assessed the health co-benefits of these three policies and illustrated that they could range from 26% of the cost of the policy up to approximately ten times the cost of the policy. They also found that more flexible policies are much cheaper to implement, and therefore can have much larger net benefits.

The work by Thompson and colleagues underscores how policies and actions designed to reduce carbon emissions will not only help mitigate global climate change, but also directly benefit human health. This study and others[6–10] also demonstrate that existing models are robust enough to include health co-benefits through improved air quality in analyses of climate mitigation policies, and that they can be a vital component of the total benefits of these policies. Climate change is global and mitigation is long-term, whereas health improvements from decreased air pollution provide localized and more immediate benefits — an important issue from a policymaking standpoint. In other words, health benefits can occur in the same areas that are bearing the costs of the policy and within a timeframe more relevant for policymakers.

Future climate and health assessments can build on the work by Thompson *et al.*, and other analyses[6–10], to include additional elements, such as improvements in water quality or the health improvements from more active forms of transportation. This is possible using readily available scientific tools from public health and other fields. The co-assessment of health and climate benefits when evaluating policies is emerging as an important and powerful instrument to choose strategies that help achieve a high standard of human health and maintain a liveable climate, while still providing the energy necessary for the functioning of society today. Thompson and colleagues contribute significantly to the body of research that points a way forward to meet these goals. ❐

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OCEANOGRAPHY

Oxygen and climate dynamics

Low oxygen levels in tropical oceans shape marine ecosystems and biogeochemistry, and climate change is expected to expand these regions. Now a study indicates that regional dynamics control tropical oxygen trends, bucking projected global reductions in ocean oxygen.

Scott C. Doney and Kristopher B. Karnauskas

The subsurface ocean in the eastern tropical Pacific contains a large volume of water with very low dissolved oxygen (O_2) levels. Reduced O_2 in the ocean can exclude fish and other marine life that need O_2 for aerobic respiration and, at low enough O_2 levels, even alter key pathways of microbial biogeochemical cycling[1–3]. Historical observations indicate that the size of oxygen minimum zones (OMZs) around the world are growing with time[4], consistent with a global trend of ocean deoxygenation that has been linked to ocean warming and climate change[2,5]. Writing in *Science*, Curtis Deutsch and colleagues[6] argue the opposite, that the size of the eastern tropical North Pacific OMZ (Fig. 1) has been shrinking over a century timescale in response to weakening tropical trade winds and that this trend should continue in a future, warmer world.

Periods of climate warming are expected to reduce subsurface O_2 because of lower gas solubility in warm sea water and strengthened vertical stratification limiting the direct vertical exchange of oxygen[7]. Dissolved O_2 gas levels in the subsurface ocean reflect a balance between transport of freshly ventilated water from the surface and biological O_2 demand driven by the consumption of organic matter by microbes and animals. The main source of organic matter is plankton growth in overlying surface waters and the subsequent sinking of dead cells and fecal pellets into the ocean interior. Coastal upwelling along the eastern margins of the tropical Pacific, and other ocean basins, supplies a rich source of nutrients that supports some of the highest biological productivity (and therefore organic matter formation) in the ocean. In the tropical thermocline (an area with a sharp temperature gradient separating the warm surface waters and the cold deeper waters, found below the productive zone at 100–1,000 m depth) oxygen levels are already low because of the long pathways the waters have travelled since their most recent contact with the atmosphere in subtropical or temperate latitudes. Combined with the high stratification found in the tropics and high productivity, unsurprisingly this results in the formation of bands of very low oxygen waters.

Ocean field observations often span only the past few decades and can be heavily aliased by natural interannual and decadal climate variability. Proxy records are therefore critical for extending our time horizon back further in time to identify long-term anthropogenic trends. Deutsch *et al.*[6] use a new sediment-proxy reconstruction, a high-resolution time series of the nitrogen isotope content of organic matter buried in several sediment basins along the eastern tropical Pacific Ocean margin, to investigate the long-term trend in the OMZ. In suboxic waters, where oxygen concentrations are less than about 5 mmol m^{-3} or roughly a couple of per cent of atmospheric saturation, microbes switch from using molecular O_2 to nitrate (NO_3^-) to oxidize organic matter. This process, known as denitrification, preferentially removes the lighter nitrogen isotope, ^{14}N, relative to the heavier isotope, ^{15}N, leaving behind a signature in the $^{15}N/^{14}N$ isotope ratio of organic matter formed from the remaining NO_3^-. Deutsch *et al.* interpret the sediment nitrogen isotope data as a measure of the integrated rate of denitrification that is in turn roughly proportional to the volume of suboxic waters in the eastern tropical Pacific.

Based on the 150-year nitrogen isotope time series[6], the volume of suboxic waters in the tropical North Pacific declined gradually over most of the twentieth century before increasing sharply in the late 1990s. The authors argue that the long-term contraction is the result of anthropogenic climate change, as described below. The recent expansion, which corresponds to the period of expanding OMZ seen in the field data[4], instead seems to be a temporary anomaly due to natural decadal variability. Their expectation is that the observed OMZ trends in the tropical North Pacific will reverse sign at some point and start shrinking again, in contrast with most global Earth system model projections[7,8].

Using field-data analysis and an ocean physical–biogeochemical model, Deutsch *et al.*[6] explain their findings through a multi-step mechanism: climate warming weakens the easterly trade winds (that is, the Walker circulation), manifest as a reduced east–west sea-level pressure gradient across the tropical Pacific[9]; weaker trade winds prescribed in the model experiment result in a deeper thermocline that in turn lowers the nutrient upwelling that fuels biological productivity[10]; a deeper thermocline and lower productivity both contribute to reduced biological oxygen demand and denitrification in the OMZ. While Deutsch *et al.* suggest a causal link between trends in the Walker circulation and those of the Pacific OMZ, the equatorward alongshore winds in the eastern Pacific — part of the Hadley circulation (Fig. 1) — may be relevant to the thermocline depth, productivity and ultimately the OMZ in the study region as well[11].

The implication that if the equatorial Pacific trade winds resume their predicted weakening trend, the Pacific OMZ will contract, despite a general deoxygenation throughout the rest of the world ocean, underscores the importance of regional warming patterns, rather than just the global mean trend. Spatial temperature gradients ultimately drive the winds, contribute to ocean circulation and can, apparently, lead to regional changes that are powerful enough to override the expected global response. Variations in the very low O_2, suboxic core of the Pacific OMZ where denitrification occurs may not, necessarily, always represent trends in the overall extent of low O_2 waters. Simulating the suboxic core is challenging[8], and accurate representation in future model projections may require more detailed information on changing local winds and ocean turbulence[12]. The study by Deutsch *et al.*[6] also further highlights the need to understand the root of the decadal variations in tropical winds. Linkages may exist between low-frequency trade wind variability and the recent so-called global warming 'hiatus' or 'pause'[13], but an iron-clad mechanism has yet to emerge despite many interesting hypotheses. It remains an open question whether this is stochastic decadal variability, related to El Niño/Southern Oscillation variability, a coherent mode of centennial-scale variability[14], or indeed part of the response to global radiative forcing. ❐

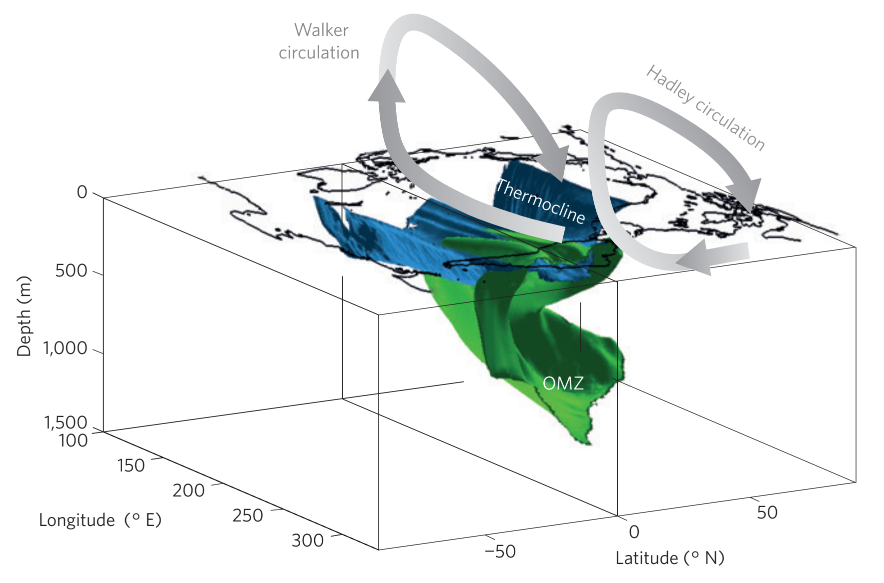

Figure 1 | A three-dimensional visualization of the Pacific oxygen minimum zone (OMZ). The annual mean O_2 isosurface (50 mmol m^{-3}; green) from the National Center for Atmospheric Research Community Earth System Model version 1 (ref. 15) and the annual mean 13 °C isotherm (blue) from the Simple Ocean Data Assimilation[16].

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