Final Report

NASA NAGW-3145 /4637

Satellite Analysis of Ocean Biogeochemistry and Mesoscale Variability in the Sargasso Sea

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Duration: 1 Jan 1994 – 31 Dec. 1996

Project Summary:

The objective of this study was to analyze the impact of spatial variability on the time-series of biogeochemical measurements made at the U.S. JGOFS Bermuda Atlantic Time-series Study (BATS) site. Originally the study was planned to use SeaWiFS as well as AVHRR high-resolution data. Despite the SeaWiFS delays we were able to make progress on the following fronts:

- Operational acquisition, processing, and archive of HRPT data from a ground station located in Bermuda.

The BBSR HRPT facility (SeaSpace TeraScan, obtained via cost-sharing agreement with BBSR) was installed in June 1994. We developed automatic routines for acquiring and processing AVHRR mcsst data, and developed an archive strategy (description in the Proposed Research section). We now have archived 2 ½ years of Level 3 gridded AVHRR mcsst data on two scales (see Objective 1, Proposed Research). These data are accessible by request, and we have filled data requests for interested researchers, in particular the AEROCE atmospheric chemistry program, which conducted an intensive study in Bermuda in 1996.

In addition to data files, we have prepared browse images of mcsst and AVHRR channel 2 and 4 data in GIF format which are accessible via the World-Wide-Web immediately after capture. There has been considerable interest in these images in the U.S., Bermuda and elsewhere (8000 downloads in March 1997).

We also successfully participated in the **SeaWiFS End-To-End System Test** (1996), in which we processed simulated SeaWiFS Level 0 datasets to Level 1 (3x daily), and delivered the processed data to GSFC. Software and data transmission proceeded without difficulty.

- Validation of AVHRR SST data using BATS time-series and "spatial validation cruise" CTD data.

Coefficients used in the mcsst algorithm are specific to each AVHRR instrument flown, and are derived from NOAA buoy SST measurements made along the U.S. east coast. Atmospheric conditions may differ in the western Sargasso Sea, therefore ongoing validation of SST retrieved from satellite at our site is important. We compared satellite SST data from NOAA-9, 11, 12, and 14 AVHRR instruments with 1 m depth quality-controlled temperature measurements made using the BATS program CTD. While considerable pass-to-pass variability was evident (ca. 1.5° C), filtered SST data (3-day averages, 6-12 measurements) were in reasonable agreement with the BATS measurements (root-mean-square difference < 0.55° C, linear correlation coefficient > 0.98, J. Bauza and N. Nelson unpubl. data). This is slightly better than reported rms differences between AVHRR mcsst and buoy data (ca. 0.7° C, McClain et al. 1985).

We also compared spatial patterns of SST on a June 1996 BATS 'Validation' cruise in the area 30.5-33N, 63.5-65W. Approximately 24 CTD surface temperature measurements were made over a four day period in a grid pattern. CTD-measured SST varied approximately 2° C over this area, and satellite composite SST patterns were in close agreement (R. Johnson and N. Nelson, unpubl. data). D. Siegel and D. McGillicuddy also used TOPEX data concurrent to this cruise to analyze the mesoscale eddy field (see below).

- Use of AVHRR sea surface temperature imagery and ancillary data to assess the impact of mesoscale spatial variability on pCO_2 and carbon flux in the Sargasso Sea.

We used an empirical formula relating SST and pCO_2 (Bates et al. 1996) to compute the spatial variability in surface pCO_2 from satellite SST measurements, using 3-day composite AVHRR SST images of the Sargasso Sea (Nelson et al. in prep). These pCO_2 estimates were then combined with atmospheric pCO_2 estimates and NMC gridded analysis wind fields to produce estimates of air-sea CO_2 flux, using standard relationships between wind speed and piston velocity. Flux estimates were found to be highly sensitive to the statistical distribution of wind speed and duration because of the non-linear relationship between wind speed and flux, in agreement with Boutin and Etcheto (1991). Air-sea CO_2 exchange estimates were computed for the BATS time-series site, using in situ pCO_2 measurements (Bates et al. 1996) and satellite-retrieved pCO_2, were found to be in close agreement. The impact of spatial variability on air-sea CO_2 exchange was assessed in the Sargasso Sea west of 50W by comparing spatial satellite-derived flux estimates (spatially variable pCO_2) to fluxes assuming spatially invariant pCO_2 equal to that of the BATS site. Over this large area, summertime air-sea exchange estimates from satellite data were on the order of 10% larger than those derived from non-spatially variable pCO_2 estimates. Since this magnitude of difference is similar to the annual carbon sink at the BATS site (Bates et al. 1996), spatial variability of pCO_2 will be essential in determining the annual carbon budget of the Sargasso Sea.

These investigations have resulted in two presentations and one manuscript in progress (see below).

- Spatial and temporal extent of tropical cyclone induced surface modifications.

During 1995 and 1996 we repeatedly observed sea surface cooling due to hurricanes in the Sargasso Sea (Nelson 1996; Dickey et al. 1997; Nelson 1997). Our position in the Sargasso Sea allows us to collect high-resolution HRPT data out to 50W, giving us considerable areal coverage with regards to these phenomena. In 1995 on the order of 10% of the Sargasso Sea west of 50 W was impacted by tropical cyclones (SST anomaly greater than -1C, Nelson 1997). One exciting and unexpected result in 1995 was the close passage of Hurricane Felix near Bermuda, the BATS time-series station, and the Bermuda Testbed Mooring (Nelson 1996; Dickey et al. 1997). HRPT data acquisition during the hurricane was not possible (lab roof came loose) but resumed after Felix' passage. AVHRR images revealed SST anomalies near Bermuda approaching -4 C over an area 4 degrees longitude in width. In addition to the dramatic surface cooling and thermocline erosion, strong inertial currents were observed for days following the event (Dickey et al. 1997). Collaborative efforts on analysis of the extensive Hurricane Felix data set are continuing.

Our SST measurements have been combined with observations from the BATS program and from the Bermuda Testbed Mooring to produce integrated analyses of the effects of hurricanes on biogeochemical processes (e.g., Malone et al. 1993). Our ongoing satellite time series is uniquely positioned to continue studying the effect of these phenomena on the Sargasso Sea. These investigations have resulted (so far) in three manuscripts and one presentation.

- Assessment of eddy variability using TOPEX/Poseidon data.

Dr. Siegel and colleagues have developed objective analysis schemes for interpolating between TOPEX/Poseidon lines. These routines have been used to examine mesoscale variability in the Sargasso Sea near Bermuda over a 3 year period of TOPEX/Poseidon observations. Sea-level anomaly (SLA) estimates from TOPEX/Poseidon were in agreement with BATS ctd observations. The mesoscale eddy field around BATS is dominated by westward-propagating eddies with SLA signatures as large as 25 cm, propagation rates > 5 cm/s, temporal scales of roughly a month and spatial scales of 100-200 km. More eddy activity appears to occur north of Bermuda than in the BATS region. These signatures can be used in conjunction with BATS time-series measurements to produce estimates of nutrient supply due to eddy pumping. This research has been the subject of one presentation and Dr. Siegel has a manuscript in process.

Human Resources Development:

Student participation in the satellite program included student internship projects and a summer course taught by program scientists. In the summer of 1995 we organized a three-week intensive course in Remote Sensing Oceanography at the Bermuda Biological Station for Research. The instructors were Norman Nelson, Postdoc on the project, Frank Muller-Karger of USF, and Dave Siegel. The course was a hands-on intensive introduction to theory and practice of remote sensing of the oceans. Twelve students

(mostly M.S. level graduate students) attended, from the mainland U.S. and Puerto Rico, and countries overseas including Hong Kong, Ecuador and Pakistan. The funding for the summer course came from a NASA education grant to A.F. Michaels and D. Hansell (NAGW-3777), but satellite project resources (including computer time and data) were made available to the students. IDL software was loaned to the course by Research Systems, Inc. Each student was able to spend considerable time using UNIX graphical workstations and conduct an independent research project using satellite data and state-of-the-art techniques. Two American minority students and one disabled (deaf) student attended the course. Students in the course have gone on to work in remote sensing and remote-sensing related projects.

Two undergraduate students in the BBSR REU (NSF Research Experience for Undergraduates) program and one BBSR Bermuda Program intern worked on projects related to the satellite program. Heather Kelley of UC Santa Barbara, REU intern, used high-resolution AVHRR data from the BBSR HRPT site to map 'hot spots' on the Bermuda Platform that could be related to coral bleaching events in 1994. Douglas DeCouto, MIT, Bermuda Program intern 1995, developed a compositing program for MCSST images that uses statistical techniques to identify cold spots as possible cloud errors. Olga Polyakov, REU intern 1995, used HRPT AVHRR data to investigate possible coastal upwelling off the south shore of Bermuda. Kelley is now working for a scientific visualization software firm, DeCouto has been accepted into the MIT computer science Ph.D. program, and Polyakov has also had internships at Horn Point Environmental Laboratory, and the Goddard Space Flight Center. She was a summer intern at the Monterey Bay Aquarium Research Institute this year.

Publications citing NAGW-3145:

Nelson, N.B., 1996, The wake of Hurricane Felix. *International Journal of Remote Sensing*, **17**, 2983-2895.

Dickey, T.D., D. Frye, J. McNeil, D. Manov, N. Nelson, D. Sigurdson, H. Jannasch, D. Siegel, A. Michaels, and R. Johnson, 1997, Upper ocean response to Hurricane Felix as measured by the Bermuda Testbed Mooring, Accepted for publication, *Monthly Weather Review.*

Nelson, N.B., 1997, Spatial and temporal extent of surface ocean modifications by hurricanes, 1995 season. Accepted for publication pending revision, *Monthly Weather Review.*

Michaels, A.F., and A.H. Knap, 1996, Overview of the U.S. JGOFS Bermuda Atlantic Time-series Study and the Hydrostation S. Program. *Deep-Sea Research II*, **43**, 157-198.

Dickey, T.D., and others, Preliminary results of the Bermuda Testbed Mooring, submitted to *Deep-Sea Research.*

Presentations and Abstracts:

Siegel, D.A., E. Fields, D.J. McGillicuddy, and A.F. Michaels, 1997, Mesoscale motions, satellite altimetry, and biogeochemical processes in the Sargasso Sea. Presented at the Aquatic Sciences Meeting, ASLO, Santa Fe.

Dickey, T.D. and others, 1996, Preliminary results of the Bermuda Testbed Mooring Program, presented at the Ocean Sciences Meeting, AGU, San Diego.

Nelson, N.B., N.R. Bates, A.F. Michaels, D.A. Siegel, and A.H. Knap, 1995, Impact of surface pCO_2 variability on air-sea CO_2 exchange in the Sargasso Sea, Summer 1994. Presented at the XXI General Assembly of IAPSO, Honolulu, 5-12 August.

Nelson, N.B., N.R. Bates, A.F. Michaels, D.A. Siegel, and A.H. Knap, 1994, Satellite assessment of sea surface temperature and pCO_2 variability at the U.S. JGOFS Bermuda Atlantic Time-Series site. EOS 75: 272. Presented at the Fall Meeting, AGU, San Francisco, California

In Preparation (nearing completion):

Nelson, N.B., N.R. Bates, D.A. Siegel, and A.F. Michaels, Influence of spatial variability on the partial pressure of CO_2 and air-sea CO_2 exchange in the Sargasso Sea, to be submitted to *Journal of Geophysical Research*