Oceanography of the Sargasso Sea: Overview of Scientific Studies

M.W. Lomas, N.R. Bates, K.N. Buck, and A.H. Knap

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The Sargasso Sea Alliance is led by the Bermuda Government and aims to promote international awareness of the importance of the Sargasso Sea and to mobilise support from a wide variety of national and international organisations, governments, donors and users for protection measures for the Sargasso Sea.

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The Secretariat of the Sargasso Sea Alliance is hosted by the Washington D.C. Office
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COVER PHOTO: Taking water samples at Hydrostation S., Tiffany Wardman.

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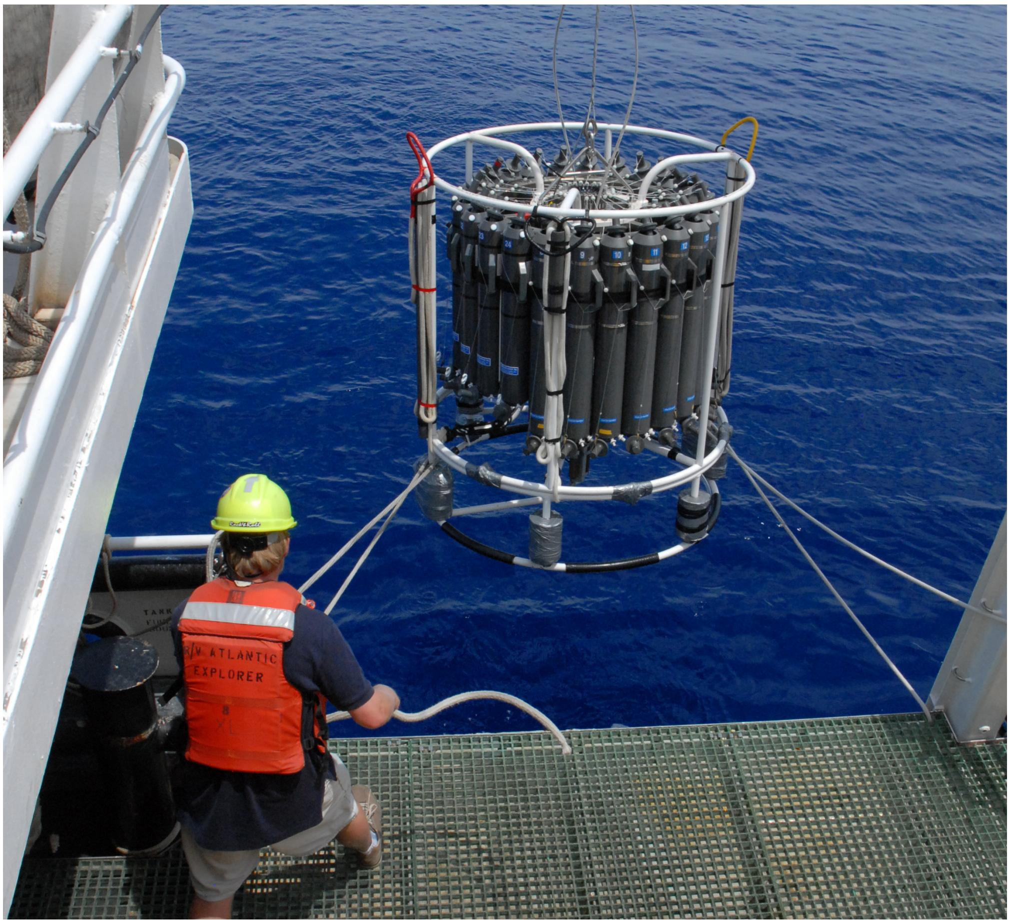

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BIOS

Bermuda Institute of Ocean Sciences (BIOS), Inc.
Founded in 1903 as the Bermuda Biological Station
17 Biological Station, St. George's, Bermuda

Foreword

BETWEEN 2010 AND 2012 a large number of authors from seven different countries and 26 separate organisations developed a scientific case to establish the global importance of the Sargasso Sea. A summary of this international study was published in 2012 as the "Summary science and Supporting Evidence Case." Nine reasons why the Sargasso Sea is important are identified in the summary. Compiling the science and evidence for this case was a significant undertaking and during that process a number of reports were specially commissioned by the Sargasso Sea Alliance to summarise our knowledge of various aspects of the Sargasso Sea.

This report is one of these commissioned reports. These are now being made available in the Sargasso Sea Alliance Science Series to provide further details of the research and evidence used in the compilation of the summary case. A full list of the reports in this series can be found in the inside back cover of this report. All of them can be downloaded from **www.sargassoalliance.org.**

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Table of Contents

CHAPTER 1: Overview of the Importance of the Sargasso Sea and this report **5**

CHAPTER 2: Physical Characteristics of the Sargasso Sea **6**
  2.1: Meteorology and Seasonal Cycling of the Upper Ocean. **7**
  2.2: Subtropical Mode Water (STMW) **8**
  2.3: Influence of the North Atlantic Oscillation on Sargasso Sea Variability **10**
  2.4: Eddy Dynamics and Implications for Short and Long Term Variability **10**
  2.5: Deep Water masses in the Sargasso Sea **12**
  REFERENCES **13**

CHAPTER 3: Chemical Characteristics of the Sargasso Sea **14**
  3.1: Nutrients in the Sargasso Sea **14**
  3.2: Trace elements in the Sargasso Sea **16**
  3.3: Organic Contaminants in the Sargasso Sea **17**
  REFERENCES **19**

CHAPTER 4: Biological Food Webs/BATS **23**
  4.1: Food Web Overview **23**
  4.2: Phytoplankton Research **23**
  4.3: Zooplankton Research **24**
  4.4: Microbial Ecology **26**
  4.5: Sediment Traps and Carbon Export **27**
  4.6: Ocean Optics and Remote Sensing. **29**
  REFERENCES **30**

CHAPTER 5: Biogeochemical Cycles in the Sargasso Sea **33**
  5.1: Marine biogeochemical cycles in the Sargasso Sea **33**
  5.2: The Global Ocean Carbon Cycle and Observations in the Sargasso Sea **35**
  5.3: Calcium Carbonate Production **36**
  REFERENCES **37**

CHAPTER 6: Air-sea Interactions **39**
  6.1: Climate Variability, NAO/ENSO Influences on the Subtropical Gyre **39**
  6.2 : Atmospheric Deposition and Acid Precipitation. **40**
  6.3: Air-sea Gas Exchange, CO_2 and DMS **41**
  REFERENCES **42**

CHAPTER 7: Climate Change and Ocean Acidification **44**
  7.1: Climate Change **44**
  7.2: Ocean Acidification **44**
  REFERENCES **46**

APPENDIX 1: Contact Information for Contributing Authors **47**
APPENDIX 2: Glossary of Important Terms. **48**
APPENDIX 3: Compilation, by year through June 2011, of peer-reviewed publications arising from work at or near the Bermuda Atlantic Time-series Study (BATS) site.. . . . **49**

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Award Number	**/ Award Title**
1012444	2010 Shipboard Scientific Support Equipment for R/V Atlantic Explorer.
1119773	2011 Oceanographic Instrumentation: R/V Atlantic Explorer.
1044934	Collaborative Research: Isotopic and Compositional Investigation of the Sources and Interactions of Reactive Nitrogen in the Marine Atmosphere at Bermuda.
0752161	Collaborative Research: Combining Flow Cytometry and Stable Isotope Techniques: A Method to Measure Phytoplankton- and Bacteria-specific Nitrogen and Carbon Uptake.
1030149	Collaborative Research: Plankton Community Composition and Trophic Interactions as Modifiers of Carbon Export in the Sargasso Sea.
0918422	Shipboard Scientific Support Equipment for R/V Atlantic Explorer.
0927567	Collaborative Research: *Prochlorococcus* and its contribution to new production in the Sargasso Sea.
0928406	BEACON: BErmuda ocean Acidification and COral reef iNvestigation.
1045966	Dimensions: Collaborative Research: Biological Controls on the Ocean C:N:P ratios.
0752366	The Bermuda Atlantic Time-series Study (BATS): Year 21-25.
0549750	Collaborative Research: Development of the Automated Dissolved Inorganic Carbon Analyzer (AMICA) for Seawater DIC Analyses.
0825701	Operation of a Community Marine-Atmospheric Sampling Facility at Tudor Hill, Bermuda.
0927453	USA GEOTRACES North Atlantic Section: The chemical speciation of dissolved iron and copper.
0648016	The Panulirus Hydrographic Stations: Years 54-59.
0927098	Time Series Particle Flux Measurements in the Sargasso Sea.
0936341	Oceanographic Technical Services, 2009-2011: R/V Atlantic Explorer.
0505888	Ship Operations Weatherbird II.

CHAPTER 1

Overview of the Importance of the Sargasso Sea and this Report

A.H. Knap

The Sargasso Sea is an anticyclonic gyre in the central North Atlantic Ocean. Noted as oligotrophic, the Sargasso Sea (also known as the North Atlantic Subtropical Gyre) has low nutrient levels and is considered to be representative of most oceanic gyres. Gyres like this one cover 60 percent of the ocean surface or roughly 40 percent of the globe. Traditionally the boundaries of the Sargasso Sea were defined by the presence of the free-floating pelagic plant *Sargassum*. Now, however, the Sargasso Sea is defined in terms of physical boundaries—the Gulf Stream to the west, the North Atlantic Current to the north, the Canaries Current to the east, and the North Equatorial Current to the south. The only landmass in the Sargasso Sea is the island of Bermuda, making it an ideal place for research.

The waters around Bermuda are home to two of the longest running time-series measurement sites in the world. In 1954, the late Henry Stommel started a time-series of ocean measurements in the Sargasso Sea at Station 'S' (32°10'N, 64°30'W) The data collected at Station 'S' has provided invaluable insight into the changing conditions of the deep ocean. In 1988, a more complex measurement program called the Bermuda Atlantic Time-series Study (BATS) was started 80 kilometers southeast of Bermuda. With funding from the US National Science Foundation as well as other US agencies, the data collected at these two stations has afforded scientists with a unique understanding of the Atlantic Ocean over time and acts as a barometer for changing climate.

From research conducted at the Bermuda Institute of Ocean Sciences (BIOS Inc.), as part of BATS, we know that, over the past several decades, portions of the western North Atlantic Gyre, namely the Sargasso Sea, have warmed ~0.3-0.5°C, and that carbon dioxide content has increased 10 percent. What we do not know is how widespread these changes are within the North Atlantic Gyre as a whole, or how other oceanographic and ecosystem parameters may have changed as a result, so further study is extremely important.

Within the boundaries of the Sargasso Sea, the major surface biological life, *Sargassum* seaweed, can be found anywhere. While it may be more consistently copious in certain sectors, abundance at any single location is quite unpredictable. The floating *Sargassum* is home to more than 60 species of organisms, with the ecosystem housing everything from small plant species to juvenile and adult fish. Generally the area is relatively free of pollution, though tar and plastic can amalgamate with the *Sargassum* community.

While the floating *Sargassum* is an important ecosystem, the majority of the Sargasso Sea life is pelagic, mid and deep-water organisms of the Atlantic Ocean.

FIGURE 1. Ocean map showing the location, extent and circulation pattern of the five ocean gyres. Credit: NOAA

This is due to the Sargasso Sea's abyssal depths of 4000 or more meters. Dr. William Beebe described many of the organisms in his record bathyscape dives off Bermuda in 1932 (These dives actually resulted in the first live radio broadcasts from the deep ocean). While there are far too many organisms to name in this article, there are some species of specific interest to the scientific community. The *Sargassum* community, the yearly eel migration/spawning activity and the migration of marine mammals are all of special interest, and there are many species of migrating fish that provide for sport fishery in Bermuda.

One of the interesting mysteries of this part of the ocean is the spawning of the American eel (*Anguilla rostrata*) and the European eel (*Anguilla anguilla*). Various sized larvae of both species were captured and studied to infer that adults of these species migrate to the Sargasso Sea and spawn and die, but surprisingly, the routes and mechanisms of the adult migration is still largely unknown. *Anguilla* occupy fresh water streams, rivers, brackish waters and the open ocean in various stages in their life cycle. They apparently spawn in the Sargasso Sea and ocean currents transport the developing larvae northward until the young metamorphose into juveniles and then move upstream along the continents. There is apparently no difference in the vertical distribution of the two species in the Sargasso Sea, as the larval (leptocephali) of both species were found in equal abundance between 0 and 350 meters. Developing eels remain in fresh or brackish water for about 10 years before they return to the sea to spawn. Although larvae of both species have been positively identified, no adult eels have been found and therefore where and what depth the mature eels occupy is still largely unknown.

The Bermuda Islands are located about half way between the major western North Atlantic humpback whale breeding areas in the Antilles and the northern feeding grounds extending from the New England coast to Iceland. Therefore they provide an excellent place for observation of this species. Adult whales reach up to 30 tons and range from 12 – 19 meters in length. The flippers are unique, they measure up to one-third of the body weight and are used as cooling planes through which a whale loses heat. This cooling allows the humpbacks to live closer to the warmer equatorial waters than other whales. They also use these large fins to defend themselves against killer whales as well as for feeding, to sweep krill into their mouths. Although there are many reports of the sighting of whales off Bermuda going back to the early settlers, it was not until Verril in 1902 where there was more of a description of their seasonality. The whales arrived off Bermuda in late February or early March and left around the first of June, most accompanied by suckling cubs. Whaling did exist in Bermuda for a time, beginning in 1911, but it was banned in 1942. Various studies have been carried out using acoustic studies of humpbacks and from 1967 to 1972 at least 10 whales were observed off Bermuda per day with up to 25 in a single day. These whales also produce "songs" which last on average 15 minutes but can extend to 30 minutes. There is some suggestion that the humpback whale population off Bermuda has decreased since the 17th, 18th, and 19th century but this may be due to the better food availability in other areas.

CHAPTER 2

Physical Characteristics of the Sargasso Sea

R.J. Johnson

Over the past several decades our understanding of the relevant physics of the Sargasso Sea (more commonly known as the North Atlantic Subtropical Gyre) has benefited from extensive field programs of this region (*e.g.*, MODE, POLYMODE, FASINEX, GEOSECS, BIOWATT, TTO, WOCE, CLIMODE, ARGO, JGOFS, BATS and Hydrostation 'S'). These programs have mostly succeeded in defining the large scale gradients and dominant seasonal cycles of the physical parameters and importantly have provided valuable insight into the temporal (diurnal to decadal) and spatial (finescale of < 10km to mesoscale <100km) variability of this region.

For this geographical province, the prevailing wind patterns of easterly trades in the tropics and mid-latitude westerlies cause surface ocean flows to converge towards the center of the gyre resulting in a net vertical downwelling for the subtropical gyre interior. The need to conserve potential vorticity following this interior downwelling creates a southward Sverdrup transport that ultimately is balanced by an intense current along the western edge of the ocean basin. These dynamics essentially define the Sargasso Sea domain where it is bounded to the west and north by the Gulf Stream, to the south by the North Equatorial current and to the east by the weak gyre recirculation flows (**FIG. 2.1**).

Climate change concerns over the past two decades have intensified, leading to more emphasis on detecting and understanding emerging patterns of long term change in the heat and salinity budgets of the upper ocean. For the Sargasso Sea, the monthly Bermuda Atlantic Time-series Study (BATS) and biweekly Hydrostation 'S' programs play a pivotal role in this challenge to better understand long term change and serve as an important reference framework for larger scale field and modeling studies due to their relatively long temporal span (**FIG. 2.1**). The locations of the BIOS operated Bermuda Time-series Sites (BTS) are 31° 40'N, 64 10'W (BATS) and 32° 10'N, 64° 30'W (Hydrostation 'S') which positions them northwest of the center of the Sargasso Sea (**FIG. 2.1**).

2.1. Meteorology and Seasonal Cycling of the Upper Ocean

During winter, the northern Sargasso Sea is conditioned by the passage of low-pressure atmospheric systems originating from North America at near weekly intervals. Air masses associated with these storms are typically cold and dry which combined with high wind speed results in a large rapid heat loss of the upper ocean predominately through latent heat flux (Michaels et al., 1994). In summer the region becomes dominated by the large Bermuda-Azores high leading to generally stable weather conditions with light winds and high humidity. Tropical cyclones can abruptly alter these conditions with a marked impact on upper ocean inventories of heat, salinity and TCO_2 (Bates et al., 1998; Nelson 1998) and single storms have been observed to reduce SST by ~ 2.5°C (Dickey et al., 1998).

Seasonal cycling in the upper ocean of the Sargasso Sea is predominately a direct response to the local atmospheric conditioning that dictates the surface flux of heat, freshwater and momentum and ultimately drives convective mixing in the upper ocean. At the BTS a relatively strong seasonal cycle of vertical mixing is observed characterized by variable deep winter mixing (150 to 400m, **FIG 2.2**) and shallow warm mixed layers in the summer months (Menzel and Ryther, 1961; Michaels et al., 1994; Steinberg et al., 2001). The transition from net warming to net cooling, during September and October, initiates convective entrainment of the shallow summer-time mixed layer that increases through the winter months ending with the erosion of the seasonal thermocline and formation of a deep mixed layer. Stabilization of the water column begins in late March in response to the net heat flux turning positive (i.e. heat gain by the ocean) and as the warming cycle continues the upper ocean at the BTS returns to a highly stratified state with a shallow diurnal mixed layer trapped above the seasonal thermocline.

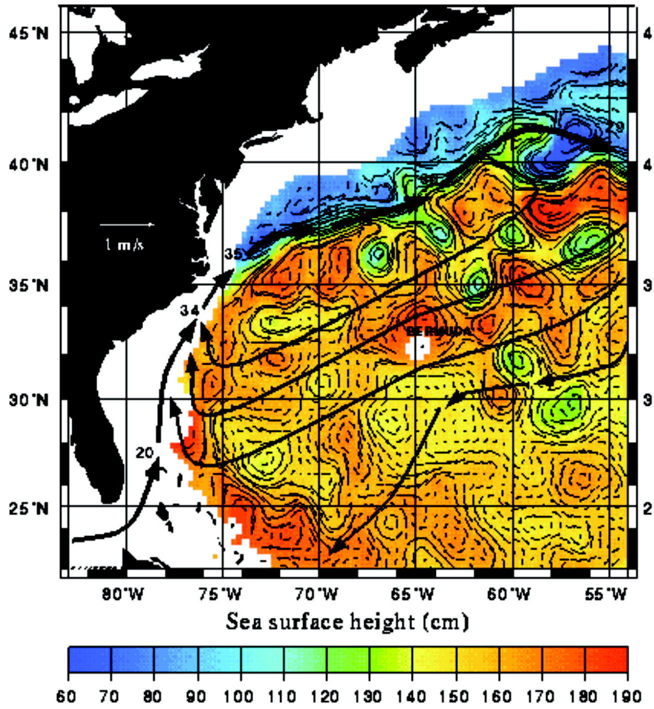

FIGURE 2.1. **Satellite image of the Sargasso Sea showing sea surface height and derived geostrophic velocity, illustrating typical mesoscale variability. The long-term mean circulation of the warm waters (>17°C) of the subtropical gyre is shown as thick black arrows where the numbers indicate transport in Sverdrup (Worthington 1976). Satellite data courtesy of University of Colorado and image adapted from Steinberg et al., 2001.**

This summer time mixed layer rarely extends below 20m allowing for rapid increases in SST (maximum ~28°C) and episodic development of shallow warm fresh layers in response to low wind high precipitation events (Michaels et al., 1993).

Regions to the north of the BTS experience more intense winter storms due to the closer proximity to the central low pressure and thus heat loss increases northwards from the BTS towards the Gulf Stream forcing deeper mixing and greater seasonality. In contrast, mixing to the south of the BTS and particularly south of the subtropical convergence zone (near 28°N) is relatively weak leading to a permanently stratified water column. Hence, a feature of the BTS locale is strong seasonal meridional gradients implying observations at the BTS are likely sensitive to interannual variations in the atmospheric forcing of the gyre and further can exhibit upper ocean properties similar to both northern and southern climates (Siegel et al., 1990).

The BTS programs provide an invaluable 57 years of repeat observations for understanding variability in the seasonal cycling of the upper ocean with linkages to climate change. As such, these data have been used extensively in climatological studies of the North Atlantic to identify inter-annual, decadal and centennial variability (*e.g.*, Dickson et al., 1996; Houghton 1996; Levitus et al., 1996; Marsh and New, 1996; Talley, 1996; Molinari et al., 1997; Joyce, 2000; Bates 2001; Goodkin 2008).

2.2. Subtropical Mode Water (STMW)

An important water mass of the Sargasso Sea is Subtropical Mode Water (STMW) or more classically referred to as '18 degree water' which forms in the northern Sargasso Sea typically north of 33°N (Worthington, 1976). As discussed above, intense cooling of the surface layers in the winter months of the northern Sargasso Sea causes deep mixed layers which extend to depths of ~400m, with mixed layer temperatures of ~18°C (Worthington, 1976). Thermohaline properties of this STMW tend to be relatively stable over time that is likely a consequence of the strong air-sea surface fluxes (Talley and Raymer, 1982). During the onset of spring, the STMW becomes capped from the air-sea interface by the seasonal thermocline and subsequently subducts to the south through isopycnal transport thereby carrying surface properties (physical and biogeochemical) to the interior of the Sargasso Sea.

At the BTS previously formed STMW is typically observed between 150 and 400m as a near homogeneous lens readily identifiable by a minimum in the potential vorticity (Talley and Raymer, 1982; Ebbesmeyer and Lindstrom, 1986). Understanding the dynamics and properties of STMW at the BTS is a key element for assessing inter-annual variability since mixed layer entrainment during the winter months extends into the underlying STMW which then becomes mixed with the local surface waters. Analyses of the Hydrostation 'S' time-series reveal the depth of STMW core is remarkably

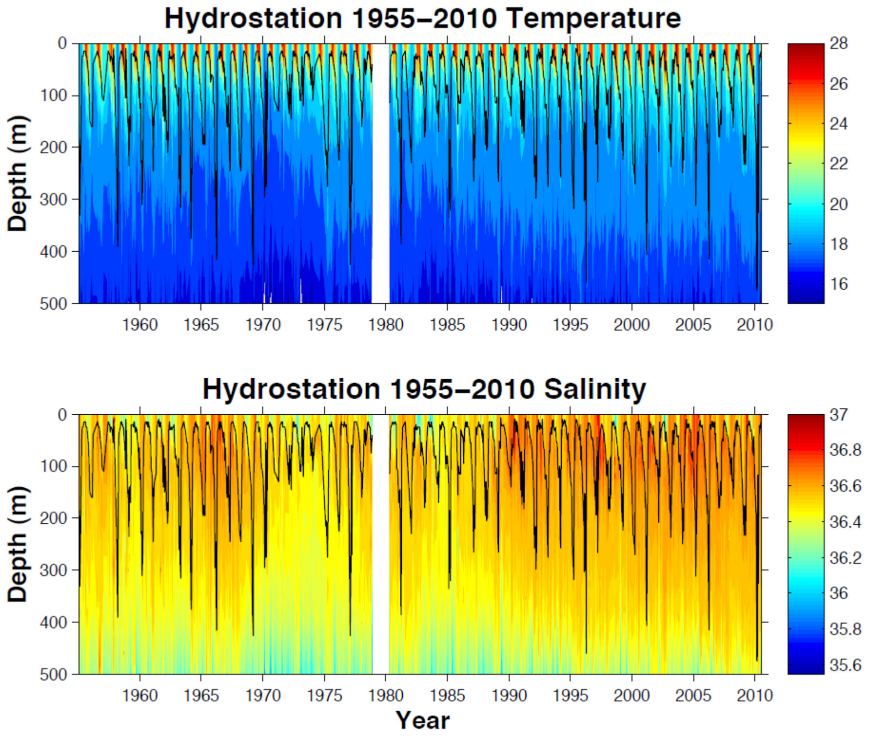

FIGURE 2.2. Contour plots of temperature and salinity for the upper 500m at Hydrostation 'S' for years 1955 to 2010. Mixed layer depth is overlaid as a solid black line.

variable over both short (monthly) and long (annual) timescales with a mean core temperature of 18.1 ± 0.4 °C (Johnson, 2003). The most striking feature of the 57 year record of STMW is the dramatic upward displacement of this lens during 1969-1973 followed by a steady relaxation through 1975 (**FIG.2.3**). During this pentad of uplifted STMW, Hydrostation 'S' observed the coldest SST's on record (**FIG 2.3**) for this location even though the mixed layer depths were not overly deep for this period. This strongly argues that the change in SST was largely due to the positioning of the STMW and hence, evolution of the surface waters at the BTS is conditioned by properties of STMW formed in previous years (Bates et al., 2002; Johnson, 2003). This upward displacement of the STMW during the 1969-1973 pentad was not isolated to the BTS region and was found to be prevalent through much of the subtropical gyre (Levitus, 1989) being attributed to the westward propagation of a Rossby wave (Ezer, 1999). In contrast to the Rossby wave theory, Marsh and New (1996) using a modeling approach were able to reproduce the STMW variability at Hydrostation 'S' during 1969-1973 concluding that the variability was due to anomalous forcing events associated with frequent outbreaks of cold dry air over the Gulf Stream. Such findings demonstrate the need to understand processes at many scales in order to asses inter-annual variability of the upper ocean and further, highlight the value of the Hydrostation 'S' observations as a reference metric for change in the Sargasso Sea.

A number of process-oriented cruises have been established to better define the properties and extent of STMW formation in the northern Sargasso Sea (*e.g.*, MODE, POLYMODE, CLIMODE) although there are no continuous time-series observations in this region. The Argo float program (Roemmich et al., 2009) helps fill this void with a hundred or so autonomous profiling floats in this region but since they are free drifting, temporal analyses are difficult. In addition to the core measurements at the BTS a number of ancillary programs using chemical tracers such as ^{3}H (tritium, for anthropogenic inputs) and ^{7}Be (berylium 7 as tracers of cosmic produced radioisotope deposited to the ocean surface ocean during precipitation events) have proven effective for determining the age of STMW at the BTS. The ^{7}Be is useful for periods of weeks to several months and has identified the rapid arrival (2 to 4 months) of recently formed STMW to the BTS (Kadko, 2009) whereas the ^{3}H studies have shown the age of STMW at the BTS to be variable ranging from one to several years (Jenkins, 1994). The integration of these other programs with observations from the BTS remain a robust framework for interpreting variability in STMW and assessing the significance of this water mass as a repository of heat and carbon (Bates et al., 2002).

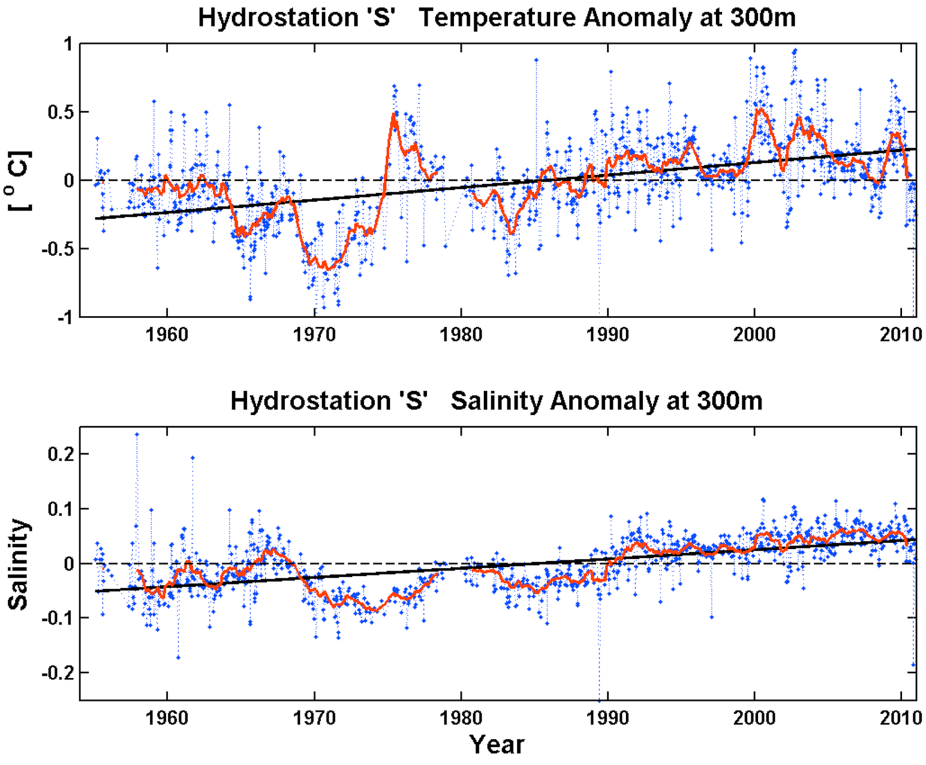

FIGURE 2.3. **Time-series plots of temperature and salinity anomaly at 300m (STMW) for Hydrostation 'S' 1955-2011. Anomaly computed by subtracting long- term mean for this depth. Red line shows a 1-year central running mean and the observed data is shown as blue dots. Long-term trends for temperature and salinity are determined as 0.009 °C year^{-1} ($p < 0.01$) and 0.002 year^{-1} ($p < 0.01$) respectively.**

2.3. Influence of the North Atlantic Oscillation on Sargasso Sea Variability

The dominant long-term mode of meteorological variability in the North Atlantic is associated with the North Atlantic Oscillation (NAO) that is typically referenced by the NAO index defined as the difference in the normalized sea level pressures between Lisbon, Portugal and Stykkisholmur, Iceland (Hurrell, 1995). Atmospheric dynamics during a positive NAO phase lead to anomalously high pressures across the subtropical Atlantic, whereas for negative phases the Icelandic low-pressure system shifts to the south driving more intense winter storms across the Sargasso Sea. Although the NAO has shown considerable variability over the past several decades it has mostly been negative for years 1950 to 1970 and since this period has switched to a positive state with short aperiodic reversals to a negative phase (*e.g.*, Talley 1996, Hurrell 1995).

Changes in the atmospheric dynamics of the North Atlantic associated with the NAO undoubtedly influence variability in the upper ocean of the Sargasso Sea (Rogers 1990). At the BTS the principal influence of the NAO on the upper ocean hydrography is the depth of winter mixing and subsequent SST. Given the greater storminess during negative NAO years winter mixing tends to be deeper with colder SST's whereas relatively shallow warm winter mixed layers are more normal for positive phases (Bates et al., 2001). Since the depth of this deep winter mixing is a key factor for deducing heat storage and carbon sequestration, the NAO state plays an intimate role in modulating the ocean's climate change response. This becomes further complicated on consideration that the STMW underlying the surface waters at the BTS has been pre-conditioned in previous years. This was highlighted by Talley (1996) using data from the BTS who showed that variations in the STMW properties are directly related to the NAO. In particular, Talley (1996) concludes that heavier STMW is formed as result of increased convective activity plus increased transport of relatively saline waters to the western subtropical gyre. In addition to changes in direct local convective activity, the intensity of the North Atlantic gyre circulation has been linked with NAO variability (Curry and McCartney 2001). Although the association is not directly covariant Curry and McCartney (2001) suggest that consideration of time integration of the ocean signal due to mixed layer memory and Rossby wave propagation gives a first order agreement with the NAO.

Evidence for the NAO accounting for a significant fraction of the variance in the hydrography of the upper ocean of the Sargasso Sea continues to emerge (Lozier et al., 2010) and data from the BTS remain a key element for assessing this important ocean-atmosphere linkage (Bates et al., 2001). More recently, emphasis has been with trying to establish the significance of the NAO induced physical variability on biogeochemical cycles of the upper ocean and it seems that some previously thought paradigms for carbon export may need alteration (Lomas et al., 2010).

2.4. Eddy Dynamics and Implications for Short and Long Term Variability

In the vicinity of the BTS, the long term flows are characterized by low (< 5cm s^{-1}) south westerly geostrophic currents (Worthington, 1976) with net Ekman downwelling rates of ~4cm day $^{-1}$ (McClain and Firestone, 1993). Given these low velocities, the BTS are presumed appropriate locations for time-series studies since advective processes should be small compared to those forced by local conditions (Michaels, 1994). However, in contrast to these long-term mean flows much of the interior of the Sargasso Sea is continually subjected to the presence of mesoscale eddies resulting in complex rotational flows with typical instantaneous speeds ranging between 10 to 50 cms^{-1} (Siegel and Deuser 1997; **FIG. 2.1**). Mesoscale eddy phenomena in the Sargasso Sea include cold core rings (Richardson, 1978) and mid-ocean mesoscale eddies (McGillicuddy and Robinson 1997). The core of these two types of eddies are quite different in that the 'cold-core' contains water from north of the Gulf Stream and thus transport foreign waters to the northern Sargasso Sea. Due to the closed recirculation flow in this region these cold core eddies tend to remain in the northwest sector of the gyre (Cornillion et al., 1986) although have been infrequently observed near the BTS (Siegel et al., 1999). In contrast, mid-ocean eddies are presumed to originate within the Sargasso Sea such that the temperature-salinity profile through the permanent thermocline of these eddies is consistent with gyre water types.

Advancements in satellite altimetry in the early 90's helped reveal the extent and ubiquitous nature of mid-ocean mesoscale eddies in the Sargasso Sea (**FIG 2.1**) that was first hypothesized in the MODE and POLYMODE programs. From satellite data these features can be recognized by changes in sea level height. While from oceanographic observations, eddies are readily identified by displacements of the density surfaces in the upper ocean. Mid-ocean mesoscale eddies can be broadly categorized into three types: (i) cyclonic- density surfaces elevated resulting in anomalously cold water and a depressed sea level at its center (ii) anticyclonic –density surfaces depressed resulting in anomalously warm water and an elevated sea level at its center and (iii) mode water or lens eddy—formed when a lens of near uniform water resides between two density surfaces causing density surfaces to be elevated and depressed for depths above and below the lens, respectively. In the case of a lens eddy, the density surface perturbation tends to be greater in the deeper layers and thus in terms of sea level height resemble a weak anticyclone (McGillicuddy and Robinson, 1997; McGillicuddy et al., 1999). Mid-ocean eddies have diameters of <100km, lifetimes of months to years with propagation speeds of 3 to 5 km day^{-1}, predominately track on a westerly to north westerly course and their signal is apparent through the base of the permanent thermocline (~1000m) (McGillicuddy et al., 1999). Mesoscale eddies represent an important mode of transport for physical and chemical properties, however, understanding their full impact through a specific region is difficult since their passage alters upper ocean inventories through both horizontal and vertical mechanisms (Woods 1988). Furthermore, it is still unclear whether mesoscale eddies are turbulent self-contained features or are the result of linear planetary wave propagation (Siegel et al., 1999) although recent field surveys off Bermuda (EDDIES Project) suggest the former (Benitez-Nelson and McGillicuddy, 2008).

In addition to modulating upper ocean physics, mesoscale eddies also impact biogeochemical processes in the upper ocean by simply lifting or depressing the nutricline into the euphotic zone. Assessment of this process is important for understanding the role of eddies in the oceanic biological pump (Volk and Hoffert 1985) and field campaigns off Bermuda (EDDIES Project) have been instrumental for investigating pertinent dynamics (Benitez-Nelson and McGillicuddy, 2008). It is clear that eddies in the Sargasso Sea drive significant spatial variability in the physics and biology over a wide range of length scales (10's to 100's km). Further, mixing and subsequent nutrient supply to the euphotic zone differs for each eddy type and importantly, eddy/wind interactions dictate the new production potential of an eddy (McGillicuddy et al., 2007). Observations from the EDDIES project reveal wind interactions with mode water eddies amplify the eddy-induced upwelling that can result in significantly large biological blooms whereas for cyclones the eddy/wind interaction reduces the upwelling signal (McGillicuddy et al., 2007). Although mid-ocean eddies are presumed to consist of water local to the Sargasso Sea, intensive surveys of these features (EDDIES project and on-going work through the BATS program) often identify anomalous water masses at the core of the eddy. Thus contrary to earlier genesis theories, mid-ocean eddies may permit a pathway for foreign waters into the Sargasso Sea (Li et al., 2008).

Analysis of the depth of specific isopycnal surfaces in the upper ocean at the BTS reveal substantial displacements over short (biweekly to monthly) timescales which are coherent with satellite derived estimates of sea level height associated with the passage of mesoscale eddies (Siegel et al., 1999). Additionally, data from BATS Spatial Validation cruises (BVAL) highlight the spatial heterogeneity of parameters (*e.g.*, temperature, salinity and nutrients) at fixed depth horizons that is found to be statistically consistent with the temporal variability observed at the BTS (McGillicuddy et al., 1999). Hence, the passage of mesoscale eddies through the BATS is the dominant mode of variability for depths below the surface mixed layer.

Impact of mesoscale eddies in the upper 100m is more complicated since other processes, principally convective mixing, interact with eddy dynamics. Modeling studies of the upper ocean heat and salinity budgets at the BTS have been performed to assess eddy influence on the mixed layer (Doney 1996; Johnson 2003). Results from these modeling exercises show significant imbalances in the heat and salinity budgets from that which can be accounted for by local atmospheric forcing in a 1-dimensional sense. This imbalance implies the need for advection to balance the system and appears to be a direct consequence of mesoscale eddies (Glover et al., 2002).

The spatial and temporal evidence from the BTS programs strongly imply that the upper ocean in this region is intimately modulated by mesoscale eddies which in turn has consequences for understanding system processes at the BTS. This is also supported by continuous measurements of velocity and temperature from the Bermuda Testbed Mooring (BTM) which suggest a de-correlation time scale of ~20 days, which is similar to the sampling frequency at the BTS (Dickey et al., 1998). However over longer time scales (years to decades) the eddy-induced variability appears to be balanced such that the 1-dimensional approximation is able to account for a significant fraction of the variance in the heat and salinity budgets of the upper ocean (Johnson 2003). Time- series analysis of data from the BTS reveals significant long-term trends in the temperature and salinity of the upper ocean above the short-term eddy variability (**FIG. 2.3**) (Johnson et al., 2008). For the upper 400m, temperature and salinity are increasing by ~ 0.01°C year^{-1} and 0.002 year^{-1}, respectively. The significance level of this trend rises with depth reaching a maximum near 300m that is approximately the long-term mean depth of STMW at the BTS (**FIG.2.3**).

2.5. Deep Water masses in the Sargasso Sea

The previous discussion has mostly focused on properties of the upper ocean, however assessment of the deep water masses of the Sargasso Sea is important for understanding variability of the Atlantic Meridional Overturning Circulation (AMOC) and ultimately climate change. Over the past decade there has been concern that the AMOC could significantly weaken during this century thus reducing the northward transport of heat to the North Atlantic (Houghton et al., 2001). Schematically, the zonally averaged components of the AMOC comprise of a northward flow in the upper 1300m, a southward return flow of North Atlantic Deep Water (NADW) between 1300 and 4000m, and a northward flow of Antarctic Bottom Water (AABW) below 4000m. Given the location of the formation sites of these water masses, observations of these deep-water masses at the BTS provide a unique framework for assessing coordinated climate change in the Atlantic basin. Direct linkages with climate conditions at deep-water formation sites with observations at the BTS have been established. For example, Curry et al., (1998) show that 'imprinted' properties of surface waters in the sub-polar Labrador basin appear in upper NADW at the BTS with an inferred 6-year transit time. At the BTS, Labrador Sea water is observed at ~2000m and analysis of the Hydrostation 'S' data reveal significant trends for this water mass (Whitefield et al., 2008). For years 1985 –2004, a dramatic decrease in temperature (~0.012 °C year $^{-1}$) and salinity (~ 0.002 year $^{-1}$) is observed which has since reversed with temperature and salinity increasing for the past pentad (**FIG.2.4**). Interestingly, the analyses by Curry et al., (1998) predicted continued cooling into the next decade which has since been proved correct at Hydrostation 'S'.

New research activities continue to investigate the physical processes of the Sargasso Sea with the time-series programs operated at BIOS central to this observational network for assessing climate processes and ocean response. The BATS program has recently expanded its spatial strategy to help deduce eddy transport and also continues to run annual transects from 35°N to 19°N to determine meridional changes in the water masses of the Sargasso Sea. A new array of deep moorings (DYNAMITE, lead PI Ruth Curry – WHOI) has recently been deployed off Bermuda with the most northern mooring situated between the BTS. The aim of DYNAMITE is to measure abyssal flows along the Bermuda Rise in order to understand interior circulation of the gyre and is likely to be complimentary to the existing time-series programs.

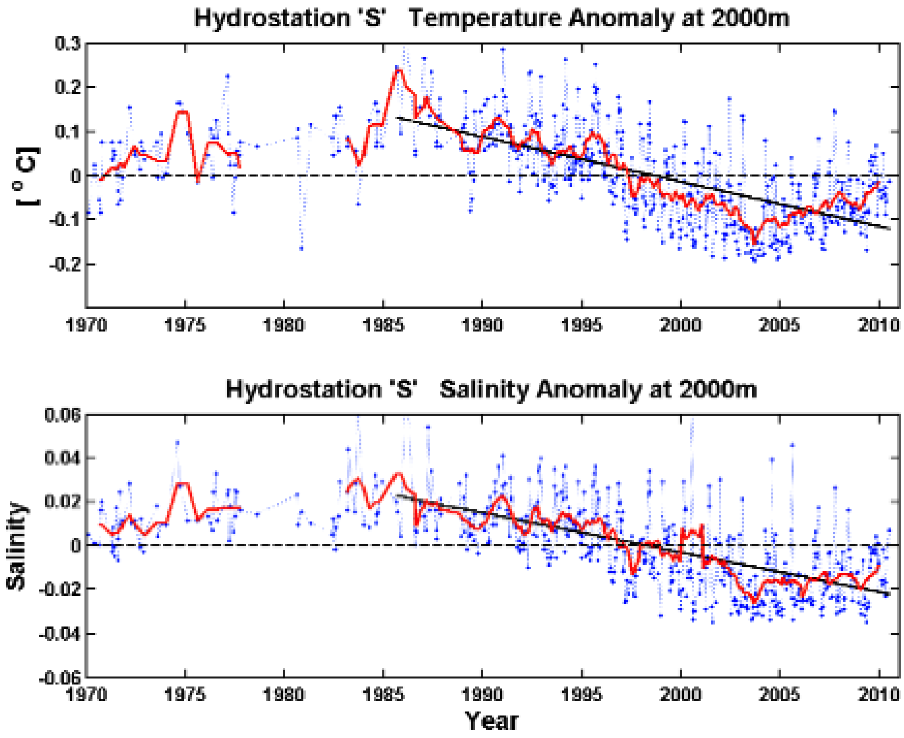

FIGURE 2.4. **Time-series plots of temperature and salinity anomaly at 2000m (Labrador Sea water) for Hydrostation 'S' 1970-2011. Anomaly computed by subtracting long- term mean for this depth. Note significant ($p < 0.01$) decline in temperature (-0.010 °C year^{-1}) and salinity (-0.0018 year^{-1}) for 1985 -2010. Red line shows a 1-year running central mean and the observed data is represented by the blue dots.**

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CHAPTER 3

Chemical Characteristics of the Sargasso Sea

3.1. Nutrients in the Sargasso Sea

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Located within the North Atlantic Gyre, the Sargasso Sea is "oligotrophic," characterized by low macronutrient concentrations (Siegel et al., 1990; Michaels and Knap 1996; Cavender-Bares et al., 2001; Lipschultz 2001; Steinberg et al., 2001; Babiker et al., 2004; Kamykowski 2008). Phytoplankton require the macronutrient elements nitrogen (N), phosphorus (P) and silica (Si) to grow and reproduce. Carbon is also a vital macronutrient, but one not generally considered to be limiting, and is discussed separately ("Biogeochemical cycles in the Sargasso Sea" and "Ocean acidification").

The distributions of macronutrient elements in the oceans reflect the assimilation of dissolved inorganic N (DIN), P (DIP) and Si (silicate) by phytoplankton into new organic matter in the sunlit upper water column, or euphotic zone. When phytoplankton cells die, they sink as particles out of the euphotic zone into deeper waters, where that organic matter is re-mineralized and dissolved inorganic pools restored over time and depth in the water column. In the Sargasso Sea, strong summer stratification isolates surface waters from the relatively enriched waters below, exacerbating depletion and resulting in undetectable macronutrient concentrations at the surface (Siegel et al., 1990; Michaels and Knap 1996; Lipschultz 2001; Steinberg et al., 2001).

The primary source of inorganic macronutrients to the euphotic zone, and associated phytoplankton communities, of open ocean regions like the Sargasso Sea, is from mixing with enriched waters from deeper in the water column. This mixing typically occurs during winter when temperatures cool sufficiently to break down the thermocline and allow overturn of the upper hundreds of meters of the water column. Year to year variability in nutrient budgets and resulting primary production and particle export from the surface ocean at the Bermuda Atlantic Time-series Study (BATS) are related to the variability in winter convective mixing in this region of the Sargasso Sea (Talley and Raymer 1982; Michaels and Knap 1996; Steinberg et al., 2001). The BATS area is located in a transition boundary between the northern and southern Sargasso Sea (Nelson et al., 2004), with the region south of BATS exhibiting less mixing and corresponding lower surface macronutrients year round (Siegel et al., 1990; Michaels and Knap 1996; Lipschultz 2001).

In the northern Sargasso Sea, winter convection is complemented as a nutrient source by additional entrainment of macronutrients from mixing during strong storm events (Lomas et al., 2009 a, b) and eddy activity (Lipshultz et al., 2002; Jenkins and Doney 2003; Bibby and Moore 2011). Mesoscale eddies in particular have been shown to be a substantial source of macronutrients fueling primary production in surface waters of the Sargasso Sea in the region of BATS (McGillicuddy Jr. et al., 2003; Sweeney et al., 2003; Cianca et al., 2007; Ledwell et al., 2008; Li et al., 2008; Krause et al., 2010). Nitrogen fixation, the conversion of N_2 gas to DIN by phytoplankton, is another source of DIN to surface waters of the Sargasso Sea (Sarmiento and Gruber 1997; Hood et al., 2001), though it may be a relatively minor contributor to the N budget in the BATS region (Hansell et al., 2004; Knapp et al., 2005).

In the southern Sargasso Sea, on the other hand, winter temperatures do not consistently cool enough to result in overturn, and there is little eddy kinetic energy, leading to a stratified water column and nearly undetectable surface DIN and DIP throughout the year (Siegel et al., 1990; Michaels and Knap 1996; Lipschultz 2001; Lipschultz et al., 2002; Nelson et al., 2004). In the absence of regular vertical mixing, nitrogen fixation and atmospheric deposition of DIN are larger sources of DIN to surface waters (Hastings et al., 2003; Hansell et al., 2004). Summer rain originating over the southern Sargasso Sea is particularly high in DIN, presumably due to lightning activity in the region (Hastings et al., 2003).

The ratio of N:P is a particularly useful tool in oceanography for predicting nutrient limitation. The canonical Redfield ratio, an N:P of 16:1, is traditionally applied to the global ocean, and deviations from this ratio may indicate potential N limitation (N:P<16) or P limitation (>16). In the Sargasso Sea at BATS, the ratio of N:P in surface waters typically exceeds the Redfield ratio of 16 (Michaels et al., 1994; Michaels and Knap 1996; Steinberg et al., 2001), and averaged ~40 between 1989 and 1998 (Babiker et al., 2004) More recently, Cavender-Bares et al., (2001), using high sensitivity methods for both DIN and DIP detection, found relatively constant N:P ratios of ~40-50 in surface waters between 31 and 37°N, consistent with the BATS dataset. Phytoplankton in this area have been found to display physiological characteristics consistent with DIP limitation (Lomas et al., 2004), as have heterotrophic bacteria (Obernosterer et al., 2003). In the southern Sargasso Sea, N:P ratios are much lower (<16:1; Cavender-Bares et al., 2001), a condition that geochemically would favor either nitrogen fixing phytoplankton or phytoplankton growing at near physiological maximum growth rates (Klausmeier et al., 2004; Mills and Arrigo, 2010) .

While DIP is the favored form of P for phytoplankton and heterotrophic bacteria in the Sargasso Sea (Michelou et al., 2011), recent studies indicate that these phytoplankton adapt to very low DIP concentrations by using organic forms of P (DOP) to acquire the needed P (Dhyrman et al., 2006; Lomas et al., 2010; Michelou et al., 2011; Mather et al., 2008). The dominant phytoplankton groups increase DOP uptake at low DIP concentrations such that total P assimilation, as a proxy for growth rate, remains essentially constant (Casey et al., 2009). In addition, phytoplankton growing in oligotrophic waters like the Sargasso Sea can also reduce their P requirements by substituting with N and sulfur-based lipids (Van Mooy et al., 2006, 2009). This is an advantageous adaptation for this region, where dissolved organic forms of N and P (DON and DOP, respectively) are typically at least 90% of the total N and P pools (Cavender-Bares et al., 2001).

Unlike N and P, which are incorporated by phytoplankton into organic matter (soft parts), Si is predominantly used by one group of phytoplankton, diatoms, to create external biogenic Si (bSi) tests (hard parts). In models of nutrient cycling in the North Atlantic (Lima and Doney 2004), demonstrate that temporal variability in diatom blooms at BATS are related to variations in southward transport of Si and seed diatom populations. Mode water eddies, which mix up high macronutrient and particularly high Si (Bibby and Moore 2011), have been shown to produce ~6x higher bSi concomitant with higher diatom abundances than reported at BATS in the absence of eddy activity (Krause et al., 2010). Unlike eddies, passage of winter storms result in enhanced primary production and a very rapid diatom growth response (order of several days; Lomas et al., 2009a, b) that does not accumulate but rather sinks on the same time scale and can account for nearly all the particulate organic carbon flux (Krause et al., 2009a). Overall, though, BATS data from 1989 to 2003 indicate a year-over-year linear decrease in Si supply to this region, due in part to decreasing winter mixing, but also to different nutrient gradients between DIN and Si that favor relatively higher DIN inputs. This decrease in Si supply is associated with a roughly 40% decline in biogenic silica (bSi) production in the upper 120 m of the water column here (Krause et al., 2009b). This data record suggests a reducing role of the productive diatom populations as a likely result of climate change at BATS.

Intra- and inter-decadal-scale natural variations in climate like the North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO) have been shown to introduce substantial variability in winter convection, eddy activity, nutrient budgets and ensuing productivity at BATS (*e.g.*, Steinberg et al., 2001; Bates and Hansell 2004; Cianca et al., 2007). Anthropogenically-forced warming of the surface ocean may be expected to present similar, though potentially irreversible, trends toward increasing stratification and reduced nutrient budgets in the Sargasso Sea. Additionally, recent research based in part at BATS (Beman et al., 2011) indicates that DIN supply to the surface ocean from depth is likely to further decrease as a result of increasing ocean acidification on the biochemical processes involved in N remineralization. On the other hand, atmospheric sources of nitrogen, and nitrogen fixation, may be expected to increase as a result of anthropogenic activity (Bates and Hansell 2004; Duce et al., 2008; Krishnamurthy et al., 2009). Given the considerable research conducted to date at BATS indicating that this system is highly sensitive to nutrient inputs, which are in turn intimately tied to climate variability, anthropogenic impacts to this region of the Sargasso Sea are likely to increasingly influence macronutrient cycling and phytoplankton growth here.

3.2. Trace Elements in the Sargasso Sea

K.N. Buck

Beyond macronutrients, phytoplankton growth in the marine environment is also heavily influenced by trace elements. Trace elements, by definition, are present at very low concentrations, on the order of parts per trillion, in open ocean regions like the Sargasso Sea. The low concentrations of these elements in the ocean, and their predominance on land, requires painstaking efforts be taken in sampling and analysis to avoid contamination. As a result, trace element data published before the 1980's are considered largely inaccurate due to likely overwhelming contamination. There are several references for trace elements in the Sargasso Sea that are not considered here (Menzel and Ryther 1961; Menzel and Spaeth 1962; Spencer and Brewer 1969; Brewer et al., 1972; Bender and Gagner 1976) because of these concerns.

In the Sargasso Sea, nutrient-type profiles are typically reported for the trace elements iron (Fe: Wu and Luther 1994, 1996; Wu et al., 2001; Wu and Boyle 2002; Sedwick et al., 2007; Cullen et al., 2006; Milne et al., 2010; Lee et al., 2011), copper (Cu: Bruland and Franks 1983; Hanson et al., 1988; Jickells and Burton 1988; Moffett et al., 1990; Moffett 1995; Milne et al., 2010; Lee et al., 2011), cobalt (Co: Jickells and Burton 1988; Saito and Moffett 2001, 2002; Milne et al., 2010), nickel (Ni: Bruland and Franks 1983; Jickells and Burton 1988; Milne et al., 2010), cadmium (Cd: Bruland and Franks 1983; Milne et al., 2010; Lee et al., 2011) and zinc (Zn: Milne et al., 2010; Lee et al., 2011), with depletion in the upper water column reflecting uptake by phytoplankton. These nutrient-type trace elements, typically referred to as "micronutrients," are used by phytoplankton in a variety of enzymes and proteins to accomplish numerous physiological tasks, including macronutrient (N, P, C) acquisition, oxidative defense, and photosynthesis itself. Iron (Fe) is arguably considered the most significant micronutrient, regulating phytoplankton processes in a number of oceanic settings (de Baar et al., 2005; Boyd and Ellwood 2010). At the Bermuda Atlantic Time-series Study (BATS) site, Sedwick et al., (2007) measured especially low dissolved Fe concentrations in the summer deep chlorophyll maximum (100-150 m) and suggested the phytoplankton community in this region of the water column may be Fe limited seasonally. Cyclonic eddies in the Sargasso Sea that have low dissolved Fe (Sedwick et al., 2007) and high macronutrients (Bibby and Moore 2011) may also be Fe-limiting to phytoplankton growth. In surface waters, there is evidence for Fe stimulation of new production from nitrogen fixation at the surface following a summer rain event (Kim and Church 2001), supporting previous suggestions that Fe deposition here may alleviate N stress (Michaels and Knap 1996; Gruber and Sarmiento 1997; Capone et al., 1997).

In general, though, the Sargasso Sea is an oligotrophic system, primarily limited by low inorganic N and P concentrations. Under these conditions, phytoplankton may use enzymes like urease and alkaline phosphatase in an attempt to access the organic pools of N and P, respectively. As these enzymes require the trace elements Ni (urease) and Co or Zn (alkaline phosphatase) as metal cofactors to function, these elements are suspected to play a particularly important role in this ecosystem. Indeed, Co and Zn concentrations are heavily depleted in surface waters of the Sargasso Sea (Bruland and Franks 1983; Saito and Moffett 2001, 2002; Jakuba et al., 2008; Milne et al., 2010), particularly when inorganic P is less than 10 nM (Jakuba et al., 2008). There is much less data available on Ni in this region, although surface depletion is apparent in depth profiles (Bruland and Franks 1983; Milne et al., 2010) and Twining et al., (2010) found that *Synechococcus* cells have higher Ni and Zn when collected from anticyclone eddies that are stressed by low inorganic N and P, reflecting the heightened need for these trace elements to acquire alternate forms of N and P. Cells collected from surface waters overall also had much higher Ni than cells collected from the deep chlorophyll maximum, reflecting the additional role of Ni in oxidative defense (Twining et al., 2010). Furthermore, the trace elements Co, Cd and Zn are also used in the enzyme carbonic anhydrase to acquire and concentrate cellular CO2. Cyanobacteria, like *Prochlorococcus* and *Synechococcus* have an associated obligate Co requirement (Saito et al., 2002), while some eukaryotic species can circumvent this issue by interchanging Zn or Cd when one of these micronutrients is depleted (Sunda and Huntsman 1995; Saito and Goepfert 2008). As the phytoplankton community of the Sargasso Sea is dominated by *Prochlorococcus* and *Synechococcus*, Co is particularly important here (Saito 2001; Saito and Moffett 2001).

Copper (Cu) in the Sargasso Sea, on the other hand, continues to be associated with concern for toxicity. The depth profile of Cu at BATS is generally nutrient-type (Bruland and Franks 1983; Hanson et al., 1988; Jickells and Burton 1988; Moffett 1995; Milne et al., 2010; Lee et al., 2011), with upper water column depletion reflecting the micronutrient role of Cu in oxidative defense and electron transport (Sandmann et al., 1983; Peers and Price 2006), as well as expected photochemical processes in superoxide production and Fe cycling (Weber et al., 2005). However, several early studies of Cu at BATS have shown that the bioavailable Cu^{2+} concentrations below the euphotic zone are high (Hanson et al., 1988; Moffett 1995), exceeding toxicity thresholds of phytoplankton (Brand et al., 1986), and may result in toxic levels of Cu^{2+} in surface waters after storm-induced mixing (Moffett 1995). More recently, Mann et al., (2002) found a negative correlation between $[Cu^{2+}]$ and *Prochlorococcus* cell densities in vertical profiles at BATS, indicating that variations in $[Cu^{2+}]$ with depth at BATS have a direct effect on phytoplankton community structure in the Sargasso Sea.

The primary source of trace elements to the Sargasso Sea is atmospheric, whether in the form of wet (rain) or dry (dust) deposition. Small surface maxima in concentrations of Fe, Ni, Co, Zn and manganese (Mn) indicate that these micronutrient elements have an atmospheric source (Milne et al., 2010; Lee et al., 2011). Wet deposition of Fe and Cu are significant inputs of the bioavailable forms of these elements to the surface Atlantic (Kim and Church 2001; Kieber et al., 2003, 2004; Willey et al., 2004; Witt and Jickells 2005). The bioavailability of these elements in rain is dependent on peroxide (Willey et al., 2004) and superoxide (*e.g.*, Weber et al., 2005) cycling, which can be highly seasonal (Kieber et al., 2001; Brooks Avery Jr. et al., 2005). Dry atmospheric aerosols in the Sargasso Sea largely originate from Saharan Africa in summer and fall, and from urban North America in winter and spring (Duce and Hoffman 1976; Chen and Duce 1983; Arimoto et al., 1995, 2003; Moody et al., 1995; Huang et al., 1999; Chen and Siefert 2004; Sedwick et al., 2007). The distinction between these two aerosol sources is important. African dust is higher in bulk Fe with low Fe solubility (Sedwick et al., 2007; Sholkovitz et al., 2009). The highest bulk dust deposition falls on the Sargasso Sea in summer, originating from Saharan Africa (Arimoto et al., 1995, 2003; Jickells 1999; Moore et al., 2002, 2004; Prospero et al., 2002), and the resulting high particle fluxes in the upper water column lead to short residence times of Fe in the surface, on the order of days to weeks (Jickells 1999; Sarthou et al., 2003; Croot et al., 2004; Weber et al., 2007). Anthropogenic aerosols from North America contribute trace elements with higher fractional solubility than their Saharan dust counterparts (Sedwick et al., 2007; Krishnamurthy et al., 2009; Sholkovitz et al., 2009, 2010). In the case of Fe, recent studies estimate that anthropogenic dust contributes ~70% of the soluble Fe deposited to the surface Sargasso Sea near Bermuda (Sholkovitz et al., 2009). Anthropogenic sources of Cu in rain are higher than marine sources (Kieber et al., 2004), and anthropogenic aerosols have higher fractional solubility of Cu than Saharan dust (Sholkovitz et al., 2010). Anthropogenic dust also contributes a significant amount of Zn and contaminant elements like vanadium (V), selenium (Se), chromium (Cr), lead (Pb) and antimony (Sb) to the surface Sargasso Sea (Duce and Hoffman 1976; Settle et al., 1982; Chen and Duce 1983; Schaule and Patterson 1983; Boyle et al., 1986; Veron et al., 1994; Wu and Boyle 1997; Arimoto et al., 2003; Connelly et al., 2006; Sedwick et al., 2007; Milne et al., 2010; Lee et al., 2011). Atmospheric inputs of mercury to this region from anthropogenic environments are significant as well (Mason et al., 1994, 1998, 2001). As such, metal budgets in this region of the North Atlantic Ocean have clearly been affected by human activities on the surrounding continents.

3.3. Organic Contaminants in the Sargasso Sea

A.J. Peters

There have been few studies of organic contaminants in seawater or marine biota from the Sargasso Sea. Some initial studies in the 1970's focused on the occurrence of petroleum products in the surface ocean, particularly "tar balls", which at that time were fairly common owing to the prevailing practices in oil tanker operations (National Academy of Sciences, 1975). Knap et al., (1980) compared the quantity of tar balls on beaches in Bermuda during 1978-79 with that from 1971-72. There was no significant change in the amount during this period, despite a reported decrease in operational discharges from oil tankers over the same period.

However, by 1985, Smith and Knap (1985) reported a significant decrease in the amount of tar balls washed up on beaches in Bermuda compared with the earlier studies. This decline was attributed to the introduction of legislation to reduce discharges of petroleum products by ships (MARPOL Convention).

Joyce (1998) reported on floating tar in the Western North Atlantic and Caribbean Sea, including the Sargasso

Sea region. The data were derived from 2786 neuston tows conducted between 1982 and 1996, during which time the amount of tar detected was shown to significantly decrease over the whole area, though significant amounts were still present in the Sargasso Sea in 1996. The decrease in amount of tar was attributed to "legal and economic forces that limit the amount of oil introduced into the ocean". Butler et al., (1998) demonstrated a general correlation of the occurrence of beach tar in Bermuda with estimated inputs of petroleum to the North Atlantic Ocean over a similar time period, 1971-1996.

Butler et al., (1998) furthermore suggested that the quantity of tar washing up on beaches in Bermuda was time-dependent, and primarily governed by the mesoscale circulation of the Sargasso Sea. This produces alternating periods of upwelling, clean water and convergences containing floating detritus, including tar, which is deposited on and removed from beaches on a tidal cycle, with resulting residence times of 6 h to a few days (Iliffe and Knap, 1979).

Sleeter and Butler (1982) sampled zooplankton and their faecal pellets from Hydrostation S in the Sargasso Sea in 1979 and determined that the rate of zooplankton grazing of particulate hydrocarbons in surface waters appeared to be the same order of magnitude as the input of petroleum residues at that time, and the incorporation of particulate hydrocarbons into zooplankton faecal pellets could provide a mechanism for rapid sedimentation of hydrocarbons through the water column.

Requejo and Boehm (1985) characterized hydrocarbons in a subsurface (c. 250 m) oil-rich layer in the Sargasso Sea (centered on 20°N, 55°W). They detected a suite of hydrocarbons with a lower average molecular mass than that reported for pelagic or stranded tar, and the molecular and isotopic composition consistent with a seep of a fossil hydrocarbon source somewhere on the Venezuelan shelf.

The contamination of the marine environment by macro-, micro- and nano-particles of plastic is an area of recent focus. These particles can be ingested by marine organisms and thus displace food in the gut or they can physically block the gut, leading to starvation (Derraik, 2002) and they can also concentrate organic contaminants in seawater by adsorption to the particle surface (Teuten et al., 2007), leading to enhanced uptake of contaminants when the particles are ingested. Moret-Ferguson et al., (2010) analyzed neuston tows from 11 cruises between New England, USA and the Caribbean

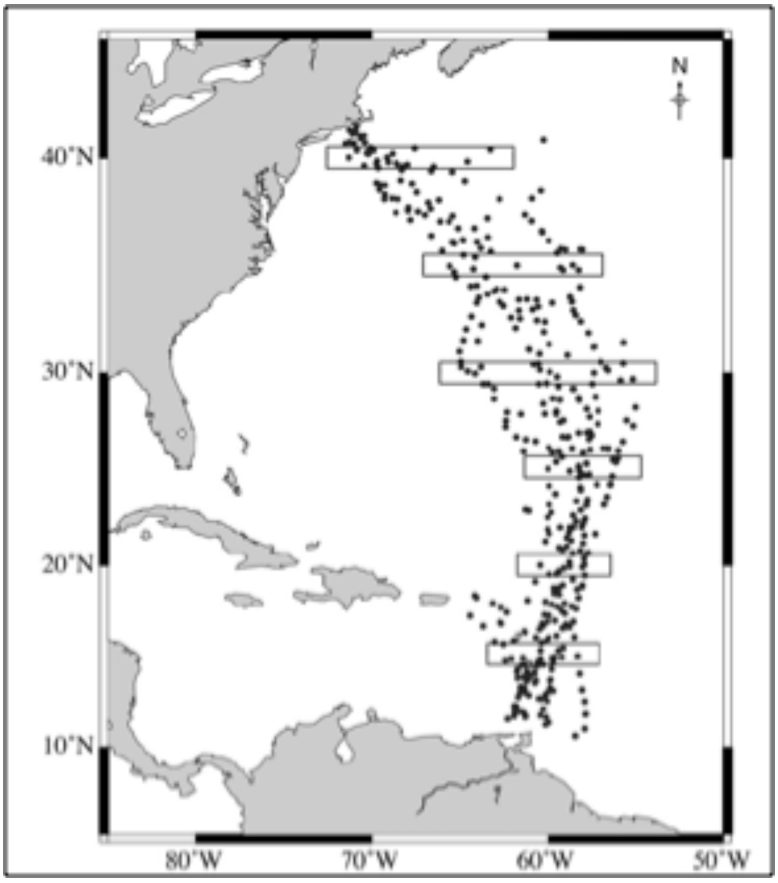

FIGURE 3. Sampling locations for plastic particles between 1991–1995 and 2004–2007 (Moret-Ferguson et al., 2010).

which traversed the Sargasso Sea in the period 1991-2007 (**FIG. 3**). They found significant amounts of particles which were mostly fragments less than 10 mm in size and less than 0.05 g mass. The particles exhibited signs of significant mechanical and photochemical degradation, with the mean particle size in samples decreasing from the 1990's to the 2000's.

There have been a small number of studies undertaken of synthetic organic chemicals and persistent organic pollutants (POPs) in the Sargasso Sea area. Knap et al., (1986) measured the flux to the deep ocean of polychlorinated biphenyls (PCBs) and some organochlorine pesticides as well as studies over the Sargasso Sea by aircraft (Knap and Binkley, 1991). Three studies have determined the levels and significance of POPs in marine mammals from the Sargasso Sea. Houde at al. (2006) measured the levels of PCBs and their bio-transformation products, hydroxylated-PCBs (OH-PCBs) in plasma from two Bottlenose Dolphins from Bermuda. Levels of both PCBs and OH-PCBs were lower in the dolphins from Bermuda than in dolphins from the coastal USA, suggesting lower levels of exposure in the open ocean environment. Yordy et al., (2010) used an endocrine screening test to look for oestrogenic activity in dolphin blubber arising from exposure to four POPs: the organochlorine pesticide *trans*-nonachlor; 4-4'-DDE (a degradation product of the insecticide DDT), and two polychlorinated biphenyl congeners, PCB 138 and PCB 180. Although estimated blood concentrations of these chemicals in the test animals from the vicinity of Bermuda were low, significant oestrogenic activity in their blubber was detected, suggesting that they may have been exposed to POP contaminants at biologically relevant concentrations. Knap and Jickells (1983) reported concentrations of PCB's and trace metals in goose-beaked whales that stranded and died on Bermuda beaches.

Other studies have considered the occurrence and potential effects of contaminants on migratory species that are resident in the Sargasso Sea on a seasonal basis and/or for certain life-stages. Larsson et al., (1991) examined the uptake of POPs such as DDT and PCBs in the European eel (*Anguilla anguilla*) and determined that significant body burdens could be accumulated during the eel's freshwater life-stage that would be subsequently depleted during the single lifetime occurrence of migration to and spawning in the Sargasso Sea. Dickhut et al., (2009) showed that differences in the ratios of POPs in Bluefin Tuna (*Thunnus thynnus*) tissue may be used to distinguish between and illustrate mixing of tuna stocks from the North West Atlantic and the Mediterranean Sea.

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CHAPTER 4

Biological Food Webs/BATS

4.1. Oceanic Food Web Overview

M.W. Lomas and N.R. Bates

The marine ecosystem is characterized by a number of trophic (i.e., nutritional) levels starting with the photosynthetic plants, macroalgae and phytoplankton, the animals that graze upon them, zooplankton, and then multiple higher trophic levels ranging from small schooling fish such as anchovies on up to apex predators. The number and specific members of each trophic level varies with location in the global ocean, but in general there are fewer trophic levels in highly productive coastal regions and more in the open ocean. In addition, there are fewer species overall within a given trophic level in cold polar seas than in the warm subtropics such as the Sargasso Sea. The complex array of processes and pathways that describe the flow of energy and carbon within and between these trophic levels in the marine environment is called a food web. Because of the importance of near-shore fisheries as a food source to coastal communities, research on how marine food webs function, specifically what controls their yield, has been conducted from the late 19th century. The study of the structure and function of open ocean food webs, however is a much younger field of study with some of the most exciting advances in our understanding coming in the past 20 or 30 years.

Traditionally, planktonic (i.e., free floating) food web structure has been roughly defined by organism size (Legendre and Lefevre, 1995; Michaels and Silver, 1988) which has led to the paradigm of two distinct food web types, the classical or "herbivorous" food web and the microbial food web. In the classical food web, large phytoplankton such as diatoms and dinoflagellates dominate photosynthesis (also called primary production as it is the mechanism by which the majority of organic matter enters marine food webs), are consumed directly by large crustacean zooplankton, which are in turn consumed by fish (Steele and Frost, 1977). Some fraction of primary production is not channeled to fish, but rather sinks into the deep ocean; this sinking carbon, relative to primary production, is termed the biological carbon pump. These ecosystems are generally highly productive at all trophic levels and tend to occur near to shore or on the continental shelf where nutrient inputs are greater. In the microbial food web, primary producers are dominated by much smaller phytoplankton that are consumed by small non-crustacean grazers (*e.g.*, ciliates), and primary production is largely recycled through dissolved organic matter and bacteria back to phytoplankton (Pomeroy 1974, Azam et al., 1983) with very little carbon sinking into the deep ocean. In both types of food webs, producer/consumer relationships govern both the composition and fate of particles and the magnitude of the energy and carbon flow.

More recent research has shown that interactions both within and between the classical and microbial food webs are more complex than originally thought. This research has emphasized the need to consider phenomena like selective grazing by zooplankton, dissolved organic carbon (DOC) production and consumption, and "active carbon transport" by diel migrators in quantifying pathways of carbon flow (*e.g.*, Carlson et al., 1994; Dam et al., 1995; Lomas et al., 2002; Richardson and Jackson, 2007; Rivkin et al., 1996; Serret et al., 2001; Steinberg et al., 2000). In addition, satellite observations, in combination with directed field work, are being used to shed light on the temporal and spatial variability of marine ecosystems (Yoder et al., 2010). These new findings continue to keep marine food webs an area of active research especially in light of the ecosystem level 'experiments' that are happening associated with ocean warming and acidification (see section 7 by Bates). These topics and others will be discussed in the following sections.

4.2. Phytoplankton Research in the Sargasso Sea

M.W. Lomas and N.R. Bates

Studies on the distribution and abundances of marine phytoplankton have been conducted in the Sargasso Sea from at least the late 1950's (Hulbert, 1962; Hulbert et al., 1960; Marshall, 1967). These early studies focussed on what were likely the most abundant groups of micro-phytoplankton (micro- meaning 20-200 μm in size) at that time, namely the diatoms, dinoflagellates and coccolithophorids. These groups were abundant during this period of the late 1950's and early 1960's in large part due to winter nutrient concentrations in the surface ocean that were much higher than has been observed over the past two decades. While not known at the time, one possible explanation for the elevated nutrient concentrations was that the 1960's were characterized by a negative phase of the North Atlantic Oscillation (NAO), a dominant climate mode now linked to variability in phytoplankton and primary production (Bates, 2001; Lomas et al., 2010a; Lomas and Bates, 2004). During the negative phase of the NAO, winter storms track closer to Bermuda and perhaps with greater frequency (Worthington, 1976), resulting in deeper convective mixing and a greater nutrient flux to the surface ocean.

Another possible explanation is mesoscale eddies, which depending upon the type can increase the flux of nutrients to the surface ocean, resulting in the accumulation of diatom biomass (McGillicuddy et al., 2007) due to enhancement of physiological capacity (Krause et al., 2010). However, from the 1970's through the 1990's the NAO has trended to a positive phase, which ultimately would reduce nutrient inputs due to convection. Perhaps not unexpectedly, diatom abundance has decreased significantly from the late 1980's through the 1990's as the result of reduced nutrients overall and suboptimal silica to nitrate ratios in the dissolved nutrient pool (Krause et al., 2009). Data on the other two groups of microplankton are much less common but suggest that absolute abundance of dinoflagellates is increasing (Best et al., 2011, Lomas et al., unpubl. data) while the abundance of coccolithophores is largely unchanged (Lomas et al., 2010a).

The importance of microplankton in the 1960's was also an artifact of technology; the technology to visualize pico-plankton (pico- meaning <2 µm in size) was not common in oceanography at the time. In fact, the most numerically abundant phytoplankton species on earth was discovered in the Sargasso Sea only in the mid 1980's (Chisholm et al., 1988). This species, *Prochlorococcus marinus*, is a photosynthetic marine bacterium that is ~1 µm in size and was only discovered through the use of a state-of-the-art optical instrument called a flow cytometer. Since its discovery, *Prochlorococcus*, along with another photosynthetic marine bacteria *Synechococcus*, is now known to dominate the phytoplankton biomass in the nutrient depleted tropical and subtropical oceans around the globe (e.g., DuRand et al., 2001; Partensky et al., 1999). Flow cytometry, when coupled with molecular techniques, has also identified a group of similarly sized organisms called picoeukaryotes which have a very high level of genetic diversity, and hypothesized biogeochemical function (Not et al., 2007). Due to their small size, the picoplankton are more efficient than their larger relatives at competing for low nutrient concentrations, however, because they dominate in low nutrient environments, they are tightly controlled by small non-crustacean grazers that rapidly recycle these nutrients through the microbial food web with little biomass buildup and sinking of carbon to the ocean interior (see section 4.4. Microbial ecology). Counter to expectations arrived from these conceptual models, phytoplankton biomass and productivity has actually increased, not decreased, by ~50% over the past two decades in the Sargasso Sea due the preferential growth and accumulation of these small cyanobacteria over that of microplankton (Lomas et al., 2010a, **FIG.4.1**).

This shift in the dominant groups of phytoplankton has had profound implications for the Sargasso Sea food web. For example, increasing abundance of cyanobacteria, if anything, should have resulted in a decrease in the oceans ability to sequester carbon in the deep ocean as these cells are not thought to contribute in a meaningful way to the biological carbon pump. However, the strength of the biological carbon pump has actually increased by nearly 50% over the past two decades. This increase in the strength of the biological carbon pump could be related to the increase in zooplankton biomass, supported by the increased phytoplankton biomass, which has resulted in an increase in the zooplankton mediated fluxes of carbon (Steinberg et al., in review). An alternate explanation is that these small cyanobacteria can form amorphous organic aggregates increasing their effective size and gravitational settling rates and enhancing their contribution to carbon export (Lomas and Moran, 2011). Interestingly, research has shown that some phytoplankton over-produce and exude polysaccharide-rich dissolved organic compounds under conditions of ocean acidification (Engel et al., 2002, Engel 2004), which is currently happening in the Sargasso Sea (see section 7 below). Regardless, these findings, which are expanded upon in sections below, highlight a disconnect between theory and practice requiring additional research to understand.

4.3. Zooplankton Research in the Sargasso Sea

D.K. Steinberg

Zooplankton (mostly small, drifting animals) occupy a key position in pelagic food webs, forming a direct link between primary producers (phytoplankton) and higher trophic levels such as fishes, sea birds, and some marine mammals. Zooplankton grazing plays a key role in the recycling of all biogenic elements, and export of these elements from the upper water column. The zooplankton contain representatives of nearly every animal phyla, and the abundance of particular taxa can dramatically affect cycling and export of nutrients and organic matter. Zooplankton are food for commercially important fish; for example, copepods in the genus *Calanus* are the primary food source for larval and juvenile cod, one of the most important commercial species in the North Atlantic (Kane, 1984), and zooplankton in subtropical and tropical environments such as the Sargasso Sea form an important link to forage fish and thus to larger commercial species.

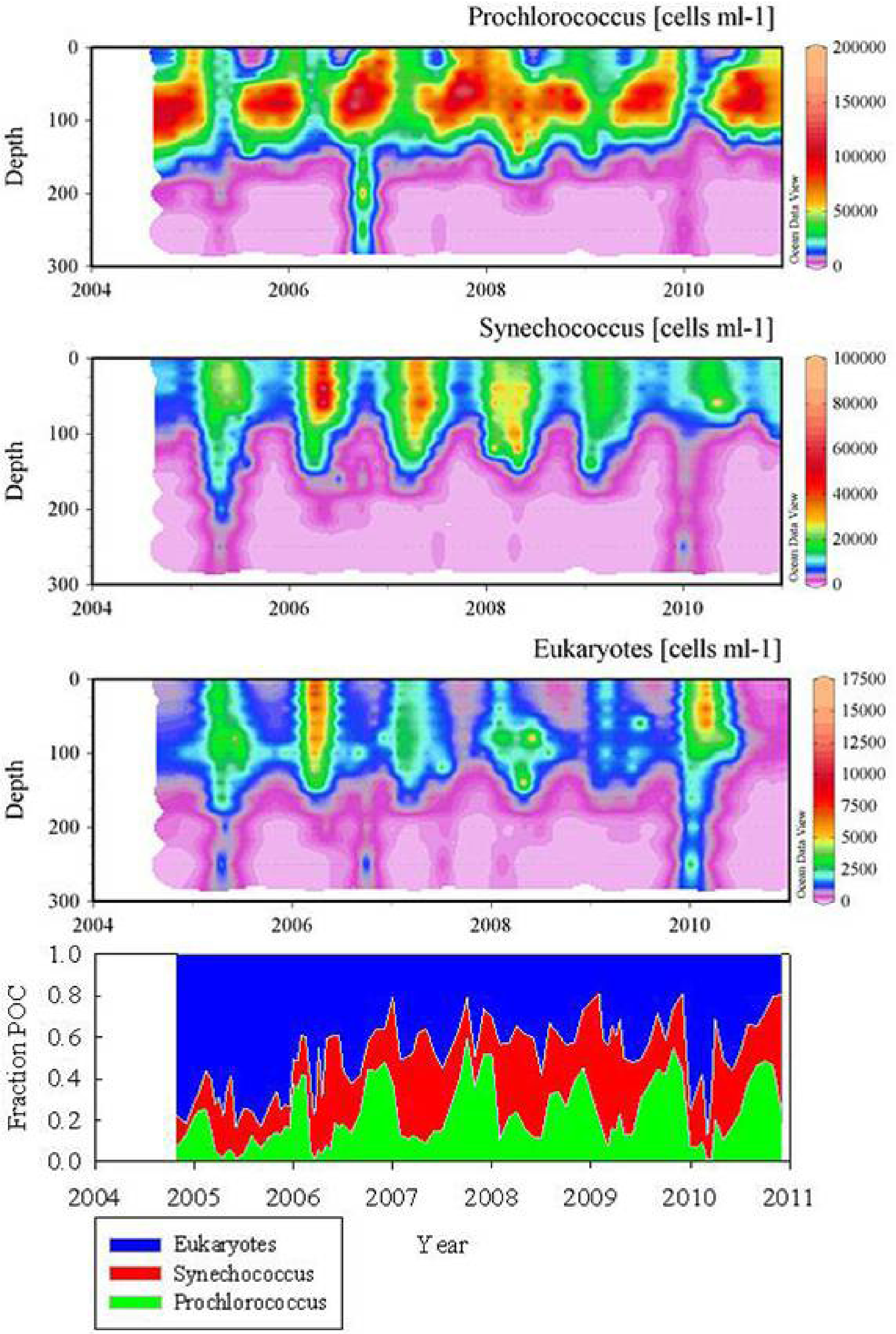

FIGURE 4.1. Contours of picoplankton abundance (cells ml^{-1}) in the Sargasso Sea from 2004 through 2010 (upper three panels) and their relative contributions to autotrophic organic carbon (bottom panel). The contour plots show the temporal (both seasonal and year-over-year) and spatial (depth) variability of *Prochlorococcus*, *Synechococcus* and picoeukaryotes. The two cyanobacterial groups have alternating niches with *Prochlorococcus* dominating at depth in the summer and *Synechococcus* competing with the picoeukaryotes to dominate in the surface waters during the winter/spring period. Over time, the combined cyanobacterial carbon biomass has increased significantly at the expense of the picoeukaryotes.

Studies of zooplankton species composition and seasonal dynamics in the Sargasso Sea near Bermuda date back over 60 years (Moore 1949, 1950; Sutcliff 1960; Menzel and Ryther, 1961; Beers, 1966; Deevey, 1971; Deevey and Brooks, 1971; Deevey and Brooks, 1977; von Bodungen et al., 1982, Wen-tseng and Biggs, 1996, Madin et al., 1996). More recent studies focused on diel or seasonal changes in biomass or community structure and the effects of zooplankton on biogeochemical cycling (Dam et al., 1995; Roman et al., 1993, 1995, 2002; Steinberg et al., 2000, 2002; Madin et al., 2001; Schnetzer and Steinberg 2002a, b; Steinberg et al., 2004; Jiang et al., 2007; Goldthwait and Steinberg 2008, Eden et al., 2009). Changes in zooplankton communities are important indicators of the effects of climate change on pelagic ecosystems (Hays et al., 2005; Richardson, 2008), and regular sampling for zooplankton biomass and species composition at the Bermuda Atlantic Time-series Study (BATS) has been a part of the program from the beginning (Madin et al., 2001; Steinberg et al., 2001).

The most comprehensive time-series studies of seasonal and interannual variation in zooplankton in the Sargasso Sea is described in Madin et al., (2001) and recently in Steinberg et al., (submitted in review). The latter examines long-term changes in zooplankton biomass at BATS, and explores possible mechanisms driving these changes. During a 16-year period (1994-2009) zooplankton biomass increased in surface waters by 50% (Steinberg et al., in review). Zooplankton biomass was positively correlated with sea-surface temperature and water column stratification, and was significantly correlated with multi-decadal climate indices—the North Atlantic Oscillation plus three different Pacific Ocean climate indices, indicating tele-connections between climate forcing in the two oceans and ecosystem response. Resultant changes in biogeochemical cycling included an increase in carbon export both by diel vertical migration and flux of zooplankton fecal pellets. The most likely mechanism driving the zooplankton biomass increase is a parallel increase in phytoplankton, translating up the food web into zooplankton. Decreases in zooplankton predators in the Sargasso Sea or displacement of tropical species northward as a result of ocean warming may also play a role.

Other recent efforts have also focused on physical processes that affect spatial distribution of zooplankton in the Sargasso Sea. Mesoscale eddies, on the order of 100-150 km in diameter, significantly affected zooplankton biomass, community structure, and nutrient cycling (Goldthwait and Steinberg 2008, Eden et al., 2009). Zooplankton biomass was enhanced in certain types of eddies compared to outside eddies, as was carbon export both by diel vertical migration and flux of zooplankton fecal pellets (Goldthwait and Steinberg 2008). Factors affecting small-scale spatial distribution of zooplankton in the Sargasso Sea have also been explored, such as the association of small zooplankton with millimeter-size colonial phytoplankton (*Trichodesmium*) (Sheridan et al., 2002), analogous to the associations of shrimp, fish, and other organisms with the larger *Sargassum* seaweed.

Future effort in zooplankton research in the Sargasso Sea should be placed in better characterizing changes in individual zooplankton species in both the surface/epipelagic community, and establishing a baseline for deep-sea zooplankton biomass and taxonomic structure (for which we have very little information) to which future studies can be compared. A multi-species inventory of zooplankton at BATS (established by D. Steinberg and L. Madin) is available as part of the Census of Marine Life's (CoML) Oceanographic Biogeographic Information system (OBIS), a repository for global marine species data (**http://www.iobis.org/**). Analysis of these species data has resulted in some significant findings, including discovery of seven new species of copepods (small crustaceans) that have never been recorded in the Sargasso Sea. Coupled with process studies examining zooplankton grazing and metabolic rates, our ability to predict how changing zooplankton community structure affects nutrient cycling and food webs in the Sargasso Sea will be enhanced.

4.4. Microbial Ecology in the Sargasso Sea

S.J. Giovannoni and C.A. Carlson

In the late 1980's, when molecular biology was first conceived of as a solution to understanding how vast populations of unknown microorganisms function in global cycles, pioneering work began from the deck of the Weatherbird I in the Sargasso Sea. The Sargasso Sea was selected for these early studies because BIOS offered access to one of the largest ecosystems on this planet and an excellent long-term scientific monitoring program.

In 1990, with a homemade Polymerase Chain Reaction (PCR) machine, genes were cloned from Sargasso Sea environmental DNA that revealed the existence of the bacterium SAR11, which is widely believed to be the most abundant organism on our planet (Giovannoni et al., 1990). SAR11 is now called *Pelagibacter*. Today we know that this organism is a major player in the global carbon cycle (Morris et al., 2002). The discovery of *Pelagibacter* was followed up with a series of papers that used genetic markers to define many other key microbial groups that have cosmopolitan distributions in marine ecosystems (SAR202, SAR86, SAR116, SAR406) (Giovannoni et al., 1996, Gordon and Giovannoni 1996, Mullins et al., 1995). Worldwide, most marine bacteria today, particularly elusive, uncultured species that are highly abundant, are named and identified using the "SAR" series nomenclature system that emerged from early work at Hydrostation S, southeast of Bermuda.

Also in the early 1990's, Giovannoni's research team began to define major patterns in ocean microbial community structure by merging molecular analysis methods with the BATS program. This work showed that ocean microbial communities were highly stratified between the euphotic zone and dimly lit upper mesopelagic ("twilight zone") just beneath it (Giovannoni, et al., 1996; Gordon and Giovannoni, 1996; Mullins, et al., 1995; Wright, et al., 1997). During this period Giovannoni and Carlson, who was studying the carbon cycle at BATS, began working together and founded the Ocean Microbial Observatory with support from the National Science Foundation. This long-term ecological study of bacterioplankton population dynamics published papers about previously unreported seasonal and spatial patterns in bacterioplankton distributions and tied them to the carbon cycle. Details emerged about the microbial carbon pump, which leads to the long-term storage of carbon in the ocean interior. For example, of DOC accumulating annually at the ocean surface was found to oxidize when winter storms mixed surface water into the upper mesopelagic (Carlson et al., 2004). The composition of DOC was shown to change with depth, correlating with shifts in community structure (Goldberg et al., 2009, Morris et al., 2005, Treusch et al., 2009) (**FIG. 4.2**). The ocean came to be viewed as a structured microbial ecosystem in which a few dozen important microbial groups form dynamically changing communities that catalyze major reactions in geochemical cycles. Studies began of viruses, an important source of microbial mortality (Angly et al., 2006). Importantly, the Ocean Microbial Observatory provided the first insights into how microbial communities would change when global warming caused increasing ocean stratification—organisms adapted to the extremely low nutrients found at the surface in the Sargasso Sea in the summer would increase their range (Treusch et al., 2009).

Because of the history of research in the Sargasso Sea, it was selected by Craig Venter to become the site of the world's first major meta-genomic study (Venter et al., 2004). Meta-genomics began providing information about how the unknown microbial groups of the "SAR" series function. But, meta-genomics filled in only part of the story. The BIOS Ocean Microbial Observatory continued to reconstruct the "operational priorities" of the ocean microbial community by applying advanced mass spectrometry technology to identify important proteins (Sowell et al., 2009). Also, the tedious task of reconstructing metabolic pathways from gene lists began to fill in details of community function (Tripp et al., 2008).

The Ocean Microbial Observatory is actively pursuing this research today. Some of its major activities were conceived of by studying genomes and microbial communities and using this data to predict novel mechanisms of DOC oxidation. This research is increasingly becoming interdisciplinary as chemistry techniques are incorporated into the long-term study to understand the interplay between microbial communities and the ocean carbon cycle.

4.5. Sediment Traps and Carbon Export

M.H. Conte

The Bermuda Time-Series Site, located in the northern Sargasso Sea, is one of the most extensively studied regions in the open ocean and is the site of several ongoing, complementary time-series measurement programs: the Hydrostation S time-series (1954-present, 32°10'N, 64°30'W) of 0-4200m hydrographic properties (Michaels and Knap, 1996 and references therein); the Oceanic Flux Program (OFP) time-series (1978 to present, 31050'N, 64010'W) of deep ocean particle flux (Conte et al., 2001 and references therein); the Bermuda Atlantic Time-Series Study (BATS) time-series of upper ocean biogeochemical parameters (1989-present, Steinberg et al., 2001 and references therein); and the Bermuda Testbed Mooring (BTM) time-series of meteorological, physical and optical properties in the 0-650 m water column (1994-2007, Dickey et al., 2001). Together with remote sensing products, these time-series are providing a uniquely detailed view of the complex interactions among the physics, chemistry and biology of the oligotrophic North Atlantic gyre.

Since 1978 the Oceanic Flux Program (OFP) time-series, headed by BIOS faculty member Maureen Conte, has continuously measured particle fluxes in the deep Sargasso Sea. The particle flux, i.e. the transfer of materials from the surface ocean to the sediments, is a primary process controlling the global cycling of elements, the removal of carbon dioxide from the atmosphere, the food supply that fuels life in the deep ocean, and the efficiency of cleansing the ocean of contaminants. The residual flux material that is preserved in the layers of underlying ocean sediments further provide a rich record of past ocean conditions that enables us to reconstruct ocean history.

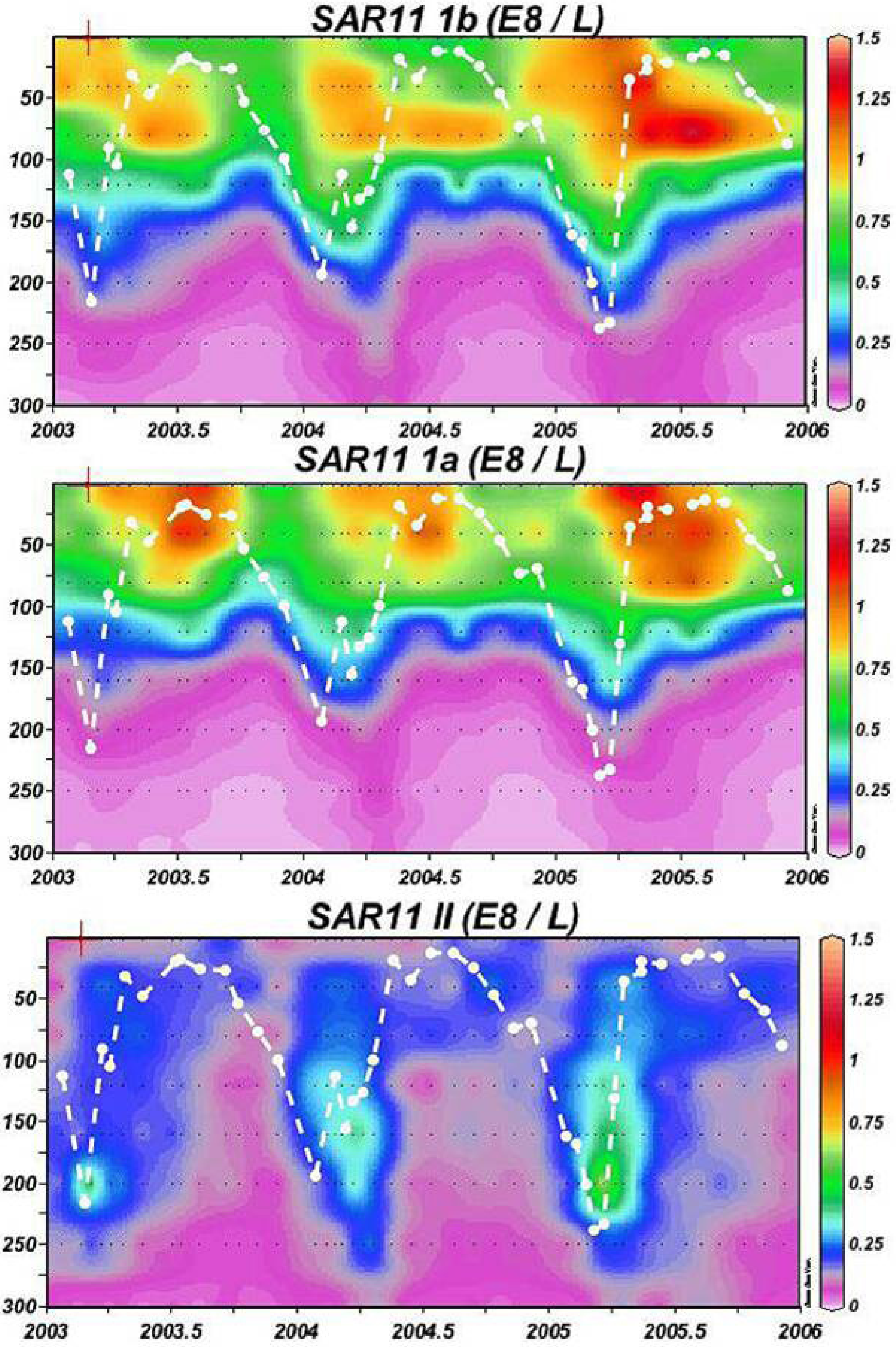

FIGURE 4.2 Contours of SAR11 ecotype cell densities in the surface 300 m from 2003 through 2005. These contour plots reveal the temporal and spatial (depth) patterns of various ecotypes SAR11 including Ia (a), Ib (b) and II (c). White dashed line represents mixed layer dept and is used to examine distribution patterns in the context of mixing and stratification. Ecotype Ia and Ib are most pronounced in the surface 80m during periods of water column stratification. Ecotype II is most pronounced within the upper mesopelagic zone (140–250m) during or shortly after deep convective mixing. The response of SAR11 Ecotype II at depth is presumably in response to the delivery of surface derived DOM upon deep mixing. Figure adapted from (Carlson et al., 2009).

At more than 33 years duration, the OFP is the longest particle time-series of its kind and has produced an unparalleled record of temporal variability in the deep ocean particle flux on time-scales ranging from weeks to decades. The OFP has elucidated many of the complex processes controlling particle flux magnitude and composition and by virtue of its length, is one of the few programs that can assess how the particle flux is affected by changes in basin-scale climatic patterns (*e.g.* ENSO and the North Atlantic Oscillation) and ocean chemistry (*e.g.* ocean acidification).

At the heart of the OFP time-series is a four km long subsurface mooring fitted with three sediment traps (500m, 1500m, 3200m depth) to collect settling particles and a current meter/sensor package to monitor deep-water currents and physical and chemical properties. Samples collected by the OFP sediment traps are studied by Conte and collaborators from around the world. Current research focuses includes studies of the coupling between deep flux patterns and near surface ocean mesoscale variability, assessment of the influence of increasing ocean acidification on the deep flux, the influence of hurricane-induced transport of sediment plumes on the deep ocean chemistry, investigations on how changing composition of the particle flux affects deep water ecosystems, and development of "proxy" indicators of ocean properties in support of paleoceanographic research.

The invaluable insights on ocean processes that have resulted from the OFP time-series could not have been realized without the record length and continuity, and the value of this time-series increases with each new observation. Advances in ocean and analytical technologies are providing greater context for the flux observations and ever more detailed information that is embedded in the chemistry of the recovered sample material. The numerous unresolved questions and hypotheses we have regarding the controls on particle flux and how the deep ocean will change due to anthropogenic forcing can only be tested by extending the time-series and protecting the region from deleterious activities that could undermine the integrity of the Bermuda Time-series site.

4.6. Ocean Optics and Remote Sensing of the Sargasso Sea

N.B. Nelson and D.A. Siegel

Environmental optics, using remote sensing by satellite or *in situ* measurements, is an important technique for understanding the physical, biological, and chemical environment of the ocean using time and space scales that are not accessible using conventional techniques. At Bermuda we have pioneered the integration of *in situ* data collected as part of the BATS project or related studies with remote sensing data to produce insightful analysis of processes in the Sargasso Sea.

Studies of ocean optics and the use of remote sensing to address science issues in the Sargasso Sea have been part of the time-series oceanographic research effort since near the beginning of the BATS program. The Bermuda Bio-Optics Project (BBOP), started by Dave Siegel (UCSB) and Tony Michaels (BIOS) in 1992, and now headed by Norm Nelson (UCSB, formerly BIOS), has compiled a continuing record of ocean optics properties that is unprecedented, by piggybacking on BATS cruises. Our researchers and colleagues used optics instruments on the Bermuda Testbed Mooring project to study ocean processes at one point on the seconds-to-seasons time scale. In addition to the field campaigns researchers have used remote sensing data, including ocean color, infrared imagery, and radar altimetry to study processes in the region. Selected results of the program are detailed here.

BBOP was started in 1992 with the goal of understanding processes controlling light propagation in the ocean and its interactions with the biological and physical environment (Siegel et al., 1995, Garver and Siegel 1997, Morrison and Nelson 2004). Initial results were startling, indicating that a hitherto unstudied fraction of chromophoric dissolved organic matter (called CDOM) was responsible for much of the variability of the underwater light availability (Siegel and Michaels, 1996; Nelson et al., 1998). This discovery led to a broad area of inquiry, including the development of methods for detecting CDOM from space-borne instruments (Siegel et al., 2002), a revolution in understanding the biological control of ocean color (Siegel et al., 2005), and connections between ocean circulation, CDOM, and climate (Nelson et al., 2007). The concentration of CDOM in the upper water column also mediates the rate of photochemical reactions, so these results stimulated studies of photochemistry that relates to the cycles of climate relevant gases such as DMS (a climate moderator, Toole et al., 2008) and greenhouse gases such as carbon monoxide (Zafiriou et al., 2008).

Remote sensing studies specifically focused on the Sargasso Sea conducted by our group have included a wide range of topics. Remote sensing at BIOS was stimulated by the presence of an HRPT satellite receiving station (1994-2000) which enabled us to obtain high-resolution imagery from old-technology spacecraft that could not store global high-res data on board. We also conducted several projects (some ongoing) to develop and validate new products from remote sensing data. Data from NOAA's AVHRR and NASA's SeaWiFS sensor collected at BIOS were used to study the impact of hurricanes on the Sargasso Sea (Nelson 2008, see also Dickey et al., 2008, Nelson 1996), large-scale spatial gradients in carbon cycling (Nelson et al., 2001) and primary productivity (Nelson et al., 2004). The importance of mesoscale eddies to productivity and carbon cycling was also identified at BATS (Sorenson and Siegel 2001, Siegel et al., 1999) and has resulted in major research efforts in the Sargasso Sea (Siegel et al., 2008) using ocean color, infrared, and radar altimeter remote sensing. Overall the results of remote sensing investigations of the Sargasso Sea have highlighted the importance of spatial data in terms of interpreting observations made at the BATS site, and the importance of a broad, high quality in situ data set for validating and interpreting remote sensing data.

Research on ocean optics carried out in the Sargasso Sea is important not only for local but also for global oceanographic research. Discoveries at Bermuda have stimulated novel oceanographic research not only in the Sargasso Sea, but all over the world. Continued research support in the form of collaboration with the BATS program will allow us to continue to validate remote sensing data and address new known and unknown science problems.

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CHAPTER 5

Biogeochemical cycles in the Sargasso Sea

5.1. Marine Biogeochemical Cycles in the Sargasso Sea

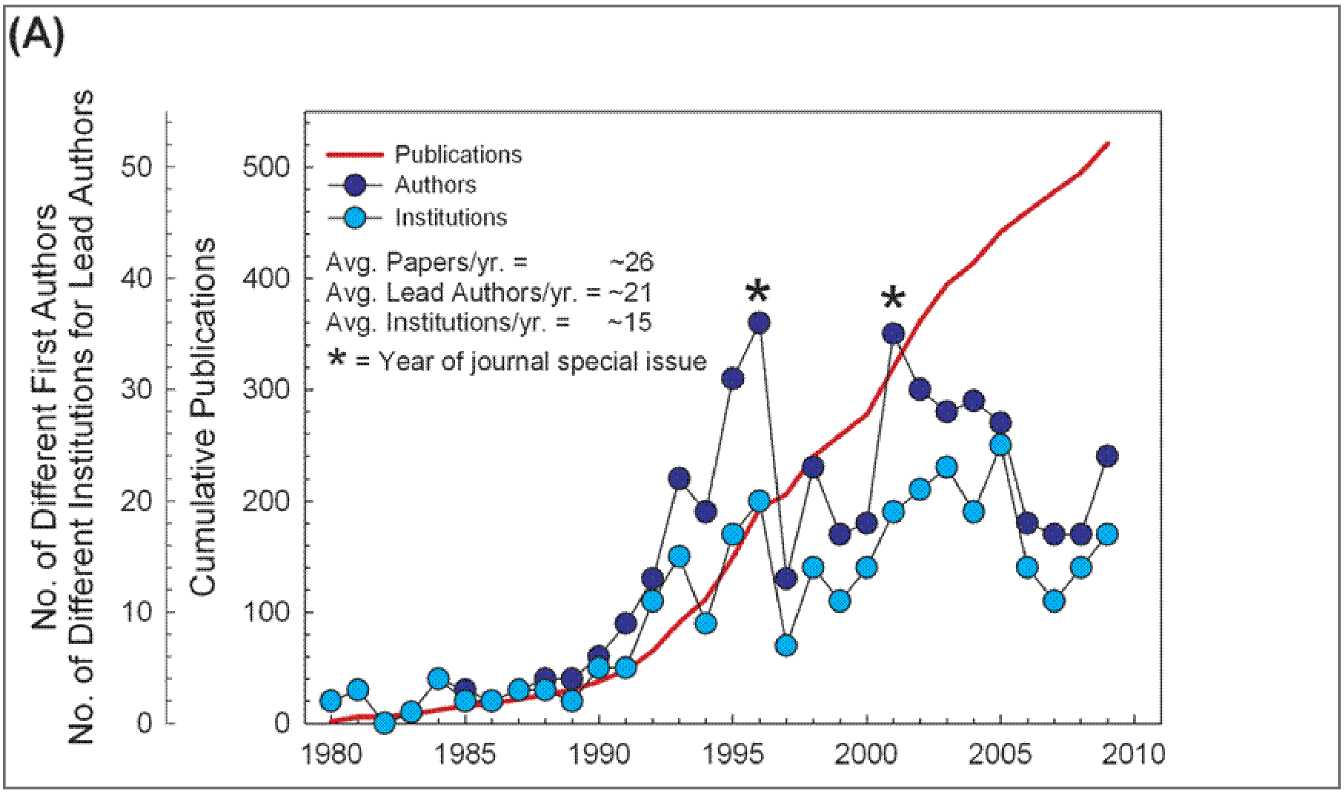
N.R. Bates and M.W. Lomas

The global ocean is responding to environmental change that includes warming, changes in the water (or hydrological) cycle and ocean nutrient availability (*e.g.*, Boyce et al., 2010) that controls the growth and accumulation of phytoplankton which in turn form the base of the marine food web. The response of marine ecosystems and the biogeochemistry of important elements such as carbon and oxygen, and nutrient compounds to environmental changes demands detailed observations and improvements in understanding of the important physical, chemical and biological processes that control them. A critical component for investigating change in marine ecosystems and biogeochemistry is the network of time-series observations in the global ocean.

In the open-ocean, time-series observations in the subtropical North Atlantic Ocean off Bermuda (i.e., the Sargasso Sea) and in the North Pacific Ocean off Hawaii comprise the two longest running studies of marine biogeochemistry and the responses of the ocean to environmental changes. In the Sargasso Sea, the ocean time-series, Hydrostation 'S' (1954 to present) and the Bermuda Atlantic Time-series Study (BATS; 1988 to present), provide critically needed data on the time-varying fluxes and sequestration of carbon and nutrients over the last few decades and more importantly the controls on marine biogeochemistry. One measure of the impact of the BATS program is the strong publication record resulting from this research. The cumulative publications and technical references for these programs since 1988, now exceed 500 articles, with an average of ~20 publications per year since BATS sampling started in 1988 (**FIG. 5**; Appendix III).

The basic hydrographic properties of seawater, temperature and salinity, control the density of seawater and ultimately vertical exchange processes in the global ocean. This control of vertical exchange has important implications for the Sargasso Sea, as it is the deeper ocean waters that contain the nutrients required to support the surface sunlit ocean ecosystem. Over the last twenty years, temperature and salinity in the upper ocean layers of the subtropical gyre at BATS has increased significantly with concurrent increases in stratification (a reduction in the potential for vertical exchange). Over the past 57 years, observations at Hydrostation S have shown significant warming of the surface ocean (~0.1°C decade^{-1}) and reorganization of the global hydrological cycle as evidenced by an increase in ocean salinity (~0.02 decade^{-1}) in the upper ~300 m. Although the warming and increase in salinity may seem small, they have large impacts on the Sargasso Sea as a whole, with complex feedbacks and interactions thus making it more difficult in the long term to entrain nutrients from depth.

The global ocean nutrient cycles that support the marine food web also appear to be impacted by human activities, climate-related physical processes, and a very dynamic marine nitrogen and phosphorus cycle. For example, the inputs of anthropogenic nutrients to the coastal ocean (*e.g.*, Galloway et al., 2008) and fixed nitrogen to the open ocean (via atmospheric deposition) are expected to increase (*e.g.*, Duce et al., 2008; Seitzinger et al., 2010). Ocean warming appears to be increasing stratification of the surface ocean potentially reducing nutrient supply and the rates of phytoplankton primary production globally (Boyce et al., 2010). However, there are complex and counteracting processes that control the physical supply nutrients to the surface ocean thereby influencing the global ocean nutrient cycles (*e.g.*, Williams et al., 2006; Cianca et al., 2007; Wong et al., 2007; Di Lorenzo et al., 2009; Steinhoff et al., 2010; Canfield et al., 2010). The marine nitrogen cycle is very dynamic, with for example, complex linkages between eutrophication, nutrients and carbon (*e.g.*, Chen and Borges, 2009; Borges and Gypens, 2010). Recent studies in the Sargasso Sea indicate that the potential rate of nitrification of ammonia is declining with ocean acidification (Beman et al., 2011), while the significance of global oceanic nitrogen fixation, especially in the Sargasso Sea, is highly debated (*e.g.*, Michaels et al., 1996; Gruber and Sarmiento, 1997; Hansell et al., 2004; Bates and Hansell 2004; Hansell et al., 2008; Gruber, 2008). Many of these processes impact one nutrient biogeochemical cycle, nitrogen or phosphorus, more than the other, resulting in potentially large deviations from the canonical Redfield Ratio, which defines not only the relative concentrations of inorganic nitrate and phosphate in the deep ocean, but also which nutrient limits primary production. The Sargasso Sea is already characterized by a ratio of inorganic nitrate and



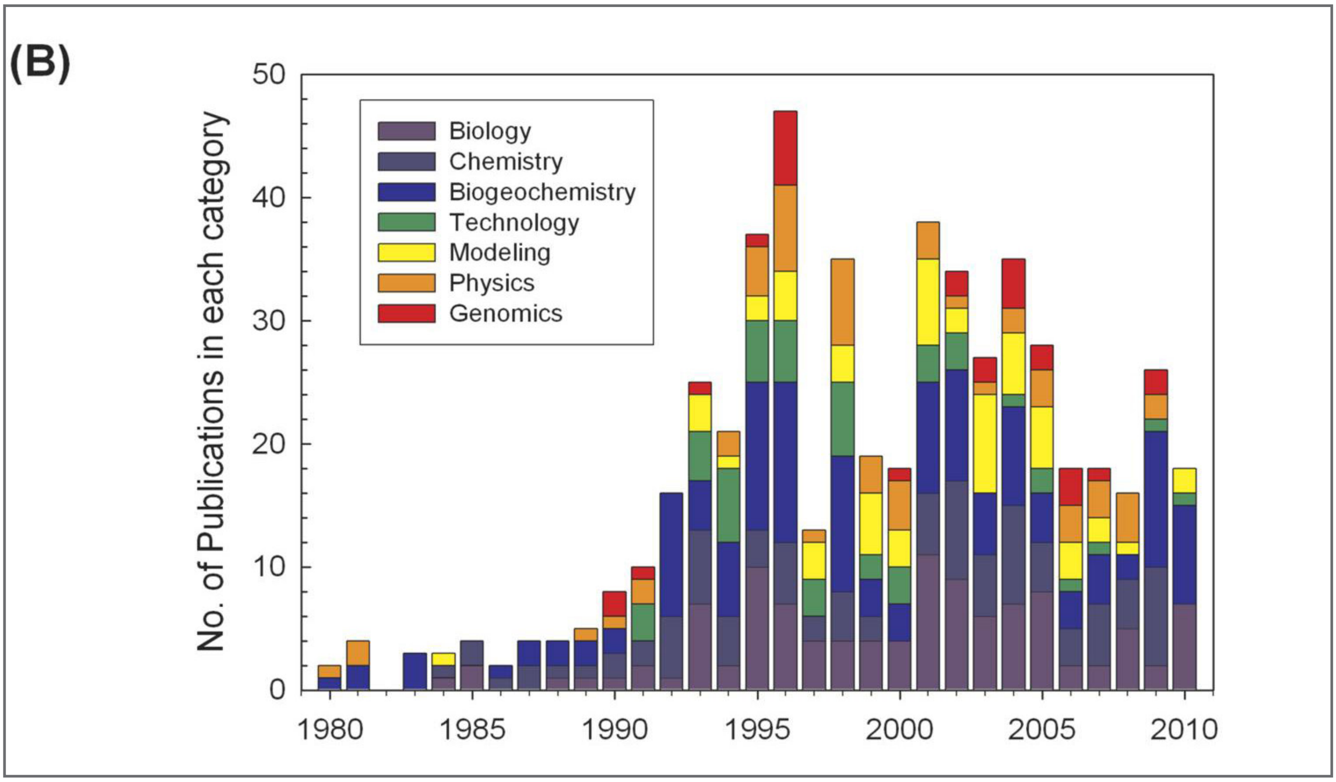


FIGURE 5. Statistics of scientific publications arising from research conducted in the Sargasso Sea from 1978 to present. (A) Cumulative number of publications (red line), and the number of different first authors (dark blue circles) and institutions (light blue circles) in each year. (B) Publications within each year divided into the seven 'disciplinary' categories listed in the legend. Statistics are current through June 2011.

phosphate that is much higher than the canonical Redfield Ratio, but the response of phytoplankton and their control over this ratio of available nutrients is currently being challenged (*e.g.*, Mills and Arrigo, 2010).

As mentioned above, primary production has been increasing in the Sargasso Sea over the past decade or more. While this may seem at odds with the lack of increase in nutrient inputs, a likely explanation is the utilization of different nutrient forms, namely dissolved organic nutrients. Specifically, it is dissolved organic phosphorus (DOP) that has been hypothesized to support over 50% of primary production in both the western and eastern North Atlantic Ocean (Lomas et al., 2010b; Mather et al., 2008; Torres-Valdes et al., 2009), although the source regions for DOP, and the complex processes which lead to its net production, appear to be different between the western and eastern North Atlantic Ocean. In addition to the use of DOP to support primary production, the particulate nutrient ratio, nitrogen:phosphorus, has steadily increased relative to the Redfield Ratio over the past ~7 years. This is consistent with the increasing importance of marine cyanobacteria (see section 4.2 Phytoplankton research) which are known to have ratios greater than Redfield, as well as the observation that ocean acidification conditions results in a still further increase in the particulate nitrogen:phosphorus ratio in marine cyanobacteria (*e.g.*, Fu et al., 2007). These observations might also explain the increased carbon flux associated with the increase in cyanobacteria in the Sargasso Sea via the COP/SS hypothesis (Carbon Over Production/Species Shift hypothesis; Lomas, Andersson and Bates, unpubl. data). This combination of DOP utilization and changes in elemental stoichiometry in response to changes in species and/or ocean acidification would comprise a negative feedback loop on increasing carbon dioxide in the upper ocean.

All of these changes in the Sargasso Sea, while presented individually, are inextricably interconnected within the ecosystem (a field of scientific study called ocean biogeochemistry) and often lead to non-intuitive results. One such outcome is the increase in biological fixation of CO_2 by single cell plants (phytoplankton) and the associated increases in their abundance. As mentioned earlier, the Sargasso Sea is warming and it is becoming more difficult—on longer timescales—to bring critical nutrients from the deep ocean to the surface that phytoplankton require to grow, and thus it is puzzling that ocean phytoplankton been able to become more abundant. In part, it is due to shifts in the large diversity and relative abundances of these phytoplankton, but it is also due to substantial changes in the physiology of these plants that allow them to rapidly adapt to a changing environment. A critical question is just how adaptable are these phytoplankton, and if they cannot adapt to a changing ocean, will they be lost from the ocean's genomic library as the ocean climate changes. Datasets like those generated at BATS are forcing oceanographers to rethink our understanding of natural processes in the global ocean and how this information is assimilated into attempts to predict the future state of the ocean.

5.2. The Global Ocean Carbon Cycle and Observations in the Sargasso Sea

N.R. Bates

On societally relevant timescales (*e.g.*, decades to centuries), the global ocean sequesters large quantities of carbon dioxide (CO_2) from the atmosphere. Photosynthetic fixation of CO_2 into particulate matter and production of calcium carbonate ($CaCO^3$) by calcifying marine phytoplankton, coupled with the subsequent downward transfer via settling of particles and biologically mediated processes represents an important export of carbon. These processes are collectively termed the ocean biological carbon pump and it sequesters carbon into the deep ocean on the timescale of the global overturning circulation (hundreds to thousands of years) *e.g.*, Broecker and Peng, 1982; Gruber and Sarmiento, 2002. The reservoir of carbon in the global ocean is approximately 60-70 times greater than that of the atmosphere. As such, even a small change in the ocean reservoir of carbon has a significant impact on the atmospheric concentration of CO_2 and the response of the climate system to the release of anthropogenic (i.e., human produced) CO_2.

At present, the global ocean sequesters about 25% of anthropogenic CO_2 in the atmosphere, with the total amount of anthropogenic carbon sequestered in the ocean estimated at ~120-140 Pg (Pg = 1015 g) of carbon (*e.g.*, Sabine et al., 2004; Khatiwala et al., 2009). The global ocean uptake of CO_2 is estimated at ~1.4 to 2.5 Pg C per year (*e.g.*, Takahashi et al., 2002, 2009; Manning and Keeling, 2006), with the ocean uptake increasing with time (*e.g.*, Le Quéré et al., 2009) as the amount of anthropogenic CO_2 released to the atmosphere has increased (Friedlingstein et al., 2010). Thus, the sequestration of CO_2 into the global ocean is one of the primary mechanisms that controls the concentrations of CO_2 in the lower atmosphere and the impact of human produced CO_2 on the climate system (IPCC, 1990, 2001, 2007).

Understanding the time-varying magnitude and controlling dynamics underlying the sequestration of carbon requires a detailed study of the biological, geological and chemical processes that control the transfer of carbon across the air-sea interface and into the deep ocean. Superimposed on long-term decadal trends in ocean sequestration of CO_2 are large regional, seasonal and inter-annual variations in CO_2 uptake that reflects changes in temperature, ocean primary production, ocean and atmosphere circulation that respond to natural and human induced climate variability such as the El Niño-Southern Oscillation (ENSO), Pacific-Decadal Oscillation Antarctic Annular Oscillation and North Atlantic Oscillation (*e.g.*, Gruber et al., 2002; Bates et al., 2002; Feely et al., 2006, Bates, 2007, Le Quéré et al., 2009; section 7.1). A critical component for investigating the present and future role of CO_2 on the climate system is the network of time-series observations in the global ocean, with observations collected in the Sargasso Sea constituting the longest record.

Although quite a few open-ocean and coastal ocean CO_2 time-series have been initiated, only four time-series sites are of sufficient length to evaluate longer-term inter-annual trends globally. These are: (1) BATS (Bermuda Atlantic Time-series Study), located near Bermuda (32°10'N, 64°30'W) in the NW Atlantic Ocean (2) Hydrostation S, (32°50'N, 64°10'W) located near Bermuda in the NW Atlantic Ocean, (3) ALOHA (A Long-term Oligotrophic Habitat Assessment) or HOT site, located near Hawaii (22°45'N, 158°W) in the North Pacific Ocean; and; (4) ESTOC (European Station for Time-series in the Ocean Canary Islands (ESTOC), located near Gran Canaria in the NE Atlantic Ocean.

These long-term observations at several ocean time-series show upward trends of dissolved inorganic carbon (DIC) and seawater pCO_2 due to the uptake of anthropogenic CO_2 (*e.g.*, Bates, 2001; Bates et al., 2002; Dore et al., 2003; Keeling et al., 2004; Brix et al., 2004; Bates, 2007; Santana-Casiano et al., 2007; Dore et al., 2009; Gonzalez-Davila et al., 2010). The anticipated rate of change in surface ocean CO_2 due to the accumulation of anthropogenic CO_2 in the atmosphere and the surface ocean buffer factor (assuming that near-surface waters in the subtropical gyres have residence times long enough to equilibrate entirely with the anthropogenic perturbation in atmospheric CO_2) can be theoretically calculated. An equilibrium rate of dissolved inorganic carbon (DIC) increase due to anthropogenic CO_2 of +0.9 µmoles kg^{-1} yr^{-1} was calculated for the subtropical gyres including the Sargasso Sea (Bates et al., 2002; Gruber and Sarmiento, 2002). Any assessment of long-term trends in oceanic CO_2 is complicated by large seasonal variability of the inorganic carbon cycle due to processes such as seasonal temperature, salinity, and density changes, vertical and horizontal mixing, biological production, diurnal warming/cooling, and storm events (*e.g.*, Bates et al., 2002; Gruber et al., 2002; Dore et al., 2003; Keeling et al., 2004; Brix et al., 2004). Interpretation of oceanic CO_2 time-series data is further complicated by variability imparted by spatial heterogeneity in the ocean as a result of mesoscale and sub-mesoscale phenomena (*e.g.*, McGillicuddy et al., 2007), and meridional and zonal physical gradients.

Long-term observations at the BATS site also indicate that the salinity normalized DIC (nDIC) of surface and deeper water layers have increased at divergent rates over time since water-column sampling began in 1988 (Bates et al., 2002; Gruber et al., 2002). In deeper subtropical mode waters (STMW), the mean rate of change of nDIC (1988-2001) was significantly higher than surface waters, increasing at a rate of 2.2 ± 0.26 µmoles kg^{-1} $year^{-1}$ (Bates et al., 2002). The STMW of the North Atlantic Ocean is formed each winter by cooling and convective mixing at the northern edges of the subtropical gyre south of the Gulf Stream (Klein and Hogg, 1996; Hazeleger and Drijfhout, 1998). The shallow depths of the subtropical gyre (~250-400m deep) are ventilated during STMW formation and the STMW layer is found throughout the subtropical gyre. This water mass is classically defined by temperatures ranging from 17.8° to 18.4°C, by a salinity of ~36.5 ± 0.05, and by a minimum in the vertical gradient of potential density (or isopycnic potential vorticity) (Klein and Hogg, 1996; Jenkins, 1998; Hanawa and Talley, 2001; Alfutis and Cornillon, 2001). The non-conservative increase of CO_2 does not result from remineralization of organic matter or density variability, but rather, weak wintertime mixing and lack of STMW re-ventilation, which appear associated with an NAO positive phase (Bates et al., 2002; Gruber et al., 2002). Since 1988, ~0.6-2.8 Pg (1015 g) of CO_2 has accumulated within the gyre STMW, representing a long-term oceanic sink of CO_2 (>10 years). The accumulation of CO_2 in STMW should continue until winters with stronger mixing (associated with a NAO negative phase) entrain STMW CO_2 into surface waters, ultimately releasing CO_2 to the atmosphere. Inter-annual variability in the uptake of CO_2 into STMW thus provides another factor and feedback controlling the global ocean uptake of CO_2.

5.3. Calcium Carbonate Production

N.R. Bates

Production of calcium carbonate ($CaCO_3$) by calcifying marine phytoplankton such as coccolithophores, pteropods and foraminfera also contributes substantively to carbon export to the deep ocean. Extensive coccolithophore blooms in other regions of the global ocean (*e.g.*, Bering Sea, Gulf of Maine, off Iceland) can significantly impact the ocean carbon cycle (*e.g.*, Robertson et al., 1994; Bates et al., 1996a; Murata and Takizawa, 2002; Murata, 2006; Harley et al., 2010). In the Sargasso Sea, episodic coccolithophore blooms have been observed (Brown and Yoder, 1994) accompanied by significant decreases in ocean alkalinity observed (Bates et al., 1996b). Unlike other taxonomic classes of phytoplankton, coccolithophores can increase seawater pCO_2 content and thus contribute to a negative coccolithophore-CO_2 feedback (Riebesall et al., 2000; Zondervan et al., 2001; Ridgewell et al., 2007) that has potentially important implications for the role of the global ocean in the uptake of anthropogenic CO_2, modulation of atmospheric CO_2 and climate responses over the next few centuries.

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CHAPTER 6

Air-Sea Interactions

6.1. Climate variability, NAO/ENSO Influences on the Subtropical Gyre

N.R. Bates

Variability in the marine carbon cycle and ocean carbon sources and sinks has been studied most thoroughly in the tropical Pacific Ocean in connection with the El Niño Southern Oscillation (ENSO). El Niño-La Niña changes have profound impacts on weather and climate globally. By contrast, little is known about the contribution of the subtropical and subpolar gyres to atmospheric CO_2 variations, despite the fact that these gyres cover more than half of the world's ocean. Natural climate phenomena, such as the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) also have strong regional (particularly in Europe) and global impacts on weather and climate.

The dominant mode of atmospheric and climate variability in the North Atlantic Ocean region is the NAO, which is a dipole meridional oscillation in atmospheric pressure between the Iceland Low and Azores High (Hurrell, 1995; Hurrell and Van Loon, 1997; Hurrell et al., 2002). The NAO is linked to the Arctic Oscillation (AO), which is a tripolar oscillation between the North Pacific and North Atlantic, centered over the Arctic region (Visbeck et al., 2001). The NAO has significant effects on climate and atmospheric variability. Strong eastward airflow between the Iceland Low and Azores High carries storms towards western Europe from North America. If the NAO index is negative, storm tracks are thought to shift southward, cooling surface waters, enhancing 18°C mode water formation and deepening winter mixed layers (Rodwell et al., 1999). In western Europe, for example, there is an increase in winter storms and precipitation during these periods. During positive NAO winters, westerlies that usually prevail in the region between Florida and Cape Hatteras (west of the Azores High) weaken. Reduced wind stress and heat exchange leads to the development of warm temperature anomalies in the subtropical gyre (*e.g.*, Cayan, 1992a,b) with a magnitude of ~0.2 to 0.4°C (*e.g.*, Davies et al., 1997; Kapala et al., 1998).

Although the NAO is the dominant mode of mid-latitude atmospheric variation, dynamical relations between El Ninõ and Atlantic climate have long been documented (*e.g.*, Enfield and Mayer, 1997; see references in Penland and Matrosova, 1998). For example, the Gulf Stream position shifts northwards after El Niño events and during NAO positive phases with a lag of ~2 years (*e.g.*, Taylor et al, 1998; Taylor and Stephens, 1998). Within 4-12 months of El Niño warming in the Pacific Ocean, warming is observed in the tropical North Atlantic, Caribbean Sea and the SE subtropical gyre (*e.g.*, 1996; Bojariu, 1997; Penland and Matrosova, 1998). The mechanism for this apparently relates to a reduction in cloud cover in the drier, more stable Atlantic atmosphere (*e.g.*, Davies et al., 1997; Jones and Thorncroft, 1998).

6.2. Atmospheric deposition and Acid Precipitation

N.R. Bates and A.J. Peters

Human modification of the global biogeochemical cycles of nitrogen and sulphur has led to acidic deposition from the atmosphere, which has affected sensitive terrestrial and ocean ecosystems (*e.g.*, Farrell, 1995; Rodhe et al., 2002; Bouwman et al., 2003; Holland et al., 2005; Lamarque et al., 2005; Dentener et al., 2006; Doney et al., 2007). In those regions with acid deposition, industrial emissions of sulphur and nitrogen compounds (*e.g.*, North America, Europe and East Asia) or intensive agricultural practices contribute to the acidity of rainwater with pH typically ranging from about 4 to 6 (*e.g.*, Rodhe et al., 2002).

The Sargasso Sea is downwind of pollution sources from the North American continent and consequently experiences acid deposition with rainfall pH levels typically ranging from about 4.4 to 5.6 (Jickells et al., 1982; Bates and Peters, 2007). Early studies of atmospheric deposition of nitrogen or sulphur were focused on the contributions from H_2SO_4, HNO_3, $CaCO_3$, organic acids, soil dust and reduced and oxidized sulphur and nitrogen compounds to the acidity of wet deposition (*e.g.*, Keene and Galloway, 1988; Whelpdale et al., 1996). The pH and chemical composition of rainwater has been monitored on the island of Bermuda since the early 1980's (Jickells et al., 1982; Galloway et al., 1993), initially as part of the Western Atlantic-Ocean Experiment (WATOX; Galloway et al., 1987 and Atmosphere-Ocean Chemistry Experiments (AEROCE; Huang et al., 1996) projects).

AEROCE was a multi-disciplinary collaborative program focused on linked atmospheric and marine chemical processes in the North Atlantic Ocean region. Under this initiative a number of atmospheric research towers were constructed at key sites in the North Atlantic Ocean region, including a 23m tower constructed in 1988 at Tudor Hill, Bermuda. This facility was used for daily sampling of gases, aerosol and precipitation for over a decade and continues to be maintained and used as a research facility. The results of the AEROCE program were summarized by Prospero (2001). Some of the key findings relevant to the Sargasso Sea include:

1. Seasonal cycles in aerosol pollutants in Bermuda are determined more by the speed and duration of atmospheric transport than by strength of source emissions (*e.g.* Moody et al., 1995).
2. Anthropogenic sources contribute a significant amount to the atmospheric loadings of sulphur and nitrogen species (*e.g.* Savoie, et al., 1992).
3. Sea-salt aersosol is a major reaction medium and sink for sulphur and nitrogen species over the North Atlantic Ocean (*e.g.* Keene et al., 1998).
4. Records of deposition of African dust to the Sargasso Sea were consistent with loadings of atmospheric dust observed at Bermuda, and annual variations in sediment trap fluxes were linked to changes in atmospheric transport rather than source strength (Jickells et al., 1998).
5. Mineral dust is the dominant light scattering aerosol over a large part of the tropical and subtropical North Atlantic Ocean (*e.g.* Maring et al., 2000).

Atmospheric deposition of nitrogen species also can support ocean primary production although it varies widely by ocean region (*e.g.*, Paerl, 1997; de Leeuw et al., 2003; Hastings et al., 2003; Spokes and Jickells, 2005; Boulart et al., 2006; Jickells, 2006). Annual rates of primary production at BATS are typically ~150 g C m^{-2} $year^{-1}$ (Steinberg et al., 2001), and the amount supported by atmospheric nitrogen deposition is typically insignificant (0.2–0.5%) except potentially for rare high rainfall events (*e.g.*, Knap et al., 1986; Fanning, 1989; Owens et al., 1992; Michaels et al., 1993). However, future changes in atmospheric nitrogen deposition (*e.g.*, Duce et al., 2008), coupled with the long term reductions in nutrient supply from below might enhance this mechanism supporting oceanic primary production. Perhaps more important than atmospheric nitrogen deposition, in terms of supporting primary production, are atmospheric iron inputs which keep the Sargasso Sea replete with a biologically important trace metal (Sedwick et al., 2007; see also section 3).

Some studies of synthetic organic chemicals in the remote marine atmosphere have been conducted in the Sargasso Sea region. Concentrations of polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCPs) have been detected in the atmosphere of the North Atlantic Ocean at levels similar to those from other remote locations (Bidleman et al., 1981; Whelpdale et al., 1990) and these compounds have been shown to be well mixed in the troposphere up to an altitude of 10,000 feet, with concentrations over the western North Atlantic Ocean generally lower than those over the continental USAA. (Knap and Binkley, 1991). A long term study of PCBs in the oceanic atmosphere undertaken at the former AEROCE facility in Bermuda in 1992-93 showed little change in PCB levels over the previous 20 years, and an atmospheric half-life of greater than 23 years was estimated for these compounds (Panshin and Hites, 1994). PCB concentrations were significantly higher in air masses arriving at Bermuda from Africa and the eastern Atlantic region. More recent work has demonstrated the presence polyfluorinated chemicals (PFCs), a relatively new class of industrial chemicals, in this region (Shoeib at al., 2010). Further long-term investigation of organic contaminants in the atmosphere of the Sargasso Sea region has continued at the Tudor Hill facility as part of the Global Atmospheric Passive Sampling (GAPS) study (Harner et al., 2006; Pozo at al., 2006; Pozo at al., 2009).

6.3. Air-sea gas exchange, CO_2 and DMS

N.R. Bates

Carbon Dioxide (CO_2). The atmosphere-ocean exchanges of CO_2 in the Sargasso Sea are discussed in section 3 and 5.2. However, the Sargasso Sea is an important region for uptake of CO_2 from the atmosphere with distinct seasonal variability in uptake and release of CO_2 (Bates et al., 1996; Bates et al., 1998a,b; Bates and Hansell, 1999; Nelson et al., 2001; Bates, 2001, 2002; Takahashi et al., 2002; Bates, 2007; Takahashi et al., 2009). The annual net ocean uptake of CO_2 in the subtropical gyre of the North Atlantic off Bermuda appears to be increasing in contrast to other parts of the North Atlantic Ocean (especially in the subpolar gyre; Watson et al., 2009; Schuster et al., 2009).

Dimethylsulphide (DMS): Dimethylsulphide (DMS) is produced through biogeochemical processes in the surface ocean food web. DMS is the primary source of natural sulphur to the atmosphere, where the gas is oxidized to sulphate and methane sulphonate aerosols (Shaw, 1983), which act as cloud condensation nuclei. Variability in oceanic DMS production and ventilation to the atmosphere has the potential to alter aerosol abundance, cloud coverage, and cloud properties, which in turn affects the atmospheric radiative balance and climate (Charlson et al., 1987).

There is a need to quantitatively understand biogenic sulphur dynamics in the oceans and the role of DMS in structuring past, as well as future, global climates. In order to accomplish this, a better understanding of the fates of the DMS and dimethylsulphoniopropionate (dissolved and particulate DMSP) pools in the ocean is required. The task is difficult because the biological and chemical processes involved in the cycling of biogenic sulphur are broad and complex. Short term (UV inhibition, nutrient pulses) as well as long-term (light regime, nutrient regime, temperature) stressors impact the biogeochemical cycling processes of the oceanic sulphur pool. Because the oceans account for > 50% of the global source of reduced sulphur to the atmosphere, it is critical to understand the various reservoirs and cycling processes. In the Sargasso Sea, early measurements of oceanic DMS and DMSP have provided the only long-term time series for DMS in the deep ocean (Dacey et al., 1998; Toole et al., 2008). The observed decoupling of DMS concentration from any measure of its precursors (i.e., DSMP) embodies the DMS "*summer paradox*" hypothesis (Simó and Pedrós-Alió, 1999). More recent studies off Bermuda (Dacey, Toole, Bates, unpublished data) have suggested that the DMS 'summer paradox' is a reoccurring phenomenon in this area of the ocean. The continuing development of more precise and accurate measurement techniques is also imperative as demonstrated by the significant reduction in DMSPd concentrations. Time-series data such as these are important for understanding present global ocean dynamics and also for modeling and predicting future fluctuations in physical, chemical, and biological processes.

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CHAPTER 7

Climate change and ocean acidification

7.1 Climate Change

N.R. Bates

The NAO, like El Niño, also has profound impacts on ocean biogeochemical dynamics and the fate of CO_2. In the North Atlantic, the NAO plays a large role in determining the exchange of CO_2 between the ocean and atmosphere (Bates, 2001; Bates et al., 2002; Gruber et al., 2002). It appears likely that there is a coordinated basinwide response in the North Atlantic Ocean to climate phenomena such as NAO (Gruber et al., 2002; Levine et al., 2011).

There is also increasing evidence that shows a strong linkage between NAO and atmospheric dust transport variability which consequently control the variability of ecosystem structure and functioning in the North Atlantic subtropical gyre (Bates and Hansell, 2004; Lomas and Bates, 2004). In the tropical and subtropical ocean, it has also been hypothesized that tropical cyclones (i.e., hurricanes and typhoons) play a significant role in determining the exchange of CO_2 between ocean and atmosphere (Bates et al., 1998a,b; Bates and Merlivat, 2001; Bates, 2002).

7.2 Ocean Acidification

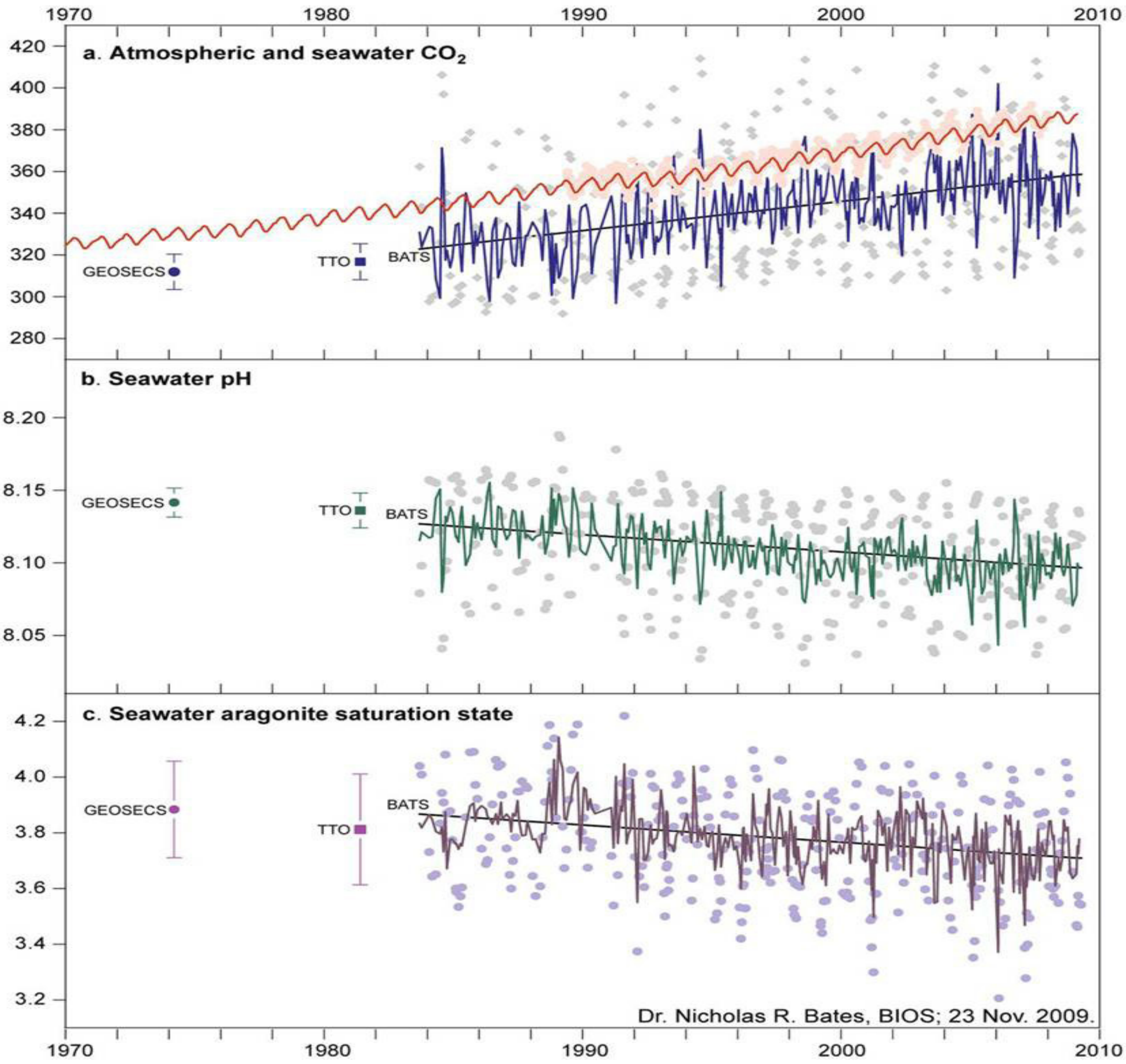
N.R. Bates

Over the last several centuries, human activities have released large quantities of carbon dioxide (CO_2) into the atmosphere (IPCC, 1996, 2001, 2007; Sarmiento and Wofsy, 1999; Wofsy and Harris, 2001). Anthropogenic CO_2, emitted primarily from fossil fuel use, cement manufacture, and land use changes (Houghton and Hackler, 2002) has not only accumulated in the atmosphere (Prentice et al., 2001), but it has also been taken up by the terrestrial biosphere and global oceans (Quay, 2002; Sabine et al., 2004).

As a consequence of the direct uptake of anthropogenic CO_2, surface seawater dissolved inorganic carbon (DIC) concentration and partial pressures of CO_2 (pCO_2) have increased while the *p*H has decreased (**FIGURE 7**; Bates et al., 1996; Winn et al., 1998; Bates, 2007; Bates and Peters, 2007; Santana-Casiano et al., 2007; Takahashi et al., 2009). This gradual process, termed *ocean acidification* has long been recognized by chemical oceanographers (Broecker and Takahashi, 1966; Broecker et al., 1971; Bacastow and Keeling, 1973). Estimates based on the Intergovernmental Panel on Climate Change (IPCC; Prentice et al., 2007) model projections of future anthropogenic CO_2 emissions and subsequent ocean absorption of anthropogenic CO_2 indicate that surface ocean pH will decrease by 0.3-0.5 units over the next century and beyond (Caldeira and Wickett, 2003; 2005). The effects of ocean acidification are potentially far-reaching in the global ocean, particularly for organisms that secrete calcium carbonate ($CaCO_3$) skeletons, tests or shells (Buddemeier et al., 2004; Royal Society, 2005; Orr et al., 2005; Doney, 2006; Fabry et al., 2008) including hermatypic corals that are the framework for coral reef ecosystems. Ocean acidification is an emerging environmental issue but one that appears to have impacts on many marine ecosystems, for example even the apparently healthy coral reef ecosystems of Bermuda (Bates et al., 2001; Bates, 2002; Bates et al., 2010).

Increasing seawater pCO_2 and ocean acidification also results in a decrease in the surface seawater carbonate ion concentration $[CO_3^{2-}]$ and the saturation state ( ) with respect to calcium carbonate ($CaCO_3$) minerals such as calcite and aragonite. This has profound negative implications for marine organisms in both high and low latitude oceans that produce tests, shells or skeletons made of carbonate minerals, such as corals, coralline algae, pelagic pteropods and coccolithophorids, mollusks, echinoderms, and foraminifera (Buddemeier et al., 2004; Royal Society, 2005; Orr et al., 2005; Doney, 2006; Fabry et al., 2008). It is also well known that dissolution of carbonate minerals will increase as a result of decreasing seawater $CaCO_3$ saturation state (Andersson et al., 2003; 2005, 2007; Kuffner et al., 2008).

The responses of coccolithophores, carbonate mineral-bearing phytoplankton, to climate change and anthropogenic induced ocean acidification, plus the feedbacks to atmospheric CO_2 and climate, are, without doubt, complex, uncertain and subject to intense scientific debate. Calcification and production of biogenic $CaCO_3$ by marine calcifiers is associated with the uptake of $[CO_3^{2-}]$ or $[HCO_3^-]$, which, in turn, acts to increase CO_2. Associated uptake of total alkalinity (TA) and dissolved inorganic carbon (DIC) in the ratio of 2:1, shifts the equilibrium of the carbonate system towards CO_2 (i.e., $[Ca^{2+}] + [CO_3^{2-}] = CaCO_3$ [1], or: $[Ca^{2+}] + 2[HCO_3^-] = CaCO_3 + [H_2O] + [CO_2]$ [2]) (Dickson et al., 2007). For coccolithophores, $[HCO_3]$ uptake, for example, is a potential source of CO_2 for photosynthesis. However, whether coccolithophore calcification is a source of CO_2 to the ocean depends on the balance of $CaCO_3$ production to organic carbon production (*e.g.*, CO_2 production occurs when $CaCO_3$ production > organic carbon production). In the field, a few studies have shown increases in seawater pCO_2 in response to coccolithophore calcification in the North Atlantic Ocean. Thus unlike other taxonomic classes of phytoplankton blooms, coccolithophores can increase seawater pCO_2 content and thus contribute to a negative coccolithophore-CO_2 feedback (Riebesall et al., 2000; Zondervan et al., 2001; Ridgewell et al., 2007) that has potentially important implications for the role of the global ocean in the uptake of anthropogenic CO_2, modulation of atmospheric CO_2 and climate responses over the next few centuries.



a. Atmospheric and seawater CO_2

b. Seawater pH

c. Seawater aragonite saturation state

Dr. Nicholas R. Bates, BIOS; 23 Nov. 2009.

FIGURE 7. **Time-series of atmospheric and ocean carbon dioxide, pH and aragonite saturation states. a. Timeseries of atmospheric carbon dioxide (in parts per million) from Mauna Loa, Hawaii (red line), and Bermuda (pink symbol), and surface ocean seawater carbon dioxide (µatm) at the Bermuda Atlantic Time-series Study (BATS) site off -Bermuda. Observed (grey) and seasonally detrended (blue line) surface ocean seawater carbon dioxide levels are shown. Earlier seawater data from the GEOSECS and TTO expeditions in the North Atlantic Ocean are also shown in this and following panels. b. time-series of surface ocean seawater pH at the BATS site off Bermuda. Observed (grey) and seasonally detrended (green line) seawater pH are shown. c. time-series of surface ocean aragonite saturation state (W) for calcium carbonate at the BATS site off Bermuda. Observed (purple) and seasonally detrended (purple line) seawater aragonite saturation state (Ω) are shown. Statistical and seasonal detrending methods follow Bates (2007), Bates and Peters (2007), and Bindoff et al., (2007).**

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Appendix I

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Appendix II

Glossary of important terms

Aerosol – solid or liquid particles dispersed and suspended in air.

Atlantic Meridional Overturning Circulation – the part of the large-scale ocean circulation in the North Atlantic that is driven by global density gradients created by surface heat and freshwater fluxes.

Anthropogenic – meaning derived from human activities, as opposed to those occurring in biophysical environments without human influence.

Biogeochemistry – is the scientific discipline that involves the study of the chemical, physical, geological, and biological processes and reactions that govern the composition of the natural environment.

Biological carbon pump – term describing the export of biologically derived particulate carbon from the euphotic zone where it is produced to the mesopelagic where it is remineralized.

CDOM – is the optically measurable component of the dissolved organic matter in water. It is also known as *chromophoric* dissolved organic matter, *yellow substance*, and *gelbstoff*.

DOC – dissolved organic carbon, major pool of exchangeable carbon in the ocean.

Eddy – a drift or tendency that is counter to or separate from a main current.

El Niño-La Niña (ENSO) – The irregular cyclic swing of warm and cold phases in the eastern tropical Pacific.

Euphotic zone – the shallow waters of the surface ocean where there is sufficient light for primary production, quantitatively defined as the 1% light depth.

Food web – term describing the complex interactions between multiple trophic levels of producers and consumers in the marine environment.

Gyre – any large system of rotating ocean currents, particularly those involved with large wind movements.

Macronutrient – chemicals that an organism needs in greatest supply to live and grow, most commonly used in reference to carbon, nitrogen and phosphorus.

Mesopelagic – a term to describe the zone or organisms inhabiting the intermediate depths of the ocean between approximately 100 and 1000 meters and below the euphotic zone.

Microbial food web – a specific type of foodweb that includes bacteria and their role in producing and consuming dissolved organic matter.

North Atlantic Oscillation – dominant long-term mode of meteorological variability in the North Atlantic.

Ocean acidification – term describing the process by which carbon dioxide accumulates in the surface ocean thus lowering the ocean's pH.

Oligotrophic – characterized by very low, nanomolar level, inorganic nutrient concentrations.

Organic – relating to, or denoting chemical compounds containing carbon (other than simple binary compounds such as CO_2 and some carbon containing salts) and chiefly or ultimately of biological origin.

PCR – abbreviation for 'polymerase chain reaction', a technique for rapidly producing many copies of a fragment of DNA for diagnostic or research purposes.

Phytoplankton – oceanic single cell plants responsible for primary production

Primary Production – fixation of carbon by marine plants, the primary mechanism by which carbon (and energy) enters marine food webs.

Sargasso Sea – a region in the middle of the North Atlantic Ocean surrounded by ocean currents. It is bounded on the west by the Gulf Stream; on the north, by the North Atlantic Current; on the east, by the Canary Current; and on the south, by the North Atlantic Equatorial Current.

Subtropical mode water (STMW) – also known as '18 degree water', it is a water mass that sits below the seasonal thermocline in the western North Atlantic subtropical gyre.

Trace elements – nutrients, commonly metals, that are required by phytoplankton usually for enzymes that are required in ultra low levels (10^{-3} nanomolar).

Troposphere – the lowest region of the atmosphere, extending from the earth's surface to a height of about 6–10 km.

Zooplankton – 'animal plankton' that are the primary grazers of phytoplankton in the open ocean.

Appendix III

Compilation, by year through June 2011, of peer-reviewed publications arising from work at or near the Bermuda Atlantic Time-series Study (BATS) site

2011

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2010

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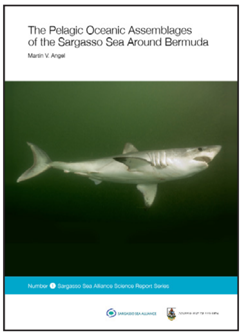

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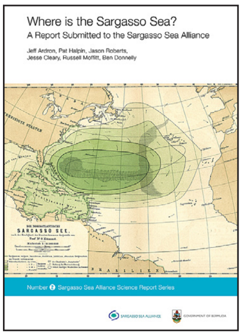

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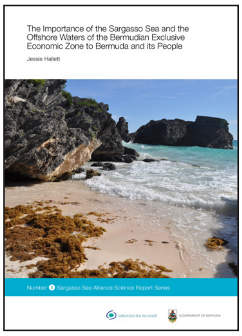

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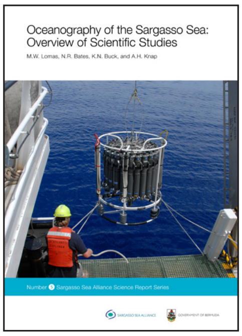

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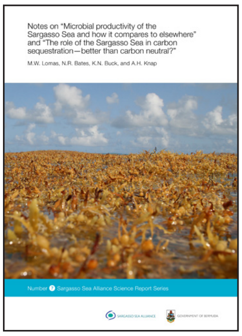

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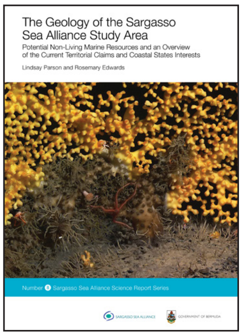

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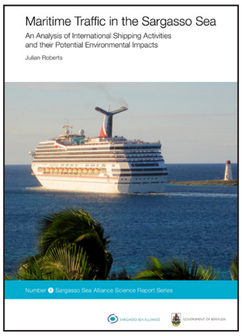

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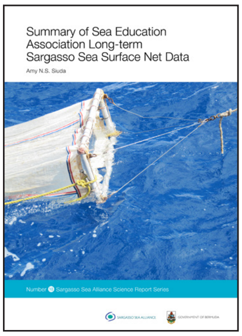

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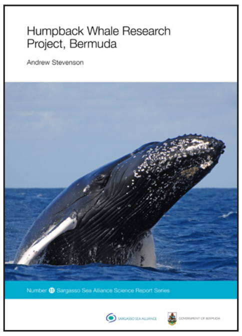

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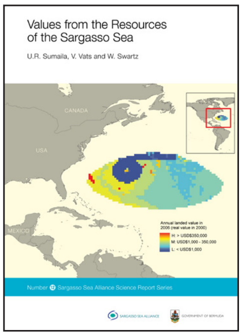

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SARGASSO SEA ALLIANCE

Since the initial meetings the partnership around the Sargasso Sea Alliance has expanded. Led by the Government of Bermuda, the Alliance now includes the following organisations.

PARTNER	TYPE OF ORGANISATION
Department of Environmental Protection	Government of Bermuda
Department of Conservation Services	Government of Bermuda
Mission Blue / Sylvia Earle Alliance	Non-Governmental Organisation
International Union for the Conservation of Nature (IUCN) and its World Commission on Protected Areas	Multi-lateral Conservation Organisation
Marine Conservation Institute	Non-Governmental Organisation
Woods Hole Oceanographic Institution	Academic
Bermuda Institute for Ocean Sciences	Academic
Bermuda Underwater Exploration Institute	Non-Governmental Organisation
World Wildlife Fund International	Non-Governmental Organisation
Atlantic Conservation Partnership	Non-Governmental Organisation