Investigating Mechanisms Driving Spatiotemporal Variability of Barrier Layers in the Western Tropical Pacific

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20 March 2025

Abstract

This study investigates the physical mechanisms driving spatiotemporal variability of barrier layers in the Western Tropical Pacific (WTP) along 149°E, with a specific focus on the La Niña phase of the El Niño-Southern Oscillation (ENSO). Barrier layers, which separate the surface mixed layer from the thermocline, regulate ocean-atmosphere interactions and influence climate dynamics. This research assesses the relative contributions of freshwater input from precipitation, and wind stress on barrier layer formation and thickness. Data were collected during a research cruise in January 2025 aboard the R/V Thomas G. Thompson from an Underway Conductivity Temperature and Density (UCTD) sensor for temperature profiles, and public-source meteorological data for atmospheric conditions (ERA5). Seven stations, spaced two degrees apart in latitude, were sampled along a transect from 4°N to 15°N. Each station provided data to analyze barrier layer thickness, with spatiotemporal variability determined by comparing different formation mechanisms across stations. Spearman Correlation analyses were used to determine dominant factors influencing barrier layer thickness and variability. We found that barrier layer thickness in the WTP shows a general positive but statistically insignificant relationship with freshwater (ρ 0.32 and p-value 0.48), and a general negative but statistically insignificant relationship with wind stress (ρ 0.18 and p-value 0.70). During La Niña conditions, these effects are expected to drive variability, with thicker layers forming in regions of high precipitation and weak wind stress. Increased freshwater input enhances stratification, while strong wind stress likely promotes surface and subsurface mixing, leading to barrier layer thinning. Understanding these dynamics has implications for improving ocean-atmospheric interaction climate models in the tropical Pacific.

Plain Language Summary

This study investigates how barrier layers in the Western Tropical Pacific (WTP) change over time and space, focusing on variable changes during the La Niña phase of the El Niño-Southern Oscillation (ENSO). Barrier layers are significant because they have different characteristics from the water masses above and below them in the vertical water column, and they are influenced by ocean-atmosphere interactions. The study examines how freshwater input from rainfall and winds influence the thickness of these barrier layers. Data were collected during a research cruise in January 2025 aboard the R/V Thomas G. Thompson using various instruments to measure marine parameters; an Underway Conductivity Temperature and Density (UCTD) sensor to measure temperature profiles, while public-source meteorological data (ERA5) were used to assess atmospheric conditions. Seven stations, spaced two degrees apart in latitude (4°N to 15°N), were sampled along the 149°E transect of study. We found that barrier layer thickness shows a general positive but statistically insignificant relationship with freshwater input (Spearman Correlation Coefficient = 0.32, p-value = 0.48) and a general negative but statistically insignificant relationship with wind stress (Spearman Correlation Coefficient = -0.18, p-value = 0.70). These patterns are especially strong during La Niña, when rainfall increases and winds decrease significantly. Understanding these dynamics helps us better understand how climate influences barrier layers in the tropical Pacific, and this knowledge could improve ocean-atmospheric interaction climate models for the region.

Introduction

Barrier layers are areas in the ocean between the base of the surface mixed layer and the top of the thermocline. These layers act as buffers to vertical turbulence and heat exchange, significantly influencing physical mixing and ocean-atmosphere interactions (Lukas & Lindstrom, 1991; Godfrey & Lindstrom, 1989). These layers are present in the Western Pacific and play a crucial role in regulating subsurface processes and their interactions with the atmosphere, affecting large-scale climate phenomena like the El Niño-Southern Oscillation (ENSO) (Sprintall & Tomczak, 1992). Barrier layers could possibly play a role in modulating thermal conductivity, mixing, and the duration of ENSO cycles (Wang & Liu, 2016).

Despite their significance, the variability of barrier layers and the mechanisms driving their formation in the WTP remain key topics of ongoing research in large-scale oceanography. Variability of barrier layers refers to spatiotemporal changes in barrier layer thickness in this region. Understanding barrier layer variability can improve ENSO predictability by adding insights into the interchange of subsurface processes interactions with atmospheric conditions (Maes et al., 2002).

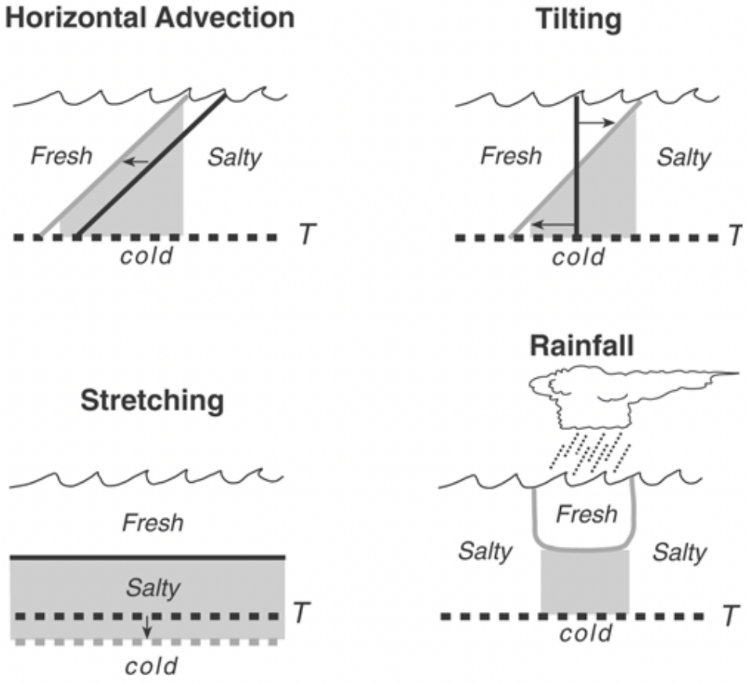

Figure 1: Mechanisms by which barrier layers can form and grow. The initial halocline and thermocline are indicated by a black solid line and a black dashed line, respectively. The resulting halocline and thermocline are indicated by a grey solid line and grey dashed line, respectively. Stippling indicates the resulting barrier layer. (Bosc et al., 2009)

Current research suggests that the mechanisms driving barrier layer formation (Figure 1) vary regionally and may include factors such as freshwater input from precipitation, advection of distinct water masses, and wind-driven mixing (Cronin et al., 2003; Bosc et al., 2009). In the WTP, barrier layer formation is likely shaped by seasonal rainfall patterns, tropical instability waves, and the dynamics of regional currents such as the North Equatorial Current. Strong wind and high rates of precipitation are dominant atmospheric conditions in the region, shaping barrier layer characteristics year-round. During the La Niña phase of the ENSO cycle, both wind speeds and precipitation rates in the WTP are typically higher than normal (Neelin et al., 1998). Given the prominence of freshwater input from precipitation and wind-driven mixing in the WTP, this study narrows its focus to these two mechanisms.

The formation of barrier layers significantly influences mixed-layer dynamics. In the Western Pacific, discrepancies between observed isothermal and isohaline depths suggest that the presence of the barrier layer prevents heat transfer through the bottom of the mixed layer (Foltz & McPhaden, 2009). Salinity often dominates density in the region, as the input of freshwater from high precipitation rates, and surface mixing significantly impact salinity. These factors, in turn, reduce the influence of temperature on density, as the sea surface temperature gradients in the region are thought to be too small for horizontal advective processes to be significant, highlighting the importance of salinity-driven stratification in barrier layers (Sprintall & Tomczak, 1992; Enfield, 1986). Barrier layers in the tropics are not uniformly distributed and exhibit variability in thickness, with wind stress being one of the primary mechanisms shaping their structure (Sprintall & Tomczak, 1992).

This study aims to investigate the specific mechanisms driving barrier layer thickness in the WTP, with a focus on freshwater input and wind stress, to determine which factors most significantly influence their spatiotemporal variability. Understanding these drivers is critical for improving climate models that incorporate subsurface dynamics in the WTP—a region with profound impacts on the global climate through teleconnections (Simmons et al., 1983).

By examining how barrier layer thickness varies in relation to these atmospheric factors, this study seeks to evaluate their relative importance and provide insights into how barrier layer thickness responds to changing environmental conditions in the region.

The primary goal of this study is to identify and evaluate the physical mechanisms driving barrier layer variability in the open-ocean regions of the WTP (Figure 2). Specifically, an assessment of how freshwater input from precipitation, advective processes, and wind stress influence barrier layer dynamics during La Niña conditions, as well as the relative impact of these mechanisms. In particular, we will investigate how these formation mechanisms contribute to variations in barrier layer thickness, considering spatial variability between stations (Figure 2).

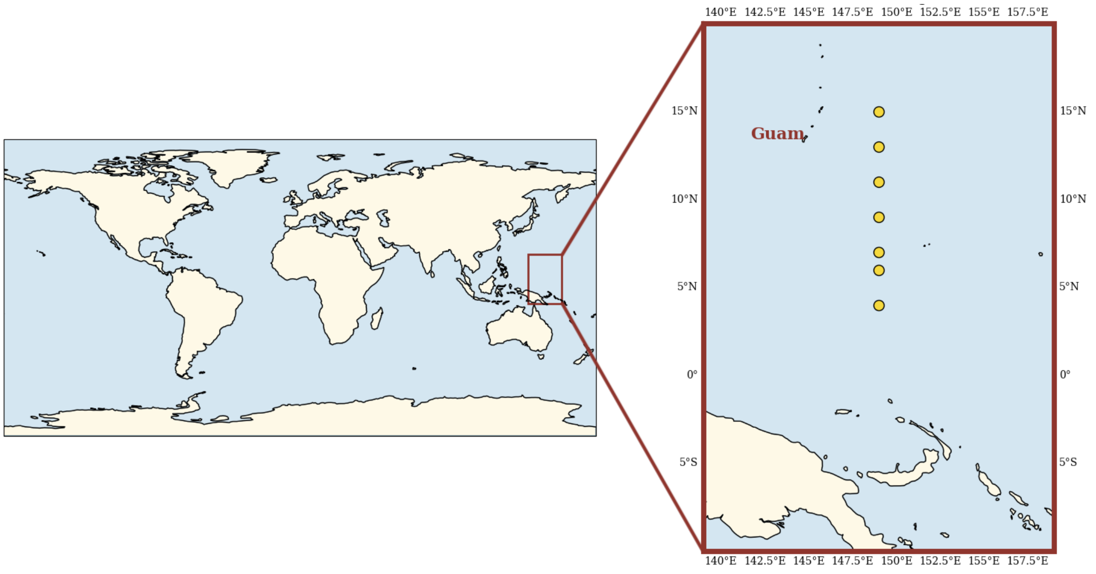

Figure 2: Global and regional map of the study region in the Western Tropical Pacific near Guam. The yellow dots highlight the research cruise transect, indicating sampling station locations along this route.

Barrier layer thickness in the WTP is hypothesized to exhibit a positive correlation with freshwater input from precipitation, leading to enhanced stratification, and a negative correlation with wind stress due to increased mixing. During La Niña conditions, the combined effects of these factors are expected to result in spatiotemporal variability in barrier layer thickness, with thicker layers forming in regions of higher precipitation and weaker wind stress. Increased freshwater input from precipitation are likely to thicken the barrier layer by enhancing the stratification of the subsurface ocean withstanding vertical mixing. Conversely, strong wind stress during La Niña conditions can promote the mixing of surface and subsurface waters, leading to a thinning of the barrier layer. The relative contributions of these mechanisms are expected to shift based on the prevailing environmental and ocean-atmospheric interactions.

Methods

We utilized an Underway Conductivity Temperature and Density sensor (UCTD) to measure temperature, salinity (conductivity), and pressure (depth), from which we could compute density and create profiles to establish the thermocline profile across the water column. Additionally, atmospheric data from ECMWF Reanalysis v5 (ERA5) for wind speed, precipitation, evaporation, and sea surface temperature were optained to analyze external environmental factors influencing ocean-atmosphere exchanges.

Each station was treated as one data point, by the average barrier layer thickness and spatiotemporal variability. Data analysis and visualization were conducted using Python, focusing on thermohaline and density profiles to identify stratification patterns indicative of barrier layer presence. We conducted mechanism-specific (Figure 1) analyses based on distinct weather conditions as follows:

Freshwater Input: A Spearman correlation analysis was conducted between meteorological data and barrier layer thickness throughout the research cruise to assess the influence of atmospheric conditions on barrier layer variability. This analysis compared total atmospheric freshwater exchange—defined as total precipitation plus total evaporation—with observed barrier layer thickness, as derived from UCTD measurements, during periods of rainfall and evaporation. To investigate the temporal effects of rainfall, barrier layer thickness was analyzed two days prior to atmospheric events, providing insight into the potential causal atmospheric conditions and barrier layer response.

Wind stress: Examined the impact of surface wind stress on barrier layer stability by viewing wind speed data with mixed layer depths observed by the UCTD measurements. This analysis focused on identifying periods of strong wind events and their influence on the vertical mixing and thinning of the barrier layer.

Correlation Analysis: To identify the primary drivers of regional barrier layer variability, we performed a Spearman correlation analysis between the stations' barrier layer thickness and key environmental variables (e.g., Freshwater input, and wind speed). This allowed us to quantify the strength of interactions between the barrier layer and these drivers. By examining these mechanisms, we gained a comprehensive understanding of how each factor contributed to barrier layer variability and helped determine which driver most significantly influenced barrier layer thickness in this region.

During the research cruise aboard the R/V Thompson, scheduled from December 27, 2024, to January 11, 2025, in the Western Tropical Pacific (WTP) near Guam, UCTD deployments occurred at 7 stations along the transect of 149°E, spaced at two-degree intervals from 4°N to 15°N (Figure 2; Table 1). We used the RBR Concerto CTD sensor, installed on an underway line and reel that was mounted to the deck of the ship. The UCTD (RBR) was limited to a maximum depth of 700 meters, but deployments were made to a depth of 400 meters at each station. The UCTD fall rate was 100 m/min, and the retrieval rate was approximately one minute longer than the fall time. Therefore, each cast took approximately 11 minutes in total if the ship was moving at 4-6 knots. The specific stations, depths, and ship speed were adjusted as needed to coordinate with other users of several different instruments during the cruise.

Table 1: UCTD Deployment Stations along the 149°E Transect (4°N to 15°N) during the R/V *Thompson* Research Cruise in the Western Tropical Pacific.

Station No.	Latitude (°N)	Longitude (°E)
1	4	149
2	6	149
3	7	149
4	8	149
5	9	149
6	11	149
7	13	149
8	15	149

The barrier layer thickness was calculated at each station using the following simplified equation (Equation 1):

Barrier Layer Thickness (BLT) = Isothermal Layer Depth (ILD) − Mixed Layer Depth (MLD)

The Mixed Layer Depth (MLD) was defined as the depth at which the potential density deviated by 0.03 kg/m^3 from the reference value of 10dbar, following the method described by de Boyer

Montégut et al. (2004). The Isothermal Layer Depth (ILD) was determined as the depth at which the potential temperature deviated by 0.2°C from the reference pressure's (10 dbar) potential temperature value (de Boyer Montégut et al., 2004). This approach allowed for consistent comparison of the BLT across stations and facilitated the identification of patterns across the 149°E transect (Figure 3).

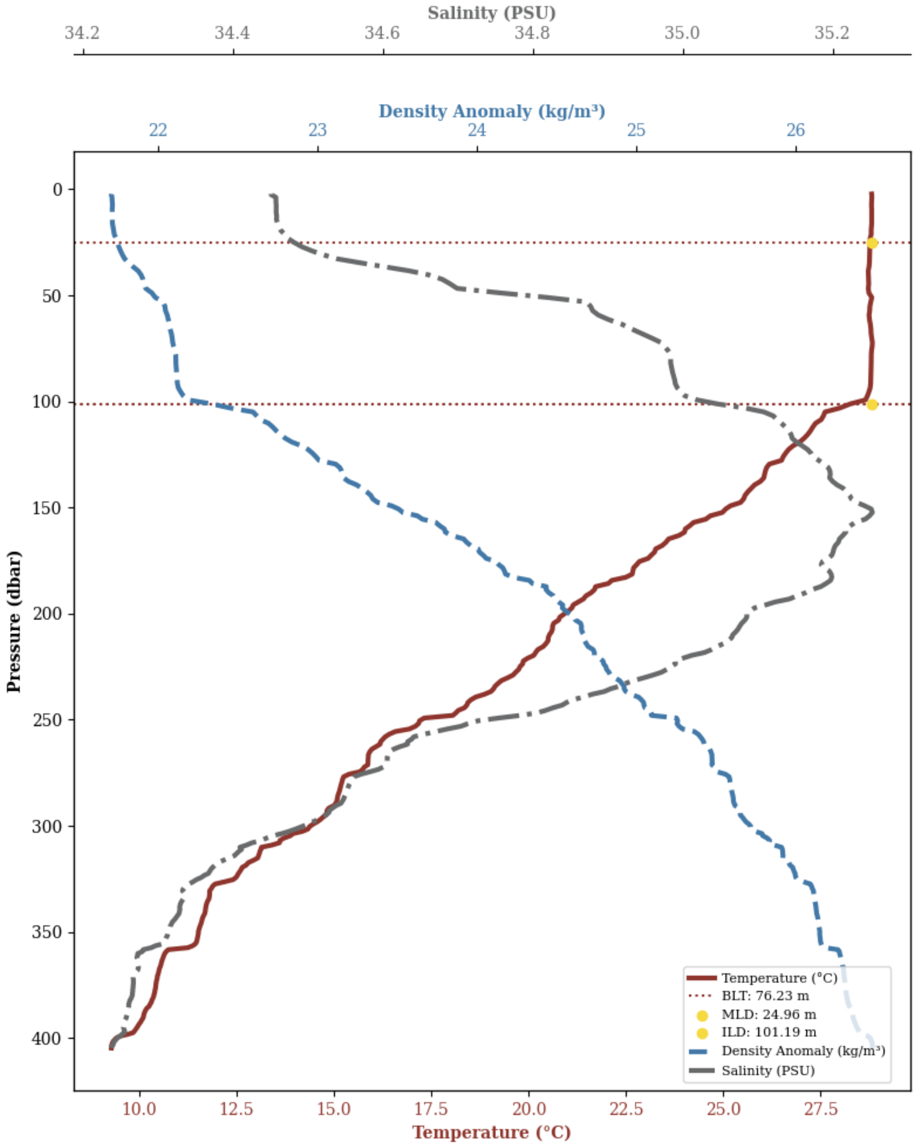

Figure 3: Example of observed hydrographic profiles at station 8 (15 °N). A vertical profile of Temperature (red), salinity (grey), and density (blue) over depth (pressure). The BLT is indicated by the horizontal (red) dotted lines.

Results

Spatial Variability

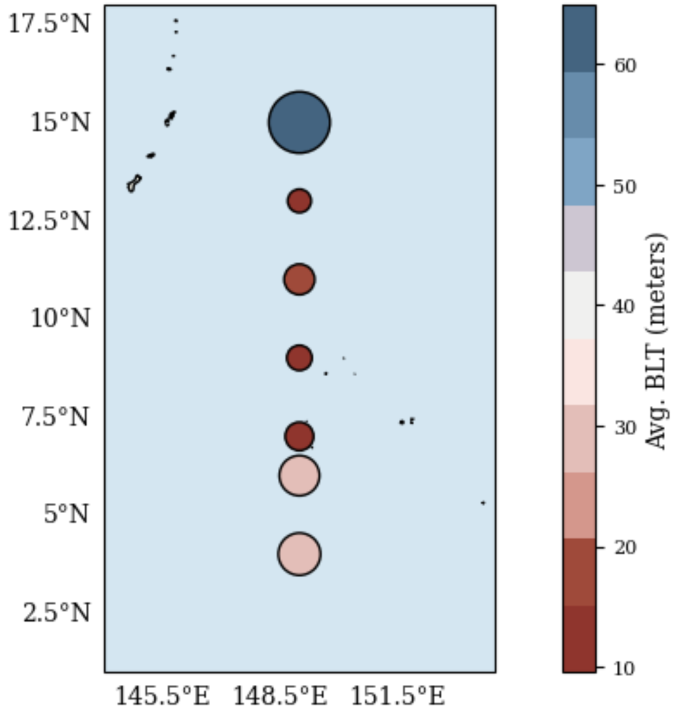

Figure 4: Average Barrier Layer Thickness (BLT) along the 149°E transect. Each dot represents a station, the magnitude of the circle corresponds with the BLT.

The spatial variation in barrier layer thickness and thermocline structure along the 149°E transect line reveals significant differences across latitudes, with no clear regression pattern observed as the transect moving toward higher latitudes of our transect (Figure 4). The thickest barrier layer observed was 106.41 meters, while the thinnest was just 2.12 meters. The depth of the mixed layer and isothermal layer depth plays a critical role in the observed variations. In general, the average MLD for each station remains relatively shallow, not exceeding 62 meters. In the middle of our study region (7°–12°N), there is a noticeable decrease in barrier layer thickness, while closer to the equator, a minor increase in BLT is observed. At higher latitudes, particularly around 15°N, a significant increase in BLT is noted. The barrier layer thickness shows strong dependence on both the MLD and ILD, with the highest barrier layer thickness observed at 15°N, where the maximum BLT reached 106.41 meters (Table 2). This corresponds to a large difference between the average MLD and ILD (Figure 5).

Table 2: Analysis of UCTD deployment stations along the 149°E transect during the R/V Thompson research cruise in the Western Tropical Pacific.

Latitude (°N)	Avg. BLT (m)	Max. BLT (m)	Min. BLT (m)	Avg. ILD (m)	Avg. MLD (m)	No. Profiles
4	30.83	54.43	9.39	92.45	61.61	17
6	27.83	46.97	14.58	73.92	46.09	3
7	14.01	62.11	2.12	56.59	42.58	14
9	11.00	31.53	4.06	70.60	59.60	20
11	16.20	21.74	10.76	86.49	70.29	4
13	9.57	20.23	3.85	85.44	75.87	16
15	64.92	106.41	25.10	92.08	27.16	17

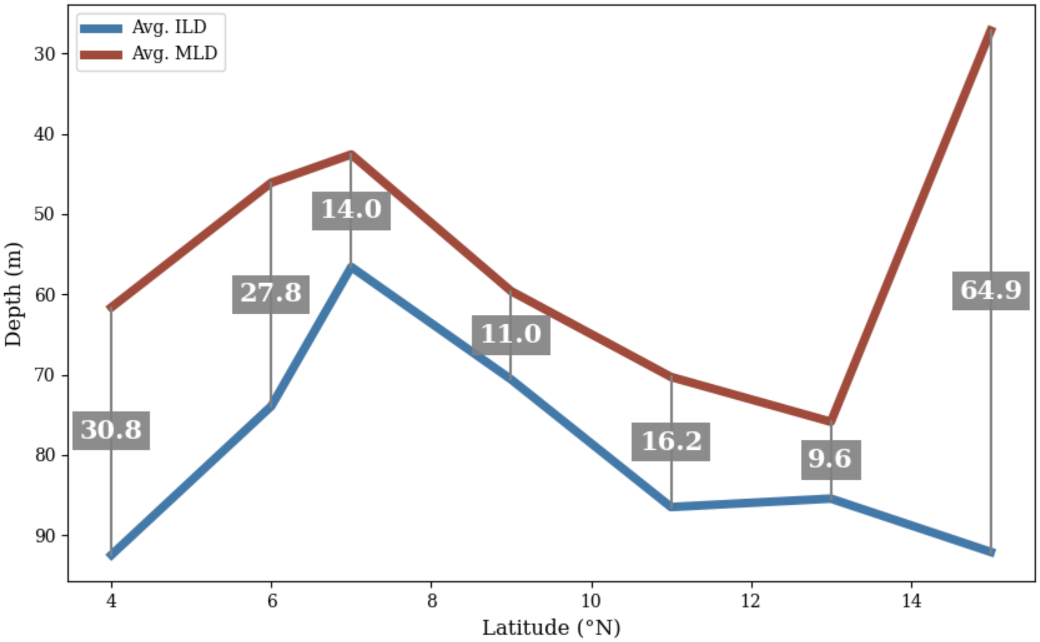

Figure 5: Average ILD, MLD, and the resulting BLT across transect stations. The grey lines represent the BLT, the grey boxes indicate the magnitude of the BLT in meters.

Meteorological Variability

During the period of our transect, average wind speeds in the study region reached 7.5 m/s and freshwater input 0.00125 mm. During periods of significantly decreased winds, there is an observed increase in freshwater input (Figure 6). However, when wind speed and freshwater input exhibit minimal changes in variability, the correlation between the two becomes much less significant. In examining meteorological parameters in relation to barrier layer thickness (Figure 7), we found that evaporation increased in the middle of our study region (7°–12°N), where a decrease in BLT was observed. In contrast, regions with higher precipitation rates (4°–6°N) showed a slight increase in BLT. At 15°N, where the thickest barrier layer was observed, sea surface temperatures (SST) were low, precipitation was minimal, and evaporation rates were moderate. The winds are primarily driven by strong zonal winds, which dominate both in direction and magnitude over the weaker meridional winds (Figure 8).

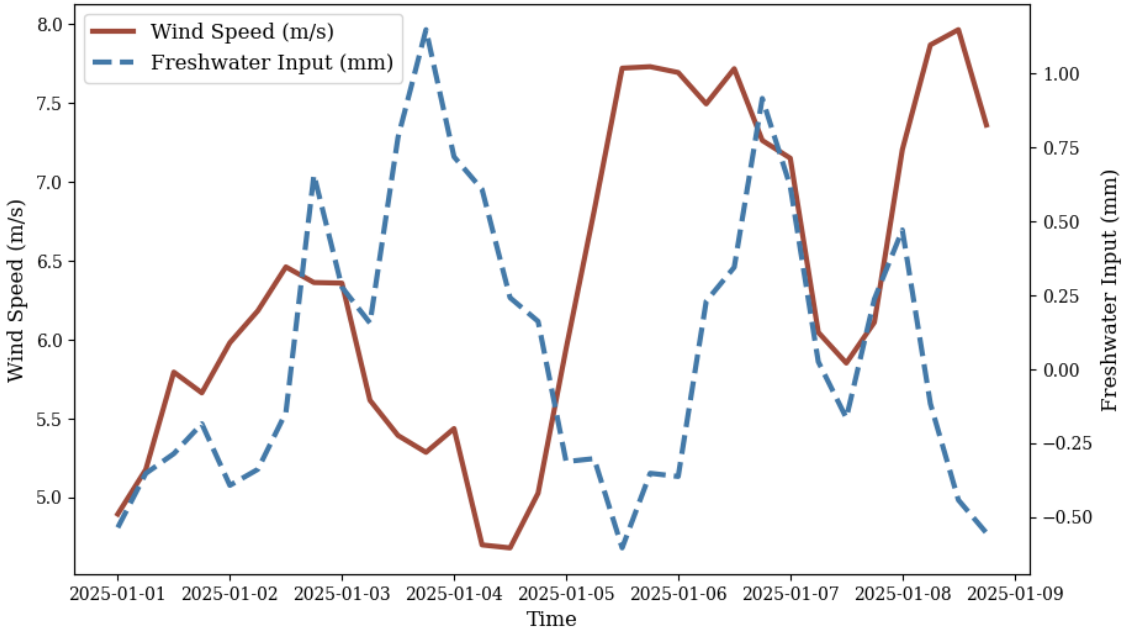

Figure 6: Meteorological time series of wind speed and freshwater input.

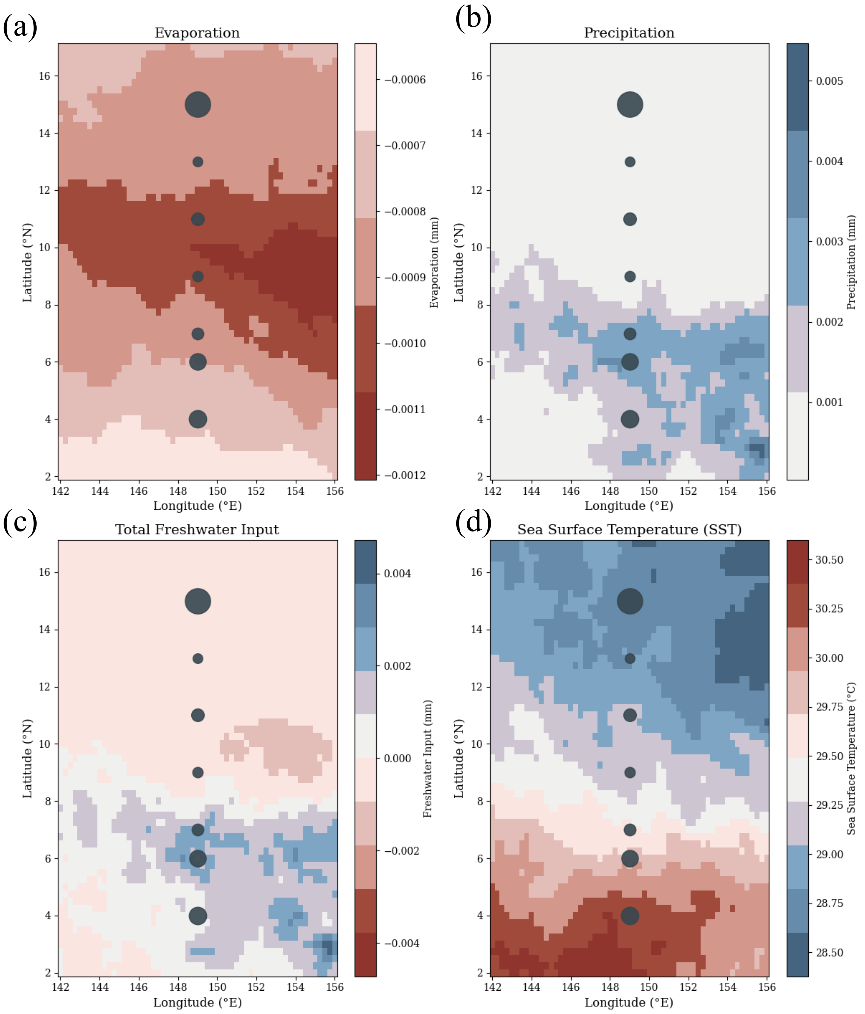

Figure 7: Data from January 1, 2025, to January 8, 2025, along the 149°E transect. (a) Average evaporation, (b) average precipitation, and (c) total freshwater input calculated from total evaporation and total precipitation, (d) average sea surface temperature (SST). The black circles represent the Barrier Layer Thickness (BLT) along the transect, with the size of the circles corresponding to the magnitude of BLT at each station.

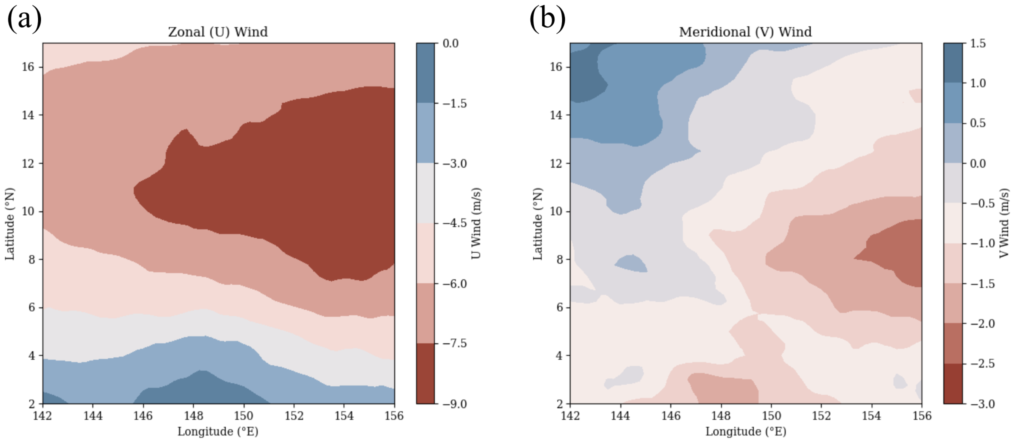

Figure 8: Data from January 1 to January 8, 2025, along the 149°E transect. (a) Zonal winds, with positive values indicating eastward winds and negative values indicating westward winds. (b) Meridional winds, with positive values indicating northward winds and negative values indicating southward winds.

Further analysis of freshwater input and wind speed correlations (Figure 9) revealed that wind speeds along our transect were faster at higher latitudes (~10°-16°N) and decreased toward lower latitudes (~3°–8°N) of our study region. At 15°N, where wind stress was strongest, we observed the thickest barrier layer. In contrast, between 4°–6°N, a slight increase in BLT was observed in regions where wind speeds were lower and freshwater input was high. When comparing stations with the thinnest (2.12 m) and thickest (106.41 m) BLT based on meteorological conditions, the thinnest BLT occurred at a location with high precipitation and increasing wind speed at higher latitudes (Figure 10). The largest showed an area of little to no input of freshwater, with high wind stress.

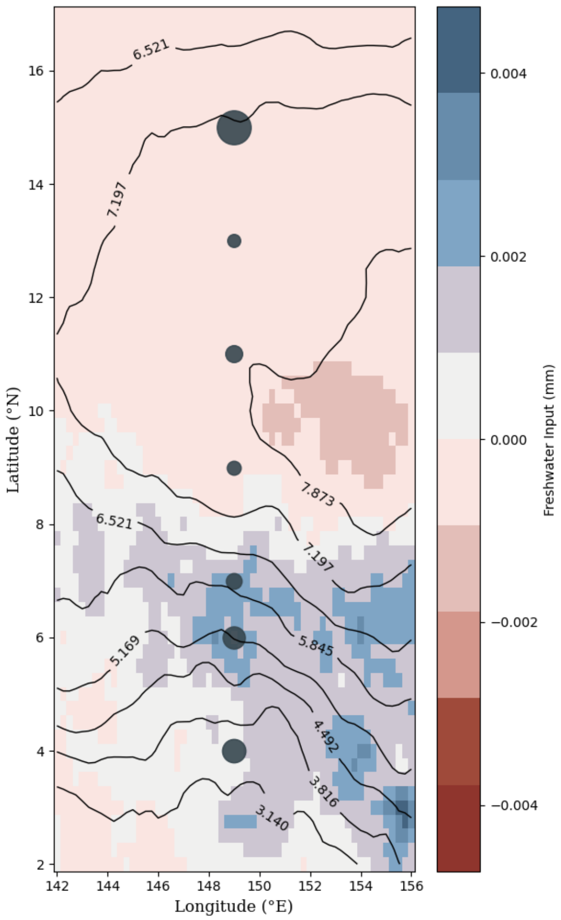

Figure 9: Data from January 1, 2025, to January 8, 2025, along the 149°E transect. Freshwater Input (shaded) and averaged wind speed (contoured). BLT is shown as black circles, the size of the circles represent the magnitude of BLT in meters.

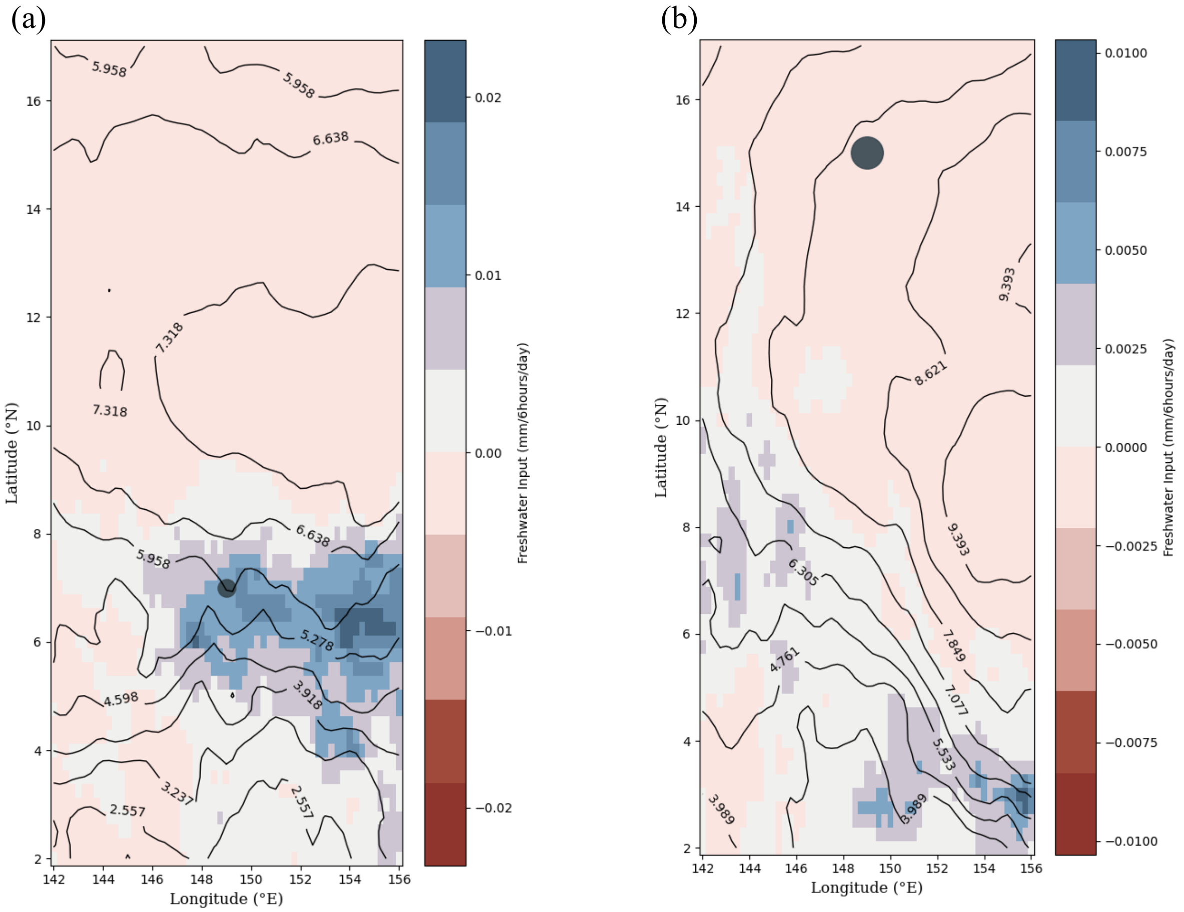

Figure 10: (a) Thinnest barrier layer thickness (7ºN) from January 3, 2025, to January 5, 2025, along the 149°E transect. Freshwater Input (shaded) and averaged wind speed (contoured). BLT is shown as a black circle, the size of the circles represent the magnitude of 2.12m. (b) Largest barrier layer thickness (15ºN) from January 6, 2025, to January 8, 2025, along the 149°E transect. Freshwater Input (shaded) and averaged wind speed (contoured). BLT is shown as a black circle, the size of the circles represent the magnitude of 106.41m.

Statistical Analysis

The Spearman correlation analysis (Figure 11) between freshwater input and barrier layer thickness (BLT) resulted in a correlation coefficient (ρ) of 0.32 and a P-value of 0.48, indicating a statistically insignificant relationship. Similarly, the Spearman correlation between wind speed and BLT yielded a correlation coefficient of 0.18 and a P-value of 0.70, indicating a statistically insignificant relationship between these variables in consideration of all stations.

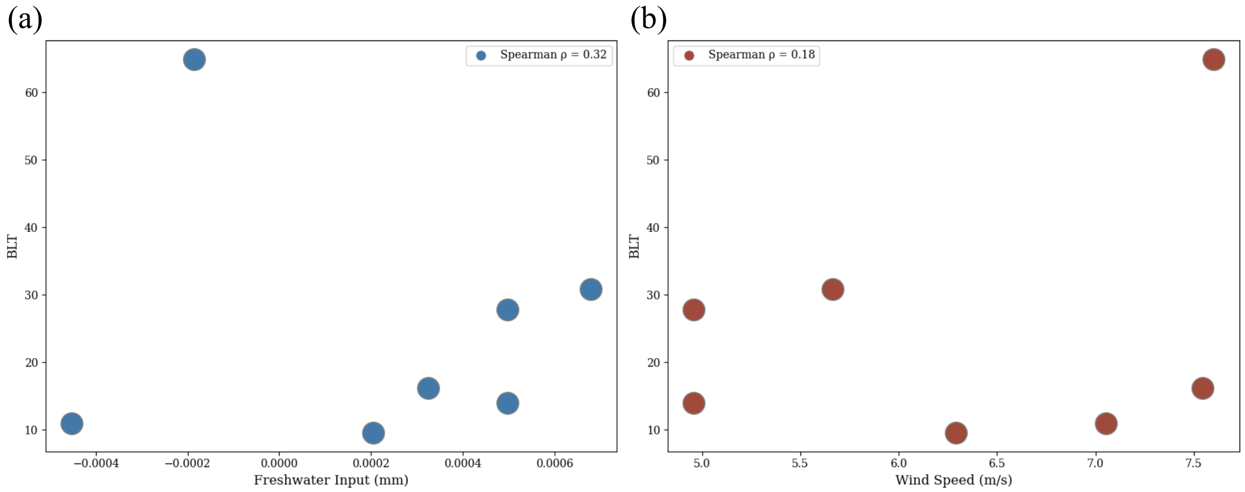

Figure 11: (a) Spearman correlation between freshwater input and barrier layer thickness (BLT) across all stations (blue). (b) Spearman correlation between average wind speed and BLT across all stations (purple).

Discussion

Our analysis revealed spatial variability in barrier layer thickness across the Western Tropical Pacific, although no specific pattern was observed. The analysis combined with meteorological data, suggests that barrier layer formation is influenced by multiple mechanisms, rather than a single dominant factor. Regionally, BLT varied across stations at different latitudes. Notably, Station 8 exhibited an interesting increase in BLT, which may indicate that the deep Isothermal Layer Depth (ILD) and thin Mixed Layer Depth (MLD) contribute to a more stratified water column, resulting in a thicker barrier layer. Atmospheric conditions and the time of year could also play a role in this variation (Ando & McPhaden, 1997). High wind speeds were generally associated with thinner barrier layers, possibly due to vertical mixing, while higher precipitation rates were linked to slight increases in BLT, likely driven by freshwater input that enhances stratification. In contrast, evaporation seemed to have an opposing effect. Additionally, the weak correlation between BLT and atmospheric properties suggests that other factors, such as advection, stretching, and/or tilting, play a significant role in the formation and maintenance of barrier layers. In this context, oceanographic factors, such as salinity-driven stratification, may also contribute to the dynamics of barrier layers (Sprintall & Tomczak, 1992; Enfield, 1986).

Although the statistical correlations were insignificant, a general trend was observed: as wind speed increased, BLT tended to decrease, while higher freshwater input was associated with a thicker BLT. The presence of an outlier at 15°N, which corresponds to the thickest barrier layer, may be contributing to the lack of a significant correlation. Further investigation into this outlier, in collaboration with and gaining insight from my classmate Mei Ettari's senior thesis project, suggests that the unusually thick barrier layer may be influenced by a counterclockwise cyclonic eddy, which could result in a shallower mixed layer depth—the thinnest average MLD compared to other stations—while maintaining relatively constant isothermal layer depth (ILD) (Table 2) (Ettari, 2025). The potential influence of a mesoscale eddy at 15°N further suggests that ocean circulation plays a crucial role in the formation and maintenance of barrier layers.

Upon examining the individual profiles, one profile with a 125m BLT stands out as a potential bias in the averaging process, especially when compared to other profiles where BLT ranged between 60-70m. Considering using the median instead of the average BLT for each station could provide a more reliable representation.

It is important to note that the number of UCTD profiles varied across stations, which could introduce bias in the observed data. Stations with a higher number of profiles provided a more comprehensive view of BLT, while stations with fewer profiles may limit our confidence in the spatial variability trends. Additionally, data collection was challenged by instrumentational issues.

Conclusion

The cumulative results of this study do not validate my hypothesis, though some general trends are substantiated. We found that barrier layer thickness in the WTP shows a general positive but statistically insignificant relationship with freshwater input from precipitation and a general negative but statistically insignificant relationship with wind stress. Barrier layer formation mechanisms are not solely responsible for influencing thickness; atmospheric conditions play a significant role in their thinning and thickening. These findings suggest that both oceanic and atmospheric factors govern the formation mechanisms of barrier layers and therefore impacting their thickness in the region. The observed barrier layer thickness during this study may be linked to broader climate patterns like the La Niña phase of ENSO. Spatial variability indicates that BLT is different depending on different weather conditions across different latitudes.

Further analysis incorporating ADCP data from the research cruise will help explore potential correlations between wind stress, mixing, and stratification at each station. The integration of Argo floats will enable long-term monitoring of barrier layers in the region. A more extended temporal analysis would offer deeper insights into large-scale ocean-atmospheric interactions in the Pacific Ocean, such as examining different magnitudes and phases of the ENSO cycle. Standardizing the number of UCTD profiles per station will also improve the statistical reliability of the results.

Future studies could explore whether other formation mechanisms of barrier layers influence their thickness along the transect of our study. Additionally, investigating salinity-driven stratification may provide further insight into the dynamics of barrier layers.

Acknowledgements

I thank the captain and crew of the R/V Thomas G. Thompson - Cruise TN440 for their assistance and support. Special thanks to Dr. Alison Gray for her invaluable mentorship and the extensive scientific knowledge and insights I have gained from her. Additionally, I express my appreciation to the other esteemed instructors of the Oceanography Undergraduate Thesis course series at the University of Washington - Dr. Ginger Armbrust, Dr. Andrea Ogston, Dr. François Ribalet, and Dr. Mark Warner - for their guidance and teaching efforts. I also thank my classmates for their general support, sampling, and data gathering on the research cruise. I appreciate the support of the University of Washington’s School of Oceanography in making this research possible.

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The writing in this proposal was improved by applying ChatGPT to the fully formed document. I subsequently proof-read the document to ensure ChatGPT did not add any content that did not come from me.

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