Tsunami Detection by GPS-derived Ionospheric Total Electron Content

Mahesh Shrivastava (✉ mahesh.shrivastava@ucn.cl)

Universidad Catolica del Norte

Ajeet Maurya

Doon University, Dehradun

Gabriel Gonzalez

National Research Center for Integrated Natural Disaster Management

P Sunil

Cochin University of Science and Technology

Juan Gonzalez

Universidad Catolica de la Santísima Concepcion

Pablo Salazar

Universidad Catolica del Norte

Rafael Aranguiz

Universidad Catolica de la Santísima Concepcion

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Abstract

To unravel the relationship between earthquake and tsunami using ionospheric total electron content (TEC) changes, we analyzed two Chilean tsunamigenic subduction earthquakes: the 2014 Pisagua M_w 8.1 and the 2015 Illapel M_w 8.3. During the Pisagua earthquake, the TEC changes were detected at the GPS sites located to the north and south of the earthquake epicenter, whereas during the Illapel earthquake, we registered the changes only in the northward direction. Tide-gauge sites mimicked the propagation direction of tsunami waves similar to the TEC change pattern during both earthquakes. The TEC changes were represented by two signals. The initial weaker signal correlated well with seismic Rayleigh waves, while the following stronger perturbation was interpreted to be caused by acoustic and gravity waves induced by earthquakes and subsequent tsunamis. As a result, TEC changes can be utilized to evaluate earthquake occurrence and tsunami propagation within a framework of multi-parameter early warning systems.

Full Text

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Figures

Figure 1

Chilean subduction zone and its tectonic setting. (A) The Chilean subduction zone experienced the 2014 Pisagua and the 2015 Illapel earthquakes. The focal mechanism solution of these earthquakes is shown in circles (green for the Pisagua earthquake and orange for the Illapel earthquake). The red triangles show the locations of GPS sites. The blue inverse triangles demonstrate the tide-gauge locations. The coseismic slip is demonstrated with the contour lines. The red stars indicate the earthquake epicenters.

The rectangular region represents the area of the vertical deformation study. (B)–(C) The coseismic slip and vertical deformation produced by the Pisagua and Illapel earthquakes. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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Figure 2

Tide-gauge locations along the Chilean coastal region. The heights of tsunamis for the Pisagua and Illapel earthquakes are shown. The data were filtered using the harmonic function to get the residual tsunami heights. The dotted lines show the first arrival of tsunamis to the tide-gauge sites. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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Figure 3

Imaginary sky view of the GPS satellites from the 2014 Pisagua earthquake (A) and Pisagua earthquake (B) epicenters. The blue circle represents the 20° elevation, which was used as criteria for the utilization of the GPS satellite data. The residual VTEC is presented for PRNs 01, 11, 20, and 23 during the 2014 Pisagua earthquake (A) and for PRNs 2, 12, 24, and 25 during the 2015 Illapel earthquake (B). The dotted lines mark the time of the earthquakes. The colored lines represent the residual VTEC regarding the

locations of GPS latitudinally from north to south. The red stars indicate the latitude of the earthquake epicenters.

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Figure 4

Spectrogram of the residual TEC changes at randomly chosen GPS sites for PRNs 20 and 23 for the Pisagua and PRNs 24 and 25 for the Illapel earthquakes. The first dotted line represents the timing of the earthquakes; the second dotted line demarcates 8 minutes after the initiation of the earthquakes; and the third dotted line represents 40 minutes after the initiation of the earthquakes.

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Spectrogram of the residual TEC changes at randomly chosen GPS sites for PRNs 20 and 23 for the Pisagua and PRNs 24 and 25 for the Illapel earthquakes. The first dotted line represents the timing of the earthquakes; the second dotted line demarcates 8 minutes after the initiation of the earthquakes; and the third dotted line represents 40 minutes after the initiation of the earthquakes.

Figure 5

(A) Hodochrone map shows variations in VTEC for PRNs 01, 11, 20, and 23 for GPS sites for two hours duration from 23 hours to 1 hours next day of the Pisagua earthquake on April 1, 2014. (B) Hodochrone plot shows residual VTEC at various GPS sites as a function of time and epicentral distance, as obtained from PRNs 2, 12, 24, and 25 for GPS sites for two hours duration from 22 hours to 24 hours of the Illapel earthquake on September 16, 2016. The positive and negative epicentral distances indicate the northern and southern directions regarding the Illapel earthquake epicenter, respectively.

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Figure 6

(A) Propagation of Raleigh wave at seismic sites TEIG (to the north) and HOPE (to the south) of the epicenter. These seismic sites are situated approximately 43° away from the Pisagua earthquake epicenter. (B) Propagation of Raleigh wave at seismic sites OTAV (to the north) and PMSA (to the south) of the epicenter. These seismic sites are located approximately 33° away from the Illapel earthquake epicenter.

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