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The persistent signature of tropical cyclones in ambient seismic noise

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ABSTRACT

The spectrum of ambient seismic noise shows strong signals associated with tropical cyclones, yet a detailed understanding of these signals and the relationship between them and the storms is currently lacking. Through the analysis of more than a decade of seismic data recorded at several stations located in and adjacent to the northwest Pacific Ocean, here we show that there is a persistent and frequency-dependent signature of tropical cyclones in ambient seismic noise that depends on characteristics of the storm and on the detailed location of the station relative to the storm. An adaptive statistical model shows that the spectral amplitude of ambient seismic noise, and notably of the short-period secondary microseisms, has a strong relationship with tropical cyclone intensity and can be employed to extract information on the tropical cyclones.

1. Introduction

Ambient seismic noise is the ubiquitous background vibration of the solid Earth recorded worldwide by seismic stations and mainly due to ocean waves driven by winds in intense storms, such as extra-tropical storms and tropical cyclones (TCs) (Gutenberg, 1936; Bromirski, 2009). Two mechanisms are responsible for ambient seismic noise generation: (A) the primary mechanism, which is the direct coupling between ocean waves and the solid Earth in shallow water, responsible for primary microseisms (Hasselmann, 1963; Ardhuin et al., 2015, period T in the range of 10 to 20 s) and the seismic "hum" (Nishida, 2013; Rhie and Romanowicz, 2004; Ardhuin et al., 2015, $T > 50$ s), and (B) the secondary mechanism, which is the interaction amongst ocean waves, responsible for secondary microseisms (Longuet-Higgins, 1950; Hasselmann, 1963, $T < 10$ s).

Much has been done towards understanding the oceanic mechanisms that control the generation of ambient seismic noise (e.g. Longuet-Higgins, 1950; Hasselmann, 1963; Kedar et al., 2008; Ardhuin et al., 2011; Gualtieri et al., 2013; Ardhuin et al., 2015; Nishida and Takagi, 2016), allowing it to be used to infer characteristics of the sea state (e.g. Ardhuin et al., 2012; Neale et al., 2017). Recent studies have shown that ambient seismic noise sources associated with isolated TCs moving across the ocean can be located using seismic methods in the vicinity of the TCs (e.g. Gerstoft et al., 2006; Zhang et al., 2010; Gualtieri et al., 2014; Farra et al., 2016). Their signature are clearly visible on land (e.g. Ebeling and Stein, 2011; Sufri et al., 2014). Other studies have focused on TCs moving over land and on the link between seismic signals and TC energy decay at landfall (e.g. Tanimoto and Lamontagne, 2014; Tanimoto and Valovcin, 2015). Still, the relationship between seismic signals and characteristics of TCs is not yet well understood (e.g. Ebeling and Stein, 2011) due to the complexity of the non-linear and frequency-dependent energy transfer between the atmosphere and the ocean (e.g. Janssen, 2004; Ochi, 2003), as well as between the ocean and the solid Earth (e.g. Hasselmann, 1963; Ardhuin et al., 2010).

Seismic ground motion is related indirectly to the intensity of TCs through ocean gravity waves (microseisms) and infragravity waves (seismic hum) excited in turn by strong winds. Therefore, ocean wave models could be employed to study the relationship between ambient seismic noise and TCs. However, the use of ocean wave models for studying ambient seismic noise generated by decades of TCs is difficult due to limitations of the wave-model data. In particular, ocean wave models, such as WAVEWATCH III (Tolman et al., 2009), use fixed grids with a resolution (0.5×0.5 degrees for WAVEWATCH III) that is too course for TCs, generating spatial aliasing and underestimation of the maximum wind and ocean wave height (e.g. Tolman and Alves, 2005, their

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Fig. 8). Moreover, these models use wind reanalyses as an input, which do not represent well the observed TC intensity and location (Schenkel and Hart, 2012; Murakami, 2014). In Fig. S1 in the supplementary material, we show the comparison between the TC wind speed dataset used in this study and the TC wind speed from the ERA-Interim reanalysis dataset from the European Centre for Medium-Range Weather Forecasts, commonly used as an input for ocean wave models like WAVEWATCH III. The wind speed in the reanalysis is underestimated with respect to observations by about a factor of two (in line with the results of Murakami, 2014). We also observe that the cycle of intensification and decay of TCs differs between observations and reanalysis. The wind speed is related to the spectrum of the ocean wave height (Hasselmann et al., 1973), which in turn is related to the spectral amplitude of noise sources (Hasselmann, 1963). Farra et al. (2016) modeled P-wave sources associated with typhoon Ioke and showed an error on the modeled amplitude (their Fig. 6) comparable with the underestimation given by the reanalysis dataset. For these reasons, we decided to rely on TC best track datasets without using information from ocean wave models.

Understanding how processes in the atmosphere and in the ocean couple into seismic waves in the solid Earth and how these can be used to monitor the global environment has been listed as one of the high-priority Seismological Grand Challenges (Lay et al., 2009). Studying this coupling is becoming more important as a new and valuable source of information on the geophysical effects of climate change at time scales not otherwise accessible and for the pre-satellite era.

2. Materials and methods

2.1. Atmospheric and seismic datasets

We analyze 13 years of atmospheric and seismic data recorded in and adjacent to the northwest Pacific to assess the relationship between the occurrence of TCs and the spectral characteristics of ambient seismic noise. TCs in this region having wind speed larger than 33 m/s are called typhoons and can develop throughout the year with a climatological peak between June and November. The northwest Pacific is the most active basin globally, where approximately 30% of the TCs forms each year, as well as where the most intense ones tend to occur (Gray, 1968). We focus on TCs occurring in the northwest Pacific Ocean between 2000 and 2012 during the peak season activity June–November (Fig. 1A). Each TC is identified by track location, intensity and size, recorded every 6 h. TC intensity is defined as the 1-min mean sustained surface wind speed. We use center locations and intensities of TCs in the northwest Pacific from the Joint Typhoon Warning Center best-track dataset (Chu et al., 2002) (http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/). A tropical cyclone dataset (Knaff et al., 2014, 2015), built by using storm-centered infrared imagery, is used to identify their size. The size of a tropical cyclone is defined as the squared radius of 5-kt (1 kt = 0.514 m/s) winds (Knaff et al., 2014, 2015), and therefore it incorporates wind speeds larger than this threshold. We select TCs within 40° of each seismic station and, since we are interested in estimating TC intensity before landfall, we retain only that part of the track moving over the ocean. Time series of TC intensity, size, propagation speed and number of simultaneous TCs are shown in Figs. S2 and S3 in the supplementary material. A scatterplot between intensity and size of TCs is shown in Fig. S4. We keep in our dataset those storms that have been identified as typhoons – i.e. with wind speed larger than 33 m/s – for at least two days. We do not include in our analysis tropical depressions, tropical storms, as well as short-lived (i.e. less than two days) category-1 typhoons. TCs on the Southern Hemisphere have peak season in January–March, and therefore have been excluded from our analysis. Including TCs on the Southern Hemisphere did not influence our results.

We also analyze continuous broadband vertical-component seismograms recorded during the same time period (2000–2012) at seven seismic stations of the Global Seismic Network (GSN) located in the same region (Fig. 1A). We use the vertical component long-period (LHZ) seismograms, with a sampling rate of 1 Hz. In case of stations with multiple seismometers, the primary sensor is used. The instrumental response is deconvolved from the original seismogram in order to get ground acceleration and the power spectral density (PSD, with respect to 1 $(\mathrm{m/s^2})^2/\mathrm{Hz}$) is computed each 15 min and in 30 frequency bands, considering overlapping windows both in time and frequency (Berger et al., 2004). Data have been cleaned from earthquakes, glitches and spurious signals by visual inspection. A time-moving median each 6 h is performed to obtain the same time step of the TC best-track dataset. Furthermore, to remove seasonality effects due to winter storms on the noise records and better isolate the effect of TCs, long-period trends (i.e. 30 days) have been removed from the seismic data.

In Fig. 1B–C, we show spectrograms of ambient seismic noise ($T = 4$–12 s) recorded in 2012 at stations (B) TATO (Taipei, Taiwan) and (C) GUMO (Guam, Mariana Islands). Black lines denote the intensity of TCs – defined as the 1-min mean sustained surface wind speed – moving above the ocean within 40° of each station. Long-lasting signals characterized by high power spectral density (PSD) at short period occur simultaneously with TCs. Fig. S5 in the supplementary material shows spectrograms of ambient seismic noise in the microseism frequency band ($T = 4$–20 s) at station (A) TATO and (B) GUMO between 2008 (bottom) and 2012 (top). Superposed is the TC intensity. In all cases, we observe a good agreement between the occurrence of TCs and large-amplitude PSDs at short periods.

2.2. Statistical data processing and estimation of TC intensity

We use a generalized linear model (GLM) with seismic and atmospheric data between 2000 and 2010 to estimate TC intensity during the TC peak season 2011 and 2012. Ordinary linear regression implies a linear relationship between a dependent variable $\mathbf{Y}$ and a set of independent variables, or covariates, $\mathbf{X}$, assuming that the dependent variable $\mathbf{Y}$, conditional to the observed $\mathbf{X}$, is normally distributed. However, TC intensity is a non-negative variable, displaying a strongly skewed marginal probability density function, which can be well approximated by a Gamma distribution (Fig. S6 in the supplementary material). The dispersion of the distribution is not small with respect to the mean value, so that an ordinary linear regression is not a realistic assumption, while a GLM is a more appropriate choice (Agresti, 2015).

In order to estimate TC intensity from ambient seismic noise, we proceed as follows. First, we specify a GLM of TC intensity given the ambient seismic noise PSD using data between 2000 and 2010. Second, we use the estimated GLM parameters to predict the TC intensity during 2011 and 2012. A limitation of this method is that, in case of simultaneous TCs, we cannot estimate their TC intensities separately. In such a case, we still estimate an equivalent TC intensity which accounts for their cumulative effect.

Our GLM has four components: 1) a dependent variable, that is the intensity of TCs $\mathbf{v^{TC}}$, 2) a matrix containing the set of independent variables $\mathbf{X}$, 3) a parameter vector $\boldsymbol{\beta}$ and 4) a link function g, such that

$$g(\mu_i) = \mathbf{X}\boldsymbol{\beta} = \beta_0 + X_1\beta_1 + X_2\beta_2 + \dots \tag{1}$$

where μ_i is the expected value of the distribution of the TC intensity given the observed values of $\mathbf{X}$ and β_0 is the intercept, which