Temporal change of Eutrophication and Hypoxia events in Chesapeake Bay.

by

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Abstract

Chesapeake Bay is a long studied estuary of North America, due to reoccurring, periodic hypoxia and eutrophication events. The long-term data available allows to assess the possible changes in these processes due to human influence. As new policies have been applied since 1987, shortly after the start of data collection, the response of the ecosystem may have changed. The relationship between the dissolved oxygen (DO), phytoplankton bloom by means of chlorophyll-*a* concentration (Chl-*a*), temperature, and nutrients (total dissolved nitrogen (TDN) and total dissolved phosphate (TDP)) through the period of study (1985 – 2019) was analyzed for three station along the bay (WT5.1, CB5.3 and CB7.4). The seasonal pattern that was observed, includes a spring bloom, demise of the bloom and regeneration, which caused low oxygen levels and hypoxia. In two out of three stations, the nutrient concentrations showed a significant decrease since 1986. Hence the different policies that have been applied in this area were effective in reducing the nutrient load in some parts of the bay. However, the results of this study did not show any significant decrease in the amount and duration of hypoxic events. The interaction between oxygen concentration and nutrient loads is not direct and influenced by other factors. The complexity of these interaction was not captured in this study.

Key words: *Time series; Hypoxia; Eutrophication; Seasonality; Chesapeake Bay.*

Introduction

Chesapeake Bay constitutes the largest estuary in North America. Situated in the East coast, it covers 11.500 km^2 and is almost 300 km long. It has a main relatively depth of 20 to 30 meters, and a narrow central channel (Shi, et *al*, 2013; Kemp et *al.*, 2005). This estuary is characterized by physical parameters such as temperature, salinity, seasonal variation, and dissolved oxygen that suffer large fluctuations. These fluctuations define the species and habitats (Breitburg, 1990). Salinity is an important parameter in this area and allowed to divide the bay in three regions: upper bay (tidal - fresh and oligohaline), mid bay (mesohaline) and lower bay (polyhaline) (Kemp et *al.*, 2005).

This area has been studied for a long time due to the periodic episodes of hypoxia (concentration of O_2 less than 2 mg/L, Adelson et *al.*, 2001) and eutrophication. This is a natural process, induced by the massive input of fresh water during spring from the nearly 150 streams that flow into the bay. This fresh water contains nutrients and sediments, stimulating the primary production and causing blooms (Qian Zhang et *al.*, 2018). Additionally, these freshwater inputs also induce stratification by suppressing vertical exchange (Du et *al.*, 2018; Kemp et *al.*, 2005). The restriction of exchange between water layers and the fast consumption of oxygen during mineralization, produce the natural hypoxic events within a seasonal (during spring-summer) and interannual frequency.

However, this natural process of hypoxia present since geologic time, has been increasing in number and intensity, being accelerated by human activities. Addition of excessive anthropogenic nutrients to the system, stimulates an intensifying eutrophication. This is due to the location of Chesapeake Bay in a densely populated area with inputs from big cities, such as Washington D.C. and Baltimore, and extended farming activity. (Du et *al.*, 2018)

Since the foundation of the Chesapeake program in 1983 until now, different policies and social actions have been implemented due to the increasing society's awareness about the bay. In 1987, the *Chesapeake Bay Agreement* (CPB, Chesapeake Bay Program, 1987) was implemented to regulate the nutrients input to the bay. More recently, in 2014, the *Chesapeake Bay Watershed Agreement* (CPB, Chesapeake Bay Program, 2014) was signed by all states bordering the bay, being the first time of an agreement of these characteristics. All the partners gathered in a common goal for the restoration of the Chesapeake Bay, connecting the environmental and economic aspects, but also engaging communities.

In this frame, our main objective is to assess if hypoxia and eutrophication events have been intensified over time, what is their relationship with other biochemical parameters and the dependence of these events with seasonality. Data available for over three decades, due to the well-established monitoring program (Chesapeake Bay Program Water Quality database) allowed us to analyze these changes over time.

Material and Methods

Area of study

Along the different salinity ranges in which Chesapeake Bay can be subdivided, three stations were selected: upper bay (station WT5.1), middle bay (station CB5.3) and lower bay (station CB7.4) (Figure 1). In this study, we focus on the bottom waters, since hypoxia will be present here (Kou et *al*., 1987). An integrated vertical analysis of the waters in Chesapeake Bay is beyond the scope of this study.

In the upper bay, with mesohaline characteristics, station WT5.1 is situated near Baltimore. It has a total depth of 18 m and bottom waters are characterized by an average temperature of 15.2 °C, a salinity of 13.5 PPT, and high nutrient loads (mean total dissolved nitrogen (TDN) of 0.838 mg/L and mean total dissolved phosphorus (TDP) of 0.038 mg/L). Station CB5.3 is located in the middle part of the bay. This station has influence from the largest tributary, the Potomac river, with inputs from Washington D.C. Station CB5.3 has a depth of 30 m, average bottom water temperature of 16.2 °C, salinity of 20.8 PPT and an average nutrient load that is lower than in WT5.1 (TDN of 0.435 mg/L and TDP of 0.023 mg/L).

Finally, station CB7.4 is situated at the end of the bay with the largest influence from the open sea of any of these stations. It has a depth of 18 m, an average bottom water temperature of 15.2 °C, is polyhaline (salinity of 30.1) and has the lowest average nutrient load of the 3 stations (TDN of 0.164 mg/L and TDP of 0.016 mg/L).

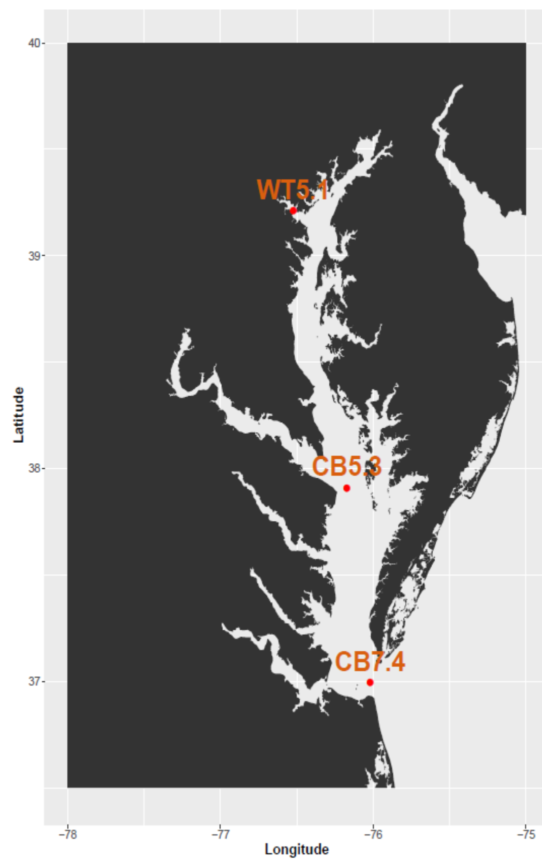

Figure 1. Map of Chesapeake Bay, with the location of the three stations studying the upper (WT5.1), middle (CB5.3) and Lower (CB7.4) Bay

Long-term data sets

Data were obtained from the Tributary Water Quality Monitoring programs of Massachusetts and Virginia (http://www.chesapeakebay.net). From 1985 to 2019 bottom water (10-29m) concentrations of dissolved oxygen (DO), water temperature, salinity, TDP, TDN, and chlorophyll-*a* (Chl-*a*) were collected every 2-4 weeks. All measurements were taken one meter above the total water depth measured during sampling.

Data analysis

2 to 4 weekly data for TDN, TDP, Chl-*a*, water temperature, and DO were averaged into monthly data to avoid gaps in the dataset. In the first part of the study, a principal component analysis (PCA) was done in order to get a first idea of the linkage between the biogeochemical parameters, the seasons, and the stations. Then, for each parameter at each station the climatology (average annual seasonal pattern) and residuals were calculated. A trend analysis was done on the residuals using simple linear regression. For each year, the months with hypoxia (DO < 2 mg/L) were calculated. Hypoxia were analyzed using: first month of hypoxia encounter, last month of hypoxia encounter and total number of months with hypoxia. All calculations were done using the software R (Version 3.5.3 © 2019, The R Foundation for Statistical Computing) and RStudio (Version 1.1.463 © 2009 - 2018 RStudio, Inc.).

Results

Station characterization and link with important variables

The importance of the variables that contribute to hypoxia and eutrophication in the different stations were assessed by doing a PCA. This was done with the three station together first and then, individually. The general PCA, including all stations, represents the variability in the dataset well in two dimensions (Figures 2 and 3). The first dimension already explains 51% and the second-dimension ads 26%. The main variables that differentiate between the stations were salinity and pH, inversely related with TDN (Figures 2 and 3a). The salinity increases toward the end of the bay, where TDN is lower. A large variability in observations is seen in station WT5.1. This variability is seen in a different axis, that is linked to water temperature, inversely related to DO (Figure 2 and 3b). Seasonality is linked to this same axis.

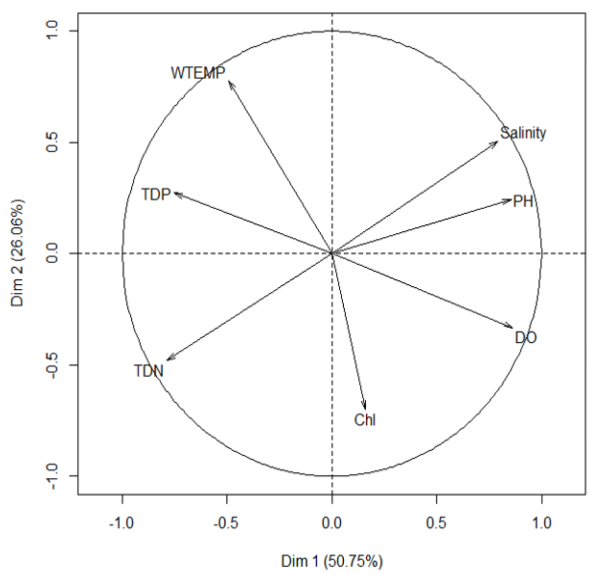

Figure 2. **Factor map.** Graphical representation of the PCA for the three stations. The variables considered were: salinity, pH, DO (dissolved oxygen), Chl (Chlorophyll a), TDN (Total Dissolved Nitrogen), TDP (Total Dissolved Phosphorous) and WTEMP (Water temperature).

During summer (July, August and September), water temperature is high and dissolved oxygen is low. While during winter and early spring (January, February, March) the water temperature is low and DO is high. For the individual PCAs per station, similar results were obtained (Appendix A1).

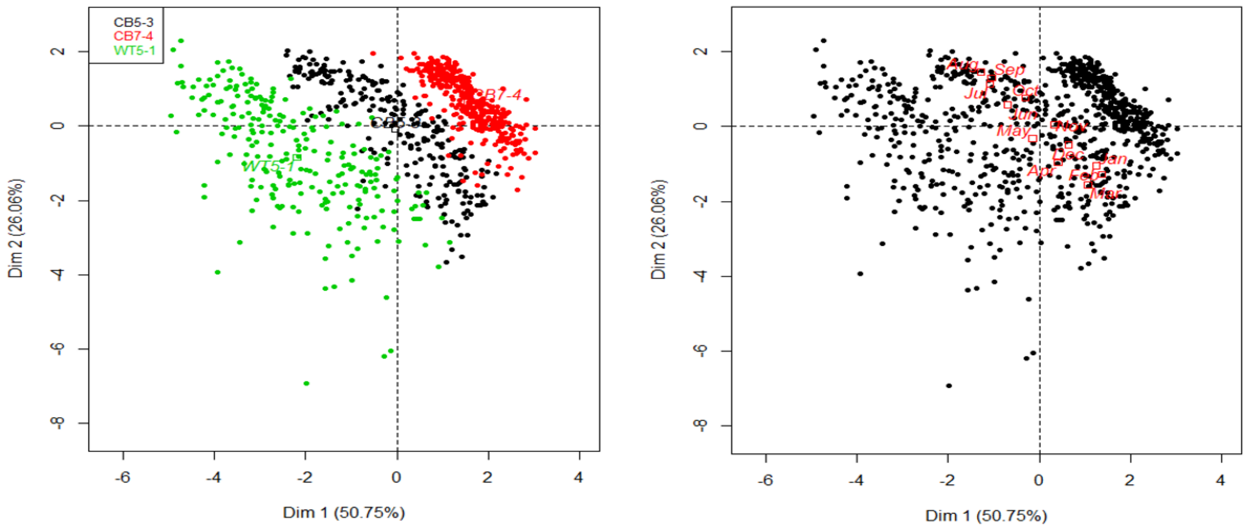

Figure 3. **Score plot.** Outcome of PCA ***a)*** Distribution of the station along a gradient of salinity; ***b)*** Representation of the different month (seasonality).

Climatology

For each parameter studied, the climatology shows the landward-seaward gradient in the Chesapeake Bay for the bottom waters (Fig. 4).

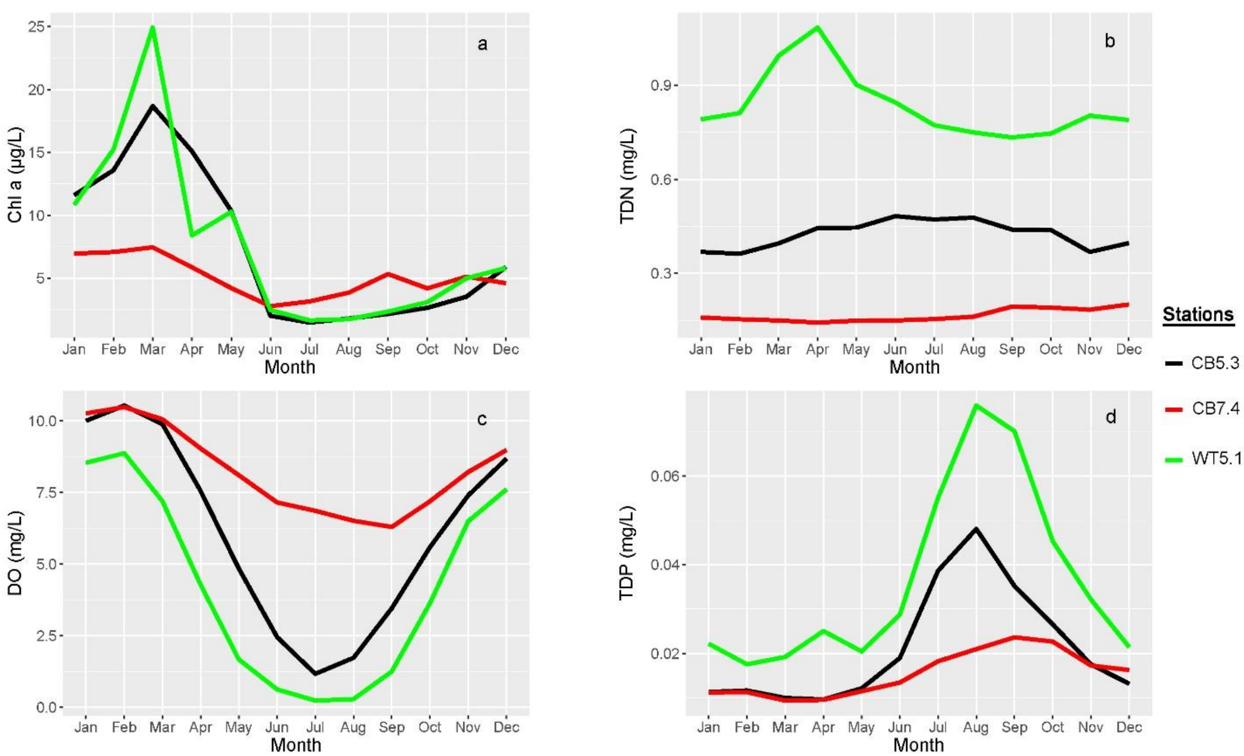

Figure 4. Climatology representation of the different variables taking into account the three stations. ***a)*** Chl-*a.* (µg/L), ***b)*** TDN (mg/L), ***c)*** DO (mg/L) *d)* TDP (mg/L).

Chlorophyll-a: For the Chl-*a* concentration (Fig.4 a), the curves for the upper and middle bay are quite similar, but there is a difference (around 7 µg/L) during the phytoplanktonic bloom peak (i.e. March). The Chl-*a* concentration is less variable for the CB7.4 station, which is lower than for the two other stations during the beginning of the year and gets higher starting in June.

Nutrients: The TDN and TDP always have a higher concentration in the upper bay (station WT5.1). These mean concentrations (Fig. 4 b), d)) are decreasing going down the bay and TDN concentration is 1.9 time smaller in the middle of the bay (station CB5.3) and 5.1 times smaller at the mouth of the bay (station CB7.4). The same pattern, with different coefficients, can be observed for the TDP, with the highest concentration always found in the upper bay (1.6 times smaller for the middle of the bay and 2.4 times smaller for the lower bay). For the middle and lower bay, we can see the same TDP concentration in winter and spring, but the middle bay has a higher peak during summer.

Dissolved Oxygen: Concerning the DO, the inverse pattern can be observed (Fig.4 c): the gradient concentration goes up toward the sea. This difference is enhanced during summer (June to August), after the phytoplanktonic activity has reached its maximum in spring: in the upper bay, the DO concentration reaches almost zero while the concentrations in CB5.3 and WT5.1 can reach around 7 mg/L and 1.25 mg/L (respectively). Hypoxic events can therefore generally be observed between June and August and between April and September in stations CB5.3 and WT5.1 (respectively).

Moreover, the seasonality cycle can be observed for each parameter except TDN. The amplitude of this cycle is enhanced further up the bay supporting the hypothesis of a significant inland influence on the water masses inside the bay.

Hypoxic events

Hypoxic events were observed in the upper bay (station WT5.1) and in the middle bay (station CB5.3) but were absent in the lower bay (station CB7.4) (Figure 5). On average the hypoxic events in station CB5.3 started in July and lasted for 2 months. Note that there were no hypoxic events in this station in 2016 and 2017. In station WT5.1, hypoxic events were present every year, throughout the entire time period. The start date of hypoxic events was more variable (from April to August). Hypoxic events lasted for 5 months on average and ended often late, in October. Linear regression showed that the hypoxia breakup in station WT5.1 was significantly later over time. During in 2010 and 2014 longest periods of hypoxia were seen during 7 months, from April until October.

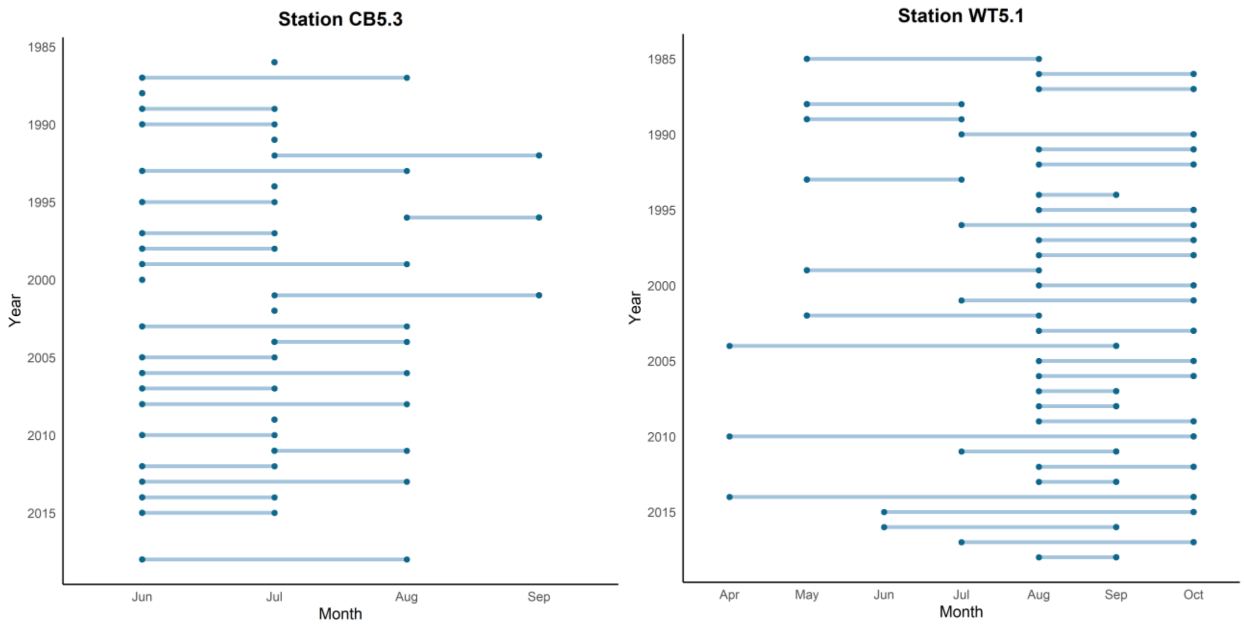

Figure 5. Occurrence of hypoxic events in Station CB5.3 (left) and in Station WT5.1 (right). The month of development and breakdown of hypoxia is given with a dark blue dot. For years with only one dot, the hypoxia was only present for one month.

Trends

Linear Regression:

WT5.1: The linear regressions (Figure 6) used on the residuals of the five different parameters have shown that Chl-*a* has significantly increased (0.15 µg/L/year, p-value = <0.01), DO has decreased (-25 µg/L/year, p-value = <0.001), TDN has decreased (-6.8 µg/L/year, p-value = <0.001) and TDP has decreased (-0.29 µg/L/year , p-value = <0.001) throughout a time span of 34 years (1985-2019) in the upper bay.

CB5.3: The linear regressions (Figure 6, Appendix) used on five different parameters for the CB5.3 station have shown a TDN decrease (-3.4 µg/L/year, p-value = <0.001) and TDP increase (0.24 µg/L/year, p-value = <0.001) that was significant.

CB7.4: For the station at the mouth of Chesapeake Bay, Chl-*a* decreased slightly (-0.037 µg/L/year, p-value < 0.05), TDN decreased (-0.75 µg/L/year, p-value < 0.001) and TDP decreased (-0.32 µg/L/year, p-value < 0.001).

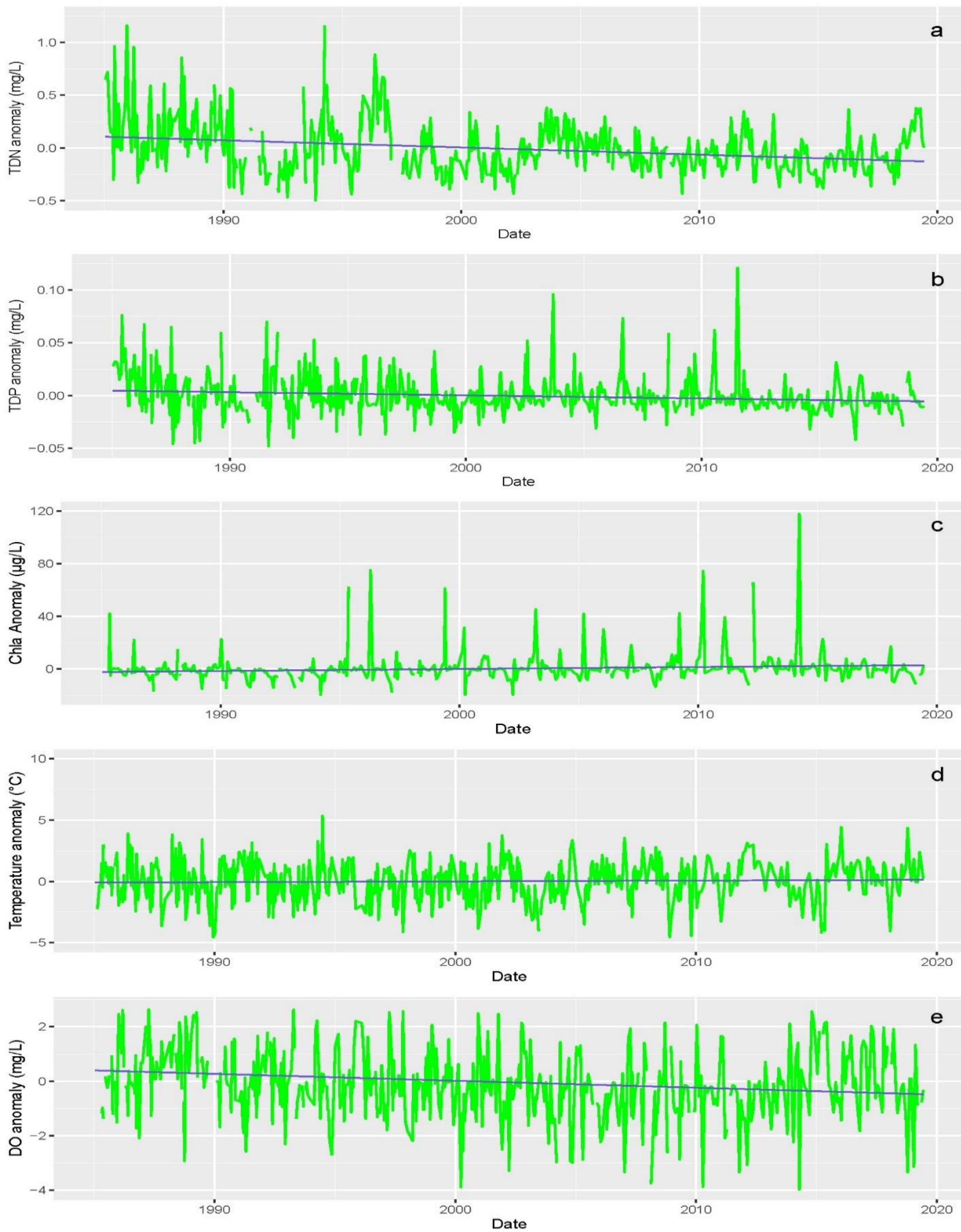

Figure 6. **Linear regressions- anomalies.** Graphical representation of the anomaly variation during the time study for each parameter in station WT5.1. **a)** TDN; **b)** TDP; **c)** Chl-*a* **c)** TDP **d)** Water temperature **e)** DO. The continuous blue line indicates the linear regression.

Discussion

This study highlights the long-term evolutions of parameters such as total dissolved nitrogen (TDN), total dissolved phosphate (TDP), dissolved oxygen (DO), and chlorophyll-*a* (Chl-*a*) along the landward-seaward gradient. These gradual changes, over a 34 years timespan, have modified the seasonal cycles in the Chesapeake Bay and have to be linked mainly with the deterioration due to anthropogenic impacts and the effects of increase of temperature due to climate change.

The principle component analysis (PCA) explained a large proportion of the variability in the dataset, using only 7 parameters. According to the PCA analysis, the sites are differentiated by their average salinity, pH and TDN concentration. In the lower bay, salinity is higher, due to the direct connection with the Pacific Ocean. In the upper bay, there is more inflow from rivers (Dauer et *al*., 2000). The main contributors to the TDN concentration there are the Chester, Choptank and Nanticoke Rivers that flow through highly cultured areas on the eastern side of the bay. Salinity is lower in the upper bay due to mixing with freshwater, coming from the numerous rivers in the bay (over 150 rivers, creeks and streams). Therefore, this PCA analysis shows that the upper bay is more influenced by freshwater input, while the lower bay is more influenced by oceanic conditions.

Even if salinity constitutes by itself a determining characterization of the three stations, seasonality also plays a key role. During winter, strong wind events and low temperatures allow a mixing between the water layers, reoxygenating the system (Goodrich et *al*., 1987). Temperature variations along the year and light regime are associated with the stratification of the water column in estuaries leading to hypoxia of the bottom waters (Hagy et *al*.., 2004). During early spring, when light is not a limiting factor, the phytoplanktonic activity increases, forming blooms that in many cases means the beginning of the eutrophication process (Smith 2003). In fact, the level of nutrient inputs, more precisely concentration of TDN, have been observed during the analysis of the climatology to be determining in the proportion of phytoplankton response. In the upper Bay, where the concentration of TDN is higher, there is also a high Chl-*a* concentration in spring. When the organic matter produced during this blooms sinks, this oxygen of the bottom layers is consumed due to degradation by bacterial activity (Kemp et *al*., 2005). The consumption of DO is faster, the higher the organic matter concentration. It is the time (beginning in April) when hypoxic levels are reached. However, this process is less intense in the lower bay, where the river influence is less strong due to the tidal regime. This means that there is a direct link between the anthropogenic nutrient input and the eutrophication processes that led to hypoxic conditions regulated by the fresh water inflow (Hagy et *al*., 2004). Respect to the levels of TDP that were found during the study of the climatology, the values increase in summer, opposed to the decrease of DO values. This could correspond to a release of phosphorous during organic matter degradation by bacterial activity. A previous study of Joshi et *al.* (2015) has shown that authigenic phosphorous is the dominant phosphorous source within the Chesapeake Bay. This is confirmed by the observations in this study.

Comparing the nutrient anomalies for the three stations (Figure 6, Appendix A2, Appendix A3), we notice a bigger variation for the upper and middle bay, whilst the nutrient concentrations stay more constant near the sea. This shows that the CB7.4 station is mainly under the influence of seawater, where the nutrients concentrations are more stable. This is in contrast to the upper stations where riverine inflow can be highly variable.

Hypoxic events were on average longer in the upper bay compared to the middle bay, while they were completely absent in the lower bay. This is confirmed by other studies (such as Testa et *al*., 2018a and Testa and Kemp, 2014). It was shown previously, that the interannual variability of hypoxic events in Chesapeake Bay is positively correlated with elevated Susquehanna river flow (Testa and Kemp, 2014). A higher Susquehanna river flow induces earlier depletion of DO. Prolonged, high riverine input might have caused the long episodes of hypoxia during 2010 and 2014. However, the DO concentration is related to different factors (such as Chl-*a* and stratification) and feedback loops (Testa et *al*., 2018b). A positive feedback loop, previously hypothesized to occur in the Chesapeake Bay (Testa and Kemp, 2012), is as follows: the low DO concentration limits nitrification of NH_4^+. This would lead to an accumulation of NH_4^+, that enhances phytoplankton production and afterwards increases the oxygen demand even more. This was previously seen by other studies in the Chesapeake Bay as in earlier summer hypoxia (such as Testa and Kemp, 2012). This feedback would become negative at the end of summer, where oxygen levels are slightly higher again and nitrification and NH_4^+ removal is increased. In this study, the hypoxic event breakup was significantly later over the time period. This is contradicting with previous studies (Testa et *al*., 2018a and Test and Kemp, 2012). However, to be able to study these feedback loops and interactions, we need the measurement of NH_4^+, which was not included in this research. Furthermore, in this study, monthly data for oxygen depletion were calculated. This is a rather rough resolution. In previous studies, the 2 to 4 weekly observations in Chesapeake Bay were used (Testa et *al*., 2018a) and interpolated to have a more precise estimate of hypoxic events start and end dates.

Looking at the long-term time scale, the area that is mostly impacted by anthropogenic changes, in terms of numbers of parameters and of amplitude of changes, is the upper bay. The increase in Chl-*a* and decrease in DO can directly be linked by knowing the fact, as it was mentioned before, that a high phytoplanktonic activity leads to a DO consumption during degradation. However, the TDN and TDP concentrations are decreasing along the timespan of this study. This was not expected according to the increase in Chl-*a* concentrations in the WT5.1 location (close to an agricultural land). Water temperature variations were explored in order to explain the DO decreasing (warm water contains less dissolved gas than cold water), but the increase in temperature was not significant (slope = 0.00642765 °C/year, p-value = 0.371). The unstable hydrodynamic and the complexity of the nutrient fluxes make the link between nutrient input and phytoplanktonic activity more complicated to establish.

Nevertheless, it is clear that all along the bay, the nitrogen availability has decreased during those 34 last years. For Chl-*a*, the pattern of this evolution is not that clear, since an increase in the upper bay, no changes in the middle bay, and a slight increase in the lower bay were seen. Therefore, phytoplanktonic activity may be caused by a complex association of different parameters and not only on the TDN. Concerning the TDP, there was a decrease in the upper and lower bay whilst the TDP concentration increased in the middle bay. The latter is located at the mouth of the Potomac river and that increase may be the visible print of the alluvial intake. The general decrease in nutrient inputs results from the Chesapeake Bay Agreement (1987) policy to work toward a reduction of nitrogen and phosphorus anthropogenic inputs. Hence, this study shows the efficiency and the importance of setting up large scale policy in order to protect and recover the water quality of an ecosystem. However, even though a decrease in nutrient inputs was seen, there was no apparent impact on the occurrence of hypoxic events.

There are a few aspects of our study for which we must be critical. Our study only looked at one stations in each of the sections of the bay. This makes it so that we cannot make general statements about the entire section with confidence. Also, by only accounting for one station within each zone, it is complex to take into account all different variables that change when comparing the results between stations. In our stations other processes than those we observed could have affected hypoxia and eutrophication. We also only looked at bottom waters in this study. This was the area we deemed most relevant to study hypoxia, but an analysis of the entire water profile would have given us the best understanding of these events (such as in Testa et *al*., 2018). Other aspects that could have been interesting to take into account, are biological data, such as phytoplankton, ammonium concentration and river discharge. These parameters, along with the geochemical parameters that were used in this study, might be able to describe the system more accurately. However, the time was a limiting factor to analyze all the available data.

Conclusion

This study tried to find drivers of eutrophication and hypoxia within Chesapeake Bay, by looking at both seasonal variation and trends over a 32 year period. Seasonal variation was observed within three different stations. This variation was seen for TDP, Chl-*a,* and DO. In contrast to TDN that remained rather constant within an average year. This seasonal pattern includes a spring bloom, demise of the bloom and regeneration, which caused low oxygen levels and hypoxia. A higher nutrient load was observed towards the upper bay stations, along with more and longer hypoxic events. The nutrient input might be explained by riverine input. The effect of the Chesapeake Bay Agreement was observed by a reduction of the TDN and TDP concentrations in two out of three stations from 1987 on. These regulation policies could only be seen through the analysis of time series. However, the impact of these nutrient reductions could not be linked to Chl-*a* concentration reduction nor a decrease in hypoxia in this study. The interaction between nutrients and hypoxia occurrence is complex as it is influenced by numerous other parameters and feedback loops.

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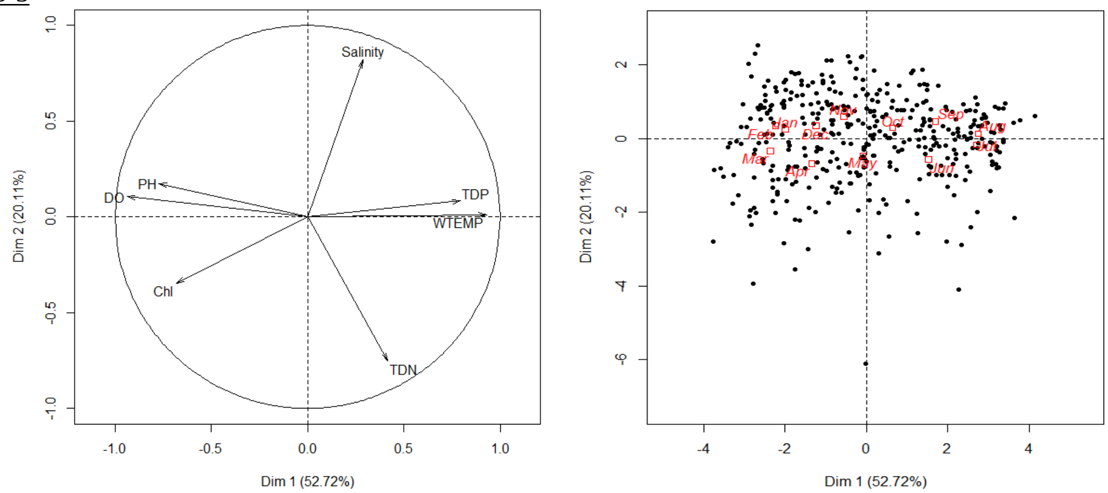
Appendix

CB 5-3



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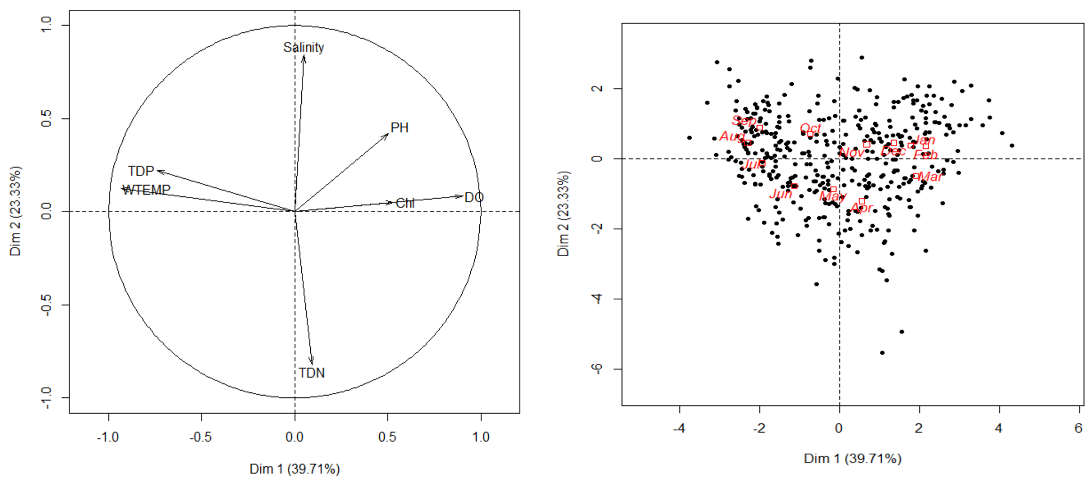
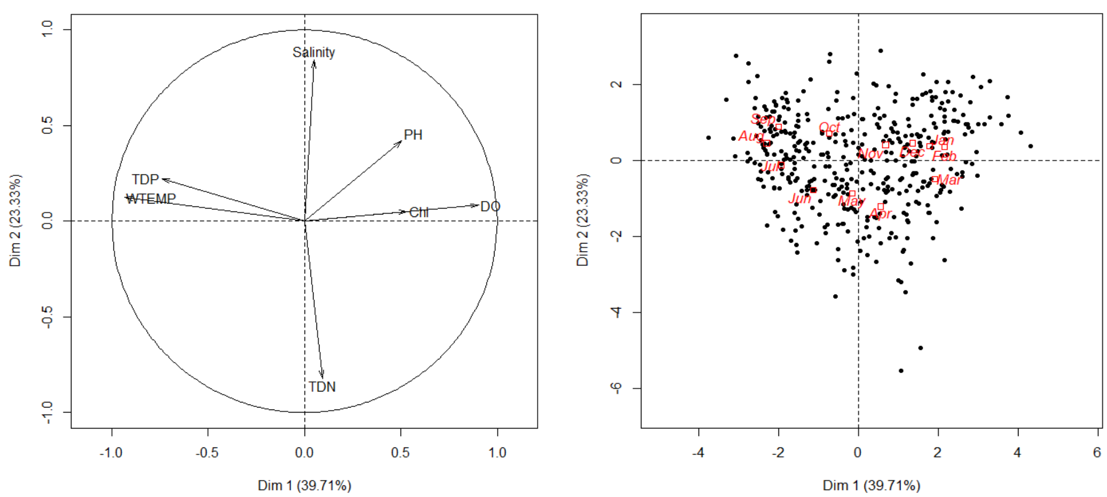
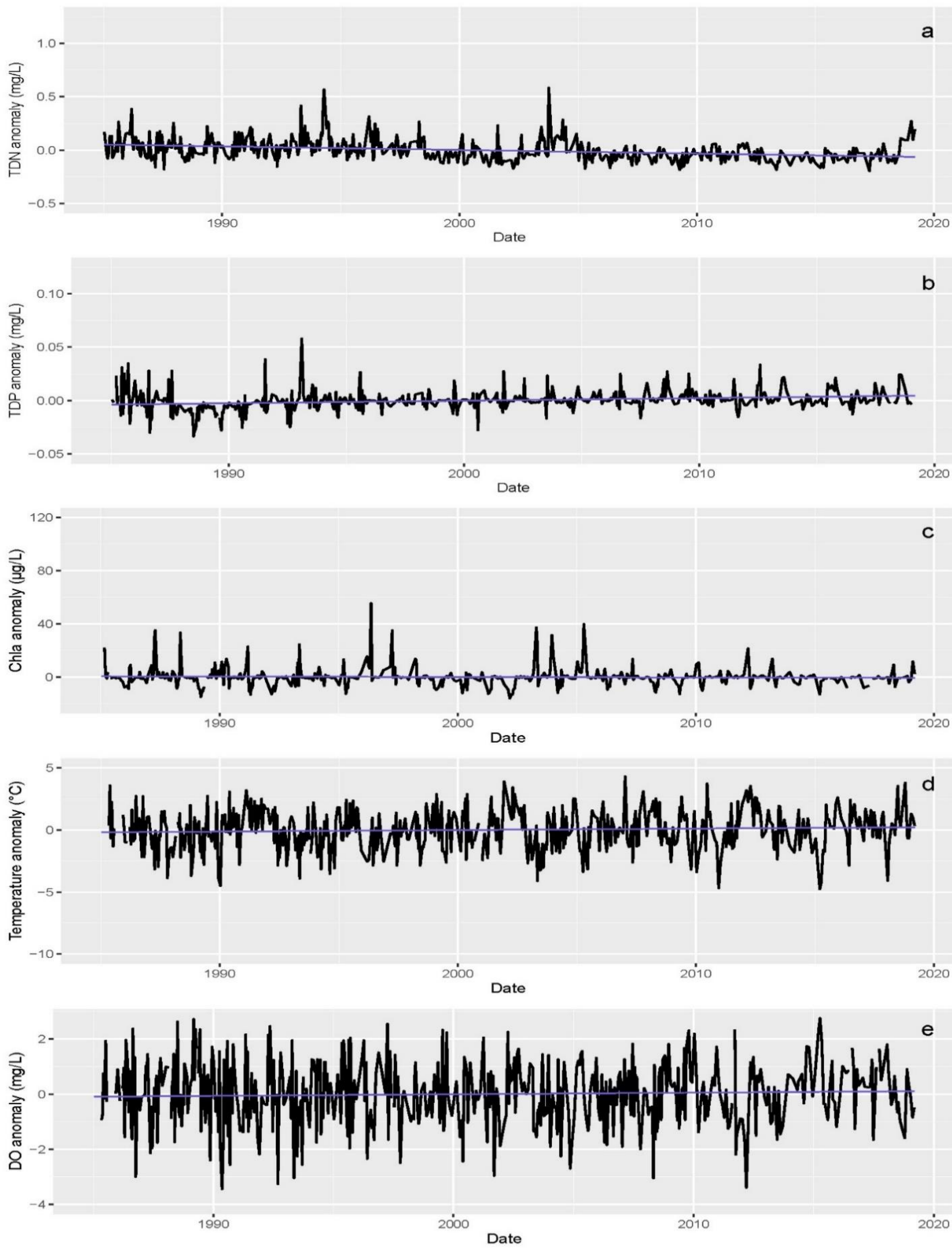


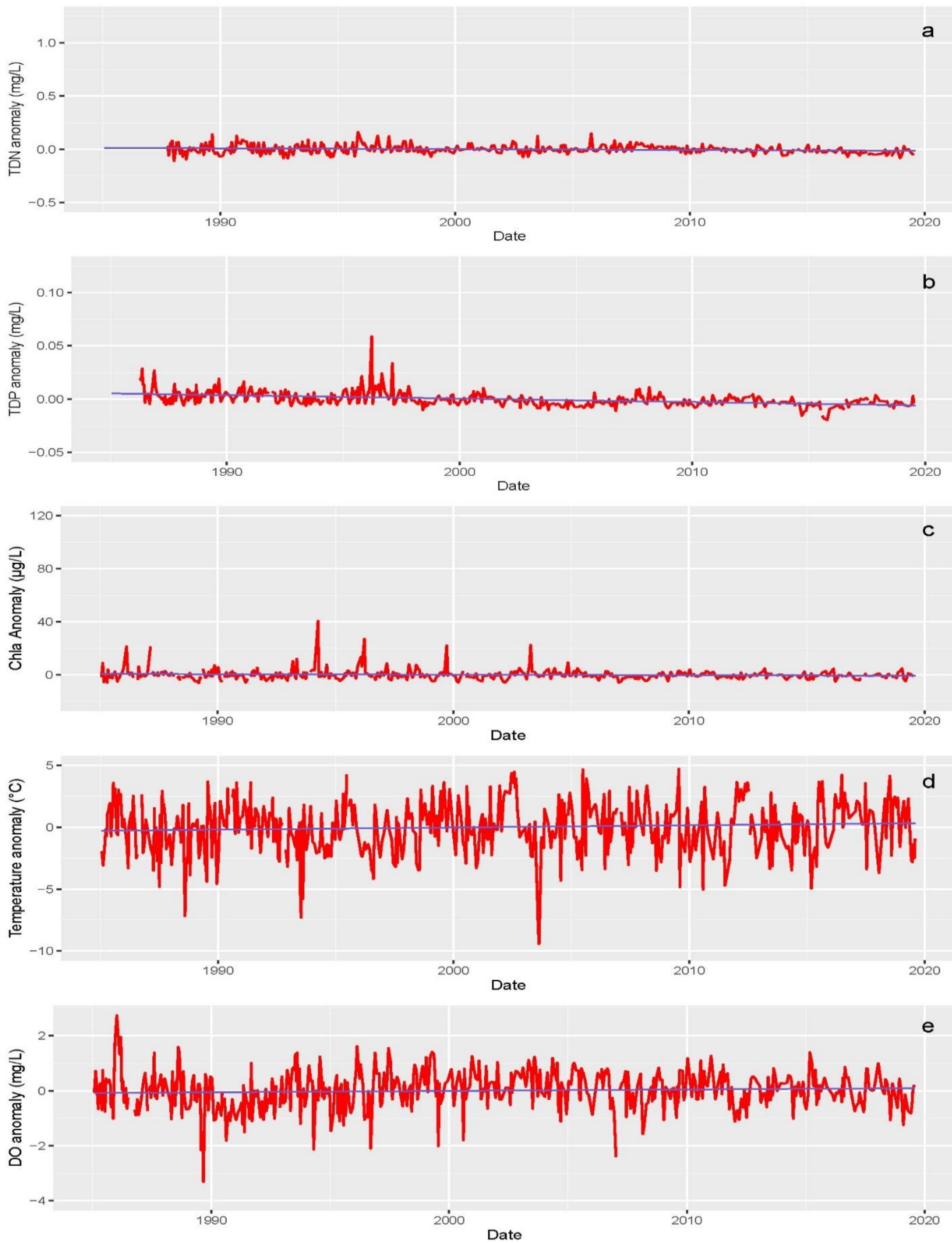
WT 5-1



A1. PCA factor and score plot for the separate analysis of the three different stations.



A2. Linear regressions- anomalies. Graphical representation of the variation during the time study for each parameter in station CB5.3. **a)** TDN; **b)** TDP; **c)** Chl-*a* **c)** TDP **d)** Water temperature **e)** DO. The continuous blue line indicates the linear regression.



A3. Linear regressions- anomalies. Graphical representation of the variation during the time study for each parameter in station CB7.4. **a)** TDN; **b)** TDP; **c)** Chl-*a* **c)** TDP **d)** Water temperature **e)** DO. The continuous blue line indicates the linear regression.