Tracking a tropical cyclone with ERS-SCAT: a CMOD model review

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ABSTRACT

The spaceborne scatterometer is a microwave radar that provides high precision radiometric measures of the normalized radar cross section (σ^0) of the ocean surface. The backscatter is related to the superficial roughness that is in turn related to the local wind. Since microwave wavelengths are used the scatterometer, at first order, can be meant as an instrument which provides measurements independent of clouds and sun illumination therefore it is able to observe the internal structure of a Tropical Cyclone (TC).

The relationship between the σ^0 and the surface wind field is described by a geophysical model function (GMF). The model used in the ERS scatterometer processing is the well-known semi-empirical model CMOD4. Unfortunately this model is not tailored for high wind speeds, such as the case of TCs. This fact causes a poor quality in the wind field estimated through the scatterometer data acquired over a TC.

In this paper we describe a study in view of a possible extension of the CMOD4 for high wind speeds. The study has been based on the ERS-2 σ^0 measurements relevant to six selected TCs and the corresponding wind speeds obtained by employing the Holland model. We have selected six TCs and for each one we have developed a 3D wind speed pattern making use of the wind speed available through the NHC (National Hurricane Center) warnings. The wind speed so obtained is then correlated with the σ^0 acquired over these six TCs.

The results obtained in this work support the need to extend the CMOD4 model.

Keywords: remote sensing, scatterometer, geophysical model function, CMOD4, wind, tropical cyclone.

1. INTRODUCTION

The wind scatterometer is a radar remote sensing instrument which is capable to measure with great accuracy the normalized backscattering σ^0 of the ocean surface. Physically the sea roughness, which is the major factor affecting σ^0, is related to the sea surface wind. Therefore from a proper set of σ^0 measurements, it is possible to retrieve the wind field by making use of a geophysical model function (GMF) which relates σ^0 to the near surface wind. The GMF is a function of wind speed V (at a given anemometric height), azimuth angle ϕ and incidence angle θ.

In particular, the WSC scatterometer deployed on board of the ERS-2 is composed by three antennas that make three σ^0 measurements. The relevant GMF to be applied in this case is the CMOD4 GMF, which has the following form[1]:

$$\sigma^0_{lin} = b_0\left(1 + b_1 \cos\phi + b_3 \tanh b_2 \cos 2\phi\right)^{1.6} \tag{1}$$

where

$$b_0 = b_R 10^{\alpha+\gamma \cdot f_1(V+\beta)} \tag{2}$$

and

$$f_1(s) = \begin{cases} -10, & s \le 10^{-10} \\ \log s, & 10^{-10} < s \le -5 \\ \sqrt{s}/32, & s > 5 \end{cases} \tag{3}$$

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α, β, γ. b_1, b_2, b_3 are expanded in terms of Legendre polynomials. b_R is the residual correction factor to b_0 and is function of incidence angle and is reported in specific tables.
The parameters are specified as follow[1]:

$$\alpha = c_1 P_0 + c_2 P_1 + c_3 P_2 \tag{4}$$

$$\gamma = c_4 P_0 + c_5 P_1 + c_6 P_2 \tag{5}$$

$$\beta = c_7 P_0 + c_8 P_1 + c_9 P_2 \tag{6}$$

$$b_1 = c_{10} P_0 + c_{11} V + (c_{12} P_0 + c_{13} V) f_2(x) \tag{7}$$

$$b_2 = c_{14} P_0 + c_{15} (1 + P_1) V \tag{8}$$

$$b_3 = 0.42 \left(1 + c_{16} (c_{17} + x)(c_{18} + V)\right) \tag{9}$$

$$b_R = LUT(\theta) \tag{10}$$

$$f_2(x) = tanh\{+2.5(x + 0.35)\} - 0.61(x + 0.35) \tag{11}$$

where the Legendre polynomials are $P_0 = 1$, $P_1 = x$ and $P_2 = (3x^2 - 1)/2$ and $x = (\theta - 40)/25$.

Parameter	Coefficient	Value	Parameter	Coefficient	Value
α	c_1	-2.301523	b_1	c_{10}	0.014430
	c_2	-1.632686		c_{11}	0.002484
	c_3	0.761210		c_{12}	0.074450
γ	c_4	1.156619		c_{13}	0.004023
	c_5	0.595955	b_2	c_{14}	0.148810
	c_6	-0.293819		c_{15}	0.089286
β	c_7	-1.015244	b_3	c_{16}	-0.006667
	c_8	0.342175		c_{17}	3.000000
	c_9	-0.500786		c_{18}	-10.000000

Table 1: The CMOD4 coefficients[1] .

It is well-known that the CMOD4 model is not suitable when high wind speeds are in question and this is a fundamental fact to be considered when TCs want to be detected. It has been shown that in the case of extreme events the scatterometer wind speed are underestimated[2,3,4]. In particular it has been proved[2] that both a C-band and Ku-band for wind speeds greater than 20 m/s the scatterometer wind speeds are inaccurate. In general it has been postulated[3] that the principle error source that limits the scatterometric performances for high wind speeds are:

1) the deficiency of the GMF;
2) the volume scattering caused by the rain drops and the surface roughness generated by the rain;
3) the high wind gradient within a big resolution cell near the eyewall where the maximum wind speeds are expected.

In the following, in accordance to what accomplished in the most recent studies[3,5] (unavailable to the authors at the time this work has been conducted) we concentrate on the GMF modelling as major fact to be analyzed to improve the quality of TC wind speed estimation.

2. THE STUDY: THEORETICAL FACTS

In this Section we describe the study we have performed in order to examine the relationship between the measured σ^0 and the independently measured V (wind speed). Although this may sound very easy in principle this is actually not at all a trivial task. In fact, within a TC the wind speed can reach 50-60 m/s and for this velocity is not possible to perform

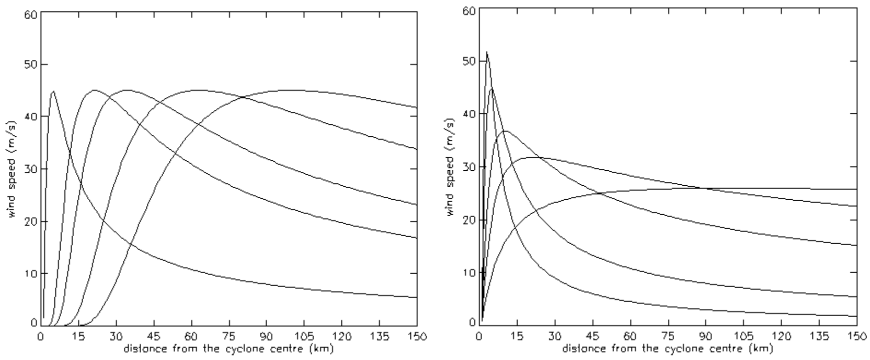
in situ measurements. In order to overcome such a major drawback we use the Holland hurricane model[6] to estimate the independent wind speed 3D pattern. The model parameters are estimated by making use of meteorological warning issued by forecast centres.
According to the Holland model, a wind speed profile, i.e. a cut of the 3D wind speed pattern, is described as follows[6]:

$$V(r)=\left[AB(p_n-p_c)\frac{exp(-A/r^B)}{\rho r^B}\right]^{1/2} \quad , \tag{12}$$

where r is the distance from the cyclone centre, ρ is the air density (assumed constant and equal to 1.15 kg/m^3), p_n is the ambient pressure (theoretically at infinite radius, in practice, the value of first anticyclonically curved isobar) and p_c the central pressure (mb). As r goes to infinity the wind speed goes to 0 as expected. A and B are positive scaling parameters that are related to the radius of maximum wind speed by the relation[6]:

$$R_{max} = A^{1/B} \quad . \tag{13}$$

As B increases, the eye expands, the pressure drop is larger and the wind field adjust to give stronger winds near the centre and weaker winds at larger radii (Fig.1).



(a) (b)

Fig. 1: The Holland hurricane model at variance of the parameters A (a) and B (b).

As show in Fig.1 we physically have that A determines the location of $V_{\max}$ relative to the origin (Fig. 1a) and B defines the shape of the profile (Fig. 1b).
We note also that $V_{\max}$ is given by[6]:

$$V_{max} = C(p_n - p_c)^{1/2} \quad , \tag{14}$$

in which

$$C = \left(\frac{B}{\rho e}\right)^{1/2} \quad . \tag{15}$$

Pressure observations are generally more stable than wind ones but they are not always available in a TC meteorological warning. Conversely, wind values are always available for a TC. As a matter of fact in this work as first approach we have chosen to fit the model by means of wind speed measurements only.
Accordingly we had better rewrite the Holland model noting that

$$(p_n - p_c) = \frac{V_M^2}{D^2} \quad , \tag{16}$$

and

$$D^2 = \frac{B}{\rho e} \quad , \tag{17}$$

hence

$$V(r) = \left[\frac{AeV_M^2}{r^B} exp(-A/r^B) \right]^{1/2} \quad . \tag{18}$$

This model can be applied to each TC, at variance of the parameters, to estimate the hurricane 3D wind speed pattern. In fact, in the case of symmetric TC, once A and B and V_{max} are properly chosen the wind speed can be obtained as function of the distance from the cyclone centre. Since it is expected to know V_{max} the free parameters to be estimated are A and B. An estimate of A and B can be accomplished performing a model fitting versus some wind speed measurements.

However in real cases symmetrical TC wind speed patterns are not appropriate. To best follow the asymmetrical wind speed pattern of a TC V_{max}, A and B must be meant as angular functions.

In practice only the overall $V_{\max}$ can be at disposal and therefore three free parameters, i.e. V_{max}, A, B, must be estimated for each wind speed profile.

In our analysis a four quadrant study has been conducted. As a matter of fact, the wind speed data made available by the meteorological forecasts centers reports are detailed for each quadrant.

In particular, in a National Hurricane Centre report, for each quadrant, among various information, are provided the distance from the centre (in nautical miles, see nm in Table 2) at which the 34, 50, 64 kt wind speeds occur are given.

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ZCZC MIATCMAT5 ALL
TTAA00 KNHC DDHHMM
HURRICANE DENNIS FORECAST/ADVISORY NUMBER  23
NATIONAL WEATHER SERVICE MIAMI FL   AL0599
1500Z SUN AUG 29 1999

HURRICANE CENTER LOCATED NEAR 30.4N  78.5W AT 29/1500Z
POSITION ACCURATE WITHIN  30 NM

PRESENT MOVEMENT TOWARD THE NORTH OR 355 DEGREES AT  9 KT

ESTIMATED MINIMUM CENTRAL PRESSURE  971 MB
EYE DIAMETER  30 NM
MAX SUSTAINED WINDS  90 KT WITH GUSTS TO 110 KT
64 KT....... 75NE  60SE  50SW  50NW
50 KT.......125NE 125SE  75SW 100NW
34 KT.......150NE 140SE 100SW 140NW
12 FT SEAS..200NE 150SE 150SW 200NW
ALL QUADRANT RADII IN NAUTICAL MILES

REPEAT...CENTER LOCATED NEAR 30.4N  78.5W AT 29/1500Z
AT 29/1200Z CENTER WAS LOCATED NEAR 30.0N  78.4W

FORECAST VALID 30/0000Z 31.7N  78.5W
MAX WIND  90 KT...GUSTS 110 KT
64 KT... 75NE  60SE  50SW  50NW
50 KT...125NE 125SE  75SW 100NW
34 KT...150NE 140SE 100SW 140NW

FORECAST VALID 30/1200Z 33.0N  77.5W
MAX WIND  95 KT...GUSTS 115 KT
64 KT... 75NE  60SE  50SW  50NW
50 KT...125NE 125SE  75SW 100NW
34 KT...150NE 140SE 100SW 140NW

FORECAST VALID 31/0000Z 34.0N  76.0W
MAX WIND 100 KT...GUSTS 120 KT
64 KT... 75NE  60SE  50SW  50NW
50 KT...125NE 125SE  75SW 100NW
34 KT...150NE 140SE 100SW 140NW

NEXT ADVISORY AT 29/2100Z
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Table 2: NHC warning of cyclone Dennis - 29/8/1999 15:00 [www.nhc.noaa.gov].

For each quadrant to perform the Holland model parameters estimation the wind speed data set has been enriched by a wind speed retrieved from scatterometer data once ensured that this wind speed is below 15 m/s.

Of course following such a quadrant approach unnatural discontinuities into the 3D wind speed pattern arise.

In order to smooth them a weighted averaging has been performed. As a result we have a 5 km x 5 km 3D wind speed grid. In order to match with the available wind scatterometer retrieved resolution an Hamming window has been applied to get to a 50 km x 50 km grid.

All this matter has been applied over a set of cyclones selected according to the following specific criteria:

1) the availability of ERS-2 scatterometer measurements in 1999 and 2000;
2) the availably of scatterometer measurements of at least 2/3 of the cyclone structure;
3) a maximum temporal span between the scatterometer measurements and the reference time of the meteorological warning of 2 hours has been considered;
4) the existence in the warning of at least three wind speed data for each cyclone quadrant.

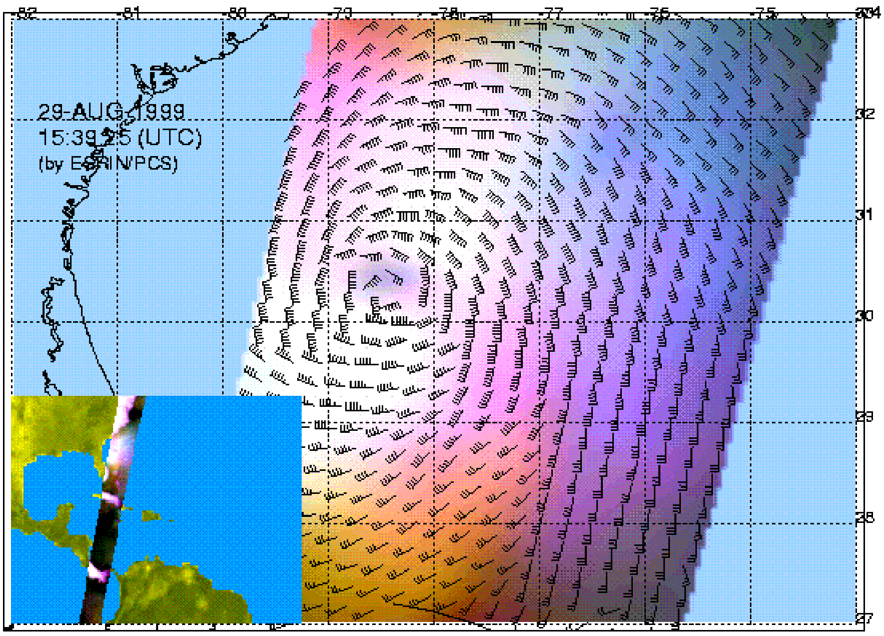


Fig. 2: The cyclone Dennis as observed by the ERS-2 scatterometer. In the inset the satellite track over the cyclone is shown.

For each quadrant, the additional wind speed data used to estimate the Holland model parameters has been chosen among the wind field retrieved by means of the scatterometer data:

1) the Holland model best fits within 200 to 300 km from cyclone centre;
2) the CMOD4 GMF is capable to best match wind speed below 15 m/s;
3) this additional wind speed is searched at a TC centre distance located in the 250-300 km range in order to best provide an independent measurements.

3. THE STUDY: EXPERIMENTAL FACTS

In this section we detail the experiments conducting according the rationale described in Section 2.

First of all we had to select a proper set of TCs (Sect. 2).

As a result of the first selection we have selected 16 cyclones. Unfortunately, only for 11 of them it was possible to find the additional wind speed point according to the requirements detailed in Section 2.

A first analysis of these latter TCs suggested to consider 6 of them as the more appropriate.

They are listed in Table 3.

NAME	DATE	FORMATION ZONE	SYMBOL LIST
Beatriz	11 July 1999	North East Pacific	*
Cindy	26 august 1999	Atlantic	✌
Daniel	29 July 2000	North East Pacific	Δ
Dennis	29 august 1999	Atlantic	◊
Dora	12 august 1999	North East Pacific	X
Isaac	29 September 2000	Atlantic	+

Table. 3: Relevant to the selected cyclones.

Once that the TCs have been selected the Holland hurricane model has been applied in each quadrant. In Fig.6 the case of cyclone Dennis is shown with reference to the NE and SW quadrants (horizontal dotted line represents the overall V_m in the cyclone). This shows the suitability of the Holland model and the asymmetrical structure of the cyclone. Note also that with respect to the 3D wind speed Holland-based pattern the plot shown in Fig.3 is actually relevant only to NE-SW wind speed profile, see Sect.2.

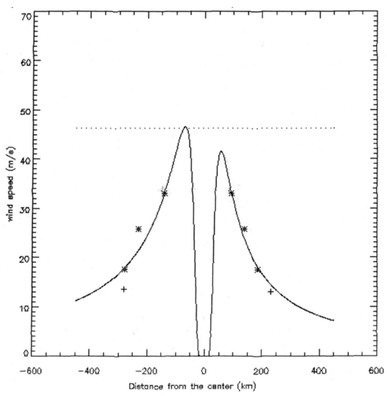


Fig.3: Cyclone Dennis - NE-SW wind speed profile.

Once that the quadrant-to-quadrant analysis the smoothing procedure has been applied to order to limit the occurring unnatural discontinuities in the 3D wind speed pattern, see Fig. 4.

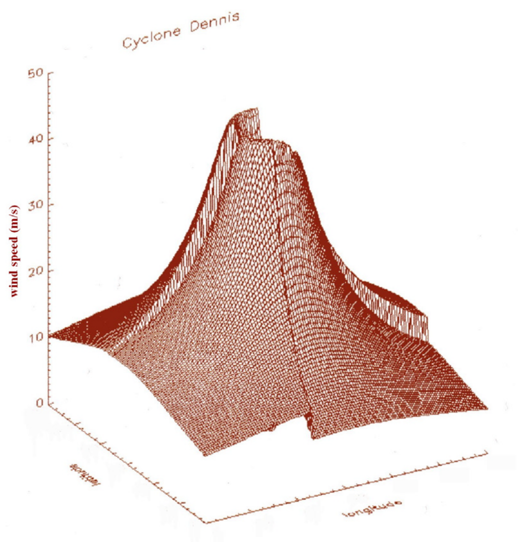


Fig.4: The cyclone Dennis 3D wind speed pattern before smoothing.

In Fig.5 the corresponding 3D smoothed wind speed pattern is shown.

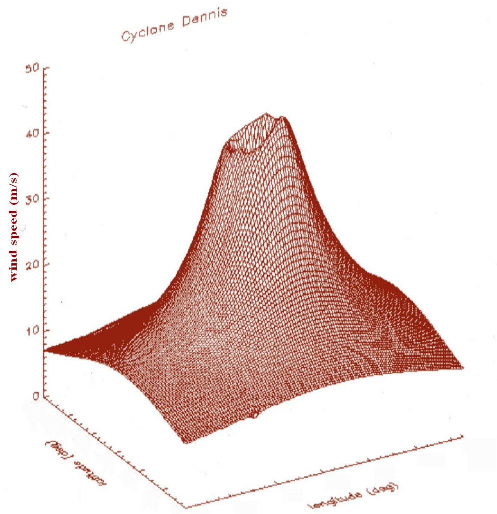


Fig.5: The cyclone Dennis 3D wind speed pattern after smoothing.

Accordingly a 3D wind speed pattern has been generated and can be employed as reference.
For each node of the scatterometer grid node three backscattering measurements (σ^0_M, σ^0_F, σ^0_A) are available but the corresponding incidence angles are different. Since the CMOD4 GMF is incident angle θ and wind direction φ dependent we fixed them in the following figure format, see Figs. 6-8. These figures show σ^0 vs. V where σ^0 is relevant to the scatterometer measurements and V to the 3D Holland-based wind speed pattern. The colour format is such that each one is associated to each antenna (red=*fore*, green=*mid*, blue=*aft*) and the symbols are relevant to the cyclones according to Table 3. The continuous curve refers to the corresponding CMOD4 GMF.

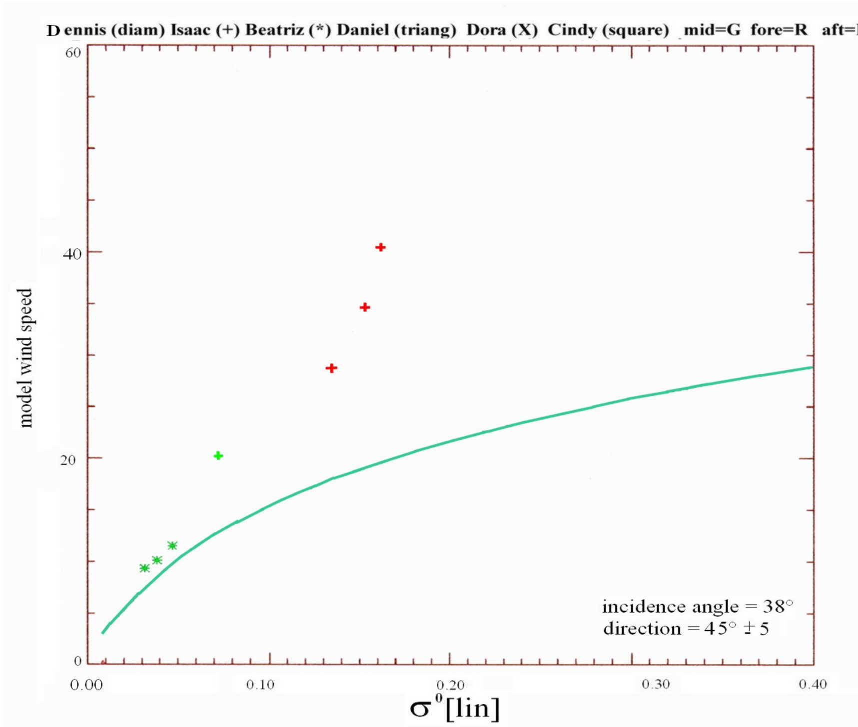
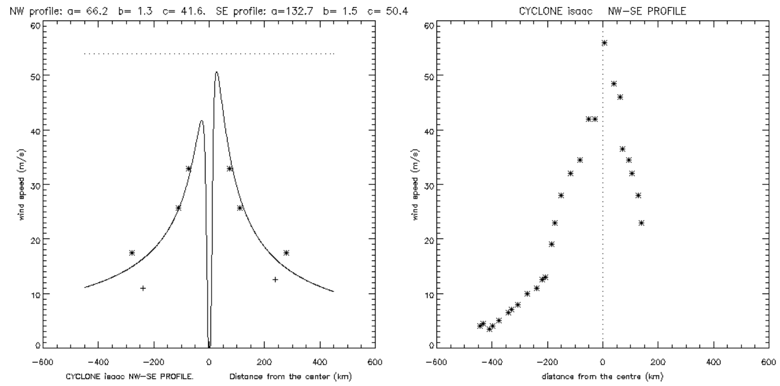


Fig.6: wind speed with respect to σ^0 for incidence angle of 38° and wind direction range of 40°-50°.



(a) (b)

Fig.7: Cyclone Isaac - NW-SE wind speed profile (a) and relevant scatterometer wind retrieved wind speeds (b).

In particular, in Fig.6 the case of θ equal to 38° and φ □□□□□□□□ 45°±5° is shown. We note that for low wind speeds the GMF agreement with the Holland wind speeds is, as expected, obtained. This is untrue for high wind speeds. In this case we also have an unexpected and significant discrepancy for a point referring to a wind speed values of about 20 m/s and pertaining to the Isaac cyclone. Other similar problems have been encountered with the Isaac cyclone. This suggests that the relevant 3D Holland-based wind speed pattern is not best tailored. As a matter of fact, if we move back to the NW-SE Holland wind speed profile (Fig.7) we have that according to the fitting for low and moderate wind speed the Holland profile does not fit adequately the wind speeds estimated through the scatterometer. If we assume that the these latter wind speeds to be considered precise this can be due to the uncertainties in the wind speed TC warning reports and/or to the Holland model itself.
Before proceeding further we note that a saturation effect appears and this has been experienced also in other cases not shown. This fact is in agreement to what stated in Donnelly et al[4].

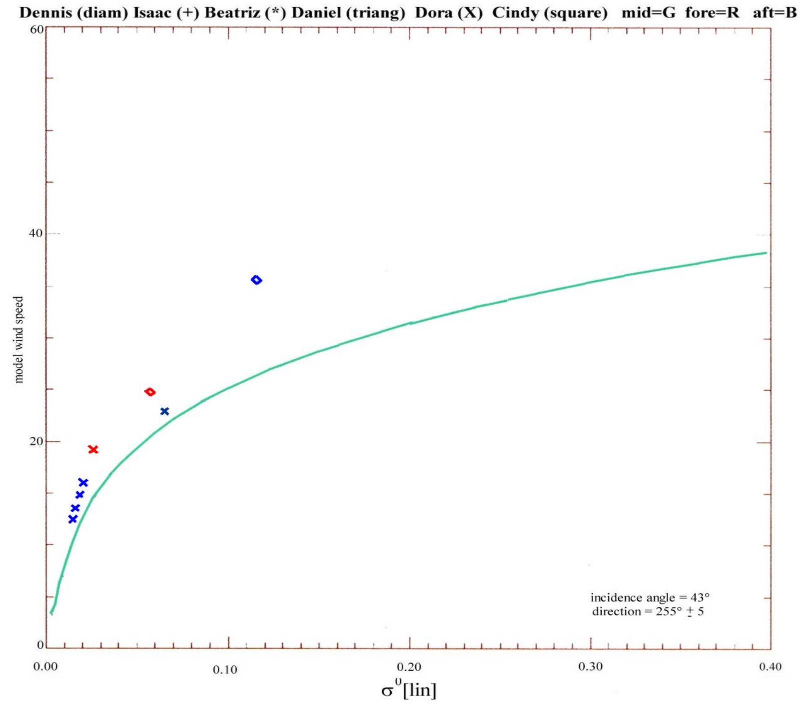


Fig.8: wind speed with respect to σ^0 for incidence angle of 43° and wind direction range of 250°-260°.

In Fig.8 the case of θ equal to 43° and φ □□□□□□□ 255°± 5° is shown. Again we have that results are dependent on the specific cyclone, i.e. to the relevant 3D Holland-based wind speed pattern and on the wind speed.

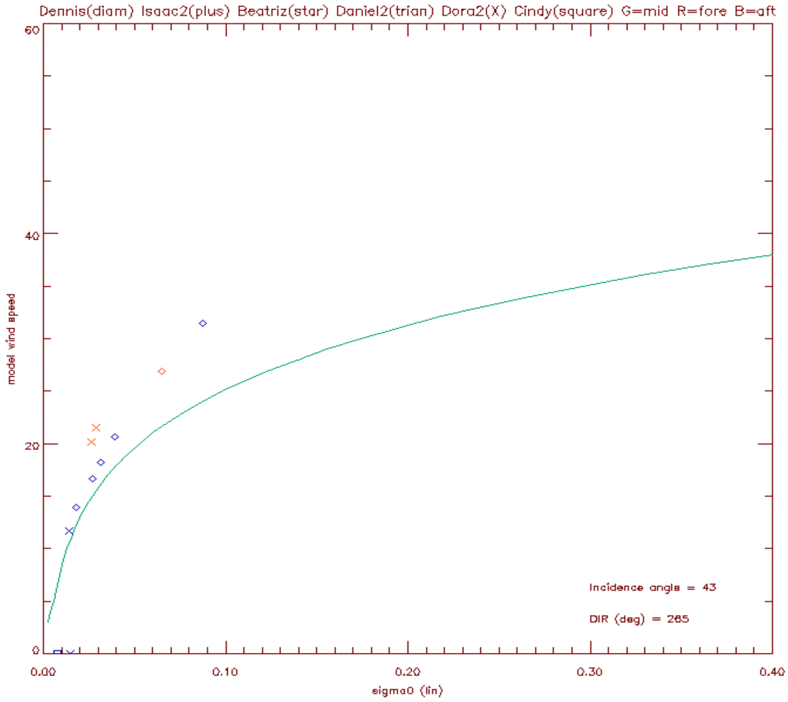


Fig.9: wind speed with respect to σ^0 for incidence angle of 43° and wind direction range of 260°-270°.

In Fig.9 the case of θ equal to 43° and φ □□□□□□□ 265°±5° is shown. Comments similar to the former cases can be made.

CONCLUDING REMARKS

A study regarding the estimation of wind speeds through scatterometer measurements have been conducted. The study has been based on the Holland hurricane model and the ERS-2 C-band scatterometer. The first results that has been obtained are not always straightforard to be physically interpreted but some conclusions can be drawn as hints of future activity. The CMOD4 underestimates the high wind speeds. The relevant geophysical relationship that can be figured out by these experiments is obviously dependent on the incidence angle and wind direction but also on the considered cyclone. This fact can be both justified in terms of the cyclone structure variability and in terms of the Holland hurricane model. In general the data at the input of the Holland model may be critical as well as its use to obtain a 3D wind speed pattern.

Finally we have to note that some interesting papers on this subject have been recently published[3,5] and made available to the authors after this piece of work has been completed. With respect to the paper of Yueh et al.[3] we note that in our case the GMF to high wind speed regimes seems to have a more involved functional form that a simple linear one. Although, as suggested in the paper of Yueh et al.[3], an analysis of the concurring rain effects is appropriate. With respect to the paper of Stoffelen and deHaan[5] and references therein we note that also in our experiments we have experienced a saturation behaviour at high wind speed regimes. Further the use of the new CMOD5 GMF developed in Stoffelen and deHaan[5] should be considered in the development of this piece of work. We note in fact that the rationale underlying this study is similar to the one of Yueh et al.[3] and therefore independent of the one of Stoffelen and deHaan[5].

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