46. OPTICAL MODEL FOR REMOTE SENSING IN TURBID WATERS - SHIP OBSERVATION IN THE GULF OF THAILAND -

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ABSTRACT; Spectral measurements of downward irradiance and upward radiance were made in the upper Gulf of Thailand to construct an optical model for ocean color remote sensing in turbid waters. Simultaneously, chlorophyll-a concentration, suspended solid concentration, and absorption coefficients of chlorophyll-a, particulate matter and CDOM were measured. Inorganic suspended solid (ISS), which is high scattering property, was also measured as an ignition loss of suspended solid. "Measured" subsurface reflectance was compared with "estimated" that to evaluate the optical model. The measured subsurface reflectance was calculated from spectral radiation measurements. On the other hand, the estimated reflectance was derived from the optical model with absorption and backward-scattering coefficients of in-water substances. The absorption coefficients were used the measured values. Although the backward-scattering coefficient of phytoplankton was used the equation given from previous study, that of ISS was estimated on the basis of Mie theory using the measurement of its absorption coefficient and size distribution. The estimated reflectance agrees with the measured reflectance in the case of lower ISS concentration, but that is 2 times as high as the measured in the case of higher ISS concentration. This mainly cause is an overestimation of the ISS backward-scattering coefficient. It is necessary to improve the estimation method and to conduct measurements in various ocean conditions.

KEYWORDS; Ocean color remote sensing, Optical model, Turbid waters, Inorganic suspended solid

1. INTRODUCTION

Coastal waters are affected by a human activity and have many environmental problems. On the other hand, coastal waters have high productivity. Therefore, the monitoring for coastal regions is important. Ocean color remote sensing is effective method for this monitoring. Many algorithms exist for open ocean (ex. for OCTS¹⁾, for SeaWiFS²⁾). However, it is difficult that these algorithms apply to coastal waters because of high concentration of suspended solid and colored dissolved organic matter (CDOM). Therefore, algorithms for turbid waters are being developed on the basis of theoretical optical model³⁾. In this time, it is necessary to clear optical properties, which are absorption and backward-scattering coefficients, of suspended and dissolved matter in water. In coastal waters, non-living particulate matter, which is almost mineral particle or inorganic suspended solid, is dominant in a scattering process in water. In this study, comparing a surface reflectance measured with submersible radiometers with a reflectance estimated from inherent optical properties of phytoplankton, suspended solid and CDOM, we estimate the optical property of ISS and evaluate the optical model for turbid waters.

2. MATERIALS AND METHODS

Observation was carried out in the upper Gulf of Thailand on May 2004. Spectral upward radiance and downward irradiance in water were measured with submersible radiometers (TriOS Optical Sensors; RAMSES ACC/ARC) equipped with depth meter. Subsurface reflection was calculated from the radiometer measurements using the following equations. The upward radiance just below the surface $Lu(0^-, \lambda)$ and downward irradiance just below the surface $Ed(0^-, \lambda)$ were extrapolated from the profile measurements of $Lu(z, \lambda)$ and $Ed(z, \lambda)$, respectively. The upward irradiance just below the surface is defined as

$$Eu(0^-, \lambda) = Q Lu(0^-, \lambda), \quad (1)$$

where we simply assumed that the upward radiance field was isotropic in water, Q was given π . The irradiance reflectance below the surface, or subsurface reflectance, is defined as

$$R(0^-, \lambda) = Eu(0^-, \lambda) / Ed(0^-, \lambda). \quad (2)$$

The water samples were collected using a Van Dorn sampler from each depth. The water sample of several decades ml was filtered onto a glass fiber filter (Whatman, GF/F). The concentration of

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chlorophyll-a was determined fluorometrically with a fluorometer (Turner Designs; 10-000R) after extracting the pigments in *N,N*-Dimethylformamide⁴⁾. The concentration of suspended solid was derived from subtracting a weight of glass fiber filter (Whatman, GF/F) before filtration from the weight after filtering of sample water. To separate inorganic component from total suspended solid, the GF/F filters were pre-processed at 500 °C in 2 hours. After measurement of total SS weight, the GF/F filters were also heated at 500 °C in two hr, and then, the ignition loss was measured. The difference between the total SS and the ignition loss means the amount of the inorganic suspended solid. The optical density of particle including phytoplankton was measured with a spectrophotometer (Nihon Bunko; V-550) equipped with an integrating sphere (Nihon Bunko; ISV469)⁵⁾. The pigments were extracted by methanol⁶⁾. The absorption coefficients of phytoplankton and particulate matter were calculated using the path length amplitude factor $\beta^{6,7)}$. The absorption coefficient of ISS was also measured using same procedure after the glass fiber filter was heated at 500 °C in two hr. The absorption coefficient of CDOM was measured with the spectrophotometer using a 10 cm cell from water sample filtered using a polycarbonate filter with pore size 0.2 μm in diameter (Whatman; Nuclepore). Water sample was filtered onto a membrane filter (Toyo Roshi; Cellulose Acetate), which is low ash, and then, it was heated at 500 °C in two hr to measure the ISS size distribution. The remained particles were suspended into Na_3PO_4 solution. The size distribution was measured using a Coulter Counter (Beckman Coulter; Multisizer III) equipped with an aperture 70 μm in diameter.

The subsurface reflectance is related to the ratio of the backward-scattering coefficient $b_b(\lambda)$ and the absorption coefficient $a(\lambda)$ and can be expressed as

$$R(0^-, \lambda) = f(\lambda) b_b(\lambda) / (a(\lambda) + b_b(\lambda)). \quad (3)$$

where $f(\lambda)$ varies with solar altitude, chlorophyll concentration, wavelength and the inherent optical properties⁸⁾. The value of $f(\lambda)$ was simply used 0.33 without wavelength dependency. The absorption and backward-scattering coefficients of pure sea water are taken from previous studies^{9,10)}. Although the absorption coefficients of particulate and dissolved matters were measured, the backward-scattering coefficients of particulate matters be could not measured directly. The backward-scattering coefficient of phytoplankton is estimated following¹¹⁾:

Fig. 1 Chlorophyll-a and SS concentrations at each observation site in the upper Gulf of Thailand. The SS concentration is shown organic and inorganic components separately.

$$b_{bph} = 0.005(660/\lambda)^{0.407} C^{0.795}. \quad (4)$$

The backward-scattering coefficient of ISS was estimated from the measured absorption coefficient and the size distribution of ISS. First, the imaginary part of refractive index of ISS was derived to agree with the measured absorption coefficient of ISS and the calculated absorption coefficient using the Mie theory varying the imaginary part with the size distribution measurement of ISS and the assumed the real part as 1.16. Next, using the assumed real part, the estimated imaginary part and the measured size distribution, we calculated the backward-scattering coefficient using the Mie theory.

3. RESULTS AND DISCUSSION

Concentrations of chlorophyll-a and each SS are shown in Fig. 1. The chlorophyll-a concentration was higher in the north and west of the upper Gulf of Thailand. It is suggested that low chlorophyll-a water flowed to the east side of the upper Gulf. The

organic SS concentration, which is related with phytoplankton, shows same pattern with the chlorophyll-a. On the other hand, the ISS concentration showed different distribution. The concentration around the mouth of the upper Gulf was higher than north part. Although the ISS concentration is low in the north of the upper Gulf, the ISS concentrations at 10 m depth are high at St. 3 and 4. At these points, the depths of seafloor are around 10 m, therefore, it is indicated that the ISS is caused by resuspension of sediment on the seafloor.

The ISS size distribution at St. 9 is shown in Fig. 2. The estimated imaginary part of ISS is shown in Figure 1. Although it is well known that the SS size distribution obeys the power-law distribution or Junge distribution, the measured size distribution is not linear on a log-log plot. Therefore, the result was conducted a curve fitting on a lognormal and a power-law distributions. The spectral imaginary part of refractive index of ISS was estimated based on Mie theory from the fitted size distribution and the measured absorption coefficient (Fig. 3). The value is high in shorter wavelength region and it has hinge points around 380, 460 and 560 nm. The backward-scattering coefficient was derived from this estimated imaginary part and the size distribution (Fig. 3). The backward-scattering coefficient decreases in shorter wavelength because of the absorptivity increasing in shorter wavelength.

Figure 4 shows the spectral subsurface reflectance measured with the radiometers and estimated from the inherent optical properties at St. 1, 9, and 16. It is clear that the estimated reflectance at St. 1 is around 2.5 times as high as the measured. But these spectral patterns are similar. At St. 9 the estimated reflectance is overestimated longer than 500 nm. The reflectance derived from the optical model agrees with the measured reflectance except shorter than 450 nm at St. 16. The causes of the overestimate are considered as follows: 1) the absorption coefficient is low, 2) the backward-scattering coefficient is high, and 3) both coefficients are incorrect. The absorption coefficient of chlorophyll-a pigment, particulate matters and CDOM were measured, therefore, it will not be considered that the absorption coefficient is significantly lower than the real value. On the other hand, the backward-scattering coefficient of phytoplankton was used the equation of the previous study. Although the species of phytoplankton are difference between the previous study and our observation, it will be not a few times as high as the real value. In addition, the overestimate is related to the ISS concentration. The ISS concentration at St.1 was the highest among the showed results. Consequently, the estimation of the

Fig. 2 Measurement of ISS size distribution at St. 9. The size distribution is fitted on a lognormal and a power-law distributions.

Fig. 3 Estimated imaginary part of refractive index and backward-scattering coefficient of ISS at St. 9.

backward-scattering coefficient of ISS is most questionable. It is considerable that the measurement of the ISS absorption coefficient is uncertainly because the scattering of the ISS particles, which has high real part of refractive index, caused the overestimation of the absorption coefficient when the measurement of the optical density. We have to correct the scattering effect on the measurement of the optical density.

In this report, the result of only one cruise is shown. Therefore, we will carry out more observation and construct a suitable optical model for turbid waters.

4. CONCLUSION

The subsurface reflectance estimated from the inherent optical properties was compared with the reflectance measured with radiometers to evaluate the optical model for turbid waters. The required ISS backward-scattering coefficient was estimated from the measurements of the size distribution and

the absorption coefficient. The estimated reflectance is overestimated especially in the case of high ISS concentration. It is considered that this mainly cause is the overestimation of the ISS backward-scattering coefficient because of the effect of the scattering of ISS particle when the optical density measurement. We have to correct the scattering effect on the measurement of optical density and conduct more observation in various conditions to estimation the correct ISS optical property.

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