

FINAL REPORT

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PROJECT TITLE:

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

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Attachments

- 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, 2001. Effects of intermittent entrainment of air bubbles by breaking wind waves on ocean reflectance and in-water light field. *J. Geophys. Res.*, 106, 31345-31360.
- Stramska, M., D. Stramski, R. Hapter, S. Kaczmarek, and J. Ston. Bio-optical relationships and ocean color algorithms for the north polar region of the Atlantic. *J. Geophys. Res.*, accepted.
- Stramska, M., and T. Petelski. Observations of oceanic whitecaps in the north polar waters of the Atlantic. *J. Geophys. Res.*, accepted.

1. Primary objectives of the project

The overall goal of this project was to validate and refine ocean color algorithms at high latitudes in the north polar region of the Atlantic. The specific objectives were defined as follows: (i) to identify and quantify errors in the satellite-derived water-leaving radiances and chlorophyll concentration; (ii) to develop understanding of these errors; and (iii) to improve in-water ocean color algorithms for retrieving chlorophyll concentration in the investigated region.

2. Summary of completed tasks

During the course of this project we completed the following tasks:

- (i) We made optical and ancillary measurements on the three Arctic cruises in 1998, 1999, and 2000, in collaboration with Polish Academy of Sciences.
- (ii) We performed analysis of collected in situ data, satellite-derived ocean color data products, and in-water chlorophyll algorithms. We derived a regional ocean color algorithm for improved retrieval of chlorophyll concentration in the investigated polar waters. The optical data collected on the cruises were submitted to the SeaWiFS Bio-optical Archive and Storage System (SeaBASS).
- (iii) We developed inverse optical models for estimating absorption and backscattering coefficients of seawater from radiometric measurements, and we also examined the dependence of whitecap coverage on wind speed and the effects of submerged bubble clouds on ocean reflectance in the investigated region.
- (iv) We presented our results at several conferences and completed several publications that are listed below.

3. Field measurements

The investigated region includes subarctic and arctic waters of the north polar Atlantic between 70 and 80°N within the meridional zone between 1 and 20°E. This study area includes waters of the Norwegian Sea, confluence zone of the Norwegian Sea and Barents Sea, West Spitsbergen Current, and Greenland Sea. Measurements were made on three cruises of R/V Oceania operated by Polish Academy of Sciences:

- (i) cruise 1: June 21 - July 16, 1998; (ii) cruise 2: June 22 – August 5, 1999; and (iii) cruise 3: June 22 - 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 underwater sensor packages:

- (i) SeaWiFS Profiling Multichannel Radiometer (SPMR, Satlantic) for measuring downwelling irradiance and upwelling radiance at 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). Hydrosat-6 sensor (HobiLabs) for measuring measurements of light backscattering at six wavelengths and two a - β 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 taken to measure particulate absorption from 350 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* were also collected.

The analyses of water samples were carried out in collaboration with the bio-optical team from Polish Academy of Sciences. In addition, a number of observations were made as part of the Polish program including measurements of water temperature and conductivity, ocean currents, meteorological parameters, marine aerosol, sky conditions, sea state, and bubbles. Digital pictures of sea surface were taken for the analysis of whitecap coverage.

4. Data processing and analysis

Data processing including data quality control and conversion to physical units was completed. The pigment determinations and calculations of various optical quantities that are relevant to ocean color algorithms such as the remote-sensing reflectance, water-leaving radiance, attenuation coefficients for downwelling irradiance and upwelling radiance, and absorption and backscattering coefficients were completed. We analyzed these results to establish bio-optical relationships and improved algorithms for chlorophyll and absorption

retrieval from reflectance measurements in the investigated region. The optical data from our cruises were submitted to the SeaWiFS Bio-optical Archive and Storage System (SeaBASS). We also analyzed acoustic measurements of submerged bubble clouds and we used these data in the radiative transfer model to examine the effects of bubbles on ocean reflectance. The analysis of whitecap coverage and wind speed data was also completed.

5. Major results and accomplishments

We will now summarize major results and research accomplishments. These results are described in detail in five publications supported by this project, which are attached with this report. The summary of results will be divided into four subject areas: (i) ocean color algorithms (see the paper by Stramska et al., *J. Geophys. Res.*, accepted, for more details), (ii) effects of bubble clouds on ocean reflectance (see Stramski and Tegowski, 2001), (iii) oceanic whitecaps (see Stramska and Petelski, *J. Geophys. Res.*, accepted), and (iv) inverse optical models (see Stramska et al., 2000; and Loisel and Stramski, 2000).

5.1. Ocean color algorithms

Our measurements show that the current NASA global algorithms, OC2, OC4, and chlor-MODIS, generally overpredicted the chlorophyll *a* concentration, *Chl*, in the investigated waters by a factor of about 2 at low pigment concentrations ($<0.2 \text{ mg m}^{-3}$) and underpredicted *Chl* at higher concentrations (20-50% at $2-3 \text{ mg m}^{-3}$). For our data set, the best 2-band algorithm for *Chl* involves the ratio of remote-sensing reflectance, $R_{rs}(442)/R_{rs}(555)$, at 442 nm and 555 nm light wavebands. We found that the general trend of variation in the blue-to-green reflectance ratio, $R_{rs}(442)/R_{rs}(555)$ or $R_{rs}(490)/R_{rs}(555)$, with *Chl* was driven primarily by *Chl*-dependent change in the green-to-blue ratio of absorption by pure seawater and particles. The effect of the blue-to-green backscattering ratio was of secondary importance. We observed a characteristic optical differentiation of waters within the investigated region. The majority of waters, which most likely were dominated by diatoms, exhibited a relatively high blue-to-green reflectance ratio. The waters at several other stations, presumably dominated by dinoflagellates and/or prymnesiophytes, showed much lower reflectance ratio. Our data also show that the seemingly random variations in particulate absorption and backscattering coefficients at any given *Chl* are significant (more than a factor of 2) in the investigated waters.

5.2. Effects of bubble clouds on ocean reflectance

An important aspect of our effort was focused on the development of understanding of the effects of air bubbles entrained by breaking wind waves on light backscattering and ocean color

remote sensing. During the cruise in 1998, our Polish colleagues made acoustic measurements of air bubbles in parallel to our optical measurements. In order to examine the effects of intermittent nature of bubble entrainment on remote-sensing reflectance, we made a series of radiative transfer simulations, in which the acoustic measurements of bubbles were used to characterize the light scattering by bubbles. We showed that the remote-sensing reflectance can increase significantly (more than twofold) due to bubble entrainment, and these large variations occur over time periods on the order of minutes or less. The bubble clouds have a spectral effect on ocean reflectance such that the water patch containing bubbles will appear greener or more yellowish than the surrounding waters with no bubbles. Therefore, the blue-to-green reflectance ratios used in chlorophyll algorithms are influenced the variable effect of bubble scattering. The light field characteristics within the bubble layer are also significantly affected, with most pronounced effects seen in the profiles of upwelling irradiance and upwelling radiance. Therefore, the bubble entrainment can be a source of error in the estimation of reflectance from extrapolation of underwater measurements at a depth up to and across the surface. As our modeling results are relevant to optical measurements made from just above the water surface with down-looking radiance meters whose spot size at the surface is of $O(0.1-1)$ m, they have important implications to the methodology of ground-truth validation determinations of water-leaving radiance.

5.3. Oceanic whitecaps

Recently, the interest in the variability of whitecap coverage of ocean surface has increased significantly due to the efforts to refine the atmospheric correction for remote sensing of ocean color. An approach to quantify the influence of whitecaps on ocean color remote sensing combines a description of wavelength dependency of whitecap reflectance and a description of the fractional foam coverage of the ocean surface as a function of environmental conditions. At present, there is a significant uncertainty in the whitecap correction algorithm. More field data are needed for better quantification and prediction of the variability of whitecap coverage under various environmental conditions. We collected and analyzed the digital photographs of the sea surface for the coverage by whitecaps in the north polar region of the Atlantic. These photographs were analyzed along with data of wind velocity, air temperature and humidity, sea surface temperature, and significant wave height. We found that whitecap coverage increased significantly with an increase in wind speed (or wind friction velocity) but our data exhibit lower values of the average whitecap coverage at low and moderate wind speeds than previous estimates from literature. Our results indicate that the prediction of whitecap coverage can be improved if the state of the development of surface waves is taken into account. Changes in sea

surface temperature (2 to 13°C) and near-water air stability showed no discernible effect on whitecap coverage at any given wind speed within our data set.

5.4. Inverse optical models

We developed two models for estimating the inherent optical properties of seawater, that is the absorption and backscattering coefficients, from light field measurements. Both models were derived from extensive radiative transfer simulations. In the first model (Stramska et al., 2000), the absorption, a , and backscattering, b_b , coefficients in the blue-green spectral region are derived from measurements of downwelling irradiance, E_d , upwelling irradiance, E_u , and upwelling nadir radiance, L_u . In the second model (Loisel and Stramski, 2000), the a and b_b coefficients are derived from the irradiance reflectance just below the sea surface, R , and the diffuse attenuation of downwelling irradiance averaged within the surface layer, $\langle K_d \rangle$. This model can be applied to remote sensing because the a and b_b coefficients can be obtained using the irradiance reflectance as the only input to the model. Both models can be used to evaluate the consistency of collected *in situ* optical data or to estimate the inherent optical properties that are not measured, either because of the lack of appropriate instrumentation or failure of instruments on the cruise. In this project, we used the model of Stramska et al. (2000) to estimate the total absorption coefficients from our measurements of E_d , L_u , and b_b . With these estimates of total absorption and the measurements of particulate absorption, we were able to evaluate the potential contribution of dissolved organic matter to absorption.

6. Publications supported by this project

6.1. Peer-reviewed research articles

- 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.
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6.2. Conference presentations

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, Albuquerque, New Mexico, February 2001. Abstract Book, p.135.

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, Albuquerque, New Mexico, February 2001. Abstract Book, p.135.

Stramski, D., M. Stramska, J. Tegowski, J. Szczucka, and Z. Klusek. 1999. Concurrent measurements of time fluctuations in the inherent optical properties and gas bubble concentration in the near-surface oceanic layer. ASLO 1999 Aquatic Sciences Meeting, Santa Fe, New Mexico. Abstract Book, p.172.