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Defining the source region of the Indian Ocean Tsunami from GPS, altimeters, tide gauges and tsunami models

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Abstract

To understand the role of the co-seismic moment magnitude, M_w, 9.1–9.3 Sumatra–Andaman Earthquake rupture mechanism on the severity of the Indian Ocean Tsunami, we used permanent Global Positioning System (GPS) data and carried out an analysis of co-seismic displacement and tsunami models. Tsunami modelling, validated against independent Jason-1 altimetry data and tsunami arrival time data as determined from tide gauges, was used to analyse the results of five co-seismic slip inversions, using GPS, seismicity and/or uplift data. In this way we determined the most likely slip distribution characterized by slip maxima of ~20 m in the South and ~20 m in the North. We used both the distribution and temporal evolution of the co-seismic slip as derived from the GPS data. We show that the ~9 min propagation time of the rupture led to constructive interference of waves radiating first from the South and minutes later from the North, strengthening the tsunami in Southern India, Sri Lanka and Thailand. We conclude that the incorporation of permanent real-time GPS stations would represent a valuable component of future tsunami warning systems.

Keywords: GPS; Sumatra–Andaman Earthquake; Indian Ocean Tsunami

1. Introduction

The Great Sumatra–Andaman Earthquake had a co-seismic moment magnitude (M_w) of 9.1–9.3, (Ammon et al., 2005; Stein and Okal, 2005). It occurred offshore of Sumatra in the subduction zone near the triple plate junction between India, Australia and Sundaland. In the Indian Ocean, the diffuse plate boundary between India

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and Australia is a wide region, affected by NW–SE compressive deformation of the oceanic lithosphere (Chamot-Rooke et al., 1993), and by active left-lateral strike slip along north-trending paleo transform faults (Deplus et al., 1998; Deplus, 2001; Abercrombie et al., 2003). In the long term, the oblique convergence between the Indian Ocean and the Sundaland Block (Simons et al., in press) is accommodated by slip partitioning between two parallel, interseismically locked tectonic entities: the Sumatra–Andaman–Arakan subduction in the forearc and the Sumatra–Sagaing strike slip fault system in the back arc, (Fitch, 1972; Curray, 1989; McCaffrey, 1991; Prawirodirdjo et al., 1997; Genrich et al., 2000; McCaffrey et al., 2000; Nielsen et al., 2004; Socquet et al., 2006). The earthquake ruptured an 1100–1300 km long section of the subduction interface, starting from the northern edge of Sumatra and ending offshore from the Andaman Islands, (Banerjee et al., 2005; Bilham, 2005; Ishii et al., 2005; Krüger and Ohrnberger, 2005; Lay et al., 2005; Ni et al., 2005; Park et al., 2005; Subarya et al., 2005; Vigny et al., 2005; Briggs et al., 2006). It lasted for approximately 8–10 min (Ishii et al., 2005; Vigny et al., 2005), and generated one of the largest tsunamis of recent times (Lay et al., 2005; Titov et al., 2005a) causing colossal devastation and loss of life as it propagated into coastal regions without any tsunami warning being issued.

This earthquake is thought to have increased the stress and raised the seismic hazard on the adjacent segments of the subduction zone. The March 2005 $M_w = 8.7$ Nias earthquake, Briggs et al. (2006) which occurred just south of the 2004 event, is an example of the triggered seismicity, there is now concern for at both ends of the rupture. To the north for example, offshore of the Myanmar coast, the Arakan Trench elastically accumulates a significant part of the relative motion between the Indian and Sundaland plates and is likely to produce a $M_w = 8.5$ earthquake every century or a $M_w = 9$ every 500 yr (Socquet et al., 2006). However, the risk of another devastating tsunami is not restricted to the Indian Ocean (Nedimovic et al., 2003; Titov et al., 2005b). The population explosion in coastal regions means that, more so than at any other time in our history, we are at risk from tsunami's resulting from submarine earthquakes.

An outstanding issue is the rapid and accurate determination of the spatial distribution of slip and its temporal evolution. This has direct implications for tsunami warning and will ultimately lead to a better understanding of earthquake rupture mechanisms and associated seismic hazards. The first estimates of the earthquake magnitude calculated from seismic data underestimated the magnitude of the earthquake, the length of rupture and hence the size of the tsunami. It took nine hours for seismologists to issue a $M_w = 9$ estimate and ~450 km rupture length, but it took days to get a more accurate estimate of the magnitude and real rupture length. To address this issue, we present the first Indian Ocean Tsunami modelling results to use co-seismic uplift fields together with estimates, every 30 s, of the position of the rupture as derived from the kinematic analysis of permanent far field Global Positioning System (GPS) stations (Vigny et al., 2005). This analysis established that the rupture first propagated toward the north–north-west at a speed of $\sim 3.5\ \mathrm{km s^{-1}}$ until 7–8° N, continuing farther north more slowly at $\sim 2\ \mathrm{km s^{-1}}$ and that all co-seismic motion ceased within 10 min.

We demonstrate how tsunami model results, validated against the independent Jason-1 altimetry data and tide gauge arrival time data, can be used to select between the results of five co-seismic slip inversions. To our knowledge this is the first time GPS data have been used together with tsunami models to improve our estimates of the slip along a thrust-fault earthquake. Here, we use permanent GPS data to gain new insights into the earthquake rupture mechanism; in so doing we demonstrate that the SE Asia GPS network in place at the time of the 2004 Sumatra–Andaman Earthquake could have been used to issue a tsunami warning and that GPS should be part of future warning systems.

2. Methods

We run co-seismic displacement models and then use the results of tsunami models, validated against independent Jason-1 satellite altimeter data and tide gauge data, to assess the quality of the inversions. In the first step the GPS and uplift data, described in Vigny et al. (2005), Subarya et al. (2005), Gahalaut et al. (2006), and Bilham et al. (2005) are inverted to obtain the co-seismic slip distribution. In the second step uplift and subsidence fields are generated by a forward elastic model using the previously calculated slip on the fault. The uplift and subsidence fields are then used to generate the initial fields for tsunami simulations, using two unstructured mesh finite volume and finite element numerical models, Delfin and Finlab, described in Ham et al. (2005) and Labeur and Pietrzak (2005) respectively. The quality of the inversions is assessed by a comparison of the simulated sea surface displacements against those measured by Jason-1. In addition, a comparison is made between the simulated and recorded tsunami arrival times around the Bay of Bengal.