Measurement of Extreme Wave Height by ERS-2 SAR and Numerical Wave Model (WAM)

Xiao-Ming LI Thomas. Koenig Susanne.Lehne
Johannes Schulz-Stellenfleth
German Aerospace Center (DLR)
Oberpfaffenhofen, 82234 Wessling, German
Email: Xiao.Li@dlr.de

Xiao-Ming LI
Ocean Remote Sensing Institute, Ocean University of China
Qingdao, 266003, P.R. China

Abstract—**The Synthetic Aperture Radar (SAR) onboard the European Satellite ERS-2 is operated in wave mode over the global oceans whenever no image mode data acquisition is requested. In the present paper new SAR algorithms to derive sea state at German Aerospace Center (DLR) are shortly introduced and used to determine SAR derived ocean parameters from wave mode data. Global Significant wave height statistics on a 3° by 3° grid derived by an empirical method (CWAVE) is presented in this paper for sea state analysis.**

A severe North Pacific storm that produced significant wave height above 10 m along the northern great circle shipping route is presented in the paper. The sea state generated is analyzed in more detail using the empirical method to derive significant wave height and compared to the ocean wave model WAM.

Keywords— SAR wave mode data; extreme sea state; WAM

I. Introduction

It is well known that SAR provides ocean wave information on a continuous and global scale from space independent of daylight and cloud coverage. This makes SAR particularly suited to investigate severe weather events over the oceans.

Generally the numerical ocean wave model (WAM) [1] agrees fairly well with the altimeter data and in situ measurements for Hs [1] [2] [3]. Some shortcomings for the determination of severe sea state, exceptional directional distribution in the spectrum and long swell wave length still exist though.

A thorough assessment of the ERA-40 wave height data revealed that they capture very well the variability of the true wave heights on all time scales, while severely underestimate the high wave heights [4]. Based on the global SAR wave mode data set, many cases with extreme sea state have been observed that the ERA-40 underestimated the sea state or totally miss them. A severe storm occurred in the North Pacific on November 1998 was selected as the case study to compare the retrieved significant wave height from SAR measurements, ERA-40 reanalysis and WAM model results.

The paper is structured as following. In the second section of the paper, the data sets used for analysis are introduced. Section III is a short introduction of SAR algorithms used for this research. The global map of significant wave height derived from SAR wave mode data and the severe storm case in the North Pacific is studied in the last section.

II. Data Set Description

A. ERS-2 SAR wave mode data

ERS-2 SAR wave mode data are acquired over the ocean every 200 km along the satellite track with the coverage of 5 km x 10 km, when image mode data are not requested.

In the scope of the Wave Atlas Project, ESA provided a two-year ERS-2 SAR wave mode raw data set of mainly collected during 1998, 1999 and 2000, which was reprocessed into single-look-complex imagettes at DLR. The processed data set contains between 1300 and 1500 images of 10 km by 5 km size daily acquired over the global ocean [5].

B. Model data

After the success of ERA-15, the European Centre for Medium-Range Weather Forecasts (ECMWF) performed their second reanalysis called ERA-40 [6], which covers 45 years, from 1957 until 2002. Starting 1991, wave height data obtained from the altimeters on board of ERS-1 and ERS-2 are assimilated into ERA-40 wave data.

The Numerical wave model used for this research is the well-known WAM. It is a third generation model (cycle 4) [7], in which the wave spectrum is computed by integration of the energy balance equation. The model spatial and temporal resolution is chosen as 1° by 1° grid and three hours respectively, and forced by the ERA-40 high resolution wind field (1° by 1°). The direction resolution of the WAM model spectrum is chosen 30°. The first bin is centered at 15°, clockwise from the true north. 25 frequencies, logarithmically spaced from 0.0418 HZ to 0.4114 HZ are used in the model runs.

III. SAR algorithms used

The following algorithms developed by DLR are used to determine ocean wave parameters:

A. *CWAVE_1.0:* A new empirical algorithm that yields integral ocean wave parameters like significant wave height or mean period directly from the C-band SAR image. It does not require a wave model first guess. The empirical algorithm can be used, too, to derive wind speed u_{10} [8].

B. *LISE_1.0:* To determine the sea surface from SAR images; The complex SAR image information is used to derive the sea surface height by a quasi-linear inversion based on the standard forward SAR imaging model [9] .

IV. Data Analysis

A. *Global statistics of Ocean Wave Parameter (H_s) derived by CWAVE*

More than one million ERS-2 SAR wave mode raw data have been processed to single look complex data at DLR by the BSAR processor with the full geometric resolution approximately 5 m by 20 m for wind field and sea state statistics [10]. Averages of the marine parameters derived from the images are given on 3° x 3° grid boxes. For the complete data set around 200 images are available in every box situated over the open ocean. Fig. 1 and Fig. 2 are the seasonal global maps of maximum significant wave height derived by CWAVE during the period of September 1998 to February 1999. As wave mode data are only acquired when image mode is not requested, in some coastal areas, e.g. China Seas and Japan Seas, data can be missing. These cases are indicated by the black boxes in the global map. It can be observed that the strong storms occur especially in the North Atlantic and the North Pacific. The maximum Hs measured by SAR are more than 10 meters.

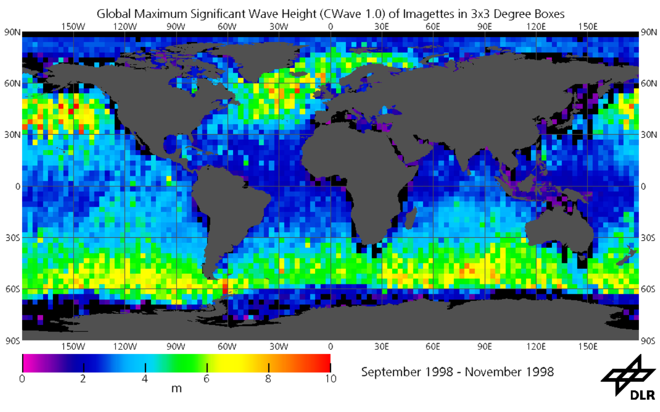

Figure 1. Seasonal (September 1998-November 1998) Global map of Maximum Hs derived by CWAVE averages over 3 ° by 3 ° degree grid. Red indicates cases with 10 m or above

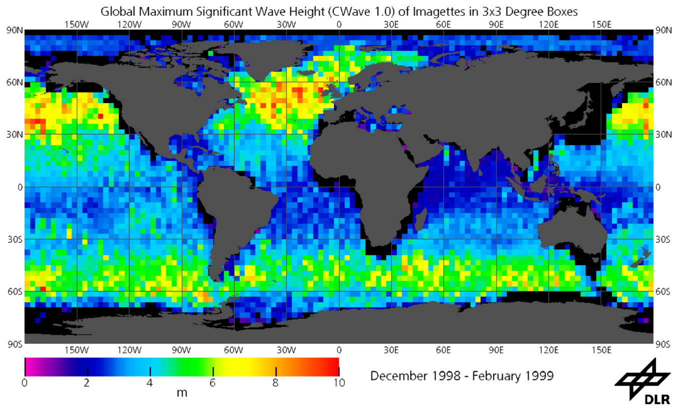

Figure 2. Seasonal (December 1998-February 1999) Global map of Maximum Hs derived by CWAVE averages over 3 ° by 3 ° degree grid. Red indicates cases with 10 m or above

B. *Case Study—A severe winter storm in the North Pacific*

The great circle shipping routes in the North Pacific used for the travelling between East Asia and the west coast of America have a high frequency of severe storm occurrence. A severe storm occurred over the North Pacific on November 1998 and was observed by ERS-2 SAR twice on ascending and descending orbits on Nov.28 at 08:39 and 20:48 UTC. For this case, the retrieved significant wave height from SAR data is more than ten meters as determined by the empirical algorithm CWAVE. Detailed features of the storm are analyzed in this paper. The retrieved results from SAR data are compared to the ERA-40 reanalysis and WAM model results.

The northern hemisphere ERA-40 significant wave height data contour plots at 06:00 UTC and 18:00 UTC are shown in Fig. 3. H_s retrieved from the ERS-2 SAR wave mode data by making use of the CWAVE algorithm are shown as squares superimposed on the ERA-40 model result map. Fig. 4 gives the SAR images obtained on Nov. 28 1998 at 08:39 and 20:48 UTC during the ascending and descending orbit nearest to the centre of the storm.

Due to rough ocean surface caused by the strong storm, the two images have a high normalized radar cross section (NRCS). This is used to determine the wind speed. The ocean wave pattern is used in the empirical algorithm CWAVE to measure the significant wave height. The retrieved significant wave height by the CWAVE empirical algorithm for the two images acquired at 08:39 UTC and 20: 48 UTC is 9.8 m and 10.5 m, respectively.

In Fig.4, the collocated hindcast WAM model spectra of the two images are given as well. ERA-40 high resolution wind field (1° by 1°) was used for WAM model forcing. The SAR images acquired are not in the centre of the storm, thus the energy of the collocated WAM model spectrum is lower than maximum Hs. The significant wave heights derived from the WAM model for these two imagettes are lower, namely 6.4 m and 7.8 m. The WAM results agree well with the ERA-40 data. From the map, the SAR satellite tracks pass in front of the storm. For both orbits the SAR measurements of Hs are consistently higher by at least 2-3 meters compared to the ERA-40 assimilated model data and WAM model run by ERA-

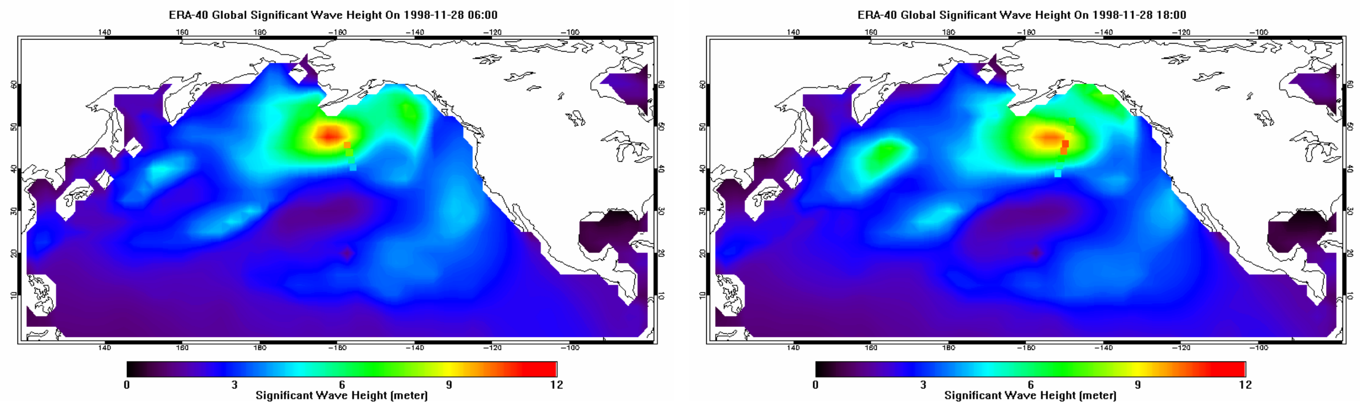

Figure 3. Map of Hs from ERA-40 at synoptic times (12:00 and 18:00 UTC) on Nov. 28 1998 with supposed measurements from ERS-2/SAR (square)

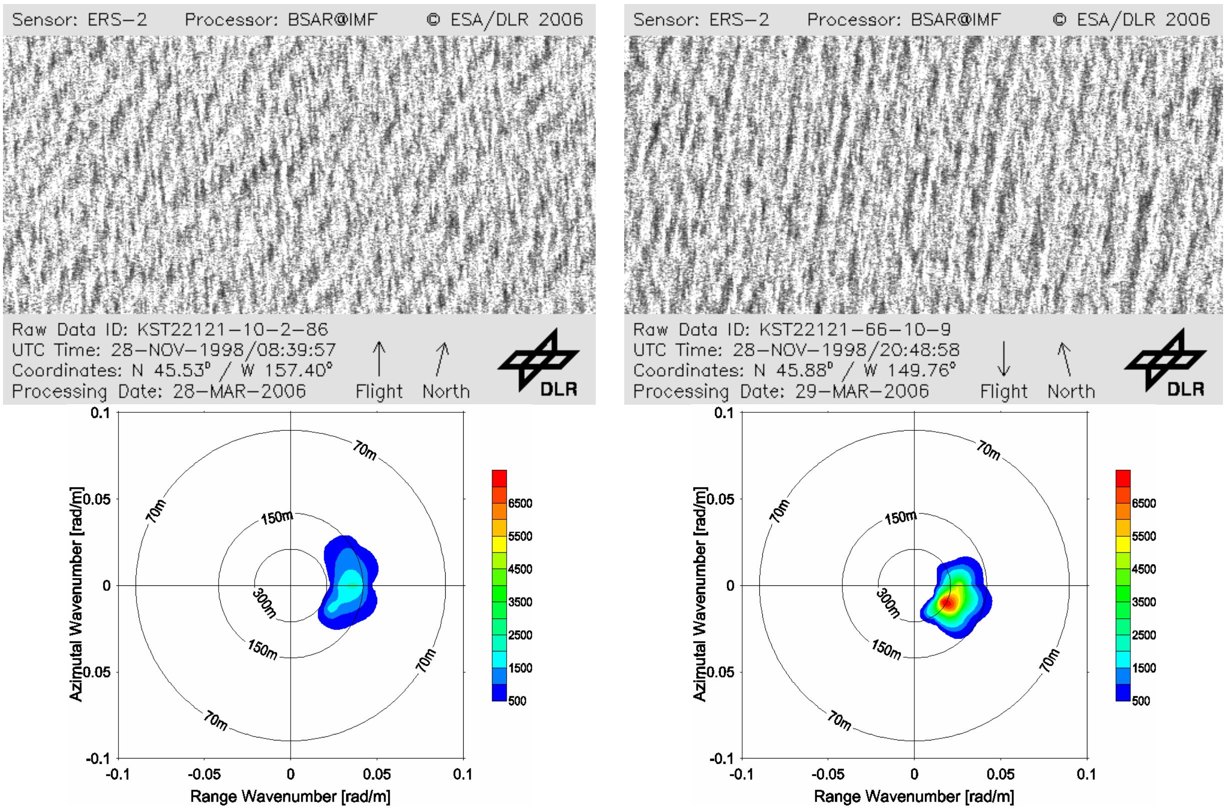

Figure 4. ERS-2 SAR wave mode images acquired in the morning (left) and night (right) on Nov. 28, 1998 in the North Pacific and collocated WAM model spectra (m^4)

40 wind input. This difference is lower for the evening descending pass as it is nearer to the centre of the storm in comparison to the morning ascending pass. The peak wavelength as measured from the SAR images is shorter than that in the WAM model spectra, though. One possible explanation is that in the model the storm is misplaced and in reality moved faster.

In extreme sea states generated by a storm, in addition to the significant wave height, the property of individual ocean waves is of interest. For this example, the maximum individual wave height of the SAR image acquired at 20:48 UTC as derived by the LISE algorithm is 22 m.

V. Conclusion

The spaceborne SAR missions, ERS-1, ERS-2 and Envisat have supplied long time series of global and continuous observations from 1991 till now. Based on the results from the project WAVEATLAS from two years ERS-2 SAR wave mode data, the presented seasonal global significant wave height map show that the largest significant wave heights are found in the North Pacific and the North Atlantic. A local maximum significant wave height observed in a severe winter storm over the North Pacific is more than ten meters. For the winter storm case, the SAR passed the storm region twice on an ascending and descending orbit in one day, which is helpful for the measurement of ocean wave and for checking the consistency of the result. In this case the model underestimates the sea state for both orbits. It is assumed that the storm present as well in the SAR moved faster than as given in the ERA-40 model result. In addition, the SAR observation supplies two-dimensional sea surface field information. By making use of the information, an estimation of maximum wave height is given. The observation of SAR can be used to improve the forecast result.

ACKNOWLEDGEMENT

The ERS-2 SAR wave mode raw data were kindly supplied by ESA in the framework of AO WAVEATLAS. We kindly thank the ECMWF as well for making the ERA-40 data set available for free.

REFERENCES

[1]. WAMDI Group, "The WAM model a third generation ocean wave prediction model,"Journal of Physics Oceanography, 18, pp. 1775-1810, 1988.

[2]. R. E. Jensen, V. J. Cardone and A. T. Cox, "Performance of Third Generation Wave Models in Extreme Hurricanes", 9th International Workshop on Wave Hindcasting and Forecast, VICTORIA, B.C., CANADA September 24-29, 2006.

[3]. Roland Romeiser, "Global validation of the wave model WAM over a one-year period using Geosat wave height data", J. Geophys. Res., 98(C3), pp. 4713–4726,1993.

[4]. A. Sterl, and S. Caires, "Variability and Extreme of Ocean Waves - The Web-based KNMI/ERA-40 Wave Atlas," Int. J. Climatology, 25(7), 963-997, doi:10.1029/joc.1175, 2005.

[5]. S. Lehner, J. Schulz-Stellenfleth, J.B. Schättler, H. Breit, J. Horstmann., "Wind and Wave Measurments Using Complex ERS-2 Wave Mode data, " IEEE TGRS, Vol.38, No. 5, pp. 2246-2257, 2000.

[6]. http://www.ecmwf.int/research/era/

[7]. H. Guenther, S. Hasselmann and P. Janssen, "The WAModel cycle 4 (revised version), " Technical report, Deutsches Klimarechenzentrum (DKRZ), Hamburg, Germany. Technical Report 4. 1992. [Available from Max Planck Institute for Meteorology, Bundestrasse 56, 20146 Hamburg, Germany.]

[8]. J. Schulz-Stellenfleth, T. König and S. Lehner, "An empirical approach for the retrieval of Integral Ocean wave parameters from synthetic aperture radar data,"J. Geophys. Res., 112, doi: 10.1029/2006JC003970. 2007.

[9]. J. Schulz-Stellenfleth and S. Lehner, "Measurement of 2-D Sea Surface Elevation Fields using Complex Synthetic Aperture Radar Data,"IEEE TGARS, Vol. 42, No 6, pp 1149-1160. 2004.

[10]. S. Lehner, Th. Koenig, J. Schulz-Stellenfleth, "Global Statistics of Extreme Wind speed and Sea State from SAR, ", 2007, unpublished.