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INVESTIGATION STATUS REPORT (May 2001)

PROJECT TITLE:

Optical and Ancillary Measurements at High Latitudes in Support of the MODIS Ocean Validation Program

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I. Primary objectives of the project

The overall goal of the project is to validate MODIS ocean color algorithms at high latitudes in the Arctic Seas. The specific objectives include:
(1) To identify and quantify errors in MODIS-derived Level-2 data of the spectral water-leaving radiances and chlorophyll concentration in the Greenland and Norwegian Seas.
(2) To develop understanding of the errors.
(3) To improve in-water ocean color algorithms for the retrieval of chlorophyll concentration in the investigated region.

II. Summary of tasks for the reporting period June 1, 2000 - May 31, 2001

During the reporting period we pursued three tasks:
(1) Carry out optical and ancillary measurements during the Arctic cruise in June-July 2000.
(2) Process the collected data and carry out analysis of data to examine ocean color algorithms including the quantification of errors in the Level-2 satellite ocean color data products and the development of improved regional algorithm for retrieving chlorophyll concentration.
(3) Present our results at ASLO (American Society of Limnology and Oceanography) conference and write publications.

Task 1. Measurements during the cruise in summer 2000

We completed our third field campaign in the Arctic on research vessel "Oceania" operated by the Polish Academy of Sciences. The study area extended from 60^{o} to 80^{o}N within the meridional zone between 3^{o} and 20^{o}E, and included Norwegian Sea, Greenland Sea, and Spitsbergen Bank. Measurements were made during two legs of the cruise:
- Leg 1: Tromso (Norway) – Longyearbyen (Spitsbergen) June 22 - July 10, 2000;
- Leg 2: West Spitsbergen Current - Greenland Sea, July 12 – July 20, 2000.

In situ optical measurements were made down to a depth of 100 – 200 m in close proximity (location and time) to water samples collected from discrete depths. We used two sensor packages:
(i) SeaWiFS Profiling Multichannel Radiometer (SPMR, Satlantic) for measuring downwelling irradiance and upwelling radiance within 13 spectral wavebands in free fall mode away from ship perturbations. The instrument is equipped with a set of filters matching

the SeaWiFS/MODIS bands as well as several wavelengths which are not included in the current satellite ocean color sensors (for example, in the UV region).
(ii) Multisensor Datalogger System (MDS) for measuring vertical profiles of physical properties and inherent optical properties of seawater. The system includes SeaBird Sealogger 25 (SB25) with temperature, conductivity, and pressure sensors, two single wavelength (488 and 660 nm) beam transmissometers (WetLabs), chlorophyll fluorometer (WetLabs), and PAR sensor (Biospherical). Hydroscat-6 sensor (HobiLabs) for measuring measurements of light backscattering at six wavelengths and two a-βeta instruments (HobiLabs) for measuring the total absorption coefficient, each at a single wavelength, were also integrated with this system.

Water samples from discrete depths were used to measure particulate absorption from 380 to 750 nm by means of filter pad technique with a bench-top double-beam spectrophotometer equipped with an integrating sphere. The measurements on filters were made in both the transmittance and the reflectance mode. We also conducted unique absorption experiments with the purpose of determining the pathlength amplification factor for natural particle assemblages collected on the filters, which is essential for accurate determination of particulate absorption. Samples for the analysis of chlorophyll-*a* and particulate organic carbon POC (dry combustion technique) were also collected. The analyses of water samples were carried out in collaboration with the bio-optical team from the Polish Academy of Sciences.

In addition, a number of observations were made as part of the Polish program including deep profiles of water temperature and conductivity, ocean currents, meteorological parameters, marine aerosol, sky conditions, and sea state. Digitial pictures of sea surface were taken for the analysis of whitecap coverage.

Task 2. Data processing and analysis

Data processing including data quality control and conversion to physical units is completed. We also completed calculations of various optical quantities that are relevant to ocean color algorithms such as remote-sensing reflectance, spectral attenuation coefficient for downwelling irradiance and upwelling radiance, and spectral water-leaving radiance. These data cover a broad range of optical water types from clear ocean waters to turbid waters of the Spitsbergen Bank, as well as variable weather conditions from calm seas to stormy weather.

Because of overcast skies during the cruise we were unable to collect in situ data for direct comparison with satellite-derived ocean color products. Therefore, a final comparison of our ship-based measurements and high resolution (HRTP) SeaWiFS data is based on the two cruises in 1998 and 1999, which was described in our previous report. These results are presented in Table 1 below.

Table 1. Statistics of the in situ and SeaWiFS match-up data for the Norwegian and Greenland Seas.

Parameter	Mean ratio SeaWiFS / in situ	Number of observations
L_{wn} (412)	0.54	13
L_{wn} (443)	0.74	13
L_{wn} (490)	0.91	13
L_{wn} (510)	0.90	13
L_{wn} (555)	0.86	13
L_{wn} (490)/L_{wn} (555)	1.06	13
Chl	2.30	20
in situ Chl < 0.5 mg m^{-3}	3.28	12
in situ Chl > 0.5 mg m^{-3}	0.81	8

The results presented above indicate large difference between in situ and satellite-derived water-leaving radiances (L_{wn}) in the blue spectral region. The $L_{wn}(490)/L_{wn}(555)$ ratio shows, however, a fairly good agreement between in situ and satellite-derived values. Therefore, the observed errors in the SeaWiFS-derived chlorophyll *a* concentration (Chl), which are greatest at low Chl, can be primarily attributed to performance of the NASA standard chlorophyll algorithm referred to as OC2 (O'Reilly et al., 1998).

Figure 1 compares the NASA OC2 algorithm with our in situ data of the chlorophyll concentration, Chl, versus the blue-to-green reflectance ratio, $R_{rs}(490)/R_{rs}(555)$. In addition, we show data for the $R_{rs}(442)/R_{rs}(555)$ ratio. All data collected during the three cruises are shown in Figure 1. We observe significant scatter about the OC2 curve and systematic overestimation of Chl by OC2 algorithm at low chlorophyll concentrations. For our data set the $R_{rs}(442)/R_{rs}(555)$ ratio provides somewhat better chlorophyll algorithm than the $R_{rs}(490)/R_{rs}(555)$ ratio. The best-fit regression formulas for the data shown as open circles are given. Our present analysis is focused on developing the understanding of the seemingly random scatter in the data points in Figure 1 and possible systematic departures from the OC2 algorithm. This understanding will be critical to making improvements in Chl retrieval from satellite-derived reflectance. As an example, we identified several data points (shown as triangles in Figure 1), which correspond to "unusual" reflectance spectra with a maximum at 510 nm. In these waters, the presented algorithms overestimate the chlorophyll concentration. We are currently examining these data in terms of the detailed pigment composition of phytoplankton. We expect that this analysis will provide explanation of the "unusual" shape of the reflectance spectra. Most data (shown as open circles in Figure 1) that were included in the regression analysis showed a maximum at wavelengths shorter than 510 nm, that is usually around 490 nm.

To a first approximation, the variability in $R_{rs}(490)/R_{rs}(555)$ is driven by a product of the spectral ratios of the backscattering and absorption coefficients, $[b_b(490)/b_b(555)]$ $[a(555)/a(490)]$. This also applies to $R_{rs}(442)/R_{rs}(555)$. Our data showed that the overall range of values for the blue-to-green b_b ratios is quite small, and that these ratios did not change significantly with Chl (Figure 2). Therefore, the observed variation in the reflectance ratio with Chl is expected to be strongly dependent on the variability in the green-to-blue absorption ratio. Accurate in situ measurements of the total absorption coefficient $a(\lambda)$ are very difficult and we did not have such a capability during our field experiments. However, we obtained reasonable estimates of $a(\lambda)$ from the model based on radiative transfer simulations (Stramska et al., 2000) using our in-water measurements of the backscattering coefficient and reflectance.

We found that the sum of absorption by pure seawater and particles dominated the total absorption in the blue-green spectral region while the dissolved organic materials had relatively small contribution. Phytoplankton contributed, on average, 80 and 70% to total particulate absorption a_p at 490 and 555 nm, respectively. The total particulate absorption and phytoplankton absorption were highly correlated in the blue ($r^2 = 0.95$ and 0.92 at 442 and 490 nm respectively) but the correlation was lower at 555 nm ($r^2 = 0.69$). In addition, we found that our estimates of Chl-specific particulate absorption in the blue is, on average, higher in the Arctic region compared to the Bricaud et al. data set. This trend was not, however, observed for 555 nm.

Figure 3 shows the green-to-blue spectral ratios of the sum of absorption by pure water and particles (a_{w+p}) as a function of Chl. The solid line is the best-fit regression for our data points and the dotted line represents the best-fit to the large data set from low latitudes described in Bricaud et al. (1998). Note that nearly all our data points are located below the regression of Bricaud et al. (1998). This suggests that for any value of Chl the Greenland and Norwegian Seas could exhibit a tendency to lower values of the blue-to-green spectral ratio of R_{rs} compared to low-latitude data sets such as that used to develop the OC2 algorithm (provided that the backscattering properties do not show significant differentiation between the high- and low-latitude systems which still remains an open question). This tendency is seen for the subset of our data collected at low chlorophyll concentration in the Greenland Sea where the OC2 algorithm shows a systematic bias. Because the variability in the absorption coefficient observed at any Chl can be an important source of error in the retrieval of pigment concentration from ocean color observations, much of our present analysis is focused on this variability. The detailed analysis of our validation results, bio-optical relationships, and chlorophyll algorithm in the Norwegian and Greenland Seas is the subject of the manuscript that is being prepared for publication (Stramska et al., in preparation).

Task 3. Publications and conference presentations supported by this project

Stramska, M., D. Stramski, B. G. Mitchell, and C. D. Mobley. 2000. Estimation of the absorption and backscattering coefficients from in-water radiometric measurements. *Limnol. Oceanogr.*, 45, 628-641.

Loisel, H., and D. Stramski, 2000. Estimation of the inherent optical properties of natural waters from the irradiance attenuation coefficient and reflectance in the presence of Raman scattering. *Appl. Opt.*, 39, 3001-3011.

Stramski, D., and J. Tegowski. The effects of intermittent entrainment of air bubbles by breaking wind waves on ocean reflectance and in-water light field, *J. Geophys. Res*. (revised manuscript submitted).

Stramska, M., D. Stramski, R. Hapter, S. Kaczmarek, and J. Ston. Bio-optical relationships and ocean color algorithms in the Norwegian and Greenland Seas (in preparation for submission to *Int. J. Remote Sens*.).

Stramska, M., D. Stramski, R. Hapter, S. Kaczmarek, and J. Ston. Algorithms for the analysis of satellite imagery of ocean color in the Arctic Seas. Presented at the ASLO Conference, Albaquerque, New Mexico, February 2001.

Stramski, D., Stramska, M., , R. Hapter, and S. Kaczmarek. On the determination of particulate absorption coefficient from a filter pad technique. Presented at the ASLO Conference, Albaquerque, New Mexico, February 2001.

III. References

Bricaud A., A. Morel, M. Babin, K. Allali, and H. Claustre. 1998. Variability of light absorption by suspended particles with chlorophyll *a* concentration in oceanic (case 1) waters: Analysis and implications for bio-optical models, J. Geophys. Res., 103, 31033-31044.

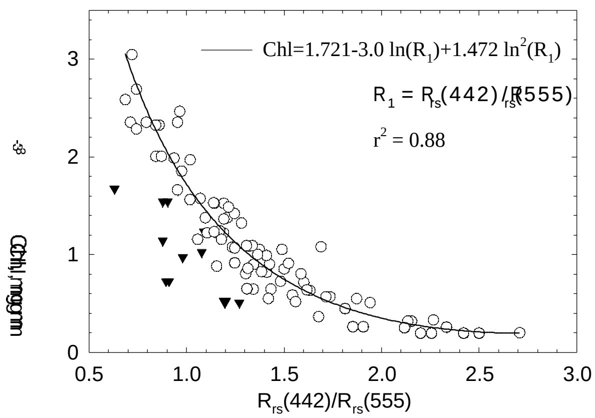
Carder, K.L., F.R. Chen, Z.P. Lee, and S.K. Hawes. 1999. Semianalytic Moderate-Resolution Imaging Spectrometer algorithms for chlorophyll *a* and absorption with bio-optical domains based on nitrate-depletion temperatures, J. Geophys. Res., 104, 5403-5421.

O'Reilly, J. E., S. Maritorena, B. G. Mitchell, D. A. Siegel, K. L. Carder, S. A. Garver, M. Kahru, and C. R. McClain. 1998. Ocean color chlorophyll algorithms for SeaWiFS. J. Geophys. Res., 103, 24937-24953.

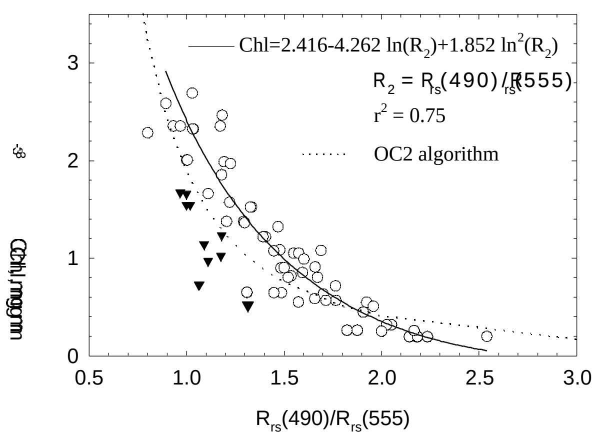
Stramska, M., D. Stramski, R. Hapter, and S. Kaczmarek, J.Ston. Bio-optical relationships and ocean color algorithms in the Norwegian and Greenland Seas (in preparation for submission to *Int. J. Remote Sens*.).

Stramska, M., D. Stramski, B. G. Mitchell, and C. D. Mobley. 2000. Estimation of the absorption and backscattering coefficients from in-water radiometric measurements. *Limnol. Oceanogr*., 45, 628-641.

Figure 1



Chl=1.721-3.0 ln(R1)+1.472 ln2(R1)
R1 = Rrs(442)/Rrs(555)
r2 = 0.88
0
1
2
3
0.5
1.0
1.5
2.0
2.5
3.0
Rrs(442)/Rrs(555)



Chl=2.416-4.262 ln(R2)+1.852 ln2(R2)
R2 = Rrs(490)/Rrs(555)
r2 = 0.75
OC2 algorithm
0
1
2
3
0.5
1.0
1.5
2.0
2.5
3.0
Rrs(490)/Rrs(555)

Figure 2

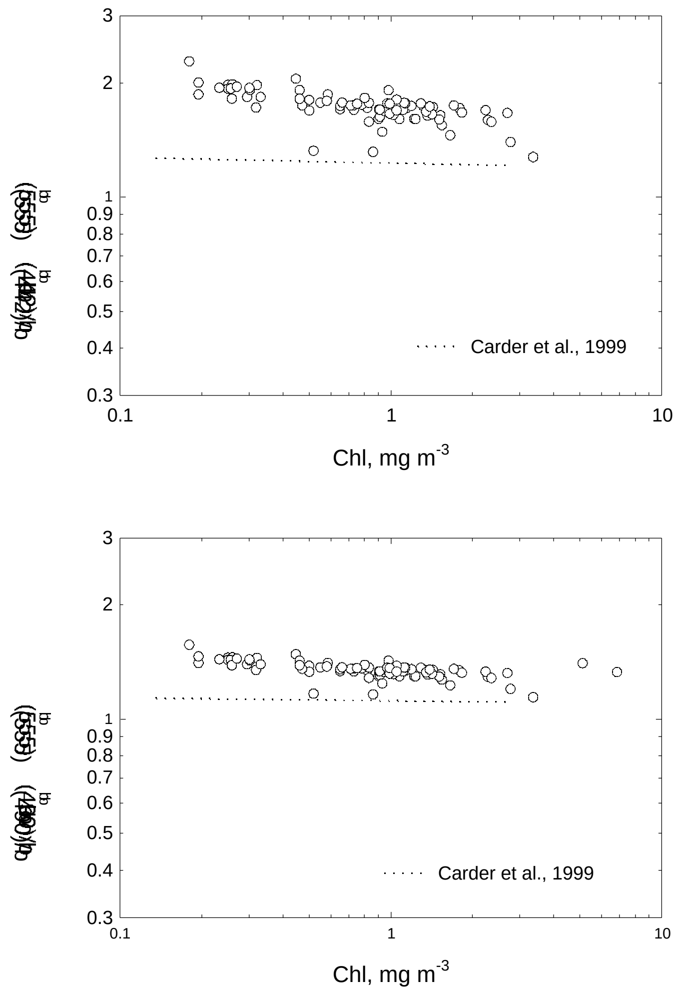
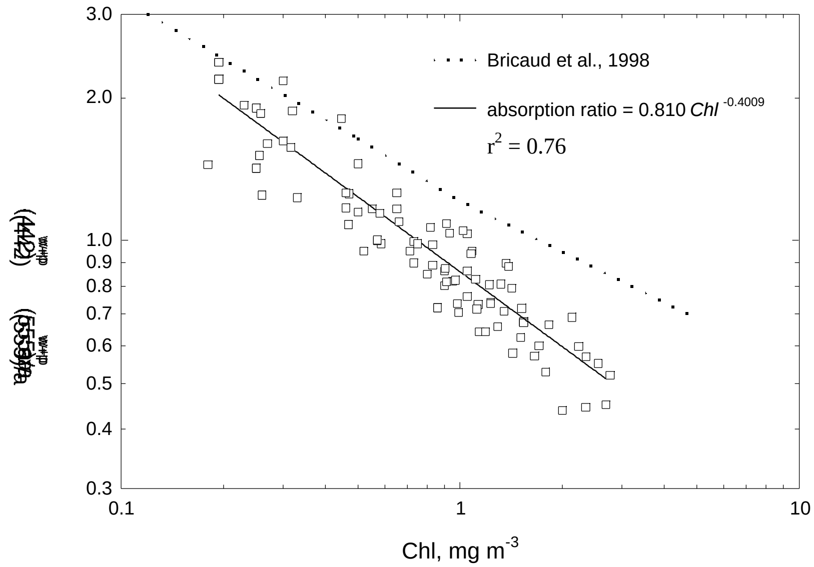
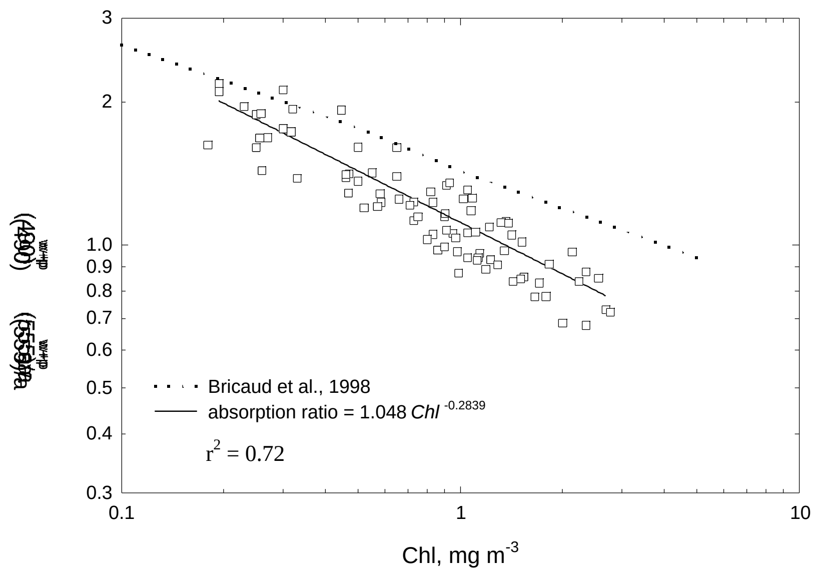

3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.1
1
10
Carder et al., 1999
Chl, mg m-3
3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.1
1
10
Carder et al., 1999
Chl, mg m-3

Figure 3



Bricaud et al., 1998
absorption ratio = 0.810 Chl -0.4009
r2 = 0.76
3.0
2.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.1
1
10
Chl, mg m-3



Bricaud et al., 1998
absorption ratio = 1.048 Chl -0.2839
r2 = 0.72
3
2
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.1
1
10
Chl, mg m-3