

# REMOTE SENSING OF EXTREME WIND AND OCEAN WAVE FIELDS

Thomas König<sup>1</sup>, Susanne Lehner<sup>1</sup>, Johannes Schulz-Stellenfleth<sup>1</sup>, Guiting Song<sup>2</sup>, A. Reppucci<sup>1</sup>

<sup>1</sup> German Aerospace Center, Remote Sensing Technology Institute, Oberpfaffenhofen, D-82234 Weßling, Germany

<sup>2</sup> University of Hamburg, Meteorological Institute, c/o DLR-IMF, D-82234 Weßling, Germany

## Abstract

Active radar satellites transmit and receive radar signals with wavelengths in the range of centimeters to one meter thus measuring the roughness of the sea surface which enables the retrieval of surface wind and ocean wave fields under nearly all weather conditions independent of sun light. Tropical cyclones and other severe mesoscale storms have strong wind speeds above 30 m/s and high mean significant ocean wave height. Up to now, most algorithms need additional input such as first guess spectrum for the derivation of two dimensional wave spectra and the wind direction for the estimation of wind speed. Additionally, empirical algorithms called Cwave are developed at DLR which are able to derive wind speed and significant wave height without input from external sources. This paper gives an overview on global wind and wave monitoring using a two years wave mode dataset which will be extended to more than 15 year statistics back to 1991 as well as the capabilities to detect details on the wind and wave fields in hurricane situations.

## INTRODUCTION

Due to its capability to work independently of daylight and cloud coverage Synthetic Aperture Radar (SAR) is used for measurements of ocean surface parameters in all weather conditions. Beginning from 1991, European satellites (ERS-1, ERS-2, ENVISAT) are collecting SAR data both in wave mode and in several imaging modes over the global oceans. When operated in wave mode, small images of size 10 x 5 km, so called imagettes, are acquired every 200 km along the orbits with nominal incidence angle of 23° and a spatial resolution of app. 30 m. Figure 1 shows a typical imagette over ocean with a more or less regular wave pattern caused by the swell. Each ERS satellite provided some 1400 imagettes per day resulting in more than 500,000 imagettes each year. A first introduction of a three week imagette dataset is given in [1].

Several studies have demonstrated that SAR images can be used to retrieve the surface wind speed and direction over the ocean [3],[4], the two dimensional ocean wave spectrum [5],[6] and currents[7]. In several papers the possibilities to identify ocean wave parameters like individual wave height[8] and groupiness [9],[10],[11] is discussed.

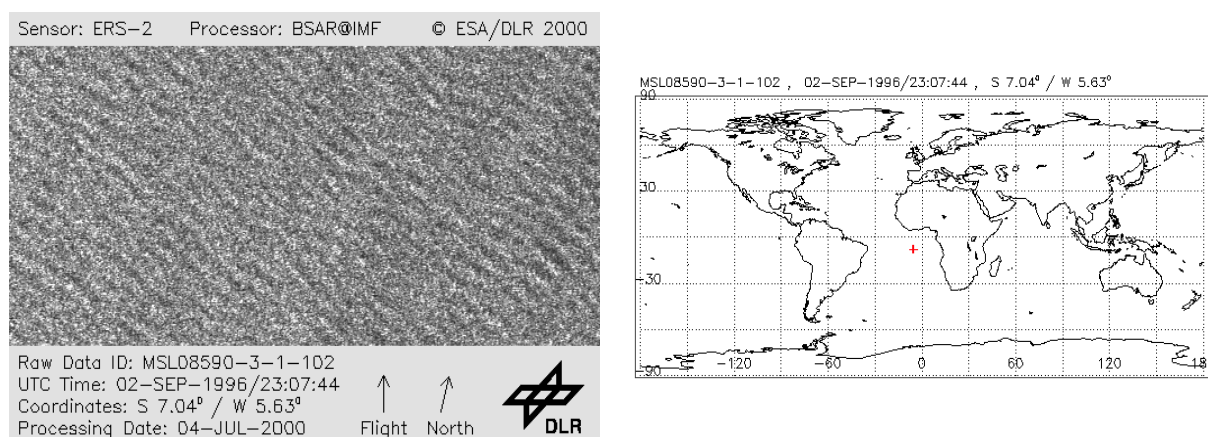
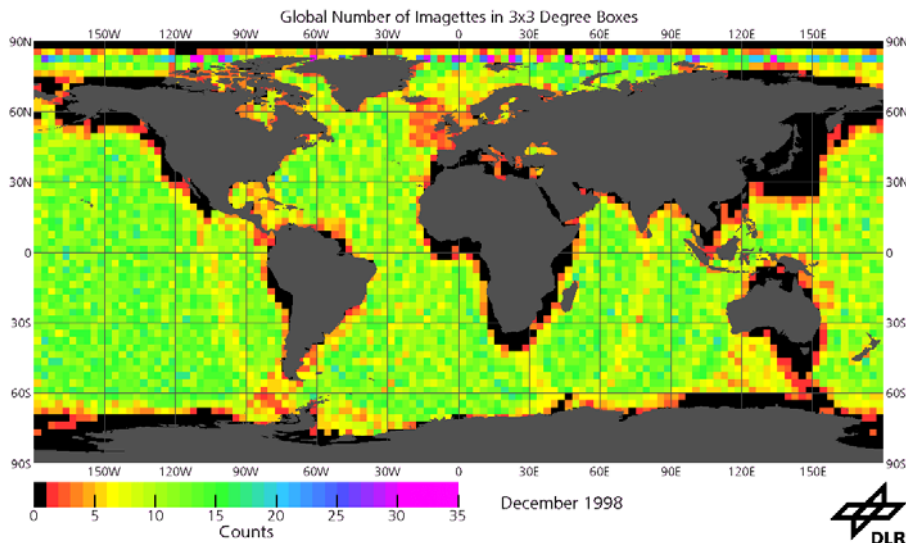


Figure 1: Example of a typical ocean imagette quicklook (left) and corresponding geographical map (right).

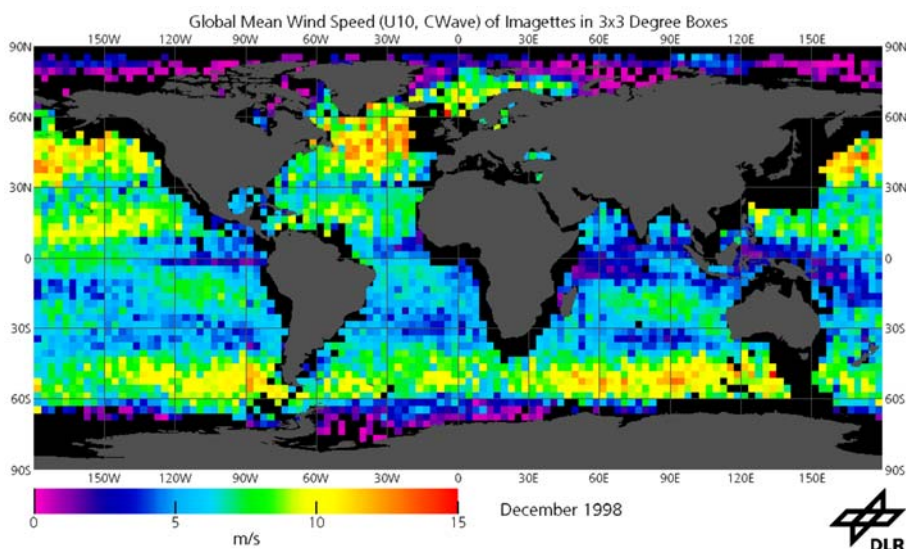


**Figure 2:** Global number of imagettes for one month (December 1998) for 3°x3° boxes over the oceans.

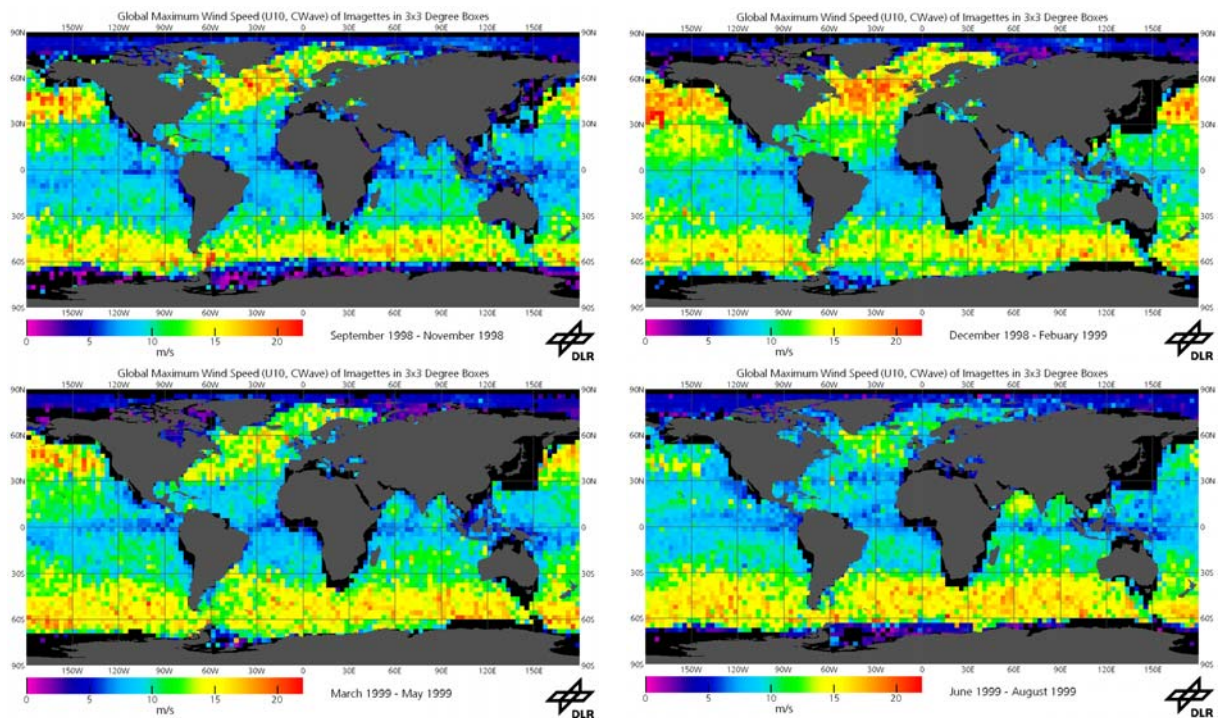
### GLOBAL WIND FIELDS DERIVED BY THE CWAVE ALGORITHM

Current techniques to derive wind and ocean wave fields usually require some first guess input taken from a model, e.g., the wind direction is required for inverting the CMOD to wind speed and a two dimensional ocean wave spectrum as, e.g., computed by the WAM model is needed for information on ocean waves shorter than the SAR measurements. This necessity of first guess input severely restricts the usefulness of SAR images, especially for real time use. In geographical areas, where ocean wave spectra change fast, no accurate first guess may be available. For these applications we derived an empirical algorithm, the CWAVE algorithm, to infer marine parameters from SAR images without further input [2].

Currently work is performed on a two year dataset from September 1998 to November 2000 containing more than 1,000,000 imagettes. As all algorithms are based on the assumption of homogeneity, it is an advantage of the imagettes that slicks, sea ice and other unwanted features can be detected and sorted out. Typically between 7 and 15 imagettes suitable for processing are available in each 3°x3° box per month (see Figure 2). These are used to derive simple statistical measures such as the monthly (Figure 2) and seasonal (Figure 3) mean wind speed globally.



**Figure 3:** Global ocean monthly mean wind speed  $U_{10}$  computed from ERS-2 imagettes of December 1998 for boxes of size 3°x3° using the Cwave algorithm.

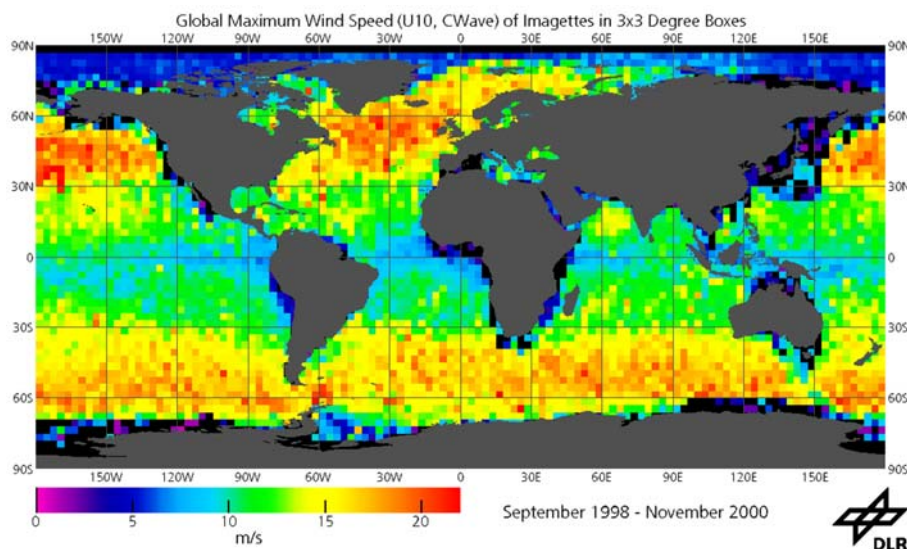


**Figure 4:** Global ocean seasonal mean wind speed  $U_{10}$  for autumn 1998 (upper left), winter 1998/99 (upper right), spring 1999 (lower left) and summer 1999 (lower right) computed from ERS-2 imagerettes using the Cwave algorithm.

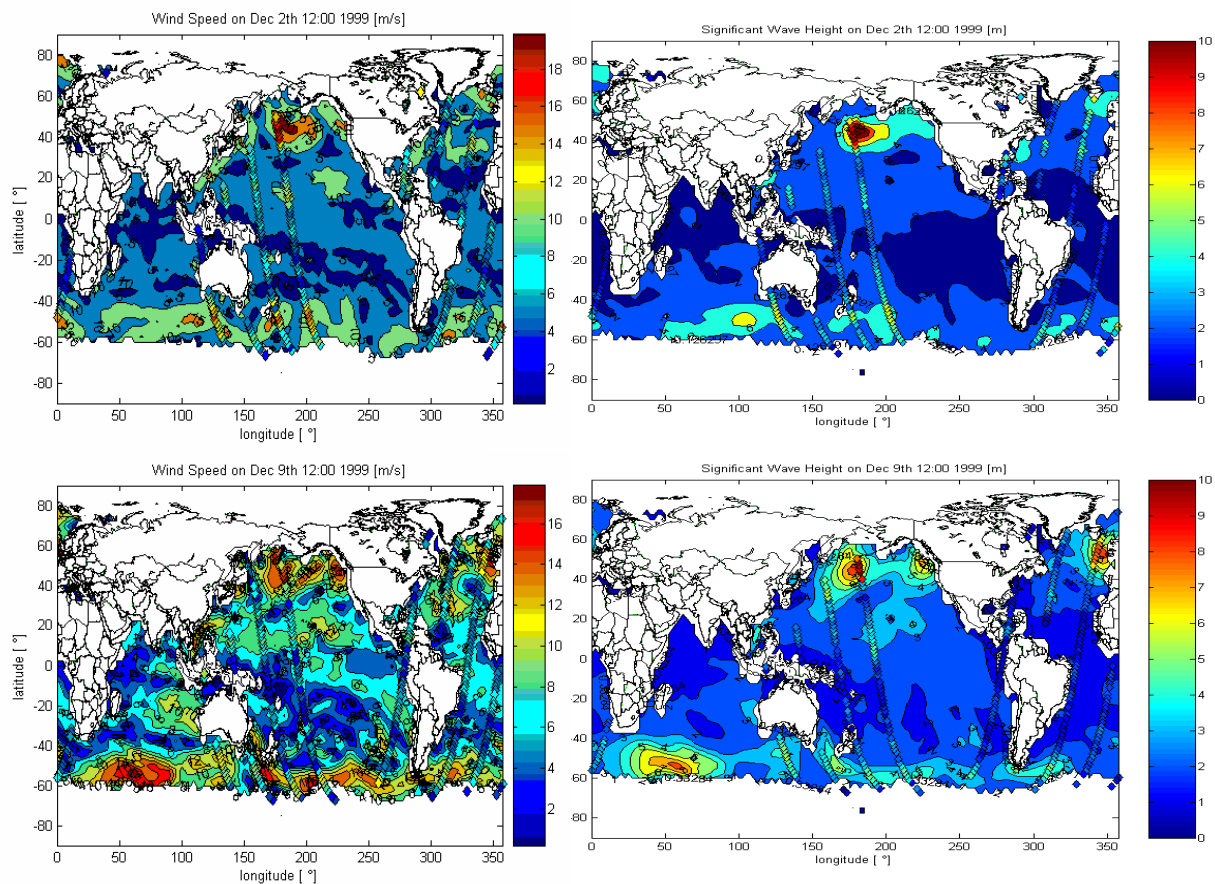
On the three week dataset mentioned above it has been shown that a root mean square error of less than 1 m/s is reached in case of the CMOD inversion technique in comparison to ECMWF. It is expected that the CWAVE technique will meet a similar accuracy.

The maps show a mainly zonal structure of the wind fields where heavy wind conditions occur around a latitude of  $50^{\circ}\text{S}$  and above  $30^{\circ}\text{N}$  and the strongest winds are found on the northern hemisphere in autumn and winter seasons. This is also well reflected by the map of strongest winds in Figure 5. The wind fields in Arctic waters are not meaningful and due to still undetected sea ice coverage.

The wind and wave measurements of single imagerettes are well comparable to ECMWF ERA40 data (Figure 6). They show similar patterns especially when crossing storms. In general it seems that the



**Figure 5:** Global ocean maximum wind speed  $U_{10}$  in period September 1998 – November 2000 as detected by ERS-2 imagerettes using the Cwave algorithm.



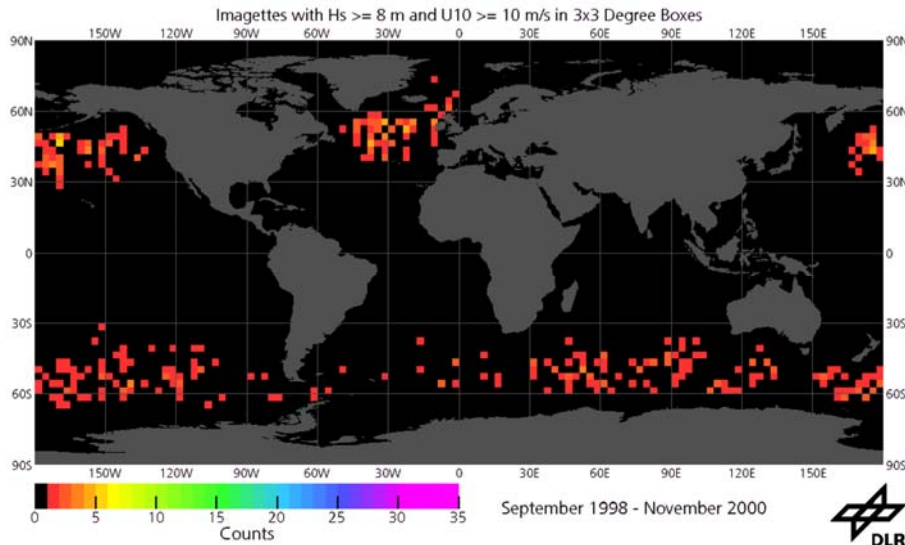
**Figure 6:** Comparison of single imagette results (displayed as boxes along suitable orbits) to ECMWF ERA40 data (background fields); top: December 2, 1999, bottom: December 9, 1999; left: wind speed  $U_{10}$ ; right: significant wave height  $H_s$ .

imagette results indicate larger extents of storms than the ECMWF data. Figure 7 shows a map of the number of extreme ocean surface conditions in the sense that wind speeds of at least 10 m/s are found together with significant wave height of 8 m and higher. The zonal structure of the occurrence of extreme conditions is prominent. Also, the density of extreme cases seem to be higher in the northern Pacific and Atlantic than on the southern hemisphere.

Up to now, neither the raw wave mode data collected by ERS-1 and ERS-2 nor the imagettes are available as orderable ESA products. Since some years ESA makes effort to transfer the low bitrate data currently stored on computer tapes (DLT's, Exabyte cassettes and high density tapes) to a modern robot archive. The wave mode data are part of the low bitrate data. Starting 2007 it is expected that ESA will conduct a reprocessing of the complete ERS-1/2 wave mode data using an extended version of the ENVISAT processor to form a more than 15 year consistent imagette dataset which will be made available to the user community.

## ANALYSIS OF HURRICANES USING SAR IMAGES

Some of the strongest storms can be analysed using the 400 km x 400 km SCANSAR data that show a synoptic image of nearly the whole storm. On August 28, 2005, 15:50 UTC, ENVISAT acquired a SAR image of hurricane Katrina. Figure 8 shows in its upper image the complete ASAR scene with 400 km width. The lower image in Figure 8 is an enlargement of its eye and a surrounding area of 200 km x 200 km. At the time of observation Katrina was a Cat 5 hurricane. The radius of maximum wind speed  $R_{max} = 25$  km around the eye as given by the NOAA/HRD model is shown in the image. Figure 8 also shows a cut at constant incidence angle through Katrina's center.



**Figure 7:** Number of imaggettes found in period September 1998 – November 2000 with significant wave height  $H_s \geq 8$  m and wind speed  $U_{10} \geq 10$  m/s representing extreme conditions.

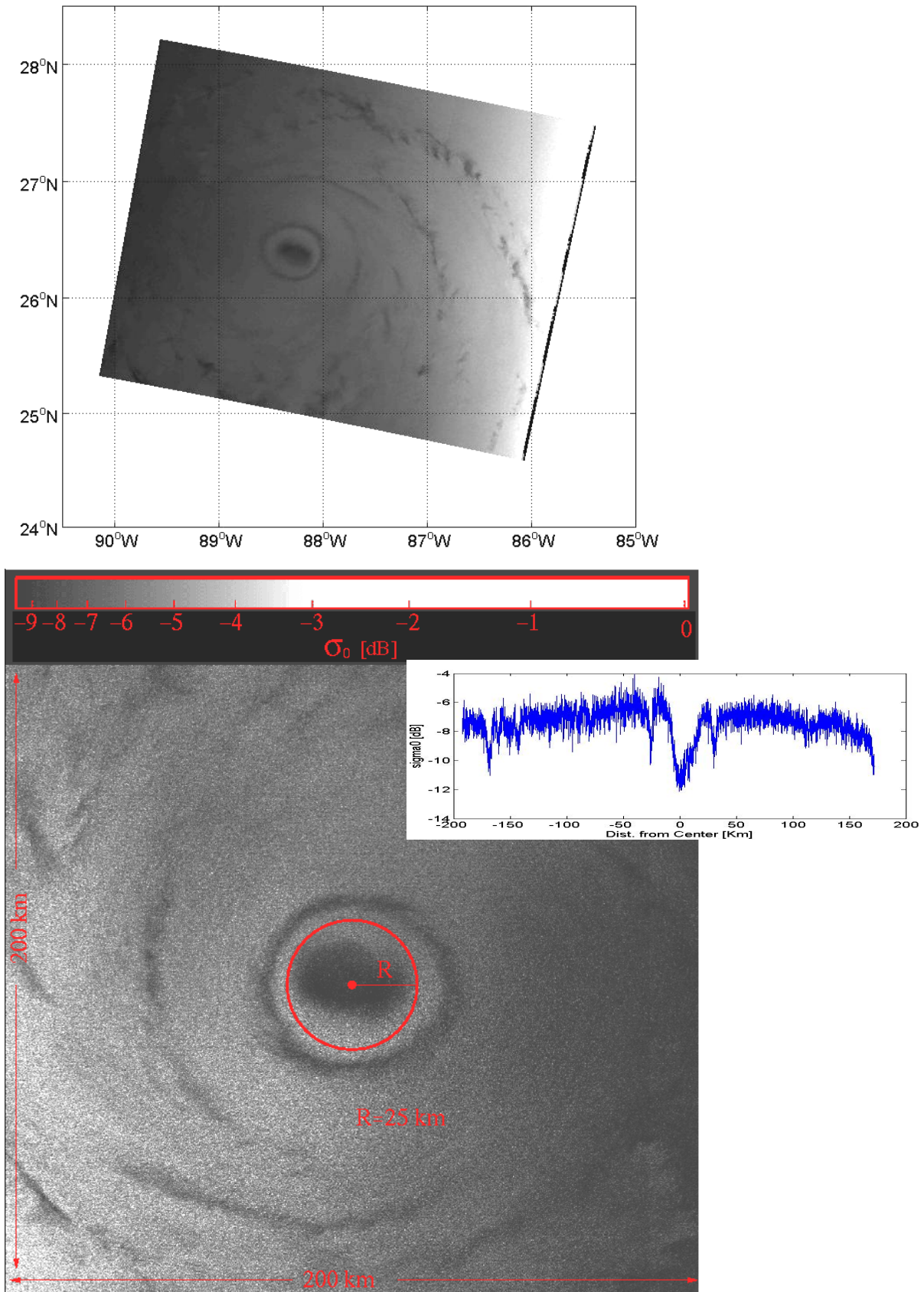
The eye as well as a ring around the eye at about 35 km distance can be observed. From a MERIS image collected at the same time it can be seen that the dark ring is related to the top of the eye wall and thus probably related to ice clouds.

SAR backscatter from the ocean surface is dependent on the small scale roughness which in turn is strongly dependent on the local wind field. Therefore the backscatter can be used as a measure for the local wind. SAR ocean surface wind retrieval from large SAR images is a 2 step process: In the first step, wind directions are estimated from wind induced streaks and in the second the wind speeds are derived from the normalized radar cross section (NRCS). The SAR wind speed retrieval is based on the C-band scatterometer (SCAT) model, usually CMOD5 which gives the empirical relation between the VV polarized NRCS, the wind vector and the incidence angle. CMOD4 is used by ESA as the standard wind retrieval model for the ERS scatterometer and was tuned to wind speeds not exceeding 15 m/s. Therefore CMOD4 should not be applied to much higher wind speeds.

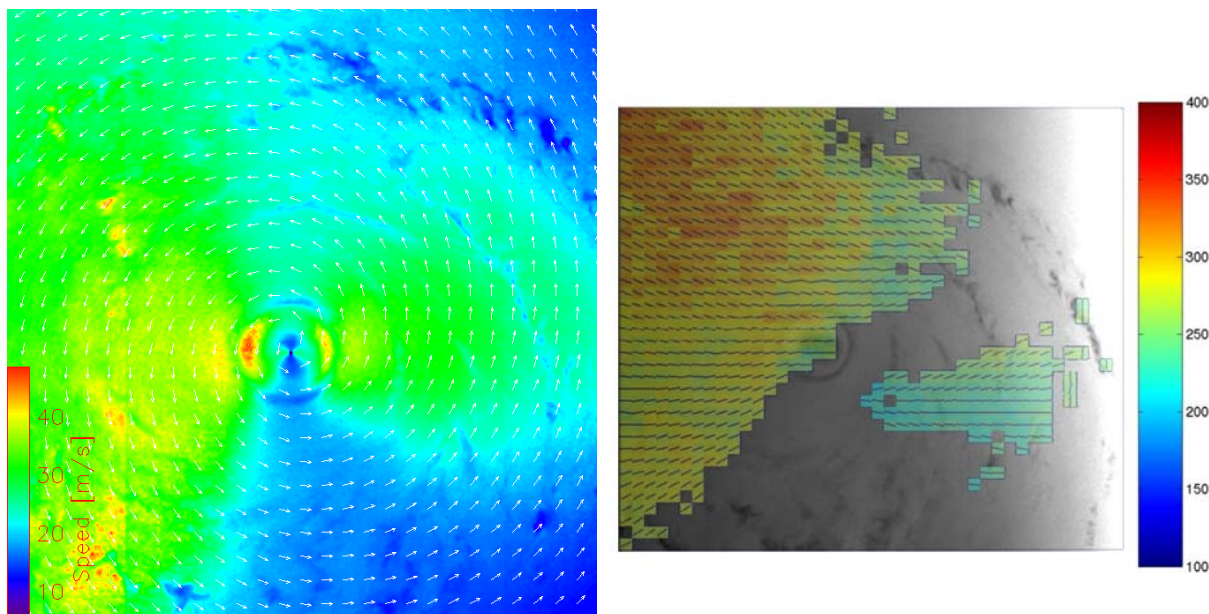
CMOD5 saturates though, depending on incidence angle, at about 20 m/s for wind blowing towards the SAR antenna. For higher wind speeds, the NRCS diminishes again slightly. This together with the fact that the NRCS is highly dependent on the wind direction and the incidence angle and is additionally influenced by rain, does make a C-band radar in this setup not ideally suited to measure hurricane wind speeds in a robust manner.

The right image in figure 9 shows the wind speed for hurricane Katrina as derived by CMOD5 using tangential wind direction. Several imaging artifacts and rain bands can be observed. As CMOD5 is obviously not suited for high wind speeds in hurricanes for VV polarized SAR imagery, we thus suggest to improve the CMOD for high wind speeds using a hurricane modes fitting wind speed and NRCS resulting in a new algorithm.

SAR images show features due to ocean waves; usually waves longer than 100 m are imaged depending on travel direction. The left image in figure 9 shows the wave length and direction of the ocean waves as observed on the SAR image of hurricane Katrina. Ocean waves of length between 250 m and 300 m can be observed, with wavelength increasing as the swell travels away from the hurricane center.



**Figure 8:** Hurricane Katrina as seen by ENVISAT on August 28, 2005. Top: full scene reprojected to rectangular latitude – longitude map; bottom: enlargement around the eye of the hurricane and a cross section through the eye center.



**Figure 9:** Wind (left) and wave (right) fields derived from ENVISAT ASAR data of hurricane Katrina collected on August 28, 2005.

## CONCLUSIONS AND OUTLOOK

In this paper maps over global oceans of different SAR-derived atmospheric / oceanic parameters such as the ocean surface wind speed  $U_{10}$  and the significant wave height  $H_s$  are presented. From these, maps of monthly and seasonal mean wind speeds and wave heights are compiled as well as a map of extreme conditions. It is shown that extreme conditions are found in strong zonal patterns both in the northern and southern hemisphere where there are indications that the density of extreme cases is highest in the northern Pacific and Atlantic in winter time. It is expected that ESA will make the SAR wave mode data available for the whole lifetime of ERS-1 and ERS-2 in near future.

A first analysis showed that ENVISAT ASAR hurricane images can be used to infer information on hurricane structure, eye size and the sea surface roughness from the image. Due to saturation, CMOD5 is not suited to derive wind speeds above 20 m/s from SAR images. Parametric models are to be used to make the measurements more robust.

For many applications current SAR systems have insufficient spatial resolution. This problem can be solved to some extent by the new upcoming German mission TERRASAR-X that will be launched in October 2006. TERRASAR-X will carry a X-band SAR instrument which can be operated in SCANSAR mode (100-200 km swath width, 15-30 m resolution), strip map mode (40-60 km swath width, 3-15 m resolution) and spotlight mode with resolution up to 1m. In spotlight mode, a limited area of 10 km x 10 km or 10 km x 5 km can be covered. This high geometrical resolution together with its beam steering capability will make TERRASAR-X an ideal tool to get high resolution information from the ocean surface which is especially useful for offshore constructions such as offshore wind farms and oil drilling platforms and their surrounding areas.

## ACKNOWLEDGEMENTS

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