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El Niño dynamics and long lead climate forecasts

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RESEARCH ARTICLE

El Niño-Southern Oscillation (ENSO) is a climatic phenomenon in the tropical Pacific arising from interactions between the ocean and the atmosphere on timescales ranging 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.

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 are known to become inaccurate when used at long lead times. 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 [V. Bjerknes, 1904]. This procedure can be repeated to know any future state at very distant times. But unfortunately, our knowledge of any past or present atmospheric state is incomplete and inaccurate, as we cannot put a thermometer and a rain gauge at every single location and altitude of the troposphere, which is the atmospheric portion of the air column where weather happens. 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 [P. D. Thompson, 1957]. This is why the behavior of the atmosphere can be described by mathematical equations (that is, it is a deterministic system), but its future evolution cannot be accurately predicted at lead times longer than a couple of weeks at most (that is, it features a chaotic behavior), due to the fast-growing increase over time of errors in the initial conditions [E. N. Lorenz, 1965]. And this limit is indeed an inevitable constraint in weather predictability, which would not be eliminated even if we had the most powerful supercomputer and the most sophisticated model of the atmosphere [E. N. Lorenz, 1982].

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, we must first understand that the atmosphere is only one element of a more complex system, which also comprises the hydrosphere (oceans, rivers, lakes), the cryosphere (sea ice, snow cover, glaciers), the lithosphere (topography) and the biosphere (ecosystems, human activities), 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. This interaction with external factors shapes the variability of the atmosphere and is at the base of climate forecasting, which allows for extended forecasts on seasonal and longer time scales. For instance, we know that in the extratropics the incoming solar radiation is larger in late spring and early summer, and therefore in a very simplistic manner we can be quite confident that temperatures in the northern hemisphere will be higher in July than in January.

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 therefore the ocean slowly imprints its inertia, which warms or cools 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, and are also communicated to distant regions by a sort of “atmospheric bridge”, collectively known as climate teleconnection [J. D. Horel and J. M. Wallace, 1981]. As a result, the longer inertia of temperatures in 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 [D. J. Karoly, 1989].

El Niño dynamics, teleconnections and predictability

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 climate feature resulting from the interaction between the ocean and the atmosphere in the tropical Pacific basin [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 anomalies that in turn modify the state the ocean. Here, the word “anomaly” refers to the departure of a climate variable from its normal or expected value, so that for instance the anomaly is warm in a mild winter day and cold in a harsh winter day. This simultaneous bidirectional interaction between the ocean and the atmosphere sometimes amplifies an initial temperature, pressure or wind anomaly (referred to as positive feedback), while 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).

In the tropical Pacific, the ocean and the atmosphere work perfectly together and amplify initial anomalies in climate variables, which explains the large magnitude of ENSO and its worldwide impact [J. Bjerknes, 1969]. The dominant winds in the tropical Pacific are the trade winds, which blow from the eastern to the western part of the basin, piling up warm waters in the western tropical Pacific, an area commonly referred to as the warm pool [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 and then to diverge as they reach the top of the troposphere [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 temperatures next to central America. This closed circulation loop in the equator, 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 global climate system [S. I. An et al., 2005]. As a consequence, 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 and 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 [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 atmospheric loop and the east-west temperature 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 to as 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 [S. D. Changnon, 2003]. For example, during the 1997-98 El Niño, California and the southern states of the United States were plagued by storms, whereas the northern half of the country experienced temperatures significantly colder than usual, and below normal precipitation and snowfall [S. A. Changnon, 1999]. Regarding human health, the state of the ocean has been found to modulate or even anticipate the effects of several diseases in distant continental regions, such as malaria, cholera or dengue [B. A. Cash et al., 2013]. For instance, a recent study [J. Ballester et al., 2013] showed that ENSO is associated with enhanced activity of Kawasaki disease [X. Rodó et al., 2014] on opposite sides of the north Pacific basin, through large-scale tropospheric winds [X. Rodó et al., 2011]. Strikingly, the worldwide impacts of ENSO are potentially predictable from several months to a few years ahead [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 surface layer of the western Pacific warm pool. Due to the continuous effect of winds, part of these accumulated water masses are forced to sink, bringing warm anomalies down to the typically colder subsurface [J. Ballester et al., 2015]. The warm waters are therefore stored in the ocean subsurface, at about 100 to 200 meters [J. Ballester et al., 2016a]. 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 (that is, absence of El Niño and La Niña conditions). 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 subsurface warm waters are favored to propagate to the east [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 [F. F. Jin, 1997]. When this happens, the warm ocean 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 the seed for the growth of a La Niña event in the ocean subsurface. 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, while 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 temperature anomalies. This memory arises because subsurface anomalies persist over long periods of time and their effect is delayed, rather than immediate. 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, when temperatures in the ocean surface are playing an active role by driving the wind circulation loop described above. Wind anomalies leading to and triggering an El Niño or La Niña 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 [A. G. Barnston et al., 2012]. The predictions of ENSO that are issued in northern hemisphere spring are still unable to foresee whether an El Niño or a La Niña will occur at the end of the year. This problem arises because no strong early sign of an incoming event is found in the atmosphere or the ocean surface this early in the year, but only eventually in the ocean subsurface [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 El Niño or La Niña event [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 chaotic and difficult to predict atmospheric winds [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 the unpredictable nature of the atmosphere (that is, its chaotic nature) is not a major limiting factor of its predictability [D. Chen et al., 2004], but forecasts providing this predictive capacity 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. For example, a recent study successfully performed retrospective forecasts of El Niño events at long lead times of at least two and a half years, showing that the theoretical limit of ENSO prediction should be sought much longer than the commonly accepted spring barrier [D. Petrova et al., 2016]. This achievement would be an unprecedented milestone for the climate sciences, modeling, forecasting and services [J. Ballester et al., 2016b], as a major result arising from years of intense research with huge positive societal and economic implications.

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