Passive Remote Sensing of Sea Foam using Physically-Based Models

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***Abstract*—Demonstrating the high variability of sea foam fraction (whitecap coverage) on the ocean surface, we justify the need for estimating foam coverage with space-based passive remote sensing as an alternative to conventional photographic measurements. We outline the concept and prove the feasibility of a method for deriving foam coverage from satellite measurements. The encouraging results of an initial implementation motivate further work addressing its drawbacks. We describe data and modeling improvements to the initial algorithm and report results on satellite-derived whitecap coverage using physically based models.**

Keywords: sea foam, whitecaps, sea spray, foam emissivity, microwave radiometer, sea surface spectrum, WindSat.

I. Introduction

Sea foam (whitecaps) on the ocean surface manifests breaking of wind waves with air entrainment into the water. By altering ocean albedo and surface roughness, sea foam affects retrievals of the ocean-surface wind vector [1] and ocean color [2]. An adequate accounting of the foam effect in satellite retrievals has the potential to improve the accuracy of the retrieved geophysical parameters. The foam-covered ocean surface actively produces sea spray via bubble bursting, which then transforms to sea-salt aerosols [3]. By producing sea spray and sea-salt aerosols, whitecaps are involved in the planetary heat budget [4], air-sea gas exchange [5], visibility studies, and aerosol radiative forcing of climate. For instance, sea-salt aerosols have the potential to mitigate global warming directly by increasing planetary albedo [6], indirectly by acting as cloud condensation nuclei (CCN) [7], and chemically by removing methane and surface ozone [8]. Sea-salt aerosols may diminish the cooling effect of the sulfate aerosols by rapid removing natural and anthropogenic sulfates from the atmosphere and by preventing the activation of sulfate aerosols as CCN [9]. The modeling of these processes requires realistic estimation of foam fraction (whitecap coverage), W, applicable to the variety of conditions encountered over the globe.

Traditionally, whitecap coverage is estimated as a function of wind speed at 10-m reference height, U_{10}, e.g. $W = aU_{10}^{b}$. Parameterizations following this and similar relations, however, do not show consensus, Figure 1. The foam fraction values that $W(U_{10})$ relations predict vary over 3-4 orders of magnitude. Differences in method of measurement and data processing and analysis can account for at most 30% of this variability, but not for the full range. A suite of meteorological and environmental factors, in addition to wind, affect the spatial and temporal extent of oceanic whitecaps causing high variability [10]. Additional factors influencing whitecap coverage include atmospheric stability (the difference between seawater and air temperatures), surface currents, wind fetch, wind duration, sea surface temperature (SST), salinity, and concentration of surface active materials. Thus, models of W accounting for these additional factors are in order.

To model the high variability of W, an extensive database of whitecap coverage and concomitant measurements of various quantities is necessary. Existing measurements of foam fraction obtained from still photographs and video images collected on ships, towers, and aircrafts in the past 42 years do not provide enough information to quantify the dependence of W on additional environmental and meteorological variables. Space-based microwave radiometers provide an alternative for estimating whitecap coverage on a global scale thus the possibility to build a database representing a wide range of meteorological and environmental conditions. Here we report work within the framework of the WindSat mission [11] on an algorithm estimating W from satellite-measured brightness temperatures.

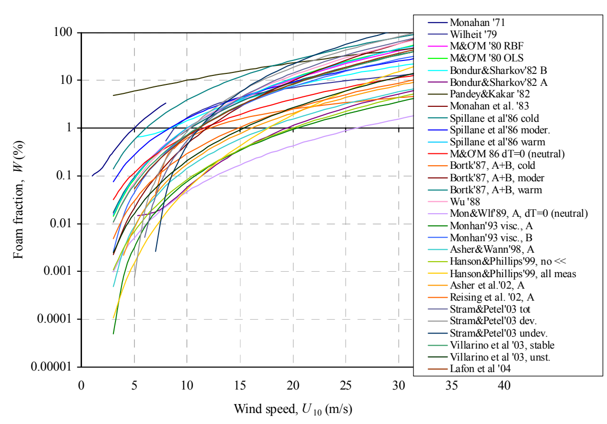

Figure 1. Various parametrizations of relation $W(U_{10})$ derived from data collected in various conditions. After [10].

II. Remote Sensing of Sea Foam

Sea foam is a mixture of air and water with dielectric properties very different from those of seawater. As a result, whitecaps have a specific signature in various portions of the electromagnetic spectrum (ems) and can be detected from space-borne remote sensors. One spots and photographs whitecaps on the ocean surface as bright white patches because in the visible part of the ems foam reflectivity is about 10 times higher than that of the surrounding seawater. As Kirchoff law dictates, high foam reflectivity is necessarily complemented with foam emissivity much lower than that of seawater. By contrast, in the microwave region whitecaps are poor reflectors compared to seawater, but excellent emitters with emissivity close to 1 [12]. Foam characteristics in the infrared (IR) region are intermediate between these two extrema as sea foam reflectivity gradually decreases while foam emissivity gradually increases providing small yet measurable signals for detection [13]. Therefore, whitecaps can be detected with remote sensing techniques in any portion of the ems: as high reflectivity in the visible or high emissivity in the microwave or a combination of reflectivity and emissivity signals in the IR. From these three possibilities, we choose to work in the microwave region since the correction of atmospheric interference, necessary to obtain data at the ocean surface, is less severe than in the visible and IR regions [14].

A method estimating whitecap coverage from satellite measurements has been developed [10]. The algorithm relies on changes of microwave emission at the ocean surface due to the presence of sea foam. Figure 2 demonstrates that it is possible to obtain global whitecap coverage with an error less than one standard deviation. Satellite-derived values of foam coverage are comparable to those photographically measured. Their global spatial distribution, however, is different from that predicted with conventional $W(U_{10})$ relation. This expected difference has been discussed in length in [10] in terms of both deficiencies in the implementation of the initial algorithm and fingerprinting of various meteorological and environmental factors. Using satellite-derived values of whitecap coverage, reasonable initial results on sea-salt aerosols flux, CO_2 transfer velocity, and ocean surface albedo have been reported [15].

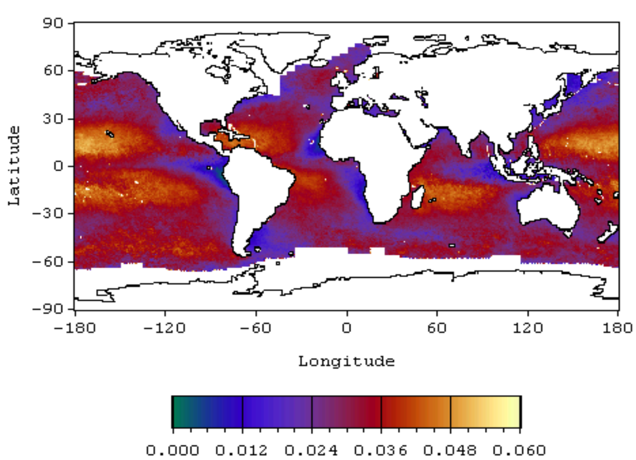

Figure 2. Satellite-based estimates of annual (1998) foam fraction.

III. Improvements of space-based sea foam estimates

While the initial version [10] of the method proves the potential and feasibility of space-based remote sensing of sea foam, it has used simple models for emissivity of rough sea, e_r, and foam, e_f, necessary for the estimates. Also, the satellite-measured brightness temperature, T_B, and the atmospheric correction variables used to compute composite (involving both rough and foamy areas) surface emissivity, e, were obtained from the same satellite data set, that of SSM/I. Thus some dependence of satellite-retrieved foam cover on the assumptions in the SSM/I retrieval algorithm is expected. To minimize correlations and error propagation, it is also highly desirable to decouple the quantities used in the emissivity models for e_r and e_f from those directly measured and used to obtain e.

With the recent launch of WindSat instrument [11] comes the possibility of using independent data sets. The database assembled for the WindSat mission combines the following data matched-up in time and space [16]: T_B, from WindSat; water vapor, V, and cloud liquid water, L, from SSM/I and TMI; wind vector from QuikSCAT; wind field and SST, T_s, from NCEP numerical weather prediction model.

The modeling issues in the initial version [10] are addressed by: i) employing the WindSat forward model for atmospheric variables and e_r [16]; and ii) developing a new model for e_f. Combining match-ups of WindSat-measured T_B and SSM/I-retrieved V and L, we developed our own parameterization for the atmospheric variables [16] needed for atmospheric correction. With these atmospheric variables we solve the radiative transfer equation to obtain the "measured" composite surface emissivity $e \equiv e_{meas}$.

Next, we represent "modeled" composite surface emissivity as $e \equiv e_{\mathrm{mod}} = e_r + \Delta e_f$, where e_r is the emissivity of rough sea surface and Δe_f is a correction mostly due to foam obtained as $\Delta e_f = e_{meas} - e_r$. Optimizing the WindSat retrieval algorithm to deliver geophysical variables with minimum error [16], we assume that contributions to Δe_f from factors other than foam (e.g., measurements and model errors) are minimized. On this basis we consider the correction due to foam as $\Delta e_f = W.e_f$. With such a concept in mind, we now need models for e_r and e_f based on more sound physical grounds than the e_r and e_f models used in [10].

We compute e_r with a two-scale emissivity model [1], [17]. This model describes well changes of surface emissivity for winds up to 10-12 m s^{-1} due to Bragg scattering from short gravity and capillary waves riding on long waves with Gaussian distribution of upwind and crosswind slopes. Many of the analytical expressions in the two-scale model involve the wave spectrum. We use the wave spectrum given in [1], [18]. In modeling e_r, it is important to clearly separate the effects of roughness and foam. We cannot ensure this requirement using the two-scale model and the wave spectrum with the well established and widely used values of their parameters [1], [18]. The reason is that some of these parameters were determined empirically from aircraft radar measurements [18], which most certainly contained signal from foam. Thus, we identify parameters, which we tune so that the output of our two-scale model represents e_r only [16].

Foam emissivity, e_f, is initially modeled with the Fresnel formula for foam reflectivity using foam permittivity with constant void fraction (defined as the volume fraction of air in a unit volume of air-water mixture) [10]. This model ensures fair emissivity prediction for thick, freshly generated foam, but it is only partially suitable for aged, thinner foam patches. A realistic physical model should account for the emission of whitecaps with a distribution of thicknesses. In addition, an e_f model should account for changes of void fraction within the foam layer depth yielding depth profiles for all foam properties. To address these issues, we developed a radiative transfer model involving various contributions to foam emissivity, such as up- and down-welling emissions within the foam layer and emission of seawater beneath the foam. We ignore the scattering in this first attempt for e_f. Multiple reflections of the various contributions at the air-foam and foam-water interfaces are also accounted for. Examining the behavior of foam properties for various void fraction profiles, we identify the exponential void fraction profile as the most suitable one. We account for foam thicknesses from 200 μm (a monolayer of small bubbles) to 25 cm with a log-normal probability distribution function.

IV. Preliminary Results

With all data and model improvements in place, we obtain Δe_f. We use six months (Sep 2003 – Feb 2004) of WindSat data. About 3×10^6 data points are binned in 1-m/s wind speed bins, thus we essentially work with global averages. Using constant salinity of 34 psu and mean T_s corresponding to each wind speed bin, we compute e_f for each bin and each WindSat frequency, H and V polarizations. With these we compute foam fraction.

Figure 3 shows the foam fraction as a function of wind speed for all WindSat frequencies, H polarization. The magnitude and the trend with the wind speed are as expected. The observed differences for the five frequencies should not be present. Ideally, foam fraction values should not depend on the frequency of measurement. Still, the results can be explained with biases in both Δe_f and e_f. Since radiation at 6.8 GHz has the largest penetration depth, it is more sensitive to thicker foam layers. At typical wind speeds, represented by our binned values, thick foam layers are less probable. But if the probability of thick foam in our thickness distribution is too high, we may overestimate e_f at 6.8 GHz. The lower values at 6.8 GHz may also be due to too low Δe_f caused by either underestimated e_{meas} due to deficiencies in our atmospheric correction or overestimated e_r. In contrast to 6.8 GHz, T_B at 37 GHz may be significantly affected by even very thin foam layers. Besides, not including scattering in our foam emissivity model, we underestimate the losses in foam. While negligible at lower frequencies, this underestimation becomes an issue at 37 GHz. Thus at 37 GHz our e_f may be biased low, giving higher values for foam fraction. As the penetration depths of radiation at 10.7, 18.7, and 23.8 GHz are comparable with

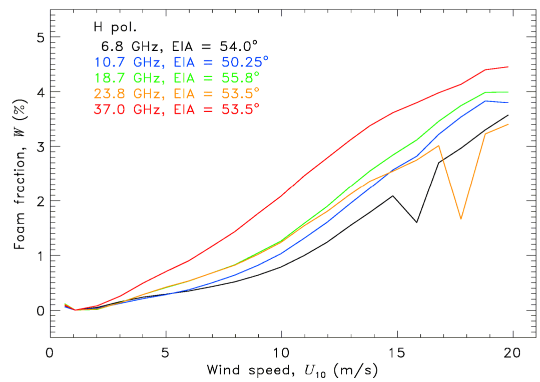

Figure 3. Satellite-derived foam fraction estimates for all WindSat frequenices, H polarization.

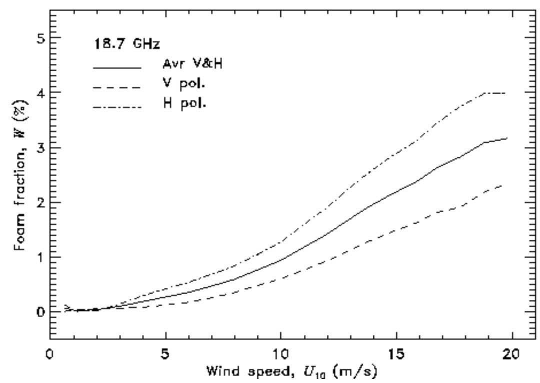

Figure 4. Satellite-derived foam fraction for H and V polarizations, 18.7 GHz.

typical sea foam thicknesses, they are considered more appropriate for estimating foam coverage. The closeness of the foam fraction values for these frequencies could be interpreted as confirmation of such a premise. Our reasoning demonstrates that the differences in foam fraction values at different frequencies can be used to gauge how successfully we perform atmospheric correction for e_{meas} and model e_r and e_f. Further improvements in our atmospheric parameterization and models for rough-sea and foam emissivity would minimize these differences.

Figure 4 compares foam fraction values for H and V polarizations at 18.7 GHz. Experiments have shown that H polarization is more sensitive to changes in wind, thus roughness, than V polarization. Foam, however, affects both, H and V polarizations. It is necessary, therefore, to consider to what extent the average of the estimates at both polarizations (solid curve in the figure) or some combination can be used.

The results reported are the first estimates of foam coverage using passive space-based measurements and physical models. Despite the discussed deviations, we believe these are

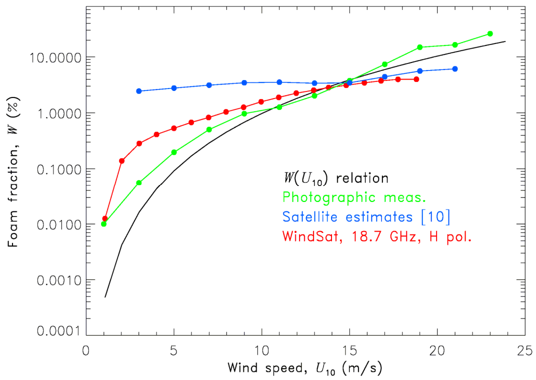

Figure 5. Initail and improved satellite-derived foam fraction estimates compared to previous photographic measuremens and $W(U_{10})$ predictions.

encouraging results. As seen in Figure 5, the introduced data and model improvements have decreased the initial striking difference between the trends of satellite and photographic measurements, especially at low winds. Still, differences are noticeable and expected.

Since this first version of the algorithm with physical models for sea surface roughness and foam emissivity, we have introduced further improvements to the WindSat measurements and retrieval algorithm. These include a new rain flag, enhanced procedures for data quality control, improved and extended match-ups, and an improved atmospheric model. The new developments provide a better screening of our database and will remove outliers in our results like those seen in Figure 3 at 6.8 and 23.8 GHz.

V. Conclusion

The fraction of the ocean surface covered with sea foam (whitecap coverage) exhibits high variability due to a suite of physical factors. Adequate modeling of foam fraction variability would improve climate model predictions of numerous processes at the air-sea interface and in the lower atmosphere. Estimates of foam fraction from satellite measurements can provide a useful database for modeling this high variability. We have outlined the concept and demonstrated the feasibility of a method estimating foam coverage with satellite-based passive remote sensing. The encouraging results of this initial implementation of the method motivated further work addressing its drawbacks. We have reported here data and model improvements of the algorithm developed at NRL within the framework of the WindSat mission. Our preliminary results for satellite-derived foam fraction using physically-based models have shown improvement over the initial implementation. We have discussed observed deficiencies in the results and used them to identify and address issues in our models.

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