PASSIVE REMOTE SENSING OF OCEANIC WHITECAPS: UPDATED GEOPHYSICAL MODEL FUNCTION

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ABSTRACT

Satellite-based estimates of whitecap fraction *W* provide consistent global, long-term data useful to quantify air-sea processes. Our first algorithm providing satellite-based *W* data uses passive microwave observations from WindSat at low spatial resolution, early version of the WindSat geophysical model function (GMF) for surface emissivity and the atmosphere, and input variables from various sources. This algorithm has been recently updated with new input data and the latest versions of the WindSat GMF to produce *W* data at higher spatial resolution. The updated algorithm yields improved *W* data as they show consistency at different microwave frequencies and expected threshold behavior at all frequencies.

Index Terms— passive remote sensing, whitecap fraction, breaking waves, brightness temperature, air-sea intercation

1. INTRODUCTION

Many air-sea interaction processes are quantified in terms of whitecap fraction *W* because oceanic whitecaps are the most visible and direct way of observing breaking of wind waves in the open ocean. Breaking waves enhance the surface fluxes of momentum, heat, and mass. Because ocean-atmosphere coupling is realized through these surface fluxes, their accuracy affects models used for weather forecast, storm intensification prediction, and climate change studies [1].

Whitecap fraction has been traditionally measured from photographs or video images collected from towers, ships, and aircrafts [2]. Satellite-based passive remote sensing of whitecap fraction is a recent development that allows long term, consistent observations of whitecapping on a global scale [3, 4]. The method estimating *W* relies on changes of ocean surface emissivity at microwave frequencies (e.g., 6 to 37 GHz) due to presence of sea foam on a rough sea surface [5]. These changes at the ocean surface are observed from satellite-born microwave radiometers as changes of the brightness temperature T_B at the top of the atmosphere (TOA). A year-long *W* database for 2006 compiled with this algorithm has proven useful in analyzing the variability of *W* [6], and quantifying fluxes of CO_2 and sea spray production [7].

2. METHOD

The algorithm to obtain *W* from satellite observations of T_B was developed at the Naval Research Laboratory within the framework of WindSat mission. It improved upon the feasibility study of obtaining *W* [5] by using independent sources for the input variables of the algorithm and physically based models for the emissivity of rough sea surface and emissivity of foam. Further developments of the $W(T_B)$ algorithm focus on two aspects: (i) New sources and products for the input variables; (ii) Updated geophysical model function (GMF).

The GMF calculates T_B at the TOA as contributions from the atmosphere and the ocean surface. The ocean surface emissivity combines the emissivity of rough sea surface and the emissivity of areas covered with foam. Figure 1 shows the flow chart of the algorithm. WindSat provides measured T_B^{TOA} at 5 frequencies (6 to 37 GHz). We obtain the brightness temperature due to rough surface (no foam) at the TOA $T_{Br\,\mathrm{mod}}^{TOA}$ using the radiative transfer equation and models for T_B due to roughness and T_B due to the atmosphere [8]. Namely, we use the two-scale model for the emissivity of surface roughness with input data for wind vector (speed *U* and direction ϕ), SST *T*, and salinity *S*; and, a model for the atmospheric attenuation with input data for water vapor *V* and cloud liquid water *L*. We obtain the observed T_B due to foam at the surface as:

$$T_{Bf} = T_B^{TOA} - T_{Br\,\mathrm{mod}}^{TOA} \qquad (1)$$

Using radiative transfer model for the emissivity of foam [9], we obtain the brightness temperature due to 100% foam-covered surface T_{Bf100}. Whitecap fraction is then estimated as:

$$W = \frac{T_{Bf}}{T_{Bf100}} \quad (2)$$

Two approaches can provide T_{Bf} from T_B^{TOA} referred to hereafter as direct and empirical approaches. The direct approach uses the WindSat data to obtain observed T_B due to foam as in Eq. (1), $T_{Bfobs} = T_B^{TOA} - T_{Br\,\mathrm{mod}}^{TOA}$. While WindSat observations are directly used in this approach, the resulting T_{Bfobs} data points contain the signal from the foam together with errors such as error due to calibration of WindSat T_B^{TOA}, model error for $T_{Br\,\mathrm{mod}}^{TOA}$, and error due to time-space match-ups between WindSat T_B^{TOA} and input variables from various sources. It is not trivial to evaluate and separate these errors, thus T_{Bfobs} data are noisy. Work on minimizing the errors in T_{Bfobs} is ongoing.

The empirical approach uses the WindSat data to obtain "measured emissivity" e_{meas} as specular emissivity plus an empirical fit for the excess emissivity due to the ocean surface roughness and foam [8]. Using this e_{meas}, we calculate empirical $T_{B(r+f)\mathrm{mod}}^{TOA}$ which includes signals from roughness, foam, and the atmosphere. We then obtain T_B due to foam as $T_{Bfemp} = T_{B(r+f)\mathrm{mod}}^{TOA} - T_{Br\,\mathrm{mod}}^{TOA}$. In this approach, the WindSat observations are used indirectly (via the empirical fit), however the resulting T_{Bfemp} errors are somewhat minimized with the modeling error remaining source of uncertainty. Until T_{Bfobs} is refined, we work with this empirical approach and use T_{Bfemp} in Eq. (2).

3. RESULTS

The first version of the $W(T_B)$ algorithm (v. 1.9.6) is built with the following elements:

a) WinSat T_B data at low resolution (footprint 50 km × 71 km) to obtain time-space matchups for model input variables.
b) Input variables from QuikSCAT or GDAS for U and ϕ; GDAS for T; SSMI (platform f13) for V and L; and constant value for the sea water salinity S = 34 psu.
c) GMF to obtain $T_{B(r+f)\mathrm{mod}}^{TOA}$ and $T_{Br\,\mathrm{mod}}^{TOA}$.

Figure 2a shows the wind speed dependence of satellite-based whitecap fraction W with version 1.9.6 of the $W(T_B)$ algorithm at all five WindSat frequencies.

The $W(T_B)$ algorithm has been recently updated to use new input variables and updated GMF. The originally used QuikSCAT and GDAS data for ocean wind vector and SST

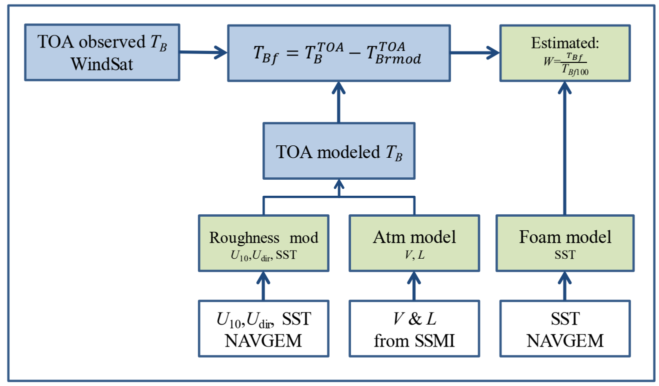
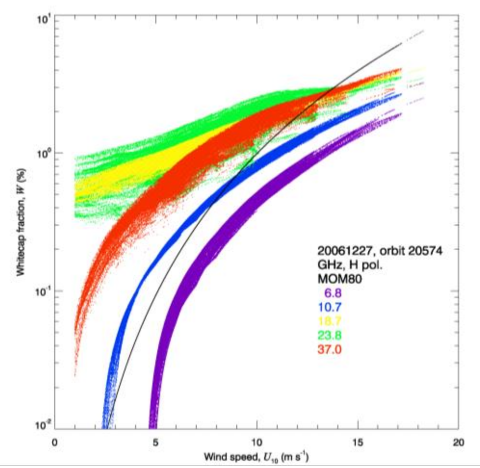
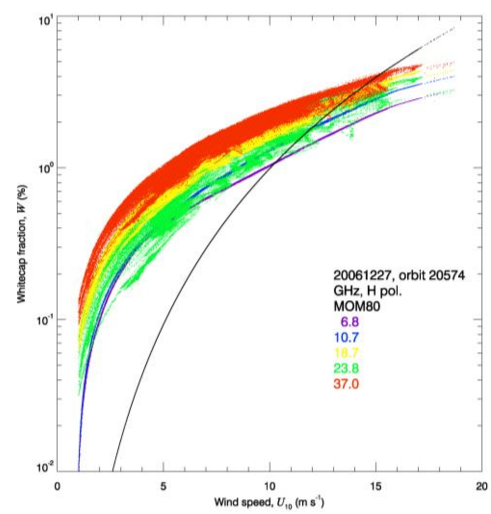


Figure 1: Flow chart of the $W(T_B)$ algorithm estimating whitecap fraction from passive microwave observations.



a)



b)

Figure 2: Wind speed dependence of satellite-based whitecap fraction W obtained using the $W(T_B)$ algorithm a) version 1.9.6; b) version 2.4.6. Parametrization $W(U_{10})$ from photographic data [11] is shown for reference (black line).

are now replaced with wind vector fields and SST from either 6-hr ECMWF (European Center for Medium range Weather Forecast) analyses or 3-hr NAVGEM (Navy Global Environmental Model) analyses. The SSMIS (platform f17) data obtained with processing algorithm version 7 [10] are now used for V and L. For S, we now use salinity climatology from the 2001 WOA (World Ocean Atlas).

The use of these new input variables allows extended data processing with our $W(T_B)$ algorithm beyond 2006. The use of NAVGEM data ensures consistency between estimates of sea spray production with satellite-based W data and their tuning and validation with NAAPS (Navy Aerosol Analysis and Prediction System).

The updated GMF of the $W(T_B)$ algorithm combines the latest WindSat GMF (version 2.4.6) for the atmosphere and surface emissivity with our radiative transfer model for foam with vertical void fraction profile. We now use WindSat T_B data at high resolution (25 km x 35 km). Figure 2b shows W estimates from the updated GMF and ECMWF input data.

Two main improvements in GMF version 2.4.6 render the updated W estimates more plausible (Fig. 2). Improved atmospheric model yields valid W estimates at 18 and 23 GHz. Improved surface emissivity model makes the W estimates more consistent between all frequencies, yet preserves two main W characteristics: (i) threshold behavior at low wind speeds; and (ii) spectral dependence of W caused by frequency sensitivity to foam layer thickness.

4. CONCLUSIONS

New input parameters and updated GMF improve estimates of satellite-based W data. Input data from 3-hr model provide more data points for W estimates. The main improvement in the new GMF is from the atmospheric model as demonstrated by the threshold behavior of W at all WindSat frequencies. Spectral (frequency) dependence of W is preserved, though weaker.

11. REFERENCES

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