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LETTERS

The Earth's 'hum' is driven by ocean waves over the continental shelves

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Observations show that the seismic normal modes of the Earth at frequencies near 10 mHz are excited at a nearly constant level in the absence of large earthquakes[1]. This background level of excitation has been called the 'hum' of the Earth[2], and is equivalent to the maximum excitation from a magnitude 5.75 earthquake[3]. Its origin is debated, with most studies attributing the forcing to atmospheric turbulence, analogous to the forcing of solar oscillations by solar turbulence[2,4–7]. Some reports also predicted that turbulence might excite the planetary modes of Mars to detectable levels[4]. Recent observations on Earth, however, suggest that the predominant excitation source lies under the oceans[8–10]. Here I show that turbulence is a very weak source, and instead it is interacting ocean waves over the shallow continental shelves that drive the hum of the Earth. Ocean waves couple into seismic waves through the quadratic nonlinearity of the surface boundary condition, which couples pairs of slowly propagating ocean waves of similar frequency to a high phase velocity component at approximately double the frequency. This is the process by which ocean waves generate the well known 'microseism peak' that dominates the seismic spectrum near 140 mHz (refs 11, 12), but at hum frequencies, the mechanism differs significantly in frequency and depth dependence. A calculation of the coupling between ocean waves and seismic modes reproduces the seismic spectrum observed. Measurements of the temporal correlation between ocean wave data and seismic data[9,10] have confirmed that ocean waves, rather than atmospheric turbulence, are driving the modes of the Earth.

Observations of the normal mode spectrum of the Earth made in the absence of large earthquakes show a roughly constant level, except for a small biannual cycle with energy peaking in January and July, which is consistent with the most energetic storm seasons (and hence largest ocean waves) in the Northern and Southern Hemispheres, respectively[3,6]. The modes appear as a series of lines between 1 and 10 mHz in spectra from quiet seismometer sites during days without large earthquakes (Fig. 1a). Above 10 mHz, distinct lines are not resolved and the Earth's hum is better described as propagating Rayleigh waves[5]. The many small earthquakes that occur each day provide insufficient seismic moment to explain quiet day spectra[1,6].

It has long been known that ocean waves drive the large 'microseism' peak in the worldwide seismic noise spectrum near 140 mHz (refs 11, 12; Fig. 1a). Components of the wave field interact to generate components that force seismic waves because ocean waves are weakly nonlinear[11]. Schematically, two ocean waves of frequencies ω_1, ω_2 and horizontal wavenumbers $\mathbf{k}_1$, $\mathbf{k}_2$, interact to produce a signal at frequency $\omega_3 = \omega_1 + \omega_2$ and wavenumber $\mathbf{k}_3 = \mathbf{k}_1 + \mathbf{k}_2$. If two waves with $\omega_1 \approx \omega_2$ are travelling in opposing directions, so that $\mathbf{k}_1 \approx -\mathbf{k}_2$, then $|\mathbf{k}_3| \ll |\mathbf{k}_1|$ and $\mathbf{k}_3$ corresponds to forcing at a phase speed $c_3 = \omega/|\mathbf{k}_3|$, much larger than the speed of the original waves. Thus energy in 14 s period (70 mHz) ocean waves ($c < 20\ \mathrm{m\,s^{-1}}$) is transferred to seismic waves ($c > 1.5\ \mathrm{km\,s^{-1}}$) near 7 s period (140 mHz) that travel worldwide to generate the microseism peak (Fig. 1a). Similarly, low frequency ocean waves interact over the shelves to force Earth normal modes and Rayleigh waves below 40 mHz. A 5 mHz fundamental Earth seismic mode is of 900 km wavelength[13], is described by spherical harmonics of angular order $l \approx 43$ ($c > 4.5\ \mathrm{km\,s^{-1}}$), and is forced by ocean waves at 2.5 mHz.

The finite extent of regions of strong winds limits the longest period ocean waves driven directly by the wind to periods shorter than 25 s. The much smaller amplitude ocean waves observed at longer period (relevant to seismic mode excitation) are called 'infragravity waves'. These waves are most energetic near the shore, and are driven by a nonlinear mechanism related to the microseism mechanism acting on short period ocean waves near coastlines. The infragravity wave spectrum on the shelves[14,15] varies greatly both spatially and in time, but remains flat in frequency from 1 mHz to 40 mHz (above which wind waves dominate, Fig. 1b). Infragravity wave spectra are typically 40 dB more energetic over the shelf than in the deep ocean because little wave energy reaches deep water (the sloping shelf acts as a waveguide).

Hasselmann[11] derived a small wavenumber approximation for the wavenumber and frequency spectrum $F_p(\mathbf{k},\omega)$ of the near surface pressure field in water of infinite depth driven by the nonlinear

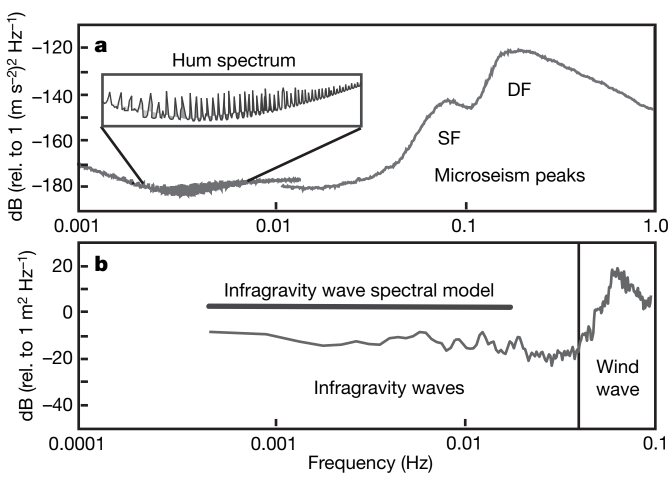

Figure 1 | Seismic waves are driven by ocean waves at half their frequency. **a**, Vertical acceleration spectrum from a quiet site (BFO, Black Forest Observatory), redrawn from data supplied by R. Widmer-Schnidrig (available at http://www-gpi.physik.uni-karlsruhe.de/pub/widmer/BFO/Noise/BFO_STS-1_BHZ_VHZ.pdf). Normal mode spectral peaks (Earth's hum) lie between 1 and 10 mHz, and are shown magnified in the inset. The DF microseism peak is driven by ocean waves near 70 mHz, the hum by lower frequency ocean waves. The 'SF' peak is probably driven by waves interacting with bathymetry[11]. **b**, Ocean wave height spectrum from the shelf off Florida[25]. Wind wave spectral peaks vary, but lie above 0.04 Hz. The model infragravity ocean wave spectrum used in the forcing calculations is also shown.

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coupling of ocean waves with the wave height frequency (σ) and direction (θ) spectrum $f_\varsigma(\sigma,\theta)$. To model the forcing of seismic modes by this pressure field, the original Hasselmann expression must be modified with a factor $G(\sigma,H)$ describing the increasing strength of the forcing towards lower frequency and in shallower water (H is water depth) (Fig. 2a). Particle motions beneath ocean waves become increasingly elliptical at shallower depth, with larger horizontal velocities relative to wave height. $G(\sigma,H)$ increases because the coupling depends on the mean squared particle velocity beneath the waves. The calculation of $G(\sigma,H)$ is shown in Supplementary Information. I obtain an expression applicable to the forcing of both Earth seismic modes and microseisms:

$$F_{\mathrm{p}}(\mathbf{k},\omega)\approx\frac{\rho^2 g\omega}{2}G(\omega/2,H)\int_{-\pi}^{\pi}f_\varsigma(\omega/2,\theta)f_\varsigma(\omega/2,\theta+\pi)\mathrm{d}\theta \quad (1)$$

(here ρ is water density, and g is the local acceleration of gravity). The pressure spectrum has no wavenumber dependence (for small wavenumber), and at a given frequency depends on the ocean wave spectrum at half that frequency: $\sigma=\omega/2$. At typical microseism frequencies (140 mHz) G is equal to 1 (Fig. 2a) except in very shallow water (<40 m depth). At Earth seismic mode frequencies, there is a frequency dependence (ω^{-2}) in G not seen at higher frequency. G at mode frequencies is about 25 dB larger on the continental shelf ($H=30$ m, Fig. 2a) than over ocean basins (>3,000 m). The shallow shelf dominates mode forcing both because the infragravity waves are much larger (an effect amplified by the quadratic dependence of the forcing on the wave spectrum) and because G is larger.

The seismic normal modes appear as narrow spectral lines in the observations (Fig. 1a) because the damping of seismic modes is weak (high quality factor, Q). The ocean wave forcing is best explained as a pressure glut, or jump in pressure acting at the sea surface in a coupled atmosphere–Earth elastic model[16]. The atmospheric component of the ocean wave forcing contributes to a small enhancement of the amplitude of the fundamental mode at 3.7 and 4.4 mHz, but otherwise I ignore weak coupling to the atmosphere and model the forcing as a time-varying vertical point force acting on the Earth's surface. The vertical acceleration spectrum at any site is related to the frequency spectrum of the point force by the function $E(\omega)$ which is the sum of terms describing the resonant forcing of each mode[5]:

$$E(\omega)=\sum_n\sum_l\frac{(2l+1)U_{nl}^4(R)}{4\pi|\Gamma_{nl}(\omega)|^2};\qquad \Gamma_{nl}(\omega)=\left(\frac{\omega_{nl}}{\omega}\right)^2-\left(1+i\frac{\omega_{nl}}{2Q_{nl}\omega}\right)^2 \quad (2)$$

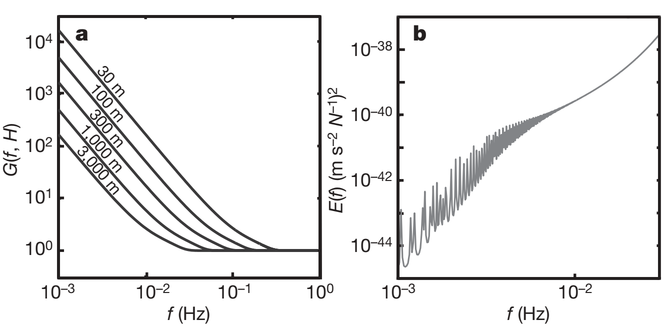

Figure 2 | Increasing mode excitation with frequency under surface forcing is partly balanced by a weakening of the wave interaction mechanism. **a**, The function $G(f,H)$ describing the relative strength of nonlinear wave interaction shown for five water depths H versus frequency f. Note enhancement of wave interaction at shallower water depth and lower frequency. **b**, The function $E(f)$ describing Earth normal mode excitation by a time-varying point vertical force at the Earth's surface versus frequency f. Peaks are associated with mode resonances.

Here ω_{nl} and U_{nl} are respectively the mode resonant frequency and the vertical velocity at the Earth's surface (R) normalized by the mode energy so that $E(\omega)$ describes a balance between mode forcing and dissipation[14]. The mode parameters were calculated using the MINOS program (by F. Gilbert and G. Masters based on ref. 17 applied to the Earth model PA5[18]). The resonant peaks associated with the many modes are obvious in $E(\omega)$ (Fig. 2b). Under forcing by ocean waves, a mode is strongly excited only by those components of the near surface pressure field at frequencies near its resonant frequency and at wavelengths comparable to the spherical harmonic describing that mode. Without a nonlinear mechanism to couple ocean wave energy into high phase velocity components, there would be little coupling to Earth normal modes.

The horizontal scales of the relevant seismic modes are large compared to the widths of the continental shelves, and the forcing is calculated by summing the forcing from many small regions covering the shelves. Beyond the shelf edge, infragravity wave amplitudes rapidly decrease and forcing is negligible. The regions are sufficiently small relative to mode wavelengths to model each region as a temporally fluctuating vertical point force uncorrelated with other regions. With some simplifying assumptions, the predicted vertical acceleration spectrum $A(\omega)$ for the background seismic mode spectrum under wave forcing is

$$A(\omega)=\pi E(\omega)F_{\mathrm{p}}(0,\omega)\Omega_{\mathrm{s}} \quad (3)$$

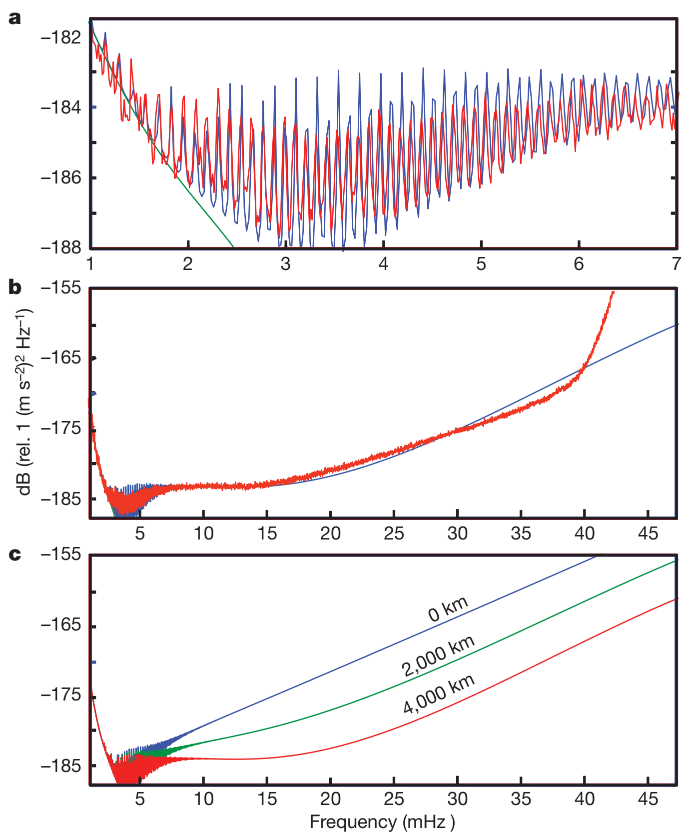

Figure 3 | Comparison of the modelled spectrum with observations. **a**, Spectrum shown (red line: redrawn from ref. 26) is an average of the 32 spectra with the lowest mode energy between 2 mHz and 8 mHz selected from a set of 738,000 hourly spectra derived from 118 GSN stations. This process should select spectra from sites distant from mode sources and time intervals with the least energetic sources. Also shown is a model (blue line) of the excitation of the Earth's hum (at a site 4,000 km into a continent) with an atmospheric gravitational attraction noise model (green line) added. **b**, Same as **a**, but plotted to higher frequency. **c**, Models of the spectrum for sites at three distances from source regions, showing the effect of attenuation.

where Ω_s is the Earth's area covered by shelves (see Supplementary Information).

The predicted spectrum matches observations of the seismic mode background spectrum (Fig. 3a) given a reasonable estimate for the infragravity wave spectrum on the shallow shelf (Fig. 1b). The quadratic dependence of equation (1) on the spectrum ensures that the excitation of normal modes is dominated by regions with the most energetic infragravity waves. A model for the local effect of the time varying gravitational attraction of the atmosphere acting on the seismometer has been added to the predicted spectrum at low frequencies.

Fitting the spectrum above 10 mHz (Fig. 3b, c) requires modifying the model to account for attenuation between the source regions and the seismometers. The model above uses the simplifying assumption that sources are distributed uniformly over the Earth. Sites that are seismically quiet are found within the interior of continents because these sites are remote from ocean waves. The attenuation of ocean wave noise with propagation into the continents is accounted for by adding a factor to $E(\omega)$:

$$E(\omega)=\sum_n \sum_l \frac{(2l+1)U_{nl}^4(R)}{4\pi|\Gamma_{nl}(\omega)|^2}\exp\left[-\frac{\omega X}{u_{nl}Q_{nl}}\right] \qquad (4)$$

Here X represents the distance from nearby ocean noise sources to a site, and u_{nl} is the group velocity associated with a mode (when expressed as a sum of propagating waves). A spectral average from quiet sites is best fitted between 2 and 40 mHz with $X \approx 4{,}000$ km (Fig. 3b). The width of the envelope of $E(\omega)$ and thus the hum spectrum envelope are also controlled by attenuation[19]: the thinner envelope at higher frequency is a result of lower mode Qs at shorter wavelength. The model fits the data within 1.5 dB from 2 mHz to 40 mHz. The remaining differences are equivalent to a 5% difference in mode Qs, and are smaller than the variability between sites, or within spectra from a single site, and less than the biannual cycle in hum energy[4]. The model diverges above 40 mHz because the single frequency microseism peak (Fig. 1a) is generated by a different mechanism (ocean waves interacting with bathymetry[11]).

Previous authors have ascribed the seismic mode background to forcing under atmospheric turbulence[2,4–7]. I believe that this is incorrect, because it was assumed that the pressure signal that can force normal modes is of the same magnitude as the typical pressure fluctuations within atmospheric turbulence: $p \approx \rho U^2$ (ρ, air density; U, wind velocity). This assumption leads to a large overestimation of the forcing because only a tiny component of the turbulent pressure field is associated with the large wavelengths and high phase velocities[20,21] required to excite Earth normal modes. Turbulence can force Earth normal modes in two ways: by developing pressure fluctuations beneath the atmospheric boundary layer that act directly on the Earth's surface, or by coupling first into infrasound above the surface that then propagates downwards to the surface. A strong Mach dependence for these processes ensures that low Mach number turbulence is an inefficient generator of sound[21] or of seismic waves. A model of the pressure spectrum under the atmospheric boundary layer at wavenumbers small enough to drive Earth normal modes calculated from a model for the pressure fluctuations beneath a shear layer[22] predicts levels 150 dB lower than previous papers that supported atmospheric turbulence as the primary source for the Earth's hum (see Supplementary Information). Estimates of the ground forcing under tornadoes[23] and in thunderstorms[24] suggest that these discrete turbulence sources are also insignificant, despite their relatively large Mach numbers.

Careful instrumentation and analysis were required to reveal the presence of a background level of excitation of the seismic normal modes of the Earth[1], and identifying the source as being within the oceans has been equally difficult, requiring processing of data from large seismic arrays[8]. I have shown here that the nonlinear ocean wave interaction mechanism provides the necessary energy to explain the mode background. An alternative mechanism for coupling energy to seismic waves[11] involves the interaction of ocean waves with bathymetry, and this could contribute to mode forcing. Future observations of the temporal correlation between ocean waves and mode spectra should help to constrain the contribution from this alternative mechanism.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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