INVESTIGATION STATUS REPORT (May 1999)

PROJECT TITLE:

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

PRINCIPAL INVESTIGATORS:

Dariusz Stramski
Marine Physical Laboratory, Scripps Institution of Oceanography
La Jolla, CA 92093-0238
Tel:(619) 534 3353
e-mail: stramski@mpl.ucsd.edu

Malgorzata Stramska
Hancock Institute for Marine Sciences, University of Southern California
Los Angeles, CA 90089-0371
Tel: (213) 740-0901
e-mail: stramska@usc.edu

I. Summary of tasks for the reporting period June 1, 1998 - May 31, 1999

We have had three major tasks:
(1) Carry out *in situ* optical and ancillary measurements during the Arctic cruise in June/July 1998;
(2) Generate a database from the cruise and carry out various analyses to examine performance of the ocean color algorithms and quantify errors in the Level-2 satellite ocean color data products;
(3) Prepare field experiment for the summer of 1999.

Task 1. Optical and ancillary measurements during the 1998 cruise.

We completed our first field campaign in the Arctic. The study area extended from 60° to 80°N within the meridional zone between 3° and 20°E, and included Norwegian Sea, Greenland Sea, and Spitsbergen Bank. Measurements were made during three legs of the cruise (see attached maps in Figure 1):
- Leg 1: Tromso (Norway) - Spitsbergen (Longyearbyen) June 21 - July 3, 1998;
- Leg 2: Kongsfjorden (Spitsbergen), July 6 - July 13, 1998;
- Leg 3: Kongsfjorden - Greenland Sea, July 14 - July 16, 1998.

In situ optical measurements were made down to 100 – 200 m in close proximity to water samples collected from discrete depths. We used two in situ sensor packages:
- SeaWiFS Profiling Multichannel Radiometer (SPMR, Satlantic) for measuring downwelling irradiance and upwelling radiance within 13 spectral wavebands in freefall 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, the UV range).
- 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) providing measurements of light backscattering at six wavelengths in the visible spectral region was 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 chlorophyll-*a* and phaeopigments (spectrophotometry) and POC (combustion of dry filters) were also collected. The analyses of water samples were carried out in collaboration with Dr. R. Hapter and his bio-optical team from the Polish Academy of Sciences.

In addition, a number of observations and measurements were carried out as part of the Polish national program in the Arctic. These observations included deep profiles of water temperature and conductivity with SeaBird CTD system, ocean currents with ADCP, meteorological and air/sea interaction parameters, sky, sea state, and sea ice observations, and acoustic measurements of air bubbles in the near surface layers of the ocean. Summary of parameters measured during the 1998 cruise is given in Table 1. During the cruise we established good working relationships with our colleagues from the Polish Academy of Sciences, which provides a solid basis for continued collaboration and our participation in the Arctic cruises on R/V *Oceania*.

Task 2. Database and data analysis

Data processing including data quality control and conversion to physical units has been completed. We also completed calculations of various optical quantities which are relevant to ocean color algorithms such as remote-sensing reflectance, vertical spectral attenuation coefficient for downwelling irradiance and upwelling radiance, and water-leaving spectral radiance. Our measurements cover a broad range of optical water types with varying chlorophyll concentration from clear open ocean waters to turbid waters of the Spitsbergen Bank dominated by mineral particles from glacier runoff, as well as variable weather conditions from very calm seas to stormy weather. Radiometric data from sunny days and discrete chlorophyll-a concentrations from all stations were submitted to the SeaBass Archive at NASA.

We developed our project's web site which includes information about our project, available data, and selected results (http://www-mpl.ucsd.edu/people/stramski/ modis.htm). The links to our web site were established on the EOS Validation page (http://eospso.gsfc.nasa.gov/directory/validation/validation.html) and MODIS Related Sites page (http://modarch.gsfc.nasa.gov/MODIS/).

Table 1. Data collected during the 1998 cruise.

In situ optical measurements:

E_d (z, λ)	In-water spectral downwelling irradiance
L_u (z, λ)	In-water spectral upwelling radiance
PAR (z)	Photosynthetically available radiation
c (z, λ)	Spectral beam attenuation coefficient
b_b (z, λ)	Spectral backscattering coefficient
Chl-fl	Chlorophyll fluorescence

Derived optical quantities:

WLR	Water-leaving spectral radiance
Rrs(0+,λ)	Remote-sensing spectral reflectance
R(z, λ),	In-water irradiance spectral reflectance
R_{Lu}(z,λ)	In-water radiance spectral reflectance
a_{ph}(λ)	Phytoplankton absorption spectrum (= a_p(λ)-a_d(λ))
b(z, λ)	scattering coefficient (=c(z,λ)-a(z,λ)
K_d(z, λ)	Vertical attenuation coefficient for downwelling irradiance
K_{Lu}(z, λ)	Vertical attenuation coefficient for upwelling radiance

Water sample analyses:

a_p(λ)	Particulate absorption spectrum
a_d(λ)	Detrital particle absorption spectrum
POC	Particulate organic carbon
chl *a*	Chlorophyll *a* concentration

Other measurements and observations:

Water temperature and conductivity profiles, horizontal current components, wind speed, air temperature and relative humidity, atmospheric pressure, sky state photographs, sea ice conditions, sea surface state and whitecap coverage.

Preliminary validation results

Our operational objectives include the direct comparisons of *in situ* data with data products derived from ocean color satellite imagery. We compared the normalized water-leaving radiances (L_{wn}) and chlorophyll-*a* concentrations (Chl) estimated from our ship-based measurements and high resolution (HRTP) SeaWiFS data. Following the criteria described by McClain et al. (1998) we excluded from this comparison the SeaWiFS data with land, cloud/ice, sun glint or atmospheric correction failure, as well as data with negative L_{wn} in any of the 5 bands. We used radiometric and chlorophyll data collected within 2 hours and 3 hours from the local solar noon, respectively. Time difference between SeaWiFS and *in situ* observations was less than 2 hours and 4 hours for radiometric and chlorophyll comparisons, respectively. Preliminary results are presented in Figures 2 and 3, and in Tables 2 and 3.

Table 2. Statistics of the *in situ* and SeaWiFS match-up data for the leg 1 of our cruise (Tromso - Spitsbergen, 70 -71.5^{o}N, 15^{o}E)

Parameter	Mean ratio SeaWiFS / in situ	Number of observations
L_{wn} (412)	0.76	6
L_{wn} (443)	0.84	6
L_{wn} (490)	0.91	6
L_{wn} (510)	0.89	6
L_{wn} (555)	0.83	6
L_{wn} (490)/L_{wn} (555)	1.12	6
Chlorophyll-*a*	0.87	5

Table 3. Statistics of the *in situ* and SeaWiFS match-up data for the leg 3 of our cruise (Kongsfjorden - Greenland Sea, 78.8 -79^{o}N, 6 - 9.5^{o}E)

Parameter	Mean ratio SeaWiFS / in situ	Number of observations
L_{wn} (412)	0.54	3
L_{wn} (443)	0.72	3
L_{wn} (490)	0.91	3
L_{wn} (510)	0.92	3
L_{wn} (555)	0.89	3
L_{wn} (490)/L_{wn} (555)	1.02	3
Chlorophyll-*a*	3.28	12

The results presented above indicate that while some quantities show relatively good agreement, others show significant deviations between *in situ* and satellite-derived values. In particular, we observed large deviations for water leaving radiances (L_{wn}) in the blue spectral region and for chlorophyll concentrations in the Greenland Sea. Comparison of our *in situ* measured remote-sensing reflectance (R_{rs}) and Chl with the NASA in-water algorithm referred to as OC2 (O'Reilly et al., 1998) suggests that the observed errors in the SeaWiFS-derived chlorophyll in the Greenland Sea can be attributed to the poor performance of the OC2 algorithm in this region. To understand this performance we analyzed the variability of R_{rs490}/R_{rs555} with chlorophyll-*a* concentration. To the first approximation this variability is expected to be driven by the ratio $(b_b/a)_{490}/(b_b/a)_{555} = (b_{b490}/b_{b555})(a_{555}/a_{490})$ where b_b is the backscattering coefficient, a is the absorption coefficient, and the subscripts 490 and 555 denote wavelengths in nanometers. In Figure 4 we plotted the ratio $(b_b/a)_{490}/(b_b/a)_{555}$ and each individual term, i.e. b_{b490}/b_{b555} and a_{555}/a_{490}, as a function of Chl. The absorption coefficient (a) was approximated as the sum of the particulate absorption (a_p) and the pure water absorption (a_w). Our data indicate that the observed variability in the R_{rs} ratio was mostly due to variations in a_{555}/a_{490} with Chl. The ratio of b_{b490}/b_{b555} remained almost constant and independent of Chl. It is noteworthy that the variations in the a_{555}/a_{490} ratio can be linked to the variability of the chl-specific absorption of particles (Figure 5). The plots in Figure 5 are useful in revealing differences between bio-optical variability in two geographical regions (leg 1 and leg 3 of our cruise), which probably reflects the differences in phytoplankton community structure and associated optical properties. In order to illustrate the significance of the observed regional differences we calculated the Rrs_{490}/Rrs_{555} ratio from the following relationship (Figure 6):

$$Rrs_{490}/Rrs_{555} = (b_{b490} / b_{b555}) [(a_{w555} + a^*_{p555}\ Chl) / (a_{w490} + a^*_{p490}\ Chl)],$$

where a^*_p was aproximated by the regressions shown in Figure 5. For comparison the OC2 algorithm is also shown in Figure 6. This graph suggests that much of the departure of our data from the OC2 algorithm may be explained by the dependence of a^*_p on Chl. Also, the modeled R_{rs} ratio changes very little in response to the observed variations in the b_b ratio, which supports the notion that in our data set the variability in absorption rather than backscattering was driving the changes in the R_{rs} ratio. These preliminary results indicate that it may be necessary to use parameterizations that account for regional differentiation within the investigated Arctic seas if we are to minimize errors in the ocean color remote sensing data products. We will continue our analyses to examine this problem in greater detail.

The effect of submerged air bubble clouds on ocean color remote sensing

An important aspect of our validation effort is focused on the development of understanding of the effects of air bubbles entrained by breaking waves on light backscattering and ocean color remote sensing. During the cruise our Polish colleagues made acoustic measurements of air bubbles in parallel to our optical measurements of the beam attenuation and backscattering coefficients. We presented preliminary results from this work at the 1999 ASLO meeting in Santa Fe in February 1999. In our talk entitled "Concurrent measurements of time fluctuations in the inherent optical properties and gas bubble concentration in the near-surface oceanic layer" (Stramski et al., 1999), we presented experimental results showing, for the first time, short-term fluctuations (on scales from seconds to minutes) in light scattering associated with fluctuations in bubble concentration in the near surface oceanic layer. The underlying hypothesis of our experiment was that occasional events of bubble entrainment by breaking waves may cause significant increases in light scattering in the uppermost few meters of the ocean. We showed an example of the temporal pattern of bubble concentration within the top 7 meters and time series of optical beam attenuation and backscattering under sea state conditions characterized by moderate development of breaking waves (wind speed ~10 m/s). The bubble concentrations were measured acoustically at a frequency of 30 kHz, which corresponds to a bubble radius of about 100 micrometers. Measurements at two other acoustic frequencies (63 and 115 kHz) were also made to provide rough estimate of bubble size distribution. The intermittent nature of bubble entrainment by breaking waves was clearly evident in the time series of beam attenuation and backscattering coefficients at a depth of 1 - 2 m. The statistical properties of time series obtained from these optical and acoustic measurements provide the first direct evidence that light scattering by seawater exhibit significant fluctuations associated with dynamics of submerged gas bubbles under a wind-disturbed sea surface.

In order to examine the effects of intermittent nature of bubble entrainment on remote-sensing reflectance we have undertaken an effort that is focused on radiative transfer modeling. We completed a series of extensive radiative transfer simulations using the Hydrolight 4.0 code based on invariant imbedding approach (Mobley, 1994). In these simulations, the scattering properties of the upper ocean were defined to represent the effect of realistic temporal and depth variations in bubble concentration. Specifically, the input to the radiative transfer model describing light scattering by air bubbles was driven by our acoustic measurements of bubble concentrations. Mie scattering calculations were first used to determine the scattering cross sections of realistic bubble populations. The most significant result from our radiative transfer simulations is that the remote-sensing reflectance in the blue and green spectral regions under moderate wind conditions (~10 m/s) can vary on short time scales (seconds to minutes) by a factor of 1.5 to 5 depending on wavelength and chlorophyll concentration in water. This finding has important implications to the methodology of ground-truth validation measurements of water-leaving radiance. In addition, even though the scattering by bubbles is nearly independent of wavelength, the reflectance spectral ratios used in ocean color algorithms (such as 490-to-555 nm ratio) are affected by the variable effect of bubble scattering. This particular study is near the completion and we are now preparing the manuscript for publication (Stramski et al., in preparation).

Task 3. Preparation of the 1999 field experiment.

Details of our involvement in the 1999 cruise were discussed with IOPAS, and according to the final plan of the cruise our team will have one berth during the first leg of the cruise (June 20- July 8, transect between Norway and Spitsbergen) and two berths during the second and third legs (July 10 – August 7, Spitsbergen Bank - Greenland Sea – Faroe Islands).

Based on the results from the 1998 cruise we defined specific areas where we plan to make modifications and improvements in the field program. Specifically, we acquired additional oceanographic instrumentation which will be used during the 1999 cruise. First, we purchased two *in situ* a-Beta (absorption/backscattering) meters (440 and 550- nm bands) from HobiLabs. These instruments will allow us to improve the characterization of spectral absorption properties of the investigated waters. Most importantly, we will be able to derive the absorption coefficient by soluble materials, which could not be measured last year. We will thus have a complete characterization of absorption by particulate and soluble constituents. The a-Beta instruments will also give additional bands in backcattering measurements. Second, we modified our Hydroscat-6 backscattering meter, which now includes an internal power supply and a new waveband centered at 550 nm, which was not available last year. Third, we made necessary arrangements to collect chlorophyll-*a* samples for HPLC analysis, but in parallel we will continue with spectrophotometric pigment analysis which was employed last year. Finally, we borrowed a portable deck spectroradiometer (Robert Frouin, Scripps Institution of Oceanography) for measuring water-leaving radiance from above the surface and atmospheric aerosol optical thickness at 443, 560, 670, and 865 nm. These measurements will allow us to better evaluate the atmospheric correction algorithm. This task will be supported by our Polish collaborators, who will collect marine aerosol samples for chemical and physical analyses. We have successfully completed tests of the equipment which is now being prepared for shipment to the Institute of Oceanology in Sopot, Poland.

II. Plan of near-term activities

This summer we will participate in the Arctic cruise on R/V *Oceania* from June 20 through August 7. Stramska will start in Tromso, Norway on June 20. Stramski will join the cruise on July 9 in Longyearbyen, Spitsbergen. After the cruise, we will process the data and merge the new data with the database generated from the previous cruise. The new data will be submitted to NASA SeaBass Archive. With the data from both cruises we will carry out various analyses as described in our proposal. In addition to the manuscript on the effect of bubbles described above, we anticipate that at least two other manuscripts will be submitted for publication within several months after the cruise.

First, we plan on writing a paper that will focus on ocean color validation issues including comparison of *in situ* and satellite-derived data products, sources of errors in the ocean color satellite data products, and improvements to the ocean color algorithms for the investigated Arctic region. This work has been in progress for the 1998 data set, but more data are needed to develop full understanding of the questions we want to address. We assume that the 1999 data set will help us achieve this understanding, but we also recognize that the amount of data that will be collected in 1999, and ultimately useful for our validation study, depends largely on weather conditions during the cruise. Therefore we still plan on participating in the third cruise in 2000 to ensure that we accomplish the goals of our proposal. Another manuscript we wish to develop and submit for publication in the near future will be focused on absorption measurements of marine particles. This absorption component is a critical driver of variability in ocean color, but accurate measurements are still very difficult to make with existing methodology. Last year we have undertaken unique measurements of the pathlength amplification factor for natural assemblages of marine particles. This factor is essential to the accurate determination of the particulate absorption coefficient, and we plan to submit a paper on this subject, which will also include new data from the 1999 cruise.

In addition, we are well advanced in developing two different models for estimating the inherent optical properties of seawater, that is the absorption and backscattering coefficients, from light field measurements, that is the downwelling irradiance, upwelling irradiance, and upwelling radiance (Stramska et al., Loisel and Stramski, both in preparation). This work is highly relevant to our project, and we expect that these two papers will be submitted for publication not later than in the fall 1999.

III. Publications

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.

Stramski, D., J. Tegowski, and M. Stramska. The effects of bubble entrainment by breaking waves on remote-sensing reflectance (in preparation, to be submitted to J. Geophys. Res.).

Stramska M., D. Stramski, B. G. Mitchell, and C. D. Mobley. An inverse model for in-water optical measurements based on radiative transfer simulations (in preparation).

Loisel, H. and D. Stramski. A model for estimating the absorption and backscattering coefficients of seawater from surface reflectance and diffuse irradiance attenuation within the upper ocean (in preparation, to be submitted to Appl. Opt.).

IV. References

McClain, C. R., M. L. Cleave, G. C. Feldman, W. W. Gregg, and S. B. Hooker. Science quality SeaWiFS data for global biosphere research. Sea Tech., Septemeber 1998, 10-16.

Mobley, C. D. 1994. Light and water. Radiative transfer in natural waters. Academic Press.

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.

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.

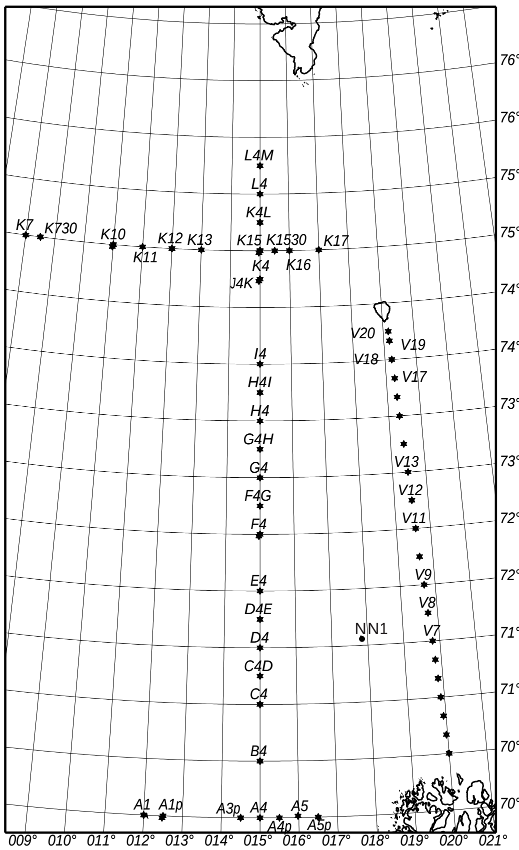

Figure 1a. Positions of stations during leg 1 (Tromso - Spitsbergen).

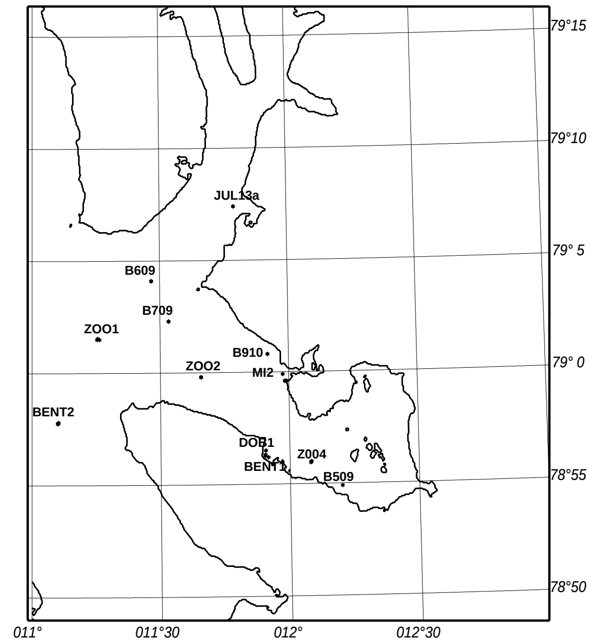

Figure 1b. Positions of stations during leg 2 (Kongsfjorden, Spitsbergen).

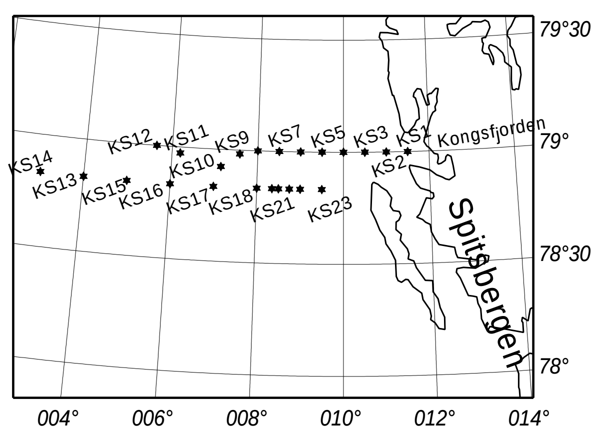

Figure 1c. Positions of stations during leg 3 (Kongsfjorden - Greenland Sea).

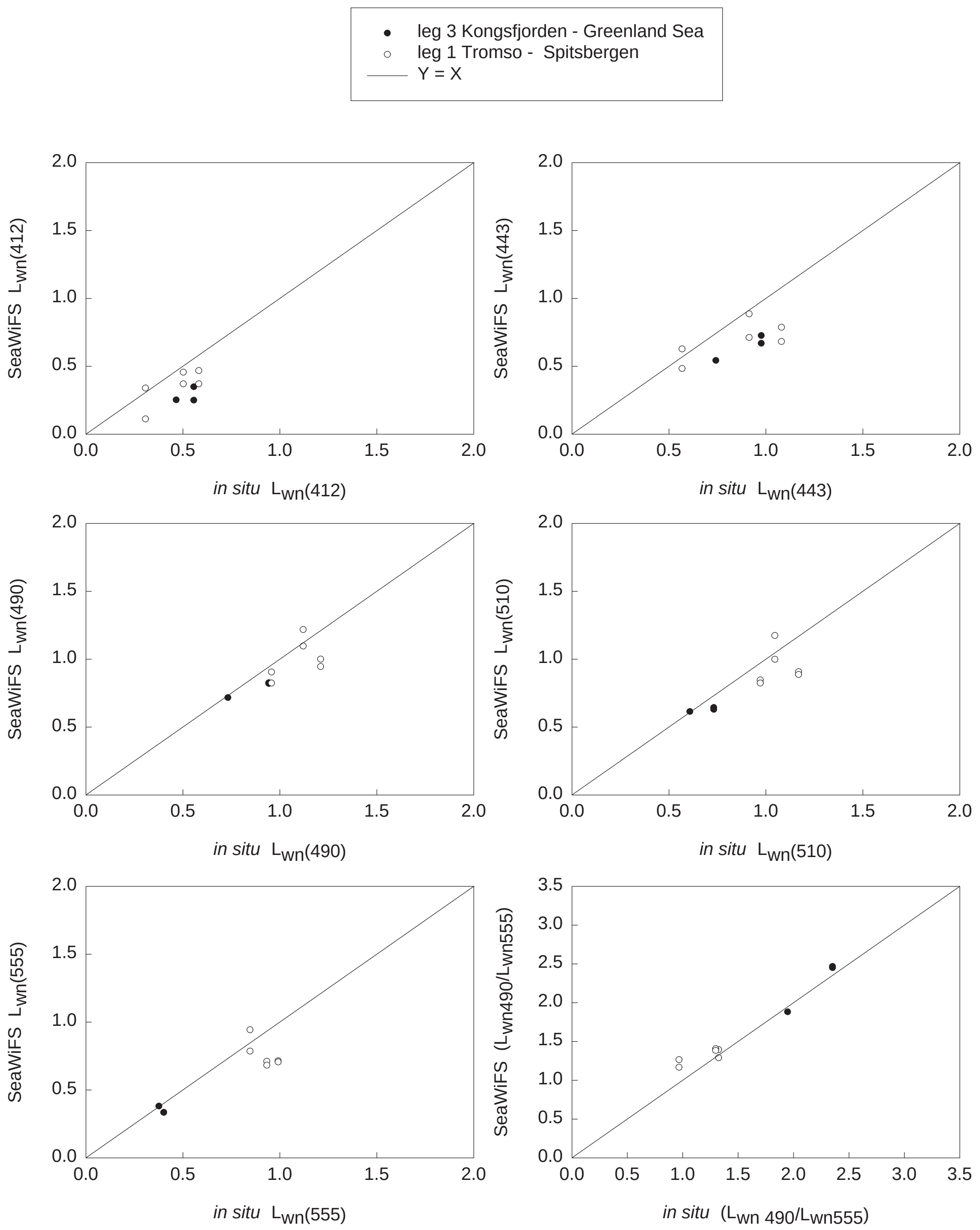

Figure 2. Comparison of *in situ* and SeaWiFS-derived water-leaving radiances.

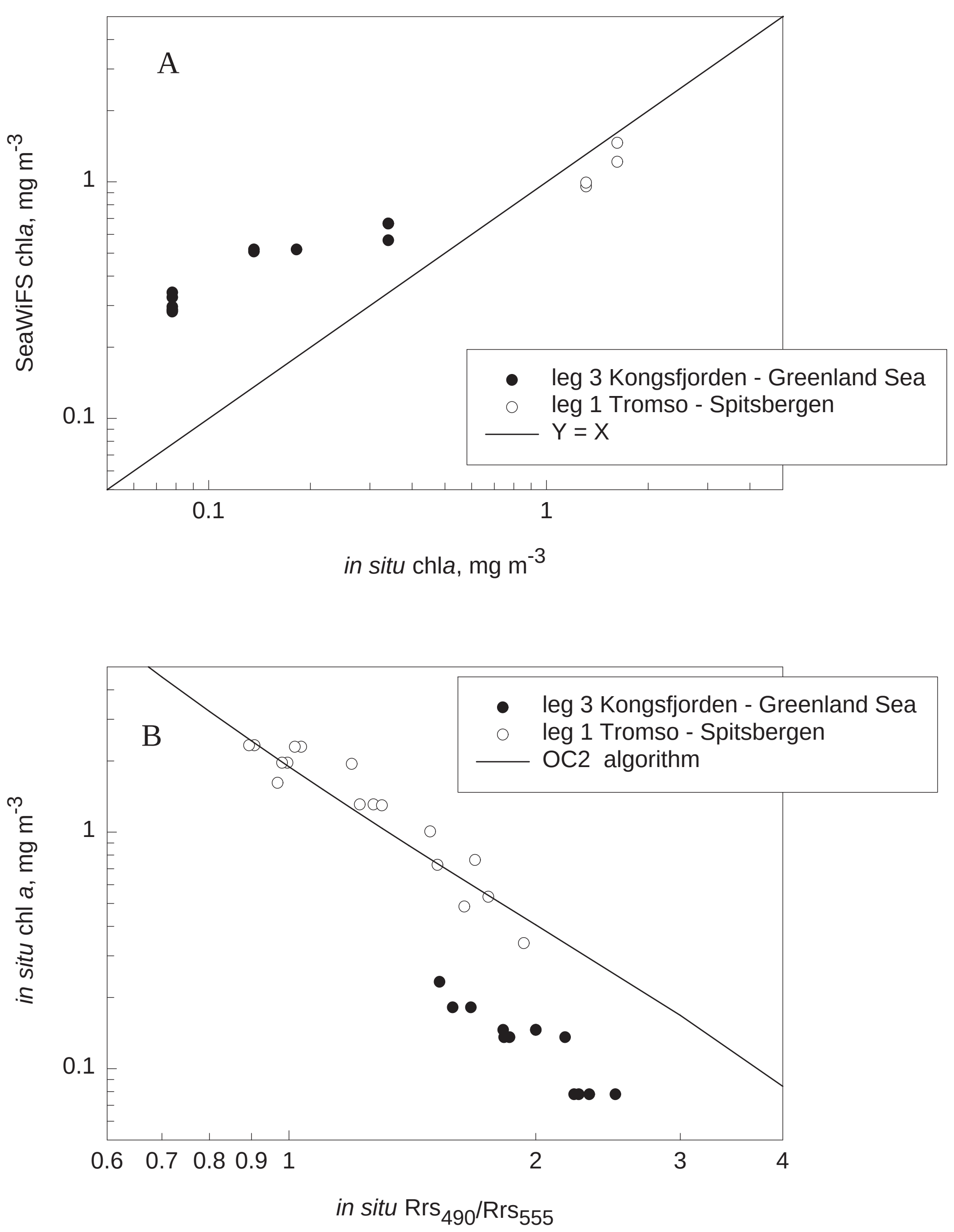

Figure 3. (A) Comparison of *in situ* and SeaWiFS-derived chlorophyll-*a* concentrations. Note significant differences between Chl estimates in the region of the Greenland Sea. (B) *In situ* chlorophyll-*a* concentration as a function of remote-sensing reflectance ratio. For comparison the curve representing the OC2 algorithm is shown. These results suggest that the observed discrepancy between SeaWiFS-derived and *in situ* Chl is most likely due to the OC2 algorithm.

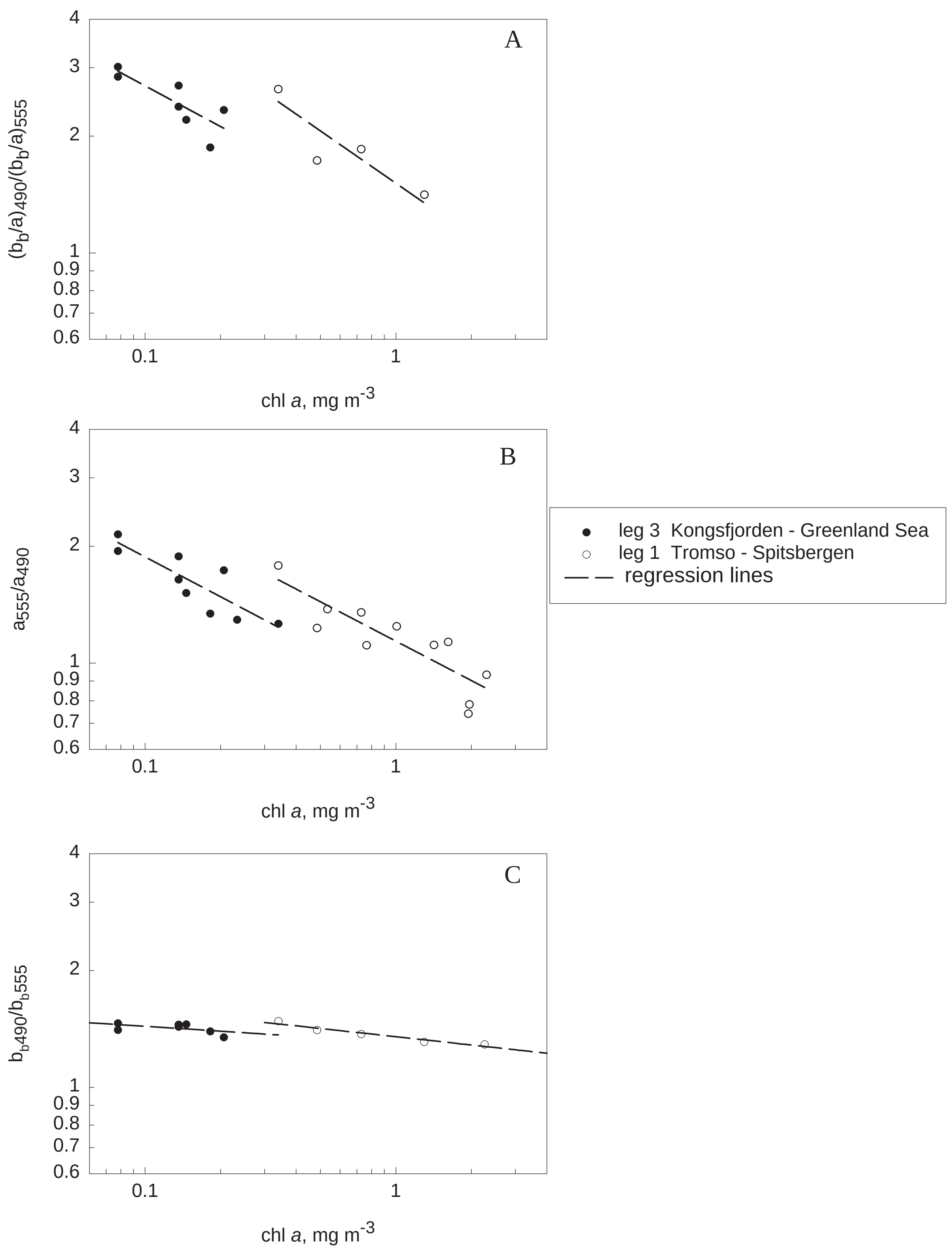

Figure 4. Variations of the ratios $(b_b/a)_{490}/(b_b/a)_{555}$ (panel A), a_{555}/a_{490} (panel B), and b_{b490}/b_{b555} (panel C) as a function of Chl. The absorption coefficient (a) represents the sum of the particulate absorption (a_p) and absorption by pure sea water (a_w), while symbol b_b is the total backsattering coefficient as measured *in situ* with Hydroscat-6. These data indicate that much of the variability in the *in situ* Rrs_{490}/Rrs_{555} is due to the variability in the ratio of a_{555}/a_{490}.

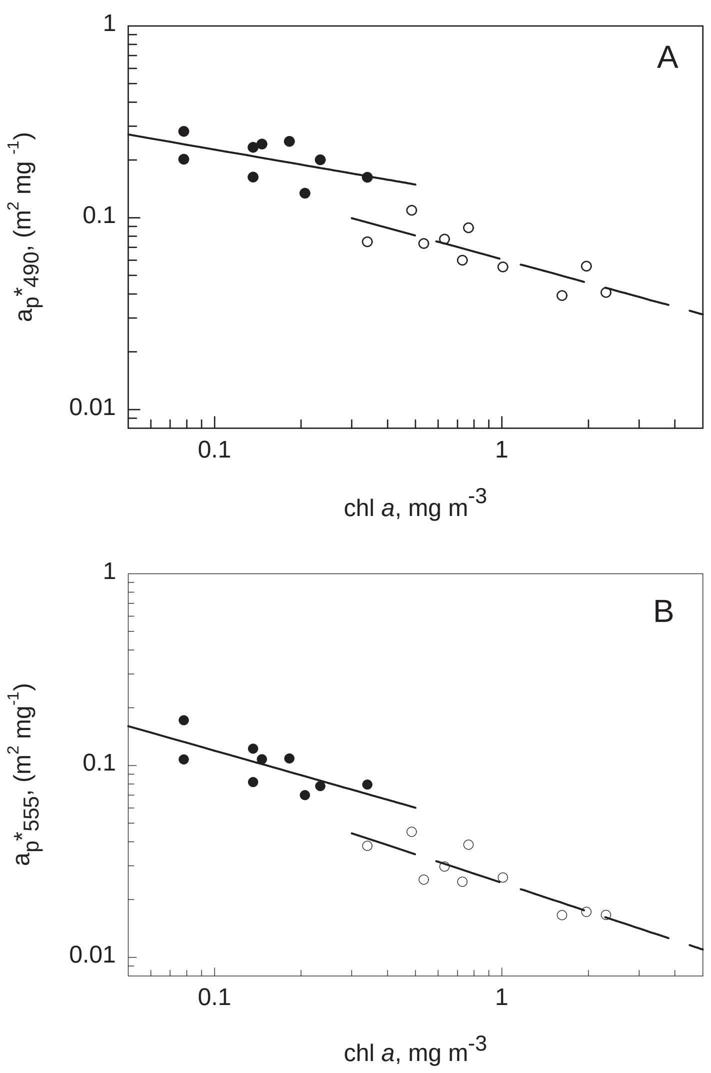

Figure 5. Variations of the chl-specific absorption coefficient of particles (a_p*) at 490 nm (panel A) and 555 nm (panel B) as a function of Chl. Symbols refer to the same areas of investigation as in Figure 4.

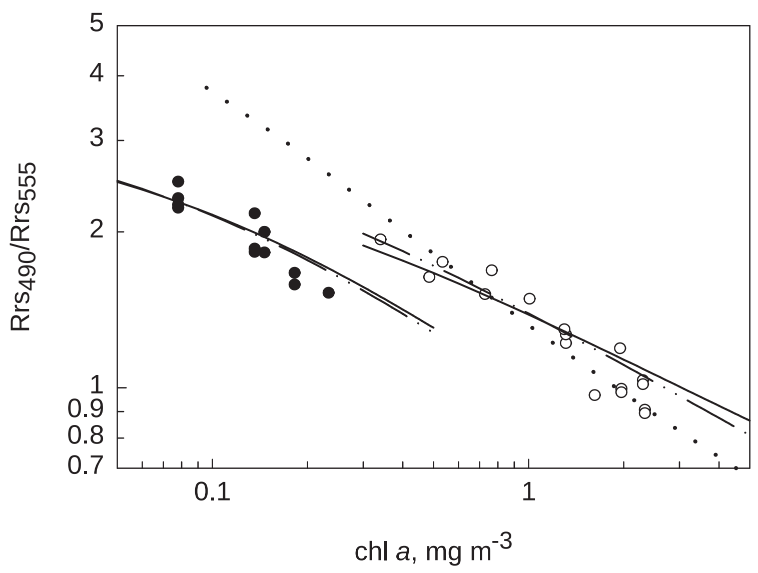

Figure 6. Comparison of the *in situ* data with modeled Rrs_{490}/Rrs_{555} (solid lines) obtained by using the regressions for $a_p{}^*{}_{490}$ and $a_p{}^*{}_{555}$ from Figure 5. Dashed lines indicate Rrs_{490}/Rrs_{555} if the variability of b_{b490}/b_{b555} with Chl (shown in Fig. 4) is also accounted for. As seen the behavior of Rrs_{490}/Rrs_{555} is almost entirely explained by the variability of the absorption ratio. The OC2 algorithm is shown as a dotted line.