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Remote triggered seismicity caused by the 2011, M9.0 Tohoku-Oki, Japan earthquake

Hector Gonzalez-Huizar,[1] Aaron A. Velasco,[1] Zhigang Peng,[2] and Raul R. Castro[3]

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[1] Seismic waves from large earthquakes have been shown to trigger seismicity large distances from a mainshock, and this is termed remotely or dynamically triggered seismicity. We performed a global search for seismicity potentially triggered by the seismic waves from the 2011, M9.0, Tohoku-Oki, Japan Earthquake. Using seismograms from global seismic networks and an event catalog, we search for earthquakes and tremors instantaneously triggered during the passing of the seismic waves, as well as for statistically significant changes in local and global seismic rates after the passing of the waves. For earthquakes, we find potential cases of instantaneous triggering in the United States, Russia, China, Ecuador and Mexico, while for tremors we find evidence for triggering in Taiwan, Armenia, Cuba and the United States. In addition, we observed a potential case of delayed triggering of larger magnitude earthquakes (including a M5.2) in Baja California, Mexico.

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1. Introduction

[2] The March, 11th 2011 Tohoku-Oki (M 9.0) Earthquake triggered a large tsunami that caused significant loss of life and damage along the Japanese coastline, and is one of the largest earthquakes of the century. Recent studies have shown that the passing of seismic waves from large earthquakes, such as this megathrust event, can trigger seismicity at large distances, ranging from small earthquakes [e.g., *Velasco et al.*, 2008] to non-impulsive seismic signals known as tremor [*Guilhem et al.*, 2010; *Chao et al.*, 2012]. Some studies suggest that non-volcanic tremor (i.e., tremor not related to volcanic regions) appears to define the depth of the locked section of faults [*Chapman and Melbourne*, 2009; *Peng and Gomberg*, 2010], providing a useful tool for understanding seismic hazards for many known faults.

[3] Observations of remote triggering can be characterized as instantaneous or delayed [*Hill and Prejean*, 2007]. Instantaneous triggering refers to the triggering of seismicity observed during the passing seismic waves from a mainshock, whereas delayed triggering refers to a significant increase in the seismicity rates, caused by the passing of seismic waves, that may initiate and/or persist after the passing of the waves. For example, several regions in the United States showed a significant seismicity rate increases, in some places for more than 3 weeks, after the M7.9, 2002 Denali Fault Earthquake [*Pankow et al.*, 2004].

[4] Large surface waves from the Tohoku-Oki Earthquake circumvented the globe and possibly impacted local and regional seismicity far from the source region. Using seismograms from global and regional seismic networks, we searched for remotely triggered non-volcanic tremor and earthquakes. We supplement our waveform search with a global earthquakes catalog analysis to investigate potential long-term changes of local and global seismic rates. We found evidence of dynamically triggered seismicity associated with this large earthquake (Figure 1).

2. Data and Analysis

[5] Data from the Bulletin of the International Seismological Centre (ISC) and waveforms from multiple seismic networks (Table S2 in the auxiliary material) were used to detect earthquakes and tremors potentially triggered during the passing waves from this large earthquake.[1] We searched the ISC catalog for the occurrence of earthquakes within a time window of 30 minutes after the arriving of the surface waves, which accounts for the occurrence of the maximum wave displacement (Figure S1). A time-reduced histogram along the velocity curve of the wave front of the Love wave [e.g., *Velasco et al.*, 2008] was used to find the number of events occurred globally after the passage of the surface waves (Figure S1). We included earthquakes with M > 2.0 that occurred within one month before and after the Tohoku-Oki event. In order to avoid the aftershocks generated by static stress changes [*Toda et al.*, 2011], we used only earthquakes that occurred more than 1000 km away from the mainshock epicenter, more than 3 times the reported rupture length (∼300 km).

[6] We also searched for tremor and small earthquakes not reported in the catalog but possibly recorded by broadband seismometers during the passing of the waves. Data from the Incorporated Research Institutes for Seismology (IRIS) Data Management Center (DMC) were obtained using the Standing Order of Data (SOD) interface [*Owens et al.*, 2004]. We requested broadband data for global and regional networks, which allowed us to perform a global review, plus focus on regions with previously documented remote triggering. Data was requested for time windows of 10 hours before and after the Tohoku-Oki earthquake, which allowed us to capture possible spurious recordings and

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[1] Geological Sciences, University of Texas at El Paso, El Paso, Texas, USA.

[2] School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA.

[3] Centro de Investigación Científica y de la Educación Superior de Ensenada Baja California, Ensenada, Mexico.

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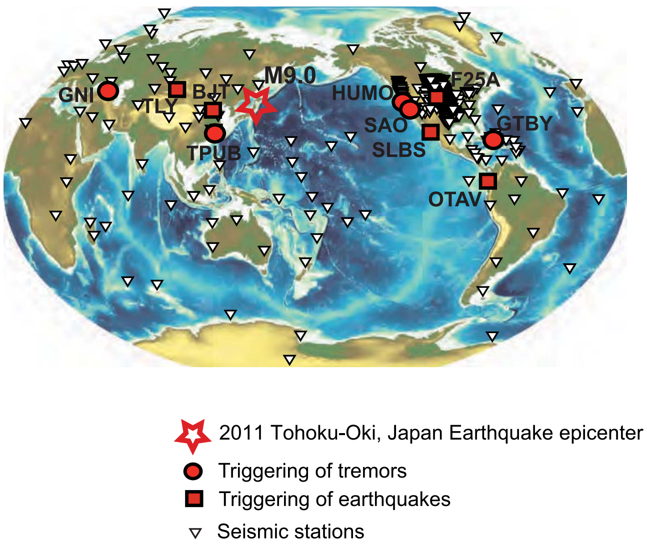

Figure 1. Map showing the epicenter of the 2011 M9.0 Tohoku-Oki, Japan Earthquake (red star), seismic stations used for the study (upside down triangles), and stations that recorded triggered tremor (red circles) and microearthquakes (red squares) (please see Table S1).

regions with elevated seismicity prior to the earthquake [e.g., *Velasco et al.*, 2008]. We performed a review of all data to test for clipping and non-linear behavior, which resulted in the use of 574 stations for our waveform analysis (Figure 1 and Table S2).

[7] For our waveform analysis, we high-pass filtered at 5 Hz all 3-component broadband recordings in order to visually identify high-frequency seismic signals, such as local earthquakes or tremor generated near the recording seismic station. Spectrograms were computed after high-pass filtering broadband recordings at 0.5 Hz, this is order to remove the high-amplitude long-period surface waves signals from the seismograms, which according to *Peng et al.* [2011], could introduce high-frequency energy artifacts in the spectrogram during the computation of the Fourier transforms. This allowed us to identify potentially triggered earthquakes as high-frequency signals with double peaks (*P* and *S* waves of local earthquakes) occurred during the passing of the large-amplitude surface waves. Similarly, we identified triggered tremor as high-frequency non-impulsive signals that are in phase with the teleseismic waves. To reduce the probability of these events being part of the local background seismicity, we checked the data before the mainshock to make sure that the triggered seismicity occurred after a period of relatively low background rates.

3. Observations

[8] Figure 1 shows regions of triggered earthquakes and tremor detected during the passing teleseismic waves from the Tohoku-Oki event. Out of 574 stations examined, we found 5 stations with potentially triggered earthquakes and 5 stations with triggered tremor (Table S1). Figure 2 shows a small earthquake potentially triggered by the surface waves in South Dakota, USA. Figure 3 shows triggered tremor in Taiwan occurred instantaneously during the passing surface waves, at station TPUB, which has been known to have previously triggered tremors [*Chao et al.*, 2012]. Additional examples are shown in Figures 4 and S2–S9.

[9] Instantaneous triggering seems to be restricted to small-amplitude signals, as we found no evidence of coincident triggering of moderate or larger size earthquakes (M ≥ 4) during the passing surface waves in the global catalog, a result consistent with previous studies [*Parsons and Velasco*, 2011]. Furthermore, using catalog data, we found no evidence of an increase on the overall global seismicity, neither in the short term (hours) nor in the long term (days), after the passing of the waves (Figure S1). Although some of the regions we identify as having triggered seismicity have been previously documented to have dynamically triggered seismicity caused by other large earthquakes [*Peng and Chao*, 2008; *Peng et al.*, 2009; *Velasco et al.*, 2008; *Wu et al.*, 2011], we also found triggered tremor in Cuba and triggered earthquakes in Baja California, Mexico, regions with no previous reports of dynamically triggered seismicity.

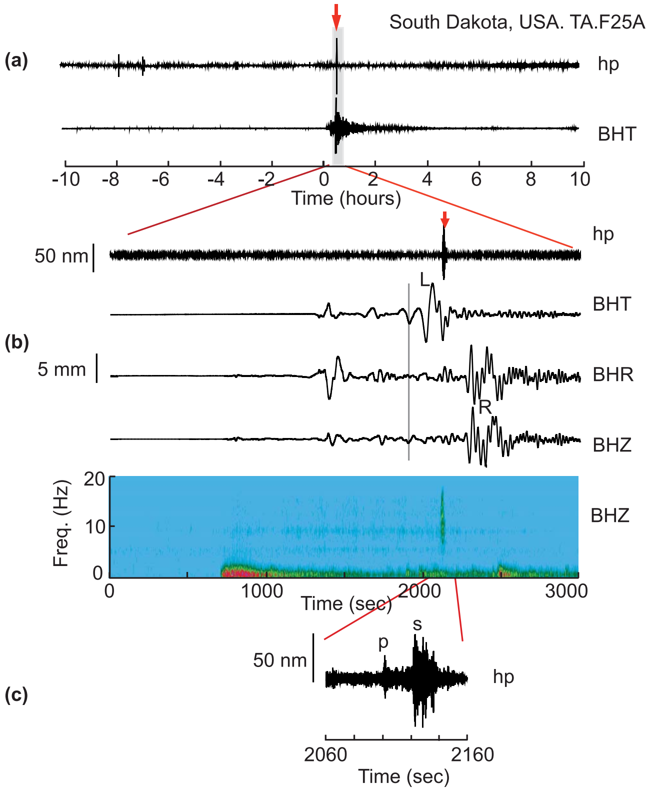

Figure 2. Potentially triggered earthquake in the US recorded by the seismic station TA.F25A of the USArray network. (a) A comparison between the broadband signals (BH) and 5-Hz high-pass filtered (hp) data 10 hours before and after the Tohoku-Oki mainshock. The red arrow marks the time of a local earthquake during the surface waves from the mainshock. (b) A zoom-in plot showing the broadband and filtered seismograms during the large-amplitude surface waves (L-Love and R-Rayleigh). The vertical gray line marks the arriving of the surface waves. The bottom panel shows the corresponding spectrogram, red and blue colors correspond to the maximum and minimum frequency-dependent energy values contained in the seismogram, respectively. (c) A zoom-in plot showing the *P* and *S* wave of the local earthquake.

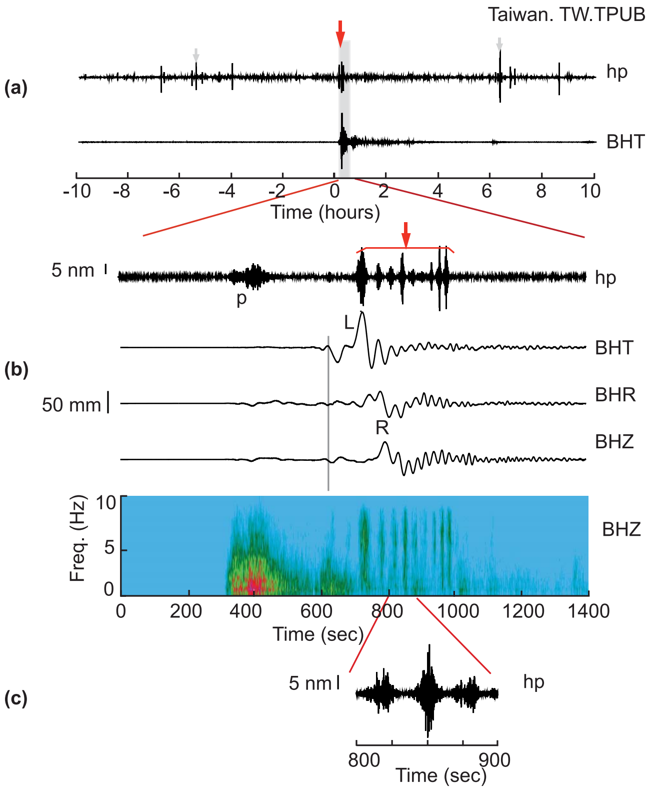

Figure 3. Triggered tremor in Taiwan recorded by the seismic station TW.TPUB that is part of the Broadband Array in Taiwan for Seismology (BATS). Red arrow marks the triggered tremor. Other symbols and notations are the same as in Figure 2. Gray arrows in (a) mark small local earthquakes (apparently) part of the local background seismicity.

We investigated these regions further for susceptibility to triggering.

3.1. Triggered Tremors in Cuba

[10] Triggered tremor from the Tohoku-Oki Earthquake was recorded near the Guantanamo Bay, Cuba at the broadband station GTBY of the Caribbean US Geological Survey (CU) seismic network (Figure S6). The station is located near a laterally slipping section of the boundary between the North American and the Caribbean tectonic plates (Figure 4a). *Rubinstein et al.* [2011] also reported triggering of tremor at this station by the Tohoku-Oki mainshock. Previous studies have shown that tremor events in places like Taiwan and the San Andreas Fault system in the U.S. are routinely triggered by seismic waves from many large earthquakes [*Peng and Chao*, 2008; *Guilhem et al.*, 2010]. Thus, we investigated recordings from other large earthquakes ($M \geq 7$) for this station. Besides the Tohoku-Oki event, we found evidence that the 2010, M8.8 Chile Earthquake, as well as two of its larger magnitude aftershocks, also triggered tremor recorded by this station (Figures 4b–4e). Tremor occurred primarily during the large-amplitude surface waves, similar to observations in other regions [*Peng and Gomberg*, 2010].

3.2. Triggered Earthquakes in Baja California, Mexico

[11] We detected earthquakes in Baja California, Mexico potentially triggered by the teleseismic waves from the Tohoku-Oki event. In addition to small earthquakes that occurred during the passing of the surface waves determined from the waveforms (Figure S5), a review of the ISC catalog for a longer period of time (hours) after the mainshock suggests the triggering of a seismic swam of larger magnitude earthquakes, including a M5.2 event. The swarm occurred during the following hours and continued for a couple of days after the passing of the waves (Figure 5). The earthquakes were located near a spreading center in the Farallon basin, a very active area in the Gulf of California where transform fault-spreading center geometry is dominant [*Castro et al.*, 2011].

[12] Figure 5 shows the earthquakes obtained from the global catalog for 30 days before (8 earthquakes) and after (69 earthquakes) the passing of the seismic waves from the Tohoku-Oki event. A total of 52 earthquakes occurred only during the first 4 days after the passing of the waves, which represents about 30% of the total number of events occurred in the same region during one year prior to this event (174).

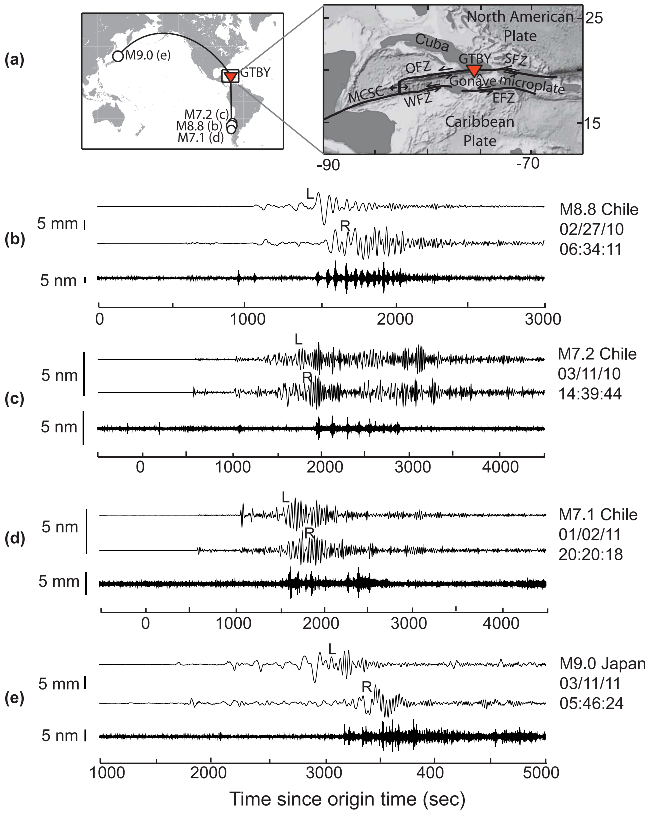

Figure 4. (a) Global map (top left) showing the seismic station GTBY (red triangle) and the great circle paths from (b) the M8.8 Chile earthquake, two of its aftershocks (c) M7.2 and (d) M7.1, and (e) the M9.0 Tohoku-Oki earthquake. Figures 4b–4e show comparisons between the transverse (upper trace) and vertical (middle trace) broadband components showing the passing teleseismic surface waves from these large earthquakes, and 5-Hz high-pass filtered seismograms (lower trace) showing locally triggered tremors. Regional map (top right) shows the station and main plate-boundary faults zones: The Mid-Cayman Spreading Centre (MCSC), the Oriente Fault Zone (OFZ), the Walton Fault Zone (WFZ), the Septentrional Fault Zone (SFZ) and the Enriquillo Fault Zone (EFZ).

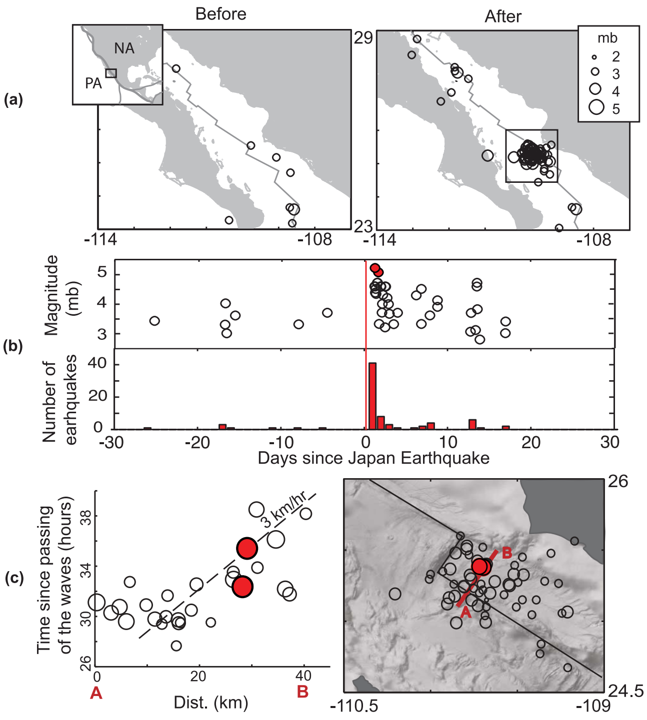

Figure 5. (a) Maps showing a comparison of seismic activity in Baja California 30 days (left) before and (right) after the Tohoku-Oki Earthquake. Inset shows a simplified tectonic map of North and Central America (NA and PA stand for North-American and Pacific plates, respectively). (b) Magnitude (top) and number of events per day (bottom) versus time relative to the Tohoku-Oki mainshock. A total of 52 earthquakes, including two M > 5 (red circles) occurred during the first 4 days after the passing of the waves. (c) Origin times of earthquakes relative to the passing of teleseismic Love waves versus the earthquake locations projected on line A-B in the map on the right. Earthquakes epicenters appear to be migrating from SW to NE with an apparent speed of ~3 km/hr (dashed line).

The occurrence of small earthquakes immediately after the passage of the high-amplitude teleseismic surface waves (Figure S5), in addition to the closeness in time between the seismic swam and the passing of the waves (Figure 5), suggest that these earthquakes were likely triggered by the Tohoku-Oki event.

4. Discussion and Conclusions

[13] We identified several places where the seismic waves from the 2011 Tohoku-Oki earthquake potentially triggered seismicity during and after the passing of the waves (Figure 1). While instantaneous triggering seems to be restricted to the triggering of tremor and small earthquakes, moderate magnitude earthquakes (M > 5) could also have been triggered with some delay after the passing of the waves in Mexico. These events are particularly interesting since previous studies have not found clear evidence of the remote triggering of moderate or large earthquakes (M ≥ 5) within few hours after other large earthquakes [*Parsons and Velasco*, 2011]. However, it is possible that larger magnitude earthquakes, such as in this case, occur at later time, representing cases of delay triggering. These and further observations of delayed triggering can provide new insights in the recent debate on whether great earthquakes cluster in time across the globe [*Brodsky*, 2009; *Michael*, 2011] and help to better define the impact of large earthquakes in the global earthquake hazard.

[14] Several mechanisms have been invoked to explain delayed triggering [*Hill and Prejean*, 2007]. Recently, *Gonzalez-Huizar and Velasco* [2011] proposed that dynamic stress acts unclamping and sliding small fragments of the fault, resulting in rock cracking and reduction of the total contact area, which creates a permanent fault contact damage and a decrease on the frictional strength [*Parsons*, 2005]. If this damage is not large enough to cause instantaneous failure, a secondary nonlinear process (pore fluid pressure redistribution, rate-and-state frictional changes, subcritical crack growth, etc.) may be activated by such contact damage, slowly evolving into failure or delayed triggering. Based on observations of triggered tremors in the San Andreas Fault, *Shelly et al.* [2011] found that seismic waves could initially trigger fault creep, which may in turn trigger tremor. They suggest that delayed triggered earthquakes and tremors could be considered as secondarily triggered, that is, driven by a triggered creep event. In the case of the swarm in Mexico, the earthquakes appear to migrate from SW to NE (Figure 5c), a behavior similarly to the aforementioned observations of triggered tremor, suggesting that this swarm could have been driven by triggered creep as well.

[15] We found no evidence of an increase in the global seismicity after this large earthquake (Figure S1). While statically triggered seismicity is restricted to regions in the immediate vicinity of the earthquake rupture, observations suggest that dynamically triggered earthquakes and tremor are most likely to occur in regions where seismic waves have previously triggered seismicity. For example, recordings from the seismic station GTBY show that, in addition to the Tohoku-Oki event, other three recent large (M > 7) earthquakes have triggered tremors in Cuba recorded by this station. This is relatively new station with recordings since 2007. Thus, it is possible that previous large events have triggered tremor in this region as well. Similarly, we found triggered seismicity at Parkfield, Taiwan, and Beijing where previous cases have been documented there [e.g., *Peng et al.*, 2009; *Chao et al.*, 2012; *Wu et al.*, 2011]. Although it is always possible that the cases presented in this study as potential cases of dynamic triggering may have occurred by chance after the passing of the teleseismic waves, the repetition of similar observations in the same regions, indicate that these events may be genuine cases of remote triggering, suggesting a high vulnerability of these regions to small stress changes, potentially revealing the local stress condition where triggering occurs.

[16] In this study, we identified coincident triggered seismicity from the 2011 Tohoku-Oki Earthquake by visually inspecting seismograms from selected permanent and temporary seismic networks in the IRIS DMC. Other studies based on regional and other networks have also found evidence of triggered tremor and earthquakes in many regions, such as New Zealand, Japan, south-central Alaska, Vancouver Island, the San Andreas Fault and the San Jacinto Fault in California [*Chao et al.*, 2011; *Hill et al.*, 2011; *Miyazawa*, 2011; *Rubinstein et al.*, 2011;

Yukutake et al., 2011]. These observations, together with this study, suggest that remotely triggered activity could be more widespread than we have already identified, and that the analysis of high-quality continuous recordings is needed to better identify regions that are susceptible to remote triggering.

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R. R. Castro, Centro de Investigación Científica y de la Educación Superior de Ensenada Baja California, Carretera Ensenada-Tijuana No. 3918, C.P. 22860, Ensenada, B. C., Mexico.

H. Gonzalez-Huizar and A. A. Velasco, Geological Sciences, University of Texas at El Paso, 500 W. University Ave., El Paso, TX 79968, USA. (hectorg@miners.utep.edu)

Z. Peng, School of Earth and Atmospheric Sciences, Georgia Institute of Technology, 311 Ferst Dr., Atlanta, GA 30332, USA.