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ANNIVERSARY RETROSPECTIVE

# Slow warming and the ocean see-saw

The slowdown in surface warming in the early twenty-first century has been traced to strengthening of the Pacific trade winds. The search for the causes identifies a planetary-scale see-saw of atmosphere and ocean between the Atlantic and Pacific basins.

Yu Kosaka

Global mean surface temperatures increased less rapidly between the late 1990s and the early 2010s than in the preceding two decades, despite comparable rates of increase in atmospheric greenhouse gas concentrations[1]. This decadal slowdown of surface warming has raised a host of scientific questions. For example, it underlines the need to update our records of aerosol concentrations and of solar irradiance in order to quantify the influence of fluctuations in radiative forcing on Earth's temperature[2]. The distribution of heat in the ocean has been invoked in order to reconcile the slow global surface warming with an increasing greenhouse effect[3]. Regional climate events such as droughts in the southwestern US[4] and the supertyphoon Haiyan[5] are investigated in relation to the global warming slowdown. In terms of the cause of this warming slowdown, natural climate variability in the tropical Pacific Ocean on decadal scales has been identified as a key ingredient. In addition, writing in *Nature Climate Change* in 2014, McGregor and colleagues[6] proposed that an inter-basin see-saw of atmosphere and ocean between the Atlantic and Pacific oceans also contributed significantly.

Modelling studies have attributed the warming slowdown to a mode of decadal climate variability inherent in the tropical Pacific that describes the variability of sea surface temperatures in the Pacific Ocean on timescales of several decades, called the Interdecadal Pacific Oscillation[7]. A negative trend of the Interdecadal Pacific Oscillation features decadal intensification of the Pacific trade winds — that is, prevailing westward surface winds over the tropical Pacific — and surface cooling in the tropical eastern Pacific. Such a pattern of change tends to reduce the global mean surface temperature by cooling the global atmosphere, and thereby counteracts the warming trend that would otherwise occur in response to radiative forcing due to increasing atmospheric greenhouse gas concentrations[8,9].

However, atmospheric and oceanic conditions in the tropical Pacific are coupled and positively feed back on each other. Stronger trade winds promote upwelling of cool subsurface seawater in the eastern equatorial Pacific while pushing sun-baked warm surface water westward. The resultant east–west contrast of sea surface temperature accelerates the trade winds. Because of this feedback, it is difficult to discern causes and effects of phase transitions in the Interdecadal Pacific Oscillation from observed data alone.

McGregor et al.[6] therefore performed a suite of numerical experiments that allowed them to investigate an external trigger that set the feedback in motion. They noted that Atlantic warming since the 1990s can potentially trigger transitions in the phase of the Interdecadal Pacific Oscillation from positive to negative. Tropical atmospheric uplift is facilitated by warmer ocean surfaces, and similarly, downward motion is induced over cool waters. The tropical Atlantic warming and eastern Pacific cooling have therefore been changing the pattern of the Walker circulation, a planetary-scale overturning circulation of the tropical atmosphere that extends in the east–west direction. The trade winds at the surface of the Pacific Ocean are part of the Walker circulation, and they affect the heat exchange between ocean and atmosphere. An intensification of the trades therefore further cools the tropical eastern Pacific and leads to an excitation of the negative phase of the Interdecadal Pacific Oscillation[6,10].

It is thus the inter-basin thermal contrast between the tropical Atlantic and Pacific oceans — rather than solely the Atlantic warming — that drives the circulation changes and initiates an inter-basin see-saw (Fig. 1a). However, ocean–atmosphere interactions in McGregor and colleagues' simulations are limited to thermodynamic effects, and are missing feedbacks in the dynamics. Follow-up studies have shown that allowing the ocean currents to interact with the atmosphere further amplifies the Pacific anomalies in sea surface temperatures and trade-wind strength[10]. Indeed, swings of this multidecadal inter-basin see-saw are found throughout the twentieth century[11] (Fig. 1b).

Moreover, it turns out that the discovery of this Atlantic–Pacific inter-basin see-saw by McGregor and colleagues could help to extend predictability of tropical Pacific climate. Seasonal prediction skill in the tropical Pacific arises from El Niño–Southern Oscillation and has been generally limited to a year, the lifetime of a typical El Niño or La Niña event. By contrast, the predictability

**a**

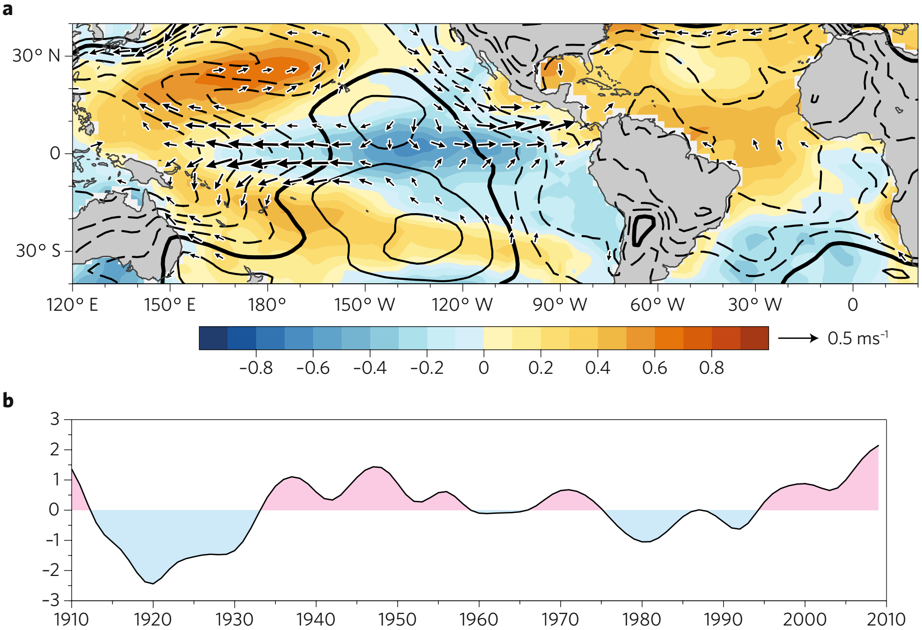


**Fig. 1 | Inter-basin see-saw. a**,**b**, The sea surface temperature see-saw between the tropical Pacific and Atlantic (**a**; colour shading for standardized anomalies) is coupled to anomalies in sea-level pressure (**a**; contours for every 0.2 standard deviation) and surface wind velocity (**a**; arrows) and they oscillate together (**b**; standardized time series). McGregor and colleagues[6] noted that the Atlantic warming since the 1990s associated with this pattern has led to an intensification of the Walker circulation and hence the tropical eastern Pacific cooling that in turn led to the slow warming period in the early twenty-first century[8,9]. The anomalies in panel **a** are regressed onto the leading principal component of standardized tropical sea-level pressure variability shown in panel **b**. Figure based on the 20th Century Reanalysis v.2c (ref. [21]) and Extended Reconstructed SST v.5 (ref. [22]), provided by US National Oceanic and Atmospheric Administration. A ten-year low-pass filter has been applied to annual means of all fields beforehand, and sea surface temperature has been linearly detrended.

associated with the Atlantic Multidecadal Oscillation extends to several years[12]. The surface signature of the Atlantic Multidecadal Oscillation is most pronounced in the extratropical North Atlantic, but it may be possible to exploit its tropical extension to improve tropical Pacific predictability through the inter-basin influence[13].

The existence of an inter-basin interaction between the Atlantic and Pacific oceans has raised the question whether the Indian Ocean has a similar remote influence. Indeed, the tropical Indian Ocean warming can also cool the eastern tropical Pacific[14], but its role is minor compared to the Atlantic[6,10,13]. Interestingly, the mutual influence between the tropical Pacific and the other two tropical basins is asymmetric. Tropical Atlantic and Indian Ocean thermal changes enhance the inter-basin temperature contrast with the tropical Pacific, whereas the Pacific variability acts to induce temperature anomalies of the same sign across the entire tropics[9,10]. Despite this apparent negative feedback from the tropical Pacific, whether and how the inter-basin contrast can sustain itself remains to be addressed.

At this point, the most important unresolved question is where the Atlantic–Pacific thermal contrast that triggered the inter-basin see-saw originated from. Radiative forcing by greenhouse gases is highly uniform globally, and cannot explain a strong east–west asymmetry in the tropics, unless oceanic dynamical effects dominate the thermodynamic responses[15]. Other possibilities include inhomogeneous influences on temperature, for example from aerosols[16,17], or the impacts of the Atlantic Multidecadal Oscillation triggered by stochastic fluctuations in the atmosphere[18]. If we can quantify those influences, along with the natural internal variability in the Pacific[19] and other ocean basins, we will be able to fully attribute the warming slowdown event.

The decadal timescale is where the spectra of natural climate variability and anthropogenic climate change overlap. Mixture of the two signals in observational records has rendered decadal variability studies difficult. Atmosphere–ocean coupled models such as the one used by McGregor and colleagues[6] can break these barriers and help advance our understanding of decadal variability. Coordinated multi-model experiments planned for the Decadal Climate Prediction Project[20] under the Coupled Model Intercomparison Project phase 6 will provide an avenue for further understanding global warming modulations and their uncertainties, and they will help with finding the causes of such events in the future. ❐

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