



## King's Research Portal

DOI:

[10.1093/acrefore/9780190228620.013.720](https://doi.org/10.1093/acrefore/9780190228620.013.720)

[Link to publication record in King's Research Portal](#)

*Citation for published version (APA):*

Adamson, G. (2019). El Niño and Society. In *Oxford Research Encyclopedia of Climate Science* Oxford University Press. <https://doi.org/10.1093/acrefore/9780190228620.013.720>

### **Citing this paper**

Please note that where the full-text provided on King's Research Portal is the Author Accepted Manuscript or Post-Print version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version for pagination, volume/issue, and date of publication details. And where the final published version is provided on the Research Portal, if citing you are again advised to check the publisher's website for any subsequent corrections.

### **General rights**

Copyright and moral rights for the publications made accessible in the Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognize and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the Research Portal

### **Take down policy**

If you believe that this document breaches copyright please contact [librarypure@kcl.ac.uk](mailto:librarypure@kcl.ac.uk) providing details, and we will remove access to the work immediately and investigate your claim.

## **El Niño and Society**

George Adamson

### **Keywords**

El Niño, ENSO, La Niña, Co-Production, Forecast, History, Walker, Bjerknes, Pacific

### **Summary**

The El Niño Southern Oscillation is considered to be the most significant form of ‘natural’ climate variability, although its definition and the scientific understanding of the phenomenon is continually evolving. Since its first recorded usage in 1891, the meaning of ‘El Niño’ has morphed from a regular local current affecting coastal Peru, to an occasional Pacific-wide phenomenon that modifies weather patterns throughout the world, and finally to a diversity of weather patterns that share similarities in Pacific heating and changes in trade wind intensity, but exhibit considerable variation in other ways. From the 1960s El Niño has been associated with the Southern Oscillation, originally defined as a statistical relationship in pressure patterns across the Pacific by the British-Indian scientist Gilbert Walker. The first unified model for the El Niño-Southern Oscillation was developed by Jacob Bjerknes in 1969 and it has been updated several times since, but no simple model yet explains apparent diversity in El Niño events. ENSO forecasting has come to be considered a considerable success, but each event still displays surprising characteristics.

### **Introduction**

For a phenomenon that is regularly described as the most significant form of ‘natural’ climatic variability, it is striking how hard it is to pin down the nature of El Niño. The National Oceanic and Atmospheric Administration (NOAA) in the US define it as ‘a phenomenon in the equatorial Pacific Ocean characterised by a positive sea surface temperature departure from the normal (for the 1971-2000 base period) in the Niño 3.4 region greater than or equal in magnitude to 0.5°C, averaged over three consecutive months’ (NOAA, 2003). The definition was adopted to capture past El Niño’s that by ‘conventional wisdom ... have historically been considered as events’ (Trenberth, 1997). This conventional wisdom (and most textbook definitions of El Niño) generally categorises El Niño as follows:

Over the equator, in the Pacific, strong trade winds blow the warm surface waters from east to west. The result of this is unusually cold water along the equator and off the coast of Ecuador and Peru, which limits evaporation and causes the coastal zone to be a dry desert. At similar latitudes in the western Pacific, near Indonesia, the water is much warmer and the region is

rainforest. For various reasons, once every 3-7 years or so the trade winds relax and the warm water flows back eastward. During these years Ecuador and Peru often experience heavy rainfall and Indonesia has drought. Anomalous weather conditions also occur in many other parts of the world including India and the US as global circulation patterns shift. The conditions last from around November until March and are called El Niño. As the sea surface temperatures and trade winds return to normal they often overshoot to create unusually cold conditions, called La Niña events. The whole cycle – including El Niño, La Niña and neutral conditions – is named the El Niño Southern Oscillation, or ENSO.

Under NOAA's definition the strongest El Niño ever recorded occurred in 2015-16. It would be expected, therefore, that Peru would experience inclement conditions in early 2016. The rainy season of January-March 2016 in Peru was, however, fairly inconsequential. Warm ocean temperatures and heavy rainfall did occur during the next year, in February and March 2017. This year was not defined as El Niño by NOAA and was in fact designated as La Niña because the central Pacific was unusually cold. Thus the 2017 conditions somewhat defied categorisation (Peruvian scientists eventually designated it as a 'coastal El Niño'). Other inconsistencies of this sort appear elsewhere in the ENSO record. The 1997-98 El Niño was expected to result in drought in India. Instead the monsoon was slightly stronger than normal and heavy drought occurred in 2004, an El Niño so weak as to barely register under the NOAA definition. During the 2015-16 El Niño, a lack of rainfall over California led one American scientist to describe it as having come 'disguised as La Niña' (Cohen, 2016). Even earlier than that, the US meteorologists Eugene Rasmusson and Thomas Carpenter (1982) had attempted to define a 'canonical' model of El Niño development. Despite being derived from observations of each of the major events before that data, 'canonical' conditions have never been witnessed in subsequent events.

This essay will try to explain how El Niño has come to be both one of the biggest forecasting successes in contemporary climate science and a phenomenon of uncanny diversity such that every event comes as a surprise. In doing so it will adopt what Sheila Jasanoff calls the 'idiom of co-production' (Jasanoff, 2004). This theoretical lens argues that science cannot be separated from the society that produced it. That is, understanding of El Niño has always been coloured by the context within which discoveries were made, and each development in El Niño science has itself respectively changed that context. The co-production lens has been applied previously within climatology to the field of climate change. For example, Clark Miller (2004) has argued that the shift in the 1980s from viewing climate as the sum of local weather statistics to a single, dynamic global system – enabled by the development of General Circulation Models – enabled the development of global climate governance organisations such as the IPCC (Intergovernmental Panel on Climate Change) UNFCCC (United Nations Framework Convention on Climate Change). These organisations then started to drive research agendas and particular research questions, feeding into specific forms of global climate governance (Mahony & Hulme, 2018). Jasanoff herself has argued that climate change alters the way that people understand their place in nature (Jasanoff, 2010). However, intermediate scales between the global climate and local weather, such as ENSO, have not yet been subject to this form of analysis.

The co-production idiom is usually focussed on the outcomes of the scientific process itself (e.g. new technologies or discoveries) and the institutions that are built around them. For ENSO it is necessary to add two other significant components. The first are the events themselves, or more specifically those events that were large enough in the size of their impacts to generate substantial scientific and/or media attention. For the purposes of this chapter these include 1891, 1925, 1957-58, 1972-73, 1982-83, 1997-98 and 2015-16, which are commonly considered as ‘extreme’ within the ENSO community (McCreary, Jr. and Anderson, 1984)(Santoso, Mcphaden, & Cai, 2017) (although as previously stated it is difficult to define exactly what an ‘extreme’ event is).<sup>1</sup> The second is the institution that mediates the relationship between science and the social order, the global media, which from at least 1997 drove public understanding of El Niño as much as scientific understanding.

This essay will thus seek to unpick the historical processes that co-produce the understanding of El Niño and frame which questions are considered relevant within El Niño research. It will begin with a comprehensive history of El Niño science, before discussing some of the most pressing questions currently facing scientists and social scientists who are researching the phenomenon.

## **The Co-Production of El Niño and Society**

### ***The Discovery of El Niño***

The term El Niño, in its original usage, referred to the *Corriente del Niño*, an annual warm water current that appears off the coast of Peru and Ecuador in December and January. This is a seasonal reversal of the strong Humboldt Current that usually brings cold water up the coast of South America from the Southern Ocean. The current reverses off the coast of Peru for about a month beginning around Christmas, bringing tropical fish species and occasional rains. It was named El Niño after the Christ Child, as these were considered a gift (S. G. Philander, 2006). The Paita fishermen that named the current (Carrillo, 1892) did not distinguish the annual events from the occasional, rarer visitations that occurred every few years and brought intense rainfall.

The transition from the El Niño Current to El Niño events began with the first scientific interest in the phenomenon during the late nineteenth century. This related to the growth of geography as a discipline, that is, the integrated study of nature and society, often for the benefit of national agendas nations (Livingstone, 1992). The *Sociedad Geográfica de Lima* had been formed by the President of Peru Andrés Avelino Cáceres in 1888 to ‘promote the application of scientific studies, facilitate the exploitation and increase of natural products of the country, and create a centre of data and information on Geography’ (Cáceres, 1888). Its programme included natural history, descriptive geography (orography and hydrology), meteorology, ethnography, archaeology and demographic statistics (socgeolima.org.pe, n.d.)

The occurrence of intense rainfall and an unusual south-flowing ocean current of warm water in early 1891 therefore interested of the nascent *Sociedad*. This had brought bananas and

oranges to the shores of the desert, as well as ‘large dead alligators and the trunks of trees’ (Pezet, 1896, p. 605). Three papers were thus contributed to the *Boletín de la Sociedad Geográfica de Lima* on the current, the first by Senor Dr. Luis Carranza, President of the *Sociedad* (Carranza, 1891), then by the Vice President Senor Camilo Carrillo (Port Captain of the Peruvian Navy) (Carrillo, 1892) and Dr Victor Eguiguren, President of the nearby *Sociedad Geográfica de Piura* (lawyer and former congressman) (Eguiguren, 1894). It was Carrillo who first mentioned of the term ‘El Niño’, stating that it had been so called by fishermen for centuries (Carrillo, 1892). Eguiguren then developed the first historical record of the phenomenon from local written records, detailing ten previous events between 1791 and 1884 (Eguiguren, 1894).

Details of the El Niño were presented to an international audience at the Sixth Annual Geographical Congress in London in 1895 by the London-born Peruvian diplomat Señor Federico Alfonso Pezet. Pezet called on ‘the great maritime powers having naval stations in the South Pacific’ to:

‘recommend to their officers serving on that coast to carefully observe every indication of the current, and to report fully thereon; such data would be of the greatest use to navigation and science generally.’ (Pezet, 1896, p. 606)

International interest in the phenomenon, however, remained limited. This was perhaps related to the focus of the *Sociedad* as an organization generating science for the national interest, giving El Niño a sense of being of local concern only. Two notable international institutions were exceptions: the North American fisheries industry, who were interested in the current’s effects on anchovy shoals, and the global guano industry who were concerned of its impact on the depleted Chincha Islands’ guano stocks (Coker, 1908). From 1906, the US Government thus funded a small number of research projects on the oceanography of the equatorial eastern Pacific and its impact on seabirds. One of these expeditions provided detailed written observations of an El Niño event in 1925, written by American conservationist Robert Cushman Murphy, who was recording local marine wildlife during a ‘remarkable change in the customary weather of the marine coast of South America’ (Murphy, 1926a, p. 26). Murphy distinguished this phenomenon into a ‘more or less annual’ cycle and a ‘longer cycle, traditionally believed to be seven years’ (Murphy, 1926a, p. 27). His report in the *American Geographical Review* introduced El Niño to the English-speaking world, framing it as a dramatic occurrence that caused severe damage to infrastructure, the collapse of housing, incidences of malaria and mass mortality in sea birds (Murphy, 1926a, p. 47).

Murphy suggested that El Niño events would adversely affect guano-producing seabirds by encouraging their anchoveta prey to swim south or to deeper depths to colder water. This idea he took from the Peruvian agronomist José Antonio de Lavelle, although Lavelle was not included in Murphy’s extensive acknowledgements. Neither were Peruvian scientists included in the network of observers Murphy set up to monitor subsequent events, instead relying on a network of largely North American and European observers coordinated by the American Ambassador in Lima (Murphy, 1926b). This therefore positioned the centre-of-action for El Niño research in North, rather than South America (Cushman, 2004b).

Murphy's work was presented at the Third Pacific Science Congress in Tokyo (Murphy, 1928) where it drew the attention of the Hendrik Petrus Berlage Jr, a Dutch geophysicist working in colonial Batavia (Jakarta). Through Murphy, Berlage then became aware of the earlier work of the *Sociedad*, and in 1927 he published a potential relationship between rainfall in Peru and Indonesia that drew on Eguiguren's record of El Niño events (Berlage, 1927). Berlage's findings were submitted to the Sixth Pacific Science Congress in Java where they drew the attention of the German oceanographer Gerhard Schott (Berlage, 1930), who was so interested in Berlage's findings he then took a trip from the Congress to Peru to learn about the phenomenon (Cushman, 2004b). Subsequent papers by Schott (Schott, 1931, 1932; Schott, Schott, & Hentschel, 1935) detailed a proposed mechanism for the El Niño, suggesting it was caused by an unusual southward displacement of the equatorial rain-band. This would result in a reduction in the trade winds and coastal upwelling (Schott, 1932, p. 98). It is significant to mention that Schott's writings were the first to refer to El Niño only as the stronger events; he noted that the Humboldt Current reversed at that time of year every year but did not call this El Niño (Schott, 1932).

### ***The Southern Oscillation***

Around the time that Murphy published his work, a British scientist named Gilbert Walker was producing a number of papers detailing mathematical relationships in meteorological parameters around the world. The social and epistemological context within which Walker was working was very different to those of the Peruvian geographers and there is no evidence that either were aware of the other's work. Walker was a pure mathematician by training, but from 1904 worked as the Director General of Observatories in India where his primary aim was to develop a formula for predicting the Indian monsoon (Adamson, forthcoming; Allan, Lindesay, & Parker, 1996; Davis, 2002). His spatial concerns were therefore more explicitly global than the national interests of the *Sociedad Geográfica de Lima*. Operating out of Shimla – the Imperial summer capital located in the Himalayas literally and symbolically above the Indian plains (Kennedy, 1996) – the Indian Meteorological Department (IMD) was concerned with generating sufficient information on the Indian climate to render it governable (Naylor & Goodman, forthcoming). Following an approach to global trade commonly adopted by colonial British officials, Walker situated India at the centre of a global network that could be understood through data.

The first Director General of Observatories, Henry Blandford, had determined that droughts were affected by high pressure in Mauritius, Australia and central Asia, as well as by Himalayan snowfall. Walker sought to develop Blandford's work by searching for mathematical correlations between meteorological parameters (pressure, temperature and rainfall) in different parts of the world. Here he was aided by his position as a senior colonial administrator. Most meteorological observatories during the early 20<sup>th</sup> century were located within the territories of a small number of European powers; therefore, it was relatively easy for Walker to gather the available data from around the world. The First World War also resulted in most senior meteorologists being called up for military service, creating a large workforce of under-utilised Indian clerks (Normand, 1953).

Walker was the first meteorologist to apply Pearson's correlation coefficients to meteorology, and he also developed his own 'criterion of reliability' to account for the high random element involved in testing such large quantities of data (Walker, 1914). The ultimate upshot of this work was to isolate three 'swayings of pressure on a big scale' (Walker, 1923, p. 109) between different regions of the world; areas where a reduction in pressure was accompanied by a rise in pressure in another part of the world. The most significant of these he called the Southern Oscillation, a pressure relationship between the Pacific and Indian Ocean (also categorised as a relationship between the east and west Pacific) (Walker, 1924). His other relationships he called the North Atlantic Oscillation – which also became a key focus of climatology from the late twentieth century onwards (Hurrell, Kushnir, & Visbeck, 2001) – and the North Pacific Oscillation, whose use somewhat fell out of favour (although not entirely, see Rogers (1981)). In 1932 he developed an index for the Southern Oscillation, which he used to determine relationships with weather patterns elsewhere in the world. He calculated a periodicity in the index of around three years (Walker & Bliss, 1932).

Walker's work had two impacts on climate science. The first was to create an idea of world weather as interconnected between non-adjacent regions. The second was the development of a methodology whereby statistics would be used to determine weather patterns, with a search for an underlying mechanism a secondary concern. The acceptance of this methodology was certainly not instantaneous. None of Walker's speculations for a possible mechanism – including 'the cold Humboldt current and ... the relatively cool SE and ESE winds blowing over from it' (Walker & Bliss, 1932, p. 136) and 'slowly changing features, such as ocean temperature' (Walker, 1936, p. 136) – were seen as adequate during his lifetime, so many contemporaries viewed the Southern Oscillation as no more than a statistical curiosity and at his death it was considered a failure (Sheppard, 1959). He did, however, gain the attention of Hendrik Berlage, who was head of meteorology at the Dutch colonial *Koninklijk Magnetisch en Meteorologisch Observatorium te Batavia* and therefore had with similar imperial concerns as Walker. In 1934 Berlage published a review of the Southern Oscillation, arguing that it followed a similar periodicity to pressure, and hence rainfall, over Indonesia (Berlage, 1934) Having previously published on El Niño, Berlage provided the link between the international concerns of Walker and the nationalism of the *Sociedad*.

Despite this development, a link between El Niño and the Southern Oscillation was not made until the 1960s, related partly to a lack of research during Second World War and partly to weak Southern Oscillation variability during the middle decades of the twentieth century. Cold War politics catalysed the resurgence of El Niño research during the 1960s, firstly with the 'International Geophysical Year' (IGY) of 1957-58. This was a global endeavour designed to thaw US-USSR relations following the death of Joseph Stalin, with the science of the natural environment – or 'Earth science' – chosen as a suitable apolitical subject to foster collaboration. The 1950s had seen renewed North American interest in the equatorial Pacific due to its importance as a fishery for US agricultural feed (Cushman, 2004a), which included observations of an El Niño event in 1953 (Posner, 1954). El Niño research was therefore an important topic of study during the IGY, with much research coordinated by the Scripps Institute of Oceanography.<sup>ii</sup> Amongst other new scientific endeavours this precipitated the

hiring of the UCLA meteorologist Jacob Bjerknes by the US-led Inter-American Tropical Tuna Commission to study the effects of El Niño on the atmospheric circulation (Cushman, 2004a).

The Cold War also intervened in El Niño science with the communist revolution in Cuba in 1959. This gave the research a further impetus as an opportunity to spread US soft power through scientific collaboration with Latin American countries. The ‘Alliance for Progress’ launched by John F. Kennedy in 1960 included a Latin American Working Group on Earth Sciences and a specific focus on spreading Western values through science. This precipitated ten seasonal cruises to the eastern Pacific as part of an ‘El Niño Project’ between 1963 and 1966, instigated by the Inter-American Tropical Tuna Commission but administered jointly by Peru, Ecuador, Colombia and Chile.<sup>iii</sup> These included observations of oceanic and atmospheric conditions during an El Niño in 1965-66 (Comisión Interamericana del Atún Tropical, 1966).

During this period Hendrik Berlage also recommenced his work on the Southern Oscillation, developing new indices of the phenomenon that represented it as pressure differences between Indonesia and the eastern Pacific Ocean near Easter Island. Berlage drew a link between the Southern Oscillation and ocean conditions across the Pacific, positing an essentially cyclical relationship. Positive Southern Oscillation years – that is, years where pressure over Easter Island was particularly high and over Indonesia particularly low – would result in stronger trade winds and hence a stronger ocean circulation, which would drive the cold water of the Humboldt Current to the western Pacific, resulting in colder temperatures there. This would reduce evaporation near Indonesia and hence raise the air pressure, decreasing the strength of the trade winds and closing the cycle (Berlage, 1957, 1961). Berlage also demonstrated correlations between the Southern Oscillation and air pressure in other parts of the world (Berlage & De Boer, 1960). He did not make a specific link with El Niño though, arguing that sunspots ultimately drove the Southern Oscillation (Berlage, 1961).

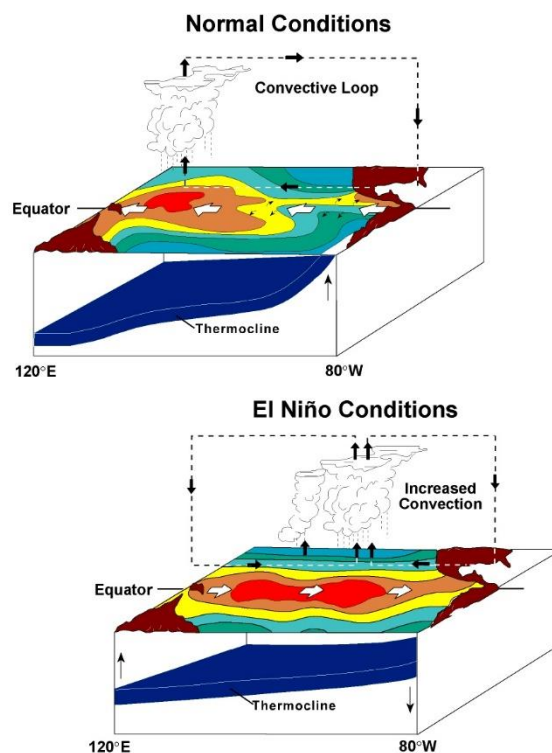
Jacob Bjerknes’ work on El Niño events for the Tuna Commission also drew a link between the Humboldt Current and wider-scale atmospheric changes, building particularly on observations of the 1957-58 El Niño that fortuitously occurred during the IGY. In a paper in 1961 he drew attention to the link between El Niño events and a weakening of the trade winds (Bjerknes, 1961). In 1966 he suggested that the weakening trade winds during El Niño events would reduce the ‘upwelling’ of deep ocean water that normally occurred in the eastern Pacific, which would warm sea-surface temperatures on the equator as far west as the dateline (Bjerknes, 1966a). Also in 1966 he asserted that the 1957-58 El Niño had affected weather patterns in the Northern Pacific and Atlantic (Bjerknes, 1966b). These papers thus expanded the spatial reach of El Niño, providing the phenomenon with global atmospheric characteristics and an oceanic component that stretched at least half-way across the Pacific.

**Bjerknes’s** most significant contribution came in 1969, following the observations of the 1965-66 El Niño. In a paper later considered as a landmark he made three assertions (Bjerknes, 1969). Firstly, the El Niño years when Peru experienced heavy rainfall were also accompanied by heavier-than-normal rainfall over Canton Island in the central Pacific, and both of these regions experienced increased sea surface temperatures during these years. Secondly, like Berlage, Bjerknes showed that these periods of heavy rainfall were accompanied by pressure changes



across the Pacific, and that these were consistent across the El Niños of 1957-58, 1963-64 and 1965-66. However, unlike Berlage he did not suggest that the atmospheric changes drove the oceanic changes; this did not match the close relationship between measured temperature and pressure changes. Neither did he suggest a role for an external forcing like sunspots. Instead he posited an internal mechanism based on the relationship between the ocean and atmosphere. He named this the ‘Walker Circulation’, out of respect for his predecessor and because the variations in the Walker Circulation that led to El Niño events were synonymous with the pressure changes of Southern Oscillation. Lastly, Bjerknes provided more detail on the global meteorological anomalies that occurred during El Niño events, which he called ‘teleconnections’.

Bjerknes’ Walker Circulation was broadly similar to the ‘conventional wisdom’ presented at the start of this essay and is presented here in figure 1. Thus he provided an accepted conceptual model for El Niño and the Southern Oscillation that was still broadly accepted 50 years later. He also vindicated Walker’s suggestion that climate patterns could be isolated by statistical analysis alone, with mechanisms deduced later, causing his method of analysis to gain considerable currency within climate science.



*Figure 1:* Conceptual diagram of the Walker Circulation under neutral and El Niño conditions. Image courtesy of NOAA Pacific Marine Environmental Laboratory, reproduced with permission.

### ***The Global Assemblage of ENSO Research***

Bjerknes’ findings began what might be called the ‘golden age’ of ENSO research. Bjerknes’ theory of El Niño provided a justification for greater scientific observation of the Pacific, notably through the installation of observation buoys but later also satellite observations and

complex computer models. Its impacts on the western US also provided an argument for the US government to divert a portion of its substantial Cold War science funding to El Niño, and it provided a site for the operation of two other new technologies that were had emerged around the time of the IGY: observational satellites and atmospheric simulation models (Fleming, 1998).

Several oceanographic projects were thus launched during the 1970s to provide data to corroborate Bjerknes' model. These were all funded by collaboration between US and Latin American scientific agencies, with one funding guideline published in 1970 specific that the 'geographical location' of partner countries should be 'decided by US national interest' (Scripps, 1970). This omitted Australia, who were also gaining interest in the Southern Oscillation (Troup, 1965), leading the two countries to develop quite different definitions of ENSO. It did, however, allow for substantial collaboration with Latin American countries. The first project, EASTROPAC, occurred from 1967 to 1969 (Tsuchiya, 1972). The second focussed on the impacts of Pacific temperature variability on North America and was called North Pacific Experiment (NORPAX). An array of around 50 observation buoys around the Pacific was originally planned for this project. However, the cost was prohibitive and by this point the focus of the US government had changed from scientific collaboration to a more direct policy of regime change, so funding Pacific oceanography became less of a priority. The combined pressures meant that the number of buoys was reduced to four; this lack of ocean observations was blamed for the failure of North American scientists to predict an El Niño in 1972-73 and thus organise an expedition to record the event in sufficient time. The event was instead observed by Latin American ships located in the region, which was considered an embarrassment by NORPAX scientists (Cushman, 2004a).

1972-73 also saw the second detailed description of the effects of an El Niño on Peru, written by César Caviedes at University of Regina. Caviedes published in the *Geographical Review* and consciously adopted the structure of Robert Cushman Murphy's earlier report on the 1925 El Niño. He adopted a less dramatic tone but still stated that the 'people of the arid northern Peruvian coast are not prepared to cope with sudden meteorological changes' (Caviedes, 1975, p. 501). In the paper he described 'genuine' El Niño years as only those that 'come from a major alteration of the tropical circulation', thereby distinguishing El Niño both from the annual event and any local manifestation, and positioning El Niño specifically as a threat to Peru.

The German-American oceanographer Klaus Wyrtki provided the next development in the theoretical understanding of El Niño. Based on observations of the 1958-59, 1956-66 and 1972-73 El Niños, he asserted that the east and west Pacific did not just have a temperature gradient but also a topographical difference (sea level is higher in the east than the west), which was most pronounced in the leadup to El Niño events (Wyrtki, 1973). This led him to propose that El Niño events would be preceded by unusually strong trade winds, which caused warm water to build up in the western Pacific. Relaxation of the trade winds would then cause the warm water to 'slosh' back to the eastern Pacific, raising sea temperatures there (Wyrtki, 1975). This gave him sufficient confidence in El Niño behaviour to predict an El Niño in 1975 and he successfully lobbied for a NORPAX-sponsored cruise in 1975 to observe the phenomenon.

However, no El Niño developed, although he claimed to have observed the conditions required for an El Niño onset (McPhaden, Timmermann, Widlansky, Balmaseda, & Stockdale, 2015; Wyrтки, Stroup, Patzert, Williams, & Quinn, 1976).

The failed forecast of 1975 highlights a common problem in El Niño research: the difficulty in deriving a universal model from a small number of events with variability characteristics. A similar issue occurred seven years later when Rasmusson and Carpenter (1982) attempted to catalogue El Niño behaviour. This was the first study to use the combination ‘El Niño/Southern Oscillation’ and was based on the same three events analysed by Wyrтки, together with 1962-63, 1969-70 and 1972-73. The ‘canonical’ composite they created built upon Wyrтки’s model, although crucially it indicated that El Niño events were usually preceded by warm sea surface temperatures off the coast of Peru earlier in the year of development. The El Niño in 1982 – the same year that the canonical model was produced – exhibited no prior warming off Peru. This led Wyrтки to confidently dismiss scattered reports that an El Niño was a developing, announcing that ‘to call this event an El Niño would be a case of child abuse!’<sup>iv</sup> This was significant embarrassment, given that the 1982-83 El Niño was subsequently considered one of the strongest ever recorded (McPhaden et al., 1998).

This failure, however, galvanised the next phase of ENSO research. This became the most ambitious El Niño project yet, the Tropical Ocean Global Atmosphere (TOGA) project. This 10-year project, initiated by the World Meteorological Association but strongly influenced by North American scientists, was launched in 1985 with three expressed aims:

1. To gain a description of the tropical oceans and the global atmosphere as a time dependent system, in order to determine the extent to which this system is predictable on time scales of months to years, and to understand the mechanisms and processes underlying that predictability;
2. To study the feasibility of modelling the coupled ocean-atmosphere system for the purpose of predicting its variability on timescales of months to years; and
3. To provide the scientific background for designing an observing and data transmission system for operational prediction if this capability is demonstrated by the coupled ocean-atmosphere system (World Climate Research Program, 1985, p. 7).

The central justification was to understand the implications of tropical ocean variability on atmospheric changes in the higher latitudes. A key component of this work was the installation of the previously cancelled sea surface observation buoy network, notably around 70 moored buoys located near the equator called the Tropical Atmosphere Ocean (TAO) array to measure sea surface temperature, current and sea level variability. This was combined with over 700 drifting buoys to observe ocean currents and a doubling of the number of tide gauges on Pacific islands. The array was installed and maintained by NOAA’s Pacific Marine Environment Laboratory (PMEL), with financial support from, and in partnership with, France, Japan, Taiwan and Korea (McPhaden et al., 1998).

Information collected from the TAO array is transmitted to shore in real time by satellite. These became increasingly important for ENSO monitoring during the TOGA period. The US Navy’s

Geosat, and then European ERS-1/2 and TOPEX/POSEIDON satellites began observing sea surface height from 1985. Surface wind velocity was measured on a number of satellites from 1987. NOAA-launched satellites had incorporated the Advanced Very High Resolution Radiometer (AVHRR) for measuring sea surface temperature from 1981 but had missed the 1982-83 El Niño, blamed on dust from the eruption of El Chichon.<sup>v</sup> Considerable work to calibrate satellite observations was therefore also undertaken during TOGA, as well as new forms of forecasting that blended satellite and in-situ data (see McPhaden et al. 1998 and references therein).

The TAO array and satellites profoundly changed the visualisation of ENSO. For satellites, the Earth-surface images produced enabled ENSO to be conceptualised as a phenomenon of the entire Pacific with anomalous Pacific conditions visible across the equator and beyond during El Niño years (Höhler, 2017). For TAO, the real-time data at and below the surface, available every day, revealed details of ocean-atmosphere interactions that would not have been possible before TOGA. New forms of visualised the global impact of El Niño also emerged through composites based on climatic anomalies (deviations from the norm), which demonstrated starkly the global pattern of teleconnections. These patterns were developed into a global composite of teleconnections by Ropelewski and Halpert (1987).

The first dynamical models of ENSO also emerged during TOGA, developed by Zebiak and Cane (1987) and Schopf and Suarez (1988). Both of these were relatively simple models of the tropical ocean and atmosphere in a thin band north and south of the equator, but it was found that they represented observed El Niño dynamics relatively well (Zebiak et al., 2015). Alongside these, a number of statistical models were developed to forecast ENSO conditions based on the relationship of observed meteorological data around the world, essentially building on Gilbert Walker's approach (Barnett, 1981; Barnston & Ropelewski, 1992; Penland & Magorian, 1993). These were later joined by a suite of ENSO forecasts developed using coupled ocean-atmosphere General Circulation Models (GCMS) (Ji, Kumar, & Leetmaa, 1994; Latif, Sterl, Maier-Reimer, & Junge, 1993; Stockdale et al., 2011). Alongside these, new indices were developed to categorise ENSO in the forecasts. The Southern Oscillation Index (Troup, 1965) was joined by a number of other indices that represented El Niño through sea surface temperatures in a number of regions in the Pacific, named Niño 1, Niño 2, Niño 3, Niño 4 and later Niño 3.4 (Barnston, Chelliah, & Goldenberg, 1997). Prediction skill increased substantially through the 1990s, although it subsequently plateaued (Barnston, Tippett, L'Heureux, Li, & DeWitt, 2012).

One further development was the suggestion that some years exhibited 'extreme-normal' conditions; that is, years where sea level and sea surface temperature were particularly high in the western Pacific and particularly low in the eastern Pacific. Given that one 'extreme' in this variability had a name, convention stated that the other would also be named, despite the fact that observations showed the two extremes to be asymmetrical. An early suggestion was Anti-Niño (Barnett, 1977), although this was dropped due to its associations with the Anti-Christ. *El Viejo* (the old man) was also suggested but didn't gain traction (Meyers & O'Brien, 1995). The name that eventually became accepted was 'La Niña', proposed by the Princeton scientist S. George Philander (S. G. H. Philander, 1985). This choice of name created an implicit

assumption, perhaps not intended by Philander, that La Niña was weaker than El Niño and hence ‘feminine’ (J. Miller, 2007), a somewhat problematic choice that also suggested La Niña conditions were less extreme, which was later suggested to be false (Goddard & Dilley, 2005).

Research during the TOGA cemented a vision of ENSO as a globally interconnected system of complex ocean-atmosphere feedbacks. This required complex technology and global scientific collaboration to understand, necessitating what the anthropologists Kenneth Broad and Ben Orlove called a ‘global assemblage that connects El Niño researchers, program administrators, applications, and many social groups with each other and with elements of universal discourses of technoscience and development’ (Broad & Orlove, 2007, p. 287). ENSO, and ENSO research thus became globalised. This echoed the development of anthropogenic climate change as a research focus during the same period, which also presented the global climate as a unified whole and required collaborative research (C. A. Miller, 2004).

### ***The Media El Niño***

The first El Niño event to gain substantial media coverage was the El Niño of 1982-83. During this event El Niño was treated as a scientific issue with television reports featuring interviews from the scientific community and newspaper articles written by science correspondents. These ‘experts’ would discuss current levels of understanding of El Niño and explain the links between the phenomenon and a particular weather event, highlighting uncertainties (Blench & Marriage, 1998). The El Niño of 1997-98 was covered rather differently. This occurred shortly after the end of TOGA and many of its impacts were forecast successfully--considered at the time a considerable accomplishment. Rapid ocean warming was measured by the TAO array in April 1997 and NOAA forecast a severe El Niño in May 1997 (D. Changnon, 2000). The Peruvian government instigated early flood reinforcement work from June 1997 and the Federal Emergency Management Agency (FEMA) in the USA released flood warnings for California and Florida in August and September. The media were therefore prepared for a spectacle before it occurred, aided by substantial media engagement by NOAA and NASA. César Caviedes’ description of the 1982-83 event – again published in the *Geographical Review* and in this case adopting a far more dramatic style that it had in 1973 – helped to cement the idea of a threatening El Niño (Caviedes, 1984).

Images taken from the TOPEX/Poseidon satellite showed repeating bands of anomalously warm water flowing across the Pacific through 1997, peaking in October with a thin band of warmth across the equator that began at the date line and spread out across the coast of Ecuador and Peru (Höhler, 2017). Heavy rains in Peru began in December 1997 and continued until the following April, a long period even for El Niño years. Rainfall affected not just the coast northwestern regions but also the centre and far south of the country (Orlove, Broad, & Petty, 2004). The *Rio La Leche* became so inundated that an artificial canal was constructed to divert excess water into the desert, with the resulting lake given the somewhat ironic nickname of *Lago La Niña*. For the US press the major point of interest was the repeated heavy rain systems that hit the coast of California, which were responsible for agricultural damage worth over \$1 billion and 17 deaths (S. Changnon, 1999). The *Los Angeles Times* alone published nearly 100 articles on the phenomenon over a 12 month period (S. Changnon, 2000). Associated flooding

caused numerous mudslides that provided news-friendly dramatic images, with one house near Laguna Niguel filmed for 24-hours a day for several weeks before it eventually succumbed (Sturken, 2001).

For US news organisations the El Niño of 1997-98 served several purposes. In simplest terms, the event provided dramatic and unfolding imagery that was attuned to the aesthetic of the new 24-hours news channels (Wilkins, 2000). The *Weather Channel* took particular advantage of this, leading the *Wall Street Journal* to nickname the El Niño '*La Oportunidad*' for the Weather Channel; its 'OJ Simpson' (Wall Street Journal, 1997). El Niño also allowed damage in California and elsewhere to be placed in the context of other global weather extremes, the idea of a globally-interconnected world suiting the post-Cold-War America of the late 1990s (Broad & Orlove, 2007; Sturken, 2001). El Niño constituted a 'conspiracy narrative' that could provide comfort by reducing complexity and offering an outlet for feelings of helplessness (Sturken, 2001, p. 186). Californian bumper stickers carried the tongue-in-cheek slogan 'Don't blame me, blame El Niño!' One journalist noted in October 1997 'We used to blame the Soviets, now we can blame El Niño' (Chicago Tribune, 1997, p. 17).

Incessant media coverage of the El Niño in 1997-98 created a new phenomenon, the (American) 'media El Niño'. During the early stages of the event, television coverage occurred roughly as it had in 1983 with the regular expert solicitation (Wilkins, 2000). As the event developed, media operators grew impatient with the uncertainty described by the scientists and the complex and often contradictory representations of ENSO. The media El Niño thus began to develop characteristics of its own; this was a global 'weather god', imbued with almost omnipotent powers of global destruction (Grove & Adamson, 2018). The US media used the Spanish nomenclature to explicitly portray El Niño as something 'Other' that was attacking the US from outside, drawing links between the phenomenon and illegal migration from Central America (Sturken, 2001). Despite rebuttals from scientists at the time, El Niño then began to be blamed on any usual event, from a heavy tornado season in the Mid-West to snow and ice storms in the northern US (Wilkins, 2000).

This alteration of El Niño from a coupled phenomenon to a dangerous scourge was reflected beyond the US news-consuming population. In Ethiopia the government blamed all El Niño for climate anomalies resulting in water shortages, although the international community suggested that weather variation was around average for the year and the blame lay with government (Blench & Marriage, 1998). The Peruvian media also portrayed El Niño as something attacking the country from outside; in this case the president Fujimori used the phenomenon discursively to present himself as the country's saviour (Broad & Orlove, 2007). In both cases El Niño ceased to be a label for Pacific phenomena and instead became an agent of destruction, aided by descriptions in the local media (Grove & Adamson, 2018).

## **The Current State of ENSO Science**

### ***El Niño Research in the Twenty-First Century***

The El Niño of 1997-98 became in many ways thought of as the ‘quintessential’ El Niño, associated with characteristic ocean patterns in the Pacific and a set of teleconnections that closely matched Ropelewski and Halpert’s (1987) composite. The event was followed by an extended La Niña in 1998-2000, then a period of relative quiet lasting around 16 years. During this time the focus of much of the research expanded in attempt to understand the diversity of ENSO structures and impacts (Capotondi et al., 2015). This concerned either way some El Niños behaved differently than 1997-98, or in some cases why the 1997-98 did not behave as *it* was supposed to, given that it apparently exhibited archetypal El Niño behaviour in so many other ways. For example during the 1997-98 El Niño the Indian monsoon did not fail, although NOAA had predicted that it would. Subsequent droughts occurred in 2002 and 2004, years classified by NOAA as ‘weak’ El Niños (Gadgil, Rajeevan, & Nanjundiah, 2005; Gadgil et al., 2002). This apparently unusual behaviour was the subject of much research during the late 1990s and 2000s, including a suggestion that anthropogenic climate change was weakening the relationship between El Niño and the monsoon (Kinter, Miyakoda, & Yang, 2002; Kumar, Rajagopalan, & Cane, 1999). Ultimately it was suggested in 2006 that the apparently changing relationship between ENSO and the monsoon was related to different ‘flavours’ of El Niño, each of which had different effects on the monsoon (Kumar, Rajagopalan, Hoerling, Bates, & Cane, 2006).

This move to classify El Niño into subcategories became a significant dimension of ENSO research between 2000 and 2014, during a period where no El Niños matched the characteristic pattern of sea-surface temperature anomalies witnessed by satellites in 1997. It began in 2003 when NOAA published an objective definition of El Niño events using Niño 3.4 sea surface temperatures (detailed at the start of this essay) (NOAA, 2003). The motivation for this was a drive by NOAA and the World Meteorological Organisation (WMO) to have a single index-derived definition to enable simpler forecasting.<sup>vii</sup> However, this definition itself led to the classification of a number of events that matched the criteria but had not been accompanied with rainfall over Peru and thus not previously considered as El Niño. These were named by Larkin and Harrison (2005) as ‘Dateline’ El Niños, to reflect that location where the maximum sea-surface warming occurred. A range of additional classifications were then added: the term El Niño *Modoki* was then introduced in 2007 to describe events like 2004-05, which exhibited changes in Pacific temperature patterns but were hardly captured by the NOAA definition, and thus neither standard nor Dateline events (Ashok, Behera, Rao, Weng, & Yamagata, 2007). In 2010 the Dateline and *Modoki* flavours were jointly referred to as ‘Central Pacific’ El Niños (Lorenzo et al., 2010) and in a separate study ‘Warm Pool’ El Niños (Kug, Jin, & An, 2009). Each of these referred generally to years where anomalously warm water was most pronounced in the central Pacific rather than the eastern Pacific. A multi-authored paper in 2018 suggested that El Niño events were in fact a complex interaction of ‘Central Pacific’ and ‘Eastern Pacific’ conditions (Timmermann et al., 2018).

This proliferation of alternative definitions derived in part from the fact that the original NOAA definition was derived only to match ‘conventional wisdom as to what have historically been considered as events’ (Trenberth, 1997), and thus assumed a regularity of El Niño events that was not born out by observations. ‘Historically’ in this case referred to the period where

detailed ocean observations were available, from the 1950s onwards (incorporating El Niño events beginning in 1957-58). Somewhat ironically, reanalysis of available data from contemporary ships logs suggest that the 1890-91 and 1924-25 El Niños witnessed very little change in the central Pacific, with sea surface changes witnessed only off the coast of Peru. These were both certainly considered El Niño by South American and have been central to the history of local South American El Niño science, yet they may not have been defined as El Niños under the NOAA definition. Takahashi and Martínez (2017) named these regional South American warmings ‘coastal El Niños’.

El Niño-type conditions affecting Peru in early 2017 also didn’t register under the NOAA definition, as has been previously mentioned. This event was associated instead with warm sea surface temperatures in the coastal eastern Pacific and heavy rainfall, but without the pattern of sea surface temperature anomalies associated with either standard El Niño definitions or ‘Central Pacific’ events. Occurring soon after Takahashi and Martínez’s (2017) paper, this was also named a ‘coastal El Niño’, its mechanism apparently being a strong version of the annual El Niño current (Garreaud, 2018). Thus El Niño research came somewhat full circle; the idea of El Niño as a local event specific to Peru that disappeared during the middle decades of the twentieth century returned, once again as a phenomenon researched by, and affecting, only Pacific South America. Challenges thus remain in defining El Niño and it is clear that “one size does not fit all”.

A ‘severe’ El Niño that occurred in 2015-16 was also described as exhibiting unusual behaviour. An event was first forecast, almost uniformly within forecast models, for late 2014. Ocean behaviour in early 2014 ‘looked strikingly similar to that observed during the onset of the 1997-1998 El Niño’ (McPhaden, 2015, p. 792). However, temperatures began to subside in late 2014 and there was a lack of consensus within the scientific community over whether an El Niño had occurred. A series of cyclones in the western Pacific during early 2015 then triggered the onset of another El Niño that rose ‘phoenix-like, from the ashes’ in 2015 (McPhaden, 2015, p. 794). Models failed to pick up on this until late boreal spring of 2015. Like in 1997-98, it was hoped that this El Niño would put an end to a 5-year drought in Southern California (Xia & Lin II, 2015). However, in terms of its impacts on the US, the event wore a ‘winter disguise as La Niña’ (Cohen, 2016) and rainfall in Southern California was minimal. The event also did not behave as expected in India; or rather, it behaved exactly as expected. Teleconnection patterns in India were exactly as had been predicted by Ropelewski and Halpert (1987) with drought over the peninsular and a very heavy northeast monsoon affecting the southeast of the country. In terms of sea temperature patterns, however, the 2015-16 El Niño was a standard ‘East Pacific’ event, not a warm pool or *Modoki* El Niño of the form that had been primarily attributed to monsoon failures ten years previously.

The final particularity that entered El Niño research during the twenty-first century was within conceptual models of ENSO. Bjerknes and Wyrski’s early theories had been enlarged upon in a number of ways since the 1980s, related to the development of computer simulations. The first conceptual model named was the *delayed oscillator*, presented by the American oceanographer Julian McCreary Jr (McCreary Jr & Anderson, 1984). This suggested that El Niño events would be instigated by ‘westerly wind bursts’ (essentially anomalies in the easterly



trade winds) over the western Pacific. These instigate large-scale ocean waves called Kelvin waves, which carry warm water to the eastern Pacific. Slower, westward-moving Rossby waves would also be generated, reflecting off the western Pacific coast as cold Kelvin waves, and ultimately triggering the collapse of the El Niño event.

Both of these waves were witnessed during the TOGA period (Boullanger & Menkes, 1995; Busalacchi, McPhaden, & Picaut, 1995; Kessler & McPhaden, 1995). However, observations during TOGA also highlighted important processes that were not included in the delayed oscillator model. Further conceptual models were therefore developed in the 1990s. The *advective-reflective model* built on the delayed oscillator and highlighted the importance of the wave reflections off the eastern Pacific in terminating El Niños; that is, the same Kelvin waves that propagated east to instigate an event would reflect and return west as Rossby waves to terminate them (Picaut, Masia, & Du Penhoat, 1997). The *recharge oscillator* highlighted the importance of warm water build up in the western Pacific under normal conditions, predicting that this would dissipate towards the north and south Pacific during El Niño events. This model is most similar to Bjerknes' and Wyrtki's ideas (Jin, 1997). The *western Pacific oscillator* developed the role of westerly wind bursts in instigating El Niño events (Weisberg & Wang, 1997).

Ultimately in 2001 a *unified oscillator* model was suggested, which incorporated elements of all of the models and highlighted the relative importance of different models under different conditions (Wang, 2001). However, as the NOAA meteorologists stated in an interview with this author in 2016, 'as far as I understand it I don't think the question is anywhere near resolved as to really what makes ENSO tick'.<sup>viii</sup>

### ***Current Research Questions in El Niño Science***

The establishment of a fundamental model of El Niño behaviour therefore remains a concern within El Niño research, made more complex with the re-emergence of the coastal El Niño as a (possibly quite distinct) phenomenon. Timmermann et al. (2018, p. 537) note that the available conceptual models of El Niño can 'neither explain the presence of its spatial diversity nor the potential remote effects of variability originating from the extra-tropical Pacific, Atlantic or Indian Ocean onto this diversity'. However, in terms of pressing questions, the establishment of neat conceptual models is secondary. Indeed, given the apparent diversity in types of events that are now categorised as El Niño – including some that may have very different underlying dynamics – it is possible that a universal conceptual model for ENSO dynamics may never be found. Some scientists have suggested that El Niño or La Niña should instead be thought of as descriptors that loosely categorise a number of different weather phenomena and are open to interpretation; like 'winter' or 'storm' (S. G. Philander, 1998); a 'blanket synopsis of what might be more likely to happen' over the next few months.<sup>ix</sup>

A more important issue is improvements in the forecasts themselves. This was named as the most pressing research area by each of 13 ENSO scientists at NOAA, the National Center for Atmospheric Research (NCAR) and the International Research Institute for Climate and Society (IRI) interviewed by the author in 2016. Forecasts remain temperamental, given the

non-appearance of El Niño in 2014 and the failure to forecast either the El Niño of 2015-16 in advance or the coastal El Niño of 2017. Most scientists identified modelling capacity as the primary problem.<sup>x</sup> The ability of models to predict ENSO states plateaued after around 2005,<sup>xi</sup> with dynamics computer simulation models becoming only slightly better at predicting El Niño events than models derived from statistical inference.<sup>xii</sup> Here ENSO models suffer from the same issues as other climate models, that is, the difficulty of representing local-scale tropical cloud formation processes, otherwise known as convection patterns.<sup>xiii</sup> General improvements in the ability to simulate these processes may help to improve El Niño forecasts.

It is also possible that westerly wind bursts – the ‘high-frequency’, or random changes in the trade winds over the western Pacific that are thought to be fundamental in the formation of an El Niño event – may have some predictability, related to a 30-60 day repeating pattern of rainfall over Southeast Asia called the Madden Julian Oscillation (MJO) (Madden & Julian, 1971). The statistics of these events are also organized by the underlying sea surface temperature anomalies, such that they are not completely random but constitute what is now referred to as ‘state dependent noise forcing’ (Eisenman, Yu, & Tziperman, 2005; Levine, Jin, & McPhaden, 2016). If these higher frequency fluctuations can be shown to be even in part predictable it is possible that the onset of El Niño events may also be easier to anticipate.<sup>xiv</sup> This could push the predictability of El Niño beyond two years. However, Penland and Sardeshmukh suggested in 1995 that forecasting would not be possible beyond 18 months (Penland & Sardeshmukh, 1995), and this time-period has not yet been exceeded. This is despite a two-year forecast that was released for an expected El Niño in 2014; the event that did not materialise (Ludescher et al., 2013).

Perhaps of greater importance than the forecasting of El Niño itself is the prediction of teleconnections associated with the phenomenon. Here is where understanding El Niño diversity, and indeed whether there really is one phenomenon that can be categorised as ‘El Niño’, becomes particularly important.<sup>xv</sup> One particular issue is that to understand El Niño’s impacts across the world it is necessary to use a full-Earth coupled General Circulation Model (GCM), of the sort that are used to understand climate change. However, these models do not represent ENSO particularly well.<sup>xvi</sup> This also presents a problem when trying to understand the effects of climate change on ENSO, the second contemporary modelling problem in ENSO research (Van Oldenborgh, Philip, & Collins, 2005; Vecchi & Wittenberg, 2010). This has been a key area of research since the late twentieth century and particularly since around 2006, given the projected role of ENSO in the ‘pause’ in surface warming. Findings have been somewhat contradictory in this field, however. Different results have respectively suggested an increase in El Niño (Trenberth & Hoar, 1997), more El Niño *Modoki* (Yeh et al., 2009), more extreme El Niño events (Cai et al. 2014) and more extreme La Niña events (Cai et al., 2015).

One finding that is fairly consistent within modelled projections of ENSO is that Pacific patterns resembling ENSO will continue under climate change, and there is little suggestion that the system as a whole will break down (Stevenson et al., 2011; Vecchi & Wittenberg, 2010). The effect of climate change on El Niño teleconnections, however, is an area that is more uncertain and remains an area of concern. Climate change is predicted to increase the amount of energy and moisture in the atmosphere which will potentially therefore affect what

happens globally during an El Niño. This could result in even greater meteorological extremes associated with El Niño and La Niña. As one El Niño researcher put it “from now on every El Niño event is going to generate all these weird extremes ... we have to be ready for the crazy stuff”.<sup>xvii</sup>

On a different note, the use of El Niño forecasts has started to gain significant attention. The forecasting system that was developed for the NOAA ENSO Diagnostic Bulletin had a specific end user in mind: regional weather forecasters in the US,<sup>xviii</sup> and amongst research centres in the US, only IRI specifically focussed on uses of forecasts outside of North America.<sup>xix</sup> However, ENSO forecasts are available online and are used by diverse actors across the world, particularly in the water management and agriculture sectors. For example, the statistical-dynamical ‘linear inverse model’ developed by Cecile Penland at NOAA-Boulder (Penland & Magorian, 1993; Penland & Matrosova, 1994) is used regularly by the Cattleman’s Association in Namibia.<sup>xx</sup> The severity of meteorological extremes associated with the 2015-16 El Niño, particularly in Southern and Eastern Africa, led to a push to understand the way that forecasts are used. This included work on use of ENSO forecasts amongst farmers in South Africa (Baudoin, Vogel, Nortje, & Naik, 2017), Nicaragua and Ethiopia (Christian Aid, 2017), and Costa Rica (Vignola, Kuzdas, Bolaños, & Poveda, 2018). A team led by Michael H. Glantz at the Consortium for Capacity Building, University of Colorado developed this further, using a survey of El Niño responsiveness across 16 countries to derive the concept of ‘El Niño Ready Nations’ where El Niño is built into governance structures (elninoreadynations.com, n.d.; Glantz, Naranjo, Baudoin, & Ramírez, 2018).

Whilst the work of the Consortium for Capacity Building is focussed on national governments, much of the impetus for the work on uses of forecasting has come from the humanitarian or ‘development’ sector, that is, Global North-dominated organisations who provide aid for the Global South. The catalyst for this work was a meeting held by the UN on El Niño in March 2016, during a period where meteorological extremes across Africa were particularly intense. Within this meeting it was agreed to develop “a document outlining steps ... to ensure collective action whenever there is an elevated risk of an event.” The document was to “be developed in consultation with relevant actors *including NGOs and donors*” (IASC, 2018) (*emphasis added*). The result of this was the publication of a Standard Operating Procedure (SOP) for the development and humanitarian sectors in the event of an El Niño forecast. This could ultimately lead to ‘forecast-based financing’, whereby humanitarian aid is allocated in advance of anticipated hazards in response to forecasting (Coughlan de Perez et al., 2015).

The SOP is significant in terms of co-production of science and the social order for two reasons. Firstly, it positions ENSO forecasts centrally within a model of global geopolitics whereby the technological and capital resources of developed countries should be used to help those that are more vulnerable to weather extremes. This increases the soft power of the countries that are creating the forecasts through ‘science diplomacy’ (Fedoroff, 2009), just as the US-Latin American collaborations did in the 1960s. Secondly, the SOP reflects a slight shift in the categorisation of El Niño away from the destructive media El Niño of the 1990s. The document specifically represents El Niño as a period where weather extremes can be forecast more easily, an idea first proposed by Lisa Goddard and Max Dilley at IRI in 2005 (IASC, 2018). Their

somewhat unexpected finding, based on the Emergency Disasters Database, was that years classified as El Niño do not exhibit more weather extremes globally than years classified as ENSO-neutral. However, during El Niño years weather extremes are more predictable. Hence, El Niño forecasts should be seen as an opportunity to reduce socioeconomic losses to weather hazards rather than a threat (Goddard & Dilley, 2005). If this becomes mainstream it will represent a profound shift from the media framing of El Niño as a global scourge (Grove & Adamson, 2018).

In the same study, Goddard and Dilley (2005) provided another finding that has implications for the way that ENSO is perceived. Despite a general sense within the media that El Niño is the stronger of the two extremes, La Niña is actually associated with a greater frequency of meteorological extremes than El Niño is. The environmental historian Julia Miller has argued that this reflects a general assumption within society that phenomena can be divided into binaries and that one – the masculine – is stronger than the other (J. Miller, 2007). This is a strong example of the social order impacting upon science and can have implications for the way that the meteorological hazards associated with El Niño and La Niña are understood. More than one US ENSO scientists interviewed in 2016 expressed a disquiet with the use of the term La Niña, or even the idea that El Niño and La Niña should be considered as clearly-defined ‘events’. Nevertheless, these names have entered common parlance and it is unlikely that they will be dropped any time soon.<sup>xxi</sup>

## **Conclusion**

This essay has shown that many questions remain unanswered within El Niño and ENSO research. It remains an ongoing research area as to whether El Niño is really one event, a number of different events with similar characteristics, or a badge that has been used to classify a wide spectrum of different phenomena that produce similar weather anomalies. These problems are far from solved and the research remains fascinating and consequential. This essay has, however, demonstrated how the context within which certain scientific discoveries on El Niño were made may have influenced the way that El Niño has been understood. The *Sociedad Geográfica de Lima* had national concerns and were therefore likely to consider the *Corriente del Niño* as a local event; however, the imperial concerns of Gilbert Walker led him to the Southern Oscillation, conceived from the outset as a phenomenon affecting the whole world. The interests of the US during the Cold War drove an image of an El Niño that affected the entire Pacific rim and required US science to understand, and the subsequent ‘globalisation’ of ENSO mirrored the globalisation of the world economy at the end of the Cold War. It is unclear whether any of these contexts directly affected the ways that El Niño was conceptualised, but it is important to understand the situated nature of the historical work on the phenomena and the ongoing ramifications of past research on subsequent understandings. Moreover, the conceptualisations of the world created by certain imaginings of ENSO have at various time fed back upon society. For example, the idea of El Niño as a global scourge in 1997-98 required global collaboration to defend against, providing a circular justification for the ‘global assemblage’ of people that worked on the phenomenon.

It is important to note that co-production is designed as a heuristic lens through which to understand the position of science in society. It is not designed to be a predictive theory; Jasanoff (2004) described co-production as an ‘idiom’. No projections can therefore be made on the direction of El Niño science, or on El Niño’s role in future societies. Neither should this lens be seen as an entirely negative critique. El Niño has encouraged interdisciplinary research; it has driven much contemporary understanding of ocean-atmosphere dynamics and has ultimately produced forecasts that can be used to reduce social harm (McPhaden, Zebiak, & Glantz, 2006). The multinational collaborations that incorporate the ENSO ‘global assemblage’ have power dynamics embedded within them, but such a cosmopolitan assemblage can also be viewed as a social good. The approach is instead envisioned as a useful critical lens to view the relationship between climate science and society. For one thing, it is hoped that this essay has highlighted the importance of considering the meteorological extremes that ENSO is associated with when undertaking this kind of research. In trying to understand the dynamics of a ‘global’ phenomenon this can too easily be overlooked.

### **Suggested Readings**

Bjerknes, J. (1969). Atmospheric teleconnections from the equatorial Pacific. *Monthly Weather Review*, 97(3), 163–172.

Changnon, S. (2002). *El Niño 1997-1998: The Climate Event of the Century*. New York: Oxford University Press.

Cushman, G. (2004a). Choosing Between Centers of Action: Instrument Buoys, El Niño, and Scientific Internationalism in the Pacific, 1957-1982. In H. M. Rozwadowski & D. K. van Keuren (Eds.), *The Machine in Neptune’s Garden: historical perspectives on technology and the marine environment* (pp. 133–182). Science History Publications.

Cushman, G. (2004b). Enclave Vision: Foreign networks in Peru and the internationalization of El Niño research during the 1920s. *Proceedings of the International Commission on History of Meteorology*, 1(1), 65–74.

Glantz, M. (2001). *Currents of Change: Impacts of El Niño and La Niña on Climate and Society*. Cambridge: Cambridge University Press.

Grove, R., & Adamson, G. (2018). *El Niño in World History*. Chichester: Palgrave Macmillan.

Jasanoff, S. (2004). *States of Knowledge: The Co-Production of Science and the Social Order*. Routledge.

McPhaden, M. J., Busalacchi, A. J., Cheney, R., Donguy, J.-R., Gage, K. S., Halpern, D., ... Mitchum, G. T. (1998). The Tropical Ocean-Global Atmosphere observing system:

A decade of progress. *Journal of Geophysical Research: Oceans*, 103(C7), 14169–14240.

Philander, S. G. (2006). *Our Affair with El Niño: How We Transformed an Enchanting Peruvian Current Into a Global Climate Hazard*. Princeton University Press.

Ropelewski, C. F., & Halpert, M. S. (1987). Global and Regional Scale Precipitation Patterns Associated with the El Niño/Southern Oscillation. *Monthly Weather Review*, 115(8), 1606–1626. [https://doi.org/10.1175/1520-0493\(1987\)115<1606:GARSPP>2.0.CO;2](https://doi.org/10.1175/1520-0493(1987)115<1606:GARSPP>2.0.CO;2)

Walker, G. T. (1924). Correlations in seasonal variations of weather. I. A further study of world weather. *Memoirs of India Meteorological Department*, 24, 275–332.

Zebiak, S. E., Orlove, B., Muñoz, Á. G., Vaughan, C., Hansen, J., Troy, T., ... Garvin, S. (2015). Investigating El Niño-Southern Oscillation and society relationships. *Wiley Interdisciplinary Reviews: Climate Change*, 6(1), 17–34.

## REFERENCES

Adamson, G. (forthcoming). Imperial Oscillations: Gilbert Walker and the construction of the Southern Oscillation. In M. Mahony & S. Randalls (Eds.), *Weather, Climate and the Geographical Imagination: Placing Atmospheric Knowledges*. University of Pittsburgh Press.

Allan, R., Lindesay, J., & Parker, D. (1996). *El Niño Southern Oscillation and Climate Variability* (Har/Cdr edition). Collingwood, Vic., Australia: CSIRO Publishing.

Ashok, K., Behera, S. K., Rao, S. A., Weng, H., & Yamagata, T. (2007). El Niño Modoki and its possible teleconnection. *Journal of Geophysical Research: Oceans*, 112(C11).

Barnett, T. P. (1977). An Attempt to Verify Some Theories of El Niño. *Journal of Physical Oceanography*, 7(5), 633–647. [https://doi.org/10.1175/1520-0485\(1977\)007<0633:AATVST>2.0.CO;2](https://doi.org/10.1175/1520-0485(1977)007<0633:AATVST>2.0.CO;2)

Barnett, T. P. (1981). Statistical Relations between Ocean/Atmosphere Fluctuations in the Tropical Pacific. *Journal of Physical Oceanography*, 11(8), 1043–1058. [https://doi.org/10.1175/1520-0485\(1981\)011<1043:SRBOFI>2.0.CO;2](https://doi.org/10.1175/1520-0485(1981)011<1043:SRBOFI>2.0.CO;2)

Barnston, A. G., Chelliah, M., & Goldenberg, S. B. (1997). Documentation of a highly ENSO-related SST region in the equatorial Pacific: Research note. *Atmosphere-Ocean*, 35(3), 367–383. <https://doi.org/10.1080/07055900.1997.9649597>

- Barnston, A. G., & Ropelewski, C. F. (1992). Prediction of ENSO Episodes Using Canonical Correlation Analysis. *Journal of Climate*, 5(11), 1316–1345. [https://doi.org/10.1175/1520-0442\(1992\)005<1316:POEEUC>2.0.CO;2](https://doi.org/10.1175/1520-0442(1992)005<1316:POEEUC>2.0.CO;2)
- Barnston, A. G., Tippett, M. K., L’Heureux, M. L., Li, S., & DeWitt, D. G. (2012). Skill of Real-Time Seasonal ENSO Model Predictions during 2002–11: Is Our Capability Increasing? *Bulletin of the American Meteorological Society*, 93(5), 631–651. <https://doi.org/10.1175/BAMS-D-11-00111.1>
- Baudoin, M.-A., Vogel, C., Nortje, K., & Naik, M. (2017). Living with drought in South Africa: Lessons learnt from the recent El Niño drought period. *International Journal of Disaster Risk Reduction*, 23, 128–137.
- Berlage, H. P. (1927). *East-monsoon forecasting in Java*. Landsdrukkerij.
- Berlage, H. P. (1930). Arguments for the existence of a seven-year cycle in the meteorological elements of the station in or near the Pacific Ocean. In *Proceedings of the Fourth Pacific Science Congress, Java, May-June 1929* (Vol. 2, pp. 11–16).
- Berlage, H. P. (1934). *Further Researches Into the Possibility of Long-range Forecasting in Netherlands India, by Dr. HP Berlage Jr* (Vol. 26). Landsdrukkerij.
- Berlage, H. P. (1957). Fluctuations of the Atmospheric General circulation of more than one year : Their nature and Prognostic Value. *Mededelingen En Verhandeligen*, 69, 152p.
- Berlage, H. P. (1961). Variations in the general atmospheric and hydrospheric circulation of periods of a few years duration affected by variations of solar activity. *Annals of the New York Academy of Sciences*, 95(1), 354–367.
- Berlage, H. P., & De Boer, H. J. (1960). On the Southern Oscillation, its way of operation and how it affects pressure patterns in the higher latitudes. *Geofisica Pura e Applicata*, 46(1), 329–351.
- Bjerknes, J. (1961). “El Niño” study based on analysis of ocean surface temperatures 1935-57. *Inter-American Tropical Tuna Commission Bulletin*, 5(3), 217–303.
- Bjerknes, J. (1966a). A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature. *Tellus*, 18(4), 820–829.

- Bjerknes, J. (1966b). Survey of El Niño 1957-58 in its relation to tropical Pacific meteorology. *Inter-American Tropical Tuna Commission Bulletin*, 12(2), 1–62.
- Bjerknes, J. (1969). Atmospheric teleconnections from the equatorial Pacific. *Monthly Weather Review*, 97(3), 163–172.
- Blench, R., & Marriage, Z. (1998). The social and technical construction of weather: El Niño and other climatic events in Sub-Saharan Africa -. *Paper Prepared for the Southern Africa Regional Outlook Forum, Pilanesberg, May 1998*, 13.
- Boullanger, J.-P., & Menkes, C. (1995). Propagation and reflection of long equatorial waves in the Pacific Ocean during the 1992–1993 El Niño. *Journal of Geophysical Research: Oceans*, 100(C12), 25041–25059.
- Broad, K., & Orlove, B. (2007). Channeling globality: The 1997–98 El Niño climate event in Peru. *American Ethnologist*, 34(2), 285–302. <https://doi.org/10.1525/ae.2007.34.2.285>
- Busalacchi, A. J., McPhaden, M. J., & Picaut, J. (1995). Variability in equatorial Pacific sea surface topography during the verification phase of the TOPEX/POSEIDON mission. *Oceanographic Literature Review*, 6(42), 512.
- Cáceres, A. (1888, February 22). Decreto del 22.02.1888.
- Cai, W., Wang, G., Santoso, A., McPhaden, M. J., Wu, L., Jin, F.-F., ... Lengaigne, M. (2015). Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change*, 5(2), 132.
- Capotondi, A., Wittenberg, A. T., Newman, M., Di Lorenzo, E., Yu, J.-Y., Braconnot, P., ... Yeh, S.-W. (2015). Understanding ENSO Diversity. *Bulletin of the American Meteorological Society*, 96(6), 921–938. <https://doi.org/10.1175/BAMS-D-13-00117.1>
- Carranza, L. (1891). Contra-corriente marítima observada en Paita y Pacasmayo. *Boletín de La Sociedad Geográfica de Lima*. 9., 344, 346.
- Carrillo, C. (1892). Hidrografía oceánica. *Bol. Soc. Geogr. Lima*, 1, 72–111.
- Caviedes, C. N. (1975). El Niño 1972: Its Climatic, Ecological, Human, and Economic Implications. *Geographical Review*, 65(4), 493–509. <https://doi.org/10.2307/213747>



- Caviedes, C. N. (1984). El Niño 1982-83. *Geographical Review*, 74(3), 267–290.  
<https://doi.org/10.2307/214939>
- Changnon, D. (2000). Who used and benefitted from the El Niño forecasts? In *El Niño 1997-1998: The Climate Event of the Century* (pp. 109–135). New York: Oxford University Press.
- Changnon, S. (1999). Impacts of 1997–98 El Niño–Generated Weather in the United States. *Bulletin of the American Meteorological Society*, 80(9), 1819–1828.
- Changnon, S. (2000). What made El Niño 1997-1998 famous? The key events associated with a unique climate event. In *El Niño 1997-1998: The Climate Event of the Century* (pp. 3–27). New York: Oxford University Press.
- Chicago Tribune. (1997, October 2). Blame it on El Niño. *Chicago Tribune*, p. 17.
- Christian Aid. (2017, July). Building resilience to El Niño-related drought: Experiences in early warning and early action from Nicaragua and Ethiopia. Christian Aid.
- Cohen, J. (2016, May 11). Weather forecasting: El Niño dons winter disguise as La Niña [Comments and Opinion]. <https://doi.org/10.1038/533179b>
- Coker, R. E. (1908). Regarding the Future of the Guano Industry and the Guano-Producing Birds of Peru. *Science*, 28(706), 58–64.
- Comisión Interamericana del Atún Tropical. (1966). *Proyecto de El Niño: Un estudio Intergubernamental de las aguas conteras del Pacífico de la América del Sur*. Guayaquil: Instituto Nacional de Pesca del Ecuador.
- Coughlan de Perez, E., van den Hurk, B., van Aalst, M. K., Jongman, B., Klose, T., & Suarez, P. (2015). Forecast-based financing: an approach for catalyzing humanitarian action based on extreme weather and climate forecasts. *Nat. Hazards Earth Syst. Sci.*, 15(4), 895–904.  
<https://doi.org/10.5194/nhess-15-895-2015>
- Cushman, G. (2004a). Choosing Between Centers of Action: Instrument Buoys, El Niño, and Scientific Internationalism in the Pacific, 1957-1982. In H. M. Rozwadowski & D. K. van Keuren (Eds.), *The Machine in Neptune's Garden: historical perspectives on technology and the marine environment* (pp. 133–182). Science History Publications.

- Cushman, G. (2004b). Enclave Vision: Foreign networks in Peru and the internationalization of El Niño research during the 1920s. *Proceedings of the International Commission on History of Meteorology*, 1(1), 65–74.
- Davis, M. (2002). *Late Victorian Holocausts: El Niño Famines and the Making of the Third World*. Verso Books.
- Eguiguren, D. V. (1894). Las lluvias de Piura. *Boletín de La Sociedad Geográfica de Lima*, 241, 258.
- Eisenman, I., Yu, L., & Tziperman, E. (2005). Westerly Wind Bursts: ENSO's Tail Rather than the Dog? *Journal of Climate*, 18(24), 5224–5238. <https://doi.org/10.1175/JCLI3588.1>
- elninoreadynations.com. (n.d.). El Niño Ready Nations. Retrieved 24 July 2018, from [elninoreadynations.com](http://elninoreadynations.com)
- Fedoroff, N. V. (2009). Science Diplomacy in the 21st Century. *Cell*, 136(1), 9–11. <https://doi.org/10.1016/j.cell.2008.12.030>
- Fleming, J. R. (1998). *Historical perspectives on climate change*. Oxford: Oxford University Press.
- Gadgil, S., Rajeevan, M., & Nanjundiah, R. (2005). Monsoon prediction—why yet another failure. *Current Science*, 88(9), 1389–1400.
- Gadgil, S., Srinivasan, J., Nanjundiah, R. S., Kumar, K. K., Munot, A. A., & Kumar, K. R. (2002). On forecasting the Indian summer monsoon: the intriguing season of 2002. *Current Science*, 83(4), 394–403.
- Garreaud, R. D. (2018). A plausible atmospheric trigger for the 2017 coastal El Niño. *International Journal of Climatology*, 38(S1), e1296–e1302. <https://doi.org/10.1002/joc.5426>
- Glantz, M. H., Naranjo, L., Baudoin, M.-A., & Ramírez, I. J. (2018). What Does It Mean to Be El Niño Ready? *Atmosphere*, 9(3), 94.
- Goddard, L., & Dilley, M. (2005). El Niño: Catastrophe or Opportunity. *Journal of Climate*, 18(5), 651–665. <https://doi.org/10.1175/JCLI-3277.1>
- Grove, R., & Adamson, G. (2018). *El Niño in World History*. Chichester: Palgrave Macmillan.
- Höhler, S. (2017). Local disruption or global condition? El Niño as weather and as climate phenomenon. *Geo: Geography and Environment*, 4(1), e00034. <https://doi.org/10.1002/geo2.34>

- Hurrell, J. W., Kushnir, Y., & Visbeck, M. (2001). The North Atlantic Oscillation. *Science*, 291(5504), 603–605. <https://doi.org/10.1126/science.1058761>
- IASC. (2018, March). Inter-Agency SOPs for Early Action to El Niño/La Niña Episodes. Retrieved from <https://interagencystandingcommittee.org/reference-group-early-warning-and-preparedness/documents/inter-agency-sops-early-action-el-ni-ola-ni>
- Jasanoff, S. (2004). *States of Knowledge: The Co-Production of Science and the Social Order*. Routledge.
- Jasanoff, S. (2010). A New Climate for Society. *Theory, Culture & Society*, 27(2–3), 233–253. <https://doi.org/10.1177/0263276409361497>
- Ji, M., Kumar, A., & Leetmaa, A. (1994). A Multiseason Climate Forecast System at the National Meteorological Center. *Bulletin of the American Meteorological Society*, 75(4), 569–578. [https://doi.org/10.1175/1520-0477\(1994\)075<0569:AMCFSA>2.0.CO;2](https://doi.org/10.1175/1520-0477(1994)075<0569:AMCFSA>2.0.CO;2)
- Jin, F.-F. (1997). An equatorial ocean recharge paradigm for ENSO. Part I: Conceptual model. *Journal of the Atmospheric Sciences*, 54(7), 811–829.
- Kennedy, D. K. (1996). *The Magic Mountains: Hill Stations and the British Raj*. University of California Press.
- Kessler, W. S., & McPhaden, M. J. (1995). Oceanic equatorial waves and the 1991–93 El Niño. *Journal of Climate*, 8(7), 1757–1774.
- Kinter, J. L., Miyakoda, K., & Yang, S. (2002). Recent Change in the Connection from the Asian Monsoon to ENSO. *Journal of Climate*, 15(10), 1203–1215. [https://doi.org/10.1175/1520-0442\(2002\)015<1203:RCITCF>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<1203:RCITCF>2.0.CO;2)
- Kug, J.-S., Jin, F.-F., & An, S.-I. (2009). Two Types of El Niño Events: Cold Tongue El Niño and Warm Pool El Niño. *Journal of Climate*, 22(6), 1499–1515. <https://doi.org/10.1175/2008JCLI2624.1>
- Kumar, K. K., Rajagopalan, B., & Cane, M. A. (1999). On the weakening relationship between the Indian monsoon and ENSO. *Science*, 284(5423), 2156–2159.
- Kumar, K. K., Rajagopalan, B., Hoerling, M., Bates, G., & Cane, M. (2006). Unraveling the mystery of Indian monsoon failure during El Niño. *Science*, 314(5796), 115–119.

- Larkin, N. K., & Harrison, D. E. (2005). On the definition of El Niño and associated seasonal average US weather anomalies. *Geophysical Research Letters*, 32(13).
- Latif, M., Sterl, A., Maier-Reimer, E., & Junge, M. M. (1993). Climate Variability in a Coupled GCM. Part I: The Tropical Pacific. *Journal of Climate*, 6(1), 5–21.  
[https://doi.org/10.1175/1520-0442\(1993\)006<0005:CVIACG>2.0.CO;2](https://doi.org/10.1175/1520-0442(1993)006<0005:CVIACG>2.0.CO;2)
- Levine, A., Jin, F. F., & McPhaden, M. J. (2016). Extreme Noise–Extreme El Niño: How State-Dependent Noise Forcing Creates El Niño–La Niña Asymmetry. *Journal of Climate*, 29(15), 5483–5499. <https://doi.org/10.1175/JCLI-D-16-0091.1>
- Livingstone, D. (1992). *The Geographical Tradition: Episodes in the History of a Contested Enterprise*. Oxford: Wiley.
- Lorenzo, E. D., Cobb, K. M., Furtado, J. C., Schneider, N., Anderson, B. T., Bracco, A., ... Vimont, D. J. (2010). Central Pacific El Niño and decadal climate change in the North Pacific Ocean. *Nature Geoscience*, 3(11), 762–765. <https://doi.org/10.1038/ngeo984>
- Ludescher, J., Gozolchiani, A., Bogachev, M. I., Bunde, A., Havlin, S., & Schellnhuber, H. J. (2013). Improved El Niño forecasting by cooperativity detection. *Proceedings of the National Academy of Sciences*, 110(29), 11742–11745. <https://doi.org/10.1073/pnas.1309353110>
- Madden, R. A., & Julian, P. R. (1971). Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. *Journal of the Atmospheric Sciences*, 28(5), 702–708.
- Mahony, M., & Hulme, M. (2018). Epistemic geographies of climate change: Science, space and politics. *Progress in Human Geography*, 42(3), 395–424.  
<https://doi.org/10.1177/0309132516681485>
- McCreary Jr, J. P., & Anderson, D. L. (1984). A simple model of El Nino and the Southern Oscillation. *Monthly Weather Review*, 112(5), 934–946.
- McPhaden, M. J. (2015). Playing hide and seek with El Niño. *Nature Climate Change*, 5(9), 791.
- McPhaden, M. J., Busalacchi, A. J., Cheney, R., Donguy, J.-R., Gage, K. S., Halpern, D., ... Mitchum, G. T. (1998). The Tropical Ocean–Global Atmosphere observing system: A decade of progress. *Journal of Geophysical Research: Oceans*, 103(C7), 14169–14240.

- McPhaden, M. J., Timmermann, A., Widlansky, M. J., Balmaseda, M. A., & Stockdale, T. N. (2015). The Curious Case of the El Niño That Never Happened: A Perspective from 40 Years of Progress in Climate Research and Forecasting. *Bulletin of the American Meteorological Society*, 96(10), 1647–1665. <https://doi.org/10.1175/BAMS-D-14-00089.1>
- McPhaden, M. J., Zebiak, S. E., & Glantz, M. H. (2006). ENSO as an integrating concept in earth science. *Science*, 314(5806), 1740–1745.
- Meyers, S. D., & O'Brien, J. J. (1995). Pacific Ocean influences atmospheric carbon dioxide. *Eos, Transactions American Geophysical Union*, 76(52), 533–533.
- Miller, C. A. (2004). Climate science and the making of a global political order. *States of Knowledge: The Co-Production of Science and the Social Order*, 46–66. <https://doi.org/10.4324/9780203413845>
- Miller, J. (2007). The Fall of an Angel: Gendering and Demonizing El Niño. *World History Connected*, 4(3). Retrieved from <http://worldhistoryconnected.press.uillinois.edu/4.3/miller2.html>
- Murphy, R. C. (1926a). Oceanic and climatic phenomena along the west coast of South America during 1925. *Geographical Review*, 16(1), 26–54.
- Murphy, R. C. (1926b). Oceanographic work originating in the New York region during 1925–1926. *Eos, Transactions American Geophysical Union*, 7(1), 97–102. <https://doi.org/10.1029/TR007i001p00097-2>
- Murphy, R. C. (1928). Oceanographic Work Originating in the New York Region during 1925–1926. *Proceedings of the Third Pan-Pacific Science Congress, Tokyo, October 30–November 11 1926, 1*, 219–220.
- Naylor, S., & Goodman, M. (forthcoming). Atmospheric Empire: Historical Geographies of Meteorology at the Colonial Observatories. In M. Mahony & S. Randalls (Eds.), *Weather, Climate and the Geographical Imagination: Placing Atmospheric Knowledges*. University of Pittsburgh Press.
- NOAA. (2003). *NOAA gets U.S. Consensus for El Niño / La Niña Index, Definition* (NOAA No. 03–119).

- Normand, C. (1953). Monsoon seasonal forecasting. *Quarterly Journal of the Royal Meteorological Society*, 79(342), 463–473. <https://doi.org/10.1002/qj.49707934202>
- Orlove, B. S., Broad, K., & Petty, A. M. (2004). Factors that Influence the Use of Climate Forecasts: Evidence from the 1997/98 El Niño Event in Peru. *Bulletin of the American Meteorological Society*, 85(11), 1735–1744. <https://doi.org/10.1175/BAMS-85-11-1735>
- Penland, C., & Magorian, T. (1993). Prediction of Niño 3 Sea Surface Temperatures Using Linear Inverse Modeling. *Journal of Climate*, 6(6), 1067–1076. [https://doi.org/10.1175/1520-0442\(1993\)006<1067:PONSST>2.0.CO;2](https://doi.org/10.1175/1520-0442(1993)006<1067:PONSST>2.0.CO;2)
- Penland, C., & Matrosova, L. (1994). A balance condition for stochastic numerical models with application to the El Niño-Southern Oscillation. *Journal of Climate*, 7(9), 1352–1372.
- Penland, C., & Sardeshmukh, P. D. (1995). The Optimal Growth of Tropical Sea Surface Temperature Anomalies. *Journal of Climate*, 8(8), 1999–2024. [https://doi.org/10.1175/1520-0442\(1995\)008<1999:TOGOTS>2.0.CO;2](https://doi.org/10.1175/1520-0442(1995)008<1999:TOGOTS>2.0.CO;2)
- Pezet, F. A. (1896). La contra-corriente " El niño ", en la costa norte del Perú.
- Philander, S. G. (1998). Who is El Niño? *Eos, Transactions American Geophysical Union*, 79(13), 170–170. <https://doi.org/10.1029/98EO00125>
- Philander, S. G. (2006). *Our Affair with El Niño: How We Transformed an Enchanting Peruvian Current Into a Global Climate Hazard*. Princeton University Press.
- Philander, S. G. H. (1985). El Niño and La Niña. *Journal of the Atmospheric Sciences*, 42(23), 2652–2662. [https://doi.org/10.1175/1520-0469\(1985\)042<2652:ENALN>2.0.CO;2](https://doi.org/10.1175/1520-0469(1985)042<2652:ENALN>2.0.CO;2)
- Picaut, J., Masia, F., & Du Penhoat, Y. (1997). An advective-reflective conceptual model for the oscillatory nature of the ENSO. *Science*, 277(5326), 663–666.
- Posner, G. S. (1954). The Peru Current. *Scientific American*, 190(3), 66–71.
- Rasmusson, E. M., & Carpenter, T. H. (1982). Variations in Tropical Sea Surface Temperature and Surface Wind Fields Associated with the Southern Oscillation/El Niño. *Monthly Weather Review*, 110(5), 354–384. [https://doi.org/10.1175/1520-0493\(1982\)110<0354:VITSST>2.0.CO;2](https://doi.org/10.1175/1520-0493(1982)110<0354:VITSST>2.0.CO;2)

- Rogers, J. C. (1981). The North Pacific Oscillation. *Journal of Climatology*, 1(1), 39–57.  
<https://doi.org/10.1002/joc.3370010106>
- Ropelewski, C. F., & Halpert, M. S. (1987). Global and Regional Scale Precipitation Patterns Associated with the El Niño/Southern Oscillation. *Monthly Weather Review*, 115(8), 1606–1626. [https://doi.org/10.1175/1520-0493\(1987\)115<1606:GARSPP>2.0.CO;2](https://doi.org/10.1175/1520-0493(1987)115<1606:GARSPP>2.0.CO;2)
- Santoso, A., McPhaden, M. J., & Cai, W. (2017). The Defining Characteristics of ENSO Extremes and the Strong 2015/2016 El Niño. *Reviews of Geophysics*, 55(4), 1079–1129.  
<https://doi.org/10.1002/2017RG000560>
- Schopf, P. S., & Suarez, M. J. (1988). Vacillations in a Coupled Ocean–Atmosphere Model. *Journal of the Atmospheric Sciences*, 45(3), 549–566. [https://doi.org/10.1175/1520-0469\(1988\)045<0549:VIACOM>2.0.CO;2](https://doi.org/10.1175/1520-0469(1988)045<0549:VIACOM>2.0.CO;2)
- Schott, G. (1931). Der Peru-Strom und seine nordlichen Nachbargebiete in normaler und anormaler Ausbildung. *Ann. Hydrogr. Marit. Meteorol*, 59, 161–196.
- Schott, G. (1932). The Humboldt Current in Relation to Land and Sea Conditions on the Peruvian Coast. *Geography : Journal of the Geographical Association; Sheffield, England*, 17(2), 87–98.
- Schott, G., Schott, W., & Hentschel, E. (1935). *Geographie des Indischen und Stillen ozeans: im auftrage der Deutschen seewarte verfasst*. Boysen.
- Scripps. (1970). Guidelines for Timely Submission of Proposals. *Scripps Institution of Oceanography Information Exchange Bulletin*, 6(33).
- Sheppard, P. A. (1959). Sir Gilbert Walker, CSI. *Quarterly Journal of the Royal Meteorological Society*, 85, 186.
- socgeolima.org.pe. (n.d.). Sociedad Geografica de Lima. Retrieved 24 July 2018, from <http://socgeolima.org.pe/>
- Stevenson, S., Fox-Kemper, B., Jochum, M., Neale, R., Deser, C., & Meehl, G. (2011). Will There Be a Significant Change to El Niño in the Twenty-First Century? *Journal of Climate*, 25(6), 2129–2145. <https://doi.org/10.1175/JCLI-D-11-00252.1>

- Stockdale, T. N., Anderson, D. L. T., Balmaseda, M. A., Doblas-Reyes, F., Ferranti, L., Mogensen, K., ... Vitart, F. (2011). ECMWF seasonal forecast system 3 and its prediction of sea surface temperature. *Climate Dynamics*, 37(3–4), 455–471. <https://doi.org/10.1007/s00382-010-0947-3>
- Sturken, M. (2001). Desiring the weather: El Niño, the media, and California identity. *Public Culture*, 13(2), 161–189.
- Takahashi, K., & Martínez, A. G. (2017). The very strong coastal El Niño in 1925 in the far-eastern Pacific. *Climate Dynamics*, 1–27. <https://doi.org/10.1007/s00382-017-3702-1>
- Timmermann, A., An, S.-I., Kug, J.-S., Jin, F.-F., Cai, W., Capotondi, A., ... Zhang, X. (2018). El Niño–Southern Oscillation complexity. *Nature*, 559(7715), 535. <https://doi.org/10.1038/s41586-018-0252-6>
- Trenberth, K. E. (1997). The Definition of El Niño. *Bulletin of the American Meteorological Society*, 78(12), 2771–2778. [https://doi.org/10.1175/1520-0477\(1997\)078<2771:TDOENO>2.0.CO;2](https://doi.org/10.1175/1520-0477(1997)078<2771:TDOENO>2.0.CO;2)
- Trenberth, K. E., & Hoar, T. J. (1997). El Niño and climate change. *Geophysical Research Letters*, 24(23), 3057–3060.
- Troup, A. J. (1965). The ‘southern oscillation’. *Quarterly Journal of the Royal Meteorological Society*, 91(390), 490–506. <https://doi.org/10.1002/qj.49709139009>
- Tsuchiya, M. (1972). A subsurface north equatorial countercurrent in the eastern pacific ocean. *Journal of Geophysical Research*, 77(30), 5981–5986. <https://doi.org/10.1029/JC077i030p05981>
- Van Oldenborgh, G. J., Philip, S. Y., & Collins, M. (2005). El Niño in a changing climate: a multi-model study. *Ocean Science*, 1(2), 81–95.
- Vecchi, G. A., & Wittenberg, A. T. (2010). El Niño and our future climate: Where do we stand? *Wiley Interdisciplinary Reviews: Climate Change*, 1(2), 260–270.
- Vignola, R., Kuzdas, C., Bolaños, I., & Poveda, K. (2018). Hybrid governance for drought risk management: the case of the 2014/2015 El Niño in Costa Rica. *International Journal of Disaster Risk Reduction*, 363–374.



- Walker, G. T. (1914). *Correlation in Seasonal Variations of Weather, III: On the Criterion for the Reality of Relationships Or Periodicities*. Meteorological Office.
- Walker, G. T. (1923). Correlation in seasonal variation of weather. VIII : A preliminary study of world weather. *Memoirs of India Meteorological Department*, 24, 75–131.
- Walker, G. T. (1924). Correlations in seasonal variations of weather. I. A further study of world weather. *Memoirs of India Meteorological Department*, 24, 275–332.
- Walker, G. T. (1936). Editorial. *Quarterly Journal of the Royal Meteorological Society*, 62(263), 1–2. <https://doi.org/10.1002/qj.94706226301>
- Walker, G. T., & Bliss, E. W. (1932). World Weather V. *Memoirs of the Royal Meteorological Society*, 4(36), 53–84.
- Wall Street Journal. (1997, October 9). La Oportunidad. *Wall Street Journal*.
- Wang, C. (2001). A unified oscillator model for the El Niño–Southern Oscillation. *Journal of Climate*, 14(1), 98–115.
- Weisberg, R. H., & Wang, C. (1997). A western Pacific oscillator paradigm for the El Niño–Southern Oscillation. *Geophysical Research Letters*, 24(7), 779–782.
- Wilkins, L. (2000). Was El Niño a weather metaphor: A signal for global warming. In S. A. Changnon (Ed.), *El Niño 1997–1998: The Climate Event of the Century* (pp. 49–67). New York: Oxford University Press.
- World Climate Research Program. (1985). Scientific plan for the Tropical Ocean and Global Atmosphere Program. *Technical Document, WMO/TD-64*.
- Wyrki, K. (1973). Teleconnections in the equatorial Pacific Ocean. *Science*, 180(4081), 66–68.
- Wyrki, K. (1975). El Niño—The Dynamic Response of the Equatorial Pacific Ocean to Atmospheric Forcing. *Journal of Physical Oceanography*, 5(4), 572–584. [https://doi.org/10.1175/1520-0485\(1975\)005<0572:ENTDRO>2.0.CO;2](https://doi.org/10.1175/1520-0485(1975)005<0572:ENTDRO>2.0.CO;2)
- Wyrki, K., Stroup, E., Patzert, W., Williams, R., & Quinn, W. (1976). Predicting and Observing El Niño. *Science*, 191(4225), 343–346. <https://doi.org/10.1126/science.191.4225.343>
- Xia, R., & Lin II, R. G. (2015, November 13). El Niño is Here, and it'll be 'One Storm after Another like a Conveyor Belt'. *Los Angeles Times*.

Yeh, S.-W., Kug, J.-S., Dewitte, B., Kwon, M.-H., Kirtman, B. P., & Jin, F.-F. (2009). El Niño in a changing climate. *Nature*, *461*(7263), 511.

Zebiak, S. E., & Cane, M. A. (1987). A Model El Niño–Southern Oscillation. *Monthly Weather Review*, *115*(10), 2262–2278. [https://doi.org/10.1175/1520-0493\(1987\)115<2262:AMENO>2.0.CO;2](https://doi.org/10.1175/1520-0493(1987)115<2262:AMENO>2.0.CO;2)

Zebiak, S. E., Orlove, B., Muñoz, Á. G., Vaughan, C., Hansen, J., Troy, T., ... Garvin, S. (2015). Investigating El Niño-Southern Oscillation and society relationships. *Wiley Interdisciplinary Reviews: Climate Change*, *6*(1), 17–34.

## Notes

---

<sup>i</sup> El Niño events follow the austral summer, hence the double-years for each event. Rainfall in Peru is usually strongest during February and March, but warming of Pacific sea surface temperatures generally peaks in the previous November.

<sup>ii</sup> The relationship between the Cold War, El Niño and the Scripps Institute during the late 20<sup>th</sup> century is discussed in detail by Greg Cushman in ‘Choosing between Centers of Action – instrument buoys, El Niño, and scientific internationalism in the Pacific, 1957-1982’

<sup>iii</sup> This was despite the fact that many US scientists believed that these countries ‘do not understand the importance of the phenomenon to themselves, or others’ (Cushman, 2004b, p. 145).

<sup>iv</sup> Michael McPhaden, interview with the author, April 2016

<sup>v</sup> McPhaden, interview with the author

<sup>vii</sup> L’Heureux, interview with the author

<sup>viii</sup> George Kiladis, interview with the author, July 2016

<sup>ix</sup> Joseph Tribbia, interview with the author, July 2016

<sup>x</sup> Kevin Trenberth, interview with the author, June 2016

<sup>xi</sup> L’Heureux, interview with the author

<sup>xii</sup> Klaus Wolter, interview with the author, July 2016

<sup>xiii</sup> L’Heureux, interview with the author; Christine Kamperidou, interview with the author, April 2016, Peter Gent, interview with the author, June 2016

<sup>xiv</sup> Lisa Goddard, interview with the author, August 2016

<sup>xv</sup> Pedro DiNezio, interview with the author, July 2016

<sup>xvi</sup> McPhaden, interview with the author

<sup>xvii</sup> DiNezio, interview with the author

<sup>xviii</sup> L’Heureux, interview with the author

<sup>xix</sup> Goddard, interview with the author

<sup>xx</sup> Cecile Penland, interview with the author, July 2016

<sup>xxi</sup> Tribbia, interview with the author; Wolter, interview with the author