

## Storm-induced sea-level changes at Saugor Island situated in north Bay of Bengal

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**ABSTRACT.** The sea level at Saugor Island is not significantly affected by freshet discharges of the river Hooghly although there are significant changes at a station about 70 miles upstream (Minist. Irrig. Pwr. 1952, 1953). Daily departures of the observed tidal heights at Saugor Island from the values predicted by the tide predicting machine were obtained for selected periods when cyclonic storms affected the north Bay of Bengal and were located 150–250 miles away from Saugor Island. The monthly mean departure  $d_m$  was subtracted from the daily departures and the resultant values of  $(\delta - d_m)$  were found to vary between 1 and 3 ft. On the assumption of (i) a mean wind distribution found as the average of a large number of cyclonic storms in the Bay of Bengal, (ii) negligible 'static' pressure effect and (iii) a wind-stress coefficient of 0.0024 (Sverdrup), the wind pile-up at Saugor Island caused by the wind systems associated with the cyclonic storms, was computed. The depths of the ocean needed for the computation were taken from the Admiralty charts. The computed values of the pile-up were found to agree fairly well with the values of  $(\delta - d_m)$ , the mean percentage deviation being 10 per cent for the six instances studied. This suggests that wind pile-up accounts for nearly 90 per cent of the departure of actual tidal heights from the predicted values. Probably the remaining 10 per cent comes from the mass-transport effects associated with the water currents generated by the wind systems.

### 1. Introduction

The transference of energy from air to water through the medium of winds has important consequences. A steady "wind drag" on the surface of the continental shelf water can cause a piling-up of water against the coast. This piling-up manifests itself as a departure of the observed tidal height (recorded by a tide gauge) from the value predicted by a tide-computing machine. Violent winds around the centre of a cyclonic storm crossing the coast can, apart from piling up water, cause a mass transport of water towards the coast (storm tide).

In all such cases or elevations of sea level at a coastal boundary, the magnitude and duration of these elevations are influenced not only by the structure of the wind field around the storm centre but also by the speed and direction of progression of the storm centre, the character of the general wind field into which the storm advances, local topography at the coastline, continental shelf features, stage of the astronomical tide, convergence or divergence due to bays or estuaries and so on.

### 3. Storm tides along the coasts

Instances are not wanting when the Bay of Bengal coast has been struck by storm tides. The rise of sea level associated with the land-fall of a storm is the principal cause of death and destruction from tropical storms. The sea may penetrate many miles inland and thereby spread salt water over vast areas of land. Wave action may also cause erosion processes far inland beyond the normal coastline.

The surge (observed tide *minus* astronomical tide) generated on the open coast moves inland as a gravity wave. If, therefore, there is a long channel opening into the sea, the peak disturbance at its end may occur a few hours after the other signs of storm fury have begun to diminish. And if the tide happens to be high at the time, severe flooding may be caused several hours after storms' peak.

### 3. Examination of the tidal heights at Saugor Island

Saugor Island is situated in the extreme north Bay of Bengal, where the river Hooghly opens into the Bay of Bengal. The tide measuring gauge is located on the southern coastline of the island.

In order to study the extent to which tidal heights at Saugor Island are affected by the movement of low pressure disturbances across north Bay of Bengal, the following analysis was carried out.

Heights of high and low waters recorded by a tide-gauge at Saugor Island during the years 1948 and 1949 and during certain selected months of the years 1950–1955 were compared with their predicted values published in the *Tide Tables of the Indian Ocean* (Survey of India). The differences designated  $\delta$  were tabulated for the high and low tides of all the days of the periods examined. Except for a few days when there was only one high water or one low water, 2 values of  $\delta$  for high and 2 for low water were obtained for each day in all the other cases. The deviation  $\delta$  represents the effect on the predicted tide of transitory meteorological factors,

TABLE 1  
Results of an analysis of the tidal heights\* of Saugor Island during 1948

Tide phase	Monthly mean $d_m$ of daily deviations $\delta^m$ (ft)		Maximum value of the residual $(\delta-d_m)$ (ft)		Minimum value of the residual $(\delta-d_m)$ (ft)		Standard deviation of $(\delta-d_m)$ (ft)	
	High	Low	High	Low	High	Low	High	Low
January	-0.59	-0.39	0.79	1.09	-0.91	-1.11	0.427	0.483
February	-0.60	-0.68	1.10	0.88	-0.60	-1.22	0.346	0.477
March	-0.63	-0.67	0.73	1.07	-0.47	-1.43	0.308	0.496
April	-0.20	-0.44	0.80	0.74	-1.10	-0.86	0.376	0.396
May	-0.21	-0.27	1.11	1.37	-0.89	-0.73	0.416	0.434
June	-0.70	-0.44	1.00	0.94	-0.90	-1.06	0.488	0.502
July	-0.67	-0.38	1.07	1.48	-0.83	-1.02	0.448	0.462
August	-0.28	-0.06	1.08	1.66	-1.22	-1.74	0.546	0.679
September	-0.56	-0.46	1.16	1.26	-0.84	-1.24	0.432	0.510
October	-0.88	-0.61	0.58	0.91	-0.92	-0.79	0.354	0.435
November	-0.3	-0.01	1.2	0.91	-1.0	-0.59	0.487	0.380
December	-0.74	-0.89	0.84	0.49	-0.76	-0.71	0.380	0.275

\*All heights are referred to Kidderpore old Docks Sill

TABLE 2  
Abnormal positive residuals associated with both high and low tide at Saugor Island

Date (1948)	High water			Date (1948)	Low water		
	$\delta$ (ft)	$(\delta-d_m)$ (ft)	$\sigma$ (ft)		$\delta$ (ft)	$(\delta-d_m)$ (ft)	$\sigma$ (ft)
23 May	2.3	1.11	0.416	23 May	2.5	1.37	0.434
7 Jul	1.8	1.07	0.448	7 Jul	2.1	1.08	0.462
				7 Jul	2.5	1.48	0.462
14 Aug	2.2	1.08	0.546	13 Aug	2.4	1.06	0.679
				14 Aug	3.0	1.66	0.679
				15 Aug	2.7	1.36	0.679
26 Sep	1.7	0.86	0.432				
27 Sep	1.8	0.96	0.432	27 Sep	2.2	1.26	0.509
28 Sep	2.0	1.16	0.432	29 Sep	2.0	1.06	0.51

TABLE 3  
Oscillations exhibited by residuals at Saugor Island

Date (1948)	High water			Date (1948)	Low water		
	$\delta$ (ft)	$(\delta-d_m)$ (ft)	$\sigma$ (ft)		$\delta$ (ft)	$(\delta-d_m)$ (ft)	$\sigma$ (ft)
1 Jan	-0.1	-0.91	0.427	2 Jan	2.1	1.09	0.483
2 Jan	0	-0.81	0.427	3 Jan	2.1	1.09	0.483
6 Mar	1.5	0.73	0.308	6 Mar	-0.3	-1.03	0.496
7 Mar	1.5	0.73	0.308	7 Mar	-0.7	-1.43	0.496
5 Oct	-0.1	-0.72	0.354	5 Oct	1.7	0.91	0.435
6 Oct	-0.1	-0.72	0.354	5 Oct	1.6	0.81	0.435

*i.e.*, the departure from the values prescribed by astronomical and climatological effects.

Monthly mean  $\bar{d}_m$  of the daily deviations  $\delta$  was computed separately for high and low water for all the months examined. The differences or residuals ( $\delta - \bar{d}_m$ ) were obtained and thus the mean monthly meteorological influence was eliminated from the individual values of  $\delta$ . The residual ( $\delta - \bar{d}_m$ ) was taken as a measure of sea level and may be regarded as the height of the 'meteorological tide'.

Monthly standard deviations  $\sigma$  of the daily values of  $\delta$  were worked out separately for high and low water. A residual ( $\delta - \bar{d}_m$ ) is regarded as abnormal or significant in a meteorological sense when its absolute value nearly equals or exceeds the value of  $2\sigma$  for the relevant month. Such significant values of ( $\delta - \bar{d}_m$ ) ranged from 1 to 3 ft for the periods examined.

The choice of  $2\sigma$  as a means of sorting out significant values of ( $\delta - \bar{d}_m$ ) was governed partly from statistical considerations and partly, with a view to ensuring a reasonable number of significant residuals. The choice of  $3\sigma$  limits abnormal residuals to a very small number.

An example of the analysis carried out on the tidal heights of Saugor Island is given in Tables 1 to 3. Table 1 is a summary of certain monthly features of the tides and Table 2 shows a few instances where both high tides and the associated low tides exhibited abnormal positive values of ( $\delta - \bar{d}_m$ ). There was also a single instance (not mentioned in the table) when ( $\delta - \bar{d}_m$ ) was significantly negative for both high tide and the associated low tide. In Table 3, some instances are listed when the residual ( $\delta - \bar{d}_m$ ) had an oscillatory character.

There were also occasions when (i) only high tides exhibited significant values of ( $\delta - \bar{d}_m$ ) and (ii) only low tides exhibited significant values of ( $\delta - \bar{d}_m$ ). However, the number of such instances was too many to be shown in tables.

#### 4. Action of wind on water surface

As long as the wind velocity does not exceed a critical value no wave development is possible on the surface of water and in such a case the tangential drag exerted by the wind, known as 'skin drag', either results in pure wind currents in regions far away from the coast, or a wind 'set-up'\* at coastal places. When waves develop there is an additional drag called 'form drag' on the water surface and this assumes great significance as the surface deviates considerably from the state of hydrodynamic smoothness.

Munk (1955) has shown that whereas the tangential drag is proportional to  $u^2$ , where  $u$  is wind velocity, the form drag is proportional to  $u^3$ . Van Dorn (1953) regards the total drag on a rough water surface as made up of two parts—a frictional drag proportional to  $u^2$  and a form drag proportional to  $(u - u_{\min})^2$ . Francis (1951), working in wind tunnels with speeds up to 14m/sec, also obtained a  $u^3$ -law for the shear stress. Vines (1959) experimented with insoluble monolayers spread on water, using a rectangular trough inside a wind tunnel. He observed that at low wind speeds (1 to 3 m/sec), the surface stress was proportional to  $u^2$ . From observations of the vertical variation of the geostrophic departure of the wind at three small low lying Pacific Islands in the trade wind belt, Sheppard and Omar (1952) found that there is no systematic departure from the  $u^2$ -law for surface wind speeds ranging from 3m/sec to 12m/sec.

When as a result of wind blowing over a water surface piling-up takes place at the downward end and a steady state is reached (*i.e.*, the total mass of water crossing any vertical plane is zero), the wind stress is balanced by the component of gravity acting on the piled-up mass. If  $\alpha$  represents the angle of tilt of the surface from its undisturbed level, it can be shown (Keulegan 1951) that—

$$\tan \alpha = (\tau_0 + \tau_b) / g\rho_w h \quad (1)$$

where  $\tau_b$  is the bottom stress,  $\tau_0$  the surface traction,  $\rho_w$  density of water and  $h$  the water depth. Writing  $n = 1 + (\tau_b / \tau_0)$  Eq. 1 becomes

$$\tan \alpha = n\tau_0 / g\rho_w h \quad (2)$$

When the bottom stress or return current is absent, ( $n = 1$ ) and therefore

$$\tan \alpha = \tau_0 / g\rho_w h \quad (3)$$

For laminar flow,  $\tau_b = \frac{1}{2}\tau_0$ , so that  $n = 3/2$ . In turbulent conditions  $n$  is much smaller.

Values of stress at different wind velocities have been computed from observations of slope of the sea surface during high value winds or storms in the North Sea or in the Baltic (Corkan 1950, Hela 1948, Palmén and Laurila 1938, and Rossitter 1953). Similar observations have also been made in shallow lakes, in a small pond (Van Dorn 1953) and in laboratory tanks (Francis 1951). When the values of stress-coefficient  $\gamma^2$  obtained under varying circumstances by different workers on the assumption of the square law,

$$\tau = \gamma^2 \rho_a u_{10}^2 \quad (4)$$

\*The term "set-up" refers to the steady state anomaly of water level caused by the tangential wind stress on the sea surface normal to the coastline

(where  $\tau$  is surface stress,  $\rho_a$  is air density and  $u_{10}$  is wind velocity at 10 m height) are examined, they show appreciable differences. It is, therefore, understandable why different authors have suggested different relationships between  $\gamma^2$  and  $u_{10}$  or what amounts to the same thing, have proposed that the stress  $\tau$  should be expressed by an equation of the type —

$$\tau = \gamma^2 \rho_a u_{10}^p$$

where  $p$  differs from 2. This would imply that  $\gamma^2$  is not a pure number, but a function of  $u_{10}$ .

Thus no definite relationship can be established between wind and stress, but for obtaining rough values of the stress from wind observations, Sverdrup (1957) proposes the simple relation —

$$\tau_0 = (2.4 \times 10^{-3}) \rho_a u_{10}^2 \quad (5)$$

$$= 2.88 \times 10^{-6} u_{10}^2$$

(if  $\rho_a = 1.2 \times 10^{-3}$  gm/cc)

especially when the wind under consideration varies over a wide range. This value of  $\gamma^2$ , i.e.,  $2.4 \times 10^{-3}$  is adopted for the present study.

#### 5. Storms in the north Bay of Bengal and wind set-up at Saugor Island

The movement of 5 storms across the head Bay during the period 1948–55, was examined for a study of the associated sea level changes at the southern coast of Saugor Island, induced by wind set-up. Details of the 5 storms are available in *India Weath. Rev.*, Annual Summary, Part C (India met. Dep. 1948, 1951, 1952, 1953, 1955).

(a) *Storm of 12 to 18 August 1948* — Figs. 1 and 2 depict the synoptic weather features at 1700 IST of 14th and 0200 IST of 15th. The crossed line in each chart shows the track of the storm.

(b) *Storm of 24 to 29 July 1951* — The storm track and the synoptic weather situation at 0830 IST of 25 July 1951 are shown in Fig. 3.

(c) *Cyclonic storm of 2 to 8 July 1952* — Fig. 4 shows the track of the storm and the storm features at 0830 IST of 5th.

(d) *Cyclonic storm of 29 July to 5 August 1953* — The situation as at 0230 IST on 3 August 1953 is depicted in Fig. 5.

(e) *Cyclonic storm in the Bay of Bengal — 28 September to 5 October 1955* — Fig. 6 gives the synoptic situation at 0830 IST of 30 September 1955.

#### 6. Computation of set-up at Saugor Island

Six occasions were selected during the movements of the above 5 storms to compute the piling-up of water against the southern coastline of Saugor Island. On these occasions, the values of  $(\delta - d_m)$  were significant and of the type shown in Table 2. Also the storms examined had their centres 150–250 miles away from Saugor Island.

For some of these storms, wind data around the storm centre were scanty. The actual wind-fields on the individual occasions of scanty data were deduced from the observed winds and the mean wind distribution found as the average of a large number of cyclonic storms in the Bay of Bengal (Koteswaram and Gasper 1956). The wind distribution in the different sectors was increased or decreased in the ratio which the observed winds bore to the winds of the mean cyclonic storm at the corresponding sectors. Wind set-up at Saugor Island caused by the wind systems associated with the cyclonic storms, was computed using the relation

$$\frac{\delta - d_m}{L} = \frac{n\gamma^2}{g} \cdot \frac{\rho_a}{\rho_w} \cdot \frac{u^2}{h} \quad (6)$$

which is obtained from Eqns. (2) and (4). Here  $(\delta - d_m)/L$  is the slope of a windfetch of length  $L$  due to a wind set-up  $(\delta - d_m)$  at one end, the other symbols have meanings already given.

When  $(\delta - d_m)$  is measured in ft,  $L$  in miles,  $h$  in ft and  $u$  in kts, Eq. (6) becomes —

$$(\delta - d_m) = \frac{n\gamma^2}{1.769} \cdot \frac{Lu^2}{h} \quad (7)$$

where it is assumed that  $\rho_a / \rho_w = 1.2 \times 10^{-3}$  and  $g = 32$  ft/sec<sup>2</sup>.

If, however, the wind causing pile-up has different directions over different portions of the fetch, a more accurate formula is —

$$(\delta - d_m) = \frac{n\gamma^2}{1.769} \Sigma \frac{Lu^2}{h} \quad (8)$$

where the summation is carried out for all the regions into which the total fetch can be divided on the basis of wind direction.

To use formula (8) for the computation of  $(\delta - d_m)$ , the north Bay of Bengal was divided into half-degree squares of latitude and longitude. The average depth of each half-degree square was deduced from Admiralty charts (Fig. 7). Average wind speed and wind direction for each of the half-degree squares were obtained from the wind-field around the storm centre.

For each of the occasions examined, the streamline passing through Saugor Island was drawn, and is shown in the relevant maps as a thick directed line. Since the total set-up at the southern coastline of Saugor Island is the sum of the individual values of the set-up in each of the half-degree squares traversed by the streamline up to Saugor Island, the summation in Eq. (8) was carried out for these half-degree squares. In most of the cases

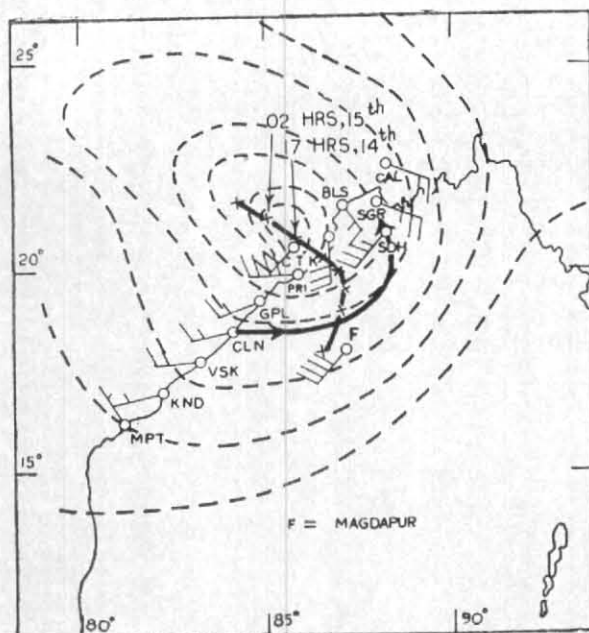


Fig. 1. Weather chart at 1700 IST on 14 August 1948

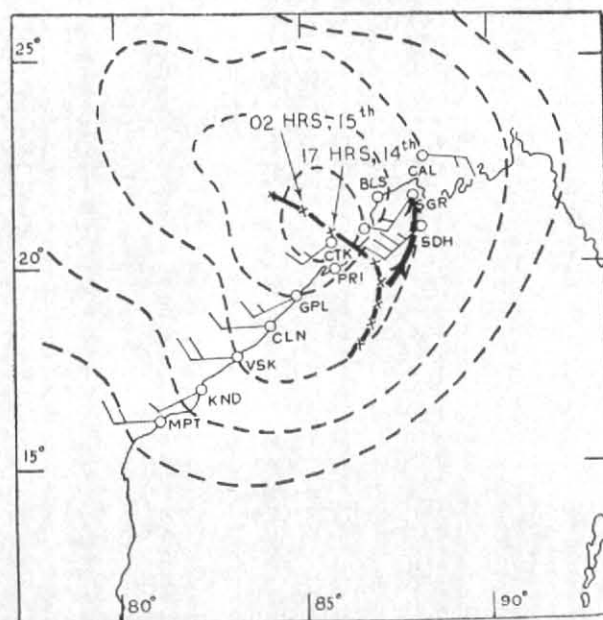


Fig. 2. Weather chart at 0200 IST on 15 August 1948

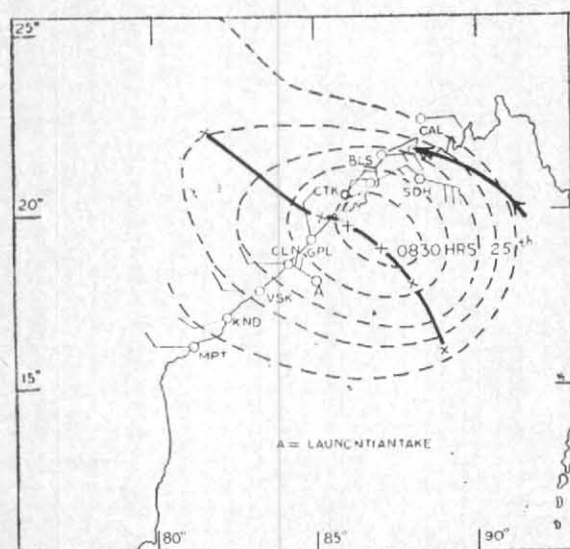


Fig. 3. Weather chart at 0830 IST on 25 July 1951

the contributions from the half-degree squares where the depth was more than 60 fathoms were negligible, so that computations were limited to half-degree squares with smaller depths. Generally, the extension of the streamline to about two degrees of latitude south of Saugor Island was adequate for the computation. A value of  $24 \times 10^{-4}$  for  $\gamma^2$  proposed by Sverdrup (1957) was used and  $n$  in eq. (8) was taken as 1.

By way of an example the results of applying the above method to the determination of the set-up

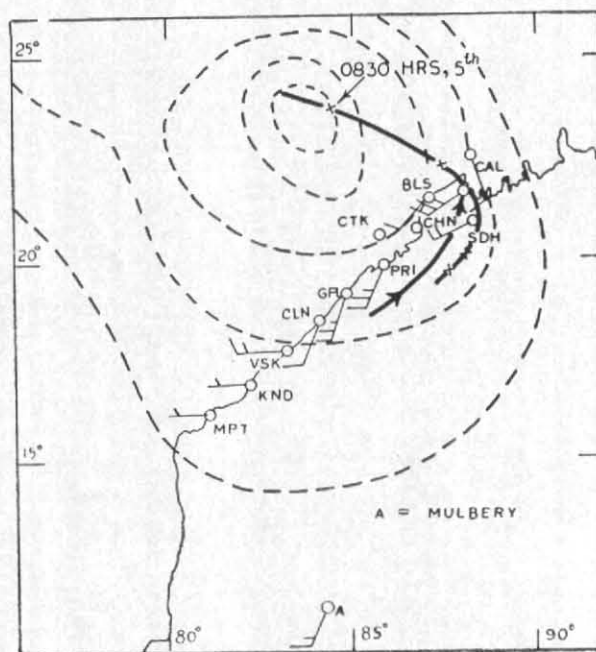


Fig. 4. Weather chart at 0830 IST on 5 July 1952

at Saugor Island at 0835 IST of 30 September 1955 are given below—

Phase of the tide at 0835 IST of

30 September 1955 : High

Storm period : 28 September to 5 October 1955

Distance of the storm centre from  
Saugor Island at 0835 IST : 135 miles

Observed value of  $(\delta - d_m) = 1.5$  ft

Referring to the synoptic weather chart at 0830 IST of 30 September 1955 (Fig. 6), the streamline

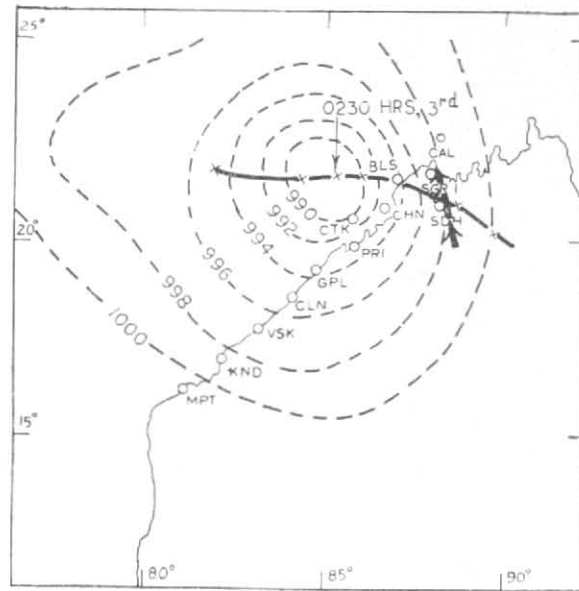


Fig. 5. Weather chart at 0230 IST on 3 August 1953

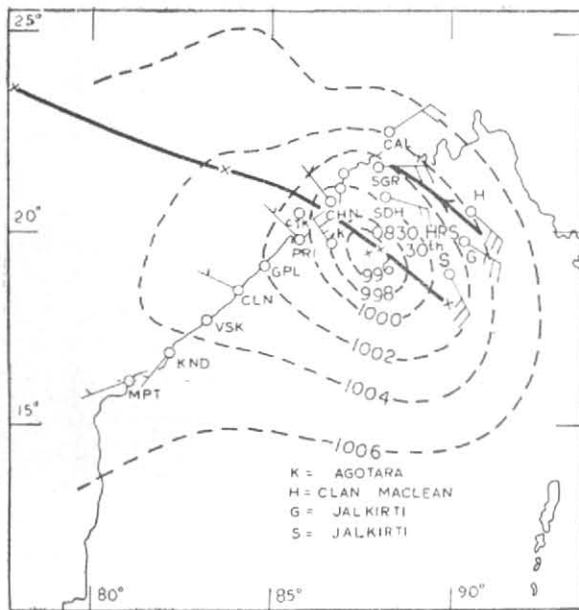


Fig. 6. Weather chart at 0830 IST on 3 September 1955

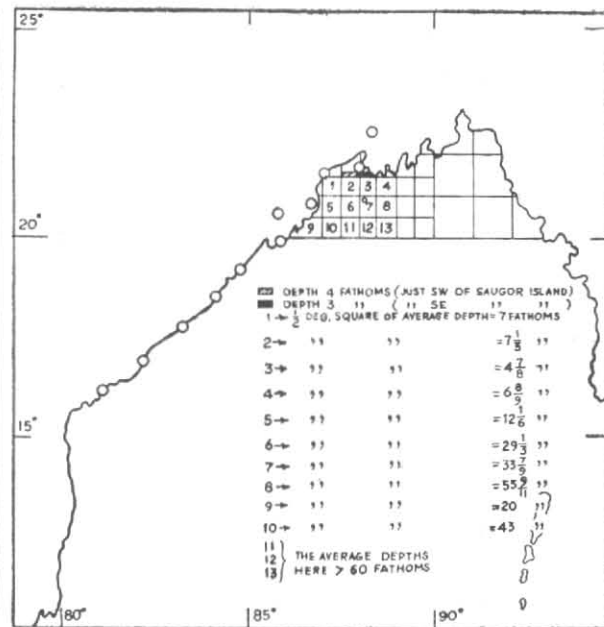


Fig. 7. Average depths of half-degree squares south of Saugor Island

TABLE 4  
Computation of wind set-up at Saugor Island on six selected occasions

Date and time of the occasion studied	Distance of storm centre from Saugor Island (miles)	Date and time of synoptic weather chart used	Phase of the tide	Observed ( $\delta - d_m$ ) (ft)	Computed ( $\delta - d_m$ ) (ft)	Observed ( $\delta - d_m$ ) minus computed ( $\delta - d_m$ ) (ft)
14 Aug 1948 at 1757 IST	190	14 Aug, 1700 IST	High	1.1	1.4	-0.3
15 Aug 1948 at 0022 IST	250	15 Aug, 0200 IST	Low	1.4	1.3	-0.1
25 Jul 1951 at 0805 IST	190	25 Jul, 0850 IST	Low	2.8	3.2	-0.4
5 Jul 1952 at 0730 IST	260	5 Jul, 0830 IST	High	1.1	1.1	0
3 Aug 1953 at 0240 IST	190	2 Aug, 2330 IST 3 Aug, 0230 IST 3 Aug, 0830 IST	High	1.5	1.5	0
30 Sep 1955 at 0835 IST	135	30 Sep, 0830 IST	High	1.5	1.5	0

through Saugor Island is first drawn (as shown by the thick directed line), so that it makes an angle of about  $20^\circ$  with the isobar passing through Saugor Island. Portions of this streamline traversing half-degree squares whose depths exceed 60 fathoms are insignificant and this stipulation divides the effective portion of the streamline into three fetches in each of which the wind direction is sensibly uniform. These three fetches designated  $L_1$ ,  $L_2$ , and  $L_3$  according to their lengths can then be seen to have the following characteristics—

Fetch  $L_1$ :  $L_1 = 20$  miles

Estimated wind : easterly, 15 kts  
Average depth  $\bar{h}_1 = 16$  ft

Fetch  $L_2$ :  $L_2 = 44$  miles

Estimated wind : eastsoutheasterly,  
22 kts  
Average depth  $\bar{h}_2 = 27$  ft

Fetch  $L_3$ :  $L_3 = 8$  miles

Estimated wind : southeasterly, 20 kts  
Average depth  $\bar{h}_3 = 88$  ft

To compute the set-up, we find that—

$$\Sigma(Lu^2/h) = 1106$$

Therefore,

$$(\delta - d_m) = 1.5 \text{ ft}$$

### 7. Results and Conclusions

The results of the computation of wind set-up on the six selected occasions together with the relevant storm and tidal data are summarized in Table 4. It can be seen from the table that the

computed values of pile-up are nearly equal to the observed values of  $(\delta - d_m)$ . The mean deviation of the computed values from the observed values for the 6 instances studied was found to be 10 per cent suggesting that the wind pile-up effect explains nearly 90 per cent of the variation from the predicted tidal height on the occasions studied. Probably the remainder is attributable to mass transport effects associated with water currents generated by the wind systems.

In another case examined (26 July 1951), the passage of a storm across the north Bay of Bengal gave value of 1.5 ft for the residual  $(\delta - d_m)$ . The computed wind set-up was 0.9 ft. The discrepancy could not be explained away as due to rainfall upstream of Saugor Island during the preceding two days, because the rainfall in fact was not heavy enough. Moreover, as already stated, freshet effects on Saugor Island sea level are negligible. It is possible that the effect of a mass transport of water could have considerably augmented the wind pile-up effect, but this requires further investigation.

In concluding, the author would like to caution that the above results and conclusions will have to be viewed in the light of inadequate wind data associated with the storms examined in the region of interest. This necessitated a certain amount of subjectivity in the analysis.

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