WindSat Ocean Surface Emissivity Dependence on Wind Speed in Tropical Cyclones

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Abstract

Radiometers are adept at retrieving near surface ocean wind vectors. The Naval Research Laboratory (NRL) launched the WindSat polarimetric radiometer with five frequency channels to observe the sea surface and test its ability to accurately measure the wind in various weather conditions. This study focuses on its performance in extreme conditions – the high wind and heavy precipitation of a tropical cyclone. Storms Dennis, Katrina and Rita from the 2005 hurricane season are used to evaluate WindSat’s retrievals using an atmospheric clearing algorithm to extract emissivity measurements from the brightness temperature observations. The emissivity values are collocated with an independent surface wind field provided by H*Wind. Results show a well-behaved relationship between emissivity and wind speed that is also monotonic. The study indicates that microwave radiometers are capable of retrieving ocean surface wind speed during extreme conditions into early hurricane categories.

1. Introduction

The Windsat polarimetric radiometer has orbited the Earth since 2003 aboard the Coriolis satellite, and provides constant coverage of upwelling brightness temperatures in its ninety minute revolutions. Its object is to provide accurate wind vector retrievals for the ocean surface. Previous studies (Brown et al., 2006; Mondaldo, 2006) have demonstrated WindSat’s ability to measure wind speed for general ocean conditions with little precipitation and winds below 20 m/s, as well as competent wind direction retrievals in significantly higher winds (Yueh, 2006). However, this study presents results of WindSat’s wind speed retrieval under the more intense conditions with high winds and heavy precipitation—a tropical cyclone.

The fundamental base for this study is ocean surface foam. When the surface water is free of foam, its brightness temperature is relatively cold. In the presence of foam, this temperature rises because foam’s emissivity is near unity due to its approximate blackbody behavior. Wind speed is its main source, since an increasing wind will roughen the sea surface and cause foam to form. The relationship is monotonic; higher winds generate more foam. Therefore a radiometer is able to
accurately determine the wind speed judging from the surface foam fraction’s contribution to emissivity. The potential limitation of this situation is saturation. Once the surface is completely covered in foam, no higher wind speed can be detected. This study demonstrates that the foam fraction saturation does not occur until well after 20 m/s, and that radiometers are still useful in the tropical cyclone range.

Section 2 describes the specific data sets used in this study. Section 3 details the developed model process. Section 4 presents the results of the study, wherein the comparison between emissivity and surface wind speed is examined.

2. Datasets

Two main sets of data are used in the comparison between emissivity and surface wind speed. The fundamental information that is put through the model is the WindSat brightness temperatures, provided by Colorado State University (CSU). The temperatures come from its five frequency channels, where 10.7 GHz, 18.7 GHz and 37 GHz are fully polarimetric and the 6.8 GHz and 23.8 GHz channels are dual-polarized (Gaiser et al., 2004). However, only the vertical and horizontal polarizations are used in this study for each channel. The three specific tropical cyclone overpasses occurred in the 2005 hurricane season, and were at least 100 km from any shorelines so as to prevent interference from land emission. The first case was on 9 July over cyclone Dennis, and the second on 28 August over Katrina shortly before it made its historic landfall. Figure 1 (Appendix) illustrates the brightness temperature observed by WindSat, clearly showing Katrina’s warmth to the relatively cold surrounding ocean. The final overpass was on 21 September over cyclone Rita.

The H*Wind wind analysis (Powell et al., 1998) provides the surface wind field for the emissivity comparison. Developed at the National Oceanic and Atmospheric Administration (NOAA) Hurricane Research Division (HRD), the program compiles available data into a representation of tropical cyclones surface winds. Readings are included if they fall within a three to six hour time window around a chosen storm time, and are placed into a storm specific coordinate system. However, since the data coverage is not complete and varies from storm to storm, the H*Wind analysis is not treated as a perfect picture of the cyclone at any specific moment. As such, the wind field is subject
to a usual error between 10% and 20% (Houston et al., 1999). Figure 2 (Appendix) gives an example of a sampling spread used to generate an H*Wind analysis, specifically for the hurricane Rita wind field used in this study. The observations come from SFMR, GPS dropsondes, QuikScat, buoys and Air Force reconnaissance flights among other sources. The imperfect sampling of such storms may lead to an underestimation of maximum wind speeds in the analysis. However, the wind fields on the whole provide an excellent estimation of cyclone wind fields and are considered suitable as the outside standard for collocation with emissivity.

3. Model Description

The brightness temperatures measured by WindSat are subjected to the atmospheric clearing algorithm developed by Brown et al. (2006) and adapted in this study. The radiative transfer equation is at the heart of the method, as given below for brightness temperature:

\[ T_B = \varepsilon T_{surf} e^{-\tau \sec(\theta)} + T_{up} + \Gamma (T_{down} + T_{cosmic} e^{-\tau \sec(\theta)}) e^{-\tau \sec(\theta)} \]  

(1)

\( T_{up} \) and \( T_{down} \) are the upwelling and downwelling atmospheric brightness temperatures, determined by the form in Brown et al. (2006). \( T_{surf} \) is the sea surface temperature and \( T_{cosmic} \) is the cosmic background temperature, both given in K. \( \varepsilon \) is surface emissivity, \( \Gamma \) is surface reflectivity and \( \tau \) is optical depth. \( \theta \) denotes the incidence angle.

The result of the method is the surface emissivity, calculated from the low frequency observations. These frequencies, 6.8 GHz in particular, are the least sensitive to atmospheric interference and thus present the best opportunity for accurate surface measurements. The higher frequencies are used to properly calculate the effect of the atmosphere on the signal. Their shorter wavelengths are more sensitive to the rain and clouds present in the cyclone, and therefore can make the best estimate of the signal’s attenuation as it passes from the surface to the satellite. Once the atmospheric interference is determined, it can be removed from the surface signal to retrieve the emissivity.

The three highest vertically polarized frequency channels—18.7 GHz, 23.8 GHz and 37 GHz—are used to estimate water vapor and liquid water measurements for each pixel of the cyclone overpass. Their brightness temperatures are submitted with a surface
emissivity model into a least squares iterative inversion of a forward model based on Equation (1), which returns the desired atmospheric parameters. The surface emissivity model is based on Wilheit (1979) and has the following form:

\[ \varepsilon (W) = \varepsilon_0 + a_0 (1 - \exp[-a_1 W - a_2 W^2]) \]  

(2)

The model assumes a combination of calm (\( \varepsilon_0 \)) and rough surface emissivity, which is dictated by the foam fraction. \( W \) is wind speed in m/s, and the equation coefficients are listed in Table 1 (Appendix).

The primary atmospheric constituents returned by the iteration are integrated water vapor (\( V \), in cm) and liquid water (\( L \), in mm), as well as wind speed as a secondary component. Figures 3 and 4 (Appendix) display maps of the two primary quantities for hurricane Katrina. Figure 4 clearly shows the characteristic spiral rain bands of the storm in the liquid water, around the eye that is located in the upper right corner. The white area of that region represents excluded unrealistic data, the result of current difficulties with the retrieval in the most extreme of conditions. As of now, the forward model does not consider scattering from high level ice, which may be the cause of unphysical returns in the intense eye region. This is one area of the model that is undergoing current development.

The atmospheric parameters are used in the following model for optical depth:

\[ \tau = c_0 + c_1 V + c_2 L \]  

(3)

where the coefficients are listed in Table 2 (Appendix). The results are combined with the 6.8 GHz horizontal brightness temperature in an inversion of Equation (1), to solve for sea surface emissivity. Once the method process is complete, each storm’s emissivity is matched against the appropriate independent wind field.

4. Results

The final collocation of the retrieved surface emissivity with the H*Wind data is shown in Figure 5 (Appendix). The total data presented is compiled from the three separate cyclones, each indicated by color. The trend presented continues to rise beyond the 20 m/s point. Any possible saturation of the emissivity signal does not begin until 50 m/s. The scarcity of extremely high wind data points lends uncertainty to the absolute point of saturation. During the chosen WindSat overpasses, cyclone Dennis was a
Category 1 and cyclones Katrina and Rita were labeled as Category 3 storms. Therefore, the maximum measured wind speed available from these cases is 60 m/s. In reality, cyclones will reach much higher wind speeds at higher category levels. More overpasses at higher intensities are necessary in order to determine the exact point of foam saturation. Nevertheless, this result shows that WindSat is very capable of retrieving surface wind speed for most early category hurricanes.

Current research in this project is integrating footprint matching between the frequency channels into the main emissivity retrieval model. This will verify that the high wind signals are physical and represent the real foam fraction situation. Misalignment between channel footprints may have introduced errors into the retrievals, but this further study will eliminate them if present. But as they stand now, the results present an excellent relationship between ocean foam and near surface winds that will be key to microwave remote sensing of extreme ocean environments.

5. Conclusion

The WindSat polarimetric radiometer collects brightness temperature data since its launch on the Coriolis satellite since 2003, demonstrating its ability to provide accurate wind vector measurements for the near ocean surface. Previous studies of its data focused on general ocean conditions with little precipitation and low wind speeds below 20 m/s. This study examines the extreme case of a tropical cyclone to evaluate WindSat’s performance in high wind and precipitation. Overpasses are taken from cyclones Dennis, Katrina and Rita from the 2005 hurricane season.

Ocean surface emissivity measurements are taken from the low frequency brightness temperatures, inverting the radiative transfer equation to remove the attenuation effects of the atmosphere. The data are then collocated with outside ocean surface wind measurements generated by the NOAA H*Wind program. The match up illustrates a noticeable monotonic trend that is visible up to 50 m/s, indicating that the emissivity retains a usable dependence on wind speed up into the low category hurricane range. This also serves to indicate that the surface foam fraction does not saturate after the 20 m/s mark. Radiometers using this technique will be capable of measuring surface wind speed even in extreme conditions.
6. References


Appendix

Figure 1. WindSat brightness temperature observations (K) for cyclone Katrina, 37 GHz vertical frequency channel. This channel is most sensitive to the atmosphere and allows best illustration of storm.

Figure 2. Data sources for Rita H*Wind analysis at 2257 UTC on 21 September 2005. Data includes SFMR, AFRES, moored buoys, QuikSCAT, GOES cloud wind drifts, GPS dropsondes and ship observations.
Table 1. Coefficients for Equation (2), the emissivity model dependent on wind speed.

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<th>Frequency</th>
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Table 2. Coefficients for optical depth model, modified from Brown et al. (2006).

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Figure 3. Retrieved integrated water vapor (cm) for cyclone Katrina. White patches indicate unphysical results.
Figure 4. Retrieved integrated liquid water (cm) for cyclone Katrina. White patches indicate unphysical results.

Figure 5. Sea surface emissivity collocated with H*Wind wind speed for cyclones Dennis, Katrina and Rita. Emissivity generated from the 6.8 GHz H-pol Windsat brightness temperatures.