Wind Retrievals under Rain for Passive Satellite Microwave Radiometers and its Application to Hurricane Tracking

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***Abstract*—We have developed an algorithm that retrieves wind speed under rain using C-band and X-band channels of passive microwave satellite radiometers. The spectral difference of the brightness temperature signals due to wind or rain allows to find channel combinations that are sufficiently sensitive to wind speed but little or not sensitive to rain. We have trained a statistical algorithm that applies under hurricane conditions and is able to measure wind speeds in hurricanes to an estimated accuracy of about 2 m/s. We have also developed a global algorithm, that is less accurate but can be applied under all conditions. Its estimated accuracy is between 2 and 5 m/s, depending on wind speed and rain rate. We also extend the wind speed region in our model for the wind induced sea surface emissivity from currently 20 m/s to 40 m/s. The data indicate that the signal starts to saturate above 30 m/s. Finally, we make an assessment of the performance of wind direction retrievals from polarimetric radiometers as function of wind speed and rain rate.**

***Index Terms*—Hurricanes, Microwave Radiometers, Ocean Wind Vector, Rain.**

I. Introduction

THE measurement of ocean surface wind speeds under rain has been a long outstanding problem for passive satellite microwave radiometers. Algorithms have been developed that are able to measure ocean surface wind speeds with a very high accuracy of 1 m/s or less as long as the scenes are free of rain [1]. Unfortunately, these algorithms break down completely as soon as even only light rain is present. There are three reasons why it is difficult to measure wind speeds in rainy atmospheres:

1) Rain increases the atmospheric attenuation, especially at higher frequencies. The brightness temperature signal and therefore the signal to noise ratio decreases with the square of the atmospheric transmittance τ^2. Under rain the radiometer is less sensitive to the surface wind speed.

2) Our rain free algorithm is a physical algorithm. It is based on Monte Carlo simulating brightness temperatures from a physical radiative transfer model (RTM), from which regressions for the surface wind speed as function of the measured brightness temperatures can be derived [1]. It is very difficult to accurately model brightness temperatures under rain, because of the high variability of rain which depends on cloud type and also the distribution of rain within the footprint (beamfilling) [2]. In addition, scattering cannot be neglected, especially at higher frequencies and/or higher rain rates.

3) The signature of rain is very similar than the signature of wind speed. Therefore the non-raining algorithm tends to treat an increase the rain the same way as an increase in wind speed.

On the other hand, for many applications such as storm forecasting, it is of course highly desirable to be able to measure wind speed under rain from passive satellite microwave radiometers. This study is a first attempt to do that. In order to mitigate the problems listed above, our wind speed algorithm under rain has the following properties:

1) The algorithm uses C-band and X-band frequencies, where the atmospheric attenuation stays relatively small, even in heavy rain.

2) We use a statistical rather than a physical algorithm. That is we do not attempt to model brightness temperatures under rain within a RTM but rather use a set of measured radiometer brightness temperatures and ocean surface winds in order to train the algorithm.

3) The algorithm is trained specifically for rainy conditions. The goal hereby is to find favorable channel combinations that reduce the impact of rain without reducing the wind speed signal too much.

II. Wind Speed Retrievals in Hurricanes

A. Study Data Set

As a first attempt, we have developed a wind speed retrieval algorithm for tropical cyclones. In order to derive a statistical regression between wind speed and brightness temperatures, we have collected WindSat overpasses over wind fields supplied by NOAA's Hurricane Research Division of AOML (HRD) (http://www.aoml.noaa.gov/hrd/index.html).

The processing of the WindSat radiometer measurements is described in [1].

The HRD wind vectors analysis is based on ground obser-

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vations (buoys, ships), aircraft observations, satellite measurements (SSM/I, TMI, ERS, QuikScat, GOES) and the use of pressure – wind relationships [3]. We have used data from 18 hurricanes during 2003 and 2004. For a valid collocation we demand that the HRD wind is within 3 hours of the WindSat overpass. We also require that all WindSat channels have a valid observation. The HRD wind fields are given on a very high resolution (about 5km) and therefore need to be resampled to the resolution of the WindSat C-band 3 dB footprint (50 km). We have weighted each HRD wind observation that lies within a distance r of the center of the WindSat cell by $e^{-\ln 2 \cdot \left(\frac{r}{r_0}\right)^2}$, where $r_0 = 50\ km$ is the 3 dB footprint size. Furthermore, we have scaled the HRD wind speeds by a factor of 0.88, which converts from 1 minute sustained winds corresponding to the HRD analysis to 10 minute sustained winds corresponding to the satellite measurements [4].

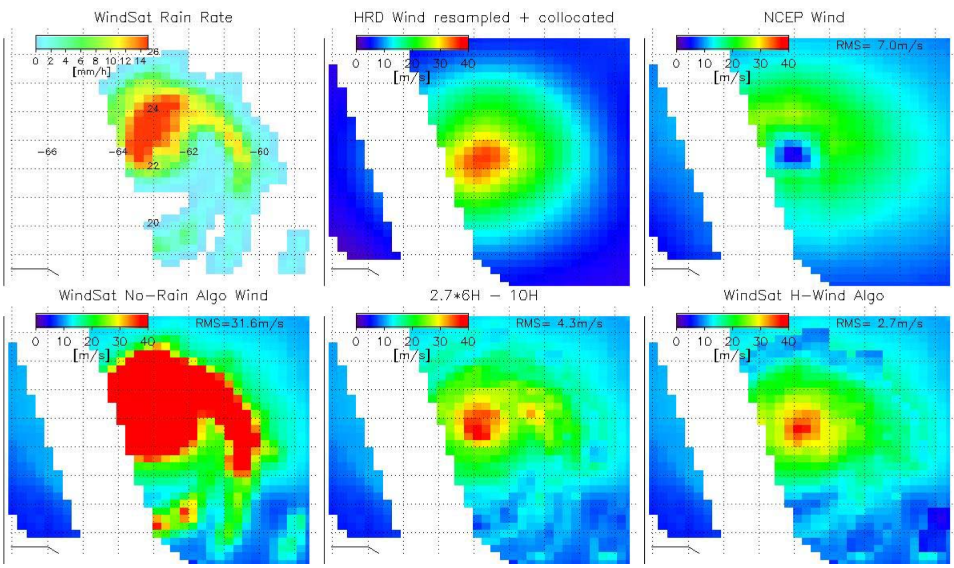

Figure 1: WindSat pass over hurricane FABIAN. The HRD analysis is from 03 September 2003 19:30Z. The time of the WindSat measurement was approximately 21:45Z. The figure shows from top left to bottom right: (a) the WindSat rain rate [mm/h], (b) the HRD wind speed after scaling and resampling to the WindSat C-band footprint, (c) the NCEP GDAS wind speed (1 deg resolution), (d) the wind speed retrieved when applying the standard no-rain algorithm [1], (e) the wind speed derived from a simple linear regression (1) using the channel combination 2.7*6H -10H and (f) the wind speed retrieved form the WindSat H-wind algorithm (section II.C). The RMS values refer to the difference to the HRD wind speed from (b) for rain flagged events.

As we want to develop an algorithm that works specifically under rain we use only rain flagged events in the training set. A simple, conservative rain flag can be derived by calculating brightness temperatures over the ocean for each WindSat channel for non raining atmospheres using our RTM [1] and flagging any WindSat measurement as rain if its brightness temperatures lies outside the boundaries of these RTM brightness temperatures. For non-raining events we use our established no rain wind speed algorithm [1].

The data set comprises about 3,200 collocations. Half of it is used for algorithm training; the other half is set aside for testing and validation.

B. Development of a Statistical Regression Algorithm

As a starting point we try a simple linear regression between surface wind speed W and brightness temperatures T_{Bi} (i being the channel index) of the form:

$$W = c_0 + \sum_i c_i \cdot T_{Bi}. \qquad (1)$$

The challenge is to be able to find a channel combination that reduces the effect of rain without reducing the sensitivity to wind speed. In order to this it is essential to have at least two different frequencies available whose spectral difference is suited to accomplish this goal. From training and testing the regression (1), we find that the C-band/X-band channel combination $c_{6H} = -2.7 \cdot c_{10H}$ is a good candidate, if one was to use an algorithm with only two channels.

C. WindSat H-Wind Algorithm

The final form of the wind speed retrieval in tropical cyclones (H-wind algorithm) is a refinement of the form (1) . It includes dependence on sea surface temperature T_s and terms that are quadratic in T_{Bi} :

$$W = \alpha_0 + \alpha_1 \cdot T_S + \sum_i \beta_i \cdot T_{Bi} + \sum_i \gamma_i \cdot T_{Bi}^{\,2}. \qquad (2)$$

Here, the index i runs over all WindSat channels. For a further refinement, one can also consider to make the regression coefficients $\alpha_i, \beta_i, \gamma_i$ in (2) dependent on the rain rate or, equivalently, on the atmospheric transmittance τ . The idea behind this, is that the algorithm will likely favor different channel combinations that are sensitive to wind speed while reducing the impact of rain depending if it the rain is light or heavy. In order to do it is necessary to de-

velop an auxiliary algorithm that is able to retrieve τ (c.f. chapter III).
We have also developed an H-wind algorithm that does not include C-band channels but all other WindSat channels. We expect of course that this algorithm performs worse than the algorithm with C-band, especially under heavy rain, as the surface signal is stronger attenuated at the higher frequencies. Its advantage is that the resolution is better (35 km at X-band versus 50 km at C-band) and it could be developed for satellite radiometers that do not use C-band frequencies, such as for example the TMI instrument.

D. Results

Figure 1 displays wind speeds that were observed during hurricane FABIAN on 03 September 2003. For comparison, we also show the rain rate in panel (a). It is immediately evident that the standard algorithm for non raining atmospheres [1] (panel (d)) measures rain rather than wind speed. That means it is not able to disentangle the rain signal from the wind speed signal. The performance improves significantly when using the channel combination 2.7*6H-10H (panel (e)) . The WindSat H-wind algorithm (panel (f)) retrieves a wind speed that compares very well with the HRD wind (panel(b)). The slight dislocation between (b) and (e) is due to the fact that there is about a 2 hour time difference between the WindSat overpass and the time of the HRD analysis. It is also obvious the NCEP GDAS 1-deg resolution wind field (panel (c)) resolves the storm center rather poorly.

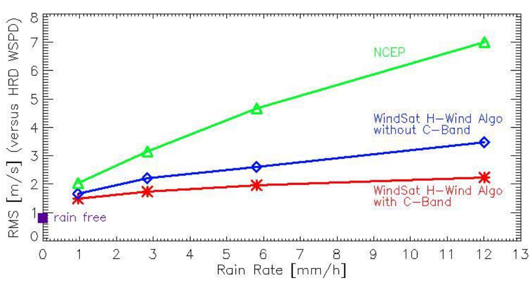

Figure 2: RMS difference between the HRD wind speed and the retrieved wind speed from the WindSat H-wind algorithm as well as NCEP GDAS. We require that the HRD wind speed is larger than 15 m/s.

Figure 2 shows the RMS difference between the HRD wind speed and the wind speed retrieved from the WindSat H-wind algorithms with and without C-band as well as the NCEP GDAS field for the test set from section II.A. As a reminder, the standard no-rain algorithm when applied for rain free cases has an RMS accuracy of about 0.8 m/s [1] (purple square).

When comparing the HRD wind speeds with WindSat it is important to keep in mind that there is a time difference of maximal 3 hours between the two measurements, which results in considerable sampling mismatch. From comparing different HRD analysis wind fields at different times we have estimated that this sampling mismatch amounts to approximately 2.5 m/s. When computing the statistics of Figure 2 we have RMS subtracted this value.

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III. Global Wind Speed Retrieval Under Rain

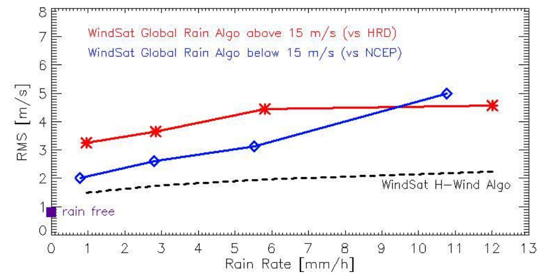

Figure 3: RMS difference between the global WindSat wind speed retrieval under rain and the NCEP GDAS analysis (for low wind speeds) or the HRD wind speeds from test set II.A (for high wind speeds).

The next step is the development of a wind speed algorithm that works globally under rain. The simplest way to do this is to train an algorithm of the form (2) using for example wind speeds from NCEP GDAS. This works well at low wind speeds (below 15 m/s), but breaks down at higher winds. The reason is that due to the sparse occurrence of high NCEP winds the algorithm will be undertrained at high winds. Moreover, we know from Figure 2(c) that large NCEP GDAS winds can be inaccurate.

The global wind speed retrieval algorithm under rain is a semi-statistical algorithm. We drive values for the atmospheric transmittance τ as well as the upwelling and downwelling brightness temperatures T_{BU} and T_{BD} from WindSat brightness temperatures that were collocated with SSM/I F13 measurements for columnar water vapor and liquid cloud water over a full year of rain flagged events. We solve the radiative transfer equations for v-pol and h-pol at each frequency. As auxiliary input we need NCEP profiles for moisture and liquid cloud water, SSM/I columnar water vapor and columnar liquid cloud water, climatology values for SST and NCEP surface wind speeds. This basic atmospheric training set for τ, T_{BU} and T_{BD} comprises a wide range of possible atmospheric conditions in rain. We then overlay surface emissivities that are calculated from our current RTM [1] using a uniform random wind speed distribution between 0 and 50 m/s. By decoupling the atmosphere, which is treated statistically based on WindSat measurements, from the surface emissivity, which is computed physically from the RTM, we are able to create a sufficiently large number of high wind speed events within the training set. This training set can also be used to derive auxiliary regression algorithms for the atmospheric parameters τ, T_{BU} and T_{BD}.

The global algorithm was tested using a full year of rain-flagged WindSat brightness temperatures that is different from the one used to derive the basic atmospheric training set and taking NCEP GDAS wind speeds below 15 m/s as truth. The RMS is about 2 m/s for light rain and increases to about 5 m/s for heavy rain. In order to test its performance at wind speeds above 15 m/s and compare with the H-wind algorithm we have also run it on the WindSat – HRD collocation set from section II.A. The results are shown in

Figure 3. As expected, the performance of the global algorithm is not quite as good as the one of the H-wind algorithm, which was specifically developed for tropical cyclones but can only be applied for those cases. For an operational algorithm it is conceivable to use the global algorithm for the general case and switch to the H-wind algorithm if a tropical cyclone is encountered.

IV. Sea Surface Emissivity at High Wind Speeds

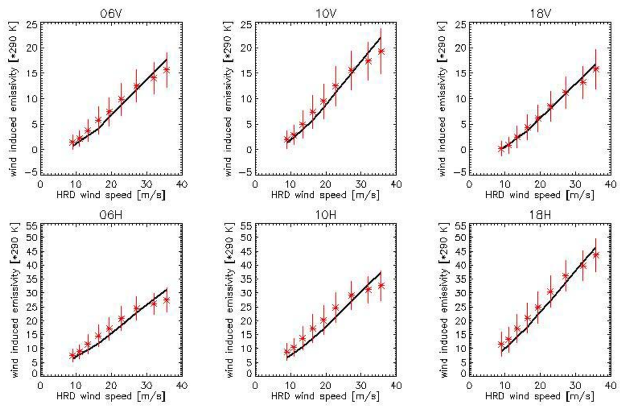

Figure 4: Wind induced sea surface emissivity: The red data points are the results from the WindSat – HRD analysis. The black lines are the results from our current RTM [1] extrapolated above 18 m/s.

The WindSat-HRD collocations from section II.A can be used to derive the wind induced emissivity at higher wind speeds. The results for C, X and Ku bands are shown in Figure 4. For comparison, we also show the results of our current emissivity model that was derived for wind speeds below 18 m/s [1]. We see that for wind speeds up to 30 m/s the results of the WindSat-HRD analysis for the wind induced emissivity are very consistent with simply linearly extrapolating our current model to wind speeds above 18 m/s. Our new analysis indicates that the wind induced emissivity might start to saturate above 30 m/s. We know that at higher wind speed the wind induced emissivity is mainly due to sea foam. The saturation of the signal might reflect the fact that at higher wind speeds the entire ocean surface is getting covered with sea foam. It would of course also mean that any algorithm for retrieving surface wind speed would start to degrade above 30 m/s. A more detailed study of this issue is under way.

V. Wind Direction Retrievals Under Rain – Hurricane Tracking

The retrieval of wind directions follows the same basic steps than the non-raining wind direction retrieval algorithm [1]. It is necessary to use the scalar wind speed of the H-wind algorithm from section II.C or the global algorithm for rain from chapter III as input and minimize over wind direction in the maximum likelihood estimate. Further necessary inputs are the values for the atmospheric parameters τ, T_{BU} and T_{BD} that are derived specifically for rainy atmospheres (c.f. chapter III).

If there is no rain, usable wind directions can be retrieved if the wind speed is above 7 m/s. For lower wind speeds the surface wind direction signal is too small to allow accurate wind direction retrievals. Due to the increased attenuation under rain, the minimum wind speed at which wind direction retrievals become feasible gets pushed to larger values, where the directional signal is stronger. From a preliminary analysis that compares WindSat with HRD wind vectors we find that wind direction retrievals under rain that use only WindSat measurements are possible as long as the wind speed is above 12 m/s and the rain rate stays below 8 mm/h. A more detailed study that also assesses radiometer versus scatterometer wind vectors is under way.

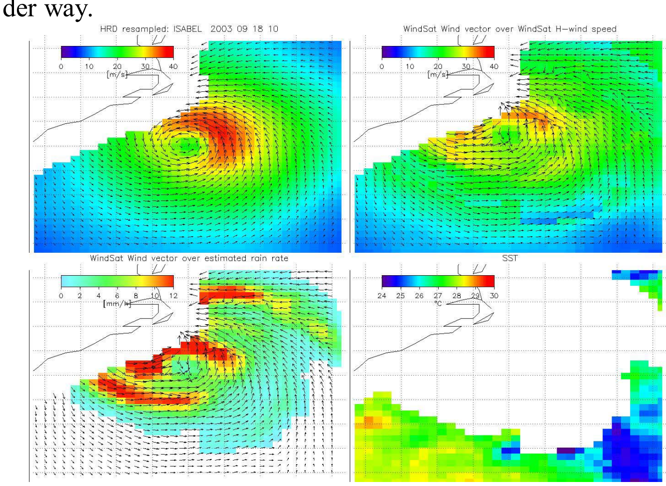

Figure 5: WindSat pass over hurricane ISABEL from 19 September 2003. Shown are the HRD wind vectors (upper left), the WindSat wind vectors over WindSat wind speed (upper right) and rain rate (lower left) and the sea surface temperature (SST) (lower right).

Figure 5 shows WindSat and HRD wind vectors during a pass over hurricane ISABEL. The WindSat vectors resolve the cyclonic flow very well beside in very heavy rain. An interesting feature is evident in the SST, which is retrieved only for non raining events. The picture shows the cold wake of the hurricane causing upwelling of cold water to the surface in high winds. This snapshot shows both the current location of the hurricane as well as part of its past track.

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