Title
Responses of Harmful Algal Bloom-Causing Phytoplankton Taxa to Atmospheric Rivers Along the California Coast

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Table of Contents

Abstract

It is important to understand the complex physical and biological interactions of the climate system for the adaptation to and mitigation of the many consequences of climate change. This study aimed to understand the impacts of Atmospheric Rivers (ARs) on Harmful Algal Bloom (HAB) causing phytoplankton taxa. ARs are ephemeral corridors of the atmosphere carrying massive amounts of water vapor from the tropics to mid latitudes and are strongly correlated with orographic precipitation. ARs are defined and characterized by the vertically Integrated Vapor Transport (IVT), which is the measured amount of water and its movement in the atmospheric column. Abundances of 13 different taxa of phytoplankton associated with HABs at 12 different monitoring stations along the California Coast were obtained from CalHABMAP. IVT magnitudes as well as a chronology of AR occurrences at 0.25° by 0.25° grid cells at each of these 12 locations were obtained from the CW3E, which acquired the information from ECMWF ERA5 Reanalysis data. Here I attempt to answer two questions: 1) When a specific HAB-causing phytoplankton taxon was present, was its abundance correlated with the IVT magnitude the week prior to sampling? 2) When this HAB-causing phytoplankton taxon was present, was its abundance different when an AR occurred during the week prior to sampling versus no AR? To reveal potential relationships between phytoplankton abundance with the IVT magnitude or presence of ARs, I quantified correlations between the phytoplankton abundances and the IVT magnitude or AR occurrence the week before phytoplankton sampling. Some dinoflagellate taxa showed consistent positive correlations in Northern California, while different dinoflagellate taxa showed more consistent negative correlations in Southern California. AR presence consistently was associated with a decrease in the abundance of phytoplankton in most diatom and dinoflagellate taxa. With little latitudinal trend in the sign of the correlation, different taxa were significantly negatively correlated with AR presence in Southern California than in Northern California. Further research should be conducted to understand the mechanisms behind these correlations and dive deeper into the nuances of these relationships. This study was meant to serve as an introduction to understanding the relationships between AR occurrence, IVT magnitude, and HAB-forming phytoplankton taxa, to advise decision making for HAB warning systems and education in the face of a changing climate.

Introduction

As the climate continues to change due to anthropogenic activities, there is a need to understand how altering the Earth's carbon budget will affect ecosystems, humans, and our economy. This requires understanding the physical and biological interactions that govern natural systems. In this study, I investigated how the hydroclimate of California impacts phytoplankton in coastal regions that are responsible for Harmful Algal Blooms (HABs). More specifically, this study aimed to answer two questions regarding Atmospheric Rivers (ARs) and HAB-causing phytoplankton taxa:

1) When a specific HAB-forming phytoplankton taxon is present, is its abundance correlated with the magnitude of the Integrated Vapor Transport (IVT) the week prior to sampling?
2) When a specific HAB-forming taxon is present, is there a consistent difference in its abundance when an AR occurred during the week prior to sampling or not?

Harmful Algal Blooms

Harmful Algal Blooms (HABs) occur when phytoplankton or macroalgae species grow beyond their usual densities or release toxins that can kill organisms that ingest them – including humans. Decay of dense blooms ("red tides") can deplete the oxygen in the water column, resulting in the degradation or death of other species in the ecosystem (Moore et al. 2019). Toxin-producing HABs can lead to mortalities, gastrointestinal disorders, neurological disorders, and epidermal irritation and lesions in fish, birds, and mammals – both marine and terrestrial – that ingest organisms that have concentrated the HAB toxins (Seller et al. 2003). Extreme HABs can harm coastal resources and have negative impacts on tourism and recreation industries as well as fisheries (Seller et al. 2003). Major HAB events occurred along the US west coast in 2015 and 2016, leading to local fishery closures, particularly for Dungeness crab, and had disproportionate impacts on small fishing fleets (Jardine et al. 2020). The Dungeness crab fishery along the United States west coast typically generates over $200 million annually for the economy; the 2015 HABs led to losses of $97.5 million for west coast commercial fisheries. Other fisheries are also impacted by HABs, including rock crab, anchovy, mussel, and razor clam fisheries (Moore et al. 2020). The economic disruption that these HABs can have, in addition to the health impacts that they have on humans, make them a particularly important topic to investigate, especially in the context of climate change.

Particular HAB-forming phytoplankton taxa that are monitored along the coast of California include *Alexandrium spp., Akshiwo spp., Ceratium spp., Cochlodinium spp., Dinophysis spp., Gymnodinium spp., Lingulodinium spp., Prorocentrum spp.,* and *Pseudo-nitzschia seriata, Pseudo-nitzschia delicatissima.* The two *Pseudo-nitzschia* taxa produce the neurotoxin domoic acid, which caused closures of the Dungeness Crab fisheries in 2015

(Moore et al. 2019). Many of the other species listed here produce the neurotoxins saxitoxin or yessotoxin. The decay of particularly dense blooms can deplete the oxygen from the water column, resulting in major fish kills and ecosystem disruption. Understanding the drivers of HABs will help predict their locations and timing and help mitigate economic loss and human health impacts.

HABs have been increasing globally over the past decades, likely as a response to anthropogenic nutrients entering the ocean and global sea surface temperature rise, promoting the growth of phytoplankton species responsible for the HABs. In dry urban areas such as along the California coast, terrestrial nutrients can build up on land until they are washed into the oceans by heavy rains, where they affect marine ecosystems. However, HABs also occur naturally, and may be controlled by ocean circulation, changes in upwelling, and river/runoff input (Sellner et al. 2003). Here I investigate how the abundances of HAB-causing phytoplankton might be impacted by precipitation patterns in California.

Atmospheric Rivers

Water is an extremely important and limited resource in California, with growing water demands from many large cities and agricultural needs (Dettinger et al. 2011). California's hydroclimate is characterized by a typically drought-like state punctuated by heavy rains brought in by the meteorological feature, ARs, which occur predominantly during the winter months. ARs are ephemeral corridors in the atmosphere that transport high volumes of water vapor, typically from tropical latitudes towards mid latitudes. Landfalling ARs in the Western US contribute up to 30–50% of annual precipitation totals (Dettinger et al. 2011), produce extreme precipitation (Lamjiri et. al 2017, 2020; Aguilera et al. 2019), challenge water resources management, and increase the winter snowpack in high elevations to later recharge watersheds in spring and summer (Neiman et al. 2008). This precipitation may also lead to flooding (Ralph et al. 2006) and heavy snow events (Guan et al. 2010) and produce high wind events along the coast and inland mountain ranges (Waliser and Guan 2017). California has a Mediterranean climate with wet winters and long, dry summers, so precipitation varies greatly seasonally as well as year to year. The region is often in a state of either drought or flood. Understanding this hydroclimate requires understanding the mechanisms underlying these intense winter storms.

ARs are categorized by the vertically Integrated Vapor Transport (IVT) of the atmosphere. IVT is not dependent on surface elevation and is directly related to the precipitation of the region. IVT is an important variable as it is the variable by which we identify ARs. Typically, features with IVT magnitudes greater than or equal to 250 kg m^{-1} s^{-1} are defined as ARs, though there is a lot of variation around that definition; some ARs making landfall in the Pacific Northwest had IVTs over 1,000 kg m^{-1} s^{-1} (Ralph et al. 2019). A schematic representation of an AR is provided by the Glossary of the American Meteorological Society that further describes the structure of an AR, including its relationship to Pacific Winter Storms, and its shape, which is often >2000 km in length and <1000 km wide (Figure 1).

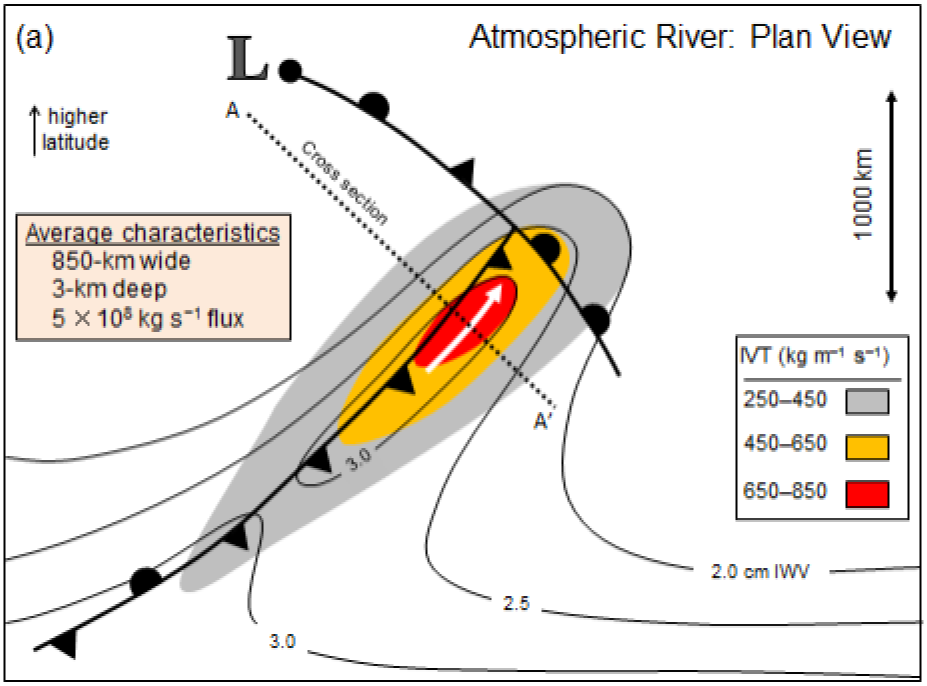


Figure 1: Summary schematic of the structure and strength of an atmospheric river based on research aircraft dropsonde measurements. (American Meteorological Society, 2022)

Global climate models (GCMs) predict that in the coming decades, most Mediterranean biomes will decrease in annual precipitation and sink deeper into a state of drought. Coastal California is also predicted to experience increased extreme precipitation events as a result of stronger AR activity in the region (Aguilera et al. 2019). This result implies that the state is likely to become, on average, drier, with more extreme precipitation events to punctuate the dry spells. Because dry spells allow pollutants to accumulate without being washed away by rain, combined with the hardening of soils and lack of vegetation to facilitate pollutant movement, extreme precipitation events can suddenly wash large concentrations of pollutants – particularly nutrients – into the coastal oceans. Warmer climates could also cause ARs to bring more rain than snow (Hayhoe et al. 2004), further increasing the potential for runoff during future ARs making landfall.

This is simply one hypothesis as to what the relationship between ARs and HAB occurrences could be and is aimed to understand a positive correlation. This explanation is a simplification of a very complex physical-biological interaction and the correlations found in this study likely require the inclusion of other variables, such as geography, seasonality, light availability, ocean currents, biological factors, and more, to fully understand.

Understanding the Contribution of ARs to Coastal Contamination

Aguilera et al. (2011) showed that ARs in California were associated with coastal pollution, leading to high levels of fecal bacteria, and posing a threat to human health. Here, I investigated the relationships between AR events and HAB-causing phytoplankton. The mechanisms causing fecal bacterial contamination may be similar to those driving increased nutrient runoff leading to HABs: increased pollutant build up over long dry spells followed by extreme precipitation events causing coastal contamination. This hypothesis for the relationship between AR occurrence and HABs is a simplification of a very complex system and would be expected to generate positive correlations. Alternate hypotheses will need to be developed to account for any negative correlations.

Understanding these relationships between ARs and HAB species could help us understand how to minimize health and economic losses through better warning systems and increase our understanding of the many complex changes that are to occur due to our changing climate. This study is meant to provide a baseline understanding of the complex relationship between this meteorological phenomenon and the HAB-forming phytoplankton that will inform future decision making.

Data and Methods

Phytoplankton Data

Weekly counts of targeted HAB-causing phytoplankton taxa were retrieved from the Southern California Coastal Ocean Observing Stations program page of the United States' National Oceanic and Atmospheric Administration's Environmental Research Division's Data Access Program website. This data was collected as part of the California Harmful Algal Bloom Monitoring and Alert Program (HABMAP), which began in 2008 with the purpose of monitoring specific phytoplankton taxa that are known to be responsible for HABs. These stations are monitored as part of the U.S. Integrated Ocean Observing System which includes two associations from California: the Southern California Coastal Ocean Observing System and the Central and Northern California Ocean Observing System. This system comprises nine university-run or municipal pier sampling stations that span San Diego County in the south to Humboldt County in the north, recording phytoplankton counts and concentrations of nutrients as well as the neurotoxin domoic acid, along with other physical and chemical properties.

For the purpose and the scope of this project, only the monitoring stations that contained regular counts of phytoplankton taxa were used. These included 12 stations overall from Bodega Bay, the farthest north, to Scripps Pier, the farthest south (Table 1). Two stations were located in Bodega Bay: one is located just offshore at the Bodega Marine Laboratory, and another farther offshore in coastal waters at a buoy. Three stations are located within Tomales Bay: one at the mouth of the bay, another mid-channel, and the third inside the bay. The rest of the observatories have one sampling location at each latitude (Table 1). Each observing station collected samples in coastal waters and has a unique time range of observations, with the longest time series being Stearns Wharf, beginning June 30th of 2008 and ending on February 29, 2023, and the shortest being the Mid-Channel and Inner Tomales Bay locations, beginning on January 29, 2021, and ending February 1, 2023. All the locations' time series are current up to early 2023.

Table 1: Phytoplankton Observation Station Locations and Time Series

Station Name	Latitude	Longitude	Time Series
Bodega Bay Marine Lab	38.31613°N	-123.0705°E	07/08/2020 - 02/13/2023
Bodega Bay Marine Lab Buoy	38.3126°N	-123.0825°E	02/20/2020 - 01/25/2023
Tomales Bay Mouth	38.23082°N	-122.9791°E	06/30/2020 - 02/01/2023

Tomales Bay Mid-Channel	38.18967°N	-122.9286°E	01/29/2021 - 02/01/2023
Inner Tomales Bay	38.11798°N	-122.867°E	01/29/2021 - 02/01/2023
Santa Cruz Wharf	36.958°N	-122.017°E	10/05/2011 - 02/15/2023
Monterey Wharf	36.60368°N	-121.8893°E	11/10/2010 - 02/22/2023
Cal Poly Pier	35.1702°N	-120.7407°E	08/15/2008 - 02/20/2023
Stearns Wharf	34.40804°N	-119.6849°E	06/30/2008 - 01/29/2023
Santa Monica Pier	34.008	-118.499	06/30/2008 - 02/20/2023
Newport Beach Pier	33.6061	-117.9311	06/30/2008 - 02/21/2023
Scripps Pier	32.867	-117.257	06/30/2008 - 02/23/2023

Counts of 13 different phytoplankton taxa were conducted at most sites. Two of the observing sites did not have all counts available. Only *Pseudo-nitzschia seriata, Alexandrium spp.,* and *Dinophysis spp.* being counted at Santa Cruz Wharf. All of the listed taxa except *Ceratium spp.* and *Cochlodinium spp.* were counted at Santa Monica Pier. In the data files, the first ten counts are of specific species or genera, including two diatom species and eight dinoflagellate genera. The final three counts are, "Other Diatoms," "Other Dinoflagellates," and "Total". The "Other Diatoms" contains counts of other diatom genera aside from the ones mentioned above, and "Other Dinoflagellates" contains counts of other dinoflagellate genera aside from the ones mentioned above (see Table 2). "Total" contains counts of all phytoplankton regardless of taxon in the sample. Each sample is counted visually, recording numbers of the genus/species present in the collection volume; counts are given as cells/L. The potential harmful effects associated with each genus can be found in Table 2.

Table 2: Phytoplankton Genera Counted, their Family, and Harmful Effects

Genera	Family	Harmful Effects
Pseudo-nitzschia seriata	Diatom	Produces DA, a neurotoxin to mammals,

		seabirds, and humans causing gastrointestinal and neurological disorders
Pseudo-nitzschia delicatissima	Diatom	Produces DA, a neurotoxin to mammals, seabirds, and humans causing gastrointestinal and neurological disorders
Alexandrium spp	Dinoflagellate	Produces saxitoxins which are neurotoxins that block nerve transmission and can cause gastrointestinal and neurological disorders in humans, sometimes paralysis and death
Akashiwo spp	Dinoflagellate	Can cause oxygen depletion and surfactants that kill birds and fish
Ceratium spp	Dinoflagellate	Responsible for hypoxic conditions in the water column that kill birds and fish
Cochlodinium spp	Dinoflagellate	Affiliated with large-scale mariculture losses of finfish and salmon but mechanism and toxins unknown
Dinophysis spp	Dinoflagellate	Produces okadaic acid which can cause gastrointestinal disorders in humans
Gymnodinium spp	Dinoflagellate	Produces saxitoxins which are neurotoxins that block nerve transmission to humans and can cause gastrointestinal and neurological disorders in humans, sometimes paralysis and death. Can form dense “red tides”
Lingulodinium spp	Dinoflagellate	Produces yessotoxin and is responsible for dense “red tides”. Decay of the red tide can lead to hypoxia
Prorocentrum spp	Dinoflagellate	This genus contains several toxic and harmful species and releases growth inhibitors for diatoms. Can form dense “red tides”

(Negrey, 2019, Nwankwegu et al 2023, Dobbs 2009)

Integrated Vapor Transport Data

Daily values of the IVT and whether they were categorized as an AR or not following the method of the AR scale posed by Ralph et al. (2019) were acquired near each location of the phytoplankton observation stations. The IVT data is derived from the European Centre for

Medium-Range Weather Forecasts (ECMWF) ERA5 Reanalysis data. It is recorded on a 0.25-degree latitude by 0.25-degree longitude grid and derived from vertical data in 25-hPa vertical bins between 1000 to 750 hPa, and 50-hPa vertical bins between 750 to 250 hPa (Hersbach et al. 2020). Multiple closely spaced phytoplankton sampling stations could fall in a single IVT grid: the two stations at Bodega Bay fell within the same IVT grid location, as did the three stations at Tomales Bay. The IVT data were collected every hour and records included the daily average and the daily maximum for each day in the time series. The IVT data spans a longer time series than the phytoplankton counts, so all the locations were provided with IVT data that began in 2008 to correspond with the longest phytoplankton count data; IVT data were updated through February 2023. In addition to the daily average and daily maximum value of IVT for each corresponding day to the phytoplankton counts, I used the logical variable that categorized each daily IVT value as an AR or not following Ralph et al. (2019).

Data Analyses

All analyses were done in MATLAB and were plotted against a map of the coast of California to visualize patterns by taxa and by location. The first analysis was done to visualize the latitudinal trend of IVT magnitude and AR occurrence. To do this, I calculated the frequency of ARs, the mean and median intensities of the IVT, and the average weekly maximum over the entire time series of the phytoplankton data at each phytoplankton sampling location.

Next, correlations (r-value) and their significance (p-value) were calculated using the "corrcoef" function in MATLAB. The IVT daily average and daily maximum data were aligned in time with the phytoplankton count data at each location. To get a representative value of the amount of water vapor in the atmosphere during the time preceding a phytoplankton count, IVT data were averaged over the 7 days prior to the day of the phytoplankton count. This was also done to account for the fact that the phytoplankton data were recorded weekly and the IVT data was recorded daily. I removed all NaN values and zeros of the phytoplankton counts, so all analyses investigate the responses of the phytoplankton to the ARs only when that phytoplankton taxon was present. Only correlation coefficients with a p-value less than 0.05 were selected as statistically significant.

Finally, to test whether phytoplankton taxon abundances were different during weeks with ARs compared to non-AR weeks, data were tested using the two-sided Wilcoxon rank sum test ("ranksum" in MATLAB). This analysis indicated whether the abundances during weeks with ARs compared to non-AR weeks were from statistically different distributions with unequal medians. An h-value of 1 indicated a rejection of the null hypothesis that they were of statistically identical distributions with equal medians. This analysis utilized the 7-day AR data from the week before the phytoplankton count.

Results

IVT Patterns with Latitude

The IVT and AR data showed distinct patterns south of Monterey Wharf (“Southern California”), and north of Monterey Wharf, including Monterey Wharf (“Northern California”) (Figure 2). The average AR frequency was 0.025 in Southern California, and 0.066 in Northern California. The median IVT intensity was 80 kg m^{-1} s^{-1} in Southern California and 113 kg m^{-1} s^{-1} in Northern California, while the mean IVT intensity was 63.11 kg m^{-1} s^{-1} in Southern California and 90 kg m^{-1} s^{-1} in Northern California. Finally, the average of the weekly maximum IVT intensities in Southern California was 124 kg m^{-1} s^{-1}, and 172 kg m^{-1} s^{-1} in Northern California.

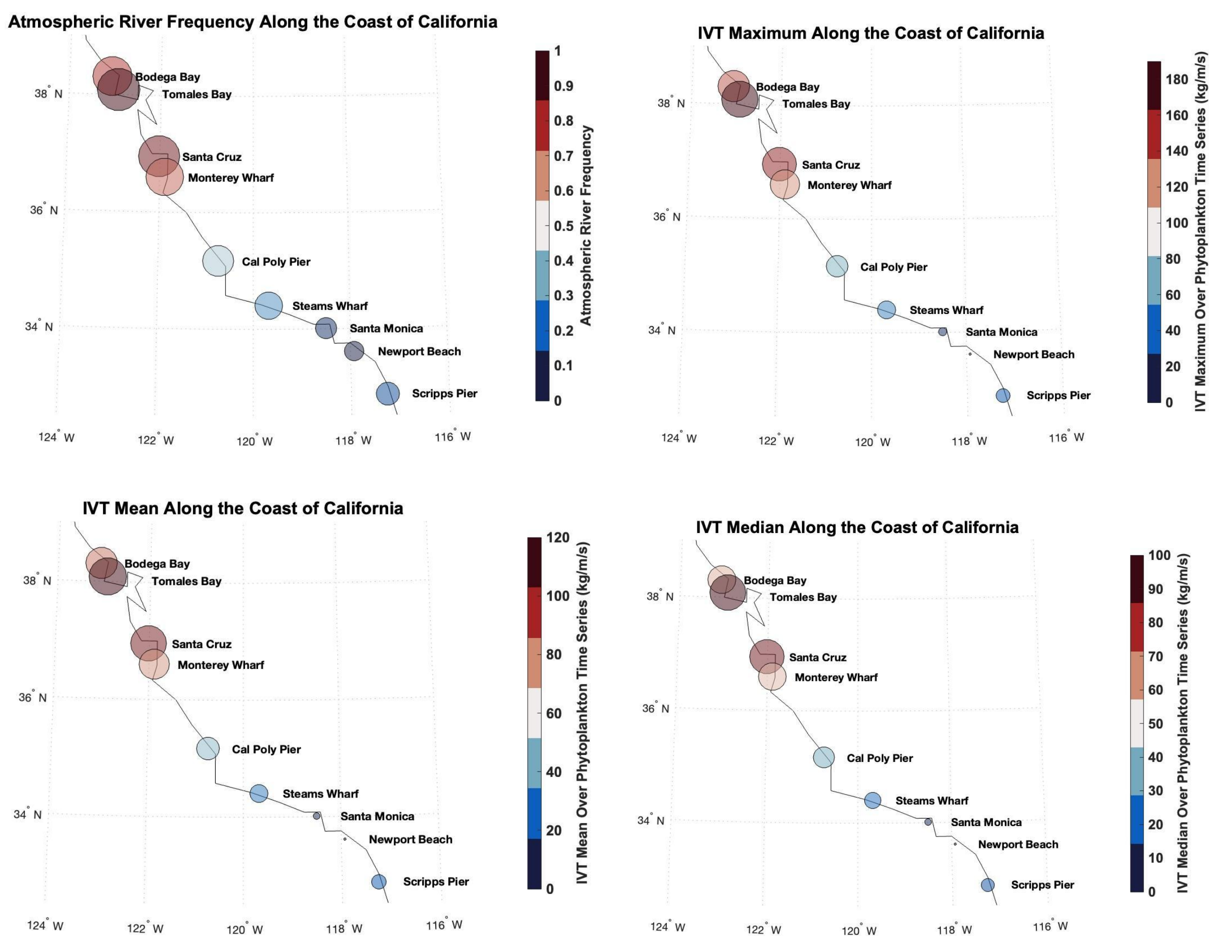


Figure 2: AR and IVT statistics at the phytoplankton sampling stations. Frequency of ARs along the California coast; the size and color of the bubbles indicates the frequency of ARs: larger red bubbles indicate a higher frequency and smaller blue bubbles indicate a lower frequency (upper

left). The average weekly maximum along the coast over the phytoplankton time series (upper right), mean IVT over the phytoplankton time series (lower left), median of the IVT over the phytoplankton time series (lower right). The size and color of these bubbles indicate the strength of the IVT, with large red bubbles indicating a greater IVT magnitude and small blue bubbles indicating a smaller IVT magnitude.

Correlations of HAB taxa with IVT Magnitude

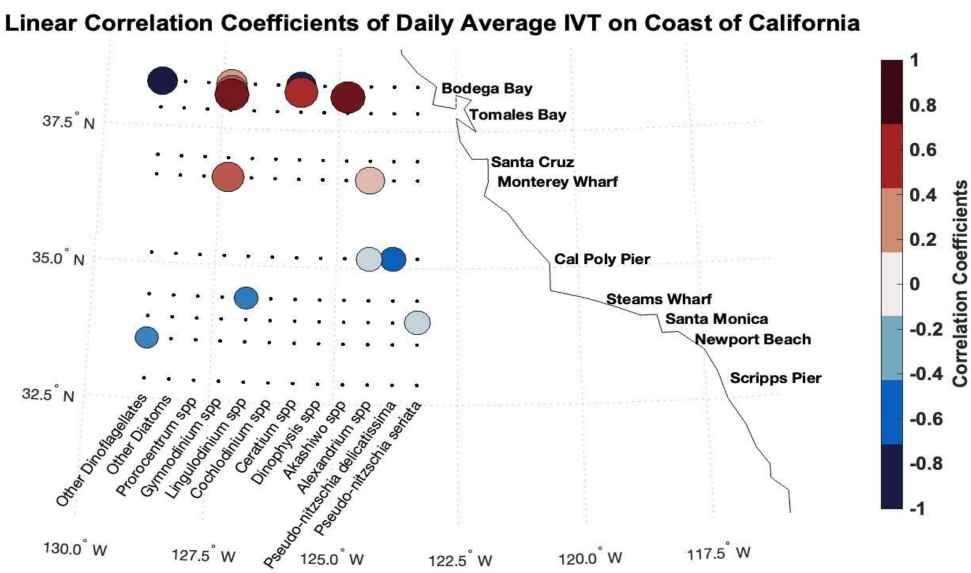
Correlations were considered significant when they had a p-value less than 0.05. The majority of the statistically significant relationships were negatively correlated, particularly in the SemiLog correlations (log_{10} of the phytoplankton counts, linear IVT data), and the LogLog correlations (log_{10} of both the phytoplankton counts and the IVT data). In other words, the nature of most of these significant relationships was as IVT magnitude increased, the species abundance decreased, in the SemiLog and LogLog analyses. The linear correlations yielded the fewest significant values and tended to yield more positive correlations. Put simply, as the IVT magnitude increased, different taxa had increasing abundances in the linear correlations in Northern California.

Linear Correlations

Analyses of the linear correlations of the IVT averaged over the 7 days prior to the plankton sampling and plankton abundances yielded 14 significant indices, with an average correlation coefficient of 0.269 (Figure 2). The analyses yielded 15 significant correlation coefficients of the averaged IVT daily maximum and phytoplankton counts, with an average correlation coefficient of 0.222. Significant linear correlations of HAB abundances with the daily average IVT were all positive in Northern California, but negative (and weaker) in Southern California.

The taxon which yielded the most significant correlations was *Gymnodinium spp.*, which was positively correlated with IVT daily average and daily maximum at the Bodega Bay locations, Tomales Bay locations, and at the Monterey Wharf. In other words, *Gymnodinium spp.* showed the strongest relationship with the IVT magnitude, and consistently increased as IVT increased. The average correlation coefficients for the significant *Gymnodinium spp.* analyses were 0.662 and 0.680 for the analysis with the IVT daily averages and the IVT daily maxima, respectively. *Ceratium spp.*, *Akashiwo spp.,* and *Alexandrium spp.* were also positively linearly correlated with the IVT daily average values at Tomales Bay Mid-Channel ($r = 0.742$), Inner Tomales Bay ($r = 0.890$), and Monterey Bay ($r = 0.401$). These correlation coefficients were 0.735, 0.901, and 0.396, respectively, using the IVT daily maximum values. All these positive correlations occurred in Northern California; fewer significant correlations were found in this linear analysis in the southern region of California (Figure 3).

The "Other Dinoflagellates" category was negatively linearly correlated with the IVT daily average at Bodega Bay and Newport Beach, with correlation coefficients of -0.445 and -0.090 (-0.412 and -0.100 for the analyses using the IVT daily maximum values). Both analyses also yielded a correlation with *Alexandrium spp.* and *Pseudo-nitzschia delicatissima* at Cal Poly Pier with correlation coefficients of 0.196, and -0.199 with the IVT daily average values, and 0.153 and -0.197 with the IVT daily maximum values, respectively. The linear analyses revealed a correlation of *Pseudo-nitzschia seriata* at the Santa Monica Pier with the IVT daily average values (r = 0.187), and with the IVT daily maximum values (r = 0.144). In the analysis using the IVT daily average values, *Lingulodinium spp.* yielded a significant correlation at the Stearns Wharf (r = -0.117). Significant correlations were found between IVT daily maxima and *Prorocentrum spp.* at Bodega Bay (r = -0.464) and *Dinophysis spp.* at the Santa Cruz Wharf (r = -0.080).



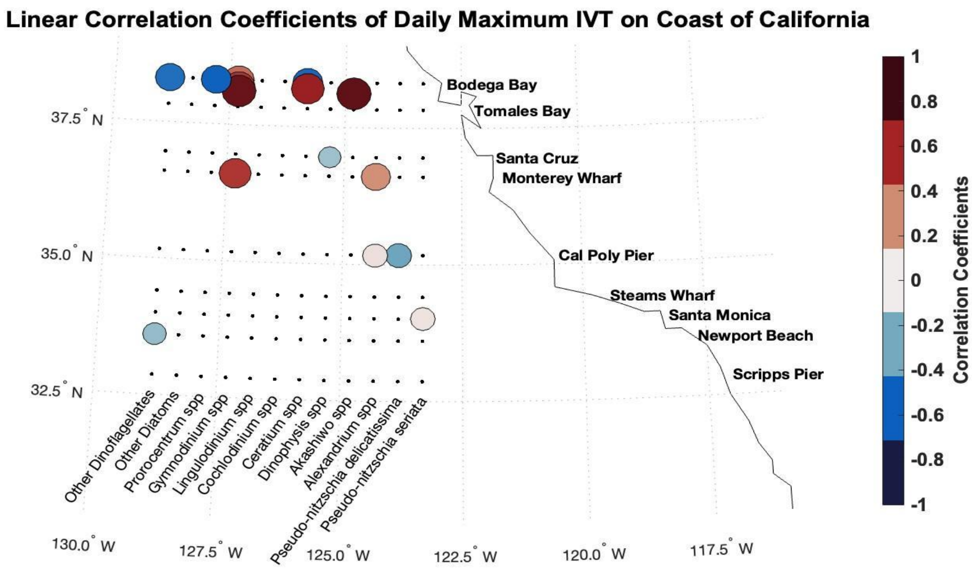


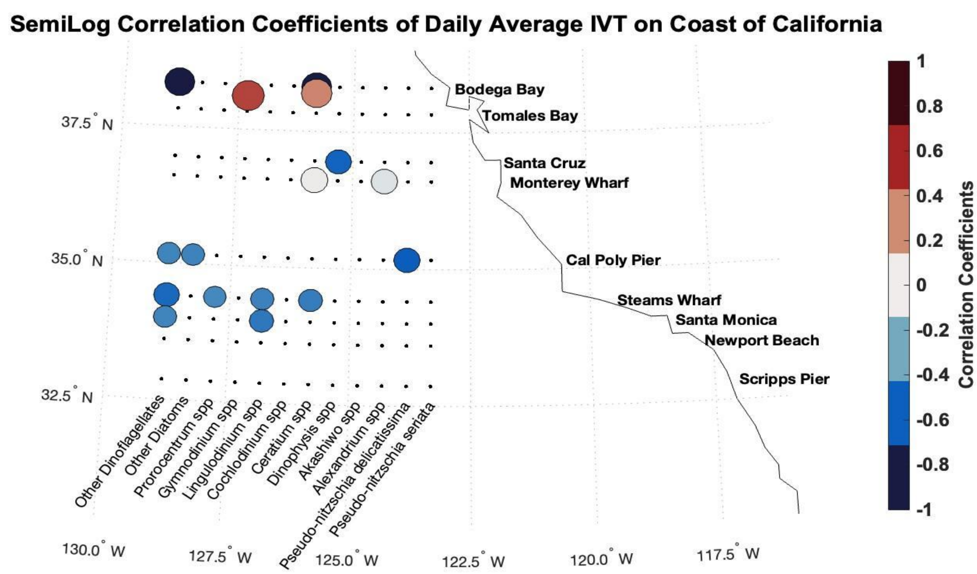
Figure 3: Linear correlation coefficients plotted along the coast of California, using the IVT daily average (upper) and the IVT daily maximum (lower). The color corresponds to the magnitude and sign of the correlation coefficient and the size of the bubble corresponds to the magnitude of the correlation coefficient.

Semilog Correlations

Correlation coefficients calculated using the $\log_{10}$ of the phytoplankton counts showed 19 significant correlations with the IVT daily average values, with an average correlation coefficient of -0.050; 23 significant correlations were found with the IVT daily maximum values, with an average correlation coefficient of -0.075. The significant correlations were found to be predominantly negative, unlike the linear analysis (Figure 4). Specifics of the results are as follows.

Only three taxa displayed positive correlation coefficients: *Gymnodinium spp.* at the Inner Tomales Bay (r = 0.681 with the IVT daily average value; r = 0.672 with the IVT daily maximum values), *Ceratium spp.* at Tomales Bay Mid-Channel (r = 0.524 with the IVT daily average values; r = 0.549 with the IVT daily maximum values), *Ceratium spp.* at the Monterey Wharf (r = 0.259 with the IVT daily average values; r = 0.243 with the IVT daily maximum values), and *Alexandrium spp.* at Monterey Wharf (r = 0.228 with the IVT daily average values; r = 0.229 with the IVT daily maximum values). In Southern California, many taxa were found to be negatively correlated with the IVT, including *Pseudo-nitzschia delicatissima* at the Cal Poly Pier, *Ceratium spp., Lingulodinium spp.* and *Prorocentrum spp.* at Stearns Wharf, *Lingulodinium spp.* at the Santa Monica Pier, “Other Diatoms” at the Cal Poly Pier, and “Other Dinoflagellates” at the Cal Poly Pier, Stearns Wharf, and Santa Monica Pier. These correlations with the IVT daily average averaged -0.128, and ranged from -0.083 (*Prorocentrum spp.* at Stearns Wharf) to -0.224 (*Pseudo-nitzschia delicatissima* at Cal Poly Pier). Similarly, correlations with the IVT daily maximum averaged -0.144, ranging from -0.101 (“Other Dinoflagellates” at Cal Poly Pier) to -0.246 (*Pseudo-nitzschia delicatissima* at Cal Poly Pier).

In Northern California, “Other Dinoflagellates” was negatively correlated at the Bodega Bay Buoy (r = -0.467 with the IVT daily average values; r = -0.433 with the IVT daily maximum values). *Dinophysis spp.* was also negatively correlated at the Santa Cruz Wharf (r = -0.206 with the IVT daily average values; r = -0.248 with the IVT daily maximum values). *Ceratium spp.* yielded correlation coefficients of -0.461 at the Bodega Bay Buoy with the IVT daily average values and -0.459 with the IVT daily maximum values. Three additional significant correlations were *Prorocentrum spp.* with the IVT daily maximum values at the Santa Monica Pier (r = -0.091), Newport Beach Pier (r = -0.102), and Scripps Pier (r = -0.168) (Figure 4).



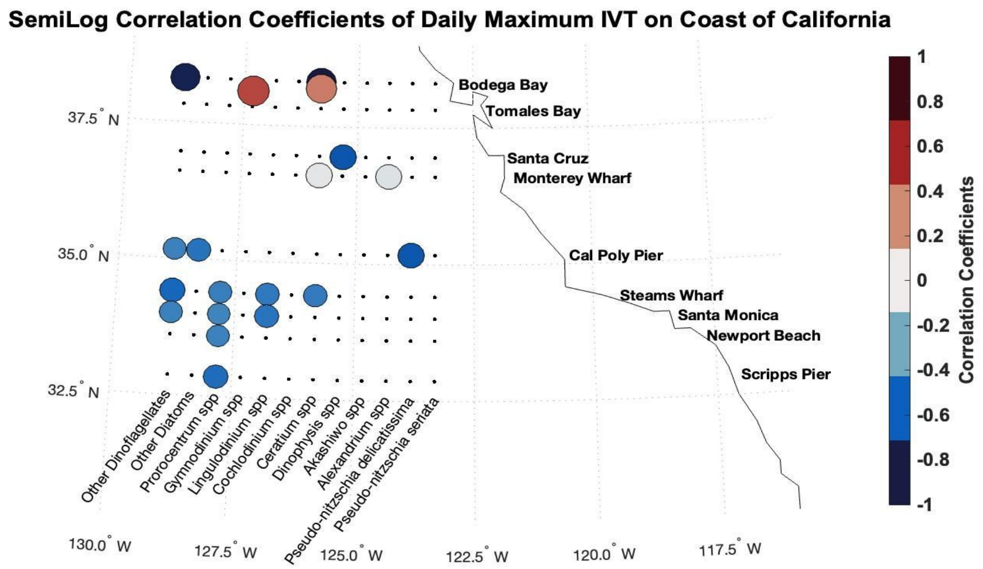


Figure 4: Correlation coefficients plotted along the coast of California of Log_{10} phytoplankton counts (SemiLog), with the IVT daily average (upper) and the IVT daily maximum (lower). The color corresponds to the magnitude and sign of the correlation coefficient and the size of the bubble corresponds to the magnitude of the correlation coefficient.

LogLog Correlations

For the LogLog analyses, correlation coefficients were calculated using the $\log_{10}$ of both the IVT values and the phytoplankton counts. These analyses yielded 18 significant correlation coefficients of phytoplankton taxa with the IVT daily average values (mean = -0.074). The analyses with the IVT daily maxima values yielded 20 significant correlation coefficients with a mean correlation coefficient of -0.094. The significant correlations were mostly negative, with a few positive correlations at higher latitudes (Figure 5). More specifics of the results are as follows.

The positive indices were found with the same species and locations correlations that yielded positive correlations in the SemiLog analyses above. *Gymnodinium spp.* produced a correlation coefficient at the Inner Tomales Bay (r = 0.687 with the IVT daily average values; r = 0.689 with the IVT daily maximum values). *Ceratium spp.* yielded positive correlation coefficients at Tomales Bay Mid-Channel (r = 0.505 with the IVT daily average values; r = 0.559 with the IVT daily maximum values), and at Monterey Wharf (r = 0.271 with the IVT daily average values; r = 0.249 with the IVT daily maximum values). Finally, *Alexandrium spp.* produced significant positive correlation coefficients at the Monterey Wharf (r = 0.207 with the IVT daily average values; r = 0.207 with the IVT daily maximum values).

Some negative correlations were found in Northern California as well. “Other Dinoflagellates” at the Bodega Marine Lab was negatively correlated with the IVT daily average values (r = -0.199) and the IVT average daily maximum values (r = -0.173). “Other Dinoflagellates” also provided negative correlation values at the Bodega Bay Buoy (r = -0.484 with the IVT daily average and r = -0.456 with the IVT daily maximum values). At the Bodega Bay Buoy, *Prorocentrum spp.* was negatively correlated with the IVT daily average values (r = -0.479) and the IVT daily maximum values (r = -0.470). *Dinophysis spp.* also yielded correlations of -0.184 and -0.231 at the Santa Cruz Wharf, with the IVT daily average and the IVT daily maximum, respectively. All the correlations in Southern California were negative. At the Cal Poly Pier *Pseudo-nitzschia delicatissima* was negatively correlated with the IVT daily average (r = -0.226) and the IVT daily maximum (r = -0.243). *Ceratium spp.* was negatively correlated with the IVT daily average (r = -0.460) and the IVT daily maximum (r = -0.494) at the Bodega Bay Buoy. *Lingulodinium spp.* was correlated at Stearns Wharf with the IVT daily average (r = -0.112) and the IVT daily maximum (r = -0.126), and at Santa Monica Pier with the IVT daily average (r =-0.118) but did not show a significant relationship the IVT daily maximum. “Other Dinoflagellates” at Cal Poly Pier were significantly correlated with the IVT daily average (r = -0.115) and IVT daily maximum (r = -0.113), at Stearns Wharf with the IVT daily average (r = -0.187) and IVT daily maximum (r = -0.180), and at the Santa Monica Pier with the IVT daily average (r = -0.077) and IVT daily maximum (r = -0.084).

There were a few additional significant correlations of phytoplankton taxa with the IVT daily maximum that were not significantly correlated with the IVT daily average: “Other Dinoflagellates” at the Tomales Bay Mouth (r = -0.400), and “Other Diatoms” at the Cal Poly Pier (r = -0.111). Finally, *Prorocentrum spp.* also had a correlation at Stearns Wharf (r = -0.089) (Figure 5).

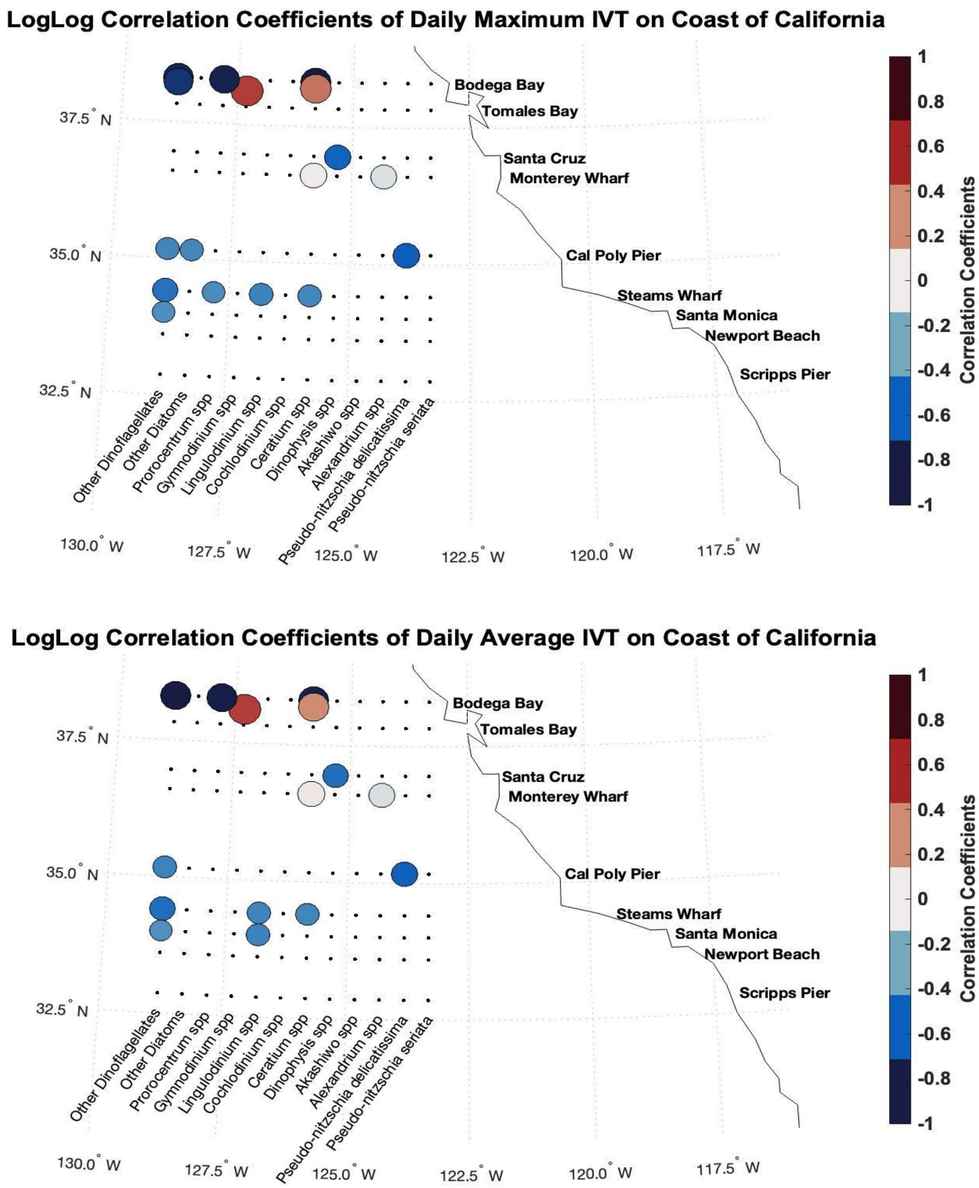


Figure 5: Correlation coefficients of LogLog relationships ($\log_{10}$ of both the phytoplankton counts and IVT magnitude) plotted along the coast of California, using the IVT daily average (upper) and the IVT daily maximum (lower). The color corresponds to the magnitude and sign of the correlation coefficient and the size of the bubble corresponds to the magnitude of the correlation coefficient.

HAB abundance preceded by ARs versus non-ARs

I compared the abundances of each HAB taxon indexed for whether there was an AR in the 7 days prior to the count or not. These analyses provided insight as to the occurrence of an

AR and its impact on phytoplankton, as opposed to the magnitude of the IVT and its impact on phytoplankton.

The two-sided Wilcoxon Rank Sum test showed many locations and taxa where the HAB abundances during an AR were statistically different distributions with unequal medians from the abundances when there was no AR. There were 31 occurrences of an h-value of 1, which signified rejection of the null hypothesis that the abundances during periods with and without an AR the week before were statistically identical.

Among the significant comparisons, all but one showed significantly larger abundances when there was no AR prior to the count compared to when there was an AR. Only *Ceratium spp.* at the Newport Beach Pier showed larger abundances after an AR (Figure 5).

Locations with significant negative relationships of abundance and AR presence included *Pseudo-nitzschia seriata* at the Tomales Mid-Channel, the Monterey Wharf, and the Cal Poly Pier, and *Pseudo-nitzschia delicatissima* at the Tomales Bay Mid-Channel, the Cal Poly Pier, the Newport Beach Pier, and the Scripps Pier. The “Other Diatoms” group also yielded significant differences at the Tomales Bay Mouth, Tomales Bay Mid-Channel, Cal Poly Pier, and Newport Beach Pier, and Scripps Pier. Dinoflagellate taxa with significantly lower abundances during AR vs. non-AR included *Alexandrium spp.* at the Tomales Bay Mouth, *Dinophysis spp.* at Santa Cruz Wharf, *Lingulodinium spp.* at the Santa Monica Pier and Scripps Pier, *Prorocentrum spp.* at the Monterey Wharf and the Newport Beach Pier, and *Gymnodinium spp.* at the Santa Monica Pier and the Scripps Pier. The “Other Dinoflagellates” showed significantly lower abundances during ARs at the Tomales Bay Mouth, Tomales Bay Mid-Channel, the Newport Beach Pier, and Scripps Pier (Figure 5).

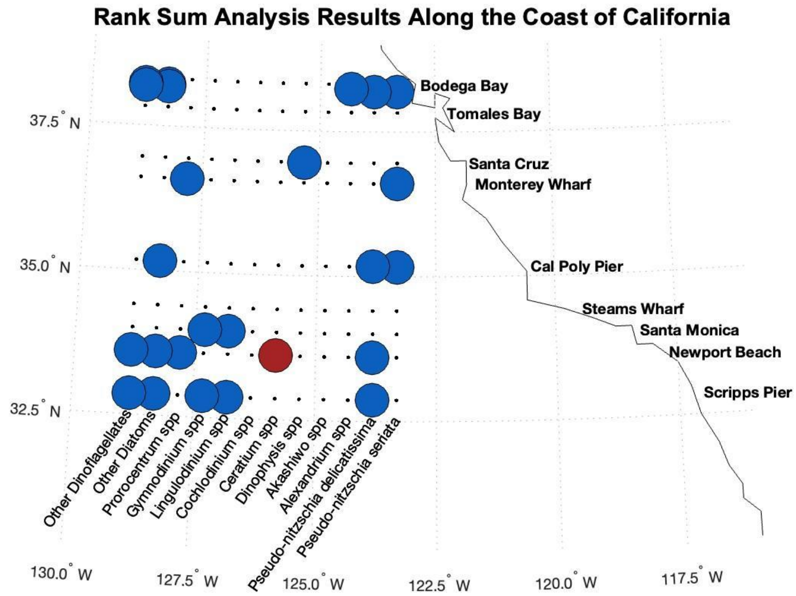


Figure 6: Wilcoxon Rank Sum Results with h-value = 1 plotted along the coast of California with blue signifying a significantly lower median phytoplankton abundance of that taxon when there was an AR at the sampling location the week before, and red signifying a significantly higher median phytoplankton abundance of that taxon when there was an AR at the sampling location the week before.

Discussions and Conclusions

Discussion

The aims of this project were to answer the questions:

1) When a specific HAB-forming phytoplankton taxon is present, is its abundance correlated with the magnitude of the IVT the week prior to sampling?
2) When a specific HAB-forming taxon is present, is there a consistent difference in its abundance when an AR occurred during the week prior to sampling or not?

These results clearly show that when HAB taxa were present, there were correlations between their abundance and the IVT as well as their abundance and the occurrence of an AR near the sampling site. However, the patterns were complex, requiring further exploration of the underlying mechanisms, and the implications and limitations of these results.

IVT Latitudinal Trends

My analyses showed that stations in Northern California (i.e., at and north of Monterey Wharf) experience ARs about 2.6 times more often than the southern stations, with IVT magnitudes about 1.4 times greater than in Southern California (i.e., south of Monterey Wharf). These patterns help us to understand the patterns of correlations between HAB abundances and IVT/AR properties that were found during this study. My analyses showed that regions with more frequent ARs and more water vapor in the atmosphere are more likely to have positive correlations of specific HAB taxa abundances and IVT magnitude; in the drier regions with fewer ARs and less water vapor in the atmosphere, the HAB abundances are more likely to have a negative correlation with IVT magnitude. All locations showed that AR events were likely to decrease certain HAB taxa abundance.

Correlation Results

Linear Correlation Results

It is clear that there are positive linear correlations between HAB taxa abundance and the IVT value the week before sampling for some dinoflagellate species. This was particularly noticeable with *Gymnodinium spp.* in Northern California. This Northern California trend was also seen with *Ceratium spp., Akashiwo spp.,* and *Alexandrium spp*. Some positive correlations were seen a bit farther to the south as well, with the correlation of *Akashiwo spp.* at the Cal Poly Pier and *Pseudo-nitzschia seriata* at the Santa Monica Pier. The other correlations were negative, and were mostly found in Southern California with the IVT values; some positive correlations did appear in the northern regions for "Other Dinoflagellates" and *Prorocentrum spp*. In addition to this regional north-south pattern of more positive correlations in the north and negative correlations in the south, the two analyses using the different IVT variables (the daily average values versus the daily maximum values) yielded similar results, with a few more significant correlations with the IVT daily maximum values than the daily averages.

The positive correlations also appeared to be stronger with the IVT daily averages than the IVT daily maxima. However, the average correlation coefficient was larger for the IVT daily maxima, which may indicate a stronger relationship of phytoplankton abundances to the maximum IVT experienced than the average IVT. This shows us that the intense values of water vapor in the atmosphere impact the community structure and abundance of HAB causing taxa more than moderate IVT values. This observation may help us to understand mechanisms by which climate change impacts ecosystem health, human health, and our economy.

SemiLog Correlation Results

The SemiLog analyses yielded the greatest number of significant correlations, particularly when phytoplankton abundances were compared to the IVT daily maximum values; these correlations were primarily negative. The correlations showed a similar trend across latitudes as the linear analyses: positive correlations were exclusively at the Monterey Wharf and farther north, while many more significant correlations – all negative – were found at the Cal Poly Pier and south. The only species that yielded positive correlations in these analyses were *Gymnodinium spp.*, *Ceratium spp.,* and *Alexandrium spp*. These positive correlation coefficients were very similar for the analyses using the IVT daily average values and the IVT daily maximum values; no analysis gave a consistently higher correlation coefficient.

Negative correlations with IVT were found for *Pseudo-nitzschia delicatissima, Dinophysis spp., Ceratium spp., Lingulodinium spp., Prorocentrum spp.,* the "Other Diatoms" group, and the "Other Dinoflagellates" group. There were several more significant correlations when using the IVT daily maxima than the IVT daily averages, which further underscores the strong negative relationship between the higher occurrences of the IVT magnitude and decreased phytoplankton taxon abundances. The most significant correlations were *Prorocentrum spp.* with the IVT daily maxima, and the "Other Dinoflagellates" with both IVT maxima and daily averages. The diatom counts that did yield significant correlations – *Pseudo-nitzschia delicatissima* and "Other Diatoms" – only occurred at one location each. These results indicate a stronger relationship of the dinoflagellate populations with the IVT magnitude than the diatom populations and the IVT magnitude. *Ceratium spp.* was the only taxon that provided both significant positive and negative correlations, which could indicate a more complex relationship for that species with fluctuations of the IVT. Between the analyses using the IVT daily averages and IVT daily maxima, there was no significant differences in the magnitudes and signs of the correlation coefficients, but the number of significant correlations was higher when using the IVT daily maxima.

LogLog Correlation Results

The LogLog analyses, in which I took $\log_{10}$ of both variables, yielded almost as many significant correlations as the SemiLog analyses, but had a stronger negative correlation on average than the SemiLog analyses did. In this analysis, the same taxa yielded the same few positive correlations, and at the same locations as the SemiLog analyses. While these positive correlations remained the same as the SemiLog analyses, fewer of the negative correlations in Southern California were significant. Using the IVT daily average values, the species negatively correlated with IVT were *Pseudo-nitzschia delicatissima, Dinophysis spp., Ceratium spp., Lingulodinium spp., and* "Other Dinoflagellates". The correlation of *Prorocentrum spp.* with IVT that was extremely prominent in the SemiLog analysis did not show up at all with the IVT daily average values in the LogLog analysis and only appeared at the Stearns Wharf when using the IVT daily maximum values. The correlation with *Lingulodinium spp.* was also not significant at the Santa Monica Pier in the LogLog analyses, though it was in the SemiLog analyses. The correlations with the "Other Dinoflagellates" remain unchanged in terms of the locations of the significant correlations, but the correlation coefficients were significantly lower than the corresponding SemiLog correlations. Overall, the LogLog correlations displayed similar patterns to the other analyses: more positive indices in Northern California and more negative indices in Southern California, in addition to greater correlations between IVT and the dinoflagellate taxa than the diatom taxa, and more frequent significant correlations with the IVT daily maximum values.

HAB Abundances during AR versus non-AR

I found 31 cases (HAB taxon and location) where the HAB abundances were significantly different after a week with an AR vs. no AR for that week. 15 of these were in Southern California, and 16 in Northern California. However, there were latitudinal differences as to which taxon showed significant relationships, with the "Other Diatom," "Other Dinoflagellate," *Prorocentrum spp.*, *Dinophysis spp., Alexandrium spp., Pseudo-nitzschia delicatissima* and *Pseudo-nitzschia seriata* yielding significant differences in Northern California. In Southern California, significant differences were found for *all* taxa except *Alexandrium spp., Akashiwo spp., Dinophysis spp.,* and *Cochlodinium spp.* Both *Cochlodinium spp.* and *Akashiwo spp.* did not return any significant indices for any of the analyses. The only location that had significantly higher abundances after a week with an AR than a week with no ARs was in Southern California: *Ceratium spp.* at the Newport Beach Pier. Interestingly, the positive correlations between the IVT magnitude and the phytoplankton counts were found almost exclusively in Northern California; the only positive correlation between HAB abundance and AR presence was found in Southern California. These results indicate that the relationships between HAB abundance and the occurrence of ARs is different than the relationship between HAB abundance and the magnitude of the IVT magnitude: the patterns of the AR analyses were strikingly different than those of the IVT correlations.

Large Scale Trends

The relationship of HAB taxon abundances and the magnitude of the IVT shows more frequent positive correlations near Bodega Bay and Tomales Bay and more frequent negative correlations at the Cal Poly Pier and south. This positive correlation is most apparent for *Gymnodinium spp.* in the linear analyses with the IVT daily maxima. Other taxa that tended to have positive correlations with the IVT were *Ceratium spp.*, *Akashiwo spp.,* and *Alexandrium spp*. It is important to note that *Gymnodinium spp.* and *Alexandrium spp.* are potential sources of saxitoxins, and can cause red tides, and all four taxa are associated with hypoxia which kills other organisms. The fact that there was a positive correlation of *Pseudo-nitzschia seriata* with IVT at the Santa Monica Pier is also worth noting, as that species produces domoic acid, which causes major fisheries closures.

The most unexpected trend was the frequent negative correlations of IVT magnitude with HAB taxa abundance in Southern California. These taxa included *Prorocentrum spp., Lingulodinium spp., Ceratium spp., Dinophysis spp.* and *Pseudo-nitzschia delicatissima.* The only taxon that did not have any significant correlations was *Cochlodinium spp*. *Pseudo-nitzschia delicatissima* is a major producer of domoic acid, *Dinophysis spp.* is known to produce okadaic acid, *Lingulodinium spp.* is known to produce yessotoxin, *Prorocentrum spp.* contains several toxic and harmful species, and all of them are known to cause hypoxia upon the decay of dense blooms. The negative correlations of HAB taxon abundances with IVT magnitude suggest that increases of IVT as a result of climate change could reduce the likelihood of these species blooming in Southern California.

HAB abundance correlations tended to be more significant with the IVT daily maximum data, which revealed strong negative relationships of abundance with extremes of IVT, but before they become ARs. There was no strong latitudinal trend of HAB abundance with AR, and almost all the taxa had larger mean abundances when there was no AR present the week before sampling. The only taxa that did not have statistically different abundances with/without an AR at any location were *Cochlodinium spp.* and *Akashiwo spp.* The only taxon with higher abundances when an AR was present the week before was *Ceratium spp*. These results suggest that the AR presence is less informative than the magnitude of the IVT in predicting the HABs from these phytoplankton taxa.

Proposed Mechanisms

The primary mechanism proposed to explain the positive correlations of some HAB taxon abundances with IVT and ARs is described in Aguilera et al. (2019): precipitation in regularly dry areas can cause large, sudden influxes of nutrient-rich anthropogenic pollutants that stimulate the growth of the phytoplankton. However, this mechanism only explains the positive correlation seen with some taxa in Northern California; it does not explain the negative correlations of HAB abundance and IVT and ARs found in Southern California. Increased IVT does not always produce runoff into the ocean in dry climates because it can go into recharge, which is one possible reason why the correlations have different signs in at different latitudes and other mechanisms must be addressed.

An alternate explanation for the negative correlations is the impact of ARs on the temperatures and salinities of coastal regions. Byrne et al. (2023) identified strong freshwater signals in the coastal surface ocean that persisted for multiple days after major rain events, primarily as a result of ARs in the region. Such freshwater plumes may have negative consequences for HAB-forming species, by inducing osmotic stress, by the inclusion of toxic compounds from terrestrial runoff, by changing the vertical stratification and creating unusually warm surface layers, or by enhancing transport of surface waters away from the coast. All these mechanisms require further study.

Other proposed mechanisms that could result in the complex correlation patterns uncovered in this study include the impact of wind stress associated with ARs, light availability decreasing with increased IVT, topographic variables, seasonal variability, or ocean currents associated with the Southern California Bight.

It is clear that further research needs to be conducted to gain a better mechanistic understanding of the relationships between IVT, ARs and HAB taxa. Potential mechanisms can only be speculated from the analyses done here; additional analyses should be explored to test some of these ideas, such as removing the seasonal cycles of both phytoplankton and IVT, looking at additional locations, exploring variables such as nutrient levels, isolating species-specific lags in these correlations, and quantifying the relationships of phytoplankton counts with precipitation and wind data in the region. It would also be fruitful to explore differences among anomalously wet and dry years, El Niño versus La Niña years, and marine heat waves versus normal years, to better understand the effects of interannual variability on the HAB patterns in the region.

Light availability is typically decreased by the presence of ARs due to dense cloud formation; this might have a negative effect on phytoplankton growth as they need sunlight to photosynthesize. The more water vapor in the atmosphere, the less light reaches phytoplankton in the coastal waters. However, while light effects would be predicted to have overall negative consequences for phytoplankton abundance, they may play less of a role due to the lag accounted for in the week-long average analyses done in this study.

Another thing to note in the context of climate change is the general decreasing trend in phytoplankton that has been cited over the last century. This is mainly attributed to increasing temperatures, particularly in tropical and subtropical regions (Boyce et al. 2010). This study could provide additional insights into the mechanisms behind the global decrease in phytoplankton, suggesting a larger role for the hydroclimate in phytoplankton community structure and HAB formation.

Limitations

The greatest limitation of this study was the time available to perform the research. Due to the fact that this paper is a capstone project for a one-year master's program which was focused on coursework for much of the year, only a few months were available to dive into the research. For this reason, there was limited time for additional analyses that would support further insights into the relationships between HABs and IVT/ARs. Further research must be performed on these additional variables to give more confidence in our conclusions.

Other limitations of this study include the possible sources of error. The phytoplankton data used in this study were counted visually, which can result in variation based on the sample taken for the day, the person conducting the count, and the instruments used. There are also assumptions being made about the relationships between HAB taxa and IVT/ARs that could contribute to errors. This research simplified the extremely complex air-sea interactions and physical-biological systems that led to these observations. Other elements of the system, such as evaporation, grazing, seasonality, and turbulence were not accounted for here, but should be in order to fully understand the observed patterns.

Implications

The purpose of this study was to uncover potential relationships between the hydroclimate of California and HAB-forming phytoplankton taxa in coastal regions. HAB-forming phytoplankton taxa, in particular, can have major implications for the health of humans and the ecosystem, as well as economic drivers including fisheries. A primary result from this study was the identification of positive correlations between IVT magnitude and some dinoflagellate taxa in Northern California – particularly *Gymnodinium spp.*, as well as weaker signals with *Alexandrium spp., Akashiwo spp.,* and *Ceratium spp.* The trend of more positive correlations to the north of the study region is important, as much of the fisheries along the West Coast are located in Washington, Oregon, and Northern California. If the latitudinal trend identified here continues beyond the boundaries of California, this suggests that increased IVT could have negative implications for the fisheries in the areas through increased HAB occurrences. This study's results support the idea that warning systems for HABs blooms can be improved by the inclusion of IVT data; these results might also be utilized to mitigate fisheries economic losses and human health impacts. The raw IVT data should be implemented into warning systems rather than the AR-categorized data, as stronger correlations with dinoflagellates were found with the IVT magnitudes than the AR data. The positive correlation of IVT with *Pseudo-nitzschia seriata* at Santa Monica Pier is notable, as this species produces domoic acid – a toxin affecting fisheries and human health. Such positive correlations of HAB taxa and IVT also need to be considered in the context of climate change and strengthening IVT intensity: our analyses predict that there will be more HABs in northern latitudes, particularly due to *Gymnodinium spp.* However, *Gymnodinium spp.* did not have a significantly different abundances in these northern latitudes with the occurrence of an AR, so the predicted increase in ARs might not affect the species in these regions.

Another significant result of this study were the strong negative correlations between the abundance of certain HAB taxa and the magnitude of the IVT in the region, particularly the daily maxima values in the southern half of the state. These correlations indicate a decrease in certain species, such as *Prorocentrum spp.* and *Ceratium spp.* with stronger IVT values. In terms of preventing the negative impacts of HABs in this region, this could provide some useful information for fisheries and human health in Southern California.

The final significant trend found by this study was the negative correlations between AR events and HAB taxa. This suggests decreasing likelihoods of HAB occurrences as AR frequencies increase with climate change. It is not clear whether the predicted decreases in HAB taxa would extend to the entire phytoplankton community. Phytoplankton are the primary producers of the oceans, and the rest of marine ecosystems rely on them as the base trophic level. Potential IVT-AR-driven decreases in the phytoplankton community could have further negative impacts on the ecosystem through overall decreases in the productivity of the oceans, including impacts on fisheries productivity in the region. Exploring such mechanisms could aid in the development of HAB warning systems, and improved educational programs to avoid health and economic impacts of IVT-driven changes in these phytoplankton taxa.

It also should be noted that the positive correlations of HAB abundance and IVT were found in regions where ARs are much more common and the IVT magnitude is usually larger. This could indicate that ARs present larger, unpredictable disturbances to the ecosystem in Southern California but are more frequent elements of the ecosystem in Northern California, where the phytoplankton might better adapt to them.

Conclusions

Here I found that there were complex relationships between IVT/ARs and HAB-causing phytoplankton taxa when the specific taxon is present. Correlations between the IVT magnitude and the phytoplankton were typically stronger among dinoflagellates than diatoms. Some dinoflagellates showed consistently positive correlations of abundance with IVT in Northern California, while other dinoflagellates were consistently negatively correlated with IVT in Southern California. The HAB taxa with the most consistent significant correlations were *Gymnodinium spp.* (positive linear correlations in Northern California), and *Prorocentrum spp.* (logarithmic negative correlations in Southern California). The "Other Dinoflagellates" abundance was also consistently negatively correlated with IVT in the study region. Most taxa had significantly lower abundances when there was an AR the week before; only one observation had higher abundances after ARs. With little latitudinal trend in the sign of the correlation, there were differences in the taxa that showed significantly different abundances in relation to AR presence in Southern California than Northern California.

These results help to quantify HAB dynamics in the context of California's fluctuating hydroclimate; in the greater context of climate change, the analyses showed that IVT can be a significant predictor of HAB abundance, particularly in Northern California. The implementation of IVT data into HAB warning systems in Northern California could add additional skill to mitigate economic losses for fisheries and minimize human health impacts.

Finally, further research should be done to understand these correlations fully. I hope that this study has opened a door to quantifying the relationships between California's hydroclimate and the occurrence of HAB-causing phytoplankton species along the California coast. This research has demonstrated how much more needs to be done to understand and prepare for HAB events and climate change.

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