activation and inhibition levels are expected to be individual-specific, which may result in tooth proportions that differ between individuals of the same species. It is therefore possible that the rule they describe would not be so simple had interindividual variation been included in the model.

Despite this limitation, Evans and colleagues' paper advances palaeoanthropology in three fundamental ways. First, it draws on experimental data from mice, which are the most common model organism, to explain the variation observed in the hominin fossil record. Second, it develops a rigorous quantitative framework to formally test hypotheses related to that model. And finally, it improves our understanding of the human fossil record by identifying evolutionary changes that are developmentally linked.

More importantly, Evans and colleagues' results are relevant beyond the study of fossil teeth. Many of the developmental constraints that influence dental evolution are shared by other systems formed by the repetition of serially homologous components, such as vertebrae, ribs, limbs and digits. Teeth can therefore be useful in identifying developmental mechanisms operating in these other systems[9]. By extension, the authors' model has the potential to help us understand the evolution of human traits that are associated with serially homologous structures, including our upright posture (which is influenced by vertebral anatomy), bipedal locomotion (which is linked to limb anatomy) and precision grip (which depends on the anatomy of digits). As with third-molar reduction, we tend to consider these traits the result of human-specific selective pressures, but their evolution is also fundamentally channelled by general developmental rules that humans have not escaped. ■

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CLIMATE SCIENCE

Hidden trends in the ocean carbon sink

Simulations of the flux of atmospheric carbon dioxide into the ocean show that changes in flux associated with human activities are currently masked by natural climate variations, but will be evident in the near future. SEE LETTER P.469

TATIANA ILYINA

The world ocean has absorbed about one-third of the carbon released by humans[1], and therefore has a key role in moderating climate change. Observations[2] of the ocean interior confirm that increases in carbon dioxide emissions from fossil-fuel burning are accompanied by an increase in carbon content in the upper ocean. But, surprising as it may seem, McKinley *et al.*[3] report on page 469 that, in many ocean regions, changes in the uptake of CO_2 induced by human activities are currently indistinguishable from changes driven by natural climate variations. So, are anthropogenic trends in the ocean carbon sink concealed by Earth's own variability?

As atmospheric CO_2 levels increase, the ocean takes up this gas at a rate proportional to the difference of the partial pressure of CO_2 (a measure of CO_2 concentration in a mixture of gases) between the air and sea[2]. The strength of the ocean carbon sink is determined by chemical reactions in seawater, biological processes such as photosynthesis and respiration, and physical processes, including ocean circulation and vertical mixing[4]. But even though these key mechanisms are known, there are considerable uncertainties regarding their year-to-year (interannual) and decadal variations[5]. These variations are tightly linked to modes of internal variability in the climate system — such as the El Niño–Southern Oscillation (ENSO) — that have regional to worldwide effects on weather and climate, and thereby modulate air–sea CO_2 fluxes and ocean biogeochemical cycles.

Advances in observations and models have shed light on how internal climate variability controls the ocean carbon sink. Modern Earth-system models (ESMs) that were analysed in the fifth Coupled Model Intercomparison Project (CMIP5, which compared the output of

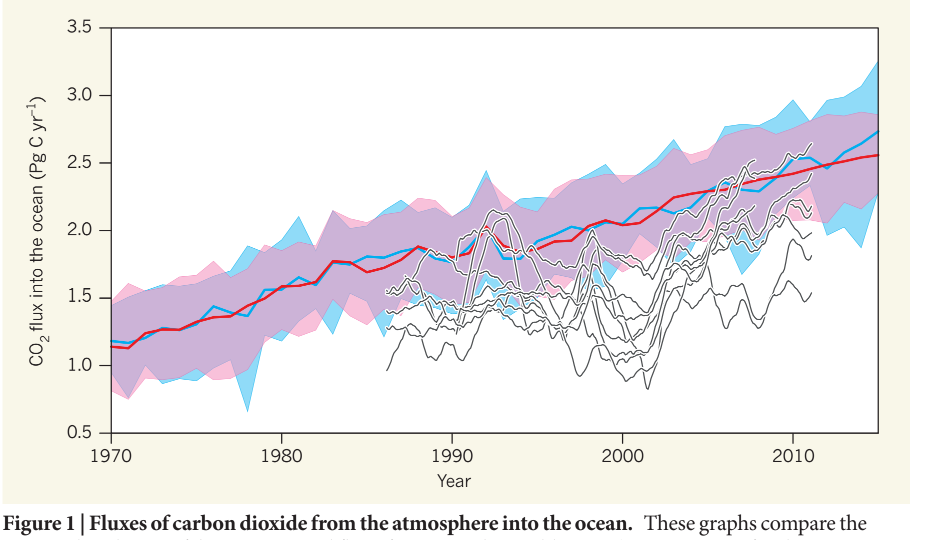

Figure 1 | Fluxes of carbon dioxide from the atmosphere into the ocean. These graphs compare the temporal evolution of the mean annual flux of CO_2 into the world ocean (in petagrams of carbon per year; 1 Pg is 10^{15} grams) predicted by different model simulations, and from observations. Although the models and observations reveal a similar trajectory for the global change of flux, the plotted values vary considerably because of uncertainties in models and gaps in observations. The model predictions are from the fifth Coupled Model Intercomparison Project (CMIP5; blue) and from an ensemble of 100 simulations made using the Max Planck Institute Earth System Model (MPI-ESM; red). Solid lines show the average of an ensemble of model data; shaded areas show the upper and the lower boundaries of the ensemble data. Findings based on observational data[7] are in black. McKinley *et al.*[3] report simulations suggesting that anthropogenic changes in the air–sea carbon flux are currently obscured by naturally occurring flux variations. (CO_2 fluxes into the ocean in CMIP5 models and in the MPI-ESM were calculated by Hongmei Li.)

models in which components of Earth's system are coupled) consistently predict that ocean carbon uptake increases in line with rises in fossil-fuel carbon emissions. But these ESMs poorly capture natural climate variability. Furthermore, CMIP5 projections generate a large spread in estimates of the ocean carbon sink because the models have different numerical schemes, process descriptions and spatial resolutions[6].

Further complications arise because there is a large spread in observed variations of CO_2 fluxes, due to both the use of different mapping procedures and gaps in the observational record[7]. This spread of variation from observational data is at least as large as the spread from the CMIP5 ensemble of models (Fig. 1). Estimates of the internal variability of the ocean carbon sink therefore remain unconstrained, impeding the detection and attribution of changes in air–sea CO_2 fluxes.

McKinley and co-workers report a crucial step towards detecting changes in the ocean carbon sink — they have generated a large ensemble of simulations based on an ESM. The authors repeated their model runs 32 times over the same time interval, spanning the years 1920 to 2100. The model follows historical climate evolution until the end of 2005, and then a climate-change scenario (known as RCP8.5) that projects high levels of atmospheric CO_2. Few modelling centres are able to perform so many runs because doing so is computationally expensive, but the value of using ensembles with a high number of simulations is increasingly being recognized.

External forcing factors such as the concentrations of atmospheric greenhouse gases and aerosols, volcanic eruptions and solar variability were identical across all simulations. The only difference between the ensemble members was their climate state at initialization: each simulation started with a different state generated by a small perturbation of the air temperature. As a result, individual ensemble members were not identical to each other, even though the model variables for each member followed the same general trajectory.

The authors considered two outcomes from the simulations: the forced trend, which is the average trend in model variables across all ensemble members produced under specified external forcing, and the internal trend, which is the difference between each member's trend and the forced trend, caused by the model's internal variability. They observed that the forced trends in ocean carbon uptake are indistinguishable from internal model variability in vast ocean regions between 1990 and 1999. When the period between 1990 and 2019 is considered, the forced trends become statistically significant in many more areas than during 1990 to 1999, and emerge almost everywhere in the ocean. This suggests that the predicted increase in oceanic carbon uptake is attributable to anthropogenic forcing. These trends intensify as atmospheric CO_2 levels increase, and so become detectable ocean-wide when the period from 1990 to 2089 is considered.

The researchers confirm that the spatial pattern in which trends emerge seems to be closely linked to the internal variability of the climate system. For instance, the largest internal variations are in the equatorial Pacific Ocean, a region known to be affected by ENSO. In regions such as this that exhibit strong seasonal and interannual variability, it is difficult to detect anthropogenic changes in CO_2 uptake. By contrast, anthropogenic trends emerge early in the subpolar North Atlantic and equatorial Atlantic oceans and in some regions of the Southern Ocean. A similar pattern has been reported[8] for several ocean biogeochemical parameters modelled in the CMIP5 ensemble.

McKinley and colleagues conclude that forced trends should be detectable in observations once they have emerged and become statistically significant. However, although internal model variability can give an indication of the chaotic behaviour of some natural processes, it is not equivalent to Earth's natural climate variability. Furthermore, predictions of the time of emergence are model-dependent[8,9], and may change if a different model or ensemble size is considered (Fig. 1).

Nevertheless, the current study makes a valuable contribution to the quantification of internal variability in the rates of change of the ocean carbon sink. Changes driven by human activities are undoubtedly there, but may be concealed by natural variations in many ocean regions because of the slow timescales on which ocean processes occur. Future work based on coordinated observational frameworks and large ensemble simulations using ESMs should enable the natural variability reported in this study to be verified. ■

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COSMOLOGY

Home of a fast radio burst

Our understanding of fast radio bursts — intense pulses of radio waves — and their use as cosmic probes promises to be transformed now that one burst has been associated with a galaxy of known distance from Earth. See Letter p.453

DUNCAN LORIMER

Fast radio bursts (FRBs) are bright pulses of radio waves that last only milliseconds and originate from random locations on the sky. Although the physical processes that cause these pulses are unknown, FRBs hold great promise as probes of the cosmic web, a major constituent of the large-scale structure of the Universe. On page 453 of this issue, Keane *et al.*[1] report the discovery of a fading radio source associated with an FRB (FRB 150418) that was found on 18 April 2015. From observations with various telescopes, they show that FRB 150418 and its fading counterpart come from an elliptical galaxy some 1.9 billion parsecs (6 billion light years) away. Just as happened with γ-ray bursts almost 20 years ago, knowing both the location of origin and the distance of that location from Earth will help to reveal the physical nature of the event that caused the FRB.

A group that I led discovered[2] the first FRB while searching archival data taken with the 64-metre Parkes radio telescope in New South Wales, Australia. That burst, now known as FRB 010724, showed a clear dependence of pulse arrival time on frequency, with the highest-frequency signals travelling fastest through the ionized interstellar medium and arriving earlier than their lower-frequency counterparts. This well-known dispersion effect has allowed astronomers to map out the ionized material in the interstellar medium, and has helped us to understand the distribution of matter in the Milky Way[3]. For FRB 010724, however, the amount of dispersion observed is roughly ten times greater than