Simulation of ocean glint reflectance and determination of sea surface roughness

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Introduction

Satellite remote sensing under glint conditions remains a challenging problem. Current glint correction algorithms rely on a crude glint estimation. We use an optimized version of the Discrete-Ordinate Radiative Transfer model (DISORT3, Lin et al. 2015) to simulate and validate ocean glint reflectance at a near IR wavelength (1,036 nm). Measurements of complete sets of the bidirectional reflectance distribution function (BRDF) were obtained from the NASA Cloud Absorption Radiometer (CAR) deployed on an aircraft. A radiative transfer model (RTM) was used that for the first time successfully reproduced the measurements by matching model outputs with observations. In addition, the RTM simulations were used to retrieve sea surface roughness and other parameters through a nonlinear Levenberg-Marquardt regression method.

BRDF Measurement

The BRDF measurements used were obtained under clear sky conditions from the National Aeronautics and Space Administration (NASA) Cloud Absorption Radiometer (CAR) deployed aboard the University of Washington Convair 580 (CV-580) research aircraft (Gatebe et al., 2005). The airplane flew in a circle about 3 km in diameter, taking roughly 2-3 minutes to complete an orbit. The BRDF measurements were generally obtained at an altitude of about 200 m above the surface. Multiple circular orbits were acquired over a selected surface so that average BRDFs would be smooth.

Model setup and BRDF treatment

In the simulations, we adopted two atmospheric layers: one Rayleigh (molecular) layer (2-10 km) and one layer with aerosols and molecules homogeneously mixed (0-2 km). We then assumed that the ocean was totally absorbing at 1,036 nm and therefore ignored the water leaving radiance.
At the bottom of the atmosphere ($\tau = \tau_a$), the upward reflected radiance $I_{up}(\tau_a, \mu, \phi)$ is connected to the downward incident diffuse radiance $I_{down}(\tau_a, \mu', \phi')$ and the attenuated direct radiance $F_0 e^{-\tau_a/\mu_0}$ through the sea surface BRDF $\rho(\mu, \mu', \Delta\phi)$, $\Delta\phi = \phi' - \phi$:

$$I_{up}(\tau_a,\mu,\phi) = \int_0^{2\phi} d(\Delta\phi) \int_0^1 \mu' \rho(\mu,\mu',\Delta\phi) I_{down}(\tau_a,\mu',\phi') d\mu' + \mu_0 \rho(\mu_0,\mu,\Delta\phi) F_0 e^{-\tau_a/\mu_0}. \quad (1)$$

Since DISORT3 is a plane parallel model, the BRDF $\rho(\mu, \mu', \Delta\phi')$ is given by:

$$\rho(\mu,\mu',\Delta\phi) = \frac{1}{4\mu'\mu(\mu_n)^4} \cdot p(\mu_n,\sigma) \cdot r(\cos\Theta, n) \cdot s(\mu,\mu',\sigma) \quad (2)$$

where $p(\mu_n, \sigma)$ is the slope probability function, $r(\cos\Theta, n)$ is the fresnel reflection coefficient, and $s(\mu, \mu', \sigma)$ is a shadow function.

Gaussian Rough Sea Surface

As shown in Eq. (1), since we have split the radiation into a direct beam and a diffuse contribution, in the RTM simulations we may assume a 2-D Gaussian rough surface for the direct beam and a 1-D Gaussian surface for the diffuse radiation:

- a 2-D Gaussian surface slope probability function is assumed for direct beam incidence:

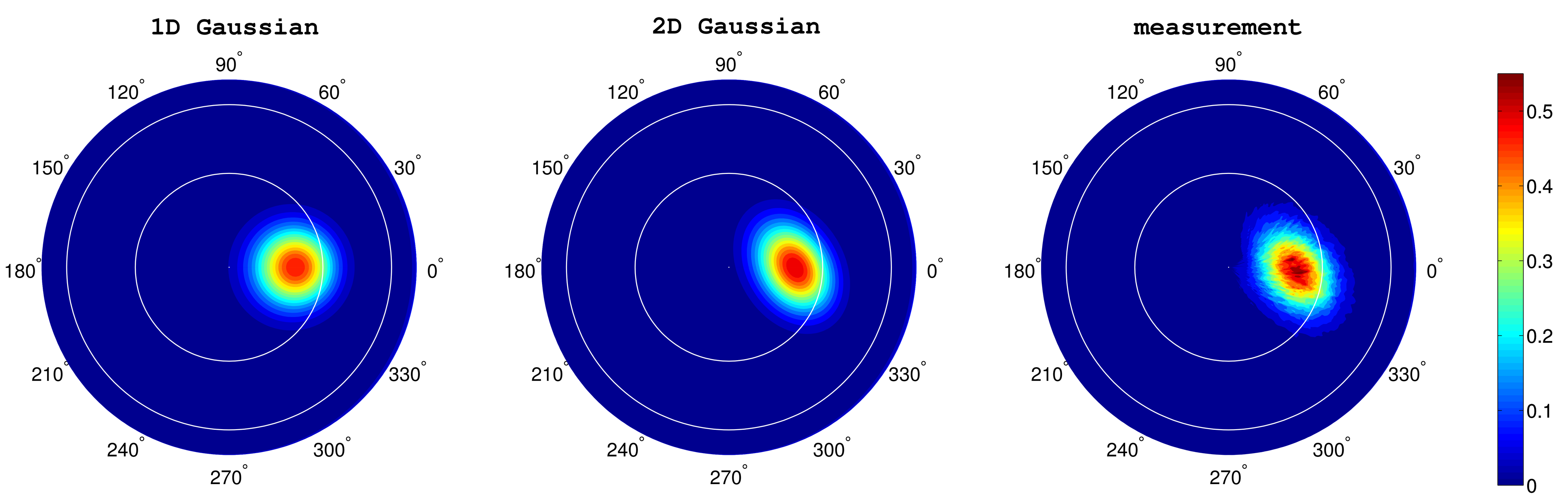
$$p(\mu_n,\sigma) \to p(z_x,z_y) = \frac{1}{2\pi\sigma_x\sigma_y} \exp\left[-\frac{1}{2}\left(\frac{{z_x}^2}{\sigma_x^2} + \frac{{z_y}^2}{\sigma_y^2}\right)\right] \quad (3)$$

- a 1-D Gaussian surface slope probability function is assumed for diffuse light incidence:

$$p(\mu_n,\sigma) = \frac{1}{\pi\sigma^2} \exp\left(-\frac{\tan^2\theta_n}{\sigma^2}\right) \quad (4)$$

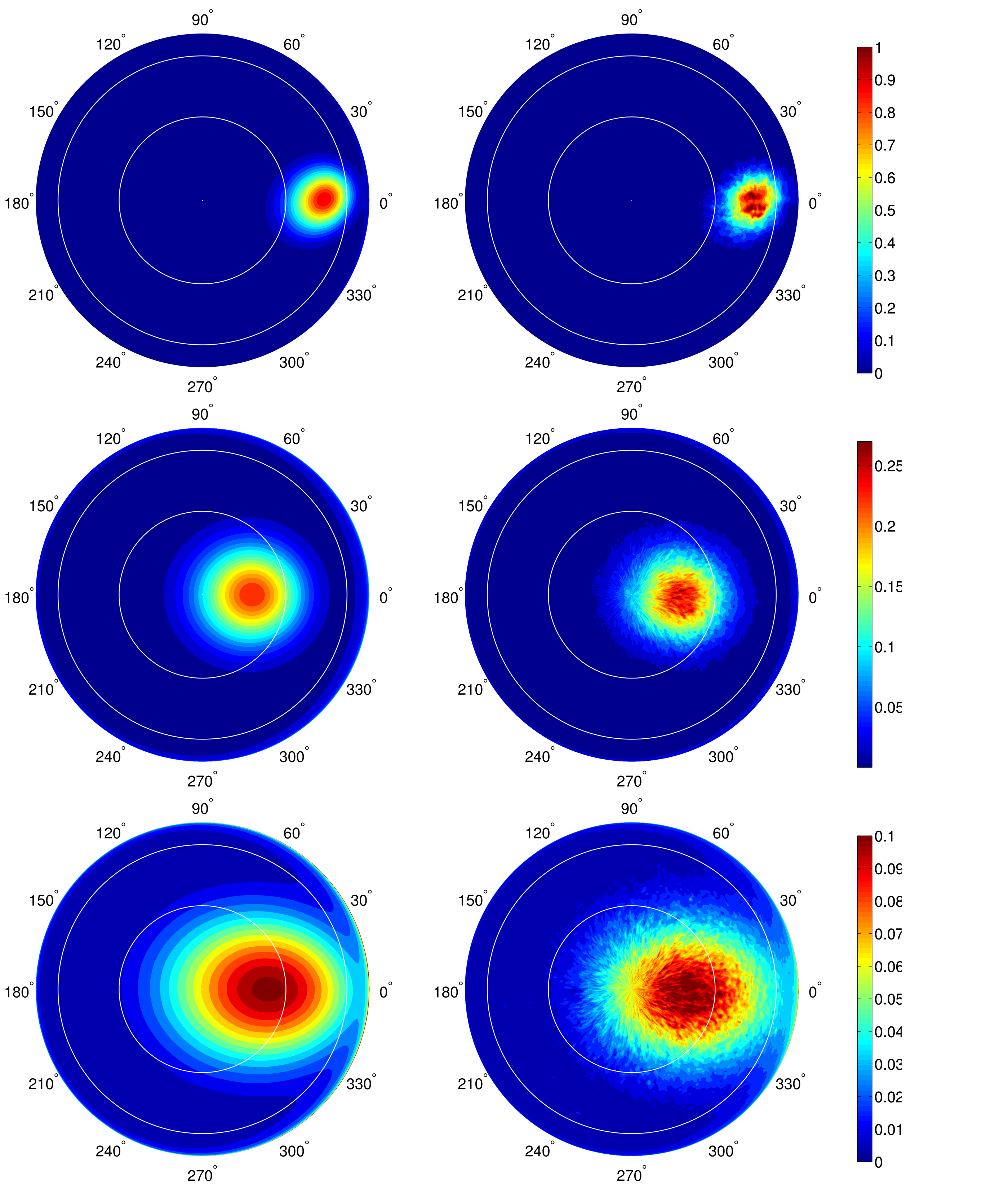
where σ_x^2 and σ_y^2 are defined as sea surface slope variances, and $\sigma^2 = \sigma_x^2 + \sigma_y^2$.

Importance of 2-D asymmetrical BRDF



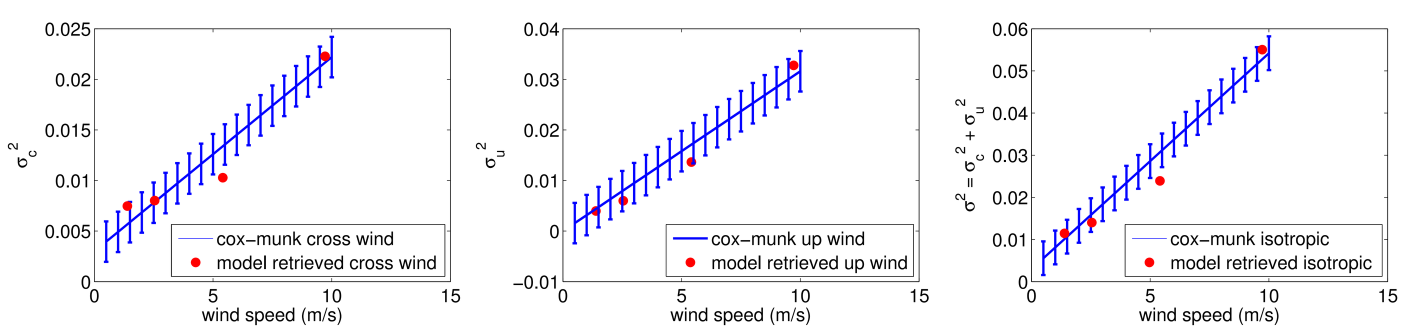
Comparison of best match between simulated symmetric (1-D) and asymmetric (2-D) BRDF with measurements. Since the observed glint pattern is a tilted ellipse that is not symmetric, a 2-D Gaussian slope distribution is essential to accurately reproduce the glint pattern.

BRDF: Simulation vs Measurement

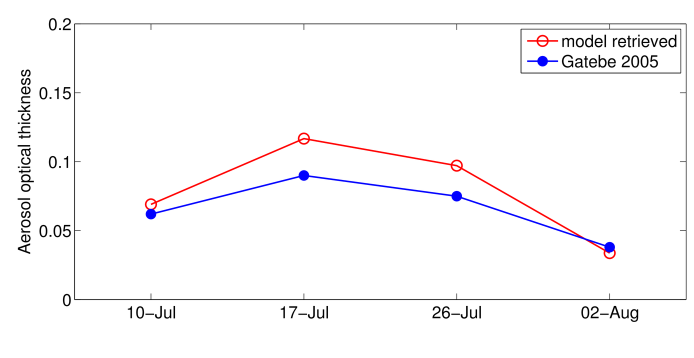


Simulation (left) vs Measurement (right) for different surface wind speeds, wind directions and incident solar illumination angles.

Retrieved result:



Comparison between retrieved slope variance and variance computed from the Cox-Munk glint model. The latter is computed using wind velocity data from NOAA Buoy measurements.



Retrieved aerosol optical thickness.

Summary

- DISORT3 was modified to simulate ocean glint reflectances that successfully match NASA airplane BRDF measurements at the 1,036 nm wavelength.
- The use of a 2-D Gaussian rough surface for singly scattered light and a 1-D Gaussian for multiply scattered light in the RTM simulations is quite successful in reproducing the BRDF measurements.
- Slope variances (roughness) of sea surface are also retrieved that agree well with the Cox-Munk glint model.

References

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