ENSO-Induced Variability in Vertical Mixing in the Central Equatorial Pacific

Cody Cruz

University of Washington

School of Oceanography

Seattle WA 98105

[openonic@uw.edu](mailto:openonic@uw.edu)

12/7/2023

**Project Summary**

The natural El Nino Southern Oscillation (ENSO) sets an important global background state for climate and weather. Evaluating the environmental factors that influence the onset and sustenance of El Nino and La Nina conditions is invaluable for predicting their length and severity. As trade wind velocity varies in response to pressure differences and sea surface temperature (SST), feedback in the Equatorial Pacific Ocean leads to further change in trade wind velocity. One important feedback in SST is turbulent mixing. As wind velocity decreases, Equatorial Undercurrent (EUC) velocity decreases, reducing subsurface shear and thus mixing, which decreases SST and wind velocity further. Turbulent mixing can be parametrized by calculating such metrics as Thorpe Scales , turbulent dissipation rates *e*, and Richardson numbers . Data to calculate these can be obtained with Acoustic Doppler Current Profilers (ADCP) and Conductivity, Temperature, and Depth (CTD) profiles. These metrics will be calculated with ADCP and CTD data from warming El Nino and warming La Nina cruises. The results will be compared with those driven with model data as described in Deppenmeier et al. 2021. It is predicted that there will be decreased mixing during warming El Nino and increased mixing during warming La Nina.

1. **Introduction**

ENSO is a naturally occurring atmosphere-ocean phenomenon that oscillates between El Nino and La Nina conditions, respectively defined as warm and cold anomalies in Eastern Equatorial Pacific SST. The impact of ENSO on the world is far-reaching. In the United States, El Nino is associated with increased hospitalizations due to vector-borne diseases (Fisman et al., 2016), and La Nina with increased damages due to hurricanes (Pielke & Landsea, 1999). Global sectors impacted include agriculture, fishing, tourism, and population health and safety.

El Nino and La Nina can be divided into warming and cooling stages, with both the beginning of an El Nino and the ending of a La Nina defined as warming. After three years of La Nina conditions, the region experienced a major shift in SST and sea surface height (SSH) in 2023, marking the arrival of a warming El Nino winter in 2024. A close-up of different colors

Description automatically generated

FIG 1. SSH anomaly in mm before winter maximum for two notably strong El Ninos and 2023. Higher and lower SSH regions are shown by reds/whites and blues/purples, respectively. The thin black line indicates the Equator. Figure generated with NASA SSH satellite data. Figure from NASA, 2023.

Mitigation of negative ENSO impact can depend on predicting the temporal scale and magnitude of its oscillations. Continued study of the ocean and atmosphere conditions that control ENSO is crucial for this. Though El Nino forecast centers suggest 2023 is expected to be notable in severity, comparative satellite SSH measurements demonstrate it will likely not be as extreme as the El Nino events of 1997 or 2015 (FIG. 1).

A map of a mountain

Description automatically generated with medium confidence

FIG. 2. El Nino mean velocity with depth and latitude at 170o West. Contours indicate mean zonal velocity; the contour interval is 10 cm/s and heavy contours are at 50 cm/s intervals. Red dashed lines draw attention to the region between 2o S and 2o N. This figure was generated with averaged cruise data from the 1990’s during El Nino conditions. Figure after Johnson et al. 2002, red dashed lines added.

The plethora of interconnected systems that control ENSO oscillations render it dynamic and non-trivial; however, components that impact it can be identified. ENSO can be influenced by positive feedback between SST and the trade winds. During a La Nina, the trade winds intensify, forcing surface water to build up in the Western Pacific. The zonal pressure gradient due to SSH difference produces the EUC that flows eastward, predominantly between 2o S to 2o N at 170o West (FIG. 2). The shear between this and the oppositely directed surface current induces vertical mixing, and heat is sequestered to depth. This cools the surface, which intensifies the trade winds (Yang et al. 2022). Surface cooling is especially potent in the Eastern Equatorial Pacific, giving rise to a phenomenon known as the Equatorial Cold Tongue, which exhibits an expression similar to the time average (FIG. 5); it should be noted that the Cold Tongue is strongly controlled by upwelling, an equatorial feature distinct from vertical mixing.

During an El Nino, the trade winds weaken or reverse direction in the Eastern Equatorial Pacific, resulting in lower Western Equatorial Pacific SSH (FIG 1), a slower EUC, reduced mixing, and a warm SST that diminishes the trade winds further. Both the arrivals of El Nino and La Nina can result in more extreme conditions with time. While satellites make atmospheric and surface-ocean conditions readily accessible, naturally, sub-surface phenomena are less documented. In the context of an Equatorial heat budget, the most important impacts on SST are solar heating and vertical mixing (Deppenmeier et al., 2021). Therefore, quantifying how vertical mixing strength changes with ENSO conditions is important to understanding the broader system. This project will employ three metrics to quantify turbulent, vertical mixing: Thorpe Scales (Eq. 1), turbulent dissipation rates *e* (Eq. 2), and Richardson numbers (Eq. 3).

(Eq. 1)

The Thorpe Scale is described in Eq. 1 where *d* is a water parcel’s vertical displacement from buoyant equilibrium; it quantifies the “largest vertical overturns … observed in a density profile [by] sorting the unstable profile to produce a stable one, keeping track of individual water parcels vertical displacements [in order] to use their root mean square displacement … as a proxy for the overturn scale” (Cusack et al. 2022).

The Thorpe Scale method is based on observing density instabilities within high resolution CTD profiles. Density inversions with depth are strong indicators of active mixing (Caulfield, 2021). These density inversions are caused by breaking internal wave structures at the interface between two layers in the fluid, gradually mixing the two in turbulent spirals (Wykes and Dalziel, 2014). It should be noted that density in the Equatorial Pacific is predominantly controlled by temperature, not salinity. On prolonged time scales, density-driven mixing results in more homogeneous temperature with depth. If water is already well-mixed, then density-driven mixing will be reduced as there is less of a driving force to make internal waves break. A drawback to only considering density profiles is that they could have been homogenized previously, regardless of the magnitude of mixing where they were measured. Furthermore, if the shear discussed in Eq. 3 is not strong enough, overturning may not happen at all. Regardless, high magnitude layers are high in *e* (Eq. 2) value, implying stronger internal wave energetics.

(Eq. 2)

The turbulent diffusivity of kinetic energy *e* measures the magnitude of vertical mixing (Cusack et al. 2019) and is shown in Eq. 2 where is an *O*(1) proportionality constant, is buoyancy frequency, a measure of the stratification with units Hz, and is the reference density of seawater (Cusack et al. 2022). The greater the mixing, the greater the turbulence, the more kinetic energy is spread out to be absorbed by the water (Woods, 1980). In the context of the Equatorial Pacific, *e* acts against solar heating, cooling the sea surface.

Another powerful method that can be employed to identify mixing uses the relationship between intense turbulence and strong shear, i.e., changes in current velocity and direction with depth, as observed by an ADCP (Nystrom et al. 2007). There is an inherent competition between stratification and shear in the control of turbulence as indicated in their ratio (Eq. 3). The greater the shear, the greater the turbulent mixing as internal waves on water layer interfaces are induced. The lesser the stratification, the greater the turbulent mixing as the water column becomes less stable. Thus, lower denotes more mixing.

(Eq. 3)

The Richardson number is described in Eq. 3 where shear (Galperin et al. 2007). See Eq. 2 for the definition of *N*. Mixing is significant and turbulent when the unitless numbers are below a critical value of 0.25.

Research on mixing in the Equatorial Pacific is ongoing; the consideration of two recent studies will build context for the planned analysis of research cruise data. Study of a decade of monthly-averaged data from NOAA’s Tropical Atmosphere Ocean (TAO) mooring in the Equatorial Cold Tongue at 0o, 140o West provides relative environmental forcings, water column structures, and resultant *e* between warming and cooling El Ninos and La Ninas (FIG. 3). While wind stresses between warming El Ninos and La Ninas are roughly the same, Tropical Instability Wave (TIW) forcings are stronger during warming La Ninas, supporting the greater mixing values (FIG. 3). TIWs are a collection of equatorial wave phenomena such as “surface-trapped Yanai wave[s]…[and] first-meridional-mode Rossby wave[s] just north of the Equator” (Moum et al. 2009). The mixed layer depth is deeper for El Ninos, reflecting greater stratification due to less mixing (FIG. 3). The 20 °C isotherm is also deeper during El Ninos, a result of less mixing (FIG. 3). The data from χpods, instrumentation that directly measures turbulence, demonstrate that ** and thus mixing is most diminished during warming El Ninos and much stronger during warming La Ninas; this is supported by two other mixing metrics that will not be considered in this project, diathermal heat flux due to turbulence and turbulence diffusivity (FIG. 3). A diagram of different types of data

Description automatically generated with medium confidenceWhile study of data from cruises, satellites, and moorings is crucial, development of models to simulate environmental conditions is also important for cost-effective analysis of large climate systems. The diabatic cross-isothermal flow is a parameter that models the Lagrangian temperature change of water parcels predominantly due to vertical mixing (Deppenmeier et al. 2021). Study of in the Equatorial Pacific Cold Tongue at 0 o, 140o West with model data from the Parallel Ocean Program (POP2) configured the same way as in Bryan & Bachman, 2015, found El Nino to exhibit lesser and thus lower (Eq. 3) values than during a La Nina (FIG. 4).

FIG. 3. “Histograms of mixing rates (a, d, and g), water column structure (b, e, and h), and forcing mechanisms (c and f) during the four [ENSO] regimes from monthly [0o, 140o West TAO mooring] averages. Circles show means and lines show the 95% bootstrap confidence intervals of the means. (a) Turbulence kinetic energy dissipation rates [*e*] from χpods between 29 and 69 m, (b) mixed layer depth (h), (c) zonal wind stress (τx), (d) diathermal heat flux due to turbulence ( urn:x-wiley:grl:media:grl59875:grl59875-math-0008), (e) EUC core depth (zEUC), (f) tropical instability wave kinetic energy (TIW KE), (g) turbulence diffusivity (KT), and (h) depth of the 20 °C isotherm (z20).” Figure and caption from Warner & Moum, 2019.

A diagram of different types of data

Description automatically generated with medium confidence

FIG. 4. “POP2 profiles at 0°, 140°W for El Niño (red), La Niña (blue), and neutral (black) conditions: (a) meridional and (b) zonal velocity components and (c) total shear squared and (d) buoyancy squared, from which (e) the gradient Richardson number Ri is calculated …. Dashed horizontal lines show the depth of the EUC maximum per ENSO condition” (Deppenmeier et al. 2021). (f) shows zoomed-in Richardson numbers for the upper 100 m of the water column. Figure and caption from Deppenmeir et al. 2021.

The lowest values for both El Nino and La Nina were found to be in the upper 100 meters of water (FIG. 4), corresponding to where the EUC is strongest (FIG. 2); the EUC is also shown in the zonal component of velocity (FIG. 4). The values of will be lower west of the Cold Tongue (FIG. 5), implying larger will be calculated on the proposed cruise. Though the planned study will include analysis of data west of the Cold Tongue, learning how well POP2 models ocean turbulent mixing parameters will be valuable. Considering both Warner & Moum, 2019 and Deppenmeir et al. 2021 focus on mixing in the Cold Tongue, studying mixing to the west of it will be important to characterizing ENSO-controlled vertical mixing zonally across the Equator.

A screen shot of a heat map

Description automatically generated

FIG. 5. time-averaged across 36 years along the 22°C isotherm from POP2 model data. Red colors indicate elevated . Figure from Deppenmeier et al. 2021.

1. **Proposed Research**

It is hypothesized that vertical mixing during a warming El Nino will be decreased compared to a warming La Nina and it is expected that these results will be consistent with those from POP2 model data. This will likely be a direct result of the slowed EUC and diminished shear during the warming El Nino. While moorings such as the TAO array can provide a wealth of data at specific locations across time (FIG. 3), ship-based measurements can be used to calculate high-resolution cross sections with latitude (FIG. 6). Data from a cruise on the R/V Thomas G. Thompson out of Pago Pago, American Samoa from 12/28/23 to 1/11/24 will be used in the equations described above to supply El Nino mixing metrics. La Nina mixing metrics will be calculated in the same way with data from a cruise in late February 2023 across the Equator along 180o.

Differences in time and location between the cruises make it necessary to consider how mixing metrics might be inherently dissimilar when comparing the two. The EUC shoals towards the east and is depth-modulated by ENSO, with deeper current cores found in El Ninos (FIG. 3). This will impact the magnitudes of mixing relative to depth given the difference in longitude and ENSO oscillation between the two cruises. As both cruises are during winter, *wci* will be elevated compared to other months (Deppenmeier et al. 2022), suggesting increased mixing during this time.

For the upcoming El Nino cruise, the main cross-Equator sampling route will be from 5o S to 5o N along 167o West with casts using a SeaBird 9+ CTD occurring every degree of latitude; between 1o S and 1o N, the SeaBird 9+ CTD will sample every half degree of latitude (FIG. 6). An underway CTD will sample relatively continuously from 2o S to 2o N for increased spatial resolution over the EUC (FIG. 2). CTD casts will provide temperature and salinity, with temperature predominantly used to characterize water column stability. The SeaBird 9+ CTD and underway CTD will be calibrated to one another by performing a cast with each in the same location, one right after the other; a second option could be performing a cast with the underway CTD instruments affixed to the SeaBird 9+ CTD. Calibration could occur at CTD cast station 2 (FIG. 6).

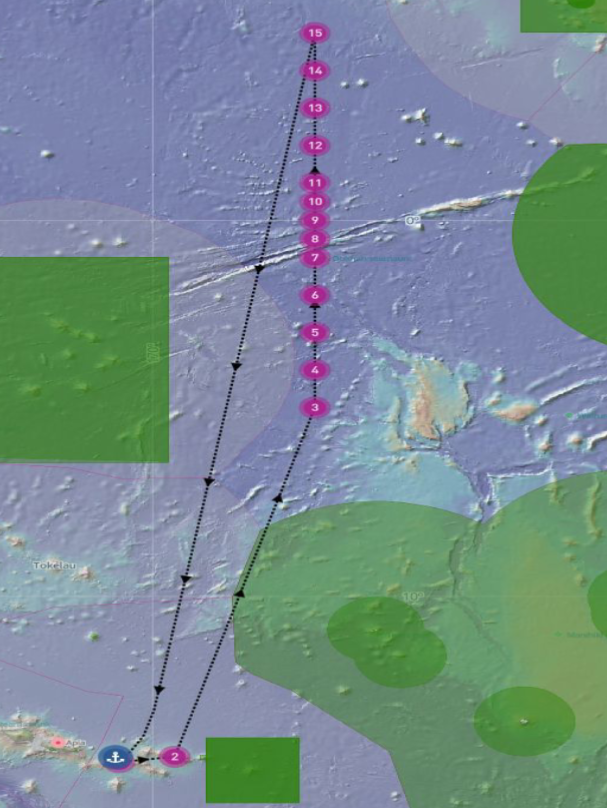


FIG. 6. El Nino Cruise Plan. Black lines indicate the cruise path. Purple dots signify CTD cast locations and are positioned along 167o West. For reference, one degree of latitude separates CTD cast locations 3 and 4; half a degree of latitude separates CTD cast locations 7 and 8. Underway CTD sampling will occur between the red dashed lines, corresponding to those in FIG. 2. Green spaces represent Exclusive Economic Zones. The blue anchor symbol shows Pago Pago, American Samoa, the start and end port. Figure after UW OCEAN 443 slides, red dashed lines added.

The ship’s two ADCPs will operate continuously on both the main sampling route and cruise directly back to Pago Pago from 5o N (FIG. 6). Mounted to the vessel’s hull, these instruments will be used to measure zonal water velocities, averaged over discrete depth bins. The 300 kHz and 75 kHz ADCP units can measure velocity from the surface to 200 and 700 meters, respectively. Mixing metrics will be evaluated through 700 meters, though as the EUC is greatest at around 170 meters of depth near 167o West (Johnson et al. 2002) the upper water column will be the main research focus. For the upper water column, the 300 kHz ADCP data could be averaged with the 75 kHz ADCP data depending on the distributions of results. ADCP data will be post-processed using UHDAS+CODAS software (<https://currents.soest.hawaii.edu/docs/adcp_doc/codas_setup/index.html>). Neglecting vertical and meridional velocity relative to the much larger zonal velocity components, shear will be calculated from the velocity profiles by taking the gradient of velocity with respect to depth using the *numpy* *gradient* function (<https://numpy.org/doc/stable/reference/generated/numpy.gradient.html>). Vertical stability as a function of latitude, whereis potential pressure, can be found by interpolating between CTD casts. Using the calculated shear and vertical stability, (Eq. 3) will be determined with depth and latitude.

Metrics for diapycnal mixing intensity (Eq. 2) will be calculated from the CTD profiles with the use of python package *mixsea* (Cusack et al. 2022) and its dependencies with *matplotlib* used for data visualization (<https://matplotlib.org/>). Sorted density will be found by rearranging the measured densities of all layers in the water column with greater density at depth. The sum of differences between sorted density and measured density is the scale of density-imbalance in the water column, leading to density inversions. Thorpe displacement quantifies the vertical distance a given depth layer is to its buoyant equilibrium position, with (Eq. 1) detailing the average vertical displacement from buoyant equilibrium in layers of the water column (Gargett and Garner, 2008). Thorpe stems from the difference between sorted density and measured density, showing where water masses are moving vertically due to density inversions from turbulent mixing. *Mixsea’s* overturn.eps\_overturn functionwill be used to return Thorpe displacement values and a Thorpe scale for the mixing layers at each CTD cast location (Cusack et al. 2022), although as noted above, density inversions may not be present.

To calculate the *e* (Eq. 2) from Thorpe displacements, the data from each down cast will be isolated and pressure values that are not monotonically increasing will be eliminated. Missing values will also be removed. *N2* values will be calculated and denoised by averaging in discrete bins. *Mixsea’s* overturn.eps\_overturn function will again be used to evaluate each identified mixing layer’s *e* and *N2* (Cusack et al. 2022) value based on “an overturn ratio criterion of 0.25 … to reject highly asymmetric patches” likely coming from “instrumental error” (Cusack et al. 2019).

With data from 2024’s warming El Nino and 2023’s warming La Nina cruises, the mixing metrics will be calculated following the above descriptions. The results will be qualitatively compared with the results of Deppenmeier et al. 2021 (FIG. 4). In the event of sampling over a TIW, mixing values will be elevated (Moum et al. 2009). The presence of TIWs will be determined with NASA’s SSH (<https://sealevel.jpl.nasa.gov/>) and SST datasets (<https://podaac.jpl.nasa.gov/dataset/MUR-JPL-L4-GLOB-v4.1>).

1. **Proposed Timeline and Financial Estimate**

The following timeline is preliminary, with some of the steps subject to change due to delays. It is expected that some components will take longer than initially proposed. Regardless, the goal is to submit the completed thesis by March 8th, 2024. Prior to the El Nino cruise, data analysis for the La Nina cruise data will be performed. Departure for Pago Pago, American Samoa, will be on December 28th, 2023, to collect ADCP and CTD data on research cruise TN-427 Sr. Thesis. During the cruise, NASA’s SSH data will be used to determine whether the vessel is sampling over a TIW, with preliminary data analysis occurring as data becomes available. Upon returning to Seattle, Washington, on January 12th, 2024, two weeks will be spent developing code and running analyses. Interpretation of results and their relation to historical data, model-driven calculation data, and last year’s senior thesis cruise data will begin on January 29th, 2024. Two weeks later, around February 12th, writing will start, with the first draft of the thesis complete two weeks later on February 26th. The second draft of the thesis should be done March 4th, a week later. This leaves a final week to conclude the project with the final draft.

The total expense estimate is $44,500. Ship expenses are $60,000 a day for 14 days, divided by 25 total projects, totaling $33,600. Airfare is roughly $1,900 roundtrip. At a $40,000 per year salary, the 2.5 months of work should result in $8,300 compensation. There is an additional $700 factored in for food and additional fees that may come up.

**References**

Bryan, F., and S. Bachman (2015), Isohaline salinity budget of the North Atlantic Salinity Maximum, *Journal of Physical Oceanography*, *45*(3), 724–736, doi:10.1175/jpo-d-14-0172.1.

Caulfield, C. P. (2021), Layering, instabilities, and mixing in turbulent stratified flows, *Annual Review of Fluid Mechanics*, *53*(1), 113–145, doi:10.1146/annurev-fluid-042320-100458.

Cusack, J. M., G. Voet, M. H. Alford, J. B. Girton, G. S. Carter, L. J. Pratt, K. A. Pearson-Potts, and S. Tan (2019), Persistent turbulence in the Samoan passage, *Journal of Physical Oceanography*, *49*(12), 3179–3197, doi:10.1175/jpo-d-19-0116.1.

Cusack, J., H. Drake, and G. Voet (2022), Mixsea 0.1.1 Documentation, *mixsea*. Available from: https://mixsea.readthedocs.io/en/v0.1.1/index.html (Accessed 29 November 2023)

Davies Wykes, M. S., and S. B. Dalziel (2014), Efficient mixing in Stratified flows: Experimental study of a rayleigh–taylor unstable interface within an otherwise stable stratification, *Journal of Fluid Mechanics*, *756*, 1027–1057, doi:10.1017/jfm.2014.308.

Deppenmeier, A.-L., F. O. Bryan, W. S. Kessler, and L. Thompson (2021), Modulation of cross-isothermal velocities with ENSO in the tropical pacific cold tongue, *Journal of Physical Oceanography*, *51*(5), 1559–1574, doi:10.1175/jpo-d-20-0217.1.

Deppenmeier, A.-L., F. O. Bryan, W. S. Kessler, and L. Thompson (2022), Diabatic upwelling in the tropical pacific: Seasonal and subseasonal variability, *Journal of Physical Oceanography*, *52*(11), 2657–2668, doi:10.1175/jpo-d-21-0316.1.

Fisman, D. N., A. R. Tuite, and K. A. Brown (2016), Impact of el niño southern oscillation on infectious disease hospitalization risk in the United States, *Proceedings of the National Academy of Sciences*, *113*(51), 14589–14594, doi:10.1073/pnas.1604980113.

Galperin, B., S. Sukoriansky, and P. S. Anderson (2007), On the critical Richardson number in stably stratified turbulence, *Atmospheric Science Letters*, *8*(3), 65–69, doi:10.1002/asl.153.

Gargett, A., and T. Garner (2008), Determining Thorpe Scales from ship-lowered CTD density profiles, *Journal of Atmospheric and Oceanic Technology*, *25*(9), 1657–1670, doi:10.1175/2008jtecho541.1.

Johnson, G. C., B. M. Sloyan, W. S. Kessler, and K. E. McTaggart (2002), Direct measurements of upper ocean currents and water properties across the tropical Pacific during the 1990s, *Progress in Oceanography*, *52*(1), 31–61, doi:10.1016/s0079-6611(02)00021-6.

Moum, J. N., R.-C. Lien, A. Perlin, J. D. Nash, M. C. Gregg, and P. J. Wiles (2009), Sea surface cooling at the equator by subsurface mixing in tropical instability waves, *Nature Geoscience*, *2*(11), 761–765, doi:10.1038/ngeo657.

NASA. 2023. El Niño 2023. JPL NASA. Available from: <https://sealevel.jpl.nasa.gov/data/el-nino-la-nina-watch-and-pdo/el-nino-2023/> (Accessed 7 December 2023)

Nystrom, E. A., C. R. Rehmann, and K. A. Oberg (2007), Evaluation of mean velocity and turbulence measurements with ADCPs, *Journal of Hydraulic Engineering*, *133*(12), 1310–1318, doi:10.1061/(asce)0733-9429(2007)133:12(1310).

Pielke, R. A., and C. N. Landsea (1999), La Niña, El Niño and Atlantic hurricane damages in the United States, *Bulletin of the American Meteorological Society*, *80*(10), 2027–2033, doi:10.1175/1520-0477(1999)080&lt;2027:lnaeno&gt;2.0.co;2.

Warner, S. J., and J. N. Moum (2019), Feedback of mixing to ENSO phase change, *Geophysical Research Letters*, *46*(23), 13920–13927, doi:10.1029/2019gl085415.

Woods, J. D. (1980), Do waves limit turbulent diffusion in the ocean?, *Nature*, *288*(5788), 219–224, doi:10.1038/288219a0.

Yang, F., L. Zhang, and M. Long (2022), Intensification of pacific trade wind and related changes in the relationship between sea surface temperature and sea level pressure, *Geophysical Research Letters*, *49*(8), doi:10.1029/2022gl098052.