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OCEANOGRAPHY

Leading the hiatus research surge

The recent slowdown in global warming challenged our understanding of climate dynamics and anthropogenic forcing. An early study gave insight to the mechanisms behind the warming slowdown and highlighted the ocean's role in regulating global temperature.

Shang-Ping Xie

The rate at which global mean surface temperature (GMST) was increasing slowed down during 1998–2012 by a factor of 2 compared with the preceding 15-year periods. This was despite a comparable rate of increase in atmospheric CO_2 concentration. The apparent inconsistency between the unabated intensification of anthropogenic forcing and the early-2000s surface-warming hiatus has generated intense scientific and political debates[1]. Early on, internal variability emerged as a plausible hypothesis — climate models produce decade-long hiatus periods[2], albeit usually not at the observed timing.

In a study published in *Nature Climate Change* in 2011, Jerry Meehl and colleagues[3] took a crucial step forward by demonstrating that in model simulations, hiatus periods are associated with a La Niña-like cooling pattern over the tropical Pacific Ocean (Fig. 1a). This is consistent with the observational fact that GMST increases a few months after the peak of El Niño, as occurred following the strong El Niño event of 1997. Through atmospheric convection, a change in tropical Pacific sea surface temperature (SST) is felt by the entire tropical troposphere. Pacemaker experiments that forced tropical Pacific variability to follow the observed evolution successfully reproduced the early-2000s hiatus[4–5], providing an explicit demonstration of the tropical Pacific effect on GMST. When such constraints were removed and the Pacific was able to evolve freely, the same models simulated a much faster increase in GMST in the early 2000s compared with observations.

Unlike first-order spatially uniform anthropogenic warming, the negative swing of tropical Pacific SST that slowed down the GMST increase left clear regional fingerprints (Fig. 1a) — including the intensified equatorial Pacific trades[5], the weakened atmospheric low pressure system over the Aleutians of the North Pacific, and the decadal drought of the Southwest US[6]. The intensified Pacific trades, in addition, halted sea level rise on the west coast of the Americas while accelerating it in the tropical

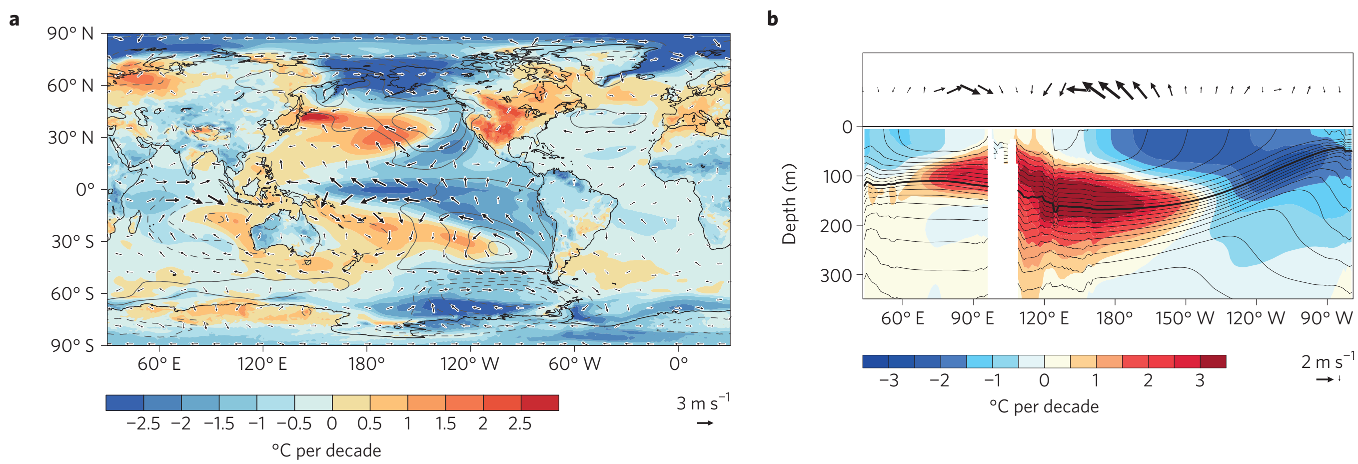

Figure 1 | Ocean–atmospheric trends during hiatus periods. **a**, Decadal trends of surface temperature (colour shading, °C), surface wind velocity vectors (m s^{-1}) and sea level pressure (contours at 1 hPa intervals). **b**, Trends of horizontal wind velocity (vectors at the top) and ocean temperature (colour shading) at the Equator, along with temperature climatology (black contours at 1 °C intervals; the 20 °C isotherm thickened). Trends are the composite difference between four pairs of hiatus and surge decades during which GMST increase slows down and accelerate, respectively. The data is from the analysis of a large-ensemble coupled model simulation[10].

western Pacific[7]. The deepened thermocline in the western Pacific contributed to the record-setting super-typhoon Haiyan that devastated the Philippines in 2013[8].

As well as identifying the tropical Pacific cooling pattern, Meehl *et al.*[3] also pioneered an energy-based characterization of the hiatus. In their model, the net radiative imbalance that heats the planet shows little difference between hiatus and reference periods. As the surface layer of the ocean is not heating up, the deep layer beneath must take up more heat during a hiatus compared with reference periods. In search of this extra heat in the subsurface ocean, a growing body of literature has developed[5,9–11]. Upper-ocean adjustments in the tropical Indo-Pacific fit both the energy change and tropical Pacific SST patterns. The intensified equatorial trades during the hiatus steepen the east–west tilt of the thermocline[5] — the boundary between the warmer surface waters and the cooler deeper water — thereby increasing the warm water transport into the Indian Ocean via the Indonesian Throughflow[10–11] (Fig. 1b). The deepened thermocline in the western Indo-Pacific and the shallower one in the east create an apparent vertical dipole of temperature anomalies in the east–west mean, as is required by the energy view.

The concept of planetary energy budget is fundamental for understanding global warming. As the planet warms, it radiates more energy into space. The rate of the energy loss per degree GMST increase (namely climate feedback) determines the magnitude of temperature response to a change in radiative forcing. Existing theory predicts that the negative swing of internal variability would accelerate planetary energy uptake during the hiatus, but in observations, the global energy uptake has remained nearly constant since 2000[12]. This contradiction forced a re-evaluation of planetary energy budget theories. Climate feedback, as it turns out, differs between anthropogenic warming and internal cooling[13], and the difference is such that planetary energy uptake actually decreases during the surface warming hiatus. This conceptual shift has important implications for studying ocean heat uptake.

The hiatus spurred great interest in planetary energy uptake and redistribution in the ocean. A rigorous test of energy theory requires sustained global observations of planetary energy budget and ocean measurements beyond a depth of 2,000 m. A challenge is to reconcile ocean heat redistribution and the regional sea surface temperature modes that cause hiatus events. From the growing body of hiatus research, tropical Pacific decadal variability has emerged as an important pacemaker of global climate, but its mechanism remains to be elucidated. In the central equatorial Pacific, the surface cooling during the hiatus rides above a subsurface warming (Fig. 1b, at 100–250 m depth), highlighting the importance of ocean dynamics.

Much as weather forecasting improved over time through daily verification, the early-2000s hiatus provides a valuable case study to test our observations, understanding and models of the climate system. Climate models have withstood the test and scrutiny of the surge of research following the Meehl *et al.* study[3]. The La Niña-like pattern of tropical Pacific cooling not only proved to be a major driver for the early-2000s hiatus, but also explained regional anomalies — from the western Pacific sea level rise to California droughts. The need to track decadal changes in heat uptake provides a new impetus and raises the bar for ocean observations.

The early-2000s hiatus showed that we live in a special time in Earth's history, when anthropogenic warming and internal variability contribute equally to GMST change on timescales of a decade and longer. By exploiting the predictability from both initial conditions and radiative forcing, decadal prediction holds the promise of forecasting when the hiatus will end[14]. Stepping back in time, the first successful seasonal prediction of El Niño was made 30 years ago, using only a simple model of minimum essential physics[15]. It is clear that, to predict, we must first understand. ❐

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FOREST CARBON FLUXES

A satellite perspective

Reducing deforestation and forest degradation offers a quick win for climate mitigation. Using satellite data we are now able to better constrain pantropical estimates of forest loss, reshaping our understanding of the annual to decadal variability in land sources and sinks in the global carbon cycle.

Douglas C. Morton

Smoke plumes billowed from Borneo and Brazil in 2015, brought on by El Niño conditions that allowed fires to burn through tropical forests and peatlands. The damage from these fires, as measured by greenhouse gas emissions, depends on the amount of carbon stored in these tropical forest ecosystems. Writing in *Nature Climate Change* in 2012, Baccini *et al.*[1] used NASA satellite data to map tropical forest carbon stocks. Those data formed the foundation of a revised estimate of the net carbon fluxes from tropical forests, helping to shape the policy efforts to Reduce Emissions from Deforestation and Forest Degradation (REDD+), a core component of the Paris Agreement[2].

Using satellite data to estimate carbon stocks, rates of forest loss and degradation — and the fate of forest carbon