El Nino in a Warming World: Science, Impacts, and the 2026 Forecast

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Abstract
El Niño, the warm phase of the El Niño–Southern Oscillation (ENSO), stands as the most significant driver of interannual climate variability globally. Originating from periodic sea-surface temperature anomalies in the central and eastern tropical Pacific, El Niño triggers large-scale atmospheric reconfigurations that fundamentally alter precipitation patterns, temperature regimes, storm tracks, and ocean productivity across all inhabited continents. This review synthesises the historical scientific evolution of ENSO, tracing the progression from early twentieth-century observations by Peruvian fishermen and Indian monsoon meteorologists to the foundational work of Gilbert Walker and Jacob Bjerknes. It further highlights the transition from conceptual frameworks to modern coupled ocean–atmosphere models and satellite-era predictive capabilities. The scope of this analysis spans the multifaceted impacts of El Niño, examining its consequences for agriculture and food security, marine ecosystem stability, water resource management, public health, energy demand, and macroeconomic stability. By surveying the differentiated regional footprints across the Americas, the Asia-Pacific, Australia, and Africa, the review provides a comprehensive look at how this phenomenon reshapes terrestrial ecosystems and biodiversity. Finally, the analysis evaluates the emerging 2026 El Niño event—projected to be among the strongest on record—within the context of anthropogenic climate change. It concludes by assessing the efficacy of current early-warning systems and adaptation strategies essential for mitigating the profound human and ecological vulnerabilities inherent to this global climate driver.

Keywords: El Niño-Southern Oscillation (ENSO), Climate Variability, Marine Ecosystems, Predictive Modelling.

1. Introduction

Every three to seven years, a massive swath of the tropical Pacific Ocean—stretching across a distance roughly equivalent to the width of the continental United States—warms by one to three degrees Celsius above its long-term average. This phenomenon, known as El Niño, is far more than a localised oceanic curiosity; it serves as the surface signature of a profound and planetary-scale reconfiguration of the global ocean–atmosphere engine. Because this engine drives the world's weather patterns, the consequences of El Niño ripple outward to touch nearly every inhabited continent. Its impacts are felt through disrupted monsoon rains over India, altered wheat yields in the Argentine Pampas, widespread coral reef bleaching in the Coral Triangle, heightened wildfire seasons in Australia, recurring cholera outbreaks in East Africa, and volatile coffee prices on New York trading floors. Few natural phenomena illustrate as clearly how deeply interconnected the Earth system—and the human economy layered upon it—truly are [1]. El Niño and its cooler counterpart, La Niña, together constitute the El Niño–Southern Oscillation (ENSO), which is widely regarded by climate scientists as the most influential mode of natural climate variability on timescales of one to several years. Unlike the steady, slow-moving signal of long-term anthropogenic climate change, ENSO delivers its effects in irregular, potent pulses. Each event possesses a distinct character, intensity, and geographic fingerprint, making the phenomenon simultaneously predictable in its broad outlines and yet stubbornly difficult to forecast in its finer details more than a year in advance [2]. This comprehensive review is structured to accomplish four primary objectives. First, it retraces the scientific evolution of ENSO, moving from nineteenth-century anecdotal observations by colonial meteorologists and Peruvian fishermen to the sophisticated coupled ocean–atmosphere theory developed in the late twentieth century. Second, it provides a detailed explanation of the physical mechanisms that generate an El Niño event and the robust monitoring infrastructure that enables today's forecasting capabilities. Third, it examines the documented impacts of El Niño across diverse sectors of human development—including agriculture, fisheries, water resources, public health, energy systems, macroeconomics, and disaster risk—alongside its profound effects on terrestrial and marine ecosystems. Fourth, it evaluates the critical question of how anthropogenic climate change is altering ENSO itself, closing with a status report on the strong El Niño event that was developing through the middle of 2026. El Niño and La Niña represent the opposing warm and cold phases of the El Niño-Southern Oscillation (ENSO), a natural climate cycle driven by shifts in tropical Pacific sea-surface temperatures and atmospheric circulation. During El Niño, weakened trade winds cause warm waters to pool in the central and eastern Pacific, whereas La Niña—the cold phase—features strengthened trade winds that enhance equatorial upwelling, resulting in cooler eastern surface temperatures. While El Niño events typically endure for up to 18 months, La Niña episodes are often more persistent, sometimes lasting up to three years. These cyclical ocean anomalies fundamentally reorganise global weather patterns, leading to significant, geographically differentiated impacts on regional precipitation, temperature extremes, and disaster vulnerability. By synthesizing evidence from the peer-reviewed literature and international agencies—including the World Meteorological Organization (WMO), the U.S. National Oceanic and Atmospheric Administration (NOAA), the World Health Organization (WHO), and the Food and Agriculture Organization (FAO)—this review provides a structured account of a phenomenon that, event after event, fundamentally reshapes the fortunes of billions of people [3, 4].

2. The Evolution of El Niño Science: From Folklore to Coupled Theory

Origins of the name: The term "El Niño"—Spanish for "the little boy," in reference to the Christ child—was coined by Peruvian and Ecuadorian fishermen in the nineteenth century to describe a warm ocean current that appeared off the coast of South America around Christmastime in certain years. For these local communities, the arrival of this current was synonymous with a suppression of the usually rich anchoveta catch, which was the backbone of their local economy. For decades, the phenomenon was understood only as a local oceanographic event, geographically confined to the eastern Pacific coast of

South America. It took the better part of a century, and the concerted work of scientists on three continents, before the research community recognised that this localised warming was merely the visible edge of a basin-wide, planetary-scale reorganisation of both ocean and atmosphere [5].

Gilbert Walker and the Southern Oscillation: The first major scientific breakthrough in understanding ENSO came not from oceanography, but from an urgent, government-backed effort to forecast the Indian monsoon. Following a catastrophic famine linked to a monsoon failure in the late nineteenth century, the British colonial government dispatched the mathematician and physicist Sir Gilbert Walker to India to search for reliable statistical predictors of monsoon rainfall. Throughout the 1920s, Walker rigorously built regression relationships between Indian rainfall and a wide range of remote climate indicators, including Himalayan snow cover. In the process, he identified a seesaw in surface air pressure between the eastern and western tropical Pacific—high pressure over one region tended to coincide with low pressure over the other, and vice versa. He named this the "Southern Oscillation" and devised an index based on the pressure difference between Tahiti and Darwin, Australia, which remains a key diagnostic tool today. Although Walker's statistical work was incredibly rigorous, he lacked a physical explanation for why the atmosphere behaved in such a rhythmic, seesaw manner, and for several decades, the Southern Oscillation was treated largely as a mathematical curiosity rather than a physical reality [5].

Jacob Bjerknes and the coupled ocean–atmosphere feedback: The conceptual breakthrough that finally connected Walker's atmospheric seesaw to the ocean warming that Peruvian fishermen had observed for centuries occurred in the 1960s, thanks to Jacob Bjerknes, a Norwegian-American meteorologist at the University of California, Los Angeles. Drawing on new satellite observations and surface data from Canton Island in the central Pacific, Bjerknes recognised that sea surface temperatures in the eastern tropical Pacific are, in an average year, markedly cooler than those in the western Pacific. He realised that this east–west temperature contrast drives a direct atmospheric circulation cell—rising air and heavy rainfall over the warm western Pacific, sinking air over the cooler eastern Pacific, and easterly trade winds along the surface connecting the two. Bjerknes named this the "Walker Circulation" in honour of Gilbert Walker. His key insight was that the ocean and atmosphere reinforce one another in a self-sustaining feedback loop, since termed the "Bjerknes feedback." Strong easterly trade winds push warm surface water westward and draw cold, nutrient-rich water up from depth in the east, which sharpens the east–west temperature gradient and further strengthens the trade winds. Conversely, when trade winds weaken for any reason, upwelling slackens, the eastern Pacific warms, the temperature gradient weakens, and the trade winds weaken still further—a chain reaction that produces the sustained basin-wide warming known as El Niño. Bjerknes thus supplied the essential physical mechanism that Walker's statistics had lacked, and the hybrid term "ENSO" entered scientific usage to reflect that the ocean warming and the atmospheric pressure seesaw are two faces of a single coupled phenomenon [6].

Refining the theory: delayed oscillators and ENSO diversity: Bjerknes's positive feedback loop successfully explained how an El Niño event, once triggered, would intensify, but it did not explain why the event eventually decays and reverses into a cool La Niña phase, nor why events recur irregularly every few years rather than locking into a permanent state. Throughout the 1980s and 1990s, oceanographers, including Klaus Wyrtki and later theorists, developed "delayed oscillator" and "recharge-discharge" models. These models describe how slow-moving subsurface ocean waves—Kelvin and Rossby waves that take months to cross the Pacific basin—carry a delayed negative feedback that eventually shuts an event down and can even precondition the ocean for its opposite phase. This theoretical work was substantially aided by a major international field campaign, the Tropical Ocean Global Atmosphere

(TOGA) program of the 1980s. TOGA deployed a permanent array of moored ocean buoys across the tropical Pacific and, together with satellite altimetry, gave scientists for the first time a continuous, basin-wide view of subsurface ocean heat content. More recently, research has emphasised that not all El Niño events are alike. So-called "Eastern Pacific" (or "canonical") El Niño events feature peak warming hard against the coast of South America, while "Central Pacific" (or "Modoki") events feature peak warming further out in the mid-Pacific, producing a different pattern of global impacts. Distinguishing between these "flavours" of El Niño has become an active area of research because it materially affects the reliability of regional impact forecasts [2].

Paleoclimate perspective: While instrumental records of ENSO are largely confined to the twentieth and twenty-first centuries, scientists have turned to natural archives—coral cores, tree rings, ice cores, and lake sediments—to reconstruct ENSO behaviour over centuries to millennia. This paleoclimate evidence indicates that ENSO has varied substantially in strength over the past thousand years. Furthermore, it suggests, with medium confidence according to the Intergovernmental Panel on Climate Change (IPCC), that both the amplitude of ENSO swings and the frequency of high-magnitude events since the mid-twentieth century are higher than at any point in the preceding several centuries. This serves as an early, significant hint that human-caused warming may already be leaving a detectable fingerprint on the phenomenon, a subject that remains an urgent frontier of modern climatology [7, 8].

3. The Physical Mechanism of ENSO

The normal (neutral) state: In an average year, persistent easterly trade winds blow from the Americas toward Asia along the equator. These winds effectively pile up warm surface water in the western Pacific, around Indonesia and the Philippines, where sea levels are typically tens of centimetres higher than in the eastern Pacific and sea surface temperatures often exceed 29–30°C. Along the coast of South America and across the central-eastern Pacific, these same trade winds drive coastal and equatorial upwelling, drawing cold water from depths of several hundred meters up to the surface. This "cold tongue" of water, rich in nutrients, sustains one of the most productive marine ecosystems on the planet—the Humboldt Current system off the coasts of Peru and Chile. Meanwhile, warm, moist air rises over the western Pacific "warm pool," fueling heavy rainfall over Indonesia, while dry, stable air sinks over the cooler eastern Pacific, completing the Walker Circulation loop [9].

The onset of El Niño: An El Niño event typically begins when the easterly trade winds experience a period of weakening. This relaxation is sometimes triggered by powerful bursts of westerly wind in the western Pacific associated with the Madden–Julian Oscillation, a shorter-lived atmospheric wave pattern. As the trade winds relax, less warm water is pushed westward, upwelling weakens in the east, and warm water that had been banked in the western Pacific begins to slosh east ward along the equator as a slow-moving oceanic Kelvin wave. This wave deepens the thermocline (the boundary between warm surface water and cold deep water) across the central and eastern Pacific. As eastern Pacific sea surface temperatures rise, the Bjerknes feedback takes hold: the weaker temperature gradient further weakens the trade winds, which allows still more warm water to migrate east. Consequently, the event intensifies over a period of months, typically peaking during the Northern Hemisphere winter, between December and February [9].

Atmospheric reorganisation: As the eastern and central Pacific warm, the centre of tropical rainfall and rising air—normally anchored over the Indonesian warm pool—shifts eastward, sometimes by thousands of kilometres, into the central Pacific. This relocation of the rising branch of the Walker Circulation is the single most important mechanism by which El Niño reorganises weather worldwide. Because this shift involves a massive amount of latent heat release, it displaces the giant atmospheric "teleconnection" wave patterns (known as Rossby waves) that transmit tropical heating anomalies into the mid-latitude jet streams. By doing so, it alters storm tracks over North America, changes precipitation patterns over southern Africa, and modifies climate conditions globally, as detailed in various teleconnection studies [6].

Decay and reversal: El Niño events do not last indefinitely. As warm water spreads and thins across the vast Pacific basin, delayed oceanic Rossby waves—which are reflections of the initial Kelvin wave off the western Pacific boundary—propagate back eastward beneath the surface. This process gradually re-shoals the thermocline and cools the subsurface ocean. Combined with a discharge of accumulated heat toward the poles and a natural recovery of the trade winds, this negative feedback loop typically brings an event to an end within twelve to eighteen months. Pacific conditions often overshoot into a La Niña phase, characterised by cooler-than-average eastern Pacific waters and a stronger-than-average Walker Circulation, before eventually returning to neutral conditions. This complex cycle explains why El Niño and La Niña tend to alternate, albeit irregularly, on a roughly two-to-seven-year period, with extended neutral periods in between [2].

4. Monitoring, Indices, and Forecasting

Key indices: Scientists track ENSO using several complementary, internationally recognised indices. The Oceanic Niño Index (ONI), maintained by NOAA's Climate Prediction Centre, is the most widely used metric; it is based on a three-month running average of sea surface temperature anomalies in the Niño 3.4 region of the central-eastern Pacific (roughly 5°N–5°S, 170°W–120°W). An El Niño is formally declared when the ONI reaches or exceeds +0.5°C for at least five consecutive overlapping seasons. A newer metric, the Relative Oceanic Niño Index (RONI), adjusts for the background warming of the tropical Pacific under climate change, aiming to better isolate the atmospheric and ecological impacts of an event from the effects of long-term global warming. The Southern Oscillation Index (SOI), which is Walker's original tool, tracks the atmospheric pressure difference between Tahiti and Darwin and typically moves in the opposite direction to the ONI. Events are further classified by their strength—weak, moderate, strong, and very strong (or "super")—according to how far above the +0.5°C threshold the peak sea surface temperature anomaly rises, with "very strong" events generally defined as those exceeding +2.0°C [4].

The observing system: Real-time ENSO monitoring rests on an extensive observing infrastructure that has been built up since the 1980s. This system includes moored ocean buoy arrays across the tropical Pacific, autonomous Argo profiling floats that measure subsurface ocean temperature and salinity worldwide, and satellite altimetry that tracks sea-surface-height anomalies associated with the shifting thermocline. Furthermore, satellite-based sea surface temperature and outgoing longwave radiation measurements are used to track the location of tropical rainfall. Collectively, these components provide scientists with a continuous, basin-wide view of subsurface ocean heat content and atmospheric coupling, which is critical for understanding the evolution of any given event [9].

Forecasting: Because the ocean changes far more slowly than the atmosphere, ENSO is one of the few climate phenomena that can be predicted with meaningful skill six to twelve months in advance, though forecast skill drops sharply for predictions made across the Northern Hemisphere spring—the so-called "spring predictability barrier." Operational forecasts are generated by an ensemble of dynamical models (physics-based coupled ocean–atmosphere general circulation models run by centres such as NOAA, the

European Centre for Medium-Range Weather Forecasts, and the Australian Bureau of Meteorology) and statistical models. These predictions are pooled into probabilistic outlooks—for example, a forecast might state a given per cent chance of El Niño, La Niña, or neutral conditions in a coming three-month season. These forecasts, disseminated through mechanisms such as the WMO's El Niño/La Niña Update and NOAA's monthly ENSO Diagnostic Discussion, serve as the indispensable foundation for the early-warning and anticipatory-action systems used to protect vulnerable populations [3, 4].

Major El Niño events: The instrumental record confirms that ENSO is a recurring phenomenon, yet each event exhibits significant variability in its strength and character. The 1982–83 and 1997–98 "very strong" (or "super") El Niños were among the first events to be widely recognised in real-time as historically extreme, with later studies attributing trillions of dollars in global income losses to their impacts. Similarly, the 2015–16 event was very strong and drove the third global mass coral bleaching event. By contrast, the 2018–19 event was relatively weak, illustrating that not all El Niños produce extreme global consequences. The 2023–24 El Niño coincided with record global mean temperatures and drove the fourth global mass coral bleaching event. Most recently, the developing 2026–27 event is being monitored as a potentially "strong to very strong" phenomenon, with major forecast centres assigning high odds of a super-event intensity by late 2026, underlining the constant need for readiness and preparedness [1, 10].

5. Global Teleconnections

Atmospheric wave propagation: The mechanism by which a sea surface temperature anomaly confined to the tropical Pacific influences weather as far away as Europe, southern Africa, and the Arctic is known as "atmospheric teleconnection." When the centre of tropical rainfall and convective heating shifts eastward during El Niño, it perturbs the upper-atmosphere jet streams via large-scale Rossby wave trains that propagate poleward and eastward. These waves alter the position and strength of storm tracks over the North Pacific and North America, shift the subtropical jet, and modulate rainfall thousands of kilometres from the original anomaly. Because these wave trains interact with the Earth's mean atmospheric circulation, their effects are strongest and most reliable in the Northern Hemisphere winter, when El Niño typically peaks, and weaker or more ambiguous in other seasons and in the deep tropics away from the Pacific. The Pacific anomaly essentially acts as a pacemaker for climate variability worldwide [6].

Regional tendencies: In broad terms, a canonical El Niño tends to bring wetter-than-average conditions to the southern United States, coastal Peru and Ecuador, and parts of East Africa and central Asia. Conversely, it brings drier-than-average conditions to Indonesia, the Philippines, northern Australia, southern Africa, and parts of India and Southeast Asia. It is also associated with a weaker, less active Atlantic hurricane season due to increased upper-level wind shear, but a more active eastern and central Pacific hurricane season. La Niña generally produces a broadly opposite pattern. However, these are statistical tendencies drawn from historical composites rather than guarantees for any single season. Each event's specific strength, type (Eastern versus Central Pacific), and interaction with other modes of variability—such as the Indian Ocean Dipole, the Madden–Julian Oscillation, or the North Atlantic Oscillation—shape its precise regional expression. It is this teleconnected reach, more than the modest area of ocean initially involved, that gives El Niño its outsized significance for global development [4].

6. Impacts on Agriculture and Food Security

Global staple crops: A large-scale analysis published in Nature Communications, drawing on yield records from roughly 12,000 political units worldwide, found that ENSO phases measurably affect the yields of the four dominant global staple crops—maize, rice, wheat, and soybean. However, the direction and magnitude of these effects vary sharply by crop and region. El Niño was found to reduce yields across roughly 22.0 to 24 .0 per cent of global harvested cropland while simultaneously improving yields across a larger 30.0 to 36 .0 per cent of harvested area elsewhere. This illustrates that El Niño is best understood not as a uniformly "good" or "bad" phenomenon for agriculture, but as a redistributive one that creates significant winners and losers. Soybean is the clearest example of an El Niño beneficiary at the global scale: mean yields rise by an estimated 2.1 to 5.4 per cent during El Niño years, largely because the United States, Brazil, and Argentina—together the source of the majority of the world's soybean supply—tend to experience cooler, wetter growing-season conditions that favour reproductive development. Maize tells a different story: global mean yields fall by up to roughly 4.3 per cent, with the sharpest losses concentrated in the southeastern United States, China, East and West Africa, Mexico, and Indonesia [11].

Price transmission and markets: Because El Niño's effects on the major grain-exporting regions are not perfectly correlated, its net effect on global food prices in any given year depends on the balance of gains and losses across producing countries, the state of global grain stocks, and unrelated shocks such as conflict or energy-market disruption occurring at the same time. Analysts note that the translation of crop disruption into higher retail food prices is not instantaneous—it typically takes several months to work through complex supply chains—but that fertiliser availability, freight costs, and other inputs can transmit cost pressure to consumers even faster than the crop losses themselves. For import-dependent, food-insecure countries, even a modest ENSO-driven production shortfall can translate into a significant rise in malnutrition risk among children, pregnant women, and the elderly. This is why organisations such as the FAO treat ENSO forecasts as a core input to famine early-warning systems, and why analyses of anticipatory humanitarian action suggest that every dollar invested ahead of a forecast El Niño-related shock can avert several dollars in losses and downstream relief costs. Commodity markets react to ENSO forecasts well before physical harvests are affected, as traders price in anticipated supply risk. Markets for coffee, cocoa, palm oil, and sugar are particularly sensitive to these outlooks, making the economic footprint of an approaching strong El Niño felt months before physical crop losses are realised [12, 13].

7. Impacts on Fisheries and Marine Ecosystems

The Peruvian anchoveta: No fishery illustrates El Niño's ecological power more starkly than the Peruvian anchoveta fishery, the largest single-species fishery on Earth by volume. Worth an estimated one to three billion U.S. dollars annually, this fishery supplies roughly a fifth of the world's fishmeal, which in turn provides nearly half of the protein feed used in global aquaculture. The anchoveta depends entirely on the cold, nutrient-rich upwelling of the Humboldt Current. When El Niño suppresses that upwelling, the phytoplankton and zooplankton that anchoveta feed on collapse, and the fish either die, fail to reproduce, or migrate to cooler waters, sometimes moving into neighbouring maritime jurisdictions. During the very strong El Niño events of the early 1970s, anchoveta catch fell by more than half in successive years, precipitating a fishery and economic collapse. This event, compounded by overfishing, forced sustained government intervention in the industry that persists in modified form today [14, 15].

Coral reefs and ecosystems: Because El Niño elevates sea surface temperatures across large swaths of the tropical Pacific, Indian, and sometimes Atlantic Oceans, it is closely associated with global-scale coral bleaching events, in which corals expel the symbiotic algae that supply most of their energy and colour, and in severe or prolonged cases, die outright. The strong El Niño events of 1997–98 and 2015–16 were each associated with major global bleaching episodes, and the 2023–24 El Niño drove what agencies have identified as the fourth global mass coral bleaching event on record, with widespread coral mortality projected across the Pacific, Indian, and Atlantic basins. Because reefs support an estimated quarter of all marine species at some stage of their life cycle and underpin coastal fisheries and tourism economies worth tens of billions of dollars, repeated bleaching—increasingly compounded by the background warming from climate change—is pushing many reef systems toward ecological thresholds from which recovery becomes progressively harder between events. Beyond fish and coral, El Niño-driven marine heatwaves have been linked to damage to seagrass meadows and kelp forests, increased disease in aquaculture operations, and harmful algal blooms. Collectively, these heatwaves are estimated to cost the global economy billions of dollars annually through their combined effects on fisheries, aquaculture, and coastal ecosystems [16].

8. Impacts on Water Resources and Hydrology

Precipitation redistribution: Because El Niño redistributes rainfall on a continental scale, it is one of the leading drivers of year-to-year variability in freshwater availability. In the western Pacific, Southeast Asia, northern Australia, and southern Africa, El Niño years are frequently associated with below-normal rainfall, reduced river flow, and depleted reservoir levels, sometimes culminating in severe multi-year droughts when several dry El Niño seasons follow in succession or coincide with an unfavourable Indian Ocean Dipole phase. In the southern and southwestern United States, coastal Peru and Ecuador, and parts of the Horn of Africa and central Asia, the opposite tends to hold, with El Niño winters bringing above-normal rainfall that can replenish reservoirs and groundwater but also trigger destructive flooding and landslides, particularly in steep or deforested terrain. Urban water utilities in vulnerable cities have increasingly incorporated seasonal ENSO forecasts into reservoir management and drought contingency planning, given the multi-month lead time such forecasts can provide relative to the more limited lead time of conventional weather forecasting [4].

Hydropower exposure: Hydropower-dependent economies are especially exposed to this variability. Countries that rely heavily on hydroelectric generation—including much of Latin America, parts of East Africa, and Southeast Asia—can face generation shortfalls and rolling blackouts when El Niño-driven drought lowers reservoir levels. Conversely, some hydropower systems benefit from El Niño-enhanced rainfall in other basins. For these nations, the energy-security risk posed by ENSO is significant; consequently, utilities are increasingly factoring hydropower risk into resource-adequacy and grid-planning exercises. By diversifying their energy portfolios to include less ENSO-sensitive generation sources, such as wind or solar, where meteorological conditions allow, and by utilising early warning systems, these countries aim to dampen the economic shock of a potential drought. The necessity of this planning has been underscored by the recurrence of strong El Niño events in the 21st century, which have forced many nations to confront the fragility of their power grids in the face of climate-driven hydrological shifts [14].

9. Impacts on Public Health

Disease transmission: El Niño's alterations to temperature, rainfall, and humidity have long been linked to shifts in the transmission of vector-borne diseases. Historical episodes have documented rises in malaria in Venezuela and Brazil, dengue outbreaks across the Pacific Islands, and outbreaks of Rift Valley fever and Murray Valley encephalitis associated with anomalous rainfall in East Africa and Australia. During the 2023–24 El Niño, health authorities reported significant increases in dengue cases in Bangladesh, and Brazil experienced one of its worst-ever dengue outbreaks, with more than 6.5 million cases and roughly 5,000 deaths recorded amid extreme flooding in Rio Grande do Sul that displaced hundreds of thousands of people. Studies from Colombia covering nearly two decades of surveillance data have found statistically significant associations between El Niño conditions and increased incidence of dengue, chikungunya, and Zika, alongside independent effects from rising temperatures and deforestation [17, 18].

Waterborne disease and health systems: Both the flooding and the drought associated with El Niño can elevate the risk of waterborne illness—flooding by contaminating water supplies and drought by concentrating pathogens in dwindling water sources and degrading hygiene conditions. Major cholera outbreaks in Tanzania and elsewhere in East Africa have historically coincided with strong El Niño years, including 1997 and 2015, as have cholera outbreaks in Peru, Colombia, and Ecuador during the 1982–83 event; the WHO has again flagged cholera and other waterborne diseases as very-high risks during the 2023–24 and 2025–26 El Niño episodes, compounding an already severe multi-year cholera crisis across parts of East and southern Africa. Leptospirosis, typhoid, shigellosis, and hepatitis A and E outbreaks have similarly been linked to El Niño-associated flooding. Beyond disease incidence, El Niño-linked disasters can directly damage or close health facilities, disrupting routine services—including maternal care, vaccination campaigns, and chronic disease management—well beyond the acute emergency period. Because health resources and baseline vulnerability vary enormously between and within countries, agencies including the WHO now maintain standing early-warning and preparedness frameworks—pre-positioning emergency medical stocks, training surge staff, and strengthening surveillance—explicitly keyed to seasonal ENSO forecasts [19].

10. Impacts on Energy Systems

Generation and demand: Energy systems are exposed to El Niño through several channels. Hydropower-reliant grids—a substantial share of installed capacity in Brazil, Colombia, Ecuador, Venezuela, Kenya, Zambia, Vietnam, and elsewhere—face generation risk when El Niño suppresses rainfall in their catchment basins, sometimes forcing utilities to ration power or switch to costlier thermal generation; conversely, El Niño-enhanced rainfall can boost hydropower output in other basins, such as parts of the southern United States. Demand-side effects also matter: warmer-than-average winters in parts of North America, Europe, and northern Asia during El Niño years typically reduce heating demand and can ease natural gas and electricity prices in those seasons, while unusually hot conditions in other regions raise cooling demand and peak-load stress. Weaker Atlantic hurricane activity during El Niño years has historically reduced the risk of storm-related disruption to U.S. Gulf Coast oil and gas infrastructure, even as more active eastern Pacific cyclone activity raises risk elsewhere. Renewable generation is not immune: altered wind patterns and cloud cover associated with El Niño's rainfall shifts can affect wind and solar output in exposed regions, and utilities increasingly incorporate seasonal ENSO outlooks into resource-adequacy and grid-planning exercises given the multi-month forecast lead time available [14].

11. Macroeconomic and Trade Impacts

Aggregate costs: For decades, the macroeconomic cost of El Niño was assumed to be a short-lived, largely self-correcting shock—a few bad harvests, a temporary spike in food prices, absorbed and forgotten within a year or two. A landmark 2023 study published in Science by Dartmouth researchers Christopher Callahan and Justin Mankin overturned that assumption. Examining global economic growth trajectories following every El Niño event from 1960 to 2019, they found that El Niño produces a persistent drag on economic growth lasting five years or more, rather than a one-off hit followed by rapid recovery. On this basis, they attribute 4.1 trillion dollars in cumulative global income losses to the 1982–83 El Niño and 5.7 trillion dollars to the stronger 1997–98 event—estimates roughly a hundred times larger than earlier assessments that considered only the immediate year of the event. Extrapolated forward and combined with projections of how climate change may intensify future ENSO variability, the study projects cumulative global economic losses on the order of 84 trillion dollars over the course of the twenty-first century [1].

Unequal exposure: The Callahan and Mankin analysis, along with related research, finds that El Niño's growth-dampening effect is sharply unequal across countries. The United States saw gross domestic product roughly three per cent lower in 1988 and 2003 than it would otherwise have been, attributable to the 1982–83 and 1997–98 events respectively—a meaningful but comparatively modest hit. By contrast, low-income, tropical, coastal nations most directly exposed to El Niño's teleconnected extremes—Peru, Ecuador, Indonesia, and the Philippines prominent among them—saw GDP more than ten per cent lower by 2003 than counterfactual trajectories would suggest, a gap the researchers describe as reflecting the deeply unequal global distribution of both wealth and climate risk. Because these are the countries least responsible for the greenhouse gas emissions now amplifying ENSO variability, the finding has become a touchstone in debates over climate justice and loss-and-damage financing. Labor productivity losses linked to extreme heat, a channel documented in companion research by the same authors on the economic effects of extreme heat more broadly, appear to compound the more visible losses from crop failure and infrastructure damage, particularly in tropical, lower-income economies where outdoor labor makes up a larger share of employment and where adaptive capacity—air conditioning, climate-resilient infrastructure, social safety nets—is comparatively limited [20].

12. Disaster Risk, Extreme Weather, and Infrastructure

Shifting hazard landscapes: El Niño reshapes the geography of extreme weather risk each year it occurs, rather than uniformly increasing or decreasing disaster losses everywhere. In the tropical Atlantic, increased upper-level wind shear associated with El Niño typically suppresses hurricane formation, reducing landfall risk for the U.S. Gulf and East Coasts and the Caribbean in most (though not all) El Niño years; NOAA's 2026 seasonal outlook, issued as El Niño strengthened, forecast a below-normal Atlantic hurricane season on this basis. In the eastern and central Pacific, the reverse holds, with more favourable conditions for tropical cyclone formation. Along the west coast of the Americas, El Niño winters can bring an elevated risk of coastal flooding, since a strong event both raises regional sea levels through thermal expansion and warm-water accumulation and increases the frequency of low-pressure systems that generate storm surge. In Australia, Indonesia, and parts of Southeast Asia, El Niño's characteristic drying and warming elevate wildfire risk, most dramatically illustrated by Indonesia's recurring peatland and forest fires and by severe Australian bushfire seasons. Disaster-risk agencies increasingly treat a strengthening El Niño forecast as an actionable trigger for anticipatory action—pre-positioning relief supplies, issuing early warnings, and releasing contingency financing before a hazard materialises—an approach the FAO and partner agencies estimate can return roughly seven dollars in avoided losses and other benefits for every dollar spent in advance [12].

13. Regional Impacts: The Americas

Peru, Ecuador, and the Southern Cone: As the region where El Niño was first named and observed, Peru and Ecuador remain among the most directly affected countries. Coastal El Niño events bring torrential rainfall, flash flooding, and landslides to a normally arid coastal strip, as occurred dramatically during the 2017 "Coastal El Niño," while simultaneously collapsing the anchoveta fishery and associated fishmeal industry that anchor a significant share of Peru's export economy. The scale of exposure is such that Peru and Ecuador feature prominently in every major cross-country study of El Niño's economic toll, including the Callahan and Mankin finding of GDP more than ten per cent below counterfactual trends in the years following the 1997–98 event. El Niño's effects diverge sharply across Brazil's regions: southern Brazil, Uruguay, and northern Argentina tend to receive above-normal rainfall, generally benefiting soybean production but also raising flood risk, as illustrated by the catastrophic 2024 floods in Rio Grande do Sul that displaced roughly 600,000 people and were followed by one of Brazil's worst dengue outbreaks on record. Northeastern Brazil, by contrast, tends toward drought during El Niño, stressing a region already prone to water scarcity and cattle and subsistence-crop losses [19].

North America and the Caribbean: The continental United States experiences one of the most consistent and well-studied El Niño signatures anywhere in the world: a southward-shifted jet stream typically brings a wetter, stormier winter to the Gulf Coast and southern tier of states, increased snowfall risk to the southern Rockies and Sierra Nevada, and milder, drier winters to the Pacific Northwest and Ohio Valley. A weaker Atlantic hurricane season is a near-universal El Niño feature, offset by elevated eastern Pacific cyclone risk affecting Mexico's Pacific coast and, on occasion, California via remnant moisture. Coastal California faces elevated flood and erosion risk during strong events owing to both higher wave energy and modestly elevated regional sea level. El Niño years frequently bring reduced rainfall to Mexico and Central America, straining maize and bean production—dietary staples across the region—and stressing coffee cultivation through both heat and moisture stress on flowering trees. The Caribbean, while benefiting from suppressed Atlantic hurricane activity in most El Niño years, can face compounding drought stress on water-scarce islands, requiring careful water resource management [4].

14. Regional Impacts: Asia and the Pacific

Indonesia and Southeast Asia: Indonesia sits astride the western Pacific warm pool, whose eastward displacement defines El Niño, making it one of the most reliably and severely affected countries on Earth. El Niño years bring extended dry seasons, delayed monsoon onset, and sharply elevated risk of peatland and forest fires that periodically blanket the region in smoke haze, damaging respiratory health as far afield as Singapore and Malaysia, and threatening the non-human primates and other wildlife documented in systematic reviews of El Niño-driven fire impacts on Southeast Asian biodiversity. Rice, palm oil, and coffee production all face downside risk in strong events, with Indonesian farmers frequently adjusting planting calendars in anticipation. The Philippines regularly experiences El Niño-linked drought affecting rice and sugarcane output, alongside reduced water availability for the capital region. Small Pacific Island states face a particularly acute and geographically inverted set of risks: some low-lying atoll nations near the international date line, such as Kiribati, can experience unusually heavy rainfall and flooding during El Niño even as neighboring island groups face drought, reflecting the sensitivity of these small, dispersed land areas to the precise longitude at which the shifted Walker Circulation's rainfall belt settles [21].

India and South Asia: In India, the consequences of El Niño were far from benign, as the region experienced catastrophic drought cycles during the late nineteenth century. The Great Drought of 1876–

1878 triggered widespread famine, resulting in an estimated death toll of 6 to 10 million people [28]. During this period, the essential summer monsoon rains failed unexpectedly, devastating agricultural output. This pattern of tragedy recurred during the famines of 1896–1897 and 1899–1900, both of which were either triggered or significantly worsened by El Niño conditions, though the underlying climatic link remained unrecognised at the time. Consequently, while the phenomenon occasionally brought años de abundancia to Peruvian fishermen, it simultaneously inflicted mortal suffering upon the agrarian population of India. Because El Niño research began, historically, with the search for monsoon predictors, India's exposure is well documented: El Niño years show a statistical tendency toward below-normal southwest monsoon rainfall, though the relationship is neither universal nor deterministic, as monsoon outcomes also depend on the Indian Ocean Dipole and other regional factors, and some El Niño years have produced near-normal monsoons. When monsoon deficits do occur, they threaten rice, pulses, and oilseed production across a country where agriculture remains a major source of rural livelihoods, with downstream effects on rural incomes, food prices, and, per PAHO- and WHO-documented patterns elsewhere, potential increases in mosquito-borne disease transmission in a warming, altered-rainfall environment. China's vast geography produces a spatially complex El Niño response: southern and eastern China frequently see increased rainfall and flood risk along the Yangtze basin during the developing and mature phases of an event, while northern China can experience drier, warmer conditions. Agricultural effects are correspondingly mixed by crop and province, and Chinese meteorological and agricultural authorities maintain dedicated ENSO monitoring and seasonal outlook programs given the scale of the country's grain production and food-security stakes [14].

15. Regional Impacts: Australia

Climate extremes: Australia is among the countries most reliably and severely affected by El Niño, which tends to suppress rainfall, particularly across the eastern and northern parts of the continent, and elevate the risk of heatwaves, drought, and bushfires. Most of Australia's major twentieth- and twenty-first-century droughts—including the severe episodes of 1982, 1994, 2002, 2006, and 2015—coincided with El Niño years, and research at the Australian Research Council Centre of Excellence for Climate Extremes has traced part of this drying signal to local land–atmosphere feedbacks that suppress the conversion of available moisture into rainfall during El Niño conditions. Reduced pre-wet-season rainfall also tends to delay the onset of the Australian monsoon and is associated with a less active, though not necessarily less intense, regional tropical cyclone season. Bushfire risk is shaped by El Niño but not dictated by it: drier, hotter conditions raise fire-weather danger, but the fuel load available to burn depends on antecedent rainfall—a wet period that boosts vegetation growth can, if followed by an El Niño-driven dry, hot, windy spell, produce an especially dangerous fire season, while some of Australia's most severe fire seasons, including the 2019–20 "Black Summer," have occurred without a strong concurrent El Niño, underscoring that ENSO is one contributing factor among several. Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Bureau of Meteorology maintain some of the world's most sophisticated ENSO-linked seasonal outlook and bushfire-preparedness systems in direct response to this recurring exposure, and by mid-2026, with a strong El Niño developing, Australian authorities were again forecasting elevated risk for the 2026–27 season [14].

16. Regional Impacts: Africa

The Horn of Africa and East Africa: East Africa experiences one of the more complex and, at times, counterintuitive El Niño signatures: the October–December "short rains" season frequently sees above-normal, sometimes torrential, rainfall during El Niño, in contrast to the region's broader reputation for drought vulnerability, while the June–September long-rains-adjacent season in parts of the Horn, including South Sudan, can instead see drier-than-normal conditions. This has produced a whiplash pattern in recent cycles—including a prolonged multi-year drought followed, in the 2023–24 El Niño, by severe flooding in Kenya, Somalia, and Ethiopia—that has strained agricultural systems, displaced communities, and, per WHO documentation, contributed to one of the worst and longest-running cholera outbreaks recorded in the region, as flooding degraded water and sanitation infrastructure across several countries simultaneously. Southern Africa more closely follows the drier stereotype of El Niño impact: reduced rainfall across Zambia, Zimbabwe, Malawi, and parts of South Africa during El Niño years threatens maize production, a regional dietary staple, and can trigger significant hydropower shortfalls, since several countries in the region depend heavily on shared river systems such as the Zambezi for electricity generation. Malnutrition risk among children rises correspondingly in the most affected countries, prompting sustained humanitarian appeals during strong events. West Africa's El Niño relationship is more geographically mixed and less uniformly characterised in the literature than East or southern Africa's, with documented effects on maize yields in parts of the region and interactions with the West African monsoon that vary by sub-region and by event [12, 19].

17. Impacts on Terrestrial Ecosystems and Biodiversity

Amazonia and Southeast Asia: Beyond the marine realm, El Niño's rearrangement of rainfall and temperature has measurable consequences for terrestrial ecosystems. In Amazonia, El Niño-linked drought reduces river levels, stresses rainforest vegetation, and has been linked to increased tree mortality and elevated wildfire risk in a biome not naturally fire-adapted, raising concern among ecologists about long-term shifts toward more fire-prone, degraded forest states, particularly where El Niño drought interacts with ongoing deforestation. In Southeast Asia, the drought and haze associated with El Niño-driven peatland and forest fires in Indonesia and Borneo directly threaten orangutans and other endemic wildlife through habitat loss, smoke inhalation, and disrupted fruiting cycles that primates depend on for food; a systematic review of the impacts on non-human primates in the region has documented population and health effects tied to repeated El Niño fire seasons. El Niño-linked drought and heat also elevate wildfire risk in savanna, grassland, and eucalypt forest ecosystems across Australia and parts of southern Africa, with cascading effects on fire-sensitive species and, over repeated cycles, potential shifts in vegetation composition toward more fire-tolerant types. Migratory and wide-ranging species—from Pacific seabirds that must travel further to find prey as fish stocks relocate, to ungulates in East Africa tracking rainfall-driven grazing conditions—show behavioural and demographic responses to ENSO phase that ecologists increasingly incorporate into conservation planning, particularly for already-threatened populations for which an added climate stressor can be consequential [22].

18. El Niño in a Warming World: Interaction with Climate Change

Altered frequency and intensity: Whether and how anthropogenic climate change is altering the frequency, intensity, or character of ENSO itself is one of the most actively studied—and still only partially resolved—questions in climate science. The IPCC's Sixth Assessment Report states with medium confidence that both the amplitude of ENSO sea surface temperature variability and the frequency of high-magnitude El Niño and La Niña events since 1950 exceed anything reconstructed from paleoclimate proxy

records extending back to roughly 1400 CE, though attributing this change unambiguously to human activity, rather than natural variability, remains difficult given the short length of reliable instrumental records. Looking forward, climate model ensembles offer a more consistent, if still imperfect, signal. Multiple studies using the Coupled Model Intercomparison Project (CMIP) generations of climate models project a robust increase in the amplitude of ENSO-driven rainfall extremes over the twenty-first century, particularly under higher-emission scenarios, even where models disagree on the trajectory of ENSO sea surface temperature variability itself. Several research groups have projected that the frequency of "extreme" El Niño events—those associated with the most severe, far-reaching global impacts—could roughly double under continued warming, although more recent work correcting for common systematic biases in earlier-generation climate models suggests this doubling may be overstated and that the Pacific's mean-state response to warming remains a significant source of uncertainty [23, 24].
Compounding impacts: Regardless of how ENSO's own statistics evolve, its interaction with a warmer baseline climate is already compounding its impacts in observable ways. El Niño years are now more likely to set new global temperature records than they would be against a stable climate baseline, because the natural ocean-to-atmosphere heat release of an El Niño event is layered on top of decades of accumulated background warming—a dynamic widely discussed in connection with 2023 and 2024, both El Niño-influenced years that set successive global temperature records, and again raised as strong El Niño conditions developed through 2026. Marine heatwaves, coral bleaching thresholds, and wildfire fuel-dryness thresholds are all reached more readily when El Niño's warming and drying add to an already-elevated baseline, meaning that even an El Niño of historically ordinary strength can now produce ecological and human impacts that would have been associated only with the strongest events of the twentieth century [25].

19. Current Status and Outlook (2026)

2026 event status: As of July 2026, El Niño conditions are firmly established across the tropical Pacific and are strengthening. NOAA's Climate Prediction Center placed the Niño 3.4 sea surface temperature anomaly at roughly +0.9°C in May 2026, rising to approximately +1.7°C by the week centered on June 17, 2026, with official forecasts assigning roughly 88 .0 per cent odds of the event reaching at least "strong" intensity and above 60.0 per cent odds of a "very strong"—colloquially, "Super"—El Niño by autumn or early winter 2026. Independent forecast centres, including the European Centre for Medium-Range Weather Forecasts and the Australian Bureau of Meteorology, along with NOAA's own CFSv2 model, converge on a similar trajectory, with some analyses suggesting the pace of intensification in 2026 is outrunning that of the historic 1997–98 and 2015–16 Super El Niño events at comparable points in their development. The WMO's global producing centres likewise placed the probability of El Niño conditions persisting through the second half of 2026 above 90.0 per cent as of mid-year, with redevelopment of La Niña considered unlikely before 2027. Early sector-specific signals in mid-2026 were consistent with the historical pattern: forecasters flagged elevated drought and bushfire risk for Australia; Southeast Asian governments issued early warnings on rice and palm oil production risk; the WHO and PAHO issued anticipatory health guidance; and NOAA's below-normal 2026 Atlantic hurricane season outlook was issued explicitly based on the strengthening El Niño's wind-shear effect. A notable complicating factor identified by several analysts is that this El Niño is developing amid separate, unrelated disruptions to global fertiliser and energy markets linked to ongoing geopolitical conflict, which could reduce the resilience of vulnerable farming communities to absorb simultaneous climate and market shocks [4].

20. Early Warning, Adaptation, and Policy

Anticipatory action: Because ENSO can be forecast with meaningful skill six to twelve months ahead—a far longer lead time than conventional weather forecasting affords—it has become a cornerstone of "anticipatory action" frameworks that seek to trigger preparedness and even release funding before a hazard fully materialises. The WMO's monthly El Niño/La Niña updates, NOAA's ENSO Diagnostic Discussions, and regional climate outlook forums feed directly into national drought and flood contingency plans, humanitarian pre-positioning of food and medical stocks, and, increasingly, parametric insurance and forecast-based financing mechanisms that release funds automatically once defined ENSO-linked thresholds are crossed. Adaptation strategies increasingly incorporate seasonal ENSO outlooks directly into operational decision-making: agricultural extension services use ENSO forecasts to advise farmers on planting date adjustments, drought-tolerant variety selection, and irrigation scheduling; water utilities adjust reservoir operating rules; energy utilities factor hydropower risk into resource-adequacy planning; and health ministries pre-position surveillance and response capacity for climate-sensitive diseases. Index-based agricultural and livestock insurance products tied to rainfall or ENSO indices have expanded across parts of Africa, Asia, and Latin America as a mechanism to help smallholder farmers manage otherwise uninsurable climate risk [12].

Remaining gaps: Despite this progress, significant gaps persist. Forecast skill remains lower for rainfall than for the underlying Pacific sea surface temperature anomaly, for Central Pacific-type events relative to classic Eastern Pacific events, and for any single season relative to the multi-season average—meaning that even a confident ENSO forecast leaves considerable uncertainty about precisely how a given region's rainfall or temperature will evolve. Humanitarian and development financing for anticipatory action, while growing, still lags far behind the scale of after-the-fact disaster relief spending. And the countries facing the most severe El Niño-linked development impacts—as the Callahan and Mankin economic findings make clear—are disproportionately low-income, tropical nations with the least capacity to invest in the observing systems, insurance markets, and infrastructure resilience that wealthier, less-exposed countries can deploy, a mismatch that remains central to international discussions of climate finance, loss and damage, and equitable adaptation support [1].

20A. Tourism, Insurance, and the Private Sector

Private sector impacts: Tourism-dependent economies are increasingly attentive to ENSO forecasts, since El Niño's rearrangement of temperature, rainfall, and storm risk directly affects the attractiveness and safety of destinations. Ski resorts in parts of the western United States can see boosted snowfall in El Niño years, while others in the Pacific Northwest see reduced snowpack; coral-reef diving destinations across the Indo-Pacific face the risk that a strong event coincides with, or triggers, a mass bleaching episode that can take years to visually and ecologically recover; and destinations exposed to bushfire, heatwave, or flood risk face periodic disruption to visitor numbers and air travel. Industry analysts have noted that proactive communication and climate-resilience planning by tourism operators can help maintain traveller confidence even as underlying climate risk rises. The insurance and reinsurance industry has become one of the more sophisticated private-sector users of ENSO science, given the phenomenon's direct bearing on catastrophe risk across property, agriculture, and marine lines of business. Reinsurers incorporate ENSO phase into catastrophe models used to price flood, wildfire, drought, and tropical cyclone risk in exposed regions, and the growth of index-based or parametric insurance products has been particularly important for smallholder farmers who previously had no practical access to weather risk insurance. Commodity trading firms, food and beverage manufacturers reliant on coffee, cocoa, sugar, or grain inputs, and shipping and logistics companies exposed to canal and river drought risk likewise treat ENSO forecasts as a standard input to hedging and supply-chain contingency planning, particularly ahead of a forecast strong event such as the one developing through 2026 [26, 27].

21. Conclusion

From its origins as a name given by Peruvian fishermen to a mysterious warm current, to its recognition by Gilbert Walker as one half of a planetary pressure seesaw, to Jacob Bjerknes's discovery of the self-reinforcing ocean–atmosphere feedback that drives it, El Niño's scientific story is a case study in how patient, cross-disciplinary observation over the better part of a century can reveal the hidden machinery behind phenomena that had, for generations, seemed like unconnected local events. That machinery is now understood well enough to forecast El Niño's onset months in advance, even as many of its regional and sectoral consequences remain difficult to pin down with precision. What the accumulated evidence surveyed in this review makes clear is that El Niño is not a peripheral curiosity for climate scientists but a first-order determinant of global development outcomes in the years it occurs: it redistributes agricultural fortune between hemispheres, collapses and relocates entire fisheries, elevates disease transmission across continents, drags down economic growth for the better part of a decade in the most exposed nations, and reshapes wildfire, flood, drought, and storm risk on every populated continent. Its burden falls overwhelmingly and disproportionately on the low-income tropical nations least responsible for the greenhouse gas emissions that are now measurably amplifying its extremes—a fact that increasingly places ENSO at the intersection of climate science and climate justice. As a strong, and potentially historic, El Niño event took hold through the second half of 2026, the accumulated lessons of more than a century of research—about mechanism, about forecasting, and above all about which communities need support earliest and most—offer the clearest available guide to reducing the human and ecological toll of the event still to come, even as the deeper scientific questions about how a warming world will ultimately reshape El Niño itself remain an active and urgent frontier of research [2, 8].

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