Summer 2005

Interannual Variation of Stratification in Lower Chesapeake Bay

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INTERANNUAL VARIATION OF STRATIFICATION IN LOWER CHESAPEAKE BAY

by

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B.S. May 1995, United States Naval Academy

A Thesis Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirement for the Degree of

MASTER OF SCIENCE

OCEANOGRAPHY

OLD DOMINION UNIVERSITY
August 2005

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ABSTRACT

INTERANNUAL VARIATION OF STRATIFICATION IN LOWER CHESAPEAKE BAY

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Stratification in the water column can prove to be an important indicator to the state of the water column and ecosystem. The focus of this research is to evaluate trends in stratification in the Lower Chesapeake Bay. Detailed analysis was performed on a 14 year data set to study interannual variation in the region of study. Potential energy anomaly was used to quantify stratification. Potential energy anomaly is the amount of energy required to mix a water column. It is determined from the vertical density structure of density. Potential energy anomaly is the departure of potential energy from climate conditions. The research did find trends in the periodicity of the potential energy anomaly. Three stations are described in detail through this paper but 14 stations were evaluated by the methods in the paper. The work indicated an annual frequency through frequency analysis of the data. A secondary signal was one of approximately 3 years. An indicative station from the research was Station 6.3C that displayed periods of one year and three years from the analysis. The results could be further analyzed and explained in the future by increasing the number of stations in the northern part of the Bay and using more up to date data.

This thesis is dedicated to my wife, Jennifer and my parents, Phillip and Martha

ACKNOWLEDGMENTS

I wish to thank my colleagues at the Center for Coastal Physical Oceanography from 1999-2001. I would also like to thank my committee of professors who oversaw work on the research, as well as, various other professors (Dr. Klinck, Dr. Hofmann, and Dr. Grosch) in the Center for Coastal Physical Oceanography who provided background and education on topics and programming that proved to be beneficial in my research. Specifically, I would like to thank Dr. Atkinson. Dr. Atkinson has served as my thesis advisor and also as a colleague who has guided me on career decisions always considering my interests and skills developed in the field of Physical Oceanography. The research work and journey to Chile will never be forgotten. I would like to thank Dr. Royer for his instruction on course work and local research work near the campus. I would like to thank Dr. Valle-Levinson for his guidance, challenging course work, and the opportunity to participate in a research cruise to Argentina and Chile. The knowledge and life experiences of these professors helped shape the path of my research and the knowledge base needed to complete the analysis and evaluation of the data. Lastly, I would like to thank the students. Your assistance with programming, classes, and research cruises not only helped form the knowledge I now possess but gained a core of knowledgeable colleagues.

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CHAPTER I

INTRODUCTION

The Chesapeake Bay is one of the world's largest estuaries extending from Maryland to southern Virginia (Figure 1). It is about 320 kilometers (200 miles) long along the axis and varies between 5.5 kilometers (3.4 miles) near Aberdeen, MD and 56.3 kilometers (35 miles) wide near the mouth of the Potomac River. The average depth is 6.51 meters (21 feet) with most of the Bay being shallow. The Bay is a volume flux of freshwater, receiving about half of its water volume from the Atlantic Ocean, the rest drains from many rivers and small streams (approximately 150) into the Bay from a catchment basin of 165,760 km^2 (64,000 mi^2) [www.chesapeakebay.net, 2004]. The Bay is both dynamically and biologically complex with processes that occur on a variety of time and space scales. The fluctuations and changes in these processes can be caused by forces within the Bay, in the drainage basin, or at the mouth of the estuary where the ocean and the Bay meet [Carter and Pritchard, 1988].

There is much concern about the state of the Bay, its response to human activities and its responses to changing weather and climate. Of the many parameters that characterize the Bay, stratification is one of the most fundamental. It expresses the net effect of many physical forces such as runoff (volume), heating and cooling, wind and general circulation. Variations in stratification can significantly affect the fundamental physical, biological, and chemical characteristics of estuaries. Surprisingly, there has been little research on stratification in the Chesapeake Bay.

Although there have been no studies on the interannual variations in stratification there have been studies on stratification in the Bay. Wang [1975, 1976] demonstrated that there was a strong correlation between winds and density induced circulation in the Bay. His work provided a basis for further investigation into stratification in the water column. In 1984, Officer et al. concluded that the beginning of stratification in the spring is a major factor in the development of bottom water anoxia in the middle and upper Chesapeake Bay [Goodrich, 1987].

The journal model for this thesis is the *Journal of Geophysical Research (Oceans)*.

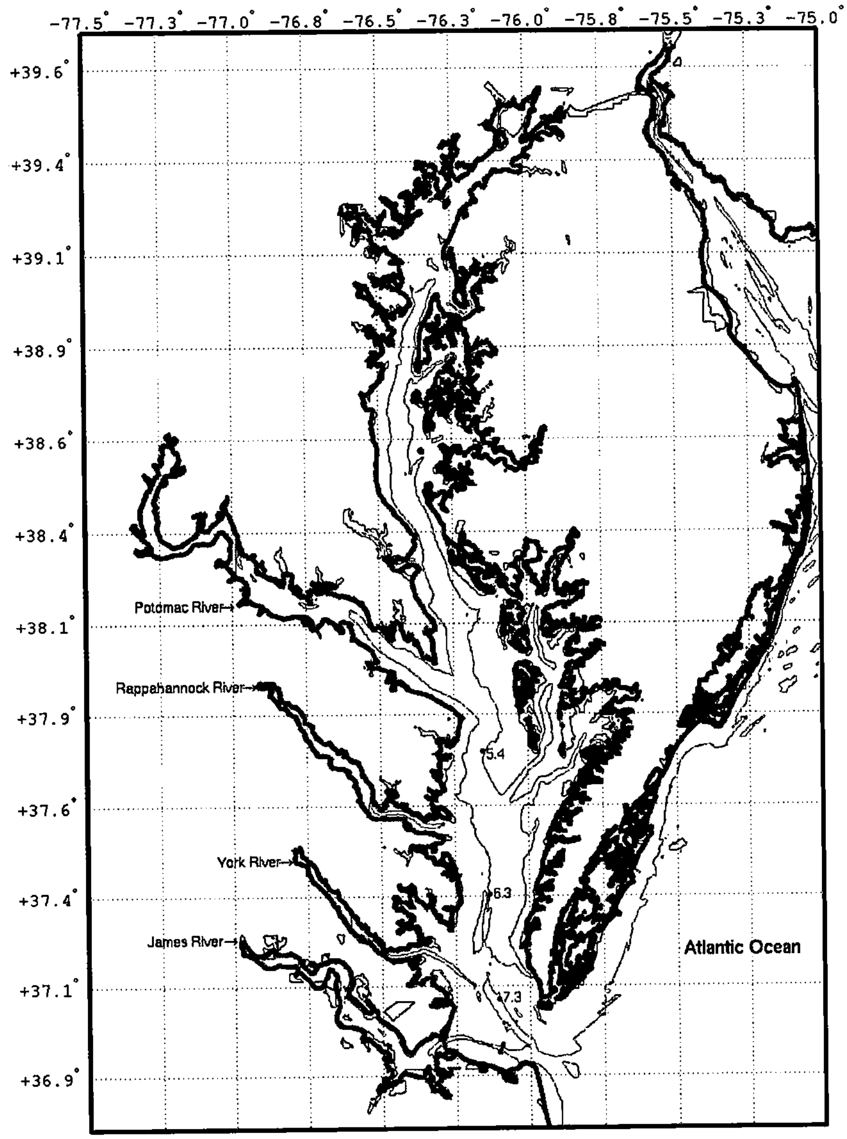

Figure 1: Chesapeake Bay Stations, 11 m contour

Figure 1. Chesapeake Bay Stations, 11 m contour shown to indicate main channel in Bay. The three stations analyzed are indicated.

In the fall vertical mixing into areas of bottom water causes oxygen to be replenished [Goodrich, 1987]. Goodrich [1987] concluded that time-dependent stratification in the middle of the Chesapeake Bay is a dynamic balance of forces. The mixing energy provided by the wind and tides balance the buoyancy flux driven primarily by runoff or estuarine flow. Goodrich's research also found that in the stratified conditions in the Chesapeake Bay, the response to wind forcing was dependent on depth. But precluding a mixing event, the response was independent of depth due to altering the response of the velocity field to subsequent wind forcing. A large velocity shear precedes mixing events that eluded to a possible mechanism causing dynamic instability across the pycnocline. Valle-Levinson et al. [1988] showed that enhanced stratification follows strong wind events follow by a neap tide. The study was focused on extreme wind events, but again supported the influence of tides and winds on stratification in the Chesapeake Bay. Predictions of future runoff from statistical models of salinity variations to investigate climate change indicates, *in* the majority of the models, an increase in runoff in the Chesapeake Bay which would result in stratification changes due to the parameters input into the system [Gibson, 2000] and suggest stratification in the Bay may change in the future. In a basic approach, buoyancy inputs drive stratification and mixing through mechanical stirring by winds and tides acting independently. The competition between the influences determines the level of stratification. This would be the simplest model that has heating and tidal stirring as primary parameters. More elaborate models are developed to include wind and surface heat fluctuations, but we not used for this research.

Stratification has been studied in the Irish Sea [Simpson et al., 1971, 1974, 1977, 1978], Long Island and Block Sounds [Bowman et al., 1981], North Sea [Van Aken, 1986], Spencer Gulf in Australia [Nunes, 1987], Gulf of California [Argote at al., 1995], Hudson estuary [Nepf et al., 1996], North Sea-Baltic Sea [Lund-Hansen et al., 1996], and the Yellow Sea [Lee and Beardsley, 1999]. None of the papers addressed interannual variability in stratification.

In the Chesapeake Bay, many factors affect the stratification of the water column. Runoff, rain, and heating stratify the Bay while winds, tidal currents, and cooling destratify the Bay. In this paper we use the stratification parameter, Ψ, as defined by

Simpson et al. [1978] to quantitatively examine interannual variability in stratification in the lower Chesapeake Bay and how it is affected by runoff.

CHAPTER II

MATERIALS AND METHODS

DATA SOURCES

The primary data source was the United States Environmental Protection Agency's Water Quality Monitoring Program. Forty-nine main stem monitoring stations in Virginia and Maryland are sampled in the program. Twenty-four of the stations are located in the lower Chesapeake Bay region. From those stations, three were chosen for analysis (Table 1). See Figure 1 for locations. The three were chosen to represent conditions in the northern, central, and southern part of the lower Bay. They are all in the main channel of the Bay although the northern station (5.4) is deeper (32.4 m) than the central station (6.3)(12.8 m) and southern station (7.3) (13.6 m). The data sets contain many parameters but this study only required the depth, temperature, and salinity values. The stations were sampled 14 to 18 times per year. The data set used in this study extended from June 1984 to August 1998: a 14-year period. However for trend analysis the set was truncated to January 1985 to December 1997.

Table 1. Station Summary (n = number of samples from each station)

Section	Station	Depth (m)	N	Segment ID	Latitude	Longitude
North	CB5.4	32.4	250	LCB Lower Chesapeake Bay	37° 48' N	76° 10.5' W
Central	CB 6.3	12.8	250	WLCB Western Lower Chesapeake Bay	37° 24' 41" N	76° 09' 36" W
South	CB 7.3	13.6	253	ELCB Eastern Lower Chesapeake Bay	37° 07' 00" N	76° 07' 32" W
Average		19.6	251			

Daily river discharge data were obtained from the United States Geological Survey (USGS) data archive. The 9 rivers located in the Chesapeake Bay watershed include the Susquehanna, James, Potomac, Appomattox, Pamunkey, Rappahannock, Choptank, Mattaponi, and Patuxent. The daily discharge values from these rivers were summed to establish monthly discharge values for the Bay.

Tidal information was obtained from the "Tides and Currents" software marketed by Nobeltec/Nautical Software, Inc. NOAA nautical charts #12221 and #12225 and Chart View software were used for positioning.

The temperature and salinity data from the three stations were first examined to eliminate obviously bad data or stations where no intermediate depths were taken. Only 0.53% of the stations were eliminated. The cause was usually erroneous salinity data. Data removed from the dataset were as follows: Station 5.4 January 16, 1986, Station 6.3 June 24, 1986, and Station 7.3 October 8, 1986 and December 6, 1991.

POTENTIAL ENERGY ANOMALY (Ψ) CALCULATION

The potential energy anomaly, Ψ, is defined as the amount of mechanical energy required to eliminate stratification [Simpson et al., 1977]. The anomaly has been used in coastal areas and estuaries to study the effects of runoff, heating, and cooling on stratification. The potential energy anomaly is defined as follows:

$$\Psi = \frac{1}{h}\int_{-z}^{0}(\rho - \overline{\rho})gz\,dz \qquad (1)$$

Where, Ψ is the stratification parameter, (Jm^{-3}), h is the water depth, (m), $\rho\,(z)$ is the water density, (kgm^{-3}), $\overline{\rho}$ is the depth average density, g is the gravitational constant $(9.8\ ms^{-2})$, and z is the depth of a specific sample in the water column (m). After the Ψ calculation, all values of $\Psi < 0$ where eliminated. One half of a percent of the data was removed for this reason. The primary cause was erroneous decreasing salinity data.

TIDAL ALIAS CALCULATION

The EPA monitoring stations are not sampled relative to any tidal stage and thus may yield aliased information. To assess the degree of aliasing, the times of high and low tides were obtained and compared to the EPA stations. EPA stations were paired to nearby NOAA tide stations for analysis as follows: Great Wicomico, 37°48'N, 76°16'W, was compared to Station 5.4, 37°48'N, 76°10'30"W (5.74 miles). Wolf Trap, 37°23'N, 76°11'W, was compared to Station 6.3, 37°24'41"N, 76°09'36"W (2.96 miles). Fisherman's Island, 37°06'N, 75°59'W was compared to Station 7.3, 37°07'N, 76°07'32" W (7.5 miles). The analysis indicates no degree of comparison to the sample at the EPA monitoring stations and the high or low tide events.

SPECTRAL AND TREND ANALYSIS

The time series stratification data from the three stations was analyzed in two ways. A spectral analysis was used to determine the dominant periods and a trend analysis was used to determine long-term trends in the time series.

Since the time series was irregular with some gaps the 'Lomb method' [Lomb, 1976; Vanicek, 1971; Emery and Thompson, 1997] was used for the spectral analysis. This method is particularly well suited to this type of data set, as it does not create erroneous low-frequency oscillations similar to the length of the gaps. The Lomb's normalized periodogram is defined as follows:

$$P(\omega)=\frac{1}{2\sigma^2}\left\{\frac{\left[\sum_{n=1}^{N}(x_n-\bar{x})\cos[\omega(t_n-\tau)]\right]^2}{\sum_{n=1}^{N}\cos^2[\omega(t_n-\tau)]}+\frac{\left[\sum_{n=1}^{N}(x_n-\bar{x})\sin[\omega(t_n-\tau)]\right]^2}{\sum_{n=1}^{N}\sin^2[\omega(t_n-\tau)]}\right\} \qquad (2)$$

where N is the data values, ω is the frequency, tn is the times data is measured, τ is the time offset with $\bar{x}$ being the mean and σ^2 is the standard deviation [Emery and Thomson, 1998].

Trends were analyzed using the seasonal trend decomposition routines [Cleveland et al., 1990]. This routine uses a LOESS (local regression) scheme. It is referred to as STL (Seasonal Trend LOESS). The analysis determines the seasonal, long-term trend and the remainder components of the signal. LOESS is a regression routine that uses weighted least squares giving more weight to points near the value whose response is being estimated and less weight to points further away. The value of the regression function for the point is then obtained by evaluating the local polynomial using the variable values of that data point. These descriptive values will make the data point unique for use in the regression function. The LOESS fit is complete after regression function values have been computed for each of the n data points in the data set. The subsets of data used for each weighted least squares fit in LOESS are determined by a nearest neighbors algorithm [Cleveland et al., 1990].

The spectral and trend analysis methods used required regular monthly data. ψ values were linearly interpolated to obtain monthly values for evaluation of the spectral energy (Lomb's method) and trend analysis of the time series (STL-Seasonal Trend Decomposition) at each station: some months had several samples and some had none. Dates were standardized to the first day of each month for the 13-year period: 1985 to 1997. The resulting data was evaluated using Lomb's method and STL (seasonal trend decomposition) for spectral and trend analysis respectively. The interpolated Ψ values and monthly river discharge data were analyzed using a seasonal trend decomposition procedure (STL). A least squares spectral analysis method for unevenly spaced data [Vanicek, 1971; Lomb, 1976] was used to evaluate linearly interpolated data from 1985 to 1997. Data was linearly interpolated so multiple monthly samples could be standardized for analysis. Lomb's method is used to interpolate data to a standardized grid, which has irregularly sampled data or data gaps. The data used for this research included both types of data sets. The method has shown to perform well if the data does not contain too many gaps and gaps are relatively short compared to the signals of interest [Emery and Thomson, 1998].

CHAPTER III

RESULTS AND DISCUSSION

This section presents the results of the analysis including tidal aliasing, basic runoff and stratification statistics, and spectral, seasonal, and interannual trend analysis.

TIDAL ALIASING INFLUENCE

It is important to know if Ψ observations are aliased at any location because of the stage of the tide relative to the sampling time. The time of high tide was compared to the time of data acquisition from the station cruises for stations 5.4, 6.3, and 7.3 (Figure 2). The differences in the two times were plotted versus the calculated potential energy anomaly for each sample. The scatter of variation in sampling time reflected no obvious correlation. The other factor seen by these figures was that higher potential energy anomalies did not occur at ebb or flood at these particular stations. As a further check, data from March (Figure 4) and April (Figure 3) were examined. Again, no obvious aliasing was observed.

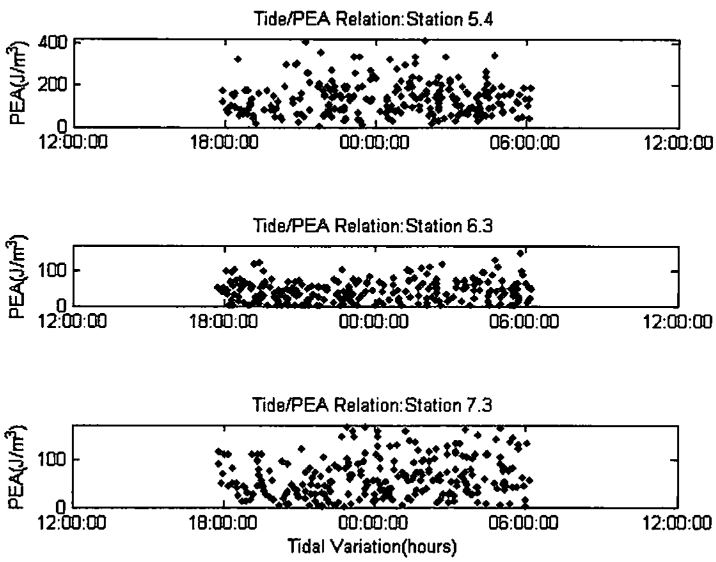

Figure 2. Relation of observed tides to the calculated Ψ at Stations 5.4, 6.3, and 7.3 to determine tidal influence on data used to calculate potential energy anomalies.

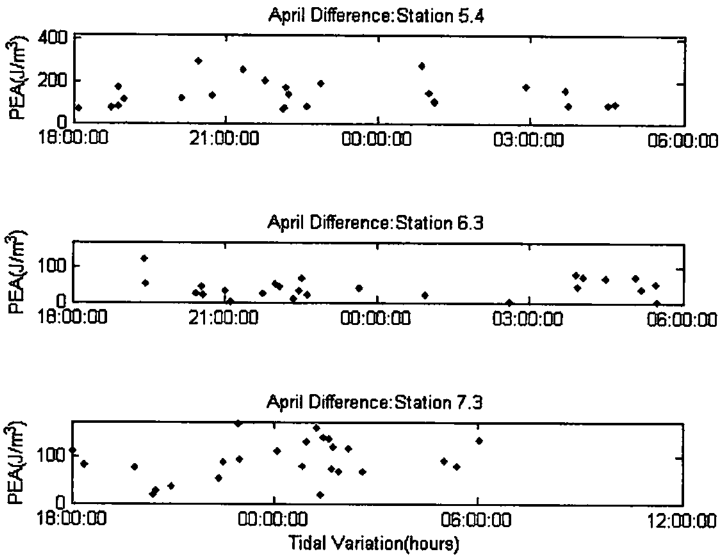

Figure 3. Observed Tides were evaluated versus Ψ for the month of April to further evaluate the tidal influence on the calculations on a monthly time scale.

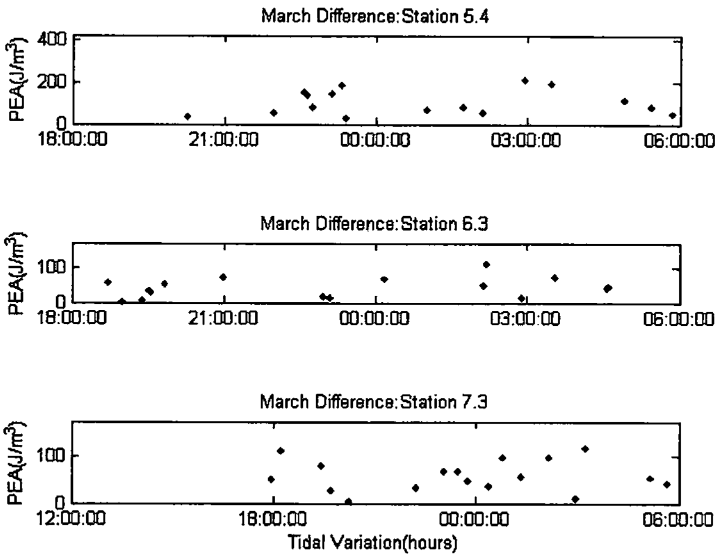

Figure 4. Observed Tides were evaluated versus Ψ for the month of March to further evaluate the tidal influence on the calculations on a monthly time scale.

Stratification and River Discharge Time Series

Combined river flow data (Figure 5) illustrates the highly seasonal nature of the signal and the occasional very high flow episodes. Daily discharge values from the listed rivers were summed to establish monthly discharge values that will be used for the analysis in this section. The average flow of all rivers into the Bay was 22,240 m^3s^{-1} with a standard deviation of 24,330 m^3s^{-1}. The flow ranged from nearly 1,196 m^3s^{-1} to 30,905 x 10^4 m^3s^{-1}.

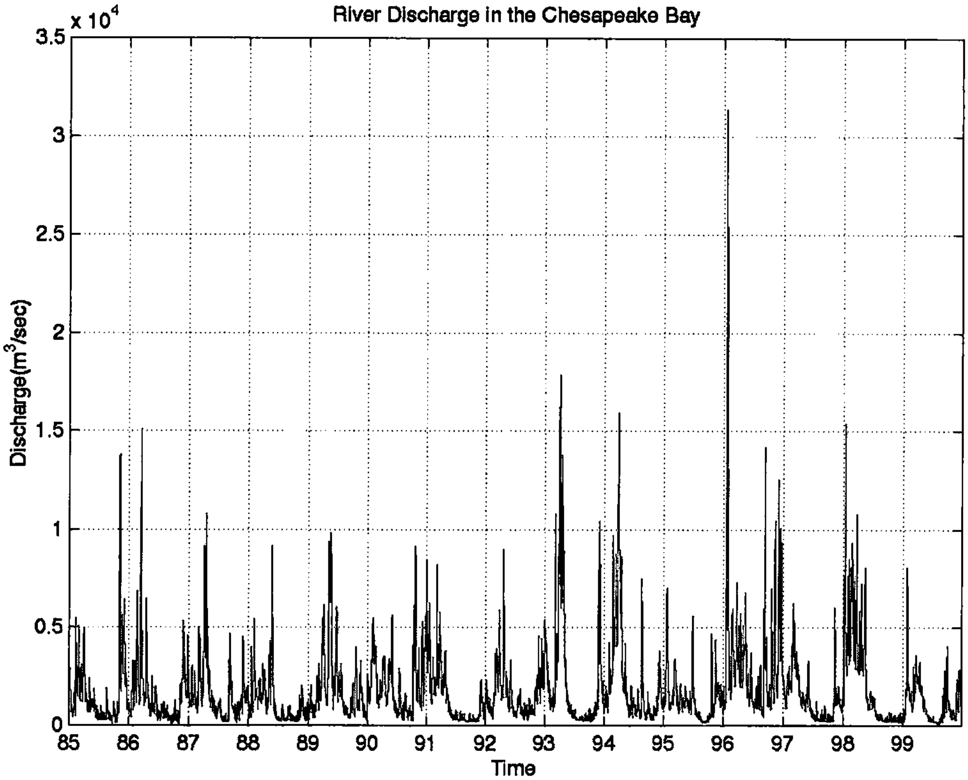

Figure 5. Runoff and PEA Time Series

Highest yearly river runoff years were observed in 1993, 1994, 1996, and 1998 (Figure 5). The highest annual flow on record was observed in 1996. The tributary with the largest effect on runoff in the Chesapeake Bay is the Susquehanna River. It represents over 62% of the total runoff in the Chesapeake Bay and is the only tributary that flows directly into the main stem of the bay. The Potomac, James, and Rappahannock Rivers are the other major tributaries, however, their total volume usually amounts to less then 27% of the total inflow.

The daily discharge values for the nine rivers in the Chesapeake Bay from 1985-2000 were also evaluated for this project. The discharge for the Susquehanna River was shown to have the largest flow of the nine rivers. The highest discharges from the Susquehanna occurred on January 21, 1996, April 2, 1993, and April 3, 1993 respectively. The next two largest discharges into the Bay were the James and Potomac Rivers. The Potomac had highest discharges on January 21, 1996, November 7, 1985, and September 8, 1996. The James River had highest on November 6, 1985, November 7, 1985, and April 18, 1987. The remaining rivers discharging into the Chesapeake Bay, are the Rappahannock, Pamunkey, Appomatox, Patuxent, Mattaponi, and Choptank Rivers.

The monthly mean Ψ data show maximum values in June, a mid-summer minimum in July, a second August maximum, then the destratification during the fall and winter. Runoff (lower panel) peaks in March-April before the stratification peak in the summer. This illustrates the importance of heating and wind in establishing stratification. Winds in the region are distinguished by Northeast winds that are frequent in the fall and winter. The spring has Southeast and Southwest winds. The strongest winds are the north and northeast winds, commonly known as the nor'easters. The variability shown in the overlaid monthly time series will now be examined.

The basic statistics of ψ over the 14-year period of observations at the three stations were evaluated, compared, and are summarized in Table 2.

Table 2. Basic ψ Statistics for the 3 Hydrographic Stations (Jm^{-3})

Station	Mean	Minimum	Maximum	Median	Standard Deviation
5.4	136	0.18	415	131	79
6.3	43	0.21	153	42	31
7.3	65	1.79	180	56	43

Ψ varied from essentially zero to 415 Jm^{-3}. Average Ψ ranged from 43 to 136 Jm^{-3}. The monthly means are shown in Table 3. Ψ peaked in May when runoff peaks, winds decrease, and heating increases. Minimum values of Ψ occurred in November and December when winds and cooling are high and runoff is low.

Table 3. Mean Monthly ψ for the 3 Hydrographic Stations (Jm^{-3})

Stn	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
54	126	128	106	140	181	161	141	120	90	69	55	68
63	26	41	43	43	59	58	56	56	39	22	18	12
73	47	51	60	92	95	86	74	71	43	37	37	33
Mean	49	55	58	70	84	80	81	72	50	38	31	34

PERIODICITY OF THE TIME SERIES

The results of the frequency analysis using Lomb's method on the interpolated Ψ values is shown in (Figure 6-8). The principal three frequencies are shown in the bottom panel for each station beside the spectra.

Results are summarized as follows:

- Station 5.4 had a low frequency signal not found at the other stations but were seen in other stations not included here.

- The strongest signal appeared to be annual at all stations.
- A signal at about 3 years was also seen at Stations 6.3 and 7.3.

The values again reflected the stations having an annual signal (1 year) as the dominant period shown by Lomb's method with a 10% error of calculation of the potential energy anomaly. Therefore, the annual cycle was dominant to the stations in the Chesapeake Bay.

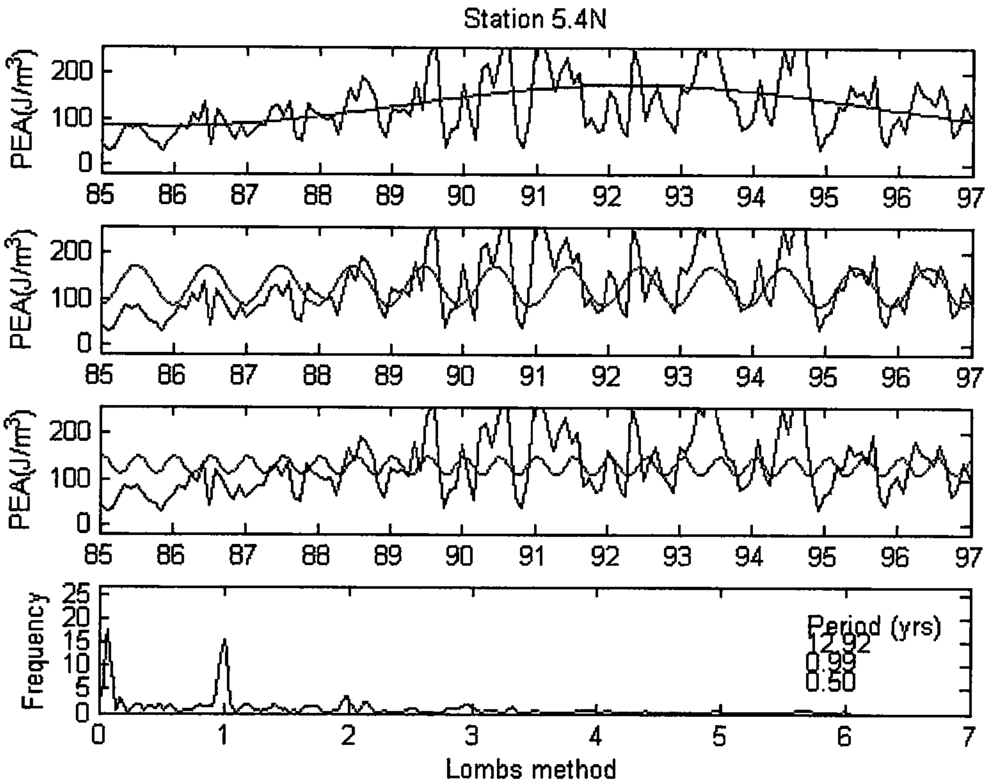

Figure 6. Dominant frequencies determined by Lomb's method for Station 5.4. Upper panel: Interpolated ψ data and least squares fit of principal frequency; Upper middle panel and lower middle panel - Second and third principal frequencies; Lower panel - Principal frequency plot.

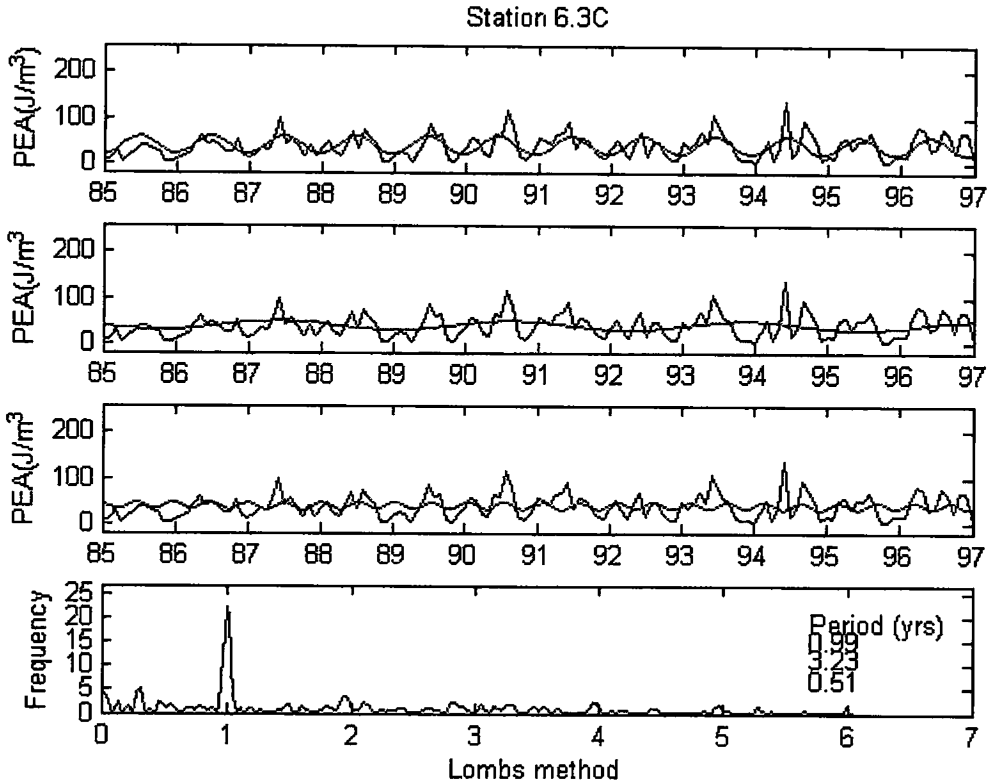

Figure 7. Dominant frequencies determined by Lomb's method for Station 6.3. Upper panel: Interpolated ψ data and least squares fit of principal frequency; Upper middle panel and lower middle panel - Second and third principal frequencies; Lower panel - Principal frequency plot.

ψ TRENDS

The previous section showed that there was a dominant annual signal, but longer-term periods were present. Interannual trends in stratification are evaluated by STL and compared to trends in the river discharge data. The trends from STL were plotted versus the monthly runoff data. The trends of the potential energy anomaly were plotted versus the interpolated anomalies in (Figure 9). The results of this analysis were used to determine interannual trends in the data.

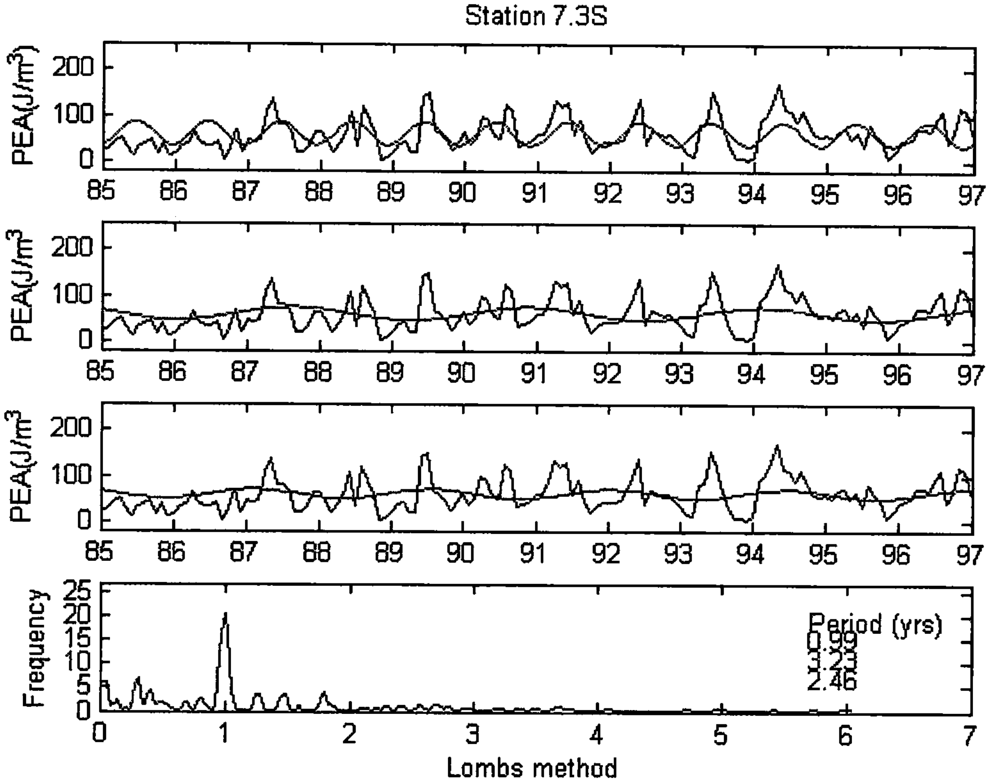

Figure 8. Dominant frequencies determined by Lomb's method for Station 7.3. Upper panel: Interpolated ψ data and least squares fit of principal frequency; Upper middle panel and lower middle panel - Second and third principal frequencies; Lower panel - Principal frequency plot.

RIVER DISCHARGE TRENDS

To further explain the trends represented in the previous sections, a discussion will follow on an evaluation of river discharge trends and recent studies on discharge in the Chesapeake Bay. In a recent study of freshwater discharge into the Chesapeake Bay, Gibson used a physical model that was calibrated using monthly salinity values and Susquehanna River flow from 1984 to 1994. The middle bay displays the best fits due to the dampening of river discharge and tidal influence in the physical model. Salinity is greatly affected by the Susquehanna River, which is 62% of the gauged freshwater into the bay and the only river defined by Schubel and Pritchard to empty directly into the

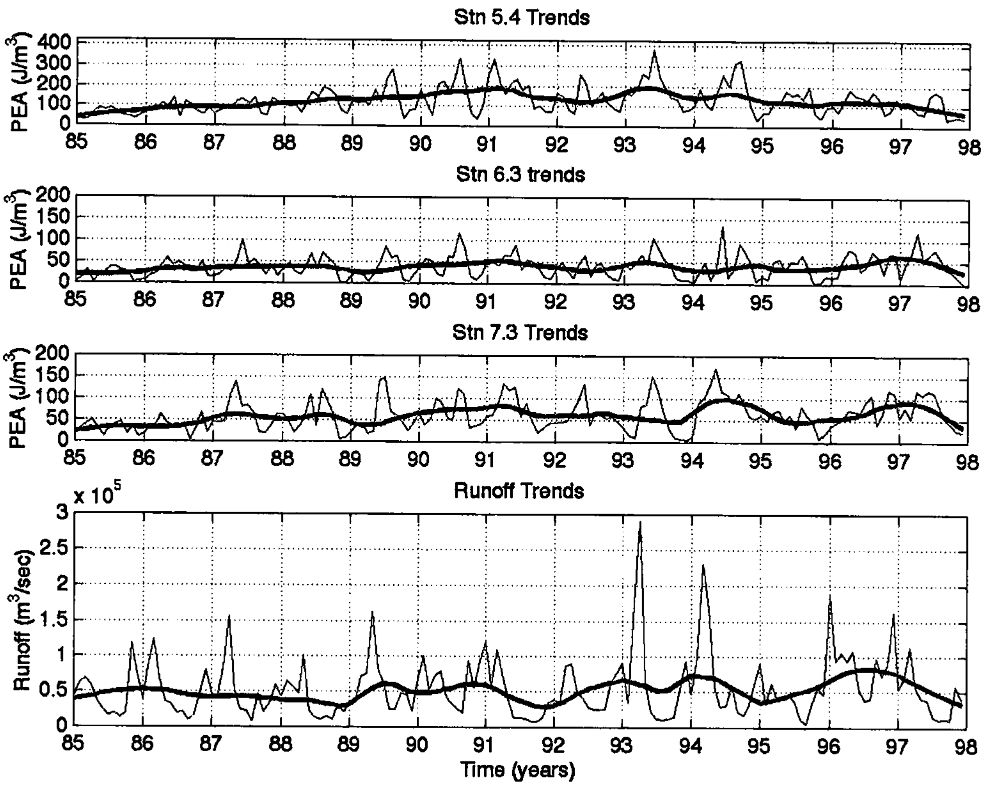

Figure 9. Interannual trends in ψ as evaluated by STL.

main stem. The model's values improve when the James and Potomac River are added because of the combined values relating to the Susquehanna. These rivers do not empty directly into the bay and are downstream of much of the bay's region. Much of the Potomac River and James River mean flow variance are attributed to the Susquehanna River from 1984-1994 [Gibson, 2000].

A drought in September through October reduced buoyancy, causing a well-mixed system for one month. In late October, a large influx of freshwater discharge quickly restratified the region [Goodrich, 1987]. A study in the South Atlantic Bight shows that annual heating and cooling, runoff, and winds are significant in determining overall stratification of a water column. Approximately 10^{-4} to 10^{-3} W/m^2 of power would be required to mix freshwater discharge in this region. This is a much larger value than that needed to compensate for the effects of heating on the water [Blanton and Atkinson, 1983].

(Figure 9) was used to evaluate the interannual trends in the monthly river discharge data from 1985 to 1998. The darkened line confirmed that 1996 was the combined highest flow on record followed by 1994 and 1993 respectively. Low values were shown in 1989, 1992, and 1995. The monthly discharge data also shown on this figure show the highest month of flow occurred in 1993 and 1994, but numerous events in 1996 produced high flow for the entire year. (Figure 9) will be furthered used to compare results.

In 1988, there was the lowest combined annual flow for the 14-year span. Four out of nine stations in the north and central defined regions exhibited high anomalies during 1988. This high percentage of stations reflects other driving forces behind stratification for these regions that have been shown to be more dampened by the tidal effect of the bay. 1996 was the highest flow on record for the Chesapeake Bay, yet no station had its highest potential energy anomaly during this year and only 4 out of 14 stations had high anomalies in 1996. The results from the stations support the effect of river runoff as the driving force to more stratification and less mixing during the seasonal cycle, but the absence of high values in 1996 and the presence of these values in 1988 suggested a more detailed analysis. The data suggests, as displayed by the comparison of 1996 runoff data and 1997 potential energy anomaly data for Station 7.3, that there is a delay in the response of stratification from the mixing of the runoff. The highest low frequency stratification occurred in 1997 for the station after the 1996 runoff peak. A relation of mixing from runoff with a stratification response is shown by this example.

The interannual trends in Ψ as determined by STL are shown in (Figure 9). In the northern section station (5.4), there was a peak in Ψ in 1993 and 1994, but not in 1996. These results will be discussed in more detail later. There was also a peak in 1991, which was consistent with the runoff trends. The central section station (6.3) also shows similar results to the northern region. Peaks were present in 1993 and 1994, but not in 1996. A peak was present in 1997 also. The southern station (7.3) showed peaks in 1993 and 1994 and also a weaker peak in 1996. The trends showed relations to the river discharge data, but also suggest that other processes drive the potential energy anomaly in the three regions of the study.

Monthly mean flow was analyzed for the three stations of the study. The river flow was divided into three sections to most closely represent the regions of stations used in the study as previously mentioned. The north section was comprised of rivers above the Rappahannock, central section included the north section plus rivers south to the York River, and the total, or south section, totaled all rivers flowing to the mouth of the Chesapeake Bay. Highest discharge was shown in March and April with a sharp decrease in May to lower values in the summer months of June through August. Values began to increase in September and continued to rise through February. Monthly cycle plots were used to show the peaks in each year of the sampling study period for each month of the three station studies for comparison to potential energy anomaly calculations.

REPRESENTATIVE SAMPLING STATIONS

Following the calculation and analysis of river discharge and potential energy anomaly, an explanation is offered for the selection of representative stations based upon these parameters. Values are shown for the 14-year period based upon maximum events and correlation to river runoff and potential energy anomaly. The following sections also offer explanation due to geography of the selected stations and possible effects on the stated parameters. As shown by the 3 stations, location and strength of runoff can have varying effects on the potential energy of a region.

Northern Station (5.4)

The northern station had the highest potential energy anomaly means of the stations calculated, which reflects the highest stratification in the region. Station 5.4 is in the main stem of the bay, thus reflecting the influence of the Potomac, as well as, the flow from the Susquehanna River. The highest potential energy anomalies for the northern stations occurred in 1993 and 1994. 1996 was a middle range peak year for only one of the four stations. The northern station is no doubt most affected by runoff because of proximity to the Susquehanna and Potomac Rivers. This is signified by the high stratification corresponding with river flow in the years 1993 and 1994.

Central Station (6.3)

The central region was a reflection of the annual flow of the Rappahannock River due to its vicinity in the estuary. Station 6.3 appeared to be in the outflow of the Rappahannock and in the main stem of the bay, but had one of the lowest potential energy anomalies of the 14 stations. The station is also at a very shallow region of the Bay near the 11-meter contour. Wind or cooling may need to be further evaluated through wind and temperature data as the possible cause of more mixing to occur. The highest values also did not reflect high overall annual flow areas. The maximum anomaly occurred in 1988, 1990, and 1991. The central region had some of the lowest stratification values in the 3 regions calculated. The station again displayed the absence of maximum potential energy anomaly in the year 1996, but instead indicated) high values in the low mean flow year of 1988. The station was shown to be located outside the channels in the bay.

Southern Station (7.3)

The station to the south was shown to reflect outflow from the James and York Rivers in Figure 9B. 1998 was the highest anomaly with 1993, 1994, and 1998 also reflecting high runoff. Stratification was also low in 1990-1992 at this station. There was not a clear monthly transition between stratified and mixed conditions.

FRESHWATER AND TIDAL INFLUENCES

Buoyancy from freshwater input has been shown to be the primary influence on stratification. In addition, estuaries are shown to be difficult to model due to lateral boundaries [Simpson et al., 1990]. Stratification in the Spencer Gulf in Australia has shown a correlation to the reduced effects of tidal and wind stirring [Nunes and Lennon, 1987]. Freshwater was shown as the dominant factor of stratification for my research since the region is usually tidally mixed followed by wind mixing. Surface heating has been proposed as an easier approach to study estuaries. A horizontal gradient is driven by estuarine circulation caused by freshwater input. Models have been developed to study some regions, but not for regions with significant freshwater input such as an estuary. A model for Liverpool Bay in 1990 shows that the main controls for stratification for the region are tidal straining, tidal mixing, and estuarine circulation [Simpson et al., 1990].

CHAPTER IV
CONCLUSIONS

The Chesapeake Bay is a dynamic system that includes variation in chemical, biological, and physical processes. Variations in climate also introduce another component to the system as a whole. This research has shown that stratification has both seasonal and interannual variability in the region. Stratification follows seasonal cycles throughout most of the time series of the research. Runoff is a major component that was studied and analyzed in the lower Chesapeake Bay. Many other parameters affect the watershed as a whole beyond runoff. As shown by the analysis, however, runoff is the prime factor in the seasonal and interannual stratification of the watershed.

The data collected in the Chesapeake Bay was evaluated by a proven calculated method to determine stratification by Ψ. Stations were selected in the lower Chesapeake Bay that would best represent the region for analysis. Fourteen stations were evaluated, but narrowed to three stations for which further analysis was performed. The evaluation of these stations showed no correlation to the influence of tides on the region but did show a trend towards the runoff data collected in the region. The periodicity of the region reflected an annual trend, along with a 3-4 year trend, which would need further analysis to detect possible influence by El Nino and other factors.

The data and analysis support interannual variability for stratification in the lower Chesapeake Bay. Values of Ψ followed trends seasonally as described in the literature but did not occur year to year based on variations in runoff and possibly other environmental parameters which would need further review. Time series data were evaluated to include spectral and trend analysis in order to remove erroneous and skewed data in this study. Contours and cycle plots were also used to help better understand the effects of stratification throughout the years.

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