Ocean Carbon Flux, Transport, and Burial Within the Western and Eastern U.S. Coastal Zones

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OVERVIEW

This project has been to develop and apply a regional, eddy-resolving circulation and biogeochemistry model of both the western and eastern U.S. coastal regions, capable of simulating the processes that control the carbon cycle. Validation has been by statistical comparison with analyses from various satellite measurements, including those from EOS sensors, as well as from *in situ* measurements. Sensitivity studies were carried out to investigate how the coastal ecosystem and biogeochemical cycles respond to changes in climate, large-scale eutrophication from industrial pollution, and other anthropogenic induced changes. The research has been conducted in collaboration with research groups at UCLA, NASA/GSFC (Wallops), Rutgers, and SIO.

Overall, the project was focused on several key modeling issues, each of which tie back into completing the primary task of developing a coastal carbon model for both the eastern and western U.S. coasts. Individual groups within the entire program are still collaborating to address these specific tasks. These include: implementation of the coupled circulation/biogeochemical model within the U.S. West Coast, including high-resolution, embedded subdomains for the Southern California Bight and Monterey Bay region; development of a biogeochemical model with resolved carbon, nitrogen and oxygen cycles; development of data assimilation techniques for use of satellite data sets; reconfiguration of the model domain to U.S. East Coast; development of coastal forcing fields; development of methods to compare the model against remotely sensed data; and, the test of model sensitivity to environmental conditions. Below, we present a summary of the progress made toward achieving these goals. Because this has been a multi-institutional, collaborative effort, we note the groups involved with particular activities.

Along the Northeast North Atlantic (NENA) coast, a significant proportion of oceanic variability on time scales of days to months is driven by mesoscale ocean currents associated with the planetary wave field originating in the Atlantic Ocean, and intrinsic instabilities of the Gulf Stream western boundary current. It is recognized that boundary current variability provides a significant mechanism for the exchange of deep-ocean and shelf-sea waters along this coast, and that this exchange process provides a major source of new nutrients for NENA coastal waters. In contrast, along the U.S. West Coast, wind stress and wind stress curl are the primary physical forcing features that provide nutrients to the euphotic zone. Coupled to these upwelling centers are offshore meandering filaments that move large volumes of carbon biomass offshore. In addition to this, eastern boundary currents and local mesoscale features–including subsurface anticyclonic eddies shed from the undercurrent–add to the local biomass production capabilities by providing additional sources of nutrient fluxes. These nutrient sources are critical to maintaining biological productivity, and results in a significant proportion of net carbon export from these coasts.

Physical Modeling (UCLA, Rutgers)

West Coast Physical Simulations (UCLA, SIO)

UCLA's Contribution: Development continues for the Regional Ocean Circulation Model (ROMS), and by now a variety of capabilities have been implemented and used in several applications along the U.S. West Coast. The circulation model developments include open boundary conditions that both radiate internally generated variability and impose external influences from remotely forced, large-scale circulation (Marchesiello et al., 2001); an embedded gridding capability that supports high-resolution local subdomains within a coarse resolution larger domain (Blayo & Debrueu, 1999; Penven et al., 2002); revised time-stepping and mode-coupling algorithms for better accuracy and increased time-step size (Shchepetkin & McWilliams, 2004; accurate material advection algorithms for biogeochemical properties (Shchepetkin & McWilliams, 1998); and a new algorithm for calculating pressure gradient force over steep topography (Shchepetkin & McWilliams, 2003). Papers have been written on the statistical equilibrium dynamics of the California Current System (Marchesiello et al., 2003), ecosystem and carbon cycling in the California Current System (Gruber et al., 2004; DiLorenzo et al., 2004a) interannual variability of the Southern California Current (DiLorenzo et al., 2004b), and the wind sensitivity of upwelling events near Monterey Bay (Capet, McWilliams, and Marchesiello, 2004).

The primary physical-circulation application has been added to the equilibrium U.S. West Coast circulation under mean-seasonal forcing (Marchesiello et al., 2003; Chao et al., 2004), which also serves as the initial test problem for biogeochemical (BGC) studies (see below). The results depict the California Current System as full of intrinsic variability–eddies, squirts, jets, meanders, and filaments–that provide important material and dynamical fluxes which establish the mean distributions both along-shore and cross-shore. We originally configured this problem on uniform grids, with various horizontal resolutions, in an approximately 1000 by 2000 km domain. Later, however, we used the embedded gridding capability with high-resolution subdomains for the central upwelling region around Monterey Bay (Penven et al., 2004) and for the Southern California Bight (Fig. 1; Marchesiello et al., 2002) where observational comparisons are especially abundant. We have also studied the different wind climatologies (including both a regional COAMPS product from Naval Research Laboratory in Monterey and ERS and QuikSCAT scatterometer analyses) that demonstrate significant solution sensitivity to near-shore wind patterns and to synoptic winds. In collaboration with Dr. Yi Chao (JPL), we analyzed interannually forced, whole-Pacific solutions with ROMS, to replace the regional climatological boundary conditions and investigate interannual coastal variations (*e.g.*, ENSO; Nezlin & McWilliams, 2002; Nezlin, 2002).

Finally, we have made a good start on the development of a sediment model that eventually will consist of two sub-modules, one that describes the physical transport and resuspension of sediments, and one that describes the biogeochemical transformations within the sediments and suspended particles and the exchanges at the sediment/particle -water interfaces. The appropriate sediment-transport model is one for time scales averaged over all surface gravity-wave currents and for bottom depths outside both the nearshore surf zone (*i.e.*, greater than 10 m) and the abyss (suspended sediments are generally more active on the continental shelf than in deeper waters where the bottom currents are much weaker). The model is based on a suspended concentration field (with 1-2 size classes), which is transported as any other dissolved material plus gravitational settling towards the bottom at the appropriate Stokes velocity and injection by resuspension (*i.e.*, bottom erosion) at a rate determined by the bottom stress. The settling, bottom stress, and resuspension rules depend upon the sedimentary material type, which we will specify geographically, and the statistics of the surface gravity waves, which can be specified either climatologically or diagnostically from local wind stress and operational swell forecasts. The settling is accelerated from scavenging by "marine snow" (*i.e.*, large biogenic particles). Fluvial fluxes provide the coastline boundary condition. An accompanying module accounts for the evolving sedimentary bedload and its transport. The model is a generalization of the prototype implemented within ROMS by Dr. Hernan Arango, based on the formulation by Styles & Glenn (2000). Our intended applications are on the continental shelves within the high-resolution embedded sub-domains for Monterey and Southern California (see above).

SIO's Contribution: The long-term changes in the observed temperature and salinity along the Southern California coast were studied by Di Lorenzo et al. (2004a,b) using a four dimensional space-time analysis of the 52 year (1949-2000) California Cooperative Oceanic Fisheries Investigations (CalCOFI) hydrography combined with a sensitivity analysis of an eddy permitting primitive equation ocean model under various forcing scenarios. A warming trend in temperature and a deepening trend in the depth of the mean thermocline between 1950 and 1998 are found to be primarily forced by large-scale decadal fluctuations in surface heat fluxes combined with horizontal advection by the mean currents. After 1998 the surface heat fluxes suggest the beginning of a period of cooling, which is consistent with colder observed ocean temperatures.

Salinity changes are decoupled from temperature and are primarily controlled by horizontal advection by anomalous currents. A cooling trend in SST is driven in the ocean model by the 50 year NCEP wind reanalysis, which contains a positive trend in upwelling favorable winds along the Southern California Coast. The magnitude of this cooling (0.2 degrees Celsius), however, is small compared to the observed warming trend (1 degree Celsius) and is not detectable in the CalCOFI hydrography. The signature of the increased winds also is evident in both model and observations as an intensification of the mean currents of the Southern California Current System (SCCS). Model mesoscale eddy variance significantly increases in recent decades in response to both the stronger upwelling winds and the deepened isopycnals, suggesting that the stability properties of the SCCS have also changed. Within 50 to 100 km of the coast, the ocean model simulations show strong evidence that the isopycnal deepening reduces the nutrient flux to the ocean surface, counteracting any effects of the increased upwelling winds. The long-term trend of the model proxy for surface nutrients is consistent with the observed decline in zooplankton concentration.

SIO Created Datasets:

4D Objective Analysis of entire 50+ year temperature and salinity dataset of CalCOFI

1952-1999 ocean model hindcasts of the Southern California Current System (three forcing scenarios: winds, winds+surface heat fluxes, wind+surface heat fluxes+ boundary condition changes)

East Coast Simulation (Rutgers, NASA/GSFC)

Rutgers' Contribution: To adequately simulate the physical circulation processes that influence biological production and carbon uptake in coastal waters, a model of the NENA shelf waters must simulate both local wind and buoyancy forced flow, and also the remotely-forced deep-ocean shelf exchange processes that are the dominant source of new nutrients to the coastal marine ecosystem. Open boundary conditions for a shelf model based solely on climatological hydrographic observations of temperature and salinity, and velocity inferred from these, cannot represent the intensity of episodic mesoscale events that are known to bring nutrients onto the shelf.

Therefore, our CO2 modeling effort for the U.S. East Coast entails forming complementary shelf/slope region and North Atlantic basin models. The North Atlantic basin model has resolution and forcing specifications adequate to generate a vigorous Gulf Stream and associated mesoscale variability, plus the influence of remotely forced seasonal and interannual variability due to wind variability in the central Atlantic Ocean. We utilized the NATL simulation to specify the conditions at the oceanic perimeter of the shelf model.

The North Atlantic (NATL) basin model development is well advanced, with integrations now completed for over 4 years of simulation. The model formulation closely follows other successful simulations of the North Atlantic undertaken through the DAMEE model 7 intercomparison project, with our most notable improvements being principally in the incorporation of higher spatial resolution. After 4 years of integration with climatological buoyancy fluxes and mean monthly wind forcing, the NATL model is approaching an equilibrium in the intensity of mesoscale currents and exhibits a realistic Gulf Stream circulation.

For example, Figure 4 shows the NATL solution at day 1140 of the calculation, corresponding to a climatological date in mid-February. The solution shows a well developed Gulf Stream separating at Cape Hatteras, and a backward breaking meander of the flow at 70W, 38N.

The formulation of the NATL simulation has recently been enhanced to introduce daily wind forcing from the NCEP re-analysis. This is a step that is easily made with present model configuration and the forcing data available. Including wind variability on time scales of few days, instead of the monthly-scale used in the 4-year spin-up, will potentially introduce new sources of variability in the simulation. More importantly, at the completion of several years of simulation the interannual variability introduced by using a re-analysis product will enable us to distinguish characteristic years of deep ocean conditions that we may wish to examine in detail for possible influence on year-to-year variability on the shelf. Furthermore, the NCEP re-analysis winds were introduced starting from January 1993, so that we might compare ultimately the interannual variability in the simulation with observations from the TOPEX/Poseidon mission.

The NENA shelf model has been prototyped. We are evaluating the manner in which we effectively nest the shelf model within the NATL model by applying conditions at the NENA 8 open boundaries. The nesting approach is essentially a 1-way nesting procedure; the NENA solution is not subsequently used to influence the outcome of the NATL simulations.

The prototype NENA domain is shown in Fig. 5. It is the shelf model solution with NATL conditions imposed at the model perimeter using the open boundary scheme of Marchesiello et al. (2001). These open boundary conditions allow the interior solution to exit the domain by application of a adaptive radiation condition, while in regions of inflow to the domain the solution is weighted heavily toward the conditions determined by the local NATL solution. The NENA domain is rotated with respect to the northeast coordinates for efficiency, which introduces the need to 2-dimensionally spatially interpolate the NATL output to the NENA grid. Results from NATL are saved each simulated day in a band of 'stations' that bracket the open boundary points in NENA. The dots plotted in Fig. 4 and show the location of the output time series stations. These data are subsequently interpolated to the NENA grid in an offline pre-processing step. In this evaluation phase of the 1-way nesting method, NATL and NENA grid resolutions are comparable, and the bathymetries and surface forcing are identical.

Biogeochemical Modeling (NASA/GSFC, SIO, UCLA)

UCLA's Contribution: The foci of our 2nd-year efforts have been on the further development of the coupled circulation biogeochemical model, including a detailed analysis package for a complete flux and transport analysis of all materials, as well as making detailed comparisons of the simulated fields with observations.

We have developed a NPDZ (nutrient, phytoplankton, zooplankton, detritus) model with a single limiting nutrient (nitrogen) and diatom-like phytoplankton class (Moisan & Hoffman, 1996) to ROMS (Stolzenbach et al., 2004). The model includes explicit formulations for photoadaptation and other factors affecting the chlorophyll to nitrogen ratio. This upwelling biome model is coupled to the cycling of carbon and oxygen to this ecosystem model, whereby we have assumed constant stoichiometric ratios for all biological processes, except for zooplankton whose C:N ratio is elevated relative to the phytoplankton pool. The model includes a time varying carbon to chlorophyll ratio and explicitly simulated coagulation and 9 decoagulation processes. The main simplifications are the exclusion of an explicitly modeled bacteria pool, derived by assuming a constant background population of bacteria, and the neglect of dissolved organic nitrogen-as well, of course, as the neglect of other nutrients and plankton groups. We have now calculated a large number of exploratory biogeochemistry-ecosystem model solutions for the whole U.S. West Coast domain at the rather coarse horizontal resolution of 20 km. This configuration requires the creation of lateral boundary conditions for all inorganic carbon species, which were taken from a recently new gridded Pacific wide data set prepared by Sabine et al. [pers. comm.] on the basis of the recently completed Joint Global Ocean Flux Study/World Ocean Circulation Experiment large-scale CO2 in the ocean survey. For oxygen and nitrogen, we use the values from the World Ocean Data climatology. For a standard simulation, we run the model forward in time for 10 years and then analyze the 11th year. By that time, the state variables as well as the fluxes have reached a statistical steady state in the upper ocean.

Figure 6 shows the annual-mean surface profiles of Chlorophyll a along a line that intersects the SCB for the model, the *in situ* CalCOFI climatology, and satellite measurements from SeaWiFS and AVHRR. There are some evident biases–notably at the coastline, where the model's upwelling is excessive, and far offshore, where the model lacks an oligotrophic ecosystem group-but the discrepancies with observations are generally not much larger than those between the different observations. An interior view along the same line in Fig. 7 indicates that the thermocline structure is reasonably well simulated, except perhaps for an excessively thin nutricline in the model.

Figure 8 shows annual-mean and instantaneous fields of CO2 flux between the surface ocean and the atmosphere as simulated by ROMS (an animated version of this figure is at ftp://quercus.igpp.ucla.edu/pub/gruber/movies/roms_co2flux.mpg).

Three distinct zones emerge from this figure. In the near shore region, the intense upwelling brings carbon-rich waters from below to the surface, leading to large supersaturation and consequently large fluxes into the atmosphere. As these waters are transported offshore, this supersaturation is relatively rapidly reduced as the nutrients that are upwelled together with the dissolved inorganic carbon are fueling the growth of phytoplankton. In the central California region, this reduction in dissolved inorganic carbon is so efficient that it leads to the generation of undersaturated waters and therefore to a reversal of the flow of carbon across the air-sea interface. This zone persists in the annual mean and is depicted in Figure 8 as a region of ocean uptake of atmospheric CO2 stretching southward in the offshore region. The third region is the far-offshore region (i.e. more than 500 km from the shore), where the ocean acts as a source to the atmosphere. This flux is primarily driven by the net gain of heat in this region, since the biological activity in upwelling-biome model is very weak there.

The separation between the upwelling region and the outer zone is also characterized by the separation between net divergence in the horizontal transport of phytoplankton and the net convergence in the horizontal transport (Fig. 9). Inshore of this separation, the strong offshore transport by both the mean transport as well as eddies lead to a divergence of the phytoplankton and all other organic bioactive materials. Figure 10 shows the annual mean carbon budget for this net divergence region (see Fig. 9 for boundaries). In this near-shore region, up to 30offshore, leading to a substantial lateral bleeding of the system (Fig. 9, right). This offshore transport is about of equal magnitude of the total vertical carbon flux in this region. By contrast, the net import of organic material increases the 11 heterotrophic processes in the offshore region dominated by net convergence substantially. While this horizontal input is large, it constitutes only about 20in this region, so the system still remains net autotrophic. This lateral transport has large implications for the local export ratio (i.e. the ratio of vertical export to NPP) between the two regions. In the nearshore region, only about 30exported, whereas in the offshore region, more than 50NPP is vertically exported. This comparison is misleading, however, since it does not reflect fundamental changes in the recycling efficiency between the two regions, but simply the impact of the lateral transport. This comprises a good illustration how carbon and energy flow fundamentally depend in coastal upwelling regions of the lateral fluxes. We expect that higher resolution versions of this coupled model (see below) will result in even larger transport divergences, dramatically illustrating how the traditional paradigm of the local equilibrium balance of the vertical supply of nutrients and vertical export flux is completely inadequate to represent the processes in the coastal ocean.

SIO's Contribution: The sensitivity of the 7-component ecosystem model was studied in 3D time-dependent comparisons to the February 1998 CalCOFI survey and concomitant SeaWiFS observations. Because of the complexity of the parameterizations in the 7-component model, reduced versions of the model were also studied. These included a 3-component NPZ model and 2-component NP model. The tests assessed the deterministic evolution of the ecosystem over a 3-week period in which the estimated physical forcing (determined from inverse fits of the physical model to CalCOFI and TOPEX data) was assumed to control the bulk of variability in the ecosystem response. The models were run for different parameter choices and compared to the available observations (SeaWiFS Chl-a, CalCOFI upper-ocean Chl-a and nitrate). Extensive efforts were made to allow the biology to equilibrate to the estimated physical forcing. Qualitative comparisons between ecosystem model and observations suggested that the physical forcing may not have been adequate to establish the observed biological distributions (nearshore maximum of chl-a, subsurface chl-a maximum, weak offshore blooms around eddies, etc.). Additional work to develop a balanced physical and biological state is needed.

NASA/GSFC's Contribution: Our efforts at NASA have focused on: (a) continuing the development of the biogeochemical model components; (b) analyzing 1D and 3D model solutions (see http://oosa.wff.nasa.gov) and developing analysis packages for inter-comparison of the model solutions to both NASA remotely sensed data sets and available field data; and, (d) developing forcing fields for coastal boundary conditions related to biogeochemical model.

Biogeochemical Model Development: In the past year, we have continued to develop the biogeochemical model by adding to it the more detailed microbial loop processes and a benthic biogeochemical component. Last year's effort introduced the full carbon cycle to the model by adding in gas transfer modules for CO_2 and O_2 as well as inclusion of the required inorganic carbon variables, alkalinity and TIC. The model presently has 18 individual components. 13 Additional components may be added as we investigate the requirements to work to resolve phytoplankton functional group variability and limiting nutrient variations (i.e. silicate, nitrate, phosphate, iron). The present configuration of this model is shown in Figure 11. This model is now being tested within a 1D configuration to investigate the model parameter sensitivities. It will later be merged into the 3D models. In addition to the added features of the model, we have been working to develop a dynamic modeling ability-one where parameters are less constrained or set to one variable. We have completed a study (Moisan et al., 2002) on the effects of temperature on phytoplankton growth and plan to merge these results into the model. Present efforts are focused in the lab using a newly developed "modeling workbench" to develop similar parameterizations for nutrient uptake and light adaptation (see: http://oosa.wff.nasa.gov/modelingwor-kbench.html)

1D and 3D Model Analysis and Data Comparison: We continue to develop a data comparison analysis package for comparing the 1D and 3D model results against both satellite and field data sets. All of these comparisons are available at http://oosa.wff.nasa.gov. As an example, Figure 12 shows a comparison of the model simulated and satellite-measured annual mean SeaWiFS chlorophyll a estimate. The program used to create this image is also designed to carry out similar comparisons with AVHRR data sets. Additionally, the software can carry out 1D and 2D comparisons between the model results and the large CalCOFI data set. Additionally, we have used the model solutions to begin accessing potential U.S. coastal ocean observing strategies. We carried out some probability calculations with the output from the 3D model to determine how many actual moorings would be required to properly measure the offshore carbon flux using moorings (see Figure 13). By allowing our model grid points to represent potential "mooring" locations, we randomly chose an increasing number of potential moorings to define the probability curve of the various estimates. From this analysis we are able to demonstrate that it is unlikely that the U.S. will be able to afford to carry out such a field campaign. However, we plan to investigate further the utility of using the model simulation to develop a more sophisticated way to plan future possible field studies. For instance, we would like to know if a 14 better estimate could be obtained by placing moorings into a range of energetic locations rather than use a spatial distribution-i.e. sample in the energy domain rather than in the spatial domain.

We presently are archiving the entire GAC data sets for the SeaWiFS and AVHRR satellite data sets. We have begun to collect the LAC data sets as well for both data sets. In addition, we are archiving a local copy of the CalCOFI data set. Additionally, we maintain a copy of the NODC data sets and the Carbon Dioxide data sets from CDIAC. All of these are being used for model-data inter-comparisons.

Development of Coastal Ocean Biogeochemical Forcing Fields: In August of 2001, a project was begun creating a data set of selected water quality constituents and associated streamflow values for streams and rivers that flow into the Atlantic Ocean and Gulf of Mexico along the Atlantic and Gulf coasts of the United States. The data will be used to extrapolate nutrient and other constituent loads along both coasts, which can then be used as input into the ocean modeling program.

Data collected from USGS monitoring stations were chosen as the richest source of historical and current water quality and flow data available, with approximately 1.5 million sites in all 50 States, the District of Columbia, and Puerto Rico. The USGS has recently made this data available through its website which can narrow the retrievals according to a variety of search parameters.

The most daunting task in the creation of the data set is selecting the best sites. The ideal site has at least five years of streamflow and water quality data and is located just above the head of tide in a watershed that narrows to a single river which empties into the ocean without any diffusion into marsh. Such sites are rare due to a variety of geographical factors and portions of the coast (notably Florida and Louisiana) have extremely complex and unexpected flow patterns.

To aid in site selection, Arcview GIS software is being used to display the coastal watersheds available through the National Hydrography Dataset, as well as the location of USGS water monitoring stations and other relevant information. One important feature of the NHD is its navigation utility, which can trace all upstream or downstream reaches from a particular location. This aids in selecting sites that involve as much drainage area as possible, and also prevents selecting sites with overlapping drainage areas, which would bias the data.

In addition to the challenges of flow patterns, locating where a stream ceases to be influenced by tidal waters is in no way a straightforward process. The natural fall line, artificial structures, elevation, high and low flows, as well as high and low tides all affect tidal influence. The Coastal Assessment Framework identifies approximate head of tide locations for many rivers based on data collected from several sources. These locations were used to select the best possible sites for those rivers. For other streams and rivers, the most downstream site was usually chosen. Then the individual state USGS offices were contacted and asked to verify that the sites were below the head of tide. This verification was considered the best information since it is based on local knowledge.

Once site selection is completed, the water quality and flow data will be downloaded from the USGS website and analyzed. A preliminary sample showed a strong correlation between flow and load. If this relationship holds with a larger sample, Principle Component Analysis will be used to determine the function associated with each water quality parameter. These functions will then be used to extrapolate the loads for points of outlet along the coasts. Finally, the load information will be input into the modeling program to observe and evaluate the affect that coastal water quality has on the ocean biogeochemical cycle. Efforts in the third year of this project will work to include the entire U.S. West coast.

West Coast Modeling (UCLA, NASA/GSFC, SIO)

UCLA's Contribution: During the third year, we further developed our coupled ecosystem-biogeochemistry model by (i) including multiple nutrient limitations (silicate and iron), (ii) adding three more phytoplankton groups representing the most important functional groups (e.g. diatoms, coccolithophores, small phytoplankton, and large non-diatomeous phytoplankton), (iii) adding dissolved organic material, and (iv) by starting to add a biogeochemically active benthic layer at the bottom.

The analyses of the ecosystem and carbon cycles for the equilibrium U.S. West Coast solutions (described above) are being completed and published (Gruber et al., 2004; Plattner et al., 2004). Furthermore, we are continuing to calculate solutions with vigorous eddy activity and stronger near-shore topographic influences using the embedded grids for the Monterey Bay and Southern California Bight regions. These have have synoptically and interannually varying forcing, boundary conditions specified from the whole-Pacific solutions, the ecosystem and carbon-cycle modules, and sediment transport, plus extensive data comparisons and flux/budget analyses. The further generalizations are work in progress.

SIO's Contribution: During the third year of this proposal, we will continue to assemble and analyze datasets of physical fields and biogeochemical fields, especially NASA satellite products, in the CCS. These will be compiled and evaluated for use in validating seasonal, interannual and interdecadal simulations of the CCS. We will continue to develop procedures and codes for quantifying model-data discrepancies in collaboration with UCLA and Wallops. We will continue to develop and tune the ecosystem model in collaboration with Rutgers, UCLA and Wallops.

We continue to assess the sensitivity of the physical-biological simulations to changes in surface and boundary conditions. Interannual and interdecadal dynamics in the SCB were studied in a long-term model integration using the 50-year (1950-2000) CalCOFI data as a time varying oceanic boundary condition (Di Lorenzo et al., 2004a,b). Surface forcing functions for this integration are derived by projecting the NCEP reanalysis data onto structure functions determined by the regional atmospheric model (RSM). Once the physical model proves to be capable of reproducing the observed variability, the ecosystem model will be included in the run to assess long-term changes in the biology. These integrations will also allow us to address fundamental questions on decadal-scale regional changes in the carbon cycle.

NASA/GSFC's Contribution: In the third year of the project, we will work with UCLA and SIO to continue developing the biogeochemical model (Gruber et al, 2004). We will also work to pass over the watershed forcing data fields once they become available.

East Coast Modeling (Rutgers, NASA/GSFC)

Rutgers's Contribution: The next development step in enhancing the NENA model will the refinement of spatial resolution to allow a better representation of the shelf bathymetry and improved simulation of coastal and deep-ocean/shelf-sea interaction processes. However, before further refinements of the NENA model undertaken an assessment will be made of the practicality and utility of expanding the NENA domain to incorporate the Gulf of Mexico. The magnitude of the Mississippi River outflow represents a substantial input of terrestrial nutrients to the marine ecosystem, and presents a compelling argument that the Gulf of Mexico be included in any model of the carbon cycle on the US East Coast. A suitable curvilinear model domain has been identified (Figure 14).

NASA/GSFC's Contribution: We will continue to develop and test the biogeochemical model in both the 1D and 3D configurations. We will work with SIO/UCLA/Rutgers to maintain similar biogeochemical model configuration and to pass off newer model versions and forcing conditions for the watershed forcing. Additionally, we will continue to develop model to data intercomparisons. We will begin carrying out coupled circulation/biogeochemical simulations for the U.S. East Coast domain and also begin to compare and contrast the U.S. East Coast versus West Coast ocean carbon cycle budgets and their sensitivities to forcing perturbations.

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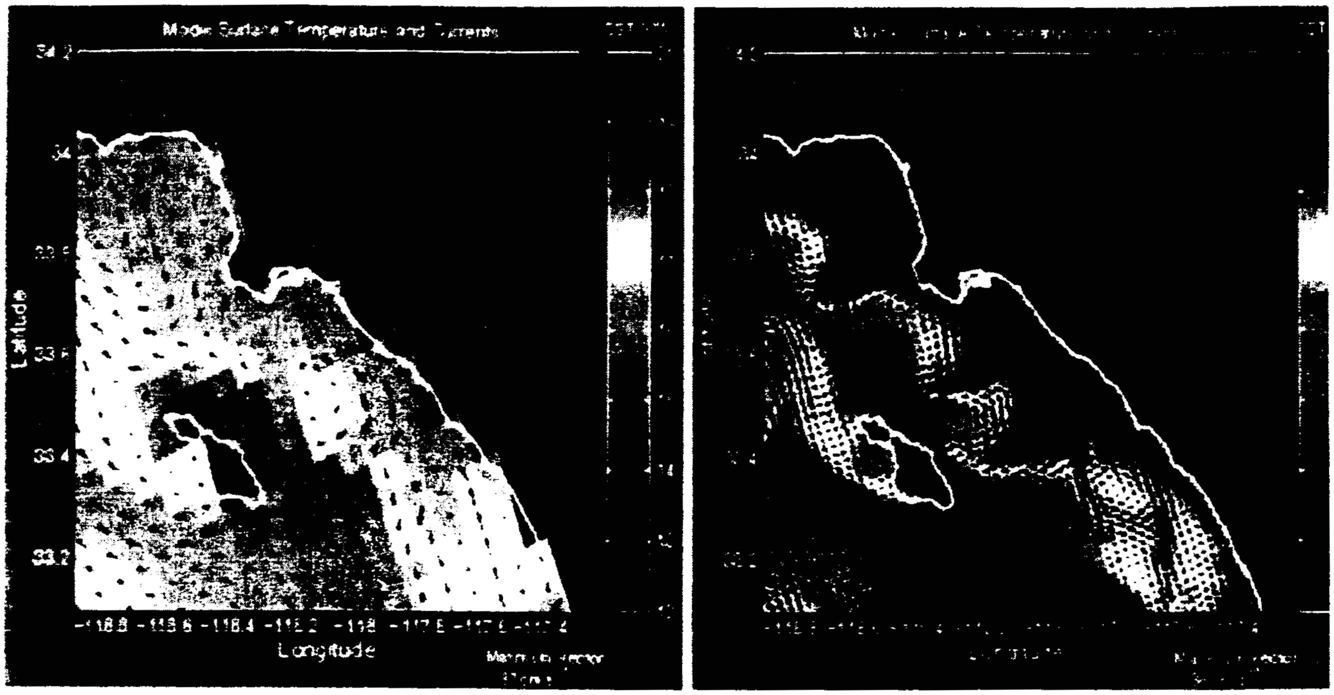

Figure 1: Southern California Bight surface temperature and currents for the two finer-resolution sub-domains in a 3-level (i.e., 18+6+2 km) configuration. Note the strong influences of island and coastline topography around Santa Monica Bay in the 2 km sub-domain. (Marchesiello et al., 2003.)

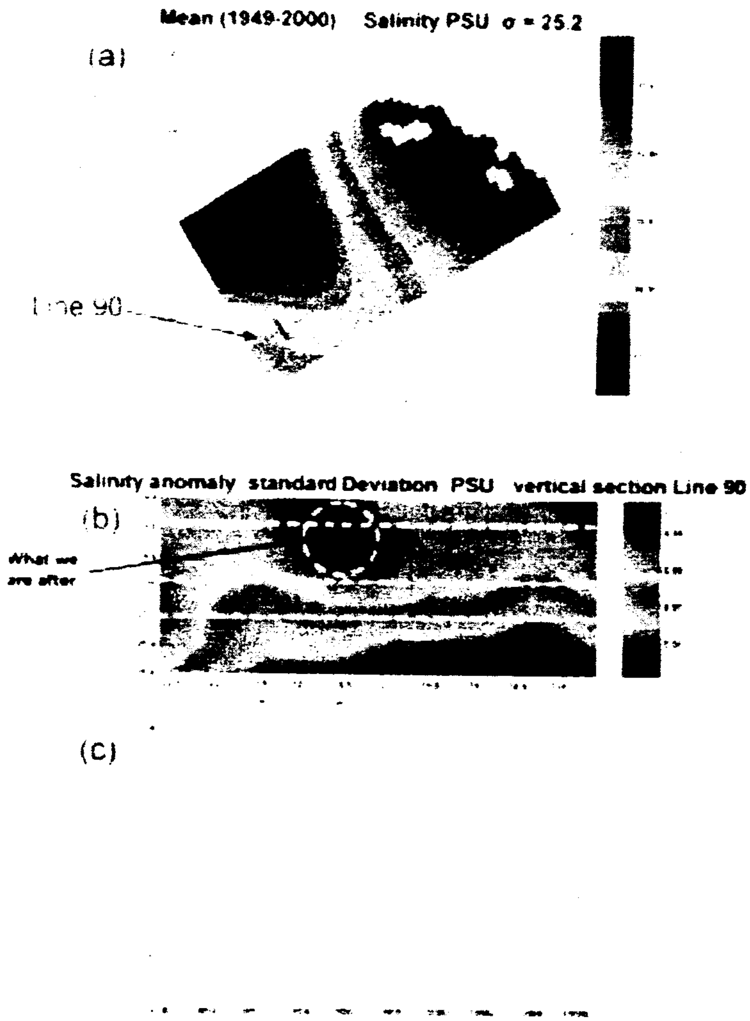

Figure 2: (a) Mean salinity (1949-2000) from CalCOFI observations. (b) Vertical section along line 90 of standard deviation of salinity anomaly relative to the mean (a). (c) Low-pass filter time series of cross-shore average of salinity anomaly (green) lagged 4 years from the low-pass Nino-3 index (blue). [for (b) x-axis denotes longitude along line 90 and y-axis denotes sigma-t values; for (c) x-axis denotes time in years and y-axis denotes salinity anomaly (unitless) values]

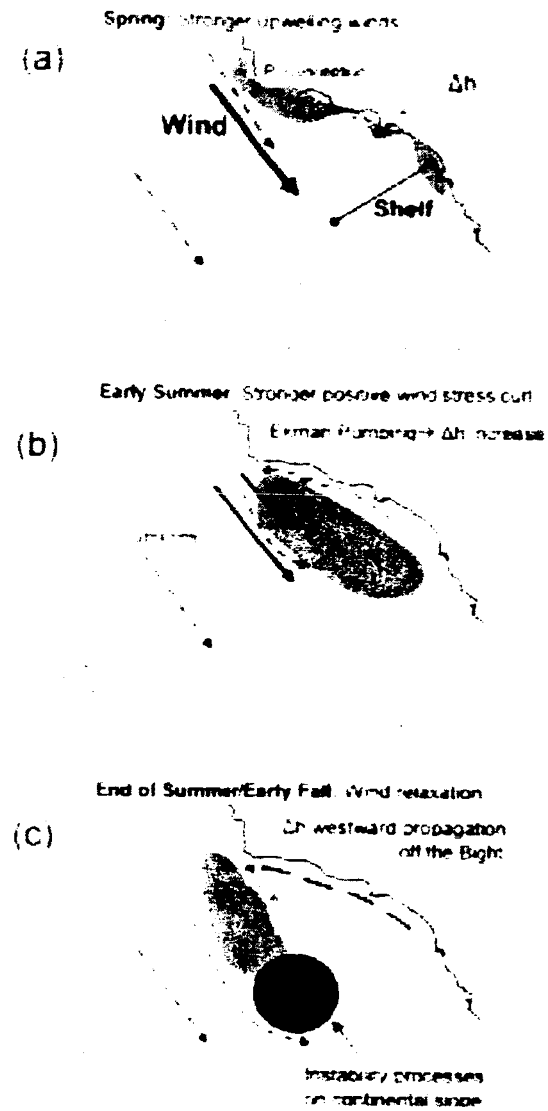

Figure 3: Schematic of the seasonal dynamics in the Southern California Current System from spring (a), early summer (b) through fall (c). Black arrows are wind stress, red arrows are current and shaded areas denote regions of shoaling isopycnals (h; positive density anomaly).

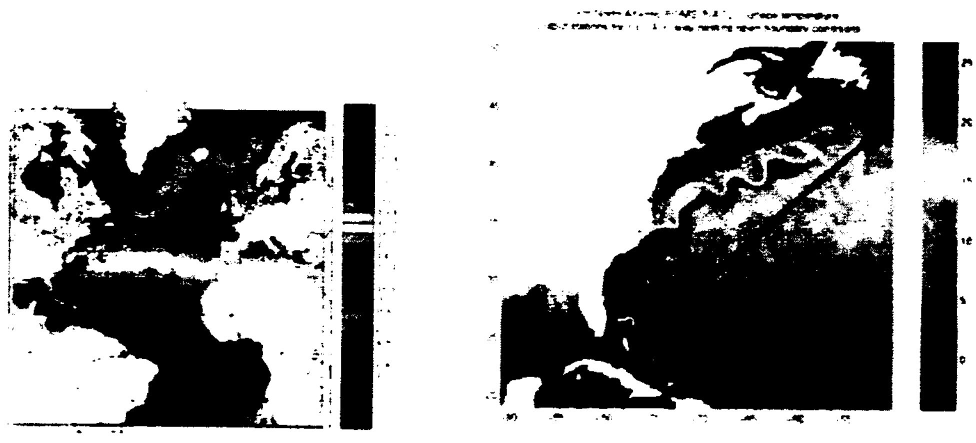

Figure 4: (Left) Sea Surface Temperature (SST) image of the full domain of the North Atlantic (NATL) basin model. SST solution (right) shown for day 1140 of the calculation using a 10 km horizontal grid resolution. The solid black line/boundary denotes the output stations for the 1-way nested open boundary conditions for the North-East North Atlantic (NENA) domain.

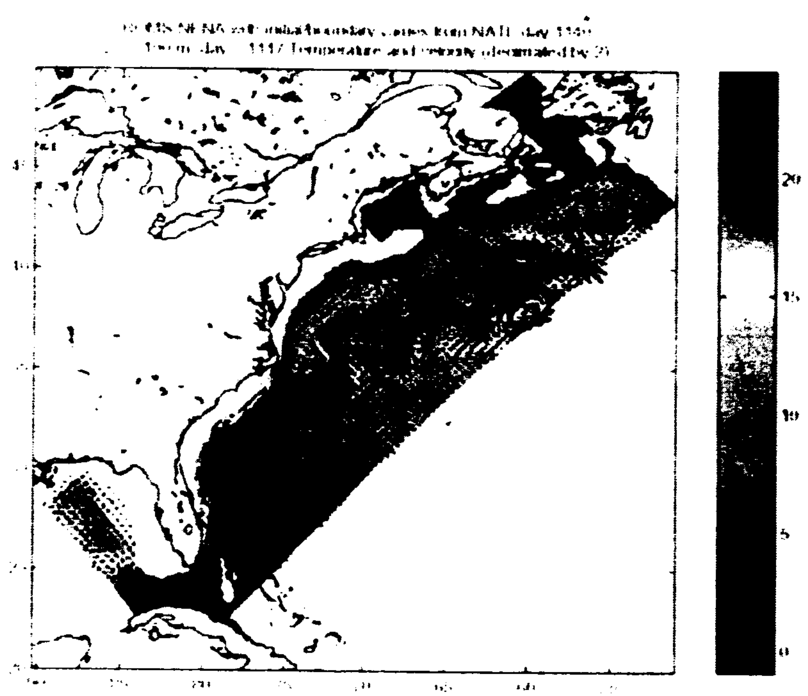

Figure 5: Prototype North East North Atlantic (NENA) domain. The color bar indicates the temperature at 100 m depth and the vectors denote velocity.

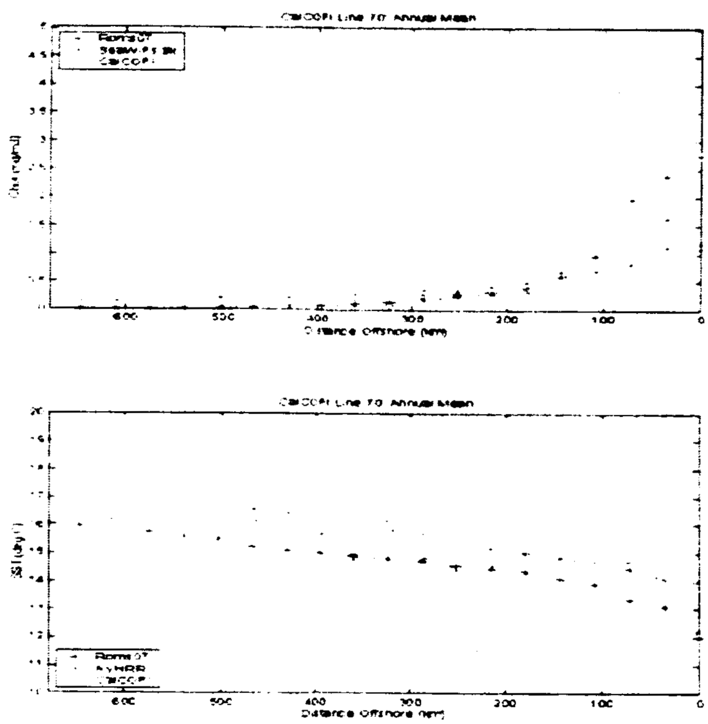

Figure 6: Annual-mean surface values of Chlorophyll A (top) and Sea Surface Temperature (bottom) along CalCOFI Line 70 along the U.S. West Coast. In each panel are model, in situ, and satellite results. (Gruber et al., 2004.)

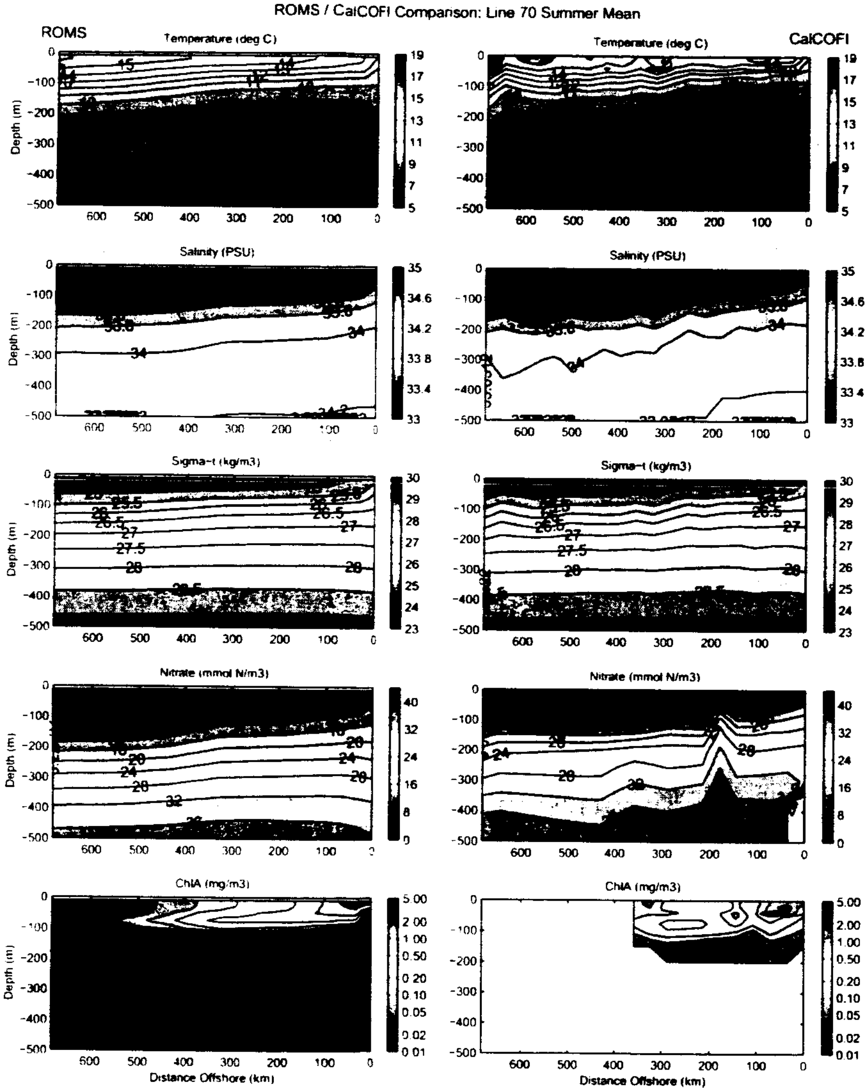

Figure 7: Cross-section of summer mean hydrographic and biogeographical quantities for model result (left) and in situ data (right) along CalCOFI line 70. Model results represent the summer mean of a 10 year simulation. CalCOFI data represent the long-term summer mean from 1949 to 2000 (Gruber et al., 2004).

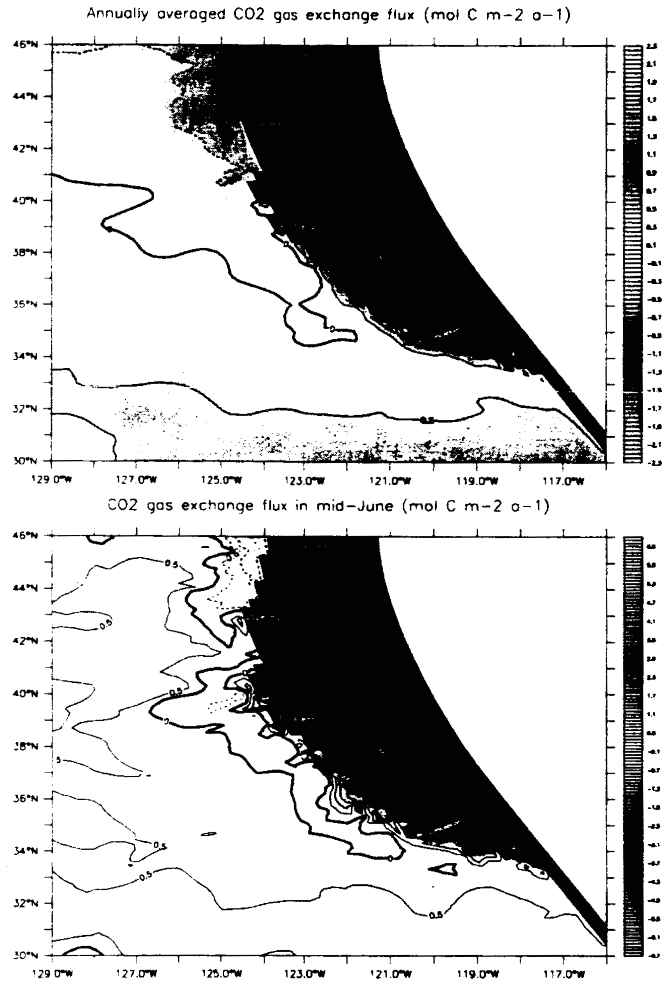

Figure 8: Air-sea flux of CO2 along the U.S. West Coast: annual mean (top) and instantaneous (bottom).

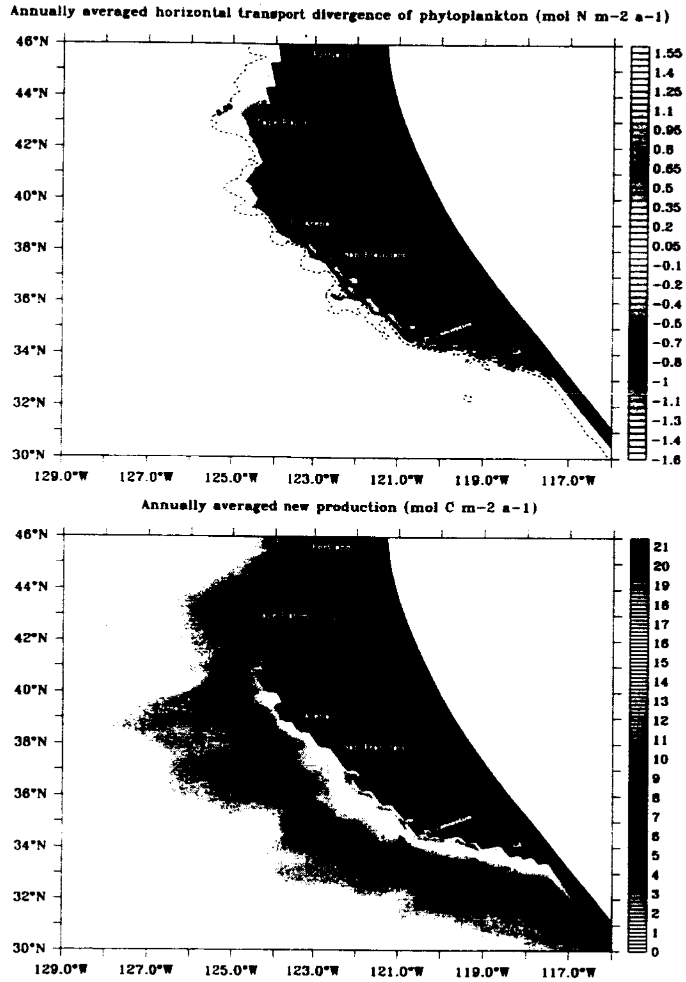

Figure 9: Air-sea flux of CO2 along the U.S. West Coast: annual mean (top) and instantaneous (bottom).

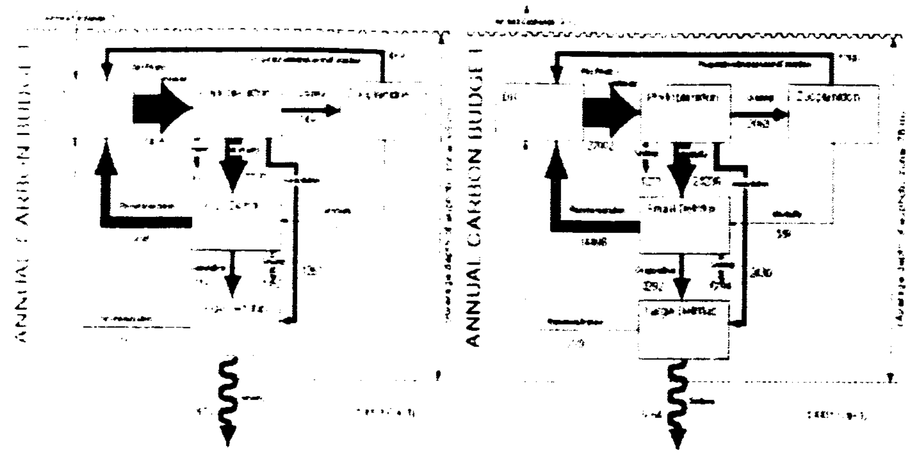

Figure 10: Carbon budgets for the near-shore (left) and off-shore regions (right) along the U.S. West Coast.

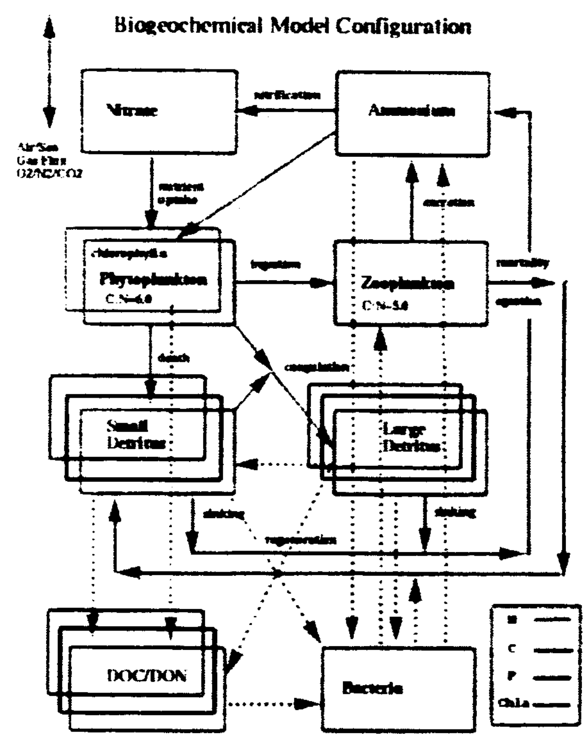

Figure 11: Present biogeochemical model configuration. Not shown are the boxes for Oxygen, TIC, and Alkalinity. Carbon, Nitrogen, Phosphate, and Oxygen pathways are now being resolved. All of the model pathways follow stoichiometric balances while maintaining variable C:N:P ratios for different model variables.

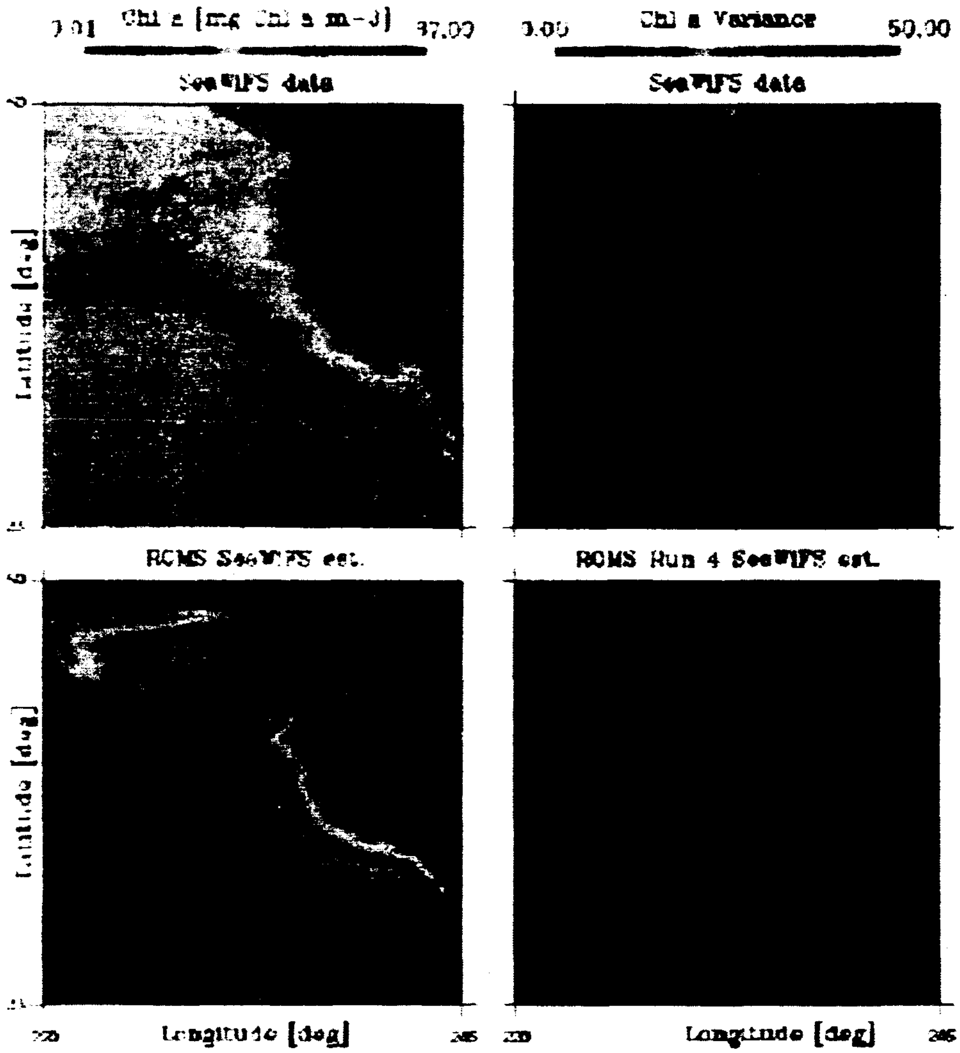

Figure 12: Comparison of the annual mean (left panels) and variance (right panels) chlorophyll a between the SeaWiFS data (upper panels) and the model simulation (lower panels).

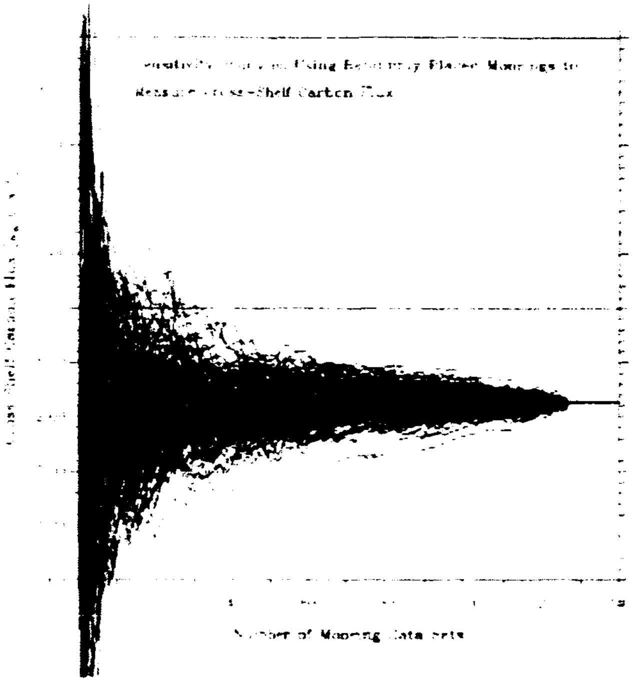

Figure 13: Composite plot of a suite of cross-shelf carbon flux estimates made by randomly choosing an increasing number of grid points "simulated moorings" to calculate/estimate the flux. As the number of "moorings" increases, the estimate approaches the model solution. Of interest to field oceanographers is the large range and sign changes observed at low-yet typical numbers-of "moorings."

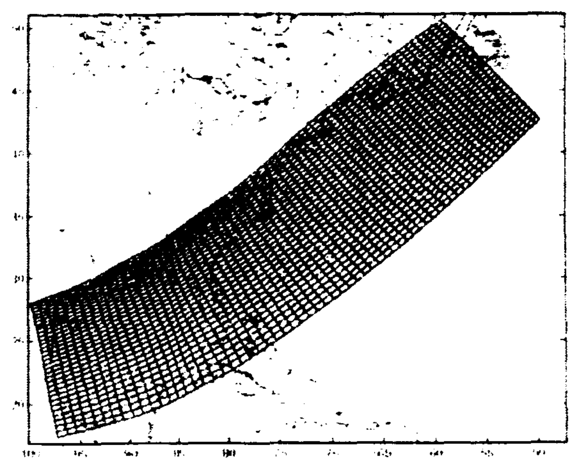

Figure 14: Figure 14: Curvilinear model domain for the U.S. East Coast expanded to include the Gulf of Mexico.