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THE 2004 INDIAN OCEAN TSUNAMI: DESCRIPTION OF THE EVENT AND ESTIMATION OF LENGTH OF THE TSUNAMI SOURCE REGION BASED ON DATA FROM INDIAN TIDE GAUGES

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ABSTRACT: The Great Tsunami of 26 December 2004 in the Indian Ocean is described using data from tide gauges along the coast of India. The tsunami struck the Indian east coast around 0330 UTC. The amplitude was 2.0 m above the tide at Chennai and Paradip, 1.5 m at Visakhapatnam and less than a metre at Tuticorin. The tsunami propagated into the Arabian Sea from the south and Kochi was hit at 0541 UTC. The maximum amplitude had decayed to about 80 cm at Kochi and it was less than 10 cm at Okha in Gujarat. All these tide gauges are to the west of the earthquake zone and the detided sea levels show first a rise in sea level with the arrival of the tsunami, and then a sharp decrease. Spectral and wavelet analysis of the residuals shows that the maximum amplitude was at a period of 35-45 min, with another maximum around 20 min. Along the Indian east coast, however, there is another broad peak between 1-2 hours within the first few hours after the first tsunami wave. Numerical simulation of this event is critically dependent on the initial perturbation used to force the model. The extent of the tsunami source region remains a key bottleneck. Arrival times recorded on the tide gauges provide additional constraint on the northern extent of the tsunami source location. Using the newly available tide-gauge data from Paradip, the northernmost station along the Indian east coast and therefore the most critical constraint on the northern extent of the tsunami source region, we investigate the northern extent of the source region of the Indian Ocean tsunami. Using backward ray tracing, we show that the tsunami travel times as recorded on the tide gauges at Paradip, Vishakhapatnam, and Chennai imply that the tsunami source region extends to ~ 11° N, implying a source region about 900 km long, about 30% greater than earlier estimates.

1. INTRODUCTION

An earthquake with a moment magnitude M_w = 9.3 occurred at 3.307° N, 95.947° E (255 km south-southeast of Banda Aceh, Sumatra, Indonesia) at 0059 UTC on 26 December 2004 [1] (Fig. 1). This earthquake, which ruptured 1600 km of India's eastern plate boundary and is the second largest instrumentally recorded (after the Chile earthquake of 1960), triggered a tsunami that devastated the coastal areas in the entire Indian Ocean. The death toll has exceeded 300000 [2], making this the biggest "killer" tsunami in recorded history [3].

Though the tsunami was also observed in a timely pass of the altimeter Jason (http://www.noaanews.noaa.gov/stories2005/s2365.htm), the best instrumental records of the tsunami waves are contained in the tide-gauges at coastal and island stations [4]. We briefly describe the tsunami as seen in the tide-gauge records from India. We first describe the progress of the tsunami in the Indian Ocean based on these data and then subject the data to spectral and wavelet analysis to determine the frequencies present.

Next we proceed to estimate the length of the tsunami source region using a backward ray tracing method. Determining the length of the tsunami source region is one of the keys to understanding the complex nature of the rupture and other geological processes involved [1]. Numerical simulation of tsunami propagation is critically dependent on the initial perturbation used to force the model. Thus the length of the tsunami source region remains a key bottleneck. From the arrival times recorded on the tide gauges, the tsunami travel times to the respective tide gauges can be computed by subtracting the time of earthquake from the recorded arrival times. These travel times are then used to provide additional constraints on the tsunami source location using the backward ray tracing method [5]. Lay et al. [2] provided an estimate of the 2004 Indian Ocean tsunami source region. Assuming an instantaneous rupture and total slip on the fault, Lay et al. used backward ray tracing to estimate a source region extending up to 600 km (~ 9° N) north-northwest of the epicentre. The extent increased to about 10° N on considering the time delay [2] due to finite rupture propagation and slip rise. In the analysis of Lay et al., the northern extent of the tsunami source region was constrained by the tsunami travel times reported from the tide gauge stations at Chennai, Visakhapatnam, and Port Blair (Fig. 5(a)). At the time of the tsunami, however, the clock of the Port-Blair gauge was 46 min. ahead of the actual time [6]. A data gap of 24 min. (between 35-59 min. after the earthquake) in this record adds to the uncertainty in the tsunami arrival time at Port Blair [6]. Hence, we exclude Port Blair from our analysis and re-estimate the length of the tsunami source by including the newly available tide-gauge data from Paradip.

2. DATA

The Survey of India (SOI) maintains a network of tide gauges along the coast of India (Fig. 1). The tide gauge at Nagapattinam (south of Chennai), which was the worst affected region on the Indian mainland, did not survive the tsunami. It was damaged along with the housing and the records could not be retrieved. Data are available for Paradip, Vishakhapatnam, Chennai, Tuticorin, Kochi, Mormugao, and Okha (Fig. 1). Data are not available from the Andaman and Nicobar islands; the SOI tide gauge at Car Nicobar was destroyed by the tsunami and that at Port Blair was under repair at the time of tsunami.

The SOI gauges are either stilling-well (float-type mechanical) gauges or pressure sensor - type gauges (Table 1) [7]. The mechanical tide gauges produce an analog record that has been digitized at an interval of 5 or 6 minutes for the tsunami event. The pressure sensor gauges also record data at an interval of 5 or 6 minutes. The tsunami signal was obtained from these data by detiding the record using the TASK (Tidal Analysis Software Kit) package [8]; data for 30 days were used for detiding.

3. DESCRIPTION OF TIDE GAUGE RECORDS

The residuals for the tide-gauge stations along the Indian coast are shown in Fig. 2 and a summary of the observations is provided in Table 1. The stations on the Indian east coast were hit almost at the same time (around 0330 UTC). Tuticorin, which lies on the gulf of mannar (Fig. 1), was hit at 0423 UTC. Though hardly any damage was reported from Paradip (or from its neighbourhood), the data show that the tsunami wave was highest there (note that data for Nagapattinam are not available). At none of the three Indian east coast stations was the first wave the highest (Fig. 2 , Table 1), but the amplitude of the first wave as well as the maximum recorded amplitude were highest at Paradip. The first wave struck the Indian east coast around high tide; the maximum amplitude of the tsunami was, however, recorded around low tide, and this was also the maximum water level recorded at the three stations. At Tuticorin, the amplitude was less (~100 cm), but the first wave was the highest; That the tsunami wave struck Tuticorin around low tide explains the lack of damage recorded on the Indian coast in this region.

The tsunami wave propagated into the Arabian Sea from the south. Kochi, on the Indian west coast, was hit at 0541 UTC. The tsunami amplitude continued to decrease as the wave propagated north to Mormugao and Okha. As at most of the Indian stations, the first wave was not the highest (Table 1); the maximum amplitude and maximum water level occurred much after the first wave.

For information on other tide-gauge stations (Fig. 1) in the Indian Ocean, see Merrifield et al. [4] and Nagarajan et. al. [7].

4. SPECTRAL ANALYSIS

A Fast Fourier Transform (FFT) of the residuals shows that a dominant period is ~35 - 45 minutes at most stations (Fig. 3), with another peak at ~ 20 minutes at some stations. The stations on the Indian east coast also show a broad peak between 1-2 hours.

Wavelet analysis of the residual data shows (Fig. 4) that the 1-2 hour peak is the result of the low-frequency oscillation along the Indian east coast within the 6 - 7 hours of the first tsunami wave, with the peak occurring around noon (0630 UTC) in the northern stations (Paradip and Visakhapatnam) and in the afternoon (~0930 UTC) at the southern stations (Chennai and Tuticorin).

5. LENGTH OF THE TSUNAMI SOURCE REGION OF 2004 SUMATRA EARTHQUAKE

5.1. Backward Ray Tracing Method

The linearised shallow water equations provide a reasonably good model for tsunami wave propagation. These equations can be solved in the geometric optics limit using the eikonal approximation. It is well established that the resulting ray diagrams can be used to compute the travel times of the leading tsunami wavefront to a reasonably good approximation [9]. We use the conventional planar ray equations for our analysis.

$$\frac{dx}{dt} = c\cos\chi$$

$$\frac{dy}{dt} = c\sin\chi$$

$$\frac{d\chi}{dt} = \sin\chi\frac{\partial c}{\partial x} - \cos\chi\frac{\partial c}{\partial y}$$

where x is the longitude, y the latitude and χ the angle between the ray direction and the positive x-axis. $c(x,y)$ is the local speed of the ray and is equal to $\sqrt{gh(x,y)}$, $h(x,y)$ being the local depth.

The ray equations do not incorporate diffraction effects and are exact in the limit of the wavelength being much smaller than the length scale at which the depth varies. There is therefore a need to smoothen the bathymetry before applying ray techniques to analyse tsunami wave propagation [10]. We do this by replacing the speed at every grid point by the average speed over a box of size 1° around it. The smoothening is done only over the ocean points and does not involve the land points. We prefer to smooth the speeds rather than the depths because the latter amounts to replacing the speed by the root mean square value of the speeds in the smoothening box. We obtain speed at any point by bilinear interpolation using the smoothened speeds at the grid points. The underlying bathymetry considered for the present study is from ETOPO2 data [11].

The backward ray tracing method uses the fact that the ray equations are reversible to put constraints on the location of the initial leading tsunami wavefront. The ray equations are solved numerically with the tide-gauge station location as the initial point, for all initial ray directions, and for a time equal to the observed travel time. The set of points thus obtained forms a curve that we refer to as the backward wavefront. The initial tsunami wavefront cannot include points in the region between the backward wavefront and the tide gauge location. The envelope of all the backward wavefronts then gives the allowed locations of the initial wavefront, which we term the "admissible region". The initial wavefront need not include the entire admissible region, but it has to include at least one point from the backward wavefront of every tide gauge station.

5.2. Estimation of the Length of the Tsunami Source Region

The tide gauges along the east coast of India show that the entire coast was struck by tsunami waves at almost the same time. That Paradip, the northernmost of the stations, was hit at almost the same time as Chennai and Visakhapatnam, and that the tsunami amplitude here was comparable to that at these stations (Fig. 2), motivates us to examine the compatibility of the tsunami source region reported by Lay et al. [2] with the recorded travel time of Paradip. (Paradip travel time has not been included in their analysis.) A forward ray tracing simulation shows that while the rays starting from the estimated tsunami source region reach Chennai and Visakhapatnam in the recorded travel times, this is not the case with Paradip [12], implying that the estimated source region is not consistent with the travel times of all three stations. The tsunami source region must have extended farther north for Paradip to be hit at the recorded travel time [12].

Including the Paradip travel time as a constraint (in addition to Visakhapatnam and Chennai) and assuming instantaneous rupture propagation and total slip on the fault, we use backward ray tracing to re-estimate the northern extent of the tsunami source region. The backward wavefront for Paradip is in the admissible regions of those of Visakhapatnam and Chennai only around 11° N (Fig. 5 (a)), implying a source region extending into the Andaman Islands and around 900 km long (from the epicentre), ~200 km (~30%) longer than the estimate of Lay et al. Including the time delay [2] (a maximum of 9 minutes) due to tsunami excitation may extend the effective tsunami source region farther north.

This new northern extent constrains the tsunami arrival time at Port Blair to be around 30 min. (Fig. 5(b)), close to the data gap in the tide-gauge record. The tsunami had already struck Port Blair by the time the tide gauge started recording again [6].

6. DISCUSSION & CONCLUSION

We have used tide-gauge data from stations to the west of the rupture zone to describe the tsunami. At all these stations the water level first rose, then fell. Available data from Indonesia show that stations to the east first saw a drop in water level [4].

Spectral and wavelet analysis pick the 35-45 minutes and ~20 minutes bands as the prominent periods. Along the Indian east coast, there is another prominent peak between 1-2 hours. Since the signal occurs in both float-type and pressure sensor-type tide gauges, the design of the tide gauge is ruled out as a possible cause. This frequency is much weaker at other stations.

One possible cause of this low frequency peak along the Indian east coast is coastally trapped edge waves triggered by the reflection of the shallow-water tsunami waves. Such edge waves have been shown to produce a low-frequency response distinct from the higher frequencies of deep-water waves and shallow-water tsunami waves. It needs to be shown if edge-wave trapping can explain the differential frequency response seen in the tide gauges or if this "anisotropy" in the spectrum is because of lower frequencies triggered by the rupture propagated more to the north-northwest towards the Indian coast. Available geophysical evidence suggests that such anisotropy existed in the forcing: the propagation speed and rate of slip were not uniform along the rupture arc [1]. Also the slow slip with period greater than 1 hour in the northern part of the fault [13] may be a cause for the presence of this low-frequency peak along the Indian east coast.

Next, the additional constraint imposed by Paradip arrival time implies that the tsunamigenic slip must have occurred over a longer arc than estimated earlier [2]. The increase in tsunami source length is ~200 km (~30%), making the event much more destructive. This result also has direct implications [1] for slip distribution on the fault and should help constrain the set of possible geophysical solutions, leading to a better understanding of the processes involved in this mega-event.

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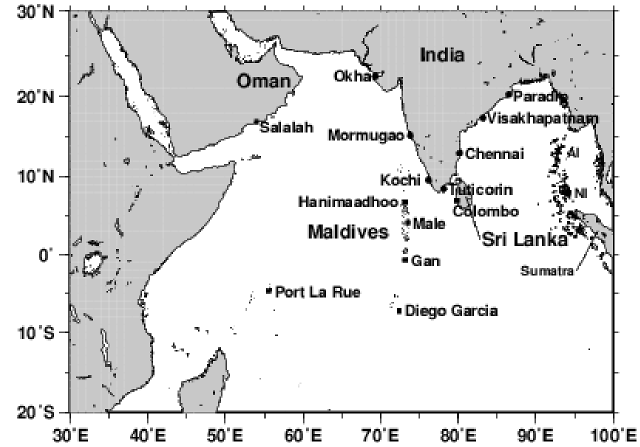

Fig 1. The asterisk marks the epicentre and the dots mark the location of the aftershocks till 10 February 2005. The locations of the tide-gauge stations operated by the Survey of India are marked by filled circles; GLOSS stations are marked by filled squares. AI: Andaman Islands; NI: Nicobar Islands.

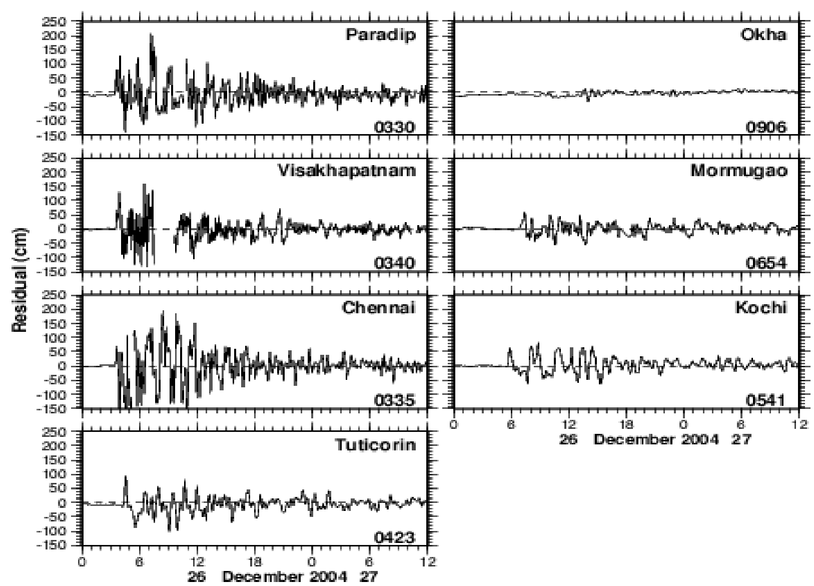

Fig 2. The residual (cm) of the tide-gauge record. The tsunami arrival time (UTC) is given in the bottom right corner.

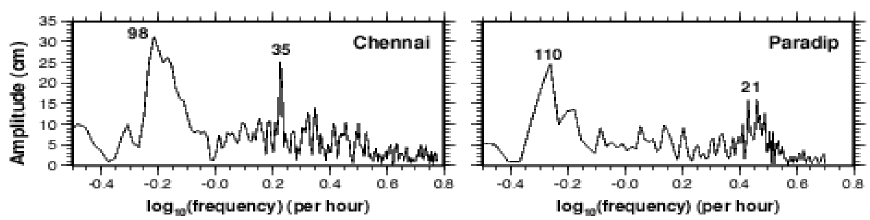

Fig 3. Spectral analysis (FFT) of the residual. The period corresponds to the prominent peaks is shown by the numbers (in minutes).

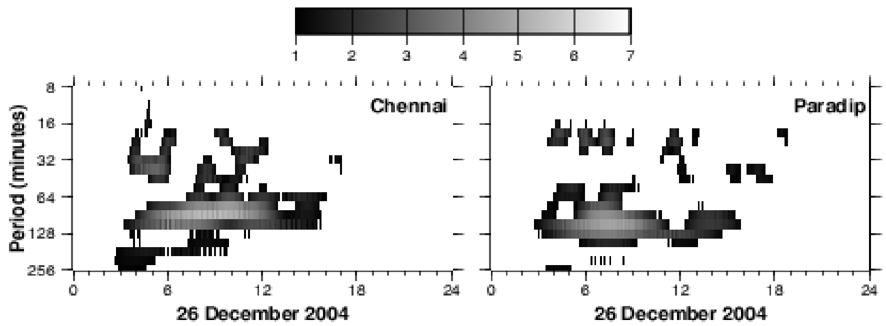

Fig 4. Wavelet analysis of the residual. Note that the ordinate is plotted in $\log_2$ scale. The shading gives the wavelet power spectrum (cm^2); $\log_2$ (wavelet power) is shaded and each successive shade indicates doubling of the wavelet power. Note that more power is present at the stations along the Indian east coast in the 1-2 hour period range.

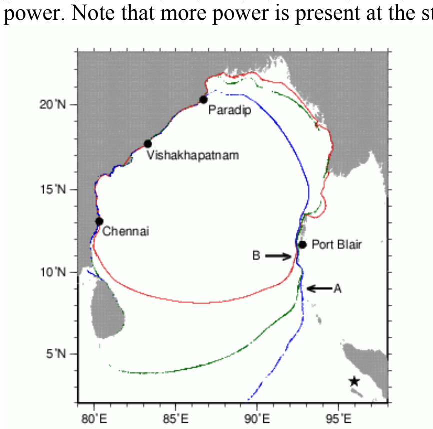

Fig. 5 (a)

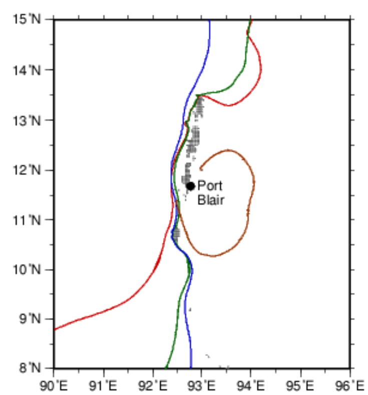

Fig. 5 (b)

Fig 5. (a) Backward wavefronts for Paradip (red), Vishakhapatnam (green), and Chennai (blue) corresponding to their respective observed travel times. The asterisk marks the epicenter of the earthquake. The northern limit (~ 9° N) reported by Lay et al. is indicated by arrow A. The arrow B marks the new estimate (~ 11° N). (b) The ~ 30 min. backward wavefront of Port Blair (brown) is consistent with those of Paradip (red), Vishakhapatnam (green), and Chennai (blue).

Table 1. Description of the tsunami. Column 2 gives the arrival time (AT, UTC), column 3 the amplitude of the first wave (residual) (FW, cm), and column 4 the maximum amplitude over the tide (residual) (Max, cm). Other acronyms are as follows: FW, first wave; HT, high tide; LT, low tide; MWL, maximum water level; and MR, maximum residual; FT, Float-type gauge; PT, Pressure sensor-type gauge. Column 7 gives the sampling (digitised) interval (minutes) for PT(FT) gauges. For information on other stations, see *Merrifield et al*. (2005) [4].

Station	AT	FW	Max	Remarks	Gauge type	Interval
Paradip	0330	89	215	FW just after HT, max just before LT(also MWL)	PT	6
Visakhapatnam	0340	65	159	FW around HT, max close to LT (also MWL)	FT	5
Chennai	0335	64	190	FW around HT, max around LT (also MWL)	FT	5
Tuticorin	0423	100	100	FW after LT (also MWL)	PT	6
Kochi	0541	64	84	FW around HT (MWL), MR during intermediate tide	PT	5
Mormugao	0654	57	57	FW during intermediate tide, MWL near HT in the night	FT	5
Okha	0906	7	-	-	FT	6