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 2001 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. Moore, T. S., J. W. Campbell and H. Feng. "A fuzzy logic classification scheme for selecting and blending satellite ocean color algorithms" *IEEE Trans. in Geosciences and Remote Sensing*, 39(8), 1764-1776, 2001.

2. Campbell, J.W., T.S. Moore, Mark D. Dowell, "Observing Dynamic Bio-optical Provinces: A Global Study," (submitted, Aug. 2001).

3. Mahadevan, A. and J. W. Campbell. "Biogeochemical Variability at the Sea Surface" *Geophysical Research Letters*, (accepted, Dec. 2001).

4. J. Campbell, 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 Biogeochemical Cycles*, (accepted, Dec. 2001).

5. Liu, A.K., Y. Zhao, W.E. Esaias, J. W. Campbell, T. S. Moore. "Ocean Surface Layer Drift Revealed by Satellite Data." EOS, Transactions, American Geophysical Union, (in press, Dec. 2001).

Presentations (July-Dec. 2001):

6. Janet Campbell, "Satellite-based estimation of marine primary production: current status and future directions" presented at the JGOFS Global Synthesis Task Team Meeting, Amsterdam, July 2001.

7. Mark Dowell, Timothy Moore, and Janet Campbell "Dynamic Ecological Provinces: An Objective Bio-Geography Based on Global Satellite Data" IGBP meeting "Challeges of a Changing Earth" Amsterdam NL, 10-13 July, 2001.

8. Janet Campbell, "Ocean Color Remote Sensing: New Frontiers in Algorithms and Applications." Seminar given at University of Rhode Island, Ocean Engineering Department, December 6, 2001.

9. Janet Campbell and Timothy Moore. "Comparison of MODIS and SeaWiFS Chlorophyll Products" presented at the MODIS Science Team Meeting, Dec. 2001.

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

The strategy for this work has been to promote the use of a standard semi-analytic model that relates remote-sensing reflectance to inherent optical properties (absorption and backscattering coefficients), and then to prescribe methods for parameterizing the IOPs as functions of the constituent concentrations of interest (chlorophyll, colored dissolved organic matter, and suspended sediment). We also advocate the need for regional- or class-specific models to accommodate the wide range of bio-optical variability found in natural waters. A method has been developed (paper # 1) to select and blend bio-optical algorithms for ocean color thus allowing smooth transitions across ocean water boundaries (e.g., Case I to Case II). We have extended this approach to the global scale (paper #2) where a finite number of distinct optical classes are identified and considered adequate to describe the global variability in optical properties. A cluster analysis based on the fuzzy *c*-means (FCM) method was performed on a global in-situ data set of over 1,700 reflectance measurements in which 6 distinct optical classes were identified. Of these 6 classes, 4 are oceanic and exhibit optical properties consistent with Case I waters. The two remaining classes may be broadly considered coastal/Case II waters, each of

which has distinct optical characteristics and active constituents. This work has been presented in several venues, and a paper has been submitted to JGR on the topic.

When applied to satellite data, the core of the method is the fuzzy membership function that assigns class memberships to all pixels in a satellite image. This function uses class-specific reflectance statistics derived from in-situ data to calculate a membership value ranging from 0 to 1 for each pre-defined class, allowing each pixel to have partial membership to one or more classes. When applied to SeaWiFS global composite images, class membership maps reveal coherent regional and global-scale patterns representing optically-distinct ocean provinces. These class membership values can be used to weight and blend class-specific algorithm retrievals (i.e., chlorophyll a, CDOM absorption, and particle backscattering).

Primary productivity algorithms

Work in this area is progressing on several fronts: (1) We are working on an algorithm for computing primary production in coastal waters based on a wavelength-resolved model of photosythetically usable radiation (PUR). The manuscript is still in preparation. (2) Toward the application of the fuzzy logic scheme to primary production algorithms, we have identified 9 distinct classes or ecological provinces based on SST, chlorophyll, and surface PAR. The provinces were identified from in-situ data using the data base of Behrenfeld and Falkowski (http://marine.rutgers.edu/opp) augmented with coastal data at 85 stations. Our goal is to determine a model of ψ^* for each province. Thus when a satellite image is processed, the fuzzy memberships can be calculated and results blended to yield a global PP map. We have evaluated the performance of each of the current MODIS primary productivity algorithms in the 9 different provinces. At present, we are limited in available PP data sets for validation, since this should involve an independent data set not used in any of the algorithm development processes. (3) A graduate student (Seung-Hyun Son) is working on primary productivity algorithms for the Yellow Sea.

Protocol for "Stitching Together" Algorithms

A manuscript describing this protocol (paper #1) was published in the *IEEE Transactions on Geoscience and Remote Sensing*. A possible application of this to MODIS chlorophyll products was described in detail in our July 2001 progress report. It is not possible (or desirable) to blend MODIS chlorophyll products as part of the normal processing. However, products can be blended after they are produced. We intend to experiment with this for our two demonstration areas.

Demonstration in Gulf of Maine and Yellow Sea Regions

We are continuing to assemble a data base of in-situ bio-optical data for the two demonstration sites: Gulf of Maine and Yellow Sea. Our current archive of MODIS data for these areas will be replaced with reprocessed data based on the new Version 4 code.

We are planning to serve MODIS data for the Gulf of Maine (including blended chlorophyll and primary productivity maps) through a new web-based server being developed within the Institute for the Study of Earth, Oceans and Space. The new system is being developed to provide data and associated services for coastal ocean observation and analysis. Over the next few months, we will begin to place our MODIS data for the Gulf of Maine onto this web-based data server.

Development of Monitoring Strategies

No further progress has been made in this area. The establishment of a web-based 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 continued to evaluate MODIS chlorophyll products and compare them with SeaWiFS data acquired at the same location and on the same day. At the MODIS Science Team team meeting in Baltimore, December 2001, we presented a comparison of MODIS and SeaWiFS chlorophyll products. The Powerpoint presentation for this talk is available at the MODIS website.

We have assumed responsibility for the chlor_a_2 product. Based on recommendations made in April 2001, the algorithm for chlor_a_2 was changed to the OC3M algorithm to be more consistent with the current SeaWiFS chlorophyll (NASA TM 2000-206892, Vol. 11). I have prepared an overview document that summaries the various MODIS chlorophyll products and refers (links) to the respective Quality Summaries. In addition, I prepared a Quality Summary for the chlor_a_2 product.

I will continue to evaluate and be responsible for the chlor_a_2 product.

Progress in Related Areas

Amala Mahadevan and I are exploring a simple technique for characterizing scales of variability in surface waters. This work aims to characterize the spatial distributions of various tracers in terms of a variance-based measure of their patchiness. Using a scaling argument and a numerical model, we relate the patchiness of a tracer distribution to the characteristic response time of the tracer to processes that alter its concentration in the upper ocean. This enables us to relate the distributions of different tracers in the upper ocean and provide an estimate for the relative size of the grid spacing needed to observe or model different tracers. We are applying this method to MODIS chlorophyll and SST data. The MODIS data are particularly suited to this analysis because of the simultaneous acquisition of both SST and chlorophyll. Previously (in paper #3) we applied it to SeaWiFS and AVHRR data acquired on the same day at the same place, but the time differences between the two satellite overpasses made direct comparisons much more difficult.

As a member of an IOCCG working group, I have participated in writing a report on binning algorithms. In my contribution to this report, I demonstrate how various

averaging methods introduce systematic differences in level-3 (binned) data products. In addition, I explored an issue related to the time scale of the input data used in producing primary productivity (level-4) products. It is common practice to apply primary productivity algorithms to monthly averaged input fields (Behrenfeld and Falkowski, 1997; Behrenfeld et al., 2001). An alternative approach is to apply the algorithms to level-2 data, and then average the resulting daily primary production maps over a month. The MODIS approach lies in between: to apply the algorithms to weekly average input fields. In the IOCCG report, I addressed the question: what effect does the use of monthly average input data have on the estimation of monthly primary production? We used the vertically generalized production model (VGPM) of Behrenfeld and Falkowski (1997) and calculated euphotic primary production (PP) by alternative methods. Our results are specific to the VGPM algorithm. In the process of investigating this question, we realized that there is a fundamental difference in the PAR used by the different methods. Unlike other ocean color products, PAR can be calculated under clouds. Thus, the weekly or monthly average PAR is based on all pixels (not only those that are cloud free). However, if the daily PAR is matched with level-2 chlorophyll and SST to calculated primary productivity on a given day, then only the cloud-free PAR is used. This introduces a bias to the primary productivity products calculated at high temporal resolution (e.g., daily). We have concluded that the method used by MODIS (i.e., involving the use of weekly input) is a good compromise.

Mark Dowell is participating in the current Primary Productivity Algorithm Round Robin exercise with his global province-based algorithms. Mary-Elena Carr (JPL) is taking the lead in conducting this activity.