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Evaluation of Suspended Sediment Retrieval from above Water and Satellite Reflectance in Fjord Waters of Svalbard

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ABSTRACT

The sky and sun glint correction of in situ measurements is most important in estimating R_{rs} from above water. If glint effect is not estimated accurately, significant errors can occur in the estimated R_{rs}. In this study, we evaluated the performance of five sky glint algorithms for above sea surface reflectance data collected from fjord waters of Svalbard. Based on the visual inspection of the R_{rs} spectra and the correlation with the SSC measurements, Ruddick's algorithm showed the best results in our evaluation for sky glint correction. The result of Ruddick's algorithm exhibited high correlation coefficient between R_{rs} and in situ SSC at 645 nm ($r^2 = 0.86$).

KEY WORDS: Remote sensing reflectance; Suspended sediment; Sky glint correction

INTRODUCTION

The use of ocean remote sensing has been focused on the water leaving reflectance (R_{rs}) properties associated with chlorophyll a, suspended sediment (SS) and colored dissolved organic matter (CDOM) in visible and near infrared (NIR) wavelength (Doxaran et al., 2002; Darecki and Stramski, 2004; Dall'olmo et al., 2005). The sky and sun glint correction of in situ measurements is most important in estimating R_{rs} from above water. Frequently, the NIR R_{rs} was assumed to be zero for the glint correction (Gordon and Wang, 1994; Quillion et al., 1996). However, this assumption is not true in turbid waters due to the back scattering on particles. The retrieval of suspended sediment concentration (SSC) can be measured in NIR if the R_{rs} intensity is strong enough to be measured (Gould et al., 2001; Ruddick et al., 2006). In this study, we investigate and assess which glint correction approach and wavelength region is effective to retrieval SSC from Arctic above-water reflectance.

METHODS

In situ data (above water reflectance and water samples) were collected at 28 stations in the Kongsfjorden of Svalbard between 06 and 11 August 2006. For SS measurements, 500 ml surface water samples are collected and filtered through a 25 mm GF/F filter. The filter weight was measured by drying in an oven at 60 ° C for 4 hours before filtering. After filtering, the filter was washed with distilled water to remove the salt remaining on the surface of the filter. The weight of filter after filtration was measured in the same way as the filter weigh measurement before filtering. The SSC was calculated by the filter weight difference before and after filtration. Above water reflectance measurements were collected using a ASD FieldSpec 512 channel radiometer covering spectral range of 350 -1050 nm. A dual spectrometer unit with two fiber optic cables was used to measure downwelling irradiance (E_d) and total upwelling radiance (L_t) simultaneously from above water. The L_t and L_s (sky radiance) were measured at a viewing direction of approximately 30° from nadir and zenith respectively. The azimuth angle to measure L_t and L_s was maintained at 135° from the Sun. The R_{rs} was calculated according to Eq. (1),

$$R_{rs} = \frac{L_t - \rho L_s}{E_d}, \tag{1}$$

where ρ is the sea surface reflectance factor on sky conditions, wind speed, solar zenith angle, and viewing geometry. If ρ is not estimated accurately, significant errors can occur in the estimated R_{rs}. Lee et al. (1997) proposed a value of ρ = 0.021 for the removal of the Rayleigh component of the reflected skylight when the viewing angle is 30°. Mobley (1999) suggested that for viewing direction of 40° from the nadir and 135° from the Sun, a value of ρ = 0.028 is acceptable for wind speeds less than 5 m s^{-1} and overcast sky. The above corrections using a ρ value is often inaccurate due to the residual surface reflection, ε in Eq. (2),

$$R_{rs} = \frac{L_t - \rho L_s}{E_d} - \varepsilon. \tag{2}$$

Gould et al. (2001) presented a surface correction algorithm based on two assumptions which are at 715-735 nm that total absorption is due primarily to pure water absorption and that the surface reflected sky/cloud light and backscattering spectra are nearly flat. They calculated ε according to Eq. (3),

$$\varepsilon = \frac{R_t(735)a_w(735) - R_t(715)a_w(715)}{a_w(735) - a_w(715)} - \rho R_s(735), \tag{3}$$

where $R_t = L_t/E_d$, $R_s = L_s/E_d$ and a_w is the pure water absorption coefficient from Kou et al. (1993) and Pope and Fry (1997). With a similar approach, Ruddick et al. (2005, 2006) proposed an algorithm for the improvement of sky glint correction. They analyzed and tabulated as a similarity spectrum by normalization at 780 nm, and estimated the ε using measurements at 720 nm and 780 nm as follows

$$\varepsilon = \frac{\alpha(720,780)R_{rs}(780) - R_{rs}(720)}{\alpha(720,780) - 1}, \quad (4)$$

where $\alpha\,(720, 780)$ can be read from the tabulated similarity spectrum from Ruddick et al. (2005). Kutser et al. (2013) recently developed a simple method for glint correction where reflectance values in the 350–380 nm range are used to determine the slope of the power function and reflectance values in the 890–900 nm range are used to determine the absolute value of glint. We tested above five approaches for sea surface reflectance correction and investigated the correlation between the sky glint corrected R_{rs} and in situ SSC.

RESULTS AND DISCUSSION

Figure 1 shows the in situ R_{rs} spectra corrected by the proposed algorithms for glint removal. A solid red line in Figure 1 indicates zero reflectance to comparison the performance of each correction algorithm. Dashed lines of different colors are representative in situ spectra to show the variations of R_{rs} according to SSC (red and blue: high SSC, green: moderate SSC, yellow: low SSC). The SSC of the black solid line spectra ranges from 0.5 to 6 mg/l.

The result for Mobley's correction showed that the R_{rs} values of some spectra are below zero at above 700 nm (Figure 1(a)). It seems to be due to overcorrection for glint. On the other hand, despite low SSC, some R_{rs} values are too high in NIR (700-900 nm). It may be because this correction does not consider the residual surface reflection (ε). Lee's algorithm exhibited a little improvement in overcorrection due to difference in ρ value, but did not show any significant differences from Mobley algorithm result (Figure 1(b)). Gould's algorithm exhibited better result than Mobley and Lee algorithms (Figure 1(c)). The residual surface reflection calibration resulted in significant differences at blue, green (400-500 nm) and NIR wavelengths (700-900 nm). Especially, the corrected spectra in the NIR clearly show the R_{rs} intensity difference due to SSC. However, some R_{rs} values were negative in the 800-900 nm. The steep decline of R_{rs} indicates that there is a polar environmental or instrumental error rather than an algorithmic problem. The Ruddick's algorithm result is similar to Gould's algorithm result (Figure 1(d)). This is because the two algorithms are based on similar assumptions. Kutser's algorithm did not produce good result in our experiment. They used R_{rs} values at two ranges of wavelengths (350–380 nm and 890–900 nm) for glint correction, but our in situ R_{rs} data were not good in that wavelengths because of lot of instrumental noise.

The correlation using linear regression between sky glint corrected R_{rs} and in situ SSC at wavelengths corresponding to MODIS band 1 (645 nm) and 2 (859 nm) is shown in Table 1. Table 1 shows that $R_{rs}(645)$ exhibits better results than $R_{rs}(859)$. The poor correlation result for $R_{rs}(859)$ may be because the SSCs of our field samples are too low. The R_{rs} of water with low SSC is generally close to zero in the NIR. Among five glint correction approaches, Ruddick's algorithm showed highest correlation coefficient between R_{rs} and in situ SSC at both 645 nm ($r^2 = 0.86$) and 859 nm ($r^2 = 0.68$).

CONCLUSIONS

This study evaluated the performance of sky glint algorithms for above sea surface reflectance data collected from fjord waters of Svalbard. Based on the visual inspection of the R_{rs} spectra and the correlation with the SSC observations, Ruddick's algorithm showed the best results in our evaluation for sky glint correction. However, our SSC measurements are too low and there are too few stations. Therefore future works need to further evaluation in various regions and periods with high SSC. We will analyze the long-term SSC variation in Svalbard fjord sea surface from 2006 to 2013 using in situ above-water surface reflectance and satellite reflectance data.

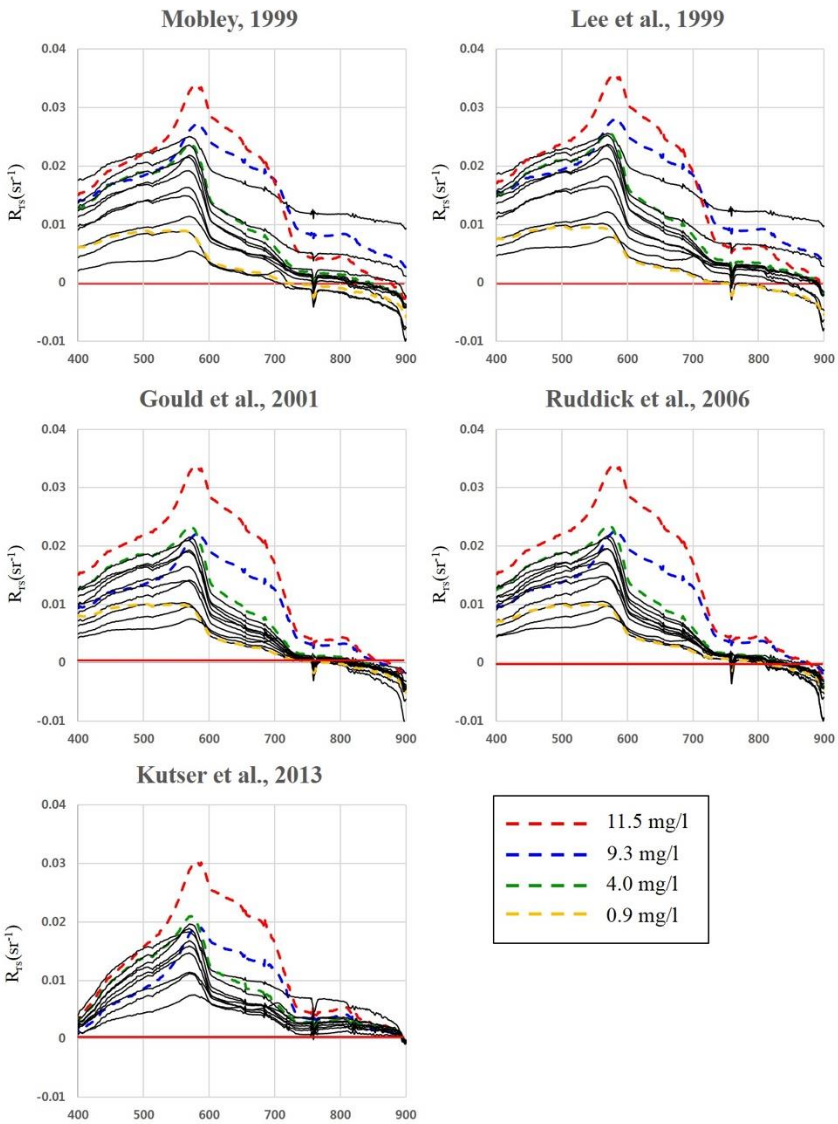

Figure 1. Above water R_{rs} spectra after sky glint correction using five approaches. Different colors of the dashed lines show SSC variation, representatively.

Table 1. Result of correlation coefficients using liner regression between in situ SSC data and above water R_{rs} after performing five glint correction approaches. The selected two wavelengths correspond to MODIS band 1 (645 nm) and band 2 (859 nm).

Wavelength (nm)	Mobley (1999)	Lee et al. (1999)	Gould et al. (2001)	Ruddick et al. (2006)	Kutser et al. (2013)

$R_{rs}(645)$	0.78	0.79	0.86	0.86	0.77
$R_{rs}(859)$	0.15	0.18	0.60	0.68	0

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