

**WHAT FACTORS EXPLAIN HARMFUL ALGAL BLOOMS OF  
*DINOPHYSIS* ALONG THE TEXAS COAST?**

An Undergraduate Research Scholars Thesis

by

LAUREN ELAINE REPLOGLE

Submitted to the Undergraduate Research Scholars program  
Texas A&M University  
in partial fulfillment of the requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by  
Research Advisor:

Dr. Lisa Campbell

May 2016

Major: Meteorology

# TABLE OF CONTENTS

|   | Page |
|---|------|
| ABSTRACT .....  | 1    |
| DEDICATION .....  | 3    |
| ACKNOWLEDGEMENTS .....  | 4    |
| CHAPTER   |      |
| I    INTRODUCTION .....                                       | 5    |
| Concerns of <i>Dinophysis</i> harmful algal blooms .....      | 5    |
| Background of harmful algal blooms in the Gulf of Mexico..... | 6    |
| II    METHODS .....   | 8    |
| III   RESULTS .....   | 11   |
| Winds .....   | 11   |
| Salinity .....  | 13   |
| Sea surface temperature .....                                 | 14   |
| Mean wave direction.....                                      | 14   |
| Surface-based runoff.....                                     | 14   |
| Other factors.....  | 15   |
| IV    DISCUSSION .....  | 22   |
| REFERENCES .....  | 24   |

## ABSTRACT

What Factors Explain Harmful Algal Blooms of *Dinophysis* Along the Texas Coast?

Lauren Replogle  
Department of Oceanography  
Texas A&M University

Research Advisor: Dr. Lisa Campbell  
Departments of Biology and Oceanography

The toxic dinoflagellate *Dinophysis ovum* is one of the harmful algal species that bloom along the Texas coast. Blooms of *D. ovum* can be explained by several factors that work together to cause bloom initiation. This work utilized image counts collected by the Imaging FlowCytobot (IFCB) at Port Aransas, TX and modeled winds from the European Centre for Medium-range Weather Forecasts. Based on a previous study of another dinoflagellate species, it was hypothesized that winds will be highly correlated with harmful algal bloom (HAB) years versus non-HAB years for *D. ovum*. Weak northerly winds and downwelling along the coast will be associated with HAB years, while strong northerly or southerly winds will be associated with non-HAB years. In non-HAB years, wind-driven currents caused by upcoast or strongly flowing downcoast winds will result in northward or southward movement of *D. ovum* cells, respectively. In HAB years, weaker downcoast winds will allow for accumulation of *D. ovum* at the coast. Results showed that weak downcoast winds occurred in the weeks preceding HAB events in 2008, 2010, 2011, 2012 and 2014, and likely contributed to the accumulation of *Dinophysis* cells along the Texas coast. When winds moved upcoast or strongly downcoast in the weeks preceding bloom months, *Dinophysis* blooms did not occur. Additional factors (e.g., sea surface temperature, surface-based runoff, mean wave direction, El Niño Southern Oscillation, North

Atlantic Oscillation, and salinity) were analyzed to better define a favorable environment for bloom formation. Sea surface temperature and surface based runoff were significantly correlated with bloom occurrence, whereas El Niño Southern Oscillation and the North Atlantic Oscillation were not.

## **DEDICATION**

This thesis is dedicated to my parents, Brian and Karen Replogle, who showed me the ways of the ocean and always encouraged me to reach for the stars.

## **ACKNOWLEDGEMENTS**

I would like to express my gratitude towards my research advisor Dr. Lisa Campbell for her full support, guidance, and encouragement throughout my research. She has led me towards a road of success.

I would also like to thank Dr. Darren Henrichs for his generous effort towards mentoring and giving me advice throughout my research.

I am grateful for the Campbell lab group for encouraging and motivating me in my undergraduate career. Without their precious support, it would not have been possible to conduct this research.

# CHAPTER I

## INTRODUCTION

### **Concerns of *Dinophysis* harmful algal blooms**

Harmful algal blooms (HABs) of the toxic dinoflagellate *Dinophysis ovum* have become a problem along the Texas coast since it was first detected by the Imaging FlowCytobot (IFCB) off the coast of Port Aransas, TX [Campbell *et al.*, 2010]. Blooms typically arise during the months of January to April and are problematic because this dinoflagellate produces several toxins, okadaic acid and its derivatives, that can result in diarrhetic shellfish poisoning (DSP) when toxic shellfish are ingested [Aubry *et al.*, 2000; Nielsen *et al.*, 2012; Yasumoto *et al.*, 1985]. DSP toxins cause symptoms of diarrhea, vomiting and abdominal pain as well as the promotion of tumor growth in humans, thus causing a threat to shellfish consumers [Nielsen *et al.*, 2012]. Owing to its potential impact to human health, early detection and future prediction of *D. ovum* is desired to reduce this risk.

### *Living conditions*

*Dinophysis ovum* differs from *Karenia brevis*, another HAB species that causes red tides in the Gulf of Mexico, in several ways. *Dinophysis ovum* is a mixotrophic species that can use photosynthesis for energy production or ingest other organisms for nutrients and energy [Nagai *et al.*, 2008; Thyng *et al.*, 2013].

## **Background of harmful algal blooms in the Gulf of Mexico**

*Karenia brevis* is a major harmful algal bloom species in the Gulf of Mexico, where advection by wind and ocean currents cause an accumulation at the Texas coast. In a case study by *Thyng et al.* [2013], several correlations were made between wind and *K. brevis* accumulations. Using wind data from a buoy off the coast of Port Aransas and bloom data from the IFCB, a correlation was found between winds and HAB and non-HAB years. Weak northerly wind patterns along with coastal downwelling resulted in an accumulation in the years that *K. brevis* bloomed, also known as HAB years. The mean winds along the shore were small and directed either upcoast or onshore in HAB years. In non-HAB years, the resulting wind was stronger than HAB years and was directed more downcoast. In HAB years, *K. brevis* cells drift with the surface currents leading to the conclusion that they originate from the south and can contribute to blooms. Wind data from the study were taken from the monthly average  $u$  and  $v$  components and was rotated  $50^\circ\text{N}$  to have the numerical model only read data with winds flowing onshore. Years with winds that were greater than  $1.65\text{ m s}^{-1}$  usually corresponded with years with no bloom of *K. brevis*.

### *K. brevis case study and assumptions made for D. ovum case study*

A case study for *Dinophysis* conducted by *Harred and Campbell* [2014] found that strong downwelling occurred for HAB years while weak downwelling occurred in non-HAB years. The alongshore wind component was used as an indicator for strength of coastal upwelling/downwelling. A monthly averaged along-shore wind component was used to determine if downwelling strength was correlated with bloom presence. Downcoast winds induce Ekman transport toward the coast of Texas, leading to downwelling. It was concluded from this study that alongshore wind patterns during bloom initiation showed no difference between HAB



and non-HAB years. The assumption that *K. brevis* can overcome the downwelling current is due to their phototactic ability. This was shown to be reasonable by *Hetland and Campbell* [2007].

The same assumption was used when making conclusions with *D. ovum* and winds.

The objective of this study was to determine the favorable environmental conditions for a *D. ovum* bloom to occur. This will allow preparation for early detection of *D. ovum* blooms, thus reducing the risk of DSP in humans along the Texas coast.

## CHAPTER II

### METHODS

Methods from previous studies, showing seasonal downwelling winds created accumulations of *Karenia brevis* along the Texas coast, will be used in parallel to gather information about the relationship between winds and *Dinophysis* blooms [Thyng *et al.*, 2013].

Previous data received from the IFCB in Port Aransas, TX (27.8304° N, -97.038° W) from years 2008 – 2015 were analyzed to determine the timing and duration of *Dinophysis* bloom events [Campbell *et al.*, 2010; Olson and Sosik, 2007].

Wind data were gathered for the approximate latitude and longitude of the IFCB in Port Aransas, TX. To determine if the resulting modeled currents were downwelling or upwelling, it was necessary to rotate the coordinate system to allow the  $u$  and  $v$  components of the wind to orient along the Texas coast. Using a rotation angle of fifty degrees [Ogle, 2012],  $u$  and  $v$  were rotated by equations 1 and 2,

$$ur = u * \cos(\theta) - v * \sin(\theta) \quad (1)$$

$$vr = u * \sin(\theta) + v * \cos(\theta) \quad (2)$$

The resulting values,  $ur$  and  $vr$ , are the rotated wind vectors with respect to the angle along the coast, theta ( $\theta$ ) at 50°.

Daily resolution data of the  $u_r$  and  $v_r$  wind components at 10 meters, sea surface temperature, mean wave direction, and surface based runoff were gathered at  $0.125^\circ$  grid intervals for the Gulf of Mexico from the European Centre for Medium-Range Weather Forecasts (ECMWF).

Additional wind and salinity data was collected from a numerical ocean circulation model run using the Regional Ocean Modeling System (ROMS) [Shchepetkin and McWilliams, 2005]. The region includes the Texas/Louisiana coastal shelf and has recently been validated using salinity [X. Zhang *et al.*, 2012] sea surface height, currents, and temperature data [Zhang *et al.*, 2012].

Wind and salinity data of *in situ* observations at Texas Automated Buoy System (TABS) buoys B and D were obtained from the National Data Buoy Center (NDBC). Winds were then rotated into the along- and across-shore directions [Ogle, 2012]. The Multivariate El Niño Southern Oscillation (ENSO) Index (MEI) data were collected at a monthly resolution from National Oceanic and Atmospheric Administration's (NOAA) Earth System Research Laboratory (ESRL). Data for the North Atlantic Oscillation (NAO) were also gathered at a monthly resolution from NOAA's Climate Prediction Center (CPC). All data were collected for years 2008 to 2014. To draw better conclusions, data from NOAA's National Centers for Environmental Information (NCEI) for daily air temperature and daily precipitation totals were collected at a land based station in Port Aransas, TX ( $27.8363^\circ$  N,  $-97.0530^\circ$  W) from January to April for the years 2008 to 2014.

The data were analyzed in Matlab and used to compare all factors with *Dinophysis* cell abundance. The Matlab function `xcov` was used to determine the best lag and the function `corrcoeff` was used to gather the correlation coefficients and test for significance on all variables against cell abundance. Additional analysis conducted in Matlab using the statistical toolbox

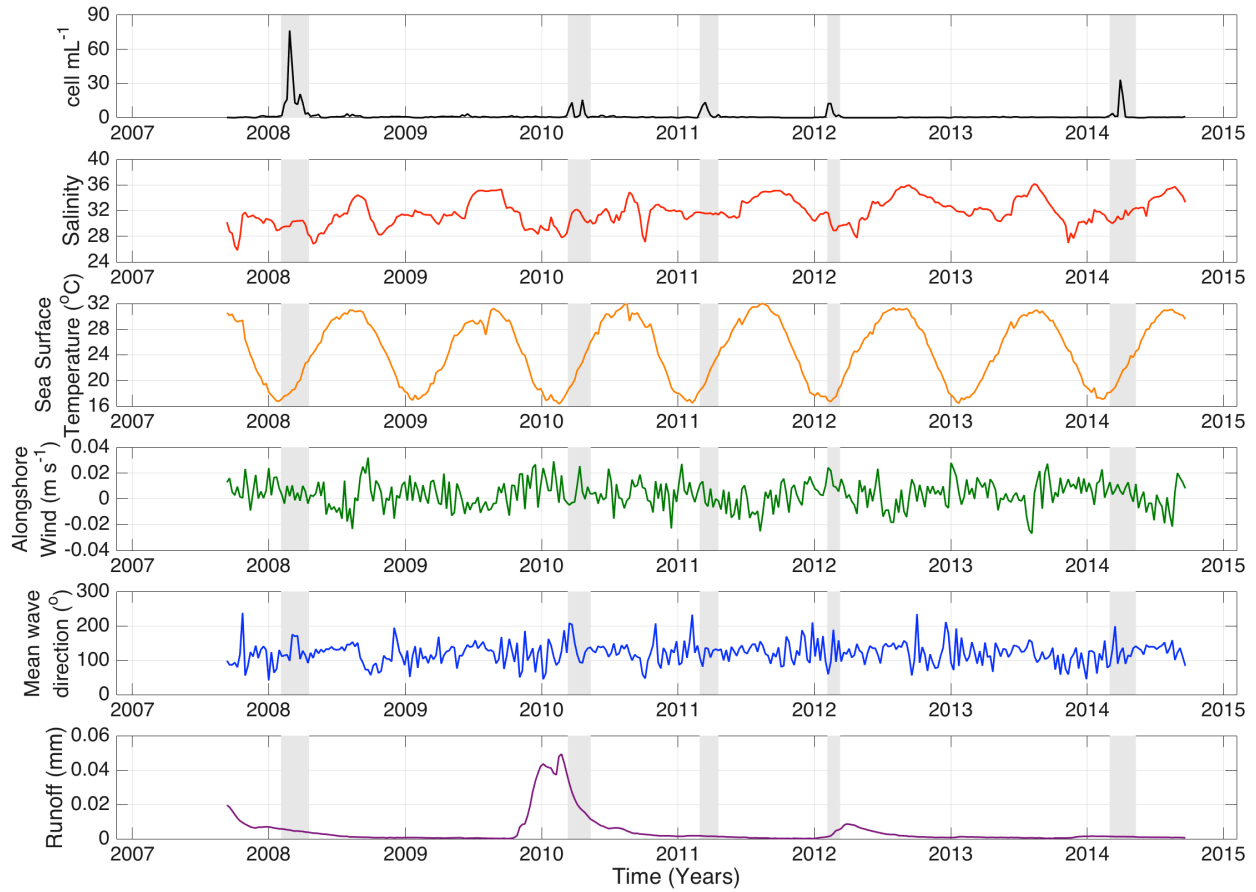
(mean and standard deviation functions) and visual comparison was used to relate air temperature and precipitation totals to help draw conclusions based off the data. The case study by *Thyng et al.* [2013] was used to act as a guideline for this study of *D. ovum*.

## CHAPTER III

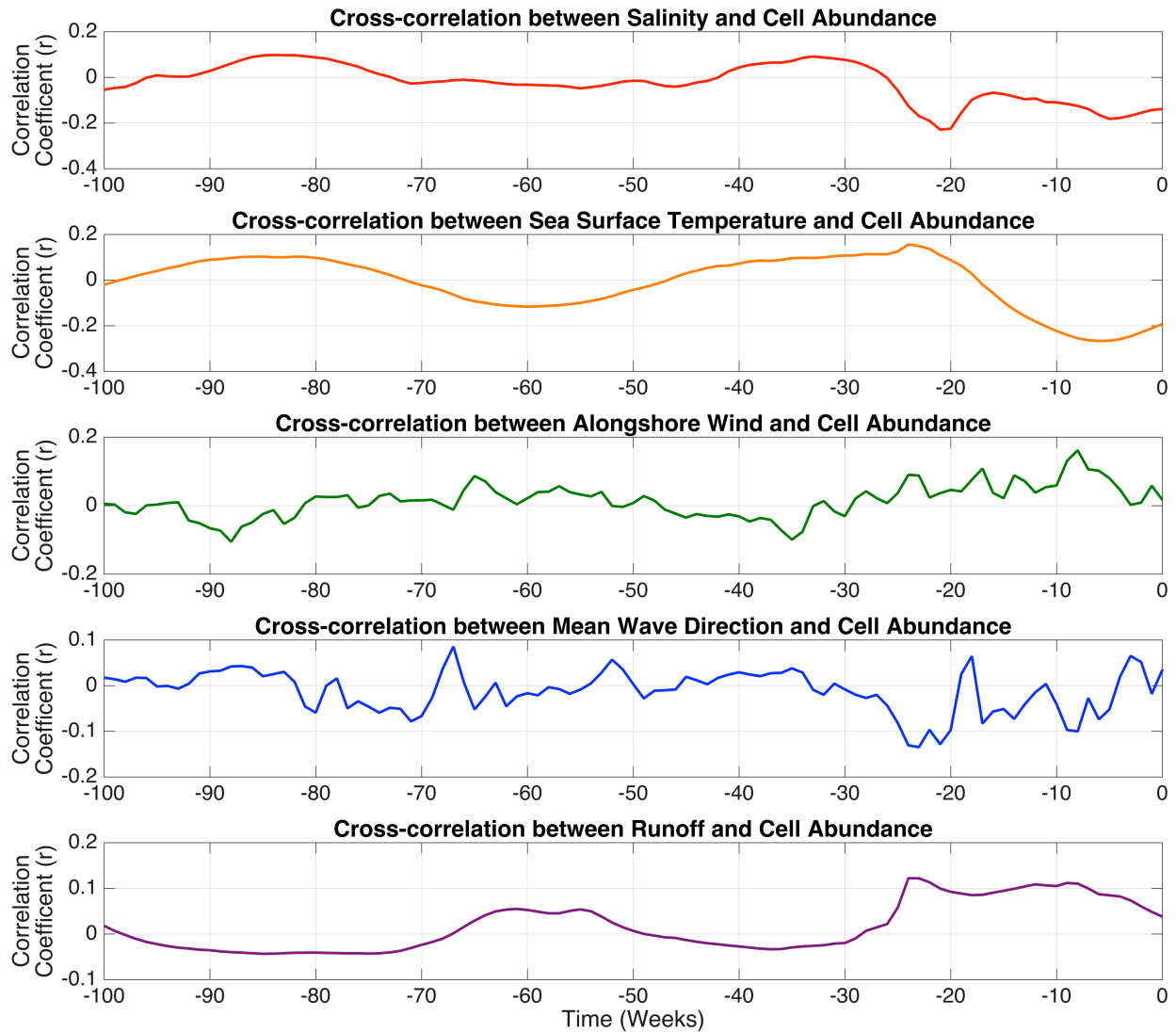
### RESULTS

#### **Winds**

Monthly, weekly, and daily rotated wind data were compared with *Dinophysis ovum* events to determine the relationship between HAB occurrence and wind for a given year. HAB years consisted of years 2008, 2010, 2011, 2012 and 2014 while non-HAB years were years 2009 and 2013. Since the focus was on the alongshore wind component, only values for  $ur$  were used. It was revealed that weak ( $< 2 \text{ m s}^{-1}$ ) downcoast winds occurred in the weeks prior to bloom initiation (Fig. 1; negative values indicate downcoast winds, while positive values indicate upcoast winds). With downwelling (downcoast) winds, this allows cells to accumulate causing blooms to occur. During a bloom, cells accumulated during winds less than  $6 \text{ m s}^{-1}$  that weakly fluctuated between upcoast and downcoast. When winds were greater than  $6 \text{ m s}^{-1}$ , regardless of direction, accumulation of cells did not occur and prevented blooms from forming. For the two non-HAB years, winds were greater than  $6 \text{ m s}^{-1}$ . The fast moving winds prevented the cell accumulation necessary for a bloom to occur. It was concluded alongshore winds and cell abundance were negatively correlated during bloom months. The negative correlation indicates that weaker downcoast winds allow for an increase in cell abundance.



**Figure 1.** Weekly mean of *Dinophysis* cell abundance (cells mL<sup>-1</sup>), salinity, sea surface temperature (°C), alongshore wind (m s<sup>-1</sup>), mean wave direction (degrees from true north), and surface-based runoff (mm). Areas highlighted in gray indicate HAB years.



**Figure 2.** Cross correlation of weekly means of salinity, sea surface temperature, alongshore wind, mean wave direction, and runoff versus *Dinophysis* cell abundance.

### Salinity

Values of salinity were compared and cross-correlated with cell abundance. During HAB years, salinity was less than 33.5 during the entire bloom period. When salinity was higher than 33.5, blooms did not occur (Fig. 1). The greatest correlation occurred at a lag of 24 weeks, indicating that salinity was negatively correlated with cell abundance (Fig. 2). It was determined by the negative correlation coefficient that when salinity decreases, cell abundance increases.

### **Sea surface temperature**

Sea surface temperature was compared with *Dinophysis* counts to see if a relationship exists between the two. Figure 1 shows blooms only occur during cooler sea surface temperatures. The mean sea surface temperature in which blooms typically occur is approximately 20°C. This supports the notion that *Dinophysis* can survive and bloom in cold-temperate coastal waters [Steidinger and Tangen, 1996]. Sea surface temperature and cell abundance were also negatively correlated (i.e., blooms typically occur during cooler temperatures; Fig. 2).

### **Mean wave direction**

HAB years showed the mean wave direction moving downcoast (80°) or towards the Texas coast (100-140°) before a bloom occurred. During a bloom, the mean wave direction moved towards the coast between 100° and 160°. The mean wave direction during non-HAB years moved either upcoast or downcoast during a bloom at 200° or 70° (Fig. 1). When the mean wave direction moved toward the coast (~120°), cell abundance typically increased. The correlation coefficient of mean wave direction and cell abundance indicated a positive correlation between the variables.

### **Surface-based runoff**

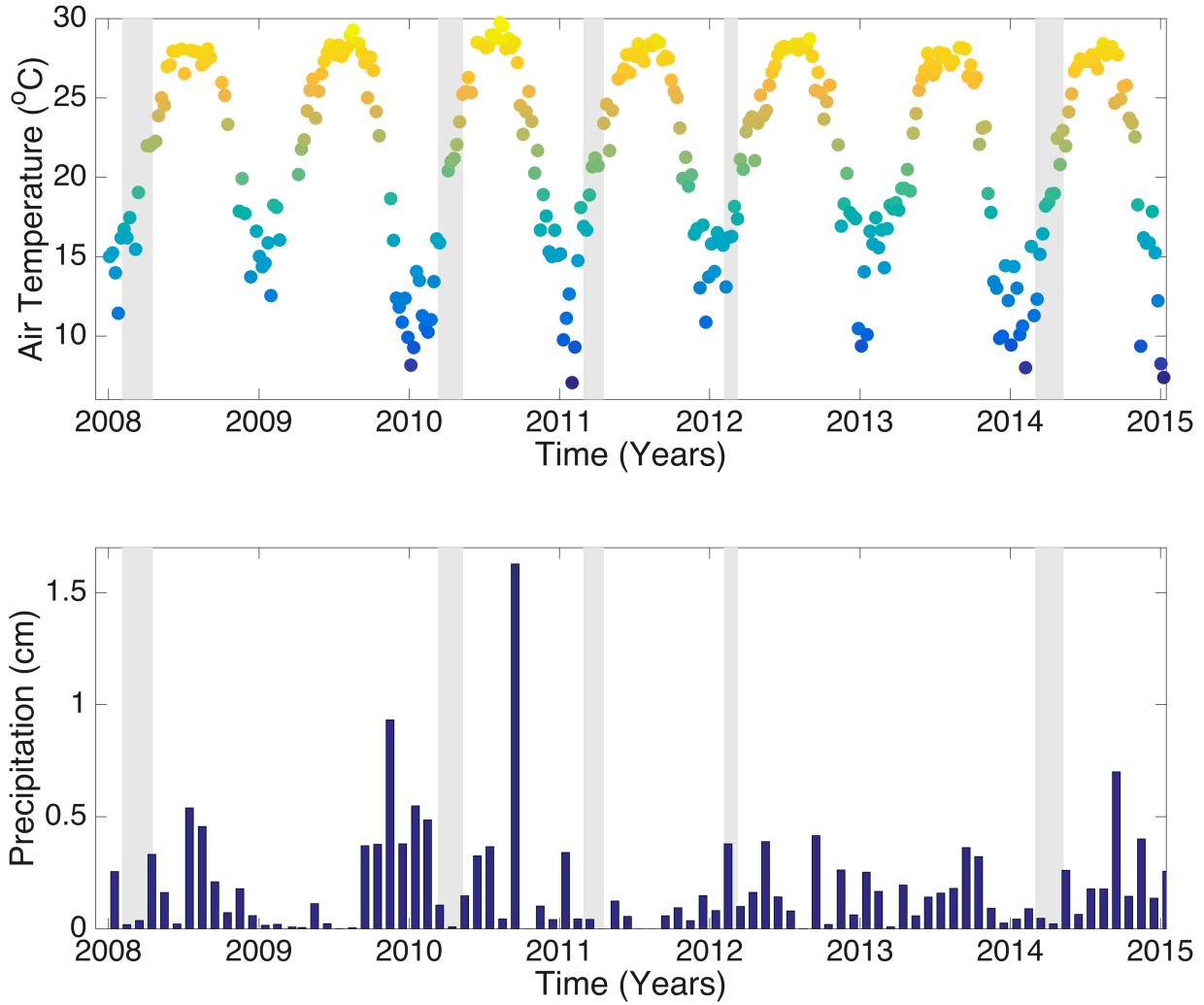
Another factor considered was surface based runoff. Runoff brings nutrients into the ocean and with increased nutrients there is typically an increase in plankton. When comparing *Dinophysis* cell abundance against runoff, it was determined that when there is any amount of runoff, a bloom occurred. When runoff (Fig. 1) is compared with precipitation totals (Fig. 3), the idea that large amounts of precipitation result in surface based runoff into the ocean and is followed by a



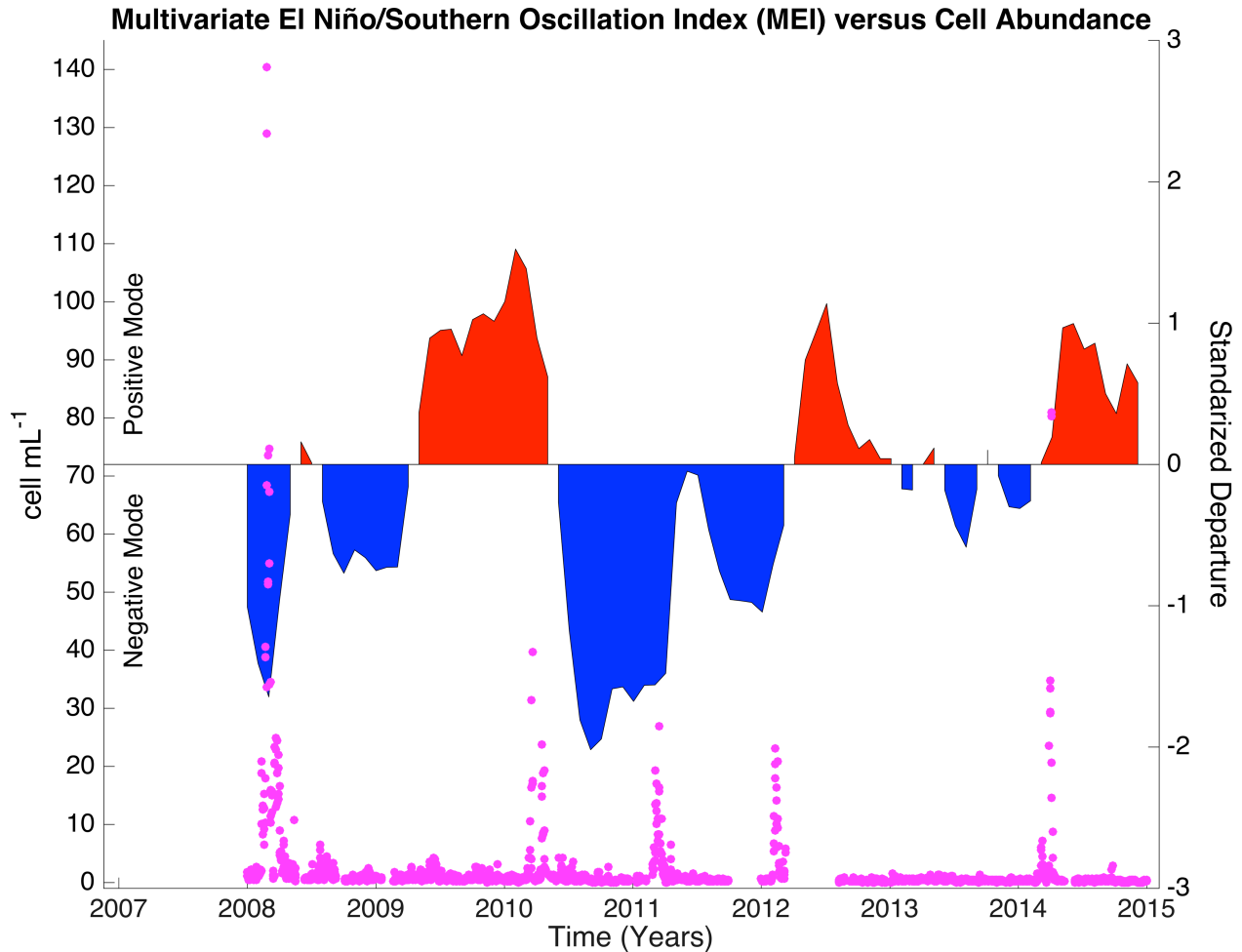
bloom is supported. Runoff from land adds a surplus of nutrients to surface waters, thus stimulating phytoplankton growth, especially in areas with high concentrations of agricultural land use [Beman *et al.*, 2005]. The amount of runoff and precipitation were positively correlated with bloom intensity but was not significant.

### **Other factors**

Since *Dinophysis* is a temperature sensitive genus [Reguera *et al.*, 2014], the Multivariate El Niño Southern Oscillation (ENSO) Index (MEI) and North Atlantic Oscillation (NAO) were compared to the counts to see if any relationship existed with HAB years and non-HAB years. MEI is calculated from six variables: sea-level pressure,  $u$  and  $v$  components of the wind, sea surface temperature, surface air temperature and total cloud-fraction of the sky. This index is considered to be the best indicator for El Niño and La Niña phases in the Pacific Ocean [Wolter and Timlin, 2011]. Figure 4 shows the comparison between MEI and counts of *Dinophysis*. HABs typically occurred during La Niña years, with the exception of year 2010 when a bloom occurred during a moderate El Niño phase. Both non-HAB years occurred during weak La Niña phases.



**Figure 3.** Daily values of air temperature ( $^{\circ}\text{C}$ ) and precipitation totals (cm) were averaged weekly and monthly, respectively, as shown by the scatter plot and bar graph. Areas highlighted in gray indicate HAB years. Precipitation occurred before a bloom in both El Niño and La Niña years. Average monthly air temperature was cooler in HAB years versus non-HAB years.



**Figure 4.** The comparison of daily *Dinophysis* counts in magenta (cell mL<sup>-1</sup>) at Port Aransas, TX versus MEI (multivariate ENSO index) colored by El Niño in red and La Niña in blue. Three blooms occurred during La Niña years, and one bloom occurred in year 2010 when it was an El Niño year.

During strong La Niña phases, the Gulf of Mexico is warmer and drier than average. This is due to the jet stream moving northward, causing less precipitation over the state of Texas. During El Niño phases, the jet stream is farther south than usual causing more precipitation and cooler temperatures over Texas [Ropelewski and Halpert, 1986]. HAB year 2010 is the only year to occur in an El Niño year while the rest of the HAB years occurred during La Niña years.

To explain the occurrence of a *D. ovum* bloom during a moderate El Niño year (2010), precipitation totals were compared among years (Table 1).

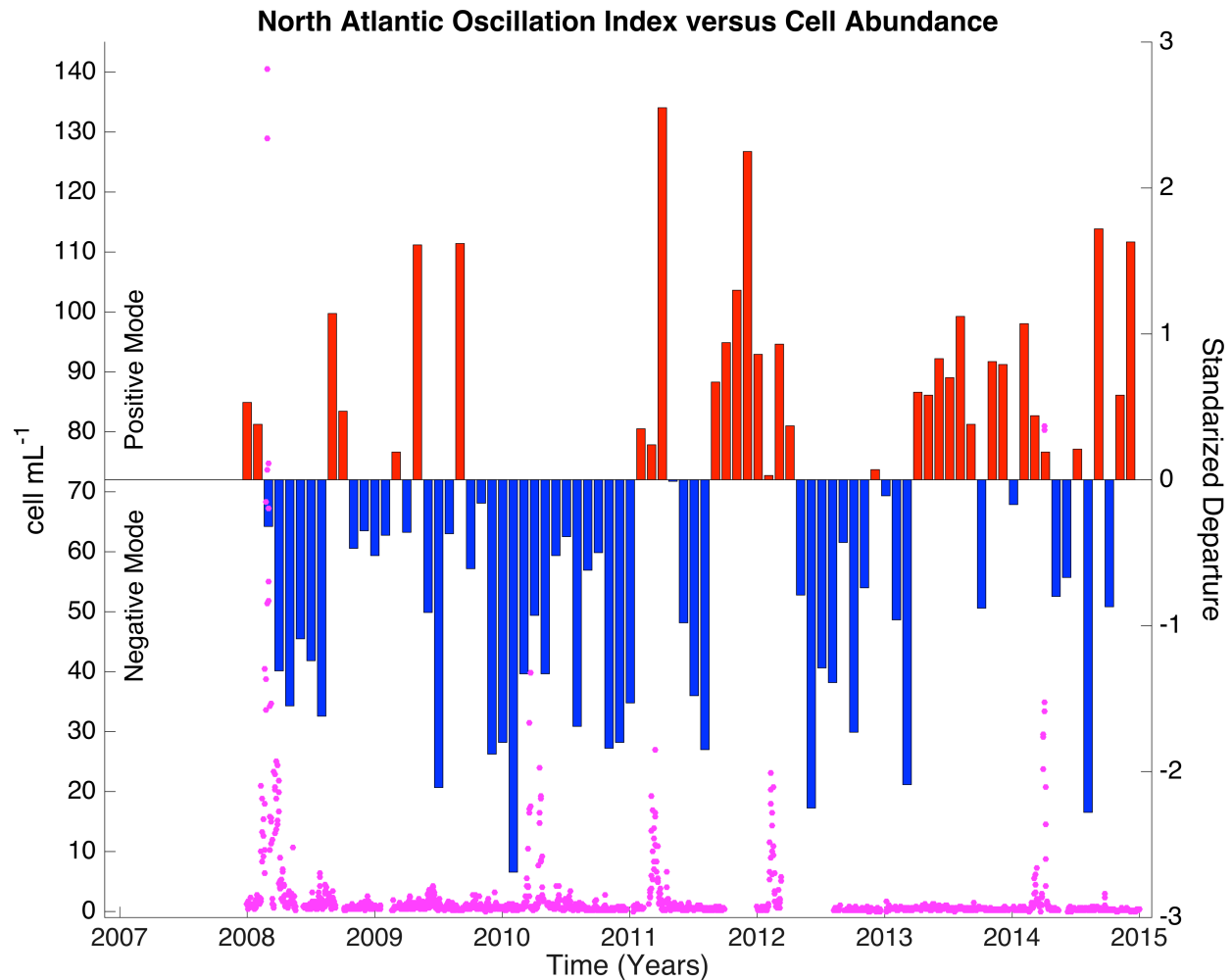
It was determined that in the months preceding a bloom, above normal precipitation occurred, resulting in more runoff and thus delivering more nutrients into the ocean to stimulate phytoplankton growth [Beman *et al.*, 2005]. This trend was observed in all years in which blooms occurred, regardless if it was an El Niño or La Niña year. The El Niño year received more precipitation than other years at an average of 0.19 cm, which resulted in slightly cooler average air temperatures (approximately 17°C) over the bloom months. La Niña years had an average air temperature of approximately 19°C and precipitation average of 0.14 cm over the bloom months. It was slightly warmer than the El Niño year of 2010 due to the lesser amount of precipitation and other possible factors. However, the difference between El Niño years and La Niña years was not significant enough to deter a bloom from occurring.

When comparing average air temperature and average precipitation totals over bloom months between HAB years and non-HAB years (Table 1), average air temperature was cooler (17.82°C) during HAB years versus non-HAB years (18.55°C). Average precipitation was slightly greater for HAB years than non-HAB years (0.17 cm and 0.06 cm, respectively). In the months preceding blooms, precipitation averages were greater in HAB years (0.18 cm) versus non-HAB years (0.05 cm). This supports the idea that *D. ovum* blooms usually occur when air and sea temperatures are cooler and there are likely more nutrients available [Beman *et al.*, 2005].

**Table 1.** Daily air temperature (°C) and precipitation was averaged for the months January to April for HAB years and non-HAB years. Daily precipitation preceding bloom months was averaged for only the two months preceding the blooms (January and February).

|                             | <i>Air Temperature (°C)</i><br>$(\bar{x} \pm SD [n])$ | <i>Precipitation (cm)</i><br>$(\bar{x} \pm SD [n])$ | <i>Precipitation<br/>Preceding HAB<br/>Months (cm)</i><br>$(\bar{x} \pm SD [n])$ |
|-----------------------------|---|---|--|
| <b><i>HAB Years</i></b>     | 17.82 ± 5.29 (590)                                    | 0.17 ± 0.76 (602)                                   | 0.18 ± 0.70 (267)  |
| <b><i>Non-HAB Years</i></b> | 18.55 ± 4.00 (209)                                    | 0.06 ± 0.37 (215)                                   | 0.05 ± 0.41 (118)  |
| <b><i>El Niño Year</i></b>  | 16.63 ± 5.44 (115)                                    | 0.19 ± 0.76 (120)                                   | N/A  |
| <b><i>La Niña Years</i></b> | 19.08 ± 4.99 (329)                                    | 0.14 ± 0.76 (336)                                   | N/A  |

To further understand factors influencing the development of *D. ovum* blooms, the NAO was also considered. The NAO is a large scale pattern of natural climate variability. It is located in the North Atlantic region and it has important impacts on the weather and climate over the region and surrounding continents. It is measured based on the strength and track of storms and depressions across the Atlantic Ocean and into Europe, as well as the strength of the prevailing winds or the westerlies associated with the storm tracks. In a positive mode of NAO, the Icelandic low pressure system and Azores high pressure system strengthen. This increases the pressure gradient across the North Atlantic and causes the jet stream to strengthen, allowing for colder air to move into the eastern United States. In a negative mode of NAO, the low and high are weakened which causes the pressure gradient to decrease. This in turn causes the jet stream to weaken and allows for colder air to move south into Georgia and Florida [Osborn, 2006].



**Figure 5.** The comparison of daily *Dinophysis* counts in magenta ( $\text{cell mL}^{-1}$ ) at Port Aransas, TX versus NAO index colored by the positive mode in red and negative mode in blue. Blooms typically occur in negative modes years, with two blooms occurring in a positive mode.

When comparing NAO modes with *D. ovum* counts, it was determined that three blooms occurred during strong negative NAO modes and two blooms occurred during strong positive modes of NAO as shown in Figure 5. The two non-HAB years occurred during weak negative modes of NAO. With a weaker (stronger) jet stream in a negative (positive) mode, the southern United States is cooler and wet (warmer and dry). With two out of the five bloom years occurring during negative modes, a possible connection could be made with *D. ovum* blooms

occurring cooler air temperatures and more precipitation. More observations are required to draw further conclusions.

A study by *Rogers* [1984] examined the correlation between the NAO and ENSO. Both patterns of atmospheric variability work in conjunction with each other to bring a certain climate to the United States and other countries around the world. Together, the NAO and Southern Oscillation (SO) are associated with significant pressure and height variations in the Northern Hemisphere except for the western portion of the United States and Siberia. Both significantly influence pressure and height distributions over eastern North America and western Atlantic. This results in large surface air temperature variability over the southeastern United States when there is an extreme of NAO and SO. The low index modes of both oscillations (negative NAO and La Niña) are correlated with below normal winter temperatures in the southeastern U.S [*Rogers*, 1984]. Correlating NAO, MEI and cell counts supported this previous work. When looking at Figures 3 and 5, it can be noted that positive (negative) phases of ENSO and positive (negative) modes of NAO typically occur at the same time. In the years where both NAO and ENSO were in negative phases, air temperature was cooler and precipitation rates were above normal. It can then be suggested that NAO and ENSO work together to create an ideal environment for *D. ovum* blooms to occur.

## CHAPTER IV

### DISCUSSION

This study showed that several factors play a role in making an environment favorable for *Dinophysis ovum* blooms. Weak downwelling winds occurring before a bloom allows for cell accumulation according to the conceptual model created by *Hetland and Campbell* [2007]. For survival and the need for sunlight, plankton need to swim against the downwelling current, accumulating into a patch of plankton thus resulting in a bloom. Conversely, an upwelling current cannot break apart the patch of cells; instead the patch moves with the ocean currents.

*D. ovum* cells also thrive in colder sea surface temperatures. The data analysis showed that blooms only occur when temperatures in the water are in the lower twenties, with an average temperature during HABs to be 20°C. For HAB years, salinity was less than 33.5, while for non-HAB years, salinity was greater than 33.5. It is postulated that *D. ovum* is a temperature dependent species that thrives in lower salinity waters.

Blooms also typically occur during La Niña years with the exception of year 2010, which took place during an El Niño year. After examining the monthly precipitation and monthly air temperature to further understand the occurrence during the El Niño year, it was determined that precipitation preceding a bloom is important for bloom initiation for all HAB years. This allows for runoff to flow into the ocean and gives nutrients to the plankton. Although the El Niño year was slightly cooler and wetter than the La Niña years, the comparison between HAB and non-HAB years showed that there was more precipitation and cooler air temperatures in HAB years



versus non-HAB years. The months preceding the blooms also had large precipitation totals compared to the months preceding the non-bloom months, which had very low precipitation. It was determined that precipitation totals have a large impact on HAB and non-HAB years. Runoff also plays a significant role in *D. ovum* blooms because it occurred in the weeks leading up to a bloom. When there was no runoff, a bloom did not occur. This was verified by the precipitation data; when there was low precipitation, a bloom did not occur and *vice versa*.

High cell counts of *D. ovum* also tend to occur during negative modes of the North Atlantic Oscillation. The negative mode allows for cooler and wetter winters for the southeastern United States. It was also shown that NAO and ENSO are correlated with each other and when NAO and ENSO are both in negative phases, this enhances the conditions for a wet and cool winter in the southeastern U.S. Cool temperatures and high precipitation are favorable conditions for this species along the Texas coast.

All of these factors work together to create an environment favorable for *D. ovum* blooms to occur. Typical expected factors for bloom initiation include: weak downwelling winds (less than  $2 \text{ m s}^{-1}$ ) before a bloom occurs, salinity less than 33.5, cool sea surface temperatures, mean wave direction moving towards the coast, and precipitation with runoff in the 2 months preceding a bloom. Other factors that most likely would occur during a HAB year include a La Niña year and a negative mode of NAO, although it was not highly correlated.

## REFERENCES

- Aubry, F. B., A. Berton, M. Bastianini, R. Bertaggia, A. Baroni, and G. Socal (2000), Seasonal Dynamics of *Dinophysis* in Coastal Waters of the NW Adriatic Sea (1990-1996), in *Botanica Marina*, edited, p. 423.
- Campbell, L., R. J. Olson, H. M. Sosik, A. Abraham, D. W. Henrichs, C. J. Hyatt, and E. J. Buskey (2010), First Harmful *Dinophysis* (Dinophyceae, Dinophysiales) Bloom in the U.S. Is Revealed by Automated Imaging Flow Cytometry<sup>1</sup>, *Journal of Phycology*, 46(1), 66-75, doi: 10.1111/j.1529-8817.2009.00791.x.
- Harred, L. B., and L. Campbell (2014), Predicting harmful algal blooms: a case study with *Dinophysis ovum* in the Gulf of Mexico, *Journal of Plankton Research*, 36(6), 1434-1445, doi: 10.1093/plankt/fbu070.
- Hetland, R. D., and L. Campbell (2007), Convergent blooms of *Karenia brevis* along the Texas coast, *Geophysical Research Letters*, 34(19), n/a-n/a, doi: 10.1029/2007GL030474.
- Michael Beman, J., K. R. Arrigo, and P. A. Matson (2005), Agricultural runoff fuels large phytoplankton blooms in vulnerable areas of the ocean, *Nature*, 434(7030), 211-214, doi: [http://www.nature.com/nature/journal/v434/n7030/supinfo/nature03370\\_S1.html](http://www.nature.com/nature/journal/v434/n7030/supinfo/nature03370_S1.html).
- Nagai, S., G. Nitshitani, Y. Tomaru, S. Sakiyama, and T. Kamiyama (2008), Predation By The Toxic Dinoflagellate *Dinophysis Fortii* on the Ciliate Myrionecta Rubra and Observation of Sequestration of Ciliate Chloroplasts<sup>1</sup>, *Journal of Phycology*, 44(4), 909-922, doi: 10.1111/j.1529-8817.2008.00544.x.
- Nielsen, L. T., B. Krock, and P. J. Hansen (2012), Effects of light and food availability on toxin production, growth and photosynthesis in *Dinophysis acuminata*, *Marine Ecology Progress Series*, 471, 37-50.
- Ogle, M. T. (2012), Physical Mechanisms Driving Harmful Algal Blooms Along the Texas Coast, Master's thesis, Texas A&M University.
- Olson, R. J., and H. M. Sosik (2007), A submersible imaging-in-flow instrument to analyze nano-and microplankton: Imaging FlowCytobot, *Limnology and Oceanography: Methods*, 5(6), 195-203, doi: 10.4319/lom.2007.5.195.

Osborn, T. J. (2006), Recent variations in the winter North Atlantic Oscillation, *Weather*, 61(12), 353-355, doi: 10.1256/wea.190.06.

Reguera, B., P. Riobó, F. Rodríguez, P. A. Díaz, G. Pizarro, B. Paz, J. Blanco (2014). *Dinophysis* Toxins: Causative Organisms, Distribution and Fate in Shellfish. *Marine Drugs*, 12(1), 394–461, doi: <http://doi.org/10.3390/md12010394>

Rogers, J. C. (1984), The Association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere, *Monthly Weather Review*, 112(10), 1999-2015, doi: doi:10.1175/1520-0493(1984)112<1999:TABTNA>2.0.CO;2.

Ropelewski, C. F., and M. S. Halpert (1986), North American Precipitation and Temperature Patterns Associated with the El Niño/Southern Oscillation (ENSO), *Monthly Weather Review*, 114(12), 2352-2362, doi: 10.1175/1520-0493(1986)114<2352:NAPATP>2.0.CO;2.

Shchepetkin, A. F., and J. C. McWilliams (2005), The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model, *Ocean Modelling*, 9(4), 347-404, doi: <http://dx.doi.org/10.1016/j.ocemod.2004.08.002>.

Steidinger, K. A., and K. Tangen (1996), Chapter 3 - Dinoflagellates, in *Identifying Marine Diatoms and Dinoflagellates*, edited, pp. 387-584, Academic Press, San Diego.

Thyng, K. M., R. D. Hetland, M. T. Ogle, X. Zhang, F. Chen, and L. Campbell (2013), Origins of *Karenia brevis* harmful algal blooms along the Texas coast, *Limnology and Oceanography: Fluids and Environments*, 3(1), 269-278, doi: 10.1215/21573689-2417719.

Wolter, K., and M. S. Timlin (2011), El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext), *International Journal of Climatology*, 31(7), 1074-1087, doi: 10.1002/joc.2336.

Yasumoto, T., M. Murata, Y. Oshima, M. Sano, G. K. Matsumoto, and J. Clardy (1985), Diarrhetic shellfish toxins, *Tetrahedron*, 41(6), 1019-1025, doi: [http://dx.doi.org/10.1016/S0040-4020\(01\)96469-5](http://dx.doi.org/10.1016/S0040-4020(01)96469-5).

Zhang, X., M. Marta-Almeida, and R. D. Hetland (2012), A high-resolution pre-operational forecast model of circulation on the Texas-Louisiana continental shelf and slope, *Journal of Operational Oceanography*, 5(1), 19-34, doi: 10.1080/1755876X.2012.11020129.

Zhang, X., R. D. Hetland, M. Marta-Almeida, and S. F. DiMarco (2012), A numerical investigation of the Mississippi and Atchafalaya freshwater transport, filling and flushing times on the Texas-Louisiana Shelf, *Journal of Geophysical Research: Oceans*, 117(C11), n/a-n/a, doi: 10.1029/2012JC008108.