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Impact of Oceansat-I MSMR data on analyzed oceanic winds and wave predictions

Vihang Bhatt *, Abhijit Sarkar, Raj Kumar, Sujit Basu, Vijay K. Agarwal

Oceanic Sciences Division, Meteorology and Oceanography Group, Space Applications Centre (ISRO), Ahmedabad 380 015, India

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Abstract

The present study makes an assessment of the impact of satellite data on ocean surface wind analysis and predicted wave heights. The surface wind analysis data utilized in this study were generated by assimilation of satellite data in numerical weather prediction models. The impact of these winds on the wave heights predicted by a third generation ocean wave model (WAM) was also studied. Results of several numerical experiments involving analysis products generated with a multi-frequency scanning microwave radiometer (MSMR) on board the Oceansat-I satellite and their comparison with those generated by the SSM/I radiometer onboard the DMSP satellites, as well as without these satellite products, have been presented. Extensive comparison results of MSMR ingested surface wind analyses (and corresponding model predicted wave heights) with ocean buoy data and co-located and concurrent measurements of the Topex/Poseidon altimeter over the Indian Ocean are presented in this work. The impact of satellite derived winds was also seen through time series analysis. The results of the experiments carried out show that ingestion of MSMR data produces significant improvement in the surface wind analysis and predicted wave heights for the corresponding winds compared to those generated without ingestion of satellite winds. The experiments also show that the surface wind analysis with MSMR ingested surface wind speed is almost as good as that obtained with SSM/I.

Keywords: Oceansat-I; MSMR; SSM/I; Buoy; WAM; Analyzed winds; Wave height

* Corresponding author. Tel.: +91-079-26916058; fax: +91-02717-235431.
E-mail address: vihang-75@yahoo.com (V. Bhatt).

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1. Introduction

Surface winds over global oceans are critical for driving numerical sea state prediction models, like ocean wave and ocean circulation models. Hence the accuracy, density and observation frequency of ocean surface winds are expected to have a perceptible influence on the prediction of sea state parameters like waves, currents, sea level, etc. Observations of ocean surface winds from space borne sensors can be a potential data source for driving the numerical sea state prediction models. The various space borne wind sensors capable of providing oceanic wind data are the scatterometer, altimeter and radiometer. While scatterometers provide wind vectors, altimeters and radiometers provide only wind speed. However, even these wind speeds can be used in the assimilation system of numerical weather prediction centers to generate gridded wind vector products. These wind vectors can in their turn be used to drive numerical ocean circulation and ocean wave models.

The Indian Space Research Organization launched a satellite called Oceansat-I on 26 May 1999. The satellite, deployed in a sun-synchronous orbit at an altitude of 720 km, covers the globe every two days. This satellite carried on board a multi-frequency scanning microwave radiometer (MSMR) to cater to a swath of 1360 km. MSMR is a four-frequency, dual-polarized scanning microwave radiometer to measure the brightness temperature of the earth–atmosphere system. The frequencies at which MSMR operates are 6.6, 10.65, 18.0 and 21.0 GHz (Misra et al., 2002). These frequencies are appropriate for deriving geophysical parameters such as sea surface temperature, sea surface wind speed, integrated water vapour and cloud liquid water in the marine atmosphere. The parameters were retrieved by a radiative transfer based statistical algorithm by Gohil et al. (2000) and were subjected to validation by Ali et al. (2000). Sharma et al. (2002) have described in detail the identification of large-scale atmospheric and oceanic features from Oceansat-I. They also studied zonal averages of these parameters to examine the consistency of MSMR data over large spatial scales. In short, their analysis showed the potential use of MSMR products in studying various atmospheric and oceanic phenomena. In the present study, we seek to demonstrate the potential use of a product that can be derived from MSMR data products. This is the gridded wind vector obtained by using the MSMR wind speeds in the assimilation system of a numerical weather prediction center.

Winds at the surface and at multiple levels in the overlying atmosphere are important for numerical models for the creation of initial fields for atmospheric models, while for ocean state models, surface winds play the key role in driving the models. Atlas et al. (1996) first described the technique of assimilation of ocean surface wind speed derived by a microwave radiometer in an atmospheric general circulation model (AGCM). An exercise was carried out by Rizvi et al. (2002) and Kamineni et al. (2002) to assimilate two MSMR derived geophysical products (viz., the surface wind speed and integrated water vapour) in addition to global meteorological data received via Regional Telecommunication Hub (RTH) in the Global Data Assimilation System (GDAS) used in the analysis/forecast system of the numerical weather prediction model being run at the National Centre for Medium

Range Weather Forecast (NCMRWF), New Delhi. The six-hourly gridded analyzed surface wind fields thus generated (with the inclusion of MSMR data) as well as the similar analyzed surface wind fields (without inclusion of MSMR data) have been used in this work. We have also used surface wind analysis generated with the inclusion of wind speed derived by SSM/I (Wentz, 1997) onboard the US Navy's DMSP satellite. Analyzed wind fields with the inclusion of SSM/I were used since SSM/I is a state-of-the-art operational microwave radiometer. It is thus quite natural to evaluate the performance of MSMR vis-à-vis SSM/I.

Since these analyzed wind fields are vital for driving the sea state models, one has to first assess the accuracy of these winds. In the present work, such an attempt has been made by comparing them with co-located buoy data and Topex/Poseidon (T/P) altimeter data over the Indian Ocean. These analyzed wind fields were used to drive the global ocean wave model (WAM). The accuracy of the waves thus predicted was also assessed by comparing the model predicted wave heights with those measured by the Indian Ocean buoy and T/P altimeter measurements.

2. Data used

The wind data used in carrying out the experiments are (i) surface wind analysis generated without assimilation of MSMR or SSMI data (July and August 1999), (ii) surface wind analysis generated with assimilation of MSMR data (July and August 1999; May 2001) and (iii) surface wind analysis generated with assimilation of SSMI data (May 2001). The surface wind analysis is available at six-hourly interval and with a spatial resolution of $1.5^\circ \times 1.5^\circ$.

We have also used surface wind and wave data measured by several deep ocean buoys, deployed by the National Institute of Ocean Technology in the seas around India. Wind and wave measurements of these buoys are available every three hours.

The Topex/Poseidon satellite system carrying the state-of-the-art altimeter sensor, launched on 10 August 1992, has been providing wind and wave (besides sea level) information over global oceans regularly. The revisit period of each track is 9.9156 days with a track separation of 316 km at the equator (Fu et al., 1994). Such resolutions and density of data cover make it an ideal sensor for studies on wave climatology. The T/P geophysical data record includes the significant wave height and surface wind speed. The significant wave height is derived from the average wave form of radar returns. There are several algorithms for wind speed retrieval; the one being used for geophysical retrieval is that of Witter and Chelton (1991). T/P derived wind speed values pertain to winds at the height of 10 m.

In the present study, we have used T/P derived significant wave height and sea surface wind speed for July–August 1999 and May 2001. These data periods were selected due to the availability of analyzed wind fields during these periods.

3. Wave model used

The wave model used in this study is a state-of-the-art third generation wave model (WAM Cycle 4) (WAMDI Group, 1988; Gunther et al., 1992; Komen et al., 1996). The model is formulated in spherical coordinates and can be run for global as well as for regional grids. It solves the energy balance equation for two-dimensional wave spectrum $F(f,\ \theta,\ \lambda,\ \varphi,\ t)$, which is a function of frequency f, direction θ, longitude λ, latitude φ and time t:

$$\frac{\partial F}{\partial t}+\frac{\partial}{\partial \varphi}(\dot{\varphi}\cdot F)+\frac{\partial}{\partial \lambda}(\dot{\lambda}\cdot F)+\frac{\partial}{\partial \theta}(\dot{\theta}\cdot F)=S \tag{1}$$

$\dot{\varphi}$, $\dot{\lambda}$ and $\dot{\theta}$ are the rates of change of the position and propagation direction of a wave packet travelling along a great circle path. The source function S is represented as a superposition of the wind input S_{in}, white-capping dissipation S_{dis}, and nonlinear transfer S_{nl}

$$S=S_{\mathrm{in}}+S_{\mathrm{dis}}+S_{\mathrm{nl}} \tag{2}$$

The source term for wind input is given in Eq. (3):

$$S_{\mathrm{in}}=\gamma\cdot F \tag{3}$$

where γ is the growth rate of the waves and is a function of friction velocity, wave direction, wind direction, the phase speed of the waves and the roughness length. The dissipation term is represented as

$$S_{\mathrm{dis}}=\gamma_{\mathrm{d}}\cdot F \tag{4}$$

γ_{d} is the proportionality constant for dissipation of waves, the exact form of which is given in WAMDI Group (1988). The wave model is capable of predicting the ocean wave spectrum. The spectrum has been decomposed into 26 frequency bins and 12 directional bins. The 26 frequencies of the model range from 0.04 to 0.41 Hz on a logarithmic scale with $\Delta f/f=0.1$, and the direction bins are at 30° resolution. In the present study, significant wave height computed using this spectrum has been used for the analysis. The spatial resolution of the wave model used in this study is $1^{\circ}\times 1^{\circ}$ and the integration time step is 20 min. The wind analysis data were interpolated to the wave model grids using the bi-cubic spline method and the linear time interpolation scheme. The model runs were made with surface wind analysis for the Indian Ocean covering the region bound by latitudes/longitudes 50° E–100° E, 10° S–25° N.

4. Analysis

As stated earlier, the main objective of the present study is to evaluate the changes in accuracy levels of the new surface analysis of winds (after MSMR derived wind speeds were ingested in the GDAS at NCMRWF) and also to assess the impact of these new analyzed winds on the accuracy of wave heights generated by the numerical wave model. The evaluations were carried out through comparisons with wind speeds and wave heights derived by ocean buoys deployed in the seas around India and T/P altimeter measured wind speed and significant wave height data. We have divided our study into five distinct experiments.

In the first experiment, we have compared the analyzed wind speeds and the wave heights predicted by the wave model using these analyzed winds with the co-located buoy wind speeds and wave heights. For assessing the impact of MSMR winds, we have used the analyzed winds with the inclusion of MSMR as well as the analyzed winds without the inclusion of MSMR.

In the second experiment, buoy data have been replaced by T/P altimeter data. Although the importance of buoy data as in situ data can never be underestimated, T/P data have been validated quite extensively and are believed to be reasonably accurate (Gower, 1996; Cotton et al., 1997; Kshatriya et al., 2001) and can serve the purpose of being used as reference. Also, an enormous number of co-located T/P observations are easily available while the number of co-located buoy observations are relatively few.

The third and fourth experiments aim at the comparative study of two analyzed surface wind fields—one generated with assimilation of MSMR derived surface wind speeds and the other generated with assimilation of SSM/I winds. As mentioned earlier, SSM/I is a state-of-the art sensor providing reasonably accurate ocean surface winds for nearly two decades (Hollinger, 1990). Hence, it is natural to evaluate the performance of the MSMR sensor by comparing the analyzed MSMR winds vis-à-vis analyzed SSM/I winds. In Experiment 3, we have used buoy data for intercomparison, whereas in Experiment 4, T/P data have been utilized. The wave model runs were made using both the analyzed winds using MSMR as well as the analyzed winds using the SSM/I. The quantitative evaluation of model derived wave heights was done through comparison exercises with respect to buoy measured and T/P altimeter derived wave heights.

5. Results and discussion

The numerical experiments reported in this paper have demonstrated the impact of satellite derived surface wind speed data after being included in the analysis system of a numerical weather prediction center. The results of Experiment 1 show that there is a remarkable improvement in the quality of surface wind analysis and subsequent model simulated wave heights after inclusion of the MSMR winds in the analysis since the RMS difference (RMSD) between analyzed surface wind speed and buoy wind speed is much less (1.8 m/s) than the RMSD between analyzed wind speed without inclusion of the MSMR winds (2.73 m/s) and the corresponding buoy wind speed. There is also a significant improvement (from 0.51 to 0.74) in correlation (Table 1). Fig. 1 shows the comparison of model analyzed wind fields with buoy wind speed for the months of July 1999 and May 2001. The inclusion of satellite data clearly shows the improvement in the wind speed, as is seen by the near 45° slope of its best fit line. Model winds without ingestion of the

Table 1
Comparison of surface wind analysis and predicted wave height with and without inclusion of MSMR data in assimilation, with buoy data (Experiment 1)

Year	Month	Number of points	Parameters	Range	RMSD	Correlation coefficient
1999	July	151	WS (m/s)	3.6–16.4	1.8 (2.73)	0.74 (0.51)
		153	SWH (m)	2–5.2	1.32 (1.43)	0.8 (0.79)

The results for 'without' MSMR data are given in brackets. In this and subsequent tables, WS represents analyzed wind speed and SWH represents significant wave height simulated by WAM.

MSMR data, however, show large bias and RMSD. Similarly, the comparison of wave height (Fig. 2) also reveals improvement in predicted wave height on inclusion of the MSMR data in the analysis. The number of points for comparison with buoy data in the first experiment was small, whereas the number of co-located, concurrent points of T/P altimeter data was large (Experiment 2). This led us to place more emphasis on comparison with T/P data. The results suggest that there is an improvement of 0.3 m/s (i.e., about 15%) in RMSD in wind speed and 0.24 m (about 25%) in RMSD for SWH, respectively (Table 2). Improvements, though small, were also noticed in correlation for wind speeds and significant wave heights. The results of impact of satellite derived surface winds on the model generated significant wave heights are consistent with those obtained in earlier studies

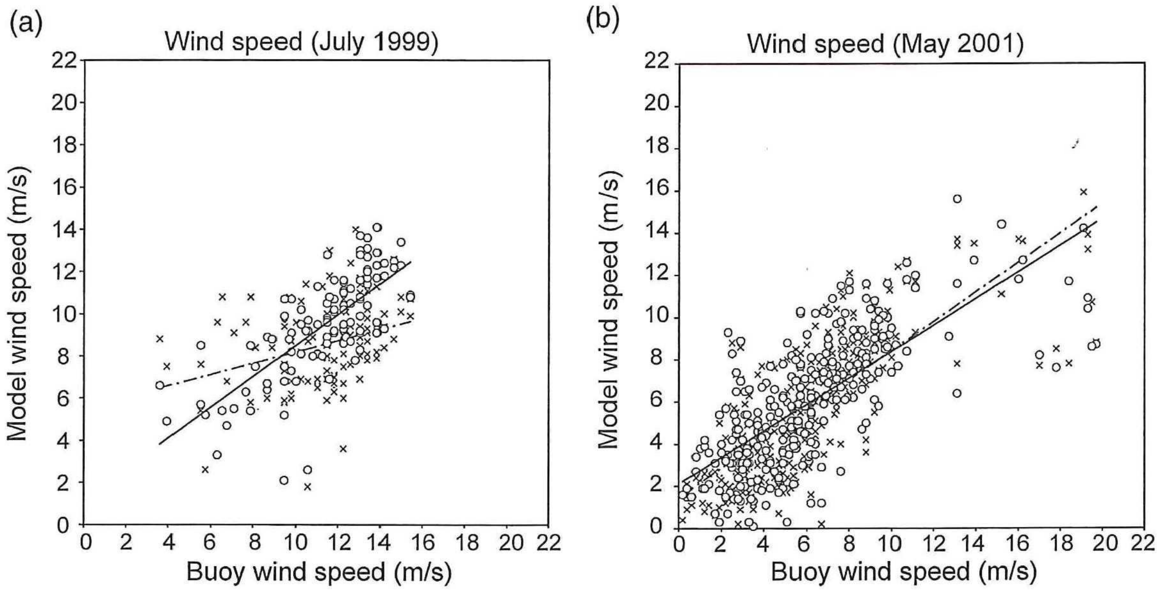

Fig. 1. Scatter plot of wind speed (atmospheric model vs buoy). (a) July 1999. (b) May 2001. In these figures, crosses indicate wind speeds whose ordinates represent wind speeds produced by the atmospheric model without ingestion of MSMR winds whereas open circles indicate wind speeds whose ordinates represent wind speeds produced by the atmospheric model with ingestion of MSMR winds. The solid line is the best fit line for the wind speeds with ingestion of MSMR winds whereas the dashed line is the best fit line for the wind speed without ingestion of MSMR winds.

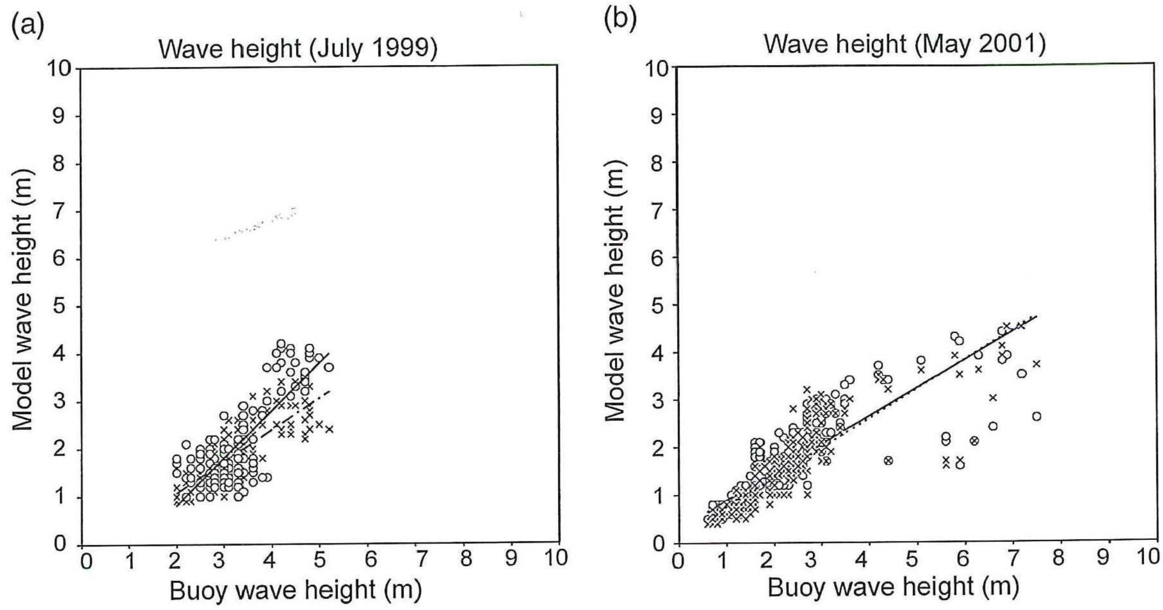

Fig. 2. Scatter plot of significant wave height (wave model vs buoy). (a) July 1999. (b) May 2001. The symbols and the lines have the same meaning as in Fig. 1. One only has to replace the words 'wind speed' by 'wave height'.

on the sensitivity of ocean waves (Kumar et al., 2000). Fig. 3 shows the comparison of model analyzed wind field with T/P derived winds. Though the improvement in this case is not significant, there is a definite impact of the MSMR data in model analyzed winds. The comparison of wave height with T/P data has been depicted in Fig. 4, which also shows improvement in the predicted wave height. In these figures, by 'model wind speed' we mean the analyzed wind speed with the inclusion of MSMR wind speed in the analysis system of NCMRWF, whereas by 'model wave height' we mean the wave heights simulated by the wave model forced by these analyzed wind fields.

Experiments 3 and 4 carried out with data of May 2001 suggest that the impact of MSMR wind speed and SSM/I wind speed on surface wind analysis and the resultant model predicted wave heights are comparable. For the case of wind speed, the two RMS differences are within 10% of each other, whereas for the case of SWH, the two RMS differences are within 5% of each other (Tables 3 and 4). The correlation with sea truth and T/P varied between 0.65 and 0.85. This brings

Table 2
Comparison of surface wind analysis and predicted wave height with and without inclusion of MSMR data in assimilation, with T/P altimeter data (Experiment 2)

Year	Month	Number of points	Parameters	Range	RMSD	Correlation coefficient
1999	July	3816 (3678)	WS (m/s)	0.6–16.8	2.27 (2.56)	0.75 (0.71)
			SWH (m)	0.6–6.0	1.13 (1.37)	0.73 (0.70)

The results for 'without' MSMR data are given in brackets.

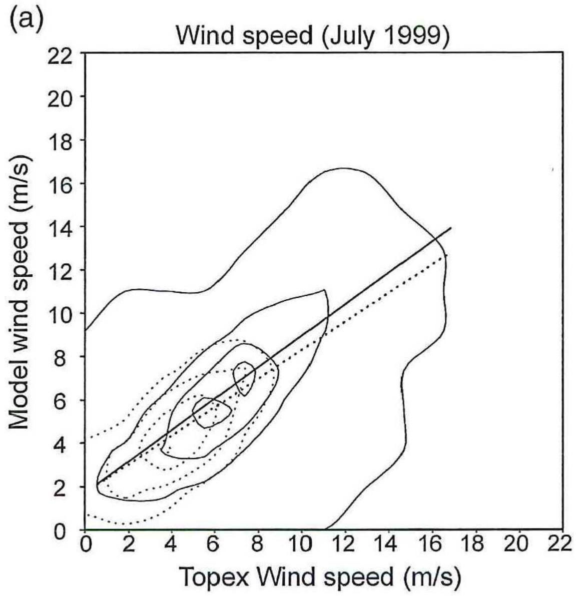

Fig. 3. Scatter plot of wind speed (atmospheric model vs T/P). (a) July 1999. (b) May 2001. In these figures, the solid contours indicate a cluster of points with the ordinates representing wind speed produced by the atmospheric model with ingestion of MSMR winds whereas the dashed contours indicate a cluster of points whose ordinates represent atmospheric model derived wind speeds without ingestion of MSMR winds. The solid line is the best fit line for the model wind speed with ingestion of MSMR winds whereas the dashed line is the best fit line for the model speed without ingestion of MSMR winds.

out the importance of assimilation of satellite derived surface winds for generation of the wind fields used for forcing the wave models.

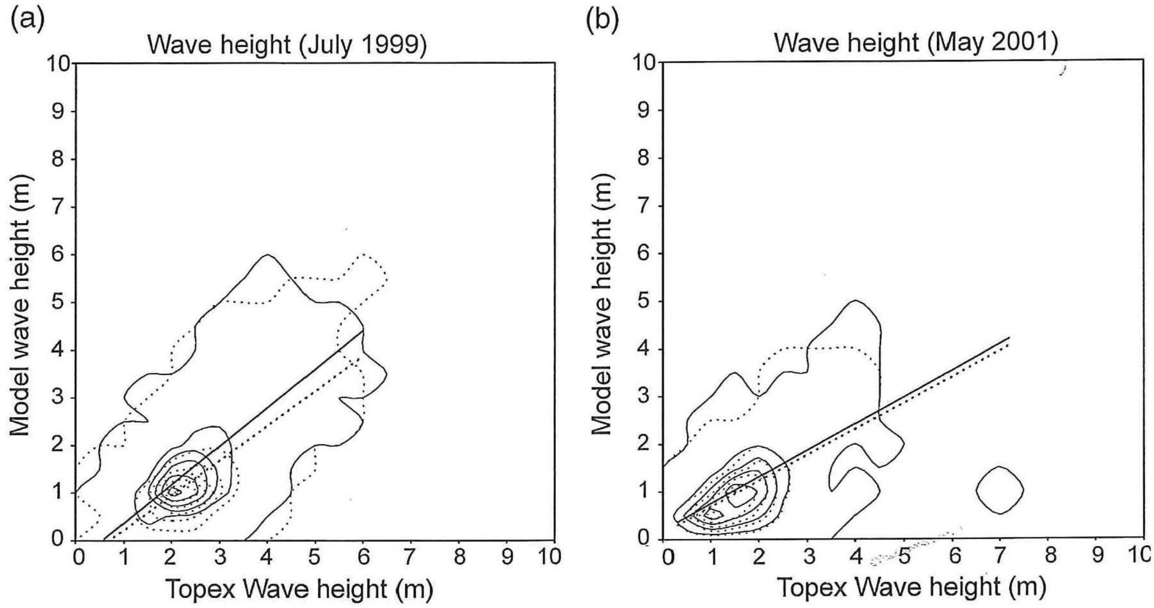

Fig. 4. Scatter plot of wave height (wave model vs T/P). (a) July 1999. (b) May 2001. The contours and the lines have the same meaning as in Fig. 3 with the words 'wind speed' replaced by the words 'wave height'.

Table 3
Comparison of surface wind analysis and predicted wave height generated with inclusion of MSMR data in assimilation and those generated with SSM/I data for the same period, with buoy data (Experiment 3)

Year	Month	Number of points	Parameters	Range	RMSD	Correlation coefficient
2001	May	301	WS (m/s)	0.2–22.16	2.47 (2.30)	0.72 (0.78)
			SWH (m)	0.6–7.5	0.88 (0.92)	0.85 (0.87)

The results for 'without' MSMR data (but with SSM/I data) are given in brackets.

Table 4
Comparison of surface wind analysis and predicted wave height, generated with inclusion of MSMR data in assimilation and those generated with SSM/I data for the same period, with T/P altimeter data (Experiment 4)

Year	Month	Number of points	Parameters	Range	RMSD	Correlation coefficient
2001	May	3671	WS (m/s)	0.6–15.6	2.24 (2.10)	0.66 (0.69)
			SWH (m)	0.3–7.2	0.82 (0.86)	0.62 (0.65)

The results for 'without' MSMR data (but with SSM/I data) are given in brackets.

In Fig. 5, we show the time series of analyzed wind speed with inclusion of the MSMR data. We also show the time series of analyzed wind speed without MSMR data as well as the time series of buoy wind speed for the purpose of comparison. In Fig. 6, we show the corresponding three time series for wave heights. The analysis clearly indicates that the ingestion of satellite winds brings the time sequence

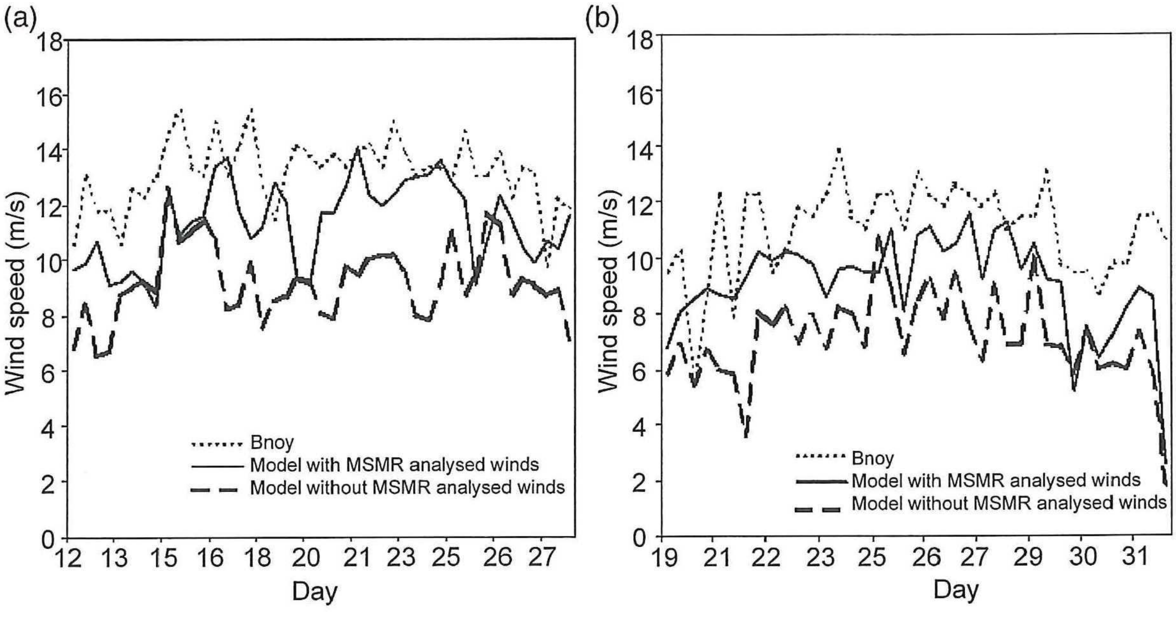

Fig. 5. Time series of wind speeds. (a) At the buoy location DS1 (15.5° N, 69.25° E). (b) At the buoy location DS3 (12.17° N, 90.75° E). In these figures, 'model' means atmospheric model.

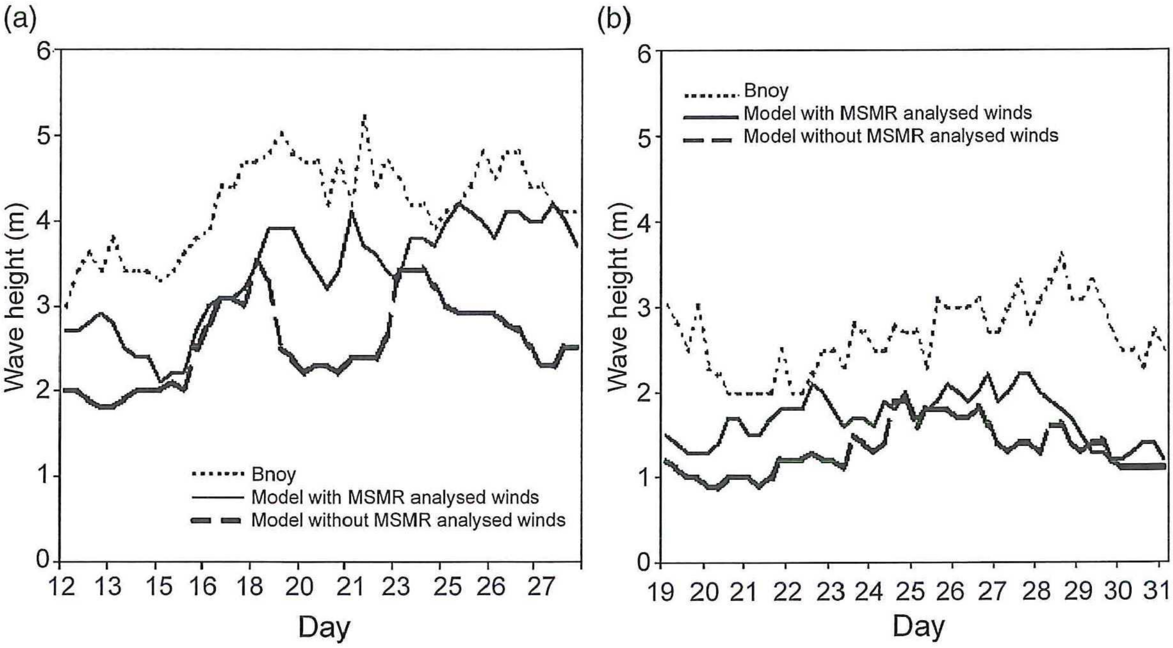

Fig. 6. Time series of significant wave heights. (a) At the buoy location DS1. (b) At the buoy location DS3.

curves for both winds as well as the wave height values closer to the curves obtained for buoy data. However, the new surface analysis underestimates the winds, especially during high sea conditions. This is reflected in the time series plots for wave heights too, indicating the need for corrections for such cases.

A representative difference plot (Fig. 7) shows the impact of the ingestion of MSMR winds on model estimated wave height. Fig. 7a shows the deviation of model predicted monthly mean wave height for July 1999 using MSMR ingested analyzed wind fields with those obtained with T/P altimeter measured wave height. Fig. 7b shows the deviation of wave heights without MSMR ingested analyzed wind fields. While the impact is small around the equator, it is moderate in the Bay of Bengal and strong in the Arabian Sea. Especially in the central and western Arabian Sea, the difference with mean T/P derived values is quite small (<1 m) after ingestion of satellite data, whereas in the case of Fig. 7b, the difference is approximately 1.5 m and more. The area average difference in wave height improves to 0.73 m on ingestion of satellite data from 1.12 m in the case of 'without satellite data'. Ingestion of satellite winds in the analysis system of numerical weather prediction centers can thus improve the quality of resultant surface wind analysis. Such analyzed wind fields have a significant positive impact on the prediction of oceanic waves.

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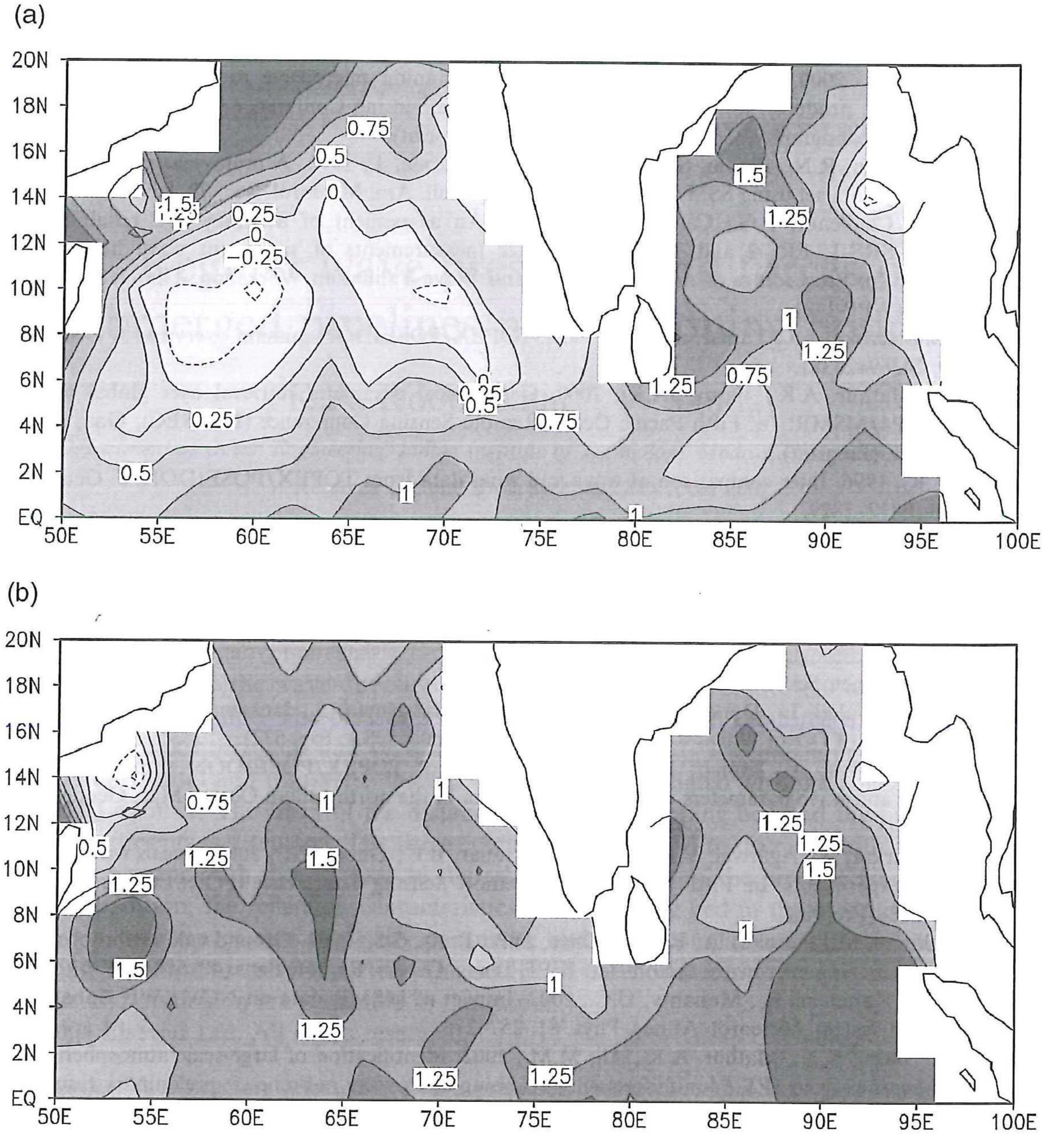

Fig. 7. The deviation of monthly mean (July 1999) significant wave heights generated by the wave model by two different wind products from those measured by T/P altimeter data. (a) represents the waves using winds produced by the atmospheric model with ingestion of MSMR winds and (b) represents the waves without ingestion of MSMR winds.

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