GLOBAL ENERGY BUDGET

Elusive origin of warming slowdown

Global surface warming was slower than expected in the first decade of the twenty-first century. Research attributes similar events to ocean or atmosphere fluctuations, but the subtle origins of these events may elude observational detection.

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Historical records in global warmth and severe weather extremes experienced during 2016 were the culmination of a long-term warming trend caused by human activities, boosted by the natural El Niño climate event. Yet the first decade of the twenty-first century experienced slow increases in global average surface temperature relative to the preceding two decades and compared with most climate model simulations[1]. When accounting for deficiencies in radiative forcing or surface temperature records[2], chaotic climate fluctuations are centre stage in explaining this discrepancy[3] yet their exact origin remains elusive. Writing in *Nature Climate Change*, Christopher Hedemann and colleagues[4] present a step towards understanding the root causes of periods experiencing slower-than-expected planetary warming.

There has been no hiatus in anthropogenic climate change. Despite lumps and bumps in the global temperature record, energy has continued to accumulate throughout the past two decades, primarily in the ocean, at a rate equivalent to the heating power of 300 billion 1-kilowatt electric heaters[5,6]. Energy absorbed from sunlight currently exceeds that lost to space by thermal infrared emission due to the inexorable rise in greenhouse gas concentrations in the atmosphere. How this steady heating reconciles with periods of slower or faster surface warming relates to the energy budget of the upper ocean.

Global surface temperature closely follows the heat content of the well-mixed upper-ocean layers. Energy fluxes at the sea surface and to deeper depths determine heat content in the uppermost layer, which links closely to global surface temperature[7]. If, on average, more energy enters than leaves this layer from the sea surface and the deeper ocean combined, the global surface temperature will rise (Fig. 1). Employing this energy balance perspective, Hedemann *et al.*[4] use sophisticated computer modelling techniques to understand the role of unforced fluctuations known to affect both Earth's top-of-atmosphere energy balance[8] (through cloud, circulation, and temperature patterns for example) and the episodic redistribution of heat between upper and lower layers of the ocean[9].

Over 100 detailed simulations of the global atmosphere and ocean were produced covering the period 1850–2005. These were fed with best estimates of historical radiative forcing — heating and cooling effects driving climate change. On top of this forced change, each simulation also generated its own unpredictable internal climate variability, sometimes capable of temporarily suppressing the rise in global surface temperature (Fig. 1). These hiatus events are defined as where the global mean surface temperature trend depicted by each simulation over a 15-year period is at least 0.17 °C per decade less than the average of all simulations. From hundreds of identified events, a detailed depiction of energy fluxes into and out of the upper 100 m ocean layer is possible.

Compared with the average of all simulations, differences in the fluxes at the ocean surface and through the bottom of the upper ocean layer are quantified for each of the hiatus events. The results show that a remarkably modest 0.08 $\mathrm{W\,m^{-2}}$ depression in heating of the upper layer (roughly 10% of the current rate of energy accumulation in the oceans[6]) can generate a significant slowing in surface warming. Atmospheric as well as oceanic fluctuations are implicated in these simulated events, while knock-on effects over land amplify the ocean's influence on global average surface temperature. Yet due to the modest signal and sizable observational uncertainty, it is seemingly not possible to attribute slow warming in the early twenty-first century to atmosphere or ocean fluctuations.

The climate is a complex coupled system: fluctuations in the ocean affect the top-of-atmosphere energy balance and vice versa[8]. Therefore it is somewhat artificial to diagnose purely ocean-based or atmosphere-based causes of suppressed surface warming episodes. Furthermore, the depiction of internal processes, feedback loops and ocean heat uptake by climate models may not adequately reflect the real world. Also, estimates of observed top-of-atmosphere and ocean energy budget differences from the simulations convolve sizable uncertainties from both. A combination of atmosphere and ocean climate fluctuations were likely involved in the unusual climatic conditions during the early twenty-first century.

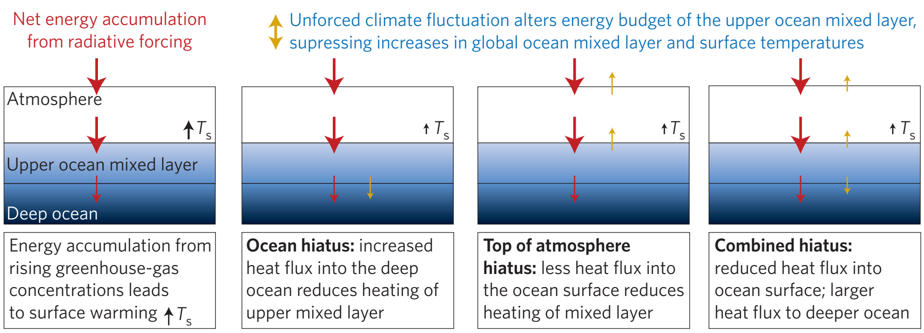

Figure 1 | Hiatus in surface warming and the upper-ocean heat budget. Energy accumulation due to radiative forcing (red arrows) is also affected by internal unforced climate variability (yellow arrows). These alter the flow of heat into and out of the upper mixed ocean layer, influencing the rate of surface temperature rise (↑T_s) in response to radiative forcing. Detailed modelling[4] suggests a hiatus in surface warming can originate from the deeper ocean, the top of Earth's atmosphere or both.

Human-caused climate change is continuing to be driven by the rapid accumulation of energy in the oceans, with increasingly severe impacts on societies and the ecosystems upon which they depend. The magnitude and rate of change depends upon how sensitive the surface climate is to the heating effect of rising greenhouse gas concentrations and how effectively the deep ocean subsumes accumulating heat. Energy budget approaches[10] offer a vital tool in gauging the realism of climate model simulations and their projections looking forward to progressively more distant decades. Extending this approach to include the budget of the upper ocean layers, as reported by Hedemann and colleagues[4], further elucidates the links between ongoing climate change and the global surface temperature that affects the many sheltering on the surface. Yet the subtle origin of slow early twenty-first century warming may elude detection. ❐

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