**Title**
Oceanography:
Deoxygenation and Climate Dynamics


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

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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 time-scale 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 seawater 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 the 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 which supports some of the high biological productivity (and therefore organic matter formation) in the ocean. 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 100-1000m depth) oxygen levels are already low because of the long pathways the waters have traveled since their most recent contact with the atmosphere in subtropical or temperate latitudes. This combined with the high stratification found in the tropics and high productivity results, not surprisingly, in the formation of bands of very low oxygen waters in the thermocline.

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 in order to identify long-term anthropogenic trends. Deutsch et al. 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 percent 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 20th 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 with the period of expanding OMZ seen in the field data[4], instead appears 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 to most global Earth system model projections[7,8].

Using field data analysis and an ocean physical-biogeochemical model, Deutsch *et al.* explain their findings through a multi-step mechanism: climate warming weakens the easterly trade winds (i.e., 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 – 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 wind, contribute to the ocean circulation, and can, apparently, lead to regional changes that are powerful enough to override the

expected global response. Variations in the very low O₂, suboxic core of the Pacific OMZ where denitrification occurs may not, necessarily, always represent trends in the overall extent of low O₂ 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 (ENSO) variability, a coherent mode of centennial-scale variability, or indeed part of the response to global radiative forcing.
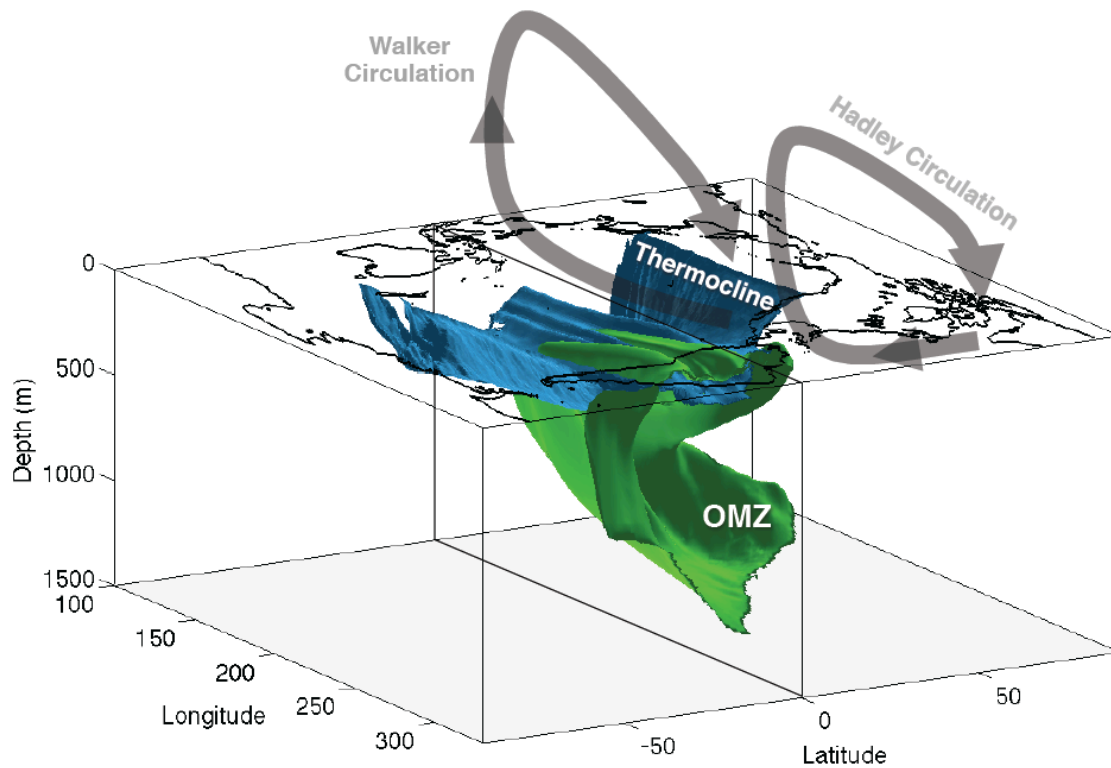


**Figure caption:** A 3D visualization of the Pacific oxygen minimum zone.. An annual mean O₂ isosurface (50 mmol m⁻³; green) from the National Center for Atmospheric Research (NCAR) Community Earth System Model version 1 (CESM1; ref. 14) and the annual mean 13°C isotherm (blue) from the Simple Ocean Data Assimilation (SODA; ref. 15).

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