

Semi Annual Report

(July 1 — December 31, 2000)

Contract Number NAS5—31363

OCEAN OBSERVATIONS WITH EOS/MODIS: Algorithm Development and Post Launch Studies

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(Submitted January 16, 2001)

Preamble

This document describes our progress thus far toward completion of our research plans regarding two MODIS Ocean-related algorithms.

- A. Retrieval of the Normalized Water-Leaving Radiance (Atmospheric Correction).
- B. Retrieval of the Detached Coccolith/Calcite Concentration

Our plans for Fiscal Year 2001 are included in this report as **Appendix I**. [In this report, we have combined items 2 (*Implement the Initial Algorithm Enhancements*) and 3 (*Study Future Enhancements*) from Appendix I into item “2 and 3” (*Algorithm Enhancements*).]

Fiscal Year 2000 was to be heavily focused on validation of MODIS-derived products. Unfortunately, the delay of the launch of Terra required some modification of our initial plan. Our approach thus far has been to use SeaWiFS for *validating* MODIS *algorithms* in the absence of MODIS itself, and after the required initialization when well-calibrated MODIS data become available, to validate the MODIS products directly. In addition, as we already know that there are certain situations in which the algorithms are unable to perform properly, or that there are items that have not been included in the initial implementation, a portion of our effort will be directed toward algorithm improvement. Thus, we break our effort into two broad components for each algorithm:

- Algorithm Improvement/Enhancement;
- Validation of MODIS Algorithms and Products.

Of course, these components will overlap in some instances.

RETREIVAL OF NORMALIZED WATER-LEAVING RADIANCE **(ATMOSPHERIC CORRECTION)**

Algorithm Improvement/Enhancement

1. Evaluation/Tuning of Algorithm Performance

Task Progress:

As indicated in our last Semiannual Report, considerable effort has been expended by R. Evans and co-workers toward removing the instrumental artifacts from MODIS ocean imagery. Examples of such artifacts are severe striping, mirror side difference effects and the variation of the instruments response as a function of scan angle. Much progress has been made along these lines, but much more needs to be done, especially now that there has been a shift from the “A-side” to the “B-side” electronics, that modifies the artifacts and requires a re-initialization of the sensor. On the positive side, the MODIS imagery shows considerably more detail than SeaWiFS, particularly in the green. On the negative side, there is still a strong East-West asymmetry in retrieved water-leaving radiances. We are trying to understand this asymmetry and are attempting to determine if it is related to bidirectional effects in the water-leaving radiance. To this end, we are making measurements of the BRDF of the subsurface radiance to see if it could account for a portion of the variation. This effort is described in Section 2 under the heading “Subsurface upwelling BRDF.”

Anticipated Future Actions:

We will continue the evaluation of MODIS imagery, and work closely with R. Evans on removing the artifacts from the imagery. We will compare the BRDF effects with the MODIS asymmetry to see if that can be ruled out. Other possibilities for this asymmetry that we will examine include a lack of understanding of the MODIS response-versus-scan-angle variability or error in the polarization-sensitivity correction.

2. and 3. Algorithm Enhancements

There are two important issues we are examining for inclusion into the MODIS algorithm: effecting atmospheric correction in the presence of strongly absorbing aerosols; and including the influence of the subsurface upwelling BRDF on water-leaving radiance. The BRDF influence may be important in the MODIS scan asymmetry.

Strongly Absorbing Aerosols

The first of the two enhancements we have been considering concerns absorbing aerosols. Although success with SeaWiFS has shown that the MODIS algorithm

performs well in ~ 90% of Case 1 water situations, it does not perform adequately everywhere; most notably in atmospheres containing strongly absorbing aerosols. Strongly absorbing aerosols constitute a previously unsolved atmospheric correction issue for Case 1 waters, and have a significant impact in many geographical areas. Two important situations in which absorbing aerosols make an impact are desert dust and urban pollution carried over the oceans by the winds. In the case of urban pollution the aerosol contains black carbon and usually exhibits absorption that is nonselective, i.e., the imaginary part of the refractive index (the absorption index) is independent of wavelength. In contrast, desert dust absorbs more in the blue than the red, i.e., the absorption index decreases with wavelength.

Task Progress:

We are in the process of extensively examining two significant enhancements in dealing with absorbing aerosols: (1) the spectral matching algorithm (SMA) [Gordon, Du, and Zhang, "Remote sensing ocean color and aerosol properties: resolving the issue of aerosol absorption," *Applied Optics*, **36**, 8670-8684 (1997)]; and (2) the spectral optimization algorithm SOA [Chomko and Gordon, "Atmospheric correction of ocean color imagery: Use of the Junge power-law aerosol size distribution with variable refractive index to handle aerosol absorption," *Applied Optics*, **37**, 5560-5572 (1998)]. Simulations reveal that both algorithms have the potential to perform well in the presence of strongly absorbing aerosols. In earlier reports we have described our implementation of these algorithms and their performance with SeaWiFS imagery. In particular, the SMA has been used extensively for atmospheric correction in the presence of desert dust, and the SOA has been used to process imagery off the US East Coast, where aerosols resulting from urban pollution are an issue.

During the present reporting period we revised two manuscripts "Assessment of Saharan dust absorption in the visible from SeaWiFS" to *JGR* and "Atmospheric correction of ocean color imagery through thick layers of Saharan dust," to *Geophysical Research Letters*. Both have now been accepted for publication. We have also used the SMA in the Saharan dust zone in a novel manner. We used it to select the "best" aerosol model from a set of 18 we developed for use in this region. The selected model was then used to subtract the aerosol component from the imagery yielding the normalized water-leaving radiance (nL_w). These values of nL_w were used as input to the now-standard SeaWiFS OC4v4 bio-optical algorithm to estimate the concentration of chlorophyll *a* (*Chl*). Eight-day composite imagery of *Chl* processed in this manner agreed well with that derived by the SeaWiFS Project; however, the SMA coverage was considerably increased because the standard SeaWiFS algorithm cannot operate in areas subjected to even moderate concentrations of desert dust. In addition, we have been modifying the SMA to provide an estimate of radiative forcing by the dust on a pixel-by-pixel basis.

In the last reporting period we demonstrated a successful processing of SeaWiFS imagery in the Saharan dust zone using the SMA and the application of the SOA to SeaWiFS imagery off the U.S. East Coast. These implementations both used the Gordon *et al.* ["A Semi-Analytic Radiance Model of Ocean Color," *Jour. Geophys. Res.*, **93D**, 10909-

10924, 1988] two-parameter radiance model (that provides the water-leaving radiance as a function of the pigment concentration and a scattering parameter) to provide the oceanic reflectance. More complete three-component radiance models are now available. For example the Garver and Siegel [“Inherent optical property inversion of ocean color spectra and its biogeochemical interpretation: 1 time series from the Sargasso Sea,” *Geophys. Res.*, **102C**, 18607—18625, 1997] provides the reflectance as a function of three parameters (in addition to water): (1) the absorption coefficient of colored detrital matter — particulate and dissolved — [a_{cdm} at 443 nm]; (2) the absorption coefficient of phytoplankton at 443 nm [a_{ph}] and (3) the backscattering coefficient of particulate matter [$(b_b)_p$]. Briefly, in both the Gordon *et al.* and the Garver and Siegel models, the water-leaving reflectance (ρ_w) is provided as a function of the absorption (a) and backscattering (b_b) coefficients. The absorption and backscattering coefficients are separated into the above components plus that of water (subscript “w”): $a = a_w + a_{ph} + a_{cdm}$, and $b_b = (b_b)_w + (b_b)_p$. Spectrally, in the Garver and Siegel model the non-water components are written

$$\begin{aligned} a_{ph}(\lambda) &= a_{ph0}(\lambda) C, \\ a_{cdm}(\lambda) &= a_{cdm}(443) \exp[-S(\lambda-443)], \\ (b_b)_p(\lambda) &= (b_b)_{p0} [443/\lambda]^{1.03}, \end{aligned}$$

where C is the concentration of chlorophyll a , $(b_b)_{p0}$ is the backscattering parameter, and S is the CDM “slope” parameter (taken to be 0.0206 through tuning to the SeaBAM data set). Therefore,

$$\rho_w = \rho_w(\lambda, C, a_{cdm}(443), (b_b)_{p0}).$$

We added this reflectance model to our SOA to provide water-leaving reflectances. Recall that in the SOA, optimization techniques are used to estimate both aerosol and ocean parameters. In the atmospheric portion of the SOA there are four parameters in the atmospheric model: ν , the slope parameter of the Junge size distribution; $\tau_a(865)$, the aerosol optical thickness at 865 nm; m_r , the real part of the aerosol’s refractive index, and m_i , the imaginary part of the aerosol’s refractive index. Thus, we must now optimize on 7 parameters:

$$C, a_{cdm}(443), (b_b)_{p0}, \nu, \tau_a(865), m_r, \text{ and } m_i;$$

using 8 spectral bands.

We applied this algorithm to the SeaWiFS image from the Middle Atlantic Bight (MAB) acquired on day 279 of 1997. Figure 1 provides the image of the retrieved $a_{cdm}(443)$. Superimposed on the image are three tracks flown by the Airborne Oceanographic Lidar (AOL) on the same day under the direction of Frank Hoge. The AOL was used as described in Hoge *et al.* [“Inherent optical properties of the ocean: retrieval of the absorption coefficient of chromophoric dissolved organic matter from airborne laser spectral fluorescence measurements,” *Applied Optics*, **34**, 7032—7038 (1995)]. Their technique retrieves the dissolved component of a_{cdm} at 355 nm. The dissolved component at 443 nm is derived by multiplication by $\exp[-S(443-355)]$. Using the Garver and Siegel

value of S , in Figure 2 (a) we compare the retrieved $a_{cdm}(443)$ with the AOL retrieved dissolved component. We see that there is excellent agreement between the two estimates in and south of the Gulf Stream; however, this agreement is degraded to the north. There are two reasons for the disagreement. First, we use the Garver and Siegel value for S (0.0206/nm, and the same value used in the SOA) to reduce the AOL data. Such a value may be characteristic of oligotrophic waters of the Gulf Stream, but lower values are more representative of mesotrophic waters to the north. Second, the SOA retrieves *both* the absorption of dissolved and suspended detrital material while the AOL retrieves just dissolved material, and therefore the AOL should retrieve smaller values. With regard to the S values, we have also analyzed the AOL data using the value of (0.018/nm) preferred by Hoge (Personal communication). These results are presented in Figure 2(b), where AOL with ($S = 0.0180$ /nm) is compared with SOA with ($S = 0.206$ /nm). One should note that using ($S = 0.0180$ /nm) in the SOA, as would be more consistent in such a comparison, would change the SOA results only slightly. This clearly improves the agreement in the higher $a_{cdm}(443)$ regions.

These comparisons suggest that the SOA is performing well in retrieving $a_{cdm}(443)$ from the SeaWiFS imagery. The patterns of increases and decreases are well matched, and there is reasonable quantitative agreement, considering the differences in the retrieved quantities and the uncertainty in the S value used in transforming the AOL retrievals from 355 to 443 nm. They also suggest that the SOA is capable of separating absorption of detritus and phytoplankton in the remotely sensed water-leaving reflectance.

We are attempting to apply the SOA with the Garver and Siegel reflectance model to Case 2 waters. These waters are mostly in the coastal zone and are difficult to atmospherically correct because the water-leaving reflectance in the NIR is not negligible. We are modifying the SOA so that we no longer employ the simplifying assumption of negligible marine reflectance at 765 nm (but still do make the assumption at 865 nm). Such a modification will enable use of the SOA in waters with moderate sediment concentrations. This modification is now undergoing testing.

Finally, we have started an initial implementation of the Garver and Siegel model in the SMA for use in the Saharan dust zone. This implementation is now undergoing initial testing.

Anticipated Future Actions:

We will continue to evaluate the performance of these algorithms for possible inclusion in the MODIS processing software, as we believe they are the most versatile. However, we need to (1) be sure they perform as well as experiments thus far indicate, and (2) optimize their performance to decrease processing time. During the next reporting period we expect to have the SMA fully implemented with the Garver and Siegel model and tested off the coast of Africa. We also anticipate effecting the initial testing of the preliminary Case 2 algorithm.

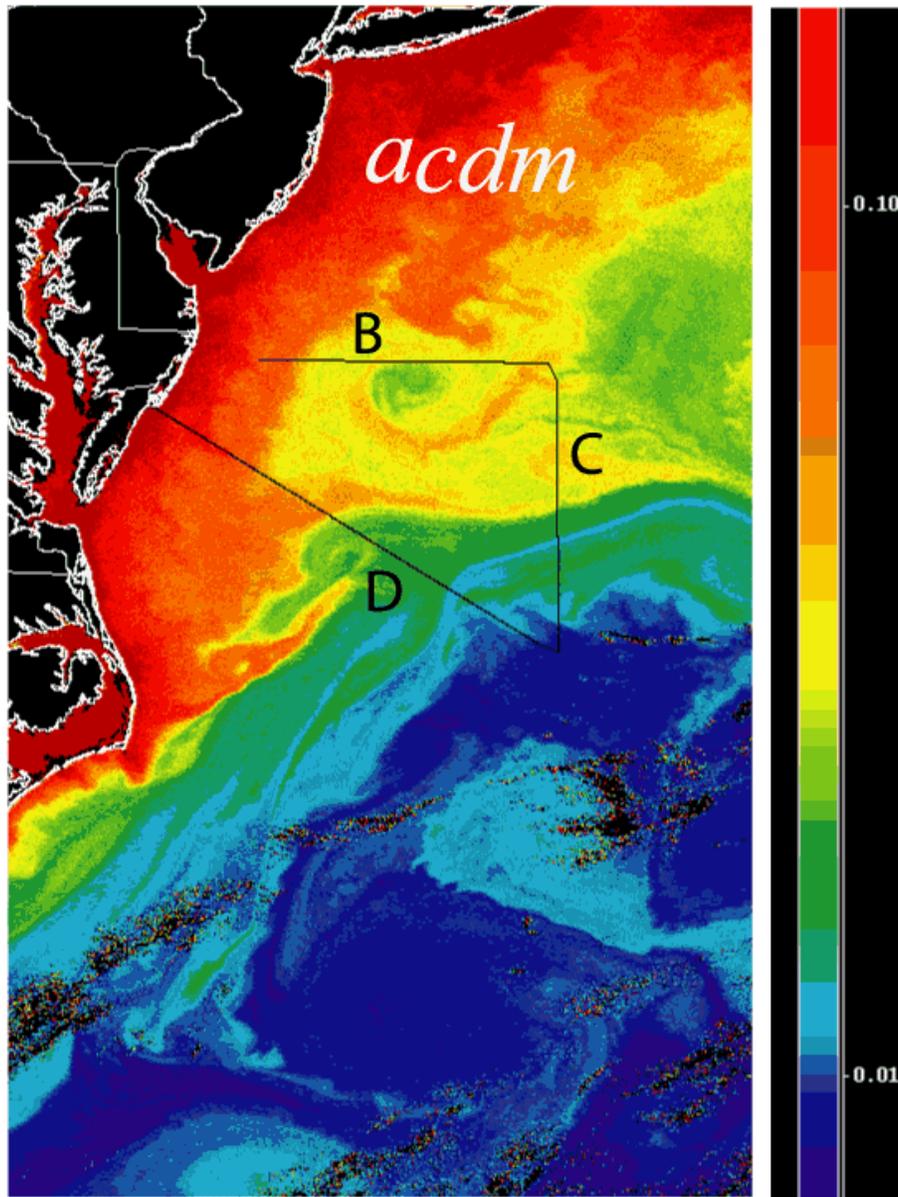
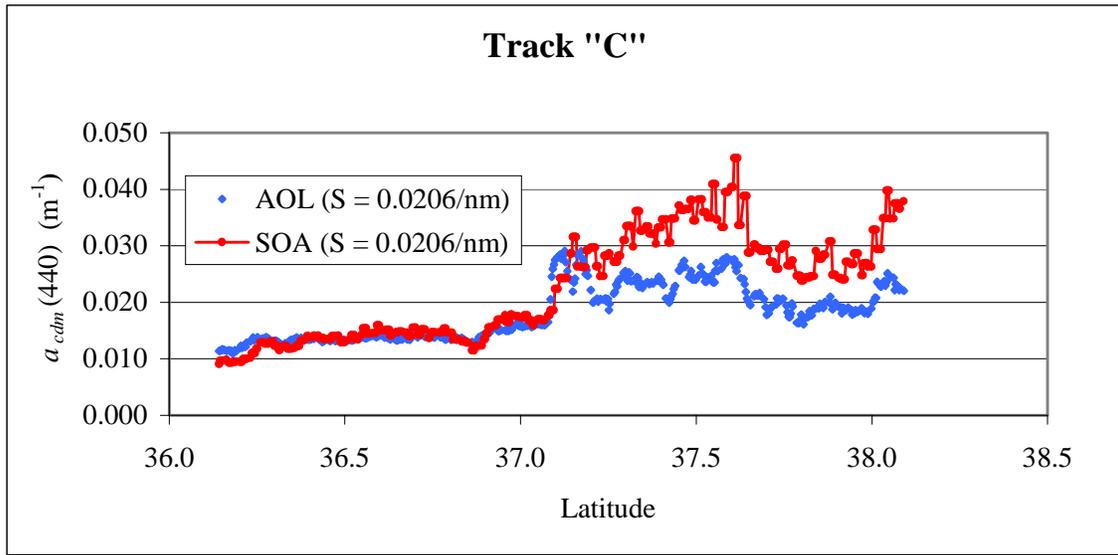
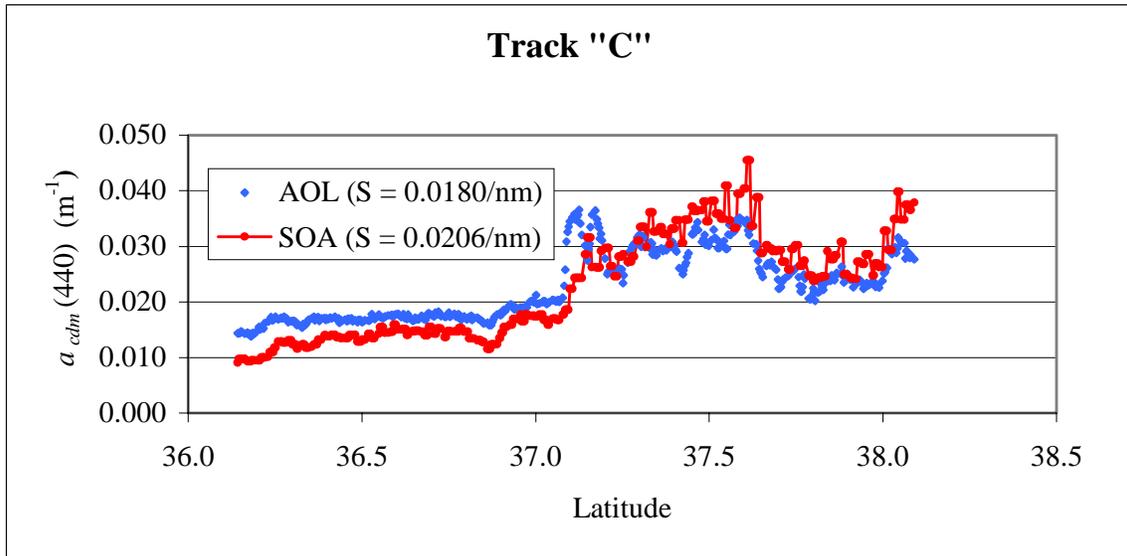


Figure 1: a_{cdm} derived from the SeaWiFS image for Day 279 of 1997 in the Middle Atlantic Bight. “Surface truth” data were obtained with the AOL along tracks “B”, “C”, and “D”. Color scale is logarithmic and the units are m^{-1} .



(a)



(b)

Figure 2. $a_{cdm}(440)$ derived from the AOL and the SOA.

The subsurface upwelling BRDF

The subsurface BRDF issue revolves around the fact that nearly all measurements of the upwelled spectral radiance (used for bio-optical algorithm development, sensor calibration and product validation of all ocean color sensors) are made in the nadir-viewing direction, while the water-leaving radiance estimate from the signal at the remote sensor is for a particular viewing geometry that is rarely nadir. Thus, we need to understand the BRDF of the subsurface radiance distribution to reconcile these measurements. Our approach is to directly measure the BRDF as a function of the chlorophyll concentration and to develop a model that can be used for MODIS.

Task progress:

We have reduced the data from the MOCE-5 SeaWiFS validation cruise in the Gulf of California, and the MOCE-6 MODIS cruise that occurred in the vicinity of the MOBY site in Hawaii. Each of these data sets has distinct features. The MOCE-5 cruise provided a wide range of chlorophyll *a* concentrations, thus allowing our modeling efforts to have a validation data set for a wide range of water properties. Examples of the contrast between the low chlorophyll case and high chlorophyll case are shown in Figure 3, that provides the upwelling radiance distribution (normalized to nadir) just below the sea surface for several azimuthal cuts through the distribution. In both of these examples the sun zenith angle is approximately the same, 28-29 degrees. The four plots show cuts through the upwelling radiance distribution for the 4 measured wavelengths. Filter 1 is 450 nm, Filter 2 is 500 nm, Filter 3 is 560 nm, and Filter 4 is 670 nm. The low chlorophyll case ($C = 0.2 \text{ mg/m}^3$ at the top) shows that the radiance over the range from $\pm 40^\circ$ is fairly constant. This is the range in which radiance, after refraction through the surface, will be viewed by the MODIS sensor. In the high chlorophyll case (4.9 mg/m^3 at the bottom) there is a much stronger variation of the upwelled radiance over even this restricted angular range. This demonstrates that the upwelling radiance distribution is very dependent on the optical properties of the water, and that a model must be used to relate the distribution to the chlorophyll concentration.

The MOCE-6 cruise provided data in the clear water typical of Hawaii, which will be useful for the validation efforts with the MOBY site, but did not provide a wide variation in Chlorophyll levels. The results are useful, however, because they show how the radiance varies with viewing angle at the MOBY site.

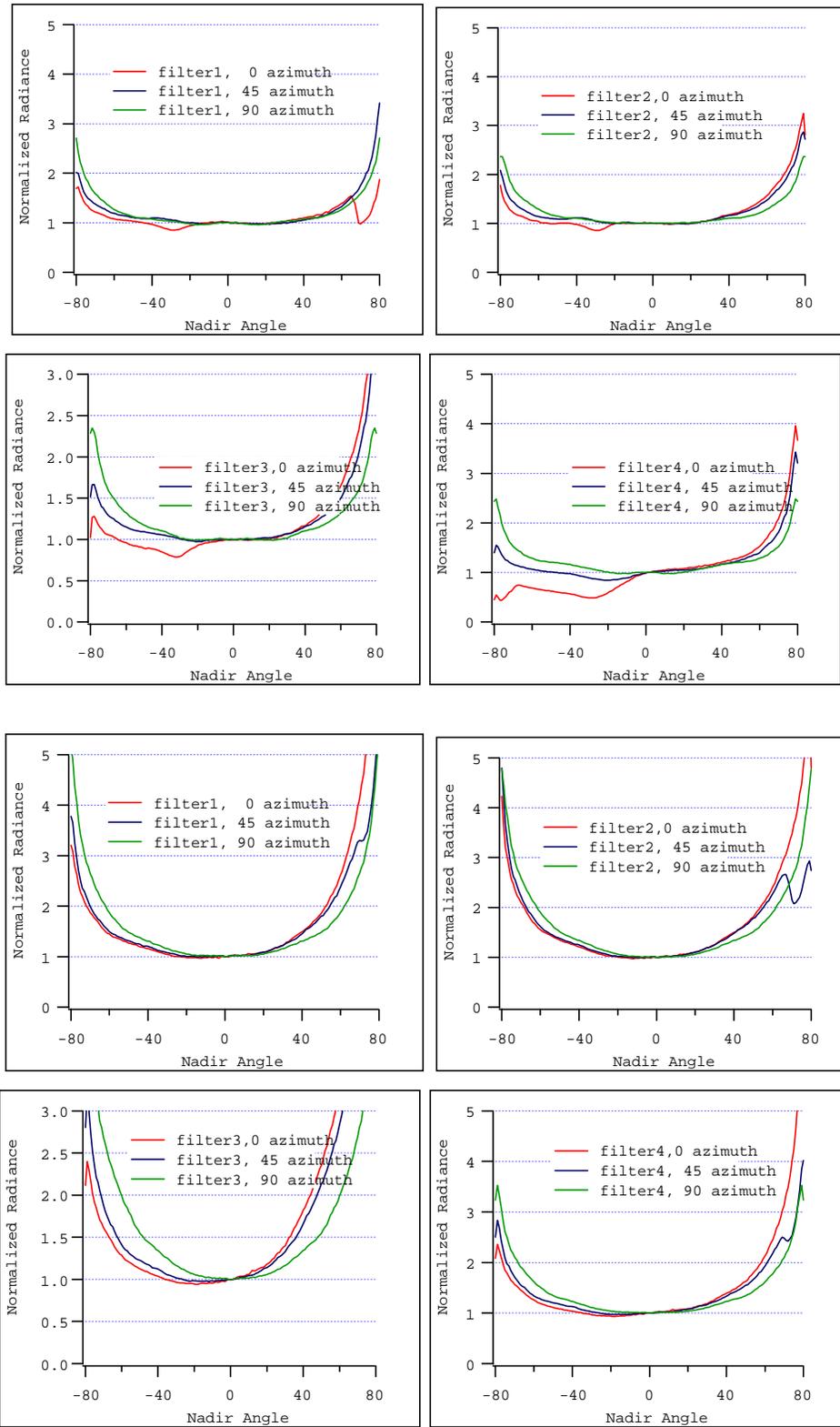


Figure 3: Top four panels $C = 0.2 \text{ mg/m}^3$, bottom four panels $C = 4.9 \text{ mg/m}^3$.

For example, Figure 4 illustrates the measurement geometry for MODIS. This image shows the upwelling radiance distribution at 450 nm for a 30° solar zenith angle. Nadir is in the center of the image. The angle between a specific viewing angle and nadir is directly proportional to the distance from the center (nadir). The direction toward the sun is at the top. There are instrument artifacts shown near the horizon (outside edge), where portions of the instrument intrude into the image. This image is an average of several radiance distribution measurements. The line with boxes is the MODIS scan. This geometry is typical of the measurement geometry near the MOBY site. The scan line goes from the direction towards the sun to away from the sun as one moves from east to west across the scan, the center of the scan line is at the center of the image. In contrast, the SeaWiFS scan would be nearly horizontal in this figure.

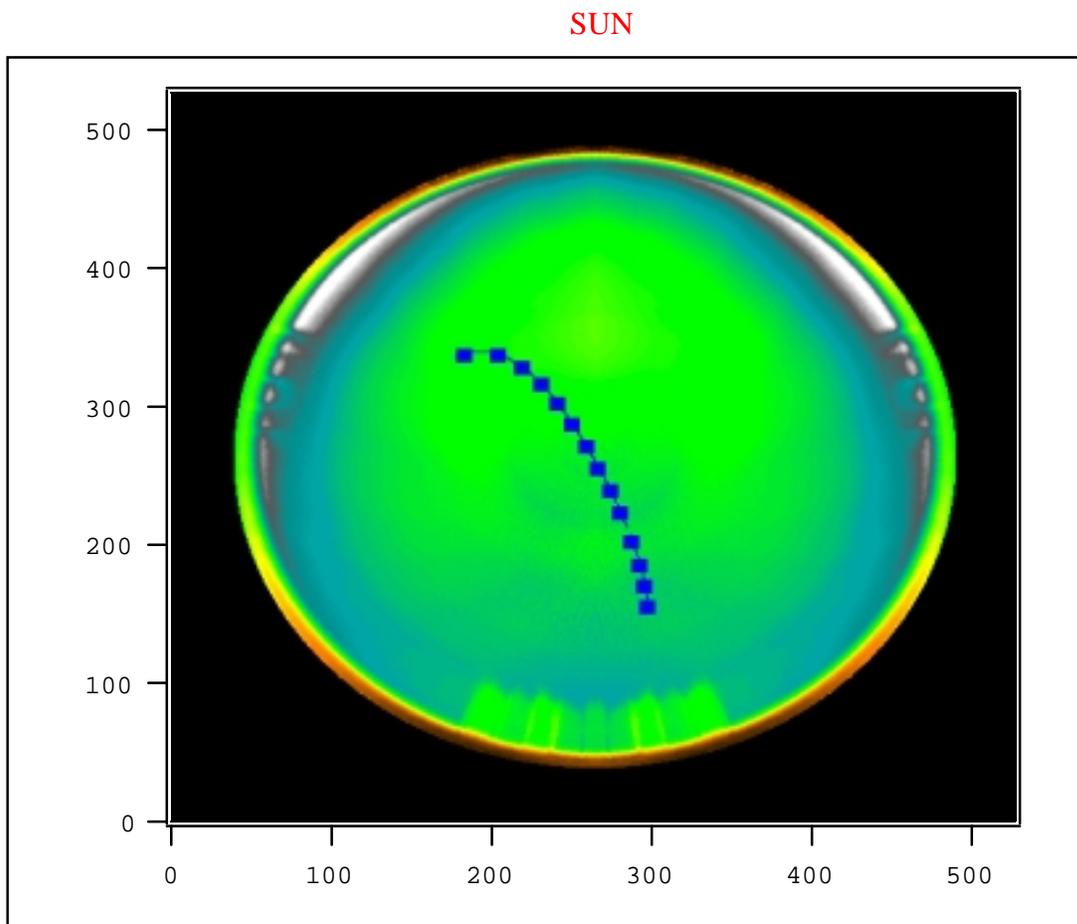


Figure 4: BRDF for subsurface upwelling radiance distribution at 450 nm measured with RADS near the MOBY site. The sun is at the top of the image. The line and points are the MODIS scan with the points closest to the top the eastern edge of the scan and those at the bottom the western edge of the scan. Note that the image is symmetric with respect to reflection through the plane of the sun and nadir.

For a quantitative view of the implications of this scan geometry, we provide two examples (Figures 5 and 6). In both figures the y-axis is the upwelling radiance normalized to nadir, the x-axis is the pixel number along the MODIS scan line (1 on the west). The Figure 5 is for the same 30° solar zenith angle shown in Figure 4. Here one can see that there is a large variation in normalized radiance depending on viewing angle. In Figure 6 the solar zenith angle is approximately 10° . Here you can see that the variation across the scan line is much less severe. In these graphs the view toward the sun is towards the right; away from the sun is towards the left. As can be seen, at 30° solar zenith angle the minimum in the viewed upwelling radiance is on the *sun side* of the image. This minimum goes away as the chlorophyll increases, shown in the MOCE-5 cases above (Figure 3).

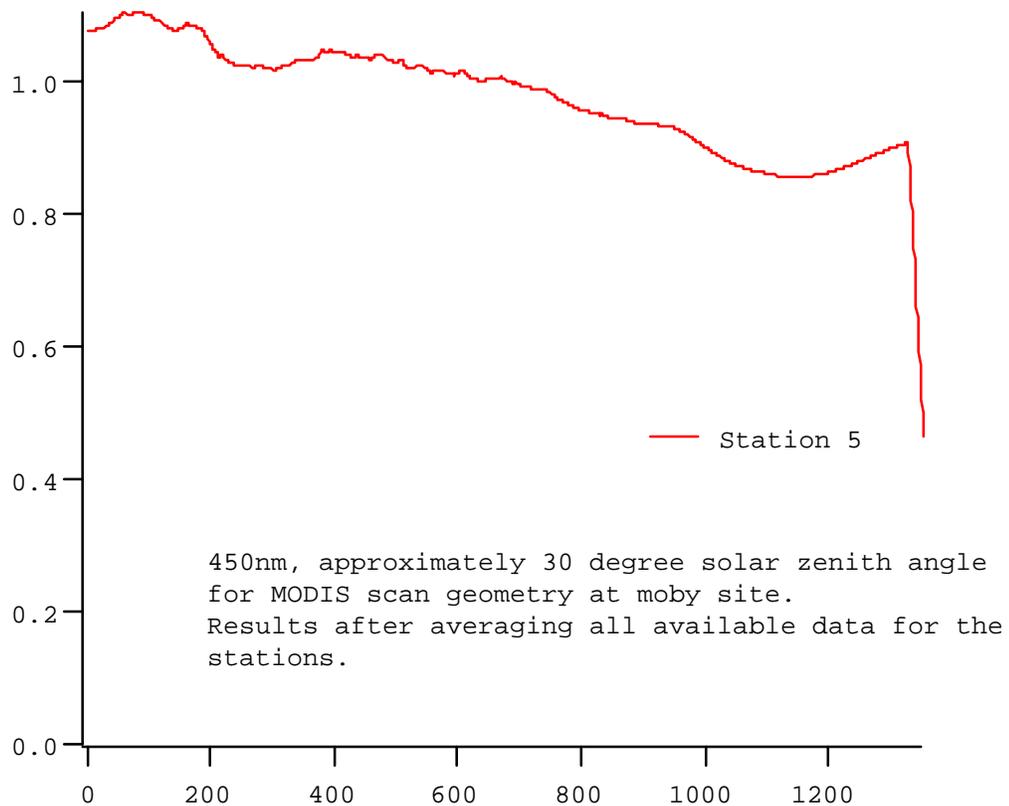


Figure 5: Variation of the water-leaving radiance (normalized to nadir) as a function of pixel number (x -axis) along the MODIS scan. West is on the left and East is on the right.

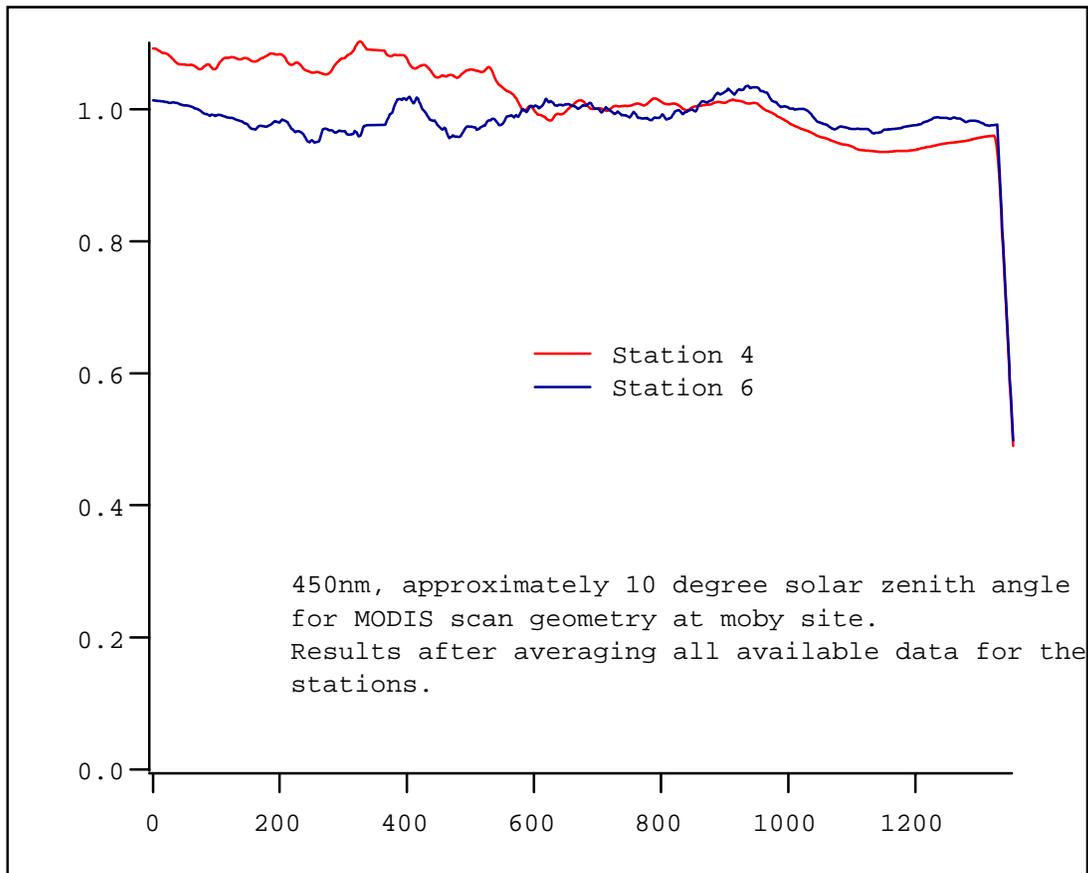


Figure 6: Same as Figure 5, but for a 10° solar zenith angle.

In addition to this work we have been working with Dennis Clark on the WARS instrument, which is a wide-angle radiance camera system that can be mounted on MOBY to measure the upwelling radiance distribution at the buoy. We also obtained additional radiance distribution data during the December, MOCE-7 cruise.

Anticipated Future Actions:

We are investigating how the variation of the ocean BRDF we see with the RADS system compares with some of the apparent artifacts in the MODIS imagery. Figures 5 and 6 show that there is a definite variation across the scan line, and an asymmetry to the scan from east to west in clear water. We will compare this asymmetry with that seen in MODIS imagery to see if the BRDF can explain the east-west asymmetry in the MODIS retrievals. Also, we will continue to model the BRDF to try to improve the retrieval of normalized water leaving radiance.

In addition, we are in the process of designing and constructing a smaller radiance distribution camera system (RADS-III). This system will be devoted to only measuring

the upwelling radiance distribution, in the configuration we have been using RADS-II. Our goal is to make a much smaller system, going from a 0.75m long \times 0.5m diameter to a 0.25m long \times 0.2m diameter container. The smaller sized system will be lighter, thus easier to deploy and float at the surface. The combination of lighter and smaller will also make the instrument shadow much smaller and allow us to improve the data quality. As there have been significant improvements in the CCD sensor technology, the data will also be less noisy and therefore more accurate.

Validation of MODIS Algorithms and Products

4. Participate in MODIS Initialization/Validation Campaigns

This task refers to our participation in actual Terra/MODIS validation/initialization exercises.

Task Progress:

During the last six months we participated in a shortened MODIS initialization cruise (MOCE-7). On this cruise there were 7 in-water radiance distribution stations, and 6 sets of sky measurements. In addition, the MPL lidar was operated continuously during the 8 days at sea. Because of the delays in the launch of Aqua, we anticipate another short cruise in the spring of 2001, with a longer cruise during the fall of 2001. We have been reducing data from MOCE-6 and have just started reducing data from the MOCE-7 cruise, which ended on December 12, 2000. We are also performing all of the post calibrations of the instruments used during this cruise (sky and in-water radiance distribution system, aureole camera system, MPL and whitecap radiometer system).

In addition, we continued to maintain our CIMEL station in the Dry Tortugas during this period. During much of this period our CIMEL instrument was undergoing extensive repairs by the AERONET group. It was returned only recently (late December) and will be put back in place in early January. This station will be used to help validate the MODIS derived aerosol optical depth (AOD), and aid in investigating the calibration of the near infrared (NIR) spectral bands of MODIS.

Anticipated future efforts:

We will finish our analysis of the MOCE-6 data and use the MOCE-7 data to provide an initial vicarious calibration for MODIS ocean bands. We will participate in the next MODIS ship campaign when it occurs. We will make measurements of the sky radiance distribution (large-angle and aureole), the in-water radiance distribution, AOD, and whitecap radiance. The Micropulse lidar (MPL) will not be used in this next short cruise. We feel it is a higher priority to have a working MPL during the longer cruise next fall. Therefore, we are collaborating with the SeaWiFS project to have a backup MPL during the longer fall cruise. In exchange, our MPL will be used as a backup during their ACE-Asia cruise in the spring. The specific group using the instrument during ACE-Asia is based at NASA/GSFC and was a leader in developing the MPL technology. In addition the specific person operating the system was a graduate student and postdoc here, so we are confident the instrument will be returned in good condition.

5. Complete Analysis of SeaWiFS Validation Campaign Data

Task Progress:

We have completed analysis of our measurements during the Aerosols99 and INDOEX campaigns, and submitted several papers for publication (See CY-2000 Publications). In addition, we have completed the reduction of the MOCE-5 BRDF data.

Anticipated future efforts:

We will continue our effort to model the MOCE-5 BRDF data as a function of the chlorophyll concentration.

RETRIEVAL OF DETACHED COCCOLITH/CALCITE CONCENTRATION

This last half year of work has focussed on several areas: 1) revision of a Deep-Sea Research manuscript on coccolithophore distributions from the Indian Ocean, 2) revision of a manuscript on a new 3-band coccolithophore algorithm, 3) implementation of a large-scale manipulative experiment for testing the MODIS suspended calcite algorithm, 4) finishing coccolith counts from 2000, 5) evaluating the early MODIS coccolith products using a Gulf of Maine bloom which formed during the summer of 2000 and 6) presentation of MODIS results at the “Oceans from space-2000” meeting in Venice, Italy.

Algorithm Evaluation/Improvement

Task Progress:

A second manuscript on our Arabian Sea has been revised for publication [Balch, W. M., D. Drapeau, B. Bowler, and J. Fritz. Continuous measurements of calcite-dependent light scattering in the Arabian Sea. Submitted to *Deep Sea Res. I*]. The abstract was given in the previous Semi-Annual report. The observation that calcium carbonate accounted for 10-40% of the total optical backscattering, is particularly significant in oceanic optics, as the particles responsible for the observed backscattering in the sea are still a mystery. The manuscript revision involved a significant error analysis for our underway technique to measure suspended particulate inorganic carbon.

We also helped revise a manuscript concerning a new algorithm for retrieval of coccolith calcium carbonate from MODIS imagery. This algorithm utilizes only red and near infrared bands and does *not* require knowledge of the chlorophyll concentration, which is very difficult to estimate remotely in coccolithophore blooms. The new coccolithophore calcite algorithm has been added into the MODIS processing code and is now being tested.

Anticipated future efforts:

We shall continue validating the new coccolithophore algorithm with MODIS data. The principal difficulty in validation being that of simultaneous acquisition of coccolithophore data and satellite imagery because of the ephemeral nature of coccolithophore blooms. We measured a coccolithophore bloom during the last half year. Data analysis from this work will be continued over the next 6 months.

Validation of MODIS Algorithms and Products

Task Progress:

Chalk-Ex

In order to validate a high concentration bloom with MODIS, we made a small calcite patch in August of 2000. The concept was relatively straightforward. Bloom concentrations of calcium carbonate are $\sim 10 \text{ g C as CaCO}_3 \text{ m}^{-2}$ of ocean water (integrated over the top 50m of the sea). Concentrations of coccoliths are thus $\sim 200 \text{ mg C as CaCO}_3 \text{ m}^{-3}$. Thus, in one km^2 of sea, there are ~ 10 metric tons of CaCO_3 (or ~ 10 cubic yards). We performed two initial experiments during April and May 2000, testing the feasibility of this approach. Our first large-scale "Chalk-Ex" experiment was designed to sea-truth the MODIS coccolith algorithm at slightly lower concentrations than found in a bloom, but still high enough to be easily visible to MODIS. The chalk that we used was ground so that it all passed a $10 \mu\text{m}$ sieve, with 50% of the particles had diameter $<1.9 \mu\text{m}$. The chalk was $\sim 98\%$ pure

Note, previous Gulf of Maine coccolithophore blooms contained as much as ~ 8.3 million metric tonnes of CaCO_3 in the form of coccoliths, hence our experiment was quite innocuous compared to the real thing. The fate of this inert chalk was to sink onto the Continental Slope. It is well known that the sediments of the continental slope SE of Georges Bank consist of mostly CaCO_3 coccolith ooze [Milliman, J.D., Pilkey, O.H. and Ross, D.A., "Sediments of the continental margin off the eastern United States," *Geological Society of America Bulletin* **83**, 1315-1334, 1972.].

On 6 August 2000, weather forecasts provided us the clear-sky window that we needed, and beginning 0400h, we diluted 25 cubic yards (~ 25 metric tons) of Cretaceous coccolith chalk with surface sea water, and adding it to the wake of the steaming vessel in order to further mix it as the ship steamed in an outward concentric spiral. We had a Satlantic SAS radiometer mounted on the bow of the R/V Cape Hatteras, as well as underway measurements of surface inherent optical properties (spectral absorption, attenuation, and backscattering), chlorophyll fluorescence, temperature, salinity, and particle size. at 39.8°N by 67.8°W (Figure 7, water depth $\sim 2000\text{m}$) which made a patch of a few square kilometers. The MODIS overpass was scheduled for mid-day of 8/6/00. Unfortunately, the MODIS satellite sensor began having unexpected data formatting problems some 1h before we began diluting the chalk, and the instrument was turned off a few hours before our overpass! This was a most unfortunate stroke of bad luck, especially given that every other part of the experiment, including the weather, had gone perfectly. All was not lost, however, as SeaWiFS did see the patch (Figure 8), and we were able to do a vicarious check of the CaCO_3 algorithm performance (but regrettably, SeaWiFS does not have the sensitivity of MODIS). (The backscattering coefficient $b_b(550)$ retrieved from the SeaWiFS image in Figure 7 and displayed in Figure 8 was $\sim 0.002\text{-}0.003 \text{ m}^{-1}$ outside the patch and 0.016 and 0.018 m^{-1} for the two bright pixels in which the patch is visible in Figure 8.) We occupied the patch for $\sim 1.5\text{d}$ as the chalk

sank, mapping its distribution (horizontally and vertically). By the end of 1.5d, we were having trouble locating the chalk as it was being mixed downward from increasing winds and sea-state. Cloudy conditions prevailed for the next 10d, so we never had any subsequent satellite images to examine, but all indications are that the chalk sank out of surface waters, towards the underlying chalk sediments of the Continental Slope.

This experiment, plus processing of the data, occupied most of our MODIS effort for the latter half of 2000. As part of this work, we purchased a free-fall Satlantic radiometer for acquiring vertical radiance data within and outside the patch, and for calculation of diffuse attenuation coefficients.

Coccolith, Coccolithophore Counts and Suspended CaCO₃ analyses

Discrete samples for the 2000 field season were all processed, including coccolith concentration (microscopy, which was by far the most laborious). The 1999 and 2000 data sets have a wealth of information on coccolith concentrations in non-bloom conditions. All the atomic absorption samples from 1999 were sent to Scripps Inst. Of Oceanography and have been processed. The 2000 field samples from Chalk-Ex are being processed at the time of this writing. The suspended CaCO₃ samples from the 2000 coccolithophore bloom will be processed by SIO in the next few months.

2000 Coccolithophore Bloom in the Gulf of Maine

As outlined in the previous semi-annual report there was a coccolithophore bloom directly along our SIMBIOS ferry track this summer, which provided us with an unprecedented opportunity to monitor 1) pre-bloom conditions, 2) bloom growth, and 3) bloom demise. Coccolith concentrations were highest around Jordan Basin (on east and west sides). The bloom continued well into July, and by mid-August, 2000, it had disappeared. Perhaps the most impressive aspect was that MODIS was able to detect the bloom at concentrations lower than we originally imagined. This bodes well for the MODIS calcite algorithm. As of this writing, we have completed all microscope counts. Peak coccolith concentrations were ~100,000 coccoliths ml⁻¹.

Anticipated future efforts:

We will spend the first half of 2001 analyzing the results from the 2000 Chalk-Ex work (as well as some final sample processing). Moreover, we will do further work on the coccolithophore bloom results and write a manuscript on the results. Beginning June '01, we will start preparation for the November '01 Chalk-Ex work aboard the R/V Endeavor. The Office of Naval Research will add in 9d of ship time for this experiment as well as funds in '02 for a complete experiment at the same sites (ONR will fund 12d of ship time and purchase the chalk).

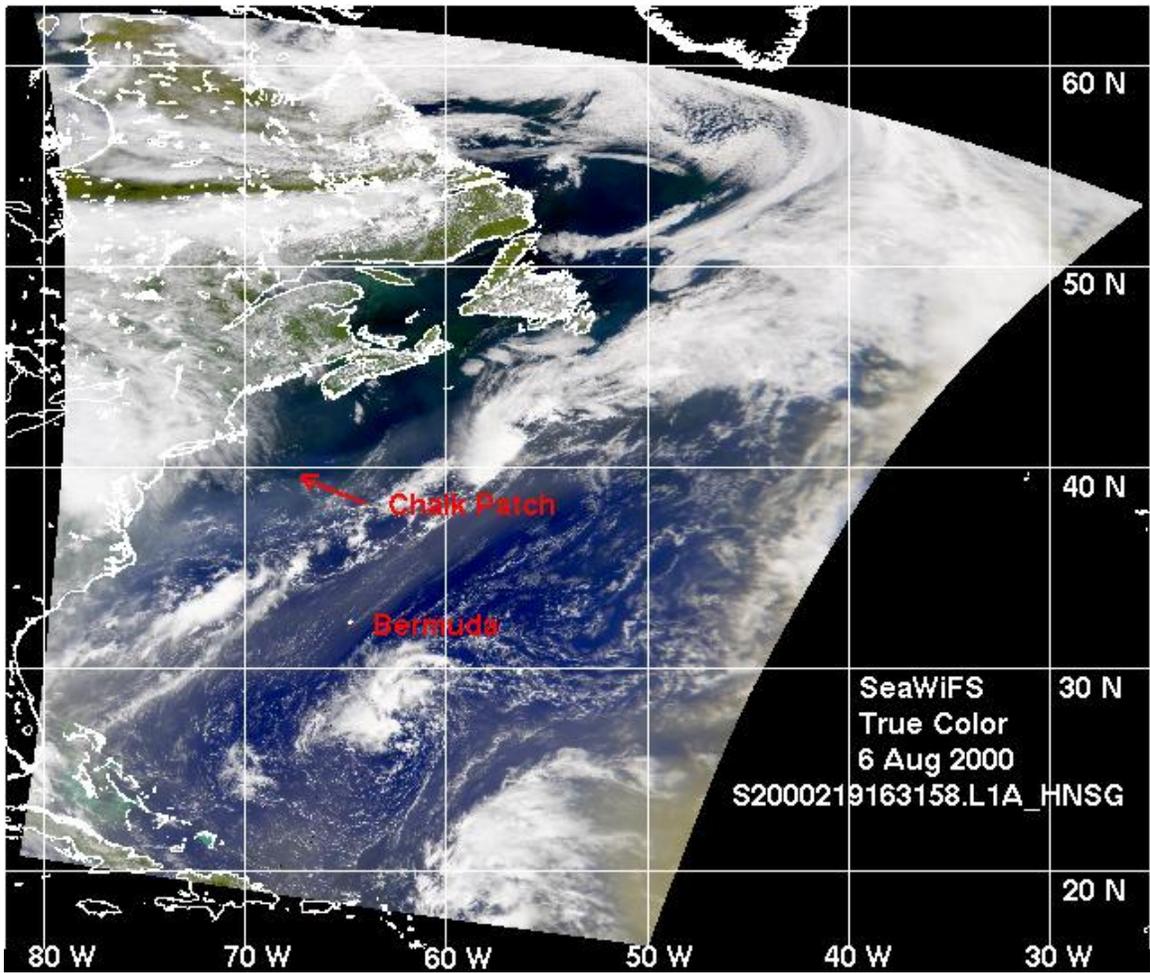


Figure 7: SeaWiFS true color image showing the position of the Chalk-Ex. release. (Courtesy of C.G. Feldman)

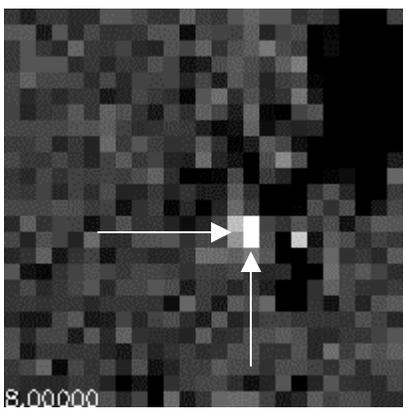


Figure 8: $b_b(550)$ for the Chalk-Ex release (position indicated by arrows) retrieved from the SeaWiFS image in Figure 7

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APPENDIX I

NASA/GSFC Contract No. NAS5-31363

OCEAN OBSERVATIONS WITH EOS/MODIS Algorithm Development and Post Launch Studies

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Plans for FY 01

Preamble

This document describes plans for Fiscal Year 2001 regarding two MODIS Ocean-related algorithms.

- A. Retrieval of the Normalized Water-Leaving Radiance (Atmospheric Correction).
- B. Retrieval of the Detached Coccolith/Calcite Concentration

Fiscal Year 2001 will be heavily focused on the evaluation and validation of MODIS-derived products. However, as we already know (from theoretical studies and from SeaWiFS) that there are certain situations in which the algorithms are unable to perform properly or that there are items that have not been included in the initial implementation, a portion of our effort will be directed toward algorithm improvement. Thus, we break our effort into two broad components for each algorithm:

- Algorithm Improvement/Enhancement;
- Validation of MODIS Algorithms and Products.

These components will overlap in some instances.

RETRIEVAL OF NORMALIZED WATER-LEAVING RADIANCE
(ATMOSPHERIC CORRECTION)

Algorithm Evaluation/Improvement

1. Evaluation/Tuning of Algorithm Performance

Now that MODIS imagery has become available the process of evaluation of the MODIS performance is underway. Examination of the imagery shows several major challenges that must be dealt with before the imagery can be usefully employed for ocean studies. Among these difficulties are the fact that

- the imagery is striped suggesting that the individual detectors in each band have different sensitivities,
- that the severity of the striping appears to depend on the scan angle, and
- that there is excessive sun glint in the imagery in the tropics.

We have been working with R. Evans and the RSMAS group to alleviate these problems. This collaboration will continue. Once the principal radiometric challenges are overcome, we will use the MOBY and MOCE-6 data to initialize the overall radiometric calibration. After this initialization procedure, the imagery will be examined on a regular basis to ensure that the algorithms and the instrument are operating properly. Specifically, the sensor-algorithms should provide the expected “clear water radiances” [Gordon and Clark, “Clear water radiances for atmospheric correction of coastal zone color scanner imagery,” *Applied Optics*, **20**, 4175-4180, 1981] in the blue-green region of the spectrum, and should retrieve water-leaving radiances that agree with measurements at the MOBY site [Clark *et al.*, “Validation of Atmospheric Correction over the Oceans,” *Jour. Geophys. Res.*, **102D**, 17209-17217, 1997]. Any deviation from expectation or measurement must be reconciled. Deviations could be due to time dependence of the sensor calibration coefficients (i.e., instability in the sensor’s radiometric response), improper initialization, improper correction for the sensor’s polarization sensitivity, etc. Such analysis of necessity involves a statistical study of the derived water-leaving radiances with sufficient observations to unravel possible effects due to viewing angle, solar zenith angle, and other factors that could influence the retrievals. In addition, the performance of the atmospheric correction algorithm will be carefully studied. For example, does the algorithm choose candidate aerosol models that do not vary significantly from pixel to pixel? Such variation could indicate poor performance of the sensor in the NIR. Do the models that are chosen suggest that $\epsilon(749,869)$ is undergoing a systematic variation with time? Such a variation would indicate that the radiometric response of the sensor is varying in time.

These studies will enable the algorithms to be tuned to the sensor and, in the event of an expected degradation in the sensor response, provide the necessary corrections to the response.

2. Implement the Initial Algorithm Enhancements

Several algorithm enhancements were planned for implementation into the processing stream in the immediate post-launch era. Among those implemented since launch are

1. the addition of wind-induced surface roughness effects in the computation of the Rayleigh-scattering contribution to the top-of-atmosphere radiance, and
2. our correction of the MODIS residual polarization sensitivity [Gordon, Du, and Zhang, "Atmospheric correction of ocean color sensors: analysis of the effects of residual instrument polarization sensitivity," *Applied Optics*, **36**, 6938-6948] using MCST/SBRS-supplied MODIS polarization sensitivity characterization data.

As mentioned in Section 1, examination of MODIS imagery $\pm 20^\circ - 30^\circ$ from the solar equator reveals significant contamination due to sun glitter, even outside what would normally be considered to be the "glitter pattern." This high glint contribution is particularly troublesome at the MOBY site, which is used to monitor the performance and calibration of MODIS. Thus to fully utilize the MOBY site, and to extend the usefulness of MODIS imagery in these areas, we need to remove as much of the sun glint contribution as possible. At present the glitter pattern is masked using computations described in our ATBD. This mask needs to be refined into a validated scheme for removing sun glint. This will be a major focus of our enhancement effort.

3. Study Future Enhancements

The principal focus of enhancing the basic algorithms are absorbing aerosols. We consider correcting for absorbing aerosols to be the most important of the unsolved atmospheric correction issues because it has such a significant impact in many geographical areas. Algorithms to effect such correction are under intense development now. Among the possibilities we are studying are the spectral matching algorithm (SMA) [Gordon, Du, and Zhang, "Remote sensing ocean color and aerosol properties: resolving the issue of aerosol absorption," *Applied Optics*, **36**, 8670-8684 (1997)], the spectral optimization algorithm SOA [Chomko and Gordon, "Atmospheric correction of ocean color imagery: Use of the Junge power-law aerosol size distribution with variable refractive index to handle aerosol absorption," *Applied Optics*, **37**, 5560-5572 (1998)], and application of a model of Saharan dust transported over the ocean by the winds that is currently in the testing phase (Moulin *et al.*, in preparation).

The SMA is now being studied extensively because it can be added to the present MODIS algorithm with minor impact, as it uses the same look-up-tables (LUTs) as the existing algorithm. Another attractive feature is that it is completely compatible with our present plans for dealing with wind-blown desert dust. We plan to implement this algorithm in phases. In the first phase, the algorithm will be used to provide a flag that signals the presence of absorbing aerosols. In the second phase, the SMA will actually perform the atmospheric correction and retrieve the ocean products. In the third phase, it will be applied to wind-blown dust. Our goal is to implement all three phases during FY00. A question that needs to be resolved is whether or not the SMA, which employs a semi-analytic model of ocean color [Gordon *et al.*, "A Semi-Analytic Radiance Model of Ocean Color," *Jour. Geophys. Res.*, **93D**, 10909-10924, 1988], is compatible with more sophisticated ocean color models, e.g., Lee *et al.* ["Method to derive ocean absorption coefficients from remote sensing reflectance," *Applied Optics*, **35**, 453—462, 1996] or Garver and Seigel ["Inherent optical property inversion of ocean color spectra and its biogeochemical interpretation: 1 time series from the Sargasso Sea," *Geophys. Res.*, **102C**, 18607—18625, 1997].

The SOA is attractive in that it does not require detailed aerosol models to effect atmospheric correction and it has been successfully operated off the U.S. East Coast using the Garver and Seigel [1997] model for the ocean's reflectance. Unfortunately, its efficacy in dealing with wind-blown desert dust, which displays absorption that varies strongly with wavelength, is unclear. The performance of this algorithm will be studied in parallel with the SMA development.

There are two additional enhancements that are now in the research phase: (1) developing an accurate model of the subsurface upwelling radiance distribution as a function of view angle, sun angle, and pigment concentration, and (2) evaluating the performance of the SMA and SOA algorithms in the presence of high concentrations of colored dissolved organic matter (CDOM). The study of these will continue during FY 2000.

Most validation measurements of upwelled spectral radiance (BRDF) in the water are made viewing in the nadir direction. In contrast, ocean color sensors are usually non-nadir viewing. Thus, an important question is how does one validate the sensor performance when the quantity being measured differs from the quantity being sensed? Obviously, one must either correct the validation measurement to the correct viewing angle of the sensor, or correct the sensor observation to what it would be if the view were nadir. Either strategy requires a model of the subsurface radiance distribution. We are using measurements made near the MOBY site to develop such a model. We started using the model of Morel and Gentili ["Diffuse reflectance of oceanic waters. II. Bidirectional aspects," *Applied Optics*, **32**, 6864—6879 (1993)]; however, that model did not agree well with the experimental results. We are now trying to understand the source of the disagreement by examining processes left out of the computation of the radiance distribution, such as instrument self-shadowing and polarization. Once a model of the BRDF is available, we will use it to correct the diffuse transmittance for BRDF effects as described by Yang and Gordon ["Remote sensing of ocean color: Assessment of the

water-leaving radiance bidirectional effects on the atmospheric diffuse transmittance,” *Applied Optics*, **36**, 7887-7897 (1997)].

Initial work with MODIS imagery shows a pronounced asymmetry in the normalized water-leaving radiance in the visible across the scan (higher on the east). This is exactly what might be expected from water BRDF effects. Thus the BRDF will be given more attention than we felt was justified prior to acquiring the initial MODIS imagery.

The SMA and the SOA identify the presence of absorbing aerosols by using the full spectrum of radiance at the top of the atmosphere (TOA). Typically, absorbing aerosols cause a depression of the TOA radiance in the blue portion of the spectrum. Unfortunately, CDOM in the water leads to a depression in the blue. We are examining the interference of these two effects. Strong interference could limit the usefulness of ocean color sensors in coastal waters where CDOM is high and absorbing aerosols (from urban pollution) are likely to be present.

Validation of MODIS Algorithms and Products

Our participation in validation and initialization exercises requires that an array of instrumentation be maintained and fully operational at all times. Furthermore, data analysis skills need to be maintained as well. Personnel for such maintenance are included in our cost estimates.

4. Participate in MODIS Validation Campaigns

Present plans developed by D. Clark are to have a short validation field campaign in December 2000, followed by a major campaign in the spring of 2001. We will participate in these campaigns by providing several data sets: (1) we shall use our whitecap radiometer [K.D. Moore, K.J. Voss, and H.R. Gordon, “Spectral reflectance of whitecaps: Instrumentation, calibration, and performance in coastal waters,” *Jour. Atmos. Ocean. Tech.*, **15**, 496-509 (1998)] to measure the augmented reflectance of the water due to the presence of whitecaps; (2) we shall use our radiance distribution camera system (RADS) to measure the BRDF of the subsurface reflectance; (3) we shall employ our micro pulse lidar (MPL) to measure the vertical distribution of the aerosol (of critical importance when absorbing aerosols are present); (4) we shall use our solar aureole cameras and all-sky radiance camera (SkyRADS) to measure the sky radiance distribution to provide the aerosol scattering phase function; and (5) we will measure the aerosol optical depth (AOD). All measurements will be carried out at the station locations with the exception of the MPL which will operate continuously during the campaign. This data will be combined with the data from MOBY to fine tune the sensor and algorithms.

In addition, we will continue to operate our CIMEL station in the Dry Tortugas as part of the Aeronet Network [Holben, *et al.*, “AERONET--A federated instrument network and data archive for aerosol characterization,” *Remote Sensing of Environment*, **66**, 1-16].

Data from this site will be used to validate MODIS-derived AOD and possibly provide a means to examine the calibration of the near infrared (NIR) spectral bands.

5. Complete Analysis of SeaWiFS Validation Campaign (MOCE-5) Data

We will complete our analysis of the MOCE-5 data acquired in the fall of 1999 simultaneously with SeaWiFS imagery. This data set will serve as a validation platform of the MODIS atmospheric correction algorithm, and a test bed for the more advanced algorithms described in Section 3.

Retrieval of the Detached Coccolith/Calcite Concentration

Algorithm Evaluation/Improvement

1. Evaluation/Tuning of Algorithm Performance

Evaluation of the coccolith/calcite concentration has focused on two sets of observations: a) a coccolithophore bloom which occurred in the Gulf of Maine during the summer of 2000, and b) a large-scale manipulation experiment performed in August, in which 25 tons of coccolith chalk was disseminated into a patch (initial size = 3km²). As with the retrieval of normalized water-leaving radiance (above), the coccolith algorithm suffers from the striping and sun glint issues. The Gulf of Maine coccolithophore bloom of 2000 formed in June, and extended well into July. We first observed it during our NASA SIMBIOS cruises aboard the M/S Scotia Prince ferry. During these trips, the acid-labile backscattering increased significantly (to ~50% of the total backscattering). MODIS imagery from this bloom (Fig. 1) showed remarkable detail, and a first look at the acid-labile backscattering values (and assumed calcite-specific backscattering coefficients of the coccoliths) revealed that the algorithm-derived calcite concentrations were reasonable. The true test, however, will await final processing of our coccolith count samples, and suspended calcite analyses (being done by Scripps Analytical Facility on their inductively-coupled atomic absorption spectrometer). These will then be directly compared to the MODIS imagery.

The second part of the algorithm tuning work involved “Chalk-Ex”, a large-scale manipulation experiment in which finely ground coccolith chalk was spread into a patch. The ship work was done aboard the R/V *Cape Hatteras* from 4-10 August, 2000. Twenty five cubic yards of the chalk particles (median size = 2µm--the same size as coccoliths) were mixed with seawater, and dispersed into the wake of the research vessel, as it steamed in widening circles. The weather was excellent for the dispersal, with almost completely clear skies, and low winds. The patch was finished late morning on 6 August 2000, and was ~3km in diameter.

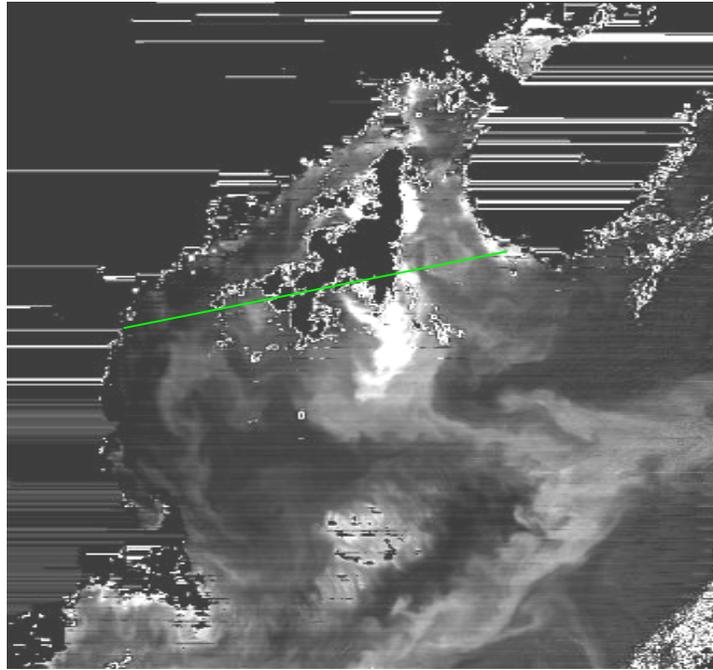


Figure 1- MODIS image of PIC concentration in Gulf of Maine from June 20, 2000. Note advection of coccoliths around northern flank of Georges Bank, with fine-scale eddy structure along the frontal boundary. Scale- White = 3×10^{-3} moles PIC m^{-3} ; light grey = 2×10^{-3} moles PIC m^{-3} ; dark grey = 0.75×10^{-3} moles PIC m^{-3} ; black = $0-0.1 \times 10^{-3}$ moles PIC m^{-3} . Ferry track is shown with green line.

Unfortunately for Chalk-Ex, there was an unexpected formatting problem aboard MODIS 10h before chalk deployment was to begin (~1800 EDT 5 August). The MODIS operations team discovered that the formatter circuitry was resetting itself (~ 330 resets were observed). There was a mixture of valid and invalid data packets observed for some time after which no valid data packets were sent (6:21 PM EDT (22:21 Zulu)). At approximately 11:30 EDT (August 6, 2000 03:30 Zulu; ~1 hour before the first valid MODIS overpass) MODIS was placed in low power mode with the mirror stopped and survival heaters turned on. The instrument was not turned on again until several days following the mishap, thus, no MODIS imagery was collected of the chalk patch. Fortunately, the chalk patch was observed with SeaWiFS and analyses of the derived backscattering values are being done at this time.

2. Implement the Initial Algorithm Enhancements

The initial coccolith algorithm has been implemented with MODIS data. Gordon et al (1988) first described the scheme to derive coccolith concentrations from estimates

of blue and green water-leaving radiance. The technique essentially uses a ratio algorithm (Gordon and Morel, 1983) to provide a first guess of chlorophyll concentration. Next, for each unique water-leaving radiance and chlorophyll level, a look-up table is consulted (derived from the specific scattering coefficient of calcite coccoliths and chlorophyll, as well as the specific absorption of chlorophyll) which provides an estimate of the CaCO₃ concentration. The process is iterated several times until stable chlorophyll and CaCO₃ concentration are achieved. This approach has been implemented after MODIS launch and global maps of suspended CaCO₃ concentration are now available.

A new three-band algorithm for deriving suspended CaCO₃ concentration has been submitted to *Geophysical Research Letters* for publication:

H. R. Gordon, G. C. Boynton, **W. M. Balch**, S. B. Groom, D. S. Harbour, and T. J. Smyth. Retrieval of Coccolithophore Calcite Concentration from SeaWiFS Imagery. *Geophysical Research Letters* (Submitted)

This paper examines blooms of the coccolithophorid *E. huxleyi*, observed in SeaWiFS imagery, with a new algorithm for the retrieval of detached coccolith concentration. The algorithm uses only bands in the red and near infrared (NIR) bands to minimize the influence of the chlorophyll and dissolved organic absorption. We used published experimental determinations of the calcite specific backscattering and its spectral dependence, and assumed that the absorption coefficient of the medium was that of pure water, to estimate the marine contribution to the SeaWiFS radiance. The aerosol (and Rayleigh-aerosol interaction) contribution to the radiance was modeled as an exponential function of wavelength. These allow derivation of the coccolith concentration on a pixel-by-pixel basis from SeaWiFS or MODIS imagery. Application to a July 30, 1999 SeaWiFS image of a bloom south of Plymouth, England indicates that the SeaWiFS estimates are in good agreement with surface measurements of coccolith concentration.

3. Study Future Enhancements

It is anticipated that, provided future algorithm performance is adequately validated, the three-band algorithm will be implemented for use with MODIS data rather than the two band approach (since it is not affected by chlorophyll and dissolved organic matter).

4. Participate in MODIS Validation Campaigns

We plan to continue MODIS-validation work in '01. At this time, we are planning two 13 ton Chalk-Ex deployments in the summer of 2001. One will be in blue water, SE of Georges Bank. The other patch will be created in a more productive part of the Gulf of Maine (yet to be determined). MODIS will pay for 3d of this cruise, while the Navy will cover the other 11d. A second cruise is planned for November 2001, in which two more 13 ton patches will be deployed in the same locations as during the first cruise. Ship time for the second cruise will be provided completely by the Office of Naval Research. We also will monitor ocean color imagery for Gulf of Maine Blooms. In the event a Gulf of

Plans for FY 01 NASA/GSFC NAS5-31363 H.R. Gordon (10/24/00)

Maine feature is observed, we will endeavor to sample it. Our ferry program is currently under review to the NASA SeaWiFS program. If funded, we will collect more coccolithophore data from the ferry during twelve cruises in 2001. These data will be used in MODIS validation.