STORM SURGES IN THE MARGINAL SEAS OF THE NORTH INDIAN OCEAN

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ABSTRACT

One of the major natural marine hazards on the globe is the storm surge phenomenon. Large storm surges with amplitudes of up to several meters generated by tropical cyclones occur in many areas of the world, including the Gulf of Mexico and the Northern Indian Ocean. The storm surges in the marginal seas of the North Indian Ocean are discussed here. These marginal seas include the Bay of Bengal, the Arabian Sea, the Persian (Arabian) Gulf and the Red Sea. Since storm surge prediction also involves tides, some tidal regimes are also discussed. Finally, some comments are made on the possible influence of the greenhouse warming and the El Niño phenomenon on storm surges.

1. INTRODUCTION

Storm surges are oscillations of the water level in a coastal water body due to the tangential wind stresses and atmospheric pressure gradients mainly associated with the meteorological forcing fields of travelling synoptic scale weather systems such as tropical cyclones (TC's) and Extra-Tropical Cyclones (ETC's). On occasion, meso-scale weather systems embedded in the larger scale synoptic systems can also provide the required forcing mechanisms to generate surges. These meso-scale systems include mostly squall lines, also referred to as pressure-jump lines.

Most of the surge is generated by the wind field, with the pressure field accounting for about 10 to 15 per cent. In the higher latitudes of the globe, surges are generated by ETC's which generally travel from west to east, with some north-south component. In the lower latitudes, TC's mostly travel from east to west with a south to north (in the Northern Hemisphere) component, usually referred to as recurvature.

In this study, our focus is on surges generated by TC's only and Gray (1978) discussed their genesis mechanisms. We confine our discussion to the marginal seas of the North Indian Ocean. These include the Bay of Bengal, the Arabian Sea, the Persian (Arabian) Gulf and the Red Sea (Figure 1).

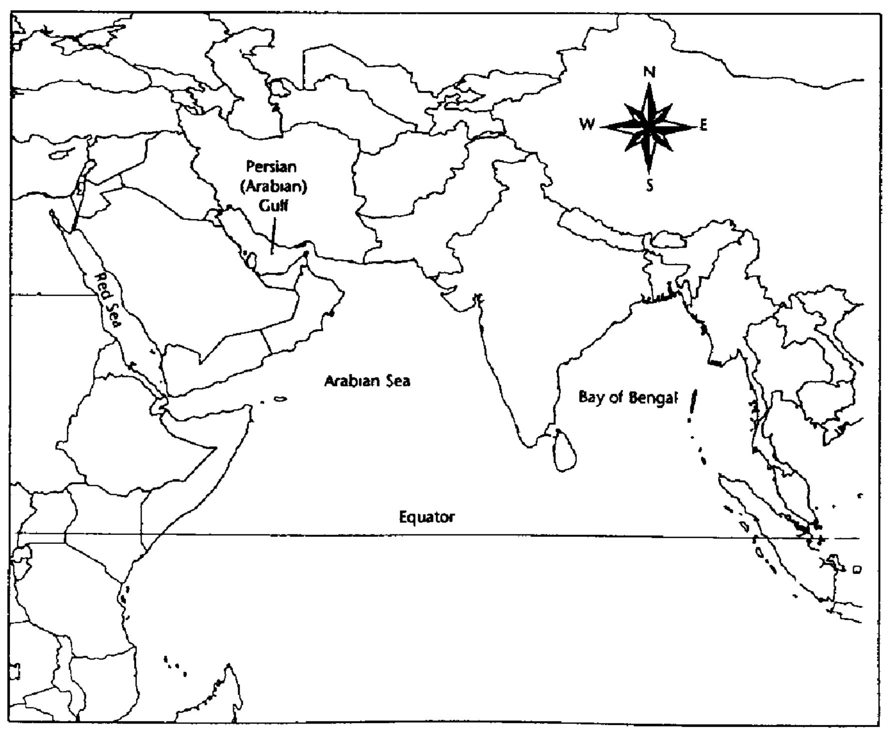


Figure 1. Northern Indian Ocean.

There are three types of pure wave motions in the atmosphere and the ocean (Figure 2). The first type is the acoustic (sound) wave or the longitudinal wave. As these waves propagate in the horizontal direction, the particles move back and forth in the direction of propagation (compression and rarefaction).

The second type of waves are gravity waves, which are vertically transverse waves. As the waves propagate in a horizontal direction, the particles move up and down in the direction of gravity. Since these waves have a vertical component, these are relevant from a hazard point (i.e. land inundation)

The third type is the horizontally transverse wave or the Rossby Wave. As the wave propagates in a horizontal direction, the particles move north and south, due to the so-called beta parameter associated with the Earth's rotation. Rossby waves are extremely relevant for circulation in the atmosphere as well as in the oceans.

Figure 3 shows the short wave part of the ocean wave spectrum. In the ocean, electro-magnetic waves cannot penetrate to great depths, and acoustic waves provide a mechanism somewhat like radar in the atmosphere.

Under wind waves, there are capillaries, sea waves and swell, and their periods are of the order of a few seconds. These are the waves that one observes while standing on a beach.

These waves could be quite hazardous over water because they can attain amplitudes up to several meters. However, because of their short wave lengths (at most a few tens of meters) they break at the coastline and cannot cause any significant land inundation. However, they cause a set-up at the coastline, which should be added to the storm surge.

Figure 4 shows the long wave part of the spectrum, by long wave we mean that the wave length is much greater than the water depth over which it travels. Generally, under long waves, one includes tides, storm surges and tsunamis. Here we will confine our discussion to storm surges and tides only.

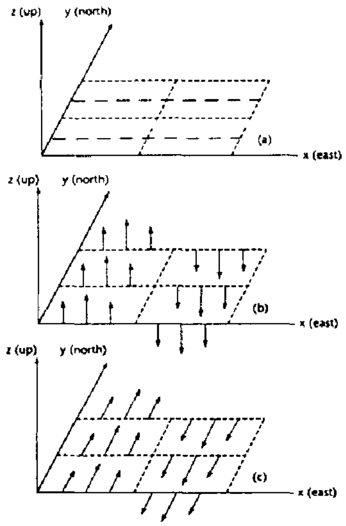


Figure 2. Schematic distribution of velocity perturbations associated with (a) eastward moving compression waves; (b) eastward moving vertical transverse waves and (c) eastward moving horizontal transverse waves (after: Thompson 1961).

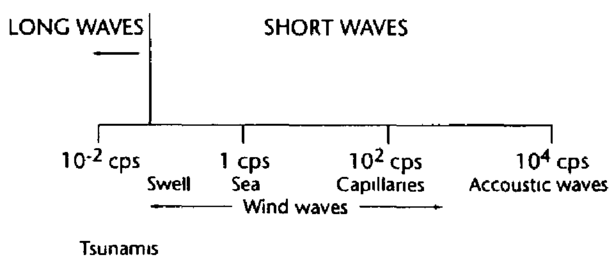


Figure 3. Ocean wave spectrum for short waves (cps = cycles per second) (Modified from Platzman, 1971).

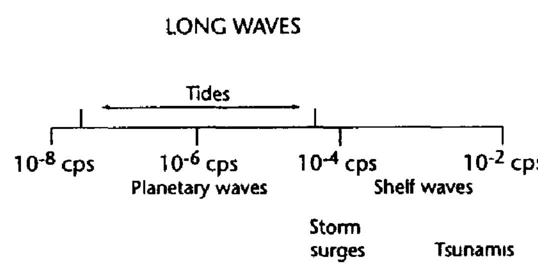


Figure 4. Ocean wave spectrum for long waves (cps = cycles per second) (Modified from Platzman, 1971).

3. STORM SURGE

Figure 5 shows the area of Genesis (hatched regions) and the tracks of tropical cyclones.

Rao (1968) classified the Bay of Bengal and Arabian Sea coasts (mainly for India) from a storm surge point of view (Figure 6).

Figure 7 (Dube et al, 1994) shows the maximum probable surge amplitudes for the Bay of Bengal coast.

Table 1 lists the peak surge amplitudes for various return periods on the Indian coastlines (Jayanthi and Sen Sarma, 1986).

Figure 8 shows how the storm surge builds up as the water depth decreases In the deep water, the surge (which is a long gravity wave as explained in Section 2) travels much faster (with a speed which is approximately proportional to the square root of the water depth) than the weather system travelling over the water body. As the water depth decreases, there is a match between the speeds of movement of the surge and the cyclone and efficient resonance transfer of energy takes place from the cyclone to the surge.

Figure 5. Area of genesis and tracks of tropical cyclones

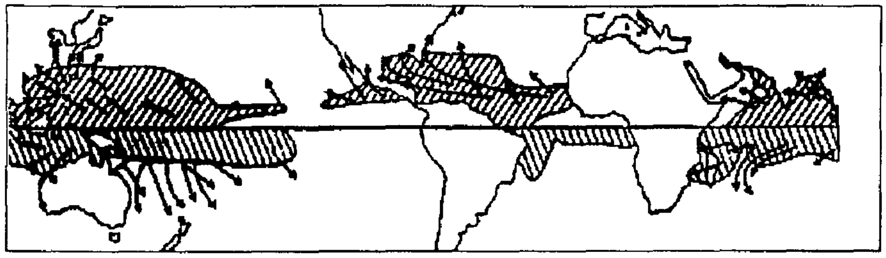


Figure 6. Storm surge amplitudes on the coasts of the Arabian Sea and the Bay of Bengal (Rao, 1968).

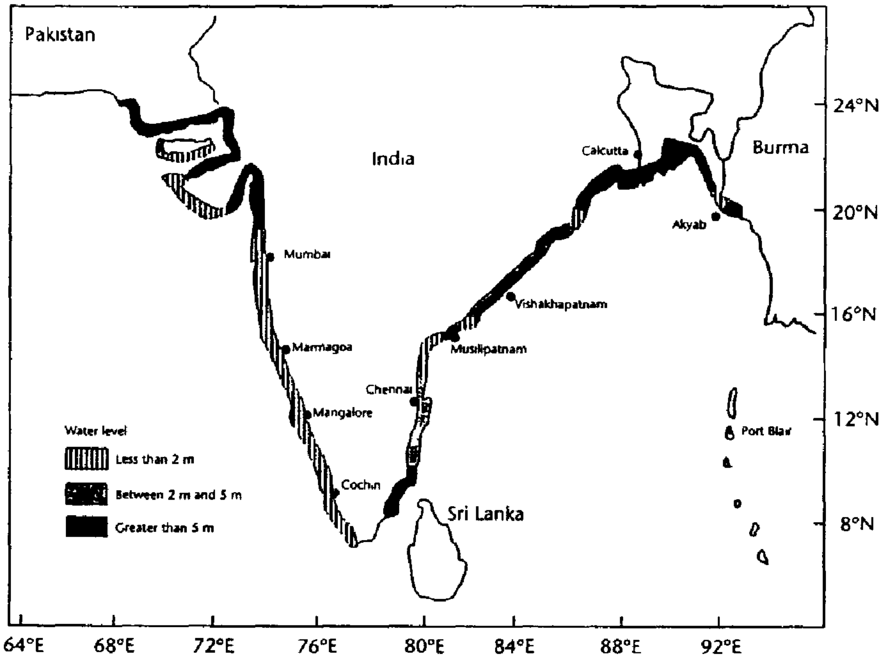


Figure 7. Maximum probable storm surge amplitudes (m) on the Bay of Bengal coast (Dube *et al*, 1994).

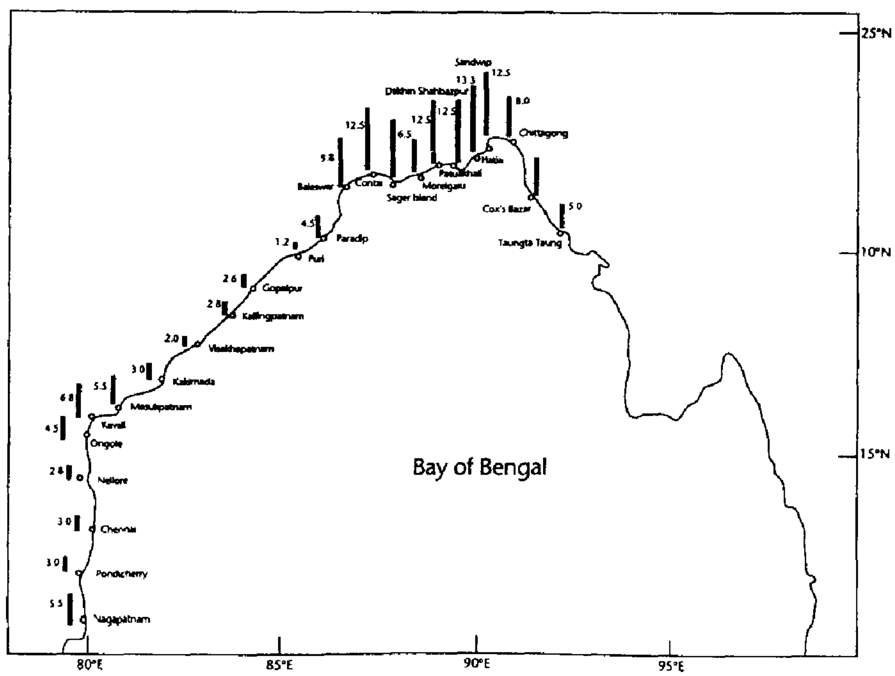


Table 1. Peak surge amplitudes (m) for various return periods, on the coastlines of India, based on data for 1890 to 1984 (from Jayanthi and Sen Sarma, 1986).

State	*Peak Surge (m) for Return Periods (Years of 1890–1984)*				
	10	25	50	100	200
Tamil Nadu South of 10°N	4.8	5.9	6.6	7.5	8.1
Tamil Nadu North of 10°N	2.2	2.7	3.0	3.4	3.7
Andhra Pradesh	3.8	4.2	4.8	5.2	5.6
Orissa-S. of 20.5°N	2.0	2.7	3.2	3.8	4.4
Orissa-N. of 20.5°N	5.1	6.4	6.9	8.8	10.4
West Bengal	4.5	6.3	7.8	9.2	10.9
Maharashtra	1.1	1.4	1.6	1.8	2.0
Gujarat	1.9	2.2	2.4	2.6	2.9

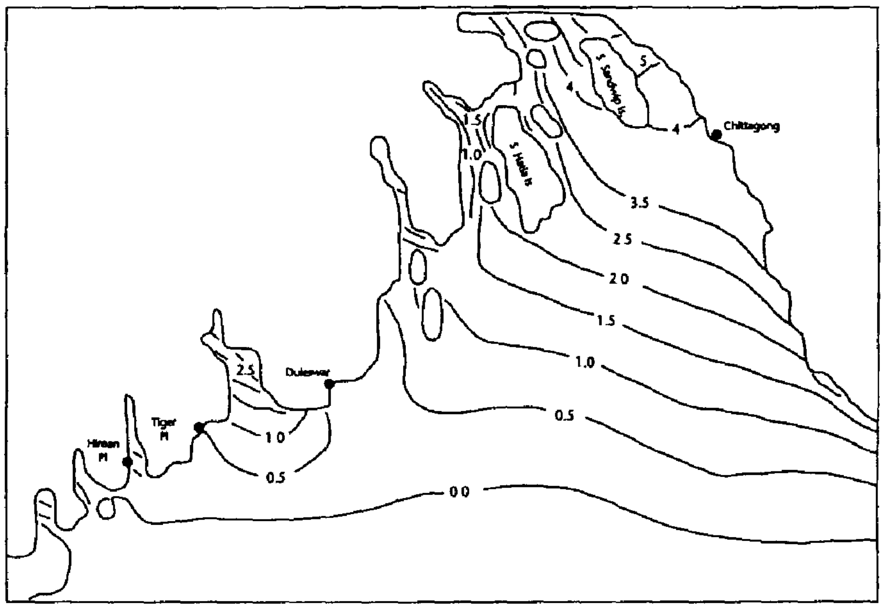


Figure 8. Storm surge heights in the northern part of the Bay of Bengal from a hypothetical storm modeled after the November 1970 storm.

Another qualitative way of explaining the build-up of the surge is in terms of the wind field associated with the weather system. The tangential wind stress pushes the water towards the coast. In deep water, the water could escape laterally or sideways, whereas in shallow water, it cannot go anywhere but up. This is a very simple explanation of how the surge is generated.

The peak surge usually only occurs on a relatively small stretch of the coastline (a hundred km at most, usually a few dozen of km), as can be seen from Figure 9. The fact that the peak surge occurs on only a small stretch of the coastline can also be seen from Figures 10, 11 and 12 (Rao, 1968). It should be noted that in the Northern Hemisphere, the peak surge occurs to the right of the storm track (and to the left in the Southern Hemisphere).

In Figure 12, the fact that the surge did not occur continuously everywhere on the coast needs some explanation. The orientation of the coastline with reference to the storm track as well as the local bathymetry also plays an important role.

Computation and prediction of the land inundation in river deltas is a complex problem involving interaction of the surge with tide, river flow and precipitation Figure 13 and 14 show inundation limits for two major river deltas on the east coast of India. Such inundation computations can be done more accurately through the use of finite element (f-e) models employing irregular triangular grids rather than the traditional finite-difference (f-d) models with regular grids Figure 15 shows an irregular triangular grid for the northern part of the Bay of Bengal and Figure 16 shows a zoom-in for the northern extremity of the grid.

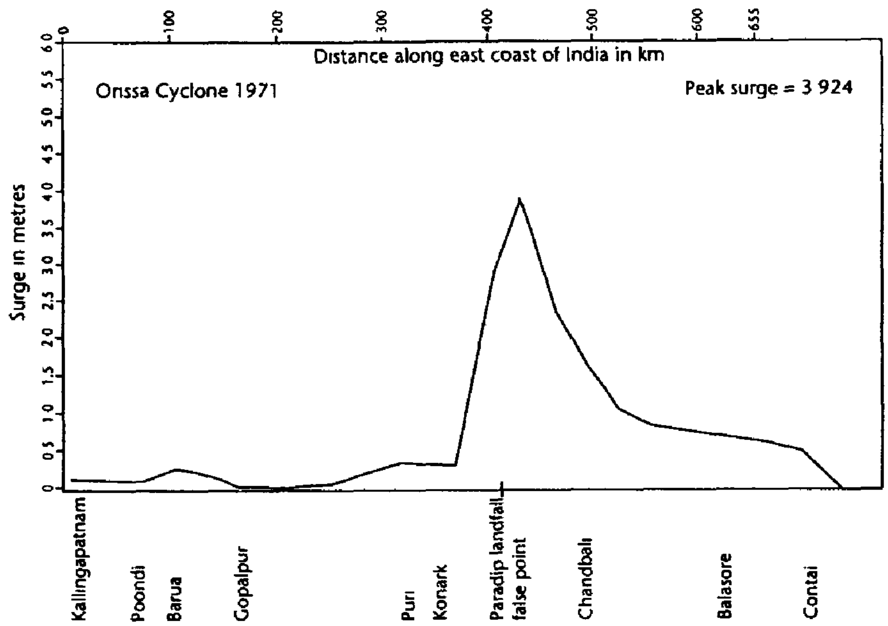


Figure 9. Peak surge (m) along the east coast of India for the Orissa Cyclone of 1971 (Dube et al., 1997).

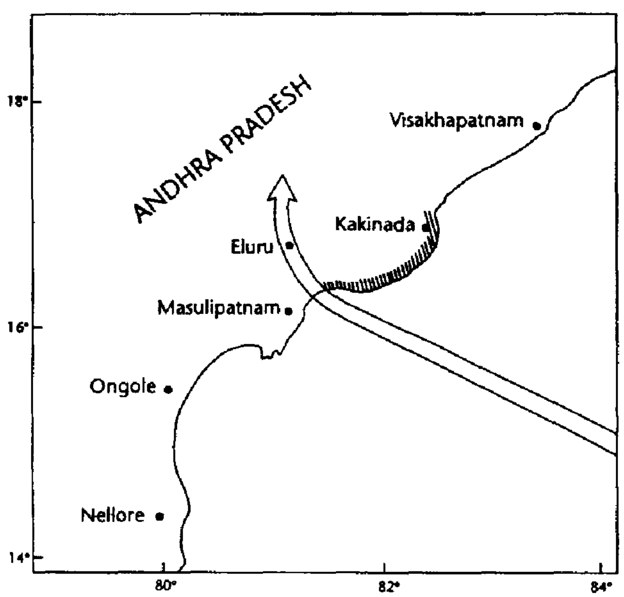


Figure 10. Track of the storm of October 1949 on the southeast coast of India. Hatched area shows the coastline affected by the storm surge (Rao 1968).

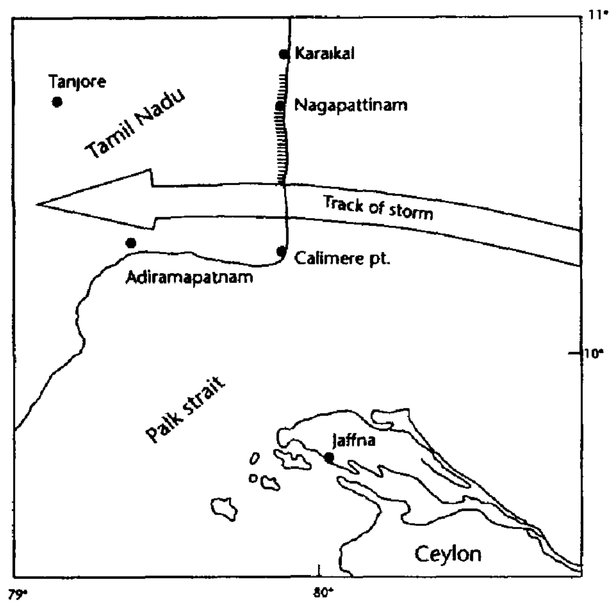


Figure 11. Track of the storm of November 1952 on the southeast coast of India. Hatched area shows the coastline affected by the storm surge (Rao 1968).

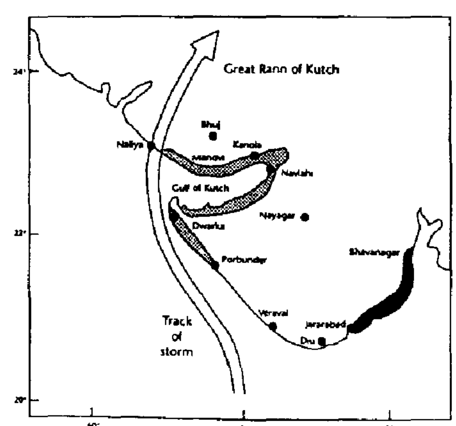


Figure 12. Track of the Kutch cyclone of June 1964 on the west coast of India. Dark grey area is affected by minor surges; light grey areas are affected by major surges (Rao 1968).

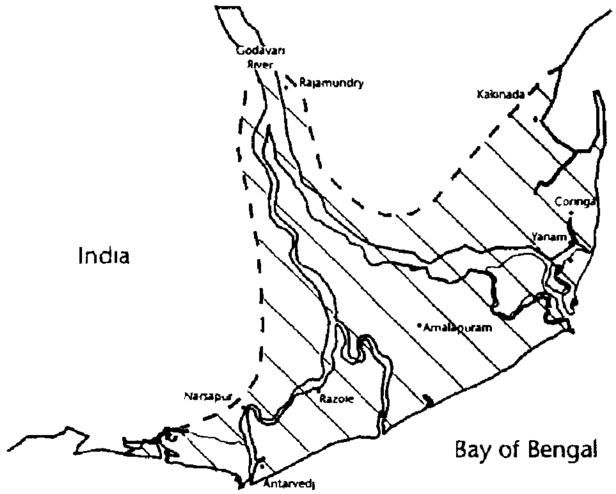


Figure 13. Composite cyclone flood map for the Godavari river.

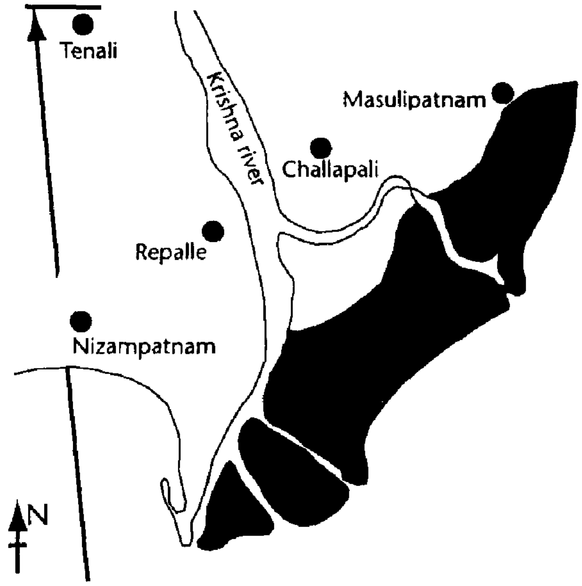


Figure 14. Cyclone map for the Krishna River.

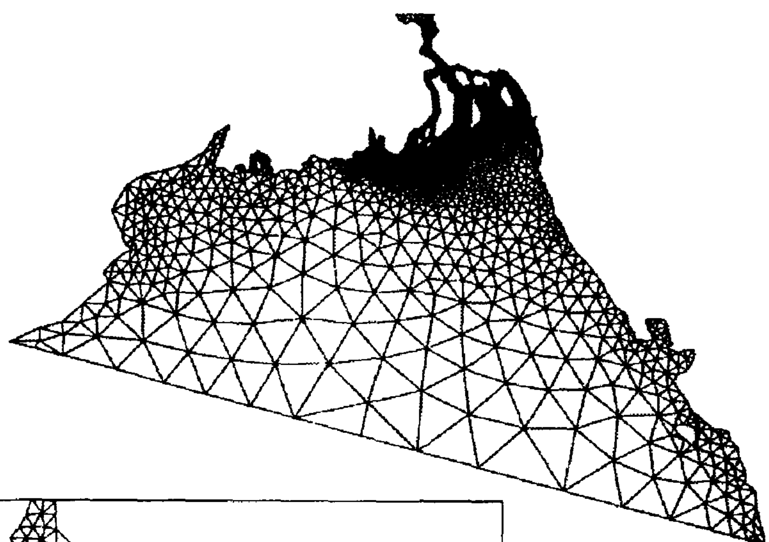


Figure 15. Irregular triangular grid for the northern part of the Bay of Bengal (Henry et al., 1997).

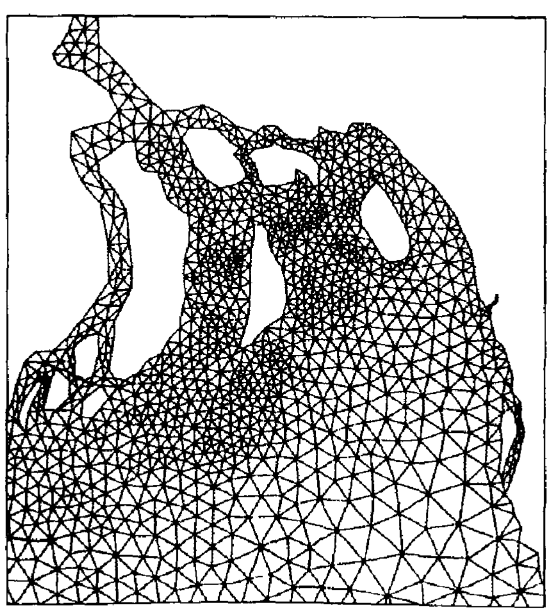
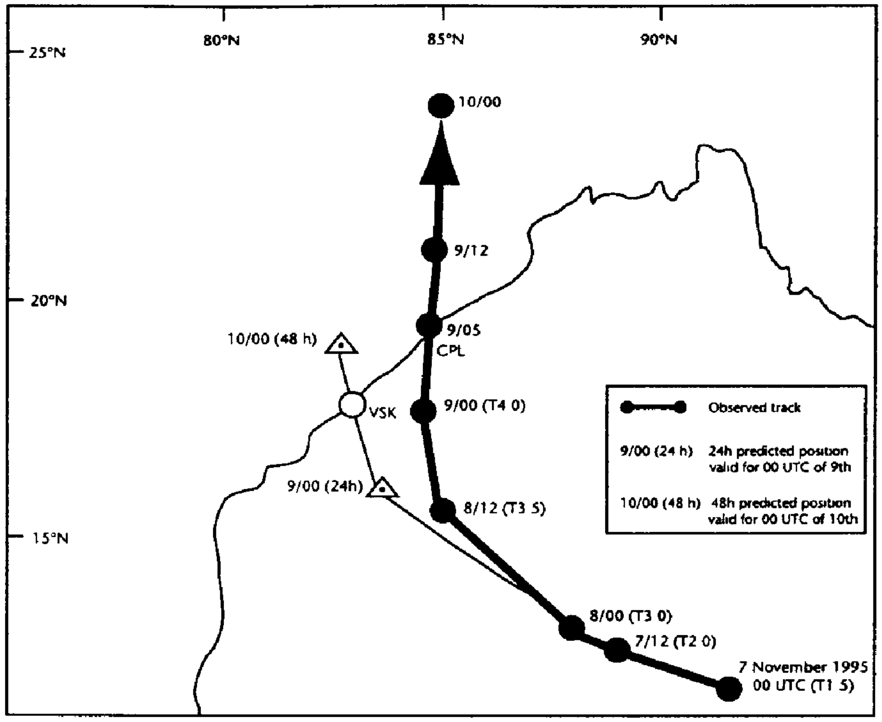


Figure 16. Zoom-in for the northern extremity of the grid.

Figure 17. Comparison of predicted track with observed track for a cyclone on the east coast of India (Prasad, 1997).



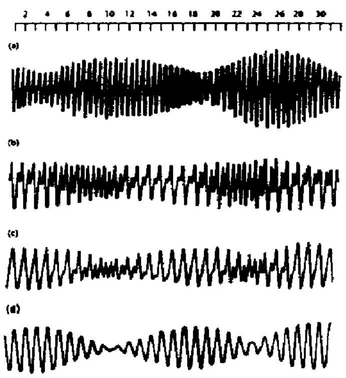


Figure 18. Schematic representation of a 1- mo-long tidal record. (a) Semi-diurnal; (b) mixed, mainly semi-diurnal; (c) mixed, mainly diurnal; (d) diurnal.

Figure 17 compares a predicted track with an observed track for a cyclone on the east coast of India. Even though the agreement may be termed satisfactory under the present state-of-the-art of tropical cyclone track prediction, from a practical point of view, the prediction is not satisfactory. For a densely populated coast such as this one, even an error of a few km in the track prediction means evacuating a large number of people in the wrong place.

4. TIDES

For storm surge prediction one uses the concept of the total water level envelope (TWLE) which is made up of the surge, the tide and the wind wave set-up. Hence, tidal prediction is needed to understand the surge-tide interaction. Figure 18 shows the classification of the tides into four different regimes. A semi-diurnal tide has two high waters (HW) and two low waters (LW) everyday. A mixed mainly semi-diurnal tide has two HW's and two LW's everyday, but the two HW's (and the two LW's) do not have roughly equal amplitudes. A diurnal tide has one HW and one LW everyday. Upon these is superimposed the spring-neap tidal regime. Table 2 lists the principal semi-diurnal and diurnal tidal constituents.

Because of the earth's rotation, amphidromic points as shown in Figure 19 occur. At these points, the vertical motion associated with a given tidal constituent is zero and the horizontal component of the motion is a maximum.

Figure 20 shows the amphidromic point for the K1 tide in the Arabian Sea.

Figure 21 shows the half range of tide for the Bay of Bengal.

Figure 22 shows the amphidromic point in the Red Sea for the M2 tide.

Figure 23 shows the amphidromic points in the Persian (Arabian) Gulf.

Table 2
Principal Tidal Constituents

Symbol	*Name of Partial Tides*	*Argument (deg./hr) (hr. min)*	*Period in Solar Hours*	*Coefficient Ration M2.100*
M_2	Principal lunar	28.98	12.25	100.0
N_2	Larger lunar elliptic	28 44	12.39	19 2
S_2	Principal solar	30.00	12.00	46.6
K_2	Luni-solar semi-diurnal	30.08	11.58	12.7
O_1	Principal lunar diurnal	13.94	25.49	41.5
P_1	Principal solar diurnal	14.96	24.04	19.4
K_1	Luni-solar diurnal	15.04	23 56	58.4

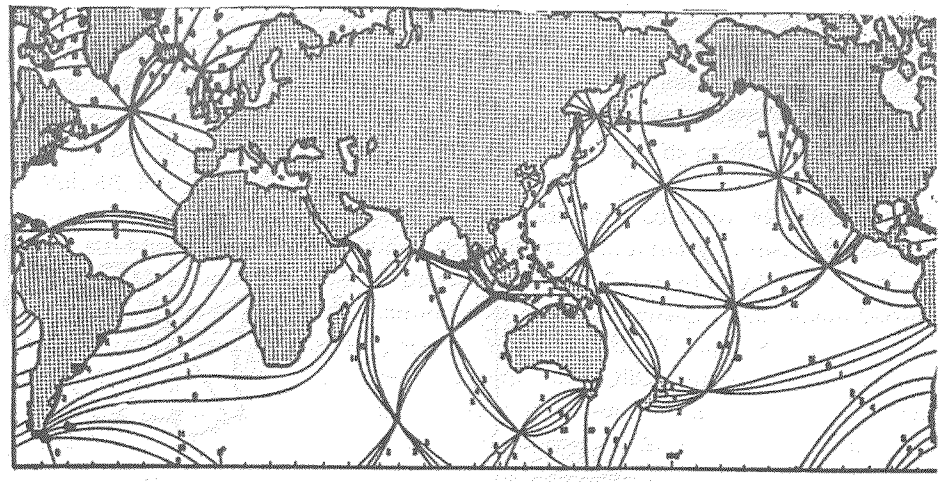


Figure 19 Co-tidal lines of the semi-diurnal tide in the Oceans (Sterneck, 1920)

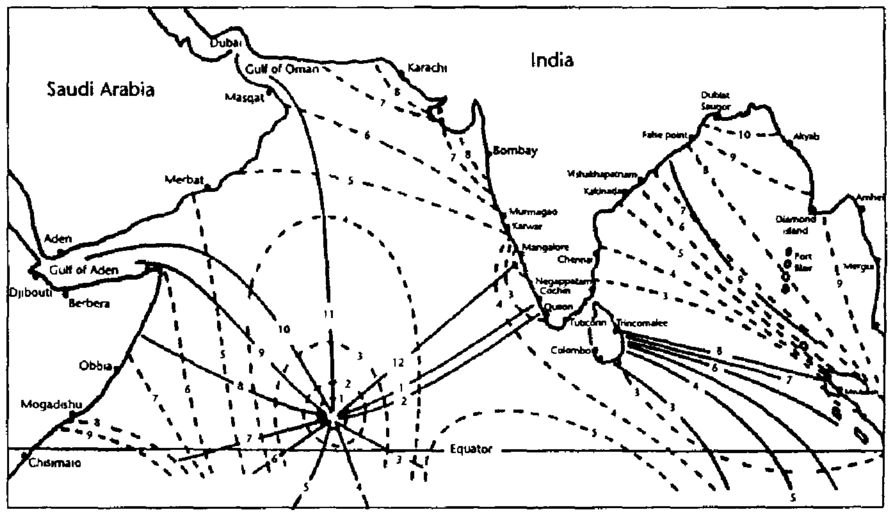


Figure 20. Co-tidal and co-range lines for the constituent K1. Numbers on solid lines are the time (hours) of high water that are half of the period, the time origin the standard meridian. Numbers on broken lines are the amplitudes (centimetres) (Fairbairn, 1954).

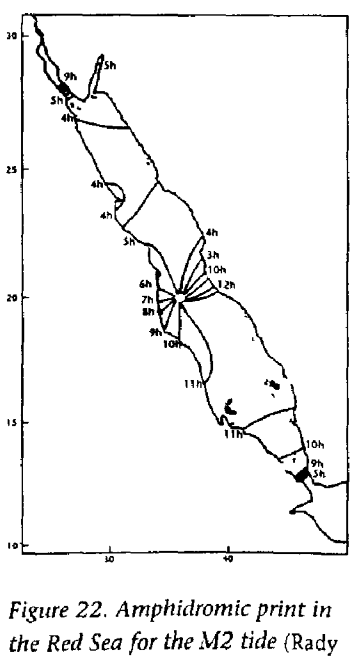


Figure 22. Amphidromic print in the Red Sea for the M2 tide (Rady et al., 1994)

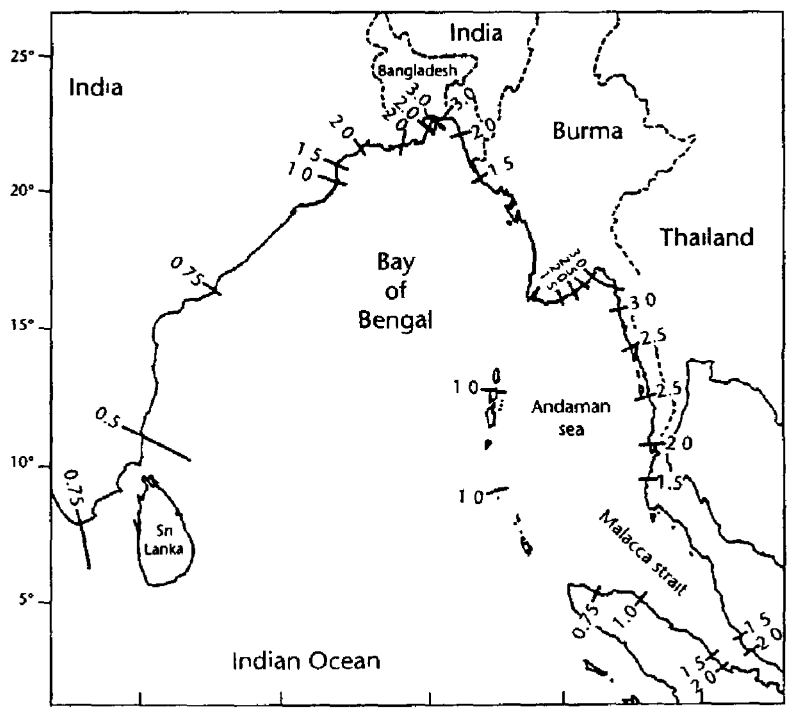


Figure 21. Half range of tide (m) in the Bay of Bengal (Murty et al., 1986).

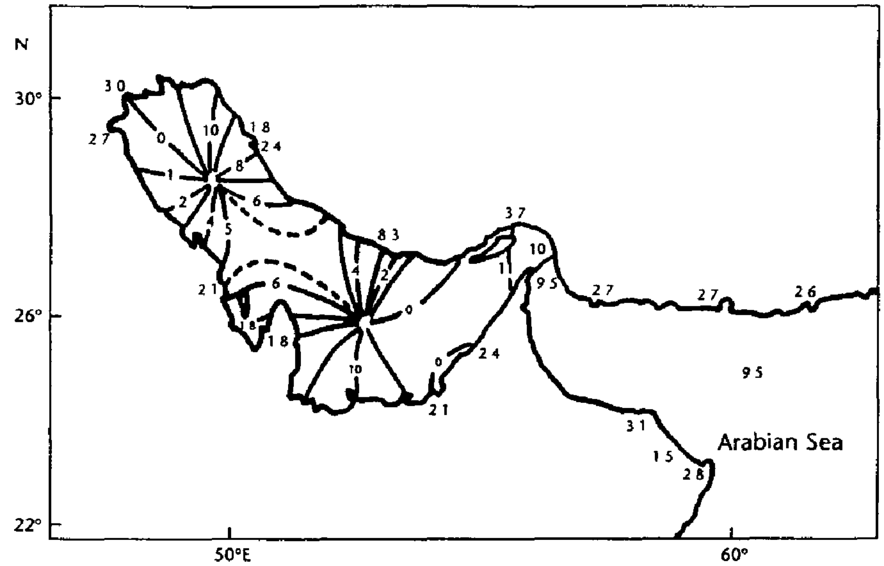


Figure 23. Phase (lunar hours and amplitude (cm) of the springtides in the Persian (Arabian) Gulf derived from observations (Defant 1961)

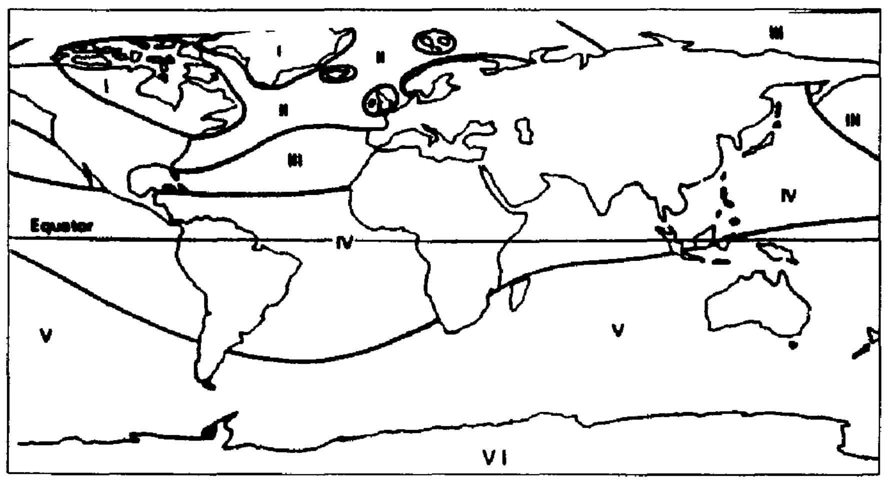


Figure 24. Six predicted zones of relative sea-level change: emberged beaches are dictated for zones I, III, V and VI and submergence in zones II and IV (S Jelgersma and M.J. Tooley, 1993).

5 INFLUENCE OF GREENHOUSE EFFECT AND EL- NIÑO EVENTS

There is a lot of literature on the possible influence of greenhouse warming on tropical cyclones and all of it is inconclusive. Before worrying about how the greenhouse warming may or may not influence future storm surges, it is more appropriate to recognize the seriousness of the existing problem and try to mitigate it.

Due to global warming, if there is any sea-level rise in the Northern Indian Ocean, it will have some effect on future surge amplitudes. Sinha *et al* (1997) studied the effect of sea-level rise on tides in the Hoogly estuary of the Bay of Bengal

When one thinks of sea-level rise, one should also consider possible land subsidence. Figure 24 shows that land subsidence is expected for the coastlines of the North Indian Ocean. If this comes true, the storm surge amplitudes could become greater.

Regarding the influence of ENSO events, again there is a lot of literature (Dong, 1988; Gray and Sheaffer, 1991; Evans and Allan, 1992 and Wu and Lau, 1992). Gupta and Muthuchami (1991) and Murty and Neralla (1996) studied this problem with respect to the north Indian Ocean. Although, there are some indications that ENSO events may have some influence on the location of the storm tracks, this problem needs further study.

6. SUMMARY

There is a storm surge problem in the marginal seas of the North Indian Ocean, the severest being in the Bay of Bengal. It is not clear at this time how much influence greenhouse warming and ENSO events would have on future surge amplitudes. However, if sea-level rises and also if the land subsides, the surges will be somewhat greater than at present.

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