Eddies in the Southeast Pacific and their influence on the upper ocean

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An extensive survey of the Southeast Pacific's (SEP) upper ocean properties was conducted in October and November 2008 as part of VOCALS-REx (VOCALS Regional Experiment) – a large, international, multidisciplinary and collaborative field program to investigate the ocean-atmosphere-land coupling in a region characterized by a persistent stratocumulus cloud deck (see Wood et al., this issue). While the long-term goal of the ongoing ocean measurements (which included a synoptic survey, the recovery and re-deployment of two moorings carrying oceanic and meteorological sensors, and the deployment of floats and drifters) is to improve our understanding of the processes that influence the upper ocean structure, and its variability on diurnal to interannual time scales, the focus of the synoptic measurements described here was to map the mean to sub-mesoscale features of the SEP's upper ocean. The particular interest in the eddies is motivated by their hypothesized role in maintaining the cold sea surface temperature (SST) tongue that stretches across the SEP (Colbo and Weller, 2007).

The survey was centered along 20 ºS from the coast of Chile to 85 ºW (Figure 1). This region covers the ~150 km coastal band, characterized by upwelling driven by the along-shore winds (Brink et al. 1983; Strub et al. 1998), and the wider offshore region that is part of the S. Pacific subtropical gyre. The survey took place in the boreal spring of 2008 just as the wintertime mixed layer was beginning to re-stratify. It included over 400 underway Conductivity-Temperature-Depth (uCTD; Rudnick and Klinke 2007) profiles, with a spatial resolution from 1 to 20 km and a depth range from 200 to 800m, 35 CTD casts extending to 1000-3000 m, shipboard Acoustic Doppler Current Profiler measurements (0-500 m) and the deployment of 10 Profiling SOLO floats and 20 surface drifters (Figure 1).

The region of interest is the northeast extension of the subtropical gyre of the South Pacific and its waters are strongly influenced by the advection of waters from neighboring but distinct oceanic regions. The water column is temperature stratified to the extent that salinity is a useful tracer for water mass origin. From the surface down the upper ~500 m contain: 1) warm, salty Subtropical Surface Water (STSW; Tsuchiya and Talley 1998), 2) fresh, relatively cold Eastern South Pacific Intermediate Water (ESPIW) readily identified as a salinity minimum around 100-200m, that is associated with the subduction of cold, fresh waters from the southeastern edge of the subtropical gyre, off the coast of Chile between 33 and 38 ºS (Schneider et al. 2003), 3) Equatorial Subsurface Water (ESSW) characterized by a salinity maximum and low oxygen content and 4) Antarctic Intermediate Water (AAIW) – low salinity and high oxygen content (see water mass stacking in Figure 2b). The depth at which these water masses are found increases westward across the SEP consistently with the bowl shape of the subtropical gyre. Similarly, the strong permanent pcynocline which coincides with the salinity minimum layer (ESPIW) outcrops in the upwelling region but deepens to ~250m at 85 ºW (Figure 2 and 3).

Key to understanding the ocean-atmosphere coupling in the SEP is identifying which oceanic processes influence the mixed layer properties and, in particular, the SST. Global climate models (e.g. Delworth et al. 2002; Wittenberg et al. 2006) exhibit a warm bias in the region suggesting that ocean processes that contribute to a 'colder' SST may not be adequately represented in these models. Since there exist both lateral temperature gradients (both due to coastal upwelling and to the bowl shape of the subtropical gyre) as well as vertical temperature gradients, it is possible that either lateral or vertical advective/mixing processes (or a combination of both) which are ill-represented in models may be responsible for the models' biases. Here, we present some evidence based on preliminary and ongoing analysis that both sub-mesoscale and mesoscale eddy structures can contribute to a cooling of the surface layers of the SEP.

Our surveys revealed that the SEP's upper ocean is characterized by a high degree of sub-mesoscale and mesoscale variability on scales ranging from a few to 100 km, that are embedded on the larger scale structure of the subtropical gyre. The sub-mesoscale variability is evident, for example, in the patchiness within the salinity minimum layer (the ESPIW) or in the salty ESSW layer beneath (Figure 2b). In addition, we were able to map six large mesoscale eddies (4 cyclones, C1 to C4, and 2 anticyclones, A2 and A3) whose horizontal scales were on the order of 100-200 km (Figures 1 to 3).

The observed anticyclones are wide, surface intensified features that rapidly decay with depth. Their properties are not distinct from the neighboring waters except for the surface 'bowl' of warmer, saltier waters. Anticyclones are associated with a depression of the thermocline and with deeper-than-neighboring mixed layers. The cyclones, on the other hand, were all characterized by thicker and more distinct sub-surface core of salty ESSW water (of equatorial origin) and an uplift of the AAIW beneath – resulting in pinching of isopcynals around 300 m (see, for example, C1 and C2 in Figure 2). The velocity structure reflects a narrow ~20 km sub-surface rotating core that coincided with the equatorial water thermostad, and a wider (but not necessarily more intense) cyclonic circulation at the surface (Figure 2d). The cyclones were, in all cases, associated with a shallower, fresher and colder mixed layer relative to the neighboring waters and with an uplift of the thermocline (salinity minimum layer).

The thicker layer of salty, sub-surface equatorial water contained in the cyclones suggests that they originate from an instability of the Peru-Chile Undercurrent, a sub-surface and offshore current (Tsuchiya and Talley 1998; Chaigneau and Pizzarro 2005) which carries Pacific Equatorial 13º C Water (TDW, thirteen degree water; Tsuchiya 1981) poleward along the coast of S. America, Figure 3. The fact that one of the cyclones observed in the proximity of the upwelling region contained a thick core of equatorial water which was otherwise only observed in the undercurrent is indeed suggestive of this mechanism (Figure 3). The cyclones strongly resemble the eddies described in a recent study of Argo float profiles from the SEP which shows that they are long-lived and widespread throughout the region (Johnson and McTaggart 2009).

The mesoscale eddy surveys suggest that there exists a relation between the proximity of the thermocline/salinity minimum layer to the surface and the properties of the mixed layer. Specifically, an uplift (depression) of the thermocline as found in the cyclones (anticyclones) is associated with a shallower (deeper) and colder/fresher (warmer/saltier) mixed layer. Furthermore, we observed that this relation holds not only for the eddies but for all of the profiles (uCTD and CTD) collected during VOCALS-REx. We illustrate this by showing that the mixed layer temperature throughout the SEP is strongly correlated with the depth of the salinity minimum layer (Figure 2c). (Note that the salinity minimum layer itself does not need to outcrop to induce a cooling.) Indeed all of the mixed layers observed end at the large vertical stratification associated with the salinity minimum layer.

Our results thus suggest that both sub-mesoscale and mesoscale structures which displace the thermocline (and associated ESPIW) feedback onto the mixed layer properties and, presumably, the SST[1]. Amongst the various eddies observed, cyclones that appear to originate from instability of the Peru-Chile Undercurrent contribute to colder, fresher and shallower mixed layers through an uplift of the thermocline. We also found that the depth of the salinity minimum layer is a good indicator for the mixed layer properties throughout the large SEP region. These results support the VOCALS hypothesis which suggests that oceanic mesoscale eddies (and cyclones in particular) play a role in ‘cooling’ the SEP. However, the mechanism by which they do it is not simply through the advection of cold, upwelled surface waters offshore. Instead, their influence is through the uplift of the thermocline which, in turn, feedbacks on the mixed layer properties. These findings do not rule out that vertical mixing processes (driven, for example, by the large inertial oscillations observed) may result in cooling the surface layers by mixing the cold waters of the thermocline into the mixed layer. Rather, it is entirely possible that sub-mesoscale and mesoscale eddies that associated with enhanced vertical mixing may amplify this feedback.

Finally, we also found that the eddies’ boundaries were characterized by strong frontal regions which, invariably, were associated with increases both in the dissolved and in the airborne DMS (dimethylsulfide). This not only suggests that the oceanic mesoscale contributes to creating a highly heterogeneous oceanic DMS distribution but, also, that oceanic processes may influence aerosol production and hence cloud formation.

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[1] We do not expect to see a high correlation with the instantaneous SST since this is largely governed by the short-term atmospheric variability.

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References

Brink, K. H., D. Halpern, A. Huyer, and R. L. Smith, 1983. The physical environment of the Peruvian upwelling system. *Prog. Oceanogr.*, 12(3), 285-305.

Chaigneau, A. and O. Pizarro, 2005. Eddy characteristics in the eastern South Pacific. *J. Geophys. Res.,* 110, doi:10.1029/2004JC002815.

Colbo, K. and R. A. Weller 2007a: The variability and heat budget of the upper ocean under the Chile-Peru stratus. *J. Marine Res.,* 65, 607-637.

Delworth, T. L., R. J. Stouffer, K. W. Dixon, M. J. Spelman, T. R. Knutson, A. J. Broccoli, P. J. Kushner, and R. T. Wetherald, 2002. Review of simulations of climate variability and change with the GFDL R30 coupled climate model. *Climate Dynamics*, 19, 555-574.

Johnson, G. C. and K. E. McTaggart. 2009. Equatorial Pacific 13°C Water eddies in the eastern subtropical South Pacific Ocean. *Journal of Physical Oceanography*, in press, doi:10.1175/2009JPO4287.1.

Rudnick, D. L. and J. Klinke, 2007. The underway conductivity-temperature-depth instrument. *J. Atmos. Ocean. Tech.,* 24, 1910-1923.

Schneider, W., R. Fuenzalida, E. Rodriguez-Rubio, and J. Garcés-Vargas, 2003. Characteristics and formation of Eastern Pacific South Pacific Intermediate water. *Geophys. Res. Let*, 30 (11), doi:10.1029/2003GL017086.

Strub P.T., Mesías J., Montecino V., Ruttland J., Salinas S.,1998 Coastal ocean circulation off western South America. In Robinson A.R. and Brink K.H. (Eds.). The Sea (John Wiley, New York) pp. 273–312

Tsuchiya, M. and L. D. Talley, 1998. A Pacific hydrographic section at 88°W: water property distribution. *J. Geophys. Res*. 103 (C6), 12899-12918.

Wittenberg, A. T., A. Rosati, N.-C. Lau, and J. J. Ploshay, 2006. GFDL's CM2 Global Coupled Climate Models. Part III: Tropical Pacific Climate and ENSO. *J. Climate*, 19, 698-722.

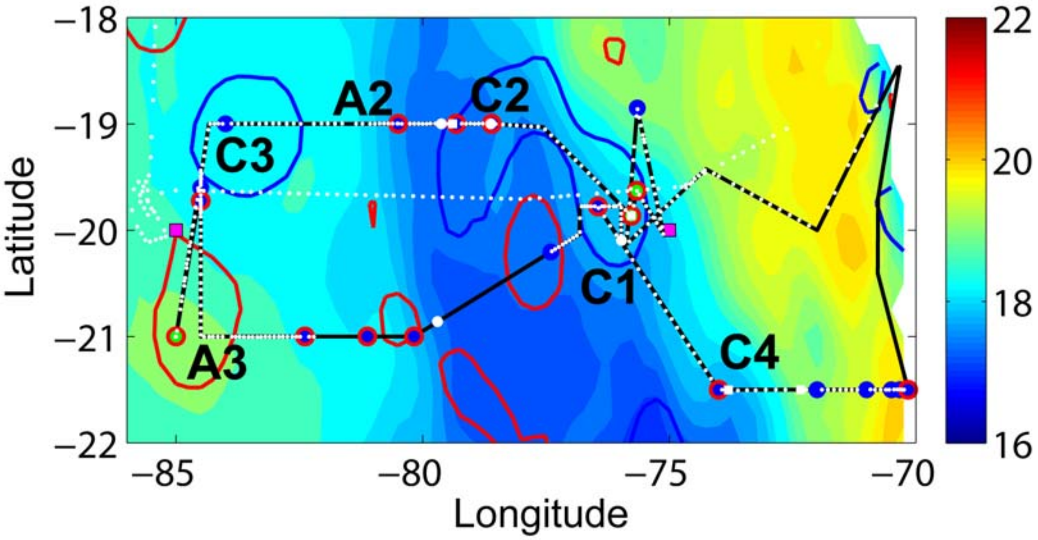

Figure 1 Upper ocean survey during VOCALS-REx from the R/V Ron Brown superimposed on the SST field for November 18th 2008 and showing the 5cm positive (red) and negative (blue) SSH contour from the same day (both courtesy of P. Gaube and D. Chelton, OSU). The letters indicate the 4 cyclones (C1 to C4) and the 2 anticyclones surveyed (A2 and A3). The measurements included over 400 underway CTD (white dots), 35 CTDs (blue circles), 15 VMPs (red open circle), 10 float (white squares) and 20 surface drifters deployments (white circles).

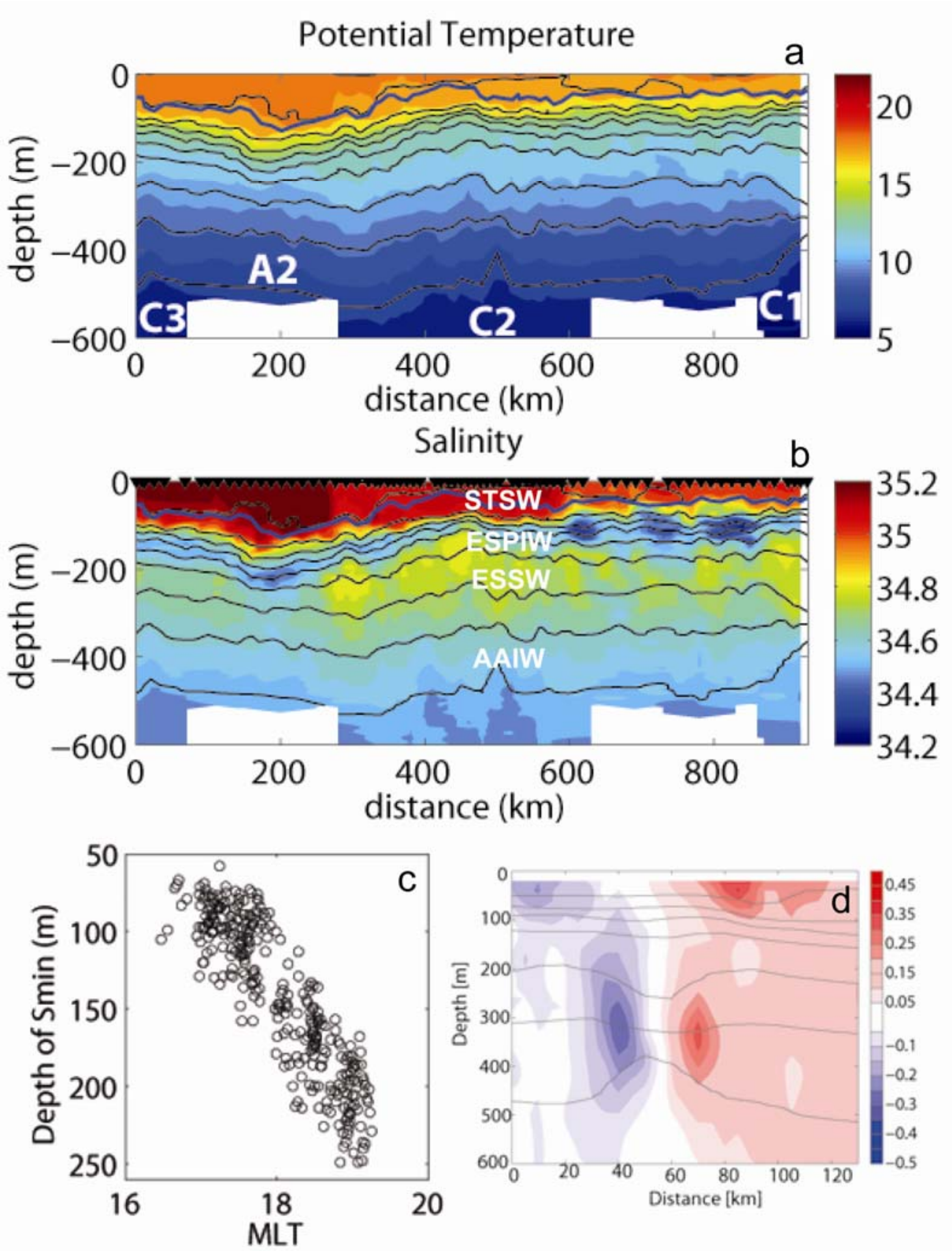

Figure 2 Impact of mesoscale and sub-mesoscale structures on the upper ocean. Hydrographic section from C3 to C1 (mostly along 19 S starting from 85 W (0 km) ending at 75 W (900 km), see Figure 1) showing **a)** Potential Temperature **b)** Salinity. Isopycnals are overlaid in black, and the mixed layer depth is overlaid as a thick blue line. The location of C1, C2, C3 and A2 is indicated on a). The station locations are indicated in b) as inverted triangles at the top. The approximate location of the water masses described in the paper is shown in b). **c)** Depth of the salinity minimum layer versus temperature of the mixed layer (MLT) for ALL profiles collected during VOCALS-REx. **d)** Velocity (m/s) across C1 showing the narrow subsurface core and the shallow wider surface flow.

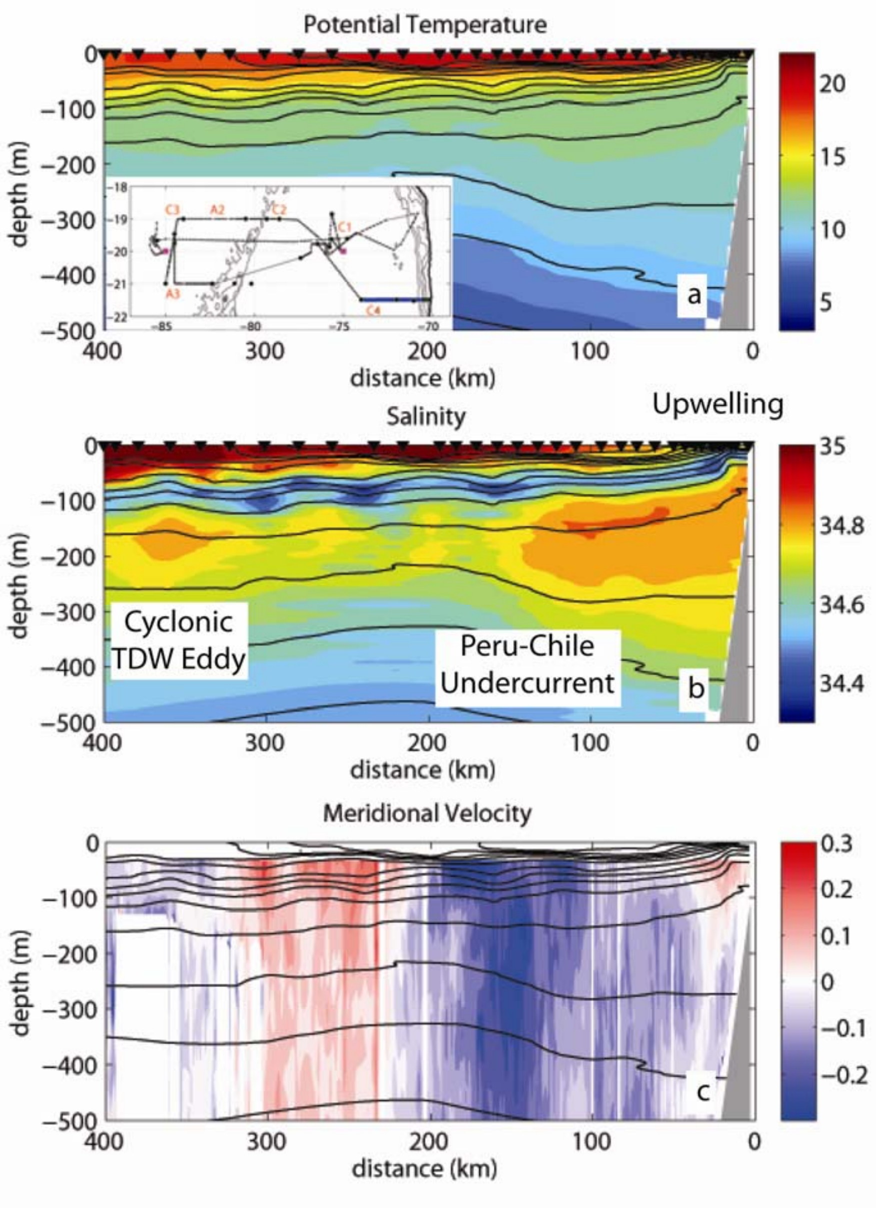

Figure 3 Section along 19.5º S from 74 W to the coast (see inset in a) showing upwelling of cold, low salinity waters at the coast and the associated surface trapped, equatorward surface flow. Approximately 150km offshore is the Peru-Chile Undercurrent, a subsurface, poleward current characterized by opposite (to the upwelling front) sloping isopycnals and characterized by a core of salty, Pacific Equatorial 13 ºC Water (TDW). A cyclonic lens of TDW, associated with a thermostad centered at 150 m and a salty core is visible 350 km offshore. The properties of its core are very close to those of the undercurrent. **a)** Potential Temperature (ºC). **b)** Salinity **c)** Meridional velocity (m/s) from the shipboard Acoustic Doppler Current Profiler. Isopycnals are overlaid on all three panels (black lines).