https://doi.org/10.1038/s41561-023-01134-1

Unravelling ENSO complexity

Progress in understanding and modelling ENSO complexity provides a promising opportunity to both improve seasonal climate prediction and constrain future anthropogenic warming.

The El Niño/Southern Oscillation (ENSO) is one of the most influential fluctuations in the global climate system. Alternating patterns of sea surface temperature in the tropical Pacific give rise to two distinct phases that have far-reaching impacts on the weather and environment. The warm phase — known as El Niño — is characterized by warmer than average temperatures in the eastern tropical Pacific, whereas La Niña occurs when the temperatures drop. The basic dynamics that govern this oscillation are generally understood, yet current climate models struggle to capture the full complexity of ENSO in terms of its spatial and temporal evolution[1]. This hinders our ability to predict and prepare for the widespread associated changes in rainfall, temperature, and other affected climatic conditions. ENSO variability is also responsible for substantial uncertainties in future warming patterns[2]. Therefore, improving the representation of ENSO complexity in climate models could help constrain future anthropogenic warming and allow us to better anticipate seasonal ENSO-driven hazards.

The full extent to which ENSO influences our environment is becoming ever more apparent as further teleconnections — climate impacts that occur far from the source region of variability — are uncovered. The oscillation between El Niño and La Niña phases in the Pacific Ocean influences atmospheric circulation, temperature, and precipitation globally, with a multitude of knock-on effects on weather hazards, agriculture and society. El Niño and La Niña events have been linked to widespread flood risk[3], tornado frequency in the USA[4], wildfire occurrence in China[5], and shifts in the Gulf Stream[6]. The impacts even stretch as far as Antarctica, where ENSO plays a role in sea ice trends[7]. In this issue of *Nature Geoscience*, an Article by Kilian Vos and co-authors shows that ENSO even reshapes coastlines. They make use of extensive satellite observations to reveal that La Niña and El Niño events produce distinct patterns of beach erosion across large portions of the Pacific rim.

Given the range of teleconnections and societally important phenomena governed by ENSO, the value of accurate prediction is clear. However, predicting the phases of ENSO is a complicated task. The year-to-year climate fluctuations arise, broadly speaking, because of ocean–atmosphere feedbacks that modify tropical atmospheric circulation. A broad range of dynamical processes are involved that interact on timescales ranging from weeks to decades. This results in considerable diversity in event characteristics such as amplitude, spatial pattern, and temporal evolution — collectively referred to as ENSO complexity[1]. This complexity makes it difficult to accurately predict ENSO events and their associated impacts, with global models exhibiting persistent biases[1].

The inability to accurately represent ENSO complexity is also problematic for understanding how ENSO is likely to respond to ongoing anthropogenic warming. Some robust responses to greenhouse gas-driven warming have been identified in model simulations, such as intensification of ENSO-driven variability in rainfall[8], and an increase in extreme El Niño and La Niña events[9]. However, there are notable inter-model differences, and some model results contradict observed changes[9]. Inter-model differences in how the amplitude of ENSO responds to warming have been shown to account for 50% of the uncertainty in projections of future Southern Ocean warming[2]. As the Southern Ocean plays a major role in absorbing excess heat from global warming, this suggests that better representation of ENSO complexity in global climate models could help to further constrain future warming projections.

More advanced modelling techniques are helping to better illuminate some of the remaining questions regarding ENSO in a warmer world. The use of large ensembles of climate model simulations has revealed the importance of the butterfly effect for changes in ENSO[10], whereby very small differences in initial conditions can strongly impact the evolution of ENSO characteristics. This dependence on the past highlights the importance of correctly capturing ENSO complexity in the current climate state. Small-scale ocean eddies (less than several hundred kilometres in size) have been shown to play a key role in the growth of El Niño and La Niña events[11]. The use of high-resolution models allows these small-scale eddies to be explicitly resolved, and accounting for these eddies can reduce longstanding overestimation of the strength of El Niño and La Niña events[11].

Encouraging progress is being made through the use of such innovative modelling techniques. Continued efforts are needed to further improve understanding of the complexities of ENSO, and enable better prediction of its widespread climatic impacts.

Published online: 10 February 2023

References

1. Timmermann, A., An, S. I. & Kug, J. S. et al. *Nature* **559**, 535–545 (2018).
2. Wang, G., Cai, W. & Santoso, A. et al. *Nat. Clim. Chang.* **12**, 649–654 (2022).
3. Ward, P. J. et al. *Proc. Natl Acad. Sci. USA* **111**, 15659–15664 (2014).
4. Allen, J., Tippett, M. & Sobel, A. *Nat. Geosci.* **8**, 278–283 (2015).
5. Fang, K., Yao, Q. & Guo, Z. et al. *Nat. Commun.* **12**, 1764 (2021).
6. Taylor, A., Jordan, M. & Stephens, J. *Nature* **393**, 638 (1998).
7. Crosta, X., Etourneau, J. & Orme, L. C. et al. *Nat. Geosci.* **14**, 156–160 (2021).
8. Hu, K., Huang, G. & Huang, P. et al. *Nat. Geosci.* **14**, 377–382 (2021).
9. Cai, W., Santoso, A. & Collins, M. et al. *Nat. Rev. Earth Environ.* **2**, 628–644 (2021).
10. Cai, W., Ng, B. & Geng, T. et al. *Nature* **585**, 68–73 (2020).
11. Wang, S., Jing, Z. & Wu, L. et al. *Nat. Geosci.* **15**, 112–117 (2022).