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EARTH SYSTEM MONITOR

A guide to NOAA's data and information services

INSIDE

Inter-annual variability of phytoplankton chlorophyll

Monitoring slope waters linked to the Gulf Stream

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Situated between the continental shelf of the eastern U.S.and the Gulf Stream flowing eastward from Cape Hatteras, the Slope Sea is a transition region between the coast, where the nutrient budget is affected by human activities, and the open ocean, where the nutrient budget presumably has minimal anthropogenic influence. The dynamic physical environment of this region has important implications for biological processes (Rossby, 1936; Redfield, 1936; Yentsch, 1974; Csanady, 1990). With the launch of the

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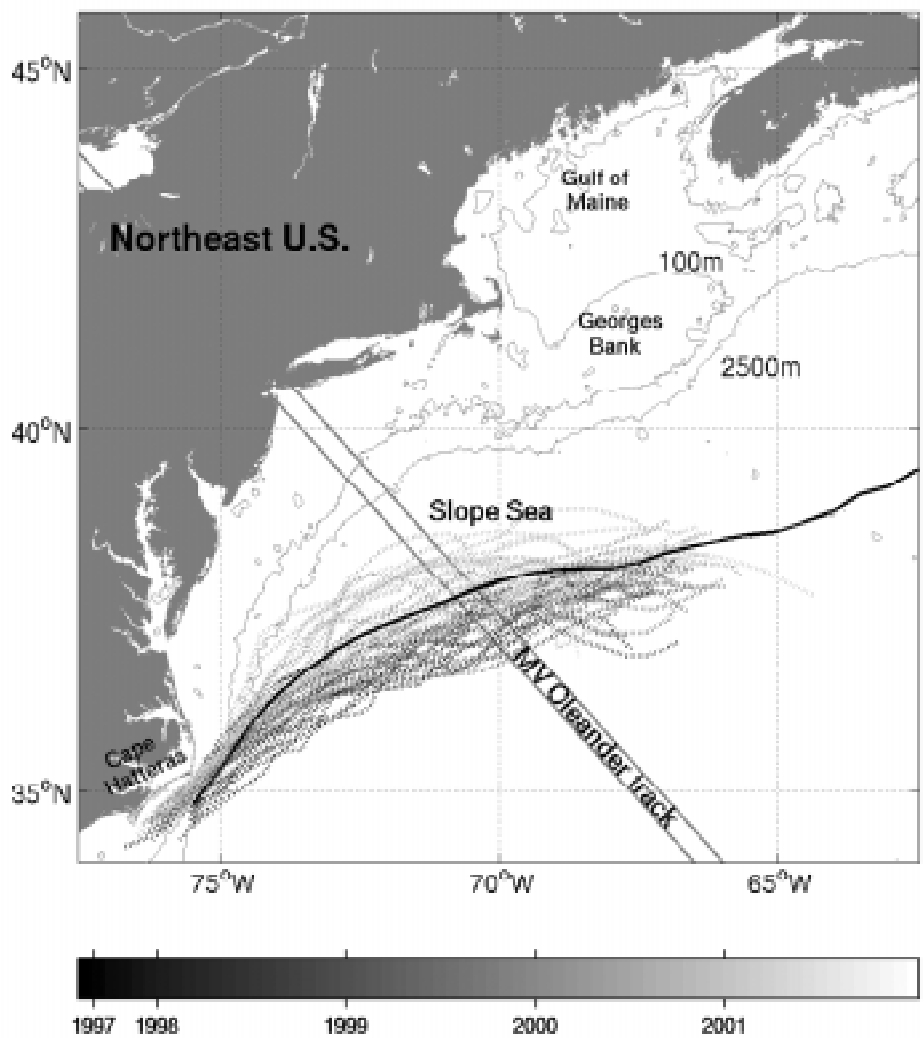

▲ **Figure 1.** Study area off the northeast U.S. coast along the *MV Oleander* track within the Slope Sea: defined here as between the 2500 m isobath (fixed) and the monthly average Gulf Stream north wall position (dynamic). Gray contours delineate 100 m and 2500 m bathymetry. The thick black line delineates the 20-year average north wall position of the Gulf Stream from AVHRR SST. Dotted lines indicate the monthly position of the Gulf Stream north wall from monthly composites of AVHRR SST from September 1997 (black) through August 2001 (light gray).

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satellite-born Sea-viewing Wide Field-of-view Sensor (SeaWiFS) in, 1997, it became possible to monitor the ocean's primary productivity on a large scale, using phytoplankton chlorophyll as a proxy. During the first four years of the SeaWiFS mission, the spring blooms in the Slope Sea increased in magnitude. At the same time, the mean path of the Gulf Stream shifted northward, as evidenced in satellite sea-surface temperature imagery and *in situ* temperature, salinity, and current vector information collected by the container merchant vessel *CMV Oleander* on its weekly trip between New Jersey and Bermuda (Figure 1). A collective increase in phytoplankton chlorophyll, temperature, and salinity over the four years (Figure 2) is contrary to the commonly observed inverse relationship between temperature and chlorophyll in surface waters of this region.

A more detailed discussion of this study may be found in our article to the *Deep Sea Research II* special SeaWiFS issue (Schollaert et al., 2002), in which we examine the impact of the Gulf Stream's low frequency path variation upon biological productivity in the Slope Sea and evaluate the evidence for a sub-surface Gulf Stream nutrient supply. Here we summarize those results more generally.

Data and methods

High resolution (1 km/pixel) daily SeaWiFS chlorophyll concentrations (O'Reilly et al., 1998; O'Reilly et al., 2000) were averaged into monthly composites and then binned every 20 km along the *Oleander* track between New Jersey and Bermuda.Likewise, *Oleander in situ* measurements of upper ocean temperature, surface salinity, and horizontal velocity (Rossby and Benway, 2000) were averaged over each month and binned. We determined the monthly location of the southern limit of the Slope Sea by determining the northern edge of the Gulf Stream, using declouded sea-surface temperature (SST) scenes derived from the satellite-born Advanced Very High Resolution Radiometer (AVHRR) (Cayula and Cornillon, 1992), mapped to the same projection as the chlorophyll. An animation of monthly chlorophyll composites for the four years may be seen at *http://www.po.gso.uri.edu/color/nec.html*. During the *Oleander* transits, Continuous Plankton Recorder (CPR) surveys were also conducted. At a standard depth of 10 m, the CPR captures zooplankton and large phytoplankton taxa on s silk gauze mesh for subsequent identification and enumeration at the National Marine Fisheries Service Narragansett Laboratory. Unfortunately, the CPR data had not yet been processed beyond 1999 when we performed this study.

Results and discussion

Inter-annual variations in the SeaWiFS chlorophyll show that cold, fresh Slope waters with a more southerly Gulf Stream position were associated with relatively low spring bloom chlorophyll concentrations during 1998 and, to a lesser extent, 1999. Years with warm, saline Slope waters and a northerly Gulf Stream position, 2000 and 2001, were associated with higher chlorophyll concentrations. During the four year period of interest, the Gulf Stream exhibited considerable northward migration, evidenced in the monthly north wall positions (Figure 1). There was a general increasing chlorophyll concentration trend during the time series, with the largest bloom in spring 2000 (Figure 3). Salinities and temperatures began to increase during 1999 (Figure 4), indicative of a decreased supply of Labrador water and a Gulf Stream migration northward on the order of 100 km along the *Oleander* track at its peak in 2000 (Rossby and Benway, 2000). Two anomalous events in the chlorophyll and hydrographic records coincided with the two extremes in the Gulf Stream's position: in 1998, the earliest and smallest spring bloom following a cold, fresh surface layer; in 2000, the largest and longest spring bloom followed a very deep warm, saline intrusion.

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News briefs

GOES-12 activities

Geostationary Operational Environmental Satellite (GOES)-12 replaced GOES-8 as the operational GOES-East spacecraft on April 1, 2003 at 1815 UTC. GOES-12 data continues to flow and is being captured within Satellite Services Division (SSD) for use in GOES-12 product testing and validation. Numerous GOES-12 products are being routinely created and have been made available to users including National Center for Environmental Prediction's Environmental Modeling Center (EMC) for upcoming implementation into EMC's numerical models. Additional testing took place to test satellite imagery distribution to the Advanced Weather Information Processing System (AWIPS) on March 12 and 13 with full success.

NOAA education conferences

NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) cosponsored the Satellites and Education Conference March 27-29, 2003, at California State University in Los Angeles, California. This conference is internationally recognized as the premier conference for educators who are interested in learning processes and the technology skills to help students understand Space and Earth Science. It promotes the use of satellites and related technologies as a vehicle for helping students to understand the complex interrelationships among science, technology, individuals, societies, and the environment, while developing and applying query and technology skills to study authentic questions and problems.

NCDC and auto racing

NOAA's National Climatic Data Center was queried by a consultant working with a weather insurance and derivatives firm contracted to the auto racing industry. If a race is interrupted, delaed, or cut short as a result of rain, it affects TV and sponsors, as well as the track and track owners. Surface hourly observations, including hourly precipitation data, will be used to determine the likelihood of a certain amount of precipitation on a given date at a site close to a specific race track. With this information, a derivative could be structured and priced to protect those who stand to lose if Mother Nature does not cooperate.

Satellite images of Iraqi oilwell fires

On Thursday, March 20, 2003, after the initiation of military action by U.S. forces in Iraq and Kuwait, the Operational Significant Event Imagery (OSEI) program in the Satellite Services Division began processing imagery of Iraq and surrounding areas from all available Advanced Very High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS), and METEOSAT data. The image taken by AVHRR on board NOAA-16 at 10:05 UTC, March 20,2003, was a false color composite of channels 1 (visible) expressed as red, 2 (near infrared) as green, and 4 (thermal infrared) as blue. The dark east - west trending plumes in southeastern Iraq are believed to be smoke from oil wells reported to have been set on fire. The location corresponds to the Ar Rumaylah oil field identified in maps of the area.

C-GTOS meeting in Italy

The Coastal Working Group of the Global Terrestrial Observing System (C-GTOS) met at Ispra, Italy from March 2-6 in its second scoping meeting to define a coastal observing strategy. David Clark and John Kineman attended the meeting, representing NOAA and leading various subgroups. John Kineman led the Habitat working group, which outlined an observing strategy based on complex, integrative, and functional units of the coastal zone.

A preliminary list of early data products to be recommended by C-GTOS was developed as an outcome of the meeting. These plans will be developed further between meetings and finalized in an implementatin plan after the third C-GTOS meeting scheduled for October. A significant accomplishment at the meeting was adoption of a mapping approach for living components, that is congruent with the National Geophysical Data Center's efforts to develop capabilities in this area. The proposed application has been incorporated into an ESDIM proposal to develop the needed modeling capabilities.

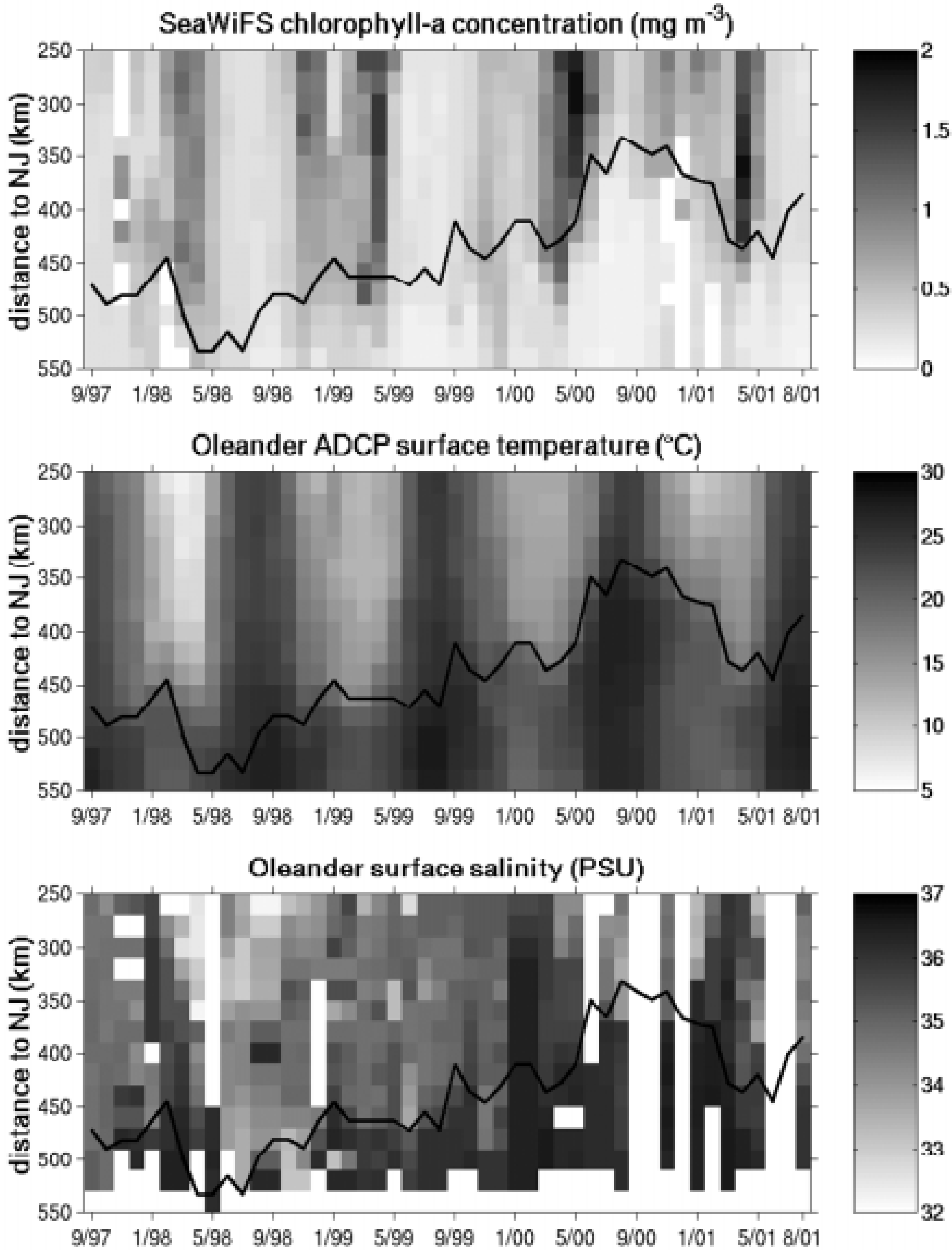
State of Vermont receives personal locator beacon alerts

On February 26-27, the Search and Rescue Satellite Aided Tracking (SARSAT) Program met with officials from the Vermont State Police and the U.S. Air Force Rescue Coordination Center (AFRCC) to initiate the steps that will allow the State of Vermont to be the first state in the contiguous U.S. to respond directly to distress alerts emitting from Personal Locator Beacons (PLBs) beginning July 1, 2003. Previously, PLBs had not been authorized for use in an experimental program since 1994. The recent authorization by the Federal Communications Commission (FCC) to allow PLBs for nationwide use beginning July 1, 2003 holds significant life-saving advantages for those who venture into the remote corners of our country.

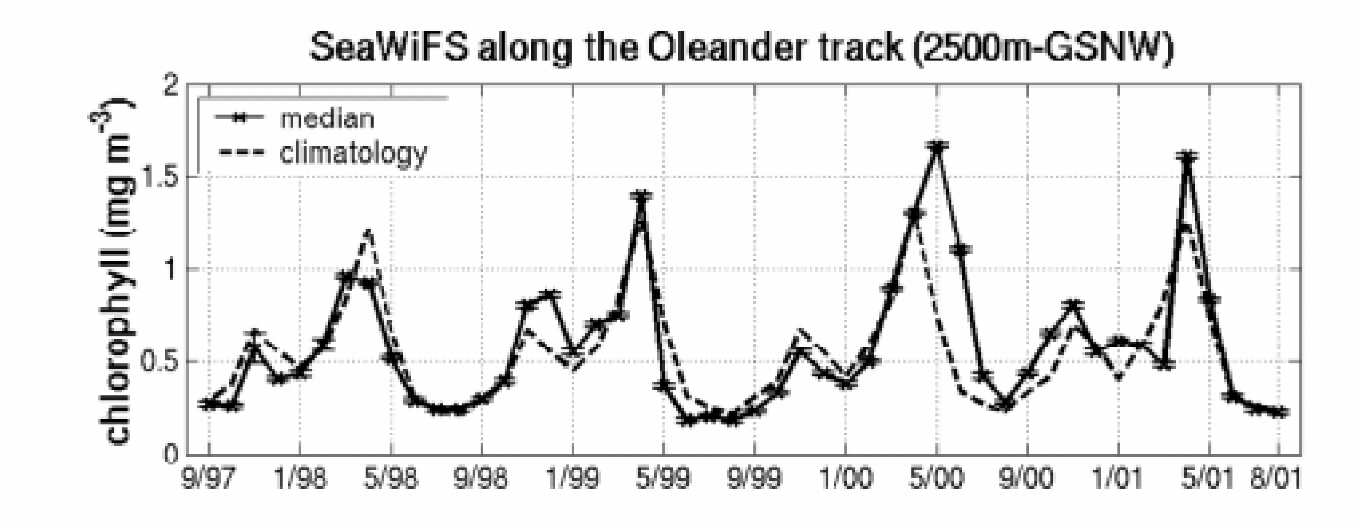
The National Oceanic and Atmospheric Administration (NOAA)- SARSAT Program was instrumental in working with the FCC on the authorization. Once available this summer, the AFRCC at Langley AFB, Virginia will be responding to all PLB distress alerts in the contiguous U.S. except for those in Vermont. Instead, the Vermont State Police will be using a unique PLB alerting system which will allow the State Police to respond to and dispatch search and rescue teams to the PLB alert. Eventually, all 50 states will respond to their own PLB alerts as the alerting systems are installed nationwide. NOAA-SARSAT's U.S. Mission Control Center in Suitland, MD detects, locates, and transmits all emergency beacon distress alerts to RCC's around the country.

NCDC completes evaluation

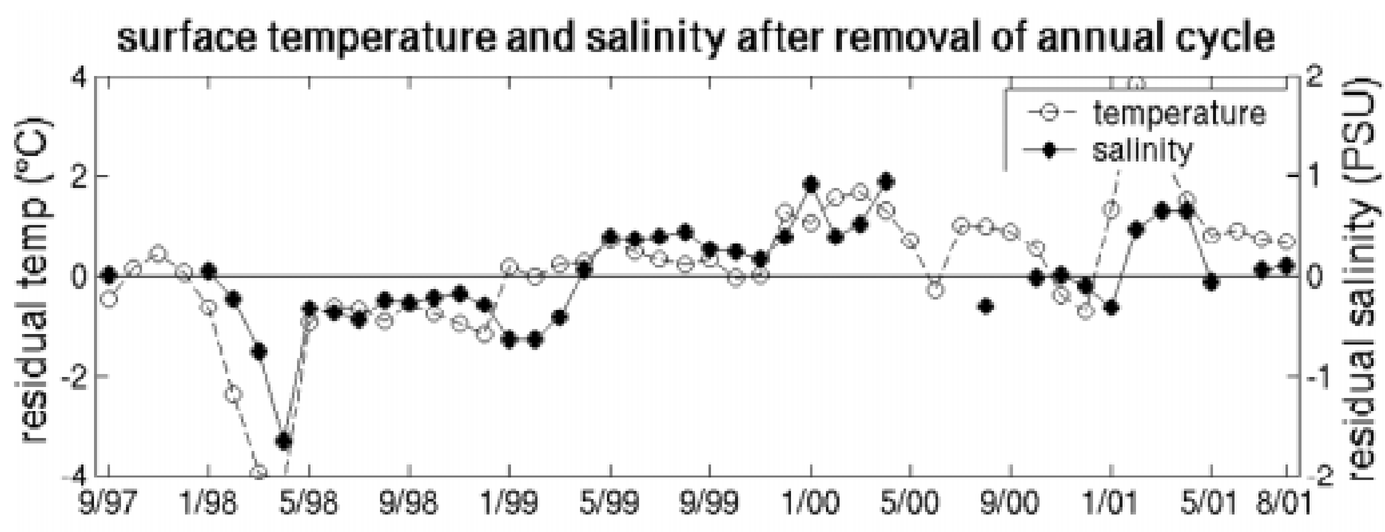
The National Climatic Data Center completed an evaluation of a $3.4 million proposal initiated by the Space Science and Engineering Center (SSEC) of the University of Wisconsin to the NASA Office of Earth Science. The 54-page proposal is entitled, "Daily Internet Delivery of Kilometer-Scale Remote-Sensing Data Products for U.S. Agriculture, Weather Forecasting, and Water Management." SSEC is requesting NASA funding over a five-year period for the project. These products would then be used by customers, such as the U.S. Department of Agriculture in crop assessments and the National Weather Service in forecast models for better soil moisture initialization.



▲ **Figure 2.** Hovmoller plot along the *Oleander* track within the Slope Sea and northern edge of the Gulf Stream for monthly, 20 km binned chlorophyll (top), ADCP surface temperature (middle), and surface salinity (bottom). The 2500 m isobath is approximately 250 km from New Jersey. Gulf Stream north wall position from AVHRR monthly SST composites is superimposed (black line). Note the greatest southward extent of Gulf Stream in spring 1998; the greatest northward, in late summer/fall 2000. White bins indicate missing data.



▲ **Figure 3.** Monthly chlorophyll concentrations within the *Oleander* Slope Sea area: median values (solid line) and 4 year climatology (dashed line).



▲ **Figure 4.** Average surface temperature and salinity for the Slope Sea area after the removal of the annual cycle. Note the cold, fresh intrusion between January-April, 1998 and the saline, slightly warm anomaly between January-April, 2000. Also note there was another warm, saline anomaly between February-April, 2001 which appeared to be restricted to the surface (in contrast to the warm, saline anomaly in 2000 which extended quite deep).

Phytoplankton chlorophyll, *from page 2*

Phytoplankton blooms can be caused by several factors, one of the most important of which is the availability of nutrients (Sverdrup, 1953). Nutrients are most abundant in locations which are usually light-limited and, consequently, tend to be cooler: toward the poles in winter as well as at depths below the main thermocline. An inverse relationship between chlorophyll concentrations and surface temperature had been observed in shelf to upper slope waters off the coast of the northeast U.S. (Yoder et al., 2002). While maximum chlorophyll concentrations along the *Oleander* track (Figure 2) occur each year during the spring bloom (March-May), following the coldest sea surface temperatures at the end of winter (February/March), the inter-annual differences between the spring blooms in the Slope Sea do not follow an inverse relationship with temperature. Instead we find a greater abundance of wintertime Labrador Sea water is associated with low spring bloom chlorophyll concentrations, and years with less Labrador Sea water are associated with higher chlorophyll concentrations. While the Gulf Stream surface waters are depleted of nutrients and low in biomass content, waters at depth are rich in nutrients. Although the Gulf Stream usually serves as a barrier between Sargasso waters to the south and Slope waters to the north (Bower et al., 1985), cross-stream exchange occurs when there is upward flow along density surfaces toward the surface waters of the Slope Sea. We estimate that the Slope Sea receives a more or less constant supply of nutrients of sub-surface Gulf Stream origin and that the position of the Gulf Stream determines the area over which these nutrients are mixed, so that generally a larger Slope Sea associated with a southerly Gulf Stream position has a lower concentration of chlorophyll while a smaller Slope Sea has a higher chlorophyll concentration (Figure 5). Under certain conditions, warm core rings shed by the Gulf Stream may also bring nutrient-rich water up into the euphotic zone (Tranter, 1980). Yentsch and Phinney (1985) specified two mechanisms by which productivity is enhanced by warm core rings: through upwelling of nutrient-rich waters toward the surface in the periphery of the ring and through convectional mixing followed by stratification in the ring center.

The early spring bloom of 1998 in the Slope Sea was probably caused by a strongly stratified Labrador surface layer which enabled the bloom to occur as soon as enough light was available. Because the Labrador water had been at the surface for a few months by the time it reached the Slope Sea, its nutrient content was probably relatively low. Although the spring bloom of 1998 was the smallest of the four year study, the CPR recorded an abundance of cold water species between April-July, 1998 (e.g. *Ceratium Arcticum, Thalassiotrix Longissima*, and *Candacia Armata*) [Jack Jossi, personal communication], corroborating a Labrador water intrusion.

The spring bloom of 2000 had the longest duration of the time series, actually peaking in May with the highest chlorophyll concentrations of the entire time series. The hydrographic record indicates early 2000 was warm and salty in the Slope Sea, suggesting an increased supply of sub-surface Gulf Stream waters, perhaps enhanced by warm core rings shed from the meandering Gulf Stream. Inspection of satellite SST and chlorophyll images composited at weekly time scales over the four years reveals that winter and spring 1998 had negligible warm core ring activity in the Slope Sea. By contrast, winter and spring of 2000 exerienced a total of four warm core rings formed between January and March, three of which persisted into April and May. While the shelf/slope experienced spring bloom 2000 during April, the warm core rings experienced spring blooms during May. One particular warm core ring sustained a bloom through early June, with chlorophyll values around 4 mg m^-3 compared to background Slope Sea values around 1-2 mg m^-3. In addition to experiencing a greater number of warm core rings which likely underwent convective mixing, spring 2000 was also approaching the time of the greatest northward extent of the Gulf Stream. The reduced Slope Sea area during spring 2000 means that a greater proportion of the Slope Sea experienced warm core ring activity than in any other year of the study. It seems plausible that warm core rings contributed not only to the enhanced spring bloom of 2000 but more significantly to its long duration.

Conclusions

Biological productivity in the Slope Sea exhibits inter-annual variability which is related to the low frequency migration of the Gulf Stream. Years when the Gulf Stream is farther south, Slope Sea chlorophyll concentrations are lower than average while years with a northerly Gulf Stream have higher than average Slope Sea chlorophyll concentrations. It seems the supply of high nutrient sub-surface Gulf Stream waters to the Slope Sea is fairly constant over this four year time series. Thus, the supply of Labrador water to the Slope Sea seems to affect both the position of the Gulf Stream and the extent to which nutrients are diluted: years when the Gulf Stream is farther south the average chlorophyll concentrations are smaller, and vice versa when the Gulf Stream is offset to the north. While spring 2000 is consistent with this generalization, its greater bloom and longer duration imply other mechanisms, such as warm core rings, further enhanced the nutrient supply then. A greater number of warm core rings which experienced deep convection during winter and persisted into the spring may have played a role in supplying additional nutrients to the surface waters within the rings through convective overturning. While the north-south migration by the Gulf Stream seems primarily related to Slope Sea chlorophyll concentrations by the amount of nutrient dilution within the gyre, there are secondary effects which we continue to investigate, such as the possibility of increased upwelling resulting from increased Gulf Stream meandering. Ultimately, understanding how the Gulf Stream's migration affects

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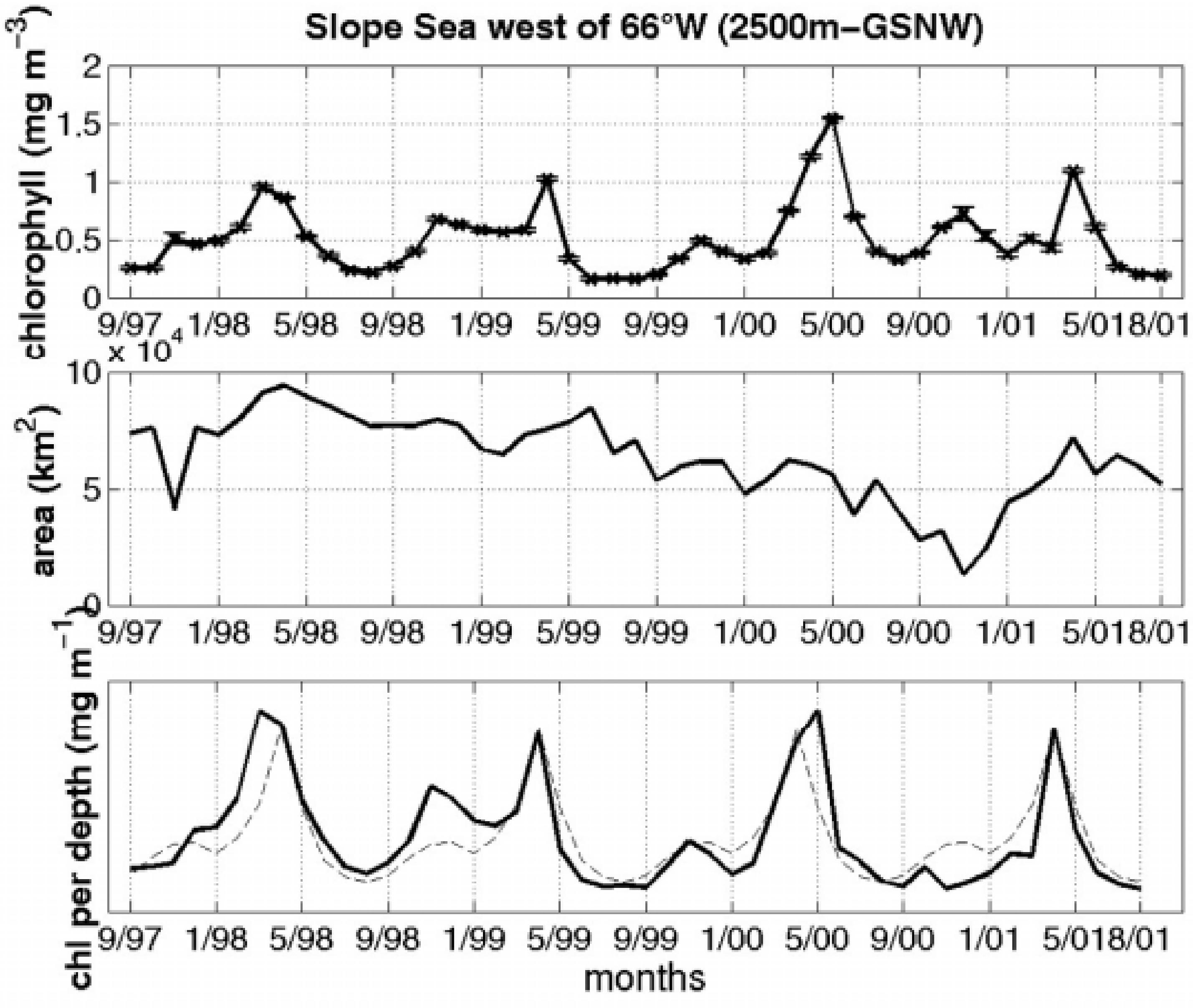

▲ **Figure 5.** Entire Slope Sea (west of 66°W) average chlorophyll (top), area (middle), and average chlorophyll integrated over the area (bottom: solid line) with 4 year monthly climatology (bottom: dashed line). Note the spring blooms of 1998 and 2000 were higher earlier and later than the other years, respectively.

Phytoplankton chlorophyll, *from page 6*

biological productivity in the Slope Sea will help us to make inferences about large-scale, low frequency climatic effects upon the carbon cycle of ocean margin waters.

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