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UNIVERSITY OF CALIFORNIA SAN DIEGO

Microfiber Variability in the Southern California Coastal Ocean

A Thesis submitted in partial satisfaction of the requirements
for the degree Master of Science

in

Earth Sciences

by

Jack Weil

Committee in charge:

Professor Arthur Miller, Chair
Professor Alexander Gershunov
Professor Joel Norris

2022

The Thesis of Jack Weil is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

University of California San Diego

2022

DEDICATION

This paper is dedicated to my family and, especially, my parents, Mark and Jane Weil, for their unwavering support, and without whom I would not have had the opportunity to pursue a master's degree. And to all the incredible professors, mentors, classmates, and friends that pushed me throughout my academic career; I wouldn't be here without you.

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I would like to acknowledge Art Miller for his much-needed expertise and support, Sarah-Jeanne Royer, Melissa Carter, and Carla Costa for their roles in creating the dataset that was integral to this paper, Laurel Dehaan for her help averaging San Diego area precipitation data, and Kara Wiggin for providing me with valuable papers on microfibers to review. I would also like to acknowledge Sasha Gershunov and Joel Norris for agreeing to serve on my committee and for their suggestions throughout this process. I would also like to acknowledge John McGowan, the McGowan Plankton and Chlorophyll Program, and the California Harmful Algal Bloom Monitoring Program for their archived samples from which microfiber concentrations were measured, and private donors, the MacArthur Foundation, and the Southern California Coastal Ocean Observing Systems for funding those projects. Partial support from the National Science Foundation (OCE-2022868) is greatly appreciated.

ABSTRACT OF THE THESIS

Microfiber Variability in the Southern California Coastal Ocean

by

Jack Weil

Master of Science in Earth Sciences

University of California San Diego, 2022

Professor Arthur Miller, Chair

Microfibers in the marine environment pose a threat to aquatic ecosystems and organisms, as well as to humans. Most microfibers are land-based and are transported to the ocean via different processes, including through wastewater effluent and riverine discharge. Measurements of microfiber (MF) concentrations in Southern California coastal surface waters, collected approximately monthly from archived samples between 1983-2019, were available for study and were used in this paper to examine the role of climate in explaining variability in microfiber concentrations. These MF measurements were distinctly non-

Gaussian, measuring mostly between 10-50 fibers per 50mL, and showed no seasonal cycle. Time series data was collected for five climate variables (coastal upwelling, precipitation, significant wave height, wind speed, and tidal level), and regression analyses between these variables and MF concentrations were conducted. This study shows that the concentration of microfibers in surface waters in the La Jolla area do not correlate with weather and climate events that presumably would transport microfibers to the marine environment. No more than 1% of microfiber variability can be explained by any variable investigated.

INTRODUCTION

The study of microfibers, the small fibers shed from various anthropogenic sources including clothing and automobile tires, is a growing field that has become increasingly prevalent in scientific literature over recent years (Mishra et al., 2020). The presence and impact of microfibers in the environment, and particularly in the marine environment, is a relatively unstudied topic, but nonetheless an important one. Because of the many different materials used in the production of textiles and other microfiber sources, the identification of microfibers and their size definition can be relatively complex and varies throughout the literature. Liu et al. (2019) proposed a general definition of microfibers as “any natural or artificial fibrous materials of threadlike structure with a diameter less than 50 μm, length ranging from 1 μm to 5 mm, and length to diameter ratio greater than 100.” Microfibers are comprised of a variety of materials, separated into categories of synthetic (plastics such as nylon or polyester), human-made cellulosics (such as rayon), natural or plant-based fibers (such as cotton, hemp, or linen), and animal fibers such as wool or silk (Liu et al., 2019; Suaria et al., 2020). These fibers can enter the marine environment in a number of ways, including wastewater treatment plant (WWTP) effluent from textile production and domestic laundering, urban dust (fiber shedding from weathering of clothes, automobile tire abrasion, and road wear), and breakdown of marine equipment and marine macrofibers (fishing nets and boat paint/protective coatings) (Mishra et al., 2020). Microfibers can also enter the marine environment from land-based sources through rivers and streams, which transport microfibers accumulated in soils from fibrous materials used in farming or construction projects and from agricultural fertilizers created from sewage sludge, as this sludge can contain larger plastics that break down in the land environment (Liu et al., 2019). Rivers can further accumulate microfibers from hand washing of clothes, which is still the most common method of laundering in many parts of the world that lack wastewater treatment infrastructure (Liu et al., 2019). In fact, a study by Schmidt et al. (2017) estimated that the ten most polluted river catchments contribute between 88-95% of the total plastic waste discharged to the ocean. Through these methods of discharge, microfibers accumulate in the marine environment. Microplastic pollution surveys from around the globe estimate that microfibers are the most common type of human-made particle (Suaria et al., 2020). They comprise over 85% of all microplastics on shorelines, and fibers from clothes alone comprise up to 35% of all marine microplastics (Liu et al., 2019). However, there is some disagreement about these metrics, as fibers collected in many studies are not proven to be solely plastic and may instead be made of other categories of material, therefore overestimating the amount of microplastic fibers in the environment (Suaria et al., 2020). A study by Suaria et al. in 2020 showed that most fibers (79.5%) are actually cellulosic in nature, and that a much smaller percentage (8.2%) are plastic or synthetic (Suaria et al., 2020).

Microfibers overall, regardless of their inclusion in plastics data, have a significant negative impact on the marine ecosystem and potentially far-reaching impacts beyond the ocean. The detrimental impacts of microfiber ingestion can be seen throughout trophic levels, affecting microorganisms, fish, crustaceans, and humans (Mishra et al., 2020, Hu et al., 2020, Rochman et al., 2013, Kosuth et al., 2018, Gasperi et al., 2018). In zooplankton species, the ingestion of microfibers can accumulate particles in their digestive tracts and can breakdown into nanofibers, which can cause cytotoxicity through phagocytotic absorption of these nanofibers (Mishra et al., 2020). A study by Hu et al. (2020) revealed that exposure to microfibers caused structural changes in the gills of adult Japanese medaka, including aneurysms (artery clogging) in gill tissues. Crabs fed microfiber-laced food had a lower energy budget for reproduction and ate less food than crabs fed food without microfibers (Watts et al., 2015). There are also impacts for marine animals due to the sponge-like nature of microfibers. These particles accumulate pollutants present in the water, creating a toxic biofilm on the microfiber. This toxicity is then passed on to aquatic organisms through ingestion, and can result in a number of negative effects, including liver toxicity, tumors, and cell necrosis (Rochman et al., 2013). The impact of microfibers on the human population is less well understood, but they have been detected in seafood, tap water, beer, and even human lung tissue and stool (Rochman et al., 2015, Kosuth et al., 2018, Pauly et al., 1998, Schwabl et al., 2019). To better understand the presence, transport, and impact of these microfibers, we present here an investigation into the variability of observed microfiber concentrations in coastal surface waters off the Scripps Pier. Strong and non-Gaussian fluctuations in microfiber concentrations are identified and then compared with various climatic variables. Our results reveal that the variables investigated (coastal upwelling, wave height, precipitation, wind speed, and tidal level) are unable to accurately explain the high variability in microfiber concentrations, so that other factors must prevail in controlling these fluctuations.

METHODS AND DATA

This study is based on a time series of microfiber (MF) concentrations in surface water samples taken from the Scripps Pier in La Jolla, California. This time series was compiled by Sarah-Jeanne Royer of the Center for Marine Debris Research at Hawaii Pacific University. Archived seawater samples dating back to 1983 were used to determine microfiber concentrations (Royer, 2022b). All samples were taken in the top 1 meter of the ocean, and all were taken in the mornings, although exact timing of the samples varied. Most sample volumes were 50 mL, although in some archived cases all 50 mL of seawater was not available. The entire available sample volume was used in each measurement. In the cases where 50 mL was not available, total microfiber concentration was extrapolated to ensure each measurement indicated the number of microfibers per 50 mL. Seawater samples were run through filter paper using vacuum filtration to ensure that all microfibers in the samples were captured. A representative portion of the filter paper was then selected and imaged using a Nikon stereoscope with UV filter 390 nm and processed with Q-Capture Pro7. The final microfiber concentration for the entire filter was extrapolated based on the percentage of filter that was imaged. Fibers were identified visually by researchers, which increases the potential for error in the accuracy of microfiber concentration data (Royer, 2022a). Furthermore, there were seven sampling dates

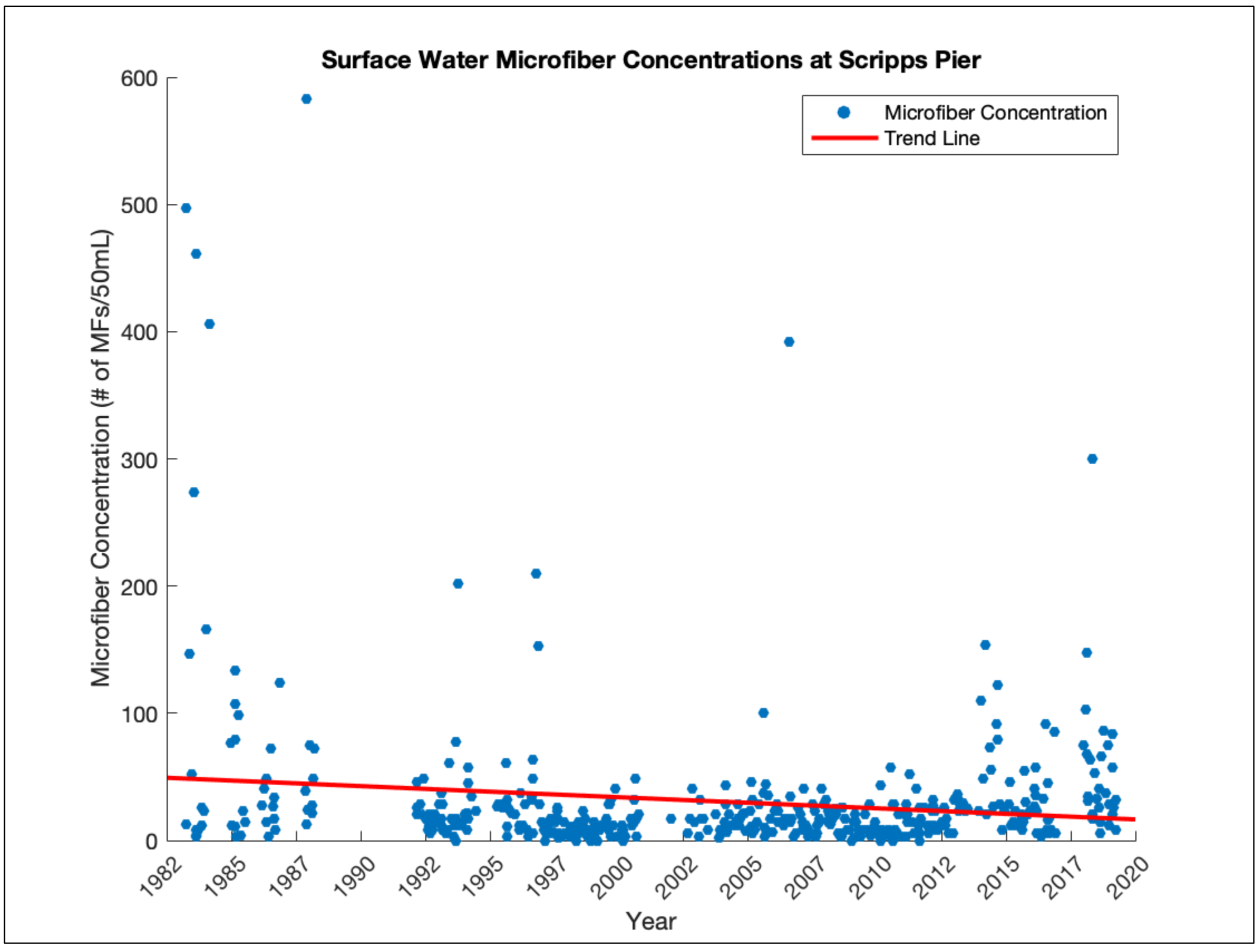

Figure 1: Microfiber (MF) concentrations in surface water from 1983-2019. MF concentrations in units of number of fibers per 50mL of seawater.

where two samples were analyzed, and a total of 14 microfiber measurements that were extrapolated from samples with less than 50 mL analyzed. These instances of extrapolation and double sampling could also decrease confidence in microfiber measurement values. This dataset can be seen in Figure 1, with associated linear trend line (Royer et al., 2019).

The microfiber concentration time series reveals strong variability (Fig. 1) with values typically seen in the 10-50 counts range, but occasionally exceeding 500. The mean microfiber concentration value was 30.97 fibers/50mL, and the standard deviation was 57.71 fibers/50mL. However, the distribution is clearly non-Gaussian as seen in Figure 2, as evidenced by its strong asymmetry around the mean. Furthermore, microfiber concentrations do not follow any

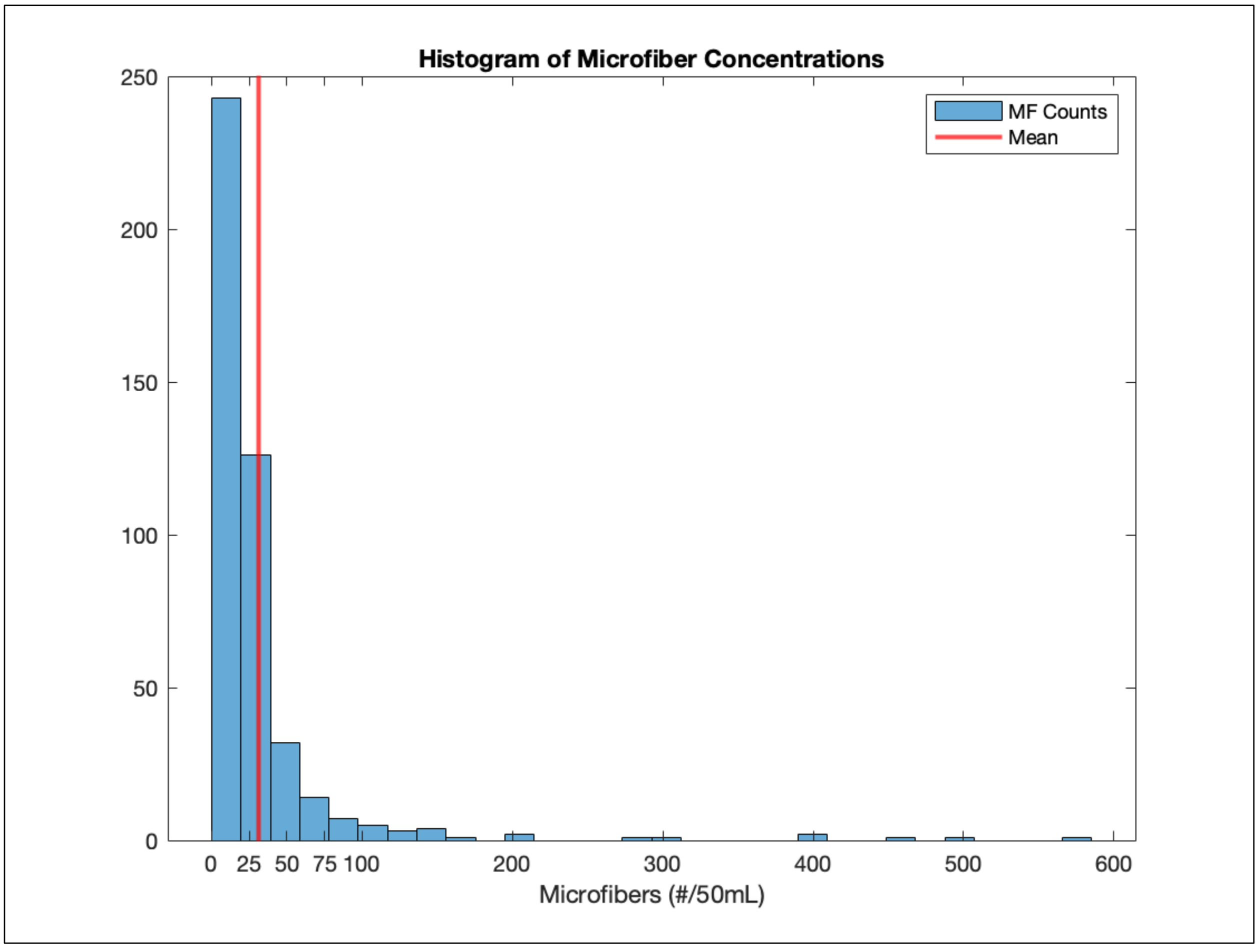

Figure 2: Histogram representation of MF data. Red line indicates mean value in microfibers per 50mL, and y-axis indicates number of measurements within each bin.

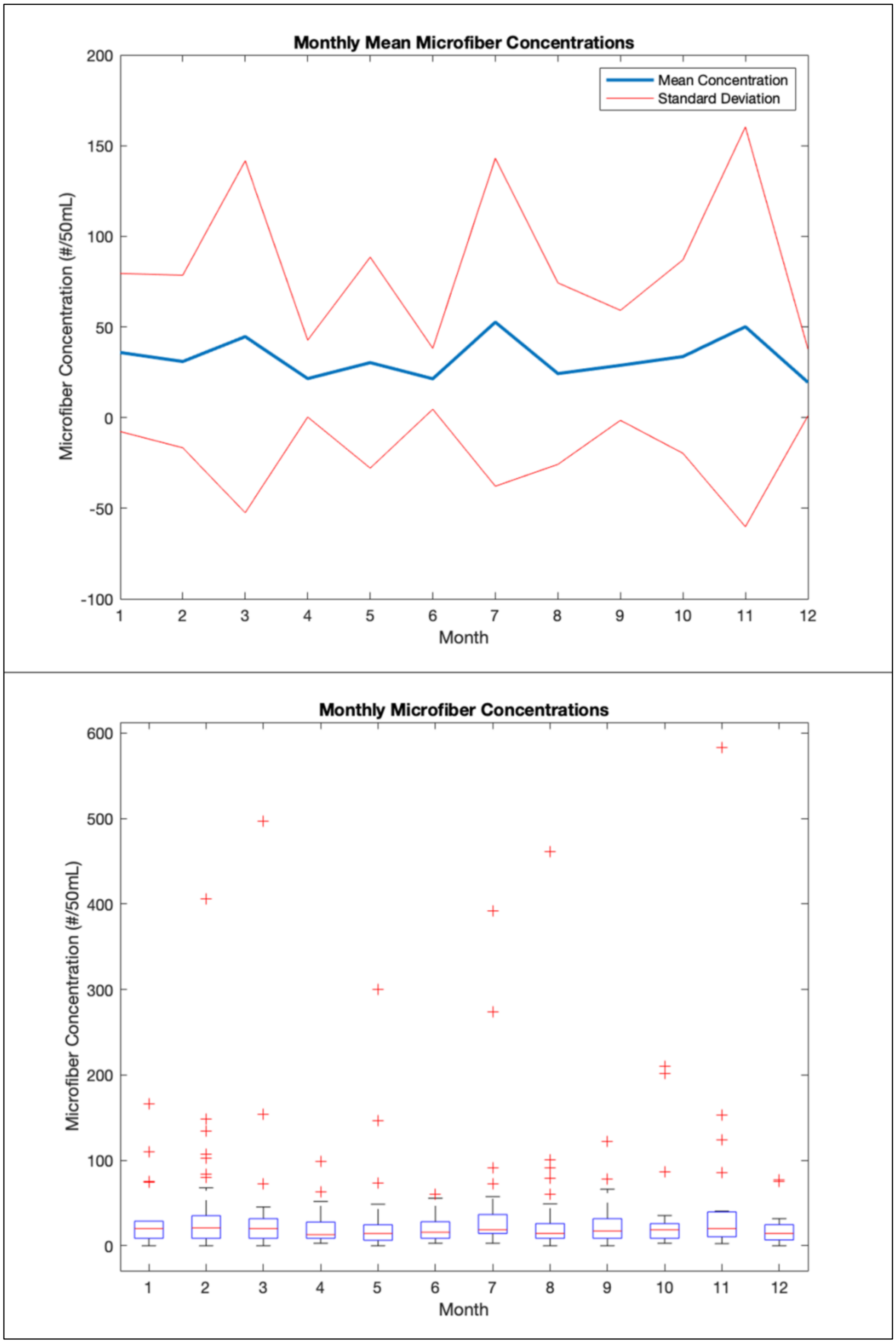

Figure 3: Monthly microfiber concentrations. Monthly mean microfiber concentrations with blue line representing mean concentration and red lines representing standard deviation (top). Monthly microfiber concentrations with blue box representing 25-75 percentile values (or interquartile range, IQR), red line representing monthly median value, "T" bars representing 25 and 75 percentiles ± 1.5*IQR, and red crosses indicating outliers (bottom).

discernable seasonal cycle, as seen in Figure 3. The top plot in Figure 3 indicates that there is no significant increase in the mean concentration values across any season, and the bottom plot indicates that extreme or outlier values do not preferentially occur in a certain season.

In order to attempt to explain the variability of the microfiber concentration data, we considered several oceanographic and atmospheric variables that might conceivably be controlling these changes through mixing processes, dilution, deposition, or water mass advection. We considered an upwelling index (related to water mass advection), wind speed (related to surface mixing or deposition), precipitation (related to dilution or deposition), surface wave height (related to surface mixing), and tidal level (related to water mass advection or

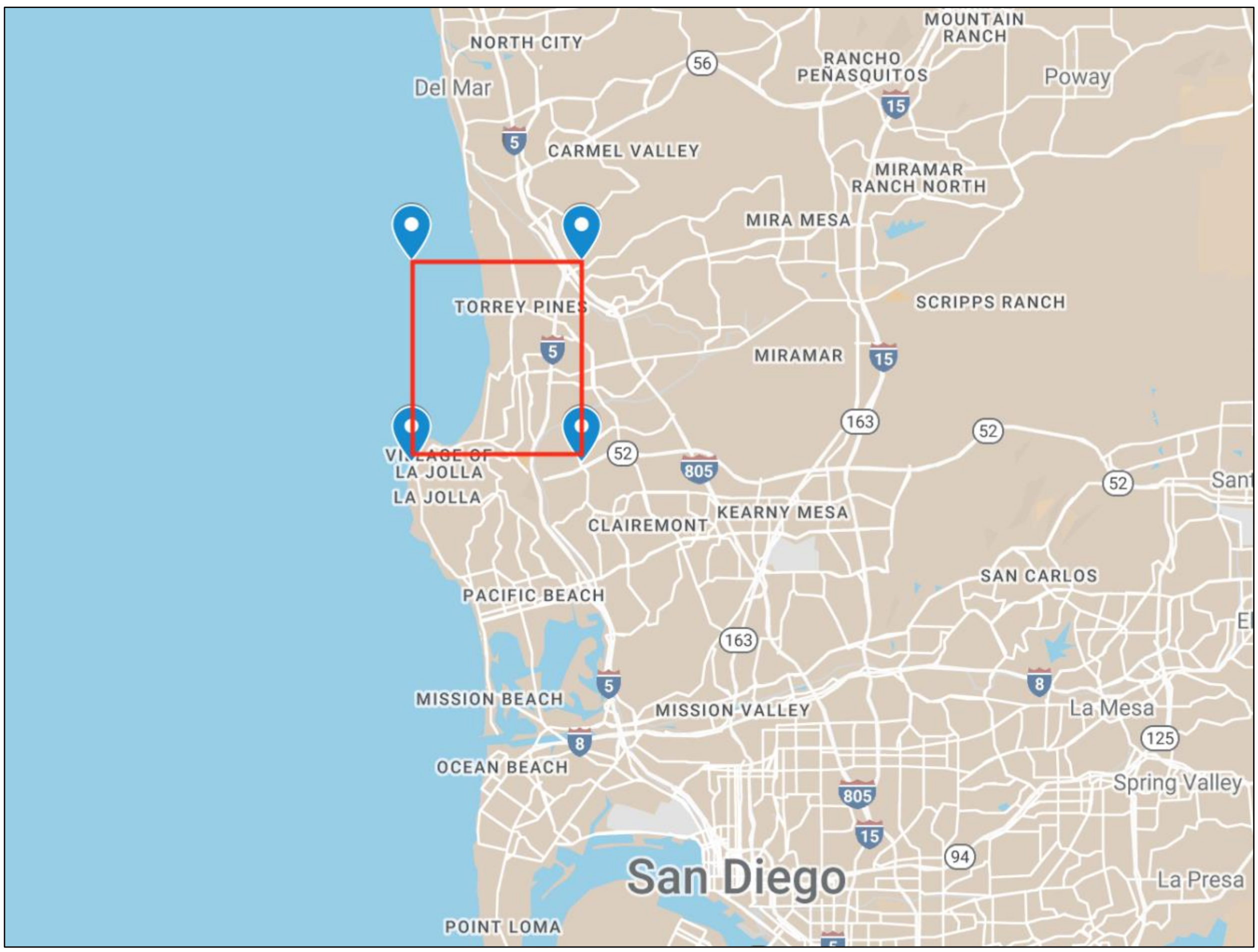

Figure 4: Wind speed measurement locations. Locations were used to compute daily wind speed averages from 1983-1994 (from Livneh et al. 2015).

deposition) as possible controls.

Upwelling values were taken from NOAA Fisheries Environmental Research Division, which used a traditional Bakun calculation for upwelling values at 33° N, 119° W. Daily averages for upwelling values were calculated using six-hourly surface pressure measurements (NOAA, 2022). Wind speed data for 1983-1994 was taken from Livneh et al. 2015, who created a dataset of gridded daily wind speed averages (Livneh et al., 2015). Wind speed values from this dataset were averaged using measurements from (32.8438° N, 117.2813° W), (32.8438° N, 117.2188° W), (32.9063° N, 117.2813° W), and (32.9063° N, 117.2188° W). These locations are shown in Figure 4. Wind speed data for 1994-2019 was taken from the Coastal Data Information Program (CDIP) Station 73 at Scripps Pier (CDIP, 2022). Wave height measurements from 1983-2019 were also taken from CDIP Station 73 data (CDIP, 2022). The daily precipitation dataset was created from averaged rainfall measurements in the San Diego region south of 33° N, west of 117° W, and north of the California-Mexico border (Dehaan, 2022). Rainfall measurements for 1983-2011 were taken from Livneh et al.'s 2013 paper (Livneh et al., 2013). Rainfall measurements for 2012-2018 were taken from Su et al.'s 2021 paper (Su et al., 2021). Values are total rainfall in mm per day. Tidal level data was taken from the University of Hawaii Sea Level Center based on tide gauge measurements from a NOAA buoy stationed at Scripps Pier (Caldwell et al., 2015). Tidal levels at 9:00AM were used as an approximation of the microfiber sampling times. The histogram representation of all available data for all meteorological variables can be seen in Figure 5.

Meteorological data was collected to investigate changes in microfiber concentrations within the study area. Data for all microfiber sampling dates was used to determine a viable relationship between climate variables and microfiber concentrations. Data was also separated into "peak events," where microfiber concentration measurements exceeded one standard deviation from the mean. Meteorological measurements at or before peak events were used to examine relationships between high microfiber concentrations and extreme climate events.

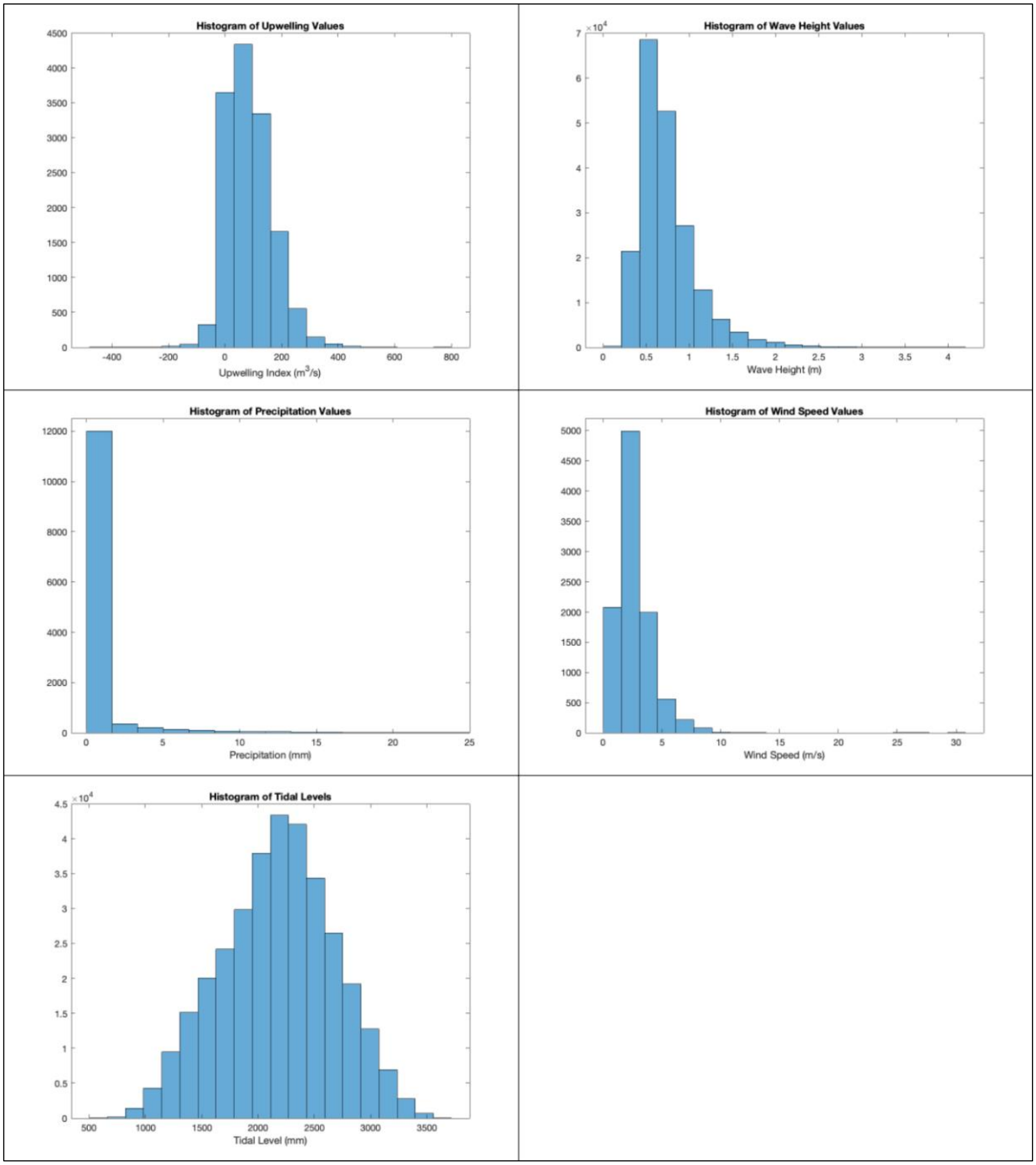

Figure 5: Histogram representation of meteorological data. Wind speed data from 1983-2019, precipitation from 1983-2018, wave height from 1976-2019, upwelling from 1967-2022, and tidal level from 1983-2022. Y-axes indicate number of measurements within each bin.

RESULTS AND DISCUSSION

Microfiber observations were next regressed against the five climate time series. With the exception of tidal levels, regression analysis was performed for each pair of variables for both the day preceding microfiber sampling dates and the day of sampling to determine the highest correlation. The resulting R^2 values for each regression are summarized in Table 1. Microfiber concentrations were found to have little to no correlation to the climate variables chosen for this study. R^2 values indicating the proportion of MF variability explained by linear regression lines did not exceed 1% for any variable. R^2 values for wind speed and wave height were greatest for the days preceding microfiber measurements, while correlation with upwelling measurements was greatest for the day of MF sampling. The R^2 value for precipitation was the same for the day preceding microfiber sampling and the day of sampling. The most accurate descriptor of microfiber variability was precipitation, with an R^2 value of 0.0095. Due to the wide range of MF concentrations on days with no precipitation, and the comparatively dry climate in Southern California, the regression for precipitation was calculated without considering data points from sampling days in which precipitation did not occur. Wind speed

Table 1: R^2 values for climate variables. Values indicate the proportion of microfiber variability explained by each variable's regression analysis. Percentage of MF variability explained is included in parentheses.

Climate Variable	R^2 for day preceding MF sampling	R^2 for day of MF sampling
Precipitation	0.0095 (0.95%)	0.0095 (0.95%)
Upwelling	0.00059 (0.059%)	0.0034 (0.34%)
Wave Height	0.0041 (0.41%)	0.00035 (0.035%)
Wind Speed	0.0083 (0.83%)	0.0077 (0.77%)
Tidal Level	--	0.0051 (0.51%)

and wave height on days preceding microfiber sampling explained 0.83% and 0.41% of MF variability, respectively, while upwelling on MF sampling days explained 0.34%. Due to its distinct daily cycle, only tidal level at the time of MF sampling was included in the regression analysis. Same-time tidal level explained 0.51% of microfiber variability.

Precipitation data and associated trend line can be seen in Figure 6. Precipitation has the highest correlation to microfiber concentration, and it should be noted that it also has the largest spread in the 95% confidence interval, especially at larger precipitation measurements. However, the trend line was computed without the use of zero values for precipitation, which removes a large portion of the data and thereby reduces significance levels. The slight trend

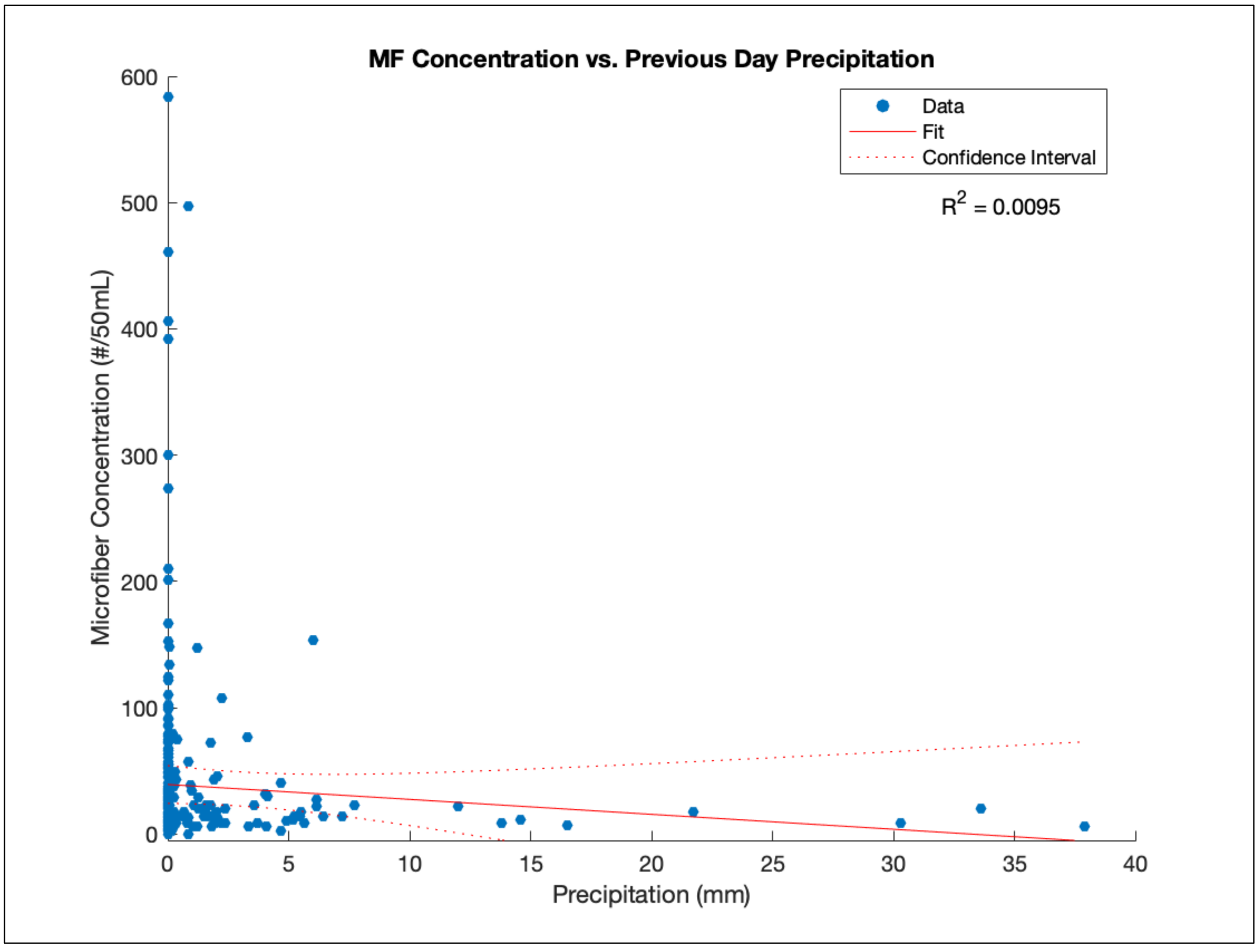

Figure 6: Comparison plot of MF concentrations versus precipitation measurements from the day preceding MF sampling date. Solid red line indicates linear regression fit; dotted red line represents the 95% confidence interval.

indicates that larger rainfall measurements weakly correlate to lower concentrations of microfibers. This could be due to surface water dilution; light precipitation would introduce land-based microfibers to the ocean, while larger rainfall values would introduce fresher water to the surface ocean after land-based microfibers make it to the ocean.

Upwelling data and associated trend line can be seen in Figure 7. Upwelling values for Southern California were overwhelmingly positive, indicating upwelling for most MF sample dates. Because of this, variability in MF concentration is not surprisingly poorly explained by upwelling values. However, the slight trend indicated by the linear regression line in Figure 6 suggests that higher upwelling values correlate weakly with lower microfiber concentrations.

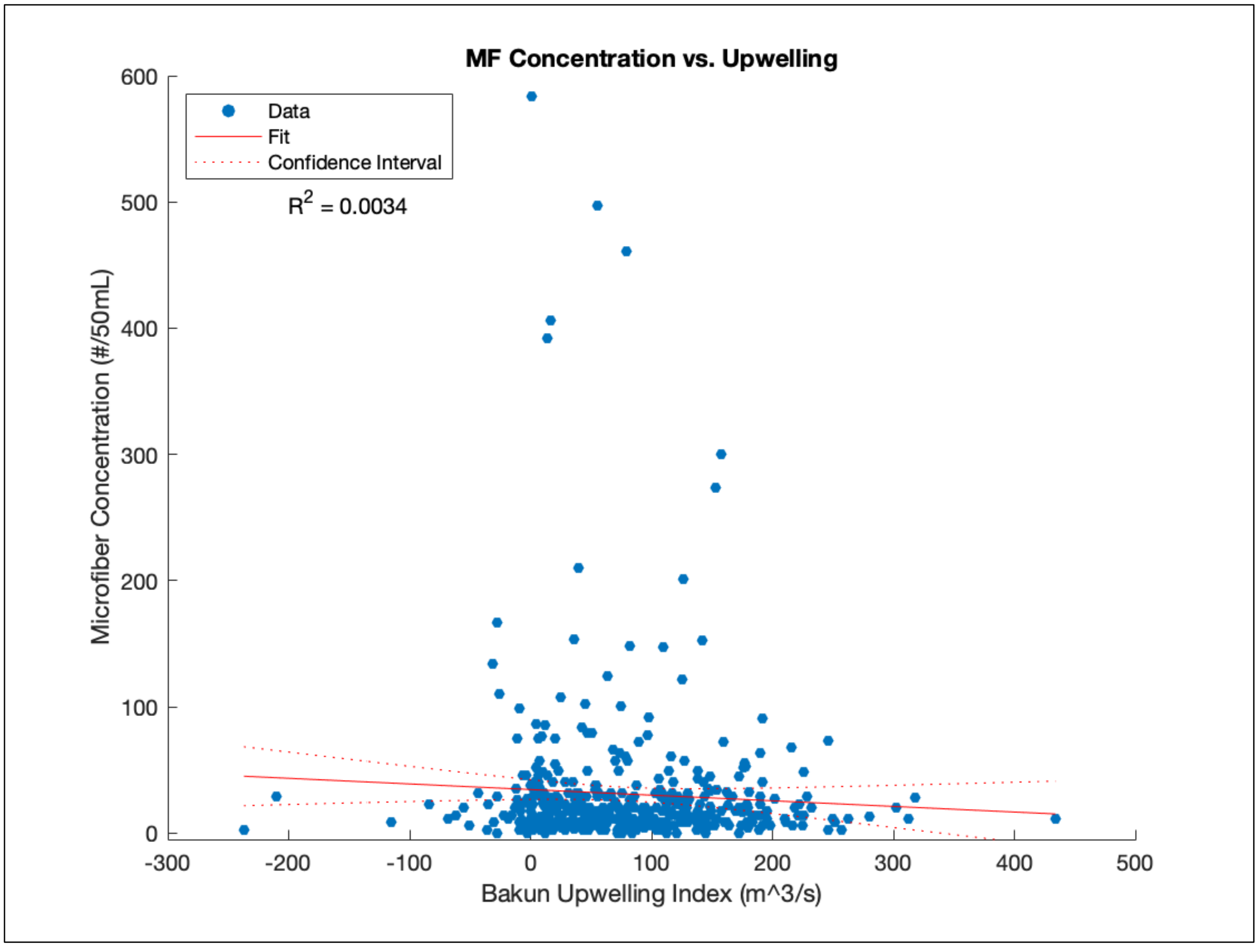

Figure 7: Comparison plot of MF concentrations versus upwelling measurements from the MF sampling date. Solid red line indicates linear regression fit; dotted red line represents the 95% confidence interval.

This could be due to the transport of deeper, cleaner water to the surface and therefore the dilution of microfibers in the surface water environment.

Wave height data and associated trend line can be seen in Figure 8. Wave height measurements from the day preceding MF sampling dates were similarly poorly correlated with MF concentrations. Wave height data was relatively sparse compared with the other variables measured in this study, with many gaps in the data. However, available days were used to estimate a trend. 0.41% of the variability in microfiber concentrations was explained by previous day wave height, with a weak trend indicating larger waves correlate with higher

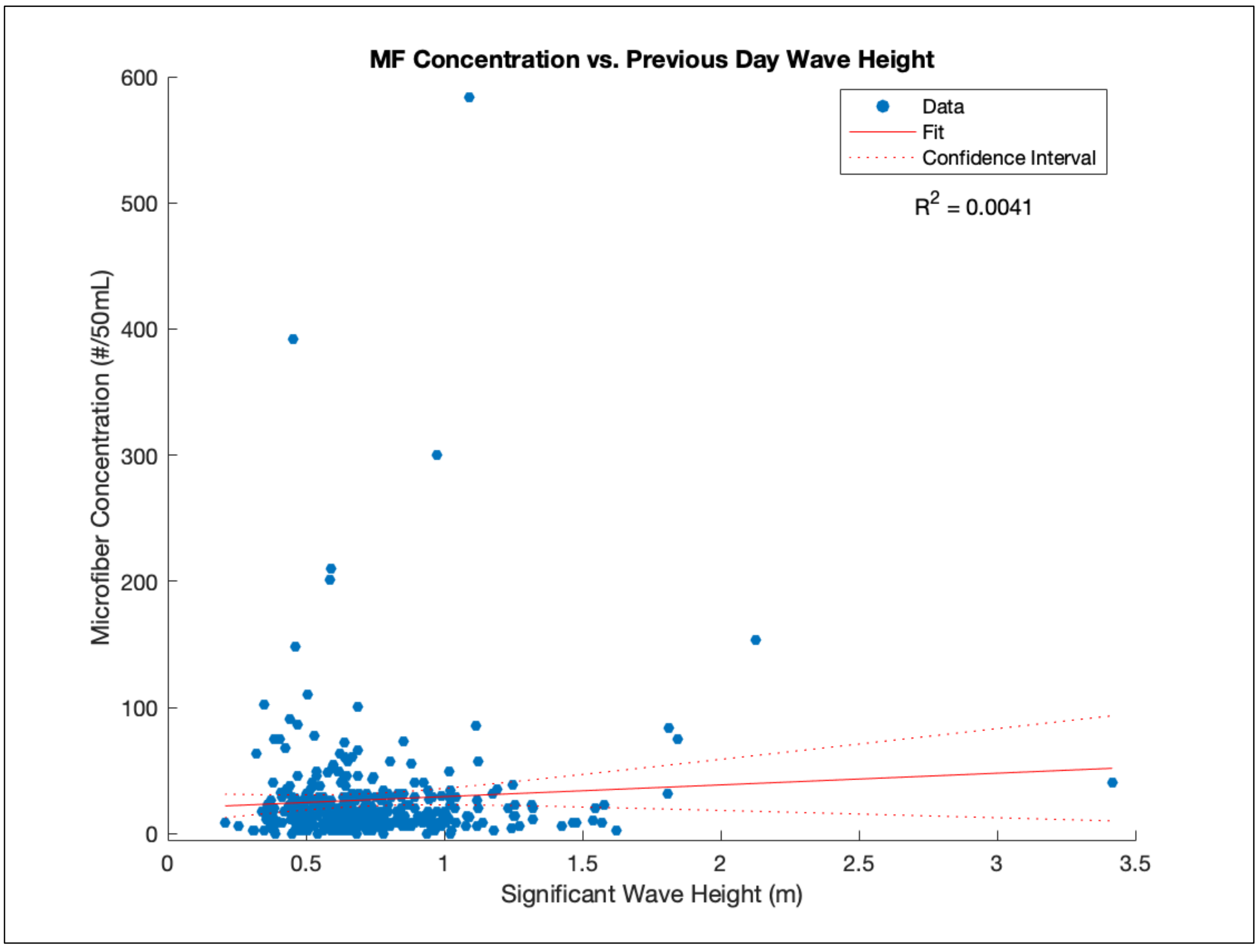

Figure 8: Comparison plot of MF concentrations versus significant wave height measurements from the day preceding MF sampling date. Solid red line indicates linear regression fit; dotted red line represents the 95% confidence interval.

concentrations of microfibers in surface water. This could be due to turbulent mixing of microfibers in the shallow water environment or the increased shedding of microfibers from beachgoers in more aggressive waters.

Wind speed data and associated trend line can be seen in Figure 9. Wind speed was the second most correlated variable in this study, with an R^2 value of 0.0083. This is still a very weak correlation, explaining less than 1% of MF variability. Furthermore, only wind speed data was utilized, and not wind direction. However, this value indicates that higher wind speed

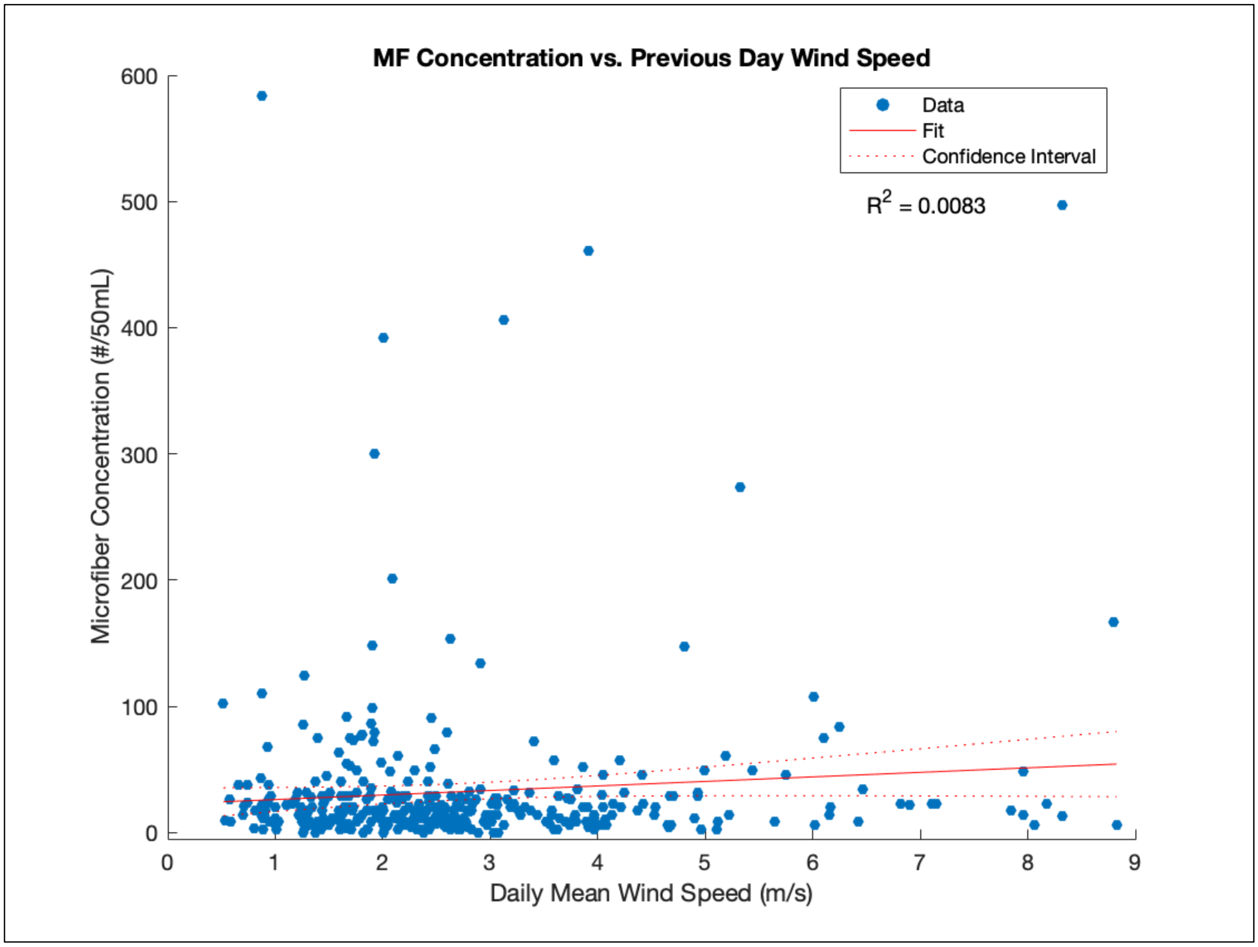

Figure 9: Comparison plot of MF concentrations versus wind speed measurements from the day preceding MF sampling date. Solid red line indicates linear regression fit; dotted red line represents the 95% confidence interval.

correlates with higher MF concentrations. This could be due to mixing processes or increased aerial transport of land-based microfibers.

Tidal level data and associated trend line can be seen in Figure 10. Tidal levels were weakly correlated with microfiber concentrations, explaining only 0.51% of microfiber variability. This slight trend indicates that high tides correlate with higher concentrations of microfibers in surface waters. This could be due to landward transport of fibers from farther asea or the introduction and mixing of beach-bound fibers from contact with ocean waters.

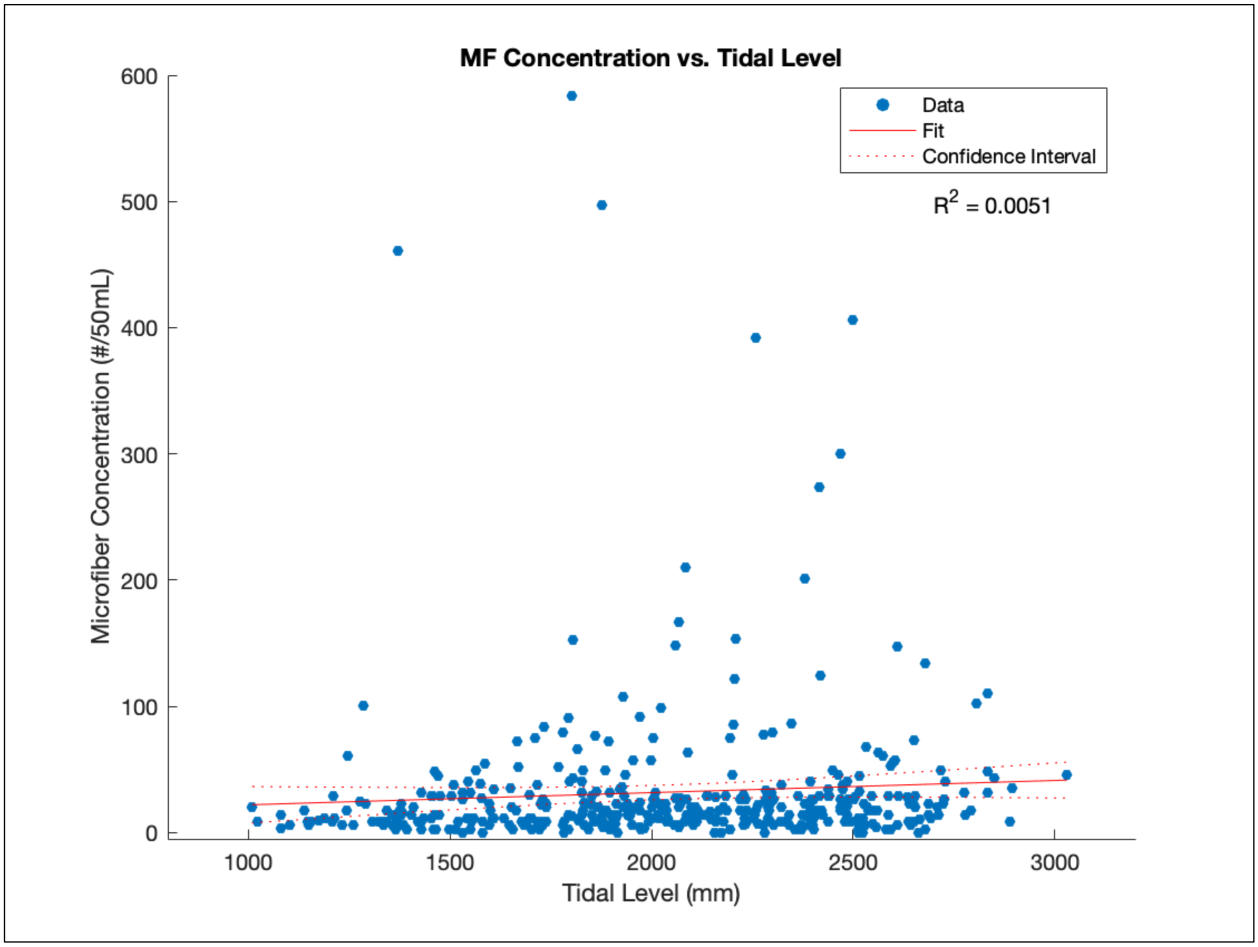

Figure 10: Comparison plot of MF concentrations versus tidal level measurements at the time of MF sampling. Solid red line indicates linear regression fit; dotted red line represents the 95% confidence interval.

Correlations between weather and tide variables and microfiber concentrations for all 444 sample dates were all insignificant. In fact, the correlations were so small as to mimic the relationship between random variables. To get a more focused insight into potential correlations,

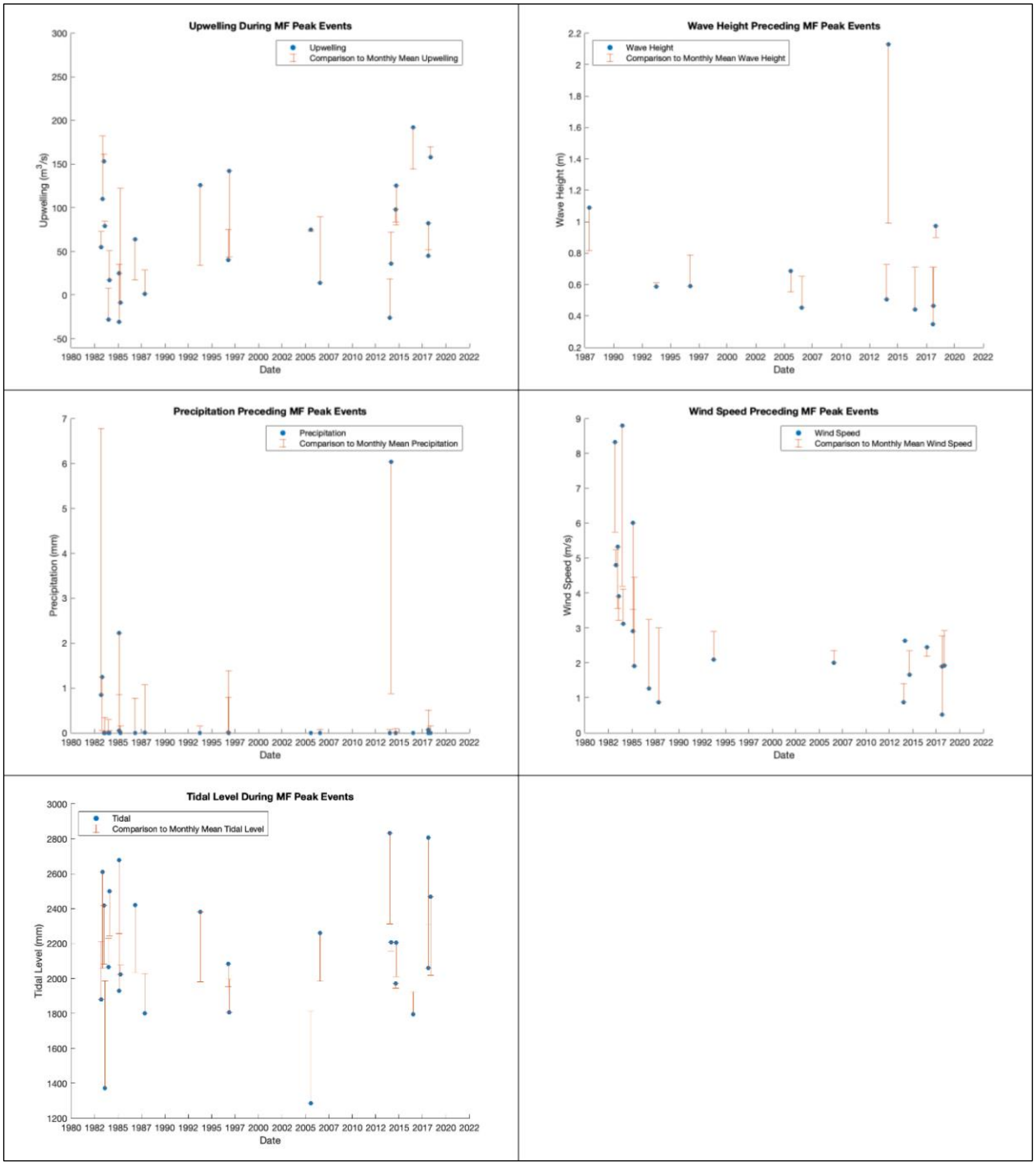

Figure 11: Peak event meteorological data. Axes indicate date of peak events vs measurement value. Red lines indicate offset from monthly mean values, with "T" bar indicating the monthly mean value.

we also investigated microfiber peak events, or sampling days where microfiber concentrations were greater than one standard deviation from the mean MF concentration. This yielded 24 peak events. It should be noted that 6 out of these 24 peak events were from dates where a full 50 mL of sample was not available. 5 out of those 6 events also happen to be the 5 largest values measured. These values could skew the data and reduce trend line significance, and certainly increase the variability in the microfiber concentration data. These outlier measurements could be due to contamination in the archival process, as microfibers are ubiquitous in indoor environments. If samples were opened previously without proper precautions, airborne microfibers could have contaminated the sample and affected the measurement. Nevertheless, measurements at peak event dates were analyzed and compared to monthly means to investigate significance. This did not reveal any new information about the relationships between meteorological factors and microfiber concentration. Upwelling at peak events was lower than the monthly mean 16 out of the 24 days, precipitation was lower than the monthly mean 19 out of the 24 days (but was zero in all but 6), wave height only had data for 11 out of 24 peak dates and was lower than the monthly mean 7 out of the 11 days, wind speed was lower than the monthly mean 13 out of the 24 days, and tidal level was higher than the monthly mean tidal level at 9:00AM 14 out of the 24 days. This matches the trends for precipitation, upwelling, and tidal levels, but is opposite the trends for wave height and wind speed. Most peak events were not significantly different from mean values and do not indicate a correlation between extreme weather and high microfiber counts. Peak event data can be seen in Figure 11.

CONCLUSION

The results of this investigation into the variability of microfibers in the Southern California coastal ocean leave more questions than answers. The infrequency of microfiber sampling, subjective identification of fibers, and the use of samples with less than the desired volume indicate large potential for error in microfiber counts. Furthermore, more research is needed to determine the fate of microfibers once introduced into the marine environment. An analysis of the physical distribution of microfibers in the vertical and horizontal could provide insight into sinking rates and transport patterns of microfibers, especially in surface waters. In this study, it was not known whether fibers were sinking or rising in the water column. This information could better inform the processes influencing microfiber concentrations. It is possible that microfiber concentrations are a very patchy variable, controlled by small-scale oceanic processes that are not resolved by the spatial and temporal climate variables considered in this study. Thus, the concentration behavior can be described as a random process that is not readily explained by the observed larger-scale physical processes in the nearshore environment. Or, microfiber concentrations may be a uniquely human-controlled variable, with variability more readily explained by human processes like wastewater discharge that were not investigated in this study. However, future studies that involve more extensive sampling could help provide more information on this topic. For example, samples from different times of the day at the same location as well as samples taken at the same location at shorter sampling times (such as minutes, hours, etc.) would help to better explain the coherency patterns of microfiber transport and their potential relation to oceanographic and meteorological phenomena.

Acknowledgements

I would like to acknowledge Art Miller for his much-needed expertise and support, Sarah-Jeanne Royer, Melissa Carter, and Carla Costa for their roles in creating the dataset that was integral to this paper, Laurel Dehaan for her help averaging San Diego area precipitation data, and Kara Wiggin for providing me with valuable papers on microfibers to review. I would also like to acknowledge Sasha Gershunov and Joel Norris for agreeing to serve on my committee and for their suggestions throughout this process. I would also like to acknowledge John McGowan, the McGowan Plankton and Chlorophyll Program, and the California Harmful Algal Bloom Monitoring Program for their archived samples from which microfiber concentrations were measured, and private donors, the MacArthur Foundation, and the Southern California Coastal Ocean Observing Systems for funding those projects. Partial support from the National Science Foundation (OCE-2022868) is greatly appreciated.

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