Orbit-induced changes in the seasonality of the Pacific cold-tongue region explained

Simulations reveal that the annual temperature cycle in the Pacific cold-tongue region is influenced by the shape of Earth's orbit, as well as by the planet's axial tilt. Together, these influences drive remarkable changes in the cold tongue's seasonality across a cycle of about 22,000 years.

The problem

The Pacific cold tongue — a region of relatively cool water in the eastern equatorial Pacific — forms an integral part of the tropical Pacific Ocean–atmosphere coupled system. The cold tongue has a seasonal cycle of temperature thought to originate from Earth's axial tilt, which modulates the thermal contrast between hemispheres and, therefore, the strength of the southeasterly trade winds[1,2]. The warm and cold months of the cold tongue should theoretically not change, because the calendar year is also determined by Earth's tilt. However, an Earth-system model[3] showed that the Pacific cold tongue's seasonal cycle changes as the longitude of perihelion (LOP) changes, even though the tilt is fixed (Fig. 1). The LOP reflects the orbital angle between the perihelion (the point at which Earth is closest to the Sun) and Earth's position at the equinoxes. This angle undergoes a complete revolution in approximately 22,000 years, called a precession cycle. Current understanding of the cold tongue's annual cycle cannot account for this behaviour.

The discovery

We reproduced the curious cold-tongue seasonal behaviour in several different Earth-system models, indicating that it is robust. Using one Earth-system model, we simulated the cold tongue's seasonal cycle over the range of orbital changes that have occurred over the past million years — namely, with different LOP angles and varying orbital deviations from a perfect circle. We showed that changes in cold tongue's seasonality result from a simple sum of two annual cycles: one that arises from the 'tilt effect' (from equinox to equinox, called the tropical year), and another that arises from the 'distance effect' (from perihelion to perihelion, called the anomalistic year). Although the prevailing theory of the cold tongue's seasonality factored in the tilt effect, it did not consider the distance effect. The anomalistic year is slightly longer than the tropical year (by about 25 minutes, currently). Interference between the two annual cycles results in a complex evolution of the cold tongue's seasonality over a precession cycle.

The distance effect drives seasonal fluctuations in the intensity of sunlight received by Earth, which, because of the heat capacity of the Pacific Ocean relative to that of the Africa-centred hemisphere opposite it, results in a seasonal shift in airflow patterns in the western equatorial Pacific. In turn, seasonal wind changes cause variations in the depth of the upper ocean layer of the equatorial tropical Pacific. These variations produce the cold tongue's seasonal cycle.

The implications

Our results call for a reassessment of the mechanisms that govern the Pacific cold tongue's annual cycle. They also have bearing on the understanding of the tropical Pacific's periodic cooling and warming known as the El Niño–Southern Oscillation (ENSO), which is modulated by the tropical Pacific seasonal cycle[4]. Our findings also have implications for reconstructions of palaeoclimate. Proxy measurements of the Pacific cold tongue in the past are typically interpreted as reflecting variations in the ENSO, but our results suggest that the cold tongue's seasonal cycle should also be considered.

Although reproduced by several Earth-system models, the changing seasonality of the cold tongue is still a model result and therefore requires real-world testing. Analysis of proxy measurements of the cold tongue in the past could achieve this, although it will require records that measure the annual cycle and, crucially, a way to correlate the calendar with them. We are not aware of a proxy method that achieves the latter but, if ancient semiannual cycles can be resolved, they might provide a suitable reference, because they are also caused by the tilt effect.

We wonder whether the distance effect influences seasonal cycles of other regional climates. Our research demonstrates that valuable insights into the climate system can be gained from systematic examination. It might also have had implications for changes in global ancient climate across previous precession cycles, because the climate of the tropical Pacific affects those in other parts of the world, similar to how the ENSO affects regional climates around the world[5] today.

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EXPERT OPINION

"This work re-examines the annual cycle of the Pacific cold tongue. The authors provide compelling evidence that the annual cycle partly arises from Earth's orbital precession, adding to the widely accepted contribution of the tilt effect. This work calls for rethinking of what causes seasonal cycles not only in the tropical Pacific, but also beyond — especially given that seasonal cycles are often taken for granted and rarely (if ever) questioned."

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FIGURE

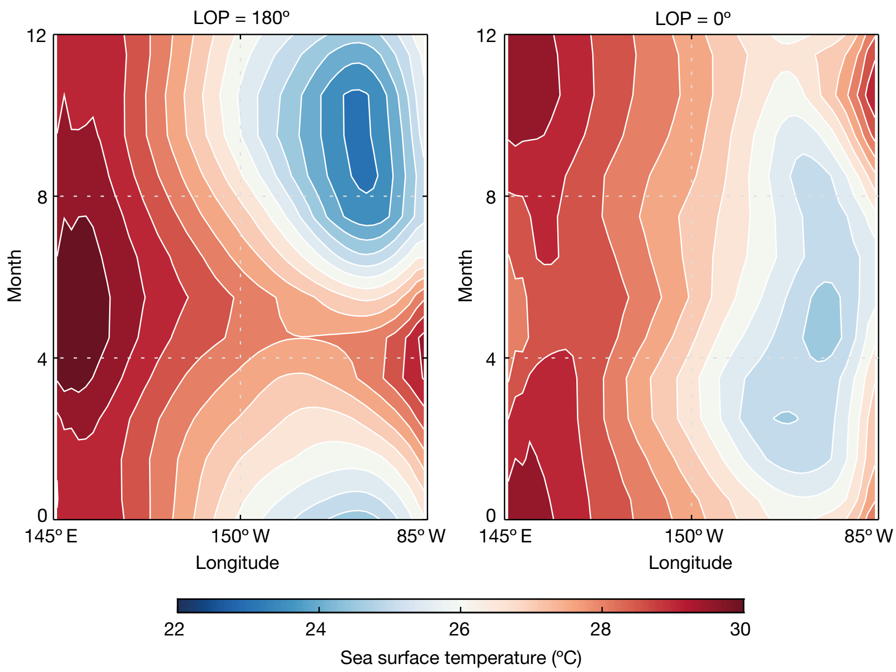

Figure 1 | Change in the seasonality of the Pacific cold-tongue region with orbital changes. The seasonal cycle of temperature in the cold-tongue region of the eastern equatorial Pacific as simulated in an Earth-system model by Erb *et al.*[3]. The left and right panels show the cycle when the perihelion (Earth's closest position to the Sun) is at the Northern Hemisphere's spring equinox or autumn equinox, resulting in an angle called the longitude of perihelion (LOP) of 180° or 0°, respectively. The deviation of the orbit's shape from a perfect circle is set at a relatively high value, with the Earth–Sun distance at perihelion about 5% shorter than the mean. The timing of the cold and warm months over the region, and the cycle's amplitude, change considerably with the LOP.

BEHIND THE PAPER

A theory of the cold tongue's seasonal cycle was developed in the 1990s, but the topic has been (as described by a knowledgeable colleague) "off the radar for a while now". When Erb *et al.*[3] showed a drastic change to its seasonality with orbital precession, the result was fascinating yet puzzling to me and my co-authors because we realized that the theory failed to explain this behaviour. We initially drafted a 'position paper' noting this failure and highlighting the implications of a varying Pacific cold-tongue seasonality for both climate dynamics and palaeoclimate. However, a sabbatical year afforded me the time to work on solving the problem, specifically by undertaking simulations that spanned the space of orbital changes. The 'eureka' moment came with the realization that the sum of the distance-effect and tilt-effect annual cycles essentially explains the cold-tongue changes of those simulations.

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FROM THE EDITOR

It is rare for a paper to successfully address the "wait a minute, why doesn't this make sense?" question in climate science, in which many topics are deeply entrenched. Chiang *et al.* do exactly that, elegantly staging a series of model experiments to unravel some of the complexities governing the variability of the tropical Pacific. The work should break off a fresh bout of research into the orbital controls of climate variability, more generally.

Michael White, Senior Editor, *Nature*