Contribution of the 2004 Sumatra-Andaman earthquake to Sea-Level Change

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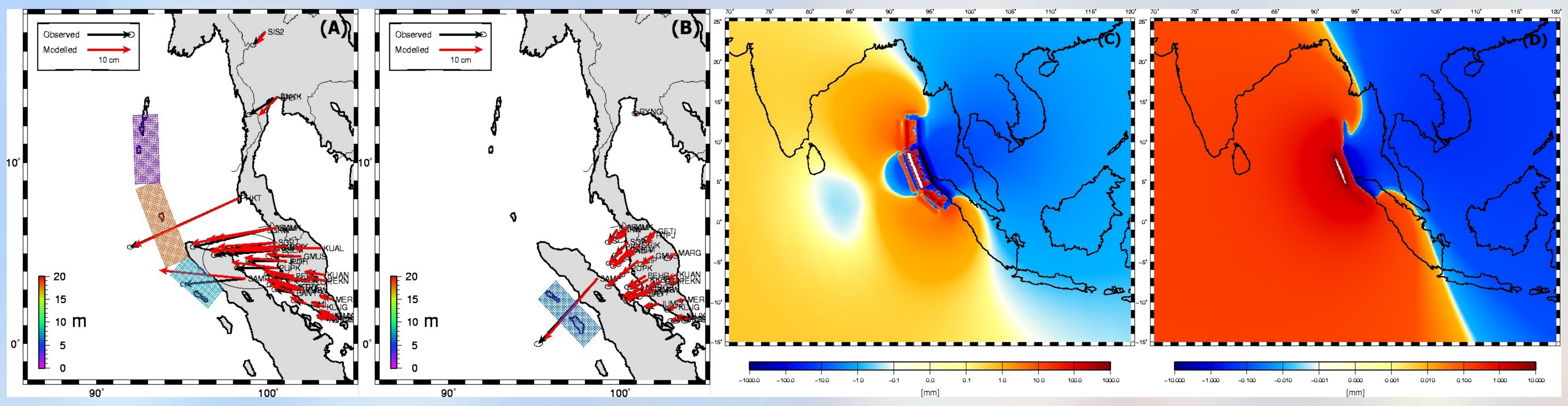
Abstract

GPS-observations have demonstrated that the 2004 Sumatra-Andaman earthquake resulted in very large horizontal co-seismic displacements, still up to 27 cm at a distance of 400 km from the epicenter [1]. Three months later, the Nias earthquake occurred just to the south. During this event GPS measured horizontal displacements up to 20 cm. Earthquakes with such magnitudes are expected to have a significant effect on the co-seismic vertical and gravitational displacement fields as well. Therefore, earthquakes will change both the relative sea level (RSL), defined as the radial distance between the sea floor and the geoid level, and the absolute sea level, which is assumed to be consistent with the geoid.

Both the seismic deformations and the resulting sea level changes have been simulated by means of a spherical, self-gravitating, radially stratified Earth model with linear viscoelastic rheology. The sea level equation has been implemented to ensure water mass conservation.

The results show that the RSL change has a maximum value of 3.5 meters over the fault plane, decreasing fast with distance. At the coast of Sumatra values of several decimeters are found and even at the coast of Thailand a rise of approximately 20 mm is predicted. The absolute sea level changes are maximally 15 mm, close to the epicenter. In the far-field the influence of the earthquake on the sea level does not exceed ±1 mm.



Coseismic deformation

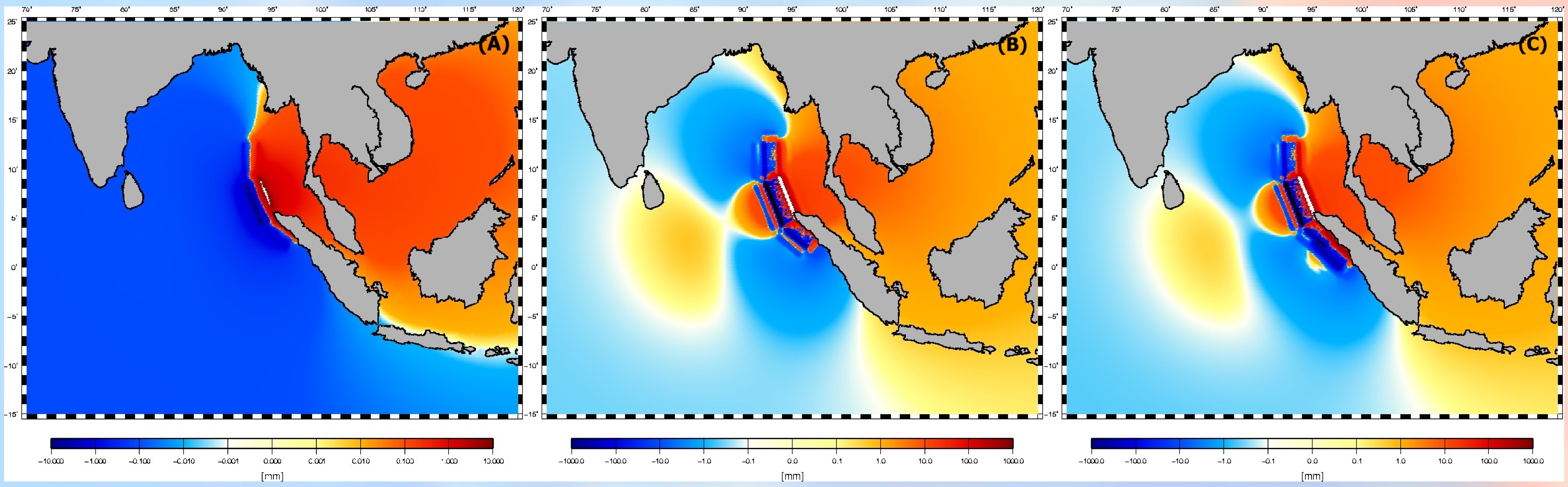
The horizontal coseismic displacement for the 26 December 2004 Sumatra-Andaman (Panel A) and the 28 March 2005 Nias (Panel B) earthquakes are given at the location of the SEAMERGES Global Positioning System (GPS) sites in southeast Asia. This network mainly consists of permanent GPS stations maintained by Chulalongkorn University, DEOS, DSMM and BAKOSURTANAL [1]. The GPS-observed displacements and the corresponding ellipses of 90% confidence level are given in black.

The seismic deformations are modeled as dip-slip point dislocations in a spherical Earth model, according to the theory proposed in [2]. For both earthquakes the point dislocations are confined to fault planes with each a constant depth, slip, dip angle and strike angle. The values (see Table) are chosen so a reasonable correspondence with the GPS observations is obtained. The total moment magnitude M_w for the Sumatra earthquake is equal to 9.13, where as the Nias event corresponds to a magnitude of 8.62.

This difference is noticeable in the figures. Despite that during the Sumatra earthquake the nearest GPS sites were located at more then 400 km from the epicentre, very large displacements of 27 cm at PHKT (Thailand), 15 cm at SAMP (Indonesia) and 17 cm in LGK (Malaysia) were observed. The maximum coseismic displacement measured during the Nias earthquake equals almost 20 cm at station SAMP. However, for this event the site is closer to the epicenter and the observed displacements decrease faster to values less then 4 cm in Malaysia.

The Sumatra megathrust event resulted in very large vertical (Panel C) and gravitational (Panel D) displacements with maximum values of ±3.5 m and ±12 mm, respectively. Due to its smaller magnitude the deformations caused by the Nias earthquake have smaller maximums of ±1 m and ±4 mm, respectively. In both cases the magnitude of the deformation decreases fast with increasing distance to the fault planes.

	Sumatra-Andaman			Nias
	Upper	Middle	Lower	
depth [km]	15	15	15	25
slip [m]	2	16	6	4.5
dip angle [deg]	8	8	8	7
strike angle [deg]	358	338	310	315

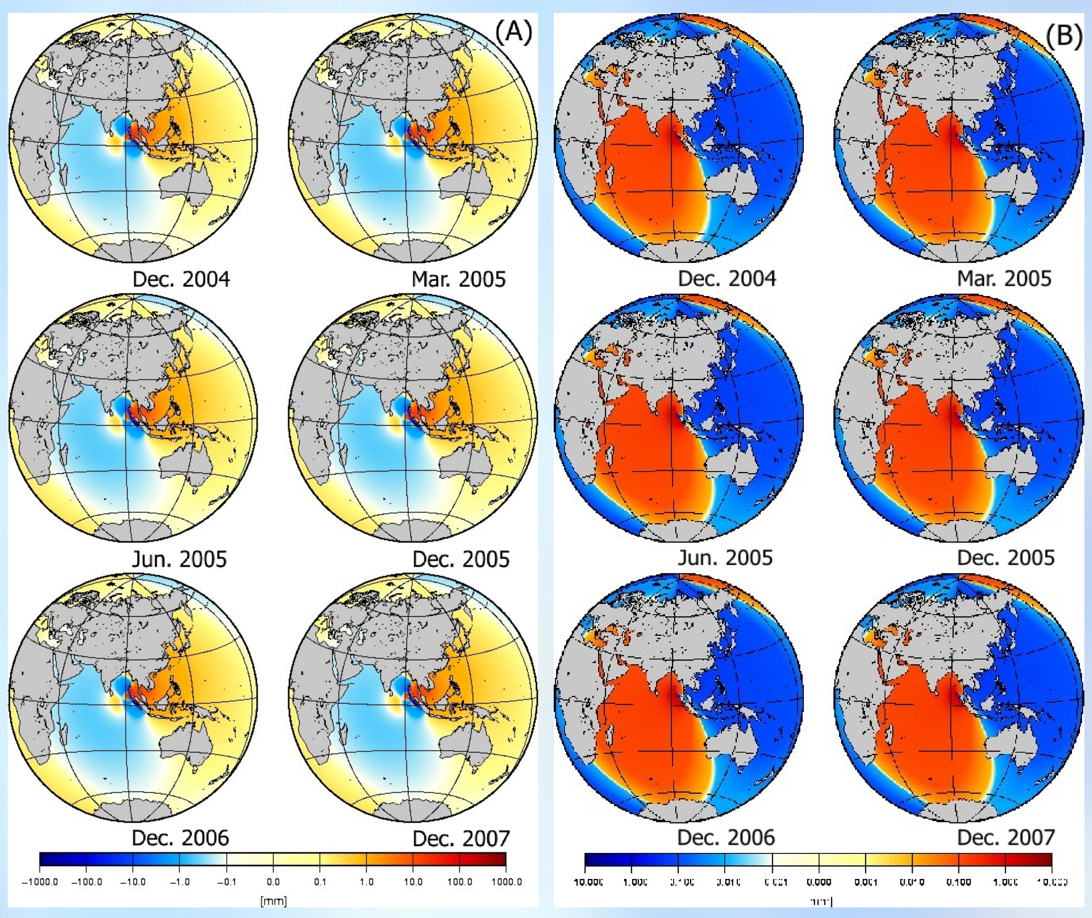


Relative sea level change

The relative sea-level (RSL) is defined as the radial distance between the ocean floor and the geoid height. Since is has been shown that the earthquakes deform both, it can be stated that there will be an abrupt change in the relative sea level at the time of occurrence. This change in relative water height causes a change in the load working on the ocean bottom, which results in an additional elastic deformation of the Earth's surface and gravitational field. To simulate the change in sea level the method described in [3] has been adopted. A comparison between this extra change in relative sea-level (Panel A) with the total change in RSL (Panel B) shows that it is only about 1% of the total RSL variation at the moment of the Sumatra earthquake.

Panel C shows the RSL after three month at the moment of the Nias earthquake, thus combining the effect of both events. When compared to Panel B, it is demonstrated that this event causes an extra RSL change with the maximum localised to the west of the Sumatra island. The nett effect of the Nias event on the sea level is considerably smaller.

The panels show that the earthquakes have a significant effect on the RSL in the near-field. The Sumatra earthquake raised the RSL with several decimeters at the northern coast of Sumatra and at the coast of Thailand the result is still a raise of approximately 20 mm. The Nias event expands this effect towards the south and amplifies the change. To the north and the south of the earthquakes the RSL decreases with several decimeters. Because the effect is reduced fast with increasing distance, changes of only ±1 mm are predicted at the coast of India.



Global Postseismic Sea level change

The Earth model used to simulate the postseismic deformations and the resulting sea level change consist of 5 layers with an 80 km thick elastic lithosphere and a 120 km thick asthenosphere with a viscosity of 10^{20} Pa s. The 670 km discontinuity separates the mantle in an upper part with 5.10^{20} Pa s and a lower mantle with 5.10^{21} Pa s. The fifth layer is an inviscid core which is modelled by means of boundary conditions at the Core-Mantle Boundary.

The influence of these deformations since the Sumatra earthquake as far as three years later on both the RSL and the absolute sea level are shown in Panel A and B, respectively. The absolute sea level is assumed to coincide with the geoid level. Both plots show that the occurrence of the earthquakes have a significant effect on the sea level in the near-field. The influence decrease to absolute value of 1 mm or less in the far-field.

As nearly no change is observed after March 2005, it is stated that the effect on sea level change of the viscoelastic relaxation is negligible in the first three years. The explanation is found in the chosen Earth model and more specific in the high value of the asthenosphere viscosity, thus increasing the Maxwell relaxation time.

Conclusions

It has been demonstrated that by modeling the Sumatra and Nias earthquakes as fault planes with constant parameters, the GPS-observed coseismic horizontal displacements can be reasonably well approximated. By combining two existing, extensively used theories a gravitationally self-consistent solution for the resulting time dependent sea level change due to these events had been found. Because the sea level equation was solved over a spherical model it is possible to take global water conservation into account.

The results show that the earthquakes mainly effect the sea level in the region near the epicenters. There, changes in relative sea level up to several decimeters are predicted at the coastlines. For the absolute sea level the simulations result in maximum values of approximately 1 cm. For both the absolute and relative sea level the effect decreases fast with increasing distance to absolute values below 1 mm.

For Earth models with a high asthenosphere viscosity the viscoelastic relaxation associated with the earthquakes hardly effects the sea level in the first three years.

[1] Vigny, C. et al., Insight into the 2004 Sumatra-Andaman earthquake from GPS measurements in southeast Asia, Nature 436, 201-206 (2005)
[2] Piersanti, A. et al., Global postseismic deformation, Geophys. J. Int., 120(3), 544-566 (1995)
[3] Mitrovica, J.X. and Peltier, W.R., On postglacial Geoid Subsidence over the Equatorial Oceans, J. Geophys. Res., 96, 20053-20071 (1991)

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