# A NEW METHOD OF RETRIEVAL OF WIND VELOCITY OVER THE SEA SURFACE IN TROPICAL CYCLONES OVER THE DATA OF MICROWAVE MEASUREMENTS

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ABSTRACT

A method is described to determine the most important structural parameters of tropical cyclones (effective dimensions of storm and hurricane wind zones, maximum wind velocity and effective dimensions of the maximum wind zone, sizes of a tropical cyclone "eye" and the thickness of the "eye" cloud wall) over the data of microwave sounding of the system "ocean-atmosphere" that allowed to retrieve a smoothed spatial distribution of the sea surface wind velocity in the whole range of the cyclone action – from the center to periphery. The method is based on the connection of tropical cyclone radiobrightness characteristics in different channels of the radiometer with its most important structural parameters. Based on the comparison results of tropical cyclone soundings in the Atlantic in 1998 and 1999 obtained with the use of the microwave radiometer SSM/I with the data of independent observations the accuracy of estimating the effective dimensions of storm and hurricane wind zones and tropical cyclone intensity was determined. Some examples are given of retrieval of the sea surface wind velocity spatial structure in tropical cyclone active zone for several days of their lifetime.

## 1. Introduction

The acquisition of reliable satellite information on water surface wind field in the zones of storms and hurricanes is an urgent and practically important problem that is still unsolved. Modern radiation-geophysical models allow one to retrieve with good accuracy the sea surface wind velocity V only outside the storm wind zone, where V < 17.5 m/s (Wentz. 1997, Nerushev et al. 2000, Nerushev et al. 2001). The wind velocity in the tropical cyclone (TC) zone at the hurricane stage is more than 33 m/s. The presence in the TC central zone of intensive precipitation and a shield of cirrus clouds containing a crystalline fraction and screening significantly the ocean surface excludes the application of the existing models to correctly estimate the sea surface wind velocity field within the range of a radius R < 150 km around the TC center.

An escape of this situation, as we believe, can be in the development of a semi-empirical model based on the existence of relationships between the peculiarities of tropical cyclone radiobrightness images in different channels of a microwave radiometer and the parameters of the TC central zone. Knowing the parameters of a TC central zone (maximum wind velocity, location and dimensions of the maximum wind zone, configuration and effective sizes of the hurricane wind zone) and the storm wind zone configuration and effective dimensions one can completely retrieve the smoothed spatial structure of the sea surface wind velocity within the zone of TC action.

The present paper gives a semi-empirical method allowing one to retrieve smoothed characteristics of the sea surface wind velocity in the whole range of tropical cyclone action – from the center to periphery from the measurement data obtained in different channels of the SSM/I radiometer. The method is based on the connection reveled by us of TC radiobrightness image typical features in the radiometer microwave channel with most significant structural parameters of a TC (Nerushev et al. 2001). The method was tested on the TC sounding data of the Atlantic in 1998 and 1999.

## 2. Experimental Data

The sounding data of 10 tropical cyclones in the Atlantic in 1998 and 8 tropical cyclones in 1999 obtained by the radiometer SSM/I and the data of an independent determination of tropical cyclone parameters from the storm-warnings were the experimental basis of the study. The microwave radiometers SSM/I are functioning on board several US satellites of the DMSP series (Defense Meteorological Satellite Program). The satellites are on the solar-synchronous quasi-polar orbit at an angle of 98.8° and the altitude of 805 ± 72 km. The sounding data obtained from the satellites of the DMSP series – F13 and F14 were used in the work. The radiometer SSM/I measures the Earth's radiation in seven channels: 19.35 (v, h); 22.235 (v); 37.0 (v, h) and 85.5 (v, h) GHz (v, h are the vertical and horizontal polarizations of the radiation received, correspondingly) by conical scanning at the constant angle of view of 45° to nadir with the viewing band of the Earth's surface of 1400 km. The spatial resolution on the ground surface for different angles varies within the limits of 13 - 69 km.

The SSM/I data were obtained by us via the Internet from GHCC (Global Hydrology and Climate Center), Huntsville, Alabama, USA. The data are archived in the HDF format (Hierarchial Data Format) for separate semiturns. The fragments of measurements corresponding to satellite passages over TC were separated from these data with the help of a special program based on the information on TC trajectories and parameters obtained from The Russian Hydrometcenter. Several hundreds of TC images were obtained in the channels of high and low resolution. For further analysis several tens of them meeting several requirements were selected. In particular, the requirements were the remoteness of the TC center from the continents and islands, TC location in the center of the picture if possible, etc. Due to some obstacles the number of images applicable for determining different parameters of a TC and the wind field over the ocean surface was different. Therefore the information on the number of sounding images over which a certain parameter of TC was determined will be given in corresponding sections.

## 3. Determination of Most Important Structural Parameters of TC

Several parameters important for practical application are separated in the spatial distribution of wind at the ocean surface in the zone of TC action. These parameters are: maximum wind velocity ($V_m$) and the distance from the TC center at which it is attained ($R_m$ ), the distances from the TC center at which the wind velocity exceeds some certain values, in particular, 34 kn (storm wind) and 64 kn (hurricane wind).The corresponding parameters are called the dimensions of the storm (R34) and hurricane (R64) winds. The parameters are the input ones for some models of TC movement with the help of which zones of potential damages are estimated. The values of R34 and R64 in storm-warnings are, as a rule, based on the data of independent measurements (aerial reconnaissance, data of drifting meteorological buoys, of automatic meteorological stations, images obtained by geostationary satellites in the visible and IR wavelength ranges, etc.).

The analysis of sounding data made it possible to state that the radio images of tropical depression, storm and hurricane at the frequency of 85.5 (h) GHz differ practically for all the frames analyzed. The image structure observed at the hurricane stage ($V_m$ > 33 m/s) has typical features: a bright region of increased radiobrightness temperatures in the TC center is surrounded by a dark ring of decreased radiobrightness temperatures followed by a quasi-closed bright zone of increased radiobrightness temperatures. Fig. 1 gives, as an illustration of the above-said, the images of TC Jeanne at the stage of the storm (21.09.98) and hurricane (26.09.98) and TC Georges at the hurricane stage (18.09.98). The locations of the regions mentioned are indicated by arrows.

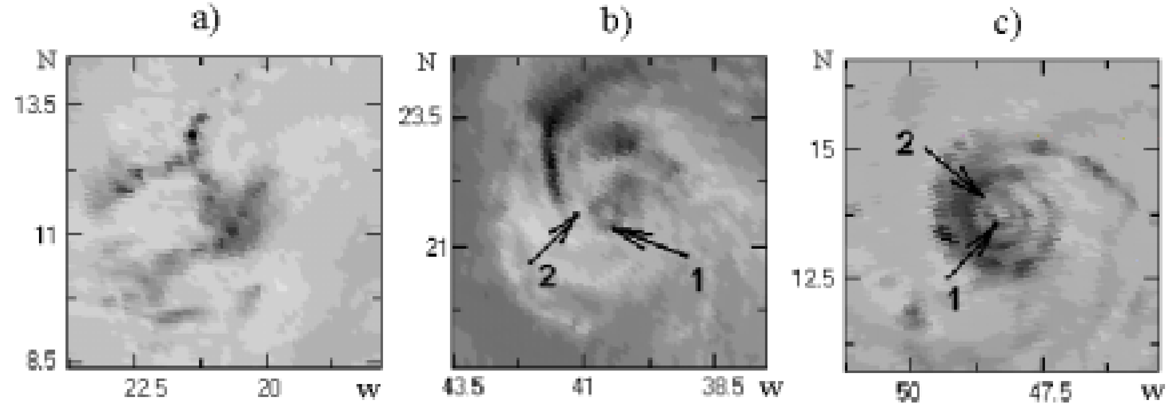


Fig. 1. TC Jeanne radiobrightness images at the stage of storm (a) and hurricane (b) and of TC Georges at the hurricane stage at the frequency of 85.5 (h) GHz. Arrow 1 indicates the location of the dark zone of decreased radiobrightness temperatures, arrow 2 shows the quasi-closed bright zone of increased radiobrightness temperatures coinciding with the hurricane wind zone.

A comparison with the data of TC soundings within the visible and IR wave ranges allows one to consider the bright central region the hurricane "eye". The dark ring is the image of the hurricane "eye" cloud wall. Table 1 gives the average characteristics of the hurricane "eye" and cloud wall calculated on the basis of sounding data for the TC in the Atlantic mentioned above. The "eye" radii given in Table 1 are in good agreement with the values found from the data of more than 500 radar and aircraft measurements (<r> = 26±16 km).

Table 1. The values of the hurricane "eye" mean radius (<r>) calculated over the SSM/I radiometer data, its standard deviation ($\sigma_{<r>}$), mean radiobrightness temperature of the "eye" at the frequency of 85.5 (h) GHz ($<T_e>$) and its standard deviation ($\sigma_T$); the cloud wall average width ($<\Delta r>$), its mean radiobrightness temperature at the frequency of 85.5 (h) GHz ($<T_{\Delta r}>$) and their standard deviations ($\sigma_{<\Delta r>}$ and $\sigma_T$) for hurricanes in the Atlantic in 1998 and 1999.

| Year | "Eye" characteristics " | | | | Cloud wall characteristics | | | |
|---|---|---|---|---|---|---|---|---|
| | <r>, km | $\sigma_{<r>}$ | $<T_e>$, K | $\sigma_T$ | $<\Delta r>$, km | $\sigma_{<\Delta r>}$ | $<T_{\Delta r}>$, K | $\sigma_T$ |
| 1998 | 23 | 7 | 259 | 14 | 29 | 7 | 234 | 15 |
| 1999 | 33 | 6 | 254 | 10 | 33 | 9 | 235 | 7 |

A most probable cause of the radiobrightness temperature decrease at the frequency of 85.5 (h) GHz around the TC center is in the existence of vigorous ice clouds in the hurricane "eye" wall that accompany, as a rule, the lower cumulus rain-producing clouds. "Warmer" radiobrightness temperatures of the first quasi-closed zone are most likely induced by the location of this zone beyond the boundaries of the central system of cumulus rain-producing and cirrus clouds, where scattering on ice crystals is low and the radiobrightness temperature at the frequency of 85.5 (h) GHz is governed by radiation of water vapor and liquid droplet clouds. The hurricane "eye" increased radiobrightness temperature is in a similar way determined mainly by radiation of water vapor and liquid droplet clouds in the lower troposphere almost always present in the "eye".

It has been stated that the hurricane wind zone dimensions observed ($R_o64$) coincide with the location of the above-mentioned first quasi-closed zone of increased radiobrightness temperatures in the 85.5 (h) GHz, and the radiobrightness temperature itself in this zone varies in rather a narrow range. For hurricanes of 1998 an average temperature in the 85.5 (h) GHz channel (<T85h>) appeared to be equal to 278K at a standard deviation $\sigma$ = 9K. Relative constancy of <T85h> allows one to introduce a quantitative criterion for defining the hurricane wind zone effective dimensions, namely, the range of radiobrightness temperature variation T85(h) according to which the location of the first quasi-closed zone around the TC center is found.

To calculate the hurricane wind zone effective dimensions ($R_c64$) on the basis of the above-mentioned method 38 frames appeared appropriate (21 for TC of 1998 and 17 for TC of 1999) at the hurricane stage. Additional to the criteria formulated in the second section to choose the frames was the requirement for the discontinuities in the quasi-closed zone to be less than the half of its surface area. After the high-frequency noise was removed radial cuts were constructed from the TC center with the step of $45^0$ (8 cuts) with the length of 300 km. The values of radiobrightness temperatures were taken along the line of a cut, based on which corresponding values of $R_{ic}64$ were determined. The value of $R_c64$ was calculated as the arithmetic mean of the values of $R_{ic}64$ found. The linear regression equation describing the link of the values of observed ($R_o64$) and calculated ($R_c64$) for the hurricane wind zone effective dimensions has the form of

$$R_o64 = 12.107 + 1.012 * R_c64 \quad (1)$$

The correlation coefficient $r(R_o64, R_c64) = 0.57$ is significant at the level $p<0.05$. The linear connection of $R_o64$ with $R_c64$ explains 32% of scattering of the points.

The analysis of precision in defining the parameter R34 was based on the methods used by us earlier (Nerushev et al. 2000, Nerushev et al. 2001). To determine the sea surface wind velocity over the SSM/I data we used the model developed specially for the SSM/I and tested at rather a considerable sample of experimental data (Wentz, 1997). For the calculations of the storm wind zone effective dimensions ($R_c34$) appropriate appeared 55 frames (39 for TC of 1998 and 16 for TC of 1999) at the storm and hurricane stages. Additional to the criteria formulated in the second section for the choice of the frames was the requirement for the isoline V = 34 kn to be closed. The linear regression equation describing the connection of the observed ($R_o34$) and calculated ($R_c34$) values of the storm wind zone effective dimensions has the form of

$$R_o34 = 11.084 + 0.892 * R_c34 \quad (2)$$

The correlation coefficient $r(R_o34, R_c34) = 0.76$ is significant at the level $p<0.05$. The linear connection of $R_o34$ with $R_c34$ explains 58% of the scattering of the points.

Table 2 shows accuracy characteristics of a comparison of the observed and calculated values of R34 and R64. The precision of determining R34 is likely to be considered satisfactory as the mean square of the difference ($R_c34 – R_o34$) equal to 47 km practically coincides with the SSM/I radiometer spatial resolution in the channels used to determine V. The calculated values of R64 are somewhat higher than the observed ones.

Table 2. A comparison of the calculated over the SSM/I radiometer data ($R_c34$ and $R_c64$) and observed ($R_o34$ and $R_o64$) values of the parameters R34 and R64

| | $R_c34$, km | $R_o34$, km | $R_c$ - $R_o$, km | ($R_c$ - $R_o$)/ $R_o34$ | $R_c64$, km | $R_o64$, km | $R_c$ - $R_o$, km | ($R_c$ - $R_o$)/ $R_o64$ |
|---|---|---|---|---|---|---|---|---|
| Arithmetic Mean | 209 | 203 | 6 | 0.03 | 97 | 86 | 11 | 0.13 |
| Mean Square | | | 47 | 0.23 | | | 38 | 0.44 |

The most important characteristic of a TC is its intensity determined by the maximum wind speed ($V_m$) or minimum pressure in the center ($P_0$) connected functionally. In earlier studies based on the data of the microwave radiometers SCAMS (SCAnning Microwave Spectrometer) of the satellites Nimbus-6 and MSU (Microwave Sounding Unit) of the NOAA satellites the measurements were made in the channels receiving radiation with the wavelength of about 5 mm, sensitive to the temperature of the upper troposphere (Kidder. 1978; Velden et al. 1991). An indirect determination of TC intensity on the basis of a relation of the measured characteristics of the TC temperature anomaly (the so-called warm core) with $V_m$ and $P_0$ is general for all the works mentioned.

The connection revealed by us for typical characteristics of TC radiobrightness images at the frequency of 85.5 (h) GHz with the TC structural parameters makes it possible to approach the problem of the determination of $V_m$ and $P_0$ in view of the data of microwave sounding. The analysis demonstrates that an average radiobrightness temperature of the zones at the hurricane stage described above has a significant correlation link of $V_m$ and $P_0$. Here the highest correlation with $V_m$ and $P_0$ is typical of the radiobrightness temperature of the dark ring (the hurricane "eye" cloud wall, $T_{ew}$) at the frequency of 19.35 (h) GHz. The total number of the images that appeared appropriate for determining the link mentioned was equal to 53 (32 for 1998 and 21 for 1999). The requirement of closure of the decreased temperatures dark ring at the frequency of 85.5 (h) GHz was an additional criterion to those formulated in the second section.

The dependence of $V_m$ and $P_0$ on $T_{ew}$ in the form of the 3$^{rd}$ power polynomial ensures an optimum approximation of the experimental results. Corresponding correlation coefficients are equal to: $r(V_m, T_{ew}) = 0.72$, $r(P_0, T_{ew}) = -0.67$. The dependence explains 52% of the variations of the values of $V_m$ and 44% of the variations of $P_0$. The use of the polynomials of higher powers than the 3$^{rd}$ one weakly affects the variations of the correlation and determination coefficients.

## 4. Retrieval of the Sea Surface Wind Field Average Structure

The results presented above make it possible to determine an average spatial distribution of the sea surface wind velocity V in the whole range of a tropical cyclone action – from the center to its periphery. The algorithm to obtain the spatial distribution V is as follows. The values of $V_m$, $R_m$, R64 and R34 are determined in a TC region for distances $0 \le R \le R34$ from the SSM/I data on the basis of the above methods. Note that R64 and R34 can be found as functions of the azimuthal angle φ. Then, based on the four values – $V_0(0)$, $V_m(R_m)$, $V_{64}(R64)$ and $V_{34}(R34)$ – a smoothed distribution V(R, φ) is constructed. Here $V_0$ is the wind velocity in the TC center (R = 0), $V_{64}$ = 64 kn ≈ 33 m/s, $V_{34}$ = 34 kn = 17.5 m/s. The sea surface wind velocity in the TC center has a constant value close to zero. Here it is considered for certainty that $V_0 = 0$. For the TC periphery at distances R > R34, where the wind velocity is less than the storm speed (V < 17.5 m/s), the spatial distribution V is obtained with the use of the Wentz method (Wentz. 1997).

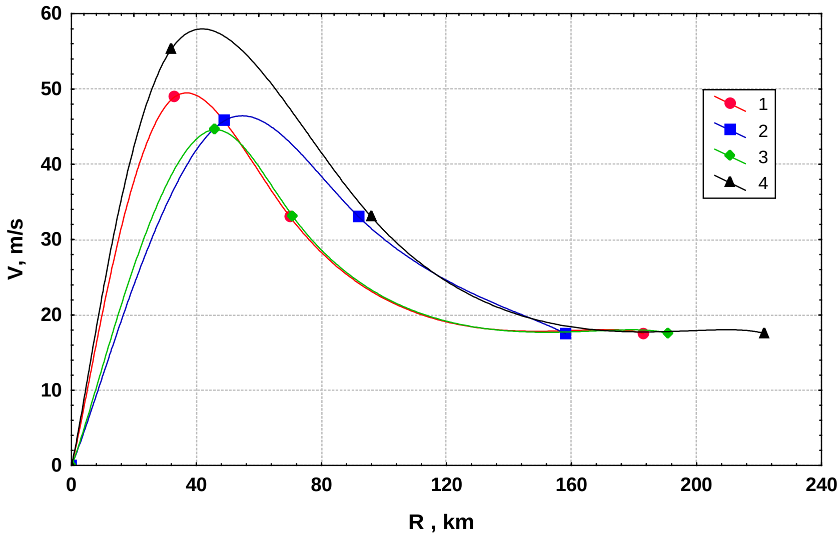


Fig. 2. Smoothed radial profiles of the sea surface wind velocity averaged over the azimuth and calculated with the above algorithm for several days of the life of hurricane Dannielle (1998): 1 – 25.08.98 (time of sounding is 20:40 UTC), 2 – 30.08.98 (1:17 UTC), 3 - 30.08.98 (13:46 UTC), 4 – 31.08.98 (1:05 UTC).

Fig. 2 gives as an example averaged over φ smoothed profiles of V(R) in the central part of hurricane Dannielle (1998) for several days of its life calculated with the above-mentioned algorithm. The curves are constructed over the experimental point with the use of the spline method. The trend of the curves V(R) in Fig. 2 for $R > R_m$ is approximated with a high accuracy by the dependence of the type of $V(R) \sim R^{-\kappa}$. In this case κ varies from 0.72 (curve 2) to 0.54 (curve 4). As far as R64 and R34 can be obtained as functions of the azimuthal angle φ, one can construct a spatial distribution of V(R, φ) as a function of the distance R and the azimuthal angle φ.

## 5. Conclusion

A new method is described to determine the most important characteristics of tropical cyclones over the data of remote sounding of the system "ocean-atmosphere" in the microwave spectrum range based on the connection of tropical cyclone radiobrightness image typical characteristics in different channels of the SSM/I radiometer with the TC structural parameters. The method allows for retrieving a smoothed spatial distribution of the sea surface wind velocity in the whole range of the cyclone action – from its center to periphery.

Some examples are given of retrieving the sea surface wind velocity structure in the tropical cyclone active zone for several days of its life based on the data of remote sensing the system "ocean-atmosphere" obtained by the SSM/I radiometer. The method proposed is promising both in search of optimum sounding frequencies and in finding distinct physical dependencies of radiation received from the parameters sought along with the improvement of instrumental resolution, that would make it possible to install the devices on a geostationary platform for practically continuous monitoring of the objects studied.

We believe that promising for future development of the work are the following directions: 1) testing of the method with significantly larger amounts of experimental data; 2) a search of optimum frequencies in the microwave spectrum range that would most properly reflect the inner structure of a TC, first of all, its link with the sea surface wind field; 3) the development of a theoretical model of a TC radiobrightness image.

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