Biological-Physical Coupling in the Gulf of Maine: Satellite and Model Studies of Phytoplankton Variability

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Final Report: Year 3 + 1 year no cost extension

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1. Overall Goals

The goals of this project were to acquire, process, QC, archive and analyze SeaWiFS chlorophyll fields over the Gulf of Maine and Scotia Shelf region. The focus of the analysis effort was to calculate and quantify seasonality and interannual variability of SeaWiFS-measured phytoplankton biomass in the study area and compare these to physical forcing and hydrography. An additional focus within this effort was on regional differences within the heterogeneous bio-physical regions of the Gulf of Maine / Scotia Shelf. Overall goals were approached through the combined use of SeaWiFS and AVHRR data and the development of a coupled biology-physical numerical model.

The research initiated under this grant continues under NASA NAG5 – 10620 (A. Thomas, PI)

2. Results

Development of Satellite Data Analysis Infrastructure

During the first year of the project, U.Maine installed and configured a SeaWiFS reception capability into our existing SeaSpace HRPT reception facility which allowed the direct download of the Level 0 data stream in encrypted mode. After approximately 6 months of successful operation, however, the GSFC HRPT reception and SeaWiFS DAAC distribution proved so reliable and efficient for local area coverage that our own reception was discontinued. FTP transfer of Level 1a data via subscription service from the DAAC was initiated and remains the ocean color (SeaWiFS) data stream for the project.

A significant component of the project was the development, testing and implementation of acquisition, processing and archiving code built around SEADAS to handle the Gulf of Maine SeaWiFS data stream. The project acquired and processed SeaWiFS and AVHRR data from the beginning of the mission (September 1997) up to the present. This provides daily coverage at 1 km resolution for SeaWiFS and 4x daily AVHRR coverage. SEADAS processing, remapping and subsetting scripts were developed during the first year and continue to be modified and upgraded. Concurrent ocean color and SST data were supplemented by 13 years of non-concurrent archived 1 km resolution PATHFINDER AVHRR data to provide statistical measurements of time and space scales of variability for comparison. Leveraging the NASA funding, additional CPU and hardware for data backup and processing have been acquired under separate funding and configured into the satellite data laboratory at U.Maine. At present the Satellite Oceanography Data Laboratory houses 2 parallel RAID disk systems and a SCSI disk farm with a combined on-line disk storage capacity of approximately 1 terabyte, 5 UNIX and 2 LINUX based workstations networked to 5 PCs, dual DLT drives and dual DAT drives for back-up and archiving and assorted printers.

Personnel Development

NASA funding provided direct calendar-year salary support for the PI and one co-PI (Chai) during the first 2 years of the project when both were soft-money research faculty. This changed in the third year when both became tenure-track faculty in the School of Marine Sciences. Thereafter, funding supported PI summer salary. This NASA funding contributed to the creation of 2 new full time jobs in the Satellite Oceanography Data Lab as salary of 2 Research Associates (currently Ryan Weatherbee, BSc, and Peter Brickley, PhD) who work for the PI as data analysts. This grant provided partial support for one PostDoctoral Fellow (Dr. M. Jiang) who worked to develop the biological model code under the supervision of Fei Chai. This grant contributed to the Student Support of 4 MSc students under the supervision of the PI and one student under the supervision of Fei Chai.

SeaWiFS Data Processing/Management

During the project, the entire mission underwent 3 separate, complete reprocessings at the DAAC, necessitating reprocessing, remapping and subsetting of the entire mission again at U.Maine. These were a severe test of our throughput. Analysis showed that default SEADAS flags for such items as Cloud-Ice and Stray Light do not perform well in the Gulf of Maine and substantial effort was been placed into selecting optimal flag settings. This effort remains ongoing. In addition, the SeaWiFS chlorophyll retrievals in the Gulf of Maine are consistently high compared to in situ surface measurements by a factor of 2 – 4. At present we are using in situ chlorophyll measurements from 3 separately funded programs which have field components (ECOHAB Gulf of Maine, Georges Bank GLOBEC, and NOAA Penobscot Bay Program) for comparisons. Interaction with other Gulf of Maine researchers (Jay O'Reilly, Barney Balch) confirms similar results, mostly due to very low, or negative, water leaving radiance in the shorter wavelength channels. In addition, strongly varying (in both time and space) atmospheric profiles create errors larger than those experienced in other oceanic regions. These two factors have meant that until very recently (2001), Gulf of Maine SeaWiFS data have not been amenable to time/space analysis as was originally proposed. Instead, we focused on preparing code and a data set such that time series analysis was possible when accuracy improved and/or the data set became long enough that realistic trends and seasonal cycles were evident.

Currently, all SeaWiFS scenes from the beginning of the mission to December 2001 have been processed to geophysical parameters, remapped to a standard grid, subset and archived as HDF files. These provide the time series for analysis.

Science Results

(presented at 2002 Ocean Sciences Meeting HI: Seasonal and Interannual Phytoplankton Variability in the Gulf of Maine, Ryan Weatherbee, Andrew Thomas, Fei Chai, Huijie Xue and David Townsend)

Four years (1997-2001) of ocean color data from the SeaWiFS mission provide the first synoptic quantification of phytoplankton variability on seasonal and interannual time scales for the Gulf of Maine. CZCS data were inadequate for this task. The time series of daily SeaWiFS images were composited to form 8-day and monthly averages. We have quantified the spatial variability of the mean seasonal cycle (see Figure 1). The climatological seasonal cycle shows elevated concentrations (>2.0 mg m^{-3}) throughout the year within 30km of the shore and a strong modulation of the amplitude of seasonal cycles over shallow bathymetry in other regions. Deeper basins exhibit a canonical Sverdrup seasonal cycle with a strong spring bloom (> 2.0 mg m^{-3}) in March-April, a fall bloom in October-November and concentrations of ~1.0 in summer and ~0.5 in winter (December-February). Strong tidal mixing over shallow bathymetry supports elevated concentrations (> 2.0 mg m^{-3}) throughout the year on Georges Bank and sustained elevated concentrations throughout the summer over Browns Bank (Figure 2). These patterns are modulated by interannual variability which is spatially variable across the study area (Figure 3). EOF decomposition of the 4 year time series of monthly composites quantifies the strong dominance of the seasonal cycle with features of the spring and fall blooms evident in the first 3 modes. These modes also quantify the interannual variability of the main spatial patterns. Mode 1 (28.8% of the variance) shows the interannual modulation of the overall seasonal cycle, weakest in 1998, with maxima over Georges Bank, Nantucket Shoals, the Bay of Fundy and the western Gulf. Mode 2 (19.6% of the variance) shows coastal intensification, again weak in fall 1998. Mode 3 (8.1% of the variance) shows fall maxima over Georges Bank / Nantucket shoals, weakest in 1998 and the spring bloom over deeper waters of the mid-Gulf, weakest in 1998.

The interannual variability evident in the SeaWiFS data is coincident with a colder surface water regime throughout 1998 evident in AVHRR SST data and associated with the only year of the time series in which the NAO index was negative. This negative NAO index is associated with wetter, colder and stormier North American winters. These results are expanded in a manuscript currently in preparation.

During the first 3 years of the project, SeaWiFS chlorophyll retrievals were so removed from available ground-truth data in the Gulf of Maine that manuscripts were not prepared. We placed extensive effort into investigation of another algorithm developed by the ocean color group at Royal Belgian Institute of Natural Sciences (MUMM) specifically for use in waters with large CDOM content but did not see a systematic improvement in performance. Effort was placed into code development, developing an AVHRR SST data set and into parallel NASA-funded work on eastern boundary current regions where the chlorophyll/atmosphere algorithms appear to work better. An MSc student of the PI, Remy Luerssen, used a time series of SST imagery and data from 10 years of coastal HAB toxicity samples to show a link between harmful algal bloom occurrence in the western Gulf and large-scale along-shore frontal strength/position. A manuscript based on this thesis is in preparation.

Modeling

The Gulf of Maine physical-biological modeling effort took place under this funding and continues under the present NASA funding. A ten-component ecosystem model developed for the equatorial Pacific by Chai et al. (2002) has been incorporated into the Gulf of Maine three-dimensional circulation model developed by Xue et al. (2000). With NASA's support during the past three years, we have successfully incorporated the latest version of ecosystem model (Chai et al., 2002, Dugdale et al., 2002) into the circulation model for the Gulf of Maine.

The Princeton Ocean Model (POM) has been configured in a domain that covers the Gulf of Maine, Georges Bank, Scotian Shelf and the adjacent slope region. The existing Gulf of Maine model has horizontal resolutions ranging from 3 km near shore to about 7 km offshore. There are 22 levels in the vertical with both the surface and the bottom boundary layer. The circulation model has been used to simulate the seasonal circulation in the Gulf of Maine responding to atmospheric, river, and tidal forcing (Xue et al., 2000). With support from the Gulf of Maine Ocean Observing System (GoMOOS), we have developed nowcast/forecast capability of the Gulf of Maine model. With the recent NASA funding, we continue the improvement of the circulation model by assimilating daily and weekly AVHRR SST into the Gulf of Maine operational circulation model. (see the modeled forecast at: www.gomoos.org).

We adopted an ocean ecosystem model that consists of ten compartments describing two-size classes phytoplankton (P1, P2) and zooplankton (Z1, Z2), detritus nitrogen (DN) and detritus silicate (DSi), two forms of dissolved inorganic nitrogen: nitrate (NO_3) and ammonium (NH_4), Silicate (Si), and total CO_2. This model has been tested against the JGOFS data over the equatorial pacific and is capable of reproducing the Low-Silicate, High-Nitrate, Low-Chlorophyll (LSHNLC) conditions in the equatorial Pacific (Chai et al. and Dugdale et al., 2002). The structure of the intercompartmental flows through the ten-component ecosystem model is presented in Figure 5.

We have coupled this ten-component biological model with the three-dimensional Gulf of Maine circulation model. The physical-biological model is forced with COADS monthly wind and heat flux. The initial conditions for nitrate and silicate are from the processed NODC station data and some historical data from Bedford Institute of Oceanography. After three years physical-biological model integration, most of the biological components establish a regular seasonal cycle. Figure 6a shows the comparison between the modeled and satellite derived surface chlorophyll fields during the spring period (March and April). Overall, the spatial patterns produced by the model and derived from the SeaWiFS are quite similar. They both suggest high chlorophyll concentrations along the coast, in Bay of Fundy, over the Nantucket Shoals and Georges Bank. Problematic areas are mostly near the open boundaries that are related to the both physical and biological conditions near the boundaries. We continue our effort to improve the boundary conditions, especially the treatment of the biological components.

The seasonal cycle of modeled and SeaWiFS climatological chlorophyll have been compared over the Georges Bank. The model captures both the timing and intensity of phytoplankton bloom over the Georges Bank, Figure 6b. In deeper areas, such as Wilkerson and Jordan Basin, the modeled seasonal cycle of phytoplankton deviates from the SeaWiFS, especially the timing of the bloom, but it is still within the range of interannual variability measured by the 4 available years of SeaWiFS. We continue our efforts to improve model performance in the central Gulf where the model and SeaWiFS seem do not agree each other. By doing so, the historical in situ chlorophyll data is used to validate both the modeled and SeaWiFS for the Gulf of Maine and the Georges Bank.

The manuscript presenting these results is in preparation for a special issue of Journal of Marine Systems on Nutrient Dynamics in Coastal Ecosystems: Linking Physical and Biological Processes.

1) Chai, F., R. C. Dugdale, T-H Peng, F. P. Wilkerson, and R. T. Barber (2002): One Dimensional Ecosystem Model of the Equatorial Pacific Upwelling System, Part I: Model Development and Silicon and Nitrogen Cycle. Deep-Sea Res. II, in press.

2) Dugdale, R.C., R. T. Barber, F. Chai, T.H. Peng, and F.P. Wilkerson (2002): One Dimensional Ecosystem Model of the Equatorial Pacific Upwelling System, Part II: Sensitivity Analysis and Comparison with JGOFS EqPac Data. Deep-Sea Res. II, in press.

3) Xue, H., F. Chai, and N. R. Pettigrew (2000): A model study of the seasonal circulation in the Gulf of Maine: in response to local forcing. J. Phys. Oceanogr, Vol. 30, 1111-1135.

3. Published Manuscripts:

NAG5-6558 provided partial support for the following manuscripts on the Gulf of Maine region:

Thomas A.C., D. Byrne and R. Weatherbee, 2002, Coastal sea surface temperature variability from Landsat infrared data, In Press, Rem. Sens. Env.

Townsend D.W. and **A.C. Thomas**, 2001, Winter-spring transition of phytoplankton chlorophyll and inorganic nutrients on Georges Bank, Deep Sea Res. II, 48:199-214.

Townsend D.W., N.R. Pettigrew and **A.C. Thomas**, 2001, Offshore blooms of the red tide dinoflagellate, Alexandrium sp., in the Gulf of Maine. Cont. Shelf Res. 21:347-369.

In addition, NAG5-6558 provided partial support for the following manuscripts:

Thomas A.C., J.L. Blanco, M.E. Carr, P.T. Strub and J. Ossus, 2001, Satellite-measured chlorophyll and temperature variability off northern Chile during the 1996-1998 La Nina and El Nino, J. Geophys. Res. 106:899-915.

Thomas A.C., P. T. Strub, M.E. Carr and R. Weatherbee, 2002. Comparisons of chlorophyll variability between the four major global eastern boundary currents. Submitted, Int. J. Rem. Sens.

Blanco J.L., M-E. Carr, **A.C. Thomas** and P.T. Strub, 2001, Hydrographic conditions off northern Chile during the 1996-1998 La Nina and El Nino, In Press, J. Geophys. Res.

Thomas A.C., M.E. Carr and P. T. Strub, 2001, Chlorophyll variability in eastern boundary currents, Geophys. Res. Lett. 28: 3421-3424.

Nixon, S.W. and **A.C. Thomas**, 2001, On the size of the Peru Upwelling Ecosystem. Deep Sea Res. I, 48:2521-2528.

Blanco J.L., **A.C. Thomas**, M-E. Carr and P.T. Strub, 2001, Seasonal climatology of hydrographic conditions in the upwelling region off northern Chile, J. Geophys. Res. 106:11,451-11,467.

Thomas A.C. and P.T. Strub, 2001, Cross-shelf phytoplankton pigment variability in the California Current. Cont. Shelf Res. 21: 1157-1190

Thomas, A.C. 1999. Seasonal distributions of satellite-measured phytoplankton pigment concentration along the Chilean coast. J. Geophys. Res. 104:25877-25890.

Carr M-E., P.T. Strub, **A.C. Thomas** and J.L. Blanco, 2002, Evolution of 1996-1999 La Nina and El Nino conditions off the western coast of South America: a remote sensing perspective, In Press, J. Geophys. Res.

4. Conference Papers Presented:

Results from research supported by NAG5-6558 were presented at the following conferences:

2002 Ocean Sciences Meeting, HI, Weatherbee, Thomas, Chai, Xue, and Townsend, Seasonal and Interannual phytoplankton variability in the Gulf of Maine.

2002 Ocean Sciences Meeting, HI, Chai, F., H. Xue, M. Jiang, A. Thomas, and D. Townsend: Modeling Nutrients and Phytoplankton Dynamics in the Gulf of Maine.

2000 National ECOHAB Meeting. Wood's Hole MA, Luerssen R., **A.C. Thomas** and R. Weatherbee, Relationships between satellite-measured surface temperature patterns and Alexandrium in the Gulf of Maine.

2000 Ocean Sciences Meeting, TX, Chai, F., H. Xue, M. Jiang, and A. Thomas: A Model Study of Biological-Physical Coupling in the Gulf of Maine: Seasonal Variability.

2000 Ocean Sciences Meeting, TX, Townsend D.W. and A.C. Thomas, Winter-to-summer chlorophyll and inorganic nutrients on Georges Bank.

1999 Sigma Coordinate Ocean Model Meeting, ME. Chai F, H. Xue, M. Jiang and A.C. Thomas. Coupled Circulation and Ecosystem Model with Coastal Applications.

5. Graduate Education:

NAG5-6558 has provided partial support for the following graduate students:

Remy Luerssen, M.Sc., University of Maine 2001. Thesis Title: Relationships between oceanographic satellite data and Alexandrium distributions in the Gulf of Maine

Jennifer Bosch, anticipated MSc 2002

Kasey Legaard, anticipated MSc 2003

Li Xu, anticipated MSc 2002

Ryan Weatherbee, anticipated MSc 2003

6. Patents

No patents were developed under this funding.

7. FIGURES

Figure 1. Climatological (Sept 1997-Aug 2001) monthly composites showing the annual cycle of chlorophyll patterns in the Gulf of Maine.

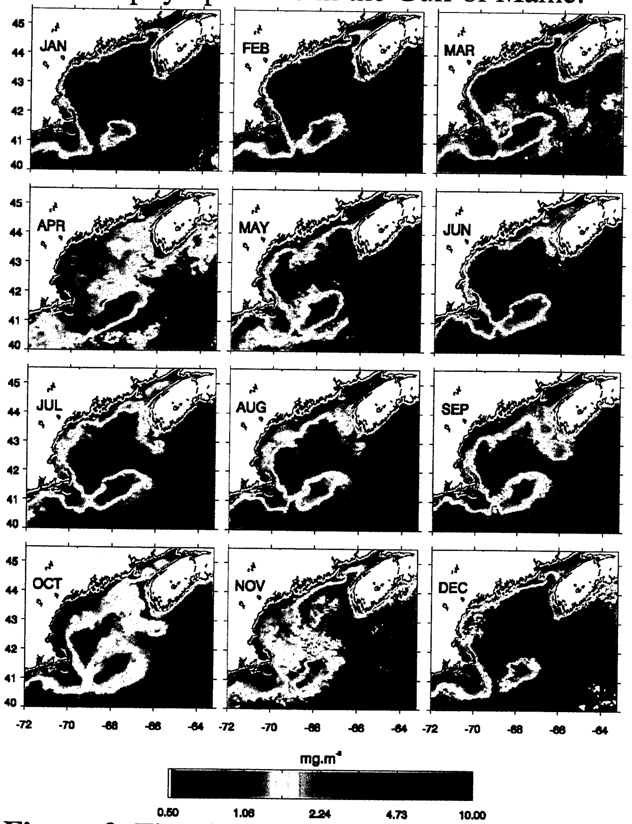

Figure 2. The climatological seasonal cycle at 8 locations within the Gulf of Maine, calculated from 45 km spatial means within 8-day composites (Georges Bank, Browns Bank, Eastern Maine Coastal Current, Western Maine Coastal Current, Wilkinson Basin, Jordan Basin, East Scotia Slope and offshore of shelfbreak). Evident are winter minima, the spring bloom with location-specific timing, a summer decrease followed by a fall bloom.

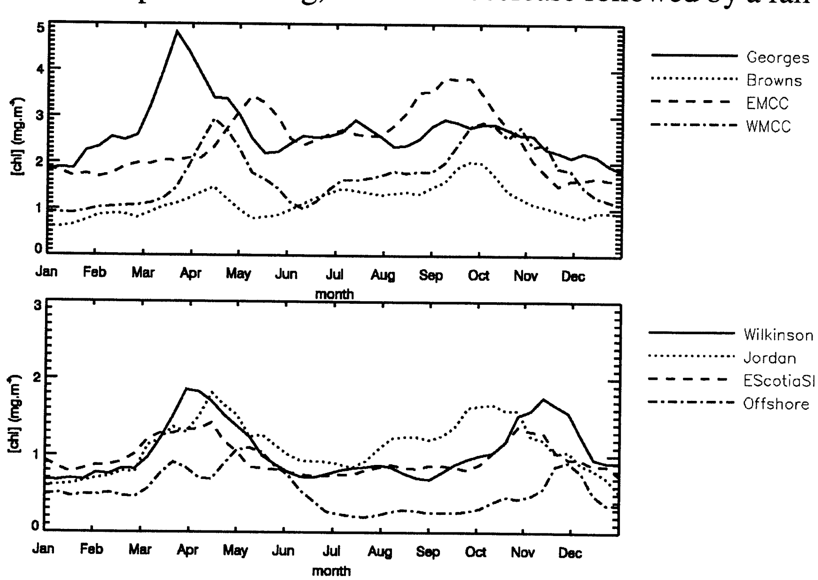

Figure 3. Interannual variability (1997-2001) of SeaWiFS chlorophyll concentrations in the seasonal cycle at 8 locations within the Gulf of Maine study area. (a) Georges Bank, (b) Browns Bank, (c) Eastern Maine Coastal Current, (d) Western Maine Coastal Current, (e) Wilkinson Basin, (f) Jordan Basin, (g) East Scotia Slope and (h) offshore of shelfbreak)

(a-d)

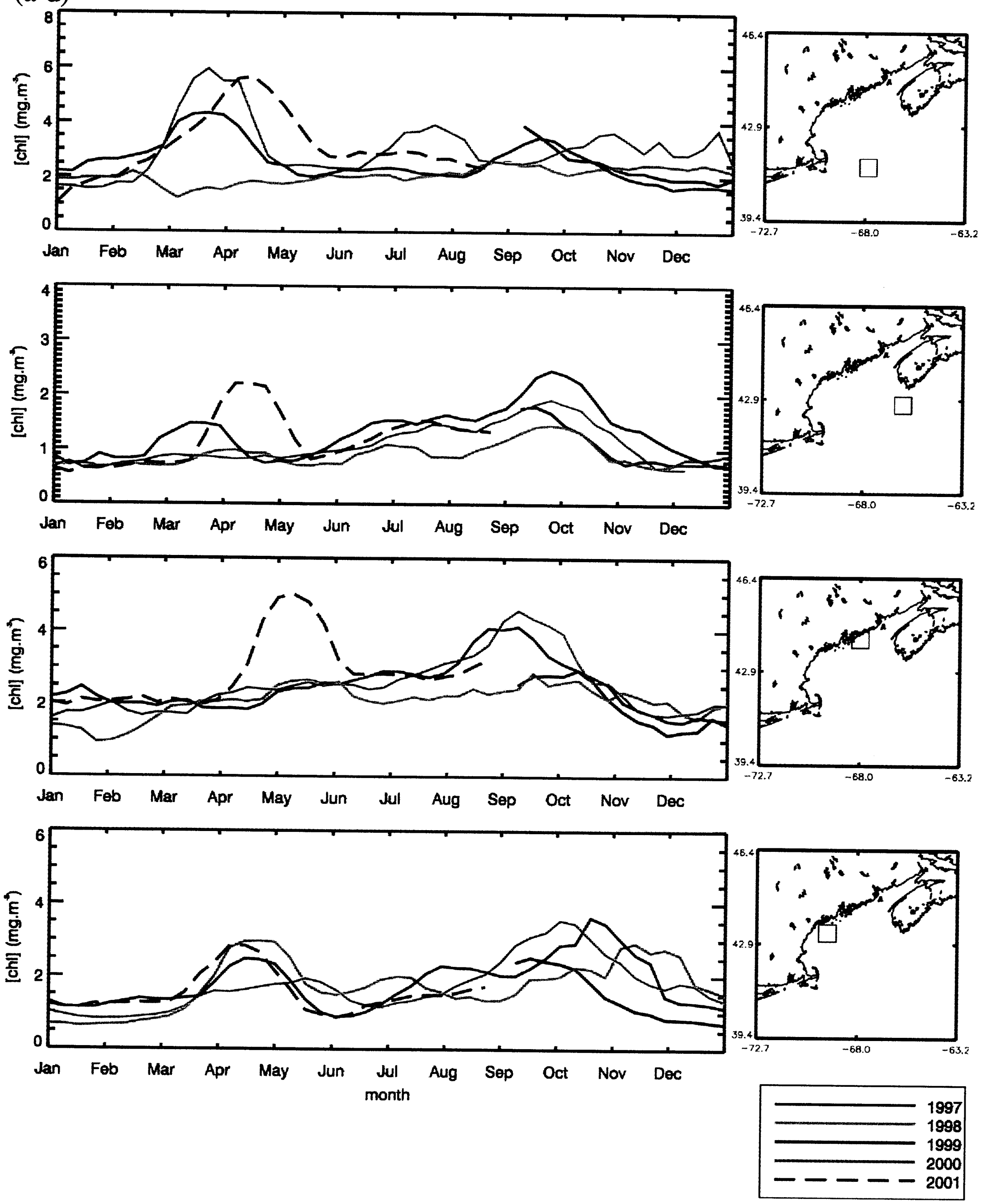

Figure 3 (e-h). continued

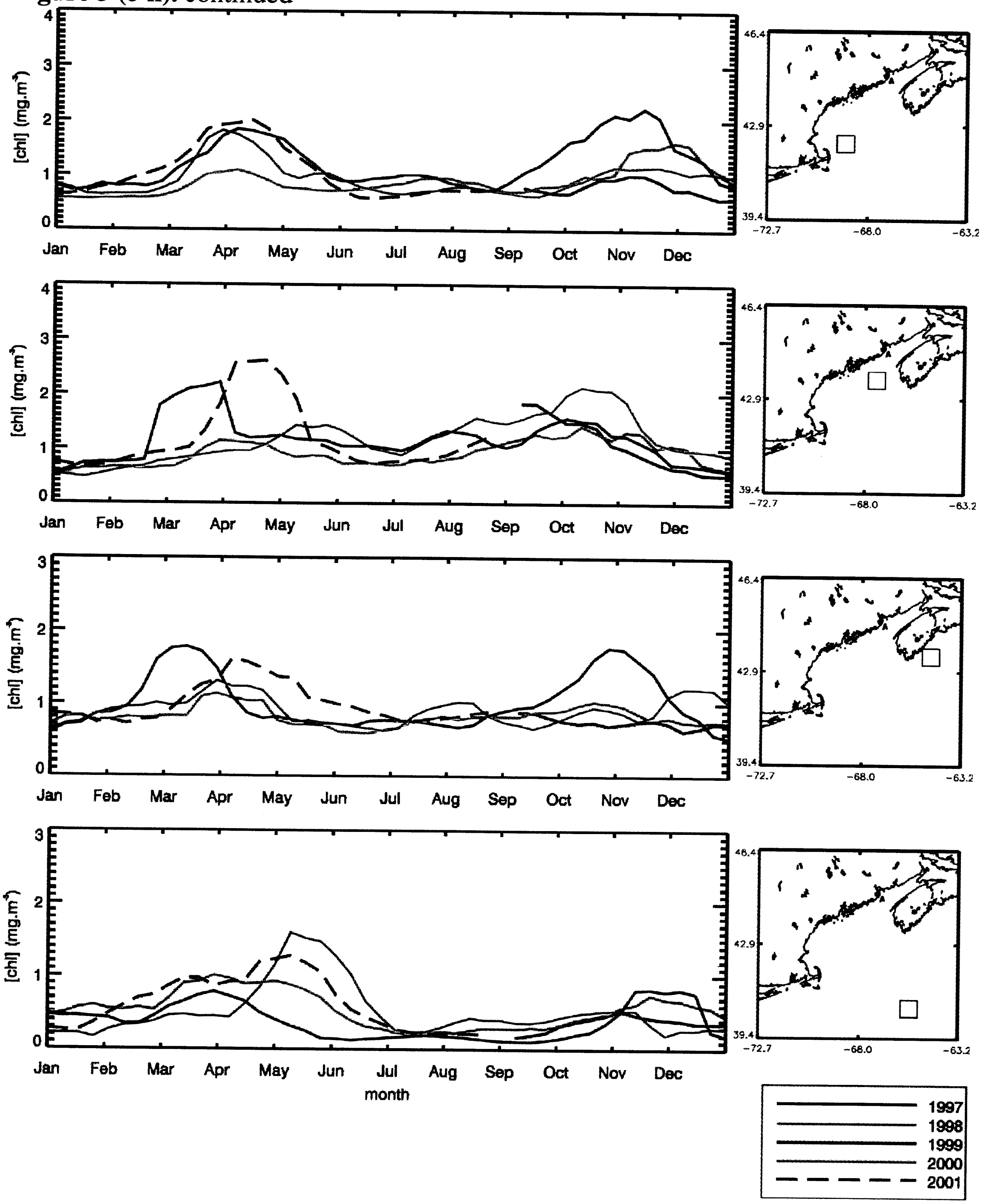

Figure 4. Empirical orthogonal function decomposition of the 48 month Gulf of Maine monthly time series, showing the 3 most dominant modes of spatial pattern and temporal modulation.

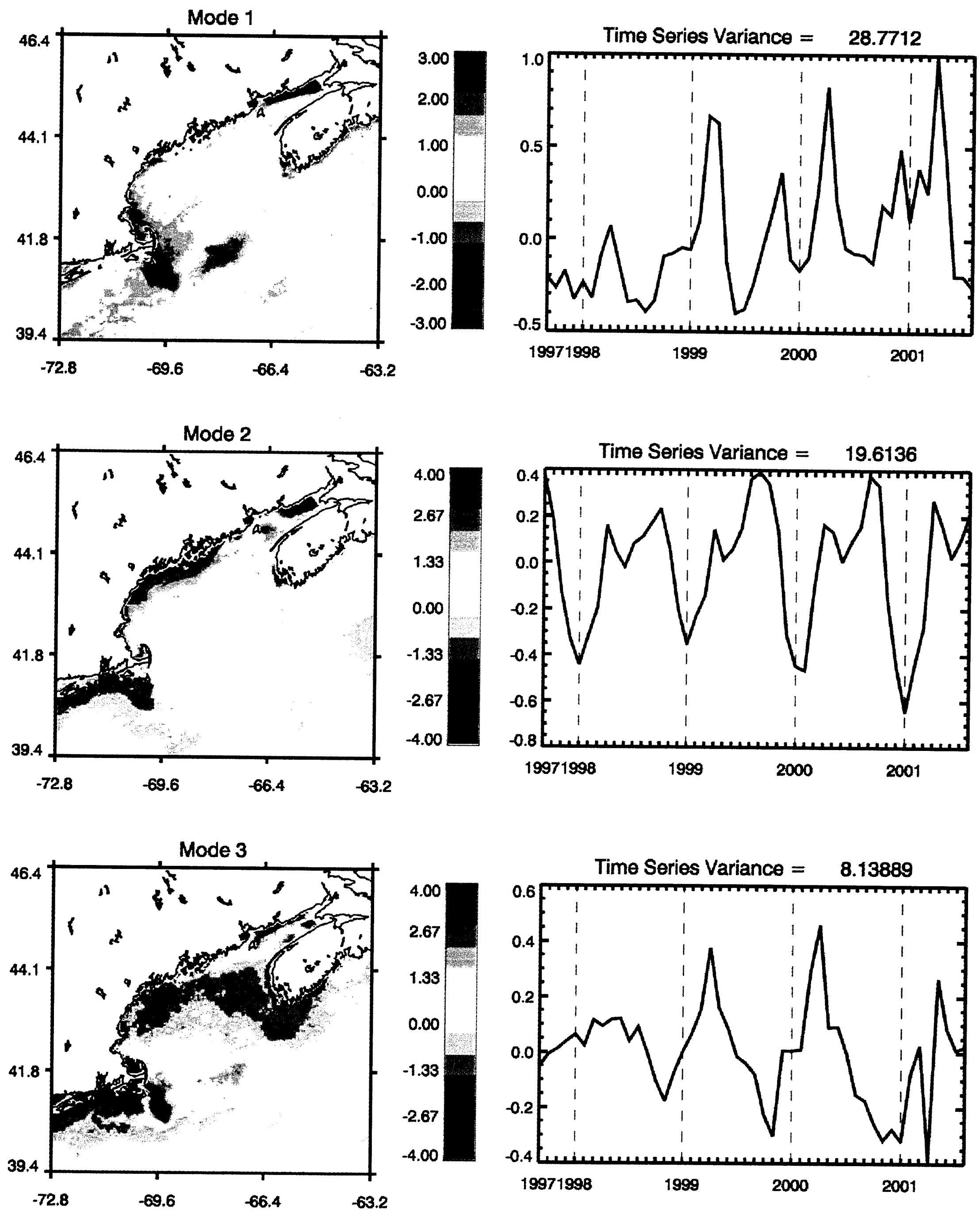

Figure 5. The NPZ model components.

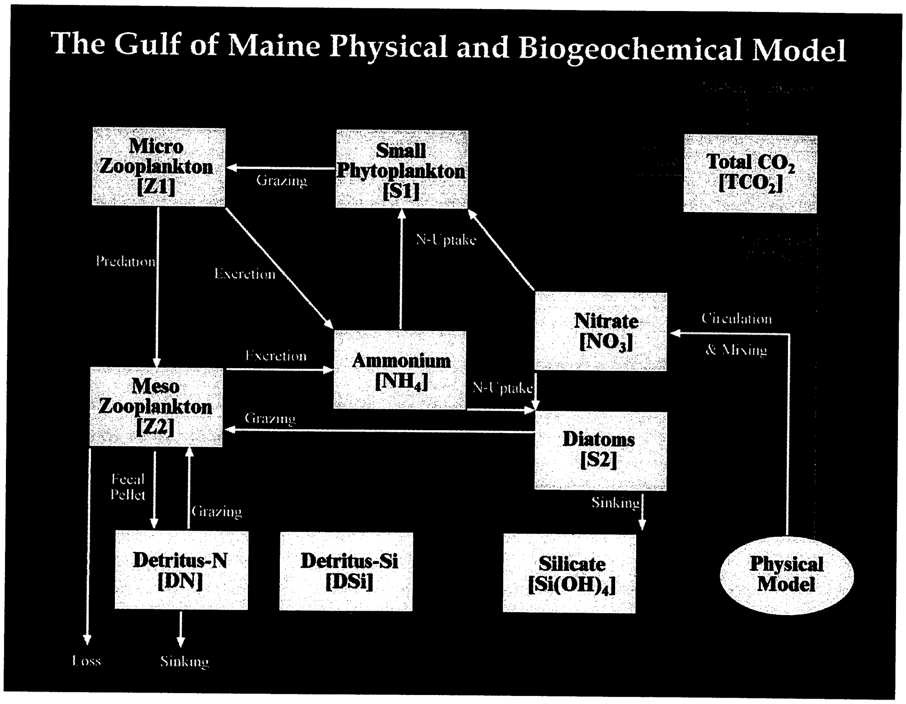

Figure 6. Model results a) spatial field of surface chlorophyll in spring compared to the SeaWiFS climatology and b) time series showing the annual cycle of surface chlorophyll from the model and SeaWiFS climatology over Georges Bank.