FINAL REPORT: NASA CARBON CYCLE Investigation NAG5-11245

PROJECT TITLE: Interannual to decadal air-sea carbon fluxes: Analysis of marine productivity and nutrient data with an inverse carbon cycle model.

PROJECT ID: NAG5-11245

Principal Investigator: Arne Winguth
Co-Investigator: Henry J. Niebauer

Members Supported:
- **Scott Bennett, Undergraduate student**
- **Matthew Dobbel, Undergraduate student**
- **Matthew Howard, MS student**
- **Yuliana Ng, Undergraduate student**
- **Heather Peto, MS student**
- **Dierk Polzin, Senior Research Specialist**
- **Jenny Puckett, Undergraduate student**
- **Jerry Tjiputra, PhD student**
- **Patrick Wetzel, invited PhD student**

1. MAJOR FINDINGS

Future changes and variability in climate, and atmospheric carbon dioxide appear imminent. They will likely drive large changes in ocean storage as well as marine productivity of phyto- and zooplankton on the seasonal to centennial time scale. In this project, we have improved estimates of carbon cycle parameters and seasonal carbon fluxes in the euphotic zone by developing an inverse carbon cycle model. By assimilation of SeaWiFS data, this model yields a better prediction of the seasonal carbon cycle, particularly if parameters are allowed to vary regionally. The fluxes from the euphotic zone to the deep sea have been evaluated by investigating the sensitivity of ocean carbon tracer distributions to particulate organic flux parameterizations. The three-dimensional carbon model has been applied to predict the interannual air-sea CO_2 fluxes for a period of 56 years using the NCEP/NCAR reanalysis data. Moreover, we supported the development of a comprehensive Earth System Model (ESM), which was applied to project long-term climate changes in the future in order to estimate the relevant interactions between climate change and the carbon cycle.

1.1. Adjoint approach: Sensitivity of ecosystem parameters to changes in seasonal chlorophyll concentration

In this project, an adjoint method is applied to a three-dimensional global ocean carbon cycle model (Hamburg Ocean Carbon Cycle; Figure 1) to optimize the ecosystem parameters based on SeaWiFS. The work is document in Tjiputra (2004) and Tjiputra et al. (submitted to Global Biogeochem. Cycles). We evaluated the recovery of several control variables (Figure 2).

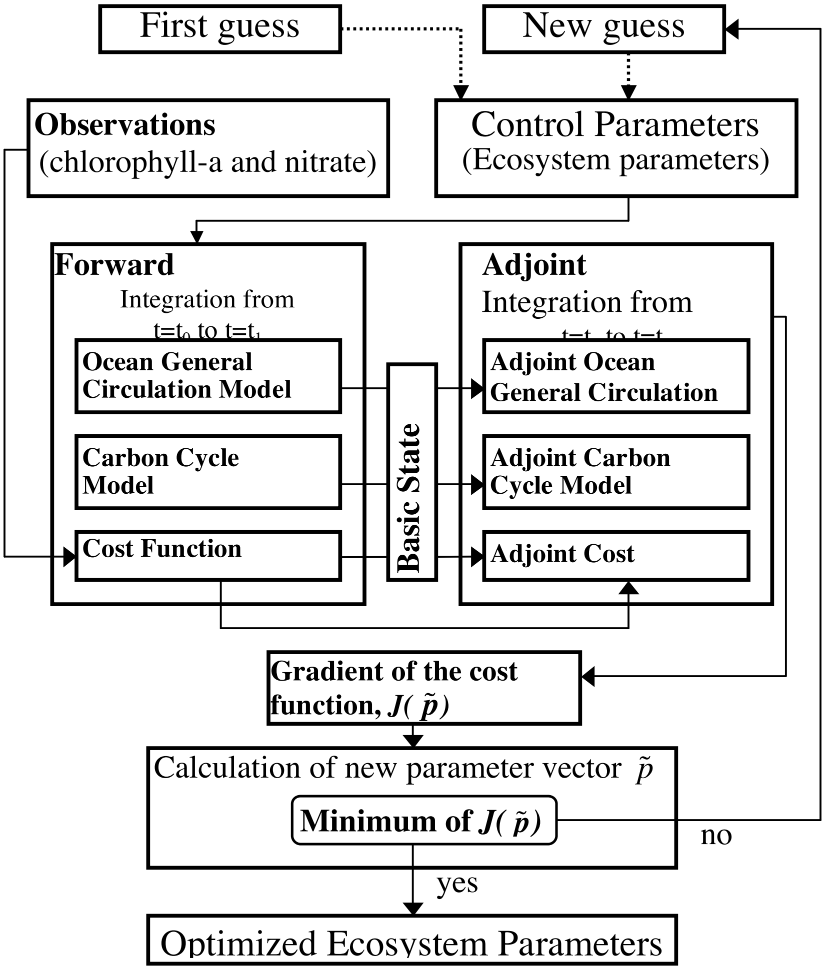

Figure 1. Schematic flow diagram of the adjoint model.

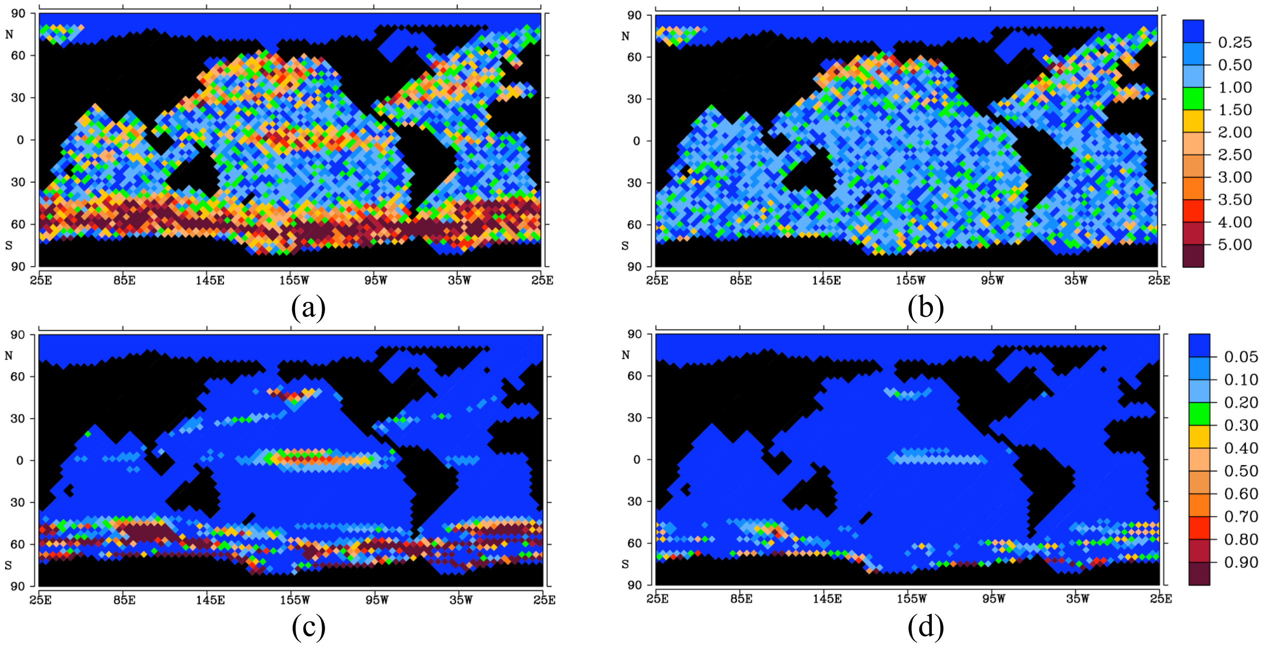

Figure 2. A priori (a) and a posteriori (b) relative cost function plot of the identical twin experiment with noise added to the artificial chlorophyll data, and a priori (c) and a posteriori (d) relative cost function of the identical twin experiment without noise added (simulation for JFM).

We showed that the assimilation with synthetic data can substantially reduce the cost function (Figure 2). If noise is added to the synthetic data in the magnitude of the uncertainties of the SeaWiFs data, the performance of the data assimilation is reduced, specifically in the Southern Ocean. Assimilation of the SeaWiFS data yields only a relatively small improvement when ecosystem parameters are kept uniform spatially, but consideration of regional variation of the ecosystem parameters substantially reduces the model-data bias. The assimilation of SeaWiFS chlorophyll data improved the results especially in high-latitude regions. Sensitivity parameters of the simulated chlorophyll concentration are the egestion as fecal pellets, zooplankton grazing, and the assimilation efficiency (Tables 1-3). Moreover, we showed with data assimilation experiments that the consideration of regional variations of ecosytem parameters reduces the model-data bias substantially (Table 1). The seasonal variability of the optimized data is particularly high in the high latitudes, which is related to the non-linear physical processes. The annual carbon fluxes between main components yielded by the marine ecosystem model are shown in Figure 3. The a priori annual global net primary production is 41 Pg C yr^{-1}, which is comprised of 10.6 Pg C yr^{-1} new production and 30.4 Pg C yr^{-1} regenerated production. The a posteriori net primary productions are 8.7 Pg C yr^{-1} and 27.3 Pg C yr^{-1}, respectively. The net primary production remains within the lower limit of annual NPP values suggested by Antoine et al. (1996) of 36 Pg C yr^{-1} (Figure 1), higher than Berger's (1989) of 27 Pg C yr^{-1}, but lower than those estimated by Falkowski et al. (1998) and Behrenfeld et al. (2005) of ~45-50 and 60 Pg C yr^{-1}, respectively. The assimilation increases the chlorophyll concentration in most of the global regions, except for the Southern Ocean in the OND months. Accordingly, the net primary productions for the months of JFM, AMJ, and JAS increase by 1.7, 0.6, and 0.6 Pg C yr^{-1}, respectively, but is relatively high because of the lower grazing rate (by zooplankton) parameter. Thus fewer phytoplankton biomass is consumed by zooplankton (reduced by approximately 6 Pg C yr^{-1}). In a steady state, the new primary production is equal to the total export of organic material out of the euphotic zone. The new set of ecosystem parameters reduces the export of DOC out of the euphotic layer by nearly 2 Pg C yr^{-1}, while the export production of POC into the deep ocean is maintained at 7 Pg C yr^{-1}. Additional constraints of nutrient data from the World Ocean Atlas helped to further reduce the model-data misfit.

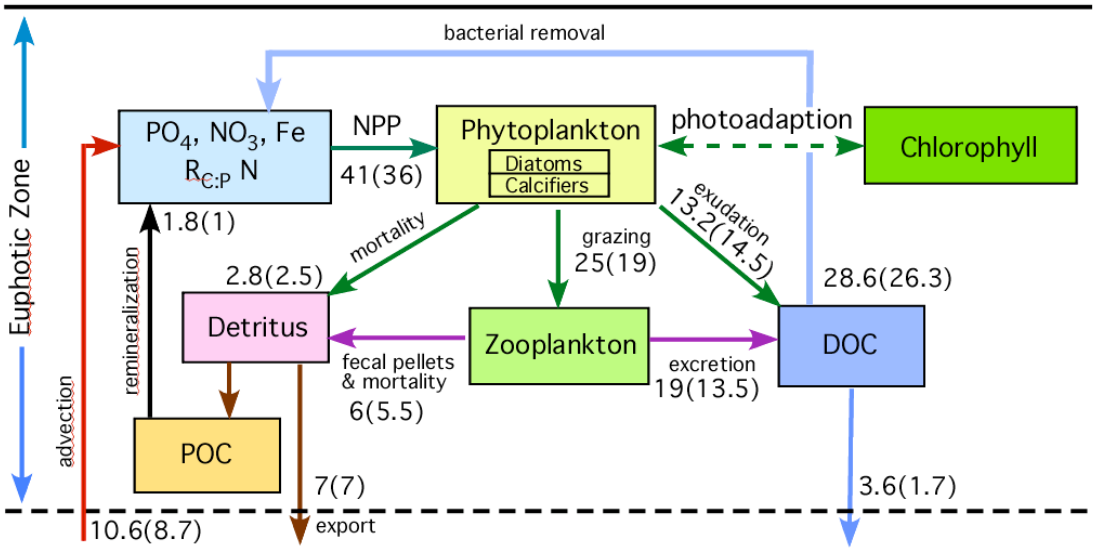

Figure 3. Schematic diagram of main processes simulated in the ecosystem model. Carbon fluxes between boxes are given in Pg C yr^{-1} (simulated value in parenthesis represent values after data assimilation).

1.2. Sensitivity of ocean carbon tracer distributions to particulate organic flux parameterizations

Another important factor to investigate the storage, sources and sinks of the carbon in the euphotic zone is the carbon export into the twilight zone. Vertical fluxes of particulate organic carbon (POC) from the euphotic zone to the deep sea are an important part of the carbon cycle in the oceans. In a study of Howard (2004) and Howard et al. (in press), oceanic fluxes of POC below the euphotic zone were simulated with the Hamburg Ocean Carbon Cycle Model (HAMOCC5.1) by using different POC-flux parameterizations, and model results were compared with sediment trap data. Overall, the geochemical distributions in the deep sea showed a high sensitivity to the selection of POC flux parameterization. Below 2000 m in the oceans, differences between simulated and observed carbon tracers (PO_4, Alk*) and model-data differences of POC fluxes are lowest when a regionally variable POC flux parameterization is used. Specifically, model-data differences are lowest in the subtropics when simulated vertical POC flux considers mineral ballasting, while lowest in the Arabian Sea and west coast of Africa when a mineral dust parameterization is used for the vertical POC flux.

1.3. Estimates of interannual air-sea CO_2 fluxes

While the previous two sections covered the sensitivities of the parameterizations to changes in chlorophyll concentration and carbon cycle, this section and the following section will focus on the prediction of the carbon cycle on the interannual to centennial prediction of the carbon cycle and its response to changes in climate, i.e. in ocean circulation. A marine carbon cycle model embedded in a state-of-the-art ocean general circulation and sea ice model has been applied to quantify the important mechanisms of the interannual and decadal sea- to-air CO_2 flux variability and the variations in the uptake of anthropogenic CO_2. The model is forced by daily NCEP/NCAR reanalysis data over a 56-year period of time, showing trends and variability on interannual and decadal scales. The average CO_2 flux of -1.49 Pg C yr^{-1} for 1980-89 and -1.74 Pg C yr^{-1} for 1990-99 agrees reasonably well with the estimates from atmospheric inversions (Rödenbeck et al., 2003; Gurney et al., 2002) (Table 4).

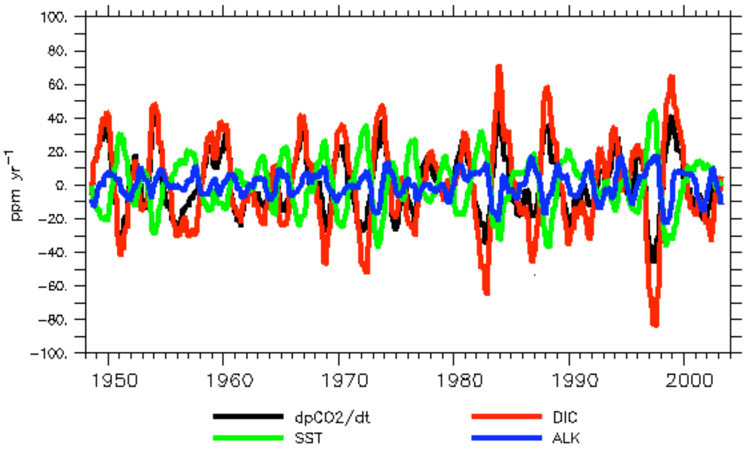

Figure 4. Component analysis for the terms of the equation below in the surface box of the equatorial Pacific from 10°S to 10°N and 80°W to 135°E. All fluxes are from the control run and smoothed with a 12 month running mean. The total change of pCO_2 can be calculated (Wetzel et al., 2005) by a change of total dissolved inorganic carbon (DIC; red), total alkalinity (TALK; blue), temperature (T; green), and salinity (S):

$$\frac{dpCO2}{dt} = \frac{\partial pCO2}{\partial DIC}\frac{dDIC}{dt} + \frac{\partial pCO2}{\partial TALK}\frac{dTALK}{dt} + \frac{\partial pCO2}{\partial T}\frac{dT}{dt} + \frac{\partial S}{\partial S}\frac{dS}{dt}$$

The temporal variability pCO2 in the equatorial sea surface is predominantly controlled by the changes in DIC.

The total interannual variability of the model is ±0.50 Pg C yr^{-1}, confirming estimates from previous studies. This is largely dominated by ocean dynamics in the equatorial Pacific, where changes in air-to-sea CO_2 fluxes have a variability of ±0.33 Pg C yr^{-1} and are characterized by wind stress-induced changes in the surface dissolved inorganic carbon concentration (Figure 4). We estimate an average CO_2 flux into the ocean of -1.74 Pg C yr^{-1} for the period between 1990 and 2000, with extremes of -1.20 Pg C yr^{-1} flux at the La Niña in 1996 and -2.10 Pg C yr^{-1} flux during the El Niños in 1993 and 1998. Overall, about 124.3 Pg of anthropogenic carbon have accumulated in the model ocean for the period from 1800 to 2000. This estimate of anthropogenic CO_2 uptake is consistent with a recent study from Sabine et al. (2004). A detailed summary of the work can be found in Winguth et al. (2004) and Wetzel et al. (2005).

1.4. CO_2 uptake of the marine and land biosphere in response to future climate change using an earth system model

A complex earth system model including atmosphere, ocean, ice sheets, marine carbon cycle and terrestrial vegetation was used in a collaborative effort with the Max-Planck-Institute to study the long-term response (100-2000 yrs) of the climate to anthropogenic carbon emissions. The model is described in Winguth et al. (2005) and a detailed description can be found in Mikolajewicz et al. (submitted to the Journal Climate Dynamics). Global mean surface temperature increases between 1 and 5 K depending on the IPCC (2001) A2, A1B, and B2 emission scenarios under the assumption that the emission will exponentially decline after the end of this century. For high emission scenarios, the breakdown with no recovery of the thermohaline circulation in the North Atlantic is predominantly controlled by an increase in atmospheric moisture transport, while melting from continental ice sheets has a secondary impact on the changes in the ocean circulation. For the next 100 years, uptake of anthropogenic carbon by land and ocean is predicted to be about equal. Thereafter, the large carbon storage capacity of the ocean dominates the uptake of anthropogenic carbon with 60-70% for the high emission SRES A2 scenario (Figure 5). Increased equatorial upwelling enhances the tropical outgassing of CO_2 from the oceans, but the simulated effect of a collapse of the deep water formation in the North Atlantic on the atmospheric CO_2 concentration turned out to be relatively small.

The consideration of the feedback between the carbon cycle and climate reduces the carbon uptake substantially by 24-26%, relative to simulations without feedback. Thus, we show that both marine and terrestrial carbon cycle have a positive feedback on climate, which has to be considered for future carbon emission scenarios.

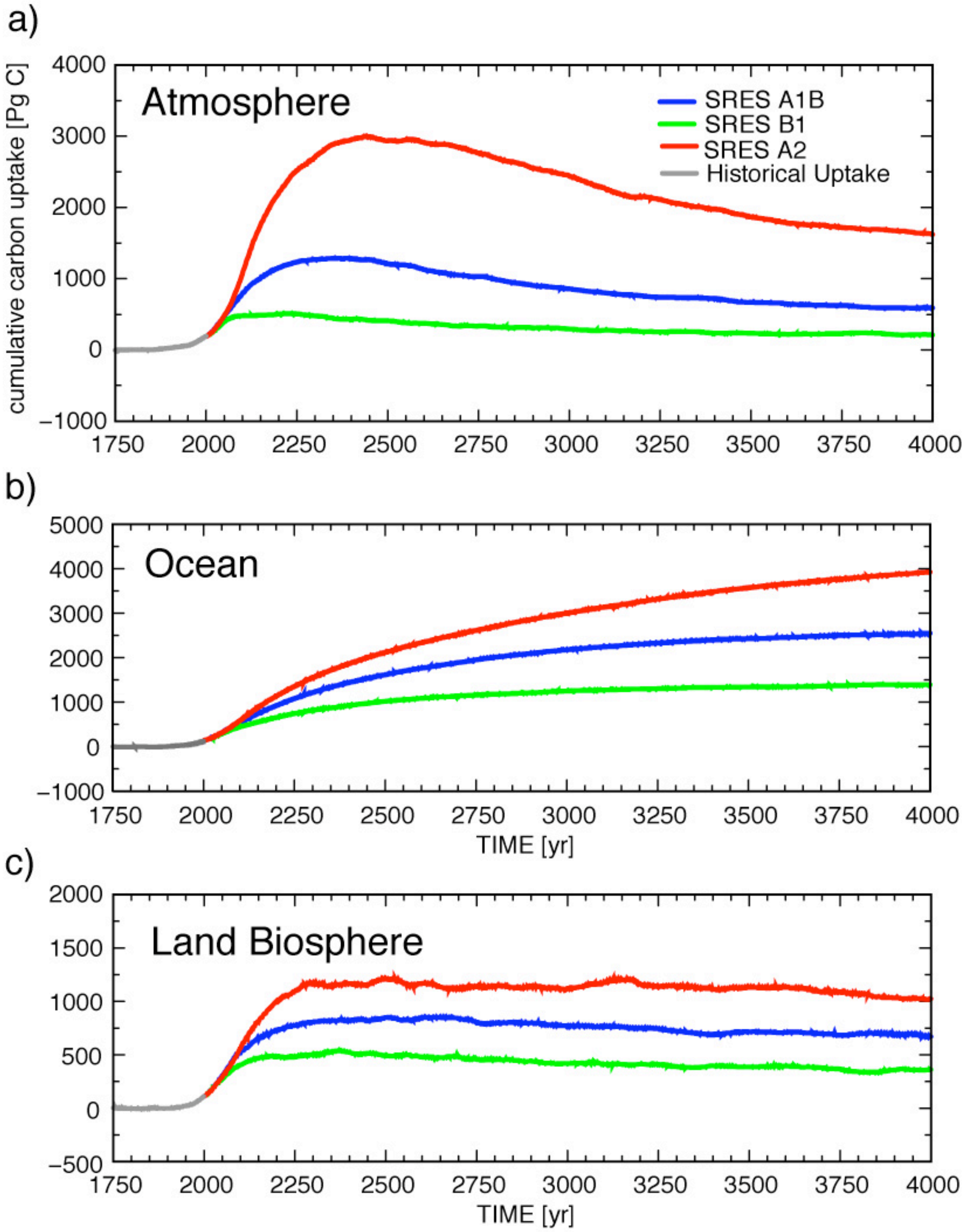

Figure 5. Cumulative carbon uptake by the (a) atmosphere, (b) ocean and (c) land. The marine change includes uptake in the water column as well as changes in the sediment.

2. IMPACT AND FUTURE WORK

A major goal of this project has been to understand and quantify processes which influence the seasonal-to-centennial fluctuations of the marine carbon cycle. We have conducted comprehensive computer simulations by utilizing the unique information provided by SeaWIFS satellite remote sensing to explore the ecosystem model framework for a regional and temporal assessment of the global carbon cycle. Our results show that the synthesis form satellite remote sensing and the comprehensive carbon cycle model provides relatively unique and spatially explicit information regarding changes in the marine biosphere structure that can improve global assessment and monitoring of carbon fluxes for the eupothic zone. We have identified sensitive parameterization like grazing and exudation rate that strongly influence the biological contribution in the fluxes. Results from that study showed that the forecast can be substantially improved if a spatial variation of these parameters is considered. Moreover we showed that the marine contribution of the interannual changes of carbon is substantial, but less than the contribution by the land biosphere. On the longer time scale the ocean with its large capacity to store carbon becomes more relevant, in particular regarding future climate change. Our model predictions also confirm that the consideration of climate change by increased anthropogenic carbon invasion significantly changes the uptake of the carbon by the ocean.

Improved estimates of remote sensing tracer distribution and more detailed hydrographic data need to be included in future carbon cycle modeling. An important goal would be to evaluate the sensitivity of air-sea pCO2 fluxes to changes in the ecosystem parameters with a higher vertical and spatial resolution of the ecosystem model. Moreover the error analysis for both remote sensing data as well as carbon cycle models needs to be investigated more systematically. For the prediction of interannual to long-term future processes, it is desirable to improve model parameterizations by evaluating them with the observations. Examples include detailed particle size classes, processes related to sediment geochemistry, and parameterizations of coastal processes for global models. Further research is needed in order to achieve these goals.

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4. TEAM ACTIVITIES

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Publications supported by this grant:

a.) Papers published and in press

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Appendix: Tables

Experiments	Data	Optimized parameters		Cost function reduction
		Months	Regions	
REF	-	-	-	-
ITE_JFM	Synthetic Chl-a (with noise)	JFM	Global	92%
ITE_AMJ	Synthetic Chl-a (with noise)	AMJ	Global	66%
ITE_JAS	Synthetic Chl-a (with noise)	JAS	Global	36%
ITE_OND	Synthetic Chl-a (with noise)	OND	Global	63%
ITEN_JFM	Synthetic Chl-a (with no noise)	JFM	Global	94%
ITEN_AMJ	Synthetic Chl-a (with no noise)	AMJ	Global	95%
ITEN_JAS	Synthetic Chl-a (with no noise)	JAS	Global	82%
ITEN_OND	Synthetic Chl-a (with no noise)	OND	Global	97%
GAC_JFM	SeaWiFS Chl-a	JFM	Global	1%
GAC_AMJ	SeaWiFS Chl-a	AMJ	Global	12%
GAC_JAS	SeaWiFS Chl-a	JAS	Global	16%
GAC_OND	SeaWiFS Chl-a	OND	Global	18%
GACN_JFM	SeaWiFS Chl-a and NO_3	JFM	Global	9%
GACN_AMJ	SeaWiFS Chl-a and NO_3	AMJ	Global	12%
GACN_JAS	SeaWiFS Chl-a and NO_3	JAS	Global	17%
GACN_OND	SeaWiFS Chl-a and NO_3	OND	Global	17%
RANC_JFM	SeaWiFS Chl-a	JFM	North	17%
RANC_AMJ	SeaWiFS Chl-a	AMJ	North	20%
RANC_JAS	SeaWiFS Chl-a	JAS	North	54%
RANC_OND	SeaWiFS Chl-a	OND	North	43%
RATC_ JFM	SeaWiFS Chl-a	JFM	Tropic	3%
RATC_ AMJ	SeaWiFS Chl-a	AMJ	Tropic	1%
RATC_ JAS	SeaWiFS Chl-a	JAS	Tropic	12%
RATC_OND	SeaWiFS Chl-a	OND	Tropic	8%
RASC_ JFM	SeaWiFS Chl-a	JFM	South	9%
RASC_ AMJ	SeaWiFS Chl-a	AMJ	South	28%
RASC_ JAS	SeaWiFS Chl-a	JAS	South	3%
RASC_ OND	SeaWiFS Chl-a	OND	South	38%

Table 1. Experiment description, set-ups, and cost function reduction for each experiments. North, tropic, and south region are defined as 90°N-22°N, 22°N-22°S, and 22°S-90°S respectively.

Parameter	Symbol	Description	Value	Units
P1	lo	POC Remineralization Rate	0.0033	W m^{-2}
P2	γZ	DOC Excretion by ZOO	0.06	d^{-1}
P3	dp	PHY Mortality Rate	0.008	d^{-1}
P4	γP	DOC Excretion by PHY	0.06	d^{-1}
P5	$(1-\eta)$	Herbivore Egestion as Fecal Pellets	(1 - 0.8)	-
P6	G	ZOO Grazing Rate	0.5	d^{-1}
P7	ψ	Assimilation Efficiency	0.5	-
P8	dz	ZOO Mortality Rate	0.008	d^{-1}
P9	$(1-\varepsilon)$	Carnivore Egestion as Fecal Pellets	(1 - 0.95)	-
P10	do	DOC Maximum Remineralization Rate	0.005	d^{-1}

Table 2. Descriptions of the selected control parameters used in the assimilation.

Experiments	P1′	P2′	P3′	P4′	P5′	P6′	P7′	P8′	P9′	P10′
(A priori)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
RANC_JFM	1.000	1.065	0.981	0.787	0.910	0.888	0.924	1.012	1.000	1.028
RATC_JFM	1.007	1.064	0.997	0.936	0.954	0.928	0.904	1.015	1.005	1.062
RASC_JFM	1.000	1.027	1.000	0.988	0.970	0.975	0.976	1.005	1.000	1.003
RANC_AMJ	1.000	1.079	0.972	0.479	0.774	0.840	0.840	1.016	1.000	1.065
RATC_AMJ	1.000	1.001	1.000	0.999	0.999	0.999	0.998	1.000	1.000	1.000
RASC_AMJ	1.002	1.114	0.991	0.845	0.888	0.845	0.910	1.022	1.002	1.028
RANC_JAS	1.002	1.781	0.958	0.298	0.100	0.198	0.100	1.148	1.020	1.247
RATC_JAS	1.003	1.216	0.997	0.914	0.798	0.810	0.746	1.041	1.014	1.035
RASC_JAS	0.998	1.100	0.995	0.862	0.929	0.879	0.960	1.019	0.994	0.978
RANC_OND	1.000	1.304	0.968	0.847	0.918	0.774	0.772	1.053	1.030	1.022
RATC_OND	1.000	1.090	1.000	0.980	0.960	0.930	0.920	1.020	1.010	1.010
RASC_OND	0.999	0.821	1.102	0.942	1.110	1.526	1.538	0.964	0.996	0.792
Mean	1.001	1.139	0.997	0.823	0.859	0.883	0.883	1.026	1.006	1.022
Variance	0.000	0.054	0.001	0.047	0.065	0.085	0.101	0.002	0.000	0.010

Table 3. A posteriori ecosystem parameters (refer to Table 1 for parameter descriptions), values with mean and variance resulting from every regional assimilation experiments.

	Time span	South (≤20°S) Pg C yr^{-1}	Tropic Pg C yr^{-1}	North (≥20°N) Pg C yr^{-1}	Total Pg C yr^{-1}
This Study (CR control)	1980-1999	-0.11	1.18	-0.88	0.18
This Study (AR anthropogenic)	1980-1989	-0.9	0.65	-1.26	-1.5
	1992-1996	-1	0.54	-1.32	-1.78
	1996-1999	-1.03	0.6	-1.29	-1.72
	1995	-1.05	0.64		-1.75
Rödenbeck et al. (2003)	1980-1989				-1.2±0.3
	1990-1996	-1.0±0.1	0.9±0.2	-1.6±0.1	-1.7±0.3
	1996-1999	-1.2±0.2	1.1±0.2	-1.7±0.1	-1.7±0.4
Gurney et al. (2002)	1992-1996	-0.9±0.7	0.5±0.6	-1.1±0.4	-1.5±0.4
Takahashi et al. (2002)	1995	-1.51	0.9	-1.03	-1.64
IPCC (2001)	1980-1989				-1.9±0.6
	1990-1999				-1.7±0.5

Table 4. Sea-to-air flux of CO_2 into the northern hemisphere, tropics and southern hemisphere in Pg C yr^{-1}. (from Wetzel et al., 2005).