Future ocean increasingly transparent to low-frequency sound owing to carbon dioxide emissions

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Low-frequency sound in the ocean is produced by natural phenomena such as rain, waves and marine life, as well as by human activities, such as the use of sonar systems, shipping and construction. Sea water absorbs sound mainly owing to the viscosity of the water and the presence of chemical constituents, such as magnesium sulphate, boric acid and carbonate ions. The concentration of dissolved chemicals absorbing sound near 1 kHz depends on the pH of the ocean[1], which has declined as a result of increases in acidity due to anthropogenic emissions of carbon dioxide[2–4]. Here we use a global ocean model[5,6] forced with projected carbon dioxide emissions[7] to predict regional changes in pH, and thus sound absorption, in the years 1800–2300. According to our projections, ocean pH could fall by up to 0.6 units by 2100. Sound absorption—in the range between ~100 Hz and ~10 kHz—could fall by up to 60% in the high latitudes and in areas of deep-water formation over the same time period. We predict that over the twenty-first century, chemical absorption of sound in this frequency range will nearly halve in some of the regions that experience significant radiated noise from industrial activity, such as the North Atlantic Ocean. We suggest that our forecast of reduced sound absorption in acoustic hotspots will help in identifying target regions for future monitoring.

Low-frequency ocean sound in the range 1–5,000 Hz is produced both by natural phenomena, for example, rain, waves or marine life (Supplementary Table S1), and by human activities such as sonar systems, shipping or construction (Supplementary Table S2). Most low-frequency noise is generated at the surface[8]. It can enter the deep sound channel either in high latitudes where the sound channel axis depth shoals as a result of latitudinal variations of the sound speed[9], or at continental shelves and slopes owing to reflection and scattering of sound waves by downslope conversion[10]. In the deep sound channel (typically at a depth of 700 m in the North Pacific Ocean), sound waves can bend and travel over many thousands of kilometres[8]. The oceanic penetration of the fossil fuel CO_2 signal can now be observed well below such depths, and thus can affect the acoustic properties of the ocean over very large distances. Seawater sound attenuation, beyond direct geometrical spherical and cylindrical energy dispersal, and bottom losses, is mainly driven by two mechanisms: absorption owing to fluid shear viscosity and owing to chemical resonances of some constituents of sea water, such as magnesium sulphate and the boric acid/carbonate system[11]. The contribution of these two mechanisms varies with sound frequency and ambient conditions, for example,
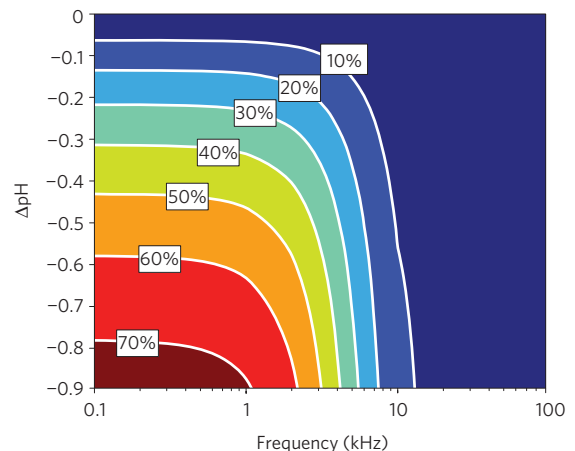

Figure 1 | Sound absorption attenuation as a function of frequency and seawater pH. Decreasing pH (increasing acidity; calculated for the surface ocean at initial pH = 8.1, temperature = 10 °C and salinity = 35) reduces the absorption of low-frequency sound, with the largest effect below about 1 kHz, corresponding to the boron relaxation frequency. The drop of the modern ocean pH by about 0.1 units corresponds to a 10–20% reduction of sound absorption in the frequency range between ~100 and ~10 kHz. Lowering of the pH by 0.6 units would decrease underwater sound absorption by >60%.

salinity, temperature and hydrostatic pressure. Whereas viscous absorption is more important at high frequencies (>300 kHz), a pH-dependent chemical relaxation from the borate/carbonate system affects low frequencies, between ~100 Hz and ~10 kHz (Fig. 1). Below 100 Hz, sound is attenuated mostly by scattering and diffraction, and energy losses occur from bottom interactions.

Surface ocean pH has already fallen by about 0.1 units[12] compared with preindustrial levels as a result of oceanic uptake of anthropogenic CO_2. At present, the most debated negative effect of ocean acidification is reduced calcification rates, which have been observed in various calcifying species under decreasing pH and carbonate ion concentration[13,14]. However, a less anticipated consequence of ocean acidification is its effect on underwater sound absorption[4]. A decrease in seawater pH lowers sound absorption in the low-frequency range and, as a result, leads to increasing sound transmission. Accordingly, a decrease of the seawater pH by 0.1 units corresponds to a decrease of 10–20% in the sound absorption coefficient at a frequency of about 1 kHz (Fig. 1). If the

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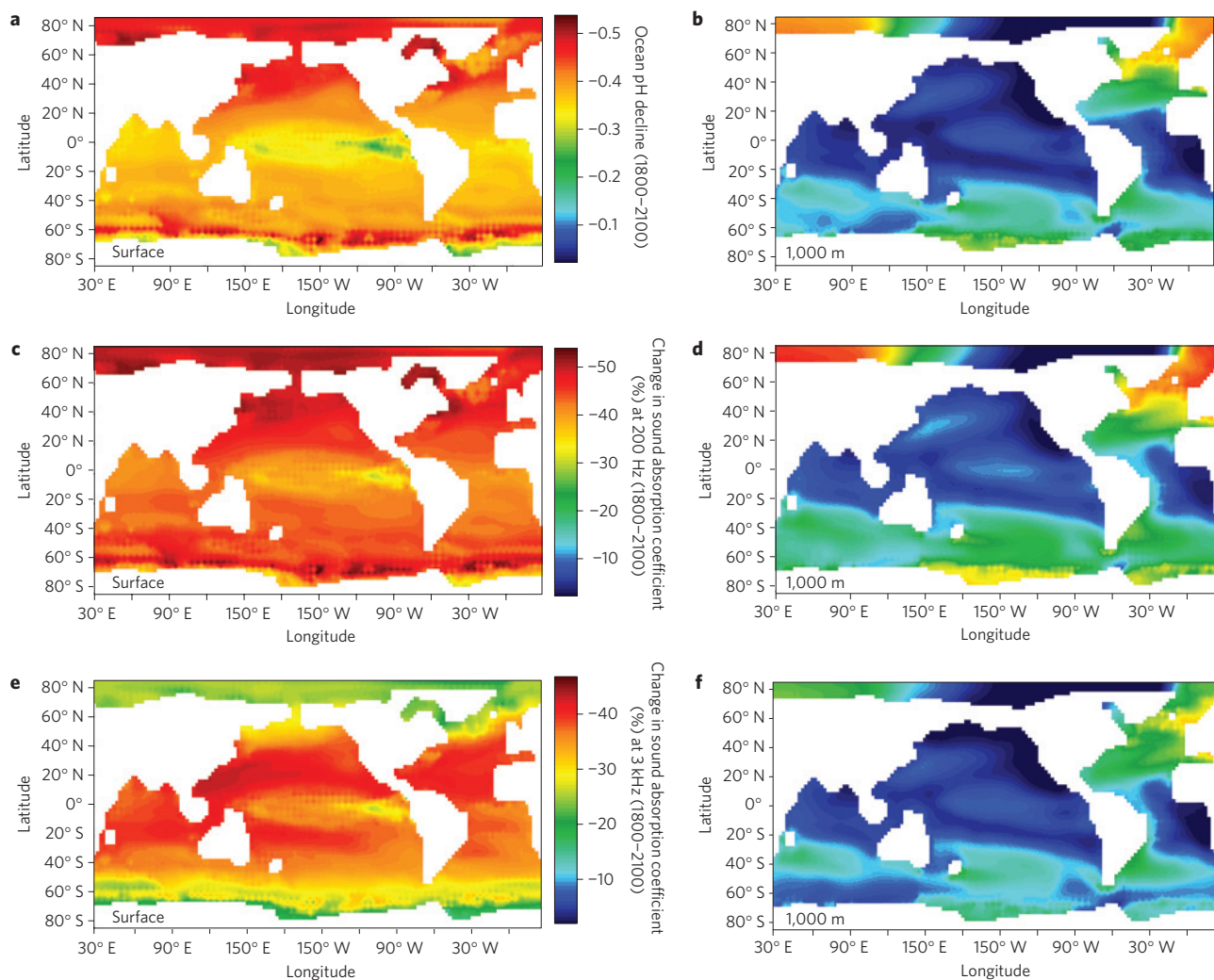
Figure 2 | Projected changes in the seawater pH and the sound absorption coefficient in 2100. a–f, Changes in the surface pH (**a**) and at a depth of 1,000 m (**b**) and corresponding changes in the sound absorption coefficient at 200 Hz (**c,d**) and 3 kHz (**e,f**) were calculated as the difference between the years 1800 and 2100 based on the IPCC A1B (business as usual) scenario.

pH of surface sea water further decreases by up to 0.6 units in the next 300 years, as predicted by model studies[15], the low-frequency sound absorption coefficient will drop by more than 60% (Fig. 1). This has important implications for technical applications that use ocean sound propagation, but possibly also for marine mammals.

We have calculated future regional changes in the underwater sound absorption owing to ocean acidification using model-based projections of seawater pH decline during the years 1800–2300 (see the Methods section). As a consequence of fossil fuel CO_2 emissions according to the moderate Intergovernmental Panel on Climate Change (IPCC) A1B scenario[7] (Supplementary Fig. S1), by the year 2100, ocean pH may drop by up to ~0.6 units in the surface and by ~0.2–0.4 units at a depth of 1,000 m (Fig. 2a,b). Corresponding decreases in the pH in a more conservative B1 scenario are 0.4 and 0.2 units and 0.7 and 0.5 units in a fossil-fuel-intensive A1FI scenario, respectively (Supplementary Fig. S2).

The pH-dependent effects influence sound absorption in the range between ~100 and ~10 kHz (Fig. 1); we examine here the effects at 200 Hz and 3 kHz so as to bracket this region. The decline in the sound absorption coefficient mirrors the pH change distributions at a frequency of 200 Hz (Fig. 2c,d). At higher frequencies, for example, at 3 kHz (Fig. 2e,f), the pH effect is weaker and the magnesium sulphate contribution exceeds the boric acid effect, but a small increase in absorption with temperature

begins to appear. Consequently, the 3 kHz decrease of the sound absorption coefficient is lower (up to 40%). Regional patterns of changes in the sound absorption coefficient at 3 kHz are mostly due to salinity effects. For instance, low salinity in the Arctic Ocean results in low sound absorption coefficient changes, because sound absorption at higher frequencies (>1 kHz) decreases as salinity decreases. It increases towards the Equator with increasing salinity. Accordingly, the largest drop in 3 kHz sound absorption is predicted for the subtropical and tropical surface ocean. At a depth of 1,000 m, however, the largest changes occur in the North Atlantic and Arctic oceans at both frequencies, 200 Hz and 3 kHz. Thus, our simulations predict a spatially heterogeneous impact of seawater acidification on ocean acoustics, with significant regional differences in the surface ocean (Fig. 2).

Sound absorption decreases with increasing pressure (and depth), as well as with increasing temperature. Changes in the seawater pH owing to the anthropogenic CO_2 invasion decrease with depth. Accordingly, the predicted decrease in the sound absorption coefficient is smaller in the deep ocean than at the surface (Fig. 3). Our calculations indicate that by the year 2100, 200 Hz sound absorption below 1,000 m will decrease by less than 10% (Fig. 3a,b) in regions where deep-water formation is weak or absent. In our calculations, CO_2 emissions decline gradually after the year 2100 (Supplementary Fig. S1). However,
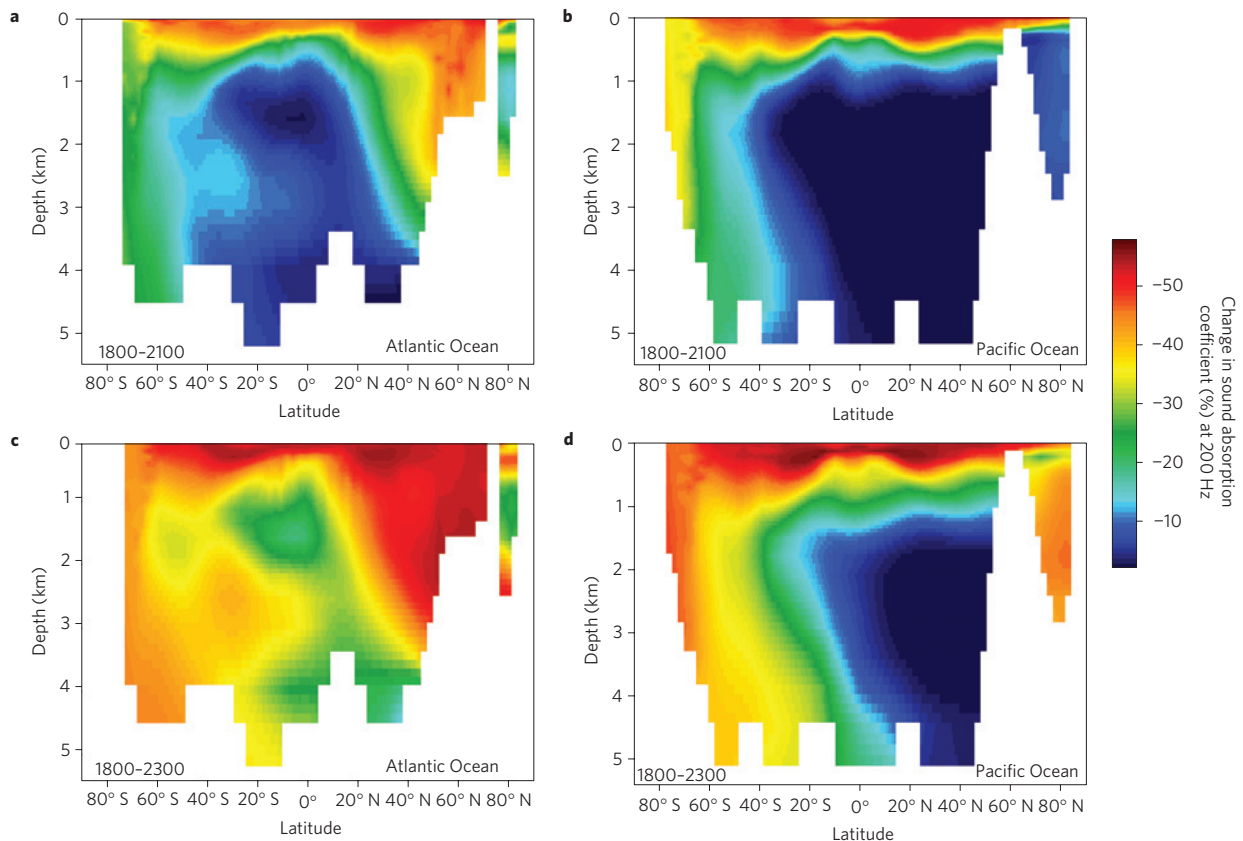
Figure 3 | Projected changes in vertical distribution of the sound absorption coefficient. a–d, Changes in the zonally averaged vertical distributions of the sound absorption coefficient in the Atlantic Ocean (**a,c**) and in the Pacific Ocean (**b,d**) projected for the years 2100 (**a,b**) and 2300 (**c,d**).

as anthropogenic CO_2 penetration depth increases with time, the changes in sound absorption coefficient will also propagate into the deep ocean, especially in the North Atlantic and Southern oceans long after the decline in emissions (that is, in the year 2300; Fig. 3c,d). In addition, future greenhouse warming may increase global surface temperatures by 1.7–4.4 °C by the end of this century[16]. The warming may further decrease the sound absorption coefficient by about 8% at frequencies below ∼10 kHz (ref. 4). Furthermore, future climate projections suggest that changes in global evaporation and precipitation patterns are likely to cause a decrease in salinity in mid- and high-latitudes and increase salinity in low latitudes[16]. Although the magnitude of these changes is uncertain, their effect on the sound absorption coefficient is likely to be minor. For instance, a change in the global surface salinity of ±0.1 would contribute an extra ±0.5% to the 3 kHz sound absorption change shown in Fig. 2.

Another consequence of a warmer and more stratified ocean is reduced ventilation, which, with continuing deep respiration, leads to increased respiratory dissolved CO_2 and therefore reduced pH, which has a further impact on sound absorption in the ocean[4]. A long-term decline in oceanic dissolved oxygen concentrations has already been documented[17,18]. Whereas warming produces the strongest O_2 decline in the surface, the effects of reduced ventilation are most pronounced at intermediate depth[19]. We provide here an estimate of the changes in seawater pH and sound absorption owing to decreased ventilation using model predictions of O_2 concentrations during the twenty-first century by Bopp and colleagues[19]. We calculate that increased respiration/decreased ventilation would further decrease the pH by up to 0.1 units locally (Supplementary Fig. S4), leading to a further decrease in the sound absorption coefficient by about 9% at 200 Hz and about 5% at 3 kHz (Supplementary Figs S3 and S4). In areas with strong

reductions in ventilation, such as the Japan Sea[18], the future decline in pH and sound absorption is expected to be substantially larger. These small-scale features should be examined in more detail with regional, rather than global circulation models as used in this study (see the Methods section).

In most areas in the ocean with only distant shipping, natural sources of noise (for example, from wind and wave processes) dominate all other sources at frequencies below 5 Hz and from a few hundred hertz to 200 kHz (ref. 8). Most human-generated ocean noise occurs in the frequency range 10–1,000 Hz. A key contribution to anthropogenic noise comes from shipping; the number of ships has approximately doubled over the past 40 years, and the gross tonnage has quadrupled[20]. Although shipping noise is mostly produced below 100 Hz, it affects large areas in the ocean, being a major contributor to noise at 5–500 Hz (ref. 8). However, owing to inadequate measurements, it is not clear whether or not low-frequency ambient noise is increasing globally at present, as would be anticipated from the reduction in acoustic attenuation.

The order of magnitude of attenuation-induced changes depends on the spatial distribution of noise sources. The areas most sensitive to changes in sound propagation ('hotspots') are probably areas with intense noise sources and large changes in the sound absorption coefficient; impacts on marine life and on naval activities will also be concentrated in these areas. To illustrate sound attenuation patterns in such areas that have the potential to become acoustic hotspots, we have selected six regions in the ocean that are located in major commercial shipping routes[21], where the largest changes in sound absorption coefficient are predicted (Fig. 2). We calculated the temporal evolution of seawater pH under different CO_2 emission scenarios and accompanying changes in the sound absorption coefficient in these regions (Fig. 4). In the high latitudes (for example, in the North Atlantic Ocean and North
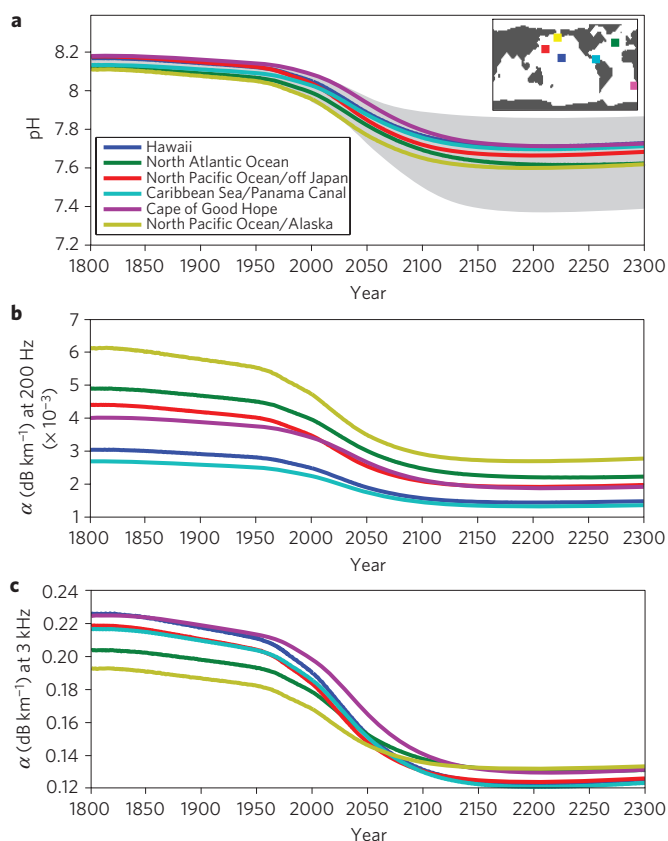
Figure 4 | Temporal evolution of seawater pH and sound absorption coefficient in acoustic hotspots. a–c, Seawater pH (**a**) and sound absorption coefficient (α) for frequencies 200 Hz (**b**) and 3 kHz (**c**) in the years 1800–2300 were averaged over regions represented by nine model grid points shown in the map at six 'acoustic hotspots', calculated under the IPCC A1B scenario. The grey-shaded area brackets the range of the decline in the pH values calculated in the fossil-intensive (worst case) IPCC A1FI scenario and in the conservative (best case) IPCC B1 scenario.

Pacific Ocean/Alaska), the absorption coefficient at 200 Hz will decrease by >50% in 2100 (see Fig. 2). Sound absorption at the 3 kHz frequency in the subtropics and mid-latitudes (for example, around Hawaii, in proximity to the Panama Canal, and near Japan) will be reduced by a factor of two by the end of this century.

High levels of low-frequency sound have a number of behavioural and biological effects on marine life, including tissue damage, mass stranding of cetaceans[22,23] and temporary loss of hearing in dolphins[24] associated with military tests using intense mid-frequency sonar. Other effects include interruption from normal activities and abandoning the custom habitat areas by some mammals (for example, humpback whales and beluga) at increased noise levels (that is, from nearby shipping)[25]. Although marine species have adapted to varying levels of noise, the consequences of increasing long-range sound transmission in the frequencies that are important for many marine mammals (see Supplementary Table S1) are unknown. Decreased sound absorption could, for example, enable marine mammals to communicate over longer distances. Thus, ocean acidification may not only affect marine organisms at the bottom of the food chain (for example, through reduced calcification in plankton), but also higher trophic level species (for example, baleen whales) by changing the propagation range of 1 kHz sound in the oceans.

These changes in propagation range will be noticeable in the operation of scientific, commercial and naval applications that are based on ocean acoustics. Our results provide the first model-based projections of the timing, location and magnitude of sound absorption changes relevant to these applications. Possible impacts on marine life are uncertain at present and require intense future research. Our forecast of future sound absorption changes in acoustic 'hotspots' should aid in identifying target regions for these research endeavours.

Methods

We have calculated changes in ocean chemistry and sound absorption using the global ocean carbon cycle model HAMOCC (Hamburg Model of Ocean Carbon Cycle[5,6]). The advection of chemical tracers in HAMOCC is calculated on the basis of the steady flow field representative for the modern ocean, which is produced by the ocean general circulation model[26]. HAMOCC uses realistic topography with a horizontal resolution of 3.5° and a vertical resolution varying from 25 m at the surface to 700 m in the deep ocean. The ocean module in HAMOCC is complemented by the sediment and the atmospheric modules[6]. HAMOCC includes nutrient, phytoplankton, zooplankton and detritus cycles[27]. The chemical cycles and trophic levels represented in the model are linked through the nutrient uptake and remineralization of organic matter. The model was forced by anthropogenic CO_2 fossil-fuel emissions (see Supplementary Fig. S1) that follow historic emissions and three IPCC scenarios[7] representing a worst case (A1FI, in which CO_2 emissions reached ~30 GtC yr^{-1} in 2100), a best case (B1, with the highest emission of 12 GtC yr^{-1}) and a business as usual (A1B peaking at about 16 GtC yr^{-1} in the year 2050) future scenario until the year 2100, and decline gradually thereafter. Calcium carbonate production rates were fixed at the preindustrial level and did not change in the model calculations (see Supplementary Information) following a constant calcification scenario[28]. Evaluation of model results carried out in an earlier study showed good agreement between modelled and observed total alkalinity distributions[28]. The pH of sea water was calculated using the relations given in Zeebe and Wolf-Gladrow[29] based on the modelled total CO_2 and alkalinity distributions. The range of our predictions of the seawater pH decline is consistent with the projections computed using an ensemble of several carbon cycle models (including the HAMOCC model used here) and scenarios of anthropogenic fossil-fuel CO_2 emissions[15]. The sound absorption coefficient (the fraction of the sound energy which is absorbed by the seawater) was calculated as the sum of the contributions from magnesium sulphate, boric acid and pure water according to the Francois and Garrison algorithm[11]. The sound absorption coefficient in acoustic hotspots (Fig. 4) was calculated as averaged values over several neighbouring model grid points.

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