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Original article

Monitoring austral and cyclonic swells in the “Iles Eparses” (Mozambique channel) from microseismic noise

Guilhem Barruol [a], [*], Céline Davy [a], Fabrice R. Fontaine [a], V. Schlindwein [b], K. Sigloch [c], [d]

[a] Laboratoire GéoSciences Réunion, Université de La Réunion, Institut de Physique du Globe de Paris, Sorbonne Paris Cité, UMR CNRS 7154, Université Paris Diderot, 97744, Saint Denis, France
[b] Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany
[c] University of Oxford, Earth Sciences Department, South Parks Road, Oxford, OX1 3AN, UK
[d] Department of Earth and Environmental Sciences, Ludwig-Maximilians-Universität München, Munich, Germany

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ABSTRACT

We deployed five broadband three-components seismic stations in the Iles Eparses in the south-west Indian Ocean and on Mayotte Island, between April 2011 and January 2014. These small and remote oceanic islands suffer the effects of strong ocean swells that affect their coastal environments but most islands are not instrumented by wave gauges to characterize the swells. However, wave action on the coast causes high levels of ground vibrations in the solid earth, so-called microseismic noise. We use this link between the solid earth and ocean wave activity to quantify the swells locally. Spectral analyses of the continuous seismic data show clear peaks in the 0.05–0.10 Hz frequency band (periods between 10 and 20 s), corresponding to the ocean wave periods of the local swells. We analyze an example of austral swell occurring in August 2013 and a cyclonic event (Felleng) that developed in January 2013, and quantify the ground motion at each station induced by these events. In both cases, we find a linear polarization in the horizontal plane with microseismic amplitude directly correlated to the swell height (as predicted by the global swell model WaveWatchIII), and a direction of polarization close to the predicted swell propagation direction. Although this analysis has not been performed in real time, it demonstrates that terrestrial seismic stations can be efficiently used as wave gauges, and are particularly well suited for quantifying extreme swell events. This approach may therefore provide useful and cheaper alternatives to wave buoys for monitoring swells and the related environmental processes such as beach erosion or coral reef damages.

1. Introduction

The Iles Eparses in the western Indian Ocean consist of the islands of Europa, Juan de Nova and Glorieuses in the Mozambique Channel and by Tromelin Island located ca 400 km east of Madagascar. Their fragile environments may suffer from anthropogenic activity but have also to face the environmental impact of combined ocean and atmosphere activity. In particular, oceanic swell events generated by local or distant storms may hit these islands hard, strongly affecting their reef barriers and their shorelines, and resulting in coral destruction and beach erosion by sediment transport. Climate change could possibly worsen this impact. Hence, more and longer-term observations are highly desirable, even if they are proxy observations of swell activity rather than actual wave-gauge data.

Here, a temporary network of five three-component broadband seismic stations (Fig. 1), which was deployed in the Iles Eparses and on Mayotte Island primarily for the study of deep earth structure (Barruol and Sigloch, 2013), is re-purposed to quantify local swell activity in terms of amplitude (swell parameter *Hs*), period (swell parameter *Tp*), and direction of propagation (swell parameter *Dp*). With the exception of Mayotte, these islands are only a few kilometres in diameter, located in harsh and remote environments, and all but Mayotte have been declared terrestrial and marine protected areas to preserve the natural environment and local biodiversity.

Quantifying local swells on remote islands requires direct or indirect observations to determine wave heights, periods and directions of propagation. Numerical models such as the NOAA

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[*] Corresponding author. Laboratoire GéoSciences Réunion, Université de La Réunion, 15 avenue René Cassin, CS 92003, 97744, Saint Denis cedex 9, France.
E-mail address: guilhem.barruol@univ-reunion.fr (G. Barruol).

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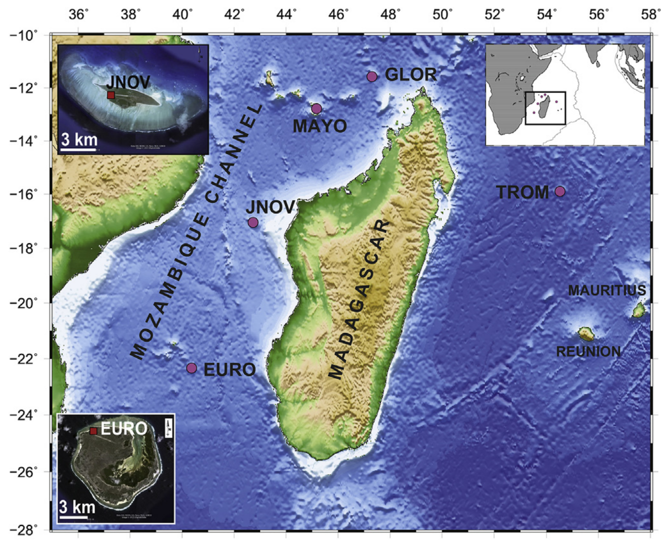

Fig. 1. Location of the seismic stations deployed in the Iles Eparses around Madagascar. Inserts show satellite images of Europa and Juan de Nova Islands, and the locations of the seismic stations.

WaveWatchIII model (hereafter called WWIII) (Tolman and Chalikov, 1996) are available at global scale, but their spatial resolution is rather poor (0.5°) and does not take into account the local interaction of swell with small islands such as those present in the Mozambique Channel. Direct and local swell observations are very scarce in the Indian Ocean and absent in the Mozambique Channel, motivating our approach to characterize swells from indirect seismological observations. These novel seismological proxies for oceanic activity may be relatively easy to acquire and can be efficiently used to evaluate the local impact of waves on the coastal environment of the islands.

After discussing the origins of various oceanic sources of microseismic noise in Section 2, we present the seismic network, the data, and our analyses, performed mostly on so-called "primary" microseisms (Section 3). We compare in some detail swell characteristics recorded during an austral swell event in the Mozambique Channel in August 2013 (Section 4) and during the passage of cyclone Felleng over Tromelin Island in January 2013 (Section 5). By "austral swell", we mean ocean waves arriving from the southern part of the Indian Ocean, generated by powerful storms and over long fetch distances, and that propagate northward over long distances with little attenuation and as coherent wave packages. "Cyclonic swell" has the same mechanism of excitation and propagation, except that the generating storms are tropical storms, called "cyclones" in the Indian Ocean, which may develop much closer to the (tropical) Iles Eparses. Section 6 analyzes seismic signals at the Iles Eparses over longer periods of several months and demonstrates that the main swell events can be well retrieved and quantified from seismic data.

2. Origins of microseismic noise

The present work is based on the analysis of the seismic "noise" generated by ocean swell and transmitted to the solid earth as seismic waves that may be recorded by terrestrial seismological instruments (e.g., Friedrich et al., 1998). This noise is called "microseismic" because it consists of continuous ground displacement of a few micrometers, as opposed to sudden, strong earthquake arrivals. It is well visible on individual seismic energy spectra that represent the distribution of noise energy as function of frequency for a given time period. Fig. 2a shows the noise power spectral density of the three seismometer components of station EURO and for two different time periods: during a quiet period before an austral swell event, on Aug. 18, 2013 and during this swell event two days later, on Aug. 20, 2013. The spectra of Fig. 2a show two clear peaks in separate frequency bands that characterize the two kinds of seismic noise, classically split into primary and secondary microseisms (hereafter named PM and SM, respectively). They represent different physical processes involving local or distant sources of ocean wave activity, briefly described below.

Primary microseisms (PM in Fig. 2a), on which we focus the present paper, are generally visible at coastal and island stations and accepted to be generated through direct interaction of swell-induced pressure variation on the sloping seafloor close to the shore (Hasselmann, 1963; Cessaro, 1994; Barruol et al., 2006). Such primary microseismic noise sources have the same periods as the ocean swell (between 8 and 20 s) and are accepted to be generated by the local interaction of swell with the sea floor in coastal areas, where water depths becomes shallower than about half the swell wavelength (Darbyshire and Okeke, 1969). Analyzing microseismic noise in this PM frequency band is therefore a way to characterize the local impact of swell on the shore. Comparing noise spectra in Fig. 2a before and after the arrival of a strong swell event, evidences a strong increase of the noise peak in the PM frequency band (at periods close to 20 s) on all three components of station EURO. The seismic spectra obtained during a quiet period two days before the swell arrival (light colours in Fig. 2a) have much lower amplitudes in both the SM and PM bands. The spectrogram covering this time period (Fig. 2b) clearly shows the development of the PM associated with this swell arrival. It also shows the swell dispersion effect, with long period swell travelling faster across the oceans than short period swell, explaining the slope observed in the arrival of the PM energy over time.

Secondary microseisms (SM in Fig. 2a) dominate seismic noise worldwide at both continental and oceanic stations. This noise exhibits a large peak at half the period of ocean waves (typically between 3 and 10 s) and is widely accepted to be excited by a depth-independent, second-order pressure fluctuation generated by interference of swells (water waves) of similar periods travelling in opposite directions (Longuet-Higgins, 1950). This nonlinear process generates stationary ocean waves whose pressure fluctuations on the seafloor excite seismic surface waves, specifically Rayleigh waves. These are polarized in the vertical plane with an elliptical retrograde particle motion and can propagate over large distances in the solid earth, with little attenuation. Secondary microseisms can be generated in the deep oceans and at large distances from coastal areas (e.g., Essen et al., 2003; Ardhuin et al., 2011; Obrebski et al., 2012; Davy et al., 2014). For the Indian Ocean, the dominant sources have been located in the southernmost part of the basin, associated with large atmospheric low-pressure systems moving around Antarctica (Reading et al., 2014; Davy et al., 2015) but they can also be generated by major tropical storms (Davy et al., 2014).

Although secondary microseisms may provide information concerning distant storms, stationary ocean waves and SM can also be generated by coastal reflection of waves (e.g., Bromirski and Duennebier, 2002; Beucler et al., 2014). If incident and reflected waves propagate in opposite directions, the incoming swell may interfere with its reflected swell, resulting in the generation of standing waves in coastal areas, oscillating at twice the frequency of the propagating wave (Bromirski et al., 2005). Some observations suggest that local and distant sources of noise in the SM frequency peak may coexist (e.g., Chevrot et al., 2007; Koper and Buriaciu, 2015). In the present study, it may be the case for station EURO