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Simulation of wind waves generated at deep sea by a tropical storm

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सार — वास्तविक प्रेक्षणों पर आधारित कुछ दाब प्रोफाइल का प्रयोग करते हुए सतह तरंगों के क्षैतिज वितरण व्युत्पन्न किए जाते हैं जो कि गहरे सागर में तरंगों के संख्यात्मक अनुरूपण के लिए प्रयोग में लाए जाते हैं। दाब प्रवणता, अपकेन्द्री, पृष्ठ घर्षण और कोरिऑलिस बल के चार मुख्य बलों का संतुलनवत् (क्वासि इक्विलिब्रियम) को माना गया है। परिचालन तरंग पूर्वानुमान के लिए ध्रुवी आरेख के रूप में तैयार तरंग चार्टों का उपयोग किया जा सकता है। यद्यपि मॉडल में प्रयुक्त अरैखिक समीकरण के हल के लिए कम्प्यूटर की सहायता की आवश्यकता है, प्रचालक पूर्वानुमानकर्त्ता को केवल साधारण प्राचलों जैसे केन्द्र में दाब गिरना, अधिकतम पवन की त्रिज्या और तूफान के संचलन की गति के प्रयोग की आवश्यकता रहती है। कुछ विश्वसनीय आंकड़ों के पश्च अनुमान से मॉडल के लिए उच्च कौशल अंक का संकेत मिलता है।

ABSTRACT. Using a certain pressure profile based on actual observations, horizontal distribution of surface winds are derived which are used for numerical simulation of waves in deep sea. A quasi-equilibrium of four major forces : pressure gradient, centrifugal, surface friction and coriolis force have been assumed. Wave charts prepared in the form of polar diagrams can be utilised for operational wave forecasting. Though the solution of the non-linear equations used in the model needs the aid of a computer the operational forecaster need to use only simple parameters like pressure drop at the centre, radius of maximum wind and the speed of movement of the storm. Hindcast of some reliable data indicate high skill score for the model.

1. Introduction

Shipping is the cheapest means of transportation of bulk and heavy cargo. The needs of the modern shipping industry are :

(*i*) Safety of navigation and weather routing,

(*ii*) Estimation of extreme values of waves and

(*iii*) Spectral distribution of waves.

Due to the importance of the global shipping in recent years, numerous empirical and numerical wave models have been developed in various parts of the globe. To prevent a ship from observing slamming or rolling in adverse wave conditions its speed or course need be changed. Different types of ships, *viz.*, a heavy deck cargo vessel, a tanker or a passenger liner deserve to be handled separately. Weather routing of ships, thus, become important economic and safety considerations. Meteorological or oceanographic information in the form of forecast for most favourable route saves time and reduces risk to an ocean liner.

Generation of ocean waves in a storm field is mainly due to high wind speed and consequent energy transfer. Prominent investigators, like Sverdrup and Munk (1947), Phillips (1957), Bretchneider (1972), Mukherjee and Sivaramakrishnan (1977, 1981, 1983) have attempted to predict waves based on semi-empirical methods. W. M. O. manual (1976) on handbook of wave analysis and forecasting details some simple graphical methods of prediction of ocean waves. Dexter (1983) summarises some more recent methods of wave prediction. Recent trends are for predicting ocean waves based on energy balance equation containing five energy transfer processes. According to these methods, in order to maintain computational stability the relation between the time step and the grid interval need to be adhered to. This puts a serious constraint on the currently available computer memory in smaller centres. Moreover, the results of semi-empirical models are quite comparable with the numerical models in use now. Some amount of dependence on empirical relations is inevitable since our knowledge of the growth mechanism of wind waves in limited.

In the present paper an attempt has been made to first generate an wind field based on semi-empirical relations. A stationary cyclone will subject an air parcel in its field to four forces : (*i*) the pressure gradient force, (*ii*) the coriolis force, (*iii*) the centrifugal force and (*iv*) the friction force. In case of a moving cyclone a fifth force, the translatory force comes into existence. Out of these forces coriolis and storm motion forces depend linearly on the wind motion while the centrifugal and friction forces are proportional to the square of the wind speed. The pressure gradient force is, however, independent of wind speed.

2. Data and methodology

One of the serious constraints of wave prediction models is lack of reliable data over the Indian seas in order to have the model output verified. However, during May-June 1976 cyclone, some very valuable wave data were available from nearby stationary oil rigs in the Bombay High area. During Monex, USSR ships also recorded some valuable wave data which have been utilized. Some commercial ocean liners' data also have been utilized for wave height verification purposes. Wave data from a north Atlantic storm also have been used for model verification.

Assuming an exponential type of variation of surface pressure profile with distance from the centre, symmetric around the central pressure, we may write the mathematical expression as :

$$\frac{P_p - P_r}{P_p - P_c} = e^{-K' (r/R)^K} \tag{1}$$

where, P_r=surface pressure at radial distance r from the centre,

P_p and P_c being the peripheral and central pressure, K is the empirical power of exponent (1.5) and R is the radius of maximum pressure gradient taken as .75 times the radius of maximum wind (R').

Also, $K' = (K-1)/K$ (1a)

Adopting the concept of equilibrium wind from Myers and Malkin (1961) which is defined as that value of wind (direction and speed) at a point in the storm field such that $\frac{dv}{dt}=0$ and $\frac{d\beta}{dt}=0$. This simply implies that momentarily there would be no change in speed (v) or in the deflection angle (β) if the wind vector equals the equilibrium value.

Following Myers and Malkin (1961) the equilibrium wind equations are :

$$\frac{1}{\rho}\frac{\partial P}{\partial r}\sin\beta + \frac{1}{\rho r}\frac{\partial P}{\partial \theta}\cos\beta - K_t v^2 = 0 \tag{2}$$

$$\frac{1}{\rho}\frac{\partial P}{\partial r}\cos\beta - \frac{1}{\rho r}\frac{\partial P}{\partial \theta}\sin\beta - fv - \frac{v^2}{r}\cos\beta - K_n v^2 + v\,\frac{V_H}{r}\sin\theta = 0 \tag{3}$$

where, ρ is the density of air near surface, P is the surface pressure, θ is the azimuth angle (positive clockwise) from the direction of motion of the storm, β is the deflection angle, r is the radius vector of a point in the storm field, positive outward, V_H is the storm speed ; K_t and K_n are empirical constants relating tangential and normal components of friction to the square of the wind speed.

Simultaneous solution of Eqns. (2) and (3) using Eqn. (1) for the pressure distribution ($\partial P/\partial r$), we get the wind field (v_{ij}) at every grid point in a model or observed storm field for assumed values of K_t, K_n and V_H. The maximum sustained wind (v_m) is thus computed from the storm field. The values of the empirical constants are taken as :

$$K_t = 4.4 \times 10^{-3}\ \text{km}^{-1}$$
$$K_n = 4.0 \times 10^{-3}\ \text{km}^{-1}$$
$$\text{and } K = 1.5$$

The value of V_H is generally taken as 15 km/hr. Decreasing or increasing the value of V_H affects the output of the model wave heights directly.

The value of the maximum sustained wind speed (v_m) is used in the following equation (wave and water level prediction, 1981) to compute the maximum significant wave height (H_m) :

$$H_m = 5.03\ e^{(R' \triangle P/4700)} \left[1 + \frac{0.29\ \alpha\ V_H}{\sqrt{U_r}}\right] \tag{4}$$

$$\text{where, } U_r = 0.865\ v_m + 0.5\ V_H \tag{5}$$

Eqn. (5) is an expression generally used for calculating the maximum sustained wind speed (m/s) at 10 metres above the mean sea surface at radius r for a cyclone moving at slow speed (V_H). Here R' and $\triangle P$ are respectively the radius of maximum wind and the pressure drop at the centre. α is an empirical coefficient depending on the forward speed of the storm. The value of α is taken as 1.5 in this study.

The final wave field is obtained by the relation :

$$H_{ij} = \frac{v_{ij}}{v_m}\ H_m \tag{6}$$

3. Result of wave hindcast

The model output of wave predictions were compared with reliable data of waves in (*a*) the Arabian Sea and (*b*) the north Atlantic Ocean. A severe cyclonic storm passed through the Bombay High area in May/June 1976. Three jack-up rigs, *Sagar Samrat, Hakon Magnus* and *Shenon Doah* maintained continuous record of waves (during the passage of the storm) alongwith other meteorological parameters. A part of the storm track with respect to the positions of the rigs are shown in Fig. 1. In Fig. 1(a) the position of the storm at 0300 GMT of 2nd is shown. The rig, *"Hakon Magnus"* (H.M.) was at a distance of about 20 km from the centre of the storm. The recorded wave height is 8 m from the rig and the predicted height is also 8 m as seen in Fig. 2(a). Fig. 1(b) shows the centre of the storm at 0900 GMT of 2nd.

The rig, *"Sagar Samrat"* (S.S, 70 km away) recorded height of waves as 28-30 ft, *i.e.,* about 9.5 m whereas Fig. 2(b) shows a predicted wave height as 10 m at 75 km away from centre. The third rig, *"Shenon Doah"* (S.D.) which was about 25 km northeast from centre at 0900 GMT of 2nd recorded waves of height 17-20 ft which is roughly 7 m. From Fig. 2 (b) we see a predicted wave height of 7 m at 25 km away. Thus, the predicted wave heights agree very well with the wave heights recorded at the rigs. The wave observations recorded at the rigs are highly reliable as they were observed against fixed marks of the legs of the rigs. Mukherjee and Sivaramakrishnan (1980) used this highly reliable data obtained through courtesy of

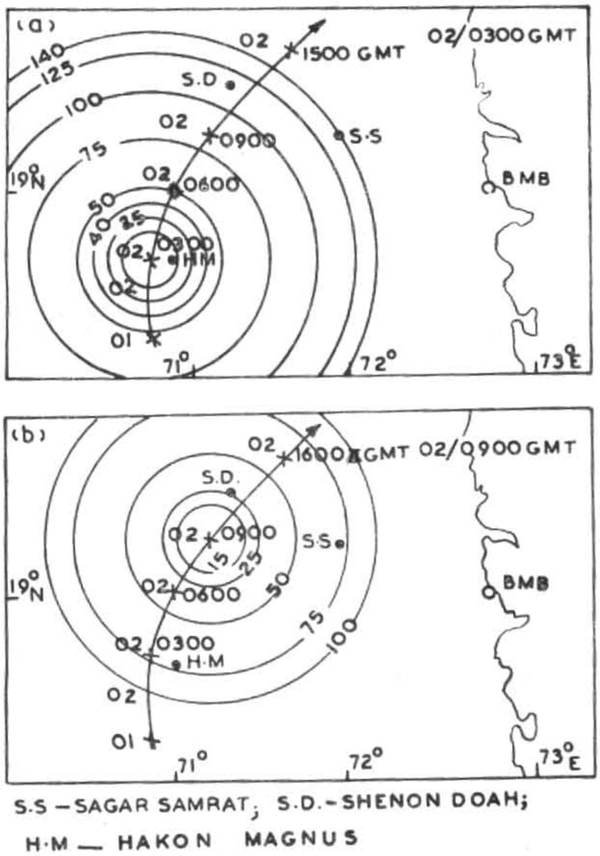
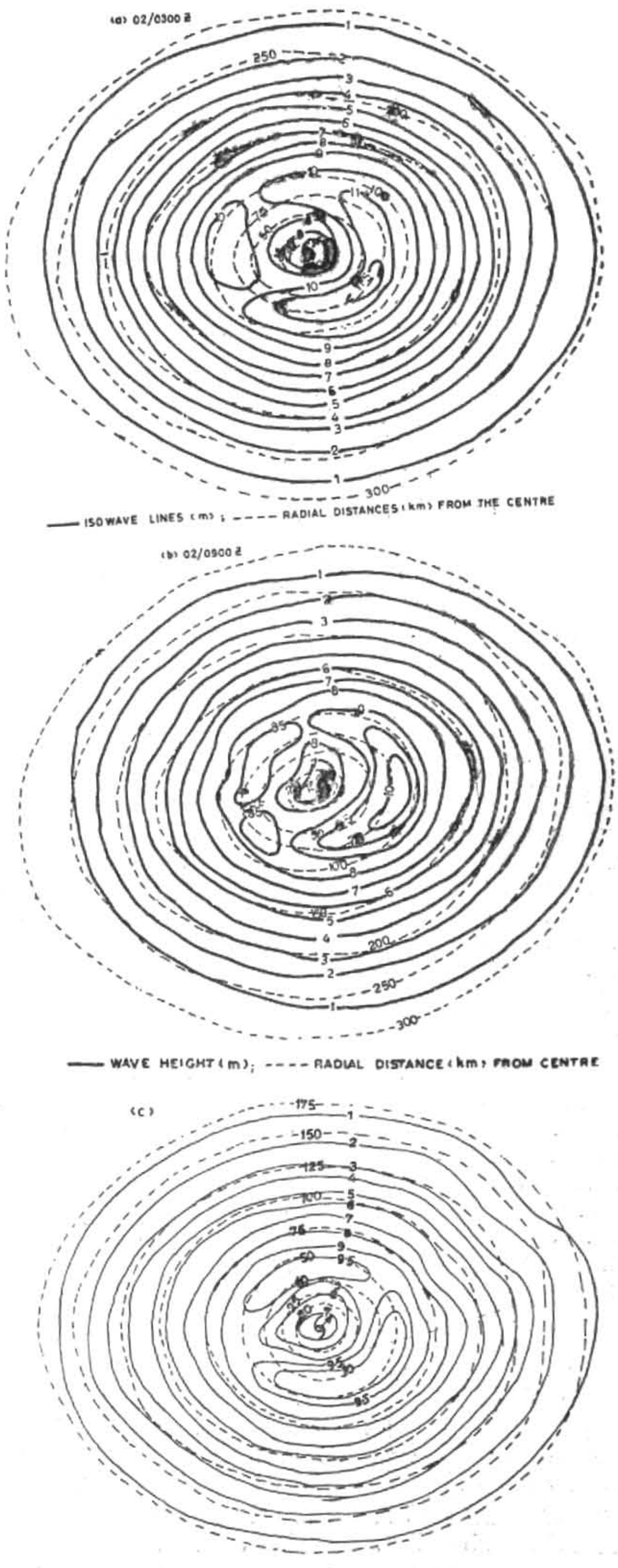


Fig. 1. Track of storm on 1-2 June 1976 with reference to the position of Bombay High area at (a) 0300 GMT and (b) 0900 GMT on 2nd. S.S.=Sagar Samrat, S.D.=Shenon Doah, H.M.=Hakon Magnus

Oil and Natural Gas Commission, Bombay, to verify their wave prediction technique. (b) the wave field used by Isozaki and Uji (1973) to verify their numerical wave prediction model has also been used in the present study for verification. The O.W.S. 'Weather Reporter' experienced very high waves off the coast of Great Britain from 16 to 18 December 1959. The detail meteorological conditions associated with the storm have been described by various authors in the past while using the data for verification of their models. The storm was associated with strong winds (60 kt) and high waves of 12 m. Isozaki and Uji (1973) depicted the predicted wave field (Fig. 3) for the storm. This shows highest wave of 10 m in the area. Using the same pressure fall and radius of maximum winds as reported by them a maximum wave of height 10 m is obtained as output of the present model as seen in Fig. 2(c). The predicted wave field (Fig. 2c) agree well with that of Isozaki and Uji (1973). It is known that the highest wave occur to the right of a storm track. From the present model we note that the highest waves are found in the right front quadrant (Fig. 4). Fig. 4 shows the wave profile in the four quadrants with distance from centre as abscissa and wave heights as ordinate. The variations of wave heights with distance can be seen in different quadrants. For rear quadrants the reader is advised to read the diagram upside down.



Figs. 2 (a)-(c). Predicted ocean waves at (a) 0300 GMT, (b) 0900 GMT on 2nd and (c) model output of predicted ocean waves field corresponding to Fig. 3

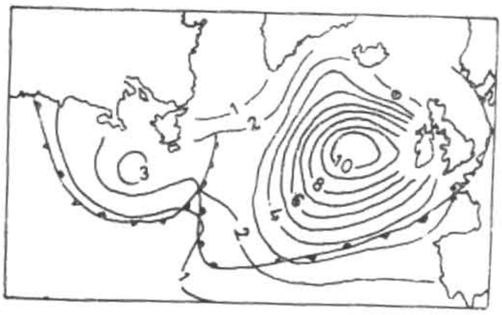


Fig. 3. Distribution of predicted significant wave height at 1200 GMT of 17 December 1959 (*Adapted from* Isozaki and Uji 1973)

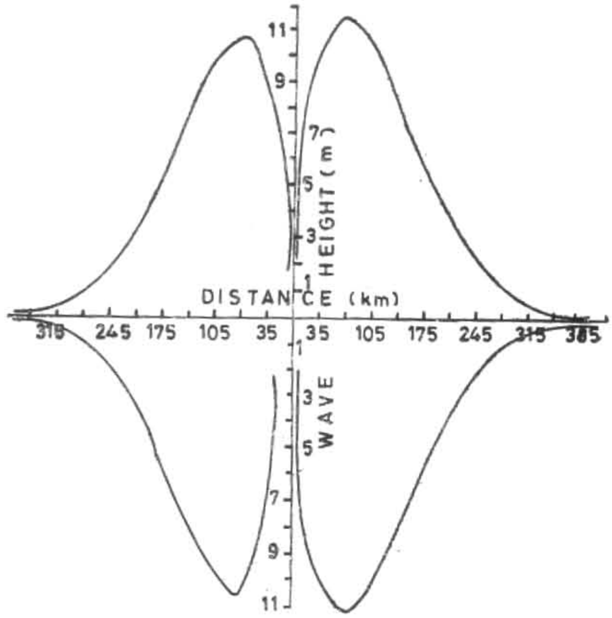


Fig. 4. Distance-height profile in the four quadrants of a cyclonic storm

4. Discussions

Though the equations used in the model are mainly non-linear, the model outputs for various pressure drops and radius of maximum winds can be used as nomograms for predicting ocean waves generated by cyclonic storms. Latest techniques based on radar observations and satellite imagery can be used operationally for estimating the central pressure drop and the radius of maximum winds. The third important factor needed as the input of the model is speed of movement of the storm. This can be estimated reasonably accurately from synoptic charts knowing the positions of the storm from radar and satellite observations.

One of the most difficult problems in the field of wave forecasting is the non-availability of reliable wave data from a storm field. Isolated wave observations from voluntary ships are not enough to verify a two dimensional wave model. This difficulty is faced by most countries of the world. An awareness need to be created amongst shipping crew to record and report wave observations more frequently. This will enable us to serve the industry better.

5. Conclusions

From the foregoing discussions one may arrive at the following conclusions :

(*i*) If the pressure fall and the radius of maximum wind can be estimated reasonably accurately the predicted wave field is within 90 per cent accuracy.

(*ii*) With increase in the speed of movement of the storm the predicted wave height increases.

(*iii*) The model is simple to use as the input data required are not difficult to estimate from the available informations operationally.

(*iv*) The right front quandrant has highest wave and sharpest gradient of wave heights with distance from the centre.

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