Korean Journal of Remote Sensing, Vol.19, No.1, 2003, pp.31~36

Wave Height from Satellite Altimetry and Its Comparison with a Model Product

Seung-Bum Kim* and Sok-Kuh Kang**

DSatellite Technology Research Center, Korea Advanced Inst. Science and Tech*

Korea Ocean Research and Development Institute**

Abstract : We extracted significant wave height (SWH) using several altimeter missions from 1987-1995 over the Northwest Pacific ocean and compared with ECMWF (European Center for Medium-Range Forecast) reanalysis (ERA) products. For large wave heights the ERA wave heights are smaller than the altimetric ones, while for small wave heights the ERA wave heights are larger. Comparison in SWH between altimetric derivations and ERA model products shows the discrepancy of 0.46-0.21 × SWH (m). Methods for propagating this differences into ERA wind error are presented.

Key Words : Significant wave height, altimetry, ECMWF, TOPEX/Poseidon, Geosat.

1. Introduction

Monitoring of wave height is important primarily for reducing storm risks at sea and along the coast. Such importance is enhanced especially since wave heights have increased more than 50% for the last 40 years (the North Atlantic; Wang and Swail, 2002). The intensified wind forcing is the most likely cause of this change. The intensification would be associated with the rise in the energy in the Earth atmospheric and oceanic system, resulting from the global warming. This suggests the link between the changes in the global wave height and climate change, thus requiring continual and intensive monitoring of the wave height.

Routine monitoring of wave heights has traditionally been made using marine buoys. More recently satellite altimetry began to offer a powerful tool for regular and extensive monitoring of wave height. The first altimetry mission that proved the efficacy of altimetric wave monitoring is the Geosat since 1987. A dedicated wave model is another source of extensive wave data. In addition, wave models are of special interest to the climate modeling because waves are important coupling parameter between ocean and atmosphere (Sterl and Bonekamp, 2000). For example, currently ERA40 (40-year European Center for Medium-Range Forecast ReAnalysis model) employs the strategy of coupling between a wave model and the conventional ECMWF atmosphere-ocean model (Simmons and Gibson, 2000). However, since the altimetric monitoring and model simulation of wave heights are only *estimates* of wave heights, their validation and performance assessment are essential.

Validation should be performed with respect to in situ

Received 22 December 2002; Accepted 25 January 2003.

measurements such as from buoys. However the availability of in situ data are limited. Therefore, alternatively, intercomparison between extensive data sets such as altimetric observations and model results would provide useful secondary insights on the quality of both data sets. For such comparison, it is necessary to use *independent* data which were not used during the ECMWF data assimilation. The independent truth data that cover the area and the ERA period are significant wave heights (SWH) derived from altimeter measurements[1]. In this paper, we compare SWHs from altimeter observations and ERA15 (15-year reanalysis) data and analyze the comparison results.

2. Data and Method

ERA15 products (Gibson *et al.*, 1997) are generated based on the ECMWF atmospheric general circulation forecast model, one of the most widely used model for numerical weather prediction. The 'analysis' procedure combines model forecasts with observations to provide optimum estimates for the model output. A scheme called 're-analysis' is required because a forecast-analysis system is continually undergoing changes. A time series of operational analysis fields is likely to lack consistency due to changes in the analysis procedure. Thus a retrospective re-analysis is applied to the observational record in order to create a consistent description of the atmosphere. For the ERA, such a re-analysis is applied to the 15-year period from January 1979 until February 1994. The ERA data are given every 6-hours interval from January 1979 onwards.

The wave heights from the ERA wind are generated by the WAve Model (WAM; Komen, 1994), which is driven by the ERA wind. This wave height is denoted as ERA_WAM wave height hereafter. The ERA_WAM wave heights are available globally on a monthly 1.5° by 1.5° grid.

The altimetric wave heights are a combination of measurements by Geosat, European Remote-Sensing satellite (ERS)-1, and TOPEX/Poseidon. The principle behind the altimetric measurement of wave heights is that the shape of the altimeter return echo depends on the sea state or wave height (Fu and Cazanave, 2001). The altimetric wave heights are available globally on a 2° by 2° grid in monthly averages from April 1985 onwards.

The area of interest is the entire Northwest Pacific. The time span runs from January 1987 to December 1993 excluding a gap in the altimeter data, from October 1989 until March 1992.

3. Results

1) Comparison of Two Wave Products

A snapshot of SWH in Fig. 1 indicates that the SWH pattern follows that of wind stress. The northern hemisphere has higher SWH since wind fields in boreal winter are stronger than that in austral summer. Along 60°S, the SWH is large due to the presence of the Antarctic Circumpolar winds. ERA_WAM SWHs are spatially smoother due to the model integration in time and space, in comparison to the temporally and spatially scattered observations of SWH by altimeter. The time series of the intercomparison in SWHs between ERA15 and altimeter solutions is presented in Fig. 2. There is a consistent feature that ERA SWHs are greater in summer and smaller in winter. Presented in the form of a scatter plot, Fig. 3, we now can find that for large wave heights, greater than 2.5 m, the ERA_WAM wave heights are smaller than the altimetric ones, while for

---

[1] Unlike for ERA15, ERS altimeter SWHs are assimilated into ERA40 products. Geosat and TOPEX/Poseidon data are not assimilated and still independent of the ERA40.

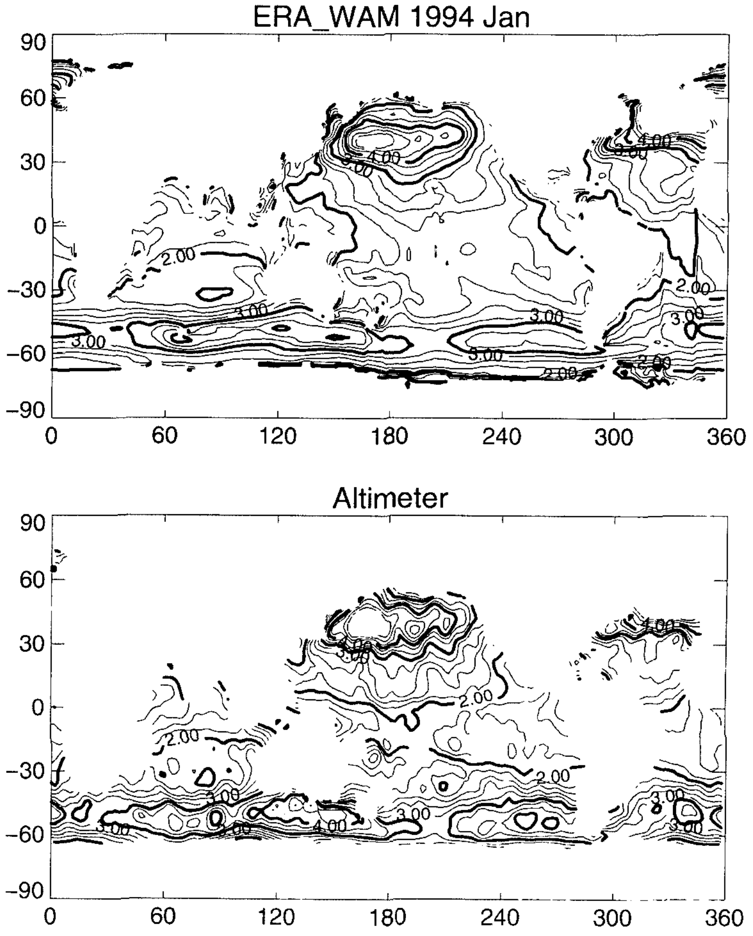

Fig. 1. Monthly snapshot of wave height. Units in m.

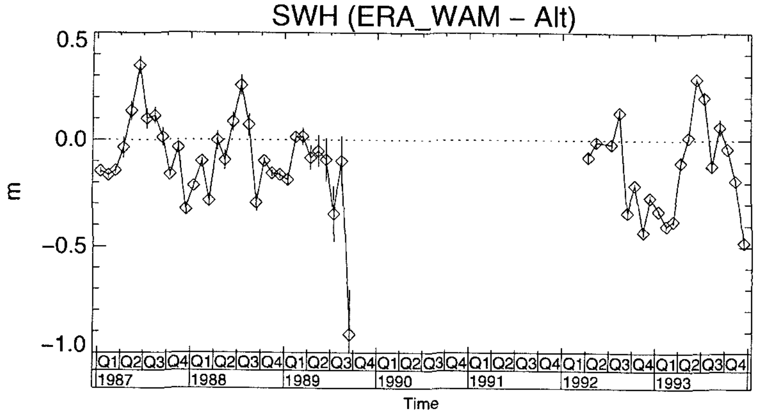

Fig. 2. Time series of SWH comparison: ERA_WAM SWH minus altimetric derivations. Q denotes the quarter of a year. There is a data gap between 3rd quarter of 1989 and 1st quarter of 1992. Vertical bars represent standard error.

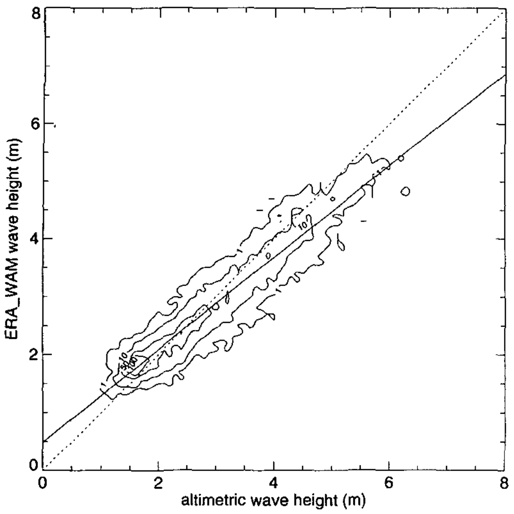

Fig. 3. Scatter plot of the comparison in Fig. 2. The solid line is a linear regression line and the dotted line is the one-to-one line. The contours represent the number of points.

small wave heights the ERA_WAM wave heights are larger.

We attribute the above discrepancy to the fact that for high winds the ERA_WAM system underestimates wave heights, because the ERA vector wind misses the peak winds due to the spatial and temporal resolutions of the ERA model (Sterl *et al.*, 1998). This argument is confirmed by the comparison of ECMWF and NASA scatterometer vector winds: ECMWF underestimates the wind on a spatial scale less than 300 km (Liu *et al.*, 1998).

For low winds, one of the reasons for the greater ERA_WAM wave heights may be that shipboard wind measurements tend to overestimate 10-m winds (Halpern *et al.*, 1994). Since shipboard wind measurements are assimilated into ERA, the effect would lead to greater ERA wind speed.

It should be noted that the above attribution of SWH variability to wind speed is based on the following assumption: on a time scale of a month and a spatial scale of our grid size (1.5° to 2°), the wave height is determined mostly by wind speed. Development of wind-driven waves is described by *wind speed, fetch* (the size of an area that wind stress is applied) and *duration* of winds. For waves with SWH smaller than about 10 m s^{-1}, when wind blows over a fetch greater than 100 km and longer than 10 hrs, SWH is determined solely by wind speed (Pierson *et al.*, 1955). In other words, waves are fully developed. Since the size of monthly winds over open oceans is within ~ 15 m s^{-1} (e.g., www.ssmi.com), our assumption is most likely to be valid.

2) Utilization of the Comparison Result

Knowledge on the accuracy of a numerical weather prediction model such as ECMWF is important since the model is used operationally. Here we present methods for determining the errors in ERA *wind speed using the errors in the ERA SWH.* Since input wind speed is found to be the critical parameter in the wave model, the ERA_WAM wave height is considered to be a good representation of the ERA wind speed. For this purpose, we allocate the difference between the altimetric and ERA_WAM SWHs solely to the error in the ERA product. The underlying assumption is that the altimeter SWHs are the truth. The following derivation is independent of the validity of this assumption.

From, systematic error in the ERA_WAM wave height is the difference between the regression line and the altimetric wave height, and is given as:

$$0.48 - 0.21 \times (\text{altimetric SWH}) \ (\text{in m}) \qquad (1)$$

Random error in the ERA_WAM wave height is the scatter about the regression line, that is, the widths of the contours in the figure. The widths are uniform with respect to the abscissa values. This means that the magnitude of random error is independent of the magnitude of the signal, altimeter wave height. Thus the random error should be treated as an absolute value. The distribution of the scatter about the regression line has a Gaussian shape with a constant standard deviation of 0.23 m.

The systematic and random errors in the ERA_WAM SWH may define errors in the wind speed using the equation (Janssen and Komen, 1984; Sterl *et al.*, 1998):

$$\mathrm{SWH} = \frac{\beta}{g} \,|(\mathrm{u}_{10}, \mathrm{v}_{10})|^2, \tag{2}$$

where β is the dimensionless growth rate of a wave (0.22 for a fully developed sea), g the gravitational acceleration and (u_{10}, v_{10}) is a u- and v- wind vector at 10-m height from the sea surface. From the above equation, it follows:

$$\frac{\delta\,|(\mathrm{u}_{10}, \mathrm{v}_{10})|}{|(\mathrm{u}_{10}, \mathrm{v}_{10})|} = \frac{\delta\,\mathrm{SWM}}{2\mathrm{SWH}} \tag{3}$$

Incorporating the systematic error in the wave height into Eq.3 gives

$$\sigma_{|(\mathrm{u}_{10}, \mathrm{v}_{10})|,\ \mathrm{sys}} = \frac{|(\mathrm{u}_{10}, \mathrm{v}_{10})|}{2} \times \left[\frac{gm}{\beta\,|(\mathrm{u}_{10}, \mathrm{v}_{10})|^2} + \mathrm{n}\right]$$

where m and n are the regression coefficients in (1): 0.48 and -0.21, respectively.

Regarding the random error in the ERA wind speed, applying the estimate of the random error in the significant wave height ($\sigma_{SWH,\ ran}$) to the formula for the error in the wind speed, Eq. 3, gives

$$\sigma_{|(\mathrm{u}_{10}, \mathrm{v}_{10})|,\ \mathrm{ran}} = \frac{g}{2\beta\,|(\mathrm{u}_{10}, \mathrm{v}_{10})|}\,\sigma_{SWH,\ ran},$$

where $\sigma_{SWH,ran} = 0.23$ m from the above.

3) Decadal Variability in Wave Height

The Pacific Ocean exhibits decadal scale oscialltions in sea surface temperature (SST) and wind fields (Mantua *et al.*, 1997). Noting the relationship between wave height and wind fields (Eq. 2), we examined if there is similar decadal trend in wave height (Fig. 4). There is clear decrease in SWH around 1989, when SST shows a decadal signal (Mantua *et al.*, 1997). Prelimi nary explanation of this synchronization is: around 1989, there is higher than normal SST in the eastern midlatitude Pacific and lower than normal SST in the western part; this generates the anomalous easterly wind (it may be possible that wind anomaly causes SST anomaly); since the mean wind field here is westerly, the absolute wind speed decreases, resulting in the smaller SWH.

4. Conclusions

We extracted significant wave height (SWH) using several altimeter missions from 1987 ~ 1995 over the Northwest Pacific. Comparison in SWH between

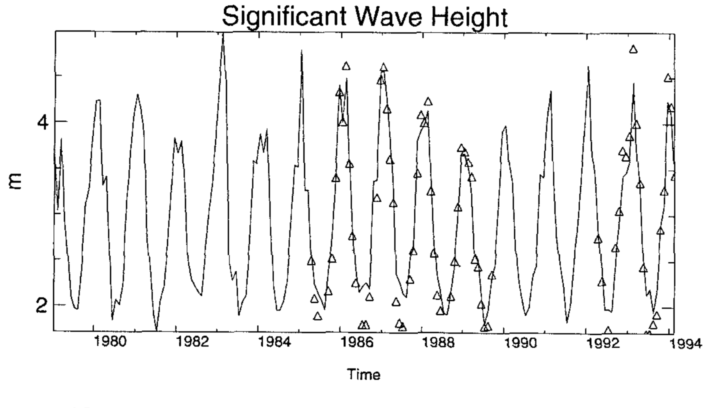

Fig. 4. Monthly mean values of SWH from ERA_WAM (solid) and altimeters (triangles), averaged over (170-210°E) × (25-45°N).

altimetric derivations and ECMWF reanalysis model products shows that: for large wave heights, the ERA wave heights are smaller than the altimetric ones, while for small wave heights the ERA wave heights are larger. These discrepancies are attributed to the underestimation of the ERA model and the overestimation of buoy in situ data assimilated into ERA model. Finally we presented formulae for determining errors in wind speed using the errors in SWH.

Acknowledgements

I am very much grateful to P.D. Cotton at Satellite Observing Systems, UK, for the altimeter SWH data and essential discussions. A. Sterl in the Royal Dutch Meteorological Institute, The Netherlands, is thanked for kind provision of the ERA_WAM data and fruitful comments on the comparison results. Comments by an anonymous reviewer were very helpful for clarifying the contents. The Ministry of Science and Technology (MOST), through a grant "Development of a mobile terminal for a data collection system and its utilization", and the Ministry of Environment (MOE) are acknowledged for supporting this research. Part of the research was conducted at Jet Propulsion Lab., California Inst. Tech., USA.

References

Fu, L.L. and A. Cazanave, 2001. *Satellite altimetry and earth sciences*, Academic Press, San Diego, 463p.

Gibson, J.K., P. Kallberg, S. Uppala, A. Hernandez, A. Nomura, and E. Serrano, 1997. ECMWF *re-analysis project report series: 1. ERA descriptions,* ECMWF, 72p.

Halpern, D., A. Hollingsworth and F. Wentz, 1994. ECMWF and SSM/I global surface wind speeds, *J. Atmos. Oceanic Technol.,* 11: 779-788.

Janssen, P.A.E.M. and G.J. Komen, 1984. An operational coupled hybrid wave model, *J. Geophys. Res.,* 89: 3635-3654.

Komen, G.J., 1994. *Dynamics and modelling of ocean waves*, Cambridge Univ. Press, Cambridge, 532p.

Liu, W.T., W. Tang and P.S. Polito, 1998. NASA scatterometer provides global ocean-surface wind fields with more structures than numerical weather prediction, *Geophys. Res. Lett.,* 25: 761-764.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997. A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.,* 78: 1069-1079.

Pierson, W.J., G. Neumann, and R.W. James, 1955. *Practical methods for observing and forecasting ocean waves,* US Naval Oceanographic Office, Publ. No. 603, 603p.

Simmons, A. and R. Gibson, 2000. *The ERA-40 project plan,* ECMWF, 60p. (http://www.ecmwf.int/research/era/Project/Plan/)

Sterl, A. and H. Bonekamp, 2000. Comparison of wind stress from ERA and from WAM, *Proc. of Second WCRP International Conference on Reanalysis,* WMO, Reading, U.K., pp. 149-152.

Sterl, A., G.J. Komen and P.D. Cotton, 1998. Fifteen years of global wave hindcasts using winds from the European Centre for Medium-Range Forecasts analysis: validating the reanalysed winds and assessing the wave climate, *J. Geophys. Res.,* 103: 5477-5492.

Wang, X. and V.R. Swail, 2002. Trends of Atlantic wave extremes as simulated in a 40-yr wave hindcast using kinematically reanalyzed wind fields, *J. Climate,* 15: 1020-1035.