EXAMINATION OF THE RELATIONSHIP OF RIVER WATER TO OCCURRENCES OF BOTTOM WATER WITH REDUCED OXYGEN CONCENTRATIONS IN THE NORTHERN GULF OF MEXICO

A Dissertation

by

LEILA BELABBASSI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2006

Major Subject: Oceanography

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Approved by:

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Committee Members,	Piers Chapman
	Ann Jochens
	Steven DiMarco
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ABSTRACT

Examination of the Relationship of River Water to Occurrences of Bottom Water with Reduced Oxygen Concentrations in the Northern Gulf of Mexico. (December 2006)

Leila Belabbassi, B.S., Institut des Sciences de la Mer et de l'Aménagement du Littoral;
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Chair of Advisory Committee: Dr. Worth Nowlin, Jr.

Six years of comprehensive data sets collected over the northern continental shelf and upper slope of the Gulf of Mexico during the LATEX-A and NEGOM-COH programs showed that low-oxygen waters (<2.4 mL·L^{-1}) are found only in spring and summer and only in water depths between 10 and 60 m. Four regions in the northern Gulf show considerable differences in the occurrence of low-oxygen waters. Low-oxygen waters are observed almost exclusively in regions subject to large riverine influences: the Louisiana and Mississippi-Alabama shelves. Hypoxic waters (oxygen concentrations <1.4 mL·L^{-1}) are found only over the Louisiana shelf. No low-oxygen water is found over the Florida shelf which has minimum riverine influence. Low-oxygen water is found at only one station on the Texas shelf; this is during spring when the volume of low-salinity water is at maximum. The distributions of low-salinity water influenced the different distributions of low-oxygen and hypoxic waters in the four regions. Low-oxygen occurrences are clearly related to vertical stratification. Low-oxygen occurred only in stable water columns with maximum Brunt-Väisälä frequency (N_{max}) greater than 40 cycles·h^{-1}. When N_{max} exceeded 100 cycles·h^{-1} in summer over the Louisiana shelf, oxygen concentrations dropped below 1.4 mL·L^{-1}, and the bottom waters became hypoxic. Salinity is more important than temperature in controlling vertical stratification. Locations where temperature influence was larger were found in summer in water depth greater than 20 m over the Louisiana shelf, along the near shore areas of the Mississippi-Alabama shelf west of 87ºW, and in the inner shelf waters of the Texas shelf. The extent of oxygen removal at the bottom of these stable water columns is reflected in the amount of remineralized silicate. Silicate concentrations are highest closest to the Mississippi River Delta and decrease east and west of the Delta. EOF analyses show that more than 65% of the oxygen variance is explained by the first mode. The amplitude functions of the first EOF modes of bottom oxygen, water column Brunt-Väisälä maxima, and bottom silicate are well correlated, indicating that much of the variance in bottom oxygen is explained by water column stratification and bottom remineralization.

DEDICATION

To my husband Rachid Baghdad-Brahim

and my

sons Younes El-Habib and Luqman

ACKNOWLEDGMENTS

I would like to express my sincere thanks to my committee members: Dr. Worth Nowlin, Jr., for his valuable suggestions and careful review of the manuscript; Dr. Piers Chapman for carefully following my work, for sharing his scientific knowledge and ideas, and for his suggestions and comments; Dr. Ann Jochens for her guidance, suggestions, and editorial comments; Dr. Steven DiMarco for his assistance with some of the programming I used in this study and for his helpful suggestions; and Drs. Guy Battle and Joseph Newton for being excellent professors.

I would like also to thank Dr. Matt Howard for providing some of the data used in this study and for assistance on locating resources needed for this work. Thanks also go to the Texas Sea Grant Program for financial support, to the Texas Institute of Oceanography for a graduate assistantship, and to the Algerian Ministry of High Education and Scientific Research for financial support.

Last, but not least, my heartfelt thanks go to my husband Rachid Baghdad-Brahim for his love and support during the entire study and always. I would like to mention my sons Younes El-Habib and Luqman for being adorable boys and very loving. Special thanks go to my extended family for their love and encouragement and for keeping my paper work always updated and taking care of all my needs in Algiers.

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CHAPTER I

INTRODUCTION

1.1. Background

Inner shelf waters (10-60 m) of the northern Gulf of Mexico receive large inputs of nutrients (e.g., nitrate and silicate) due to fluvial discharge and runoff from the adjacent land (Figure 1.1). Because of this input, primary production by phytoplankton can occur anytime, even in winter, given sufficient light (Dortch et al., 1992; Lohrenz et al., 1994; Al–Abdulkader, 1996). Thus, the inshore waters of the northern Gulf of Mexico support large fisheries (Kumpf et al., 1999). One factor that may counteract the high nutrient concentrations and light penetration at shallow depths is the large amount of terrigenous debris, which may restrict the depth of the photic zone by limiting the amount of light that penetrates the water column (Riley, 1937; Lohrenz et al., 1992; Wawrik and Paul, 2004; Wawrik et al., 2003; Gargett and Marra, 2002).

The shallow depths, turbulence, and wind mixing of the inner shelves of the northern Gulf of Mexico usually result in an ample supply of oxygen in the water column. During summer, however, heating of surface waters and regular influx of fresh water onto this inner shelf lead to the development of a strong pycnocline (Wiseman et al., 1997). This pycnocline forms a barrier that often limits the exchange between the oxygen-rich surface waters and the sub-pycnocline waters. The isolation of the sub-pycnocline waters from exchange with an oxygen source, coupled with high biological activity and slow renewal by flushing, may result in depletion of the dissolved oxygen content in these bottom waters (Wiseman et al., 1997; Rabalais et al., 1996).

Hypoxia is a recurring condition in the northern Gulf of Mexico, particularly in the inner shelf waters of the Louisiana shelf. It is defined as the condition when dissolved oxygen is below 1.4 $mL \cdot L^{-1}$, or 2 $mg \cdot L^{-1}$ (Harper et al., 1981; Pavela et al., 1983; Leming and Stuntz, 1984; Renaud, 1986). This depletion of oxygen in bottom waters may begin in spring and last through summer (Rabalais et al., 1998).

This dissertation follows the style of *Gulf of Mexico Science*.

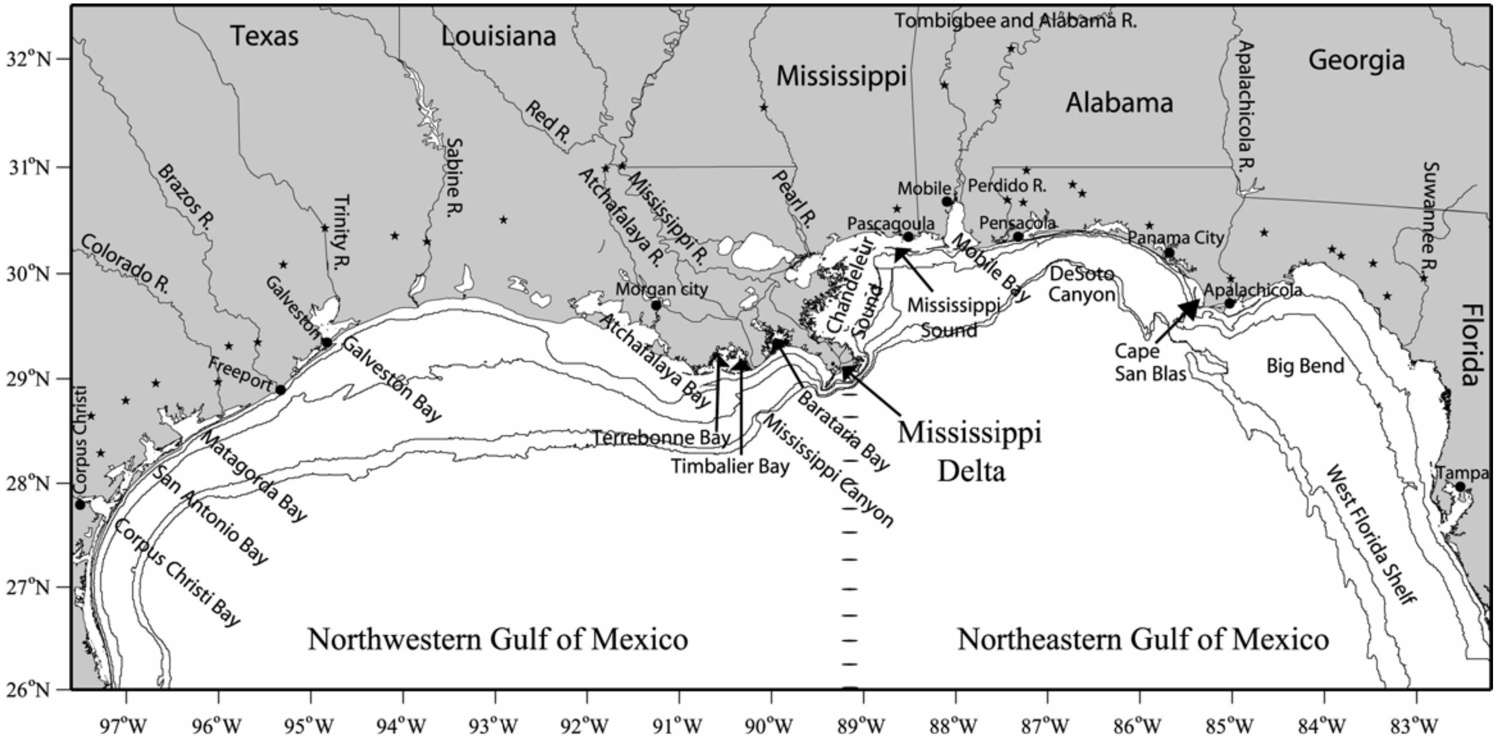


Figure 1.1. Map of the northern Gulf of Mexico showing bathymetry and key geographical locations. The stars on the land represent river gauging stations. The 10-, 20-, 50-, and 60-m isobaths are shown.

As noted by Diaz and Rosenberg (1995), hypoxia is a stressful condition for aquatic and marine ecosystems. Since the mid 1970s, there has been increasing concern regarding the potentially detrimental effects of coastal hypoxia on the marine life of the Louisiana shelf ecosystem.

Scientists have long known that hypoxia is a complex ecological phenomenon that results from the interplay of several factors. It generally affects enclosed or semi-enclosed water bodies, such as lakes, bays, estuaries, and seas (Diaz, 2001). In these systems, local conditions, such as bottom topography and the strength and direction of river discharge, determine how well mixed the water is and how long riverine water remains in the system. Wind strength and direction, especially the influence of major storms, also affect the rate of mixing (Wiseman et al., 1992). Human activities, such as increasing the freshwater discharge entering the ecosystem, also can reduce the amount of vertical mixing (Bratkovich et al., 1994). This reduction in vertical mixing increases the chance of hypoxia occurrence.

Nutrients (primarily nitrogen, phosphorus, and silica) are necessary for plant growth. High rates of external loading of these nutrients combined with adequate light can result in phytoplankton blooms. Phytoplankton blooms usually result in an intense supply of organic matter to bottom waters. The oxidation of this organic material near the bottom can lead to hypoxia if bottom waters are slow-moving and the water column is poorly mixed (Wiseman et al., 1997; Rabalais et al., 1996; Lohrenz et al., 1997, 1994, 1990; Qureshi, 1995; Justic et al., 1993; Pokryfki and Randall, 1987; Sklar and Turner, 1981).

The nutrients come from point sources such as wastewater treatment plant discharges and from non-point sources such as agricultural activities, urban runoff, groundwater, and atmospheric deposition (Carey et al., 1999). The amount of pollutants generated and the rate at which they reach rivers, estuaries, and coastal waters are increased by human activities such as the destruction of wetlands, grasslands, and forests in favor of urban or suburban landscapes as well as by many agricultural practices (Rabalais et al., 2001; Mitsch et al., 2001; Spieles and Mitsch, 2000). By the end of the

1990s, controversy had arisen regarding whether the extent and severity of hypoxia over the Louisiana continental shelf were increasing as a result of anthropogenic changes to the ecosystem.

Although the conditions that cause hypoxia are identified, there remains the need for better understanding of how interactions among the biological, chemical, and physical processes affect dissolved oxygen levels over the inner shelf. Especially important is the separation between the relative contributions to hypoxia of natural and anthropogenic effects. These contributions must be quantified in order to develop effective management guidelines for minimizing the impact from human activities. Using data sets obtained over six years of field studies, this research focuses on obtaining quantitative relationships between river-derived low-salinity water, vertical stratification, bottom nutrient enrichment through remineralization, and occurrences of reduced bottom oxygen concentrations over the northern continental shelf of the Gulf of Mexico.

1.2. Description and Limitations of LATEX-A and NEGOM-COH Data Sets

The principal data sets used were from research cruises sponsored by the Minerals Management Service (MMS) and conducted by Texas A&M University as part of two major programs: the Texas-Louisiana Shelf Circulation and Transport Processes Study (LATEX-A) and the Northeastern Gulf of Mexico Chemical Oceanography and Hydrography Study (NEGOM-COH). The LATEX-A field program was conducted over the Texas-Louisiana shelf and a portion of the upper slope from April 1992 through November 1994. The NEGOM-COH field program was conducted over the continental shelf and upper slope between the Mississippi River Delta and Tampa Bay from November 1997 through August 2000. For both programs there were three cruises each in spring, summer, and fall; LATEX-A had a tenth cruise in winter 1993. The start and end dates of the cruises are given in Table 1.1.

In this study the 60-m isobath is taken as the outer boundary for the northern Gulf shelves because, as will be shown in section 3.2, reduced dissolved oxygen concentrations over these shelves were found only in water depths less than 60 m.

Table 1.1. Program and cruise identifiers and their corresponding dates.

Program ID	Cruise ID	Start date	End date
LATEX-A	H01	1 May 1992	8 May 1992
	H02	1 August 1992	8 August 1992
	H03	4 November 1992	13 November 1992
	H04	4 February 1993	13 February 1993
	H05	26 April 1993	10 May 1993
	H06	26 July 1993	7 August 1993
	H07	6 November 1993	22 November 1993
	H08	24 April 1994	7 May 1994
	H09	27 July 1994	4 August 1994
	H10	2 November 1994	14 November 1994
NEGOM-COH	N1	17 November 1997	26 November 1997
	N2	5 May 1998	16 May 1998
	N3	26 July 1998	6 August 1998
	N4	13 November 1998	24 November 1998
	N5	16 May 1999	27 May 1999
	N6	17 August 1999	28 August 1999
	N7	13 November 1999	22 November 1999
	N8	16 April 2000	26 April 2000
	N9	29 July 2000	7 August 2000

Stations made in deeper water were excluded. The locations of CTD stations used in this study, superimposed on the bathymetry, are shown in Figure 1.2. A brief description of the data used is given below. For detailed information on the sampling methods refer to reports by Jochens and Nowlin (1994a, 1994b, 1995, 1998, 1999, and 2000).

Data used in this study include continuous profiles of pressure, temperature, and salinity made at all stations on LATEX-A and NEGOM-COH cruises. The vertical separation distance of data on these profiles is 0.5 m. Other measurements used were discrete samples of nitrate, phosphate, and silicate taken at every station, and samples of salinity and dissolved oxygen taken at more than half of the stations. For the periods of both programs, daily river discharge rates for the Mississippi River and rivers to its east and west were obtained from the U.S. Geological Survey or the U.S. Army Corps of Engineers.

Sampling plans of the LATEX-A and NEGOM-COH programs were designed to address issues other than the occurrence of hypoxia. Therefore, station locations and the vertical resolution and placement of water samples were not placed ideally to examine the features of interest to this study. For both programs, station spacing provided good resolution of the cross-isobath gradients of water properties but did not provide good along-shelf horizontal resolution for observing the structure of bottom hypoxic waters, the Mississippi-Atchafalaya River plumes, or nutrient distribution along the shelf. Water samples during the NEGOM-COH program were taken at depths determined by specific features or density values, generally at about the 3-m depth, at the chlorophyll *a* maximum as indicated by the downcast fluorescence maximum, at specified density surfaces, and about 2 m above the sea floor. During LATEX-A, water samples were taken at about the 3-m depth, at the chlorophyll *a* maximum, above and below the chlorophyll *a* maximum as determined by the fluorescence maximum, in the mixed layer, in other interesting features of temperature, salinity, relative fluorescence, or percent transmission profiles, and about 2 m above the sea floor. For this study, sampling within 1 m from the seafloor would have been ideal because the lowest oxygen

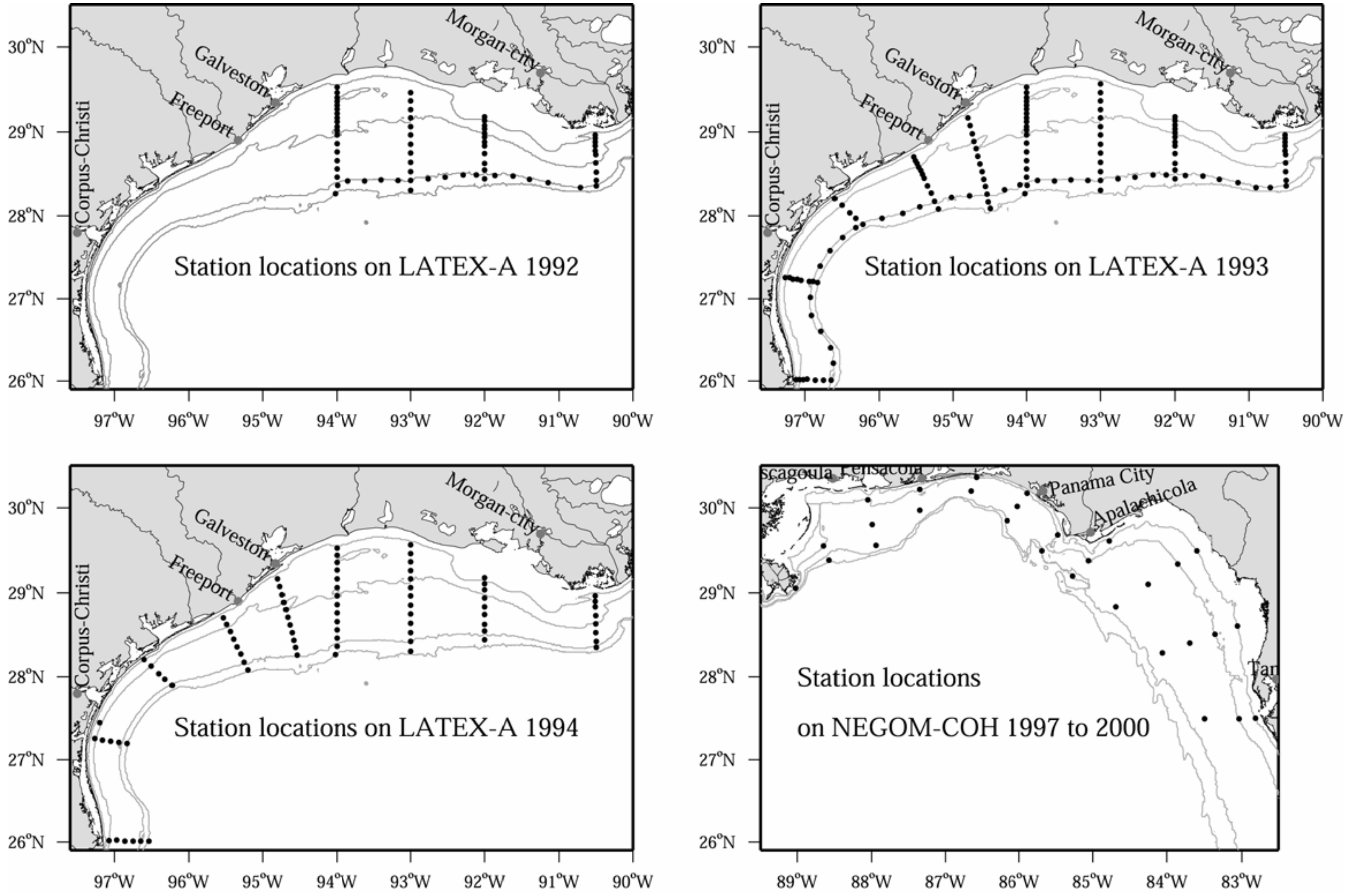


Figure 1.2. Selected station locations (dots) on NEGOM-COH and LATEX-A field programs used in this study. The 10-, 20-, 50-, and 60-m isobaths are shown.

concentrations are commonly found close to the sea floor. However, samples within 1 m of the bottom were available from few stations.

1.3. Study Objectives

Two local processes are major causal factors for low-oxygen concentrations in near-bottom waters over the northern continental shelves of the Gulf of Mexico. First, local stratification is a condition that determines the ease of vertical mixing between the oxygen-rich surface waters and the sub-pycnocline waters. Second, remineralization is a local process that determines the extent to which the concentrations of dissolved oxygen in the sub-pycnocline waters are actually depleted. Note that a decrease in dissolved oxygen concentration due to remineralization is usually reflected in an increase with depth in nutrient concentrations. Therefore, near-bottom silicate is taken to represent the remineralization process. I will show that the distribution of river water causes the spatial and temporal variability of stratification and the amount of the remineralized silicate near the bottom over the northern Gulf shelves and thereby controls the occurrence of bottom water with low-oxygen concentrations. This will be shown through achieving of the following objectives:

1. Identify an upper limit for dissolved oxygen concentration that can be used to indicate reduced dissolved oxygen concentration over the northern shelves of the Gulf of Mexico.
2. Identify distinct regions of the northern shelves as determined by the amount of freshwater discharge and the likelihood of reduced dissolved oxygen content or hypoxia in the bottom waters.
3. Determine a minimum value of the maximum Brunt-Väisälä frequency present in the water column for which low-oxygen bottom waters are found.
4. Determine the relative importance of salinity and temperature to the vertical stratification represented by the Brunt-Väisälä frequency.
5. Obtain a quantitative relationship between bottom silicate, which is taken to represent the remineralization process, and maximum Brunt-Väisälä frequency.

6. Examine the space-time relationships between the Brunt-Väisälä maxima in the water column, bottom silicate concentrations, and bottom oxygen concentrations.

1.4. Organization

Chapter II provides historical background on hypoxia. In particular, regions in the northern Gulf of Mexico where hypoxia has been observed are described and the causes and effects of hypoxia in the northern Gulf are discussed. Also described in this chapter are some additional regions outside the Gulf of Mexico where hypoxia has been observed.

Chapter III presents the study approach. The interactions between regional physical forcing and local processes/conditions are described and the effects of the forcing and processes on the vertical distribution of dissolved oxygen concentration in the water column are examined. The limiting values of dissolved oxygen concentrations used in this study are defined. Finally, the delineation of the northern shelves into four distinct regions is defined and the rational for the division is presented.

Chapter IV covers the results from the LATEX-A and NEGOM-COH observations by season and region. First, the effect of local stratification on the occurrence of low-oxygen and hypoxic waters is investigated. Next, the relative importance of salinity and temperature to the vertical stratification is determined. Then, the relationship between bottom silicate and stratification is examined. The last section of this chapter uses EOF analysis to examine the space-time relationship between stratification, bottom silicate, and bottom oxygen.

Chapter V summarizes the results presented in chapter IV and provides conclusions.

CHAPTER II

OBSERVATIONS OF HYPOXIA FROM THE NORTHERN GULF OF MEXICO AND REGIONS AROUND THE WORLD

2.1. Occurrences of Hypoxia in the Northern Gulf of Mexico

Hypoxia in the northern Gulf of Mexico has been observed in near shore waters at depths between 4-5 m to as deep as 60 m (Rabalais et al., 1991, 1999), but most frequently in waters shallower than 30 m along the Texas-Louisiana shelf between 89.5°W and 94°W (Rabalais et al., 1999). Over the Texas-Louisiana shelf, hypoxia is found typically in the lower half or two-thirds of the water column. The mid-summer areal extent of the hypoxic zone along the Texas-Louisiana shelf varies from year to year (Figure 2.1). A noticeable increase in the size of the hypoxic zone occurred after the 1993 flood of the Mississippi-Atchafalaya Rivers, although this increase has not been sustained. The size of the hypoxic zone varied between 4,400 km^2 and 22,000 km^2 from 2000 through 2005 (Figure 2.1).

One reason for the apparent large variability in the size of the hypoxic zone is because only one cruise was done each year. When this happens to follow immediately after passage of a tropical storm or hurricane, as in 2003 and 2005, then a much smaller area of hypoxia will be measured than might otherwise be expected. Also, the amount of water coming down the river does affect apparent size of the hypoxic region, as in 2000 when discharge was low.

It has been known since 1973 that hypoxia occurs over the Louisiana shelf (Harris et al., 1976; Ragan et al., 1978; Turner and Allen, 1982; Boesch and Rabalais, 1991; Rabalais et al., 2002), but there is now evidence that hypoxia goes back to as early as the 1817 (Osterman et al., 2005). On the Texas shelf, occurrences of hypoxic waters are less frequent, shorter lived, and more limited in extent than those over the Louisiana shelf (Rabalais et al., 1998, 1999; Rabalais 1992). Harper et al. (1981, 1991) first documented hypoxia along the Texas coast in June and July of 1979. The hypoxic area extended from Freeport, Texas, northeast to Sabine Pass in 10- to 33-m depths. Hypoxia also was recorded at this location in June 1982 and 1983 and possibly occurred in June 1984

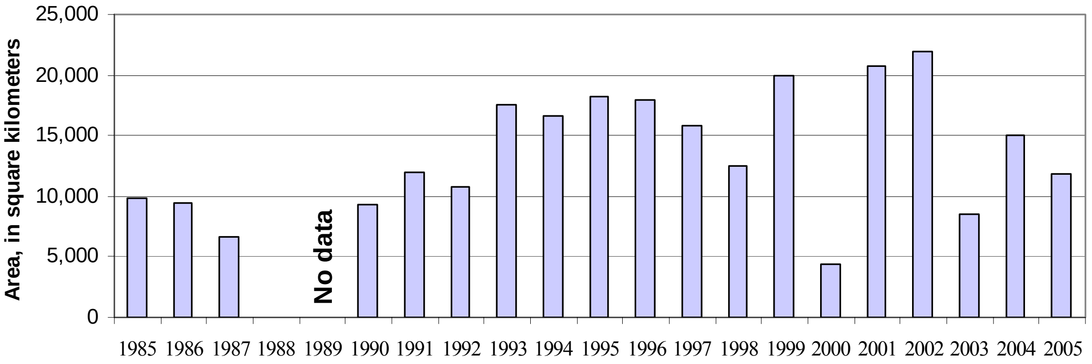


Figure 2.1. Mid-summer areal extent of hypoxic waters in the northwestern Gulf of Mexico between 1985 and 2005. In 1988, the hypoxic zone measured 40 km^2. (Data source: Nancy Rabalais, LUMCON).

(Harper et al., 1991; Kelly et al., 1983). South of Freeport, Texas, between Port O'Connor and the Rio Grande, the lowest dissolved oxygen found was 3.2 mg·L^{-1} (2.24 mL·L^{-1}) in 18-m water depth in June 1975 (Sackett and Brooks, 1976; Sackett et al., 1977, 1979). On the inner shelf between Galveston Bay and Matagorda Bay, seasonal sampling (4 times per year) revealed scattered low-oxygen concentrations in July 1973 (Oetking et al., 1974) with one value of 0.14 mL·L^{-1} in 15.5-m water depth and 1.4 mL·L^{-1} in 21-m water depth. Low-oxygen concentrations were not documented at shallower or deeper stations.

Bay systems in the western Gulf of Mexico are known to experience hypoxic conditions. For example, hypoxia has been documented in the southern part of Corpus Christi Bay, in Texas, every summer since 1988 (Montagna and Kalke, 1992; Martin and Montagna, 1995; Ritter and Montagna, 1999, 2001). Hypoxia also has occurred in parts of Galveston Bay (Seiler et al., 1991), in Offatts Bayou (Gunter, 1942) and other Texas estuaries such as in Matagorda Bay, Aransas Bay, and Laguna Madre (U.S. Environmental Protection Agency, 1999).

Unlike the Texas-Louisiana shelf, there are few documented occurrences of hypoxia over the northeastern Gulf shelf between the Mississippi River Delta and the west Florida shelf. Most reported occurrences in this region are in years of high river discharge. Rabalais (1992) reported hypoxic waters off Mississippi Sound and Mobile Bay following high flow of the Mississippi River in 1991. Waller (1998) also reported hypoxia off the Mississippi Sound and Mobile Bay following the 1993 Mississippi River flood. A recent report by Jochens et al. (2002) of the NEGOM-COH study found occurrences of near-hypoxic bottom water in the inner shelf region adjacent to the Mississippi River Delta. Bottom dissolved oxygen concentrations off Chandeleur Sound were as low as 1.9 $mL{\cdot}L^{-1}$ in summer of 1998 (a year of high Mississippi River discharge) and off Chandeleur and Mississippi Sounds were at least as low as 1.5 $mL{\cdot}L^{-1}$ in spring of 1999.

Estuaries and bays in the northeastern Gulf of Mexico also experience hypoxia. For example, Schroeder (1977) reported hypoxic water in Mobile Bay in 1973 following flooding by the Mobile River. Martin et al. (1996) noted that Mobile Bay has a history of seasonal hypoxia that often results in migration of a high number of fish and invertebrates to the shore of the bay in an attempt to escape low dissolved oxygen waters. The U.S. Environmental Protection Agency (1999) noted that in Mobile Bay low-oxygen waters were commonly observed from June through October and primarily resulted because of enhanced vertical stratification. Hypoxia also has been reported in Tampa, Sarasota, and Hillsborourgh Bays and Charlotte Harbor, Florida (Martin et al., 1996; Gray et al., 2002). Brickers et al. (1999) reported that, unlike the east and west coasts of the U.S., most estuaries around the Gulf experience periodic hypoxia because of their location in a subtropical climate.

2.2. Causes of Hypoxia in the Northern Gulf of Mexico

The major source of fresh water and nutrients to coastal waters of the northern Gulf of Mexico is the Mississippi-Atchafalaya River system (Dunn, 1996), although other rivers can and do make significant local contributions. Direct measurement of dissolved inorganic nitrogen indicates that nitrogen inputs to the northwestern Gulf of Mexico via this river system have increased since the turn of the century (Turner and Rabalais, 1991; Rabalais et al., 1996), although nitrate loading has declined somewhat since 1983. The resultant nutrient loading to the Louisiana shelf has been hypothesized as the source of enhanced productivity, which in turn is believed to contribute to the widespread hypoxia observed in the sub-pycnocline waters of the Louisiana shelf (Rabalais et al., 2002, 2003). It has been suggested that reducing nitrate loading in the Mississippi River will reduce the extent and intensity of hypoxia off Louisiana (Turner and Rabalais, 1994; Diaz and Rosenberg, 1995; Committee on Environment and Natural Resources, 2002; Howarth, 2001; Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001; Rabalais et al., 2002, 2003).

The suggested reduction of nitrogen input as the means of reducing hypoxia is based on the eutrophication paradigm—the sequence of processes generally thought to occur in aquatic and marine ecosystems that suffer from high rates of external nutrient loading. This sequence begins with input of nutrients that stimulates primary production. Much of the organic carbon produced by primary production is transferred to the benthos and fuels aerobic respiration, utilizing the available dissolved oxygen in the water. The rates of water column respiration and bottom respiration can account for the decline in bottom water oxygen in the area (e.g., Turner, 2001; Justic, 1997; Lohrenz et al., 1997; Dortch et al., 1994; Justic et al., 1993).

A temporal record of organic carbon accumulation that is about 100 years long was derived from sediment cores collected at several sites west of the Mississippi River. It indicates that the rates of accumulation of organic carbon are high now but decline back through time to a relatively constant level before 1900 (Eadie et al., 1992). The first noticeable increase began in the 1920s to 1950s (Sen Gupta et al., 1996). Eadie et al. (1994) showed that carbon accumulation in the sediments correlates with the increase in nutrient loading in the Mississippi River, thereby contributing to, or directly causing, the observed hypoxia in bottom water during summer. Carbon accumulation in the sediment was found to be from local production because there has been no evidence of an increase of organic carbon or silicate of riverine origin since the 1950s (Turner and Rabalais, 1991; Goolsby et al., 1999). Thus, the accumulated organic carbon originated primarily from marine phytoplankton. This is supported by stable carbon isotope analysis (Eadie et al., 1994; Turner and Rabalais, 1994). Nelson et al. (1994) attributed the increase in nutrient loading in Gulf waters to an increased use of fertilizers by the farm industry, thus presumably confirming the paradigm.

Based on these hypotheses, the U.S. federal government initially attributed worsening hypoxia to farming practices. It then carried out a number of studies to assess whether nitrogen used by farmers in the midwestern United States was carried by the Mississippi River into the Gulf where it caused hypoxia. The Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (2001) identified at least three causes of hypoxia, but, included suggestions for dealing with only one—nutrient loading. The three causes identified were: (1) excessive nutrient loading, (2) physical changes in the drainage basin, such as channeling the Mississippi River and loss of natural wetland and vegetation along the banks as well as wetland conversion throughout the basin, and (3) enhanced vertical stratification in the waters of the northern Gulf of Mexico. This focus on one cause, rather than consideration of the multiple contributing factors, may not lead to a full solution to the problem. Reducing the amount of nitrogen that leaves farm fields and is carried to the Gulf can only help decrease the size of the hypoxic zone (Chapman, 2004, personal communication). Whether, it would be enough to reduce the affected region to less than 5000 km^2 as suggested in Rabalais et al. (1999) would depend on the combined factors contributing to hypoxia.

Factors that might play important roles in the hypoxia issue and yet have not been quantified are the changes in the hydrology, geomorphology, and coastline that are always occurring and can affect water quality and ecosystems in coastal water. For instance, channelization and leveeing of the Mississippi River result in more rapid transit of river water to the Gulf and less opportunity for interaction with wetlands in the floodplain where nitrate removal would occur (Carey et al., 1999). Also, the increased flow down the Atchafalaya River by 1950 lead to an increase in the amount of nutrients the river system delivers to the Louisiana shelf. What is more, many of the original freshwater wetlands and riparian zones in the Mississippi basin that were connected to the streams and rivers are now disappearing (Mitsch et al., 2001). According to the U.S Fish and Wildlife Service more than 58,500 acres of wetlands are destroyed annually and with the loss of these wetlands entire ecosystems that utilized the nutrients are lost (Dahl, 2000). In the Mississippi River Delta, the highest rate of wetlands loss coincides with the build up of levees that isolate the lower Mississippi River and its tributaries from the flood plain ecosystem (Day et al., 2000).

When water flows through wetland-dominated watersheds there is a reduction in nutrient concentration, especially of nitrate (e.g., Lane et al., 1999, 2002; Spieles and Mitsch, 2000; Boustany et al., 1997). The use of coastal wetlands and shallow water bodies to condition Mississippi River water before it enters the Gulf of Mexico has been proposed as a partial solution to help reduce the size of the hypoxic zone (from Coast 2050: Toward a sustainable coastal Louisiana, 1998; Mitsch et al., 2001).

There are other indications that nitrogen fertilizer usage is not solely responsible for hypoxia occurrences. Nitrogen fertilizer input to the Mississippi-Atchafalaya River Basin increased dramatically between 1951 and 1980 and then leveled off, whereas, the mean nitrate concentrations in the Mississippi River at St. Francisville, LA, did not increase beyond the level of 1951 until 1975, and the increase of 0.5 $mg{\cdot}L^{-1}$ that did occur has not been maintained in time (Figure 2.2). Thus there is no clear relationship between the annual nitrogen fertilizer input to the Mississippi-Atchafalaya River Basin and the concentration of nitrate in the Mississippi River at St. Francisville, LA.

Furthermore, there is a similar pattern between the annual flux of nitrogen from the Mississippi River and the surface areal extent of bottom water hypoxia in the Gulf of Mexico from 1985 to 1993, but not for the period 1994-1999 (Figure 2.3 shows the annual nitrogen flux and for each year also gives the surface areal extent shown in Figure 2.1). The mid-summer areal extent of the hypoxic water for the period 1994-1999 was large, close to the size of the 1993 hypoxic zone, whereas, the annual nitrate flux from the Mississippi River Basin was about the level of nitrate flux before 1993.

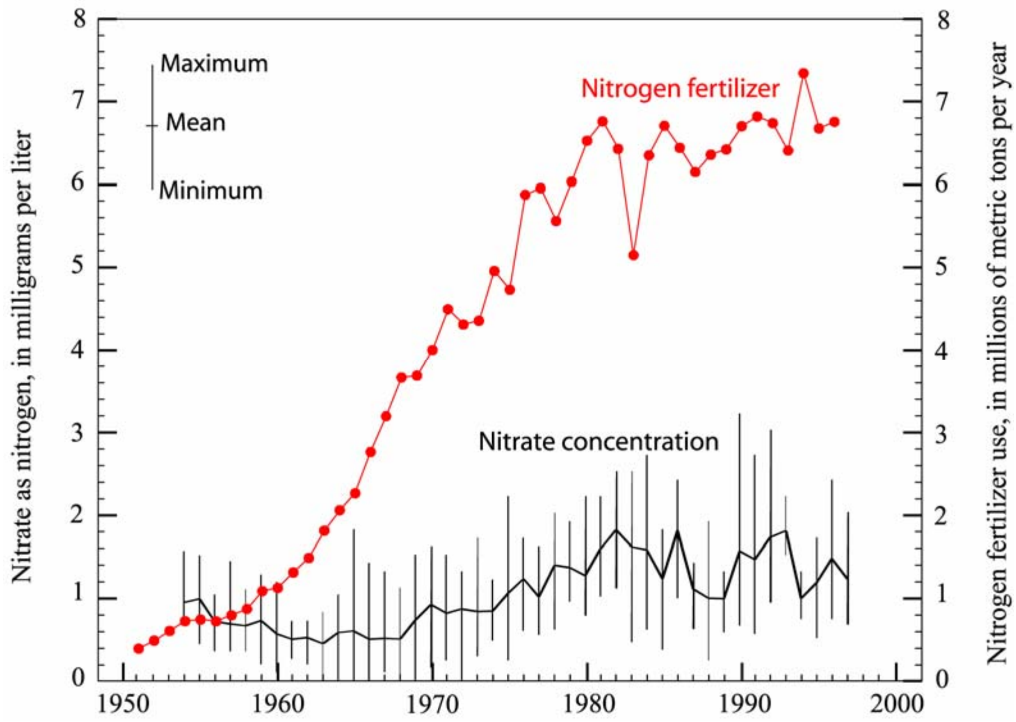


Figure 2.2. Annual nitrogen fertilizer input to the Mississippi-Atchafalaya River Basin (1951-1996), and nitrate concentrations in the Mississippi River at St. Francisville, LA (1954-1997). Figure adapted from Goolsby et al. (1999).

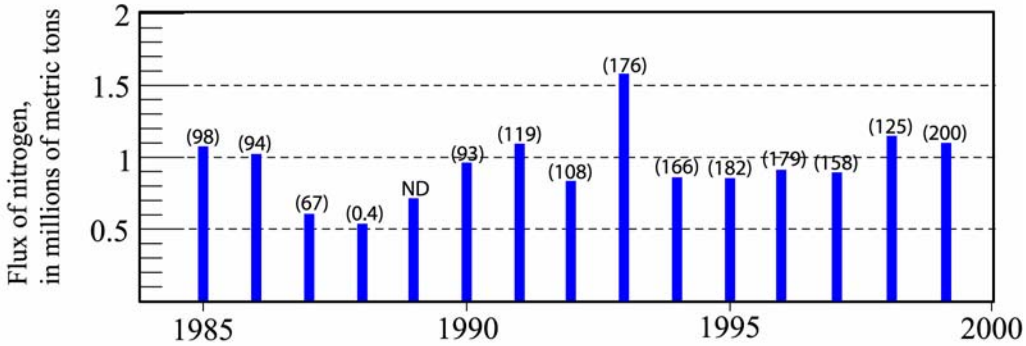


Figure 2.3. Annual flux of nitrate from the Mississippi River Basin to the Gulf of Mexico. Figure adapted from Goolsby and Battaglin (2000). The numbers above the bars represent the area of hypoxia measured that year, in 10^2 km^2. ND refers to No Data.

Some scientists are concerned that the current eutrophication paradigm is oversimplified. Rowe and Chapman (2002) addressed weaknesses in the paradigm. They proposed that vertical stratification imposed by fresh water input, not nitrate input might be at least as important a cause of hypoxia in the northern Gulf of Mexico. They noted that Wiseman et al. (1997) showed that hypoxia over the Louisiana continental shelf correlates as well with the strength of the density gradient as it does with nitrate. River discharge adds fresher, less dense water to the surface, increasing the stratification of the water column and thus reducing vertical exchange of water between the less dense, oxygenated surface water and the more saline deeper water. So, more freshwater flow to the region leads to stronger vertical density gradients and increases the likelihood of hypoxia.

Carey et al. (1999) pointed out that long-term stream flow records at Vicksburg, Mississippi, and at Simmesport, Louisiana, show that the annual average flow in the Mississippi River and Atchafalaya River, respectively, was greater at the end of the 20th century than in most years in that century. This suggests that long-term variations in Mississippi-Atachafalaya River discharge also should be considered. Rowe and Chapman (2002) observed that the 1990s were much wetter as a decade than the long-term mean and that in most years of the decade there were subsidiary peaks in the flow after the main spring runoff that might have helped maintain the density structure. What is more, Osterman et al. (2005) found that the early (1817-1910) events of hypoxia over the Louisiana shelf were related to above-normal discharge rates of the Mississippi River. Clearly, changes in river discharge rates must be considered as affecting hypoxic-favorable conditions.

Slow replacement over time of waters below the pycnocline also is required for hypoxia to occur (Rowe and Chapman, 2002). Murray (1998) reported that off the Mississippi River Delta current velocities in the sub-pycnocline layer are only about 1-3 $cm \cdot s^{-1}$ in summer. As suggested by Rowe and Chapman (2002), these very low velocities enhance the probability of occurrence of hypoxia in this region. In general, during summer, salty water is transported northward and eastward along Texas and Louisiana by a wind-driven flow regime directed from Mexico toward the Mississippi River Delta (Li et al., 1997). (This direction is referred to as upcoast because it is opposite to the direction a shelf wave would propagate, called downcoast.) Water discharged from the Mississippi-Atchafalaya River system is held over the Louisiana shelf in summer rather than being transported out of the area as in other seasons when there is downcoast flow. As low-salinity water is pooled over the Louisiana shelf, the stratification of the water column increases. This stratification facilitates the formation of hypoxic bottom waters by restricting the supply of dissolved oxygen from surface to sub-pycnocline waters. The summer upcoast flow and the continuous input of fresh water to the system provide additional time for respiration processes in both water and sediments to reduce the oxygen content of the water column and thus enhance hypoxia occurrence.

Unlike the northwestern Gulf of Mexico, observations made in the northeastern Gulf of Mexico during 1997-2000 (NEGOM-COH program) showed that the circulation over the shelf causes low-salinity water from the Mississippi and other rivers to be distributed over the inner shelf mainly in spring and not in summer (Jochens et al., 2002). In summer, most of the low-salinity discharge of the Mississippi River is advected eastward along the outer continental shelf and slope by off-shelf circulation features such anticyclones and cyclones (Belabbassi et al., 2005). Cases of low-oxygen water near the bottom at some shallow stations during the NEGOM-COH program were more prevalent on spring cruises than on summer cruises (Jochens et al., 2002).

Other processes important in the formation of hypoxic conditions are those responsible for the removal of dissolved oxygen from the water column, particularly near the bottom. Such processes are water column respiration, bottom water nitrification, and oxygen consumption by benthic communities. The rates for these processes are not known accurately. For example, microbial respiration of terrestrial particulates (Trefrey et al., 1994) and dissolved organic material (Lopez-Veneroni and Cifuentes, 1994) introduced in high concentration by rivers may be important (Carey et al., 1999), but they have not yet been quantified. Biogenic terrestrial detritus now is believed to be more reactive than thought previously (Amon and Benner, 1996; Sun et al., 1997; Mayer et al., 1998). Sulfide, Fe^{++}, Mn^{++}, NH_4^+ (Morse and Rowe, 1999; Rowe et al., 2002), and dissolved organic matter react with oxygen and contribute to its reduction, but the rates of these processes have not been estimated yet (Rowe et al., unpublished data). Rabalais and Turner (2001) pointed out that because the 1993 flood brought a large amount of organic material to the benthic systems of the Louisiana shelf and adjacent regions, it will take many years for this material to be oxidized.

Rowe and Chapman (2002) also noted that photosynthesis rates in the Mississippi River plume are relatively modest when compared with coastal environments in many other areas of the world (e.g., Walsh et al., 1989). The Gulf of Mexico is nitrate limited. Generally, the bulk of the nitrate in the Gulf is found below the euphotic zone and hence has little effect on productivity. Moreover, there is little evidence that oxygen demand on the seafloor or in the water column is exceptionally high below the plume. The respiration rates are low where they might be expected to be high, if the simple paradigm of hypoxia holds (Rowe and Chapman, 2002).

To summarize, from the examples given above nitrogen loading is not the sole cause of hypoxia in the Gulf of Mexico. There is convincing evidence that other physical and biogeochemical processes are important, perhaps equally so, for the occurrence of hypoxia. The combination of all likely causal factors must be assessed before conclusions can be drawn as to the effectiveness of management actions.

2.3. Effect of Nutrient Loading and Hypoxia in the Northern Gulf of Mexico

Nutrients in the Mississippi-Atchafalaya River system and other rivers help maintain the fisheries of the Gulf of Mexico. Primary production over the inner shelf of the Gulf of Mexico is nitrogen limited (Sklar and Turner, 1981), and nutrient inputs by rivers far exceed the capacity of the coastal oceanic system to produce nutrients (Caddy, 1993). This is important because the continued input of new nitrogen determines the total capacity of the system to produce sustainable fish harvests (Caddy, 1993). The northern Gulf of Mexico supports one of the most productive fisheries in the world. According to the National Marine Fisheries Service (NMFS: http://www.st.nmfs.gov /st1/commercial/landings/annual_landings.html), in 2004 the Gulf commercial landing for all species had an annual dockside value of about $670 million. Of this amount, 41% was produced by Louisiana, 25% by Texas, 12% by Mississippi-Alabama, and 22% by west Florida.

However, several studies suggest that nutrient enrichment over long periods leads to broad-scale degradation of the marine environment (e.g., Turner and Rabalais, 1991; Eadie et al., 1994; and Nelsen et al., 1994). Initially the increased fisheries production may offset any detrimental effects of hypoxia. But as eutrophication increases and hypoxia expands in duration and area, the fisheries production base is affected and declines (Diaz and Rosenberg, 1995).

Over the northern Gulf of Mexico, several studies examined the effect of hypoxia on living organisms. Gaston (1985) found that during the 1981 summer hypoxia event on the inner shelf off Cameron, Louisiana, the populations of most species of macrobenthos were dramatically reduced. Gaston (1985) further added that shrimp fishers in Cameron, Louisiana, pulled their nets as close to the beach as possible during the periods of summer hypoxia probably because hypoxia forced the shrimp and fish inshore to the better-oxygenated waters. While mobile species may escape hypoxic water, immobile benthic species such as tube dwellers and some surface feeders are severely affected (Gaston, 1985). Rabalais and Harper (1992) documented a decline in species abundance and species richness as water conditions progressed from oxygenated in the spring to hypoxic in the summer. Cruz-Kaegi and Rowe (1992) attributed the low benthic macrofauna biomass to high sediment loading from the Mississippi River system and seasonal hypoxia. Over the Texas shelf, Harper et al. (1981) reported a decrease in species diversity and abundance associated with the 1979 summer hypoxia (early June-August) off Freeport. At this same location, Pavela et al. (1983) reported that mobile shrimp and other bottom fish moved into areas of higher oxygen concentrations to avoid areas of hypoxia. Renaud (1986) demonstrated under laboratory conditions that white and brown shrimp avoided intruding waters with dissolved oxygen concentrations less than 1.05 $mL \cdot L^{-1}$ and 1.4 $mL \cdot L^{-1}$, respectively. Zimmerman et al. (1995) examined shrimp catch per unit fishing effort over the Louisiana shelf and found no relationship with percent of the area that is hypoxic. Note that fishing effort is generally less in periods of widespread hypoxia for unrelated reasons. In Mobile Bay, Alabama, Loesch (1960) and May (1973) explained that demersal fish and crustaceans escape hypoxic waters by moving inshore into shallow water during summer.

Most of the research examining the effects of eutrophication and hypoxia in the northern Gulf of Mexico has emphasized the loss of marine biota in general. However, Dagg (1995) proposed that increased primary production over the northern Gulf might be increasing secondary production of commercially important fishery species. He suggested that any proposed decrease in riverine nutrient loading to alleviate hypoxia should be weighed against the possible effects this decrease may have on species at higher trophic levels.

2.4. Similarities and Differences Between the Gulf of Mexico and Other Regions Where Hypoxia Is Observed

As for regions close to the Mississippi River Delta, many other areas near the mouths of the world's major river systems have experienced hypoxic or anoxic events (Degens et al., 1991; Diaz and Rosenberg, 1995; Glausiusz, 2000; Joyce, 2000; Diaz, 1997, 2001). The Rhine River in the North Sea and the Pearl River in China are two notable examples. Gray et al. (2002) listed many bays (e.g., Kiel, Germany; Vilaine, France; Tokyo, Japan; Chesapeake, USA) and estuaries (e.g., Port Hacking, Australia; Pamlico, Rappahannock, and York Rivers, USA) around the world with observed hypoxia or anoxia and gave references for each. So, in this respect, the northern Gulf of Mexico is not unique.

The decline in dissolved oxygen concentrations in many of these ecosystems has been attributed mainly to an increase in nutrient loading, similar to the attribution of hypoxia over the Louisiana shelf. The increase in nutrient loading in many of these systems was directly linked to increased human population and industrialization along coastal river drainages, modern agriculture, and loss of inland wetlands (Earles, 2000). Mass mortality of fish and benthic species and frequent loss of biodiversity often were reported in ecosystems that are moderately or severely stressed by hypoxia (Diaz, 2001).

The economic effects related to hypoxia in these systems were severe and led to collapses or declines in fisheries. Interestingly, this is not the case for the Gulf of Mexico. Diaz (2001) compared the Louisiana continental shelf to three other hypoxic regions—mainly the Kattegat, the Black Sea, and the Baltic Sea. He found that the northwestern Gulf of Mexico is the only system in which there is no documented decline in fisheries.

Many countries where the effects of hypoxia are clear have reduced nutrient input to their watersheds as a potential solution to the problem. Often improvements were observed in systems regulated for years (or sometimes for decades), but hypoxia was not completely eliminated (Charlton et al., 1993; DiToro and Blumberg, 1990; Jansson and Dahlberg, 1999; Mee and Topping, 1999).

Hypoxia in many regions around the world results from factors other than high anthropogenic nutrient input. For example, in the Rappahannock and York Rivers estuaries, tidal mixing and/or proximity to the hypoxic waters of Chesapeake Bay control the periodicity of hypoxia. In the York Bight, a study by Walsh (1988) showed that hypoxic events on the shelf were attributable to unusual hydrographic and/or climatic events, not to an increased anthropogenic input. Gray et al. (2002) cited as causes such events as "a warm winter with large terrestrial runoff, a low frequency of spring storm events resulting in a deep spring thermocline, persistent southerly summer winds, a large autochthonous carbon load, and low grazing pressure." What is more, Stoddard and Walsh (1986) showed that anoxic events might occur without any allochthonous input of organic carbon and that climatic conditions were extremely important in driving the event in the York Bight.

Another example demonstrating that factors other than the addition of nutrients and/or organic matter from anthropogenic sources can drive hypoxia is found in studies of the Agulhas Bank, south of Africa. In that region during summer, hypoxia develops even without fresh water input from the few rivers along the southern coast of South Africa. Summer solar heating and very low water movement result in the establishment of a strong pycnocline that help the development of hypoxic conditions (Chapman and Shannon, 1987; Carter et al., 1987).

Flooding associated with heavy nutrient and organic material loading also may cause a decline in dissolved oxygen concentrations. In North Carolina when the rains of Hurricane Floyd caused extensive flooding in September 1999, a heavy load of nutrients from dead animals, flooded animal waste ponds, and numerous other sources reached the sounds that lie between the coast and the outer banks, and oxygen levels in the water plummeted (Paerl et al., 2001).

In Europe, the lack of recent flushing of the deep basins of the Baltic Sea, not coastal eutrophication, has been identified as a primary cause for the observed anoxic conditions (Conley et al., 2002).

Hypoxia occurs naturally over millions of square miles of the world ocean in regions of major upwelling events (Demaison and Moore, 1980). In these areas, hypoxia or anoxia is not driven by anthropogenic changes but by mesoscale variability changes often driven by the wind field.

To conclude, hypoxia or anoxia occurrences result from the interplay of a variety of factors, including weather (e.g., frontal passages, winds, rainfall, temperature), oceanographic conditions (e.g., stratified or mixed areas, areas with a sill or without, tidal mixing, currents, waves), and anthropogenic forcing (e.g., sewage, agricultural and forestry runoff). Marine ecosystems encompass a variety of systems such that there is no simple model of oxygen depletion that can fit all these forms of variability. It is thus important that coastal zone managers take into consideration all the factors that might be important in causing hypoxia in their particular region.

CHAPTER III

THE STUDY APPROACH

Local conditions and processes that are responsible for the observed hypoxia in coastal ecosystems are but a reflection of the regional physical processes integrated over some period prior to the present conditions. In this chapter I review briefly relationships between regional physical forcing (such as wind, river discharge, heating, and currents) and the local conditions and processes responsible for low-oxygen concentrations in near-bottom waters. Also, in this chapter I define a limiting value of dissolved oxygen concentration used in the remainder of the dissertation. Finally, I discuss the rationale, based on fresh water discharge, for dividing the study area into four separate regions.

3.1. Effects of Regional Physical Forcing on Local Processes/Conditions

Local processes determine the vertical distribution of dissolved oxygen in the water column (Figure 3.1). These processes may be physical (such as air-sea interactions, vertical mixing, advection, and diffusion) or biogeochemical (such as respiration, photosynthesis, remineralization, denitrification, and nitrification). Both physical and biogeochemical processes add or remove oxygen in different parts of the water column. We may consider an upper layer that extends from the surface to just above the pycnocline and a lower layer that includes the main pycnocline and the rest of the water column.

The effects of the local biological processes in the upper layer are superimposed on those of local physical processes. In the absence of biology, oxygen in the upper layer is principally determined by gas exchange with the atmosphere. At the air-sea interface, oxygen concentrations are affected by different parameters such as: wind speed, air and sea temperatures, salinity, surface films, and wave action and bubble injection rates (e.g., Pilson, 1998). Surface waters are normally nearly saturated with dissolved oxygen, the solubility being mainly dependent on temperature and salinity. These well-oxygenated surface waters are vertically mixed through the surface layer as a result of winds. Photosynthesis, if rapid enough (as in the case of phytoplankton blooms), may supersaturate the upper layer with oxygen production. Storms also can result in supersaturation due to bubble injection (e.g., Broecker and Peng, 1982). Oxygen removal

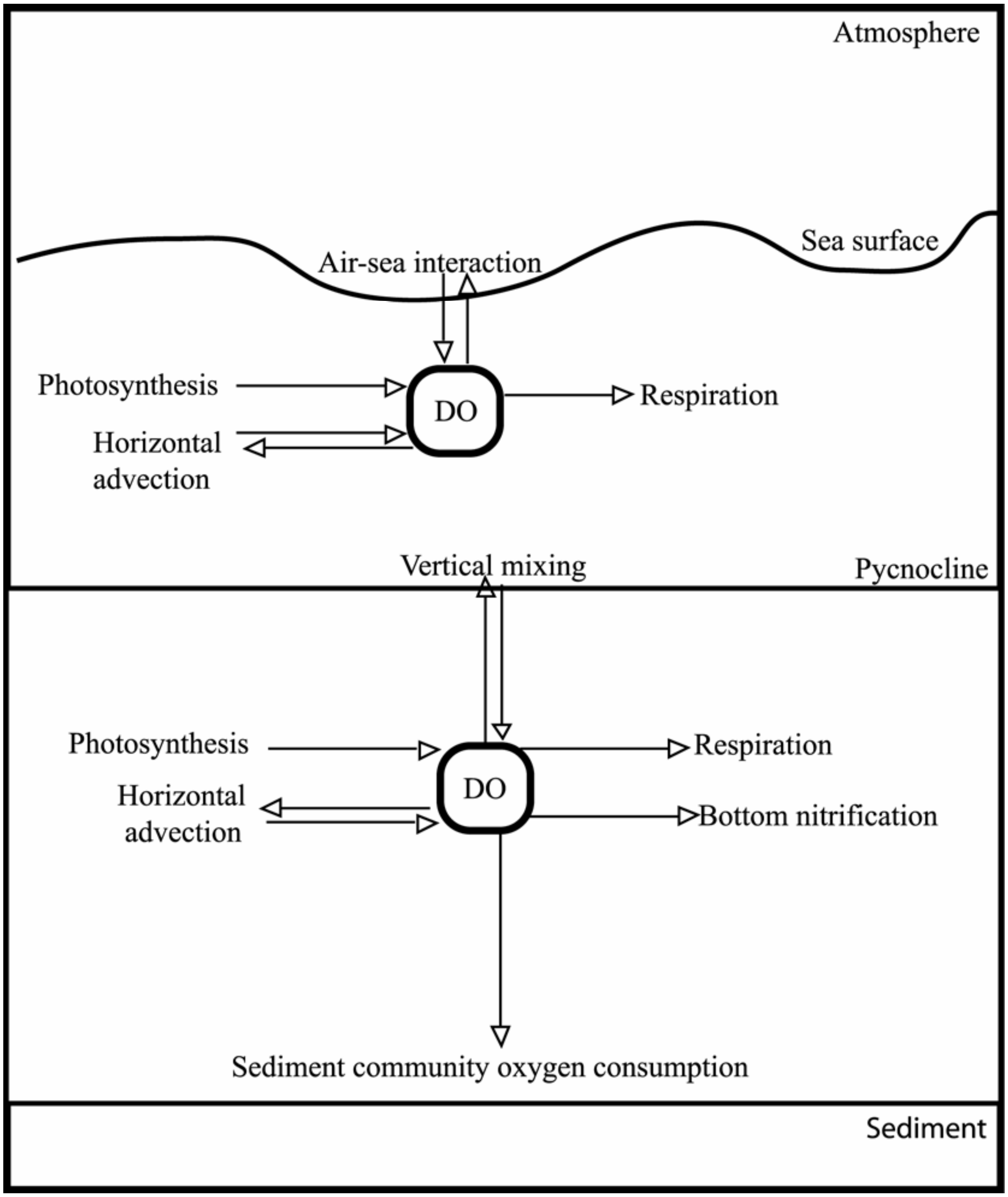


Figure 3.1. Sources (arrows into boxes) and sinks (arrows out of boxes) of dissolved oxygen in inner shelf waters.

in this layer by respiration, remineralization and nitrification has little effect on local oxygen concentrations because supply far exceeds removal.

The upper layer supplies oxygen to the lower layer mainly through vertical diapycnal mixing (Figure 3.1). Vertical transport of dissolved oxygen through molecular diffusion is negligible. When the lower layer receives sufficient light, plants can carry on photosynthesis and hence locally add oxygen to this layer. The water in this layer is usually less than saturated with oxygen because it is not in direct contact with the atmosphere and local processes of respiration, remineralization, and bottom nitrification remove oxygen faster than the replenishment needed to maintain saturation. Also, in summer, an increase in the water layer temperature results in a decrease in oxygen solubility which means oxygen levels in even the lower layer may be lower than in other seasons, so that additional oxygen removal in this layer may drive the system hypoxic more easily than in other seasons.

Note that local physical processes associated with advection, downwelling, and upwelling, import and export dissolved oxygen in both layers. In some cases, these water movements may offset the results of the local biological processes. For example, over the inner shelf downwelling events transport oxygen-rich surface water to depths increasing oxygen concentrations in the lower layer. Horizontal advection of upwelled waters can transport low-oxygen waters into an area from neighboring regions and decrease the in situ oxygen concentration. Rabalais et al. (2001) cited an example of hypoxic water masses being forced onto barrier island shores by upwelling favorable winds and causing massive fish kills.

The extent to which the concentrations of oxygen in the lower layer actually are depleted is determined by the regional physical factors that influence the local physical and biological processes. I describe first possible influences of regional processes, such as wind, heating, and river discharge, on the local physical conditions and processes, mainly vertical mixing and stratification. Then, I describe the possible influence of river discharge on local biological processes.

In the northern Gulf of Mexico, the extent to which there is vertical mixing between the upper and the lower layer depends directly on the regional wind and indirectly on solar heating and freshening of surface waters by river runoff.

Heating and/or freshening of surface water result in a decrease in the density of the upper layer relative to that of the lower layer. This layering of the water column, commonly known as stratification, is a local condition that acts to restrict or minimize vertical mixing (Garrison, 2004). In well-stratified water columns, for example, vertical mixing is reduced considerably because the pycnocline restricts such mixing. Oxygen supply to the lower layer is then limited, and low values of dissolved oxygen may occur if the rate of removal exceeds the rate of supply. In extreme cases, where the water has been stagnant for a prolonged period of time, dissolved oxygen may be completely depleted (anoxia) and replaced by hydrogen sulfide.

Replenishment of the oxygen consumed in the lower layer would be possible if the frictional effect of the wind acts to increase vertical mixing and thereby reduces the strength of stratification. A strong wind induces strong vertical mixing that destroys stratification and increases mixing of deep water with well-oxygenated surface waters (Kumpf et al., 1999). The lower layer is then enriched in oxygen. In the case of weak winds, mixing is limited to the upper layer and, hence, does not enhance oxygen levels in the lower layer. In summary, calmer seas and warmer or fresher surface waters result in a well-stratified water column. A well-stratified water column restricts the exchange of dissolved oxygen between the upper and lower layer. When the rate of oxygen utilization in the lower layer exceeds the rate of oxygen replenishment, dissolved oxygen concentrations may drop below $1.4\ \mathrm{mL \cdot L^{-1}}$, the commonly accepted criteria for hypoxia.

In the northern Gulf of Mexico, the rates of local biological processes are principally influenced by rivers that introduce high nutrient concentrations. When light is sufficient, elevated levels of nutrients stimulate photosynthesis and cause relatively high primary production that in turn leads to high secondary and tertiary production. In aquatic ecosystems in which phytoplankton production accounts for most of the organic input to the bottom (Wakeham, and Lee, 1993), the accumulation of ungrazed organic material is a condition for oxygen depletion (Officer and Ryther, 1977). That is, once phytoplankton production exceeds the grazing capacity of zooplankton the resulting excess of phytoplankton biomass sets the stages for enhanced microbial decomposition and oxygen depletion.

Nitrification, a local process that oxidizes ammonium (NH_4) into nitrite (NO_2) and then nitrate (NO_3), water column respiration by animals and microorganisms, and sediment community oxygen consumption further deplete oxygen in the lower layer. What is more, in areas of close proximity to river mouths or openings of estuaries, river-derived allochtonous organic matter results in increased respiration in the sub-pycnocline waters, especially if the organic matter is readily available for microbial oxidation (Carey et al., 1999). Sediment from the Mississippi River is thought to include important heterotrophic substrates which, upon consumption, may result in low-oxygen conditions near the bottom; however this usually occurs in the proximity of the river mouth (Gallaway, 1981). All these factors might lead to hypoxia, or in extreme cases to anoxia, if stratification inhibits vertical mixing as major source of oxygen renewal.

From the aforementioned discussion I conclude that there are two conditions for hypoxia occurrences: (1) strong stratification sustained by the introduction of low-salinity water, reduced wind stress, and heating of surface waters, and (2) oxygen removal in the lower layer through remineralization and nitrification. The first condition prevents supply of oxygen to the bottom. The second results in extensive use of the available dissolved oxygen.

3.2. Limiting Values of Dissolved Oxygen Concentrations Used in This Study

For this study, I sought a value of dissolved oxygen concentration that separates waters with depths less than 60 m from waters over the northern Gulf shelves having commonly occurring oxygen concentrations. I examined the distribution of dissolved oxygen concentrations versus salinity on all LATEX-A and NEGOM-COH cruises (Figure 3.2).

The range of observed dissolved oxygen is 0.1 to 8.3 $mL \cdot L^{-1}$. About 98% of these values fall within the more limited range of 2.4 to 5.8 $mL \cdot L^{-1}$. For all samples collected in water depths greater than 60 m, the oxygen values fall within the latter range. Dissolved oxygen concentrations less than or equal to 2.4 $mL \cdot L^{-1}$ are found exclusively in water depths less than or equal to 60 m. Therefore, I define water with dissolved oxygen concentrations less than 2.4 $mL \cdot L^{-1}$ as low-oxygen water in contrast to the commonly occurring oxygen concentrations over the Gulf of Mexico continental shelf. I will continue to use the 1.4 $mL \cdot L^{-1}$ limit to refer to hypoxic waters.

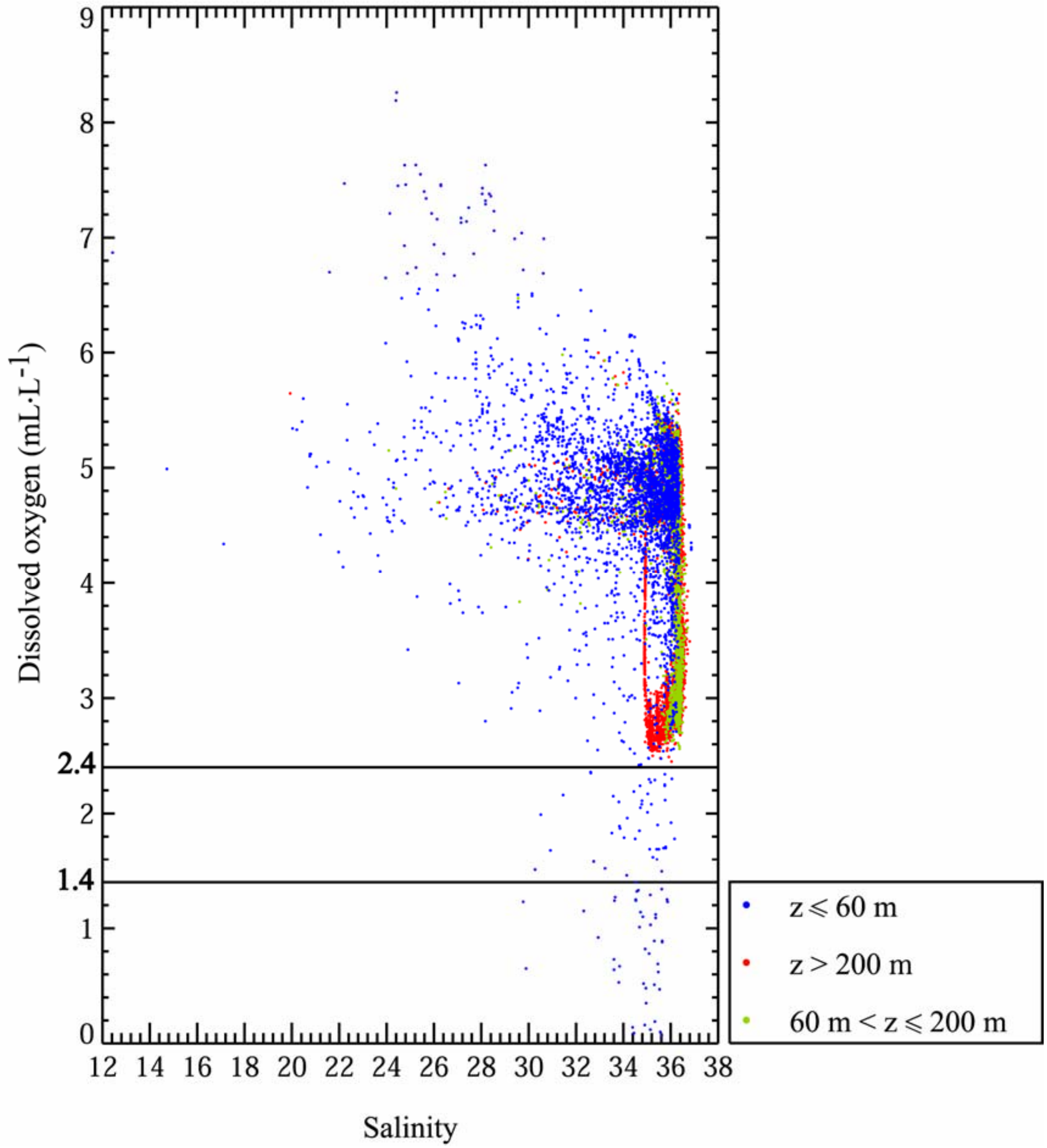


Figure 3.2. Dissolved oxygen concentrations versus salinity on all NEGOM-COH and LATEX-A cruises. z refers to depth of the water column.

3.3. Delineation of Study Subregions

The northern shelves of the Gulf of Mexico are naturally divided by the Mississippi River Delta (Figure 3.3). For this study the eastern continental shelf extends from the eastern side of the Mississippi River Delta to the west Florida shelf off Tampa Bay and the western shelf extends from the western side of the Mississippi Delta to the Rio Grande River. The principal area of interest will be the shelf with water depths of 10 to 60 m (Figure 3.3).

The eastern shelf of the northern Gulf of Mexico is relatively narrow in width (60–120 km) east of the Chandeleur Islands to Cape San Blas, where it abruptly widens to about 200 km in the Big Bend area of the west Florida shelf. On the other side of the Mississippi Delta, the western shelf is relatively wide off Cameron to Galveston (85–200 km) and then narrows to 90 km at the Rio Grande River (Figure 3.3).

Numerous rivers discharge onto the continental shelf of the northern Gulf of Mexico. Normally the majority of fresh water input to both the eastern and western shelves is from the Mississippi River. It is speculated that roughly 35 to 50% of the Mississippi discharge flows south or east from the Mississippi Delta (Dinnel and Wiseman, 1986; Etter et al., 2004).

On the western shelf, both the Mississippi and Atchafalaya rivers discharge onto the Louisiana shelf. The Atchafalaya River is the second major source of fresh water input with discharge rates maintained at approximately one third those of the Mississippi River (Table 3.1).

The Alabama and Tombigbee rivers, which discharge through Mobile Bay onto the eastern shelf, have the largest discharge next to the Mississippi-Atchafalaya River (Table 3.1). Rivers west of Mobile Bay include the Pascagoula and Pearl rivers, with discharge rates of less than or equal to 30% of the Alabama and Tombigbee rivers. To the east of Mobile Bay, the Apalachicola River has the largest discharge, but is less than 85% of that of the Tombigbee River. Discharges rates decrease further to the east, e.g., the mean discharge of the Suwannee River is approximately one quarter that of the Apalachicola River. These river discharges contribute nutrients to waters over the inner shelf. In addition they contribute to buoyancy forcing of the coastal waters. The higher discharge rates in the west and lower rates in the east result in a large decrease from west to east in

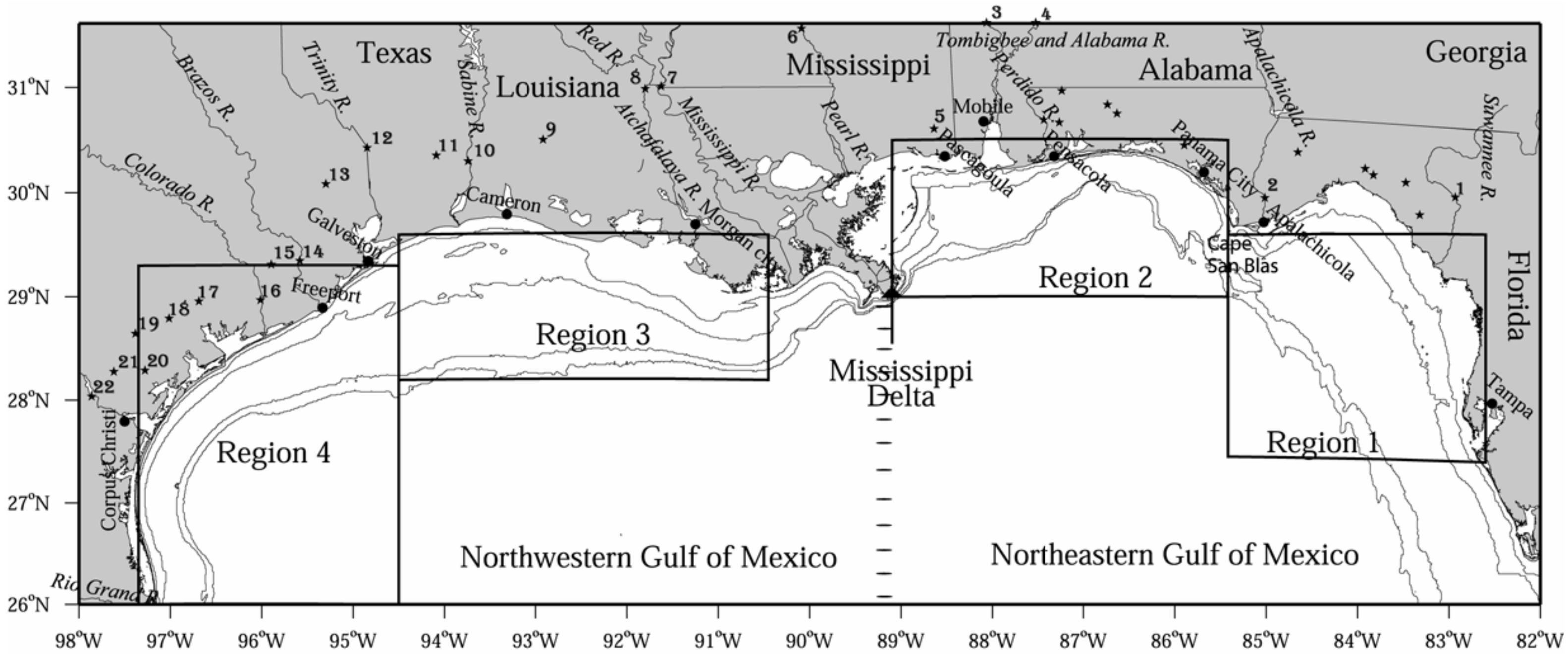


Figure 3.3. Subdivision of the study area into four principal regions. The regions are numbered from east to west. The stars on the land represent river gauging stations. Use the number next to the star to find the name of the corresponding river in Table 3.1. The 10-, 20-, 50-, and 60- m isobaths are shown.

Table 3.1. Annual average discharge rates from principal rivers east and west of the Mississippi Delta that flow onto Florida, Alabama, Mississippi, Louisiana or Texas shelves. Mississippi and Atchafalaya discharges are shown in bold. Data provided by the U.S. Geological survey and the U.S. Army Corps of Engineers (Courtesy of Matthew Howard, Texas A&M University).

River	Discharge rates $m^3 \cdot s^{-1}$	Record length (mm/dd/yyyy)
Suwannee[1]	194	07/01/1931 to 09/30/2002
Apalachicola[2]	711	10/01/1977 to 09/30/2002
Tombigbee[3]	842	08/01/1928 to 09/30/2001
Alabama[4]	926	10/01/1975 to 09/30/2001
Pascagoula[5]	169	10/01/93 to 09/30/2002
Pearl[6]	191	10/01/1938 to 09/30/2002
Mississippi[7]	**13,698**	01/01/1930 to 05/12/2004
Atchafalaya[8]	**5,789**	01/01/1935 to 05/12/2004
Calcasieu[9]	74	09/01/1922 to 09/30/2002
Sabine[10]	238	10/01/1924 to 09/30/2003
Neches[11]	180	08/01/1904 to 09/30/2003
Trinity[12]	223	05/01/1924 to 09/30/2003
San Jacinto[13]	19	05/01/1984 to 09/30/2003
Brazos[14]	229	04/01/1967 to 09/30/2003
San Bernard[15]	15	05/01/1954 to 09/30/2002
Colorado[16]	74	05/01/1948 to 09/30/2002
Lavaca[17]	11	09/01/1938 to 09/30/2002
Guadalupe[18]	55	12/01/1934 to 09/30/2002
Mission[19]	4	07/01/1939 to 09/30/2002
San Antonio[20]	21	07/01/1924 to 09/30/2002
Aransas[21]	1	04/01/1964 to 09/30/2002
Nueces[22]	21	09/01/1939 to 09/30/2002

Note: Use the superscript number next to the river name to find the river location in Figure 3.3.

buoyancy input to the shelf.

The Calcasieu is a significant river that enters the Gulf over the Louisiana shelf, but its discharge rate is small. West of the Calcasieu, there are 13 other significant rivers entering the Gulf from Texas. The Sabine, Neches, Trinity, and Brazos rivers have the largest discharge, but each account for only about 3% or 4% that of the Atchafalaya River (Table 3..1). Other rivers, such as the San Jacinto, Colorado, Guadalupe, Calcasieu, San Antonio, San Bernard, Lavaca, Nueces, Mission, and Aransas, have even smaller discharge rates, which each account about 1% or less than that of the Atchafalaya River.

It should be remembered that the discharge rates given in Table 3.1 are long-term means. During a specific time period the relative discharges of these rivers may vary widely. For example, there have been periods when the San Jacinto river discharge exceeded that of the Mississippi River (Nowlin et al., 1998b).

Based on the rates of river discharge and the morphology of the shelves, I subdivided the northern Gulf of Mexico into 4 regions (Figure 3.3). The eastern shelf may logically be divided into two regions at Cape San Blas, which separates a narrow shelf dominated by topographic influences and river discharge (Region 2: Mississippi-Alabama shelf) from a wide shelf with little discharge (Region 1: West Florida shelf). Similarly, the western shelf can be divided at 94.5°W into two regions: Region 3 (Louisiana shelf, east of 94.5°W) with a wide shelf dominated by river discharge and Region 4 (Texas shelf, west of 94.5°W) having a narrow shelf with minimum river discharge. Note that the regions are numbered from east to west.

There are other criteria that support these subdivisions. On the Texas-Louisiana shelf, hypoxic water occurs almost exclusively in Region 3. Additionally in summer, due to the upcoast or eastward currents, the 34 isohaline is almost perpendicular to the bathymetry at 94.5°W (see Figure 4.9). On the eastern shelf, near-hypoxic waters were found only in Region 2, a region of high river discharge. Circulation patterns and the rate of river discharge were found to be important for hypoxia occurrences, as discussed in Chapter IV.

CHAPTER IV

DESCRIPTION OF CAUSAL PROCESSES FROM THE LATEX-A AND NEGOM-COH OBSERVATIONS

Mapping of bottom dissolved oxygen concentrations over the northern Gulf of Mexico revealed that occurrences of bottom water with low-oxygen concentrations during LATEX-A and NEGOM-COH cruises were found almost exclusively in Regions 2 and 3 which were under large influence from rivers (Figure 4.1). Hypoxic waters were observed only in Region 3. Region 1 with minimum river discharge had no occurrences of low-oxygen or hypoxic water. Region 4, which is seasonally freshened by the advection of low-salinity water from Region 3 due to the downcoast circulation along the coast during the non-summer months, had only one station that was low in oxygen concentration near the bottom. Table 4.1 gives a detail description of the dates, locations, depths, and values of these low-oxygen and hypoxic water occurrences.

In Region 3, low-oxygen waters occupied bottom layers up to 15-m thick and were found in waters with depths between 10 and 51.5 m. In Region 2, low-oxygen waters were found in waters with depths between 14 and 29 m where they occupied the bottom 5-m or less of the water column. Thus, the occurrence of low-oxygen water was more widespread and occupied more volume in Region 3 than Region 2. For both regions there was no clear pattern between the vertical extent of low-oxygen waters, time, location, and the station water depth, except that most occurrences were in July or August. In Region 4, the only station with low-oxygen water was found in 29.3 m water depth and occupied a bottom layer less than 4 m thick. Region 1 had no occurrences of low-oxygen water. So, the occurrences of low-oxygen waters differ in the four regions. This leads to the question, "Do differences in the distribution of low-salinity water over the northern Gulf cause the regional differences in the local vertical stratification and remineralization that are responsible for low-oxygen occurrences?"

To investigate the causal processes for low-oxygen observations in bottom waters, I first examined the effect of local vertical stratification on low-oxygen and hypoxic water occurrences over the four regions. The results are given in Section 4.1. Next, in Section 4.2, I show the relative importance of temperature and salinity to the vertical water stratification. In Section 4.3 I compare vertical stratification with bottom silicate

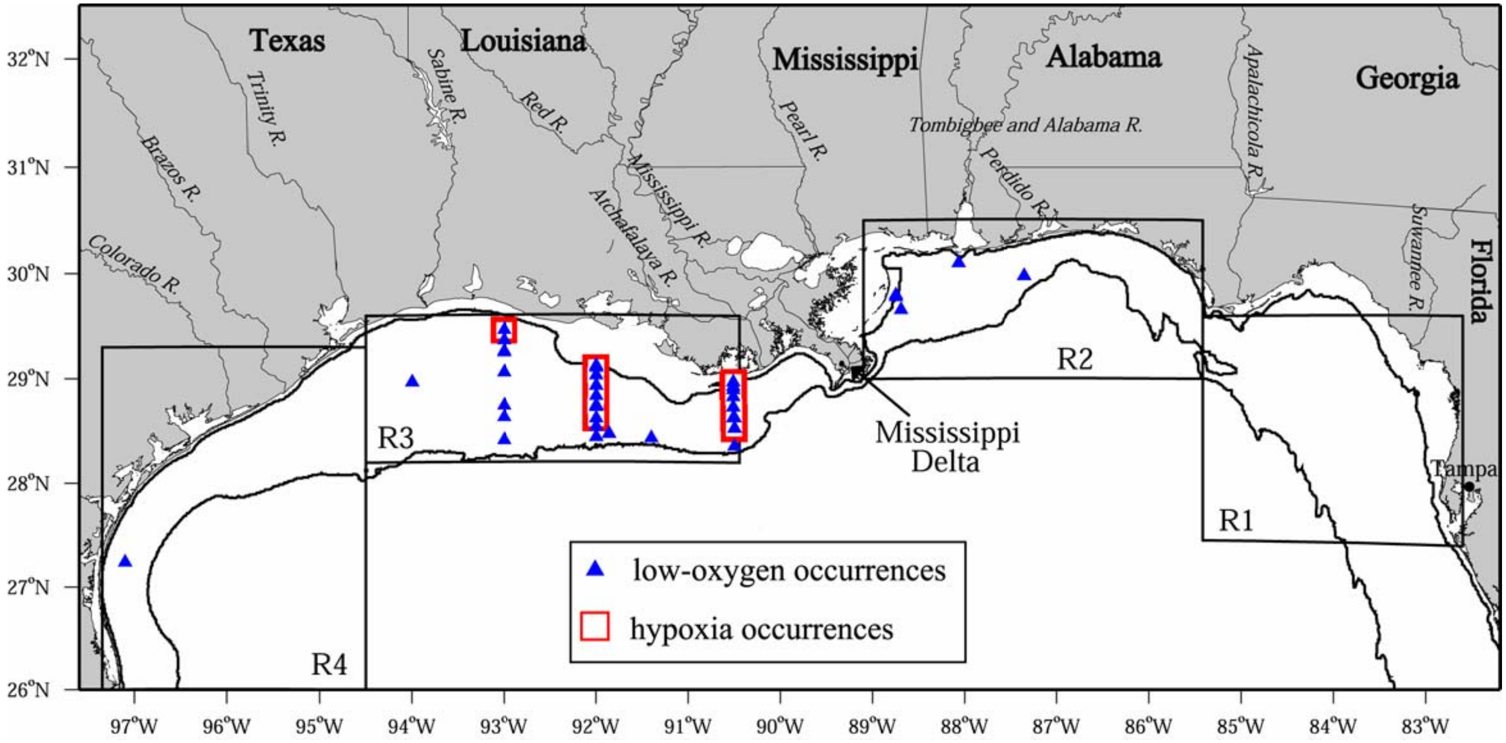


Figure 4.1. Occurrences of low-oxygen and hypoxic waters during LATEX-A and NEGOM-COH spring and summer cruises. R refers to Region. Shown are the 10-m and the 60-m isobaths.

Table 4.1. Bottles with dissolved oxygen concentrations less than 2.4 mL·L^{-1} at water depths less than 60 m.

Program	**Cruise**	**Station**	**Date (dd/mm/yyyy)**	**Longitude ºW**	**Latitude ºN**	**Water depth (m)**	**Niskin depth (m)**	**Oxygen Conc. (mL·L^{-1})**	**Depth from the bottom (m)**
LATEX	H01	32	03/05/1992	-92.1	29	16	13.4	2.24	2.6
		71	05/05/1992	-90.5	28.8	17	16.1	1.69	0.9
		73	05/05/1992	-90.5	28.9	13	8.9	2.08	4.1
							11.9	1.69	1.1
LATEX	H02	30	03/08/1992	-92.1	29.1	10.3	7.2	2.1	3.1
							8.3	1.96	2
		32	03/08/1992	-92.1	29.0	16.2	12.1	2.08	4.1
							14.7	1.62	1.5
		34	03/08/1992	-92	28.9	21.5	12.2	2.19	9.3
							15.9	1.69	5.6
							19.6	1.6	1.9
		36	03/08/1992	-92	28.8	25.8	17.9	2.27	7.9
		71	05/08/1992	-90.5	28.8	18	13.2	1.29	4.8
							17	1.34	1
		73	05/08/1992	-90.5	28.9	13.7	9.7	1.01	4
							12.4	0.48	1.3
		116	08/08/1992	-93	29.3	17.5	15.7	1.89	1.8
		118	08/08/1992	-93	29.5	13	7.2	2.36	5.8
							9.2	1.58	3.8
							11.2	0.92	1.8
LATEX	H05	18	28/04/1993	-90.5	28.8	18	15.8	1.99	2.2
		20	28/04/1993	-90.5	28.7	17.4	12.5	1.68	4.9
		21	28/04/1993	-90.5	28.6	20.5	8.5	2.16	12
							10.6	0.64	9.9
							14	0.53	6.5
							18.3	0.67	2.2
		51	29/04/1993	-92	28.6	39.8	23.7	2.01	16.1
							36.6	2.17	3.2
		52	29/04/1993	-92.2	28.8	31.5	16.2	1.87	15.3
							18.9	1.4	12.6
							21	1.24	10.5
							28.9	1.25	2.6
		53	29/04/1993	-92	28.8	26.6	14.2	1.83	12.4
							19.4	1.27	7.2
							23.6	1.24	3
		178	08/05/1993	-97.1	27.2	29.3	26.1	1.78	3.2
LATEX	H06	17	27/07/1993	-91.9	28.5	51.5	41.3	2.25	10.2
							41.3	2.24	10.2
							49.9	1.71	1.6
		19	27/07/1993	-91.4	28.4	50.6	48.7	1.92	1.9

Table 4.1. Continued

Program	Cruise	Station	Date (dd/mm/yyyy)	Longitude ºW	Latitude ºN	Water depth (m)	Niskin depth (m)	Oxygen Conc. ($mL\cdot L^{-1}$)	Depth from the bottom (m)
LATEX	H06	24	28/07/1993	-90.5	28.9	13.9	8.9	2.4	5
							11.7	0.82	2.2
		26	28/07/1993	-90.5	28.8	18.5	5.8	1.52	12.7
							14.1	0.69	4.4
							16.9	0.47	1.6
		28	28/07/1993	-90.5	28.7	18.1	6.1	1.23	12
							9.1	1.32	9
							14.1	0.78	4
							16.6	1.14	1.5
		29	28/07/1993	-90.5	28.6	22	10.5	1.51	11.5
							20.1	1.03	1.9
		30	28/07/1993	-90.5	28.5	36.4	21.3	2.11	15.1
							27.1	1.23	9.3
							34.7	1.25	1.7
		32	28/07/1993	-90.5	28.4	49.6	41.2	2.3	8.4
							47.3	1.78	2.3
		57	29/07/1993	-92	28.5	55.8	39.2	2.25	16.6
			29/07/1993	-92	28.5	55.8	46.8	2.3	9
		58	29/07/1993	-92	28.6	44.9	43.3	1.7	1.6
		59	29/07/1993	-92	28.66	39.5	31.1	1.9	8.4
							37.2	0.62	2.3
		60	29/07/1993	-92.1	28.8	31.9	23.7	1.46	8.2
							29.7	0.51	2.2
		61	29/07/1993	-92	28.8	26.3	19.1	0.73	7.2
							24.3	0.12	2
		63	29/07/1993	-92	28.9	21.4	11.1	2.35	10.3
							14.2	0.52	7.2
							19.2	0.16	2.2
		65	30/07/1993	-92.2	29.0	16.2	8.5	2.15	7.7
							11.3	0.14	4.9
							14.3	0.09	1.9
		70	30/07/1993	-93	29.5	14.7	12.6	0.65	2.1
		71	30/07/1993	-93	29.4	15.5	9	2.01	6.5
							13.3	1.5	2.2
		74	30/07/1993	-93	29.1	23.7	21.1	1.79	2.6
LATEX	H08	77	30/04/1994	-94.2	29	16.6	14.7	2.05	1.9
LATEX	H09	27	29/07/1994	-90.5	28.5	35.1	32	1.29	3.1
		28	29/07/1994	-90.5	28.6	20.8	17.2	1.85	3.6

Table 4.1. Continued

Program	Cruise	Station	Date (dd/mm/yy)	Longitude ºW	Latitude ºN	Water depth (m)	Niskin depth (m)	Oxygen Conc. ($mL \cdot L^{-1}$)	Depth from the bottom (m)
LATEX	H09	29	29/07/1994	-90.5	28.7	17.9	13.8	1.13	4.1
		30	29/07/1994	-90.5	28.8	18.7	10.2	0.35	8.5
							14.3	0.19	4.4
		31	29/07/1994	-90.5	28.9	15.8	8.7	1.05	7.1
							11.8	0.36	4
		32	29/07/1994	-90.5	29	11.5	7.1	1.1	4.4
							9.2	0.89	2.3
		34	30/07/1994	-92.1	29.1	12	6.7	0.02	5.3
							10	0.07	2
							10	0.02	2
		35	30/07/1994	-92.2	29.0	16.2	7.5	1.33	8.7
							10.2	0.07	6
							14.1	0.1	2.1
		36	30/07/1994	-92	28.9	21.8	15.6	0.42	6.2
							19.7	0.3	2.1
		37	30/07/1994	-92	28.8	27	19.2	1.12	7.8
							19.2	1.09	7.8
							24.3	0.89	2.7
							24.3	0.88	2.7
		38	30/07/1994	-92.1	28.8	32.1	28	1.72	4.1
							28	1.74	4.1
		59	31/07/1994	-93	28.4	49.6	26.8	2.3	22.8
		61	31/07/1994	-93	28.6	34.4	32	2.34	2.4
		62	31/07/1994	-93	28.8	29.3	26.7	2.29	2.6
		65	31/07/1994	-93	29.1	22.2	19.3	2.35	2.9
		67	01/08/1994	-93	29.3	16.8	14.2	2.09	2.6
		83	01/08/1994	-94	28.4	51.5	47.8	2.4	3.7
NEGOM	N2	85	15/05/1998	-88.8	29.8	16	11.6	2.12	4.4
NEGOM	N3	73	04/08/1998	-87.4	30	29	22	2.06	7
							25.5	1.89	3.5
NEGOM	N5	89	26/05/1999	-88.1	30.1	22	17.7	2.38	4.3
		91	26/05/1999	-88.8	29.8	14	12.3	1.49	1.7
		92	26/05/1999	-88.7	29.7	20	16.6	2.39	3.4
NEGOM	N6	6	18/08/1999	-88.8	29.87	14	11.2	2.3	2.8

concentrations; this provides links between remineralization, vertical stratification, and bottom oxygen concentrations. Finally, in Section 4.4 I use Empirical orthogonal Function (EOF) analysis to examine the space and time relationships between vertical stratification, bottom silicate concentrations, and bottom oxygen concentrations.

4.1. Effect of Vertical Stratification on Occurrence of Low-Oxygen and Hypoxic Water

Stratification refers to the strength of the vertical density gradient. The higher the stratification the more the water column resists vertical mixing. The Brunt-Väisälä frequency, N, is often used to express the degree of stratification (Brunt, 1927; Väisälä, 1925), or more precisely, the natural frequency of oscillation for a water parcel displaced adiabatically from its rest position. The force causing the oscillation is the buoyant force.

As pointed out by Pond and Pickard (1983), the Brunt-Väisälä frequency represents the maximum frequency of internal waves in water with frequency N. High values of N are found where the vertical density gradient is the largest. As quoted by Pond and Pickard (1983) "this is usually in the thermocline in oceanic water (where density variation may be determined chiefly by temperature variation) or in the halocline in coastal water (where density variation may be determined chiefly by salinity variation)".

For this study, the Brunt-Väisälä frequency was calculated over 0.5-m depth intervals for each hydrographic station on LATEX-A and NEGOM-COH spring and summer cruises. The method used for computing N is given in Millard et al. (1990):

$$N^2 = \rho \cdot g^2 \cdot [-\alpha \cdot ((dT/dp) - \Gamma) + \beta \cdot (dS/dp)] \text{ (radians}\cdot\text{s}^{-1})^{2}\text{, or in cycles}\cdot\text{s}^{-1}\text{: } N = N/2\cdot\Pi$$

T: temperature (°C)
S: salinity
p: pressure (decibars, dbar)
ρ: density ($\text{kg}\cdot\text{m}^{-3}$)
g: gravity acceleration ($\text{m}\cdot\text{s}^{-2}$)
α: thermal expansion ($\alpha = -(1/\rho)\cdot(\partial\rho/\partial T)$) ($°\text{C}^{-1}$)
β: saline contraction ($\beta = (1/\rho)\cdot(\partial\rho/\partial S)$)
Γ: adiabatic lapse rate ($\Gamma = -(T_a/C_p)\cdot(\partial v/\partial T)$)
v: specific volume ($=1/\rho$)
T_a: absolute temperature ($T_a = T + 273.15$) (Kelvin)
C_p: specific heat

To investigate the effect of vertical stratification on the occurrences of low-oxygen and hypoxic waters in the northern Gulf of Mexico, the maximum value of the Brunt-Väisälä frequency was compared with the bottom dissolved oxygen concentration at each station. The assumption is that a highly stratified water column facilitates the formation of low-oxygen waters by restricting the vertical mixing that can replenish oxygen in the sub-pycnocline water.

Figure 4.2 shows examples of vertical profiles of temperature, salinity, potential density, dissolved oxygen, and the Brunt-Väisälä frequency at stations 28 and 130 in summer 1993 on cruise H06 in Regions 3 and 4, respectively. The contrast between the two stations is obvious. At station 130, a poorly stratified water column, with maximum Brunt-Väisälä frequency less than 38 cycles$\cdot$h^{-1}, had concentrations of dissolved oxygen at the bottom greater than 4 mL$\cdot$L^{-1}. At station 28, however, the maximum Brunt-Väisälä frequency peaks to more than 114 cycles$\cdot$h^{-1} where the density gradient is the largest. Below this strong pycnocline, dissolved oxygen concentrations were low at the bottom with concentrations less than 1 mL$\cdot$L^{-1}. This example is consistent with the assumption stated earlier. I now investigate the validity of this assumption by examining the relation between bottom dissolved oxygen and vertical stratification in the four study regions. Note that only stations with bottom oxygen data in the lower 5 m of the water column are considered in this analysis.

Region 3 (Louisiana Shelf)

In Figure 4.3 are plotted bottom dissolved oxygen concentrations versus maximum Brunt-Väisälä frequency in Region 3 for springs and summers of 1992, 1993, and 1994. In general, for both seasons bottom dissolved oxygen concentrations decrease with increasing maximum Brunt-Väisälä frequency. Correlations between the two parameters are larger in summer than in spring, except in 1992. The square correlation coefficients shown in Figure 4.3 are all significant at the 95% confidence limit. Compared to springs 1993 and 1994 correlations, the r^2 shown for spring 1992 (cruise H01) may not be representative of the spring condition given that only 13 observations were available.

During spring and summer in Region 3, low-oxygen and hypoxic water occurred only in waters with maximum Brunt-Väisälä frequency greater than 40 cycles$\cdot$h^{-1}. Figure 4.3 shows three distinct intervals. The first interval includes maximum Brunt-Väisälä

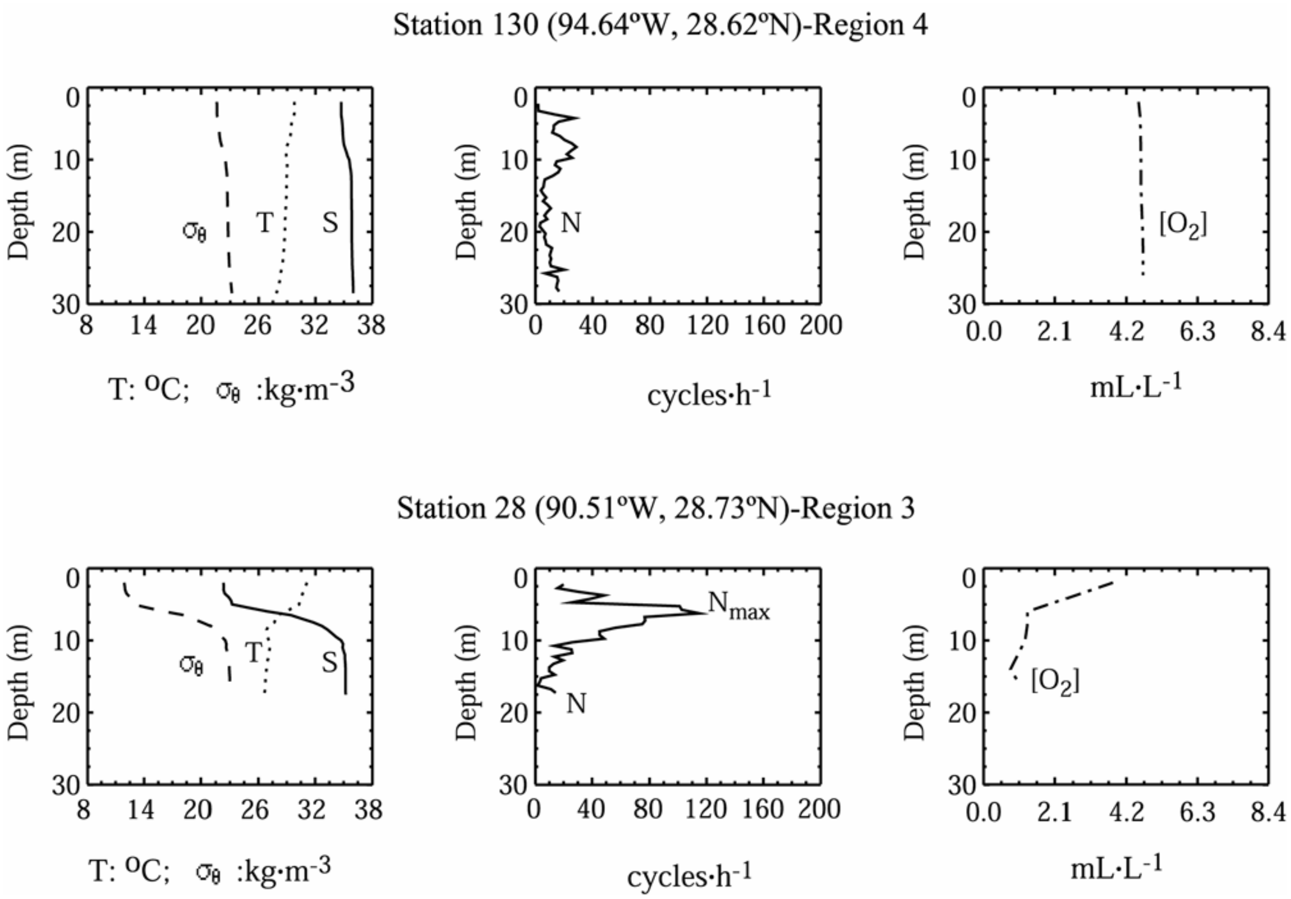


Figure 4.2. Salinity (S), temperature (T), potential density (σ_θ), Brunt-Väisälä frequency (N), and dissolved oxygen concentrations ([O_2]) versus depth for stations 130 and 28 on cruise H06 (Summer 1993).

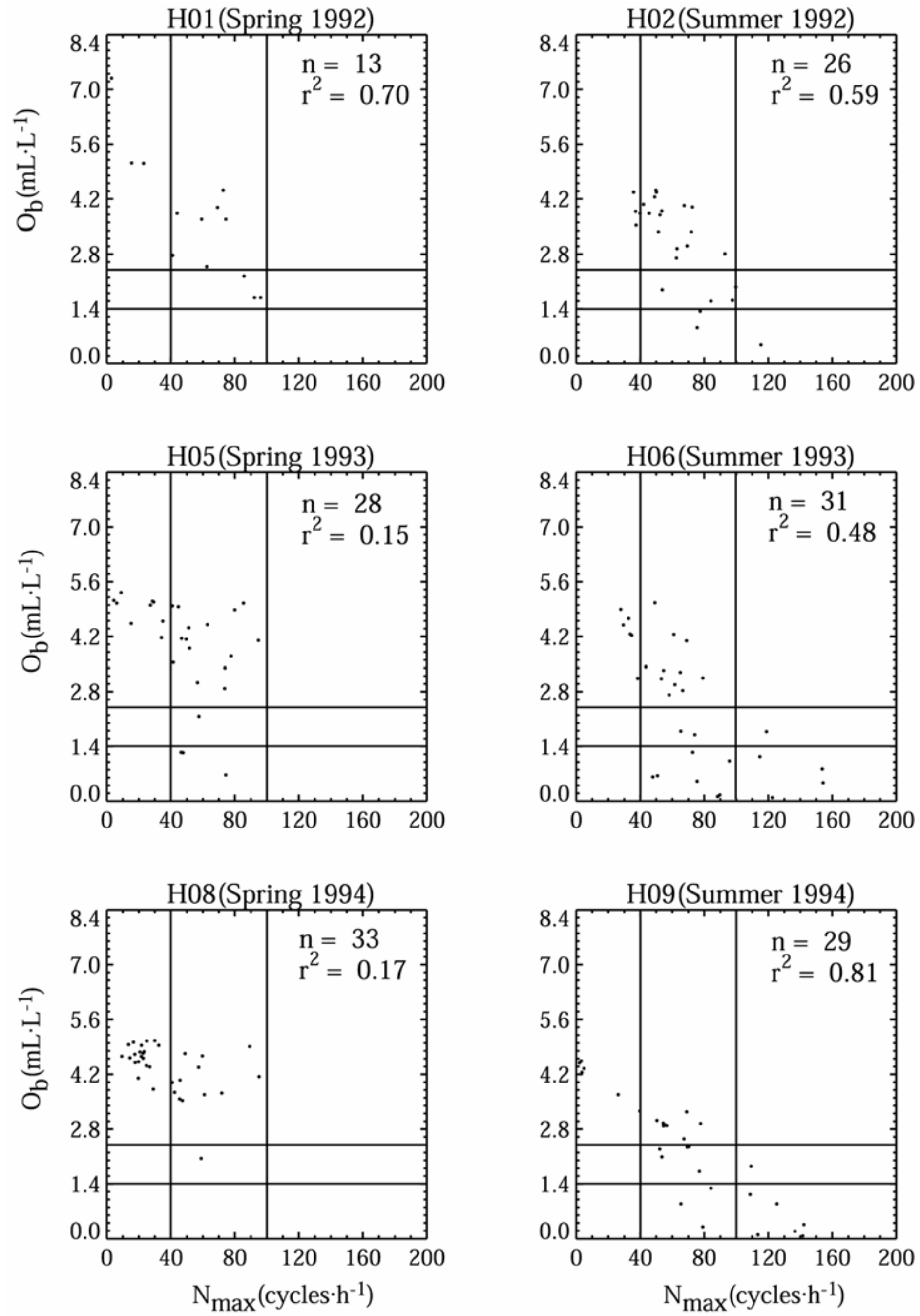


Figure 4.3. Bottom dissolved oxygen (O_b) versus the maximum Brunt-Väisälä frequency (N_{max}) in Region 3 on LATEX-A cruises. The thresholds of 2.4 mL·L^{-1} for low-oxygen, 1.4 mL·L^{-1} for hypoxia, and 40 and 100 cycles·h^{-1} are shown.

frequencies between 0 and 40 cycles·h^{-1}. In this interval, low-oxygen or hypoxic waters do not occur at the bottom because there is an ample supply of oxygen through vertical mixing. The second interval consists of maximum Brunt-Väisälä frequency values between 40 and 100 cycles·h^{-1}. Within this second interval low or hypoxic conditions may develop near the bottom if oxygen removal exceeds oxygen supply. The third interval consists of maximum Brunt-Väisälä frequency values greater than 100 cycles·h^{-1}. Within this interval, dissolved oxygen concentrations near the bottom had only low or hypoxic conditions, indicating that vertical mixing was reduced considerably. In spring, the maximum frequencies in Region 3 exceeded 100 cycles·h^{-1} at only two stations on cruise H01 and one station on cruise H08, which are not shown in Figure 4.3 because no near-bottom oxygen data were collected at these stations.

It is also clear from Figure 4.3 that in spring more stations have a maximum Brunt-Väisälä frequency of 40 cycles·h^{-1} or less than in summer. This suggests that the water over Region 3 is vertically more strongly stratified in summer than in spring, which may in part explain why most occurrences of low-oxygen and hypoxic water are found in summer in Region 3. Spring occurrences of hypoxic waters occurred only in 1993. The other springs had only three stations with low-oxygen waters near the bottom in 1992 and one station in 1994 (Figure 4.3).

Maps of maximum Brunt-Väisälä frequency and bottom dissolved oxygen concentrations in Region 3 show that in springs of 1992 and 1993 waters with maximum Brunt-Väisälä frequency greater than 40 cycles·h^{-1} and associated with low-oxygen or hypoxic conditions near the bottom were limited to the area east of 92°W (Figure 4.4). These areas are found inshore of the 20-m isobath on cruise H01 (spring 1992) and outside the 20-m isobaths near 92°W on cruise H05 (spring 1993). No oxygen data are available inside the 20-m isobath near 90.5°W to verify whether or not low-oxygen water occurred near the bottom there. On cruise H08 (spring 1994), there was only one station with low-oxygen concentration at the bottom; it was located near 94°W in water with 16.6 m depth. The maximum Brunt-Väisälä frequency at this station was 58.9 cycles·h^{-1}.

In summer in Region 3 there were only a few stations with maximum Brunt-Väisälä frequency less than 40 cycles·h^{-1}, located along the transect line near 94°W and at the outermost stations west of 93°W (Figure 4.4). On all three summer cruises, the

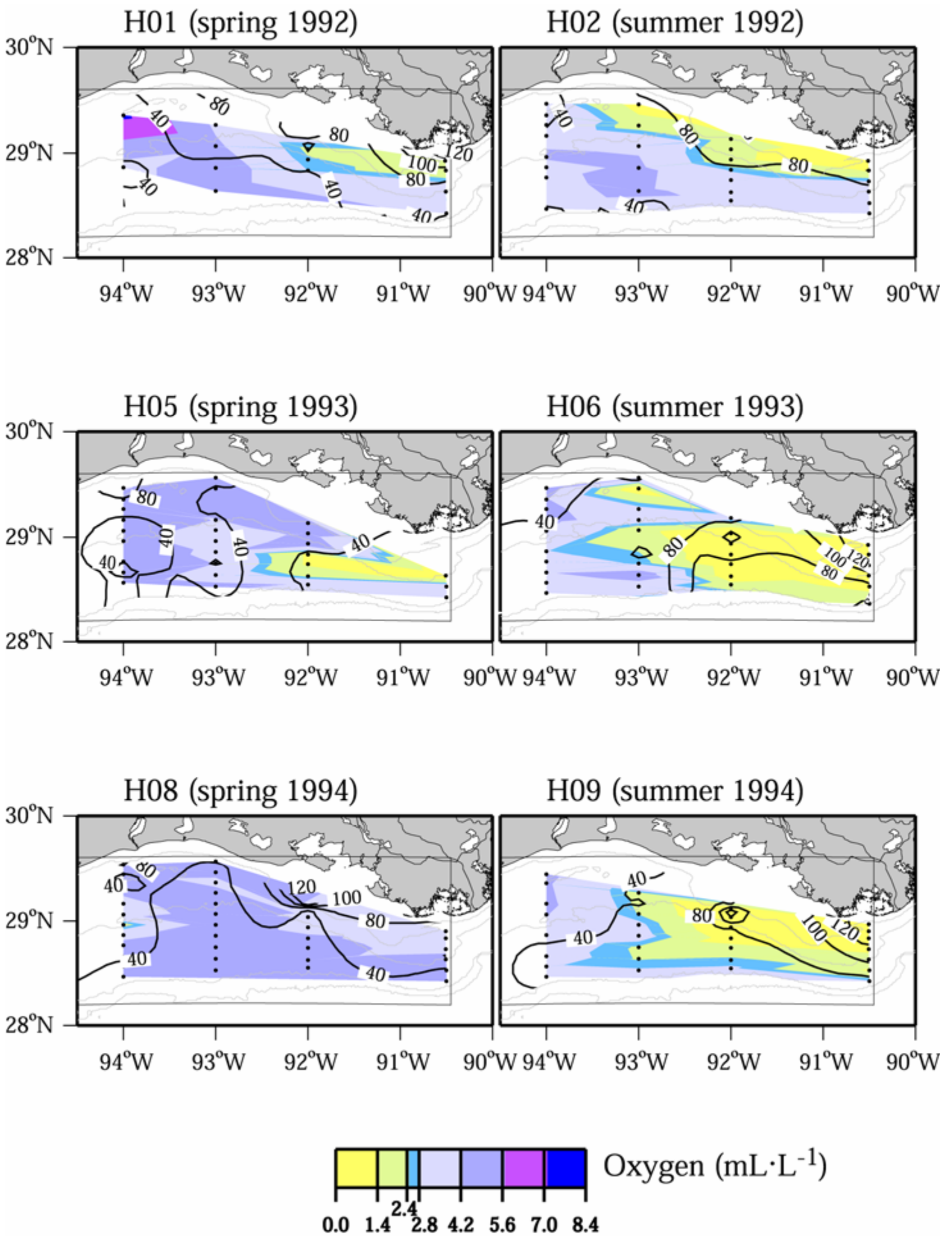


Figure 4.4. Bottom dissolved oxygen concentrations and contours of maximum Brunt-Väisälä frequency (cycles·h^{-1}) in Region 3 on LATEX-A spring and summer cruises. Dots represent station locations. The 10-, 20-, 50-, and 60-m isobaths are shown.

occurrences of low-oxygen and hypoxic bottom waters were found as far west as 93.5°W. On cruise H02 (summer 1992), these occurrences were limited to the shelf area inside the 20-m isobath, whereas on the other summer cruises low-oxygen and hypoxic waters were found as far offshore as the 50-m isobath over the eastern end of Region 3. To summarize, in Region 3 a highly stratified water column with maximum Brunt-Väisälä frequencies greater than 40 cycles·h^{-1} was more widespread and resulted in more frequent occurrences of bottom low-oxygen and hypoxic waters in summer than in spring.

Region 4 (Texas Shelf)

Bottom dissolved oxygen concentration and maximum Brunt-Väisälä frequency were not well correlated in summer in Region 4 (Figure 4.5). In general, the water over Region 4 was poorly stratified with maximum Brunt-Väisälä frequency less than or equal to 40 cycles·h^{-1}; only 4 stations on cruises H06 and 6 stations on cruise H09 had maximum Brunt-Väisälä frequencies greater than 40 cycles·h^{-1}. Summer bottom dissolved oxygen concentrations greater than 3.2 mL·L^{-1} were found at all frequencies. Thus, in summer, the water over Region 4 was vertically less stratified and less prone to occurrences of low-oxygen or hypoxic water near the bottom.

Spring conditions in Region 4 were different from summer. There were more stations with maximum Brunt-Väisälä frequencies between 40 and 100 cycles·h^{-1} in spring than in summer (Figure 4.5), but these stations had high near-bottom oxygen concentrations except for one station on cruise H05 (spring 1993). Dissolved oxygen concentration and maximum Brunt-Väisälä frequency at this station were equal to 1.78 mL·L^{-1} and 90.6 cycles·h^{-1}, respectively.

In spring in Region 4, the pattern is of bottom dissolved oxygen concentrations decreasing with increasing maximum Brunt-Väisälä frequency. Both spring cruises of 1993 and 1994 show that about 20% of the variance in bottom dissolved oxygen concentrations can be explained by variation in maximum Brunt-Väisälä frequency (Figure 4.5). So, unlike Region 3, in Region 4 it is in spring that the water is vertically more stratified and more prone to low-oxygen occurrences. In Section 4.2 I show that the increase in water column stratification in spring in Region 4 is caused by the presence of river-derived low-salinity water transported to the region by the seasonal circulation.

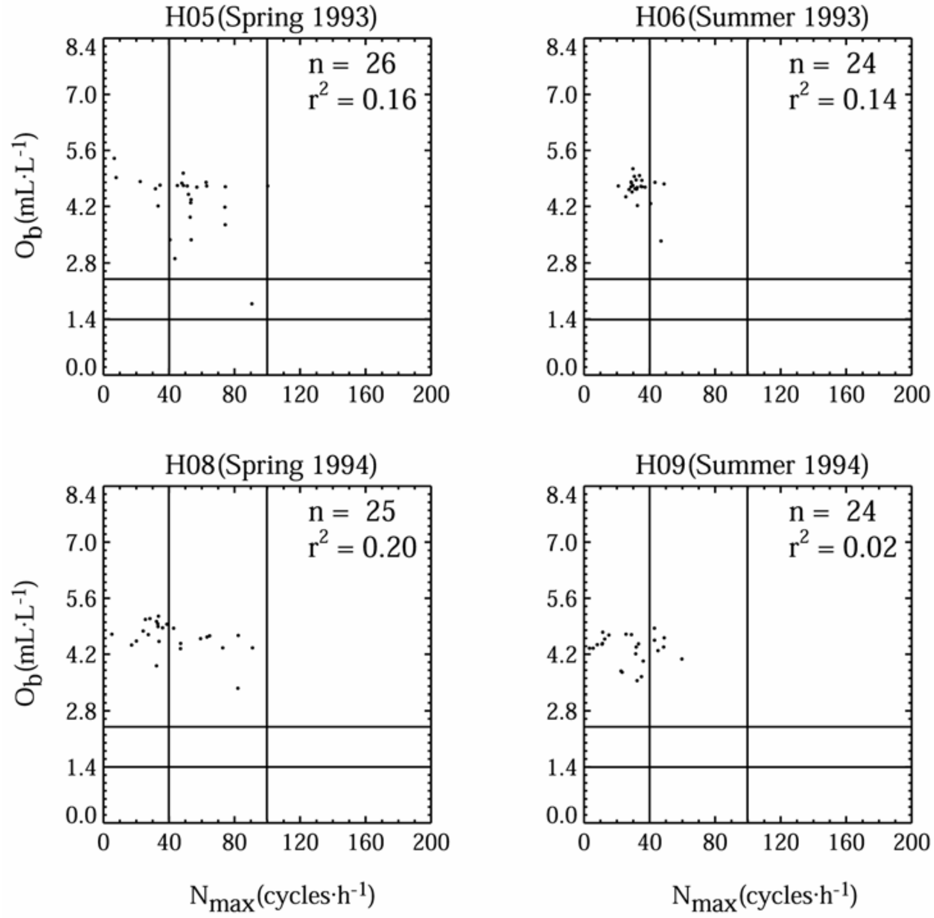


Figure 4.5. Bottom dissolved oxygen (O_b) versus the maximum Brunt-Väisälä frequency (N_{max}) in Region 4 on LATEX-A cruises. The thresholds of 2.4 mL·L^{-1} for low-oxygen, 1.4 mL·L^{-1} for hypoxia, and 40 and 100 cycles·h^{-1} are shown.

Region 2 (Mississippi-Alabama Shelf)

The pattern of bottom oxygen concentrations decreasing with increasing maximum Brunt-Väisälä frequency is seen in most spring and summer cruises in Region 2 (Figure 4.6). The square correlation coefficients shown in Figure 4.6 are all significant at the 95% confidence limit except for cruise N2 (spring 1998) when bottom dissolved oxygen concentrations and maximum Brunt-Väisälä frequency were essentially poorly correlated. On cruises other than N2, 22% to 48% of the variance in bottom dissolved oxygen concentration can be explained by variation in maximum Brunt-Väisälä frequency. In Region 2, low-oxygen waters did not occur at stations with maximum Brunt-Väisälä frequencies less than or equal to 40 cycles·h^{-1} (Figure 4.6). Even when the water column Brunt-Väisälä maxima exceeded this frequency low bottom dissolved oxygen concentrations were found at only one station during the spring and summer of 1998 and 1999. The maximum Brunt-Väisälä frequency at stations with low-oxygen were between 60 and 80 cycles·h^{-1}, only one shallow station with low-oxygen water on cruise N2 (spring 1998) had water column Brunt-Väisälä maxima greater than 100 cycles·h^{-1} (Figure 4.6). On the other cruises, bottom dissolved oxygen concentrations associated with frequencies greater than 100 cycles·h^{-1} were all high. For example, on cruises N5 (spring 1999) and N9 (summer 2000) stations with maximum Brunt-Väisälä frequencies greater than 120 cycles·h^{-1} had bottom dissolved oxygen concentrations greater than 3.8 mL·L^{-1}. These stations were located west of 87ºW in water depths greater than 20 m (Figure 4.7). Brunner et al. (paper in review) suggested that in Region 2 it is the instability in the position of the river plume, which moves inshore and offshore with the passage of eddies, that provides opportunities for the water exchange that replenishes oxygen near the bottom.

Spring occurrences of low-oxygen water were found near Chandeleur Sound, west of 88ºW, on cruise N2 and N5 (Figure 4.7). Summer occurrences of low-oxygen water were located at the outermost station of a survey line made south of Pensacola, west of 87ºW, on cruise N3 (summer 1998) and at one station near Chandeleur Sound, west of 88ºW, on cruise N6 (summer 1999). No occurrences of low-oxygen or hypoxic waters were observed at stations with a maximum Brunt-Väisälä frequency greater than 40 cycles·h^{-1} in either spring or summer of 2000.

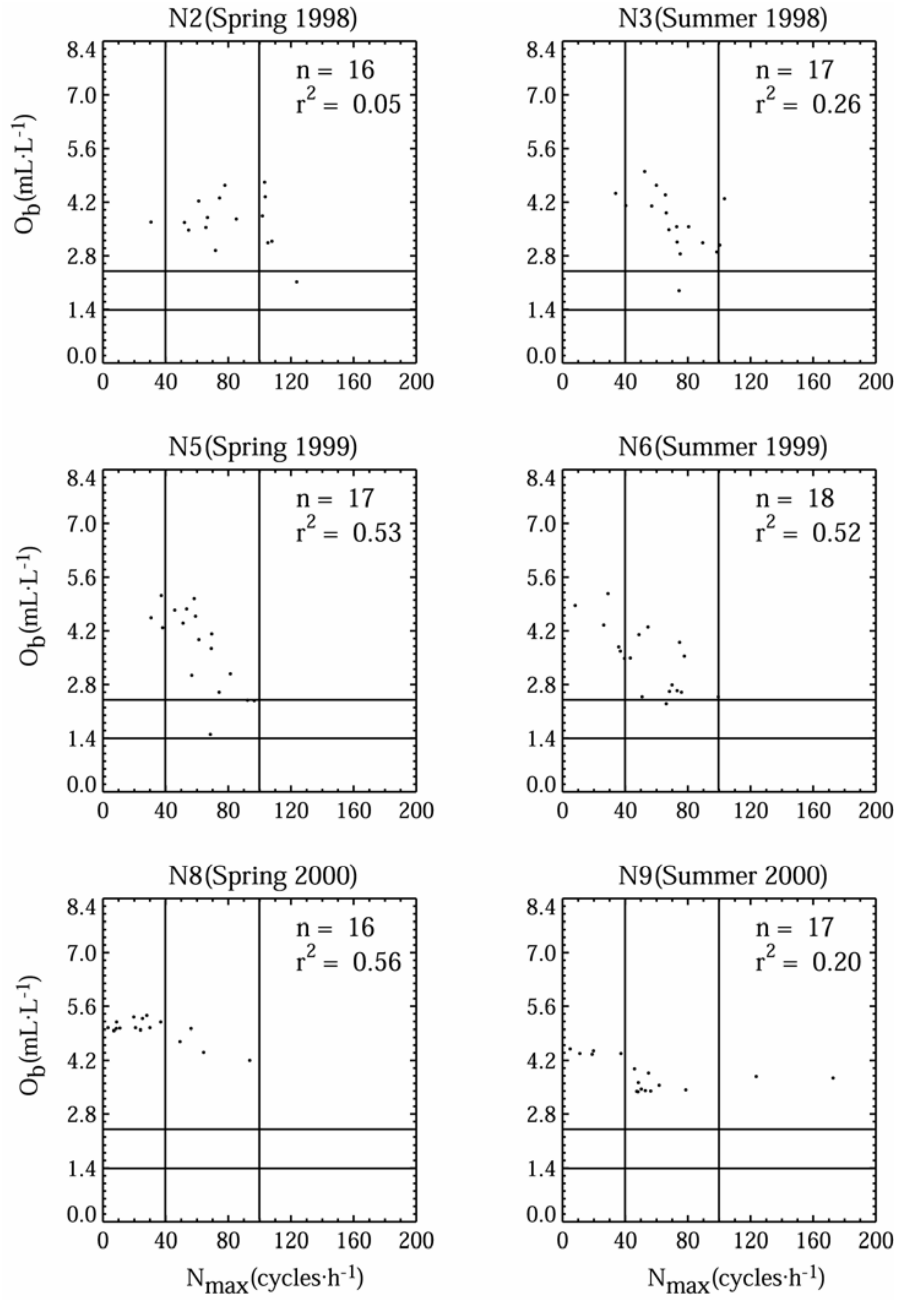


Figure 4.6. Bottom dissolved oxygen (O_b) versus the maximum Brunt-Väisälä frequency (N_{max}) in Region 2 on NEGOM-COH cruises. The thresholds of 2.4 mL·L^{-1} for low-oxygen, 1.4 mL·L^{-1} for hypoxia, and 40 and 100 cycles·h^{-1} are shown.

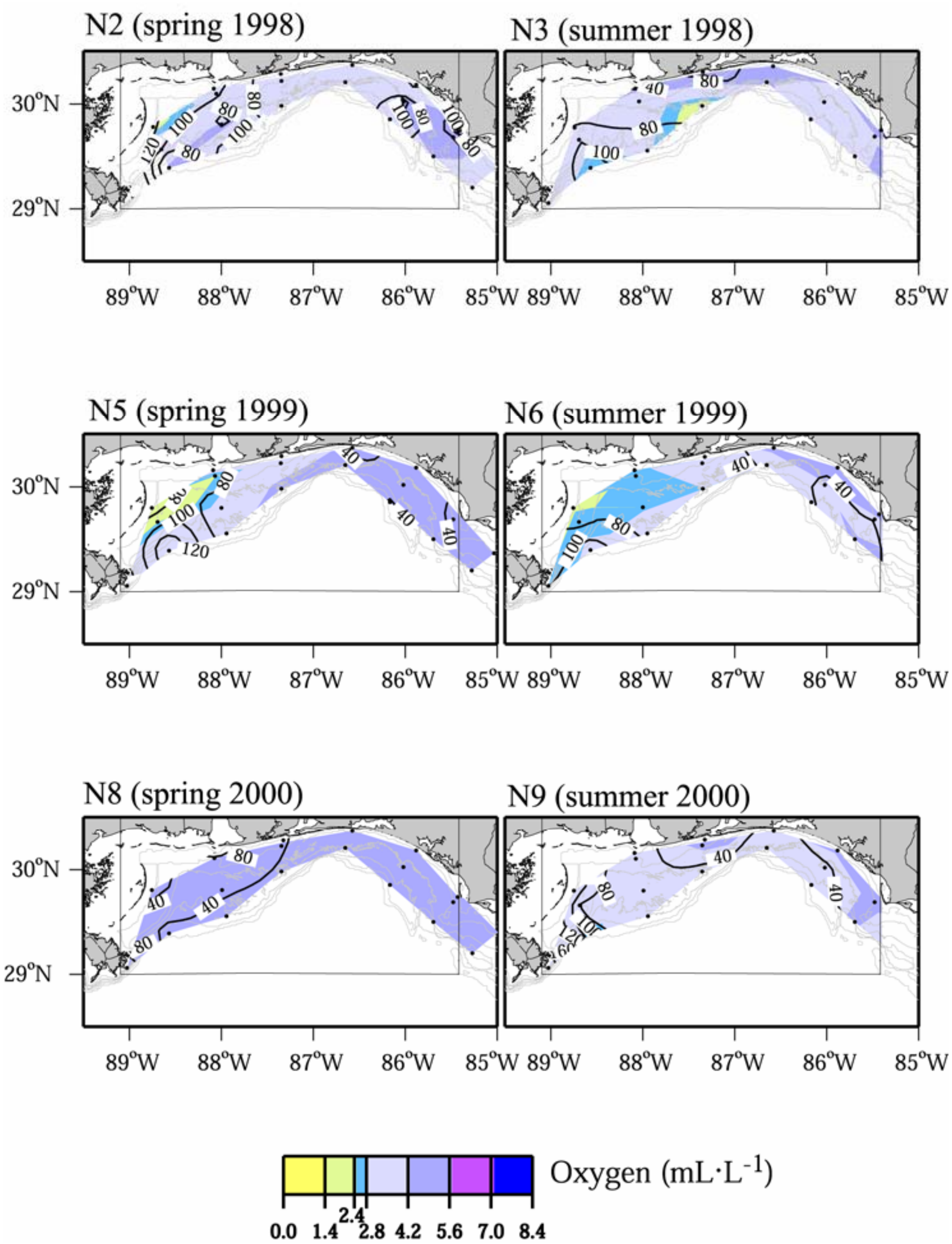


Figure 4.7. Bottom dissolved oxygen concentrations and contours of maximum Brunt-Väisälä frequency (cycles·h^{-1}) in Region 2 on NEGOM-COH spring and summer cruises. Dots represent station locations. The 10 - 60-m isobaths are shown.

So, in Region 2 a highly stratified water column with low-oxygen waters near the bottom seems to occur in localized regions on the Mississippi-Alabama shelf in some years; later I will show these years to have relatively high river discharge.

Region 1 (West Florida Shelf)

The water over Region 1 was poorly stratified. Maximum Brunt-Väisälä frequencies were less than 40 cycles·h^{-1} in spring and summer cruises of 2000. In 1999 there were only four stations on cruise N5 and one station on cruise N6 with maximum Brunt-Väisälä frequency between 40 and 50 cycles·h^{-1}. Bottom dissolved oxygen concentrations at these stations were larger than 3.6 mL·L^{-1}. Spring and summer of 1998 were different from 1999 and 2000. More than 50% of the stations had maximum Brunt-Väisälä frequencies between 40 and 80 cycles·h^{-1}. Water with maximum Brunt-Väisälä frequency greater than 40 cycles·h^{-1} covered almost all of Region 1 on cruise N2 (spring 1992). This condition was generally found in water depth greater than 20 m on cruise N3 (summer 1998) except for one shallow station located south of the Suwannee River. Bottom dissolved oxygen concentrations associated with these frequencies were larger than 3 mL·L^{-1} (not shown). In Region 1, no occurrences of low-oxygen or hypoxic water were observed in either spring or summer of 1998, 1999, or 2000.

In this section I have shown that during LATEX-A and NEGOM-COH cruises occurrences of low-oxygen and hypoxic waters were clearly related to the local vertical stratification, occurring only in waters with maximum Brunt-Väisälä frequency greater than 40 cycles·h^{-1}. Waters with high maximum Brunt-Väisälä frequency were commonly found in Regions 2 and 3, which are greatly influenced by rivers. In regions with minimum river discharge, water with maximum Brunt-Väisälä frequency greater than 40 cycles·h^{-1} were found either in a specific season (e.g., in spring in Region 4), or during years of high river discharge (e.g., in Region 1, during the 1998 and 1999 spring and summer cruises).

In the next section I show how the distribution of river-derived low-salinity water causes the local vertical stratification to differ in the four regions.

4.2. Relative Importance of Salinity and Temperature to the Vertical Stratification

Vertical density stratification is generally a function of several physical variables, including river fresh-water discharge, solar heating, and wind mixing. To examine the effect of river-derived low-salinity water on water column stratification in the four study regions, I first compared the maximum Brunt-Väisälä frequency to near-surface salinity (salinity at approximately 3-m depth) using data from the spring and summer cruises. Then, I calculated the density ratio (R_p; defined as the ratio of the thermal part of stratification to its salinity part) to determine if the calculated maximum Brunt-Väisälä frequency is determined chiefly by temperature or salinity.

According to McDougall (1987) the formula for the density ratio is:

$$R_p = [\alpha\cdot(dT/dp)]/[\beta\cdot(dS/dp)]$$

T: temperature (°C)
S: salinity
p: pressure (Decibars, dbar)
α: thermal expansion ($\alpha = (-1/\rho)\cdot(\partial\rho/\partial T)$) ($°C^{-1}$)
β: saline contraction ($\beta = (1/\rho)\cdot(\partial\rho/\partial S)$)
ρ: density ($kg\cdot m^{-3}$)

Region 3 (Louisiana Shelf)

In Region 3 the maximum Brunt-Väisälä frequency is seen to increase with decreasing near-surface salinity on both spring and summer cruises (Figure 4.8). The r^2 values shown in the figure are all significant at the 95% confidence limit. Correlations between these two parameters show larger r^2 in summer than in spring. The difference between spring and summer correlations is essentially explained by the distribution of river-derived low-salinity water, and the interannual variability in Mississippi-Atchafalaya River discharge rates.

The distribution of river-derived low-salinity water over Region 3 differed between spring and summer. In spring, the downcoast coastal current generated by the downcoast wind component advects river-derived low-salinity water along the near shore areas of Region 3. As a result, during the three spring cruises, the salinity gradient over Region 3 is directed offshore with the lowest salinity waters inshore and the highest salinity waters offshore (Figure 4.9).

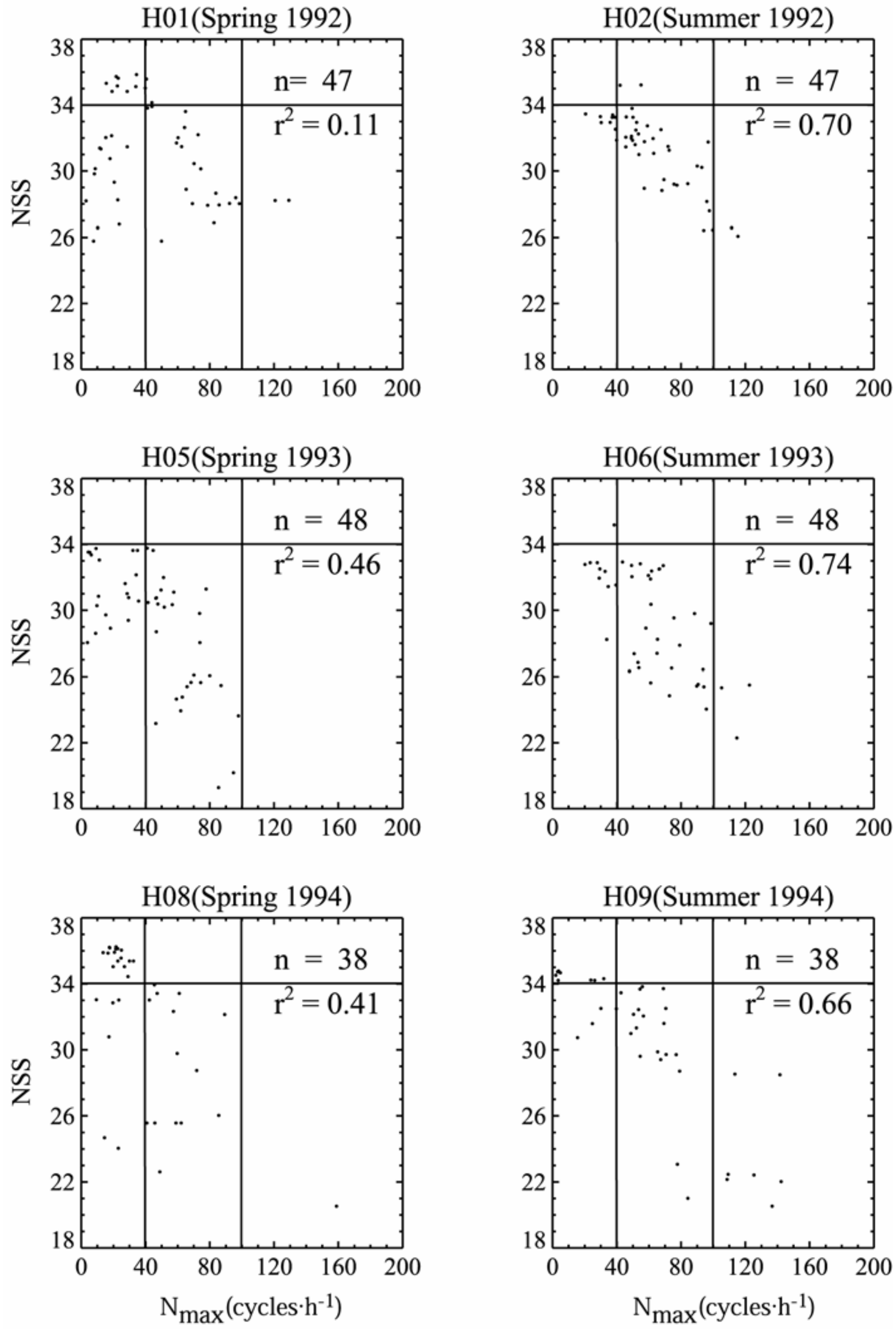


Figure 4.8. Maximum Brunt-Väisälä frequency (N_{max}) versus near-surface salinity (NSS) in Region 3 on LATEX-A cruises. The thresholds of 34 for low-salinity water and of 40 and 100 cycles·h^{-1} are shown.

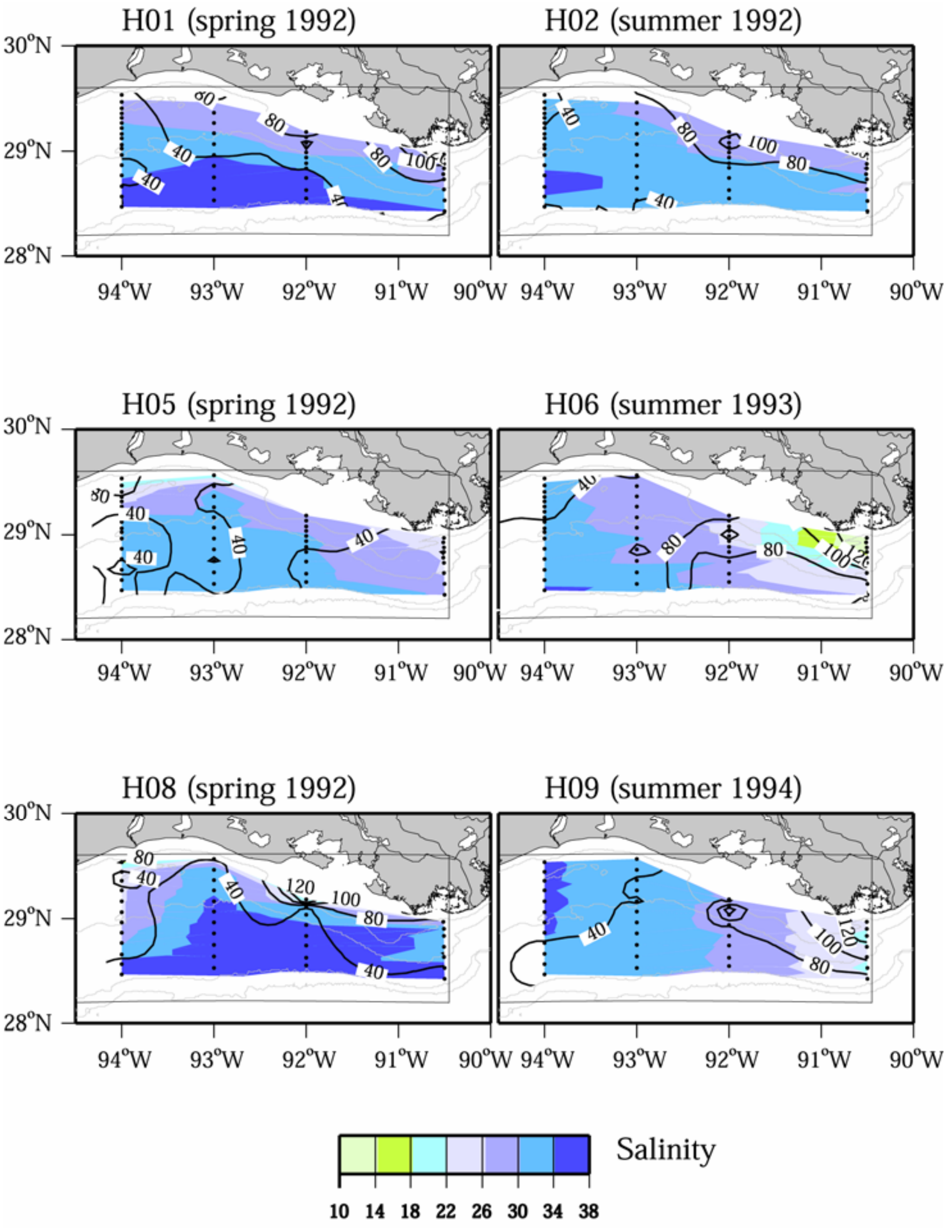


Figure 4.9. Near-surface salinity and contours of maximum Brunt-Väisälä frequency (cycles·h^{-1}) in Region 3 on LATEX-A spring and summer cruises. Dots represent station locations. The 10-, 20-, 50-, and 60-m isobaths are shown.

On cruise H05 (spring 1993), low-salinity water less than 34 covered the entire area of Region 3 (Figure 4.9). This is most likely because the rate of the Mississippi-Atchafalaya River discharge prior to this cruise exceeded the record mean by more than 73% (Table 4.2). In general, low-salinity water was associated with maximum Brunt-Väisälä frequency larger than 40 cycles·h^{-1} except at a few stations located in the middle shelf area between 92ºW and 93ºW and at the outermost stations along the transect near 94ºW (Figure 4.9).

Spring discharges in 1992 and 1994 were less than in 1993 (Table 4.2). Cruises H01 and H08 conducted in spring of these two years had many offshore stations with high salinity near the surface associated with low maximum Brunt-Väisälä frequency. Along the near shore areas of Region 3, where low-salinity water was found, the maximum Brunt-Väisälä frequency was generally larger than 40 cycles·h^{-1} (Figure 4.9). On cruise H01 and H08, a number of stations with low-salinity near the surface also had low maximum Brunt-Väisälä frequency (Figure 4.8). These stations were located along the transect line near 94ºW on cruise H01 (spring 1992) and in water depths less than 20 m near 92ºW and 93ºW on cruise H08 (spring 1994; Figure 4.9). In all three springs, vertical profiles of salinity at these stations showed a weak to a non-existent halocline suggesting that mixing had occurred. During the three springs included in the study period, 35 fronts passed over the Texas-Louisiana shelf (Etter et al., 2004). So, we would expect wind mixing of the surface layer to be important in spring and facilitate the break down of the local stratification at these stations.

There were overall fewer stations with maximum Brunt-Väisälä frequency less than 40 cycles·h^{-1} in summer than in spring (Figure 4.8) because summer circulation conditions over Region 3 are different from those in spring. In summer, water discharged from the Mississippi-Atchafalaya River system is held over Region 3 rather than being transported out of the area as in spring when there is downcoast flow. As a result, low-salinity water covered the entire area of Region 3 (Figure 4.9). The maximum Brunt-Väisälä frequencies associated with this low-salinity were larger than 40 cycles·h^{-1} (Figure 4.8). Stations with near-surface salinity greater than 35 were found along the transect line near 94°W (Figure 4.9). At those stations maximum Brunt-Väisälä frequencies were less than 40 cycles·h^{-1} except at two stations on cruise H02 (summer

1992) where the maximum Brunt-Väisälä frequency were between 40 and 60 cycles·h^{-1} (Figure 4.8).

Table 4.2. Mean river discharge (10^3 m^3·s^{-1}) associated with the 30-day period prior to each cruise for the Mississippi-Atchafalaya River (CM). The long-term mean (RM) for the same 30-day period for the Mississippi-Atchafalaya River is shown for comparison.

Year	Parameter	Spring	Summer
1992	CM	22.2	16.1
1992	RM	31.5	16.8
1993	CM	43.2	27.1
1993	RM	31.6	18.2
1994	CM	38.3	15.6
1994	RM	31.5	18.0

Also, unlike spring, in summer there were only six frontal passages total during the study period (Etter et al., 2004). So, because summer is quiescent and because of the pooling of low-salinity water over Region 3, the stratification of the water column is more prone to increase in summer than in spring. Note that if a tropical storm or a hurricane hit the region, the resulting wind mixing will temporally destabilize the water column and decrease the strength of the local vertical stratification. A study on "Mechanisms Controlling Hypoxia on the Louisiana Shelf" observed in 2005 that the pycnocline became reestablished within 2 to 4 days after the passages of a tropical storm and a hurricane in early July (Chapman, 2006, personal communication).

The discharge rates of the Mississippi River are at maximum in spring and decline to approximately half this rate in summer (Table 4.2). The variability in Mississippi-Atchafalaya River discharge rates between the three years may to some extent affect the distribution of the maximum Brunt-Väisälä frequency over Region 3. The maximum Brunt-Väisälä frequency and near-surface salinity showed better correlation in 1993 and 1994, years of high spring discharge rates, than in 1992, a year of low spring discharge rate. Also, in summer the two parameters correlated better during the high discharge year of 1993 than the low discharge years of 1992 and 1994 (Table 4.2).

Solar heating also affects the local vertical stratification. The northern Gulf shelves experience a net gain of heat in spring and summer. However, it is in summer that maximum heating of surface waters occurs (Nowlin et al., 1998a). To determine the relative importance of temperature and salinity to the vertical stratification, the density ratio (R_p) was calculated over a 0.5-m depth interval for each hydrographic station on LATEX-A and NEGOM-COH spring and summer cruises. For this analysis, I selected at each station the R_p values that corresponded to the maximum Brunt-Väisälä frequencies that are larger than 40 cycles$\cdot$h^{-1}. The selected R_p values were then plotted versus potential density for each region.

In Region 3, the spring data show the density ratio is less than unity over the whole density range (Figure 4.10), except at two stations on spring 1992 and 1993 where it was marginally greater. These stations were sampled along the 94°W transect in water depths greater than 20 m. The maximum Brunt-Väisälä frequency at these two stations is about 41 cycles$\cdot$h^{-1}. This implies that the spring time stratification is chiefly caused by the vertical salinity gradient due to the presence of low-salinity surface water. In summer, density ratios greater than unity were found in water depths greater than 20 m; so the vertical temperature gradient was largely responsible for the vertical stratification. The maximum Brunt-Väisälä frequencies at these stations ranged between 40 and 70 cycles$\cdot$h^{-1}.

Therefore, in spring, in Region 3, it is salinity and not temperature that chiefly determines the degree of water stratification. In summer, in water with maximum Brunt-Väisälä frequency greater than 70 cycles$\cdot$h^{-1} stratification again was chiefly determined by river-derived low-salinity water. However, the influence of temperature was generally seen in water depths greater than 20 m, where near-surface salinity is usually greater than 32 (see Figure 4.9).

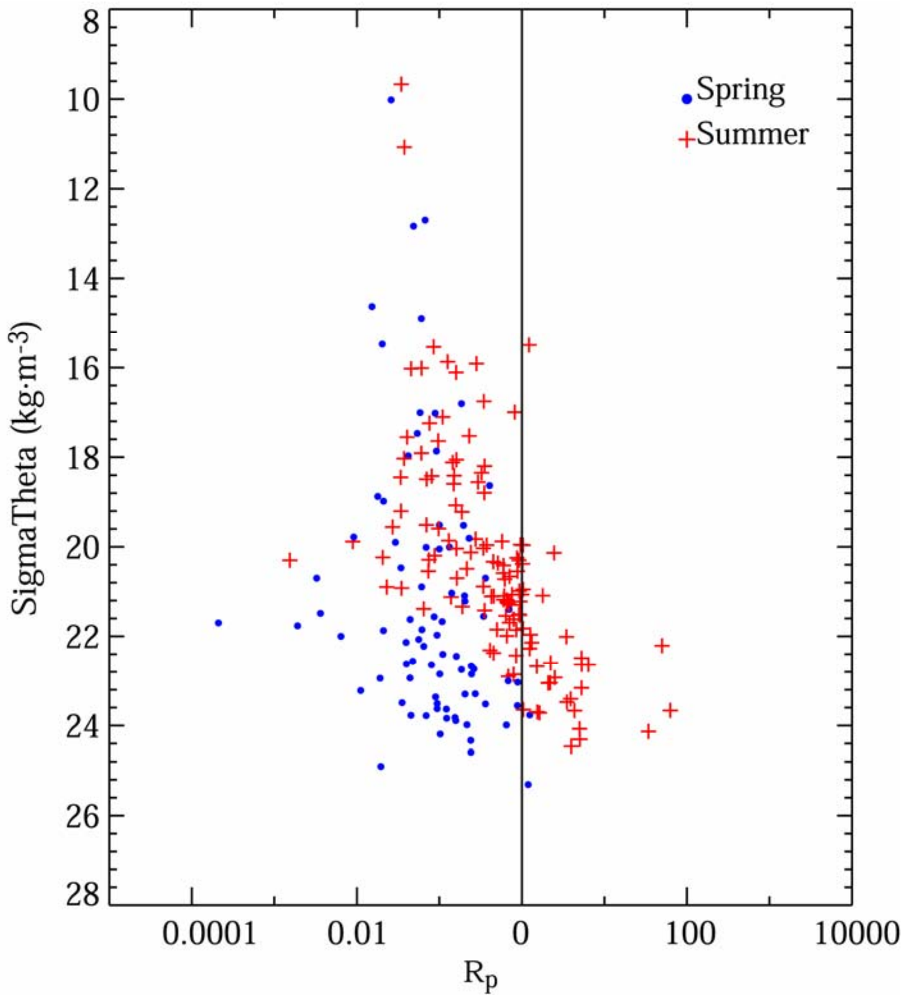


Figure 4.10. Density ratio (R_p) versus potential density (Sigma Theta) for maximum Brunt-Väisälä frequency greater than 40 cycles·h^{-1} in Region 3 on LATEX-A spring and summer cruises.

Region 4 (Texas Shelf)

In Region 4, the combination of river discharge and flow regime means that the volume of low-salinity water is at maximum in spring due to the advection of low-salinity water from Region 3 by spring downcoast flow. Similarly, it is at minimum in summer because of the transport of salty water from off Mexico by summer upcoast flow.

This is well reflected in Figure 4.11. Summer near-surface salinity over Region 4 was generally larger than 34. In spring, however, near-surface salinity was generally less than 34, with the salinity gradient directed offshore (Figure 4.12). On cruise H08 (spring 1994) stations with high salinity water greater than 34 were found in water depths greater than 20 m east of 95ºW. The presence of this high salinity water on cruise H08 is due to the fact that the river discharge rate in 1994 was less than 1993 (Table 4.2).

In summer, the maximum Brunt-Väisälä frequencies registered in Region 4 did not exceed 60 cycles·h^{-1} and did not correlate with near-surface salinity (Figure 4.11). The distribution of near-surface salinity and the maximum Brunt-Väisälä frequency did not show any specific pattern over Region 4 (Figure 4.12). Since frontal passages are infrequent in summer, I speculate that it is the absence of river-derived low-salinity water in Region 4 that caused the water column to be poorly stratified.

The maximum Brunt-Väisälä frequency was correlated poorly with near-surface salinity on both spring cruises, but the pattern of increasing maximum Brunt-Väisälä frequency with decreasing near-surface salinity still can be seen (Figure 4.11). A number of stations with low-salinity at the surface had maximum Brunt-Väisälä frequency less than 40 cycles·h^{-1}. Vertical profiles of salinity at these stations showed a weak to non-existent halocline confirming that mixing had occurred. Mixing at these stations may have resulted from the effect of frequent frontal passages over the region (Etter et al., 2004).

The density ratio of water with maximum Brunt-Väisälä frequency greater than 40 cycles·h^{-1} in Region 4 shows that in spring salinity chiefly determines the greatest density variation in the pycnocline in the same way as in Region 3 (Figure 4.13). This is consistent with the fact that the downcoast current moves low-salinity water to this region. In summer, however, water salinity over Region 4 is relatively constant throughout the water column and it is summer heating that leads to the formation of a

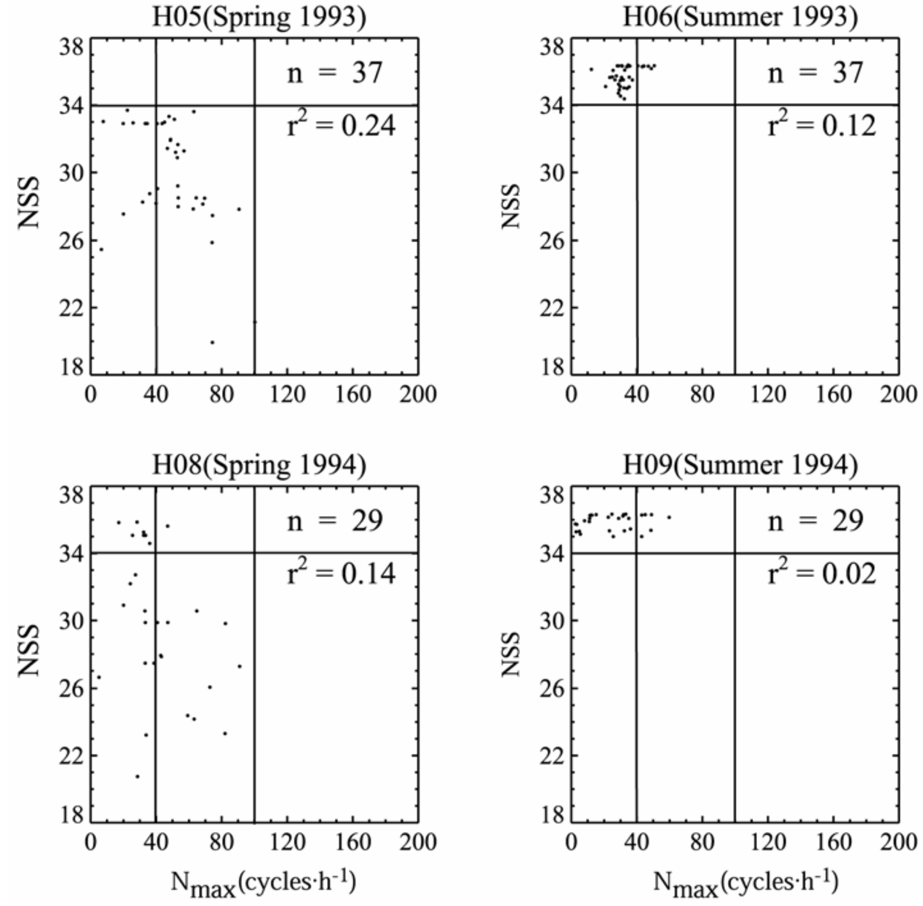


Figure 4.11. Maximum Brunt-Väisälä frequency (N_{max}) versus near-surface salinity (NSS) in Region 4 on LATEX-A cruises. The thresholds of 34 for low-salinity water and of 40 and 100 cycles·h^{-1} are shown.

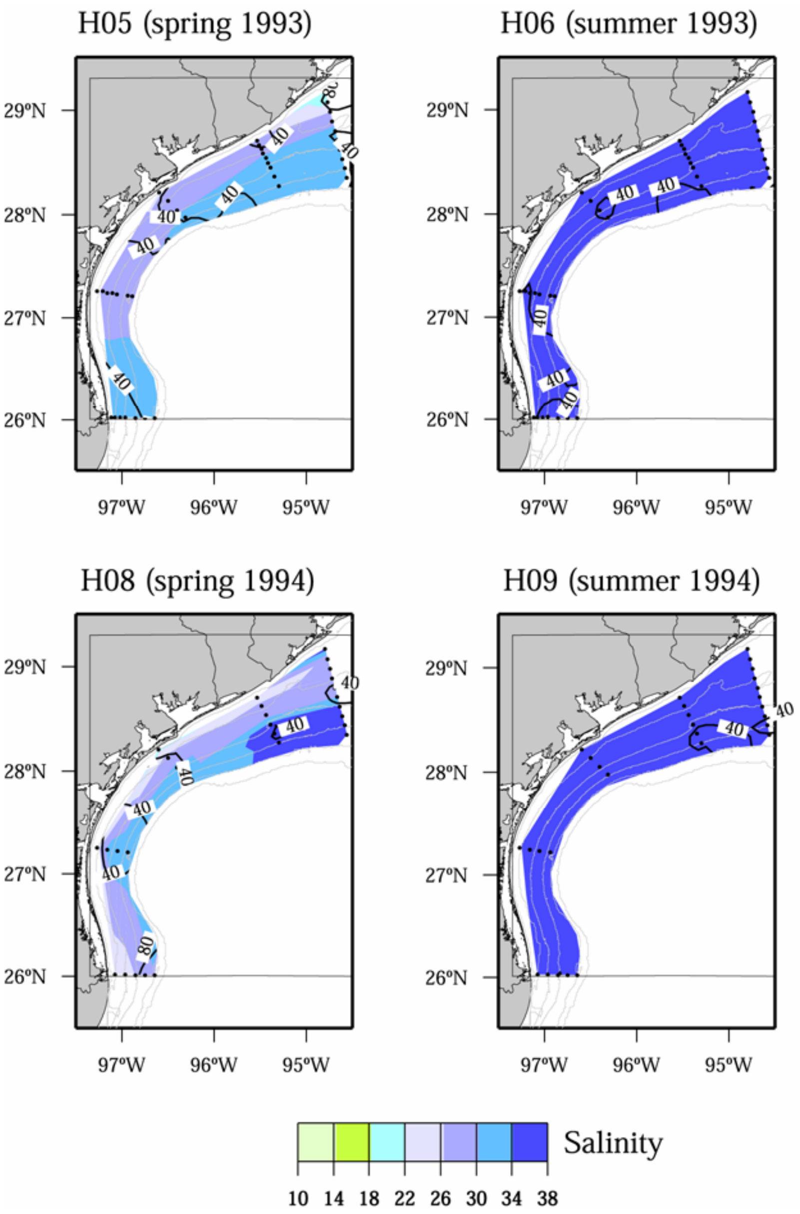


Figure 4.12. Near-surface salinity and contours of maximum Brunt-Väisälä frequency (cycles·h^{-1}) in Region 4 on LATEX-A spring and summer cruises. Dots represent station locations. The 10 – 60-m isobaths are shown.

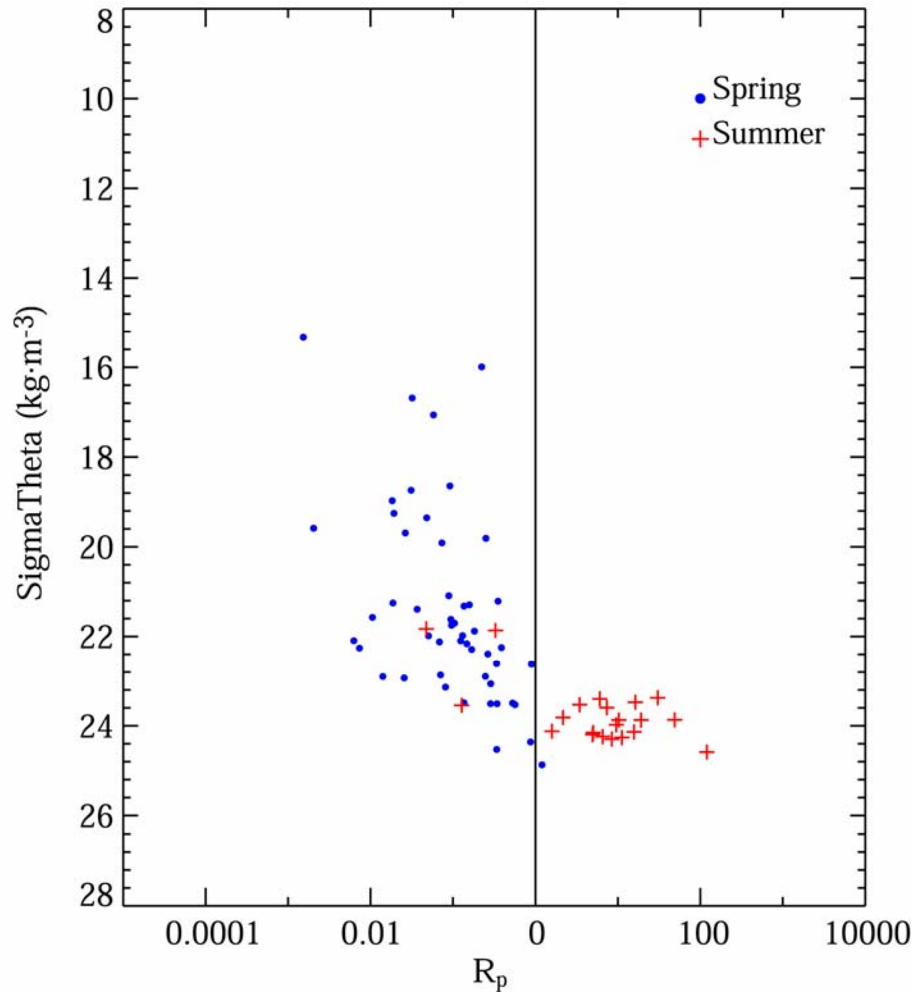


Figure 4.13. Density ratio (R_p) versus potential density (Sigma Theta) for maximum Brunt-Väisälä frequency greater than 40 cycles·h^{-1} in Region 4 on LATEX-A spring and summer cruises.

thermocline and an increase in the thermal part of the density ratio (Figure 4.13).

Region 2 (Mississippi-Alabama Shelf)

In spring 1998, on cruise N2, the Mississippi River and other rivers to the west of Apalachicola River exceeded their long-term mean, some by more than 90% (Table 4.3). As a result of these high discharge rates and the relatively strong eastward current encountered in the region (Jochens et al., 2002), low-salinity water less than 34 occupied the entire area of Region 2. This is clearly reflected in Figure 4.14, with only three stations with near-surface salinity water larger than 34. Near-surface low-salinity water associated with maximum Brunt-Väisälä frequency greater than 80 cycles·h^{-1} were generally found west of 87.5ºW, the region close to the Mississippi River Delta, and at a localized area east of 86ºW (Figure 4.15). 50% of the variance in maximum Brunt-Väisälä frequency on cruise N2 (spring 1998) can be explained by variation in near-surface salinity with the maximum Brunt-Väisälä frequency increasing with decreasing near-surface salinity (Figure 4.14).

Better correlations of maximum Brunt-Väisälä frequency with near-surface salinity are seen in spring of 1999 and 2000 (Figure 4.14). Spring 1999 was marked with a series of pulses in the Mississippi River discharge that exceeded the mean by more than 50% (Table 4.3). Other rivers discharging into Region 2 were significantly below their mean except from a very high discharge from Tombigbee River (Table 4.3). During this spring salinity water less than 34 extended from the Mississippi Delta to as far east as 86°W (Figure 4.15). There were more stations with maximum Brunt-Väisälä frequency less than 40 cycles·h^{-1} associated with the presence of high salinity water during N5 (spring 1999) than during N2 (spring of 1998, Figure 4.14).

In spring of 2000 (cruise N8) much less river water was available in Region 2 because of the low Mississippi River discharge and the advection of river-derived low-salinity water out of Region 2 by the southwestward currents (Jochens et al., 2002). Thus, low-salinity water was limited to a smaller region west of 87°W (Figure 4.15). The maximum Brunt-Väisälä frequencies associated with these low-salinity waters were greater than 40 cycles·h^{-1} (Figure 4.14).

Summer is the season of minimum discharge and weak and irregular inner shelf currents (Jochens et al., 2002). For the three summer cruises in this study (N3, N6, and

N9), deep eddies induced strong anticyclonic currents along the upper slope and outer shelf from the Mississippi River delta to the west Florida shelf (Belabbassi et al., 2005). Those currents transported Mississippi River water eastward along the outer shelf and slope adjacent to Region 2, reversing over most of the shelf the normal offshore increase in salinity (Figure 4.15). A strong east-west gradient over Region 2 was observed in all three summers. Maximum Brunt-Väisälä frequency greater than 80 cycles·h^{-1} was limited to the area immediately next to the Mississippi River Delta where the lowest salinities were observed. In all three summers the maximum Brunt-Väisälä frequency increased with decreasing near-surface salinity (Figure 4.14).

Table 4.3. Mean river discharge (10^3 m^3·s^{-1}) associated with the 30-day period prior to each cruise for the Mississippi and selected rivers (CM). The long-term mean (RM) for the same 30-day period for each river is shown for comparison.

River name	Year	Parameter	Spring	Summer
Mississippi	1998	CM	26.2	20.1
	1998	RM	21.8	12.6
	1999	CM	21.4	10.5
	1999	RM	21.4	9.5
	2000	CM	14.8	14.5
	2000	RM	21.7	12.1
Apalachicola	1998	CM	1.4	0.5
	1998	RM	0.9	0.6
	1999	CM	0.3	0.5
	1999	RM	0.8	0.6
	2000	CM	0.7	0.2
	2000	RM	1.2	0.6

Table 4.3. Continued

River name	Year	Parameter	Spring	Summer
Tombigbee	1998	CM	1.1	0.3
	1998	RM	1.5	0.4
	1999	CM	0.7	0.1
	1999	RM	1.2	0.3
	2000	CM	2.4	0.1
	2000	RM	1.7	0.3
Alabama	1998	CM	1.6	0.3
	1998	RM	1.3	0.5
	1999	CM	0.5	0.4
	1999	RM	1.0	0.4
	2000	CM	1.6	0.2
	2000	RM	1.8	0.5
Pearl	1998	CM	0.2	0.1
	1998	RM	0.4	0.1
	1999	CM	0.1	0.02
	1999	RM	0.3	0.1
	2000	CM	0.4	0.02
	2000	RM	0.4	0.1
Suwannee	1998	CM	0.5	0.1
	1998	RM	0.3	0.2
	1999	CM	0.1	0.1
	1999	RM	0.3	0.2
	2000	CM	0.1	0.1
	2000	RM	0.3	0.2

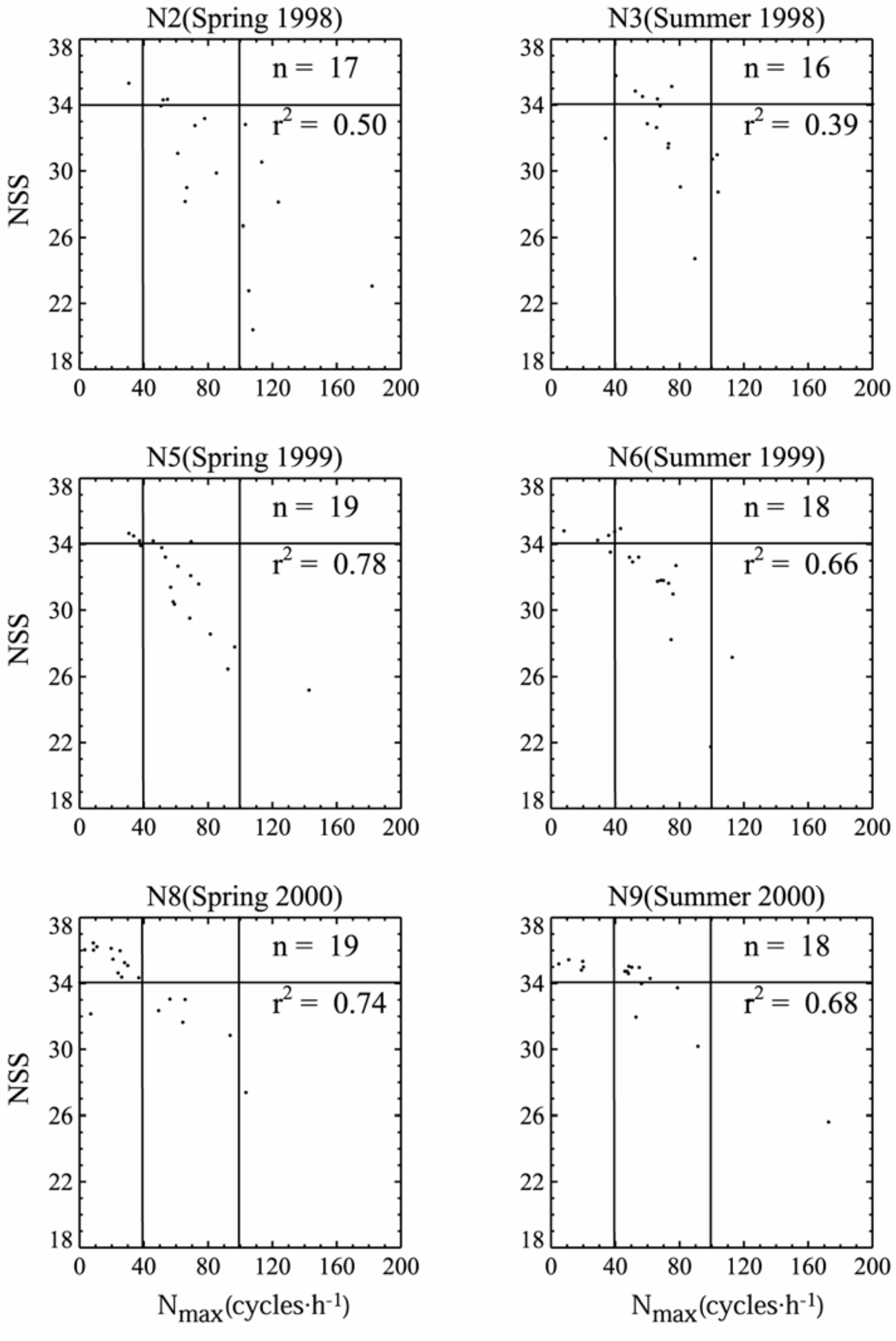


Figure 4.14. Maximum Brunt-Väisälä frequency (N_{max}) versus near-surface salinity (NSS) in Region 2 on NEGOM-COH cruises. The thresholds of 34 for low-salinity water and of 40 and 100 cycles·h^{-1} are shown.

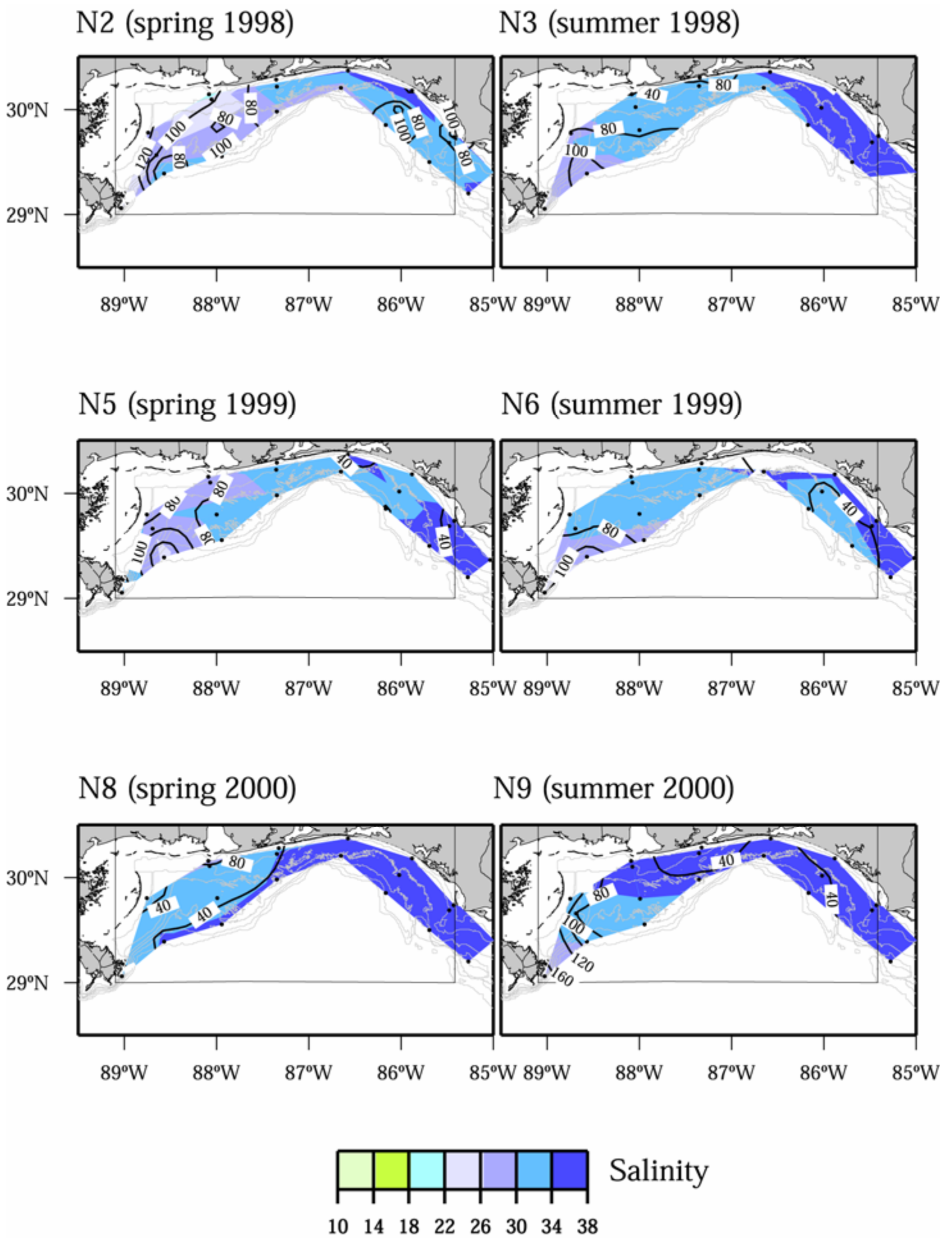


Figure 4.15. Near-surface salinity and contours of maximum Brunt-Väisälä frequency (cycles·h^{-1}) in Region 2 on NEGOM-COH spring and summer cruises. Dots represent station locations. The 10 - 60-m isobaths are shown.

The density ratio in Region 2 shows that low-salinity water chiefly determines maximum Brunt-Väisälä frequencies greater than 40 cycles·h^{-1} for both spring and summer (Figure 4.16). During summer, stations where vertical temperature gradients were largely responsible for the vertical stratification were located in the innermost shelf area east of 86.25°W during cruise N3 (summer 1998) and east of 89°W during cruise N9 (summer 1999) (Figure 4.15).

Region 1 (West Florida Shelf)

Region 1 is on the west Florida shelf and is located far from the direct influence of the Mississippi or other significant rivers. Maximum Brunt-Väisälä frequency correlated poorly with near-surface salinity on both spring and summer cruises. During spring and summer cruises of 1999 and 2000 near-surface salinities generally were greater than 34 over Region 1 and were associated with maximum Brunt-Väisälä frequencies less than 40 cycles·h^{-1} (not shown). In spring of 1998, on cruise N2, low-salinity water less than 34 was found over Region 1 inshore of the 30-m isobath as a result of high discharge rates and the relatively strong eastward current encountered in the region (not shown). On cruise N3 (summer 1998), low-salinity water was located outside the 40-m isobath except for the area south of 28ºN and at one shallow station south of the Suwannee River. There also was a clear indication of low-salinity water derived from the Suwannee River in the

Big Bend area during cruise N2 (spring 1998) and at the same location in spring of 1999. The maximum Brunt-Väisälä frequencies associated with these low near-surface salinities were generally between 40 and 80 cycles·h^{-1}.

Spring and summer data in Region 1 show that the density ratio is less than unity for frequencies greater than 40 cycles·h^{-1} (Figure 4.17). This implies that the relative importance of salinity to vertical stratification exceeds that of temperature for both spring and summer.

To summarize, differences in the distribution of low-salinity water was the chief cause of regional differences in the local vertical stratification in the four study regions. Water stability was found to increase with decreasing low-salinity water in Regions 2 and 3, which are greatly influenced by rivers. In these regions, maximum Brunt-Väisälä frequencies greater than 40 cycles·h^{-1} were found in the halocline, where the density variation is chiefly determined by salinity variation. The influence of temperature seems to be more important in summer at stations located in water depth greater than 20 m in Region 3 and over the innermost area in Region 2, generally east of 87ºW. During spring in Region 4 and during both spring and summer in Region 1, Brunt-Väisälä maxima were found in the halocline, as in Regions 2 and 3. Temperature was found to have the greater influence on density variation in the pycnocline during summer in Region 4 when the volume of low-salinity water was at minimum, due to the upcoast transport of salty surface water by the non-summer circulation pattern.

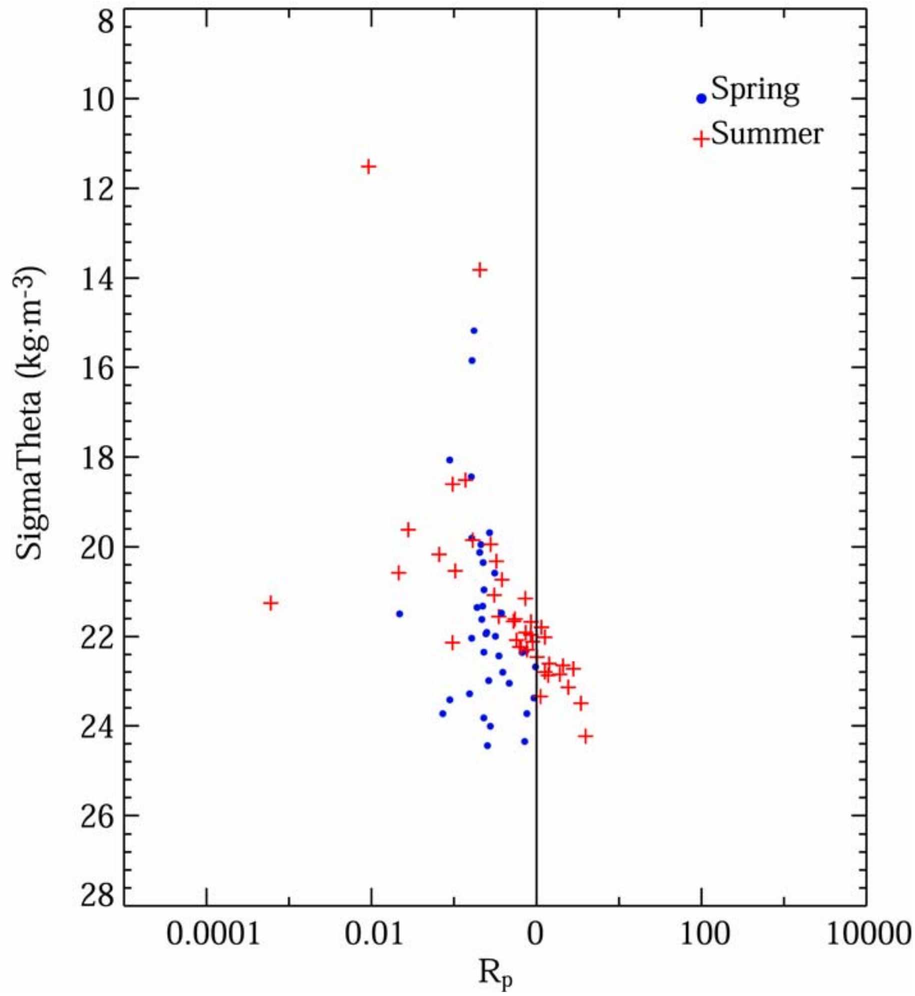


Figure 4.16. Density ratio (R_p) versus potential density (Sigma Theta) for Brunt-Väisälä frequency greater than 40 cycles·h^{-1} in Region 2 on NEGOM-COH spring and summer cruises.

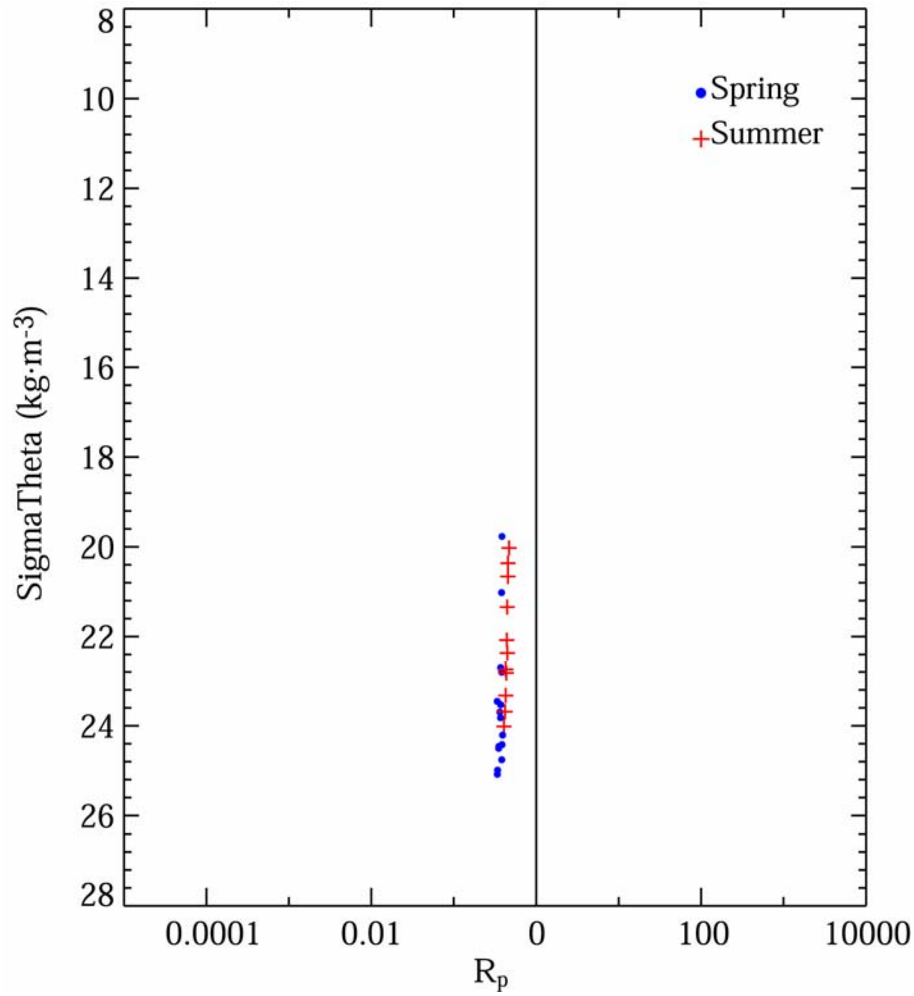


Figure 4.17. Density ratio (R_p) versus potential density (Sigma Theta) for Brunt-Väisälä frequency greater than 40 cycles·h^{-1} in Region 1 on NEGOM-COH spring and summer cruises.

4.3. Water Column Stratification Versus Bottom Silicate

In Section 4.1, I showed that vertical density stratification plays a key role in influencing the magnitude of low-oxygen water occurrences over the inner shelf of the northern Gulf of Mexico. However, it is the oxidation of the ungrazed organic material that depletes the lower layer of dissolved oxygen. Organic matter remineralization is generally reflected in the chemical concentration and distribution throughout the water column. Nutrients, such as silicate, nitrate, and phosphate, are enriched in the bottom layer as a result of the oxidation (decay) of this organic material. Therefore, an increase in the concentrations of nutrients with depth in the sub-pycnocline layer should be accompanied by a decrease in the concentration of dissolved oxygen.

The relationship of nutrients to oxygen through the process of remineralization is illustrated in Figure 4.18. The vertical profiles of nutrient and dissolved oxygen shown were made at stations 65, 117, and 27 in Region 3 during summer 1993 (cruise H06), spring 1993 (cruise H05), and summer 1992 (cruise H02), respectively. Indicated on each profile is the depth of the maximum Brunt-Väisälä frequency.

The contrast between the three stations is obvious. At station 65, the remineralization of the organic matter resulted in an increase in silicate and phosphate and a decrease in oxygen concentration at and below the pycnocline (Figure 4.18). Nitrate concentrations in the sub-pycnocline water were low, possibly indicating local denitrification at low-oxygen concentrations or local photosynthesis. The maximum Brunt-Väisälä frequency of about 123 cycles$\cdot$h^{-1} at station 65 indicates the presence of a strong pycnocline. The presence of this strong pycnocline combined with an important remineralization below the pycnocline resulted in the hypoxic conditions near the bottom. At station 117, however, the remineralization process was not important below the existing strong pycnocline, as indicated by the low nutrient and high oxygen concentrations in the bottom layer (Figure 4.18). As a result of the lack of remineralization, oxygen concentrations in the sub-pycnocline water were high.

At station 27, the maximum Brunt-Väisälä frequency was about 37 cycles$\cdot$h^{-1}, indicating weak stratification and so little change in oxygen or nutrients between the upper and the lower water column (Figure 4.18). As a result of weak stratification, bottom dissolved oxygen concentrations in the sub-pycnocline water were high.

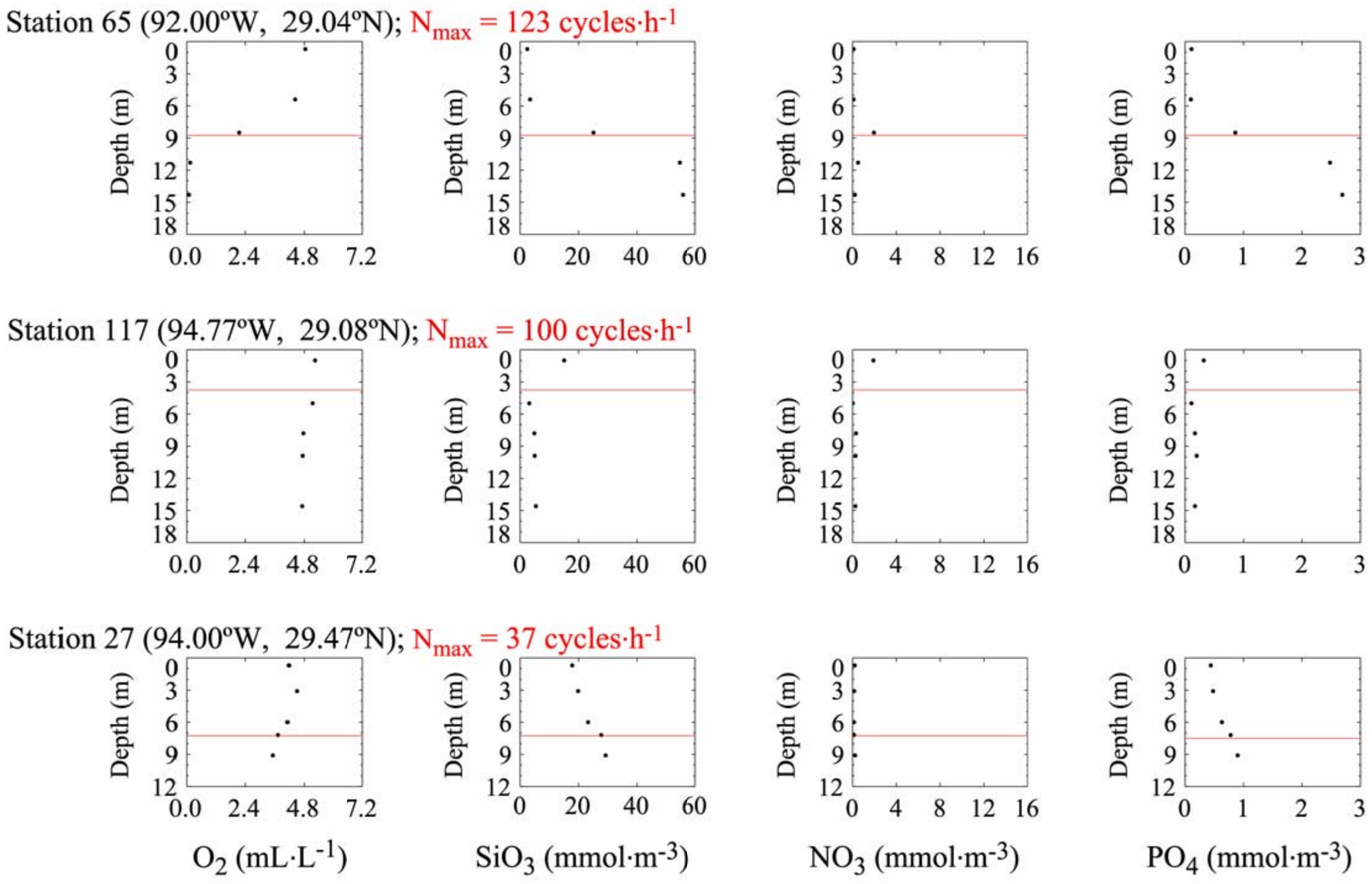


Figure 4.18. Nitrate ([NO$_3$]), phosphate ([PO$_4$]), silicate ([SiO$_3$]), and dissolved oxygen ([O$_2$]) concentrations versus depth at stations 65, 117, and 27 on cruise H06 (summer 1993), H05 (spring 1993), and H02 (summer 1992), respectively. The longitude and the latitude of each station are given between parentheses. The red line represents the depth of the maximum Brunt-Väisälä frequency (N$_{max}$) indicated for each station.

The examples shown in Figure 4.18 are consistent with the assumption that low-oxygen and hypoxic waters occur only when two conditions are met: (1) a strong stratification that prevents oxygen replenishment to the bottom layer and (2) high remineralization that depletes the oxygen within the bottom layer. I tested the validity of this assumption by examining the relationship between bottom silicate concentrations and the maximum Brunt-Väisälä frequency in the four study regions. Silicate rather than nitrate was selected as a proxy for remineralization because during LATEX-A and NEGOM-COH bottom silicate concentrations were seen to decline less rapidly than bottom nitrate concentrations. Several stations with local remineralization as evidenced by the increase with depth in silicate concentrations and a decrease in dissolved oxygen concentration showed nitrate depletion in the sub-pycnocline waters as opposed to nitrate enrichment due to local remineralization. This is not unexpected in the inner shelf water of the northern Gulf because of nitrate limitation (Turner and Rabalais, 2001). When light is not limiting, nitrate uptake by biological processes may lead to a rapid nitrate depletion in near-bottom waters and so evidence of local remineralization cannot be observed reliably by examination of the vertical distribution of nitrate. Silicate is generally found at high concentrations in the sub-pycnocline waters, which is not unexpected since high dissolved silicon is associated with river-derived low salinity water and the Mississippi River in general (Burton, 1976). So, biological uptake of silicate in near-bottom water generally will be small enough that it will not mask evidence of local remineralization. Therefore, silicate is a better proxy for bottom remineralization than nitrate. Note that only stations with both silicate and oxygen data in the lower five meters of the water column were considered in this analysis.

Region 3 (Louisiana Shelf)

In Figure 4.19 are plotted the maximum Brunt-Väisälä frequency versus bottom silicate concentrations in spring and summer of 1992, 1993, and 1994 over Region 3. Stations with low-oxygen concentrations near the bottom are highlighted in red. In spring, low bottom oxygen concentrations were found at stations with high maximum Brunt-Väisälä frequency (greater than 40 cycles·h^{-1}) and high bottom silicate concentrations (generally greater than 24 mmol·m^{-3}). In summer, stations with low bottom oxygen concentrations, found in waters with high Brunt-Väisälä maxima, were

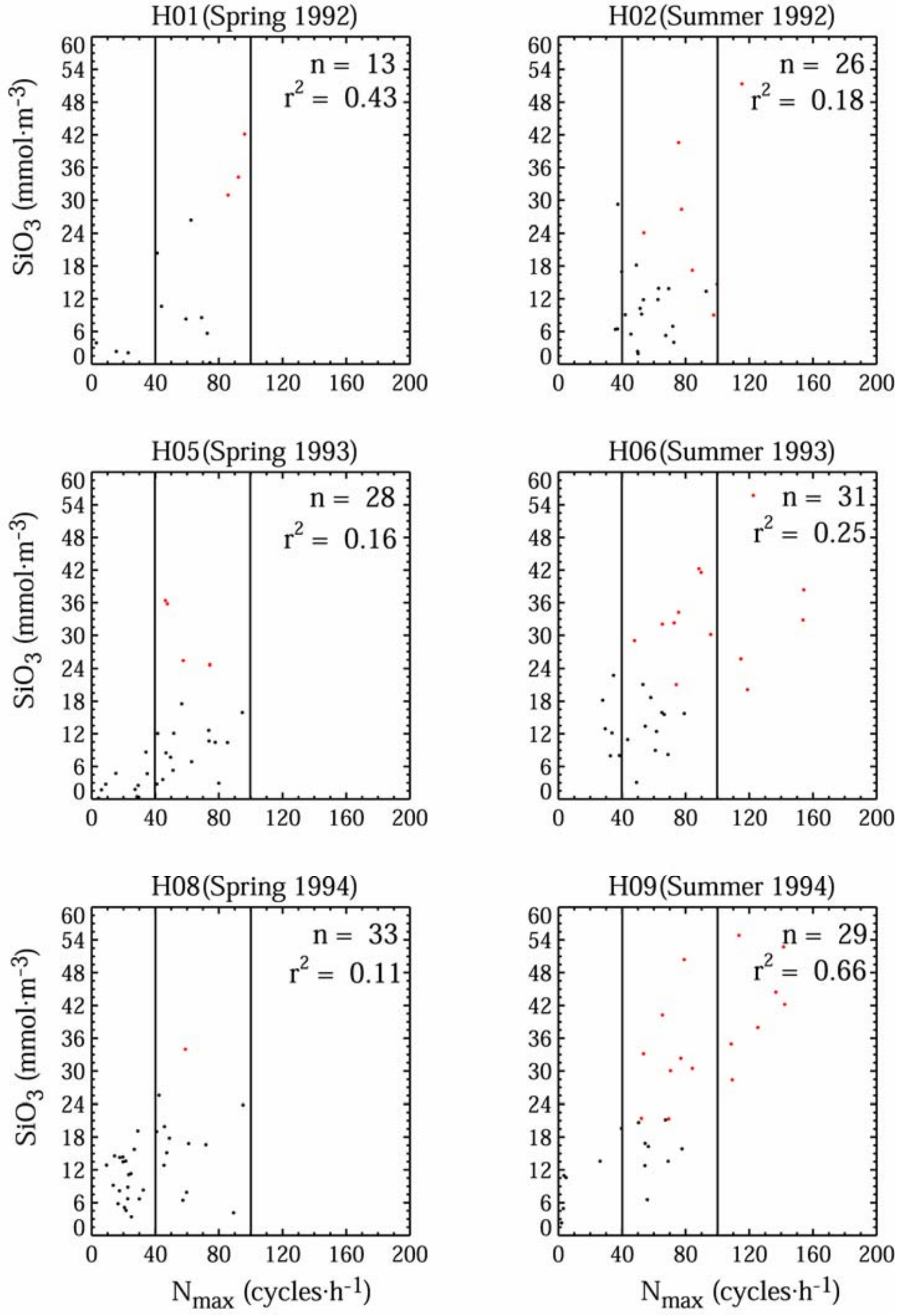


Figure 4.19. Bottom silicate concentrations versus maximum Brunt-Väisälä frequency (N_{max}) in Region 3 on LATEX-A cruises. Stations with low-oxygen values at the bottom are shown in red. The threshold of 40 and 100 cycles·h^{-1} are shown.

generally associated with bottom silicate concentrations greater than 18 mmol·m^{-3}. So, for both spring and summer, low bottom oxygen concentrations generally occurred when both stratification and remineralization were high.

The data presented in Figure 4.19 show a trend of increasing bottom silicate concentrations with increasing maximum Brunt-Väisälä frequency for both spring and summer in Region 3. In Section 4.2, I showed that the presence of low-salinity water and its distribution by local currents essentially control water column stratification in both spring and summer. Maps of bottom silicate concentrations and near-surface salinity (Figure 4.20) show the clear relationship between lower salinity in surface waters and higher bottom silicate concentrations. Overall, silicate concentrations greater than 18 mmol·m^{-3} occur at stations with near-surface salinity less than 32. As salinity increases, bottom silicate concentrations decrease. This is because river-derived low-salinity waters are usually associated with high biological production. The deposition and oxidation of this material near the bottom results in an increase in bottom silicate concentrations. Surface waters with high salinity generally have few nutrients resulting in little in situ production, little organic material deposited, and low bottom silicate concentrations.

In spring occurrences of bottom silicate concentrations greater than 18 mmol·m^{-3} were found east of 92ºW in 1992 and 1993 and west of 93ºW in 1994 (Figure 4.20), generally at stations with near-surface salinities less than 32. However, there were many stations with near-surface salinities less than 32 that had bottom silicate concentrations less than 12 mmol·m^{-3}. At these stations the water column was relatively unstable in spring and so little change in oxygen or silicate occurred between the upper and the lower water column. This condition led to the high oxygen concentrations near the bottom except at three stations on cruise H01, four stations on cruise H05, and one station on cruises H08 (Figure 4.19).

Summer differed from spring. In summer 1992, on cruise H02, bottom silicate concentration decreased offshore over the whole of Region 3 (Figure 4.20). In contrast, during summers in 1993 and 1994, the gradient of decreasing silicate concentration was directed more from east to west (Figure 4.20). High silicate concentrations associated with salinity water less than 32, were found as far west as 94ºW. Thus in Region 3, summer, is the season of high stratification and high bottom remineralization and

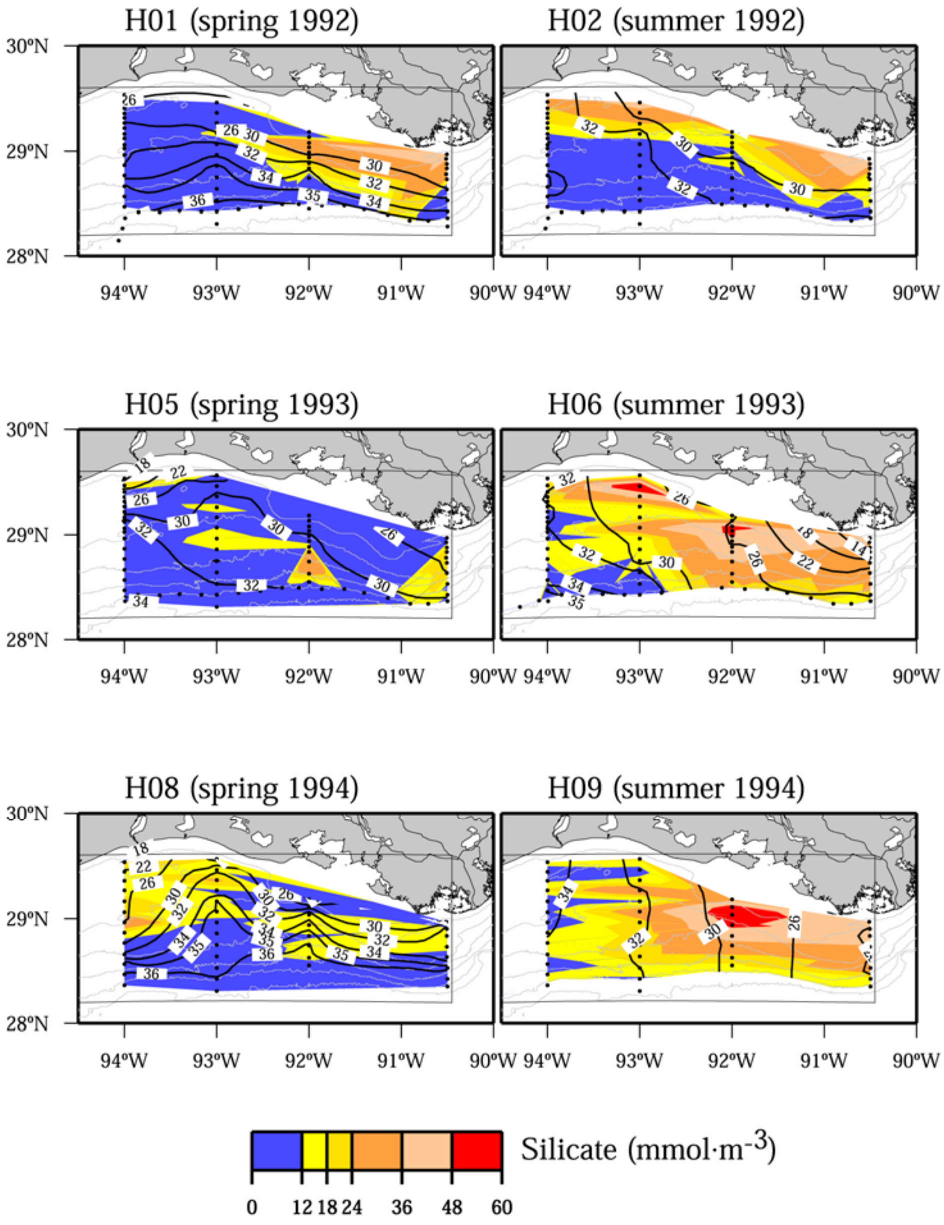


Figure 4.20. Bottom silicate concentrations and contours of near-surface salinity on LATEX-A spring and summer cruises in Region 3. Dots represent station locations. The 10 - 60-m isobaths are shown.

therefore an important time of bottom oxygen depletion.

Region 4 (Texas Shelf)

In summer bottom silicate concentrations in Region 4 were low (Figure 4.21). The vertical stratification was generally weaker than during spring. Summer near-surface salinities in Region 4 were larger than 34 due to the northward and eastward advection of high salinity water from off Mexico (Figure 4.22). These waters are generally low in biological production because they are nutrient limited. The result is little organic material near the bottom with consequent low bottom silicate concentrations. At only one station on cruise H06 and four stations on cruise H09 were bottom silicate concentrations greater than 12 m mol·m^{-3}.

As a result of the downcoast advection of river-derived low-salinity water from Region 3 in non-summer, surface water with salinities less than 32 were found over almost all of Region 4 in spring (Figure 4.22). In spring of 1993, during cruise H05, bottom silicate concentrations associated with these low-salinity waters were less than 12 mmol·m^{-3}. There were only two stations with bottom silicate concentrations greater than 12 mmol·m^{-3}: one was a shallow station located on the eastern end of Region 4, the other was found in more than 20 m water depth near 97ºW-27.25ºN. At this latter station, bottom silicate concentrations were greater than 30 mmol·m^{-3} and were found in water with maximum Brunt-Väisälä frequency greater than 90 cycles·h^{-1} (Figure 4.21). Low bottom oxygen occurred at this station because of the combined effect of high stratification and high remineralization. The other three stations with high silicate concentrations were found during spring 1994 on cruise H08 beneath weakly stratified water columns (Figure 4.21). These stations were located along the inner shore area of Region 4 north of 27ºN where near-surface salinity waters were less than 30, but near-bottom oxygen concentrations were high as a result of the weak stratification.

Region 2 (Mississippi-Alabama Shelf)

In Region 2, low-oxygen occurrences were found at stations with maximum Brunt-Väisälä frequency greater than 40 cycles·h^{-1} and silicate concentrations greater than 12 mmol·m^{-3} (Figure 4.23). This confirms the assumption that low-oxygen water occurs only when both stratification and remineralization are high.

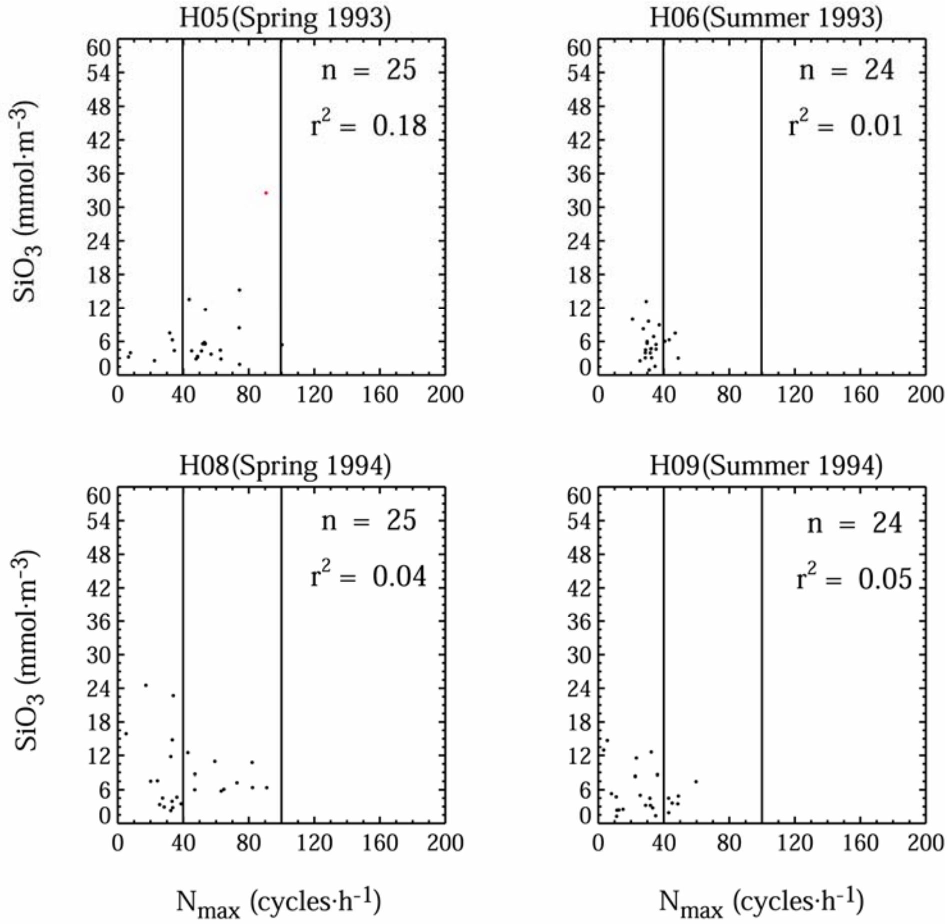


Figure 4.21. Bottom silicate concentrations versus maximum Brunt-Väisälä frequency (N_{max}) in Region 4 on LATEX-A cruises. Stations with low-oxygen values at the bottom are shown in red. The thresholds of 40 and 100 cycles·h^{-1} are shown.

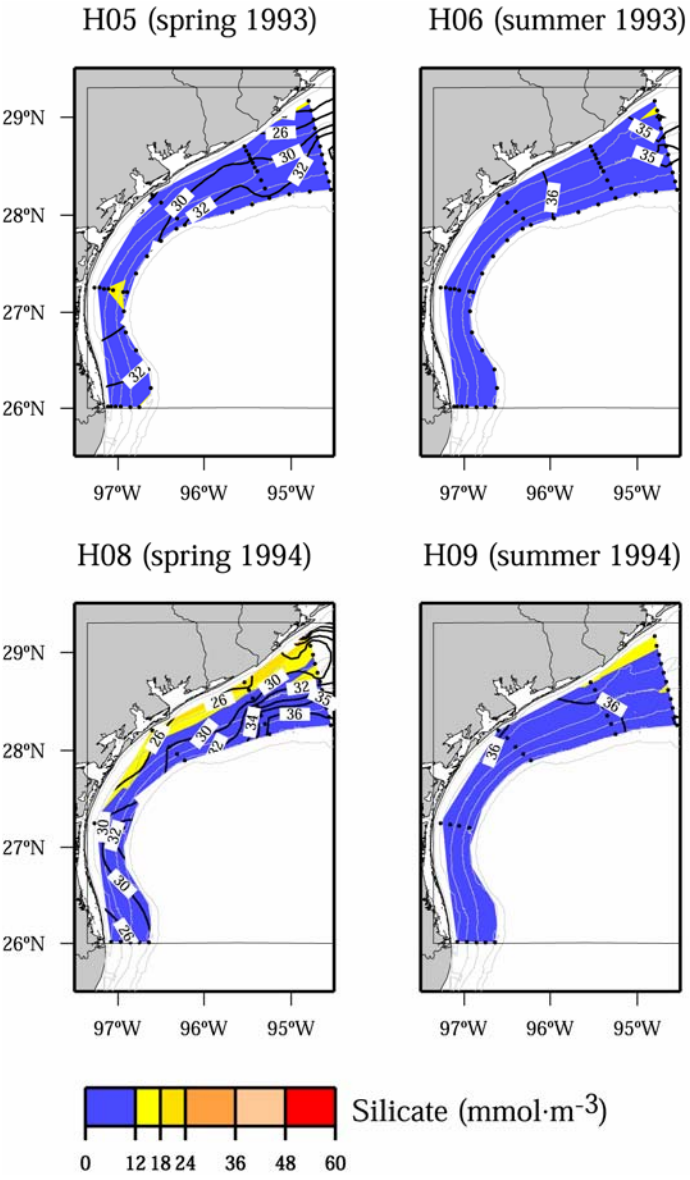


Figure 4.22. Bottom silicate concentrations and contours of near-surface salinity on LATEX-A spring and summer cruises in Region 4. Dots represent station locations. The 10 - 60-m isobaths are shown.

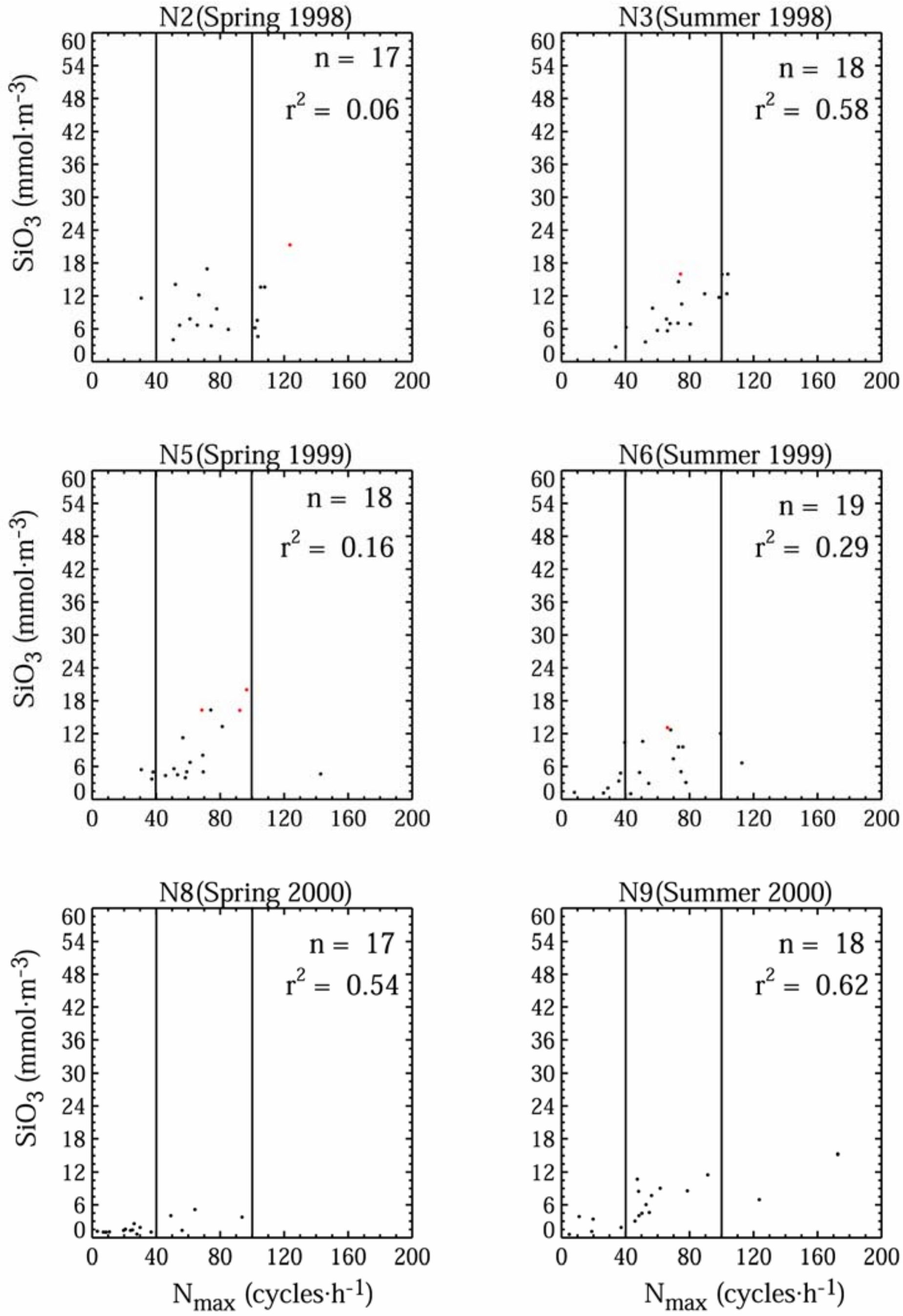


Figure 4.23. Bottom silicate concentrations versus maximum Brunt-Väisälä frequency (N_{max}) in Region 2 on NEGOM-COH cruises. Stations with low-oxygen values at the bottom are shown in red. The thresholds of 40 and 100 cycles·h^{-1} are shown.

The data presented in Figure 4.23 show a propensity for bottom silicate concentrations to increase with increasing maximum Brunt-Väisälä frequency though bottom silicate values were rather low on cruises N6, N8, and N9. Maps of bottom silicate concentrations (Figure 4.24) show that the presence of river-derived low-salinity water may be responsible for the observed bottom silicate distributions. For spring and summer of 1998 and 1999, bottom silicate concentrations greater than 12 mmol·m^{-3} were found exclusively in the area west of 87ºW where near-surface salinity was less than 32. Bottom silicate concentrations greater than 12 mmol·m^{-3} were found along the coast of this area. Silicate concentrations are higher in this area because of the close proximity to the source of the Mississippi River. In summer, however, bottom silicate concentrations greater than 12 mmol·m^{-3} were found in water depths greater than 20 m, except in the immediate area next to the Mississippi River discharge. This may be explained by the reversed salinity gradient in summer due to the transport of river-derived low-salinity water eastward along the outer shelf and slope by the off-shelf circulation features (Belabbassi et al., 2005).

In 2000, during a year of very low river discharge, spring bottom silicate concentrations in Region 2 were generally less than 12 m mol·m^{-3}. Bottom silicate concentrations greater than 12 mmol·m^{-3} were found only in summer in the immediate area next to the Mississippi River discharge (Figure 4.24).

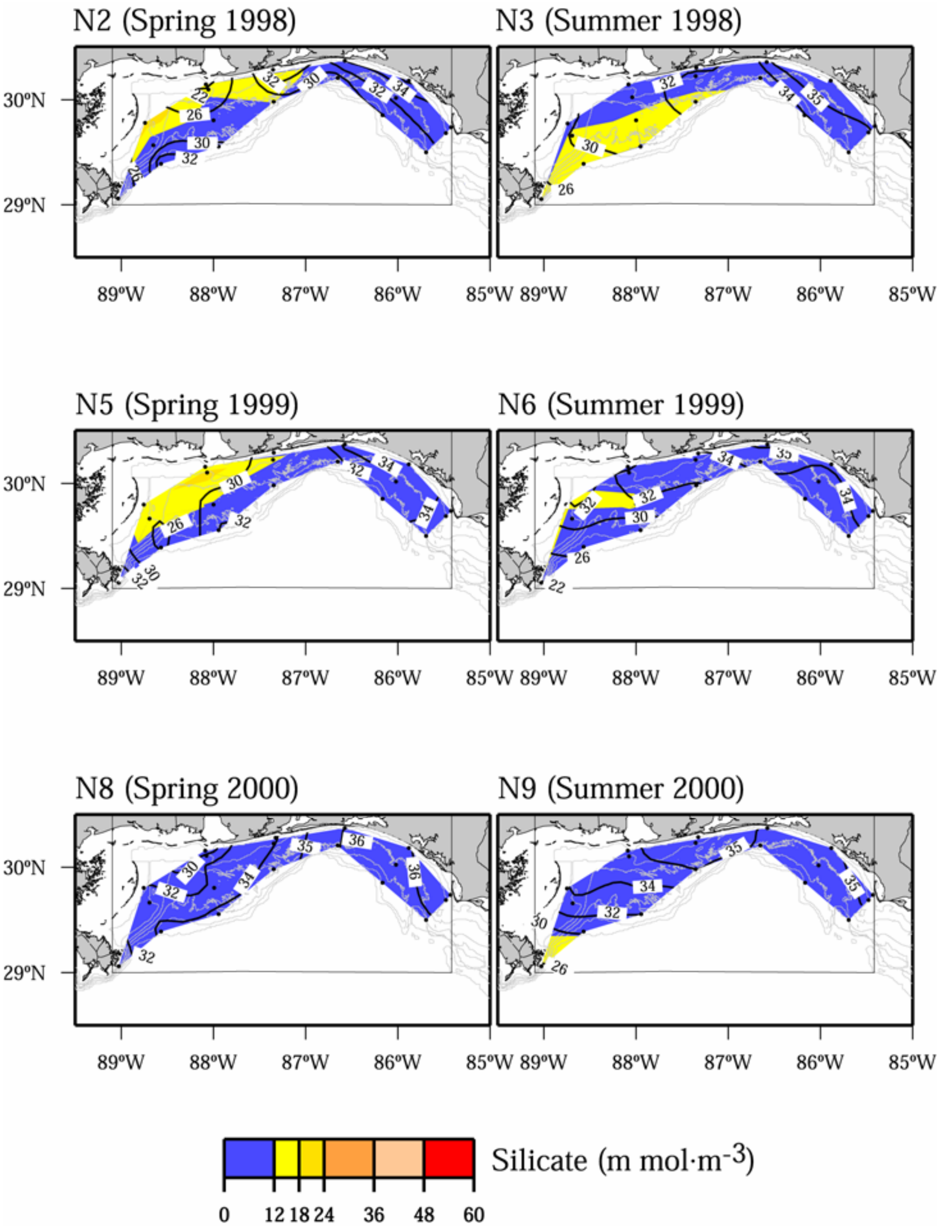


Figure 4.24. Bottom silicate concentrations and contours of near-surface salinity on NEGOM-COH spring and summer cruises in Region 2. Dots represent station locations. The 10 - 60-m isobaths are shown.

Region 1 (West Florida Shelf)

Region 1 is characterized by minimal river discharge. The average salinity over this region is generally greater than 34 except during years of high river discharge, such as in 1998. In the spring and summer cruises of 1998, 1999, and 2000, the maximum Brunt-Väisälä frequency and bottom silicate concentrations were low, being less than 40 cycles·h^{-1} and 12 m mol·m^{-3}, respectively. No bottom low-oxygen values were found in spring or summer in Region 1. Region 1 is less prone to occurrences of low-oxygen water because of the paucity of river-derived low-salinity water with its source of nutrients.

In summary, low-oxygen and hypoxic waters were found to occur only in well stratified water columns with evidence of remineralization near the bottom. Bottom silicate concentrations were associated with low-salinity water over the inner continental shelf of the northern Gulf of Mexico. Bottom silicate concentrations were found to be higher in waters with near-surface salinities less than 32, often found in close proximity to the Mississippi River Delta.

4.4. Spatial-Temporal Patterns of Vertical Stability, Near-Bottom Dissolved Oxygen, and Bottom Remineralization Using EOF Analyses

In this section I have elected to analyze for temporal and spatial patterns of vertical stability, near-bottom oxygen, and bottom remineralization using Empirical Orthogonal Functions (EOF) analyses on the surrogate variables Brunt-Väisälä maxima in the water column, bottom oxygen concentrations, and bottom silicate concentrations. This analysis was carried out only for Regions 2 (Mississippi-Alabama Shelf) and 3 (Louisiana Shelf) because, of the regions studied, those are most likely to have low values of near-bottom oxygen.

All three variables were interpolated onto regular grids shown in Figure 4.25 for each LATEX-A and NEGOM-COH hydrographic cruise using a SCAT2INTERP function built in PV-WAVE. The procedure as explained by Akima (1978) is based on a method of bivariate interpolation and smooth surface fitting applicable when the data values are given at points irregularly distributed in the x-y plane. The procedure adopts partitioning of the plan into a number of triangular cells and the application of a bivariate fifth degree polynomial to each cell to determine the interpolant. The SCAT2INTERP function in PV-WAVE does not provide error fields. Comparisons of spatial maps of the original data with maps produced using the interpolated data, as recommended by Akima (1978), showed very small differences.

For Region 3, new data sets were constructed by selecting the grid points that fall on the four transects made on LATEX-A and at locations where oxygen data in the lower 5 m of the water column were available for all cruises. For Region 2, I visually selected the grid point closest to the sampling station location with oxygen data in the bottom 5-m to reproduce the seven transects of the original sampling plan made on NEGOM-COH. Each data field has the mean removed at each selected grid point before EOF analysis.

The goal of EOF analysis is to examine the space and time relationship between the three variables, isolate and quantify the maximum amount of variation in the data that underlie the spatial and temporal variation, and determine if there is some statistical connection between the three parameters. The EOF method used follows the singular

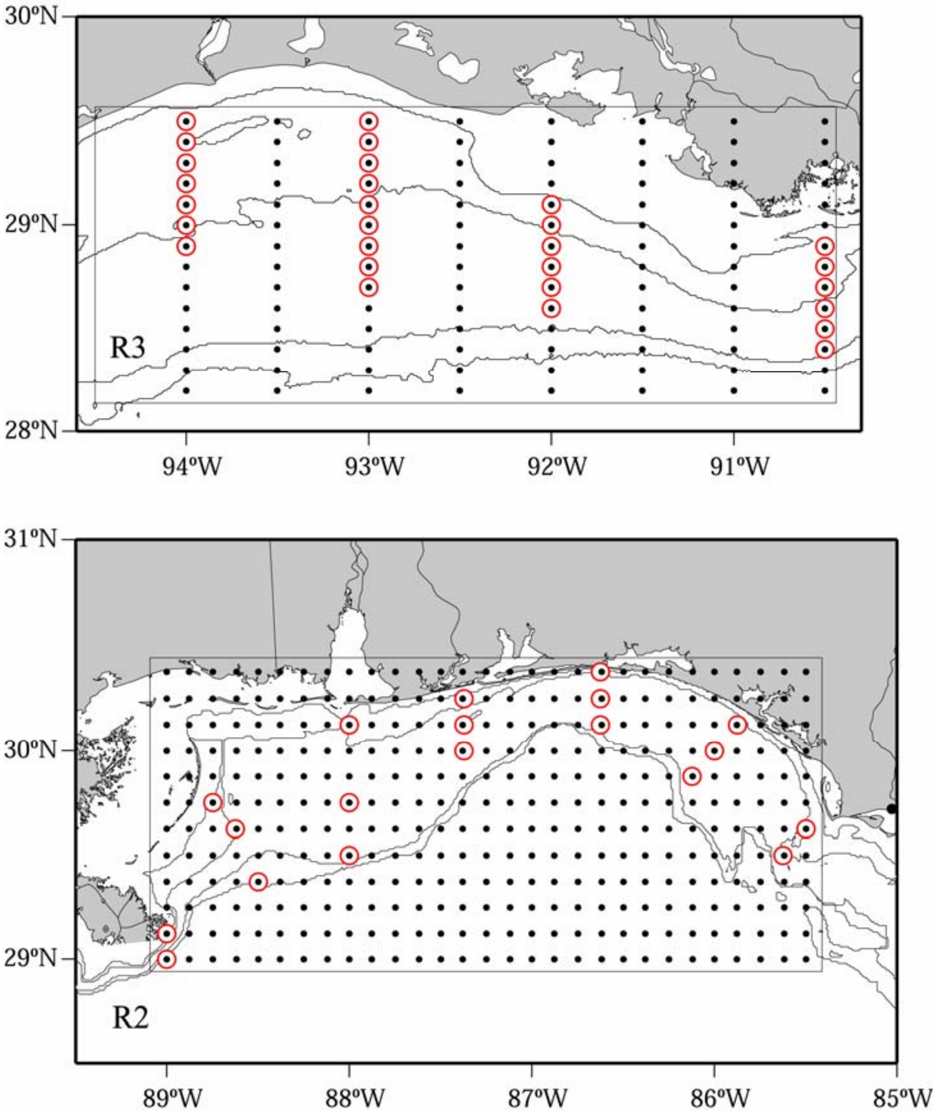


Figure 4.25. Dots represent grid point locations and red circles represent the selected grid points used to construct the new data sets. R refers to region. The 10-, 20-, 50-, and 60-m isobaths are shown.

value decomposition method given in Emery and Thomson (2001). As explained by Otero and Siegel (2004) and Nezlin et al. (2004), the EOF method decomposes a time/space series into a set of orthogonal function (spatial maps) whose amplitude varies in time about the mean. The sum of these functions explains the covariability of the data set. Each of these orthogonal functions is ranked by a measure of the fraction of the total variance explained by each EOF mode.

Region 3 (Louisiana Shelf)

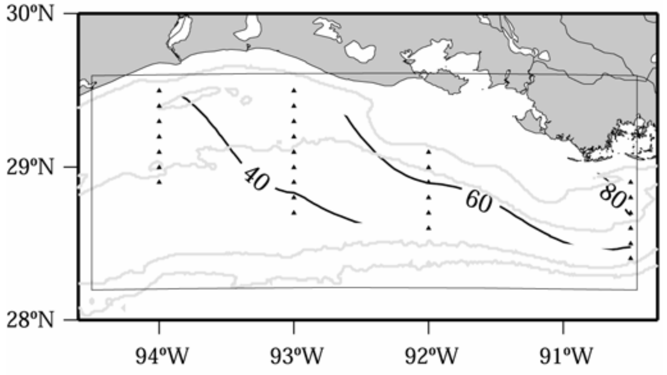
Table 4.4 shows temporal variance associated with the first five EOF modes for each variable. The first modes are dominant, contributing 65.4%, 52.7%, and 70.4%, to the total variability of Brunt-Väisälä maxima in the water column, bottom silicate concentrations, and bottom dissolved oxygen, respectively.

Table 4.4. Percentage variance of Brunt-Väisälä maxima (N_{max}) in the water column, bottom silicate concentration ($[SiO_3]_b$), and bottom oxygen concentration ($[O_2]_b$) associated with the first five EOF modes based on 1992-1994 data in Region 3.

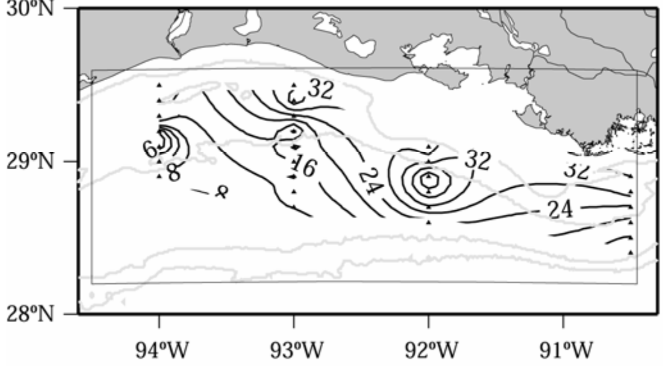
EOF modes	N_{max}	$[SiO_3]_b$	$[O_2]_b$
1	**65.4**	**52.7**	**70.4**
2	11.4	23.6	11.0
3	8.3	12.0	8.3
4	5.6	6.6	4.3
5	3.8	2.3	2.9

The patterns of the first EOF modes of all three parameters are similar with the greatest variation about the mean found in the nearshore, eastern part of Region 3 (Figure 4.26). The amplitude functions of these first EOF modes show general seasonal oscillations between summer and fall (Figure 4.27). The product of the summer

Brunt-Väisälä maxima in the water column



Bottom silicate concentration



Bottom oxygen concentration

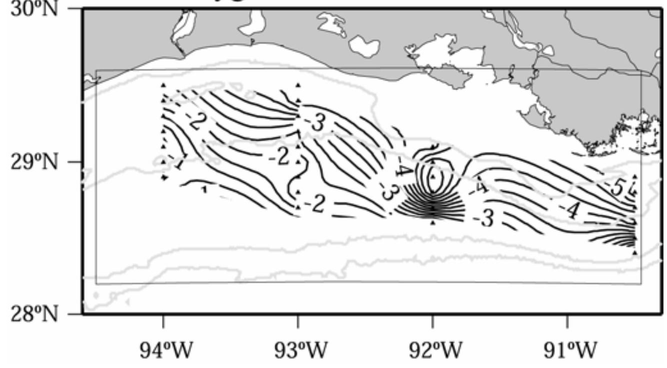
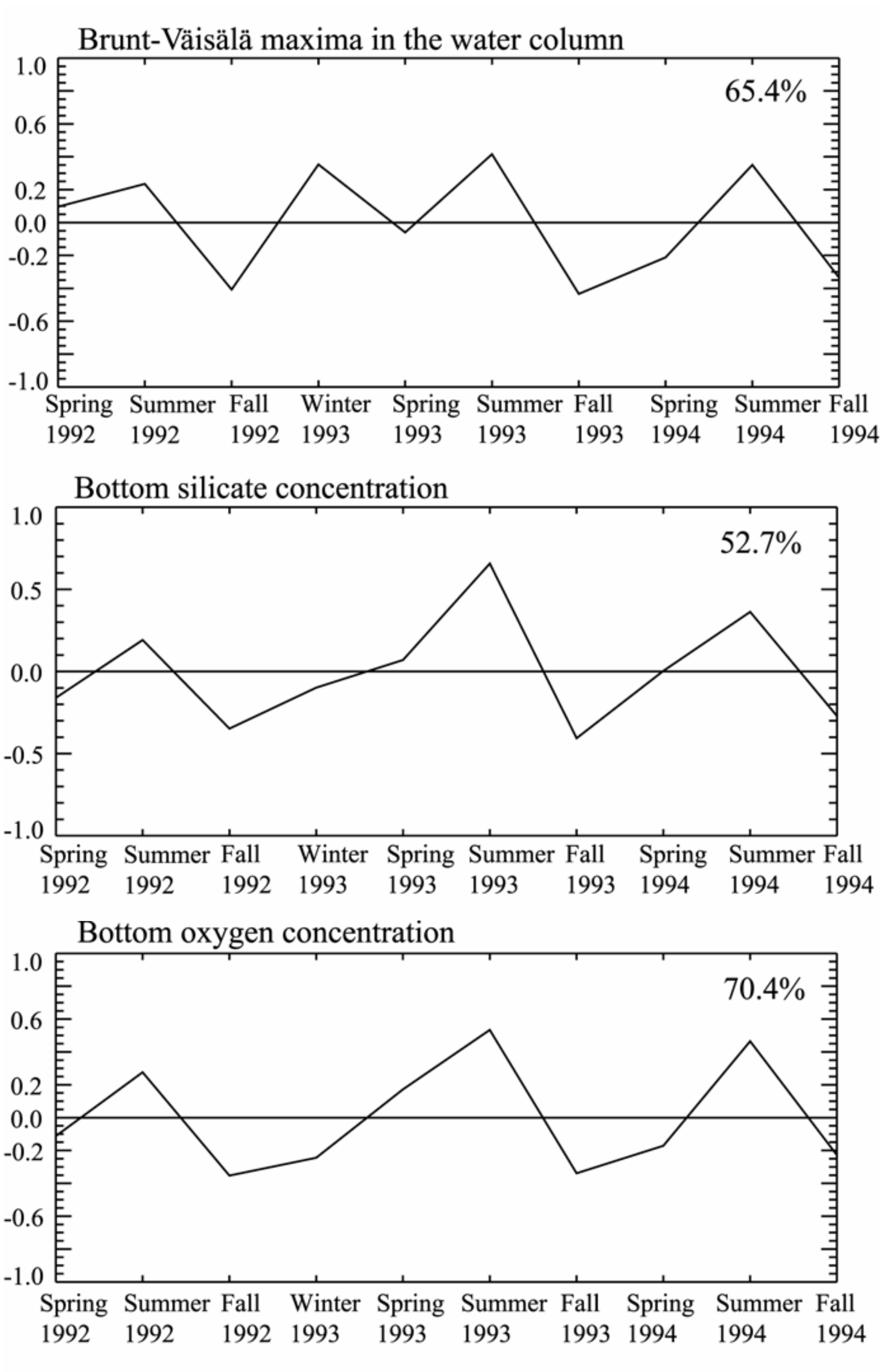


Figure 4.26. Spatial distribution of the first EOF modes of Brunt-Väisälä maxima in the water column, bottom silicate concentration, and bottom oxygen concentration for the 1992-1994 data in Region 3. Triangles represent data locations. The 10-, 20-, 50-, and 60-m isobaths are shown.



Brunt-Väisälä maxima in the water column

Bottom silicate concentration

Bottom oxygen concentration

Figure 4.27. Amplitude functions of the first EOF modes of Brunt-Väisälä maxima in the water column, bottom silicate concentration, and bottom oxygen concentration for the 1992-1994 data in Region 3. The percentage variance of the first EOF mode of each parameter is shown.

amplitudes by their first EOF mode reveals that bottom oxygen concentrations are at minimum in summer when Brunt-Väisälä maxima in the water column and bottom silicate concentrations are at maximum, whereas in fall the opposite conditions occur.

Excluding the single winter cruise of 1993, correlations between the amplitude functions of the first EOF modes of bottom oxygen concentration and Brunt-Väisälä maxima, and between bottom oxygen and silicate concentrations show high square correlation coefficients (r^2) of 0.88 and 0.92, respectively. This strongly supports the hypothesis that in Region 3 the low bottom oxygen concentrations are associated with high Brunt-Väisälä maxima in the water column and high regenerated silicate near the bottom. Moreover, correlation between the amplitude function of the first EOF mode of Brunt-Väisälä maxima in the water column and bottom silicate concentration is high with a squared correlation coefficient of 0.82. This correlation indicates that the dominant modes of these two parameters are dynamically linked over Region 3, which also is supported by the fact that they have similar spatial distributions (Figure 4.26). The spatial distributions of the first EOF mode can be attributed to the impact of fresh water discharge into Region 3. The discharge of fresh water causes salinity to decrease and stratification to increase, and is most likely reason for the increase in oxygen demand from decay of organic matter produced earlier in situ or transported in with river runoff.

The controlling processes over Region 3 are therefore the loss and gain of stratification and the intensity of oxygen removal in the lower layer through remineralization. The seasonal loss and gain of stratification as shown in Section 4.2 results mostly from: (1) the downcoast transport of river-derived low-salinity water through Region 3 in non-summer and its pooling over Region 3 in summer, and (2) the intensification of the wind (and consequently mixing) in non-summer and the calmer conditions in summer. The seasonal increase and decrease of bottom silicate concentrations, that is usually indicative of the intensity of the process of remineralization, suggest that the process of remineralization is more intense in summer than in other seasons.

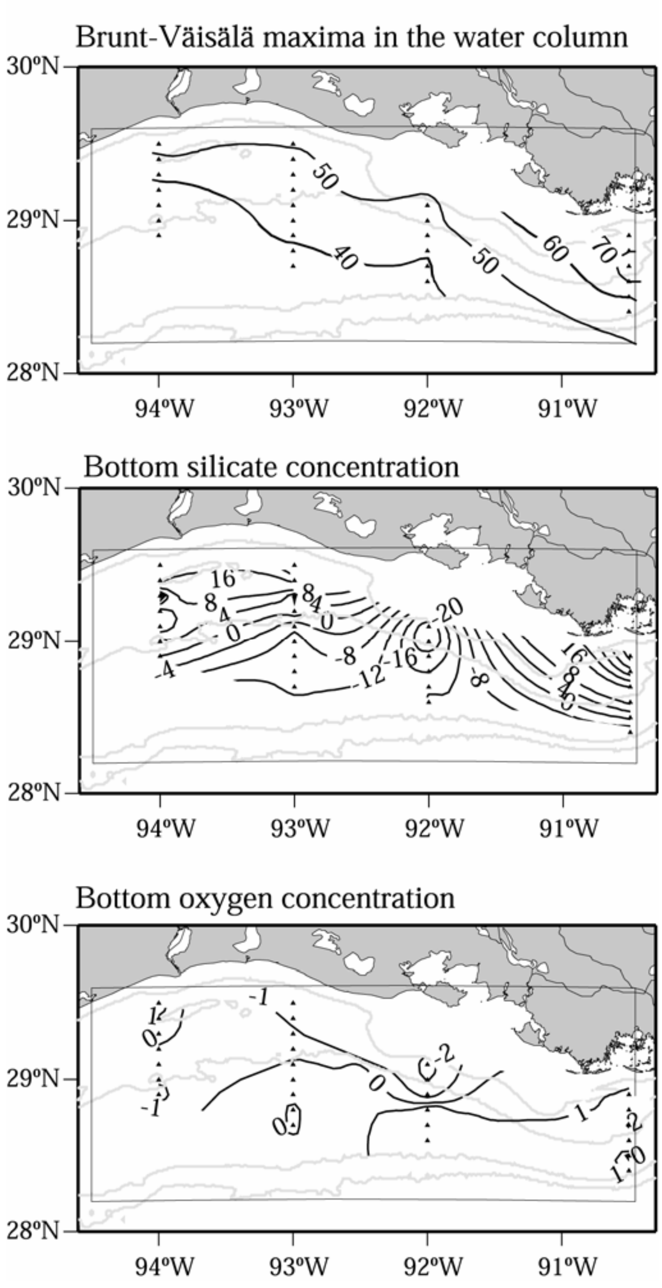
The second EOF mode shows a pattern that is generally of cross shelf gradients for all three variables (Figure 4.28). The amplitude function of the second EOF mode of water column Brunt-Väisälä maxima (Figure 4.29) show a pattern that corresponded very well with the mean Mississippi-Atchafalaya River discharge associated with the 30-day period prior to each cruise (Figure 4.29; dashed line). The values obtained by multiplying the second EOF spatial mode with the amplitude function show that the magnitude of the Brunt-Väisälä maxima in the nearshore area of Region 3 is greatest in seasons and years when the river discharge is greatest and lower when river discharge is lower (Figure 4.29). I am unable to interpret the amplitude functions for bottom silicate and bottom oxygen concentrations.

Region 2 (Mississippi-Alabama Shelf)

For Region 2, the first dominant EOF modes of Brunt-Väisälä maxima in the water column, bottom silicate concentration, and bottom dissolved oxygen concentration accounted for 71.7%, 59.1%, and 62.1% of the total variance, respectively (Table 4.5). As seen, modes three and higher contribute little to the total variability and are not included in the discussion.

Table 4.5. Percentage variance of Brunt-Väisälä maxima (N_{max}) in the water column, bottom silicate concentration ($[SiO_3]_b$), and bottom oxygen concentration ($[O_2]_b$) associated with the first five EOF modes based on 1998-2000 data in Region 2.

EOF modes	N_{max}	$[SiO_3]_b$	$[O_2]_b$
1	**71.7**	**59.1**	**62.1**
2	18.2	20.8	17.0
3	4.4	6.9	6.6
4	2.0	5.7	4.8
5	2.2	4.4	2.1

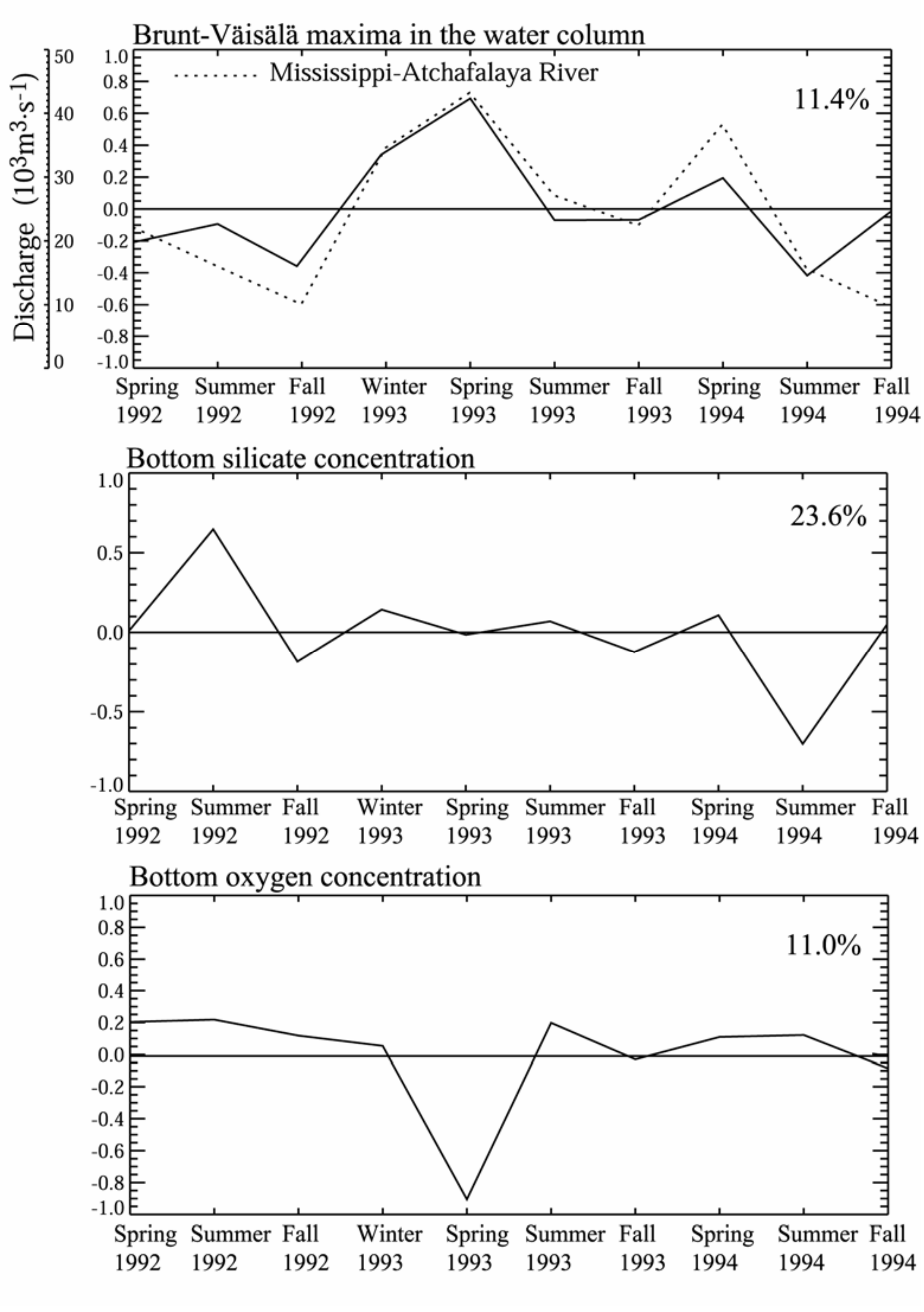


Brunt-Väisälä maxima in the water column

Bottom silicate concentration

Bottom oxygen concentration

Figure 4.28. Spatial distribution of the second EOF modes of Brunt-Väisälä maxima in the water column, bottom silicate concentration, and bottom oxygen concentration for the 1992-1994 data in Region 3. Triangles represent data locations. The 10-, 20-, 50-, and 60-m isobaths are shown.



Brunt-Väisälä maxima in the water column

Bottom silicate concentration

Bottom oxygen concentration

Figure 4.29. Amplitude functions of the second EOF modes of Brunt-Väisälä maxima in the water column, bottom silicate concentration, and bottom oxygen concentration for the 1992-1994 data in Region 3. The percentage variance of the second EOF mode of each parameter is shown. The dashed line represents the mean Mississippi-Atchafalaya River discharge associated with the 30-day period prior to each cruise.

The amplitude patterns of the first EOF modes clearly show a seasonal cycle with an interannual variability (Figure 4.30). In general, bottom oxygen concentrations are at minimum in spring or in summer when water column Brunt-Väisälä maxima and bottom silicate are at maximum. The strength obtained by multiplying the first EOF spatial modes (Figure 4.31) by their amplitudes for all three parameters is highly dependent on river discharge in that particular season and year. There is an apparent difference between years of high river discharge mainly 1998 and 1999 and year 2000 of low river discharge. In spring 2000, because of the below average amount of freshwater over Region 2, the low water column Brunt-Väisälä maxima and low bottom silicate concentrations resulted in high concentration of oxygen in bottom waters. Correlations between the first EOF modes of bottom oxygen concentration and water column Brunt-Väisälä maxima and between bottom oxygen concentration and bottom silicate concentration have squared correlation coefficients of 0.67 and 0.62, respectively, suggesting that vertical stratification and bottom remineralization are important in determining dissolved oxygen levels near the bottom in Region 2. What is more, correlation between the first EOF modes of water column Brunt-Väisälä maxima and bottom silicate concentration is high with a squared correlation coefficient of 0.81, indicating that the first dominant modes of these two parameters are dynamically linked over the region.

The spatial distributions of the first dominant modes of all three parameters are similar west of 88ºW with inshore-offshore gradients (Figure 4.31). The product of these modes with their amplitudes reveal that the highest variability about the mean is found inshore, near Chandeleur Sound, and the lowest variability is found offshore. This can be attributed to low-salinity water from the Mississippi River outflow as well as from other local rivers (Jochens et al., 2002) being found predominantly nearshore west of 88ºW. East of 88ºW, the high variability about the mean found offshore for water column Brunt-Väisälä frequency (Figure 4.31) can be directly related to the advection of low salinity water during high spring Mississippi River discharge and strong eastward currents (Jochens et al., 2002).

The spatial distribution of the first EOF mode of bottom silicate concentration and bottom oxygen concentrations east of 88ºW show the highest variability above the mean in the nearshore area between Cape San Blas and Choctawhatchee Bay at about 85.4ºW

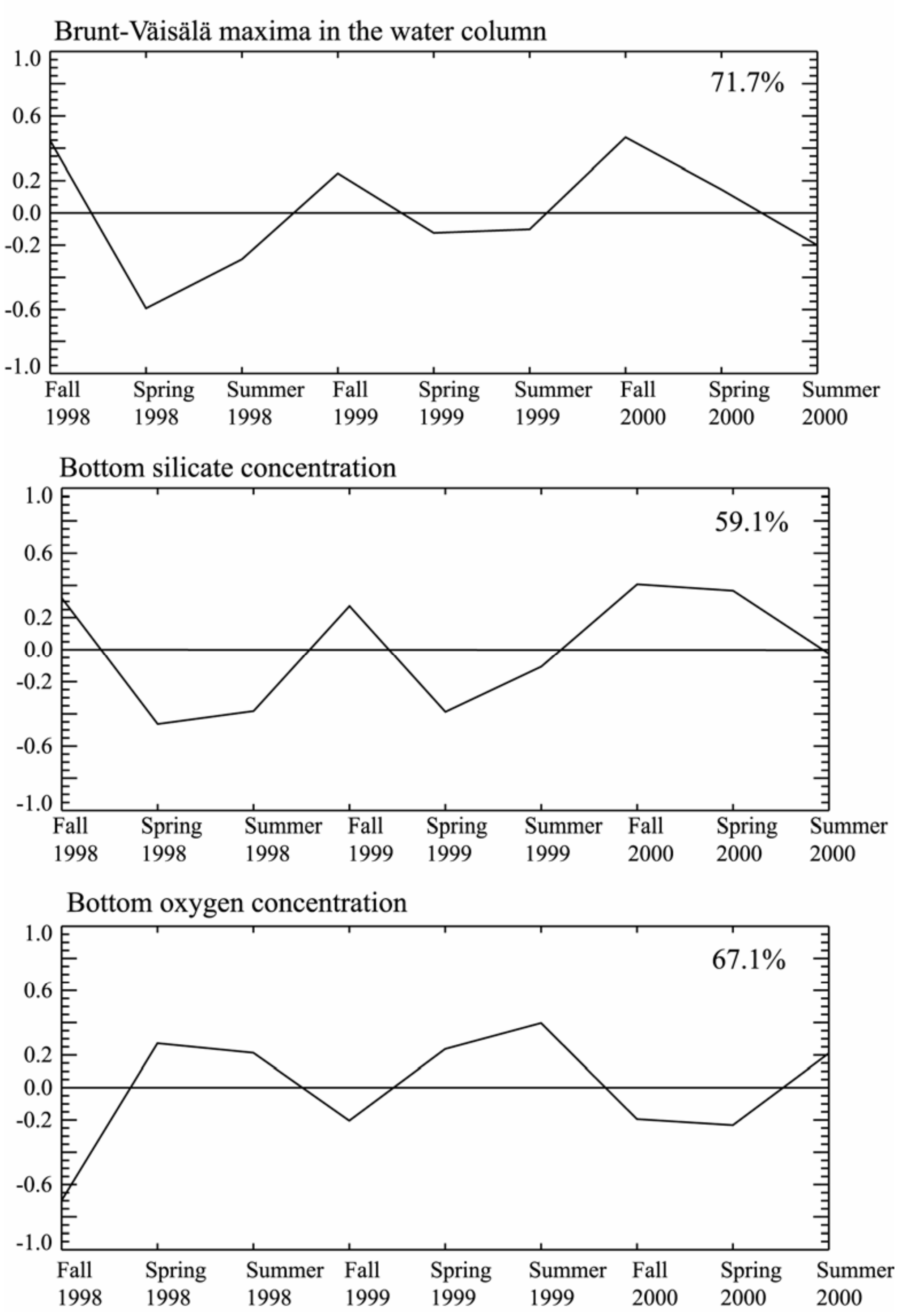
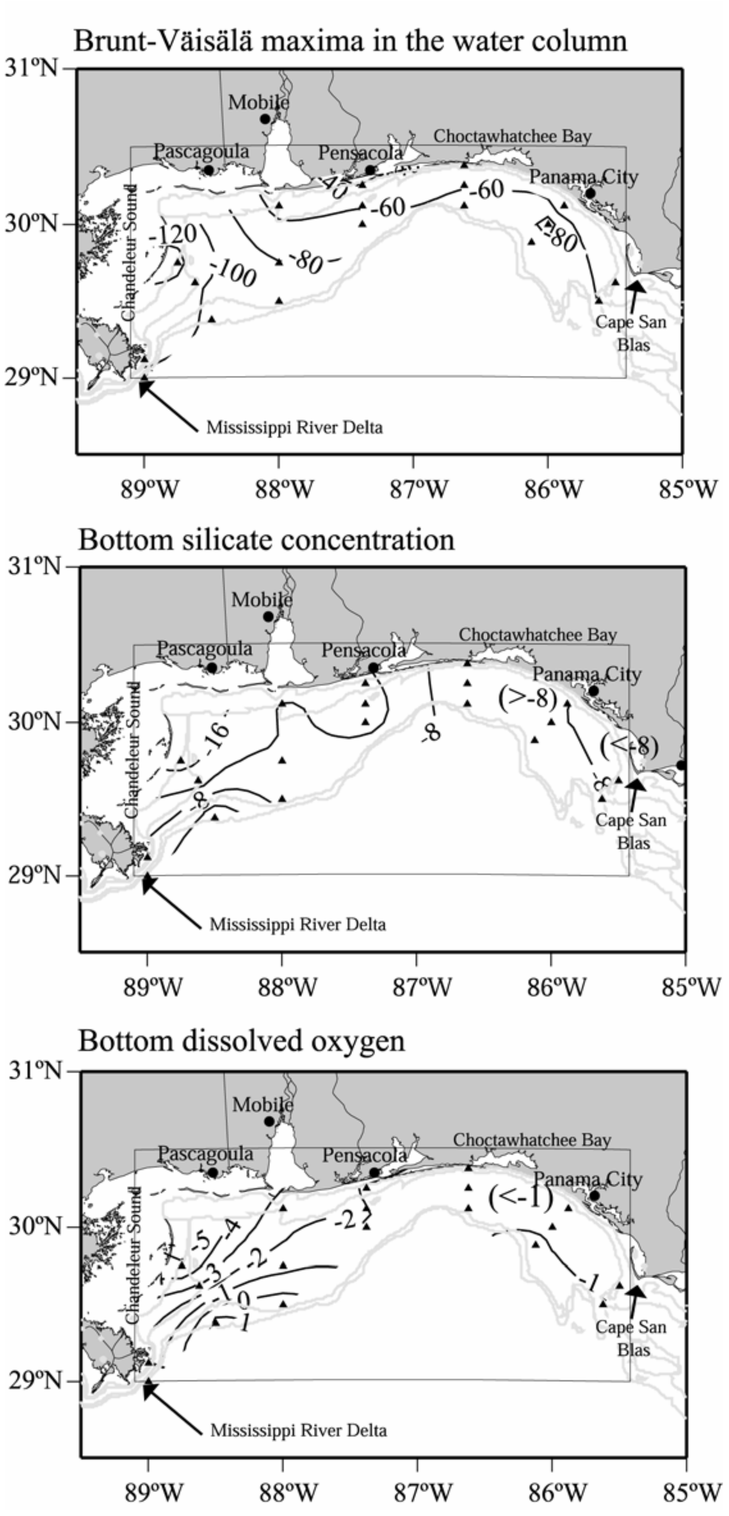


Figure 4.30. Amplitude functions of the first EOF modes of Brunt-Väisälä maxima in the water column, bottom silicate concentration, and bottom oxygen concentration for the 1998-2000 data in Region 2. The percentage variance of the first EOF mode of each parameter is shown.


Brunt-Väisälä maxima in the water column

Bottom silicate concentration

Bottom dissolved oxygen

Figure 4.31. Spatial distribution of the first EOF modes of Brunt-Väisälä maxima in the water column, bottom silicate concentration, and bottom oxygen concentration for the 1998-2000 data in Region 2. Triangles represent data locations. The 10-, 20-, 50-, and 60-m isobaths are shown.

and 86.45ºW, respectively. This nearshore area has been shown by Jochens et al. (2002) to have low salinity and high chlorophyll concentrations in the near surface waters indicating local influence of fresh water influx from the Choctawahatchee Bay.

The second EOF pattern of Brunt-Väisälä maxima shows a northeastward gradient to the east of the Mississippi River Delta (Figure 4.32). This pattern reflects the summer near-surface salinity distributions observed in this area in all three years. Near surface salinities were low near the Mississippi River Delta and increased to the northeast of this location. The explanation for the amplitude function of this mode is difficult to interpret (Figure 4.33). The EOF patterns for the second modes of bottom silicate and oxygen are similar as are their amplitudes. These patterns may be related to differences between what is happening in the region east of the Mississippi Delta along the shelf edge and upper slope and in the nearshore area from the Mississippi Sound eastward past Mobile Bay. These regions are divided approximately by 29.5° N latitude. The highest variability in bottom silicate and oxygen are of opposite signs in the two areas and in spring and summer. The values obtained by multiplying the second EOF mode with its amplitude show that bottom silicates are generally low in summer nearshore north of about 29.5ºN and high south of that latitude but reverse in spring. For bottom oxygen the relationships are reversed. This second mode likely reflects the summer minimum river flow from the Mississippi and other rivers over Region 2 and the transport of most of Mississippi river along the outer shelf edge (Belabbassi et al., 2005) resulting in high salinity water over most of Region 2 except for the region immediately eastward of the Mississippi Delta.

In summary, the processes controlling bottom dissolved oxygen concentrations in Region 2, namely vertical stratification and bottom remineralization, are affected by the distribution of low-salinity water derived from the Mississippi River and from other major rivers of the region.

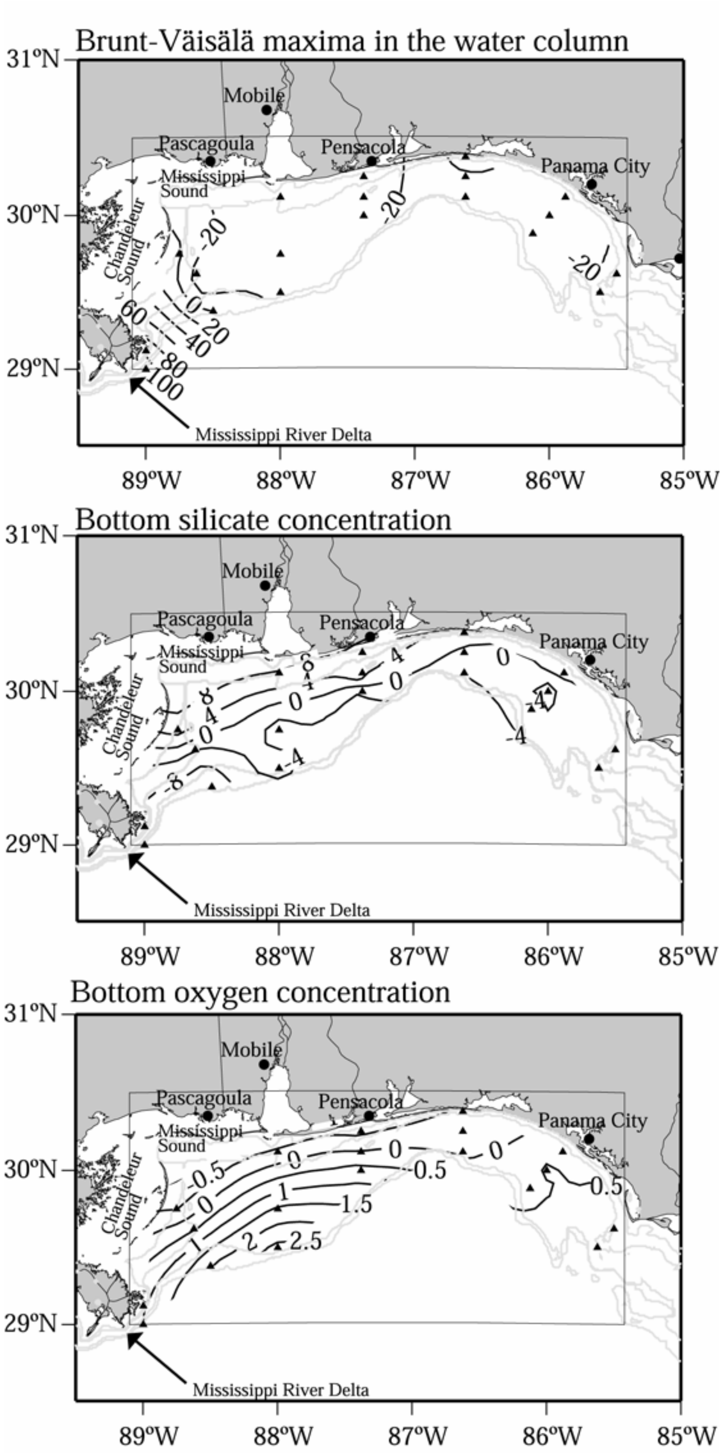


Figure 4.32. Spatial distribution of the second EOF modes of Brunt-Väisälä maxima in the water column, bottom silicate concentration, and bottom oxygen concentration for the 1998-2000 data in Region 2. Triangles represent data locations. The 10-, 20-, 50-, and - 60-m isobaths are shown.

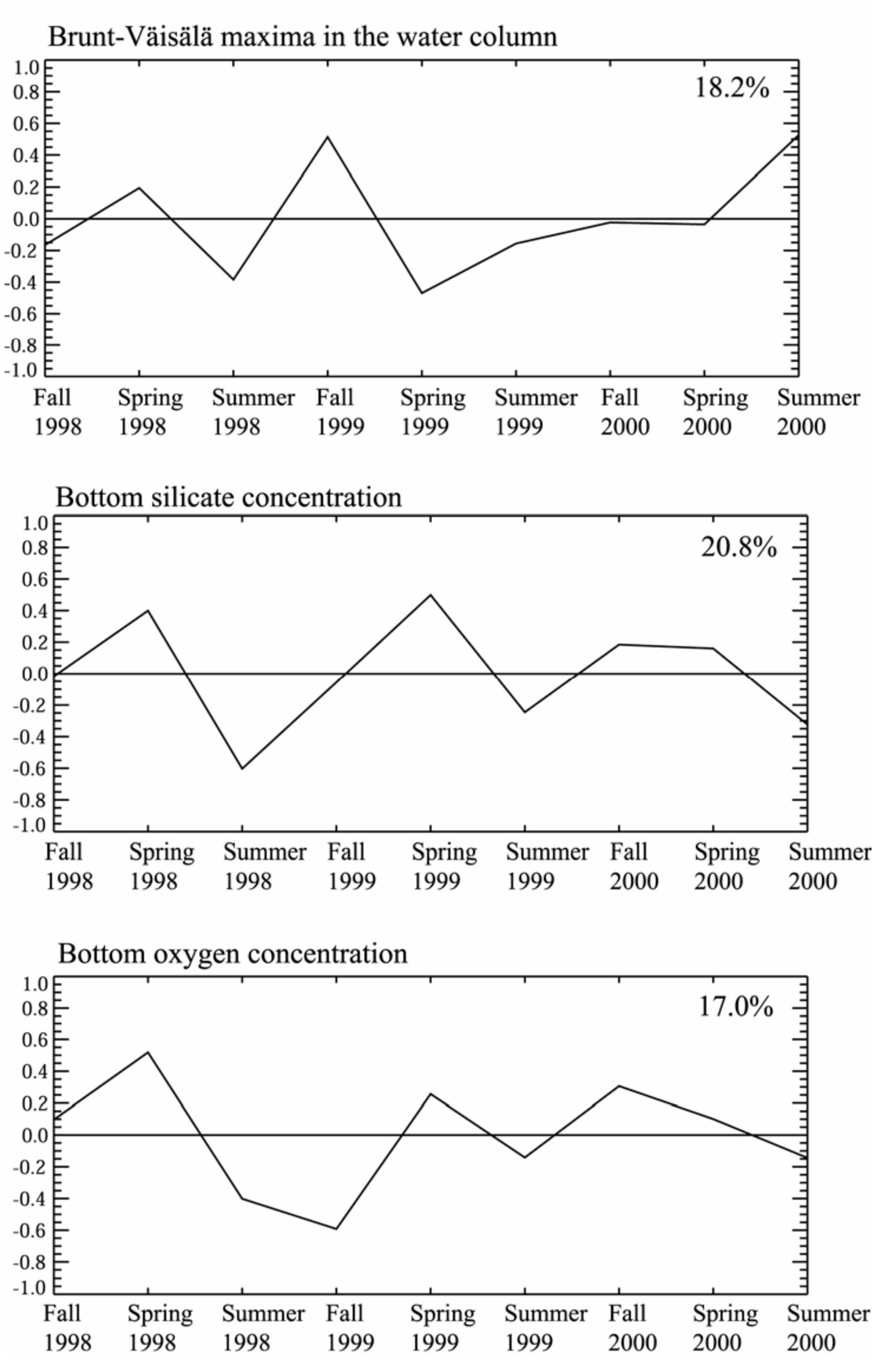


Figure 4.33. Amplitude functions of the second EOF modes of Brunt-Väisälä maxima, in the water column, bottom silicate concentration, and bottom oxygen concentration for the 1998-2000 data in Region 2. The percentage variance of the second EOF mode of each parameter is shown.

CHAPTER V

SUMMARY AND CONCLUSIONS

Because of the limitations of the LATEX-A and NEGOM-COH data sets some of the features that are of interest to this study could not be examined. The sampling plan during LATEX-A and NEGOM-COH programs did not provide the along shelf spatial resolution or the near-bottom vertical resolution that would be optimal for observing the distributions of low-oxygen bottom waters, the Mississippi-Atchafalaya River plume, or nutrient distributions. Bottom samples during both field programs were generally collected 2 m above the seafloor, whereas sampling within 1 m from the bottom would have been ideal to locate bottom waters with reduced oxygen concentrations. Therefore, the LATEX-A and NEGOM-COH data sets have definite sampling limitation to a thorough investigation of factors causing low-oxygen and hypoxic conditions in bottom waters. In this chapter I summarize results of the analyses of these data sets carried out to examine relationships between river-derived low salinity water, vertical stratification, bottom nutrient enrichment through remineralization, and occurrences of reduced bottom oxygen concentrations over the northern continental shelf of the Gulf of Mexico.

Using LATEX-A and NEGOM-COH data sets I found that over the northern continental shelf and upper slope of the Gulf of Mexico dissolved oxygen concentrations less than 2.4 $mL\cdot L^{-1}$ are found exclusively in water depths less than 60 m. For all samples collected in water depths greater than 60 m oxygen values ranged between 2.4 and 5.8 $mL\cdot L^{-1}$. Therefore, I defined water with dissolved oxygen concentrations less than 2.4 $mL\cdot L^{-1}$ as low-oxygen waters in contrast to the commonly occurring oxygen concentrations over the northern Gulf. Low-oxygen concentrations and hypoxic conditions (defined as oxygen concentrations less than or equal to 1.4 $mL\cdot L^{-1}$) in near-bottom water were found exclusively over the continental shelf of the northern Gulf in water depths less than 60 m. These occurrences differed in the four regions studied. Low-oxygen and hypoxic water occurrences were found almost exclusively in regions with large influences from rivers. The Mississippi and Atchafalaya rivers are the major sources of fresh water for the northern Gulf, although other rivers sometimes may have significant effects. Thus the occurrences were found in regions most influenced by these two rivers, namely, Region 2 (Mississippi-Alabama shelf) and Region 3 (Louisiana shelf). Region 1 (West Florida shelf) with minimum freshwater discharge had no low-oxygen occurrences, and Region 4 (Texas shelf) had only one occurrence.

The spatial and temporal variability of vertical stratification and bottom remineralization over the inner shelf of the northern Gulf were responsible for the differences in distributions of low-oxygen and hypoxic waters in the four regions. As demonstrated by the examination of water column Brunt-Väisälä maxima and bottom silicate concentrations, the regional differences and the seasonal variability are principally influenced by the presence or absence of river water in these regions. Three factors that affect this variability are wind mixing, currents, and the proximity to the Mississippi and Atchafalaya rivers.

The presence of river-derived low-salinity water in near-surface waters of Regions 2 and 3 caused water column stratification to increase. Salinity was more important than temperature in determining the vertical stratification in these regions in spring and in summer. Locations where temperature influence was larger were found in water column depths greater than 20 m over Region 3 and in the near shore areas west of 87°W in Region 2. The maximum Brunt-Väisälä frequency was found to increase as near-surface salinity decreased. Near-surface waters with salinity less than 34 were generally associated with a water column Brunt-Väisälä maximum that was greater than 40 cycles·h^{-1}, except when winds induced vertical mixing to decrease vertical stratification. In these cases the maximum Brunt-Väisälä frequency was reduced to less than 40 cycles·h^{-1}. This tended to occur in Region 3 during spring when frontal passages were frequent.

A trend of increasing bottom silicate concentrations with increasing maximum Brunt-Väisälä frequency was observed for both spring and summer in Regions 2 and 3. High bottom silicate concentrations generated by high remineralization rates were strongly associated with the presence of river-derived low-salinity water in Regions 2 and 3. The highest bottom silicate concentrations were found in areas of low-salinity surface waters near the Mississippi River Delta.

Low-oxygen and hypoxic waters were found only in waters with Brunt-Väisälä maxima greater than 40 cycles·h^{-1}. These oxygen conditions in near-bottom waters were common in summer in Region 3 east of 93.5ºW, whereas in spring they were found only at a few stations east of 92ºW. In Region 2 in both spring and summer, occurrences of low-oxygen to hypoxic conditions were rather localized in the near shore area west of 88ºW, where they occupied smaller areas and volumes than in Region 3.

Spatial and temporal patterns of bottom dissolved oxygen, water column Brunt-Väisälä maxima, and bottom silicate concentrations were examined using EOF analysis. More than 65% of the variance in bottom oxygen in Regions 2 and 3 was associated with the first EOF mode. The amplitude functions for the first EOF modes of bottom oxygen, Brunt-Väisälä maxima, and bottom silicate concentrations are well correlated indicating that much of the variance in bottom oxygen is explained by the combined effect of vertical stratification and bottom remineralization. The temporal and spatial distribution of the first mode of Brunt-Väisälä maxima and bottom silicate concentration indicated that the distributions of both are dynamically linked to the seasonal distributions of river-derived low-salinity water in Regions 2 and 3.

Regions 1 and 4 are subjected to minimum influences from local river discharges and are located far from the direct influence of major rivers, and so they differ considerably from Regions 2 and 3. The absence of river-derived low-salinity water in Region 1 during both spring and summer and in Region 4 during summer resulted in a poorly stratified water column and little remineralization in the bottom layer. Water column Brunt-Väisälä maxima in these regions were generally less than 40 cycles·h^{-1} and were associated with high oxygen concentrations near the bottom. There were a few stations with water column Brunt-Väisälä maxima greater than 40 cycles·h^{-1} in summer in Region 4. At these stations, the temperature was relatively more important than salinity in determining vertical stratification. Because of low remineralization in the near-bottom waters, those stations did not have low-oxygen concentrations.

Water column Brunt-Väisälä maxima also exceeded 40 cycles·h^{-1} in Region 4 in spring when the downcoast current regime advected low-salinity water out of Region 3 into Region 4 and caused an increase in water column stratification and a noticeable increase in silicate concentrations near the bottom. Brunt-Väisälä frequencies greater than 40 cycles·h^{-1} were found in the halocline, where the density variation is chiefly determined by salinity variation. There was little effect of river-derived low-salinity water on bottom silicate concentration because Region 4 is located far from the freshwater source. As a result, any near-surface nutrients would have been used up well before the water reached Region 4 and thus primary production would have been limited. Low-oxygen water occurred only at one station in Region 4 that had high water column Brunt-Väisälä maxima and high bottom remineralization.

In Region 1, the advection of river-derived low-salinity water from Region 2 during years of unusually high river discharge caused an increase in water column stratification and a small increase in bottom silicate concentrations. Like Region 4, because Region 1 is located far from the Mississippi River Delta the rate of oxygen removal near the bottom did not exceed the rate of oxygen supply. Thus, no occurrences of low-oxygen or hypoxic conditions near the bottom were found in Region 1.

In conclusion, the occurrences of low-oxygen concentrations in near-bottom water over the inner continental shelf of the northern Gulf of Mexico are clearly related to vertical stratification. Such occurrences are found only in waters with maximum Brunt-Väisälä frequency greater than 40·cycles·h^{-1}. Except for Region 4 in summer and other localized areas in Regions 3 and 2, these high frequencies were chiefly caused by the vertical salinity variation due to the presence of river-derived low-salinity water. The relationship between bottom silicate concentration and maximum Brunt-Väisälä frequency revealed that low-oxygen concentrations in bottom waters occur only in stable water columns with high bottom remineralization. It was also clear that the process of remineralization was more intense during summer in Region 3 and during years of high river discharge in Region 2. Thus, over the inner continental shelf of the northern Gulf of Mexico the distribution of river-derived low-salinity water by currents influences the spatial and temporal variability of vertical stratification and the amount of the remineralized silicate near the bottom, and thereby controls the occurrence of bottom waters with low-oxygen concentrations. Of course, strong surface winds can reduce significantly the vertical stratification due to low-salinity surface waters and result in an ample supply of oxygen to the bottom waters. Also, the effect of river water on bottom silicate concentrations generally decreases with increasing distance from the source. In all cases low-oxygen or hypoxic bottom waters occur only if oxygen removal exceeds supply.

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