INFLUENCE OF THE HAWAIIAN ISLANDS ON BIOGEOCHEMISTRY IN THE PACIFIC

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By
SONJA GIARDINA

Thesis Advisor

DR. BRIAN POWELL

I certify that I have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

THESIS ADVISOR

Dr. Brian Powell
Department of Oceanography

For Honokea, the first bay I got to know as a friend.

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ABSTRACT

This study explores how the Hawaiian Islands impact biogeochemistry in the Pacific Ocean, focusing on how far the islands influence on biologically important variables, namely nutrients and phytoplankton, extends into the west Pacific. In the nutrient-poor (oligotrophic) waters around Hawai‘i, the islands play a critical role in generating productivity through eddies and other ocean disturbances, supporting plankton, fisheries, and carbon export. Previous research indicates far-reaching effects of the Hawaiian Islands on physical variables such as winds, currents, vertical advection, and sea surface temperatures up to 3000 km west of the islands (Xie et al., 2001). However, the impacts of this wake on nutrients and biological variables remain underexplored, with most studies focusing only on waters near the Main Hawaiian Islands. Using the Regional Ocean Modeling System (ROMS) coupled with the Carbon, Ocean, and Lower Tropics (COBALT) model, the study investigates how physical and biological processes interact west of Hawai‘i. ROMS was run from 2000 to 2020 over a region extending west to approximately 175ºE. This study found a significant wake of eddy kinetic energy (EKE) extending to roughly 185ºE, showing that eddies generated by the islands have far-reaching impacts. Both cyclonic (upwelling) and anticyclonic (downwelling) eddies appear to influence nutrient transport and productivity far from the islands, and these effects vary based on depth. Nitrate and phosphate have wakes that extend across the entire domain, while iron and phytoplankton do show elevated levels near the islands, but do not have as far-reaching wakes. These findings highlight Hawai‘i’s broader ecological significance in structuring productivity patterns across the Pacific, with implications for ecosystem management and conservation efforts. Further

research is needed to better understand the mechanisms driving these biological responses and to predict how changing climate conditions may alter Hawai‘i’s ecological influence.

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1.0 INTRODUCTION

1.1 Motivation

This study explores Hawai‘i’s impact on productivity in the Pacific Ocean, particularly how far that influence extends to the west of the archipelago. Xie et al. (2001) have demonstrated that the Hawaiian archipelago has an influence on physical variables that extends westward well beyond the islands, but there is a lack of study on whether this long wake extends to biology as well. Most studies of biology in the region focus on the ocean near the archipelago in the direct lee of the islands, cutting the study region off on the western edge of Kaua‘i. This project aims to address the knowledge gap regarding the potential influence of the Hawaiian Islands on the western Pacific and contribute to the understanding of how island chains can influence biology many kilometers away from their shores. The primary questions this study seeks to answer are: 1) What are the impacts of the Hawaiian Islands on biologically important variables in the west Pacific, namely nutrients and phytoplankton?; 2) how far do those impacts extend?; and 3) what is causing those impacts?

This information could be valuable for others who will build on this work in topics such as the distribution of production in the western Pacific or how the Hawaiian archipelago impacts surrounding fisheries. A broad characterization of these impacts can provide a foundation for future studies on the biological wake of the Hawaiian Islands, and other isolated islands as well. Understanding the role Hawai‘i plays in production in the oligotrophic ocean provides insight into surrounding biological ecosystems, carbon uptake, and overall biogeochemical cycling.

1.2 Key Previous Research

Xie et al. (2001) is a key motivating study for this project. This study examined the long physical wake created by Hawaiian archipelago in the west Pacific Ocean, focusing on physical variables such as winds, currents, cloud liquid water, Ekman pumping velocity, and sea surface temperature. The cone of influence on such variables was found to extend far into the westward Pacific, with a decreased wind wake of up to 3000-km west of the islands (Xie et al., 2001). The 3000-km wake in the lee of the Hawaiian Islands is notably longer than wakes observed at other individual islands, with long term analyses demonstrating a consistent influence out to 175ºE.

This wake is sustained by complex interactions between SST, currents such as the Hawai‘i Lee Counter Current (HLCC), winds curl, and other atmospheric responses such as cloud liquid water, as are described in more detail in Xie et al. (2001). Figure 1 from this study shows the SST, which was filtered using an 8º moving average in the meridional direction to remove the background state, overlayed with wind vectors. This diagram shows a band of higher SST that slants to the southwest, along with winds that converge above this band. It is of note that the range of SST anomalies is rather small in comparison to other processes that affect SST, but the islands do have sustained influence on large-scale ocean circulation patterns. Wind curl created by the disruption of the islands induces westward-traveling Rossby waves, which set up the HLCC that flows eastward and continues to sustain the warm tongue wake of the islands by advecting warm water towards Hawai‘i. There have been studies that have extended the work done by Xie et al. (2001) to examine island mass effects and wakes in other locations such as Mo’orea (James et al., 2020) or Hainan Island (Sha et al., 2019).

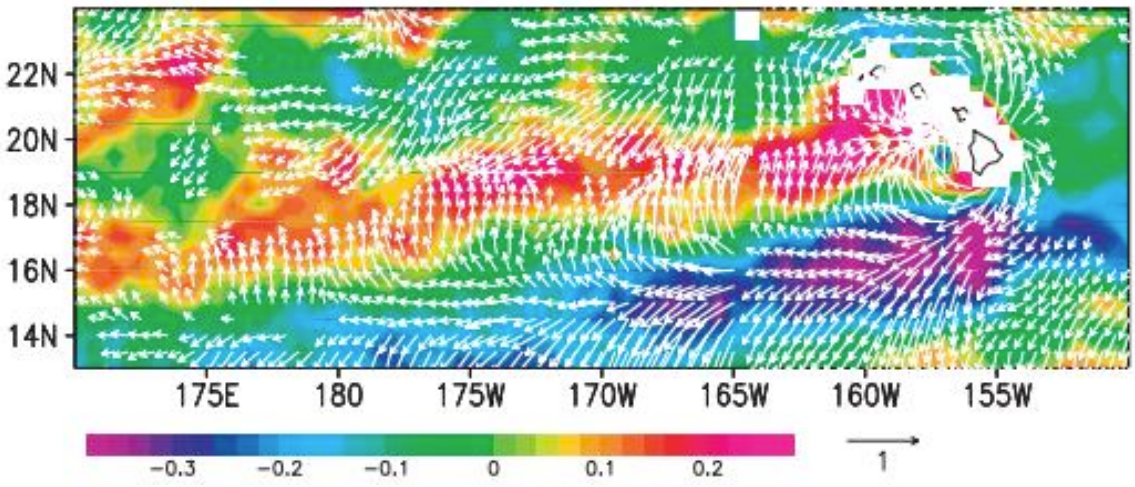

Figure 1. High-pass filtered SST anomalies (color scale is in ºC) and wind vectors (m s^{-1}). (Xie et al., 2001)

Islands and island chains are known to have impacts on both the physics and biology of the ocean. The Island Mass Effect (IME) is a phenomenon of enhanced primary production around islands that can be caused by various physical processes. The mechanisms causing the IME all lead to enhanced nutrients in the surface euphotic layer, either by upwelling and mixing, or by land-born factors such as runoff. The IME is of key importance in oligotrophic waters where nutrient availability in the euphotic zone is otherwise limited, and biomass and production are dependent on the influence of a land mass for some kind of disturbance.

One important way production around islands is enhanced is the formation of island-generated eddies. Various studies have demonstrated that eddies play a key role in chlorophyll distribution (Aristegui et al., 1997; Feloy et al., 2024; Onitsuka et al., 2009; Seki et al., 2001a, 2001b; Xiu et al., 2016). Eddies can impact production distribution in various ways, with one mechanism being eddy pumping, which is vertical motion created within eddies when geostrophic balance is disrupted, creating low- or high-pressure anomalies and subsequently a raised or depressed thermocline. This disruption initiates

the geostrophic adjustment process, leading to vertical eddy pumping. In cyclonic eddies, which are low pressure systems, eddy pumping causes upwelling that brings nutrients to the surface and can enhance productivity particularly in oligotrophic regions. In high pressure anticyclonic eddies, eddy pumping leads to downwelling, often suppressing productivity. In addition, eddies can also entrain chlorophyll from nearshore processes like coastal upwelling, and horizontally advect production offshore, carrying it further from the island. Understanding the nuances of specific islands IME is important to predict changes to ecosystems, local biodiversity, and economic well-being of surrounding fisheries.

1.3 Study Region

Hawai‘i is located in the oligotrophic ocean within the North Pacific Subtropical Gyre (NPSG), and is characterized by very low levels of nutrients and reduced primary production. Hawai‘i’s IME has been investigated (Gilmartin and Revelante, 1974), with eddy shedding in the lee of the islands being an important physical mechanism leading to enhanced productivity (De Falco et al., 2022). Jia et al. (2011) state that mesoscale eddies are frequently found in the west of Hawai‘i (Fig. 2), and majority of them are generated locally. Around the main Hawaiian Islands,

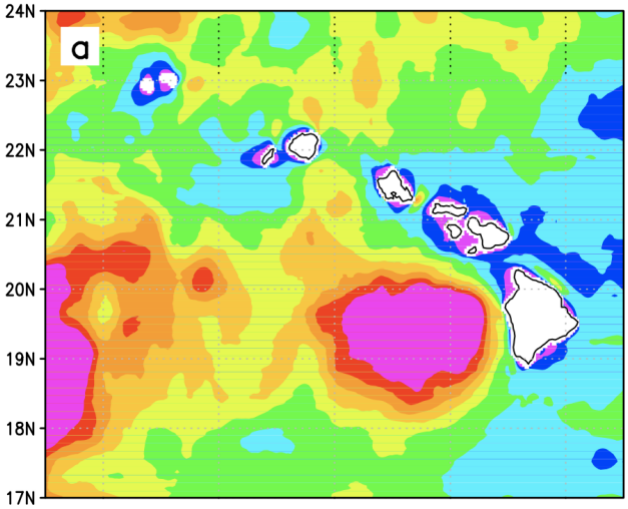

Figure 2. Surface Eddy Kinetic Energy (EKE) (cm^2s^{-2}) derived from sea surface height from the QuikSCAT experiment. (Jia et al., 2011)

phytoplankton blooms are driven by seasonal cycles along with eddy formation in the west of Hawai‘i Island (Friedrich et al., 2021). In the Hawai‘i region, eddy activity has also been linked to increased fish spawning and recruitment, which can have impacts throughout the ecosystem (Lindo-Atichati et al, 2020).

In the lee of the Hawaiian Islands, both cyclonic and anticyclonic eddies are formed. Cyclonic eddies are primarily generated off the north side of Hawai‘i island, while anticyclonic eddies typically spin off the southern edge of Hawai‘i island. After formation, cyclonic eddies tend to propagate northwestward along the southern side of the other islands in the archipelago, while anticyclonic eddies propagate west-southwest. Anticyclonic eddies, such as those that develop off the southern tip of the island of Hawai‘i, generally travel further and maintain their structural features for longer, with their signals persisting as far 4000 km west at Wake Island (Calil et al, 2008; Lumpkin et al., 1998; Mitchum, 1985). This study investigates the influence of the islands on the development of new production in the otherwise nutrient-limited region west of the islands.

1.3.1 Background Patterns

While mesoscale eddies and island wake dynamics contribute to localized nutrient enhancement around the Hawaiian Islands, it is important to situate Hawai‘i within the broader nutrient landscape of the Pacific Ocean. Hawai‘i lies near the center of the North Pacific Subtropical Gyre, a vast oligotrophic region bounded by areas of elevated nutrient concentrations both to the north and south. These remote nutrient-rich zones help define the biogeochemical gradient within which Hawai‘i’s productivity dynamics occur. Dai et

al. (2022) illustrate global concentrations of various nutrients and denoting the boundaries of each gyre using a Chl-*a* concentration threshold. Figure 3 shows these concentrations at different depth levels, demonstrating that there are clear elevations of nutrients to the north and south of Hawai‘i along the borders of the NPSG, particularly in nitrate, phosphate, and silicate. Using the method to determine the boundaries of the NPSG described in Dai et al., the gyre tilts along with these elevated regions of nutrients, along the northeast to southwest diagonal. Additionally, differences inside and outside the gyre are generally more extreme at the surface. To the south, both the Northern Equatorial Current (NEC) and Intertropical Convergence Zone influence the southern border of the gyre, bringing nutrients to the surface through divergence leading to upwelling. The NEC operates between 8-18ºN and thus can have significant impacts on nutrient concentrations just south of Hawai‘i (Liu and Zhou, 2020). These nutrient regimes frame the central

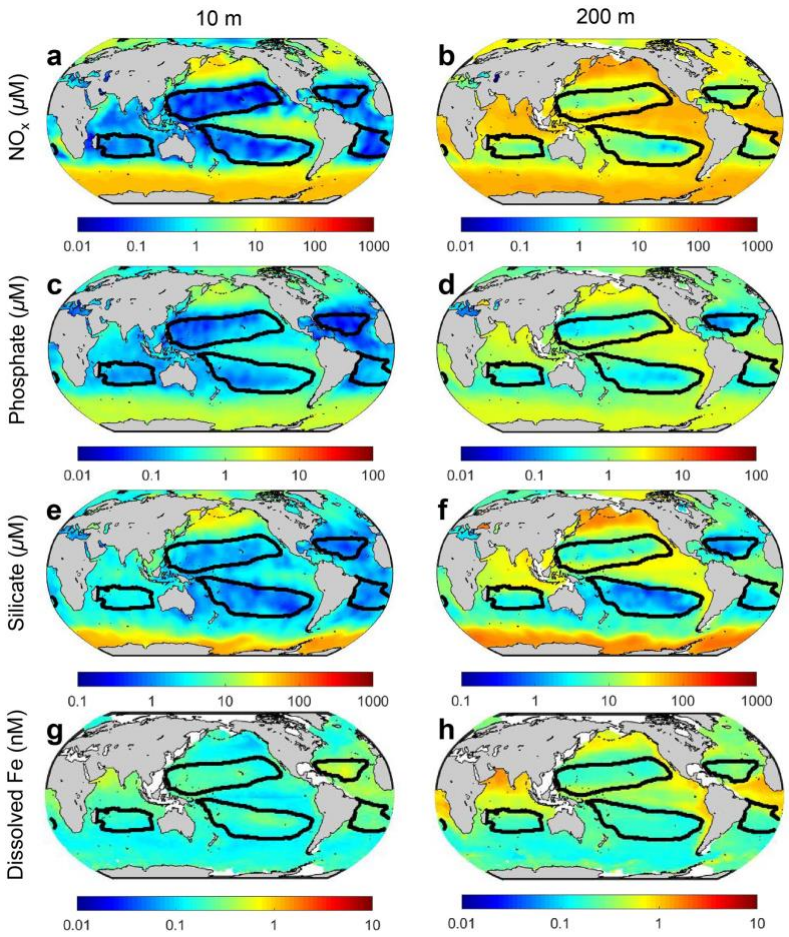

Figure 3. Climatological (a, b) NOx, (c, d) phosphate, (e, f) silicate, and (g, h) dissolved iron (Fe) concentrations (μM) at 10 and 200 m. See Dai et al. (2022) for data sources. (Dai et al., 2022)

Pacific's oligotrophic core, highlighting the isolation and ecological significance of localized enrichment processes like those drive by eddies generated in Hawai‘i.

1.4 Significance

Though studies about productivity induced by eddies and other mechanisms around Hawai‘i do exist, they focus primarily on the region of the ocean directly to the west of the Hawaiian Islands only extending to approximately 164ºW or in many cases even more eastward. Xie et al. (2001) demonstrates that Hawai‘i has a large physical cone of influence on the tropical Pacific, and that influence could extend to biology as well. Hence, the study area for this research is extended further westward to 170ºE to examine the potentially far-reaching impacts of the archipelago on biogeochemistry in the western Pacific.

2.0 METHODS

2.1 ROMS Model Setup

This study was accomplished using the Regional Ocean Modeling System (ROMS) coupled with the Carbon, Ocean, and Lower Tropics (COBALT) model to investigate biogeochemical variables. ROMS is a 3-dimensional, free-surface ocean model that has been used in a variety of applications to model the responses of a specific region of the ocean to physical forcings. The domain for this study spans the main Hawaiian Islands (MHI) along with the Northwestern Hawaiian Islands (NWHI), extending as far north as Mokupāpapa (Kure Atoll) and was integrated over the years 2000-2020. The bathymetry of the model is based on data provided by the General

Bathymetric Chart of the Oceans (GEBCO). The domain extends from 13-29ºN and 170-220ºE, with bathymetry shown in Figure 4. The model grid has 12 km horizontal resolution, starting at 18 km in at the boundaries and gradually increasing in resolution towards the center of the grid, with 32 vertical s-levels. ROMS uses a terrain-following sigma-coordinate (s-coordinate) vertical grid, meaning vertical layers conform to topography of the seafloor and are not fixed at specific depths. Each s-level corresponds to a vertical layer in the grid, and the actual depth of these layers varies horizontally and vertically throughout the grid. This allows for better resolution at the surface using stretching functions.

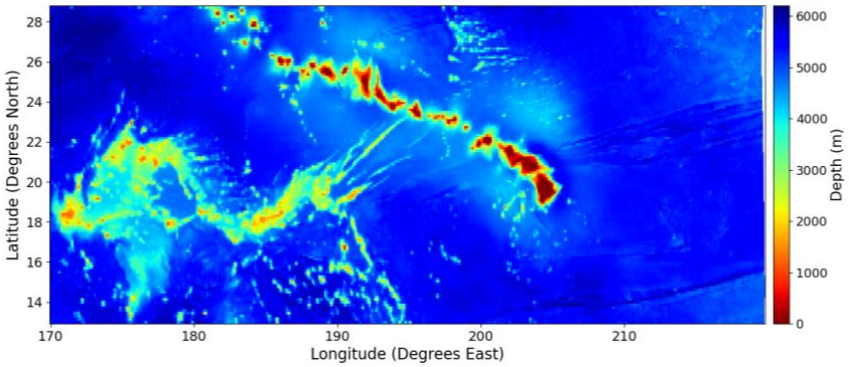

Figure 4. Model Grid Bathymetry

Atmospheric forcing of ROMS is based on the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis, referred to as ERA5. ERA5 is a global atmospheric reanalysis product from the ECMWF, which provides the necessarily 3-hourly forcing fields of surface air temperature, surface air pressure, relative humidity, rainfall rate, long- and short-wave radiation, and 10 m wind speeds. Boundary and initial conditions for physical ocean variables are derived from the Global Ocean Reanalysis and Simulations (GLORYS).

Biological variables were investigated using COBALT, a planktonic ecosystem model. Boundary and initial conditions come from a global COBALT simulation and are monthly climatologies that do not vary each year (e.g., every January is forced the same)

(Friedrich et al., 2024; Stock et al., 2014). This model resolves global carbon, nitrogen, phosphorus, iron and silica using 33 state variables, with nitrogen as the biomass currency. COBALT has three phytoplankton classes: small, large, and diazotrophs with primary production determined by various environmental variables. COBALT is on the same time step and is nested within ROMS and only impacts physical variables through light attenuation caused by chlorophyll. For more relevant details on the coupling of ROMS and COBALT see Friedrich et al. (2024) and Friedrich et al. (2021), and for an in-depth description of COBALT see Stock et al. (2014).

3.0 RESULTS

3.1 Physical Wake: EKE Maps and Eddy Dynamics

To investigate whether the Hawaiian Islands create a biological wake, and how far that wake extends, it is important to establish the presence of a physical wake in the model data. Hawai‘i disrupts the prevailing trade winds and ocean currents, generating both cyclonic and anticyclonic eddies in its lee. As a representation of the physical wake of the islands, eddy kinetic energy (EKE) was quantified. This measurement gives us a proxy for variability in the ocean due to the turbulent flow of the water from eddies, demonstrates the impact of the archipelago in their lee. Figure 5 shows the long-term 20-year mean of modeled EKE calculated using u-velocity and v-velocity via: $0.5 * [(u - \overline{u})^2 + (v - \overline{v})^2]$, highlighting persistent eddy activity west of the islands. The highest values occur directly west of Hawai‘i Island, where interactions with the Northern Equatorial Current (NEC) generate both cyclonic (upwelling-favorable) and anticyclonic (downwelling-favorable) eddies. The EKE wake extends to the edge of the

grid boundary, with a clear signature of the archipelago's cone of influence until approximately 180ºE.

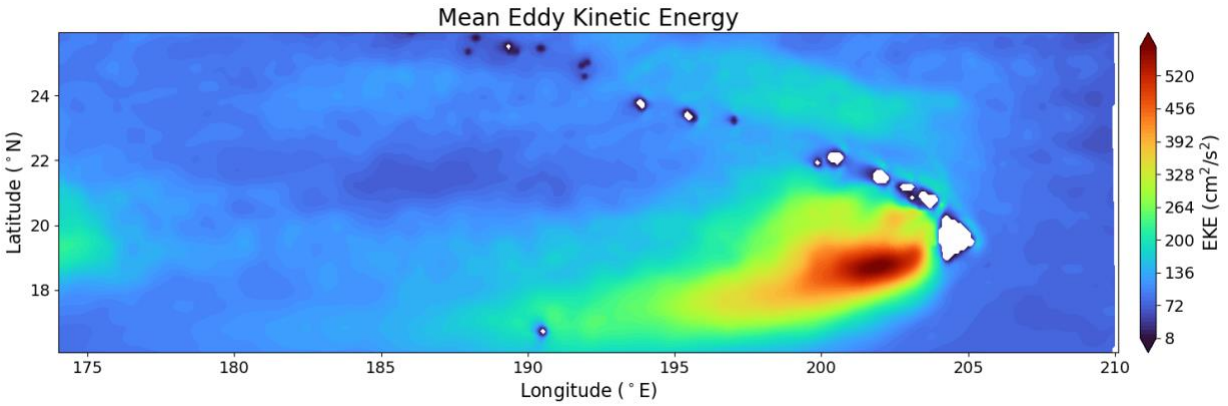

Figure 5. Mean surface eddy kinetic energy calculated with u- and v-velocities in the upper 50 meters.

When comparing this figure to Figure 1 from Xie et al. (2001), the SST wake and EKE wake have different spatial patterns. The band of max EKE in Figure 5 seems to follow along the southern edge of the peak positive SST anomaly in Xie et al. The spatial pattern of the EKE peak is more congruous with the negative wind curl generated off South Point on Hawai'i Island, as calculated by Xie et al. shown in Figure 6. Positive wind curl indicates cyclonic eddy formation, while negative wind curl indicates anticyclonic eddy formation. While this wake of wind curl is spatially smaller than the EKE peak in the lee of the islands,

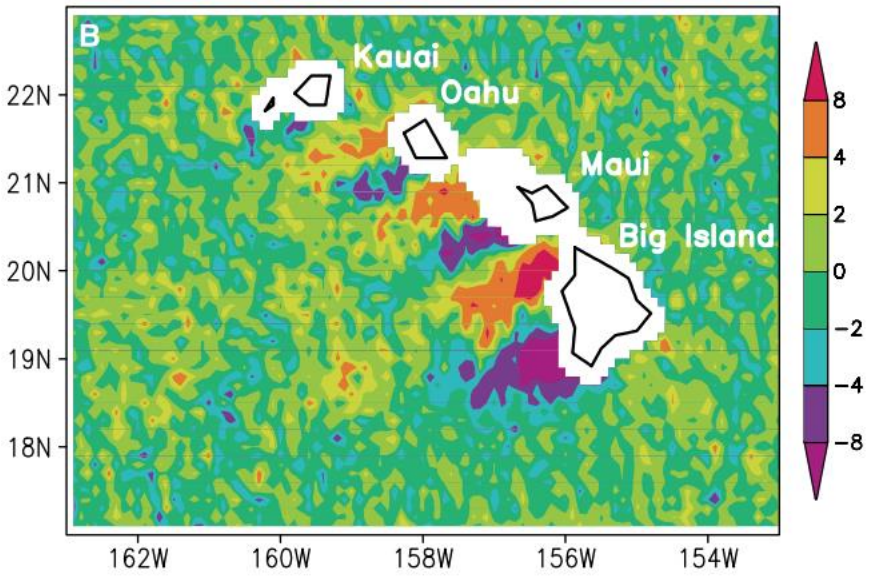

Figure 6. Wind curl observed by the QuikSCAT satellite for 1 to 31 August 1999 (Xie et al., 2001).

it is in the same spatial path to the southwest of the islands and is what sustains this high EKE tongue. While EKE demonstrates physical wake patterns, it does not inherently indicate biological enhancement. The next analyses will explore how key biological variables respond, or do not respond, to this physical forcing.

3.2 Characterizing the Biological Wake

3.2.1 Depth Levels for Analyses

Before discussing any specific analyses, this section will describe the depth levels that key nutrients and phytoplankton were averaged within. All analyses in this thesis were performed at two selected depth levels. Figure 7 shows the vertical depth profiles of nutrients and phytoplankton, demonstrating the nutriclines of nitrate, phosphate, and dissolved iron, and the deep maximum of phytoplankton. The first depth selected for the following analyses was the upper mixed layer (0-50 meters), and second depth was selected to represent the nutricline and upper nutrient reservoir (50-150 meters). The primary goal of the following analyses is to examine the spatial patterns of the biological wake of the islands, rather than specific temporal variations. Hence, these selected depth layers were fixed

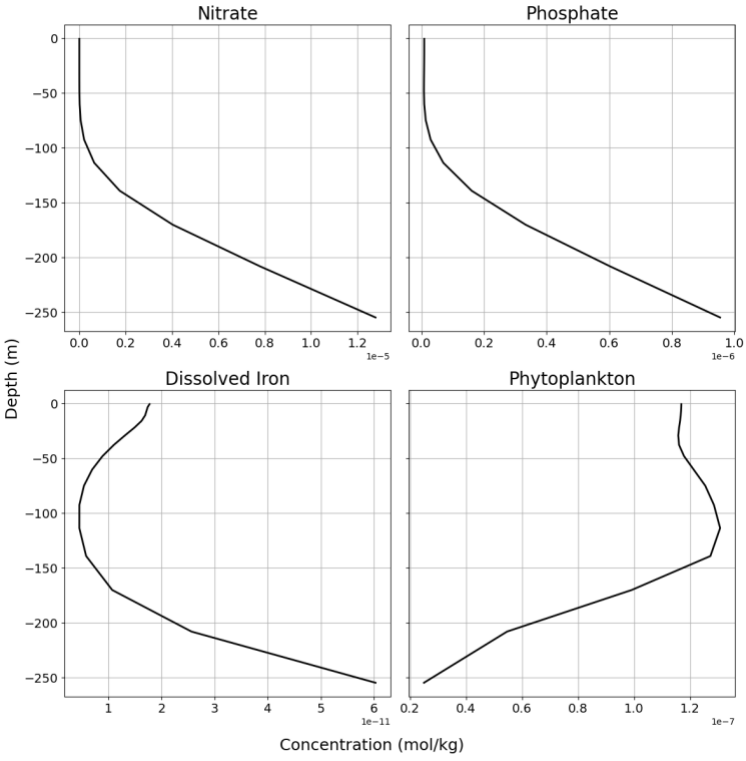

Figure 7. Depth profiles of nutrients and phytoplankton in the lee of the islands.

over time, rather than doing analyses of variables over a time-varying mixed layer, to maintain spatial consistency for comparison.

3.2.2 Mean States of Key Nutrients and Biological Variables

To begin understanding how the Hawaiian Islands influence biological processes in the west Pacific, the 20-year time means of modeled key nutrients and phytoplankton were examined. These mean state maps provide a baseline view of the spatial patterns in important variables before analyzing temporal variability, at each of the two selected depth levels.

The mean state distributions reveal several important patterns. Figure 8 shows the mean states of nitrate, phosphate, dissolved iron, and two different size classes of phytoplankton: picoplankton and diatoms. Nitrate and phosphate concentrations are largely depleted in the surface waters due to biological activity but are enriched at depth, particularly near the islands in the lee where upwelling and remineralization contribute to nutrient enrichment. Notably, nitrate is nearly an order of magnitude less abundant than phosphate at the surface, but more abundant at depth, which is consistent with the global patterns demonstrated by Dai et al. (2022).

Dissolved iron is overall higher in surface waters by a factor of two, which could be due to deposition or lower biological demand in surface waters. At depth, iron similarly is elevated near the islands, though the spatial pattern is different than phosphate, and iron shows elevation in the region southeast rather than northeast of Hawai‘i Island. Phytoplankton distributions show distinct spatial differences: picoplankton (small) dominate the oligotrophic waters at both depth levels, while diatoms

(large) are limited to the region close to the islands, likely responding to nutrient input events. Picoplankton is comparable in the surface versus at depth, though the elevation near the islands is clearer at depth, while diatoms are very limited in the surface waters compared to depth.

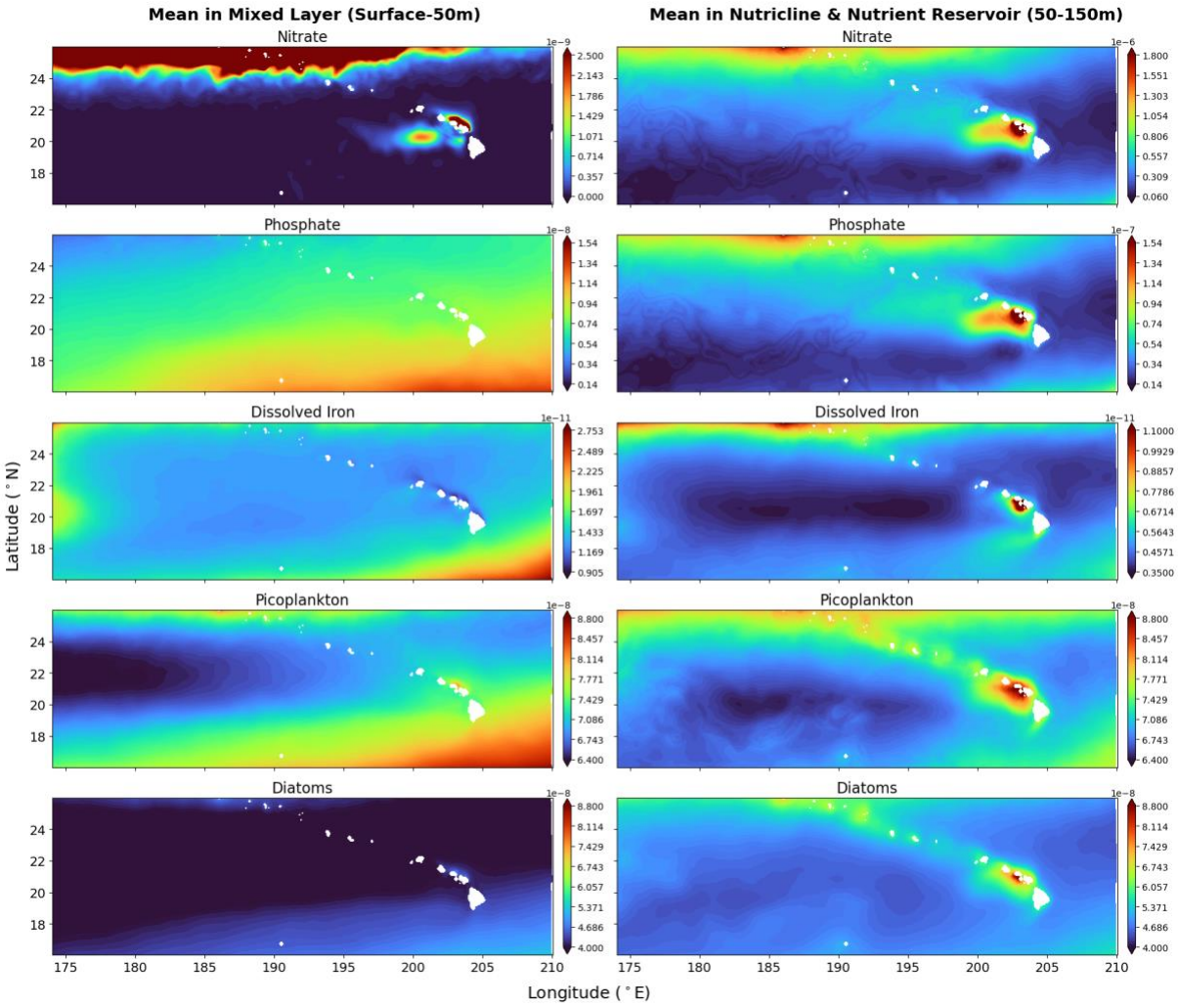

Figure 8. Mean states of nutrients and phytoplankton. Units are mol/kg for all variables. Row 1: Nitrate, Row 2: Phosphate, Row 3: Dissolved Iron, Row 4: Picoplankton, Row 5: Diatoms; Column 1: upper 50 meters, Column 2: between 50 and 150 meters.

A key challenge in studying nutrient dynamics around Hawai‘i is tracking the availability of nitrate, the primary limiting nutrient in this system. Nitrate is rapidly

consumed in surface waters (Fig. 8) making it difficult to observe stable patterns in its distribution. Above 50m in the mixed layer, it is nearly depleted, except during short-lived mixing or upwelling events. At depth, nitrate concentrations are 3 orders of magnitude higher, showing strong vertical stratification and the presence of a nutricline that supplies deeper phytoplankton populations.

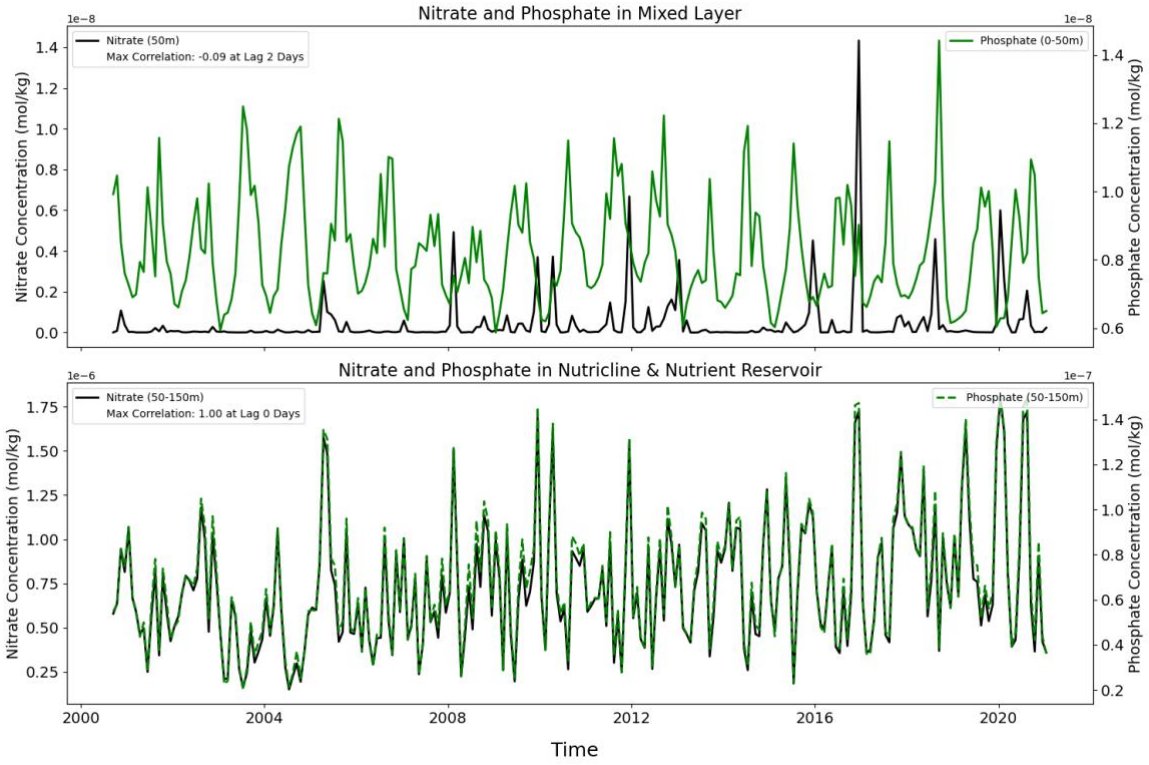

Figure 9. Time series of Nitrate and Phosphate at different depths. Top: 0-50 meters, Bottom: 50-150 meters. Nutrients are averaged over a region directly west of Hawai'i island. Max correlations at different time lags: 0-50m = -0.09 at 2 days, 50-150m = 1.0 at 0 days.

Because nitrate is so biologically reactive at the surface, phosphate serves as a more stable proxy for nitrate availability in the upper ocean. Figure 9 shows a time series of these two variables at each depth level and their maximum correlation at different time lags in the region directly west of Hawai'i Island. This figure demonstrates that phosphate and nitrate are highly correlated at depth at a lag of 0 days (correlation = 1.0),

where remineralization fuels their accumulation. However, phosphate persists longer at the surface and has a seasonal cycle, allowing us to track spatial patterns associated with upwelling and biological consumption over longer timescales. By using phosphate as a proxy, nutrient variability and its relationship with biological production in the wake of the islands can be more effectively assessed.

3.2.3 Temporal Variability: Time Series in Different Regions

While mean state maps provide a snapshot, they do not capture how biological conditions fluctuate over time. To address this, timeseries of key biological variables within four distinct regions were compared. These four regions are shown on Figure 10a. Figure 10b shows other regions that were also examined, and will be discussed later in the results:

1. *West* (center of domain, far west from the islands where EKE signal begins to diminish)
2. *Lee* (directly west of Hawai‘i Island, cyclonic eddy region, upwelling likely)
3. *South Lee* (directly west of Hawai‘i Island, anticyclonic eddy region, downwelling likely)
4. *Northeast* (control region, selected both for low EKE and low nutrients/biology)

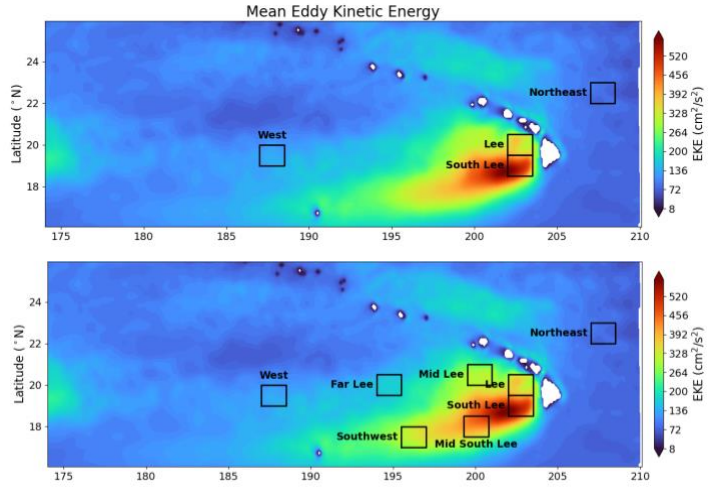

Figure 10. a) Top Panel: Main regions for time series comparison; b) Bottom Panel: other regions for future comparisons.

In each of these regions, nutrients and phytoplankton were spatially averaged to create time series within each box and demonstrate the temporal patterns at different locations throughout the domain.

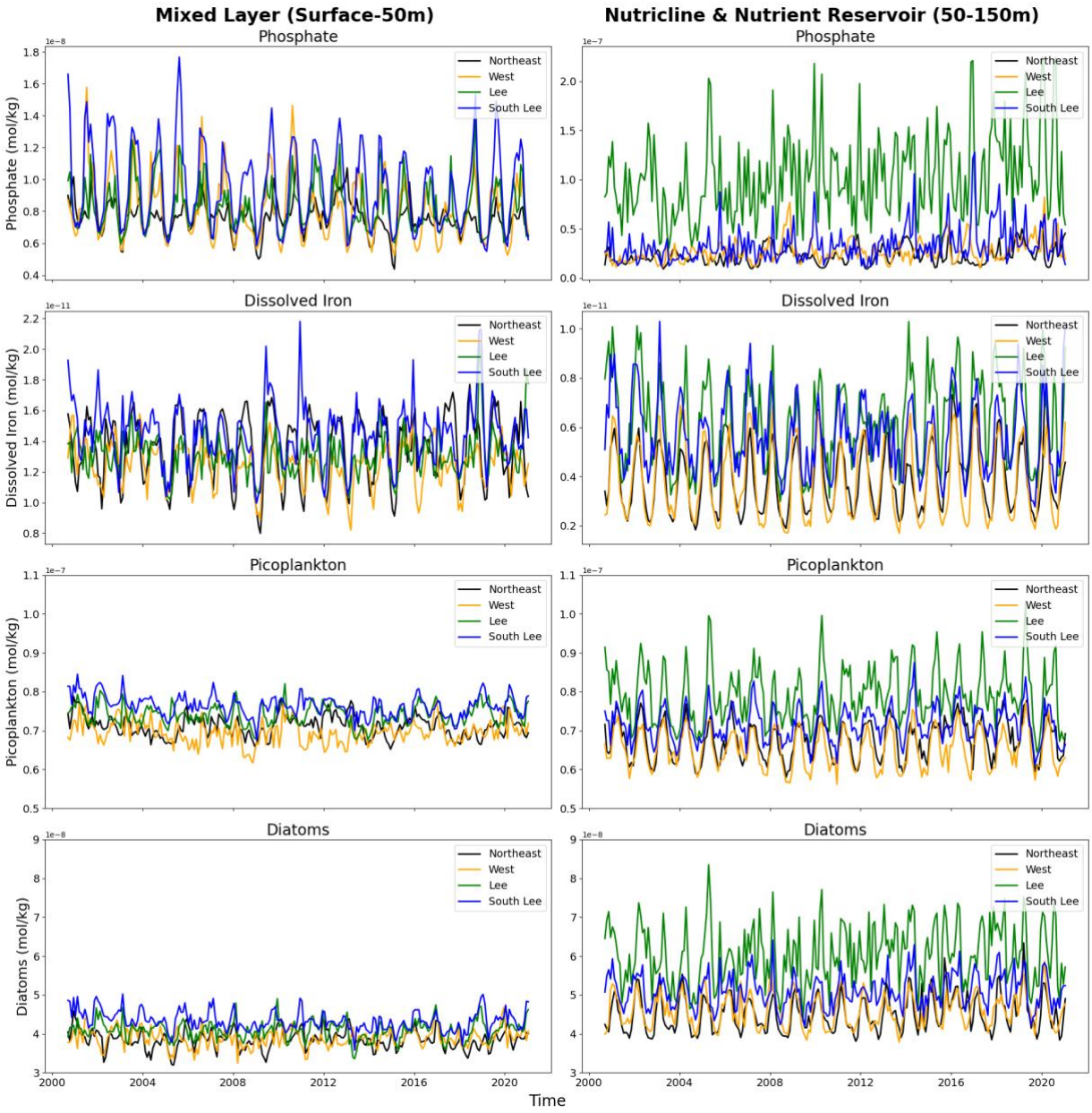

Figure 11. Time series in regions of interest. Rows in order: phosphate, dissolved iron, picoplankton, diatoms; column 1: 50 meters, column 2: 50-150 meters. Each time series plot shows variable in west, lee, south lee, and northeast regions, as defined in Figure 10.

Figure 11 highlights how nutrients and biology vary in time. Generally, the leeward regions close to the islands show higher overall means, especially in the *Lee* region, which is to be expected due to the influence of the islands. They also show higher variability, suggesting strong biological responses to episodic upwelling or mixing events. Additionally, we can see a seasonal cycle in the time series plots, with some variables and depth levels more clearly showing this seasonality. The *Lee* region, at the 50-150m depth has clearly elevated biological activity, while that elevation is seen more strongly in the *South Lee* at 50m. These two regions are expected to have the highest biological production, as they are closest to the islands. These comparisons were also performed for regions further west of the islands (see Appendix 1, Fig. 11a and Fig. 11b), and at depth in the cyclonic eddy cone of influence, phosphate was found to have a noticeably elevated mean until approximately 194ºE, while phytoplankton were elevated until about 198ºE. Generally, at further distances west, dissolved iron is higher in the anticyclonic cone of influence. Picoplankton and diatoms show similar temporal patters, though diatoms are more depressed in the surface compared to depth than picoplankton, likely due to nutrient depletion.

3.2.4 Standard Deviation Maps: Identifying High-Variability Regions

These regional time series can give us a look at what is happening in time, but it is also important to understand variability in space, because this can give us insight into where biological fluctuations are most pronounced, and how the islands might be affecting that influence. To do this, the standard deviation was computed.

Standard deviation, shown in Figure 12, provides insight how much the biological environment behind the island deviates from the average or expected conditions, which may suggest how the islands are influencing said variables. Notably, at depth 50-150m, standard deviation of phosphate and phytoplankton is elevated west across nearly the whole northeast part of the domain. In these plots, there is a clear delineation between the cyclonic cone of influence to the northeast, which elevates nutrients/biology and their variability, and the anticyclonic cone of influence to the southeast, which depresses biological activity. This depressed activity could lead to the low variability that can be observed above, because nutrients are likely depressed below 150m by anticyclonic eddy activity. There are fewer opportunities for nutrient spikes, and hence, less variability.

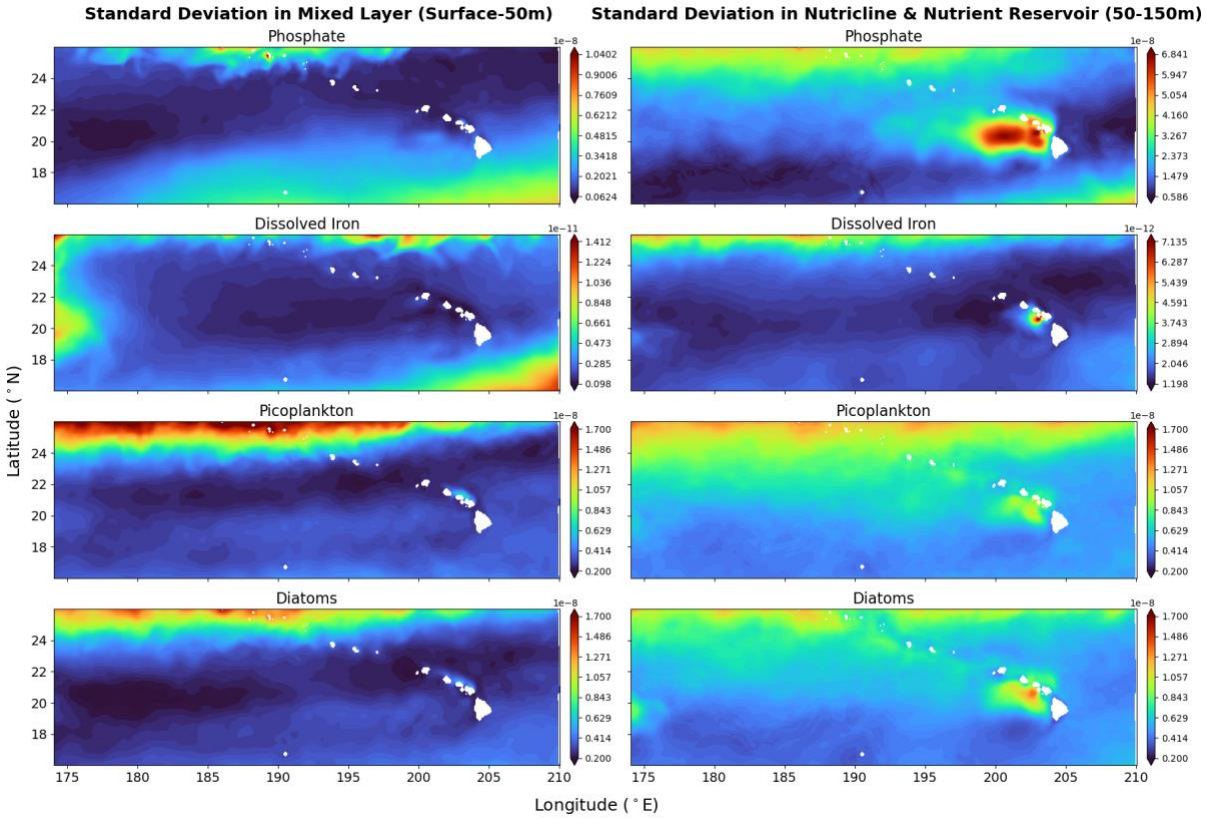

Figure 12. Standard deviation of nutrients and phytoplankton. Row 1: Phosphate, Row 2: Dissolved Iron, Row 3: Phytoplankton; Column 1: upper 50 meters, Column 2: between 50 and 150 meters.

3.2.5 Comparative Ratios: West vs. East Pacific

The goal of the final analysis in this section was to evaluate the difference between key variables in the west and east pacific, to determine how water characteristics differ on opposite sides of the Hawaiian Islands. This was quantified by examining the ratio of nutrients/biology between the west and east Pacific. This ratio was generated by dividing each point of the grid to the west of the islands by a band of values along the east of the island chain. Figure 13 shows these ratio values, specifically at the nutricline and nutrient reservoir depth, because the mixed layer depth did not show a significant wake from the islands. In this graph, red indicates that the variable is higher in the west and blue indicates that the variable is higher in the east.

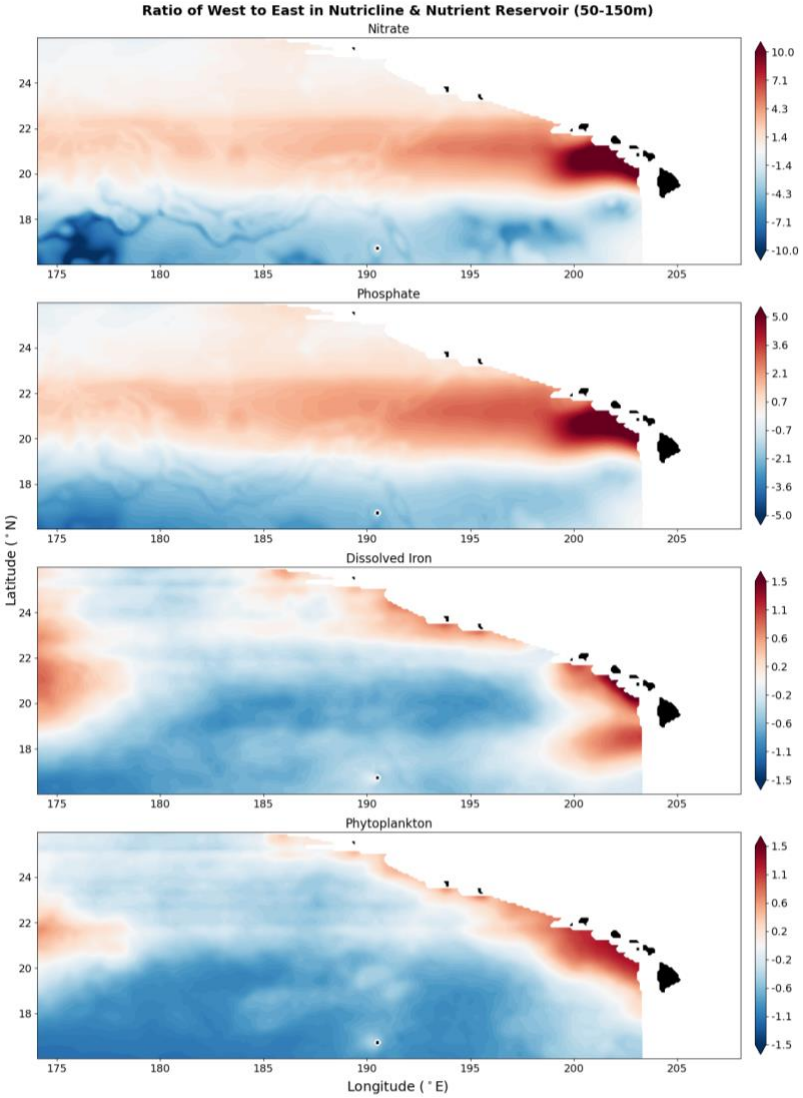

Figure 13. Ratio of west to east of each variable mean at 50-150m: nitrate, phosphate, dissolved iron, and phytoplankton. Red indicates the variable mean is higher in the west, blue indicates it is higher in the east.

Figure 13 demonstrates that nitrate and phosphate have long-reaching wakes that extend to the western boundary of the domain. Their spatial pattern is very similar,

though nitrate has slightly higher ratio values. In the lee of the islands, nitrate and phosphate are elevated higher than in the east of the islands across the entire domain, out to at least 175ºE. The nitrate/phosphate wake does not however, follow the spatial patterns of wake of EKE that we see to the southwest of the islands, or the wake in SST observed by Xie et al. (2001), which both travel primarily southwest. Rather, it seems to be separated into an elevation of nutrients in the north, and a depression in the south. This parallels the difference between the cyclonic and anticyclonic cones of influence to the northwest and southwest of the islands respectively.

Given the long extend of phosphate and nitrate, experiments were also performed to determine whether significant amounts of either nutrient were being advected from the west, by determining where mean u-velocities at the boundary of the domain were positive (indicating eastward flow) and removing the boundary nutrient values at these latitudes. This demonstrated that the HLCC does transport some nutrients eastward towards the island, but removing these impacts did not significantly change the spatial extend of either wake.

Contrastingly to nitrate and phosphate, iron and phytoplankton do not show a long-reaching wake to the same extent and are primarily elevated close to the island chain. However, dissolved iron does show a southwestern elevation in the lee of the islands that is more spatially connected to regions of elevated EKE than the other variables.

This ratio analysis was also performed on the other variables of interest, and threshold calculations were done to determine how far into the West Pacific the wake of each variable extends. Generally, the upper mixed layer primarily reflects the

surrounding nutrient concentrations of the wider pacific region and subtropical gyre, with less prominent specific impacts from the islands. The 50-150m depth layer demonstrates that nutrients have wakes to varying degrees that extend westward. The overall impacts are summarized in Table 1 below, which shows on average, how far (in kilometers) from the islands each variable remains elevated, based on the ratios calculated above. These values were calculated by determining the average distance from the islands where the ratio value permanently drops below 0.2, an arbitrarily threshold chosen to indicate where the ratio value is permanently positive. Distance in degrees was then converted to kilometers. Overall, the nutrients have more extensive wakes than the two phytoplankton size classes, which generally remain concentrated around the islands. Similar spatial patterns can be observed in the ratio of dissolved iron and phytoplankton.

Table 1. Average threshold of 0.2 value in ratio for each depth level and each nutrient and biological variable.

Depth	**Nutrient**	**Mean Distance (km)**
Mixed Layer (0-50m)	Phosphate	240
	Dissolved Iron	Insignificant
	Picoplankton	Insignificant
	Diatoms	Insignificant
Nutricline & Nutrient Reservoir	Nitrate & Phosphate	2200

(50-150m)	Dissolved Iron	433
	Picoplankton	340
	Diatoms	356

3.3 Drivers of Biological Wake

To examine what drives the biological wake, the relationship between EKE and nutrients/phytoplankton was investigated, including how these biological variables and dynamic signals change with distance from the islands, and how phytoplankton groups respond to changes in nutrients. Power spectrum analysis was used to explore dominant time scales of variability and the extent to which EKE regulates biological productivity.

3.3.1 Nutrient EKE Time Series Comparisons

First, the time series of EKE in two regions of interest is observed to demonstrate the visual connection between cyclonic and anticyclonic eddies, and productivity. Region *Mid Lee* and *Mid South Lee* are situated in the cyclonic and anticyclonic cones of influences respectively (see Figure 10 for all region boundaries).

Figure 14 demonstrates a visual relationship between EKE and phosphate in the *Mid Lee* region at both depth levels, with peaks lining up along with the overall pattern. This time series plot reflects the strong coupling of EKE and nutrients in the cyclonic eddy zone of influence. However, the correlation in the mixed layer between EKE and phosphate is 0.38, while at depth it is 0.08. These values are negligible, and so correlation is not an effective metric to demonstrate the connections between biologically relevant

variables and EKE. Given that there is no significant correlation, this indicates that the two signals are operating independently. Since the signals do seem to be visually related as demonstrated in the time series plots, there could something suppressing the signal, or a nonlinear relationship between the two that is not represented by correlations. Scatter plots of EKE vs each variable were also created to examine those nonlinear relationships,

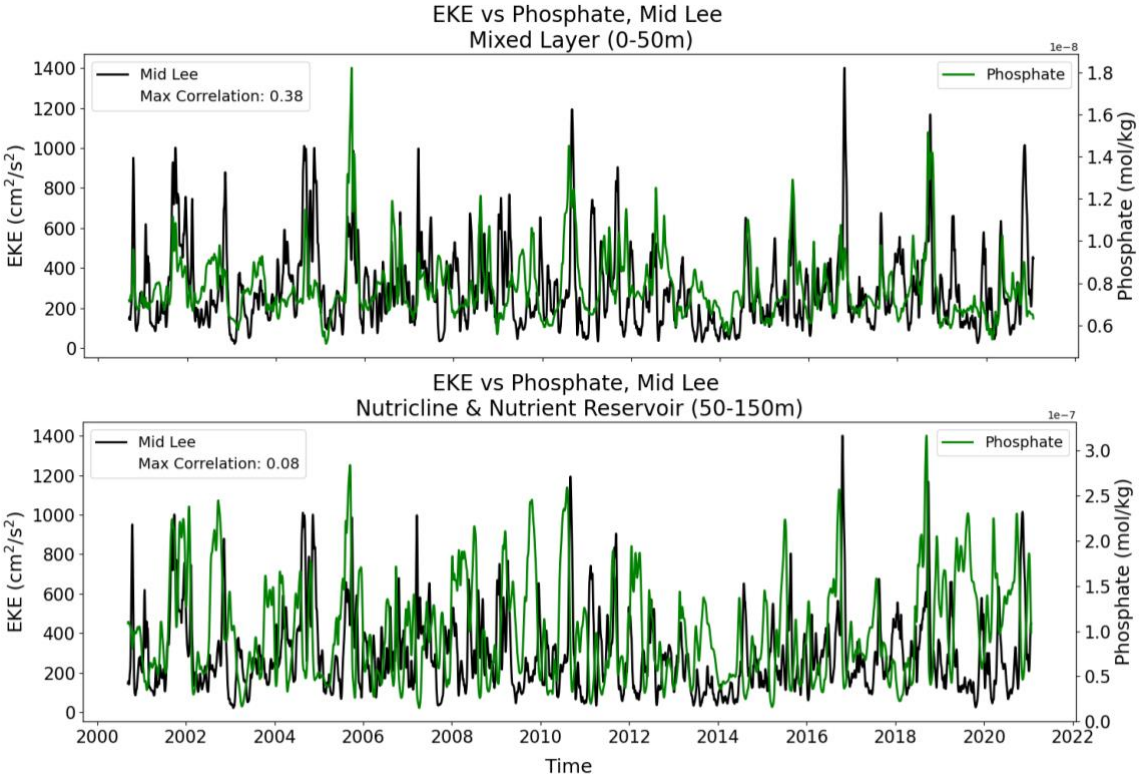

Figure 14. EKE versus Phosphate in the Mid Lee region at 50m and 50-150m.

but no significant clustering at extremes was observed.

Figure 15 demonstrates the relationship between EKE and phosphate in the *Mid South Lee* region, which is directly in the anticyclonic cone of influence. In the mixed layer, there is a clear seasonal cycle in phosphate that seems to operate somewhat independently of the EKE pattern, indicated by -0.06 correlation value. Rather, this seasonal cycle could be more representative of global patterns, such as gyre movement,

that we see in the spatial means. At depth, in the nutricline and nutrient reservoir, there are many more spikes in EKE where phosphate does not follow, which is consistent with anticyclonic eddies leading to depressed productivity. Additionally, EKE and phosphate in this region have a correlation of -0.22, which does not suggest any significant relationship between the two variables in the *Mid South Lee* region. Dissolved iron and phytoplankton also show insignificant correlations with EKE. While broad relationships exist, particularly in the cyclonic cone of influence, the lack of consistent correlations suggest that this method might not fully capture the dynamics.

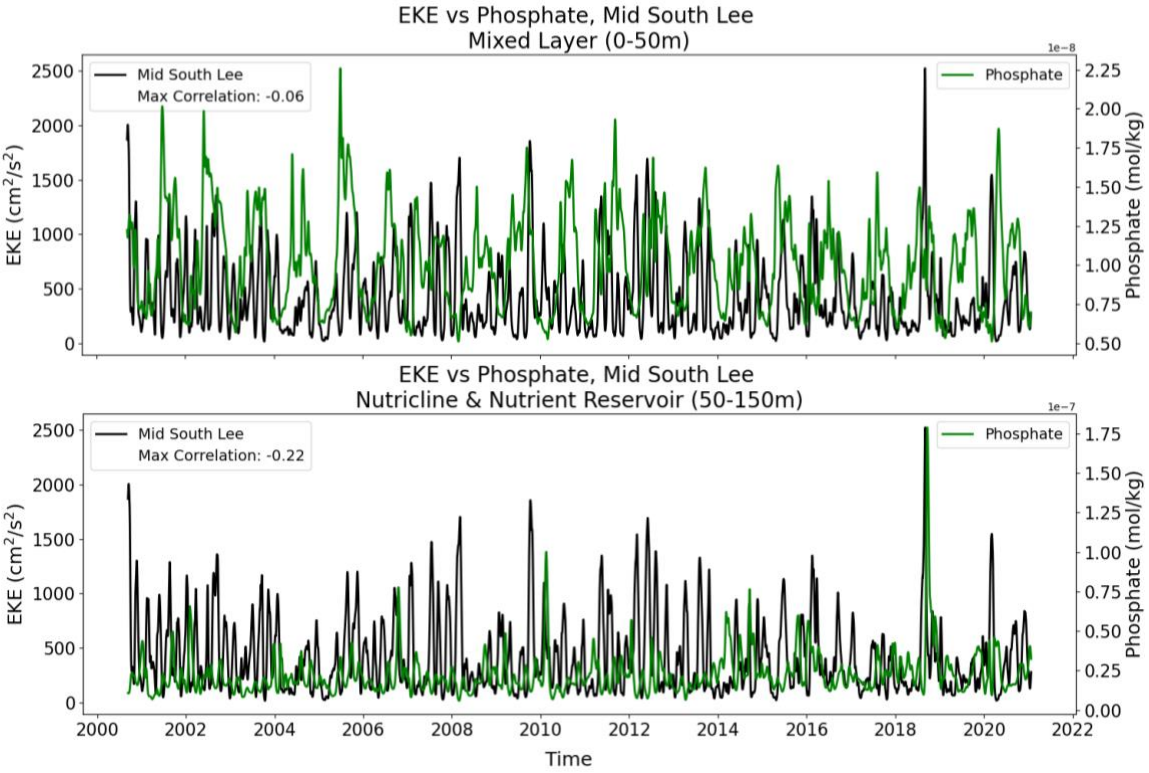

Figure 15. EKE versus Phosphate in the Mid South Lee at 50m and 50-150m.

3.3.2 Power Spectrum Analysis

Due to the low correlations between the variables, power spectrum analysis was utilized to determine the dominant frequencies at which variability occurs. This can

identify periodic signals that may not be apparent in time series visualizations. While correlations show whether two variables fluctuate together, they do not indicate whether those fluctuations are happening on the same timescales. By analyzing power spectra, we can determine whether biological and nutrient variability align with specific dynamical processes, such as mesoscale eddies (~30-120 days) or large-scale seasonal cycles (annual), providing deeper insight into the physical-biological coupling in the wake.

3.3.2.1 Dominant Timescales of Variability in Different Regions

The following graphs focus on these four regions of interest: *Northeast, Lee, West,* and *South Lee*. These regions are found in the extremes of the domain, both very close to the islands and in the remote ocean. They were chosen to better understand what frequencies of variation drive biological variables in contrasting areas of the domain. Generally, high-frequency signals are stronger in the two regions close to the islands (*Lee, South Lee*), while lower-frequency signals, such as an annual signal, are stronger in the two remote regions (*Northeast, West*).

Figure 16 shows the power spectrum analysis of variables of interest within the mixed layer, while Figure 17 is the same plot at the nutricline and nutrient reservoir. Both figures demonstrate that the strongest signal in the nutrients and biology is an annual cycle that is shown in the large peak at 360 days. While this annual cycle appears very wide in the graph, that is due to smoothing that was applied after the power spectrum was calculated to reduce noise, and this peak does occur around 360 days, not the entire range that is shown above. This strong annual signal may reflect seasonal variability in physical processes affecting the upper ocean, such as mixed layer dynamics,

thought it must be noted that this analysis uses fixed depth ranges and does not resolved changes in the mixed layer itself. Additional peaks in this spectrum, particularly in the range of 60-120 days, likely reflect eddy activity and other variation at shorter time scales. Generally, at both depth levels, though more pronounced in the nutricline and nutrient reservoir, high-energy frequency is stronger near the islands, and low-frequency energy is stronger in the remote regions. This separation is most notable in iron, but can also be seen in phosphate, diatoms, and to some degree, picoplankton.

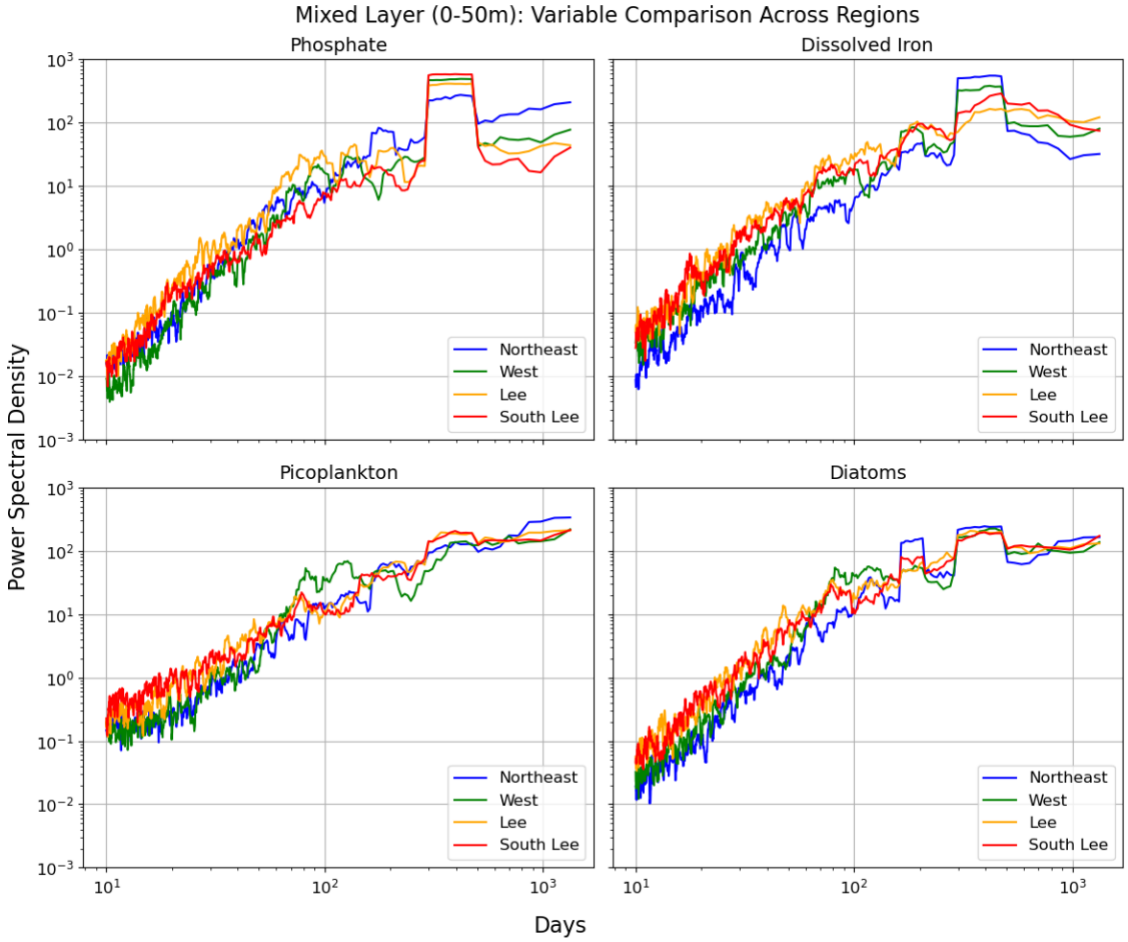

Figure 16. Power spectrum analysis of nutrients and phytoplankton at 50m in different regions (Northeast, Lee, West, South Lee) as described in Figure 10.

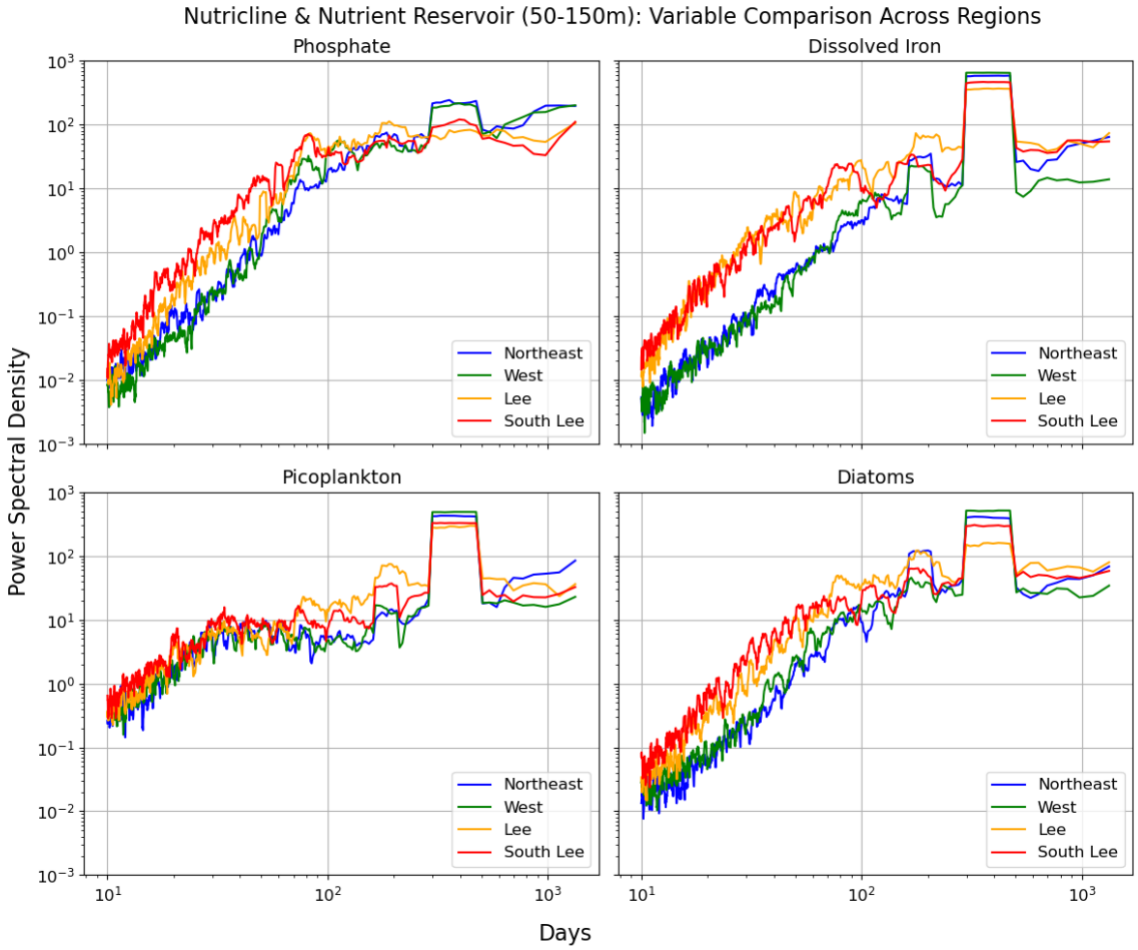

Figure 17. Power spectrum analysis of nutrients and phytoplankton at 50-150m in different regions (Northeast, Lee, West, South Lee) as described in Figure 10.

3.3.2.2 Nutrients & Biology vs EKE

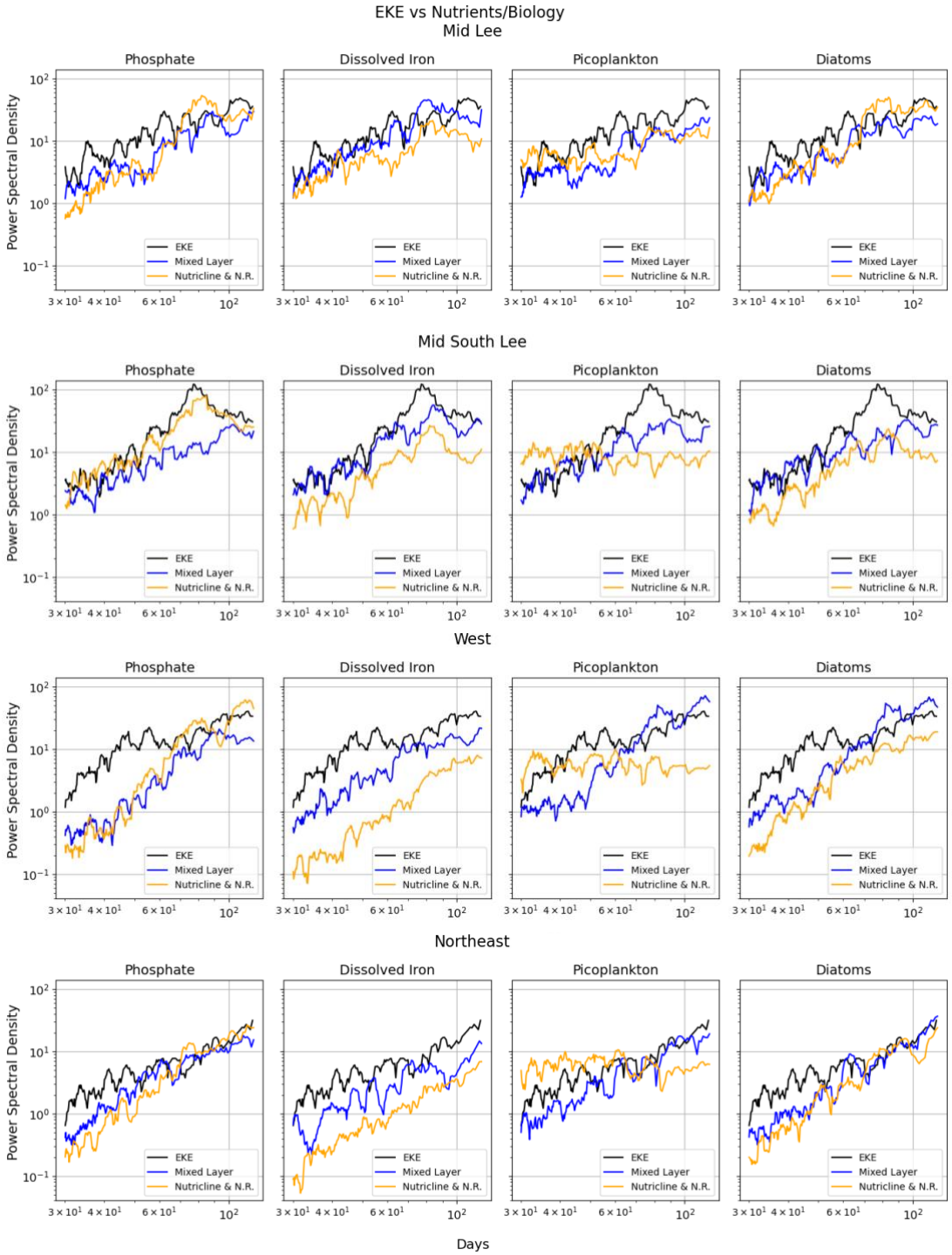

Figure 18. Power spectrum analysis of nutrients, phytoplankton, and EKE at both depth levels in different regions (Mid Lee, Mid South Lee, West, Northeast) as described in Figure 10.

Figure 18 demonstrates the power spectrum in four regions of interest: *Mid Lee, Mid South Lee, West,* and *Northeast*. In the *Mid Lee*, there are a few distinct peaks, such as at 60, 70, and 80 days. Phosphate and dissolved iron seem to loosely track the peaks of EKE, though the magnitudes are different. The strongest signal in EKE is in the *Mid South Lee* region, at approximately 80-90 days, which is to be expected given that this is directly in the anticyclonic eddy path. Anticyclonic eddies persist longer and are stronger than cyclonic eddies. Responses in dissolved iron, phosphate, and diatoms at that signal can also be observed, particularly in the deeper layer, which is likely a depression rather than an upwelling of these nutrients due to anticyclonic eddy movement. The closer relationship between diatoms and EKE than between picoplankton and EKE suggests that this larger size class of phytoplankton has higher nutrient requirements and is more related to events that spike or depress nutrients, while picoplankton is well adapted to the region and operates more independently of these events.

Though in the *West* and *Northeast* regions, nutrients and biology do track the EKE peaks to some degree, the magnitudes are quite spread out and slopes appear to be less congruous than in the *Mid* and *Mid South Lee* regions. In the *Northeast*, overall energy levels are lower, particularly in EKE. Generally, the two remote regions show less connection between nutrients/biology and EKE, while the regions closer to the islands have clearer connections in magnitude and slope — though these relationships are still weaker than anticipated. Another pattern of note is that picoplankton at the nutricline have an opposite slope to the rest of the variables, decreasing at the window of eddy activity. This further suggests that EKE and picoplankton do not vary on the same

timescales of variability because small phytoplankton are well adapted to background oligotrophic conditions and eddies promote diatom growth and competition.

4.0 DISCUSSION

4.1 Physical Wake

The Hawaiian Islands create a well-defined physical wake in EKE in the lee of the islands, extending out clearly until 185ºE (~2100 km west of Big Island), with trace effects all the way out to the edge of the domain, at approximately 175ºE (~3100 km west of Big Island) (Fig. 5). These findings align with Xie et al. (2001), who demonstrated a westward wake in sea surface temperature and wind patterns reaching up until 3000 km west of the islands. Though spatial patterns of the EKE wake and SST differ, similarity can be seen between calculated EKE and wind curl from Xie et al. (Fig. 1, Fig. 2). The presence of both cyclonic and anticyclonic eddies in the lee of the islands, along with other factors of the island mass effect, motivates the question of how physical forcing structures downstream biological and chemical processes. The persistence of EKE far into the west Pacific demonstrate that the model run represents the Hawaiian Islands exert far-reaching influences on ocean dynamics, at least in terms of eddies, potentially driving nutrients and primary production patterns in the oligotrophic Pacific.

4.2 Characterizing the Biological Wake

The biological wake, as identified in this study, extends significantly westward but varies in spatial extent depending on the variable measured. It is important to note that the islands can both increase and decrease productivity in their wake, through

cyclonic and anticyclonic eddies respectively. The far-reaching wake this study is investigating is not just the elevation of nutrients and biology in the lee of the islands, but also the depression of these same variables. Additionally, throughout the experiments, the surface layer between 0-50m tends to be more independent of the islands influence and congruous with broader basin wide patterns (Fig. 3), while the nutricline and nutrient reservoir sees a stronger influence from the island chain, so this analysis will primarily focus on the 50-150m depth horizon. As previously discussed, Hawai‘i rests between two zones of elevated nutrients to the north and south at the bounds of the subtropical gyre. It can be observed that these large-scale circulation patterns set up by atmospheric circulation and the Coriolis force dominate the nutrient regimes at the surface, with elevated nutrients to the northwest and southeast corners particularly (Fig. 8). In deeper layers the influence of the islands becomes more prominent in the lee of the island chain, though the broader patterns can still be observed.

Nitrate and phosphate exhibit the longest detectable wakes, with clear elevation in both the mean and standard deviation fields until approximately 190ºE (Fig. 8, Fig. 12), and more trace elevation across the whole domain as illustrated by the ratio comparison (Fig. 13), remaining elevated across the whole domain until 170ºE. These two nutrients also show clear negative wakes in the southwest lee of the islands, where the anticyclonic zone of influence leads to downwelling of nutrients. Iron and phytoplankton concentrations show less clear spatial relationships with cyclonic and anticyclonic eddy zones. Generally, they are strongly enhanced near the islands, but this elevation dissipates sooner than in phosphate, approximately the western edge of Kaua‘i and Ni‘ihau at about 198ºE (Fig. 8). Trace elevations to variability in phytoplankton are observable across the

domain (Fig. 12). This difference in phosphate and iron could be due to differences in remineralization rates, biological demand for the nutrients in different regions, and external nutrient sources.

There are significant differences in the spatial pattern of nitrate/phosphate and iron in the lee of the islands, with nitrate/phosphate primarily in the Northwest cyclonic eddy zone of influence, and iron in the Southwest of Hawai‘i island, primarily in the anticyclonic zone of influence. Iron particles also sink faster out of the water column than nitrate and phosphate due to their chemical properties, because they form insoluble particles and aggregate with other materials via abiotic scavenging and adsorption (Parekh et al., 2005). Nitrate and phosphate are primarily disssolved in seawater and do not sink readily on their own, relying on interaction with biology to be removed from the mixed layer. This could lead to a lack of iron in regions far from land and regions of high influx, because it does not remain suspended as long in the water column. One source of iron that could be missing from the model is volcani ash from Kīlauea on Hawai‘i island, which may intensify the southwestward wake.

Phytoplankton concentrations suggest that while eddy activity can stimulate productivity locally, the far-reaching wake primarily consists of elevated nitrate and phosphate, while iron becomes more limited in the center of the domain and potentially impacts phytoplankton concentrations. While nitrate is generally the primary limiting nutrients in the water surrounding Hawai‘i, this suggests that in certain regions and time periods co-limitation occurs with other nutrients. As discussed by Letelier et al. (2019), new nitrogen can be introduced to the system through nitrogen fixers like diazotrophs, but these organisms are limited in their growth by other nutrients. Their study focused on

the eastern region of North Pacific Subtropical Gyre, and the oscillation of limitation between phosphorus and iron.

Key differences between different size classes of phytoplankton can also be observed. Picoplankton are smaller and better adapted to low nutrient oligotrophic conditions, while diatoms are larger and thrive in conditions of episodically higher nutrients, such as during upwelling events. These patterns are reflected in the means, with picoplankton dominating the phytoplankton concentration and being elevated more ubiquitously throughout the region, while diatoms are lower in biomass and concentrated closely to the area around the islands.

4.3 Factors Influencing Biological Wake

While there is an elevation of all the biological variables in the immediate lee of the islands (Fig. 8), these effects change as waters become more remote, and the relationship between biology and EKE is not uniform. Time series correlation analysis reveals that variables in the cyclonic cone of influence are more correlated with EKE, though these correlations are still not particularly significant, while variables in the anticyclonic cone of influence show no correlation with EKE (Fig. 14, Fig. 15).

Power spectrum analysis demonstrate that dominant timescales of variability do differ based on location. Near the islands, high-frequency fluctuations associated with localized processes like mesoscale eddies, play a stronger role in regulating nutrient and phytoplankton dynamics, while in remote regions, seasonal cycles and lower-frequency processes become more prominent (Fig. 16, Fig. 17, Fig. 18). It can also be seen that phosphate and dissolved iron track EKE more closely in the anticyclonic zone of

influence than in the cyclonic zone of influence, suggesting that the depressing of nutrients due to downwelling may be relatively stronger than the elevation through upwelling. Hence, considering the lifespan of cyclonic vs anticyclonic eddies is important. Anticyclonic eddies persist longer than cyclonic eddies as observed by satellite altimetry (Chelton et al., 2011), possibly creating a longer and/or stronger wake of production suppression in their wake. Shi et al. (2024) suggest that the reason for this difference in longevity is due to asymmetries in spatial and temporal evolutions of small-scale features such as submesoscale filaments in the two kinds of eddies. In anticyclonic eddies, these filaments tend to migrate outward, and do not affect the eddy core, making it more stable. In contrast, filaments move inward in cyclonic eddies, more quickly distorting the core and leading to shorter lifespans and potentially short wakes in nutrients and production. Overall, these results suggest that eddies and local processes mediate biological regimes closer to the island chain, which can have far-reaching spatial impacts, while large-scale oceanographic processes like gyre circulation shape more remote regions, particularly in the surface ocean.

4.4 Limitations and Future Work

While this study contributes to the baseline understanding of the Hawai‘i-driven biological wake, limitations should be acknowledged. The ROMS model coupled with COBALT, while effective in capturing physical and biogeochemical interactions, does not fully represent the complexity of ecosystem dynamics. The classification of phytoplankton into two functional groups limits our ability to assess species-specific responses to nutrient changes. Additionally, there are limitations in the representation of

large-scale climate oscillations such as the El Niño-Southern Oscillation (ENSO) or Pacific Decadal Oscillation (PDO). These processes are represented in the physical variables, whose boundary conditions come from time-varying data from HYCOM and ERA5. However, changes in large-scale nutrients due global climate oscillations are not represented, because the boundary conditions for biological variables are mean climatologies that do not vary with these processes.

5.0 CONCLUSION

This study demonstrates that the Hawaiian Islands exert a significant influence on biogeochemistry in the west Pacific, generating a wake whose spatial extend varies substantially across nutrients and phytoplankton groups. The observed physical wake, primarily characterized in this study by persistent eddy kinetic energy, plays a role in shaping nutrient distributions and productivity patterns, which can be seen in the spatial nutrient differences between the path of cyclonic versus anticyclonic eddies. This suggests that Hawai‘i is not only a local hotspot of biological activity but potentially plays a key role in influencing broader Pacific ecosystems.

The notably extensive nitrate and phosphate wakes underscore the islands' significant role in sustaining nutrient availability far into oligotrophic regimes. This raises broader implications, such as the position of Hawai‘i as an ecological corridor that supports connectivity among otherwise isolated biological communities in the Pacific. Additionally, the differential responses of iron and phytoplankton suggest complex feedback mechanisms that merit further explorations, such as how the nutrient limitation of the oligotrophic ocean changes spatially within this wake or temporally in the coming century.

The differences between phytoplankton size classes highlights potential shifts in ecological balance driven by episodic nutrient pulses. These pulses preferentially boost larger phytoplankton like diatoms, while smaller phytoplankton like picoplankton may see population reductions. Episodic nutrient increases temporarily alter food web structures and potentially impact higher trophic levels, including commercially important fisheries. Thus, understanding island-influenced processes like eddies and how they shift ecological communities, may be valuable in managing fisheries and conserving biodiversity. This is especially important as changing climate conditions influence overall EKE patterns and potentially shift the dynamics of island wakes in the lee of archipelagos like Hawai‘i.

The distinction between regions close to the islands, driven more significantly by eddy-mediated processes, and remote regions influenced by broader gyre dynamics, leads to a consideration of how these varying scales of oceanographic processes interact. As global climate patterns continue to shift, the balanced between localized island effects and larger oceanographic controls could change, possibly impacting productivity regimes across the Pacific. This study begins to explore baselines of that interaction by quantifying the extent of localized processes impacts on the broader Pacific.

Future studies that integrate climate oscillations such as ENSO and PDO into large-scale nutrient variations could provide valuable insights into how the strength and extend of biological wake of Hawai‘i might respond to future climate variability. Additionally, expanding the complexity of ecosystem dyanamics to include more diverse phytoplankton and zooplankton groups could further clarify how nutrient dynamics

driven by the Hawaiian Islands cascade through marine ecosystems, offering other predictive insights for conservation and management in the Pacific region.

Characterizing the biological wake of Hawai‘i is key in understanding and predicting shifts in nutrient distributions and primary production, which have implications for ecosystem health, fisheries, and carbon export. This study provides a baseline for understanding the current conditions around Hawai‘i and in the west Pacific and expands on the limited region focused on by existing productivity studies around Hawai‘i.

APPENDIX

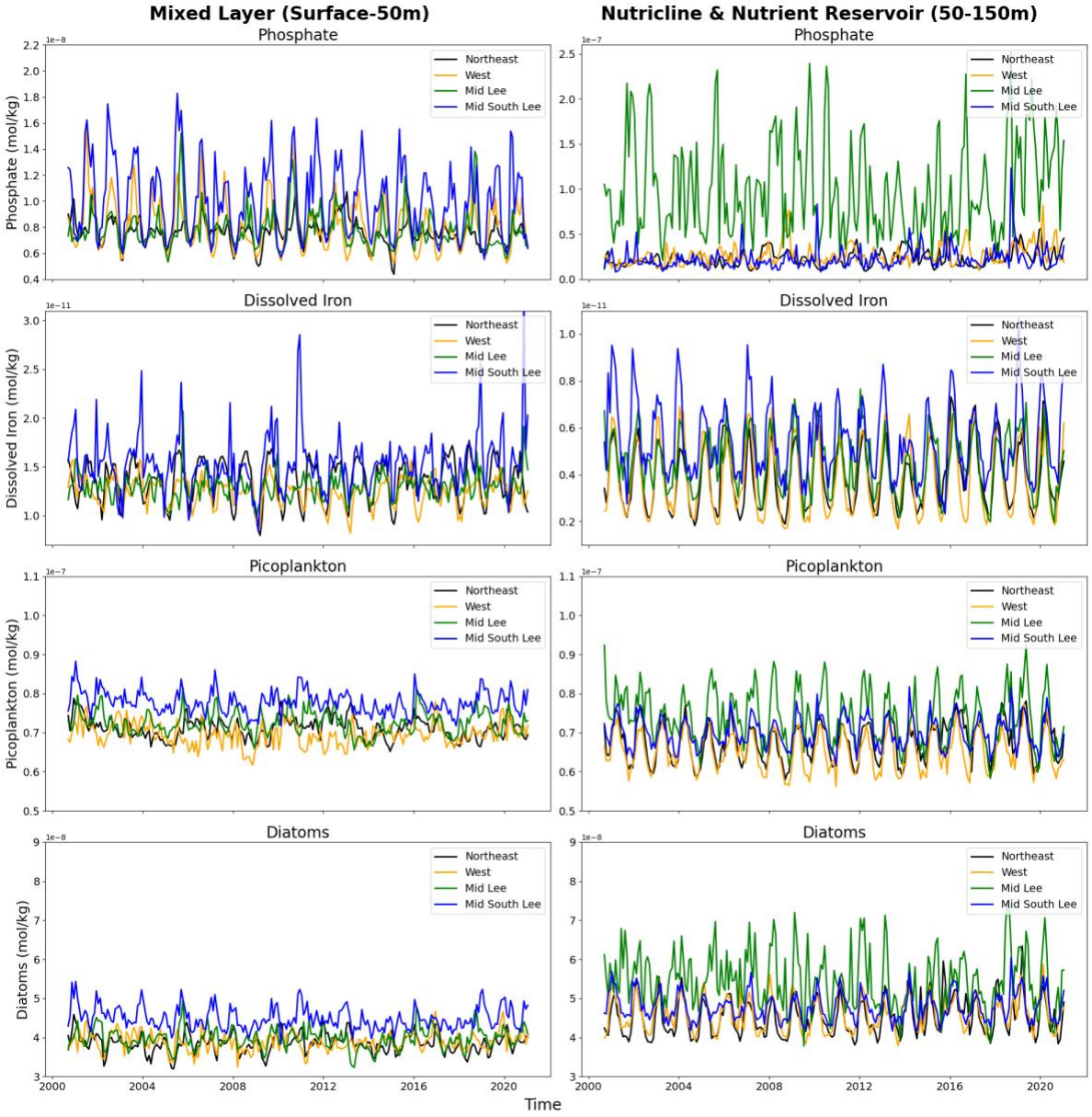

Figure 11a. Time series in regions of interest. Rows in order: phosphate, dissolved iron, picoplankton, diatoms; column 1: 50 meters, column 2: 50-150 meters. Each time series plot shows variable in west, lee, south lee, and northeast regions, as defined in Figure 10.

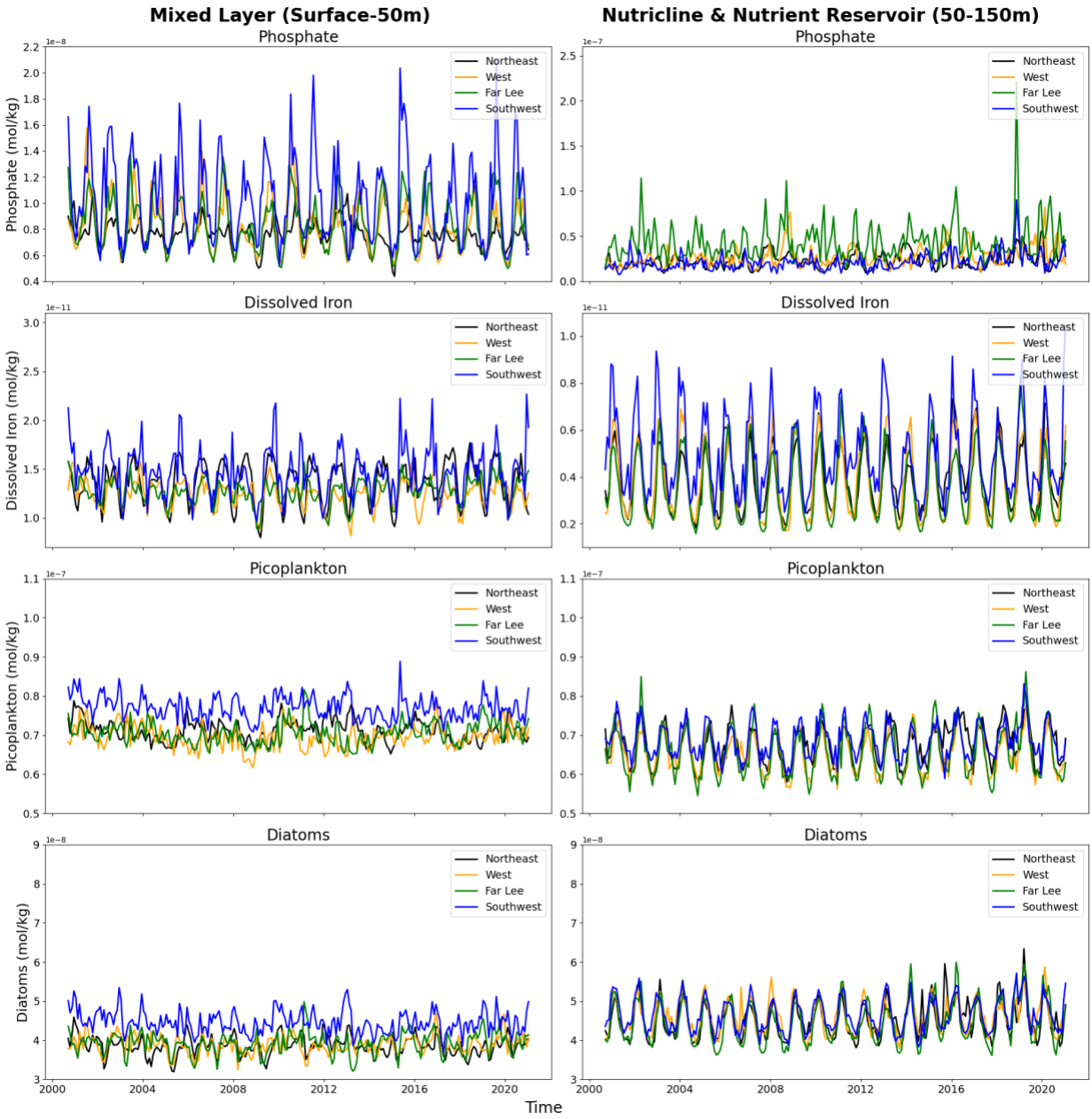

Figure 11b. Time series in regions of interest. Rows in order: phosphate, dissolved iron, picoplankton, diatoms; column 1: 50 meters, column 2: 50-150 meters. Each time series plot shows variable in west, lee, south lee, and northeast regions, as defined in Figure 10.

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