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A Technique for Forecasting Storm Waves

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ABSTRACT. The forecasting of tidal waves associated with cyclonic storms is a matter of great importance as these waves cause much devastation and loss of life, aggravating the havoc caused by hurricane-force winds and heavy rain. The vast coastline of India is exposed to the ravages of cyclones, especially those originating in the Bay of Bengal. As there is no reliable guide for predicting storm waves for the Indian coastline, a forecasting method has been developed, taking into account the three-dimensional topography of a vulnerable section of the eastern coastline.

The technique is based on the evaluation of the relative values of the different parameters that cause storm waves, *viz.*, (*i*) the astronomical tide, (*ii*) the 'inverted barometer effect', (*iii*) the effect of piling up of sea water against the coast by onshore winds of the cyclonic system, (*iv*) effect of individual waves, and (*v*) the swell of the fore-runners. The third and the fourth of the parameters mentioned above appear to be decisive in producing the total effect. Of these two, again, the former is the more important and depends upon the permanent features of depth distribution close to coast and the distribution of curvature of the coastline itself. Thus, under identical patterns of the wind, certain parts of the coastline would be far more susceptible to destructive storm waves than others. On the basis of the study, therefore, it is possible to demarcate permanently the areas which should be watched and warned with special care whenever cyclonic storms threaten the coast. This, it appears, could be of distinct assistance despite the well-known ambiguities and difficulties in regard to predictions of cyclone tracks sufficiently in advance.

A few well-documented cases of past storm-waves have been tested on the basis of the technique proposed. The areas most susceptible to storm-waves have been emphasised and it is expected that the technique will provide a basis for issuing reliable forecasts of storm surges. Further work is in progress for extending the technique to other belts of the coastline which are occasionally visited by cyclonic storms.

Introduction

Tidal waves are one of the most destructive natural calamities. They sometimes occur under certain favourable conditions along the coastal areas of India and Pakistan in association with severe cyclonic storms. Even though the storm waves are associated with only a small percentage of cyclonic storms, the devastation caused by each of them is so great that they are responsible for the major part of the loss of human lives and property accountable to cyclonic storms. The total loss of human lives in India due to storm waves during the last 25 years runs to many thousands. The most terrible havoc on record was caused by the Backergunge Cyclone of October-November 1876 in which a hundred thousand people died by drowning, following a great storm wave (Eliot 1900).

The Rameshwaram Cyclone of December 1964 caused huge tidal waves which swept across the islands of Rameshwaram (India) and Mannar (Ceylon) resulting in the loss of nearly a thousand lives. Apart from the major surges which are caused by the severe storms, many minor surges are caused by storms of lesser intensity in certain favoured localities. These surges inundate low-lying coastal areas resulting in damage to agricultural lands and fresh-water sources.

The recent Rameshwaram tragedy has again brought to the fore the urgent necessity for developing practical and dependable techniques for forecasting storm surges and waves. Such a technique, which can be put to practical use by forecasting offices, has been presented in this paper. It is hoped that the method will be of some assistance in day-to-day forecasting and storm warning work.

A brief survey of the existing knowledge on storm waves and results obtained by other investigators in the field have been given in Section I of the paper. A discussion of some of the techniques being used for forecasting storm waves and surges in other countries like U.S.A. and Japan has also been given in this section. A detailed discussion of the meteorological and topographical features that are favourable for the occurrence of tidal waves and a technique for forecasting them are presented in Section II of the paper. The necessary pre-calculations for employing the method in day-to-day forecasting work have also been carried out for the east coast of India south of Lat. 17° N and given in this Section.

Discussion of the results and a brief description of some of the major storm waves which affected this coast have been given in Section III. The verification of the technique as compared to the actuals has also been included in this Section.

SECTION 1

A brief survey of the theoretical and empirical knowledge on storm wave forecasting

The height to which the water level of the sea can rise along a coast in association with the passage of a storm depends on several contributory factors. The equation for the final height H, above the mean sea level, can be written in terms of component parts as —

$$H = A + B + P + X + F \quad (1)$$

where A is the component due to astronomical tides, B is the static rise due to the atmospheric pressure deficiency towards the centre of the storm, or the so-called 'inverted barometer effect', P is the rise due to the piling up of waters against the coast by strong onshore winds, X is the height of the crests of individual waves superimposed on the general rise of the sea level and F is effect of the 'fore-runners'.

F is the phenomena which occurs when the storm is far away from the coast and so it contributes little to the final rise. Hence, ignoring this effect the equation reduces to —

$$H = A + B + P + X \quad (2)$$

Of the four terms on the right hand side, A can be obtained from the Tide Tables. The term B is given by the simple hydrostatic relationship —

$$B = (\triangle P_a / g) \times 10^3 \quad (3)$$

where B is in cm and $\triangle P_a$ is the pressure deficiency at the place in millibars. Roughly, the pressure deficiency in millibars gives the numerical value of B in cm.

The third factor P is to be evaluated. In deep waters, strong winds do not cause sloping of the sea surface, as counter-currents in the sub-surface layers are immediately set up which tend to maintain the sea surface at level. In shallow coastal waters, the counter currents are retarded or nearly blocked by the frictional forces at the bottom of the sea, with the result that piling up of waters against the beaches occurs. The 'Trades' of the Pacific and the Atlantic pile up waters along western boundaries of these oceans, but the slopes are very small, being of the order of 4×10^{-8} (Sverdrup 1945).

When on-shore winds commence along a coast, the stress of the winds causes a slope of the free surface of the sea, which goes on increasing until it is balanced by the component of gravity of the water column below. The stress τ_a depends on the wind speed and the roughness parameter of the sea surface. From theoretical considerations, Rossby has given the formula —

$$\tau_a = 2 \cdot 6 \times 10^{-3} \times \rho_a W^2 \quad (4)$$

taking the roughness parameter of the sea surface to be 0·6 cm (Sverdrup, Johnson and Fleming 1961). In the above equation, ρ_a is the density of air and W is the wind speed at 15 m above sea level in C.G.S. units. If τ_w is the frictional resistance acting on the counter-currents, we have, under equilibrium conditions,

$$\tau_a + \tau_w = -g\rho_w \, i \, d \quad (5)$$

where ρ_w is density of sea water, i is the slope of the free surface at that point and d is the depth of the water column.

Unfortunately no evaluation of τ_w is possible as the counter currents cannot be easily measured. But empirical results are available from various studies of storm surges, especially in the Baltic, and the generally ccepted relationship between the slope of the free urface and the speed of the wind causing it, appears to be (Sverdrup 1945, Sverdrup *et al.* 1961) —

$$i\,d = 4 \cdot 8 \times 10^{-9} \; W^2 \quad (6)$$

It will be noticed that in equation (6) the numerical constant is not non-dimensional. Equation (6) can be utilised in evaluation of P. This will be dealt with again under Section III.

The evaluation of X offers the main difficulty in tidal wave forecasting. Some investigators are sceptical of the existence of a 'wave' and believe that the coastal inundations are entirely due to the piling up of water by the onshore gales. On the other hand, some other investigators postulate gigantic 'waves' to explain the sudden onrush of waters inland. One such theory is due to Tannehill (1938). According to him the waters in the storm areas take on a rotary motion similar to that of the winds acting on them. The motion is communicated to great depths. As this rotating mass of water strikes the coast, the waters of the system tend to pile up on the right of the track of the storm. Arakawa (1957), on the other hand, postulates a large solitary wave. According to him, when the speed of the storm is nearly equal to the speed of the gravity waves in shallow waters into which the storm enters near the coast, a large solitary wave can form to the immediate right of the storm centre between the gales in the right front sector and the hurricane winds in the right rear sector. With these theories and the possible value of X we shall deal again in development of our technique in Section III.

Different techniques are in use or have been suggested for use in forecasting storm waves. A statistical method has been developed by Conner and Craft for the Gulf of Mexico storms (*cf.* Dunn 1960). From a study of past storm surges, regression equations have been obtained between the central pressures of the storms and the heights of the surges caused by them. Arakawa (1957) suggests the technique based on the calculation of the contributions of different factors to the final rise of the water level. He considers the following as important—

$$H = A + B + P + D \qquad (7)$$

where H is the total height, A, B and P have the same meanings as in equation (1) and D is the dynamic effect of travelling barometric centre. The physical basis for term D has been discussed earlier in this section.

Numerical prediction of storm surges has been attempted by some workers with varying degree of success. Welander (1961), starting from the fundamental hydrodynamical equations of motion, developed a method for forecasting storm waves. His results are encouraging, but on an operational basis the method can be used only with the help of an electronic computer.

SECTION II

A technique for forecasting Storm surges and Waves

Of the different types of techniques available for storm wave forecasting, we discarded the numerical methods which necessitate the availability of an electronic computer and plentiful data from a large area including oceanic areas. The statistical technique similar to that adopted by Conner and Craft was found unsuitable for the Indian coasts. The number of occasions on which storms in Indian Seas have caused major surges is rather small from the purely statistical angle, and reliable data of minor surges are lacking. The available data are, therefore, too scanty for a satisfactory statistical study. Further, the surge height associated with a storm of a given intensity depends so much on the topography of the sea-bed near the coast that even stations separated by a short distance may be affected to different extents even if the meteorological factors are nearly the same at both the places. Thirdly, when the storm is out in the sea where data are not numerous, it is very difficult even to estimate accurately the central pressure of the storm.

In the present approach to the problem, therefore, we started with equation (2) given in Section I, *viz.*,

$$H = A + B + P + X$$

The evaluation of A and B has already been dealt with earlier.

Evaluation of P

For evaluating P, we have chosen to use the empirical relation given by equation (6)

$$i\,d = 4{\cdot}8 \times 10^{-9}\ W^2,$$

$$\text{or}\quad i = 4{\cdot}8 \times 10^{-9}\ (W^2/d) \qquad (8)$$

It will be seen from equation (8) that the slope of the free surface at a point for a given wind speed depends on the depth of the water column below it. In other words, the topography of the sea-bed near the coast plays a most important role in the creation of wind-driven surges of sea water along the beaches.

The bottom of the sea, *i.e.*, the continental shelf, usually has a gentle slope from the coast to a depth of about 200 m. The shelf extends generally to a distance of about 30—40 km from the coast, but this distance can vary considerably. For the calculation of P, it is usually sufficient if the sloping of the free surface is considered upto a depth of about 100 m. Beyond this depth, not only does the value of i as given in equation (8) become too small, but the equation itself is probably not valid at greater depths.

The topography of the sea bottom varies considerably even along small sections of the coast. This is illustrated in Fig. 1 which gives the topography of the sea bed off the east coast of India between latitudes 15°N and 17°N.

The evaluation of P from equation (8) can be done only by finite integration. If we take a small section of the sloping free surface of the sea along a line normal to the coast, we have

$$i = \triangle P / \triangle D \qquad (9)$$

where $\triangle P$ is the difference in the levels of the free surface at the two ends of the section and $\triangle D$ is the horizontal length of the section.

Combining (8) and (9) we have,

$$i = \triangle P/\triangle D = 4{\cdot}8 \times 10^{-9} (W^2/d) \qquad (10)$$

$$\triangle P = 4{\cdot}8 \times 10^{-9} (W^2/d) \triangle D \qquad (11)$$

$$\therefore\ P = \sum_{0}^{P} \triangle P$$

$$= 4{\cdot}8 \times 10^{-9} \sum_{d_1,\ \triangle D_1}^{d_n,\ \triangle D_n} \frac{W^2 \triangle D}{d} \qquad (12)$$

where n is the number of the sections into which

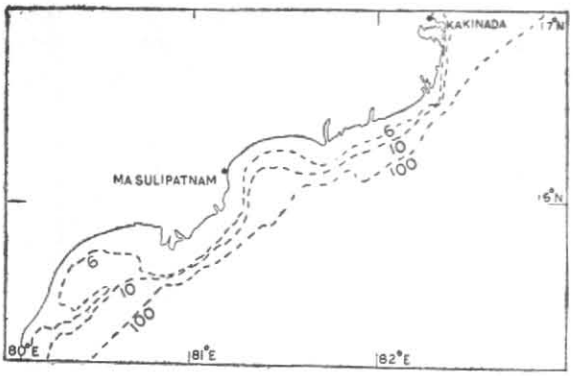

Fig. 1. Isopleths of depth off the east coast of India between Lat. 15°N and 17°N

The figures along the broken lines give the depth in fathoms

the distance has been broken up according to the chosen depth intervals.

It may be mentioned here that the wind speed entering into the above equation is the *sustained speed* of the onshore component of the winds and not the maximum speed in individual gusts. If we further take a representative wind which can be taken as a constant along the distance over which the summation has been carried out, we have, from equation (12),

$$P = 4 \cdot 8 \times 10^{-9} \times \overline{W}^2 \sum_{d_1, \triangle D_1}^{d_n, \triangle D_n} \frac{\triangle D}{d} \qquad (13)$$

The method of working out the value of P for a given wind velocity is as follows. The distance from a point on the coast to 100 m depth line is first taken along a straight line *normal* to the coast at that point. The distance is then divided into convenient sections within which the average depth can be taken as d without loss of accuracy of the calculations. Fig. 2 illustrates the stepwise integration schematically. The last three stages of integration have not been shown in the diagram. It will be noticed that the depth intervals of sections have been progressively decreased towards the coast. Also, the value of d not only includes the normal average depth but also the increase due to rise in the level of the free surface by the piling up effect of the winds on the earlier sections.

As the process of calculating P from equation (13) is time-consuming, the calculations have to be made for a range of wind speeds at different points along the coast and kept ready for forecasting purposes. The values of P for windspeeds of 20, 30 and 40 mps for 32 locations along the east coast of India south of Lat. 17°N have been calculated and given in Table 1. Admiralty Ocean Area charts were used for obtaining the depth contours of the sea bottom. The 1 : 1·4 million scale Admiralty charts give the lines for 100, 10 and 6 fathom depths. The 25 and 50 fathom depth lines used for the calculations were drawn with the help of spot values of depths given on the chart. For getting the lengths of sections in the depth ranges 0—1, 1—2, 2—3 and 3—6 fathoms, a linear interpolation was made between the coast and the 6 fathom line, when that is near the coast. But in areas where the shoals enter upto considerable distances from the coast, the chart itself gives additional lines for the 3-fathom depths. For more accurate work, the 1 : 0·3 million scale Admiralty charts can be used. Such a chart was used for studying the extended banks of the Palk Strait region.

In Fig. 2, the depth of each section is shown as the sum of the average depth of the section and the additional depth due to increase in the level of the free surface. However, in actual calculations, the latter can be neglected for sections 1, 2 and 3 (Fig. 2) although it becomes important for sections near the coast.

For obtaining the contribution of P to the storm surge height, the forecaster has to predict or estimate the likely onshore component of sustained winds acting along the horizontal distance D. As the contribution to the value of P is mostly from sections near the coast, the forecasted sustained wind (or its onshore component) at the coast itself can be used for this purpose as a first approximation.

Evaluation of X

The term X includes the contribution of the individual wave crests to the overall height to which sea-water can reach along the coast. We have not considered either the rotary motion of Tannehill's theory (1938) or the solitary hydraulic jump wave of Arakawa (1957) under this term. The sudden onrush of water in the form of a great 'wave' can also be visualised from effects other than those due to either of the phenomena mentioned above. Even though the wind speed at a coast may change gradually, the wind direction often changes rather abruptly on many occasions at a coast. This sudden change in wind direction can result in a rapid increase in the onshore component of the windspeed, resulting in fast surging of water along the coast. Further inland, the sudden or very rapid rise in water can be caused by a variety of phenomena. The frictional drag may itself delay the initial advance of water. Further, it is well known that in certain bays and narrow

TABLE 1

Evaluation of H_1 with reference to the type of coast and different wind speeds

Station name or location number	Location Lat. N Long. E	Favourable direction of wind	P (metres) Wind speeds (mps) 40	30	20	H_1 (metres) Wind speeds (mps) 40	30	20	Classification	Annual range of tides (metres)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	16°32′ 82°14′	145° (SE)	1·56	0·96	0·47	2·6	1·6	0·8	b	Kakinada —0·1 to 1·8
2	16°26′ 81°53′	150° (SSE)	1·53	0·91	0·43	2·5	1·5	0·7	b	
3	16°22′ 81°34′	205° (SSW)	1·76	1·03	0·50	3·0	1·7	0·8	b	
4	16°22′ 81°30′	190° (S)	1·70	0·97	0·39	2·9	1·6	0·7	b	
5	16°20′ 81°21′	155° (SSE)	1·44	0·94	0·45	2·4	1·6	0·8	b	
6	16°12′ 81°12′	115° (ESE)	2·04	1·35	0·72	3·4	2·3	1·2	b	
7	15°53′ 81°01′	140° (SE)	1·60	1·15	0·49	2·7	1·9	0·8	b	
8	15°52′ 80°48′	230°(SW)	4·45	2·72	1·37	7·4	4·6	2·3	c	
9	15°52′ 80°31′	160° (SSE)	2·48	1·45	0·68	4·2	2·4	1·2	b	
10	15°39′ 80°16′	110° (ESE)	2·02	1·30	0·53	3·4	2·2	0·9	b	
11	15°27′ 80°13′	110° (ESE)	2·23	1·36	0·57	3·7	2·3	1·0	b	
12	15°07′ 80°03′	090° (E)	1·37	0·78	0·37	2·3	1·3	0·7	b	
13	14°38′ 80°09′	070° (ENE)	0·56	0·33	0·15	0·9	0·5	0·2	a	
14	14°18′ 80°11′	100° (E)	0·88	0·52	0·24	1·5	0·8	0·4	a	
15	13°52′ 80°13′	060° (ENE)	1·52	0·93	0·44	2·5	1·6	0·7	b	
16	13°26′ 80°19′	090° (E)	1·24	0·72	0·35	2·1	1·2	0·6	a	
17	13°07′ 80°16′	115° (ESE)	0·52	0·31	0·13	0·9	0·5	0·2	a	Madras 0·1 to 1·5
18	12°43′ 80°14′	100° (E)	0·52	0·31	0·13	0·9	0·5	0·2	a	

TABLE 1 (*contd*)

Station name or location number	Location Lat. N Long. E	Favourable direction of wind	P (metres) Wind speeds (mps) 40	30	20	H_1 (metres) Wind speed (mps) 40	30	20	Classi-fication	Annual range of tides (metres)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
19	12°21′ 80°04′	125° (SE)	0·92	0·52	0·25	1·5	0·9	0·4	a	
20	11°45′ 79°46′	100° (E)	1·01	0·62	0·28	1·7	1·0	0·5	a	
21	11°01′ 79°50′	090° (E)	0·80	0·45	0·20	1·3	0·8	0·3	a	
Nagapat-tinam 22	10°45′ 79°52′	090° (E)	1·54	0·95	0·41	2·5	1·6	0·7	b	—0·1 to 1·0
23	10°23′ 79°51′	090° (E)	3·13	1·85	0·91	5·2	3·1	1·5	c	
Point Calimere 24	10°17′ 79°52′	165° (SSE)	4·22	2·56	1·24	7·0	4·3	2·1	c	
25	10°18′ 79°40′	195° (SSW)	5·18	3·15	1·51	8·7	5·2	2·5	c	
Adirama-patnam 26	10°21′ 79°25′	155° (SSE)	5·08	3·05	1·47	8·5	5·1	2·4	c	
Tondi 27	9°45′ 79°02′	125° (SE)	4·81	2·95	1·36	8·2	4·9	2·3	c	
Devi-patnam 28	9°28′ 78°58′	090°(E)	4·52	2·72	1·34	7·5	4·6	2·2	c	
29	9°22′ 79°00′	040° (NE)	4·58	2·65	1·24	7·6	4·5	2·1	c	
Pamban 30	9°20′ 79°17′	340° (NNW)	4·38	2·44	1·44	7·3	4·1	2·4	c	0·1 to 0 9
Ramesh-waram 31	9°20′ 79°22′	135° (SE)	6·80	4·47	2·37	11·3	7·4	2·3	c	
Dhanu-shkodi 32	9°10′ 79°28′	030° (NNE)	4·84	2·94	1·41	8·2	4·9	2·3	c	

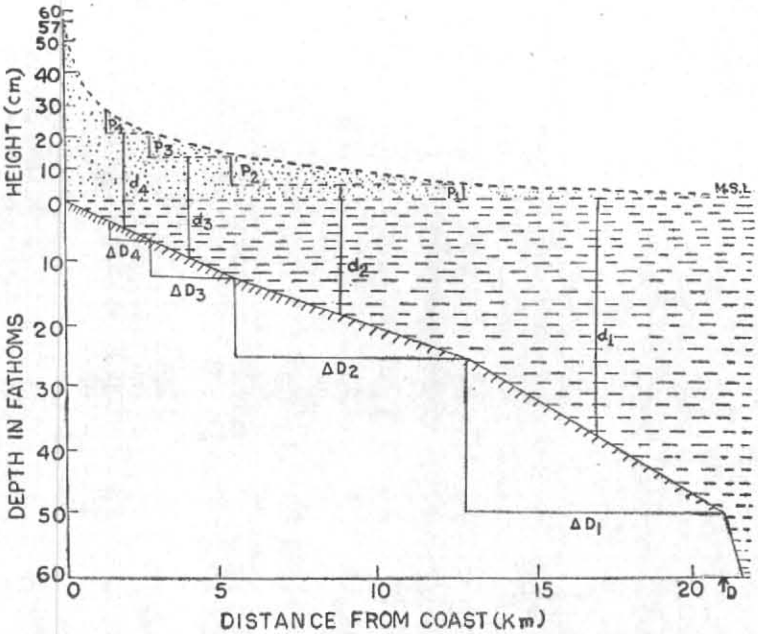

Fig. 2. Schematic diagram illustrating the piling up of waters along the beaches due to strong on-shore winds and finite deferentials method used for calculating P (W=30 m.p.s.)

Note : Scales are different for heights, depths and distances

channels even the gravitational tides cause phenomenal "bores" which advance up the channels as 'walls of water' of heights as great as 6 to 10 m. Arakawa's solitary wave is possible only when the speed of the storm attains the speed of the gravity waves. The storms of the Indian seas hardly even attain such speeds.

For the evaluation of parameter X, therefore, we considered only the ordinary wave type known as wind waves and swells. Even with this simplification, the forecast of the value X is beset with many difficulties. The forecaster has to estimate the likely height of the waves generated by the storm and then calculate what would happen to these waves as they approach the coast.

However, with the help of one observed physical fact we have been able to circumvent some of the difficulties. It has been established by a number of studies that waves break on nearing the coast when they reach an area where the depth is 1 to $1\frac{1}{2}$ times their height. If b is the ratio given by $b = d/h$ at the breaking point, the value of b has been found to be within the limits of 1 and 1·5. Steep waves break at greater depths and long swells are able to advance more towards the coast before breaking. Most of the waves break where the value of b is 1·3, which is also nearly the value at which the solitary wave breaks ($b = 1{\cdot}28$, Sverdrup 1945).

For storm wave forecasting, it is not the height of the waves in the deep waters that matters, but the height of the waves that are able to reach right upto the coast. Under normal conditions at D=0 (D being the horizontal distance from the coast line), d is equal to A. But due to the piling up of water along the beaches by the strong onshore winds, this situation is changed, and on such occasions, at D=0, d=P+A. Further, as the storm waves are usually very steep, if we assume a value of b=1·5 in their case, then the only waves that can reach the coastline are those whose heights are below the value given by the equation—

$$X = P/1{\cdot}5$$

So we have, $$X = 2P/3 \tag{14}$$

Or, if we take into consideration the contribution A and B also, we have —

$$X = \tfrac{2}{3}(A+B+P) \tag{15}$$

and hence $$H = \tfrac{5}{3}(A+B+P) \tag{16}$$

Now the question remains whether waves of the height given by equation (15) are being produced in the generating area of the storm. Two diagrams giving the wave heights in terms of 'fetch'', duration and wind speed are shown in Figs. 3 and 4 reproduced from U. S. Navy Hydrographic Office Publication No. 604 (1954). It can be seen from these diagrams that waves of heights 4 to 5 m can be produced by winds of 60 knots in as short a 'duration' as 3 hours and with as short a 'fetch' as 40 km.

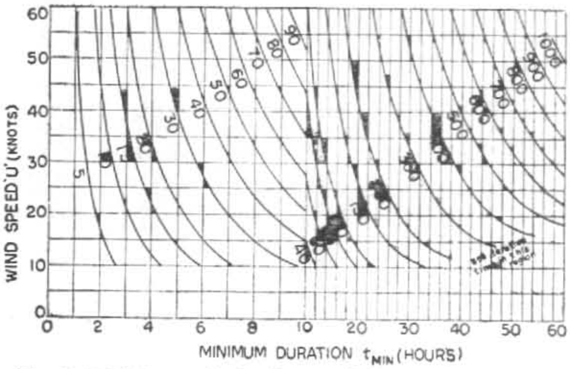

Fig. 3. Fetch in nautical miles as a function of minimum duration and wind speed

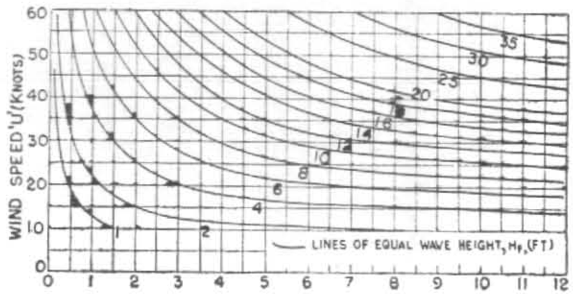

Fig. 4. Wave height as function of short duration of wind and wind speed

(Reproduced from H.O. Publ. No. 604)

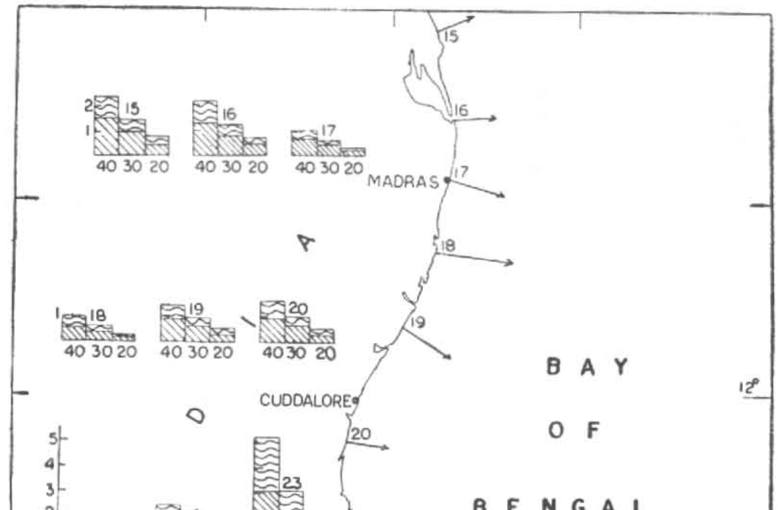

Fig. 5(a). The height to which the storms surges and waves can reach along the east coast of India between 9°N and 14°N with different speeds of onshore winds

On the inset diagrams the figures on the vertical scale indicate height in metres. 40, 30 and 20 below each block indicate the onshore component of wind speed in metres per second. The number on top of the middle column correspond to the number of the point along the coast. The arrows indicate direction normal to the coast

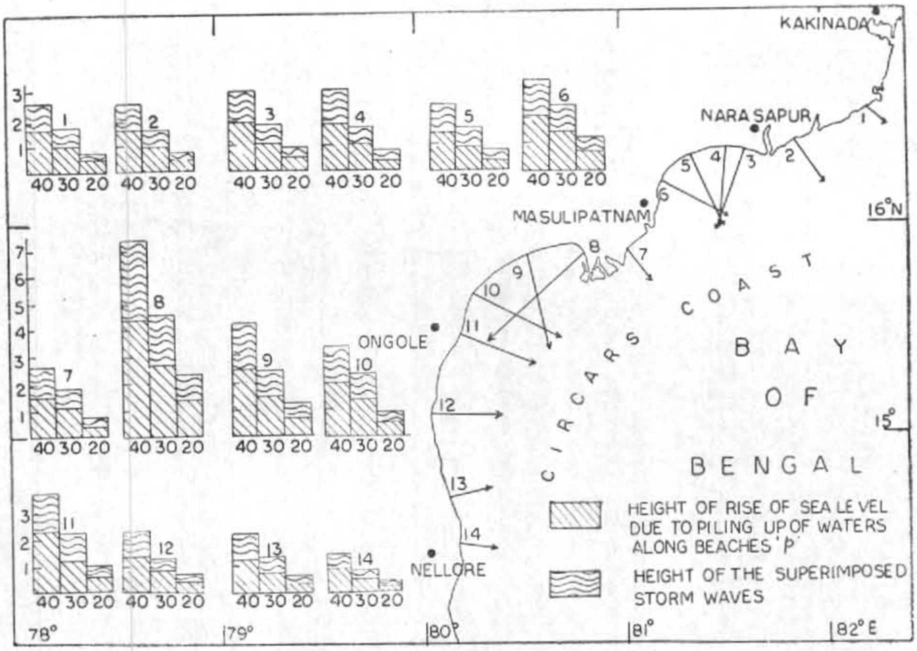

Fig. 5(b). The height to which the storm surges and waves can reach along the east coast of India between Lats. 14°N and 17°N (rest of the explanation as in Fig. 5a)

The value of H given by equation (16) can be split into two parts as —

$$H = H_1 + H_2 \quad (17)$$

where $H_1 \equiv \frac{5}{3}P$ and $H_2 \equiv \frac{5}{3}(A+B)$

H_1 can be called the wind component which depends only on the onshore component of the wind and the topography of the sea bottom off the coast. For forecasting purposes this term can be calculated for different wind speeds at different points along the coast and kept ready for use. The value of H_2 has to be evaluated at the time of forecasting. The values of H_1 are given in Table 1. Table 1 also gives the most favourable direction of the wind, at each location for the occurrence of tidal waves.

The same data are shown schematically in Figs. 5(a) and 5(b). The technique given above deals only with the surges on open beaches. The effect of surges on narrow bays and channels has to be worked out separately for each particular location in the light of its geometrical characteristics.

The value of H given by equation (16) gives the maximum possible height to which water level can reach when all the meteorological factors are most favourable. But some of the assumptions on which the above calculations have been made may not be fully realised in actual practice in all cases and the forecaster has, therefore, to take into consideration certain additional factors. These are briefly discussed below.

1. *The coastal topography*

The coastal topography will to some extent play a part in the final damage caused by the storm surges. At very steep coasts, the piled up water will enable the high waves to advance right upto the crest of the coast, which can be treated as the beginning of the endangered part of the coast line. At gently sloping coast lines the waves will suffer further erosion by the time they reach the coast.

In the above calculations, it is to be assumed that the height of the coastal crest is more than the height to which the sloping surface can reach. This assumption has to be treated with reserve in some cases. On small flat islands and capes, the general height of the coast may be much lower than around large land masses. In such cases the sea water will simply overflow and move across the island or cape even before surges can reach the value given by equation (12).

2. *The pre-condition of the sea*

In the foregoing discussion on the value of X, it was mentioned that with the help of the diagrams reproduced in Figs. 3 and 4, it is possible to determine whether waves of the required height are being produced in the generating area of the storm. It may be mentioned that the plates were prepared on the assumption that a wind

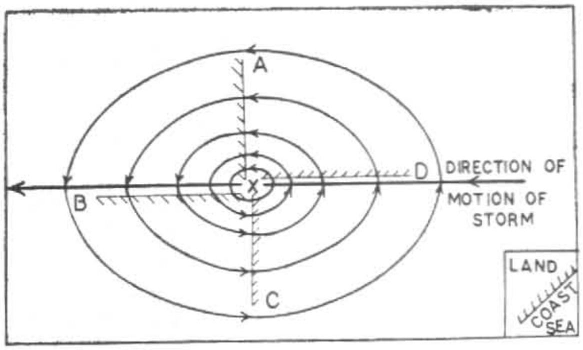

Fig. 6. Schematic representation of different orientations of the coastline with reference to the direction of the movement of the storm

suddenly starts blowing on a glassy sea. This condition is generally not satisfied in the case of cyclonic storm situations. The pre-conditions of the sea before the onset of the strong onshore winds, therefore, assumes great importance.

Fig. 6 shows the four different orientations of coasts relative to a moving storm. In the case of coast A, the sea condition will be the most favourable, as long swells oriented towards the coast would already be present in the sea before the onset of the winds. At coast B the pre-condition of the sea will be mostly indifferent or only slightly favourable. At coast C again the pre-condition will be highly favourable, but such an orientation is rather unlikely. At coast D, the pre-condition of the sea will be most unfavourable, as the sea would be highly oriented away from the coast by the offshore gales of the forward sector of the storm. In cases A and C, the effective 'duration' of the winds would be increased. In case of D, the effective 'duration' would be greatly reduced. These factors have to be taken into consideration in issuing the forecast of storm wave.

SECTION III

Discussion of Results

The technique presented in this paper and values of P and H_1 given in Table 1 for different locations along the southeast coast of India bring out some striking features of the storm wave phenomena. These can be stated as follows —

(1) The maximum height to which storm-water can reach along a coast depends almost entirely on the wind speed (onshore component) and the character of the sea-bed close to the coast,

(2) The coastal topography and the precondition of the sea determine whether the maximum height will be reached or not,

(3) Storm waves can occur on a coast in the field of strong onshore winds, even when the storm is passing by and not actually crossing the coast, and

(4) Storm waves can occur in advance of, during, or after, the passage of the storm at or near the section of coast, depending on how the coast is oriented relative to the storm movement.

The values of H_1 given in Table 1 under col. 7 can be taken roughly as the maximum heights to which the storm wave can ever reach at a place, as the sustained wind even in the severest storms will be of the order only 40 mps. The annual astronomical tide ranges for available points along this coast are given in col. 11. It will be seen that they are between 1 and 2 metres only The static rise due to the 'inverted barometric effect' will hardly ever exceed half a metre.

The east coast of India south of Lat. 17°N for which calculated values of H_1 are given in Table 1, can be broadly divided into 3 categories — a, b and c. The classifications are given in col. 10 of the table. Under category 'a' falls the coast between Lat. 11° and 15°N, where the value of H_1 is below 2 metres asl. This can be termed as a 'safe' area where major storm tides will not normally occur. The coast between 15° and 17°N falls under category 'b', where the H_1 values are between 2 and 5 metres asl. This section of the coast can be taken as a safe area for storms of moderate intensity, but where dangerous flooding from storm waves can occur in association with cyclones of severe intensity. Under category 'c' falls the coastal areas south of Lat. 11°N where the H_1 values are above 5 metres asl. This is a highly vulnerable area as far as storm surges are concerned.

An analysis of the records of past storm surges lends support to the above classification. The data regarding the number of storms which affected the coastal belt south of Lat. 17°N and the major storm waves and surges caused by them were anaysed in terms of the type of coast affected and the statistics are given in Table 2. As some of the storms affected sections of the coastline falling into two categories, they were considered for both the types of coasts.

The information about the number of storms and their track has been taken from *Tracks of storms and depressions in Bay of Bengal and Arabian Sea* (India met. Dep. 1964) and reports of storm surges from *Monthly Weather Review* published by India Meteorological Department and the reports of officers who visited some of the storm-affected areas. The data pertain to the years 1891 to 1960. The Rameshwaram Cyclone of 1964 has been added to the above list because of its topical interest. A few more storms of moderate intensity affected the 'a' and 'b' type of coasts during the years 1961 to 1964 but they have not been included in Table 2 as they do not relate to the point under consideration.

Information about minor surges is lacking, even though they must have occurred and caused some damage in coastal areas.

Apart from the statistical analysis, a qualitative comparison of the wave heights computed on the basis of the above technique and the actual heights of some of the past storm waves which occurred along this coastal belt seems to confirm the validity of the above technique, within the limits of reliability of the available data. Four important cases are discussed below.

TABLE 2
Relationship between type of coast and occurrence of storm surges

Type of coast	Intensity of storm	No of storms which affected the coast	No. of storms that caused major storm surges
a	Moderate	13	Nil
	Severe	12	Nil
b	Moderate	19	Nil
	Severe	6	4
c	Moderate	1	—
	Severe	3	3

(a) *Masulipatnam Cyclone of October 1949*

A very severe cyclonic storm struck the Circars Coast on 28 October 1949 with its centre crossing the coast just to the north of Masulipatnam. The storm was moving in a westnorthwesterly direction. The inner storm field extended to about 90 km from the centre and winds in this area were estimated to be of the order 90 to 100 mph (80 to 90 knots). Storm surges of height 3 to $3\frac{1}{2}$ metres (10-15 feet) were experienced all along the coastal belt falling in the right sector of the inner storm field. The storm crossed the coast at about the time of the high tide. The precast height of H_1 (Table 1—stations 1 to 4) works to be about $2\cdot8$ m and H_2 must have added another 1 to $1\cdot5$ m. The H works out to $3\cdot8$ to $4\cdot3$ m which agrees well with the observed height.

(b) *Nagapattinam Cyclone of November 1952*

A severe cyclonic storm struck the Coromandel coast near Lat. 10° 30′ N (about 30 km south of Nagapattinam) at about 1330 IST (0800 GMT) on 30 November 1952. The winds were of the order 80 to 100 mph (70 to 90 knots) in the inner storm field. The cyclone was moving westwards at the time of crossing the coast. It caused two major storm surges. The first storm wave swept the coastal area to the *right* of the storm track to a distance of about 40 km from the centre, just about the time when the storm was crossing the coast. The winds veered from northeast to east just prior to the first advance of the waters. The storm wave is reported to have reached a height of about 4 feet agl ($1\cdot2$ m agl) at Nagapattinam, which roughly works out to be about 3 m asl. The precast height of H_1 according to Table 1 works out to be about $2\cdot5$ m and H_2 must have added another $0\cdot5$ m giving the total $H = 3\cdot0$ m, which agrees fairly with the observed height.

The second storm surge affected the northern shores of the Palk Strait between Point Calimere and Adiramapatnam, in the field of the southerly hurricane winds at the rear of the storm. The height to which the storm surge reached is not definitely known, as it affected a swamp area, the estimated range being 2 to 10 feet. At Point Calimere the storm wave caused great damage and was probably about 3 m agl, *i.e.*, about 5 m asl. which works out to be less than the maximum value of H_1 (7 m) given in col. 7 of Table 1. As explained at the end of Section III, the pre-condition of the sea was not favourable for the particular orientation of this coast and may have been the cause for the surge height not reaching the maximum value at Point Calimere. And, for the swampy coastal belt between Point Calimere and Adiramapatnam, even the coastal topography is not favourable.

(c) *Adiramapatnam Cyclone of December 1955*

A severe cyclonic storm moved westwards across the northern fringes of the Palk Strait and struck the coast just to the south of Adiramapatnam at about 0400 IST of 1 December 1955 (2230 GMT of 30 November 1955). This storm was at least as severe as the Nagapattinam storm of November 1952. This cyclone also caused two storm surges. The first surge was experienced along the coast between Point Calimere and Vettaikaran Iruppu at about the time the storm was passing across the longitude of this coast. The maximum surge height was reached at

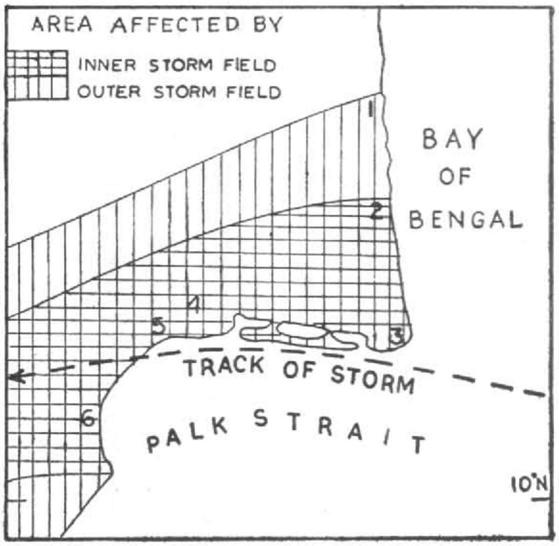

Fig. 7(a). Track of Adiramapatnam Cyclone of November 1955 with areas affected by hurricane winds of the inner storm field and the strong winds of outer storm field

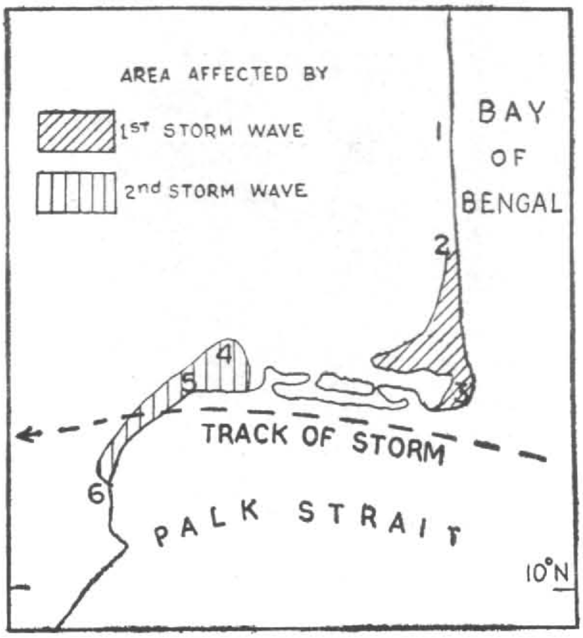

Fig. 7(b). Track of Adiramapatnam Cyclone of November 1955. The area affected by the first storm wave is shown by slant hatching and that by second storm wave by vertical hatching

Name of the places — (1) Nagapattinam, (2) Vettaikaran Iruppu, (3) Point Calimere, (4) Thambikottai, (5) Adiramapatnam, (6) Kattumavadi

(Reproduced from Shri C.R.V. Raman's report)

Vedaranyam and was estimated to be between 5 to 7 feet (about 2 m) agl or 4 to $4\frac{1}{2}$ m asl which is slightly less than the height of $H_1(5\cdot2$ m) given in Table 1 for station 23.

The second storm surge was experienced between Thambikottai and Kattumavedi. According to the report of Shri C. R. V. Raman, who made a careful study of the storm affected area, this advance 'took place when strong southeasterly winds lashed the coast immediately after the storm had moved inland'. The height of the surge was 3 to 4 feet agl. Figs. 7 (a) and 7 (b), reproduced from the report of Shri Raman, show the excellent coincidence between the coastal area affected by the onshore winds of the inner storm field and the area affected by the first storm surge. In the case of the second surge the affected coastal area extended to the south of the storm track also. This is probably due to the fact that the storm lost some latitude during its travel after crossing the coast. The extract of the report quoted above confirms that this part of the coast did experience strong winds with an onshore component in the wake of the storm. A quantitative comparison has not been possible for this storm surge for want of necessary details of wind speeds and directions at the time of the occurrence of the surge.

(d) Rameshwaram Cyclone of December 1964

A cyclonic storm of great intensity formed in the south Bay of Bengal on 20 December 1964 with its centre near Lat. 6·5°N, Long. 88° E. It moved rapidly westnorthwestwards and struck the east coast of Ceylon near Trincomalee. It then moved in a westward direction across north Ceylon and lay in the Palk Strait on the morning of 23rd. It crossed the east coast of India near Lat. 9·5°N that afternoon and weakened rapidly thereafter. The storm was of unprecedented ferocity and the estimated winds were of the order of 120-150 knots over northern Ceylon. It weakened by the time it entered the Palk Strait, the reported winds in this area being 80-100 knots. It weakened further by the time it reached the east coast of India where the winds were of the order of 60-70 knots.

The storm caused large tidal waves which inundated large parts of the islands of Rameshwaram (India) and Mannar (Ceylon). The piling up of waters along the northern shores of these islands started with the onset of strong northerly winds in the forward sector of the storm. The surges occurred at each place 3 to 4 hours before the actual arrival of the storm centre. Talaimannar on the northwestern tip of the Mannar Island

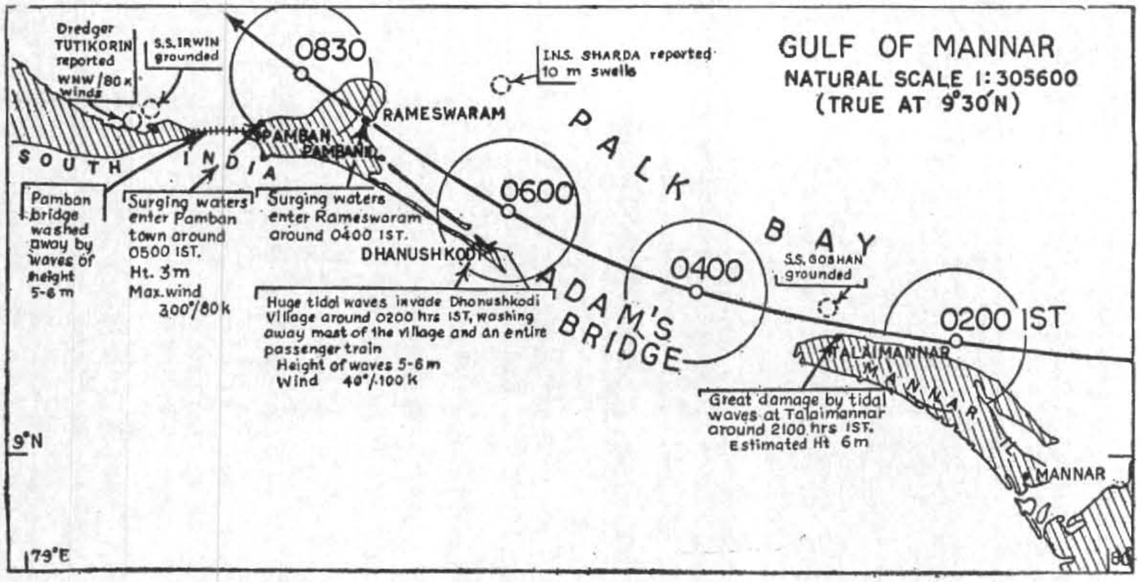

Fig. 8. Detailed map of Rameshwaram—Mannar area

The track of the storm is shown by the thick line. The probable positions of the Calm centre are shown by circle. Details of the storm wave, the destruction caused by them, the time of their occurrence and wind speed at the time of storm surges is given at each place. Approx. positions of the ships, interesting observation recorded by them are also given

and Dhanushkodi on the southeastern tip of the Rameshwaram Island, were most favourably situated relative to the storm track and from the point of view of 'fetch' for the storm swells. These stations experienced surges of the maximum height of 6 m. The details of the effects at different parts of the area are shown in Fig. 8. It can be seen that even in this small area the surges varied in height considerably depending on the orientation of the coast and track of the storm.

The minimum height of 6 m to which the surge waters rose is less than the value of H_1 given in col. 7 of Table 1. This is probably due to the fact that the comparatively flat terrain of these islands did not facilitate the piling up of waters to reach the maximum heights. The waters actually overflowed the entire island near Dhanushkodi. This has been confirmed by the officer who visited the area shortly after the storm had moved away. Even a week after the occurrence of the storm, knee-deep waters were still flowing between the Gulf of Mannar and the Palk Strait across this part of the island.

Apart from the major surges which occurred over the above islands, minor surges were reported from the nearby coastal areas of India, to the *right* of the storm track to a distance of about 20-30 miles.

Conclusions

The existing concept in vogue in our area is that storm waves should be predicted if cyclonic storms are expected to move inland near estuaries of rivers at the time of the high tide. This idea, however useful, falls far short of present-day forecasting requirements for issuing accurate warnings for coastal areas for large-scale precautionary measures, evacuation of population, etc. The simple technique and guidance material presented in this paper may be helpful to storm-warning centres in formuating their forecasts. The task of issuing successful warnings based on this technique will obviously be very much facilitated if reasonably correct predictions can also be made regarding the path and intensity of cyclones.

The technique can be applied on the meso-scale by preparing special maps of individual bays and gulfs and a careful study of the three-dimensional geometry of the coastlines. Due regard should be given to the important differences in the curvature of the exposed coast at different places.

It is felt that by a careful study of the routine and special synoptic charts, it should be possible to issue reliable warnings of storm waves at least 24 hours ahead and much suffering and loss of life can be prevented by issuing frequent bulletins over radio, keeping the public and the administrations informed of the latest outlooks.

The authors are engaged in extending the study to other important regions, including the Ganges deltaic area and the Kutch Peninsula. The results will be published in due course.

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*The scientific background on which the above technique has been built up has been obtained by reference to various earlier works. Some of the more important references are given here.