THE NOVEMBER 1977 ANDHRA PRADESH CYCLONE AND THE ASSOCIATED STORM SURGE

I. SUBBARAMAYYA, R. RAMANADHAM *and* M. SUBBA RAO
Department of Meteorology and Oceanography, Andhra University, Waltair

(*Received 8 May 1978; after revision 15 January 1979*)

The important features of the November 1977 Andhra Pradesh Cyclone as revealed by synoptic analysis and radar studies and its movement are discussed. The storm surge information, gathered by the authors, regarding its height, time and direction of approach and withdrawal are presented in the form of charts. The salient features are critically examined. The surge height is evaluated using several simple techniques developed by other workers. A method for objectively evaluating the surge from the sea-surface slope and wind relationship is also presented.

INTRODUCTION

TROPICAL cyclones are highly devastating and are only next to tornadoes in intensity but many times bigger in size. Cyclones form in all tropical oceans where the sea-surface temperature is more than 26.5 °C (Palmen, 1948). Their frequency is the highest in the western north Pacific Ocean and practically absent in the south Atlantic and the eastern South Pacific. The origin and development of tropical cyclones as a global problem was studied by Gray (1968).

In the Bay of Bengal, the frequency of tropical cyclones of all intensities is the highest in the monsoon season but those of hurricane intensity is maximum in the October-November months. These cyclones of the post-monsoon season generally develop in the south Andaman Sea and move in a west -northwesterly direction initially, and later, some continue to move in the same direction while some other would recurve either after crossing the east coast of India or over the Bay of Bengal itself. Thus, they are likely to affect any part of the east coast of the Indian sub-continent and the coasts of Bangaladesh and upper Burma. They also generate huge waves while at sea and storm surges while crossing the coast which are quite devastating in some coastal regions.

The storm surge depends on several factors : (*i*) the low pressure at the cyclone centre, because of which the sea-surface is elevated which is known as the inverted barometer effect; (*ii*) the piling up of water against the coast to the right of the track because of onshore winds; (*iii*) the configuration of the coast — if it is a narrow gulf, the piling water will be forced to rise to higher levels; and (*iv*) the off-shore bottom topography — the more flat it is, the higher the sea-surface rise. A brief account of the storm surges and their mechanism is given by Walander (1961).

19TH NOVEMBER 1977 CYCLONE

A depression developed in southeast Bay on 13th November, 1977. It moved westward and developed into a cyclonic storm by 15th November, in South Central Bay

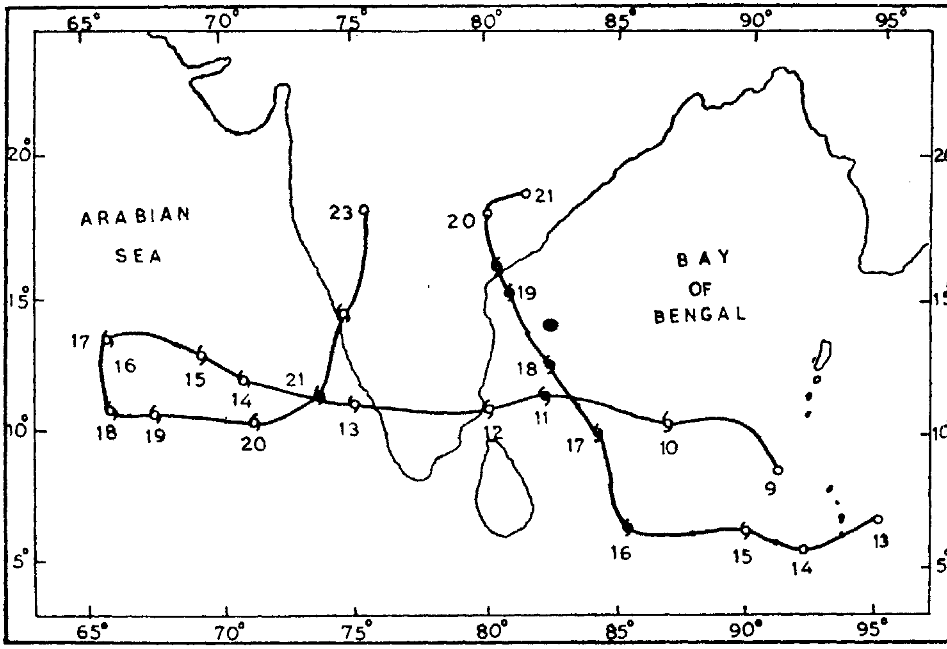

FIG. 1. Tamilnadu/Karnataka and Andhra Pradesh cyclonic storms of November 1977

(Fig. 1). It moved into southwest Bay by 16th and showed a tendency to recurve. However, it did not recurve but only changed its course from a west-northwesterly direction to a north-northwesterly direction. Earlier, another cyclonic storm moved westward and crossed Madras coast on 12th November and was in south central Arabian Sea by 16th. It remained practically stationary till 17th morning and then slowly moved eastward from 18th, which is a very unusual course. From 21st, it moved practically northwards and crossed the west coast of peninsular India on 22nd. The peculiar changes in the movements of the storms from 16th suggest the effect of interaction of the two vortices with one another, but their movements after 18th, when the two cyclones were in fact closer, the Fujiwhara effect was less impressive. The movements of the two storms, therefore, might have also been affected by a dominant outside system.

The later cyclone which crossed the Andhra Pradesh coast was accompanied by a storm surge and several thousands of persons lost their lives. Even a bigger number of heads of cattle were also lost. About sixty villages situated close to the storm track and to its right in the coastal area, inhabited by fishermen and farmers were completely washed out in the storm surge.

The authors have visited the affected area to accurately determine the landfall point and the path of the storm over land and collect information on the storm surge to determine its exact time and location and construct the shape of the surge. Necessary meteorological data and radar observations were taken from the India Meteorological Department.

The eye of the cyclone appeared on the radar in Madras since 17th night till

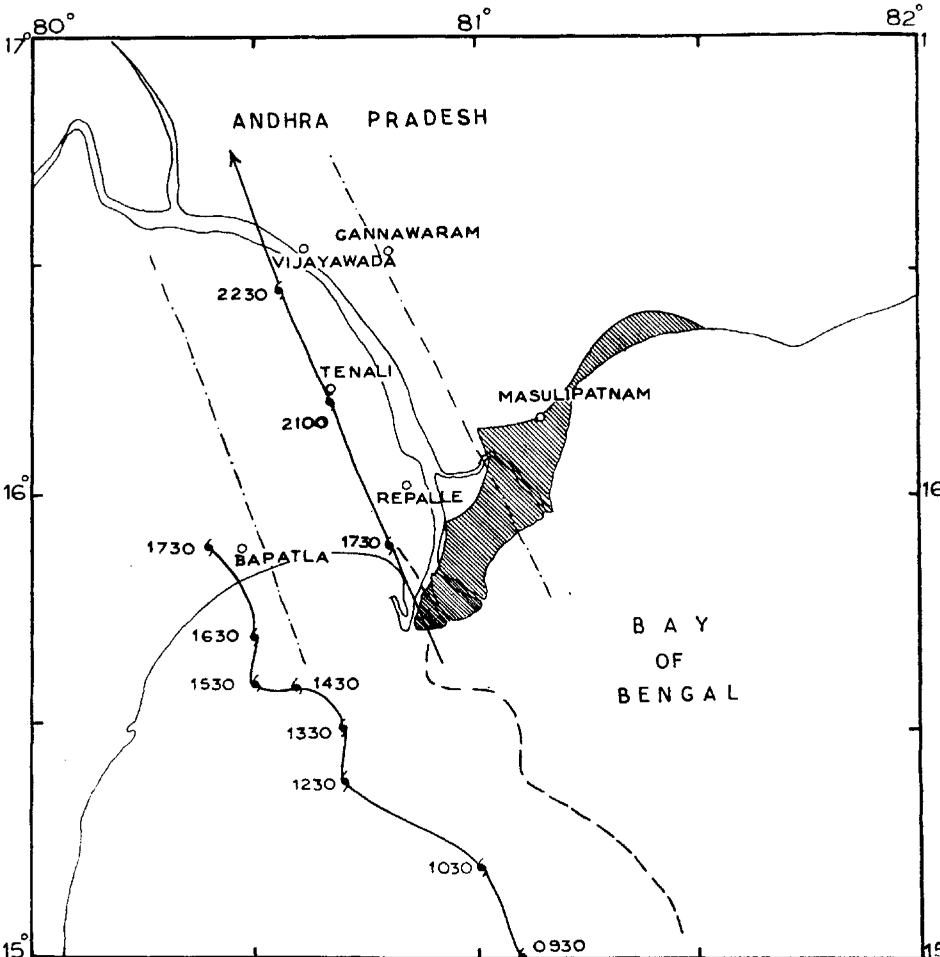

FIG. 2. Path of the cyclone at the time of crossing the coast. Times are given in hours I.S.T. by the side of the location points. Surge effected area is shaded.— . — . — Boundary of the eye. — — — — Radar track after an eastward displacement for adjustment of 1730 hrs I.S.T. position.

the landfall time. The eye was nearly circular and had a diameter of about 60 km. The rain-shield was to the left of the centre as the storm moved north-northwestward. From 19th morning there was a gradual decrease in the rain-area but a well defined circular eye-wall continued to appear till noon. Thereafter, the echoes round the eye gradually disappeared. The detailed path of the storm on the 19th till it crossed the coast, according to the radar-fixes is presented in Fig. 2. The landfall point and the path of the storm as determined by the authors from the wind changes narrated by the local people and the directions of the uprooted trees in the storm-struck area, is also presented in the same figure. The centre of the storm passed east of Nizamabad, west of Repalle, practically over Tenali and close to Vijayawada. This means, the storm crossed the coast further to the east of Bapatla at 1630 hrs.

I.S.T., while the radar observations indicate a path west of Bapatla. This difference could be because of calibration errors of the radar. However, the relative positions can be relied upon. The storm moved at a speed of 11 knots out at sea but was decelerated to 6 knots when it went close to the coast. The wavy movement of the storm could be due to the interaction of the storm circulation with the general flow (Yeh, 1960). The period of the wavy motion was about 3 hrs. the wave-length was about 3° lat. close to the coast, but out at sea it was nearly double.

A ship caught in the cyclone, reported a central pressure of 940 mb on the 17th of November. Masulipatam reported a sustained surface wind of 67 kts at 1730 hrs. I.S.T. on the 19th. The barogram at Gannavaram showed the lowest pressure of 973.3 mb on the 19th at 2230 hrs. I.S.T. and simultaneously the strongest sustained wind of 75 kts. was noted. Though Gannavaram, hence, was not in the eye, it could have been very close to the eye wall in view of the dimension of the eye. Assuming sea-level central pressure to be 975 mb (it could be less) at 2230 hrs. I.S.T. : i.e., 6 hours after the time of landfall, the central pressure at the time of landfall according to Malkin's (1959) formula would be about 962 mb. Therefore, the maximum wind in the storm at the time of crossing the coast according to Fletcher's (1955) equation would be about 106 kts.

The Storm Surge

Instrumental observations on storm surges to understand their exact characteristics are very few over the world, partly because of their rare occurrence and partly because of lack of observational set-up. Redfield and Miller (1957) described some characteristics of the storm surges accompanying the hurricanes on the Atlantic coast.

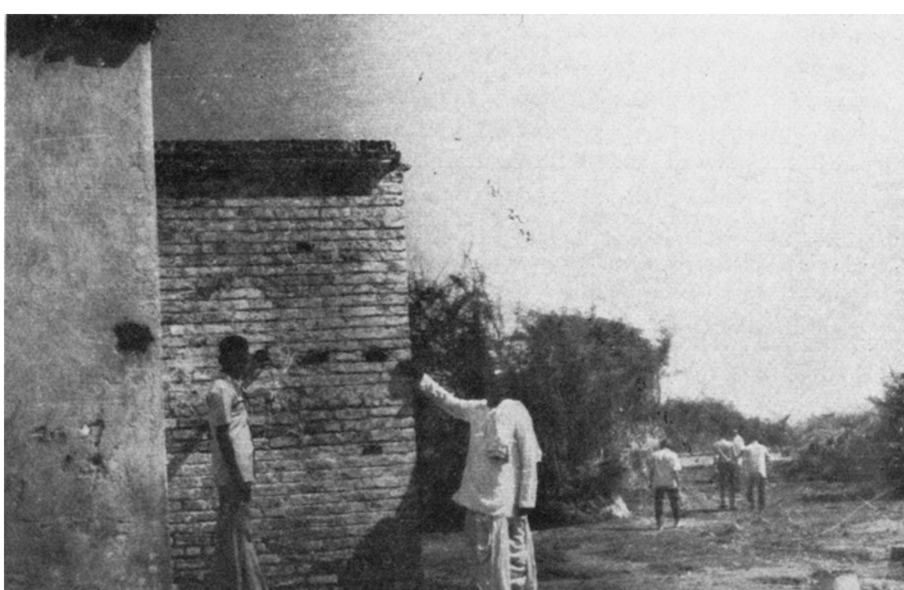

FIG. 3. The priest showing the surge-height against the temple-wall at Hamsaladevi.

Hoover (1957) made an attempt to study storm-surge-profiles in the case of hurricanes of Atlantic and Gulf of Mexico and reported peak surges near or to the right of the landfall point. Conner and Goudeau (1968) observed maximum elevation of the sea-level to the right of the storm about 2 hrs after the closest approach of the storm in the case of hurricane Besty. Such observations are practically absent for the Indian region since there has been no proper instrumental set-up along the Indian coast suitable for their study. However, post-cyclone surveys are being conducted by the India Meteorological Department and the information is recorded in the annual weather summaries.

The authors during their visit to the present cyclone affected area made enquiries with the local people that survived in the storm surge, regarding its height, direction of approach, time of occurrence and time of recession. The height reports were counter checked against watermarks left by the surge on standing walls of buildings

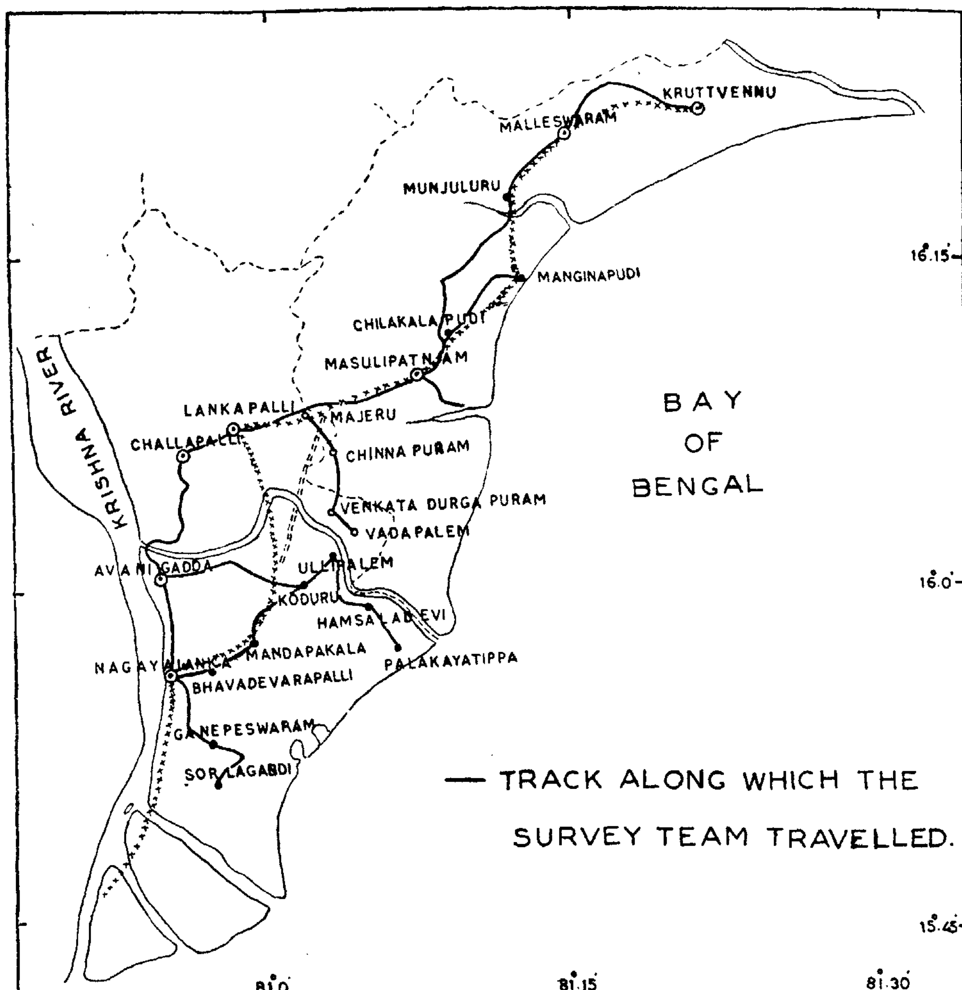

FIG. 4

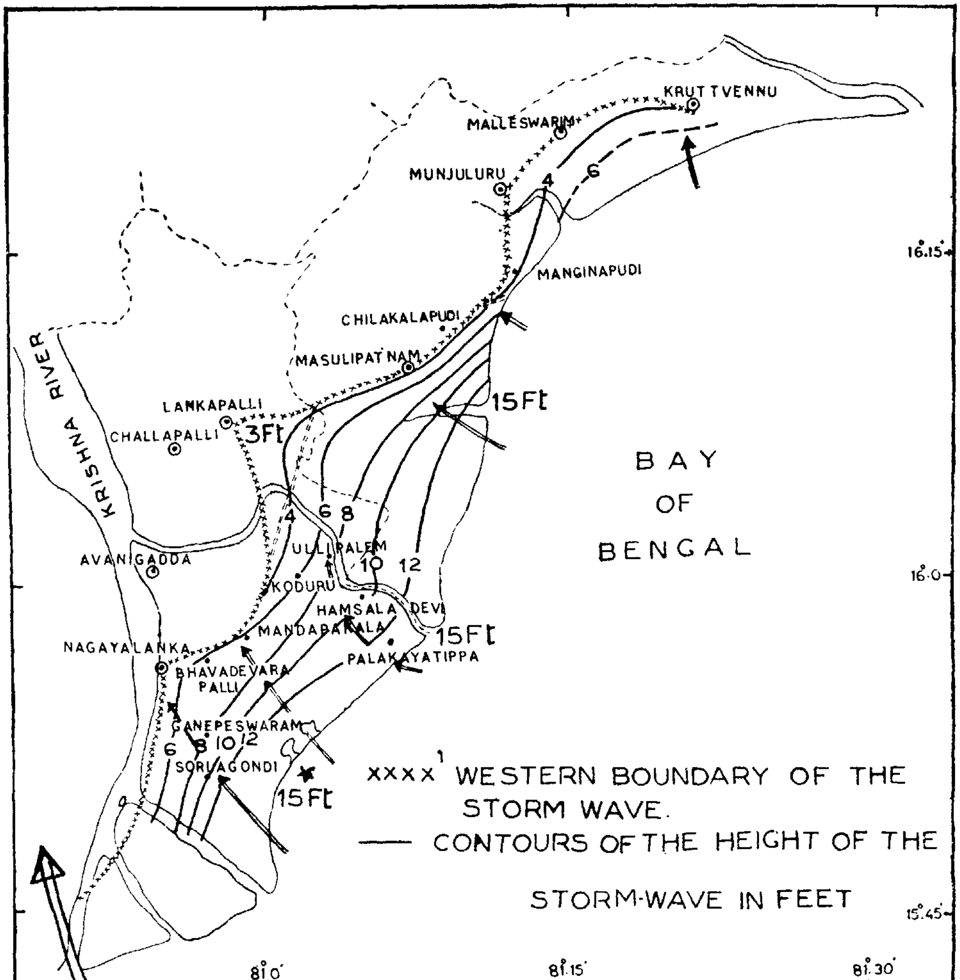

FIG. 5

(Fig. 3), the floated hay that got entangled in trees etc. The route along which the authors have travelled to make the enquiry is shown in Fig. 4. The oral reports from different individuals were also checked for spatial consistency and charts showing contours of the height field of the surge, isochrones of the surge incidence and withdrawal were prepared and presented in Figs. 5 to 7. The reports of withdrawal times showed poor consistency and therefore isochrones could not be drawn in some areas. However, times of withdrawal given by different persons independently in neighbouring areas and agreeing with one another are noted on the chart at the respective places.

Results and Discussion

The storm surge occurred practically to the right of the landfall point (Fig. 5) and extended to distances beyond 40 miles. Over a stretch of about 30 miles the surge

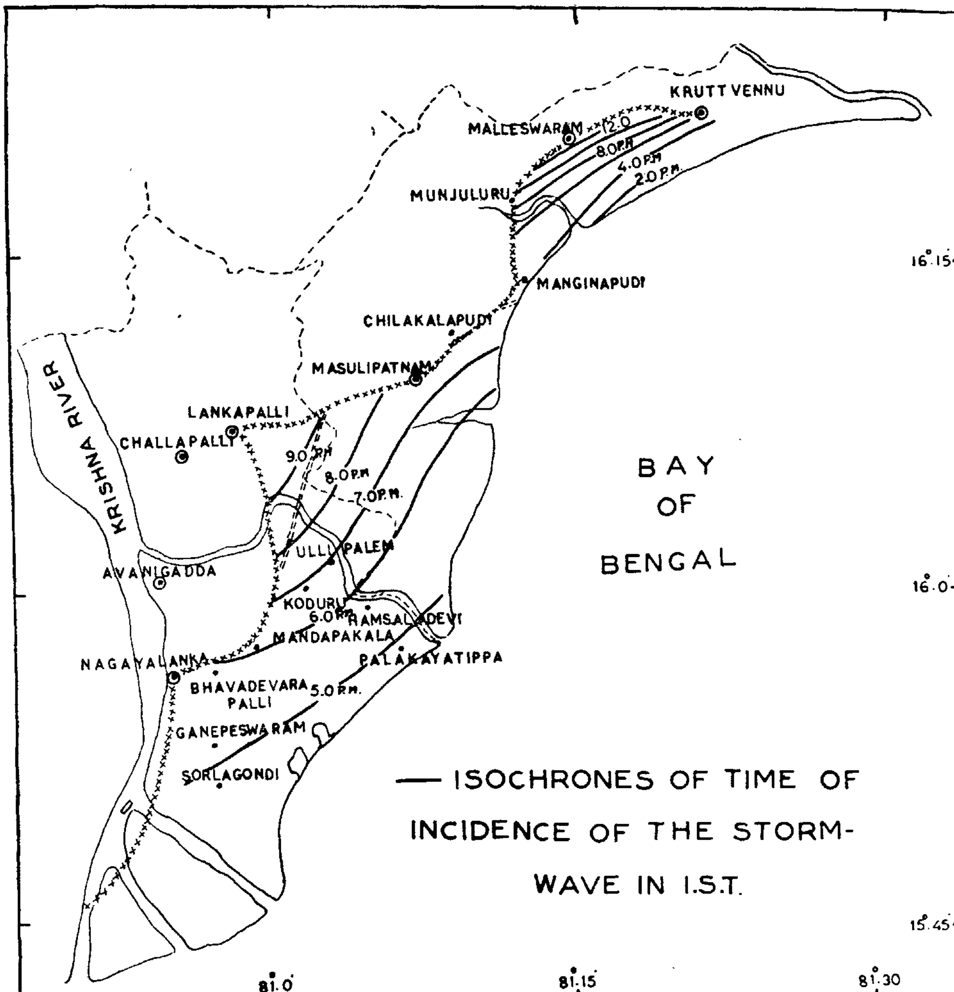

Fig. 6

was of about 15 ft height above the mean sea-level near the coast. The surge has spread inland as far as 8 to 12 miles and its height above the ground level gradually decreased inland. The ground heights given in the Survey of India charts in the locality indicate a gentle slope of about 1.5 ft in one mile. Thus the surge has spread inland upto the 15 ft ground contour while its height at the coast was also 15 ft.

Though the extent of the surge at Manginapudi was very little, farther north it had spread 3 to 4 miles inland and the height of the surge at the coast was about 6 ft. The small extent of the surge at Manginapudi could be because of the greater slope of the hinterland at that place than on either side. The total area affected by the surge relative to the path of the cyclone is shown in Fig. 2.

The surge was reported to have entered most of the places from the southeast except at Palakayatippa and Ullipalem where it was from the east and south res-

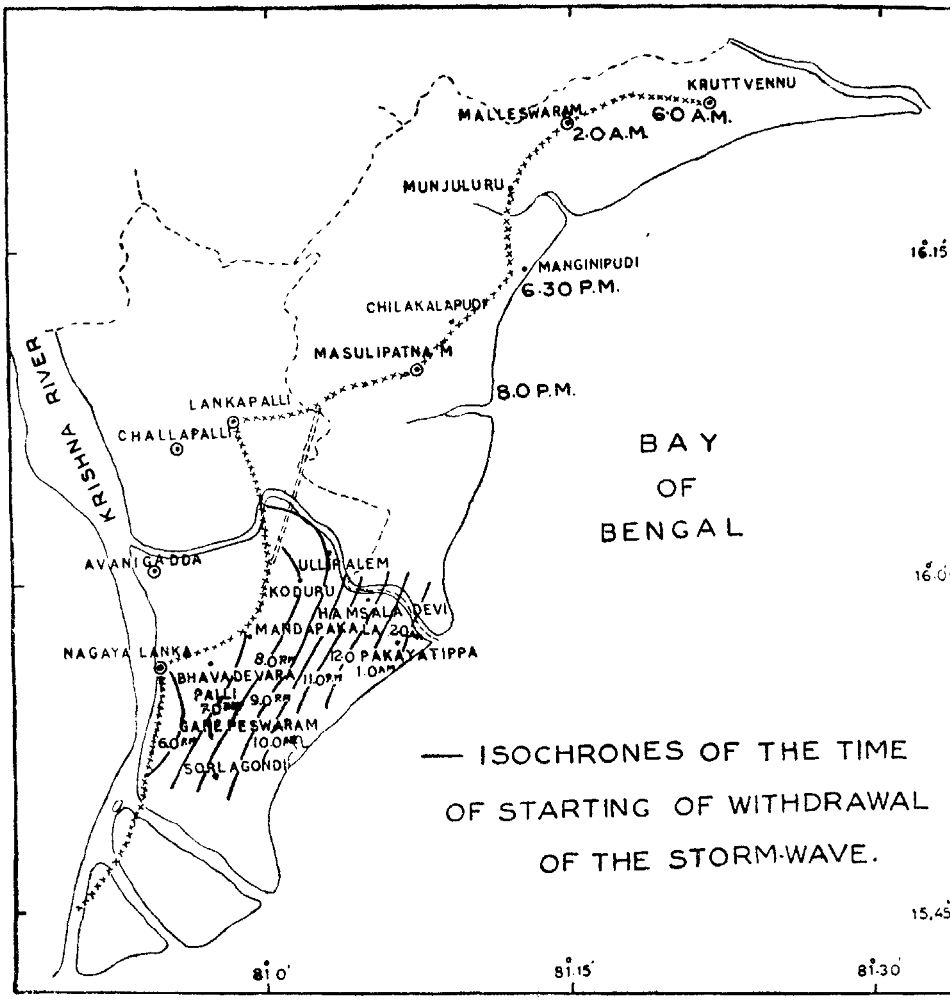

FIG. 7

pectively. The directions of advance of the surge are indicated in Fig. 5 by double line arrows. The differences in direction at the above two places may be due to the northern distributary of Krishna river and the low elevation of the neighbouring area. If the surge was equally strong at Palkayatippa and at the coast near Sorlagondi as noted in Fig. 5, the surge contours could have taken an opposite curvature to what is shown in the diagram at Hamsaladevi across the northern distributary. This leads one, therefore, to infer that the surge could have been more intense in the south near about the place indicated by a star in the figure. Here, it may be noted that Hoover (1957) observed peak surges occurring to the right of storms as far as 30 miles from the landfall point but more often at a distance of about 10 miles.

The storm surge appeared at the southern part of the coast at about 4.30 p.m. (Fig. 6) and it was about the time the storm-centre crossed the coast. That was also the high-tide (neep) time on that day. The isochrones which indicate the wave front, are nearly parallel to the height contours of the surge and are approximately perpendicular to the isobars and wind. The advance of the surge seems to be quick, about 4.5 kts., close to the coast in Sorlagondi area and relatively slow, about 2.0 kts. further north and inland.

In the north, the surge waters appeared as early as 2.0 p.m. at the coast, and at midnight 4 miles inland. Thus the waters have spread inland very slowly unlike in the south close to the cyclone centre. This rise in sea-level at this place should be due to the forerunner. In the case of Atlantic hurricanes (Redfield & Miller, 1957) the forerunner was observed to be a gradual rise in sealevel occurring along the coast preceding the arrival of the cyclone at the coast but not necessarily at the landfall point.

The surge waters started withdrawing as early as 6.0 p.m. in the south (Fig. 7) and after 9.0 p.m. farther north, from the western side of the affected area. The withdrawing took place near the coast at 2.0 a.m. at Palakayatippa and at 10.0 p.m. in the south. Thus the surge waters were standing for about 0.5 to 1.0 hour in the extreme west and 6.0 to 10.0 hours at the coast with the period increasing from south to north. The duration of the surge on the Masulipatam-coast was only 2.0 hours. The early withdrawal of the surge waters in Sorlagondi area could be because of the northward movement of the cyclone and the early changing of winds to the opposite direction in that region. The short duration of the surge between Masulipatnam and Manginapudi could be because of the steeper slope of the hinterland.

HIND-CAST OF THE STORM SURGE

Several attempts have been made and techniques developed to forecast storm surges in the past. To mention a few, Hoover (1957) and Conner *et al.* (1957) developed regression equations relating the central pressure in the storms with the surge. Schalkwijk (1947) and Reid (1957) suggested semi-empirical relationships between wind and surge. Welander (1961), Platzman (1963) and Jelesnianski (1967) followed schemes involving complex integrations of hydrodynamical equations by numerical methods. Das *et al.* (1974) examined the storm surges at some north Indian coasts adjoining Bay of Bengal by attempting numerical solutions to the governing dynamical equations. The numerical methods for forecasting storm surges are quite time-consuming and though the principle is more scientifically rigorous, because of the various assumptions involved and limitations of the inputs, the results are not yet very good. Harris and Angelo (1963) comment that "*the regression technique may be equivalent or superior to a prediction based on the same data obtained by the direct integration of the hydrodynamical equations.*"

The authors have applied some simple empirical and semi-empirical techniques and prepared hindcasts for the storm surge experienced with the November 1977 A. P. Cyclone, so that the results would be helpful in future forecasting.

According to Schalkwijk's (1947) nomogram for storm surges due to wind effect at Hoek van Holland, the predicted storm surge for 100 kts onshore wind would be about 24.0 ft which is very much greater than the observed surge in the present case.

Hoover's (1957) regression equations are,

$$H = 0.198\ (1006 - P_0) \qquad \dots (1)$$

(Atlantic Hurricanes)

and

$$H = 0.151\ (1032 - P_0) \qquad \dots (2)$$

(Gulf of Mexico Hurricanes)

while the regression equation of Conner *et al.* (1957) is,

$$H = 0.154\ (1019 - P_0), \qquad \dots (3)$$

(Gulf of Mexico Hurricanes)

where H is the surge in feet and P_0 is the central pressure in millibars. The three equations predict the surge in the present case at 8.7, 10.6 and 8.8 ft respectively. The astronomical tide at the time of landfall of the cyclone was about 1.0 ft above the mean seasonal elevation of the sea-level which itself was about 0.5 ft. above M. S. L. Hence the predicted values of the storm-tide would be 10.2, 12.1 and 10.3 ft respectively. These are smaller than the observed sea-level elevation.

The slope of the sea-surface, i, due to persistent winds of strength, w can be shown to be inversly proportional to the depth of the waters d, and a semi-empirical equation relating the three parameters is given (Sverdrup *et al.*, 1961) by :

$$id = 4.8 \times 10^{-9} \times w^2, \qquad \dots (4)$$

where the different factors are expressed in C. G. S. units. This relationship was used by Bhaskara Rao and Mazumdar (1966) and the storm surges at different places on the east coast for 40, 60 and 80 kts coast-normal winds were calculated by carrying out the necessary integration in finite steps. Since the maximum wind speed in the present cyclone was about 100 kts the corresponding surge heights cannot be obtained from their tables.

By assuming constant slope, m, for the continental shelf and expressing the depth, d, in terms of m, and the distance, x, from the coast, eqn. (4) can be written as,

$$H_0 = -4.8 \times 10^{-9} \times w^2 \int_{x_{cs}}^{x_0} \frac{dx}{mx + H} \qquad \dots (5)$$

where H_0 and H are the sea-level rise at the coast, x_0, and at distance x, respectively. x_{cs} is the distance of the periphery of the continental shelf from the coast. Eqn. (2) can be approximated (Reid, 1957) by

$$H_0 = -4.8 \times 10^{-9} \times w^2 \int_{x_{cs}}^{x_0} \frac{dx}{mx + H_0} \qquad \dots (6)$$

and

$$H_0 = \frac{4.8 \times 10^{-9} \times w^2}{m} \left[\log \left(\frac{x_{cs}}{H_0/m} + 1 \right) \right] \qquad \dots (7)$$

The value of H_0, on the left-hand side can be calculated by substituting the actual values for the different parameters and a guess value for H_0 on the right-hand side. The value of H_0, thus evaluated may be substituted on the right-hand side and H_0 on the left-hand side can again be calculated. This calculation may be repeated until the substituted and calculated values of H_0 are nearly same. If the initial guess is not far from the actual value of H_0, the actual value can be obtained in two or three repetitions of the calculations. The value of H_0, thus evaluated for an onshore wind of 100 kts in the area where the present surge was experienced, is 7.3 ft. If the astronomical tide of 1.5 ft and the "inverted barometric height" of 1.4 ft are added, the predicted storm tide is 10.1 ft which is very close to the predictions made by the regression equations of Hoover (1957) and Conner *et al.* (1957).

Welander (1961) suggested a simple approximate formula for sea-surface elevation H_0 due to wind set-up.

$$H_0 \approx 1.5 \frac{\tau_w F}{g \rho h} \quad \ldots \quad (8)$$

where, τ_w is the wind stress, F the fetch, g the acceleration due to gravity and ρ the density of water.

Further,

$$\tau_w = 2.5 \times 10^{-3} \times \rho_a \times w^2 \quad \ldots \quad (9)$$

where, ρ_a is the density of air and w_a is the wind at the anemometer level. By assuming the value of the width of the continental shelf for F, and the average depth of the shelf for h, the sea-surface rise in the present case would be 7.3 ft. This is surprisingly same as the above obtained value.

Jelesnianski (1972) developed a scheme for the evaluation of the peak storm surge from the central pressure deficit $\triangle p$, shoaling factor F_{se}, which depends on the slope of the continental shelf and the vector-motion F_m of the storm relative to the coast. The same scheme was used by Gosh (1977) who developed nomograms to help quick evaluation of storm surges in different parts of the east coast of India. The initial estimate of the surge S_p due to the present pressure deficit of 43 mb is 4.8 ft (radius of maximum wind = 30 miles) and the values of F_{se} and F_m are 2.0 and 0.85 respectively according to his nomograms. The predicted storm surge therefore is 8.2 ft.

The predicted heights of the storm surge by the various methods are strikingly close except that by Schalkwijk (1947) and all of them could predict about 2/3 of the observed surge. This discrepancy may be partly because the actual central pressure at the time of landfall could have been less than what has been estimated by the authors and the excess surge can partly be because of the curvature of the coast. In the above schemes of prediction, the coast was considered to be straight.

Summary and Conclusions

The summary and conclusions are as follows :

(*i*) The storm surge was confined only to the right of the storm centre and occurred at the time the cyclone crossed the coast.

(*ii*) The peak surge could be more than 15 feet at a place off Sorlagondi.

(*iii*) The surge waters crossed the coast at a speed of 4.5 kts from the southeast and rapidly decelerated over land to 2 kts.

(*iv*) The withdrawal of the surge waters was affected both by the cyclone winds as well as the local topography.

(*v*) The hindcast values of the surge by (*a*) the regression equations of Hoover (1957) and that of Conner *et al.* (1957), (*b*) the slope method as determined by Bhaskara Rao and Mazumdar (1966) and the present authors, (*c*) the semi-empirical equation given by Welander (1961) and (*d*) the objective scheme evolved by Jelesnianski (1972) and applied to the east coast of India by Gosh (1977) agree with each other but all of them predict 2/3 of the observed surge.

(*vi*) Direct observational facility of the central pressure of severe cyclonic storms of the Bay is important for preparing accurate forecasts of storm surges.

Acknowledgements

The authors are thankful to Sri C. P. Rao, Meteorologist-in-Charge of the Cyclone Warning Centre, Visakhapatnam, for his useful discussions on the problem. The authors are also thankful to the referee for his suggestions.

References

Bhaskararao, N. S., and Mazumdar, S. (1966). A technique for forecasting storm waves. *Indian J. Met. Geophys.*, **17**, 333–346.

Conner, W. C., Kraft, R. H. and Harris, D. L. (1957). Empirical methods for forecasting the maximum storm tide due to hurricanes and other tropical storms. *Mon. Weather Rev.*, **85**, 113–116.

Conner, W. C., and Goudeau, D. A. (1968). Storm surges over the Mississippi river delta accompanying hurricane Besty. *Mon. Weather Rev.*, **96**, 118–124.

Das, P. K., Sinha, M. C., and Balasubramanyam, V. (1974). Storm surges in the Bay of Bengal. *Q. J. R. met. Soc.*, **100**, 437–449.

Fletcher, R. D. (1955). Computation of maximum surface winds in hurricanes. *Bull. Am. met. Soc.*, **36**, 247–250.

Gosh, S. K. (1977). Prediction of storm surges on the east coast of India. *Indian J. Met. Hydrol. Geophys.*, **28**, 157–168.

Gray, W. M. (1968). Global view of the origin of tropical disturbances and storms. *Mon. Weather Rev.*, **96**, 669, 700.

Harris, D. L., and Angelo, A. (1963). A regression model for storm surge prediction. *Mon. Weather Rev.*, **91**, 710–726.

Hoover, R. A. (1957). Empirical relationships of central pressures in hurricanes to the maximum surge and storm tide. *Mon. Weather Rev.*, **85**, 167–174.

Jelesnianski, C. P. (1967). Numerical computations of storm surges with bottom stress. *Mon. Weather Rev.*, **95**, 740–756.

———(1972). SPLASH (Special Program to list amplitudes of surges from hurricanes)—I landfall storms. *NOAA Tech. Mem.*, **52**, NWS, TDL–46.

Malkin, W. (1959). Filling and intensity changes in hurricanes over land. *Natn. Hur. Res. Proj. Rep.*, No. 34, 1–18.

Palmen, E. H. (1948). On the Formation and Structure of Tropical Cyclones *Geophysica. Helsinki*, **3**, 26–28.

Platzman, G. W. (1963). The dynamic prediction of wind tides on lake erie. *Met. Monograph.*, **4**, **26**, 1–44.

Redfield, A. C., and Miller, A. R. (1957). Water levels accompanying Atlantic coast hurricanes. *Met. Mono., Am. met. Soc.*, **2**, 10, 1–23.

Schalkwijk, W. F. (1947). A contribution to the study of storm surges on the Duch Coast. *Mededeel. en verhandel. K. Nederl. Meteorol. Inst.*, S. B1, 7.

Sverdrup, H. V., Johnson, M. W., and Fleming, R. H. (1961). *The Oceans : their Physics, Chemistry and General Biology*. Prentice-Hall, Inc., Tokyo, 490.

Welander, P. (1961). Numerical prediction of storm surges. *Adv. Geophys.*, Academic Press., New York, **8**, 316–377.

Yeh, T. C. (1950). The motion of tropical storms under the influence of a superimposed southerly current. *J. Met.*, **7**, 108–113.