Sea Level and Water Temperature Data Analyses in Coastal North Carolina

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Rationale and Research Questions

Do climate change indicators, sea level and water temperature have specific time series trends and do they have a statistically significant relationship at three coastal sites in North Carolina: Beaufort, Cape Hatteras, and Wrightsville Beach?

To answer this research question, we gathered sea level and water temperature data from NOAA. Sea level and water temperature were the chosen parameters to assess because they are indicators of climate change, and we want to analyze the changes occurring on the coast of North Carolina due to this phenomenon. We predicted based on previous studies, that sea level changes have a relationship with global warming and thus there will be a correlation with increased water temperature. Three sites (Beaufort, Cape Hatteras, Wrightsville Beach) were selected because those sites are spread out across North Carolina's coast.

Dataset Information

We are using this repository to upload data from NOAA's Tides&Currents Datasets for sea level measurements and NOAA's National Data Buoy Center for water temperature measurements.

The water temperature data begins on the first day of 2011 and ends on November 31, 2022. The raw data for water temperature was in txt file, and those files did not clearly transferred into correct data frame. Thus, changed txt files into csv files and combined each year's data by rbind. The original data had place-holder values of 999 for some of the wtmp values, so we changed all 999 values into NA and replaced that value into the approximate data point using linear interpolation. Then we selected columns that we need, which was year, month, day, and water temperature. Then calculated daily and monthly averages using group_by and summarize functions. We created the processed data and saved them as csv files.

The sea level data was already in a more simplified format in comparison to the water temperature data. The data came off the NOAA website in a monthly collected data csv format from years 2011 to 2022. In order to isolate the variables of interest as the data set came with other variables such as low range and high range tide data, the select function was used concatenating the specific columns of interest. Three columns of the original data set were kept, and those were the date, the MSL (mean sea level) and MTL (mean tide level). The mutate function was then used to create a Station column in order for the sites to be differentiated when combined into a large dataset. The data from all three sites were joined with the rbind function. The date column in the data frame was calssified as a date and the date was separated into Year and Month columns, and then grouped by those columns for future data exploration and analysis. The final processed data frame was saved as a csv file.

This project will use a time series analysis to identify seasonal trends and changes in sea level and water temperature over the past 12 years using a Mann Kendall test. We will then identify if there is a statistical relationship between the two parameters using a Kendall correlation test.

Variable	Units	Source
Mean Sea Level	ft	NOAA Tide's & Currents
Mean Tide Level	ft	NOAA Tide's & Currents
Daily Temperature	°C	NOAA's National Data Buoy Center

```
# Wrangle data to combine the water temperature data for each year into one
#csv for each site
Beaufort.Water.Temp <-rbind(beaufort11,beaufort12,beaufort13,beaufort14,
                            beaufort15, beaufort16, beaufort17, beaufort18,
                            beaufort19, beaufort20,beaufort21)
names (Beaufort.Water.Temp) <- header

Hatteras.Water.Temp <-rbind(Hatteras11,Hatteras12,Hatteras13,Hatteras14,
                            Hatteras15, Hatteras16, Hatteras17, Hatteras18,
                            Hatteras19, Hatteras20,Hatteras21)
names (Hatteras.Water.Temp) <- header

Wrightsville.Water.Temp <-rbind(Wrightsville11,Wrightsville12,Wrightsville13,
                                Wrightsville14,Wrightsville15, Wrightsville16,
                                Wrightsville17, Wrightsville18, Wrightsville19,
                                Wrightsville20,Wrightsville21)
names (Wrightsville.Water.Temp) <- header
```

```
#clean-up data that has inconsistent values

Beaufort.Water.Temp <- Beaufort.Water.Temp %>%
  mutate (WTMP=ifelse(WTMP ==999,NA,WTMP)) %>%
```

```
  mutate(WTMP = zoo::na.approx(WTMP))

Hatteras.Water.Temp <- Hatteras.Water.Temp %>%
  mutate (WTMP=ifelse(WTMP ==999,NA,WTMP)) %>%
  mutate(WTMP = zoo::na.approx(WTMP))

Wrightsville.Water.Temp <- Wrightsville.Water.Temp %>%
  mutate (WTMP=ifelse(WTMP ==999,NA,WTMP)) %>%
  mutate(WTMP = zoo::na.approx(WTMP))
```

```
#Wrangle Beaufort water temperature data frames to be averaged by month
beaufort_wtmp <- Beaufort.Water.Temp %>%
  select("#YY","MM","DD","WTMP") %>%
  dplyr::rename(Year = "#YY", Month = "MM", Day ="DD") %>%
  mutate("Date" = make_date(year= Year, month =Month, day = Day))

beaufort_daily_wtmp <-  beaufort_wtmp %>%
  dplyr::group_by(Year, Month, Day, Date) %>%
  dplyr::summarise(dailywtmp = mean(WTMP),.groups ='drop') %>%
  mutate(Station = "Beaufort")

beaufort_monthly_wtmp <- beaufort_wtmp %>%
  dplyr::group_by(Year, Month) %>%
  dplyr::summarise( monthlywtmp = mean(WTMP), .groups ='drop') %>%
  mutate(Station = "Beaufort")%>%
  mutate("Date" = make_date(year= Year, month = Month))

#Wrangle Hatteras water temperature dataframe to be averaged by month
Hatteras_wtmp <- Hatteras.Water.Temp %>%
  select("#YY","MM","DD","WTMP") %>%
  dplyr::rename (Year = "#YY", Month = "MM", Day ="DD")  %>%
  mutate("Date" = make_date(year= Year, month =Month, day = Day))

Hatteras_daily_wtmp <-  Hatteras_wtmp %>%
  dplyr::group_by(Year, Month, Day, Date) %>%
  dplyr::summarise(dailywtmp = mean(WTMP),.groups ='drop') %>%
  mutate(Station = "Hatteras")

Hatteras_monthly_wtmp <- Hatteras_wtmp %>%
  dplyr::group_by(Year, Month) %>%
  dplyr::summarise( monthlywtmp = mean(WTMP), .groups ='drop') %>%
  mutate(Station = "Hatteras")%>%
  mutate("Date" = make_date(year= Year, month = Month))


#Wrangle Wrightsville water temperature data frame to be averaged by month

Wrightsville_wtmp <- Wrightsville.Water.Temp %>%
  select("#YY","MM","DD","WTMP") %>%
  dplyr::rename (Year = "#YY", Month = "MM", Day ="DD") %>%
  mutate("Date" = make_date(year= Year, month =Month, day = Day))

Wrightsville_daily_wtmp <-  Wrightsville_wtmp %>%
  dplyr::group_by(Year, Month, Day, Date) %>%
```

```r
  dplyr::summarise(dailywtmp = mean(WTMP),.groups ='drop') %>%
  mutate(Station = "Wrightsville")

Wrightsville_monthly_wtmp <- Wrightsville_wtmp %>%
  dplyr::group_by(Year, Month) %>%
  dplyr::summarise( monthlywtmp = mean(WTMP), .groups ='drop') %>%
  mutate(Station = "Wrightsville") %>%
  mutate("Date" = make_date(year= Year, month = Month))
```

```r
#combine daily datasets for water temperature

combine_daily_water_temp <- rbind(beaufort_daily_wtmp, Hatteras_daily_wtmp,
                                  Wrightsville_daily_wtmp)
write.csv(combine_daily_water_temp,
          './Data/Processed_Data/combine_daily_water_temp.csv')

#combine monthly datasets for water temperature

combine_monthly_water_temp <- rbind(beaufort_monthly_wtmp,Hatteras_monthly_wtmp,
                                    Wrightsville_monthly_wtmp)
write.csv(combine_monthly_water_temp,
          './Data/Processed_Data/combine_monthly_water_temp.csv')
```

```r
#clean-up sea level datasets
Beaufort_SeaLevel <- Beaufort_SeaLevel %>% select(c(1,6,7)) %>%
  mutate(Station= "Beaufort")
Hatteras_SeaLevel$Date <- as.Date(Hatteras_SeaLevel$Date, format = "%m/%d/%y")
Hatteras_SeaLevel <- Hatteras_SeaLevel %>% select(c(1,6,7)) %>%
  mutate(Station= "Hatteras")
Wrightsville_SeaLevel <-Wrightsville_SeaLevel %>% select(c(1,6,7)) %>%
  mutate(Station= "Wrightsville")

combine_sealevel <- rbind (Beaufort_SeaLevel, Hatteras_SeaLevel,
                           Wrightsville_SeaLevel)
write.csv(combine_sealevel, './Data/Processed_Data/combine_sealevel.csv')

#Prepare necessary data frames for the analyses

combined_sea_level_data <-
  read.csv("./Data/Processed_Data/combine_sealevel.csv")
#Add month-year column from date
combined_sea_level_data$Date<- as.Date(combined_sea_level_data$Date)
combined_sea_level_data <- combined_sea_level_data %>% mutate(Month=month(Date))%>%
  mutate(Year=year(Date)) %>% group_by(Year, Month)

combined_water_temp_data<-
  read.csv("./Data/Processed_Data/combine_monthly_water_temp.csv")
combined_water_temp_data$Date<-as.yearmon(paste(combined_water_temp_data$Year,
                                                 combined_water_temp_data$Month,
                                                 sep="-"), "%Y-%m")
```

Exploratory Analysis

```
## `geom_smooth()` using formula 'y ~ x'
```

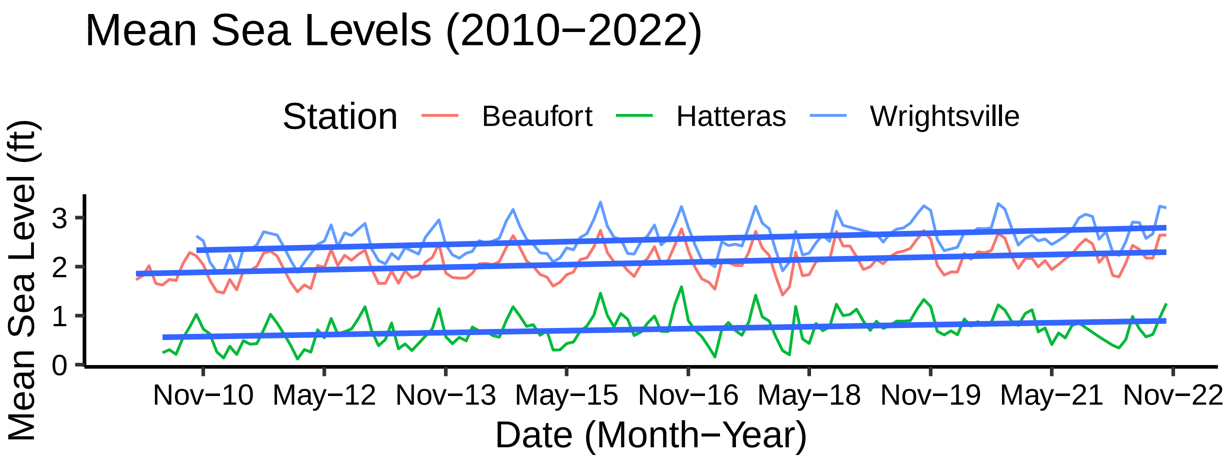

Figure 1: Sea Level Trend Exploration

```
## `geom_smooth()` using formula 'y ~ x'
```

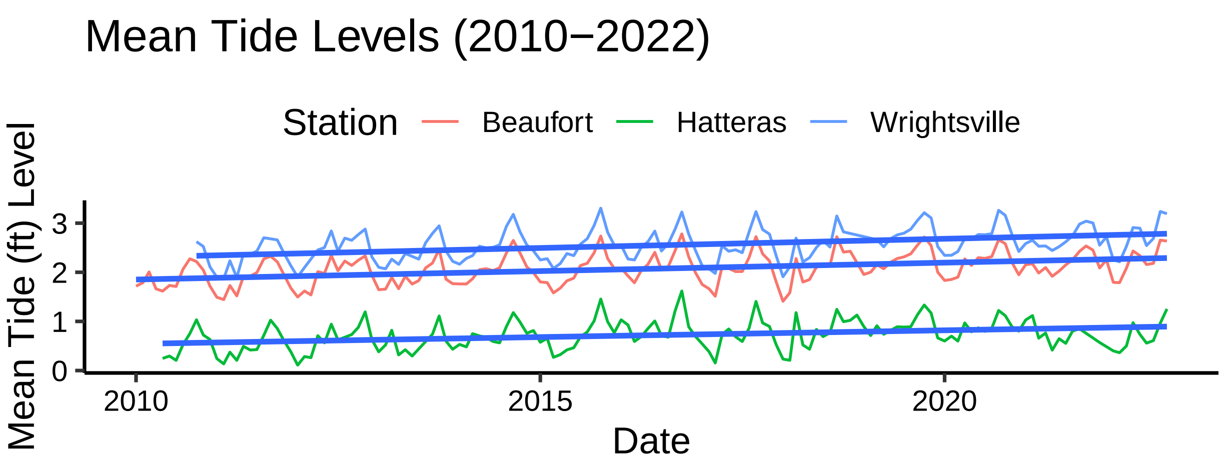

Figure 2: Sea Level Trend Exploration

```
## `geom_smooth()` using formula 'y ~ x'
## Warning: Removed 401 rows containing non-finite values (stat_smooth).
## Warning: Removed 401 row(s) containing missing values (geom_path).
## `geom_smooth()` using formula 'y ~ x'
## Warning: Removed 402 rows containing non-finite values (stat_smooth).
## Warning: Removed 402 row(s) containing missing values (geom_path).
```

Sea level data exploration

The first plot in the previous r code chunk, sea_level_plot, displays the mean sea level measurements from 2010 to 2022 for each station. There are fluctuations in sea level on a month-to-month basis, but trend lines represent a slight increase in sea level at all three sites since 2010. The tide_level plot shows the mean tide

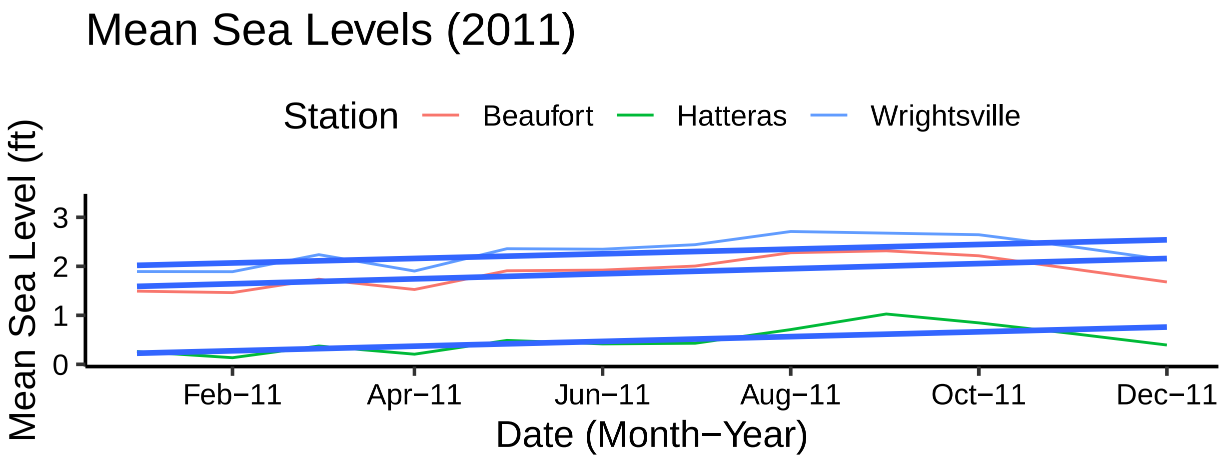

Figure 3: Sea Level Trend Exploration

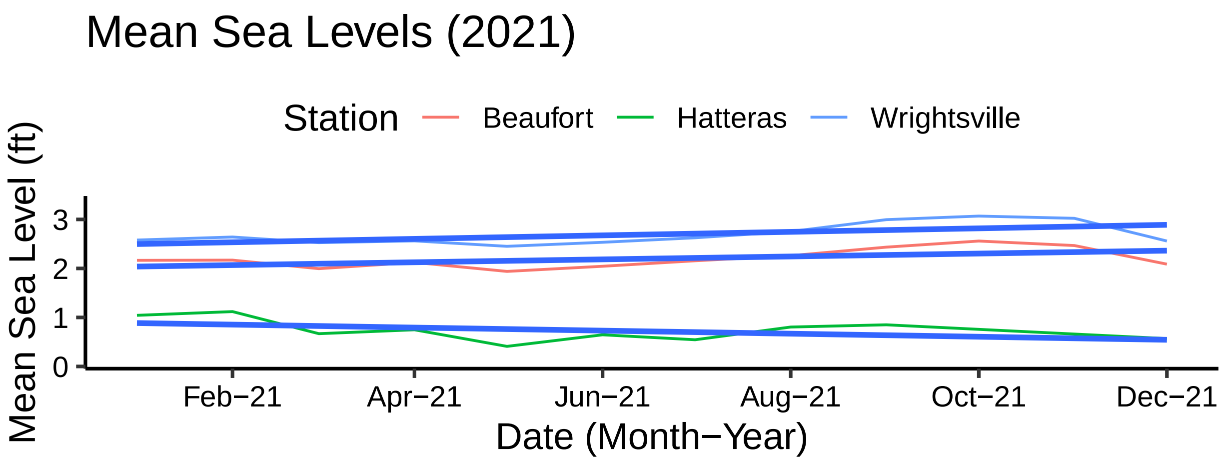

Figure 4: Sea Level Trend Exploration

levels for each station, and produced similar results. We noticed fluctuations from month-to-month, but the linear model lines show an increase in tide levels at all the sites.

The third and fourth graphs display the mean sea levels in 2011 and 2022, respectively sea_level_2011 and sea_level_2021. Both of these graphs indicate increasing mean sea levels over the course of the year for Wrightsville Beach and Beaufort, but decreasing sea levels on Hatteras Island. The trend lines look very similar between the graphs so we are interested in the results produced by the time series analyses for more information.

```
## `geom_smooth()` using formula 'y ~ x'
```

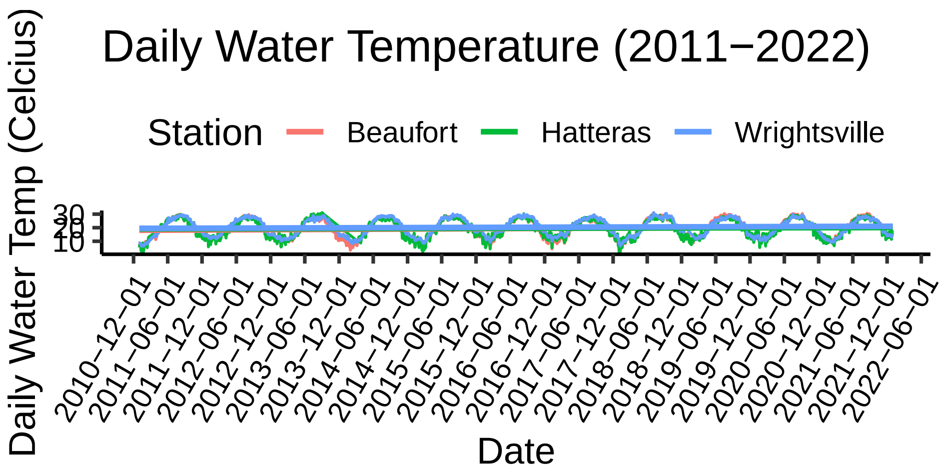

Figure 5: Water Temperature Trend Exploration

```
## `geom_smooth()` using formula 'y ~ x'
```

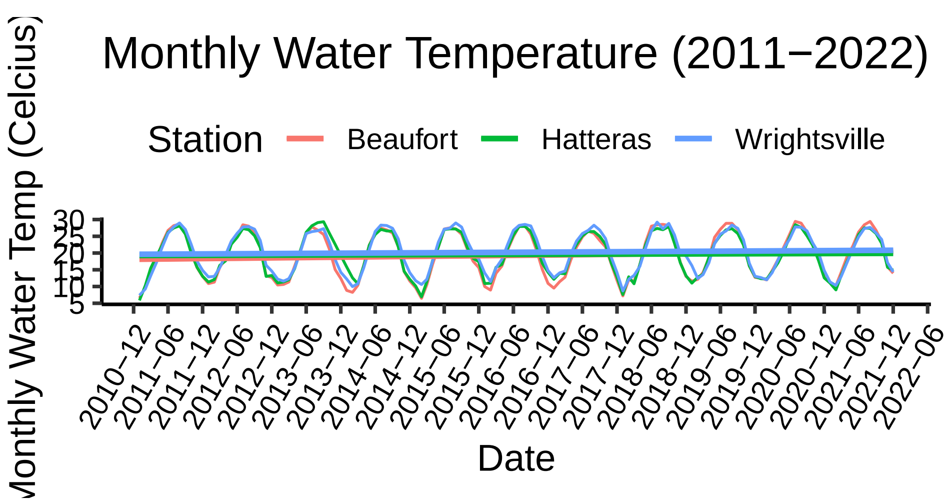

Figure 6: Water Temperature Trend Exploration

Water temperature data exploration

A clear seasonal changes is observed in water temperature data for all three sites according to the monthly_wtmp_level_plot and daily_wtmp_level_plot graphs. Water temperatures are high in the summer seasons and low in the winter seasons. There is a overall increase in water temperature in Beaufort and Wrightsville, but there was a overall decrease in water temperature in Hatteras. The biggest increase in temperature was observed in Beaufort.

Analysis

Trend of sea level and water temperature over time and the role of seasonality

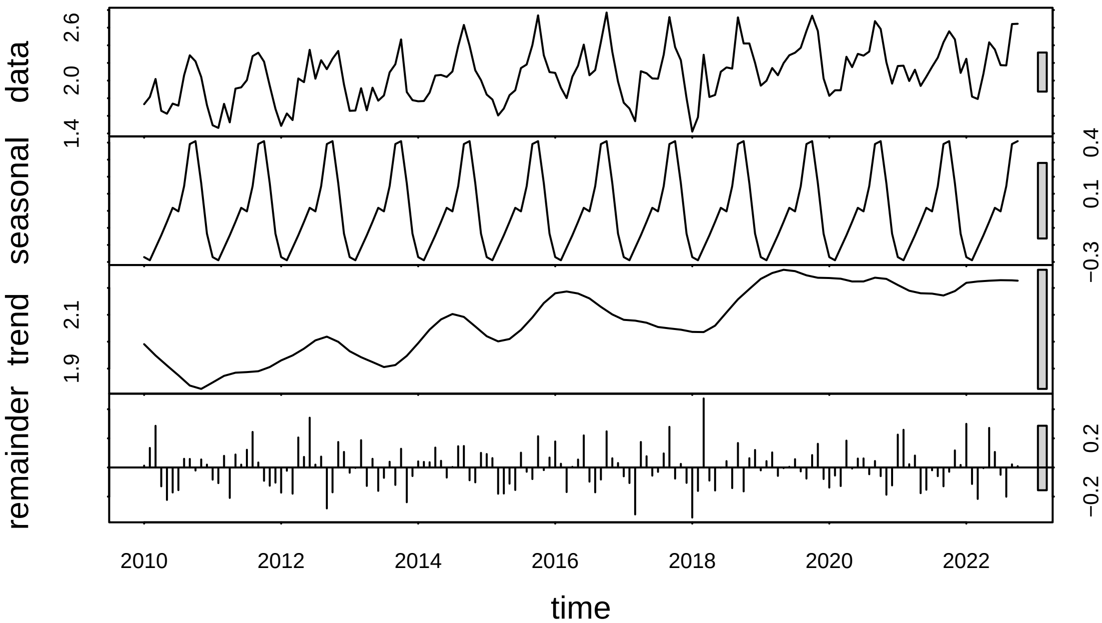

Figure 7: Beaufort Sea Level Timeseries

```
## Score =  407 , Var(Score) = 3111
## denominator =  911.4983
## tau = 0.447, 2-sided pvalue =2.9421e-13
```

```
## Score =  4862 , Var(Score) = 409716
## denominator =  11780.5
## tau = 0.413, 2-sided pvalue =< 2.22e-16
```

Beaufort Sea Level Time Series

According to the Beaufort sea level time series analyses and plot, Beaufort_Monthly_Sea_Level, it appears that the trend does seem to gradually increase over time with a couple of fluctuations. Therefore, both a non-seasonal and a seasonal Mann Kendall analysis should be run in order to see clearer quantified trends. Mann Kendall has the ability to detect, accept or reject the presence of monotonic trends. When the seasonal Mann Kendall was ran, the score was 407 with a tau of (0.447) and a 2-sided p-value of (2.94eˆ-13). This p-value is less than significance level(0.05), so we reject the null hypothesis that there is no monotonic trend. This underscores that the data has a monotonic trend and the tau value(0.447) is statistically significant. The positive value of tau signifies an increasing trend. The seasonal Mann Kendall test only compares data values of the same season. When the seasonal component was removed, the score increased to 4862, with a tau of (0.413), and an even smaller 2-sided p-value of (2.22e-16). Thus, we reject null hypothesis again, and the positive value of tau signifies an increasing trend. Based on the fact that both tests suggest there is an increasing trend, we can tentatively state that the sea levels of Beaufort are generally increasing over time.

```
## Score =  216 , Var(Score) = 2546
## denominator =  788.9886
## tau = 0.274, 2-sided pvalue =1.8623e-05
```

```
## Score =  2806 , Var(Score) = 335186
## denominator =  10293
## tau = 0.273, 2-sided pvalue =1.3113e-06
```

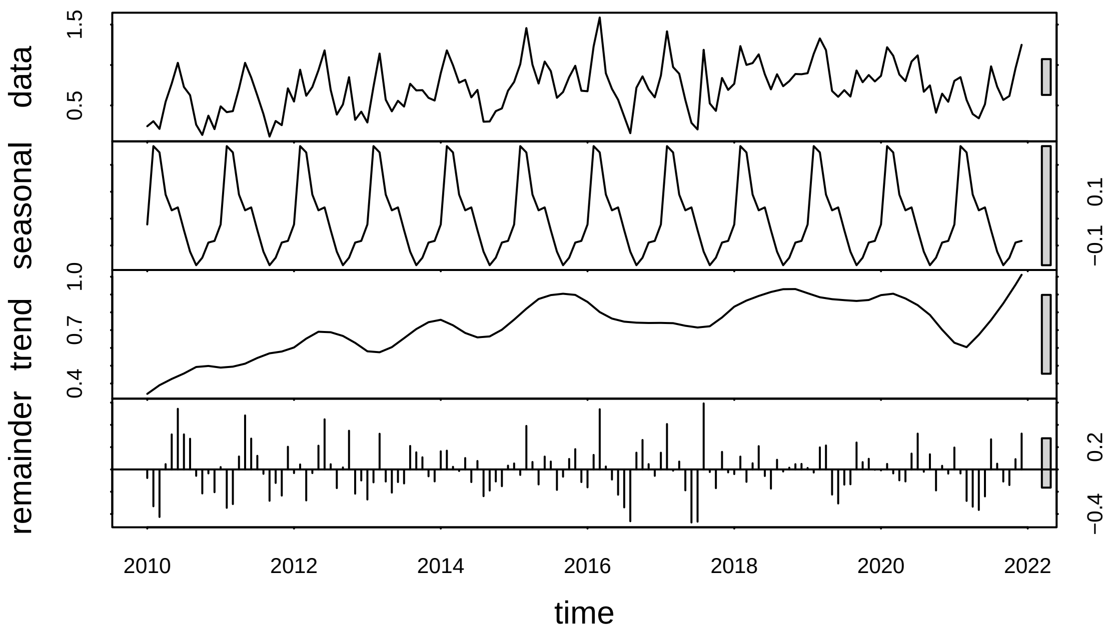

Figure 8: Hatteras Sea Level Timeseries

Hatteras Sea Level Time Series

The Hatteras sea level time series analyses and plot, Hatteras_Monthly_Sea_Level, indicate that the overall data trend in sea level rise is increasing over time. Therefore, both a non-seasonal and a seasonal Mann Kendall analysis should be run in order to see clearer quantified trends. When the seasonal Mann Kendall was ran, the score was (216) with a tau of (0.274) and a 2-sided p-value of (1.86eˆ-5). This p-value is less than significance level(0.05), so we reject the null hypothesis that there is no monotonic trend. This underscores that the data has a monotonic trend and the tau value(0.274) is statistically significant. The positive value of tau signifies that there is an increasing trend. The seasonal Mann Kendall test only compares data values of the same season. When the seasonal component was removed, the score increased to 2806, with a tau of (0.273), and an even smaller 2-sided p-value of (1.31e-6). The positive value of tau signifies an increasing trend. Based on the fact that both tests suggest there is an increasing trend, we can tentatively state that the sea levels of Hatteras are generally increasing over time.

```
## Score =  175 , Var(Score) = 2263
## denominator =  724.4943
## tau = 0.242, 2-sided pvalue =0.00023441
```

```
## Score =  2824 , Var(Score) = 295140.7
## denominator =  9451.5
## tau = 0.299, 2-sided pvalue =2.3842e-07
```

Wrightsville Sea Level Time Series

According to the Wrightsville sea level time series analyses and plot, Wrightsville_Monthly_Sea_Level, it appears that the trend of sea level seems to be gradually increasing over time with a couple of fluctuations. When the seasonal Mann Kendall was ran, the score was 175 with a tau of (0.242) and 2-sided p-value of (0.0002). The p-value of (0.0002) is less than significance level(0.05), so we reject null hypothesis that there is no monotonic trend. Therefore, the data has a monotonic trend. The positive value of tau signifies an increasing trend. The seasonal Mann Kendall test only compares data values of the same season. When the seasonal component was removed, the score increased to 2824, with a tau of (0.299), and an even smaller 2-sided p-value of (2.38e-7). The positive value of tau signifies an increasing trend. Based on the fact that both tests suggest there is an increasing trend, we can tentatively state that the sea levels of Beaufort are

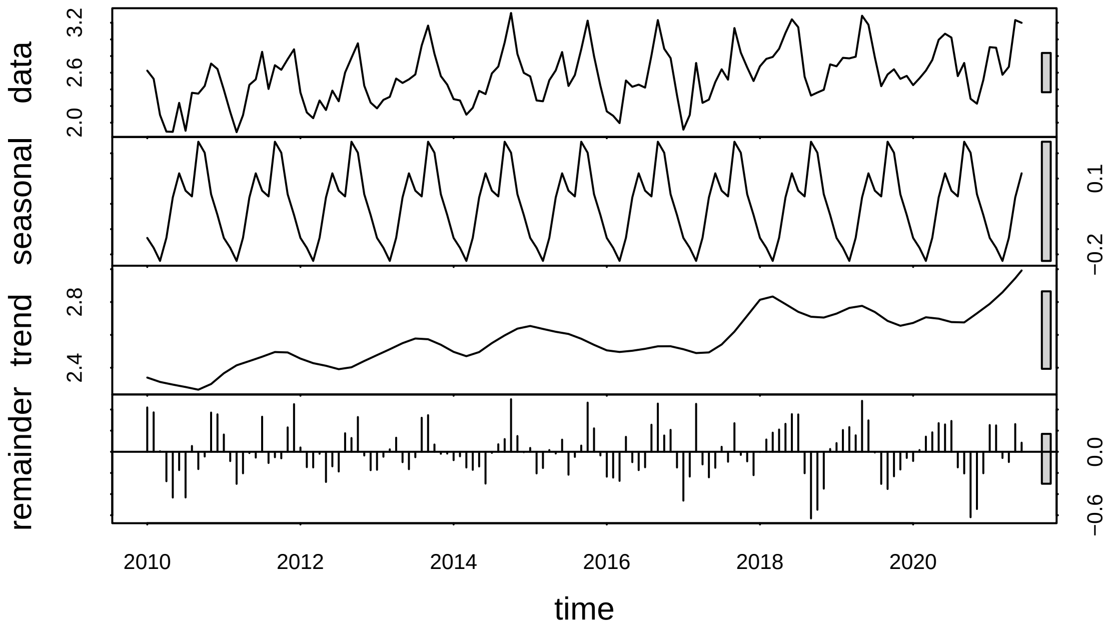

Figure 9: Wrightsville Sea Level Timeseries

generally increasing over time.

```
## Score =  190 , Var(Score) = 1980
## denominator =  660
## tau = 0.288, 2-sided pvalue =1.9553e-05
```

```
## Score =  1972 , Var(Score) = 258419.3
## denominator =  8646
## tau = 0.228, 2-sided pvalue =0.00010562
```

Beaufort Water Temperature Time Series

The Beaufort water temperature time series plot, Beaufort_Monthly_WaterTemp, suggests an overall increasing trend in water temperature over time. The seasonal Mann Kendall test resulted in a score of 190, a tau value of (0.288) and p-value of (1.96 e-5). This p-value is less than significance level(0.05), so we reject the null hypothesis that there is no monotonic trend. This suggests that a monotonic trend can be accepted and it shows a gradual increase in water temperature over time as tau is positive. Removal of seasonality resulted in a score of 1972, tau of (0.228), and less, but still statistically significant 2-sided pvalue of (0.0001) demonstrating that the removal of seasonality still highlights a monotonic trend in water temperature at the Beaufort site. Therefore we can tentatively say that water temperature is generally increasing over time at Beaufort.

```
## Score =  10 , Var(Score) = 1980
## denominator =  660
## tau = 0.0152, 2-sided pvalue =0.82219
```

```
## Score =  -54 , Var(Score) = 258419.3
## denominator =  8646
## tau = -0.00625, 2-sided pvalue =0.91696
```

Hatteras Water Temperature Time Series

The Hatteras water temperature time series analyses and plot, Hatteras_Monthly_WaterTemp, suggest a relatively random distribution of water temperature over time. The seasonal Mann Kendall test resulted in

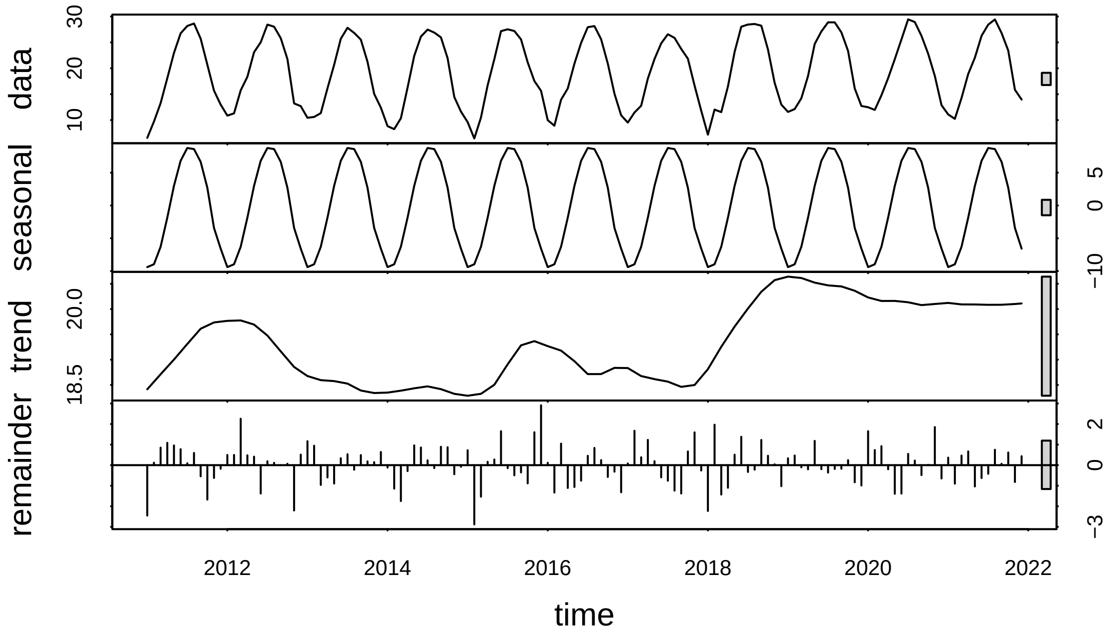

Figure 10: Beaufort Water Temperature Timeseries

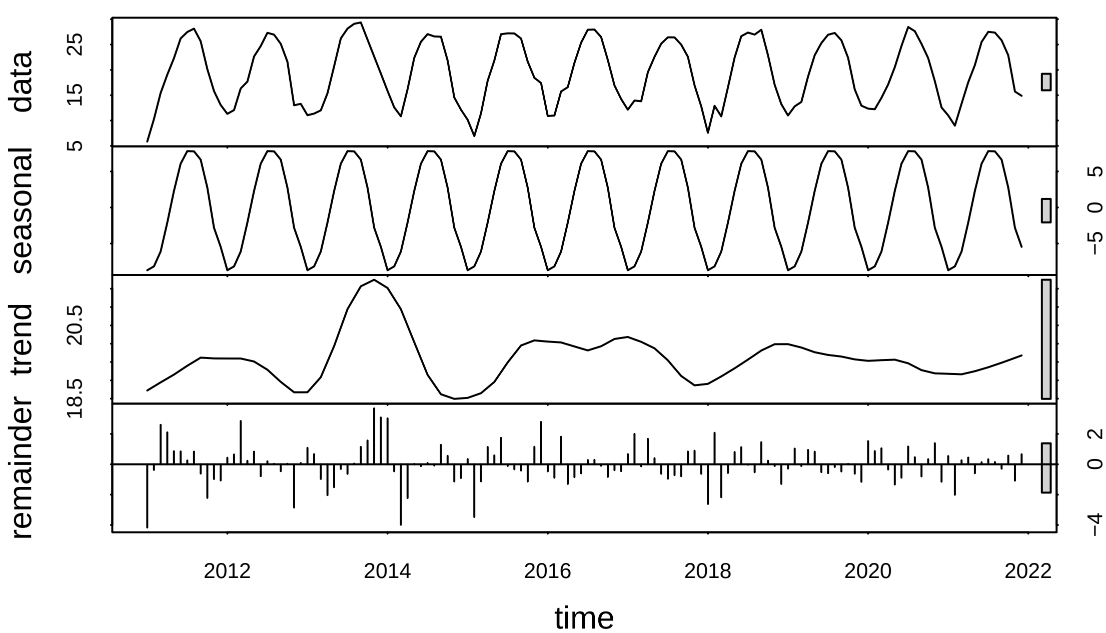

Figure 11: Hatteras Water Temperature Timeseries

a score of 10, a tau value of (0.0152) and p-value of (0.82). A p-value of 0.82 is greater than significance level(0.05), so we accept our null hypothesis that there is not a monotonic trend present. Removal of seasonality resulted in a score of -54, tau of (-0.00625), and also, a non-statistically significant 2-sided pvalue of (0.92) demonstrating that the removal of seasonality also rejects the presence of a monotonic trend in water temperature at the Hatteras site. Thus, there is no uni-direction increase or decrease in water temperature over time at Hatteras.

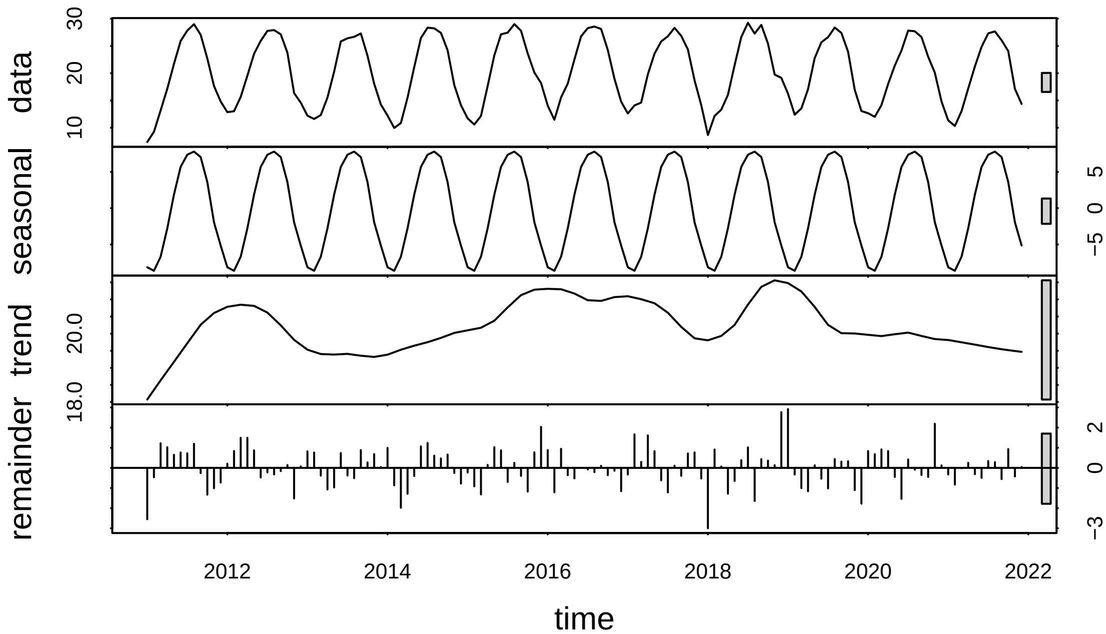

Figure 12: Wrightsville Water Temperature Timeseries

```
## Score =  4 , Var(Score) = 1980
## denominator =  660
## tau = 0.00606, 2-sided pvalue =0.92837
```

```
## Score =  100 , Var(Score) = 258419.3
## denominator =  8646
## tau = 0.0116, 2-sided pvalue =0.84559
```

Wrightsville Water Temperature Time Series

The Wrightsville water temperature time series plot, Wrightsville_Monthly_WaterTemp, and analyses suggest a relatively uniform, mildly fluctuating distribution of water temperature over time. The seasonal Mann Kendall test resulted in a score of 4, a tau value of (0.006) and p-value of (0.92). Since the p value is greater than significance level(0.05), we accept our null hypothesis that there is not a monotonic trend present. Removal of seasonality resulted in a score of 100, tau of (0.116), and also, a non-statistically significant 2-sided pvalue of (0.84) demonstrating that the removal of seasonality also rejects the presence of a monotonic trend in water temperature at the Hatteras site. Thus, there is no monotonic trend or unidirectional increasing or decreasing in water temperature observed at this site over time.

Testing stastically significant relationship between sea level and water temperature

```
knitr::opts_chunk$set(tidy.opts=list(width.cutoff=30), tidy=TRUE)

#Correlation Test Between Sea Level and Water Temperature
```

```
#Check normality of data
shapiro.test(combined_sea_level_data$MSL..ft.)
```

```
##
##  Shapiro-Wilk normality test
##
## data:  combined_sea_level_data$MSL..ft.
## W = 0.93049, p-value = 2.317e-13
```

```
shapiro.test(combined_water_temp_data$monthlywtmp)
```

```
##
##  Shapiro-Wilk normality test
##
## data:  combined_water_temp_data$monthlywtmp
## W = 0.92853, p-value = 8.056e-13
```

```
#The data is non-normal

#Complete a correlation test
combined.sea.level.correlation.edits<-
  combined_sea_level_data[-c(1,2,3,4,5,6,7,8,9,10,11,12,
                             145,146,147,148,149,150,151,
                             152,153,154,155,156,157,158,
                            159,160,161,162,290,291,292,
                            293,294,295,296,297,298,299,300,
                            301,427,428,429,430,431,432,433,
                            434,435,436),]
combined.sea.level.correlation.final <-
  combined.sea.level.correlation.edits[-c(427,428,429,430,
                                          431,432,433,434,435,436),]
combined.water.temp.correlation.edits<-
  combined_water_temp_data[-c(152,163,164,262,263,273,
                              279,294,359,360,361,362),]

Correlation.kendall<-
  cor.test(combined.sea.level.correlation.edits$MSL..ft.,
           combined.water.temp.correlation.edits$monthlywtmp, method = "kendall")
Correlation.kendall
```

```
##
##  Kendall's rank correlation tau
##
## data:  combined.sea.level.correlation.edits$MSL..ft. and combined.water.temp.correlation.edits$monthl
## z = 5.4203, p-value = 5.949e-08
## alternative hypothesis: true tau is not equal to 0
## sample estimates:
##       tau
## 0.1853611
```

```
correlation.combined<- data.frame(combined.sea.level.correlation.edits[,3],
                                  combined.water.temp.correlation.edits[,4])
names(correlation.combined) <- c("MSL", "WTMP")
cor(correlation.combined)
```

```
##            MSL     WTMP
```

```
## MSL  1.000000 0.216857
## WTMP 0.216857 1.000000
```

Correlation Test Between Sea Level and Water Temperature

According to the Kendall's rank correlation test for sea level and water temperature measurements, Correlation.kendall, the p-value is (5.949e-08) which is smaller than the significance level of 0.05. This means that we reject the null hypothesis that there is a statistically significant relationship between sea level and water temperature. Therefore, the tau value (0.1853611) is statistically significant, which measures a weak positive correlation between the two parameters. This means that there is a slight correlation that indicates when one value increases, the other will increase.

A simple correlation test between the two variables (correlation.combined) finds a slightly stronger relationship with a correlation coefficient of (0.216857). This test also indicated a slightly positive correlation between sea level and water temperature at the three sites.

Question 1:

How have sea level trends and water temperature trends changed over time and how has seasonality played role at three coastal North Carolina sites: Beaufort,Hatteras, Wrightsville?

Question 2:

Is there a stastically significant relationship between sea level and water temperature?

Summary and Conclusions

From the time series analysis, we observed an increasing trend present in sea level measurements for all three sites. Beaufort, with seasonality considered (Mann-Kandall; tau=0.447, p < 2.94eˆ-13) and without seasonality considered (Mann-Kandall; tau=0.413, p < 2.22eˆ-16), had statistically significant tau values and demonstrated an upward trend in sea level. In Hatteras, with seasonality considered (Mann-Kandall; tau=0.274, p < 1.86eˆ-5) and without seasonality considered (Mann-Kandall; tau=0.273, p < 1.31eˆ-6) had statistically significant tau values and demonstrated an upward trend in sea level. In Wrightsville, with seasonality considered (Mann-Kandall; tau=0.242, p < 0.0002) and without seasonality considered (Mann-Kandall; tau=0.299, p < 2.38e-7), had statistically significant tau values and demonstrated an upward trend in sea level.

However, monotonic increase of water temperature over time was only observed in Beaufort. Beaufort, with seasonality considered (Mann-Kandall; tau=0.288, p < 1.96eˆ-5) and without seasonality considered (Mann-Kandall; tau=0.228, p < 0.0001), had statistically significant tau values and demonstrated an upward trend in water temperature. In Hatteras, with seasonality considered (Mann-Kandall; tau=0.0152, p < 0.82 and without seasonality considered (Mann-Kandall; tau=-0.00625, p < 0.92), had tau values that were not statistically significant. In Wrightsville, with seasonality considered (Mann-Kandall; tau=0.006, p < 0.92) and without seasonality considered (Mann-Kandall; tau=0.116, p < 0.84), had tau values that are not statisitcally significant. Sea level has been increasing over all three sites, while only Beaufort has had increasing water temperature over time. Seasonality did not play a significant role at three sites in North Carolina.

The Kandall's rank correlation test produced a p-value of (5.949e-08), thus a statistically significant value of tau (0.1853611) indicates a weak positive correlation between sea level and water temperature. This indicates that when there is an increase in sea level, there will be an increase of water temperature and vice versa.

References

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