Sea level during storm surges as seen in tide-gauge records along the east coast of India

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Analysis of hourly sea level recorded by tide gauges of the Survey of India (SOI) at Paradip, Vishakhapatnam, and Chennai provides a record of non-tidal sea level during three periods, 6–10 August 1979, 6–10 August 1981, and 24–27 September 1981, when storms formed over the Bay of Bengal and crossed the east coast of India. During each event, the impact was largest at Paradip and weakest at Chennai. In the first event, the sea level at Paradip was depressed, whereas there was a surge during the second and third events. The analysis shows that historical SOI tide-gauge data would be useful for testing the numerical models that are now emerging as an important component of defence from storm surges in the bay.

THE east coast of India frequently experiences storm surges (changes in water level caused due to the passing of storms over the sea) that are triggered by cyclones and other atmospheric disturbances that develop over the Bay of Bengal or in the Andaman Sea. The flooding that occurs in the coastal areas due to the surges has been a major cause of loss of life and property[1]. Understanding the dynamics underlying the surges and developing the capability to predict them are therefore highly desirable.

The essence of the dynamics of storm surges is well known. Storm surges are atmospherically-forced oscillations of the water level in a coastal region, with periods ranging from minutes to days. They are long gravity waves and belong to the same class as tides (see Box 1). A number of numerical models have been formulated to gain the capability to predict the storm surges that occur in the Bay of Bengal (see Das[4] for an early version, and Dube and Gaur[5] for recent developments). The effort has produced encouraging results and further refinements are being sought through ongoing research. These positive aspects have also underlined a difficulty faced during modelling: observations to check the performance of the predictive models have been scarce, if at all available. The reason is that the instrumentation designed to measure normal sea-level variation, such as tides, breaks down under the onslaught of abnormally high sea level during major surges.

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The Geodetic and Research Branch of the Survey of India (G&RB–SOI) maintains a network of tide gauges installed at ports located along the Indian coastline. The network has been set up to measure sea-level variations due to tides; analysis of the data collected by the gauges is used to predict tides. Published by SOI in the form of annual tide tables, these predictions are used extensively by the global seafaring community in operations in the Indian region.

Box 1. Modelling of storm surges.

The equations that govern the generation and propagation of a storm surge have their origin in Laplace's Tidal Equations (LTE), given by Laplace[2] to explain ocean tides. The writing of these equations forms a major milestone in the evolution of the theoretical framework that is today called *geophysical fluid dynamics*[3]. The modern version of these equations, that is most suitable for the storm-surge problem, is[1]

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-fv=-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{1}{\rho h}(\tau_{sx}-\tau_{bx}),$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+fu=-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{1}{\rho h}(\tau_{sy}-\tau_{by}),$$

$$\frac{\partial \eta}{\partial t}+\frac{\partial}{\partial x}(hu)+\frac{\partial}{\partial y}(hv)=0,$$

where t = time; η = elevation of the sea surface; u, v = components of the depth-mean current, $\vec{q}$; ρ = the density of sea water, assumed uniform;
τ_{sx}, τ_{sy} = components of the wind stress on the sea surface, $\vec{\tau}_S = c\rho_a \vec{W}|\vec{W}|$, where $\vec{W}$ is the surface wind velocity, ρ_a is the air density, and c is a drag coefficient;
τ_{bx}, τ_{by} = components of bottom stress, $\vec{\tau}_b = k\rho \vec{q}|\vec{q}|$, where k is a bottom friction parameter,
p = atmospheric pressure on the sea surface,
h = total water depth (= $D + \eta$ where D is undisturbed depth),
g = acceleration due to gravity,
f = the Coriolis parameter (= $2\omega \sin\phi$, where ω is the angular speed of the earth's rotation and ϕ is the lattitude).

Numerical simulation of a storm surge involves solving the above equations, with appropriate boundary conditions, when p and $\vec{W}$ are prescribed. Experience shows that in deep water, where D is large, surges are produced mainly by changes in p, but on continental shelves and near the coast, the contribution of $\vec{W}$ dominates.

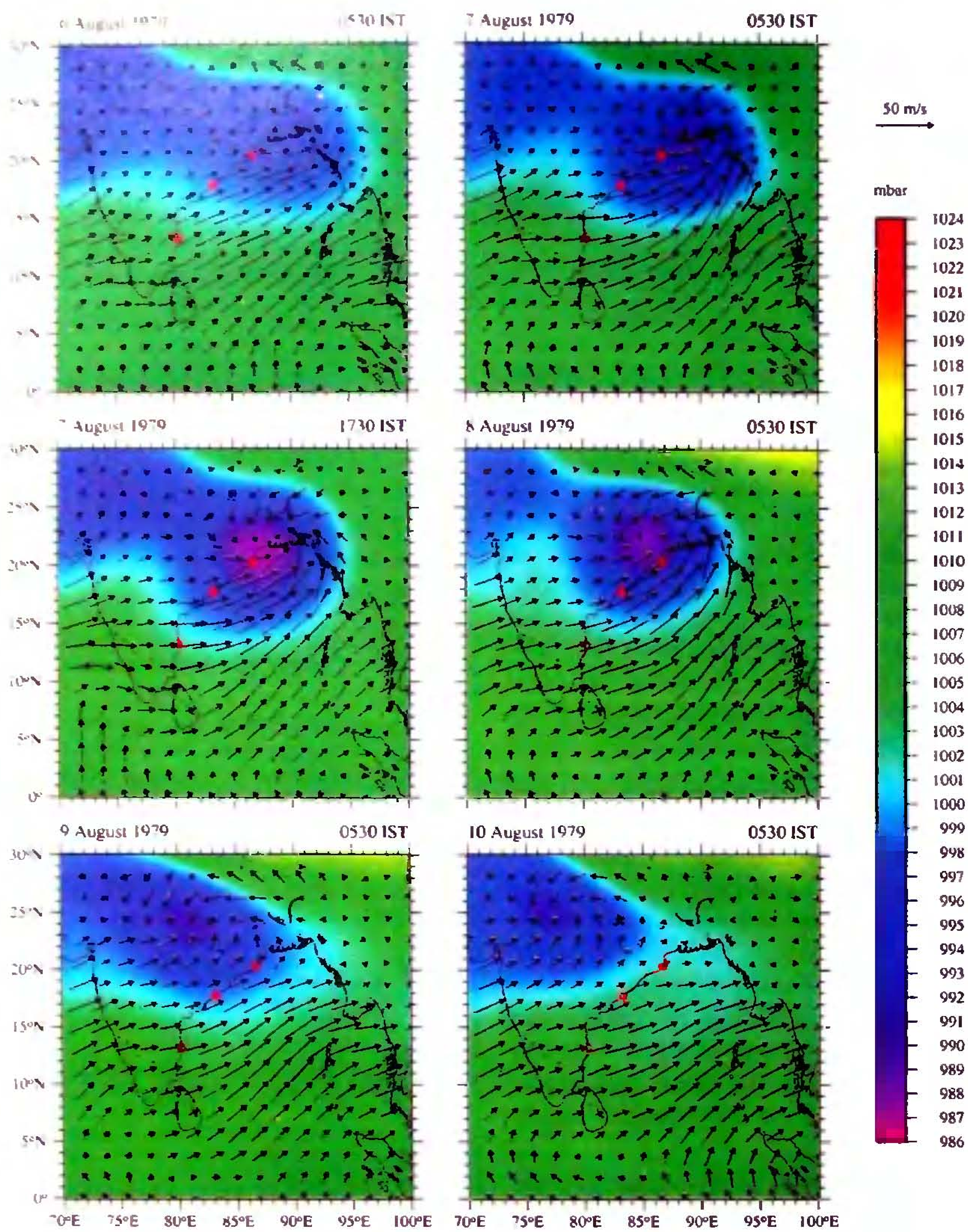

Figure 1 *a*. Atmospheric pressure at mean sea level and winds at 10 m during Event 1. The 3 red circles mark the location, from north to south, of the 3 tide-gauge stations, Paradip, Vishakhapatnam, and Chennai. On 5 August 1979, the remnant of a typhoon moved across central Myanmar (Burma) and appeared over north-eastern Bay of Bengal as a well-marked low-pressure area. It turned into a depression centered at 21°N, 90°E on the morning of 6 August, becoming a deep depression the same evening. It intensified rapidly into a severe cyclonic storm on the morning of 7 August and crossed the north Orissa coast later that day; it weakened and moved westward subsequent to landfall.

Sea-level variations due to surges triggered by storm winds form a noise superimposed on the highly periodic tides, which have astronomical origins. Though the Indian tide-gauge network was not set up to monitor storm surges, it is possible to use the tide-gauge data to determine, through analysis, the contribution to sea level due to surges. To encourage such applications of its data, the G&RB–SOI has made available to the National Institute of Oceanography hourly tide-gauge data collected during 1974–1998 at selected stations along the coast. Three of the stations are along the east coast of India: Paradip, Vishakhapatnam and Chennai. (The locations of these stations are marked in Figures 1 *a*–3 *a* by the filled red circles; from north to south, they are in the order listed above.)

The purpose of this paper is to report three storm-surge events that have been recorded in the tide gauge data. In the next section we describe the analysis used to

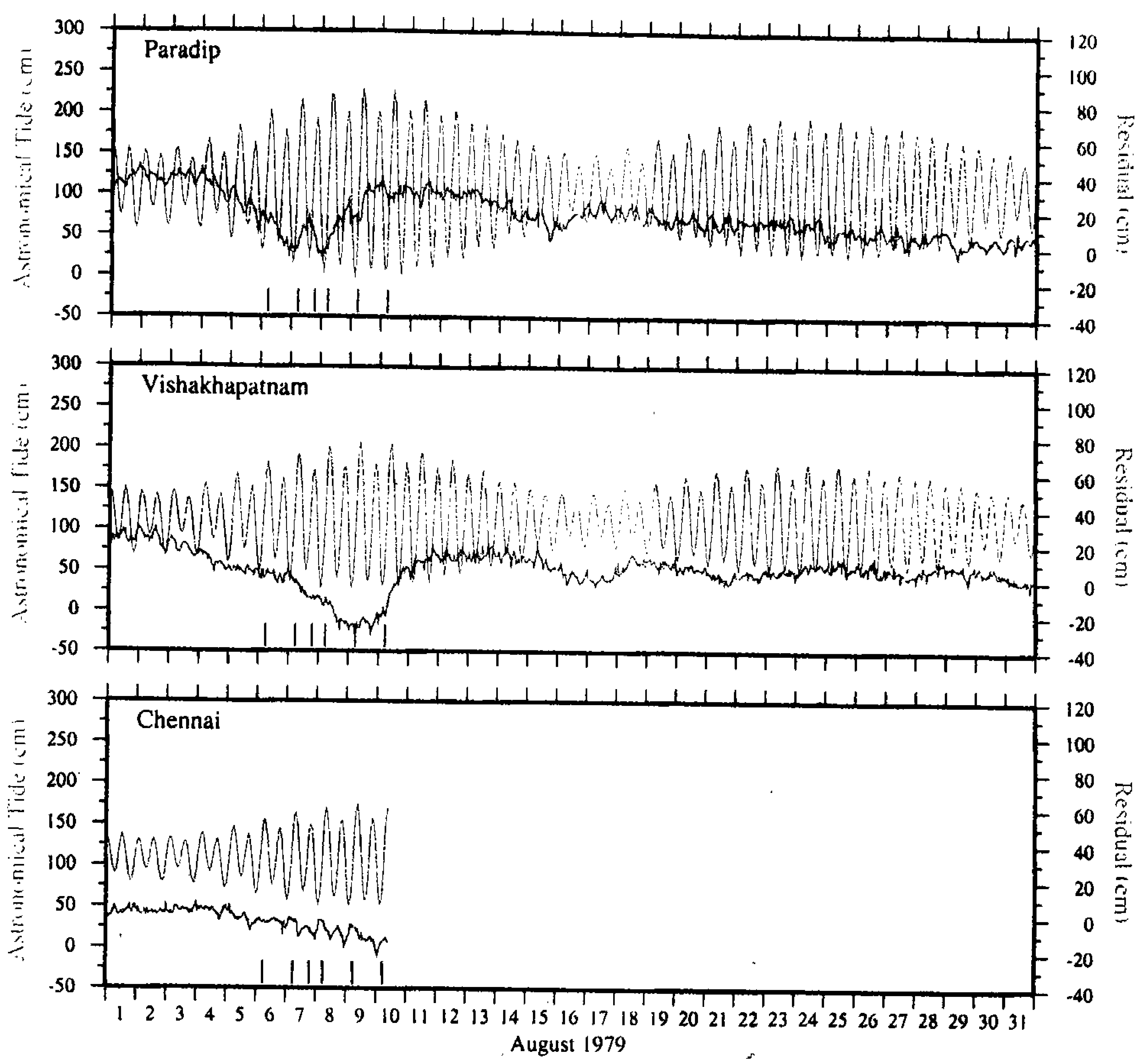

Figure 1*b*. Astronomical tide and de-tided sea level during Event 1. The dark blue vertical lines at the bottom mark the time of the six panels in Figure 1 *a*. During August 1979, the neap tide was on 2 August and the spring tide was on 9 August. The most intense phase of the storm was therefore only a couple of days before the spring tide. The storm led to a *decrease* in hourly sea level, not to the increase that one generally associates with storm surges. (It should, however, be noted that whether the sea level decreases or increases during a storm, the sea would be equally rough, and dangerous, because roughness is primarily determined by wind waves with periods ranging from a second to a few minutes; such periods are not resolved in the hourly sea level data.) The depression in sea level was not restricted to Paradip, but can also be seen at Vishakhapatnam. The maximum depression here occurred on 9 August, approximately 48 h after that at Paradip. This implies a wave speed of about 3 m/s, which is close to the wave speeds associated with the class of coastally-trapped waves known as edge waves or shelf waves. The sea-level record is missing at Chennai during 10–31 August; hence, the wave cannot be tracked beyond Vishakhapatnam.

identify the events. The events are described next, after which implications of the results are discussed.

Analysis

Analysis of the hourly sea-level data involves removal of the signal associated with the tide. It is possible to do this with high accuracy because the periods associated with tides are known accurately. They are defined by the motion of the Earth–Moon–Sun system. The water-level oscillation associated with a particular period is generally identified in terms of the tidal *constituent* for that period. Once the contribution to sea level from the major constituents, numbering about 50, is removed from the raw data, the residue can be associated with the impact of other factors, including storms.

The sea-level variation due to tides at any location can be written as

$$h = h_{\text{mean}} + \sum_{n=1}^{N} H_n \mathrm{f}_n \cos[\sigma_n t - g_n + (\mathrm{V}_n + \mathrm{u}_n)],$$

where h_{mean} is the mean sea level at a location; t is the time; n refers to a tidal constituent, and σ_n, H_n, and g_n are, respectively, the frequency, amplitude, and phase associated with that constituent. f_n, V_n, and u_n are all constants that are related to the motion of the Earth–Moon–Sun system and have been documented in manuals on the subject (for example, Schureman[6]). In our analysis, we used 58 constituents, i.e. $N = 58$. The analysis of data from a location consisted of using a year-long time-series of hourly values of sea level as

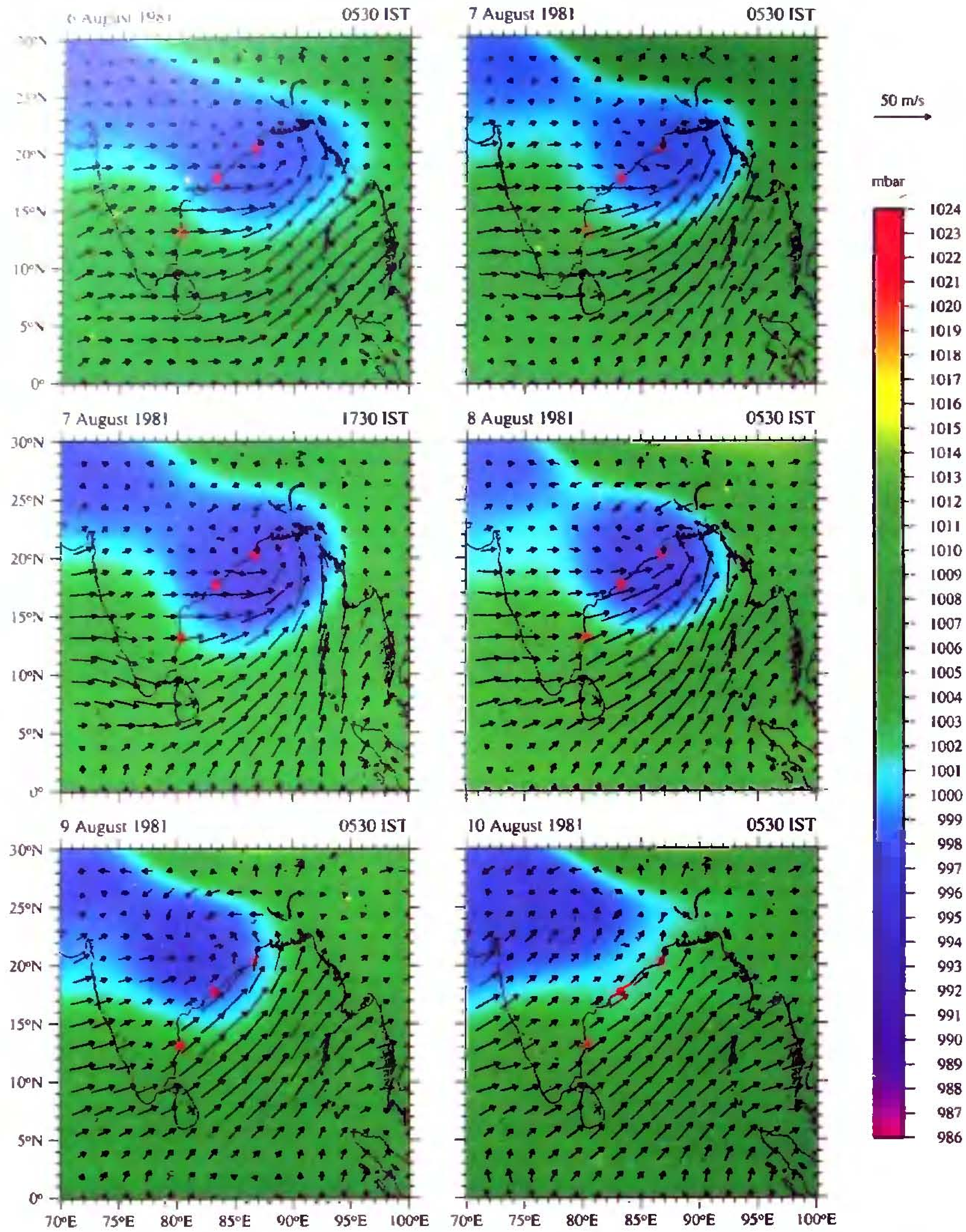

Figure 2 *a*. As in Figure 1 *a*, but for Event 2. On 5 August 1981, a feeble low-pressure area formed over north-western Bay of Bengal and Orissa. It intensified steadily into a cyclonic storm by the evening of 7 August. The storm crossed the Orissa coast near Puri and was located about 30 km west of Puri on the morning of 8 August. It moved westward subsequently.

measured by a tide gauge at that location. The data were fitted to the above equation using a least-squares technique. The smooth fitted curve was then subtracted from the data to determine the residue, i.e. the de-tided sea level. Well-known software packages are available to carry out such analyses; we used TASK, a package distributed by the Permanent Service for Mean Sea Level[7].

A year-long time-series of the de-tided sea level was then examined to identify potential candidates for storm surge records. The exercise was repeated at each of the three stations on the east coast – Paradip, Vishakhapatnam and Chennai – and for each year during the period 1974–1998 for which sea-level data exist.

Meteorological data during 1974–1998 in the Bay of Bengal were examined to identify periods with high potential for storm-surge generation. The databases searched consisted of Daily Weather Reports and Weekly Weather Reports of the India Meteorology Department; archived wind data from the European Centre for Medium Range Weather Forecasting (ECMWF); and archived wind and atmospheric pressure data from the National Centre for Environmental Prediction and

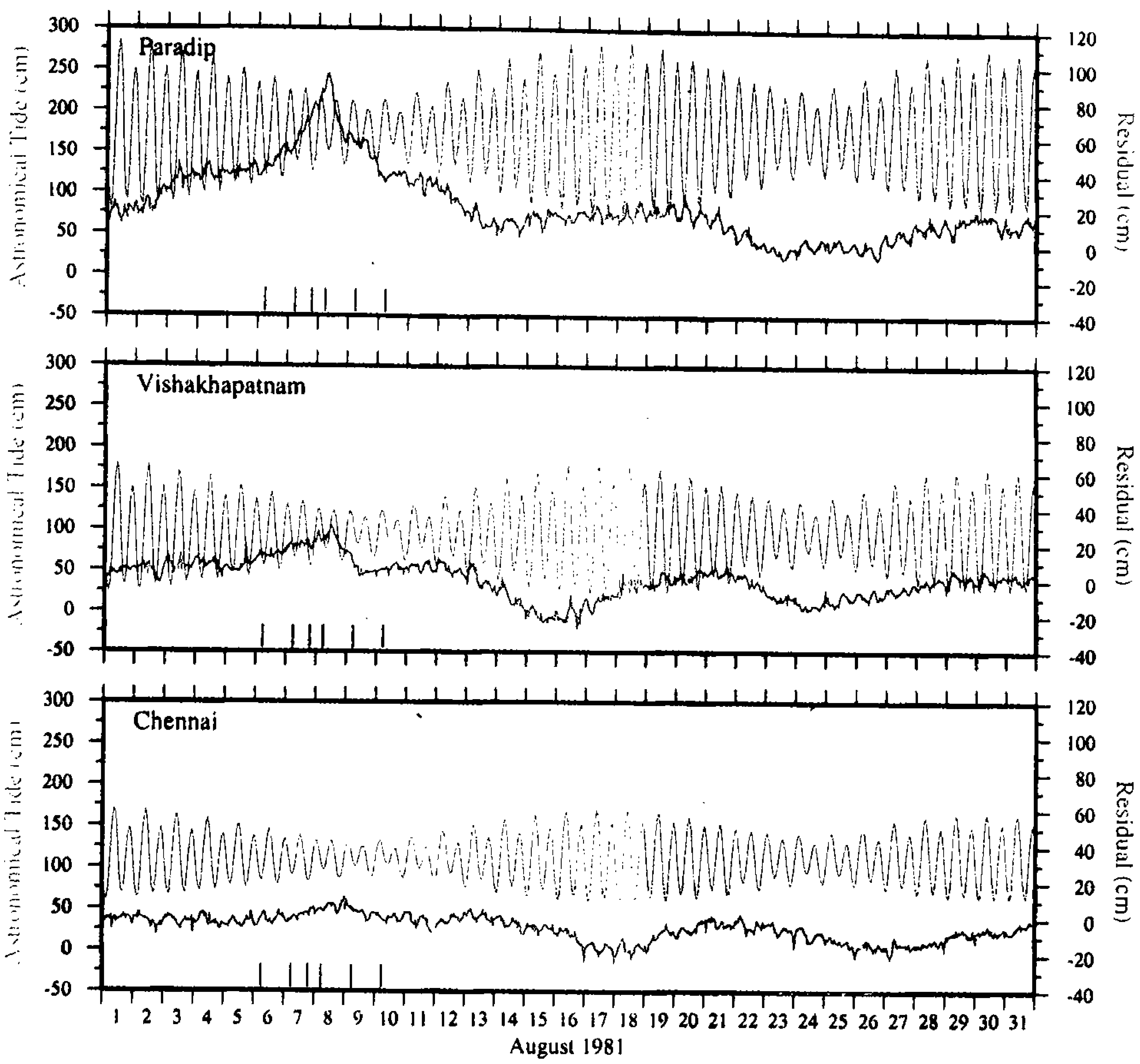

Figure 2 *b*. As in Figure 1 *b*, but for Event 2. The effect of the storm was an increase in sea level, which was largest at Paradip, where it peaked on 8 August. The magnitude of the surge was about 0.75 m. The peak occurred at the time of low tide during a neap of the spring–neap cycle. The timing was therefore such that the maximum sea level observed in the area, i.e. the sum of the tide and the surge, was not as damaging as it could have been had the surge occurred at the time of high tide. This event demonstrates how critical the timing of the surge is: if it is synchronous with the maximum tide, inundation is much higher. The storm had an impact on the sea level at Vishakhapatnam too, but the surge was weaker there, the magnitude being about 20 cm. Its largest amplitude occurred at the time of high tide, a potentially dangerous situation had the surge been larger. At Chennai, the impact of the event was hardly noticeable. The event left some long-term effects on the sea level, and these are recorded in all the three tide gauges. After the surge, there was a drop of about 20 cm in sea level. The average speed of propagation of the shelf waves was approximately 4 m/s, similar to that observed in Event 1.

National Centre for Atmospheric Research, USA (NCEP/NCAR).

Following the examination of sea-level and meteorological data, we identified three events – during 6–10 August 1979, 6–10 August 1981, and 24–27 September 1981 – that show the evolution of the winds over the Bay of Bengal, and their impact on sea level at the three locations.

Storm surges and associated winds

The perturbation in sea level during a storm is the result of two effects. First, the storm winds exert a stress on the water surface, leading to a forced response and to free shallow-water waves that can propagate away from the region of direct forcing to influence the water surface at remote locations. Second, the fall in barometric pressure associated with a storm perturbs the surface. This has often been called the *inverse barometer effect:* sea level goes up (down) by about 1 cm whenever barometric pressure falls (rises) by 1 mbar. In coastal regions the effect of wind stress generally dominates (see Box 1). In the three events described here, the contribution due to pressure drop was negligible, except in Event 1, in which there was a significant drop in pressure at Paradip. Even in this case, the contribution of the winds was much larger.

We describe the events using three fields:

1. The atmospheric pressure at mean sea level over the Bay of Bengal and its environs as the event unfolded.
2. The winds at 10 m above mean sea level in the region at this time.
3. The astronomical and de-tided sea levels during the month when the event occurred.

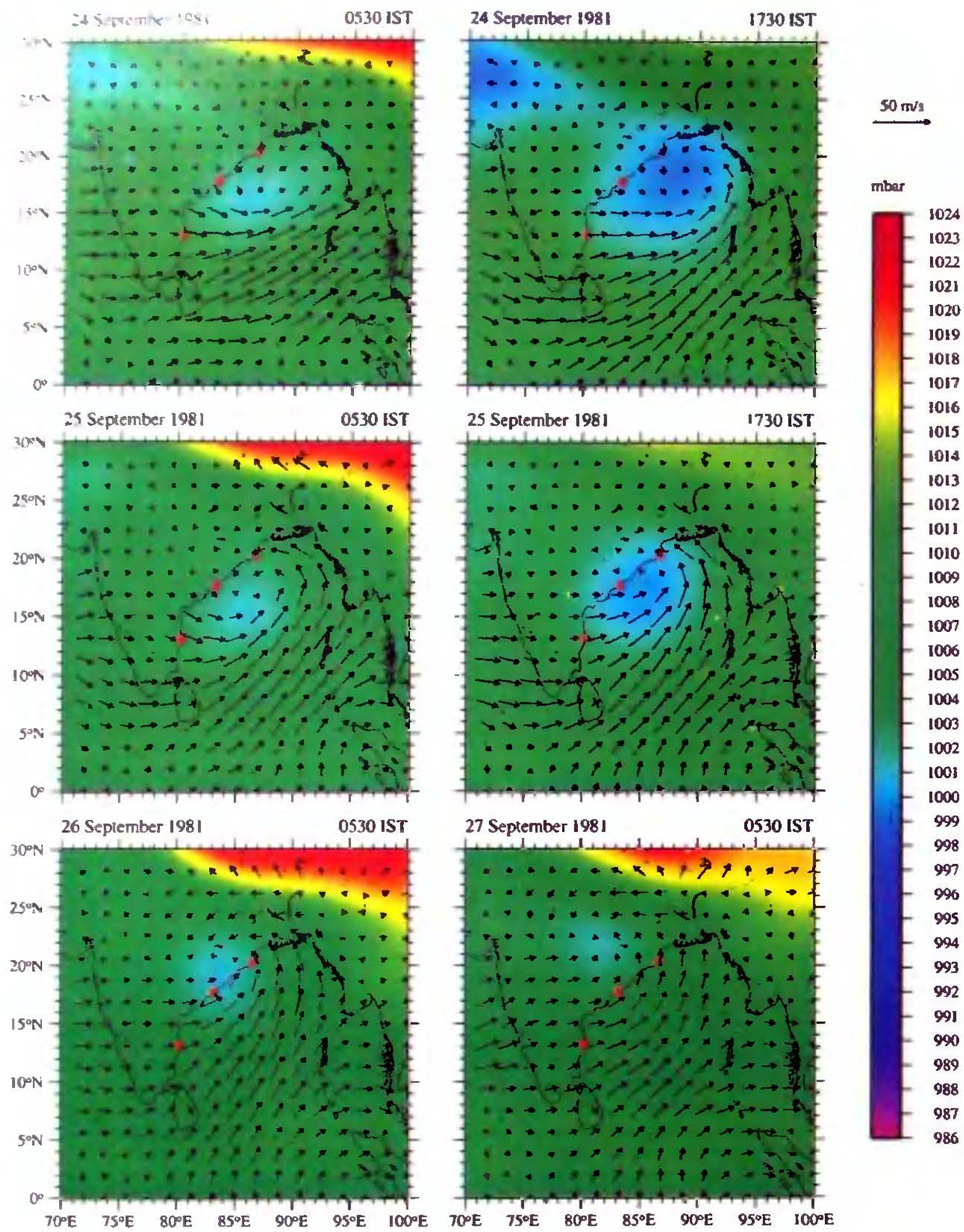

Figure 3 ***a*****.** As in Figure 1 *a*, but for Event 3. A low-pressure area formed over the north Andaman Sea, and turned into a cyclonic storm, located at 18°N, 88.5°E on the morning of 25 September. The storm crossed the Orissa coast near Puri on 27 September, and weakened as it moved westward.

The atmospheric pressure and wind fields are from the NCEP/NCAR analysis project[8] and the sea-level fields are from the SOI data. These fields are shown for each event (Figures 1–3, respectively, for Events 1–3). The first part of the figures for an event (labelled *a*) shows the atmospheric pressure and wind fields over the bay and its environs, depicting the movement of the storm over the bay, its landfall, and subsequent dissipation; this occurs over a few days. The second part of the figures (labelled *b*) shows the astronomical tide and de-tided sea level (residual) over a month. The sea level is shown over a duration much longer than the atmospheric event because the ocean response is slower than the atmospheric forcing. As a result, the storm surge, the oceanic response, lasts longer than the period of the storm, the atmospheric forcing.

Event 1: 6–10 August 1979

The severe cyclonic storm of Event 1 is described in Figure 1 *a*; the ocean's response to the storm, as recorded by the tide gauges, is shown in Figure 1 *b*. The astronomical tides along the east coast of India are

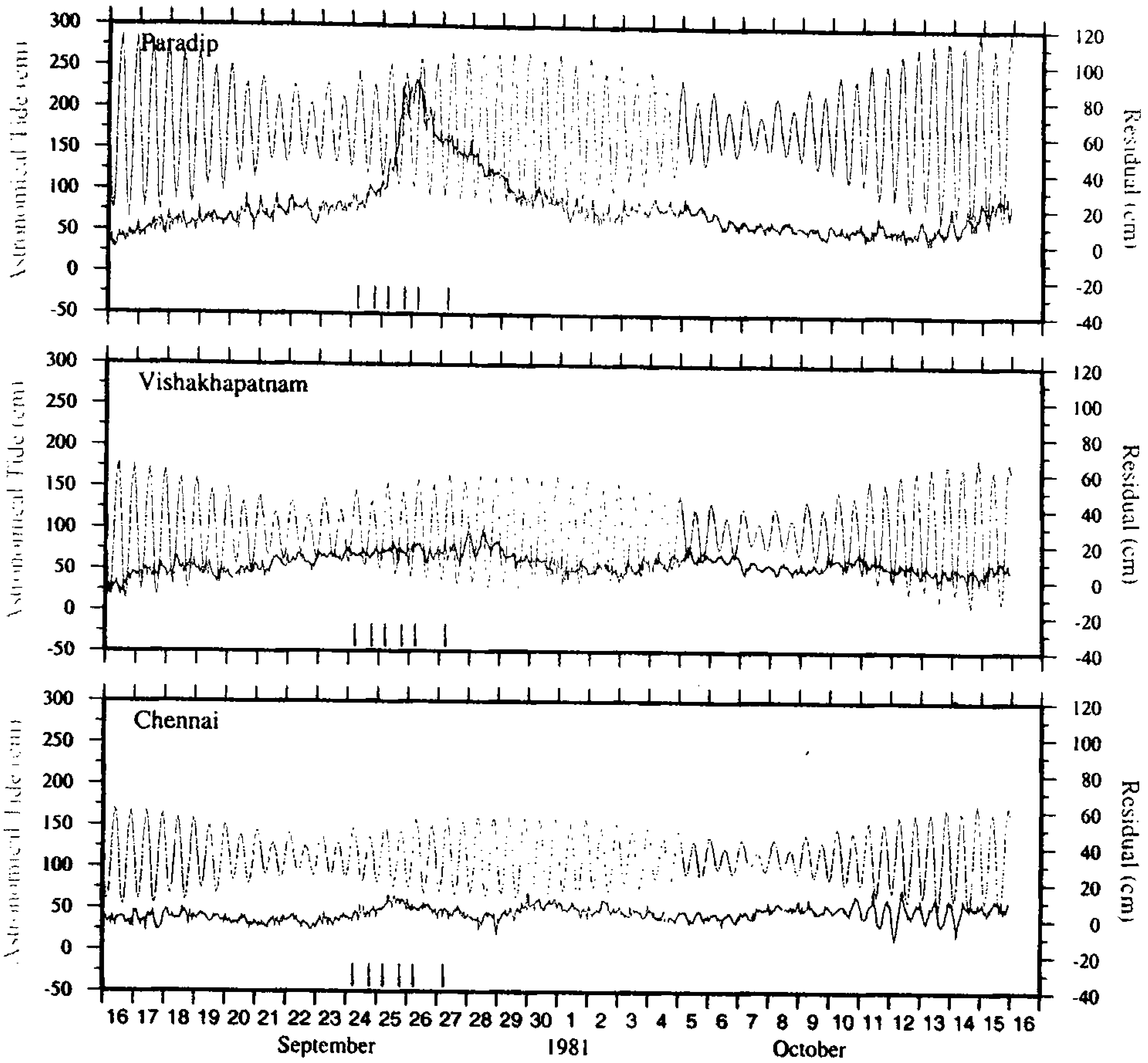

Figure 3 *b*. As in Figure 1 *b*, but for Event 3. The resulting surge was the largest, as in Event 2, at Paradip. In contrast, however, the peak surge occurred at the time of high tide. In addition, the tide at this time was mid-way between the neap and the spring tide. As a result, the water level during this event was much higher than that in Event 2, even though the storm-related surges in sea level in the two events were of similar magnitude. Had the storm surge occurred about 6 h later, at the time of low tide, the net water level would have been almost 1.5 m lower than what was actually experienced. That the difference of a few hours in the timing of the peak can make considerable difference in the resulting damage underlines the difficulties that forecasters face in predicting sea level and issuing warning regarding the peak surge. This event was recorded only at Paradip; it did not have any significant impact on the sea-level at Vishakhapatnam and Chennai.

mixed, i.e. they consist of a superposition of semi-diurnal (period of approximately 12.5 h) and diurnal (24 h) oscillations; the tidal range decreases from north to south along the coast. During a month the tide exhibits two neaps (the tidal range is small) and two springs (the range is large). During August 1979, the neap tide was on 2 August and the spring tide was on 9 August (Figure 1 *b*). The most intense phase of the storm was therefore only a couple of days before the spring tide. The alongshore component of the winds associated with this storm was such that it pushed the waters away from the coast under the influence of the Coriolis force (see Box 1), leading to a depression of sea level at Paradip in the northern bay. There were two peaks in the depression of sea level, one during the early hours of 7 August, the other approximately a day later. The double minimum is possibly the result of details in meteorological forcing, and simulating such intricate variations in sea level is indeed a challenge to skills of two types: recording the meteorological fields and simulating the sea level surges using a numerical model.

During the storm, the barometric pressure variation at Paradip showed a sudden drop by about 20 mbar on 7 August, but it recovered during the next 24 h. At Vishakhapatnam and Chennai, there was no significant drop in pressure. Even though the barometric pressure fell at Paradip, the sea level was depressed there. Such a drop could have led to an increase in sea level by about 15 cm if the inverse barometer effect alone was active. It is therefore clear that the effect of wind stress was large enough to overwhelm this effect.

The depression in sea level was not restricted to Paradip, but can also be seen at Vishakhapatnam. The maximum depression here occurred during 9 August, approximately 48 h after that at Paradip. The distance along the coastline between Paradip and Vishakhapat-