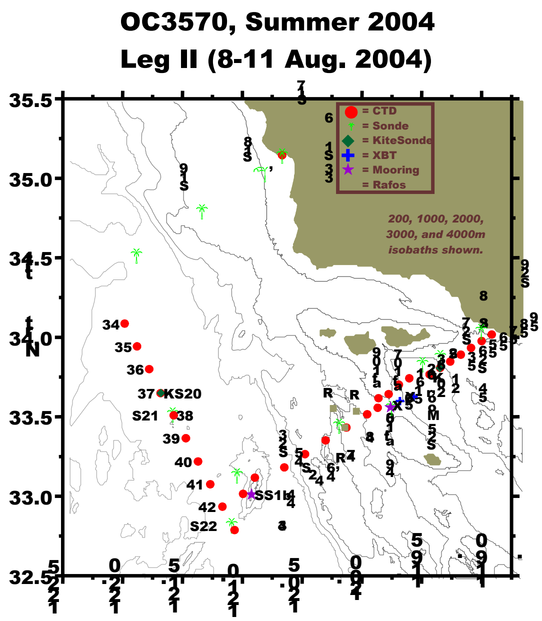
In order to calculate the wind stress at the sea surface, it was necessary to use a ~~boundary~~ surface layer model and routine to correct for instability in the marine boundary layer. Dr. Roland Garwood's MATLAB flux routine (Appendix A) , which is based on the Large and Pond 1982 flux model, was used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

Figure 8. Smooth wind data along track

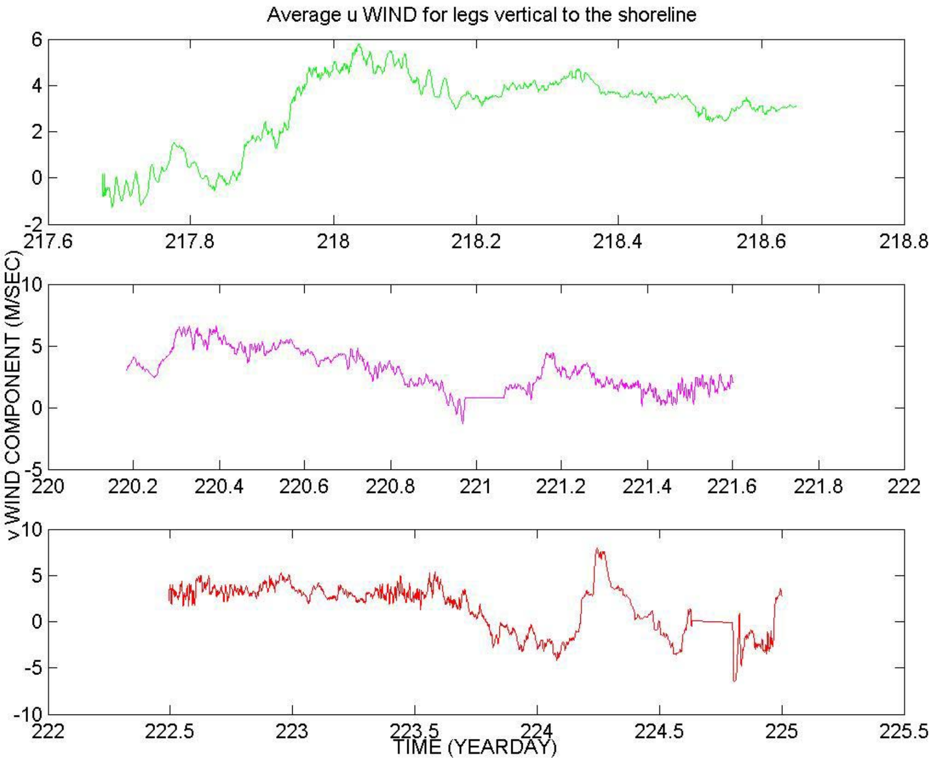
In order to calculate the components of Ekman mass transport (equation 1), the distance between data points was calculated and M_{xE} and M_{yE} were rotated into a new coordinate frame that is oriented along the box (figure.1). M_{xE} is calculated along sections parallel to the shoreline (figure 12) and M_{yE} is calculated along sections vertical to the shoreline (figure (13). 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)). Sea Temperature, Air Temperature, Pressure and Humidity along the 5 legs are shown in figures 14 through 17. Finally, the values were integrated along the ship track as shown in figure 8. The figures 9 and 10 show the actual trip (legs 1 and 2 respectively).



West Longitude
Fig. 9 Leg 1



West Longitude
Fig 10 Leg 2



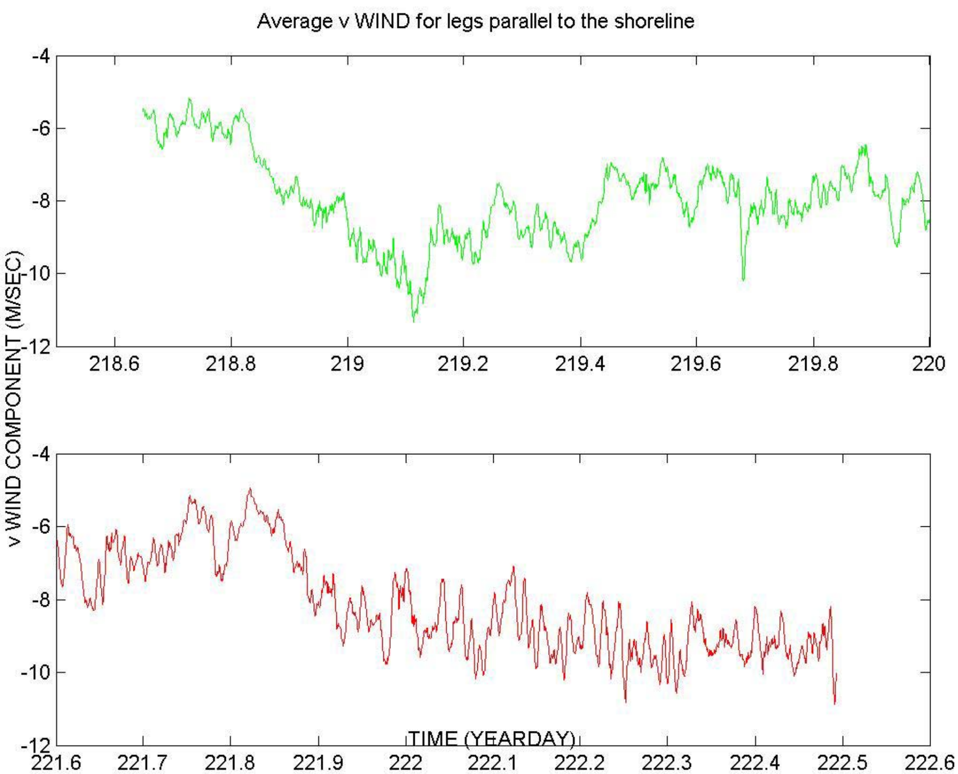
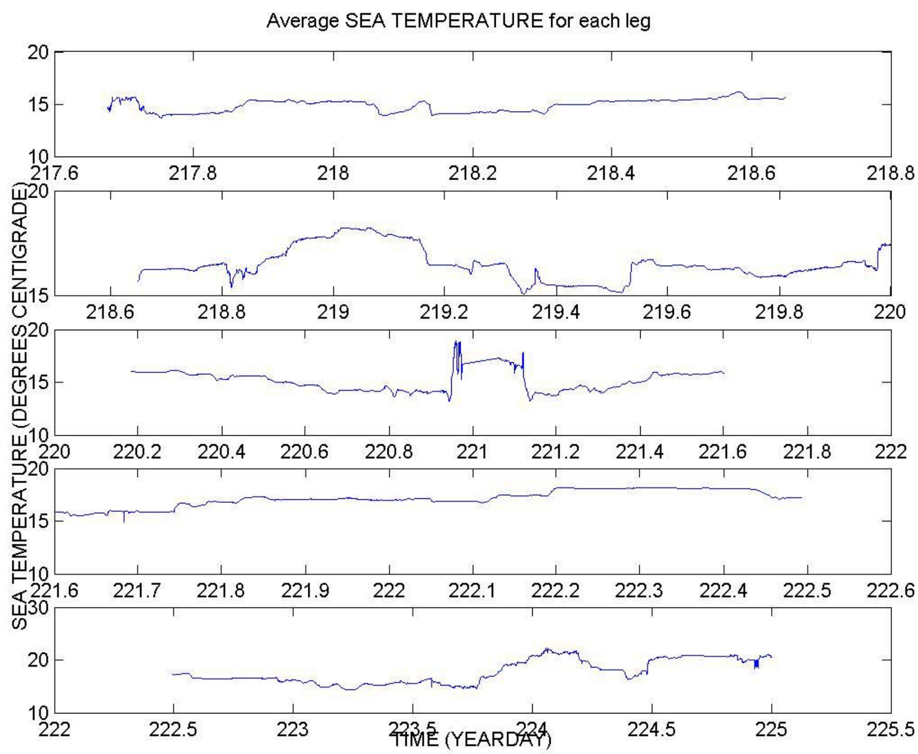


Figure 12 -13 . U and V wind along sections vertical and parallel to shoreline, respectively



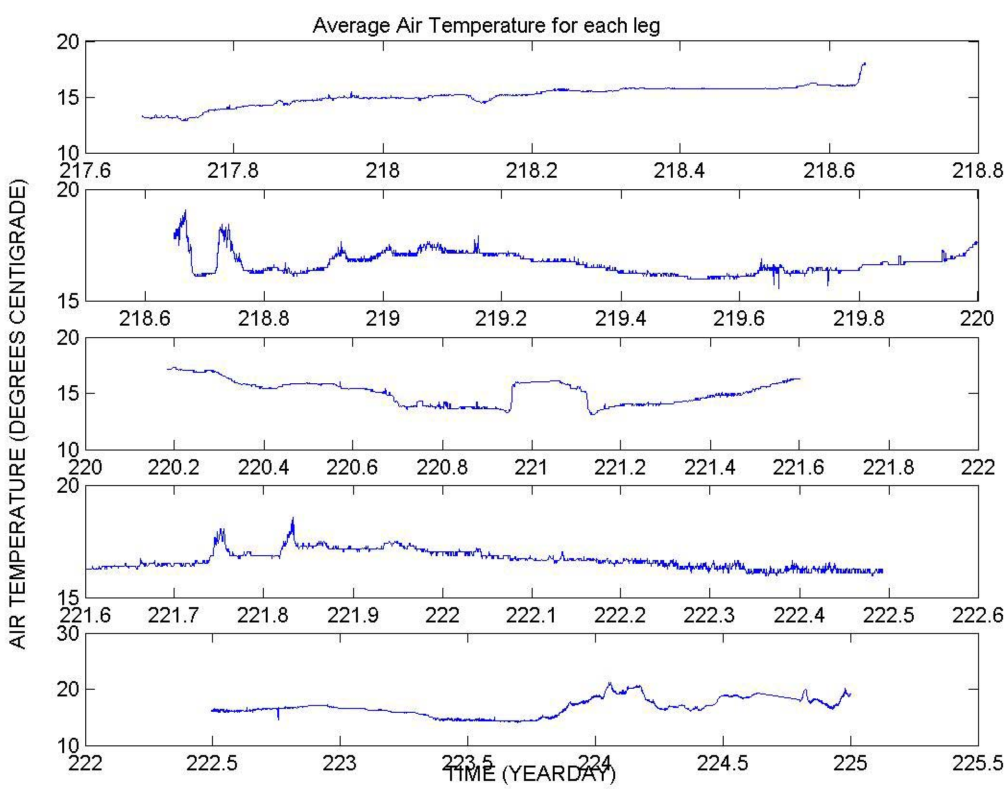
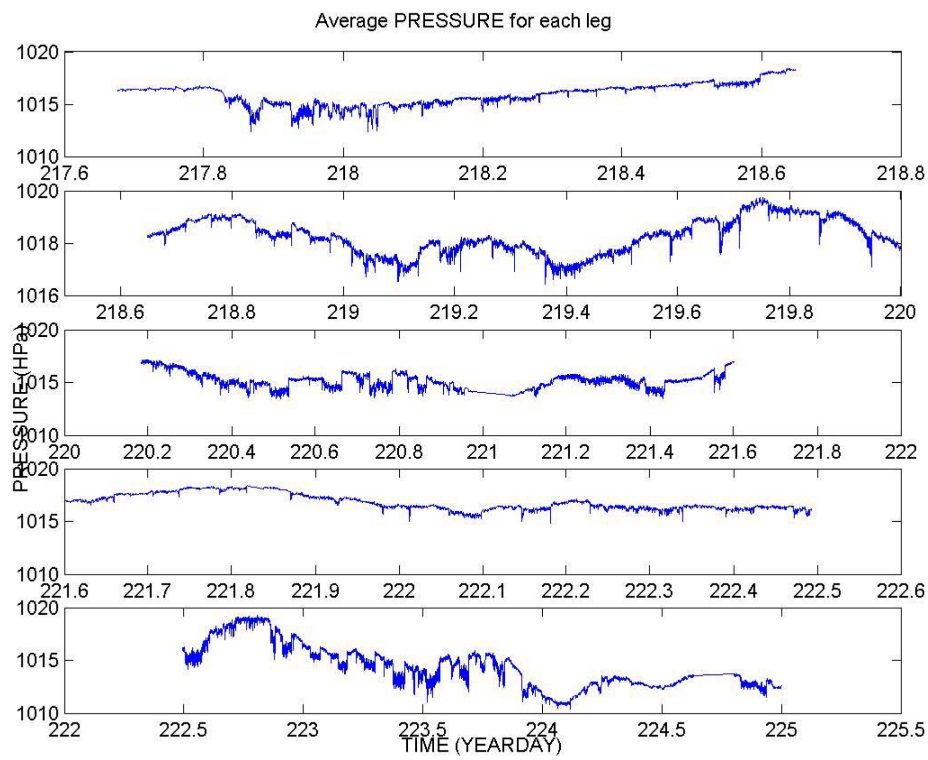


Figure 14 -15 Sea and Air Temperature along sections 1-5



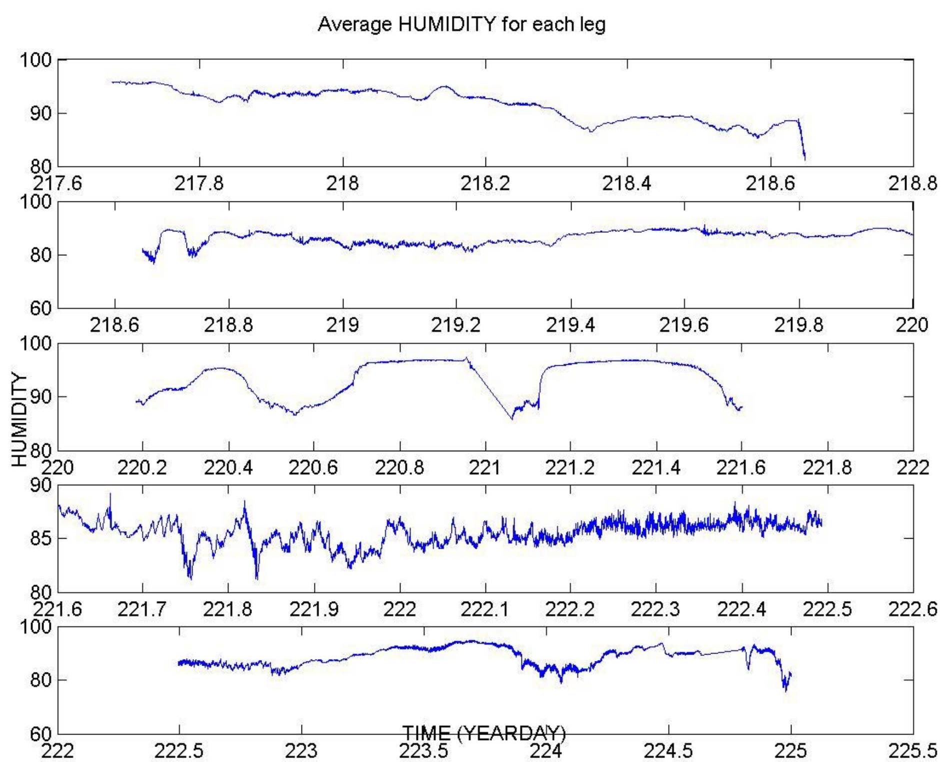


Figure 16-17. Pressure and Humidity along sections 1-5

Results

Wind measurements for the entire period indicate that the winds were generally from the northwest (figure 8), which leads one to believe that the assumption of steady-state flow is a valid approximation. [Not really there is some variability.]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 0.0012 [N/m^2] to a maximum of 0.1865 [N/m^2].

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 translated into the x',y' coordinate system (figure 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 1024.2 kg/m^3 to a maximum of 1025.6 kg/m^3. Ekman volume transport was calculated for each section of the leg that bounds the box on three sides (combining leg 1 and leg2). 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 -0.3188 Sv (-0.3367 + 0.014 + 0.0039). The negative transport values suggest mass divergence in the Ekman layer within the area encompassed by the R/V Point Sur, which means upwelling, which means we missed a good opportunity to do some fishing!

Conclusion

Differential Ekman transport generates a phenomenon known as Ekman pumping. In regions of divergence, Ekman pumping brings water up from ocean depths, known as upwelling (figures 18-19). Upwelling brings nutrients from decayed organic matter back to surface. Only if this transport occurs over a long period, the bottom waters can reach the surface. In coastal regions, besides upwelling being evident due to nutrient rich waters that support increased biological activity, we ban also see much cooler sea surface temperatures along the coast (Tomczak and Godfrey, 2003).

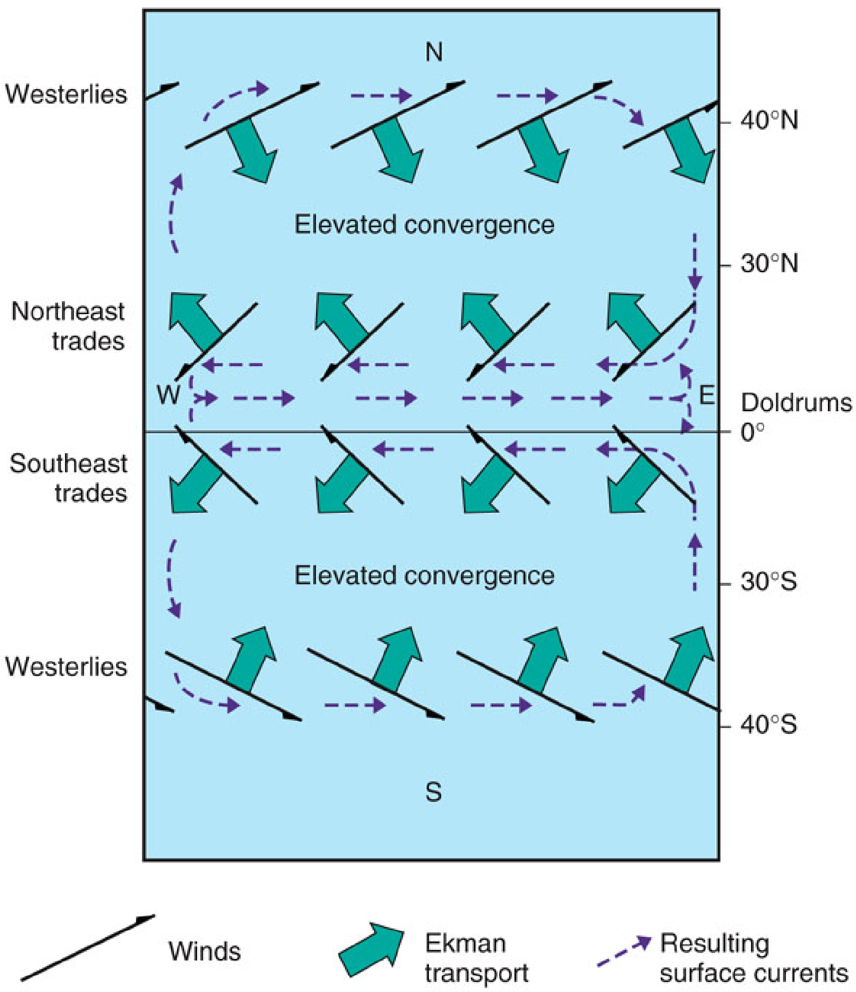


Figure 18. Ekman convergence and divergence. (Sverdrup et al., *Introduction to the World's Oceans*)

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.

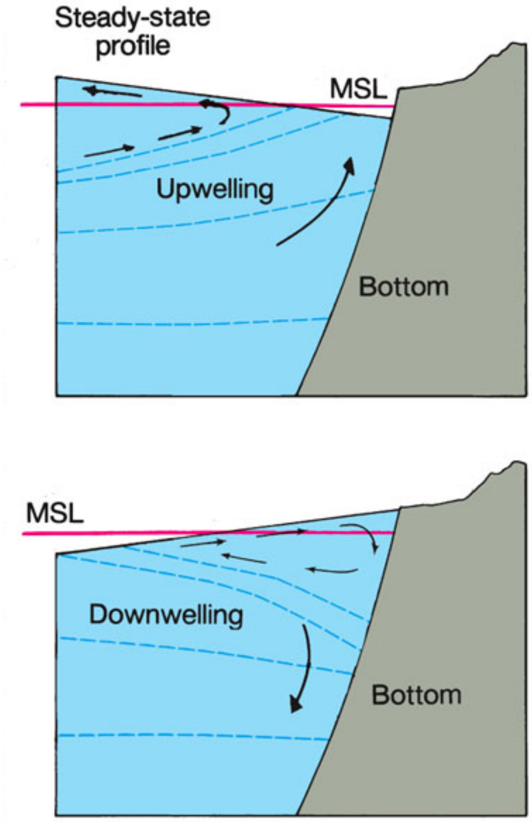


Figure 19. Resulting upwelling and downwelling from Ekman divergence and convergence . (Sverdrup et al., *Introduction to the World's Oceans)*

The final results verified what seems to be an annual trend of Ekman mass transport out of the box. The four previous studies conducted on the 0C3570 cruise in between 2001 and 2004 have very similar results as to what was found this summer. The net mass Ekman transport was shown to be –0.17467 Sv (AhChuan, 2001), -0.2 Sv (Lora Egley, 2002), -0.1098 (Catherine Williams, 2003) and -0.4 Sv (Tracey Delk, 2004). The results from this year's cruise agree with this trend as the total mass Ekman transport was -0.3188 Sv. The very small positive flow of water being transported into the box from the first and the last sections was counterbalanced by the outflow of the sections parallel to the shoreline.

Recommendations

Advice for future studies on calculating the mass Ekman transport would be to calculate more accuratety the average wind. Measurements from two anemometers and portable devices could be combined and the mean speed for each leg could be more accurate.

References

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

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

Sverdrup et al., *Introduction to the World's Oceans 8th Ed.,* McGraw Hill (2001).

Where is Appendix A?