Assimilation of significant wave height from EnviSAT in coastal wave model using optimum interpolation at variable wave height ranges

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In this study significant wave height (SWH) from EnviSAT radar altimeter data has been assimilated in the coastal ocean wave model SWAN (Simulating W Ave Near-shore). Optimum interpolation (OI) technique has been used for this purpose. A detailed validation of the model and the EnviSAT observations has been carried out prior to the assimilation for the determination of the error covariance matrix of prediction and observation. Validation of the EnviSAT data and the model is done using the in-situ buoy observations and Jason-1 altimeter data. Validation exercise reveals that at various ranges of SWH the error covariance changes significantly for both the model and the altimeter measurements. Result shows that the assimilation of EnviSAT data at various ranges of SWH, using optimum interpolation scheme in SWAN model improves the prediction by 15 -20%. Also there is reduction in the RMSE of SWH by 0.2 m. Multi-mission altimetric data assimilation using the same technique can improve the model prediction significantly.

Keywords: Altimeter, Wave prediction, Assimilation, Prediction, Topography

Introduction

Assimilation of remotely sensed observations in numerical ocean models (circulation as well as wave) is a frontline area of research in oceanography. Assimilation mostly helps in improvement of the hind-cast and forecast capabilities of the models. Coastal wave prediction is a challenging task because of various complexities such as bottom friction, nonlinear wave-wave interaction, refraction etc. Moreover, there are inevitable inaccuracies in forcing data (winds). But situation has improved dramatically in recent years with the availability of good quality wind data from satellite-borne scatterometers. Still, the hind-casts and forecasts are not accurate, because of inherent limitations of numerical models like incomplete physics, non-availability of accurate initial conditions etc. It is thus imperative to explore various techniques of assimilation of data for improving the hind-cast and forecast capabilities of numerical sea state models. Present study aims in assimilation of significant wave height (SWH) from EnviSAT radar altimeter in the 3rd generation coastal ocean wave model SWAN (Simulating W Ave Near-shore). Optimum interpolation technique has been used for this purpose.

Altimeter instruments onboard satellites and other air borne platforms are the nadir looking microwave radars that are used for measurements of significant wave height (SWH) and the wind speed over the oceans. SKYLAB from NASA, launched in 1972 has marked a modest beginning for the satellite altimetry followed by GEOSS-3, SEASAT, GEOSAT, ERS1&2, TOPEX/POSEIDON etc. All these missions are landmarks in field of altimetry with huge data resource that has been used for oceanic process studies for decades. EnviSAT altimeter data is primarily used for ice cover monitoring, land topography mapping, and coastal process studies. The exact validation of the wind and wave product is required for the applicability of the data in various studies. Further the data assimilation requires knowledge of the weights given to the data and the first-guess (FG) field. These weights depend on the ratio between the first-guess and observation errors. The error associated with the space based observations is therefore extremely crucial. Requirement of error estimates were also highlighted by certain study. In this study a details validation of the wind and waves has been carried out prior to the assimilation of the EnviSAT data in the model.
Materials and Methods

The EnviSAT radar altimeter data has been assimilated in the 3rd generation coastal ocean wave model SWAN. Model has been forced using the atmospheric wind from Global Data Assimilation System (GDAS). The 3rd generation spectral wave model SWAN used for this study is based on Wave Action Balance Equation with sources and sinks. Mathematically it is given by:

\[
\frac{\partial S}{\partial t} + \frac{\partial (C S N)}{\partial x} + \frac{\partial (C S N)}{\partial y} + \frac{\partial (C S N)}{\partial \sigma} + \frac{\partial (C S N)}{\partial \theta} = \frac{S}{\sigma} \quad \ldots \ (1)
\]

where \(x, y\) are spatial variables, \(t\) is time and \(\sigma\) and \(\theta\) are the relative frequency and direction of the propagating wave respectively. Term \(C\) with respective subscript represents the propagation velocities in \(x, y, \sigma\) and \(\theta\) space respectively. \(N(\sigma, \theta)\) is the two-dimensional wave action density spectrum and \(S(\sigma, \theta)\) represents the source and sink terms as

\[
S(\sigma, \theta) = S_{in}(\sigma, \theta) + S_{nl}(\sigma, \theta) + S_{w}(\sigma, \theta) + S_{wc}(\sigma, \theta) + S_{bf}(\sigma, \theta) \quad \ldots \ (2)
\]

where \(S_{in}(\sigma, \theta)\) represents the wind input and is normally given using the resonance and feedback mechanism. \(S_{nl}(\sigma, \theta)\) is non-linear interaction term that is responsible for the energy redistribution to the higher and lower frequency waves. \(S_{w}(\sigma, \theta)\) deals with the energy dissipation due to white-capping processes. \(S_{wc}(\sigma, \theta)\) and \(S_{bf}(\sigma, \theta)\) represent the energy dissipation due to bottom friction and depth induced breaking respectively.

The present study has been undertaken for the Indian Ocean region covering Eastern Arabian Sea and North Indian Ocean between 60°-90°E longitudes and 10.5°-22.5°N latitudes. The spatial resolution of the model is 0.5° x 0.5°. Model output is at every 6 hours.

The 6 hour analysis wind field from NCEP, Global Data Assimilation System (GDAS) available at a horizontal resolution of 1° x 1° for the year of 2005 is used both for the forcing SWAN.

EnviSAT radar altimeter was based on the heritage of ERS-1 satellite. It is a nadir looking, dual frequency, pulse limited radar altimeter onboard Envisat satellite. Envisat was launched in March 1st, 2002 in a sun synchronous, polar orbit at inclination of 98.55°, with a life time of 5 years. Orbital height of Envisat was 800 km. It operates at the nominal frequency of 13.575 GHz in Ku Band as a compromise to affordable antenna dimensions and attenuation due to the ionosphere. It also operates at the S-band at 3.2 GHz for the purpose of the rain detection and flagging. Envisat has a repeat cycle of 35 days. It measures ocean surface wind and significant wave height at both the frequencies. In this study the SWH at Ku band has been assimilated in the model. Prior to that Envisat altimeter wind and Ku-Band SWH for 2005 has been compared with in-situ observations of wind and wave from NDBC buoy and Jason-1 satellite data.

The Jason-1 satellite was a joint NASA-CNES project which was placed into orbit December 7, 2001, by a Boeing Delta 2 launcher from Vandenberg Air Force Base (VAFB), California. Jason-1 is designed to match or exceed the performance of its predecessor Topex/Poseidon. It has a circular orbit at a height of 1336 km and 66° inclination angle with a repetivity of 10 days covering 95% of ice-free ocean. Repeat cycle of the Jason-1 is 10 days. Jason-1 payloads include the dual frequency Poseidon-2 altimeter for the ocean state observations; along with a Jason microwave radiometer (JMR) for the wet tropospheric correction and DORIS instrument for determination of precise orbit. Jason-1 altimeter nominally operates at nominal frequency of Ku band (13.6 GHz) and C band (5.3 GHz) respectively.

The in-situ observations from the buoys are rare over the global oceans in particular near the Indian Ocean. There is limited number of shallow water and deep water buoys in the global ocean which provides the accurate ocean state information at high temporal resolution. In this study the hourly in-situ observations from the global NDBC buoys have been used for the purpose of inter-comparison with the Envisat data for the year 2005. Observations of wind speed and the significant wave height are first co-located with the Envisat data and then compared.

Before assimilation of the Envisat data, the data itself is compared to the in-situ buoy observations from NDBC along with the Jason-1 altimeter data in order to find out the error covariance in the observation. Range wise root mean square error of the altimeter wind and waves with in-situ observations and the Jason-1 has been calculated. Model predictions are also compared to the buoy observations in order to access the error covariance in the prediction. Once the error covariance in the model prediction and the observations are known the
assimilation of the EnviSAT data using the optimum interpolation is done.

Assimilation scheme is based on the wave model now cast i.e. the background field of wave height and the observations (altimeter wave height) which generates the analyzed model state. The analyzed wave heights are used to scale the model spectra. These directional wave spectrums are assimilated simultaneously in a multi time level scheme over an assimilation window of 6 hours. The first step of the algorithm is to compute the model forecast, which is then interpolated to the observational locations. Afterwards the observational innovations which is the difference between predicted and observed values of SWH are calculated. Finally the analyzed field is cast as the sum of the background field and field of innovations weighted by optimum weights. The choices of optimum weight are based on the prior estimates of the forecast and the observational error covariance:

\[
X^a = X^b + \sum_{i} W_i (X_i - X^b_i) \quad \text{... (3)}
\]

where, \(X^a\) is the analyzed field, \(X^b\) is the background field from the now-casting of the model, \(X_i\) is the observation at some arbitrary location at \(i\), \(H\) is the space operator to interpolate the background field to the observational point. The optimal weight is nominally given as:

\[
W = PH^T (RPH^T + R)^{-1} \quad \text{... (4)}
\]

where \(P\) is the error covariance in the prediction and \(R\) is the error covariance in the observations. The analyzed SWH field is then used to scale the model spectra.

**Results and Discussion**

The EnviSAT derived wind and Ku-band wave height were first of all compared with the hourly in-situ observations from NDBC co-located within 20 Km and the temporal interval of 30 minutes. Fig. 1 shows the comparison of the EnviSAT measured and observed wind speed for year 2005. Fig. 1 clearly indicates that the wind products are in fairly good agreement with the observations with a low bias of 0.0375 m/s. At a few instances of high observed wind conditions the EnviSAT has underestimated. On the other hand EnviSAT measured wave products in Ku-band is compared with the in-situ buoy observations. EnviSAT measured SWH at the lower observed wave conditions shows overestimations as shown in Fig. 2.

However at the higher observed SWH the EnviSAT estimates are found to be accurate. When compared to the collocated measurement of Jason-1 SWH as shown in Fig. 3b, the EnviSAT measurements nicely match to the Jason -1 measurements. Fig. 3a shows the comparison of the EnviSAT measurements of wind speed with corresponding Jason 1 measurements.

The trend of RMSE for the wave height has been shown in Fig. 4. At lower wave height ranges from 0-1m the RMSE are more which reduces considerably at the higher wave height ranges. This can be due to the fact that the accuracy of measurements is 0.5 m
and any measurement under this can contribute towards errors in the SWH in range of 0-1m. RMSE are considerably lower at the medium ranges of wave heights between 1-5 m. Beyond this range the errors are found to be growing gradually. In both cases of wind and waves the errors involved are well within the targeted ranges of accuracy which is 0.5 m for SWH and 2 m/s for wind speed. Thus EnviSAT wind and wave products can be considered to be of extremely high quality. As the Indian Ocean region is typically governed by the wave heights of the ranges of 0-3 m the average error in such ranges are typically of the order of 0.2 m in EnviSAT measurements.

Model estimations on the other hand have an error of 0.5 m (approx). Thus from this we calculate the error covariance for the prediction $P$ and the observation $R$. EnviSAT data is then assimilated in the SWAN model after a spin up of the model between 01st Jan-31st Jan 2005. Assimilation window is typically 12 hours for the passes over the designed study area. RMSE of the SWH from control run and assimilation run when compared to the measured SWH from Jason-1 has been shown in Fig. 5. Assimilation has been carried out for the period of 5 months between Feb–June, 2005. Typically the improvement in SWH after assimilation is around 15%. This percentage improvement is achieved after assimilating only the EnviSAT data. However the multi-mission data assimilation would be more beneficial for the further improvement of the model simulation.

**Conclusion**

The study aims to assimilate the EnviSAT SWH assimilation in the coastal ocean wave model SWAN. Prior to the assimilation the detailed validation of the
EnviSAT wind and wave products have been carried out. Wind and waves are compared to the in-situ observations as well as the Jason-1 measurements for year 2005. Validation exercise shows that typically the range of error in case of the SWH is 0.2 m in case of EnviSAT radar altimeter and 0.5 m in case of the model. Thus the EnviSAT data has been assimilated in the SWAN model and the corresponding simulation from both control run and assimilation run has been compared with Jason-1 measurements. Simulation is found to be improved by 15-17% using the OI scheme. Multi mission data assimilation is thus required for further improvement of the simulation of SWH.

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