Development of Algorithms and Strategies for Monitoring Chlorophyll and Primary Productivity in Coastal Ocean, Estuarine and Inland Water Ecosystems

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Summary

This is the semi-annual technical report for the period July through December 2002 for the Execution Phase of my MODIS Instrument Team investigator project. The objectives of this work are:

- Establish a protocol for developing regional or site-specific bio-optical algorithms for coastal "case 2" waters.
- Prescribe a protocol for "stitching together" local or site-specific algorithms.
- Demonstrate these protocols in two coastal seas: the Gulf of Maine/Mid-Atlantic region, and the Yellow Sea/East China Sea region.
- Develop a strategy for monitoring coastal oceans, estuaries, and inland waters.

This report reflects the efforts of a research team consisting of myself, two staff scientists (Dr. Mark Dowell and Timothy Moore), and one Ph.D. student (Seung-Hyun Son).

Papers published or submitted:

1. Campbell, J.W., D. Antoine, R. Armstrong, K. Arrigo, W. Balch, R. Barber, M. Behrenfeld, R. Bidigare, J. Bishop, M.-E. Carr, W. Esaias, P. Falkowski, N. Hoepffner, R. Iverson, D. Kiefer, S. Lohrenz, J. Marra, A. Morel, J. Ryan, V. Vedernikov, K. Waters, C. Yentsch, and J. Yoder. "Comparison of algorithms for estimating ocean primary productivity from surface chlorophyll, temperature, and irradiance." *Global Biogeoch.Cycles*, 16(3), 10.1029 / 2001GB001444, 2002.

2. Mahadevan, A. and J. W. Campbell. "Biogeochemical Patchiness at the Sea Surface" *Geophysical Research Letters*, **29**(19), 1926, doi: 10.1029/2001GL014116, 2002.

3. Mahadevan, A. and J.W. Campbell. "Biogeochemical Variability at the Sea Surface: How it is linked to process response times." Chapter accepted to be published in *Scales in Ecology*, CRC Press, Laurent Seuront, editor.

4. Campbell, J.W., T.S. Moore, Mark D. Dowell, "Observing Dynamic Bio-optical Provinces: A Global Study," (submitted to JGR, Aug. 2001, accepted with revisions July 2002, will be resubmitted January 2003).

5. Salisbury, J. E., J. W. Campbell, E. Linder, L. D. Meeker, F.E. Muller-Karger, and C.J. Vorosmarty, "The influences of discharge and winds on suspended sediment distributions in the Northern Gulf of Mexico." (submitted to DSR, July 2002)

6. Carder, K. L., F.R. Chen, J.P. Cannizzaro, and J.W. Campbell. "Performance of MODIS Semi-analytic Ocean Color Algorithm for Chlorophyll-a." (submitted to *Adv. Space Res.*, Nov. 2002)

Presentations July-December 2002:

7. Campbell, Janet W. and Timothy S. Moore. "Comparison of MODIS and SeaWiFS Chlorophyll Products: Collection 4 Results" Presented at the MODIS Science Team meeting, Greenbelt, MD, July 23, 2002.

8. Timothy S. Moore. Participated in the Discussion/Panel on Accessing MODIS Data Products (Chair V. Salomonson) representing ocean science user experiences, MODIS Science Team meeting, Greenbelt, MD, July 24, 2002.

9. Carder, K., F. Chen, J. Cannizzaro, and J. Campbell, "Performance of MODIS Semi-Analytic Ocean Color Algorithms: Chlorophyll *a*, Absorption Coefficients, and Absorbed Radiation by Phytoplankton." Invited paper presented at the World Space Congress 2002, Houston, TX, October 18, 2002.

10. Dowell, M. D., J. W. Campbell, and T. S. Moore. "Dynamic Ocean Provinces: A Multi-sensor Approach to Global Marine Ecophysiology" Invited paper presented at the World Space Congress 2002, Houston, TX, October 18, 2002.

11. Campbell, Janet W., Timothy S. Moore, and Mark D. Dowell. "Isopleths of Chlorophyll in Radiance Space" Oral presentation and poster presented at the Ocean Optics XIV Conference, Santa Fe, NM, Nov. 18-22, 2002.

12. Moore, Timothy S., Janet W. Campbell, and Mark D. Dowell. "Linking Algal Functional Groups with Bio-Optical Provinces on a Global Scale" Oral presentation and poster presented at the Ocean Optics XIV Conference, Santa Fe, NM, Nov. 18-22, 2002.

13. Son, Seung-Hyun, Janet W. Campbell, Mark D. Dowell, Il-Ju Moon, and Sinjae Yoo. "Classification of Well Mixed and Stratified Waters in the Yellow and East China Seas." Poster presented at the Ocean Optics XIV Conference, Santa Fe, NM, Nov. 18-22, 2002.

Case 2 Algorithm Protocol Development

There are two areas of algorithm development that are addressed in this project. One is the bio-optical algorithm that retrieves chlorophyll and other optically-active constituent concentrations. The second area is the primary productivity algorithm.

Bio-optical algorithms

Our approach to this goal has been to identify bio-optical provinces and to parameterize algorithms for each province. Retrievals from the various algorithms would be "stitched together" using fuzzy memberships calculated from remotely sensed reflectance spectra (Moore et al., 2001). A manuscript (paper # 4) describing global bio-optical provinces was submitted in August 2001 to the *Journal of Geophysical Research*. We finally received reviews of this paper in July 2002. The paper was tentatively accepted with revisions. We are now finalizing the revised manuscript for resubmission. In this paper, we identified 6 bio-optical provinces from in-situ reflectance spectra and mapped the provinces globally using SeaWiFS data (MODIS data were not validated at the time). (See our January 2002 semi-annual technical report for more details). The major criticism of this paper was our inference that the bio-optical provinces were related to distinct phytoplankton communities. The provinces may simply be related to ranges of chlorophyll concentration.

While waiting for reviews of this paper, we mined the SeaBASS archive at GSFC to acquire in-situ data (inherent and apparent optical properties) for parameterizing algorithms for the global bio-optical provinces. Based on the SeaBASS data, we have taken a new approach to the development of bio-optical provinces. We identified algal pigment classes based on the phytoplankton absorption spectra and attempted to relate these to reflectance classes. The results (presentation #12) were disappointing in that the reflectance spectra sorted by class were highly overlapping. However, we believe that we can identify classes using MODIS data (using SST in addition to the radiance spectra). This will comprise the Ph.D. dissertation of Timothy Moore.

Mark Dowell has one manuscript in preparation related to the bio-optical algorithms associated with the provinces:

M. D. Dowell, T.S. Moore and J.W. Campbell, "Bio-optical properties of distinct oceanic provinces." *In preparation for submission to Journal of Geophysical Research*.

In presentation #11, I was able to demonstrate that there is a fundamental (mathematical) inconsistency between empirical ratio algorithms (such as the OC4 used by SeaWiFS or the OC3 algorithm used in the MODIS "SeaWiFS analog" chlorophyll) and semi-analytic algorithms (such as that used for the Carder Chlor_a3 product). The empirical algorithms are supported by a large volume of empirical data, whereas the semi-analytic algorithms are based on theoretical models. The discrepancy can be resolved if there is covariance among the inherent optical properties which govern the water leaving radiance. I plan to submit a paper specifically comparing the OC3 algorithm and the Carder semi-analytic model in 2003.

Primary productivity algorithms

We continue to make progress in this area as described in the July 2002 technical report. Dr. Mark Dowell has been funded by NASA's Earth Sciences Enterprise (under the Oceans, Ice and Climate NRA released last year) to pursue this work. The graduate student (Seung-Hyun Son) who is working on primary productivity algorithms for the Yellow Sea passed his qualifying exam and is now working full-time on his dissertation. He is using MODIS data in this research. The long-awaited paper comparing primary productivity algorithms (paper #1) was finally published in the July 2002 issue of *Global Biogeochemical Cycles* (which appeared in November 2002). (It was originally submitted in May 2000).

Mark Dowell has two manuscripts in preparation related to primary productivity algorithms:

M. D. Dowell, T. S. Moore, J.W. Campbell and S-H Son. "The bio-optical regulation of photosynthetically usable radiation in turbid coastal waters." *In preparation for submission to Limnol. Oceanogr.*

M. D. Dowell, J.W. Campbell, T. S. Moore. "Dynamic provinces of the global oceans: biogeochemical and ecophysiological implications." *In preparation for submission to Global Biogeochemical Cycles.*

Demonstration in Gulf of Maine and Yellow Sea Regions

We are continuing to assemble a database of in-situ bio-optical data for the two demonstration sites: Gulf of Maine and Yellow Sea.

- Gulf of Maine. We are planning to serve MODIS data for the Gulf of Maine and Mid-Atlantic Bight through a new web-based server being developed within the Institute for the Study of Earth, Oceans and Space. Web-COAST is a web-based data and information server funded by NOAA as one of the projects supported by the newly established Center of Excellence for Coastal Observation and Analysis (COOA). It is modeled after EOS-WEBSTER, one of NASA's Earth Science Information Partners (ESIPs) operated at UNH. Current plans are to provide MODIS data that has been acquired from the DAAC and remapped to a standard projection. These data will include chlorophyll and SST, as well as other products. We will post weekly browse images on Web-COAST, but will make all the data available via ftp or other media. We will begin by providing data from the validated period (November 2000 to March 19 2002). In addition, we are receiving a "push order" in which we obtain data from the forward processing stream. These data still have cross-scan anomalies which are apparent when two orbits are composited. We are still unclear how we will serve these data. There is a demand for real-time or near-real time data, and these data are still quite useful for many purposes. Thus, we are tentatively considering ways to serve the data without compositing two sequential orbits.

- Yellow and East China Seas. This is the thesis work of Seung-Hyun Son, who expects to complete his Ph.D. dissertation in late 2003. He has compared (presentation #13) fronts visible in MODIS SST and chlorophyll data to the Simpson-Hunter H/U^3 criterion for mixed versus stratified waters. The latter was derived using a wind-wave model (Moon, 2000 thesis) and bathymetry data. He found that the MODIS data could be used to differentiate stratified and well-mixed regions during the periods of seasonal stratification. This will later be used to model the vertical distribution of chlorophyll and other optically active constituents in development of a primary productivity model for this region. The Ocean Optics poster on this work will be presented at an upcoming MODIS Ocean Workshop at UNH, Feb. 3-4, 2003.

Development of Monitoring Strategies

No further progress has been made in this area. The establishment of the Web-COAST server and the reprocessing of MODIS data will facilitate progress in this area.

Support of MODIS Ocean Team Activities

During this reporting period, we have been active in the evaluation and validation of MODIS products in support of new codes applied to the forward processing and the reprocessing. The new codes were put into operation in June 2002. The MODIS Oceans Team has held weekly teleconferences to discuss issues raised during this phase. We have continued to evaluate MODIS chlorophyll products and compare them with SeaWiFS chlorophyll data acquired at the same location and on the same day. Comparisons were presented at the MODIS Science Team meeting in Greenbelt, Maryland, in July 2002 (Presentation #7), were based on MODIS Collection 4 data and the SeaWiFS Version 4 processing. We concluded that the Chlor_a2 product for the period November 1, 2000 to March 19, 2002 based on its agreement with the SeaWiFS chlorophyll product. I will continue to evaluate and be responsible for the chlor_a_2 product.

I took responsibility for a major re-writing of the EOS Data Handbook sections involving MODIS Ocean Data Products. The previous edition had been published long before MODIS was launched (even before SeaWiFS was launched), and thus the Handbook needed substantial editing.

I am currently organizing the first of several regional MODIS Ocean Data Workshops. The upcoming workshop will be held at the University of New Hampshire on February 3-4, 2003. A website was developed (http://www.opal.sr.unh.edu/modisworkshop) and widely advertised.

In addition, I co-chaired the session on "Biological and Physical Oceanographic Processes from Satellite Data" at the World Space Congress 2002 in Houston, TX, October 17-18, 2002. As co-chair, I solicited invited papers from among the MODIS Oceans Team. Ken Carder presented an invited paper (presentation #9) which has subsequently been submitted to the *Advances in Space Research* (paper #6). I am now serving as an associate editor for this journal for the publication of papers in the realm of biological oceanographic processes.

Progress in Related Areas

My contribution to the IOCCG report on Binning Algorithms described in the January 2002 technical report was completed and submitted to David Antoine, who is acting as the general editor of this report. In this section, I showed compared monthly average primary productivity (PP) generated from daily input (PPd) differs from that derived by using monthly averaged input fields (PPm). I compared two algorithms: the Behrenfeld and Falkowski algorithm used by MODIS to generate the P1 product, and a modified version of the Howard-Yoder-Ryan algorithm used to generate the MODIS P2. The latter was modified to estimate euphotic rather than mixed-layer PP. It is generally believed that it is preferable to apply a nonlinear equation to daily input fields and then average the result, rather than use monthly average input fields. However, in the case of PP algorithms, when this is done, there is a clear-sky bias. That is, PPd is calculated only where there are chlorophyll and SST measurements, i.e., clear-sky conditions. The PAR fields are not affected by clouds since there is PAR beneath clouds. Using monthly input fields to derive PP, one can use the average PAR based on all pixels (both cloudy and clear). A good compromise is to derive PP from weekly average input fields as is done with MODIS.

Mark Dowell continues his participation in the current Primary Productivity Algorithm Round Robin exercise with his global province-based algorithms (as described in the July 2002 semi-annual report).

The MODIS data have several major advantages over SeaWiFS. One is the fact that MODIS provides simultaneous SST and chlorophyll. These are two properties often used as input to primary productivity algorithms. It is difficult to match SST and chlorophyll derived from different satellites (e.g., SeaWiFS and AVHRR) because of differences in the cloud masks.

Another advantage of the MODIS is its daily coverage. The time rate of change of algal biomass (dB/dt) can be used, together with estimates of primary production, to estimate the loss rate (due to sinking or grazing by zooplankton). To date a major obstacle in using satellite data to study these loss terms at global scale has been that the time step (dt) has been too large (i.e., typical cloud-free global coverage on the order of 30 days). With the advent of the MODIS sensor which provides almost perfect cloud-free coverage of the global ocean within a 7 day period, a more relevant dataset for studying phytoplankton loss terms now exists. Mark Dowell has prepared a poster to present at the IGBP Oceans Conference in Paris in January 2003. This poster will also be displayed at the upcoming MODIS Oceans Workshop in February.