The potential impact of El Niño on climate forecasts: the never-ending story of a foreseeable power switching between a little boy and his sister

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Abstract
El Niño-Southern Oscillation (ENSO) is a climatic phenomenon in the tropical Pacific arising from coherent interactions between the ocean and the atmosphere on timescales from months to years. ENSO generates the most prominent climate alterations known worldwide, even very far from where it forms. It affects weather extremes, landslides, wildfires or entire ecosystems, and it has major impacts on human health, agriculture and the global economy. Reliable forecasts of ENSO with long lead times would represent a major achievement in the climate sciences, and would have huge positive societal and economic implications. Here we provide a review of our current understanding of ENSO as a major source of climate predictability worldwide, emphasizing four main aspects: 1) differences between weather and climate forecasting, and existing limitations in both types of prediction; 2) main mechanisms and interactions between the atmosphere and the ocean explaining the dynamics behind ENSO; 3) different theories that have been formulated regarding the oscillatory behavior and the memory sources of the phenomenon; and 4) the upper limit in its potential predictability and current research endeavors aimed at increasing the lead time of climate predictions.

Geographical Sector(s): Global, Pacific Ocean
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Weather and climate forecasting: are they the same thing?

Weather has a large influence on our daily life: fair weather encourages outdoor activities, such as hikes, walks or trips to the beach, while poor weather is more likely to keep us indoor. The importance of weather in our daily activities explains the widespread use of weather forecast information by a broad audience. It is thus no surprise that recent technological advances have lead to the development of products and applications that go beyond traditional weather forecasts on TV: in short, weather science and forecasting is nowadays just one click away on any electronic device.

Nonetheless, weather forecasts have inherent limited predictability. Models used to produce forecasts typically solve mathematical equations based on physical laws to describe how the atmosphere evolves from an initial state over a given time interval (*"The problem of weather forecasting as a problem in mechanics and physics"* (V. Bjerknes, 1904)). This procedure can be repeated indefinitely to know any future state at very distant times. But unfortunately, our knowledge of any past and present atmospheric state is incomplete and inaccurate, as we cannot put a thermometer, a rain gauge and an anemometer at every single location and altitude of the atmosphere. The error associated with this inaccurate picture of the initial state, even if very small, quickly grows at each time step, so that in a matter of days, weather predictions are no better than a coin toss (*"Uncertainty of Initial State as a Factor in the Predictability of Large Scale Atmospheric Flow Patterns"* (P. D. Thompson, 1957)). This is why the atmosphere represents a deterministic chaotic system, whose behavior can be described by mathematical equations, but whose future evolution cannot be accurately predicted at lead times longer than a couple of weeks, due to the fast-growing increase over time of errors in the initial conditions (*"A study of the predictability of a 28-variable atmospheric model"* (E. N. Lorenz, 1965)). And this limit is indeed a fundamental constraint in weather predictability, which would remain even if we had the most powerful supercomputer and the most sophisticated model of the atmosphere (*"Atmospheric predictability experiments with a large numerical model"* (E. N. Lorenz, 1982)).

But, if weather forecasts are limited to a couple of weeks, does it mean that nothing can be known about the future evolution of the atmosphere months-to-years ahead? To answer this question, which is at the base of climate forecasting, we must first understand that the atmosphere is only one element of a more complex system, which also comprises the hydrosphere, the cryosphere, the lithosphere and the biosphere, and which is bounded by the outer space. The atmosphere is constantly being influenced, and to some extent determined, by its neighbors, which have their own variability on different timescales. For instance, we know that the incoming solar radiation is larger at noon, and therefore we can be quite confident that temperatures in 45 days will be higher during daytime hours than at night.

In this regard, the upper ocean is a privileged actor in climate forecasting, because it constantly exchanges energy and humidity with the overlying atmosphere ((J. Shukla and III J. L. Kinter, 2006)). Importantly, temperatures in the ocean are more persistent than those in the atmosphere, and they imprint their anomalies on the latter. The thermal inertia of the upper ocean allows to warm or cool the bottom part of the atmosphere over relatively long periods. Warm air, which is less dense, is forced to ascend, while cold air subsides, being denser: these motions affect the distribution of air masses and horizontal and vertical winds in the whole tropospheric column. Warm or cold anomalies at the surface are also communicated to distant regions by atmospheric waves (*"Planetary-Scale Atmospheric Phenomena Associated with the Southern Oscillation"* (J. D. Horel and J. M. Wallace, 1981)), which resemble the waves propagating in a pond after throwing a stone into it. As a result, the longer thermal inertia of the upper ocean generates persistent changes in the state of the atmosphere that are potentially predictable months-to-years in advance because they do not arise from the chaotic atmosphere itself (*"Southern Hemisphere Circulation Features Associated with El Niño-Southern Oscillation Events"* (D. J. Karoly, 1989)).

El Niño as a primary source of climate predictability worldwide

There are many different phenomena in the ocean that generate predictable changes in the atmosphere. The most prominent one is El Niño-Southern Oscillation, or ENSO, a coupled ocean-atmosphere mode in the tropical Pacific basin (*"Observations of Warm Water Volume Changes in the Equatorial Pacific and Their Relationship to El Niño and La Niña"* (C. S. Meinen and M. J. McPhaden, 2000)). The coupled nature of this phenomenon arises from oceanic anomalies that affect the overlying atmosphere, as well as atmospheric patterns that in turn modify the state the ocean. This simultaneous two-way interaction between the ocean and the atmosphere sometimes amplifies an initial temperature, pressure or wind anomaly (positive feedback), until it stops growing due to internal and/or external factors. In other situations, the ocean or the atmosphere tends to stop or limit the growth of any initial change that occurs in either of the components (negative feedback).

Within the umbrella of ENSO, the ocean and the atmosphere work perfectly together and amplify initial perturbations, which explains the large magnitude of the phenomenon and its worldwide impact (*"Atmospheric Teleconnections from the Equatorial Pacific"* (J. Bjerknes, 1969)). The dominant winds in the tropical Pacific, the trade winds, blow from the eastern to the western part of the basin, piling up warm waters in the western tropical Pacific area commonly referred to as the warm pool (*"How Much Energy Is Transferred from the Winds to the Thermocline on ENSO Time Scales?"* (J. N. Brown and A. V. Fedorov, 2010)). Air above these warm waters is warmer, and hence less dense, than air elsewhere. Therefore, these air masses tend to rise in the troposphere, which is the atmospheric layer where weather happens, and then to diverge as they reach the top of the troposphere (*"A new extratropical tracer describing the role of the western Pacific in the onset of El Niño: Implications for ENSO understanding and forecasting"* (J. Ballester et al., 2011)). Part of this lifted air returns to the eastern Pacific along the equator and descends near an area of cold upper ocean temperatures next to central America. This closed atmospheric circulation loop in the equatorial plane, with surface westward winds, rising air in the western Pacific warm pool, eastward moving air in the upper troposphere and descending motion over the eastern Pacific cold waters, indeed represents one of the main positive feedbacks of the climate system (*"El Niño–La Niña Asymmetry in the Coupled Model Intercomparison Project Simulations"* (S. I. An et al., 2005)). Thus, the stronger this loop, the larger the accumulation of warm waters in the warm pool, and thus the east-west contrast in upper ocean temperatures. In turn, the larger the contrast in ocean temperature, the stronger the rising and descending motions of the atmospheric loop.

But sometimes, other processes can stop and revert the growth of this coupling. It can either be that the trade winds weaken and therefore the accumulated heat in the warm pool is released to the east (*"El Niño-The Dynamic Response of the Equatorial Pacific Ocean to Atmospheric Forcing"* (K. Wyrtki, 1975)), or it can be that the east-west difference in upper ocean temperatures is weakened and therefore the atmospheric circulation is reduced. In either case, the initial oceanic or atmospheric anomaly is transmitted to its counterpart, so that the wind loop and the east-west thermal difference are weakened or even reversed. Under these conditions, the eastern Pacific becomes warmer than average, and the trade winds are weaker than normal. This situation is referred as to El Niño, which means "Christ child" (or "little boy") in Spanish, given that it normally peaks around Christmas. The opposite conditions, with strengthened trades and east-west temperature contrast, are known as La Niña ("little girl"). Both El Niño and La Niña typically persist for almost a year, from early summer to late spring of the following year. These events generate large-scale climate changes in very distant regions that affect weather extremes, landslides, wildfires or entire ecosystems, with major impacts on human health, agriculture and the global economy (*"Kawasaki disease and ENSO-driven wind circulation"* (J. Ballester et al., 2013)). These worldwide impacts are indeed potentially predictable from several months to a few years ahead (*"Climate predictability on interannual to decadal time scales: the initial value problem"* (M. Collins, 2002)). This is why the study of the mechanisms behind ENSO has been a hot topic in climate sciences during the last decades.

El Niño and La Niña: a never-ending power switching

During a La Niña event, stronger than normal easterly trade winds pile up warm waters in the western Pacific warm pool. The ocean is stratified, which means that it is organized in stable layers of increasing density with depth. This configuration with lighter waters above heavier masses disfavors vertical movements across layers of different density. The water masses that are being piled up in the warm pool would therefore diverge polewards in normal circumstances. However, these accumulated warm waters are not allowed to escape towards higher latitudes and instead are forced to sink, bringing warm anomalies down to the subsurface (*"On the dynamical mechanisms explaining the western Pacific subsurface temperature buildup leading to ENSO events"* (J. Ballester et al., 2015)). There, waters are also meridionally confined due to the influence of Earth's rotation, which is also controlled by winds: the stronger the trades, the stronger the force that retains and even pushes the waters equatorwards. This force is indeed present in the whole western and central Pacific subsurface, where the trades are stronger than normal under La Niña conditions, piling up water masses from higher latitudes and warming the subsurface right at the equator (*"An Equatorial Ocean Recharge Paradigm for ENSO. Part I: Conceptual Model"* (F. F. Jin, 1997)).

The warm waters are therefore stored in the ocean subsurface, at about 100 to 200 meters (*"Heat advection processes leading to El Niño events as depicted by an ensemble of ocean assimilation products"* (J. Ballester et al., 2016)). They are accumulated faster in the western Pacific, and only later do they start accumulating in the central Pacific, because the meridional convergence of water masses is a very slow process. They persist there, buried and isolated from the influence of the atmosphere, well after La Niña starts to decay and the basin returns to its normal state. At this stage, the seed leading to the onset and growth of an El Niño event is already planted in the ocean subsurface. As soon as a fortuitous weakening of the trade winds happens for at least some weeks to a few months, the warm waters are favored to propagate to the east throughout the subsurface (*"Tropical Pacific Sea Surface Temperature Anomalies, El Niño, and Equatorial Westerly Wind Events"* (G. A. Vecchi and D. E. Harrison, 2000)). If the accumulated heat and the relaxing of the trades are strong and long-lasting enough, the subsurface heat is able to reach the surface waters in the eastern Pacific. When this happens, the warm ocean anomaly weakens the east-west temperature difference in the tropical Pacific, which in turn weakens the wind circulation loop in the equatorial Pacific. In this way, the ocean and the atmosphere start working together again in the same, albeit opposite direction, leading to the growth of an El Niño event.

Similarly, El Niño also plants in the ocean subsurface the seed for the growth of a La Niña event. The subsequent oscillatory power switching between El Niños and La Niñas is however very irregular. For example, two consecutive El Niño or La Niña events can sometimes occur one after the other. In many other instances, they are a few years apart. This irregularity is due to the delicate relationship between the strengthening and weakening of the trade winds, and the storage and release of memory in the ocean subsurface as heat content anomalies. Winds change their direction and speed in a very rapid and irregular fashion, hence it is not very common to have relatively long temporal stretches during which the trades are either strengthened or weakened in a coherent way. This happens, for example, during the mature phase of El Niño or La Niña conditions, when the ocean surface is playing an active role by thermally forcing the overlying atmosphere and driving the wind circulation loop described above. Wind anomalies leading to and triggering an ENSO event are instead rather weak, which makes it difficult to anticipate the release of the subsurface ocean memory far in advance.

The long-lead prediction of ENSO: the final frontier

The mechanisms behind ENSO are nowadays relatively well understood, but it remains difficult to make predictions at lead times longer than 9 months (*"Skill of Real-Time Seasonal ENSO Model Predictions during 2002–11: Is Our Capability Increasing?"* (A. G. Barnston et al., 2012)). The predictions of ENSO that are issued in boreal spring are still unable to anticipate whether an El Niño or a La Niña will occur at the end of the year. This problem arises because no early sign of an incoming event is found in the atmosphere or the ocean surface this early in the year (*"El Niño prediction and predictability"* (D. Chen and M. A. Cane, 2008)). Many other weather phenomena take place in the tropical Pacific during this season, which potentially mask any incipient premonitory signal of the growth of an ENSO event (*"Seasonality in SST-Forced Atmospheric Short-Term Climate Predictability"* (X. W. Quan et al., 2004)). Nonetheless, once this spring barrier in climate predictability is overcome, the subsequent phases of the event become much easier to predict.

There is still debate in the community as to what extent this predictability barrier can be overcome: some scientists link it to difficulties in predicting the propagation of the ocean memory through the subsurface, while other scientists argue that the heat stored at depth propagates to a large extent independently from the irregular chaotic nature of atmospheric winds (*"Reassessing the role of stochastic forcing in the 1997–1998 El Niño"* (G. A. Vecchi et al., 2006)). Efforts are currently directed towards improvements of ENSO predictions at long lead times. Some unprecedented studies have shown that successful predictions are indeed possible 2 years in advance, suggesting that chaos is not a major limiting factor of its predictability (*"Predictability of El Niño over the past 148 years"* (D. Chen et al., 2004)), but forecasts providing this predictive skill are not operational yet. The key for any potential improvement in the lead time of the predictions is the use of the memory stored in the ocean subsurface, for which innovative approaches are being considered (*"Improving the Long-Lead Predictability of El Niño Using a Novel Forecasting Scheme Based on a Dynamic Components Model"* (D. Petrova et al., 2016)). The successful forecast of El Niño and La Niña events at long lead times would be an unprecedented milestone for the climate sciences, modeling and forecasting, as a major achievement arising from years of intense research with huge positive societal and economic implications.

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