WINDSAT RETRIEVAL OF OCEAN SURFACE WIND SPEEDS IN TROPICAL CYCLONES

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ABSTRACT

The WindSat polarimetric microwave radiometer measures top-of-atmosphere brightness temperature, useful for retrieving surface wind vector over the ocean. This procedure was previously documented in low to moderate wind and light precipitation [1,2]. An atmospheric clearing algorithm designed to remove the emissive and absorptive effects of stronger precipitation and extract the emissivity of the wind-driven ocean surface worked well in moderate rain but had limited success with strong rainfall and high winds [3]. This paper presents results using an improved forward model including Mie scattering from rain. We consider three 2005 WindSat hurricane overpasses for proper atmospheric conditions (Dennis, Katrina and Rita). The improved atmospheric clearing algorithm extracts ocean surface emissivity in and near the hurricane rain bands and eyewall. The emissivity is compared to NOAA H*Wind analysis of the near-surface wind field. Results show a monotonic dependence of emissivity on wind speed up to category 3 hurricane-force winds.

1. INTRODUCTION

The microwave emissivity of a calm ocean surface is relatively low, between 0.25 and 0.6 depending on the polarization. The presence of wind increases the emissivity in a monotonic relation that can be used to estimate wind speed from thermal emission. Surface wind roughens the ocean and generates foam in proportion to the strength of the wind. The foam has an emissivity near unity so its presence increases the specular emissivity. One concern with this relation is saturation; at some point, the wind-roughened surface may become entirely covered by foam and the emissivity will cease to rise with increasing wind. The relation between surface emissivity and wind speed below 25 m/s is well known. This study investigates the relationship under higher winds, such as would be found in tropical cyclones.

A major complication to emissivity retrieval is the effects of the atmosphere. The upwelling brightness temperature observed by a satellite is composed from many sources. The emission from the surface is the desired component, but the atmosphere serves to attenuate its signal as well as adding its own emission. In calm and clear conditions generally seen over the ocean, an atmosphere with light wind and little rain produces a negligible effect. For the cases examined in this study, it becomes a much more significant factor. A tropical cyclone contains a thick eyewall as well as heavy rainbands with high winds roughening the surface as well as precipitation that adds its own emission while also scattering the incoming signals. A simple or incomplete atmospheric model cannot properly describe these effects.

Another aspect required for accurate estimation of ocean surface emissivity is a forward model characterizing the complete relation between wind speed and emissivity. [4] addresses the connection between wind direction and the 3rd and 4th Stokes parameters of brightness temperature. However, emissivity and wind speed for the vertically and horizontally polarized parameters are largely uncharacterized. This study develops a robust atmospheric model for strongly precipitating atmospheric conditions and, with it, derives an empirical model for the vertically and horizontally polarized emissivity versus wind speed at hurricane force winds.

2. SATELLITE AND GROUNDBASED OBSERVATIONS

Two main datasets are used in this study: WindSat brightness temperature observations and a “ground truth” surface wind field provided by the Hurricane Research Division (HRD) of the National Oceanic and Atmospheric Administration (NOAA) [5].

2.1. WindSat polarimetric radiometer

WindSat has five channels, three of which are fully polarimetric while the remaining two are dual-polarized. The frequencies range between 6.8 GHz and 37 GHz [6].

Three tropical cyclone cases are selected for this study from the 2005 Atlantic hurricane season. In each case, the storm was more than 100 km from coastlines or islands to minimize land contamination. Cyclone Dennis was rated Category 1 (wind speeds between 74 and 95 mph) during WindSat’s overpass on 9 July, 2005. Cyclones

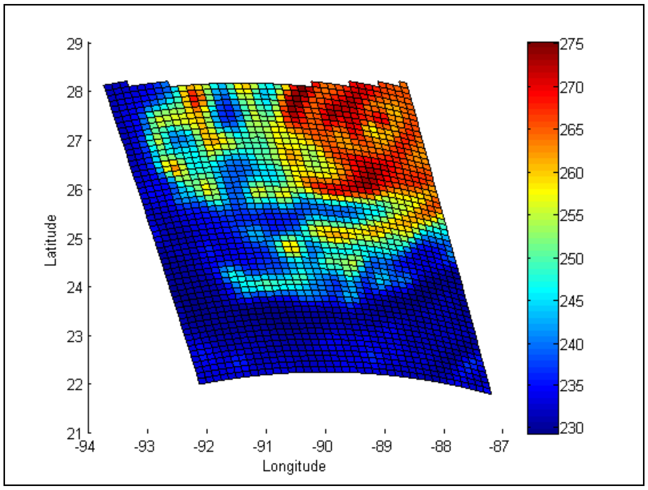

Figure 1. WindSat observations of Hurricane Katrina in Category 3 stage immediately before landfall. Data from 37 GHz V-pol channel for optimal visualization.

Katrina and Rita were both Category 3 storms (winds between 111 and 130 mph) when observed on 28 August and 21 September, respectively. Figure 1 illustrates WindSat's 37 GHz v-pol observation of Katrina during the overpass.

2.2. H*Wind analysis

The NOAA-HRD wind field analysis is used as "ground truth" for the surface winds. The analysis uses surface wind data collected within a three to six hour window of the satellite overpass from various sources such as buoys, GPS dropsondes, ship observations and the plane-based Stepped Frequency Microwave Radiometer (SFMR), among others. The data are projected to a near surface level of 10 meters and then interpolated linearly through the H*Wind algorithms to complete a wind field representative of the entire cyclone. This approach allows for external quality control during the analysis.

The wind field is not a perfect description of a cyclone's surface wind speeds. The observations are collected over a large time frame, which does not capture the quick variability in a storm's wind structure. Also, the averaging necessary to complete the wind field can decrease the resulting maximum winds from the true value, and can introduce errors between 10% and 20% [7]. The analysis generated for the three cases used in this study were carefully constructed with abundant data samples to best reduce any errors.

3. EMISSIVITY RETRIEVAL

The surface emissivity retrieval process is based on the radiative transfer equation, of the form

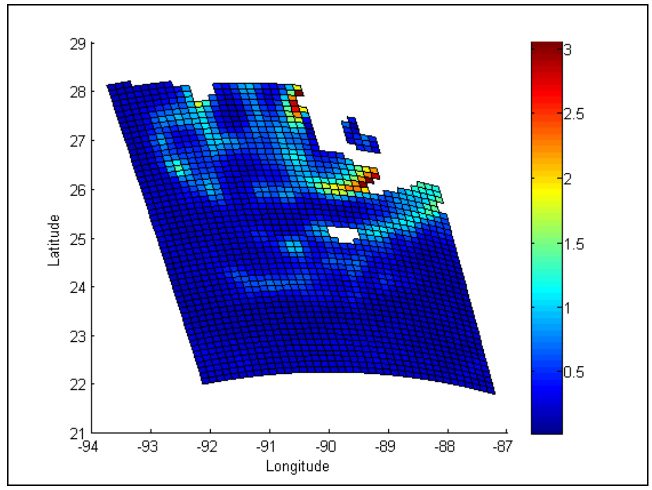

Figure 2. Integrated liquid water (mm) retrieved from Hurricane Katrina for atmospheric absorption model.

$$T_B(f,p,\theta) = \varepsilon(f,p,\theta)T_{surf}\,e^{-\tau(f)\sec\theta} + T_{up}(f,\theta) + \Gamma\,(T_{down}(f,\theta) + T_{cosmic}\,e^{-\tau(f)\sec\theta})\,e^{-\tau(f)\sec\theta} \qquad (1)$$

where f is the channel frequency in GHz, p is polarization and θ is the incidence angle. ε represents the surface emissivity, and is a functional combination of the appropriate specular and rough surface values depending on the wind. T_{surf} is the temperature of the sea surface in Kelvin. τ is the optical depth, and is the link to the atmospheric clearing model. T_{up} and T_{down} are the upwelling and downwelling atmospheric brightness temperatures, both of which are latitude dependent and are in Kelvin. T_{cosmic} is the background brightness temperature, again in Kelvin. Γ is the surface reflectivity. This model was designed by [1], wherein details for each parameter are given.

The first atmospheric clearing algorithm was developed by [3], and retrieves optical depth from the atmosphere-sensitive high frequency WindSat observations using a absorption-based parameterization. The optical depth is directly related to column integrated water vapor (V, cm) and integrated rain and cloud liquid water (L, mm) through the form

$$\tau(f) = c_0(f) + c_1(f)V + c_2(f)L \qquad (2)$$

whose coefficients are given in [3]. For this retrieval, surface emissivity must also be estimated and is considered dependent on wind speed (W, m/s) alone through the function

$$\varepsilon(W) = \varepsilon_0 + a_0(1\text{-}exp[-a_1W-a_2W^2]) \qquad (3)$$

as described in full by [3] and which is based on [8]. The three parameters (V and L as primary, W as secondary) are retrieved for the atmosphere by iterating Equation (1) until the modeled brightness temperatures have a root-mean-squared (RMS) difference from the WindSat brightness

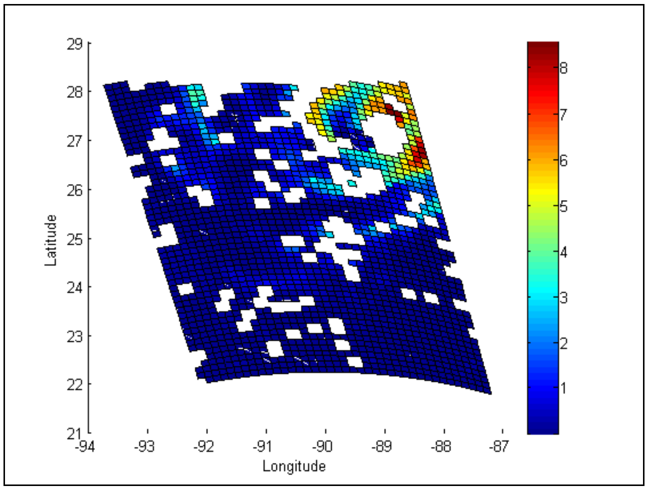

Figure 3. Rain rate (mm/hr) retrieved from Hurricane Katrina for atmospheric model including absorption and scattering.

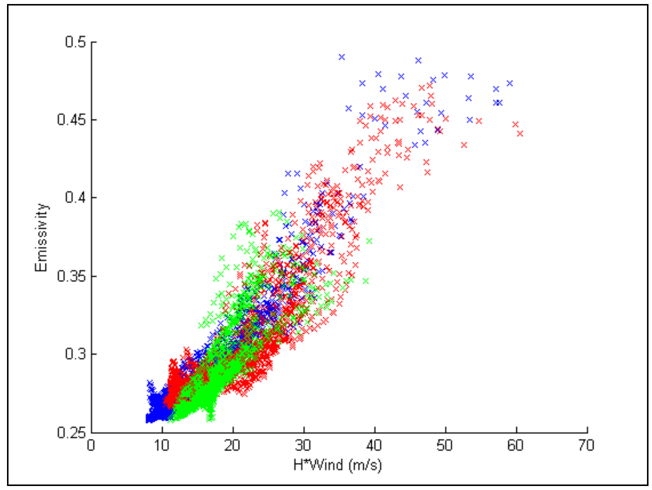

Figure 4. Emissivity versus wind speed for all three cyclone overpasses. The blue data is for Katrina, the red for Rita and the green for Dennis. The plot only includes data with RMS residual error below 3 K, and where the model with the lowest RMS was selected for each point over the storms.

temperatures at or below 3 K. The V and L estimations that satisfy this condition are then used to compute the optical depth that describes the atmospheric contribution in the surface-sensitive low frequency emissivity extraction.

Using this scattering-free model, atmospheric clearing was successful in most regions of the storm when the precipitation was not heavy enough to produce significant scattering. Figure 2 is an image of the retrieved liquid water for Hurricane Katrina over the same grid as Figure 1. The rainbands are correctly retrieved around the edges. The white gaps in the retrieval indicate points at which the RMS difference exceeded the 3 Kelvin threshold. Most of the dropouts are concentrated in the upper right portion of the figure, in the region of the storm's eye. The eyewall is where both the heaviest precipitation and surface winds exist.

The addition of scattering to the forward model is implemented using Eddington's second approximation with full Mie scattering from spherical hydrometers. The scattering signal is assumed to be dominated by liquid water, not ice, at WindSat's relatively low frequencies. A Sekhon and Srivastava [9] liquid drop size distribution is assumed. The atmospheric parameters retrieved is this case are rain rate (RR, mm/hr) and integrated water vapor (V, cm), with wind speed (W, m/s) as a secondary parameter from the surface emissivity forward model. Figure 3 displays the retrieved rain rate for the Katrina overpass, with the data gaps (in white) representing the same RMS threshold as before. The scattering model provides significantly more data in the eyewall region with the most precipitation, but performs worse than the absorption-only model in areas where little or no scattering is present.

The next step in the process is the surface emissivity extraction. The surface-sensitive low frequency brightness temperatures are applied to Equation (1), which is rearranged to solve for emissivity. The optical depth calculated from the higher frequency observations removes the atmospheric attenuation. The emissivity is then collocated to the H*Wind analysis for comparison.

4. SURFACE EMISSIVITY DEPENDENCE ON WIND SPEED

Figure 4 compares wind speed with surface emissivity at 6.8 GHz for each of the three cyclone cases considered. The high wind behavior of the emissivity appears to begin leveling out at the extreme end of the available data. This indicates that the foam fraction may start to saturate above 50 m/s (111 mph, Category 3 storm), but none of the test cases provided winds above that range.

5. SUMMARY

WindSat overpasses of three Atlantic storms are chosen from the 2005 hurricane season (Dennis, Katrina and Rita). They represent surface wind speeds up to 70 m/s. Estimates of the microwave surface emissivity, derived from WindSat TOA brightness temperatures, require a careful accounting for the effects of the intervening precipitating atmosphere. Previous attempts assumed a scattering-free atmosphere and were not successful in the high precipitation conditions near the hurricane core. An improved radiative transfer forward model that includes scattering by the hydrometeors has been presented. It markedly improved the ability to estimate the surface emissivity under heavy precipitation. Comparison of the WindSat-derived emissivity with the ground truth wind field provided by NOAA-HRD's H*Wind algorithm results in a clear monotonic relationship that can be exploited by a surface wind speed retrieval algorithm.

6. REFERENCES

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