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Key Points:
- Energetic storms can generate stormquakes exciting coherent transcontinental surface wavefields
- These stormquakes are effective point sources with equivalent earthquake magnitudes that can be greater than 3.5
- Large continental shelves, ocean banks, and strong storms are the three necessary factors for stormquake generation

Supporting Information:
- Supporting Information S1

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Stormquakes

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Abstract Seismic signals from ocean-solid Earth interactions are ubiquitously recorded on our planet. However, these wavefields are typically incoherent in the time domain limiting their utilization for understanding ocean dynamics or solid Earth properties. In contrast, we find that during large storms such as hurricanes and Nor'easters the interaction of long-period ocean waves with shallow seafloor features located near the edge of continental shelves, known as ocean banks, excites coherent transcontinental Rayleigh wave packets in the 20- to 50-s period band. These "stormquakes" migrate coincident with the storms but are effectively spatiotemporally focused seismic point sources with equivalent earthquake magnitudes that can be greater than 3.5. Stormquakes thus provide new coherent sources to investigate Earth structure in locations that typically lack both seismic instrumentation and earthquakes. Moreover, they provide a new geophysical observable with high spatial and temporal resolution with which to investigate ocean wave dynamics during large storms.

Plain Language Summary Large storms such as hurricanes and Nor'easters generate strong long-period ocean waves, which can interact with shallow seafloor features located near the edge of continental shelves known as ocean banks. Such interactions produce seismic sources with equivalent earthquake magnitudes that can be greater than 3.5. These seismic sources are termed "stormquakes," and they can excite coherent seismic wave fields that are well recorded across the North American continent. Stormquake is a newly identified geophysical phenomenon, which involves interactions of atmosphere, ocean, and the solid Earth. Therefore, stormquakes can provide useful information to investigate the Earth structure and ocean wave dynamics.

1. Introduction

About 71% of the Earth's surface is covered by water, and energy is continuously transferred from ocean waves into continuous, persistent oscillations of the solid Earth (McNamara & Buland, 2004; Nishida, 2017; Webb, 1998). Such oscillations are recorded ubiquitously on our planet (Berger et al., 2004; Peterson, 1993) and have been used to study the interior structure of the solid Earth (Gerstoft et al., 2008; Moschetti et al., 2007; Shapiro et al., 2005), tropical cyclones (Gualtieri et al., 2018; Retailleau & Gualtieri, 2019), decadal scale changes in past climate (Bernard, 1990; Grevemeyer et al., 2000), and the properties of ocean waves (Farrell & Munk, 2010).

These oscillations are generally described as seismic ambient noise and are categorized as the microseisms (Bromirski et al., 2013; Stutzmann et al., 2000) and the Earth hum (Nishida, 2013; Rhie & Romanowicz, 2004; Suda et al., 1998). The measured vertical ground acceleration spectra of the microseisms (3- to 20-s periods) and the Earth hum (50- to ~300-s periods) can be reasonably explained by the primary and the secondary mechanisms (Ardhuin et al., 2015; Hasselmann, 1963; Kedar et al., 2008; Longuet-Higgins, 1950; Nishida, 2017; Webb, 2008). The primary mechanism corresponds to interactions between ocean waves and the seafloor topography that they propagate over (Hasselmann, 1963; Nishida, 2017) and can act over a wide band with peak energy at periods around 15 s. The secondary mechanism corresponds to a nonlinear interference between pairs of ocean waves propagating in opposite directions, which can explain the most energetic seismic band (3- to 10-s periods; Gualtieri et al., 2013; Longuet-Higgins, 1950). The relatively low noise level in the 20- to 50-s period band leads to the extensive use of seismic records in this band to study

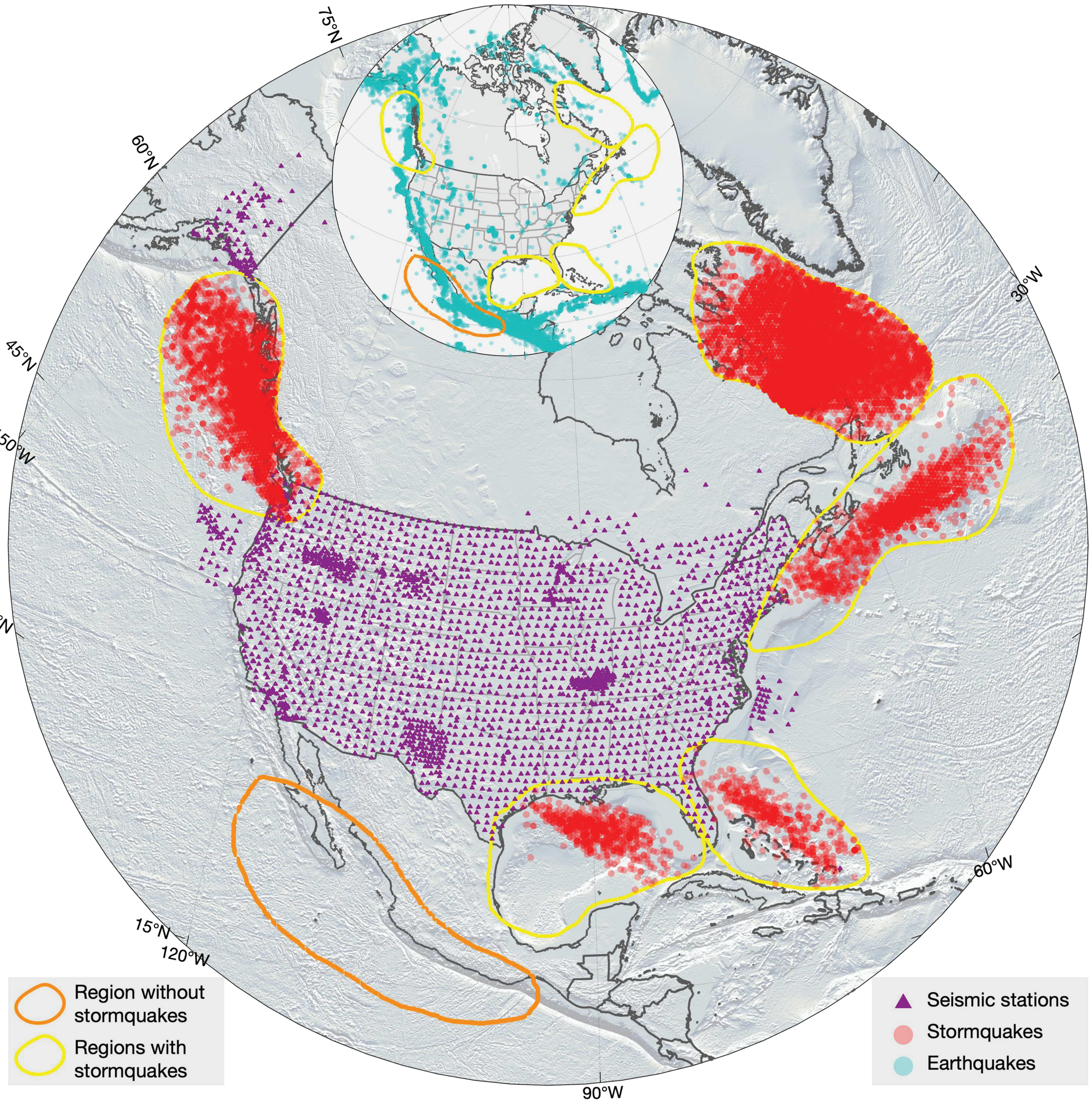

Figure 1. Stormquakes offshore North America and seismic stations from 2006 to 2015. The located stormquakes are shown as the red circles, and the seismic stations are shown as triangles. Due to the location uncertainties, some of the apparent stormquake locations are beyond the coastlines. The yellow contours show regions where stormquakes were detected. The orange contour shows a comparison region offshore Mexico that has been struck by hurricanes but without excitation of stormquakes. The insert shows earthquakes (blue dots) reported in the International Seismological Centre catalog with magnitudes greater than 3 and shallower than 40 km from 2006 to 2015.

Earth's interior (Moschetti et al., 2007; Shapiro et al., 2005) and unconventional seismic sources (Chen et al., 2011; Ekström et al., 2003; Tsai & Ekström, 2007). Occasionally, abnormal ocean swells can excite strong seismic noise in the period band that can be detected by dense arrays (Matsuzawa et al., 2012). However, the physical nature of the seismic sources exciting the ambient seismic wavefield in the 20- to 50-s period band (0.02–0.05 Hz) is not well understood and has received relatively little theoretical or observational attention.

Here, we performed a comprehensive search for seismic sources exciting this period band and found that storms, including both hurricanes and winter storms, can excite transient sources seaward of the North American coastline (Figure 1). These sources, which we call "stormquakes," cause long-lasting ground motions over hours to days, and they migrate along the shelf break coincident with the storm activity (Figure 2). These stormquakes result from interactions of storm-induced ocean waves with bathymetric features on the continental shelf and can have strengths equivalent to earthquakes greater than 3.5 magnitude.

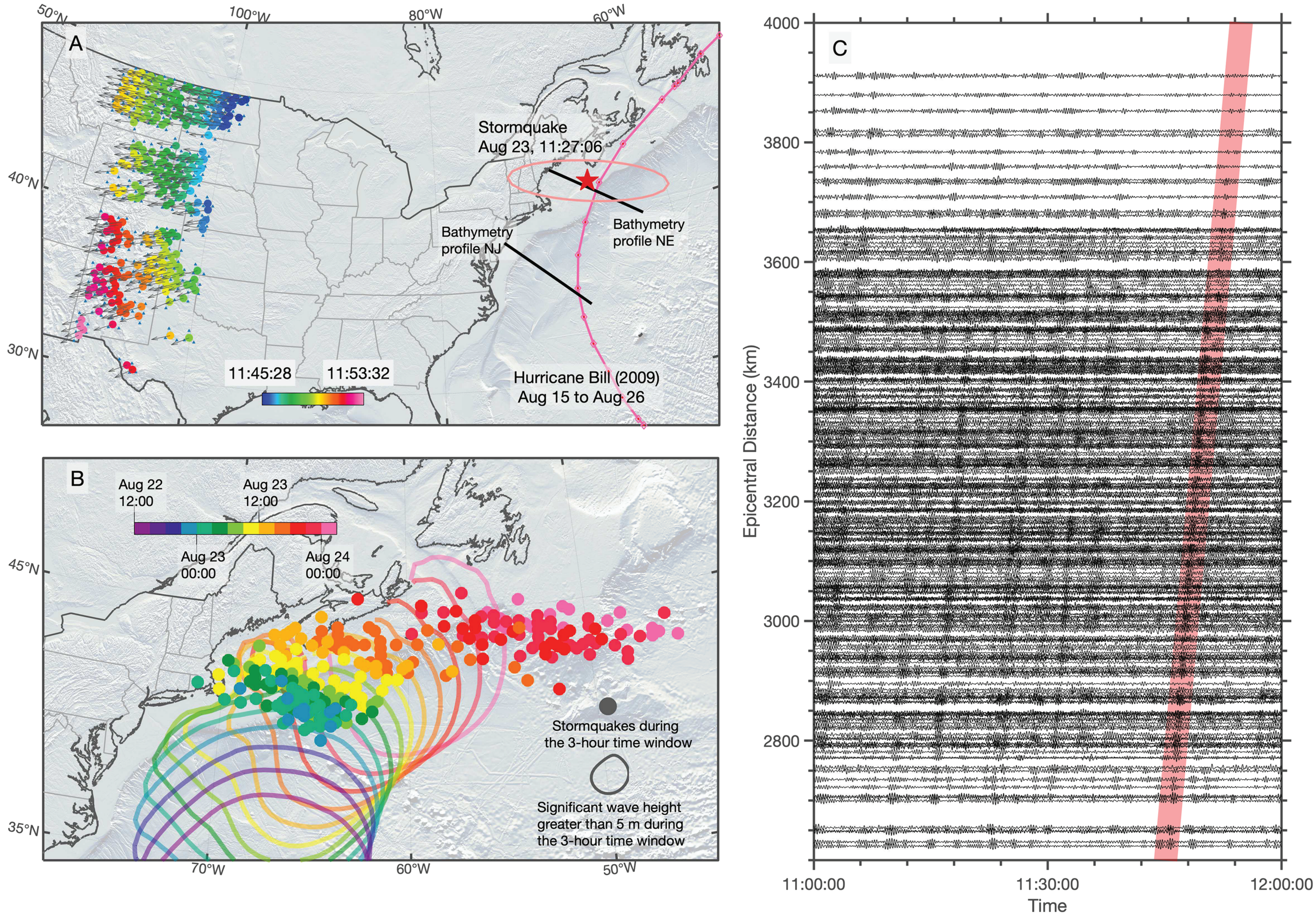

Figure 2. Stormquakes excited by Hurricane Bill (2009). (a) Rayleigh wavefield generated by the stormquake offshore New England on 23 August 11:27:06 (red star). The ellipse shows the location uncertainty of the stormquake (Fan et al., 2018). Rayleigh wave arrival times and propagation directions at each subarray (triad) are shown as the colored dots and arrows. The pink line shows the track of Hurricane Bill (2009; Landsea & Franklin, 2013). (b) Stormquakes migrating with Hurricane Bill (2009) along the continental shelf over a 30-hr period. Regions with significant wave height above 5 m are shown as the colored contours, using WAVEWATCH III at 3-hr resolution (Tolman, 2014). (C) One-hour self-normalized band-pass-filtered (20–50 s) waveforms aligned with the detected epicenter of the stormquake in (a). The red band highlights waveforms associated with the detected stormquake in (a).

This newly identified atmosphere-ocean-solid Earth coupling differs from previously categorized seismic ambient noise in that it produces deterministic seismic effective point sources, which are focused in space and time. Our results demonstrate how energetic storms transiting large continental shelves with ocean banks can excite a coherent transcontinental surface wavefield. We expect that stormquakes are a common but overlooked natural phenomenon in western Europe and Western Australia, in addition to North America. Stormquakes thus provide new coherent sources to investigate Earth structure in locations that typically lack both seismic instrumentation and earthquakes. Moreover, they provide a new geophysical observable with high spatial and temporal resolution with which to investigate the ocean and atmosphere.

2. Materials and Methods

We analyzed 10 years (2006–2015) of continuous vertical-component long-period channel (LHZ) seismic data that are primarily from the USArray Transportable Array (Figure 1; Busby et al., 2006). We applied a novel approach based on the AELUMA method (Automated Event Location Using a Mesh of Arrays) to Rayleigh waves at 20- to 50-s periods to detect and locate stormquakes offshore North America (de Groot-Hedlin & Hedlin, 2015; Fan et al., 2018). Rayleigh waves have proven useful for detecting and locating unconventional seismic sources that are depleted in high frequencies (Ekström, 2006; Shearer, 1994). The AELUMA method does not require knowledge of source type or an accurate velocity model to locate the events, permitting discovery of unknown seismic sources. The method harnesses the surface wave coherence and maximizes resolution of detections by using continental-scale arrays. The method and data processing procedure are detailed in the supporting information. These seismic arrays are first divided into Delaunay triangular subarrays (Figure S1). For each subarray, we perform beamforming to resolve the surface wave propagation directions and arrival times (Figure S2). The surface waves are assumed to propagate along geodesic minimal arc, or great-circle path, which is a valid assumption in general. For special cases when the raypaths from the source to receiver triads travel along ocean-continental boundaries, the propagation path may deviate from the great-circle path (Foster et al., 2014; Larson & Ekström, 2002). An empirical correction is applied to mitigate such effects if the candidate sources are close to Global Centroid Moment Tensor cataloged earthquakes (Fan et al., 2018). Finally, we use these propagation direction and arrival time measurements to formulate an inverse problem to locate the seismic sources and their origin times (Figure S3). Spatial uncertainties of the detected seismic sources are quantitively evaluated (Figure S4). For the best-case scenarios (e.g., stormquakes near Haida Gwaii region), spatial resolution of stormquake locations can be ~50 km. The spatial resolution for a given region is nonuniform during the USArray deployment period and evolves with the eastward migration of the array configurations (Figure S5). To assure the robustness of the detected stormquakes, seismic records of all located stormquakes are aligned with respect to their stormquake epicenters, and are visually inspected to confirm the presence of coherent transcontinental phases (e.g., Figure 2).

A detected seismic source is declared a stormquake if it passes a four-step identification procedure (supporting information), which requires the seismic source to occur during a stormy day (Figure S2c), to not associate with the International Seismological Centre (ISC) catalog (Figure S2c), to belong to a swarm in the same region on the given day (Figure 2B), and to generate a coherent phase move out (Figure 2c). Stormquakes were detected offshore North America along both the east and west coasts as well as in the Gulf of Mexico (Figure 1). To characterize the stormquake activity, we contoured regions in which the stormquakes are located, following the coastlines and offshore bathymetry. Within the contoured regions, there were 14,077 stormquakes that occurred episodically from September 2006 to February 2015 offshore of New England, Florida, and the Gulf of Mexico in the United States and offshore Nova Scotia, Newfoundland, and Labrador, and British Columbia (Haida Gwaii) in Canada. The located stormquakes lay along continental shelf breaks in regions with very low rates of earthquake activity, except the Haida Gwaii region, as reported by the ISC from 2006 to 2015 (inset, Figure 1; International Seismological Centre, 2013).

3. Results

Hurricane Bill is an example of a typical source of stormquakes (Figure 2). The hurricane originated in the eastern Atlantic on 15 August 2009 and strengthened into a major Category 4 hurricane before ultimately striking Newfoundland as a tropical storm (Landsea & Franklin, 2013; Tolman, 2014). The storm weakened into a Category 1 hurricane when it approached offshore New England on 22 August. Upon the hurricane's arrival, numerous seismic sources were located offshore New England and Nova Scotia (Figures 2 and S5). These transient seismic sources excited coherent transcontinental surface waves (Figure 2c), which are well depicted by our measurements of the surface wave propagation directions and arrival times (Figure 2a). The observed signals are different than the microseisms and cannot be directly identified in the power spectral density functions of ground motions. The successful detection of stormquakes is made possible because our approach takes advantage of coherent phase information in the time domain, rather than only inspecting the ambient noise power spectral density. Here, the observed vertical motions are dominated by Rayleigh waves. The isolated Rayleigh wave signals are prominent and can be easily identified from the filtered seismographs (Figure 2c). They are excited by sources as strong as typical magnitude 3.5 or larger earthquakes in this period band (Figure S6; Fan et al., 2018). For instance, surface waves excited offshore New England around 23 August 11:27:06 were clearly recorded by stations 4,000 km away (Figure 2a). Similar seismic sources migrate within a narrow band along the shelf break coincident with Hurricane Bill's track, causing continent-wide ground motions lasting for about 30 hr (Figure 2b). The located seismic sources robustly correlate with the leading edge of the storm track. No ordinary earthquakes were detected in the region during the passage of Hurricane Bill (Figure S5). Without any other indigenous source or other energy influx in the region during the passage of Hurricane Bill, our observations strongly suggest that the located seismic sources were excited by this hurricane.

Hurricanes and large winter storms frequently excite stormquakes near the North American margin (Figure 3). For instance, Hurricane Gonzalo (2014) also struck offshore Nova Scotia and excited stormquakes

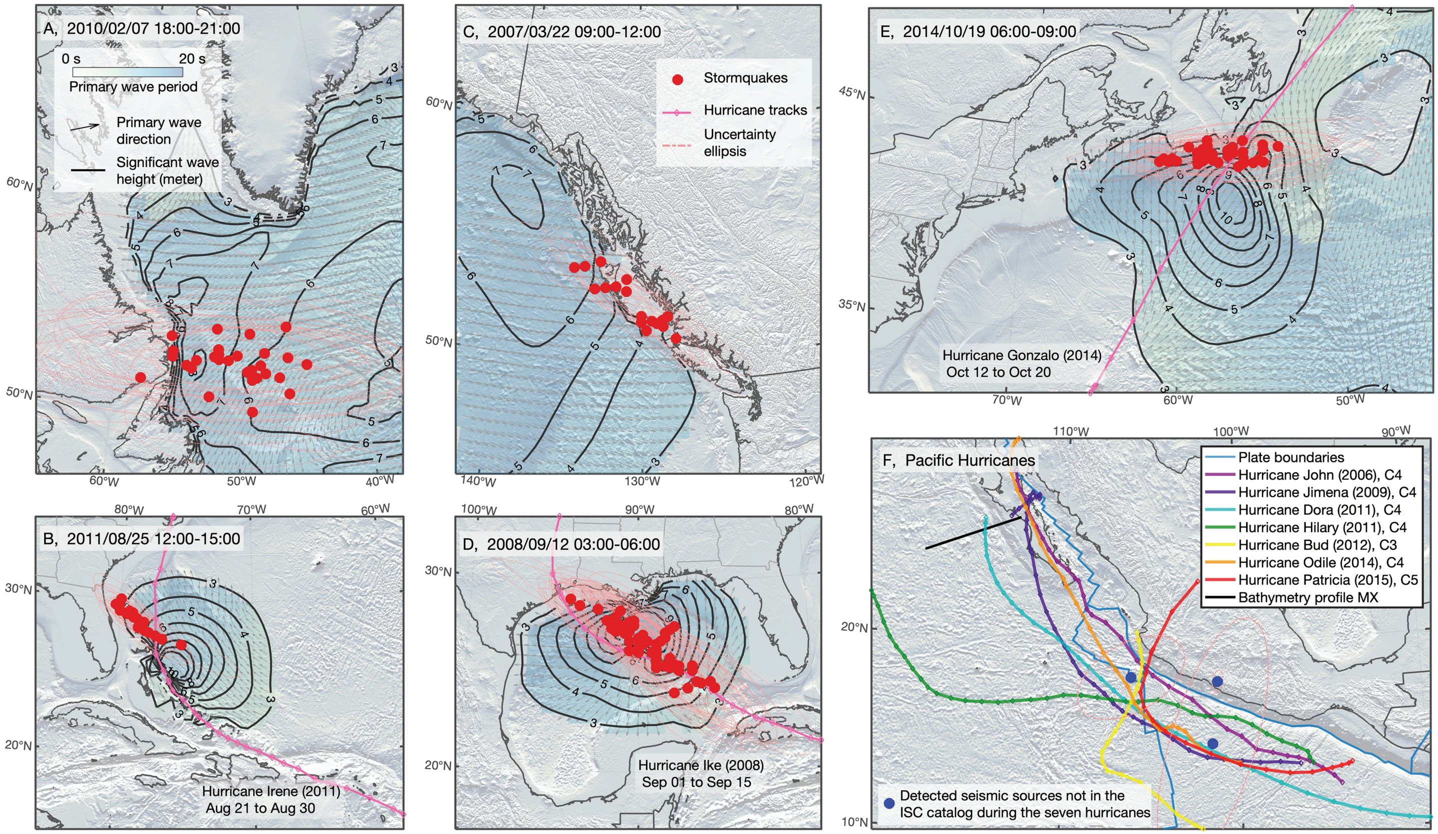

Figure 3. Examples of stormquakes excited by hurricanes and winter storms offshore Newfoundland and Labrador (a), Florida (b), Haida Gwaii (c), Gulf of Mexico (d), New England and Nova Scotia (e), and panel (f) shows seven major hurricane tracks offshore Mexico (Category 3, C3, to Category 5, C5) and the only three detected seismic sources that were not reported in the International Seismological Centre catalog during the passage of the hurricanes. The ocean wave model is WAVEWATCH III with colors indicating the primary wave period (in seconds), solid dark line showing the significant wave height (in meters), and the arrow showing the primary wave direction (Tolman, 2014).

along the shelf break (Figure 3e). Similar stormquakes were regularly detected in the Gulf of Mexico and offshore Florida and the Bahamas (Figures 3b, 3d, and 3e). For instance, Hurricane Ike (2008) caused intense stormquake activity in the Gulf of Mexico (Figure 3d) and Hurricane Irene (2011) excited stormquakes near Little Bahama Bank offshore of Florida (Figure 3b). These hurricanes propagated along different tracks and had diverse characteristics in terms of their strength, spatial extent, and wind speeds (Landsea & Franklin, 2013; Tolman, 2014), yet they generated similar magnitude Rayleigh waves easily detected within the interior of North America.

Winter storms, including Nor'easters in the western North Atlantic Ocean and extratropical cyclones in the Pacific Northwest, also regularly excite stormquakes in the Labrador Sea, the Haida Gwaii region offshore British Columbia, and offshore New England and Nova Scotia (Figures 3a, 3c, and S5). Of these regions, only Haida Gwaii corresponds to a plate boundary and has a high level of seismic activity, including a M_w 7.8 earthquake that occurred in 2012 (Figure S7; International Seismological Centre, 2013). However, stormquakes in the Haida Gwaii region do not correlate with local seismicity (Figure S7) confirming that they are excited by the ocean, not faulting. Winter storms differ from hurricanes significantly in various aspects (Landsea & Franklin, 2013; Tolman, 2014). However, no obvious differences can be identified from the stormquake activities (Figure S5), suggesting that both hurricanes and winter storms cause similar excitation conditions. For instance, stormquakes generated by a 2014 Nor'easter offshore New England and Nova Scotia also migrate within the same narrow region along the shelf break following the storm activity, similar to those excited by hurricanes (Figures 3e and S5). These observations suggest that the atmospheric events, that is, the storms, do not directly generate stormquakes. However, these storms are likely to have provided similar energy influx to excite ocean waves, which in turn can generate stormquakes.

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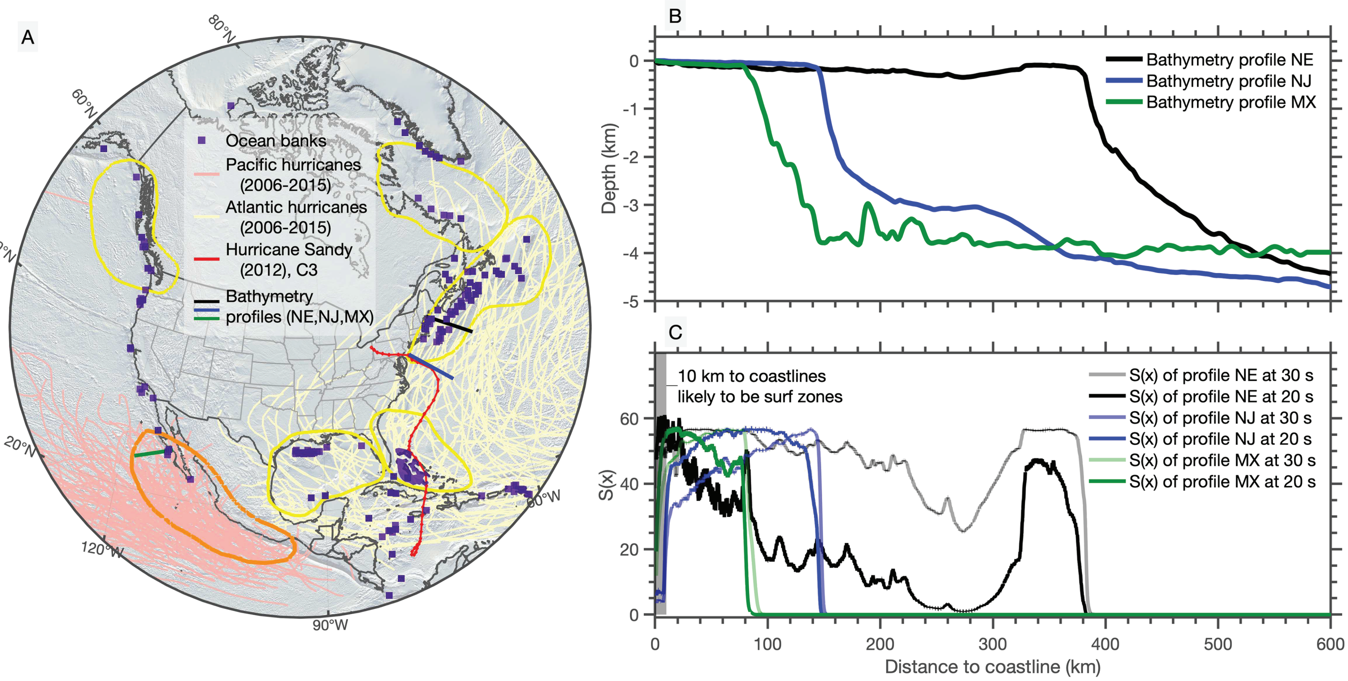

Figure 4. Hurricane tracks and ocean bottom vertical force profiles ($S(x)$) offshore New England (NE), New Jersey (NJ), and Mexico (MX). (A), Pacific and Atlantic hurricane tracks from 2006 to 2015. The track of Hurricane Sandy (2012) is shown as the red line. Ocean banks are shown as purple squares. (b) Bathymetry profiles of NE, NJ, and MX. (c) Ocean bottom vertical force profiles ($S(x)$) of NE, NJ, and MX at 20 and 30 s.

However, not all hurricanes generate stormquakes. In fact, stormquakes were repeatedly observed only in a few particular regions around North America (Figure 1). No stormquakes were detected offshore Mexico or the east coast of the United States from New Jersey to Georgia despite many major hurricanes striking these regions during the study period (Figures 1, 3, and 4; Landsea & Franklin, 2013; Tolman, 2014). For example, Hurricane Sandy (2012), the most destructive hurricane of the 2012 Atlantic hurricane season, moved ashore in New Jersey but did not excite any stormquakes along its northward movement (Figure S1). Similarly, Hurricane Bill (2009) did not excite any stormquakes as it passed by the shelf-break offshore of Maryland and New Jersey (as a Category 1 storm) but suddenly began generating Rayleigh waves once it reached George's Bank offshore of Cape Cod (Figure 2b). Similarly, many major Pacific hurricanes migrated along the west coast of Mexico without generating stormquakes. During the seven largest hurricanes to hit Mexico (55 days total), including the Category 5 Hurricane Patricia (2015), we only detected three seismic sources that were not associated with the ISC earthquake catalog (Figure 3F). In total, there were 76 seismic sources located in the contoured region offshore Mexico that are not associated with ISC catalog when 177 Pacific hurricanes passed by from 2006 to 2015 (495 days; Figure S8). In contrast, Hurricane Bill (2009) excited 298 stormquakes that can be well located offshore New England and Nova Scotia within 30 hr. This comparison strongly suggests that stormquake excitation is determined by the local oceanographic and bathymetric environments.

4. Discussions and Conclusions

The spatial pattern of stormquake activity suggests that specific seafloor topography is required for stormquake excitation and argues for the primary mechanism as the means of exciting stormquakes. In the primary mechanism, ocean waves interfere with seafloor topography to produce seismic sources (Ardhuin, 2018; Ardhuin et al., 2015; Hasselmann, 1963). When seafloor topography varies smoothly horizontally, (e.g., relatively straight and parallel depth contours in the along-coast direction), only ocean waves propagating nearly perpendicular to the coast or continental shelf can produce seismic sources (Ardhuin et al., 2015). Therefore, coast-perpendicular seafloor topography profiles (Figure 4) are valid two-dimensional approximations to investigate the excitation of stormquakes. Interference between such a topography profile (x, distance to the coastline) and ocean waves leads to an ocean bottom vertical force profile ($S(x)$), describing the spatial distribution of vertical forces acting on the seafloor (Figure 4; Ardhuin et al., 2015). $S(x)$ reveals which part of the bathymetric profile is responsible for the observed stormquakes (supporting information).

Long-period ocean waves propagating across monotonically sloped topography on the continental shelf (such as offshore New Jersey in Figures 2a, 4b, and S9) cause a smooth pressure profile on the seafloor creating seismic sources evenly distributed over the whole shelf (Figure 4c). These evenly distributed sources would excite the typical (incoherent) ambient microseism wavefield and the Earth hum (Gerstoft et al., 2006). In contrast, when a seafloor topography profile has a local bathymetric high near the shelf break, often termed a bank (e.g., offshore New England in Figures 2a and 4b), the same period wave produces a spatially focused pressure source that in many cases has a spatial extent comparable to one seismic Rayleigh wavelength at the same period as the ocean waves. For instance, George's Bank produces a bottom pressure source with about a 60-km length for 20-s period ocean waves that is centered near the shelf break (Figure 4c). This spatial footprint is about one wavelength of a Fundamental Mode R1 wave at 20 s (group velocity 3 km/s), which creates what is effectively a seismic point source for 20-s Rayleigh waves. Similarly, the net pressure source from 30-s ocean waves extends ~100 km, producing isolated Rayleigh wave packets at that period. However, the spatial focusing mechanism alone cannot explain the temporal discreteness of the observed isolated seismic surface wave packets. The ocean wavefield energized by transiting storms can last for hours. Such continuous oscillations of the ocean waves likely lead to a large-scale averaging of the pressure force field, which raises the paradox of the temporal discreteness of stormquakes. However, the excited Rayleigh waves are observed as discrete wave packets in the time domain (Figures 2c and S10), requiring the effective excitation sources to be finite in space and time. In addition, the wave packets differ from each other, have various durations, and occur irregularly in time suggesting that their excitation sources are localized (Figures 2c and S10). Such temporal effective point sources may come from stochastic averaging of the pressure field or may have been modulated by the movements of the storms. To unravel the exact physical mechanisms of stormquake excitation, in situ measurements are necessary to illuminate how ocean waves are converted into the observed coherent, prominent, and isolated seismic surface wave packets that are similar to those produced by typical earthquakes.

In addition to the persistent strong Rayleigh waves, sporadic isolated Love wave packets are also observed being in association with stormquakes (Figure S10). For instance, a few discrete Love wave packets were generated in similar regions offshore New England during the transit of Hurricane Bill (Figures 2 and S10). These Love wave packets travel at a speed around 4 km/s and are not observed as frequently as Rayleigh wave packets. The excitation mechanisms of these Love waves, that is, their seismic effective point sources, are unlikely to be the same as the pressure sources discussed above. If only a uniform vertical force acts on the seafloor, no Love waves would be excited. The observation of Love waves requires other excitation conditions (Fukao et al., 2010; Nishida et al., 2008; Saito, 2010). Possible excitation mechanisms involve friction between the ocean wave particle motion and the seafloor, friction due to water propagating over seafloor topography, pressure sources generated during shoaling as water propagates over inclined topography creating a horizontal force component, or shear traction from the fluctuations of pressure sources on the seafloor (Ardhuin & Herbers, 2013; Friedrich et al., 1998; Fukao et al., 2010; Hasselmann, 1963; Juretzek & Hadziioannou, 2016; Nishida et al., 2008; Saito, 2010). The shear traction hypothesis is favorable as it is a direct consequence of linear topographic coupling of ocean waves, which also aligns with the proposed possible mechanism above for Rayleigh wave excitations. However, the shear traction may not occur as frequently as vertical pressure sources, and the observations of sporadic Love waves but persistent Rayleigh wave packets suggest multiple physical processes might be present simultaneously during stormquake excitation (Matsuzawa et al., 2012).

Ocean banks are present in all the regions where the observed stormquakes occur (Figure 4a). Ocean banks, such as the Grand Banks of Newfoundland and Georges Bank offshore New England, are typically shallow underwater platforms, which can cause focusing effects when ocean waves interfere with their bathymetry profiles. In addition, it appears that large continental shelves are necessary for stormquake excitation. For example, there is a small bank offshore Baja California that is relatively close to shore (Figure 4b), but hurricanes in the region do not generate stormquakes (Figures 1, 4a, and S8). As shown by the local $S(x)$ of topography profile MX (Figure 4c), the interference between this bathymetry and ocean waves does not produce a seismic source that stands out from the adjacent shelf. Our observations suggest that large continental shelves, ocean banks, and strong storms are the three factors that are necessary for the generation of stormquakes. If this holds true, we would also expect intense stormquake activity offshore western Europe and offshore northern Australia.

In the primary mechanism, the ocean waves share the same frequencies with the seismic waves (Ardhuin et al., 2015; Hasselmann, 1963). Therefore, ocean waves at 20- to 50-s period band are the driving forces for stormquake excitations (supporting information). This period band is a nominal period band for higher-frequency infragravity waves (IG; Munk, 1951), suggesting that IG waves are likely to be the ocean waves driving the stormquakes. Both free and forced IG waves strongly correlate with swell-sea energy despite different generation mechanisms (Herbers et al., 1994, 1995). The WAVEWATCH III models show that strong ocean swells are present at periods below 20 s during stormy days coincident with stormquakes (Figure 3; Tolman, 2014), while the observed hurricanes produce peak periods smaller than 15 s. Highly nonlinear and energetic seas from hurricanes and storms may force strong IG waves leading to the observed stormquake activity. Alternatively, swell forerunners and long-period gravity waves can also excite stormquakes. Forerunners and long-period gravity waves are directly generated by storms through atmosphere-ocean interactions, and as progressive waves are observed in advance of a large swell event arrival (Husson et al., 2012; Munk, 1947). Our seismological observations cannot directly distinguish the ocean wave types, but the close spatiotemporal correlations between stormquakes and large significant wave heights suggest the driving-force ocean waves are concurrent with passage of the storms. Depending on the storm events and regional sea floor topography, one of these ocean waves or combinations of these ocean waves are likely to have contributed to the observed stormquakes. Reciprocally, stormquakes offer a new independent geophysical observable that has high spatial and temporal resolution to investigate ocean wave dynamics. For instance, stormquakes are sensitive to the location of high-amplitude ocean waves in remote regions on timescales of tens of seconds compared to the 3-hr resolution of current ocean wave models.

Stormquakes are a newly identified type of atmosphere-ocean-solid Earth coupling, demonstrating clear seasonality (Figure S11). No stormquakes were observed in any of the identified regions during Northern Hemisphere summers (May to August) from 2006 to 2015, consistent with the seasonality of major wind producing storms. The observations further suggest that stormquakes are energized by atmospheric events as coupled atmosphere-ocean-solid Earth responses. The discovery of stormquakes may relate to or can explain previously reported mysterious seismic noise sources near Europe, North America, and Africa, which have also been suggested to correlate with high-amplitude sea swells (Matsuzawa et al., 2012; Oliver, 1962; Schulte-Pelkum et al., 2004; Shapiro et al., 2006). Previously reported atmosphere-ocean-solid Earth couplings mostly result in seismic signals in the microseism and the Earth hum bands, for which sources are widely distributed along margins or in the deep oceans (Ardhuin et al., 2015; Nishida, 2013; Webb, 2008). The large spatial extent of these seismic sources leads to incoherent signals as the ambient noise field in the time domain. Therefore, analyses of these signals and their sources have mostly been performed in the frequency domain (Koper & Burlacu, 2015; Traer et al., 2012; Ward Neale et al., 2018). In contrast, stormquakes are transient seismic effective point sources at the 20- to 50-s period band that can excite clear, coherent, isolated surface wave packets (e.g., Figure 2). These signals can be easily observed in the time domain, enabling the location of stormquakes with a high spatial and temporal resolution (Figure S4; Fan et al., 2018). Here stormquakes are conceptualized as effective point sources because of the discrete surface wave packets requiring their excitation sources to be finite in space and time. The precise physical mechanism of how the excitation sources are spatiotemporally discrete requires further investigation and in situ measurements. However, these excitation sources are not associated with faulting activities (Figure 1). Therefore, stormquakes can likely be represented as centroid forces other than moment tensors as distinguished from earthquakes.

The discovery of stormquakes implies that the 20- to 50-s ambient seismic wavefield can have strong directionality at certain times. Ambient noise interferometry, now routinely used to image crustal and upper mantle structures, assumes that the ambient seismic sources are relatively uniformly distributed along the coastlines (Sánchez-Sesma & Campillo, 2006; Yang & Ritzwoller, 2008). Our observations show that this assumption may not be valid during the Northern Hemisphere winter and hurricane seasons when there is the greatest storm activity (Figure 1). Strong stormquake signals could potentially bias the empirical Green's functions retrieved from the ambient noise interferometry (Tsai, 2009; Weaver et al., 2009). Stormquakes are also likely to have an impact on the detection of very low frequency earthquakes in the Haida Gwaii and Cascadia region, which are depleted in high frequency and are often investigated in the 20- to 50-s period band. Cascadia hosts a wide range of slip events including large earthquakes (Ghosh et al., 2015; Rogers & Dragert, 2003), and the presence of stormquakes in the Haida Gwaii region complicates the identification of very low frequency earthquakes, which might bias estimates of the fault stress states.

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Stormquakes provide new sources to investigate Earth's structure in offshore locations that typically lack both seismic stations and earthquakes. As stormquakes can generate surface waves with amplitudes equivalent to those from magnitude 3.5 earthquakes, the clear coherent Rayleigh wave arrivals from stormquakes (20–50 s) can be used to explore the lower crust and upper mantle seismic structures via standard tomographic inversions (Jin & Gaherty, 2015). A high-resolution catalog of stormquakes will open a new avenue to image Earth's deep interior as stormquakes occur at passive margins, and hence, these new sources are complementary to the abundant seismicity at active margins. In particular, combining earthquakes with stormquakes will offer greatly improved azimuthal coverage to understand the structure of the North American lithosphere.

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