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Two Equations that Unlock El Niño

Despite the El Niño–Southern Oscillation's global reach and complex ocean–atmosphere interactions across timescales, two simple, elegant equations capture its key dynamics and defining properties.

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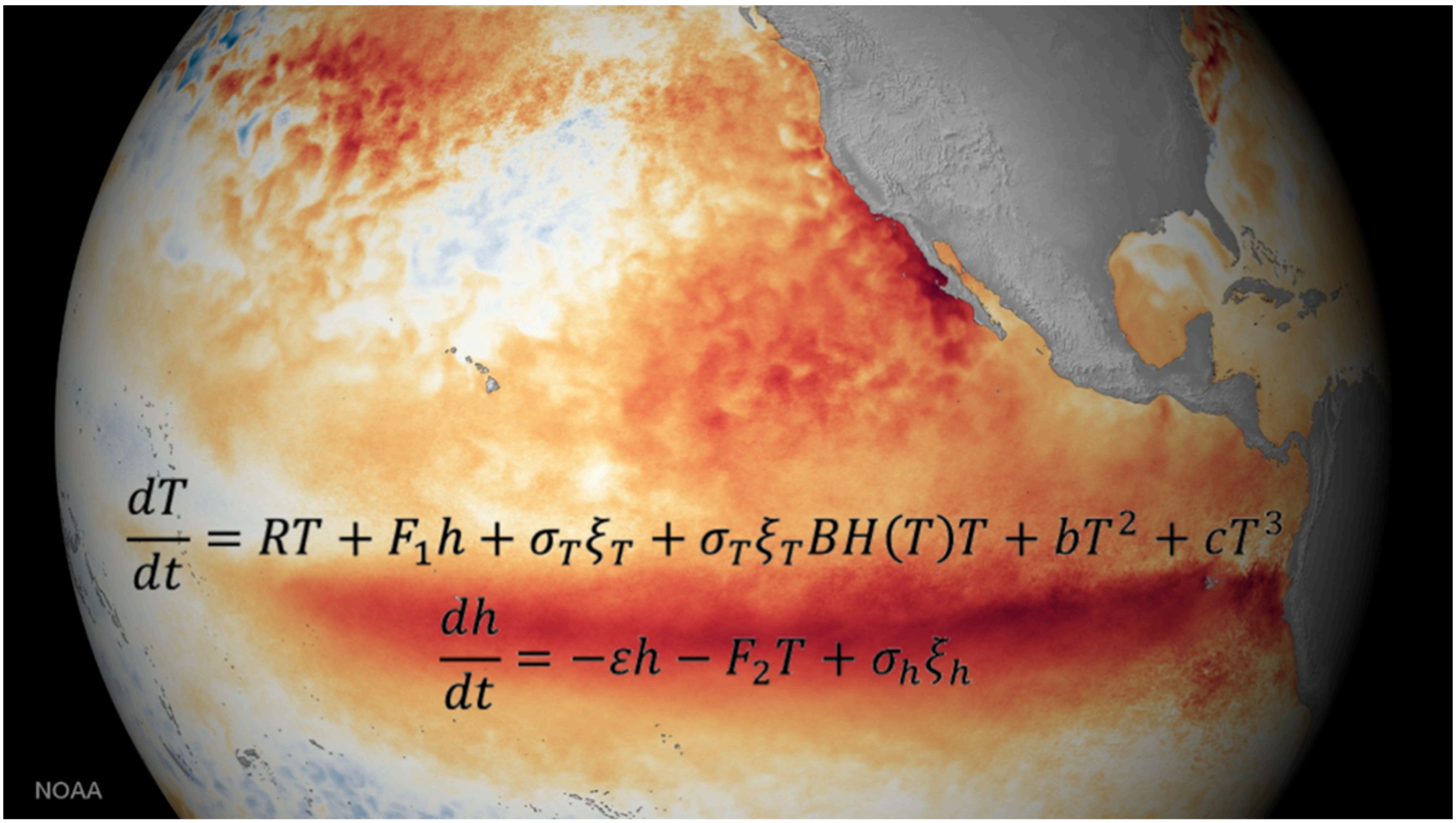
5 June 2025



The dark orange-red band across the Pacific shows above-normal satellite sea surface temperatures in October 2015, indicating El Niño. Overlaid are the recharge oscillator equations that capture ENSO's key dynamics and defining properties. Background Image: NOAA

Editors' Vox is a blog from AGU's Publications Department.

The El Niño Southern Oscillation (ENSO) is a natural climate phenomenon driven by interactions between the ocean and atmosphere in the tropical Pacific. In recent decades, major advances in observing and modeling ENSO have greatly improved our understanding, yet important challenges remain.

A **recent article** in ***Reviews of Geophysics*** highlights the recharge oscillator (RO) conceptual model, a simple mathematical representation of ENSO fundamental mechanisms. Here, we asked the lead author to provide an overview of ENSO, discuss the strengths and limitations of the RO model, and outline key open questions.

Why is the El Niño Southern Oscillation (ENSO) important to understand?

ENSO events typically last around a year and occur in two phases: El Niño, when the central and eastern Pacific Ocean becomes unusually warm, and La Niña, when it becomes cooler than normal. These temperature shifts disrupt wind patterns and rainfall, triggering anomalies such as droughts, floods, tropical cyclones, and marine or terrestrial heatwaves. These impacts strongly affect ecosystems, agriculture, and economies around the world.

Although ENSO originates in the tropical Pacific, its influence extends globally through atmospheric "teleconnections." Because of its widespread effects, understanding and predicting ENSO is essential. Today, coupled ocean–atmosphere models and statistical methods allow scientists to forecast ENSO events up to a year in advance, making ENSO a key pillar of global seasonal climate prediction.

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Over the past few decades, what advances have been made in observing and modeling ENSO?

Two major breakthroughs in the 1990s greatly advanced our ability to observe and model ENSO. First, on the observational side, the **TAO mooring array** across the equatorial Pacific and satellite altimetry provided continuous measurements of surface meteorological and subsurface ocean conditions—key data for understanding ENSO dynamics. Second, modeling evolved from simplified "intermediate" coupled models of the 1980s to more sophisticated coupled general circulation models (CGCMs), which simulate the full complexity of ocean–atmosphere interactions.

These advances provided deeper insight into the mechanisms driving ENSO. Importantly, subsurface observations also became essential for initializing ENSO forecasts improving their accuracy. Together, these observational and modeling tools laid the groundwork for modern ENSO research and prediction systems.

What are the benefits of using conceptual models to understand ENSO compared to other modeling methods?

Conceptual models of ENSO are simple mathematical representations that distill the phenomenon into just a few key variables—such as sea surface temperature in the central Pacific or equatorial ocean heat content. These models use basic equations to capture the core dynamics of ENSO, including the Bjerknes feedback (a positive loop that amplifies temperature anomalies) and slower equatorial ocean adjustment processes that help shift ENSO from one phase to another.

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> ***Conceptual models offer clarity and insight that complement the realism of full-scale simulations.***

Because they focus on essential mechanisms, conceptual models are powerful tools for teaching and for gaining physical intuition. They also allow researchers to test hypotheses about ENSO dynamics in a controlled, simplified setting. Despite their simplicity, they can make useful quantitative predictions about ENSO features like amplitude or period, and are often used to diagnose biases in more complex climate models. In short, conceptual models offer clarity and insight that complement the realism of full-scale simulations.

What is the “recharge oscillator” model and why did you choose to focus on it?

The Recharge Oscillator (RO) is a conceptual model of ENSO introduced in the mid-1990s by Fei-Fei Jin. Unlike earlier models, it includes an explicit equation for subsurface ocean heat content, capturing ENSO’s “memory.” Its flexible mathematical structure has allowed researchers to gradually increase its realism while preserving simplicity and interpretability.

In our review, we show that the RO can now reproduce key ENSO characteristics, including its amplitude, dominant period, seasonal synchronization, and the tendency for El Niño events to be stronger than La Niña events. Remarkably, recent studies show that it can even rival complex dynamical models in terms of forecast skill. Thanks to its clarity, predictive power, and widespread use in the research community, the Recharge Oscillator was a natural focus for a dedicated review.

How does the recharge oscillator model aid in understanding ENSO response to climate change?

Climate models generally project increased near-surface ocean stratification under climate change. Most predict a weakening of the equatorial Pacific trade winds, though some show a strengthening—closer to observed trends in recent decades. These shifts in the background mean state can significantly affect ENSO behavior.

The Recharge Oscillator (RO) helps explore these effects by providing quantitative links between the mean state and ENSO characteristics such as amplitude, period, and asymmetry. This makes the RO a useful tool for understanding how future changes in stratification or winds might influence ENSO—and why model projections sometimes disagree. However, using the RO to study climate change impacts is still a developing field, partly because the way mean state changes affect RO parameters is not yet fully understood. Addressing this gap is highlighted in our review as a key direction for future research.

What are the primary challenges or limitations of the recharge oscillator model?

Klaus Wyrtki famously noted that “no two El Niño events are alike.” This insight underpins the challenge of ENSO diversity—the fact that some events peak in the eastern Pacific, while others peak farther west, with differing global impacts. Capturing this diversity remains a key limitation of the RO. While recent studies have proposed promising ways to represent these variations within the RO framework, more work is needed to develop a community consensus on a physically consistent approach.

Another challenge lies in modeling two-way interactions between ENSO and other climate modes, such as the Indian Ocean Dipole or Atlantic variability, which can influence ENSO through atmospheric teleconnections. These interactions are not accounted for in the RO. However, recent work introducing an extended Recharge Oscillator (XRO) offers a promising path forward. Overcoming these limitations will strengthen the RO’s relevance for studying both ENSO diversity and its links to broader climate variability.

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What are some of the remaining questions where additional modeling, data, or research efforts are needed?

In our review, we highlight 10 open research questions—many of which are well-suited for PhD or postdoctoral projects—centered on improving the RO and using it to explore broader ENSO dynamics. These include previously mentioned challenges such as understanding ENSO behavior in a warming climate, accounting for ENSO diversity, and modeling interactions with other climate modes. Several of these topics are already being actively explored, reflecting the vitality of the field.

To support future research, we will soon release open-source Python and Matlab versions of the RO, accompanied by a technical article detailing its numerical implementation and parameter fitting methods. This will make it easier for researchers to use and extend the RO framework to address today’s pressing ENSO questions—ultimately helping bridge conceptual models and complex Earth system simulations.

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Editor’s Note: It is the policy of AGU Publications to invite the authors of articles published in Reviews of Geophysics to write a summary for Eos Editors’ Vox.

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Citation: Vialard, J. (2025), Two equations that unlock El Niño, *Eos, 106,* https://doi.org/10.1029/2025EO255018. Published on 5 June 2025.