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OPINION

Using a “Super” El Niño to understand how lakes respond to climate extremes

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> “ENSO phenomena provide tremendous opportunities for natural ecological comparisons at multiple hierarchical levels over broad geographic scales, and can effectively serve as a regional or global ecological field experiment.” – Garcia et al., 2003

A highly probable “super” El Niño will likely impact global climate starting in winter 2026

Garcia et al. (2003) [1] highlighted the need to catalog the effects of ENSO phenomena to observe the impacts of climate extremes that may be expected in the future. Limnologists have an opportunity to examine climatic variability and extreme events on a global scale [2] with the high probability of an impending “super” El Niño in the coming year (> 2 °C sea surface temperature anomaly) and likely warmer-than-average air temperatures alongside variation in precipitation and a higher potential for extreme weather events [3].

A historically strong El Niño may warm lakes, lengthen stratification, and alter their food webs

Lakes serve as ideal laboratories because they track the intersection of ENSO effects and global climate change. Their susceptibility to meteorological variability, localized runoff, and climate signals make them strong bellwethers of local and large-scale influence [4].

The upcoming ‘super” El Niño offers lake researchers a beneficial timescale in which to investigate the effects of climate variability. The aggregate of this collective research may permit a glimpse into the future state of lake behavior and verify model predictions. Moreover, it offers researchers and stakeholders more broadly the opportunity to test the resilience of future management strategies to maintain vital ecosystem services.

We hypothesize that warmer than average temperatures and variable precipitation associated with “super” El Niño events will contribute to shorter ice duration, warmer lake water temperatures, longer stratification, and fluctuating water levels all of which are predicted to intensify in a warming climate (Fig 1) [5].

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During the winter, warming temperatures in response to El Niño events diminishes ice cover (Fig 1A) [6], which may inhibit reproductive success for some fish species [7]. However, reduced ice cover during warmer winters may, paradoxically, result in cooler under-ice water temperatures and higher oxygen concentrations. This response could arise from the loss of the insulating effect of ice, enhanced winter mixing and inflows, and reduced mineralization and respiratory oxygen demand in bottom waters. Delayed ice cover may also prolong primary productivity while earlier breakup can extend the stratification period during the summer (Fig 1B).

The summer will perhaps prove the most challenging period to disentangle the signal of a warming climate from a "super" El Niño. El Niño events typically include warmer-than-average air temperatures that are likely to increase surface water temperatures and strengthen stratification [8], which are similar to the general warming signal from climate change [9]. However, El Niño events may have a stronger impact on surface waters rather than whole lake warming, significantly impacting stratification stability. Combined with warmer winters and shorter ice duration, the onset of stratification may also be earlier, significantly increasing the duration of stratification [10]. Longer and stronger stratification periods have secondary effects, such as diminishing deep-water dissolved oxygen concentrations [11] and favoring cyanobacteria growth [12], both responses that degrade water quality.

Changes in precipitation variability can generate hydrological extremes, including droughts and intense rainfall events, with substantial consequences for lake physical, chemical, and ecological processes. For example, enhanced precipitation can increase nutrient and carbon loading. Because lakes incorporate the flux of water and nutrients from their watersheds, agricultural and industrial effluent may have stronger influences in El Niño years (Fig 1C). Conversely, warmer temperatures and diminished precipitation may enhance evapotranspiration within the watershed and reduce lake levels [13]. Reduced lake levels may have compounding effects alongside increasing water temperatures and prolonged stratification, such as hypoxia, cyanobacterial growth, and degraded water quality (Fig 1D).

The influence of warming temperatures and variable precipitation can have secondary effects on lake ecosystem function. The longer stratification induced by El Niño may suppress upwelling and reduce algal production, leading to reduced fish populations [14]. Earlier ice breakup and stratification onset can shift algal bloom timing earlier in the season, interrupting the energy flow among trophic levels [10]. Prolonged isolation can diminish oxygen concentrations in deep waters, leading to upwelling of phosphorus that diminishes water quality by fueling cyanobacterial blooms [8].

Using a "super" El Niño as an analog for future climate change

Long-term ecological research stations (LTERs) do critical work to catalogue trends in lake behavior but also offer the opportunity to create critical reference points during the extreme behavior that can occur during an El Niño. However, even without prior lake data, observations collected during a super El Niño can substantially improve

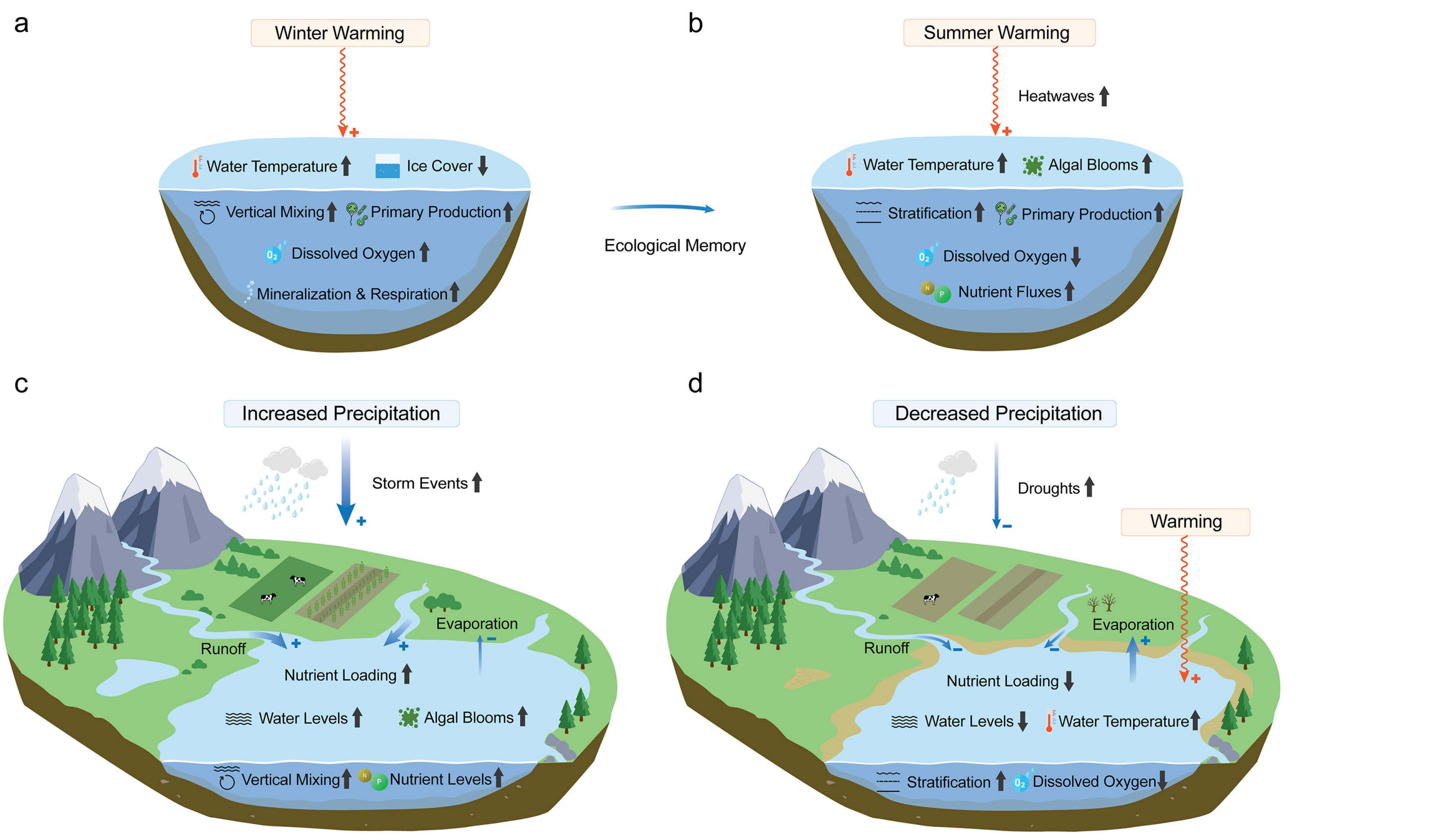

Fig 1. The potential effects of El Niño on lakes. Conceptual framework of "super" El Niño impacts on lake ecosystems based on four scenarios including: a) winter warming; b) summer warming; c) increased precipitation; and d) decreased precipitation.

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the geographical representation of lakes experiencing climate extremes, enabling cross-system comparisons and helping to characterize the diversity of lake responses to anomalous atmospheric forcing

A "super" El Niño event affords the opportunity to address key knowledge gaps including:

- Are high-magnitude or more frequent climate oscillations (like a "super" El Niño) indicative of future lake state changes?
- Will rapid shifts between "super" ENSO events (La Niña to El Niño as in 2025–2027) lead to deleterious effects on lakes? How will different lake types respond to "super" ENSO events in different regions?
- How long will a "super" El Niño event remain within the "memory" of a lake and do different lakes retain this "memory" for longer?
- Can we use these high magnitude events to learn which lakes are most vulnerable or, conversely, most resilient to future climate change?
- At what point does long-term climate change overwhelm the signals of "super" El Niño events? How can we disentangle long-term background warming from climate change from ENSO events?
- What information do we lose if we miss these signals without frequent monitoring?
- With earlier ice off and earlier spring blooms, how will trophic transfer and bloom dynamics shift?

- How will a prolonged warm period, alongside elevated nutrient loading, affect the metabolic balance of lakes and nutrient/carbon cycling?
- What challenges do warming and variable nutrient fluxes pose to water treatment and maintaining drinking water standards?

This upcoming "super" El Niño event offers an opportunity to learn more about how global lakes may respond to future climate change and to test how resilient our climate mitigation and adaptation strategies are against the challenges posed by climate change.

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References

1. Garcia AM, Vieira JP, Winemiller KO. Effects of 1997–1998 El Niño on the dynamics of the shallow-water fish assemblage of the Patos Lagoon Estuary (Brazil). Estuar Coast Shelf Sci. 2003;57(3):489–500. https://doi.org/10.1016/s0272-7714(02)00382-7
2. Stockwell JD, Doubek JP, Adrian R, Anneville O, Carey CC, Carvalho L, et al. Storm impacts on phytoplankton community dynamics in lakes. Glob Chang Biol. 2020;26(5):2756–84. https://doi.org/10.1111/gcb.15033 PMID: 32133744
3. World Meteorological Organization. WMO: Prepare for El Niño [Internet]. World Meteorological Organization; 2026 [cited 2026 Jul 14]. Available from: https://wmo.int/news/media-centre/wmo-prepare-el-nino
4. Adrian R, O'Reilly CM, Zagarese H, Baines SB, Hessen DO, Keller W, et al. Lakes as sentinels of climate change. Limnol Oceanogr. 2009;54(6):2283–97. https://doi.org/10.4319/lo.2009.54.6_part_2.2283 PMID: 20396409
5. Woolway RI, Sharma S, Smol JP. Lakes in hot water: the impacts of a changing climate on aquatic ecosystems. BioScience. 2022:biac052. https://doi.org/10.1093/biosci/biac052
6. Sharma S, Richardson DC, Woolway RI, Imrit MA, Bouffard D, Blagrave K, et al. Loss of ice cover, shifting phenology, and more extreme events in Northern Hemisphere lakes. JGR Biogeosciences. 2021;126(10):e2021JG006348. https://doi.org/10.1029/2021jg006348
7. Block BD, Stockwell JD, Marsden JE. Contributions of winter foraging to the annual growth of thermally dissimilar fish species. Hydrobiologia. 2020;847(20):4325–41. https://doi.org/10.1007/s10750-020-04428-2
8. García-Oliva O, Dix MA, Martínez-Fausto MM, Bocel JE, Garcia-Polo J, Vargas-López N, et al. Climate change and El Niño Southern Oscillation influence on mixing regime and water quality in a deep tropical mountain lake. Limnol Oceanogr Lett. 2026;11(2):e70115. https://doi.org/10.1002/lol2.70115
9. O'Reilly CM, Sharma S, Gray DK, Hampton SE, Read JS, Rowley RJ. Rapid and highly variable warming of lake surface waters around the globe. Geophys Res Lett. 2015;42(24). https://doi.org/10.1002/2015GL066235
10. Winder M, Schindler DE. Climatic effects on the phenology of lake processes. Glob Change Biol. 2004;10(11):1844–56. https://doi.org/10.1111/j.1365-2486.2004.00849.x
11. Jane SF, Hansen GJA, Kraemer BM, Leavitt PR, Mincer JL, North RL, et al. Widespread deoxygenation of temperate lakes. Nature. 2021;594(7861):66–70. https://doi.org/10.1038/s41586-021-03550-y PMID: 34079137
12. Carey CC, Ibelings BW, Hoffmann EP, Hamilton DP, Brookes JD. Eco-physiological adaptations that favour freshwater cyanobacteria in a changing climate. Water Res. 2012;46(5):1394–407. https://doi.org/10.1016/j.watres.2011.12.016 PMID: 22217430
13. Irwandi H, Rosid MS, Mart T. The effects of ENSO, climate change and human activities on the water level of Lake Toba, Indonesia: a critical literature review. Geosci Lett. 2021;8(1):21. https://doi.org/10.1186/s40562-021-00191-x
14. McGlue MM, Ivory SJ, Stone JR, Cohen AS, Kamulali TM, Latimer JC. Solar irradiance and ENSO affect food security in Lake Tanganyika, a major African inland fishery. Sci Adv. 2020;6(41):eabb2191. https://doi.org/10.1126/sciadv.abb2191