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UNDERSTANDING THERMAL STRATIFICATION AS A KEY DRIVER OF HARMFUL CYANOBACTERIA BLOOMS ON THE CAPE FEAR RIVER, NC

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Final Report

North Carolina Water Resources Research Institute/ Urban Waters Consortium Project # 19-09-U

1. **Project Title: Understanding thermal stratification as a key driver of harmful cyanobacteria blooms on the Cape Fear River, NC**

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3. Introduction

Harmful, toxigenic blooms of the cyanobacteria, *Microcystis sp*., have become common during summertime along the Cape Fear River (CFR) from Fayetteville to Lock and Dam 1 (Isaac et al. 2014). During a recent NC Sea Grant funded project, we identified thermal stratification as a likely driver of these blooms. Under low river flow conditions, we documented thermal stratification as well as super saturated dissolved oxygen conditions that indicate enhanced algal growth in the shallow upper layer (Figure 1). Monitoring data from NC Div. of Water Resources (NCDWR) and the Middle Cape Fear River Basin Association (MCFRBA) also show thermal stratification during low river flow conditions. Thermal stratification isolates the surface layer from the bottom layer and results in much higher average irradiance conditions that can stimulate blooms of the light limited CFR phytoplankton community (Kennedy and Whalen 2008). Compared to diel stratification that is destroyed by mixing at night, consecutive days of stratification, or "persistent" stratification is particularly conducive for bloom development because cells that proliferate on one day are still retained near the surface the following morning (Webster et al. 2000). Understanding the factors that lead to thermal stratification and particularly, the development of persistent stratification, will provide a greater predictive capacity for blooms and will help develop strategies to minimize bloom occurrence on the CFR.

The ability to mechanistically model thermal stratification requires defining the heat budget of the river which is governed by solar heating, and losses due to radiation, evaporation and sensible heat loss as well as vertical mixing of heat due to turbulence generated by friction as the river moves over its bed and by wind moving over the surface (Chapra 2008). As part of the NC Sea Grant project, instrumentation was deployed during summer 2018 to measure each of these terms in the heat budget to determine the rate at which the surface layer gains or loses heat under different environmental conditions (e.g. temperature, humidity, wind speed, cloud cover, etc.). This information was used to parameterize a one-dimensional model of water temperature vertical profiles above Lock and Dam 1 in the lower CFR (Han et al. 2019). Thermistor chains were deployed to measure water temperature profiles upstream of both Lock and Dams 1 and 2. Results from summer 2018, showed that diel stratification was common under low flow conditions but high river flows caused sufficient mixing to prevent stratification (Figure 2).

The 1-D heat budget model reasonably predicted the intensity of stratification though there was a slight overestimation. Hind casts of previous low flow conditions indicated that persistent stratification may occur in the CFR under extreme low flow conditions (not shown). Unfortunately, flows during summer of 2018 generally ranged from moderate to high. Low flow periods conducive for development of strong persistent stratification did not occur. However, during a period of declining flows and increasing water temperature in late June, weak persistent stratification did occur with the surface waters remained ~ 0.2 °C warmer than the bottom waters during the evening of June 22 (Figure 2). This also suggested that strong persistent stratification may occur during low flow conditions, and was part of the motivation for this project conducted during summer 2019.

4a. Research Questions:

1) How do weather and river flow conditions act in concert to promote or inhibit the development of diel and persistent thermal stratification?
2) How do the two modes (diel and persistent) of stratification impact phytoplankton productivity in comparison to well mixed conditions?

4b. Objectives:

1) Redeploy a thermistor chain to measure temperature profiles upstream of lock and dam 1, and redeploy a remote weather station to measure meteorological parameters necessary to determine the heat exchange with the river surface.
2) Use meteorological data to parameterize a one-dimensional heat budget model and use thermistor chain data to validate the model that has been calibrated using thermistor chain data from summer 2018.
3) Assess the relationship between temporal variability in stratification with phytoplankton production as measured by chlorophyll *a* at Lock and Dam 1.

4c. Methods: Thermal stratification of the CFR upstream of Lock and Dam 1 and meteorological conditions were monitored for approximately 2 months during the hottest part of summer 2019 (11 July to 3 September). Although the project plan was to conduct the deployment through September, the deployment was ended early due to the close approach of Hurricane Dorian (Sept. 5), fear that associated flooding would destroy the instruments, and likelihood that elevated river flow associated with Dorian would produce a protracted period of elevated flows, uninteresting from this project's perspective. Depth profiles of water temperature were collected every 6 minutes upstream of Lock and Dam 1 by two identical thermistor chains constructed using HOBO Pendant temperature probes and deployed on the downstream sides of the upstream-most and third from upstream lock piling (Figure 3). Each thermistor chain consisted of a float, seven HOBO Pendant temperature probes spaced at 0.5 m intervals, and a weight tied securely with parachute cord. Each thermistor chain was housed within a perforated 2" PVC tube secured to the piling using pipe straps. The perforated PVC tube kept the chain from drifting away, kept the chain vertical in the water column, maintained the chain within the upper 3 m of the water column as the river stage fluctuated, and the perforations allowed water to flow through to ensure negligible temperature differences between inside and outside the pipe. A HOBO RX3000 Remote Weather Station was installed on the lawn to the southwest of the lock to measure air temperature, relative humidity, incoming solar radiation, wind speed, and direction every 6 minutes (Figure 3). Visits to Lock and Dam 1 were conducted during the project period to download the thermistor chain data.

Precision of the HOBO Pendant temperature probes were assessed prior to deployment by immersing the 14 probes that were going to be deployed into a temperature-controlled water bath and then comparing the deviation of the temperature records amongst the probes. Over the course of approximately four days, temperatures in the water bath were set for three temperature regimes (15, 20, and 30 °C) that encompass the full range expected for the Cape Fear River during summer. Plots of the raw data under each temperature were used to identify any outlier probes and the standard deviation across probes was used to quantify the level of precision.

On the day the thermistor chains were deployed, temperature profiles were additionally collected by casting a YSI 6600 multiparameter water quality instrument just beside the PVC pipe that housed the thermistor chain, and also at main channel location. These data were compared with the temperature profile collected to by the thermistor chain to determine how representative the thermistor chain deployment location was of the conditions in the main channel and how the PVC housing may have impacted the ability to accurately measure temperature profiles. The main channel site was co-located with the MCFRBA's station B8349000 and NC DWR's station B8350000. Photic zone, depth- integrated (2 times Secchi disk depth) water samples were collected using a Labline depth-integrating sampler for fluorometric determination of chlorophyll *a* (Arar and Collins 1997). Chlorophyll *a* was compared with antecedent stratification to empirically assess the relationship between stratification and phytoplankton production. In addition to measurements made by this project, temperature profiles and chlorophyll *a* data collected by the NC DWR and the MCFRBA were additionally used to assess the representativeness of thermistor chain temperature profiles and to assess the role of stratification in determining phytoplankton productivity.

5. Results

Data completeness: The thermistor chains and remote meteorological station successfully recorded temperature profiles of the water column and meteorological conditions at Lock and Dam 1 for the duration of the 11-Jul to 3 Sep 2019 deployment period. Malfunction of several of the temperature probes occurred in the thermistor chain deployed at the third piling, but the thermistor chain mounted on the first piling captured temperature profiles for the full period.

Methods validation: The tests of precision for the HOBO temperature probes determined that the probes had a very high degree of precision (Figure 4). Across the three temperature regimes, none of the probes produced a single data point that deviated by more than 0.1 °C from the mean and the range of values across the three temperatures spanned only about 0.2 °C. The standard deviation across the probes was 0.03 °C for all three temperature regimes. Though set for 15, 20, and 30 °C, the analog temperature control system of the water bath did produce these exact target temperatures. An alcohol thermometer confirmed the average temperatures of the water bath were ~12, 20, and 29 °C. Therefore, in addition to high precision, the accuracy of the probes was also confirmed.

Temperature profiles produced by the thermistor chain agreed closely with profiles from YSI 6600 casts immediately beside the thermistors and in the mid-channel location (Figure 5). All three profiles showed a constant temperature of about 30.25 °C below 2.5 m and an increase from 2.5 m to ~30.8-31.1 °C at the surface. Additionally, a rapid increase in temperature from 2.5 to 2 m depth was captured by both the thermistor chain and YSI cast behind the piling. All three profiles showed rapid increases in temperature above 1 m depth. There were, however, some differences between the profiles. For example the maximum temperature of the thermistor chain was lower than for the YSI measurements. Additionally, the YSI measurements showed a more gradual increase in temperature from about 2 m depth to the surface while the thermistor chain showed no increase in temperature from 2 to 1 m depth. Generally, however, the close agreement between the profiles validated both the design of the thermistor chains and the manner in which they were deployed behind the upstream piling for accurately capturing temperature profiles in the main river channel.

A comparison of thermistor chain temperature profiles with temperature measurements made by the MCFRBA corroborated the validation of the thermistor chain measurements (Figure 6). On 16 and 30 July, both the thermistor and MCFRBA measurements showed a weakly stratified water column with surface values ~0.6-0.8 °C and 1.2-1.3 °C higher, respectively, than bottom water values. Deviations between the thermistor and MCFRBA measurements made at similar depths were only about 0.1 °C. On 8 August, both the thermistor and MCFRBA measurements indicated a well-mixed or very weakly stratified water column with surface to bottom temperature differences of only ~0.2 °C. The MCFRBA measurements, however, were 0.2 to 0.4

°C higher than the thermistor measurements made at similar depths. On 21 August, both sets of profiles indicated weak stratification (~0.5 °C) difference from surface to bottom but again the MCFRBA measurements were ~0.5 °C higher than the thermistor measurements made at similar depths. It is possible that these temperature differences could be caused by inter-instrument variability within the instruments used by the MCFRBA. In any case, the close agreement in representation of changes in the degree of stratification provides additional validation of the thermistor chain setup used in the project.

General description of meteorological and hydrological conditions: During summer 2019, air temperature generally varied from a minimum of about 25 °C at night to near 35 °C during the afternoon (Figure 7). In late July (23-28 Jul) a cool and rainy period occurred with night-time air temperatures less than 20 °C and unusually low daytime relative humidity (< 40%). Several other rainy periods (Aug. 2-3, Aug. 18, Aug. 25-26) also occurred during the deployment and are clearly indicated by unusually low daily maxima of temperature and solar radiation and usually high minima of relative humidity. Increases in river flow followed each of the rainy days. With the exception of the rainy periods, solar radiation generally varied daily from zero at night to a midday maximum of about 1000 W/m^2. Winds were weak throughout the study period, never exceeding 3 m/s. River flow during the study period was moderate, with baseflow around 30 m^3/s and five high flow events with peaks near 100 m^3/s.

Patterns and drivers of thermal stratification: Thermal stratification was measured by the difference in temperature from the surface and 3 m depth (Figures 7, 8). As during summer 2018 (Figure 2), the pattern of diel stratification was common during the 2019 study period with surface versus 3 m temperature differences commonly 1-2 °C but ranging up to 4 °C on day 213 (Figure 7, 8). Throughout summer 2019, thermal stratification was completely eliminated during the night with several hours of well mixed conditions before thermal stratification began to develop again the next morning. This contrasts with early part of summer 2018 when there was a day (June 22, 2018) when measurable stratification persisted overnight (Figure 2). Peak daily stratification intensities during baseflows were also higher during summer 2018 with stratification greater than >5 °C recorded for several days (Figure 2) compared to a peak of less than 4 °C during 2019 (Figures 6,7,8). Baseflows during early summer 2018 were only about 8

m^3/s (~27%) lower than during 2019, and the observed interannual differences of stratification intensity are consistent with a strong sensitivity of stratification to even small increases in flow.

The pattern of diel stratification was conspicuously absent during the five high flow events (Figure 8). The distribution of river flow versus maximum daily stratification intensity is described by a wedge envelope that captures the maximum potential degree of stratification (Figure 9). At the lowest flows of ~20 m^3/s that observed during summer 2018, the envelope includes stratification values of approximately 6 °C. As flow increases, the upper limit of the envelope decreases in a near linear fashion and reaches zero at a flow of approximately 80 m^3/s. This distribution is consistent with the combined roles of flow in determining the maximum potential degree of stratification and of meteorologically-determined water-surface heat flux in determining the degree to which the potential stratification is realized. From a management perspective, it is clear that stratification should not occur at flows greater than 80 m^3/s, and that this flow level could be used as a target for prevention of blooms that are promoted by stratified conditions. As stated below, this information has already been put to practical use for guiding flow management on the CFR to prevent algal blooms.

Predictions of stratification from a heat budget model: Overall, the heat budget model provided a reasonable prediction of the temporal patterns of thermal stratification (Figure 10). It captured the timing of the daily increase of stratification in the morning and subsequent collapse during the late afternoon with a remarkable degree of accuracy, and general trends of modeled maximum daily stratification intensity were consistent with the observations. However, on most days the model overpredicted the maximum intensity of late afternoon stratification, often by a factor of two or more. Particularly high degrees of overestimation occurred during high flow periods when the model often predicted an approximate 1°C temperature difference between surface and bottom, but negligible stratification was actually observed. Although overestimation was noted for the data collected during summer 2018 (Figure 2), the model overestimation for data collected during 2019 was much more severe (Figure 10). Evaluations of the differences in hydrological and meteorological conditions between summer 2018 and 2019 are underway to determine the cause of the difference in model overestimation. The hope is that understanding the cause of the difference may help correct the model to eliminate the prediction bias.

The model's ability to predict the average water column temperature deteriorated with time from the initial temperature profile used to set the initial conditions for the model (Figure 10). This deterioration in model performance suggests either 1) the model is improperly specifying the amount of heat entering and exiting the water surface or 2) there are processes other than surface heat flux that are important for driving changes in water temperature. Although the model needs more scrutiny, we think the latter possibility is more likely. The timing of the divergences between the modeled and predicted average water temperature coincided with times when river flow was increasing. During summertime, rain or shallow groundwater would likely have temperatures less than the river water (Byers et al. 1949), and therefore, it should be expected that the river would cool as flow increased due to precipitation events. These inputs of cooler water are not represented within the simple one dimensional heat budget/ turbulent mixing model.

Relationships between antecedent stratification regime and phytoplankton biomass: Over the course of the summer 2019 project period, eight chlorophyll *a* samples were collected to compare phytoplankton biomass against the stratification regime prior to collection (Figure 8). Surface versus 3 m depth temperature differences were used as a measure of stratification intensity. Average antecedent stratification was calculated using 1, 3, and 5 day averaging period to determine the time scale at which phytoplankton biomass responds most strongly to stratification. Spearman's rank correlations indicated that the relationship stratification intensity and chlorophyll *a* was positive and of moderate strength (Figure 11). Spearman's ρ ranged from 0.45 to 0.64 across the three averaging periods. The relationships were not statistically significant ($p > 0.05$); partly a reflection of low statistical power due to small sample size. The longest, 5 day, averaging period produced the strongest relationship. This suggests that it likely takes several consecutive days of favorable conditions with diel stratification for significant phytoplankton biomass to develop. Studies in similar bloom prone rivers have found similar bloom sensitivity to prolonged periods of stratification and have utilized this sensitivity to develop flow regulation strategies for bloom prevention (Webster et al. 2000; Mitrovic et al. 2011).

5. Stakeholder engagement and application of project findings

Through the US Army Corps' Sustainable Rivers Program, on October 1-2, 2019 the Nature Conservancy and Army Corps of Engineers convened a workshop to plan an experimental set of flow prescriptions for improving the ecological health of the middle and lower Cape Fear River. Observational and modeling information from this project on flow thresholds to prevent thermal stratification and associated harmful algal blooms played a key role in developing a strategy of summer-time pulses of flow to prevent long periods of stagnant and thermally stratified conditions. Summer-time flow pulses were conducted during summer 2020, and are planned again for summer 2021. A summary of project results were also conveyed to the MCFRBA during their November 2020 meeting.

6. Continuation of project objectives through leveraged funding

The data produced and methods that were validated by this project were leveraged to secure additional funds through the Army Corps of Engineers to monitor the effects of summertime pulses on water quality and thermal stratification during summers 2020, and hopefully again in 2021. During the summer 2020 deployment, vertical current profiles were measured in addition to temperature profiles to explicitly measure the vertical velocity shear that generates vertical mixing. This information will provide a better estimation of the drag coefficient for bed stress in the heat budget model and may alleviate the current overestimation of thermal stratification by the model that was apparent for both summer 2018 and summer 2019 datasets. The current project is also being conducted with project partners at the USGS who are using an autonomous underwater vehicle to measure thermal stratification and water quality within the whole reach between Lock and Dam 1 upstream to Lock and Dam 2. These efforts will help us understand the heat budget model results in the context of downstream gradients of water temperature, and may help provide information to reconcile the large deviations in modeled water temperatures that occurred under rising river stage conditions. Additionally, Gybe, a remote sensing company will made satellite-based measurements of suspended sediments, total phytoplankton, and cyanobacterial biomass measurements during summer 2020 and will again during summer 2021. The high temporal and spatial resolution data produced by these efforts will be extremely useful for clarifying relationships between river flow and the light field for phytoplankton photosynthesis and the relationship between flow and bloom development.

7. References

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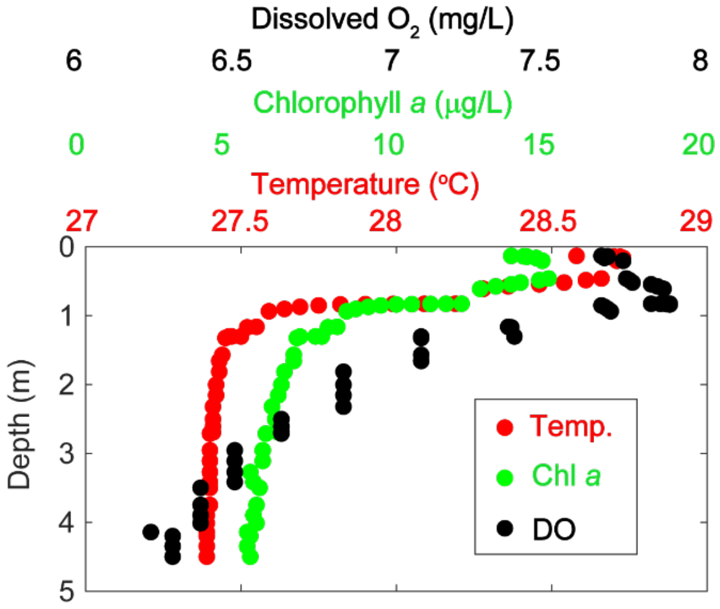

Figure 1. Depth profiles of temperature, chlorophyll *a* by *in vivo* fluorescence, and dissolved oxygen upstream of Lock and Dam 1 on 22 June 2016.

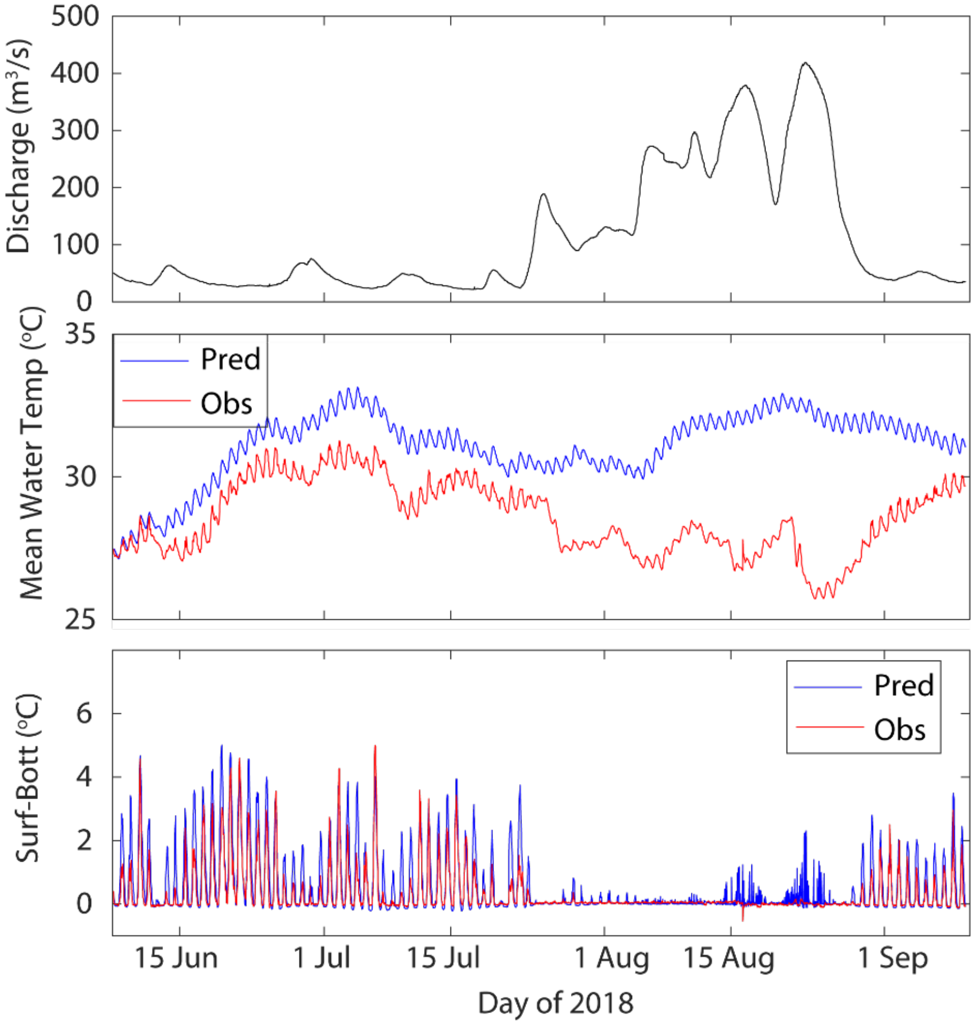

Figure 2. Observed and predicted mean water temperature and thermal stratification (surface minus bottom water temperature) at Lock and Dam 1. Top panel is river discharge at Lock and Dam 1.

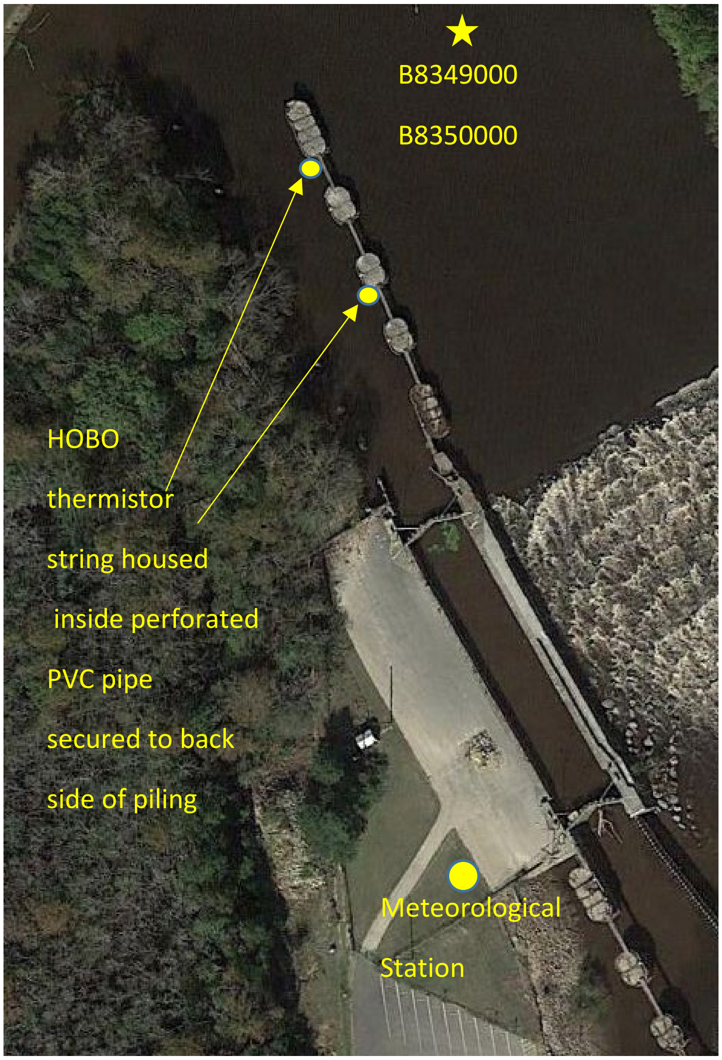

Figure 3. Arial image of Lock and Dam 1 showing deployment locations for thermistor chains, remote meteorological station, and station B8349000/B8350000 routinely monitoring by the Middle Cape Fear Basin Association and N.C. Div. of Water Resources.

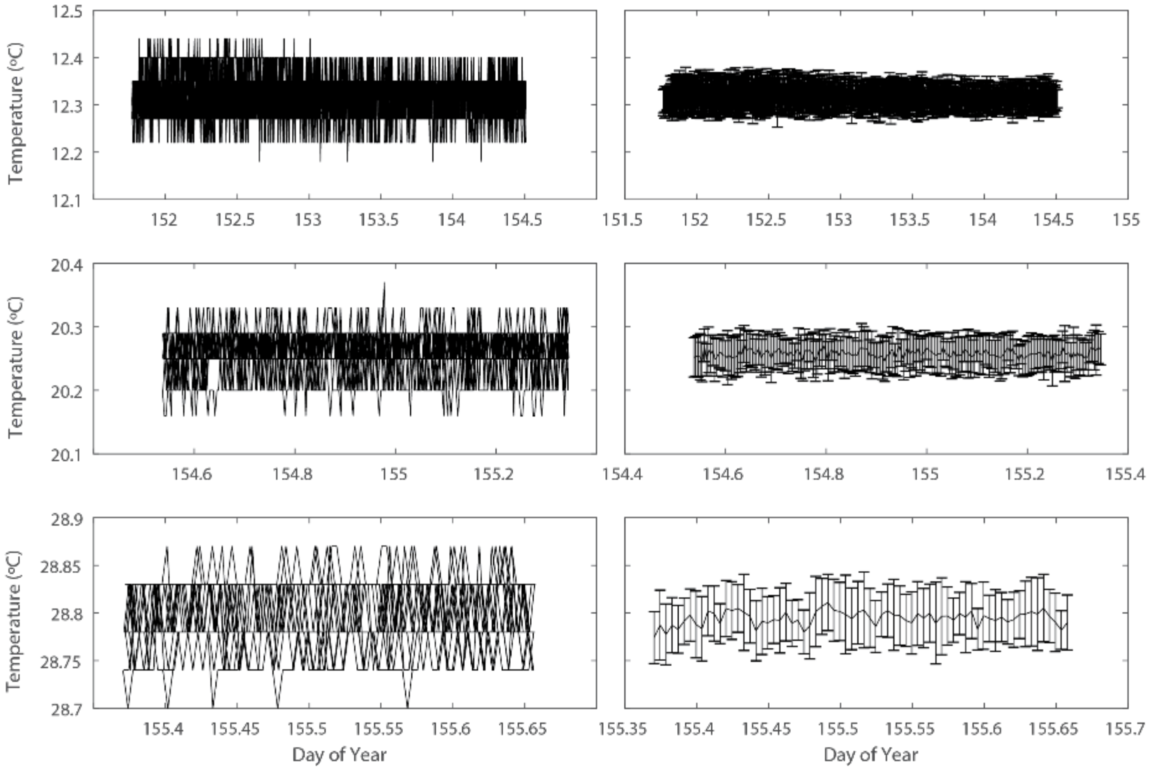

Figure 4. Test of precision for 14 HOBO Pendant temperature probes at three temperatures in a thermostatically controlled water bath. Left panels are raw data for the 14 probes. Right panels show means plus or minus standard deviation for observations collected every 6 minutes.

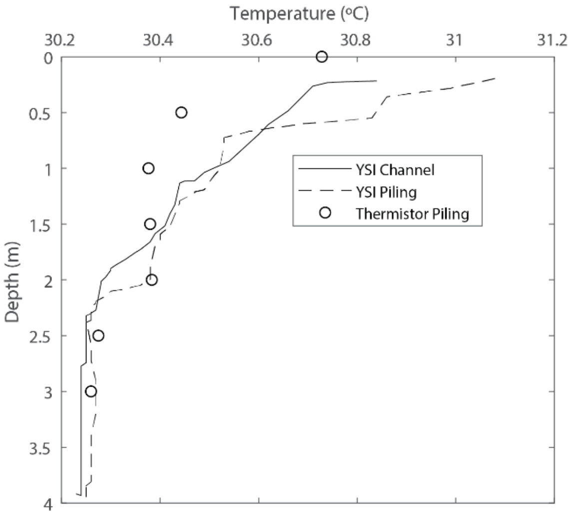

Figure 5. Comparison of temperature profiles produced by the thermistor chain behind the first piling with temperature profiles made by YSI casts behind the first piling and in a mid-channel location (station B8349000) on 11 July 2019.

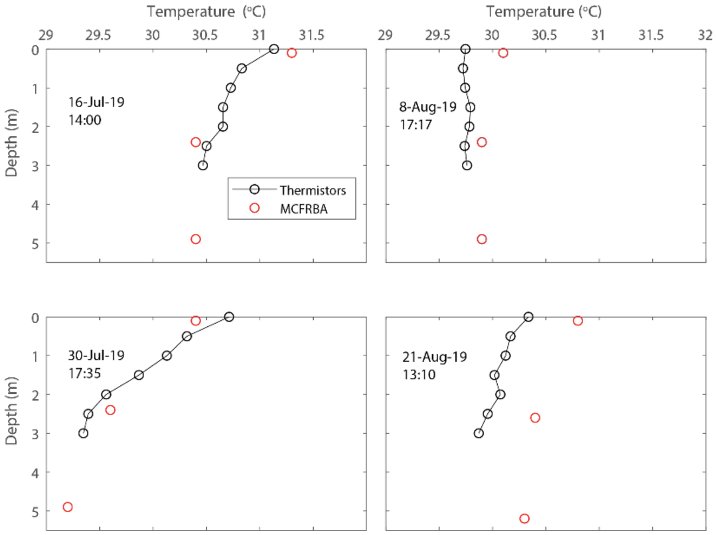

Figure 6. Comparison of temperature profiles produced by the thermistor chain behind the first piling with temperature profiles made by YSI casts at mid-channel station B8349000 by the Middle Cape Fear River Basin Association during summer 2019.

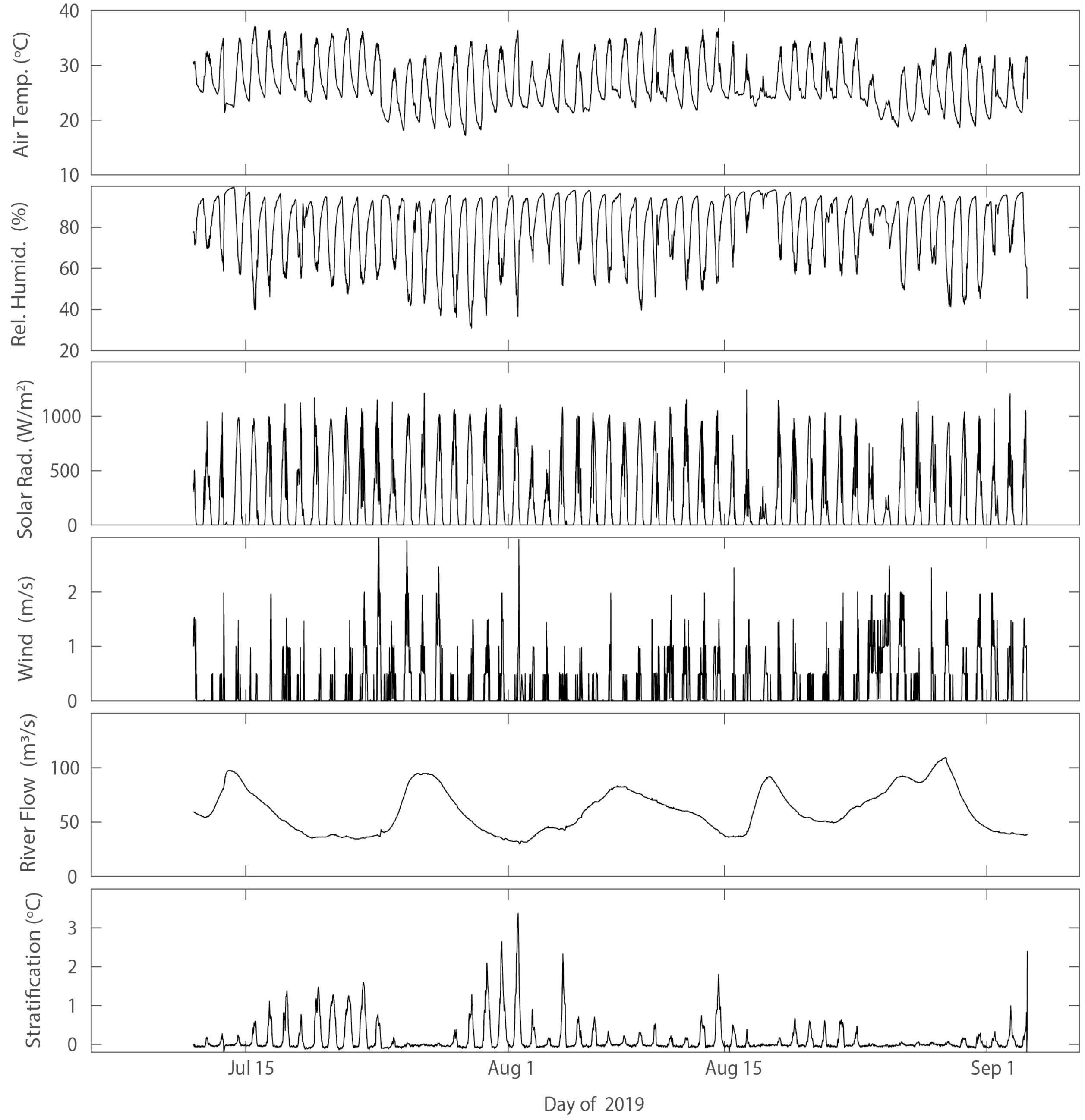

Figure 7. Time series of meteorological and hydrological conditions observed during the 2019 summer project period.

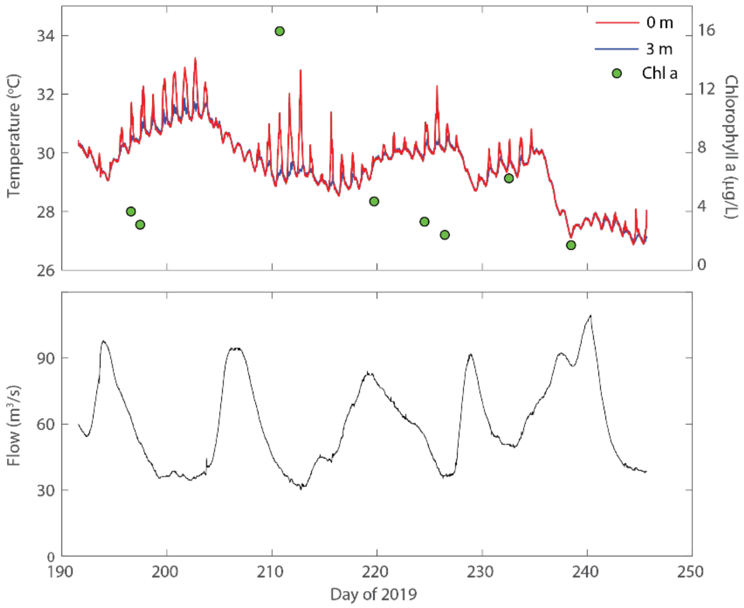

Figure 8. Time series of surface and bottom water temperature, and chlorophyll *a* in relation to river flow during the summer 2019 project period.

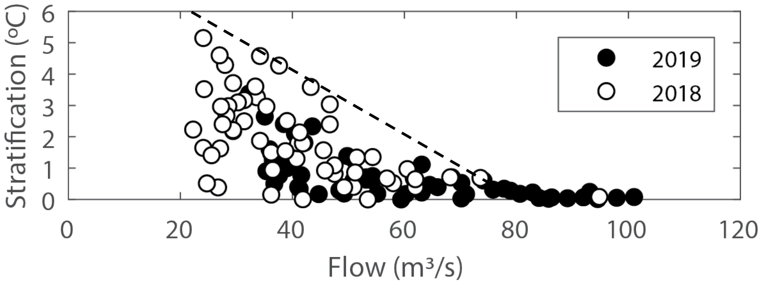

Figure 9. Effect of river flow on maximum daily stratification intensity during summer 2018 and 2019. Dashed line was drawn by eye to represent the upper-limit of stratification expected across the range of river flows.

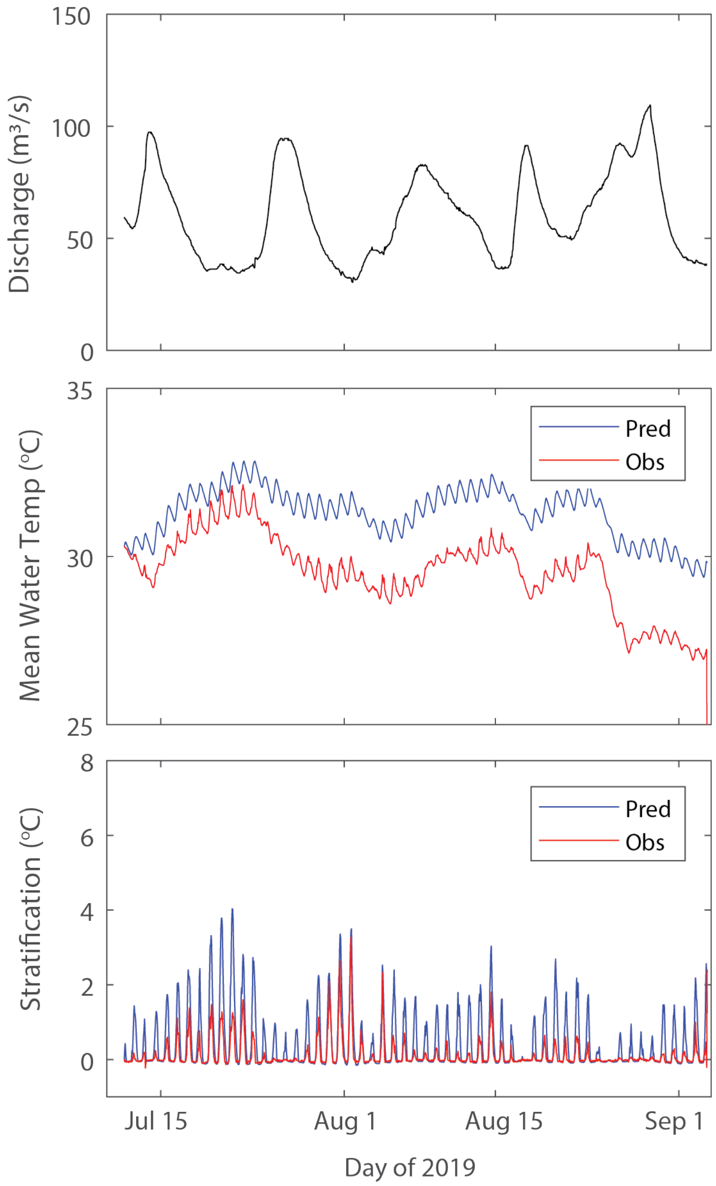

Figure 10. Comparison of observed thermal stratification versus predictions from a heat budget model at Lock and Dam 1 during the summer 2019 project period.

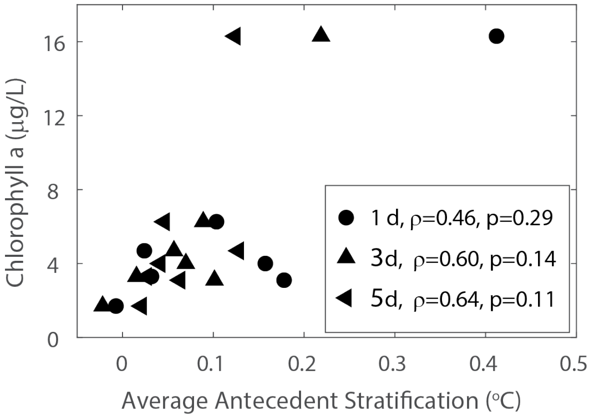

Figure 11. Comparison of chlorophyll a versus average levels of antecedent stratification at different averaging periods.