Perigean spring tides along the Indian coast

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Sea level measurements from tide-gauges, installed in harbours along the Indian coast by the Survey of India, are used to illustrate the differences in high tides during spring tides that occurred during lunar perigee and apogee (closest and farthest position of the moon in its elliptical orbit around the earth) in January and August 1974 respectively. The difference in maximum tidal heights between 9 January and 4 August of the year for Mumbai tidal record is about 87 cm, whereas for Chennai, Visakhapatnam and Paradip, the differences vary between 20 and 25 cm. Kochi record shows a difference of about 13 cm, whereas the difference in predicted high tides at Bhavnagar is more than 1 m. Similar results are found for March and April 1980 during spring tides close to perigee and apogee respectively. Perigean spring tides can cause flooding in low-lying coastal areas along the northern parts of the Indian coast, which will get enhanced in future with mean sea-level rise due to global warming.

Keywords: Coastal flooding, mean sea-level rise, new moon and full moon, perigean spring tides, tide-gauge data.

IN recent years, there have been reports of inundation in some coastal regions caused by large tides. For example, Sweet *et al.*[1] reported inundation in some coastal regions of USA, during spring tides, which is sometimes referred to as 'nuisance flooding'. Le Cozannet *et al.*[2] reported increased flooding at high tides in low-lying areas in the island of Guadeloupe, West Indies. Ray and Cartwright[3] estimated the combined tide-producing potential of the moon and the sun for 3000 years. For the 20th century, they reported it to be maximum on 8 January 1974. On this day, a full moon occurred during lunar perigee[4]. Besides, the day was close to perihelion (earth's position closest to the sun in its elliptical orbit), which occurred on 3 January. On 8 January, the combined tide-producing potential of the sun and moon was maximum (see table 1 in Ray and Cartwright[3]). The tide-producing forces were one of the lowest on 3 August of the same year.

Occurrence of perigean spring tides has been discussed in the literature for some regions, but not much along the Indian coast. The present study examines the variations in high tides between perigee and apogee during spring tides. We chose the period of January and August 1974 for the study. During this year, the tide-producing forces were the largest on 8 January and one of the lowest on 3 August. Spring tides following the full moon and lunar perigee on 8 January were also large because of the earth's perihelion on 3 January. We also analysed the tide-gauge data during March and April 1980 to compare the maximum tidal heights during spring tide following a perigee and an apogee.

A brief introduction on tides, tidal constituents and mean sea-level rise is given below.

Tides in the ocean are periodic phenomena caused by a resultant force due to the gravitational forces of the moon and the sun and centrifugal forces due to the rotation of the earth. Tides occur at different timescales varying from semi-diurnal, diurnal, fortnightly and longer. Tidal ranges at a given place are related to the position of the moon and the sun. The period from one new moon to the next is 29.5 days. During the new moon and full moon, the combined gravitational forces of attraction of the moon and the sun are aligned together, generating large tidal ranges, which are known as 'spring tides', while after about seven days of either a full moon or a new moon, when these forces are in quadrature, the tidal ranges are lowest and are known as 'neap tides'. A schematic of the positions of the sun and the moon during a new moon and a full moon can be found in many textbooks (for instance, Pugh and Woodworth[5]). Spring tides generally occur one or two days after the full moon or new moon. Tides generated in the open ocean take one or two days to propagate and arrive at the coastal regions. This 'time lag' in the occurrence of high tides at a location following a full moon or a new moon is often referred to as the 'age of the tide'. The moon completes an elliptical orbit around the earth in about 27.55 days. The

Table 1. Amplitude and phase (with respect to Greenwich) of four major constituents at selected stations along the Indian coast

Location	Tidal constituent	Amplitude (cm)	Phase g (deg)
Kochi	M_2	20.0	346.0
	S_2	7.0	47.0
	K_1	17.0	64.0
	O_1	9.0	65.0
Mumbai (Apollo Bandar)	M_2	123.0	345.0
	S_2	48.0	25.0
	K_1	42.0	55.0
	O_1	20.0	52.0
Bhavnagar	M_2	314.0	143.0
	S_2	96.0	190.0
	K_1	76.0	92.0
	O_1	34.0	75.0
Chennai	M_2	33.2	237.3
	S_2	13.7	272.6
	K_1	9.0	338.0
	O_1	2.8	310.1
Visakhapatnam	M_2	47.5	239.0
	S_2	20.9	274.2
	K_1	11.3	336.4
	O_1	4.1	320.5
Paradip	M_2	62.2	241.4
	S_2	27.9	276.9
	K_1	12.4	330.8
	O_1	4.9	320.2

Source: Admiralty Tide Tables[11].

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closest position of the moon to the earth is known as 'perigee', while the farthest position is known as 'apogee'. If spring tides occur after a perigee, they are called 'perigean spring tides' and have large tidal ranges.

A brief definition of various tidal constituents is given below. Initially, assuming a circular orbit of the moon around the earth, one can define the principal lunar constituent M_2. Similarly, assuming a uniform circular motion of the earth around the sun, the principal solar constituent S_2 can be defined. M_2 and S_2 have periods of 12.42 and 12.00 h respectively (subscript 2 indicates semi-diurnal). Two more constituents are defined to account for the elliptical motion of the moon around the earth. They are N_2 (larger lunar elliptical) and L_2 (smaller lunar elliptical). N_2 has a period of 12.658 h. T_2 is the solar elliptical constituent, and the second elliptical constituent of the sun is small and usually neglected in the tidal analysis. Diurnal constituents of the moon and the sun are defined to account for their declination. Among the lunar diurnal constituents, K_1 and O_1 (subscript 1 indicates diurnal) have periods of 23.934 and 25.819 h respectively. K_1 is also called luni-solar diurnal constituent. P_1 is another solar diurnal constituent having a period of 24.065 h. There are many more constituents having fortnightly, monthly and longer timescales. A detailed account of tidal constituents is beyond the scope of the present study. These are described in many books, for example, Pugh and Woodworth[5] and Kowalik and Luick[6].

A term known as 'form number' is used to describe the nature of tidal regime at a location. It is defined as

$$F = H(K_1) + H(O_1)/(H(M_2) + H(S_2)), \tag{1}$$

where $H(K_1)$, $H(O_1)$, $H(M_2)$ and $H(S_2)$ represent amplitudes of the tidal constituents K_1, O_1, M_2 and S_2 respectively. If $F = 0.0$–0.25 indicates a purely semi-diurnal regime, $F = 0.25$–1.50 represents a mixed, but mainly semi-diurnal type, and $F = 1.5$–3.0 represents a mixed mainly diurnal type and $F > 3.0$ shows a diurnal-type tidal regime.

Observed mean sea-level rise trends in the north Indian Ocean for the last two decades were slightly more than 3 mm/yr (refs 7, 8). The Intergovernmental Panel on Climate Change has reported that the global average sea level could rise by 0.28–0.55 m by 2100 (relative to 1995–2014) for a very low greenhouse gas emission scenario and 0.63–1.01 m for a very high emission scenario[9].

The Survey of India continuously measures sea level along the Indian coast using tide gauges installed in various harbours. Hourly tide-gauge data from five tide gauges have been used in the present study (Figure 1). These are Mumbai, Kochi, Chennai, Visakhapatnam and Paradip. Bhavnagar was also included, and in this station, predicted high tides were used for comparison[10].

Observed sea level at a location can be considered to be the sum of mean sea level, tides and 'residuals'. The residuals are often due to transients such as surges. Tides can be represented in terms of a compound harmonic, with each harmonic representing a particular motion of the moon around the earth or the earth around the sun. Each harmonic, often called a tidal constituent, has an amplitude and a phase. The resultant tide, $T(t)$ at time t can be defined as

$$T(t) = Z_0 + \sum H_n f_n \cos[\sigma_n t - g_n + (V_n + u_n)], \tag{2}$$

where Z_0 is the mean sea level, H_n and g_n are the amplitude and phase of the nth constituent respectively. σ_n is the angular frequency of the nth constituent. V_n adjusts the phases to allow for astronomical conditions at the time of origin of the data, f_n the node factor which is an adjustment factor varying slightly from year to year to account for the 18.61-yr period nodal cycle and u_n is the nodal adjustment for phase.

Table 1 shows the amplitudes and phases of major semi-diurnal constituents M_2 and S_2, and major diurnal constituents K_1 and O_1 in selected stations along the west and east coast of India[11]. Essentially, amplitudes of M_2 and S_2 determine the difference in tidal ranges between spring and neap tide. Along the Indian coast, a northward increase in amplitudes of M_2 and S_2 can be found. Computed form numbers for Kochi, Mumbai and Bhavnagar were 0.96, 0.38 and 0.27 respectively. Among these, Kochi had a mixed tidal regime, whereas tides in Mumbai were mixed type but close to semi-diurnal type. Bhavnagar was characterized by a semi-diurnal regime. Along the east coast, computed form numbers are 0.25, 0.23 and 0.18 for Chennai, Visakhapatnam and Paradip respectively, indicating a semi-diurnal tidal regime for all the stations. In general, tides become semi-diurnal towards the northern part of the west coast and the entire east coast.

The Indian Tide Tables (2022)[10] provide information on mean high water spring, mean high water neap, mean low water spring and mean low water neap. Average tidal range during spring tide for Mumbai, Chennai, Visakhapatnam and Paradip stations was 3.66, 1.01, 1.43 and 1.87 m respectively, whereas the average tidal range during neap tide was 1.44 m, 0.41 cm, 0.54 cm and 0.70 m respectively. For Kochi, having a mixed tide regime, the difference between lower low water spring near solstice and higher high water spring near solstice was about 0.85 m. Bhavnagar showed a tidal range of 8.75 and 4.79 m during spring and neap tides

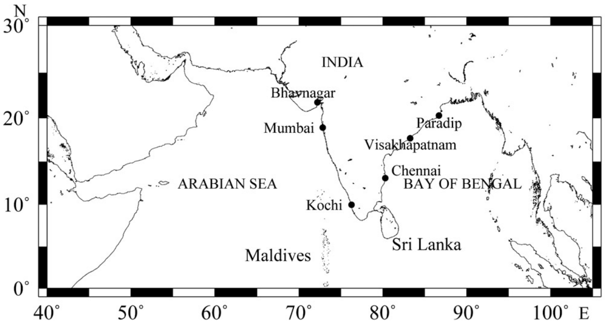

Figure 1. Location of five tide-gauge stations whose data were used in the present study. For Bhavnagar, Gujarat predicted high tides from the Indian Tide Tables[10] were used.

respectively[10]. The tidal ranges increase gradually towards the northern parts of the coast.

We chose the period of January 1974 to present the observed tides at a few stations along the Indian coast. The full moon on 8 January was close to the time of the earth's perihelion. On 8 January 1974, the combined tide-producing potential was found to be maximum during the century[3]. On 23 January 1974, a new moon with a lunar apogee occurred one and a half days earlier. Spring tides following this event on 24 and 25 January 1974 had lower high tides than those found on 9 and 10 January 1974 (Figure 2). For a close comparison of high tides during spring tides at perigee and apogee, we used the tide-gauge data during 9–10 January and 4–5 August 1974 (Table 2). Table 2 also shows high tides during spring tides following perigee and apogee that occurred in March and April respectively in 1980.

A comparison of high tides during spring tides following full moon on 8 January 1974 was made with those during spring tide following the full moon on 3 August of the same year, when a spring tide occurred close to an apogee (Table 2).

Tidal heights during high tides in these two periods are presented to describe variations of maximum tides during spring tides following perigee and apogee. Perigean spring tides that occurred on 9 January 1974 were extremely large. In Mumbai tide-gauge record, the high tide of 5.14 m was recorded, whereas following the full moon close to apogee on 3 August 1974, the maximum height of high tide recorded on 4 August 1974 was about 4.27 m (Table 2), showing a difference of about 87 cm between the two events. It may be noted that spring tides at the coastal stations are observed one or two days after the new moon or the full moon, as equilibrium tides generated in the open ocean take one to two days to propagate in the ocean and reach the coastal regions.

For the three other records considered for the east coast, viz. Paradip, Visakhapatnam and Chennai, the differences in heights of high tide between the spring tides following perigee and apogee of 8 January and 3 August 1974 were about 25, 22 and 21 cm respectively (Table 2). In the Bay of Bengal, tides are semi-diurnal with tidal ranges increasing gradually northward and reaching a maximum in the head of the Bay. Accordingly, tidal heights during high tide for spring tides following perigee and apogee were found to increase northward. Kochi records showed a difference of only about 13 cm between high tides during the two periods. The relatively low difference in heights of high tides in this station between these two periods is primarily due to the low tidal range in the region.

We also examined the predicted high tides at Bhavnagar (Gulf of Khambhat), which is probably a region along the Indian coast having the highest tidal range. The difference between the predicted height of the high tide on 9 January and 4 August 1974 at Bhavnagar was found to be more than 1 m (ref. 10).

We also documented tidal heights during high tide for spring tides after perigee and apogee that occurred in March and April 1980 respectively. Table 2 shows the astronomical events and values of high tides. The differences in high tides during spring tides at perigee and apogee in March and April 1980 respectively, were close to those found for 1974, except for Mumbai, where they were slightly lower.

It may be noted that the differences between high tides during spring tide following perigee and apogee are indicative of the changes between these two periods (Table 2).

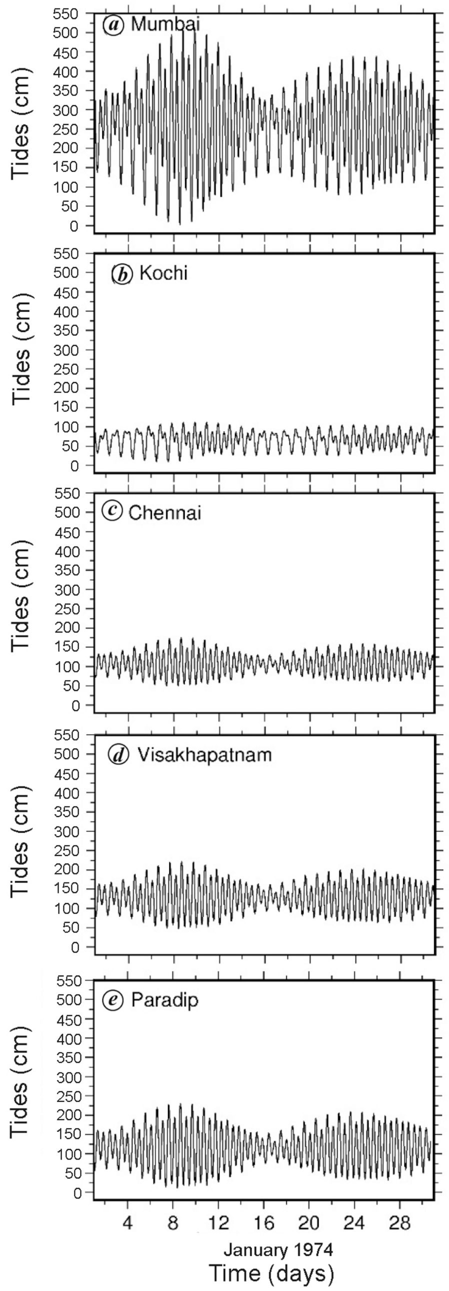

Figure 2. Observed tides at five stations, viz. (***a***) Mumbai, (***b***) Kochi, (***c***) Chennai, (***d***) Visakhapatnam and (***e***) Paradip along the Indian coast in January 1974 from hourly tide-gauge data. (Data source: Geodetic and Research Branch, Survey of India, Dehradun). Lunar perigee occurred at 11:21 h on 8 January 1974 and full moon at 12:37 h on the same day, having a difference of only about an hour. Lunar apogee occurred on 21 January 1974 at 21:39 h and a new moon appeared at 11:03 h on 23 January 1974, after one day and 13 h (ref. 4).

Table 2. Observed high tide following the lunar perigee on 8 January and lunar apogee on 3 August 1974. The highest value of tide after 24 h of the full moon or new moon is taken from the hourly tide-gauge data. Observed sea level was subjected to harmonic analysis and the residuals obtained were subtracted to obtain tides. Lunar perigee occurred at 11:21 h on 8 January 1974 and full moon at 12:37 h with a difference of only about 1 h between them. Lunar apogee occurred at 1:25 h on 3 August 1974 and full moon occurred at 3:57 h, having a difference of only 2 h between them. High tides during perigee and apogee in March–April are also shown. Lunar perigee occurred at 20:30 h on 16 March 1980, followed by a new moon at 18:57 h on the same day. Lunar apogee occurred at 11:32 h on 30 March 1980 and full moon occurred at 15:15 h on 31 March 1980 (ref. 4)

Station	Observed high tide (m) during spring tide and the time of occurrence (h) in January 1974	Observed high tide (m) during spring tide and the time of occurrence (h) in August 1974	Observed high tide (m) during spring tide and the time of occurrence (h) in March 1980	Observed high tide (m) during spring tide and the time of occurrence (h) in April 1980
Mumbai	5.14 (9 January, 19.50 h)	4.27 (4 August, 7.5 h)	5.01 (17 March, 19.5 h)	4.23 (2 April, 7.5 h)
Kochi	1.11 (9 January, 20.5 h)	0.98 (4 August, 8.5 h)	1.05 (17 March, 19.5 h)	0.94 (2 April, 8.5 h)
Paradip	2.31 (9 January, 15.5 h)	2.06 (4 August, 3.5 h)	2.27 (17 March, 15.5 h)	2.00 (2 April, 3.5 h)
Visakhapatnam	2.23 (9 January, 15.5 h)	2.01 (4 August, 3.5 h)	2.03 (17 March, 15.5 h)	1.83 (2 April, 3.5 h)
Chennai	1.76 (9 January, 15.5 h)	1.55 (4 August, 3.5 h)	1.70 (17 March, 15.5 h)	1.51 (2 April, 4.5 h)

High tides can vary slightly from one perigean spring tide to another, mainly because the sampling of the data is done only at hourly intervals. Secondly, for different perigean cycles, there will be some time difference between the occurrence of a perigee and a full moon or a new moon that will give slight differences in the height of high tides. Also, the declination of the moon and the sun could change the resultant tides at a particular time.

In the present study, we describe the tidal highs during spring tides after perigee and apogee in January and August 1974 respectively. We also describe tidal highs during spring tides following a perigee and apogee in March and April 1980 respectively. We found that in regions with large semi-diurnal tidal ranges, the difference in high tides during spring tide between perigee and apogee was significant. Perigean spring tides occur at least 3–4 times a year. Moreover, coastal inundation could increase if it coincided with an episodic event, such as a storm surge. Analysis of past tide-gauge data along the Indian coast provides examples of occurrences of very large tides. The next largest tides for the current century are predicted to be on 13 January 2036 (ref. 3).

The differences in high tides during spring tide between perigee and apogee are not large along the southern part of the Indian coast; however, they increase towards the north and become significant in regions characterized by large semi-diurnal tides. The magnitude of the differences found along the northern part of the Indian coast is comparable to future global mean sea-level projections for 2100. The combined effects of large tides and future sea-level rise could lead to inundation in low-lying areas, especially in regions having large semi-diurnal tides. Regional tidal models coupled with inundation models can provide information on likely areas of coastal flooding. If some of these events occur simultaneously with extreme waves or surges, increased coastal flooding can occur in low-lying areas.

Along the Indian coast, routine tidal predictions at harbours are made by the Survey of India. The Indian National Centre for Ocean Services also provides tidal predictions in minor ports. For tidal predictions, providing information on astronomical events as well, such as the full moon and new moon, lunar perigean cycle, etc. can enhance public awareness for preparedness for coastal flooding in low-lying areas.

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