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Source models of great earthquakes from ultra low-frequency normal mode data

Konstantinos Lentas (1,2), Ana Ferreira (1,3), and Eric Clévédé (4)

(1) University of East Anglia, Norwich, United Kingdom (K.Lentas@uea.ac.uk), (2) International Seismological Centre, Thatcham, UK, (3) Dept of Earth Sciences, Faculty of Maths & Physical Sciences, University College London, London, UK, (4) Institut de Physique du Globe, Paris, France

We present a new earthquake source inversion technique based on normal mode data for the simultaneous determination of the rupture duration, length and moment tensor of large earthquakes with unilateral rupture. We use ultra low-frequency ($f < 1$ mHz) normal mode spheroidal multiplets and the phases of split free oscillations, which are modelled using Higher Order Perturbation Theory (HOPT), taking into account the Earth's rotation, ellipticity and lateral heterogeneities. A Monte Carlo exploration of the model space is carried out, enabling the assessment of source parameter tradeoffs and uncertainties. We carry out synthetic tests for four different realistic artificial earthquakes with different faulting mechanisms and magnitudes (Mw 8.1-9.3) to investigate errors in the source inversions due to: (i) unmodelled 3-D Earth structure; (ii) noise in the data; (iii) uncertainties in spatio-temporal earthquake location; and, (iv) neglecting the source finiteness in point source moment tensor inversions. We find that unmodelled 3-D structure is the most serious source of errors for rupture duration and length determinations especially for the lowest magnitude artificial events. The errors in moment magnitude and fault mechanism are generally small, with the rake angle showing systematically larger errors (up to 20 degrees). We then carry out source inversions of five giant thrust earthquakes (Mw $\geq$ 8.5): (i) the 26 December 2004 Sumatra-Andaman earthquake; (ii) the 28 March 2005 Nias, Sumatra earthquake; (iii) the 12 September 2007 Bengkulu earthquake; (iv) the Tohoku, Japan earthquake of 11 March 2011; (v) the Maule, Chile earthquake of 27 February 2010; and (vi) the recent 24 May 2013 Mw 8.3 Okhotsk Sea, Russia, deep (607 km) earthquake. While finite source inversions for rupture length, duration, magnitude and fault mechanism are possible for the Sumatra-Andaman and Tohoku events, for all the other events their lower magnitudes do not allow stable inversions of mode singlets. Hence, only point source inversions using normal mode multiplets are carried out for these four earthquakes. We find a moment magnitude of 9.3, a rupture length of 1,277 km and a duration of 521 s for the 2004 Sumatra-Andaman earthquake, corresponding to an average rupture velocity of 2.45 km/s, which agree well with previous estimates. We also obtain the first normal mode finite source model for the 2011 Tohoku earthquake, which yields a fault length of 461 km, a rupture duration of 151 s, and hence an average rupture velocity of 3.05 km/s, giving an independent confirmation of the compact nature of this event. For all the other earthquakes studied, our new point source models are compared with those in the literature, showing average differences of 7.5 degrees in strike, 10.3 degrees in rake, 2.5 degrees in dip and 0.1 in Mw, which are comparable or smaller to reported errors in these parameters from other studies. We do not find any unexplained systematic differences between our results and those in the literature, suggesting that for the wave frequencies considered, the moment magnitude and the fault mechanism of the earthquakes studied do not show a strong frequency dependence.