THE CURIOUS CASE OF THE EL NIÑO THAT NEVER HAPPENED: A Perspective from 40 Years of Progress in Climate Research and Forecasting

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THE CURIOUS CASE OF THE EL NIÑO THAT NEVER HAPPENED

A Perspective from 40 Years of Progress in Climate Research and Forecasting

by Michael J. McPhaden, Axel Timmermann, Matthew J. Widlansky,
Magdalena A. Balmaseda, and Timothy N. Stockdale

The first-ever El Niño forecast, issued for 1975, failed;
we turn back the clock to reconstruct what happened and why.

The El Niño–Southern Oscillation (ENSO) phenomenon is the strongest year-to-year climate fluctuation on our planet, with impacts that are felt worldwide in both natural systems and human affairs (McPhaden et al. 2006). ENSO affects patterns of weather variability by perturbing the global atmospheric circulation through teleconnections that emanate from the tropical Pacific. These circulation changes, which shift the probabilities for floods, droughts, heat waves, and other extreme weather events, lead to significant socioeconomic consequences in far-reaching corners of the globe (Glantz 2001). ENSO also affects Pacific marine fisheries and ecosystems (Barber and Chavez 1983; Chavez et al. 1999), terrestrial ecosystems (Stenseth et al. 2002), and the global carbon cycle (Rayner et al. 1999; Feely et al. 2002). El Niño (the warm phase of ENSO) and La Niña (the cold phase) lead to changes in global mean surface air temperatures because of heat exchanges across ocean–atmosphere–land boundaries (Trenberth et al. 2002). One hypothesis for the recent hiatus in global warming relates to decadal changes in the character of ENSO, with more frequent, strong, and prolonged La Niña events and only weak El Niño events since the turn of the twenty-first century (England et al. 2014; Banholzer and Donner 2014).

The first mention of "El Niño" in a scientific publication dates back to the early 1890s, in which a Peruvian Navy captain reported to the Geographical Society of Lima (Carrillo 1892) on a warm ocean current that was well known to local fishermen. They gave it the name "Corriente del Niño"—the Current of the Christ Child—because it becomes more noticeable soon after Christmas. In some years, the current would persist much longer and extend over a wider region, disrupting fisheries and bringing heavy rains to the region. We now reserve the term "El Niño" for these periods of unusual warming.

For the first half of the twentieth century, El Niño was considered a local phenomenon confined to the Pacific coast of South America. Jacob Bjerknes, a Norwegian-American meteorologist, famous for his work in the early twentieth century on polar fronts, cyclones, and dynamical weather forecasting, became interested in the El Niño problem looking at data from the International Geophysical Year (IGY), which happened to coincide with a major El Niño in 1957/58. Thanks to the combination of a strong signal and enhanced oceanic and atmospheric observations during the IGY, Bjerknes recognized that El Niño was a basin-scale phenomenon not limited to the coast of Peru and Ecuador as previously believed. Moreover, he demonstrated that El Niño developed through positive feedbacks between the ocean and atmosphere, in which a weakening of the equatorial Pacific trade winds would cause a rise in sea surface temperatures (SSTs), leading to a further weakening of the trades—a process we now refer to as the Bjerknes feedback. These coupled interactions can amplify initial anomalies, resulting in unusually high SSTs that cover much of the eastern and central tropical Pacific. Positive SST anomalies further cause shifts in tropical precipitation and atmospheric heating, affecting the Hadley and Walker circulations, the position and intensity of the jet streams, and the climate over North America and elsewhere. The key oceanographic process that Bjerknes identified as responsible for rapid eastern Pacific warming was a reduction in trade wind–driven upwelling of cold water from the ocean's deeper layers to the surface.

Shortly after Bjerknes published these groundbreaking concepts (Bjerknes 1966, 1969), the major 1972/73 El Niño occurred, which caused the Peruvian anchovy fishery to collapse (Glantz 2001). At this time, Peru was the largest fishing nation in the world, with peak anchovy landings in 1970 of over 12 million metric tons. In 1972/73, El Niño–induced reductions in upwelling and nutrient supply to the surface layer led to decreased primary production and phytoplankton abundance, with effects that reverberated through all higher trophic levels of the marine food web. Combined with overfishing (Glantz 2001), the anchovy fishery crashed, with less than 2 million metric tons harvested in 1973. Anchovies were used extensively as a source of protein for poultry and livestock feed around the world, so collapse of the Peruvian fishery rippled through the global economy. These dramatic events led to an upsurge of scientific interest in El Niño and its socioeconomic consequences (Halpern 1996). Growing interest in El Niño also set the stage for an equatorward expansion of the North Pacific Experiment (NORPAX), which was originally designed in the early 1970s to study the potential effects of the North Pacific Ocean on U.S. climate (Namias 1969). However, Bjerknes's ideas on the potential impacts of El Niño on North American seasonal climate motivated adoption of a broader geographic and scientific scope for the program.

It was against this scientific backdrop that Klaus Wyrtki of the University of Hawaii began systematic studies of wind-driven ocean circulation in the early 1970s. He published a series of papers using island sea level data, shipboard hydrographic data, and winds from volunteer observing ships to examine the seasonal to interannual variability of major zonal currents in the Pacific basin and how they varied in relation to changes in wind stress (Wyrtki 1973, 1974a,b, 1975a; Wyrtki and Meyers 1976). This observational work culminated in his breakthrough theory for El Niño (Wyrtki 1975b). The prevailing paradigm at the time was that a local relaxation of the southeasterly trade winds off the coast of Peru and Ecuador would lead to a reduction in upwelling and the onset of SST warming. Wyrtki demonstrated that this was not the case and instead hypothesized that, for a 1–2-year period before El Niño, stronger than normal trade winds in the central Pacific would pile up excess warm water in the western basin via an intensified westward-flowing South Equatorial Current. A sudden relaxation of the trades in the central equatorial Pacific would then allow this warm water to "slosh back" toward the east in the form of an eastward-propagating equatorial Kelvin wave.[1]

At the same time that Wyrtki was developing his ideas on El Niño ocean dynamics, William Quinn of

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[1] Wyrtki's ideas on remote forcing and basin-scale responses during El Niño were inspired in part by studies of seiches in the Baltic Sea early in his career (Wyrtki 1952; Speidel 2006). Seiches typically result when strong winds push water from one end of an enclosed basin of water to the other. When the winds stop blowing, water rebounds to the other side of the basin, sometimes "sloshing" back and forth with preferred periodicities. On one occasion, a seiche in the Baltic caused severe flooding in Kiel, Germany, where Wyrtki studied under George Wüst for his Ph.D. in the late 1940s.

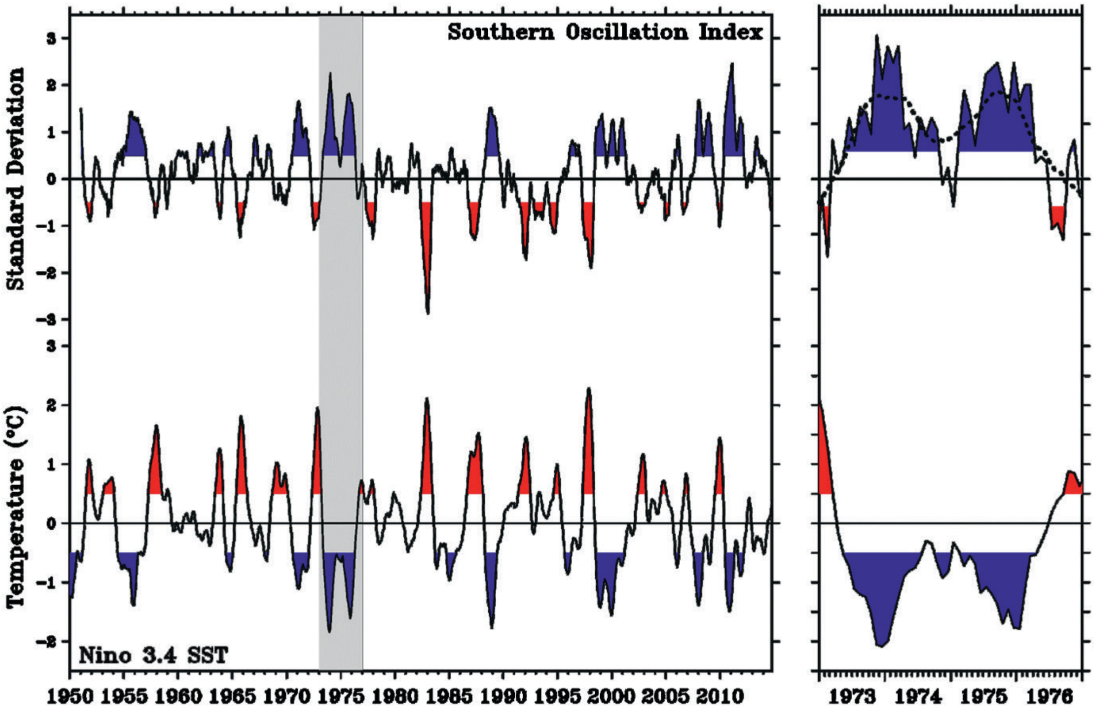

Fig. 1. Monthly Niño-3.4 SST and SOI, each smoothed with a 5-month running mean filter. The Niño-3.4 index is computed as the monthly SST anomaly averaged over the region 5°N–5°S, 120°–170°W. The SOI (see text for definition) is normalized by its standard deviation. Values between ±0.5°C and ±0.5 std dev are considered normal. Periods in red represent El Niño conditions, and periods in blue represent La Niña conditions. (left) The period 1973–76 is highlighted (shading) and (right) a blowup of monthly means for 1973–76. Overplotted in (right) are 12-month running means of the SOI (dashed line), which are equivalent to what Quinn (1974a,b) used to make his prediction.

Oregon State University was developing a prediction scheme for El Niño based on the Southern Oscillation index (SOI). The SOI (normalized difference in sea level pressure between Tahiti, French Polynesia, and Darwin, Australia) is a proxy for the strength of the southeasterly trade winds. Positive values (Tahiti unusually high relative to Darwin) correspond to strong trade winds and negative values (Tahiti unusually low relative to Darwin) correspond to weak trade winds.[2]

Based on the behavior of the SOI prior to previous El Niño events, Quinn postulated that, if 12-month running mean averages of the SOI were high for 1 year or more and began to rapidly fall, that would signal the imminent onset of a warm event (Quinn 1974a). The SOI was elevated throughout 1973/74 and began to decrease rapidly in middle to late 1974 (Fig. 1). From these observations, Quinn published the first ever El Niño prediction in 1974: "Based on current indications of these monitoring tools, it appears that we might expect a weak El Niño occurrence in early 1975, unusually heavy central and western equatorial Pacific precipitation in 1975 and below normal precipitation over Indonesia in mid-late 1975" (Quinn 1974b, p. 3). He further stipulated that the El Niño would arrive late because the SOI, though elevated for a prolonged period of time, had not reached a presumed critical threshold during the previous year (Wyrtki et al. 1976).

Quinn presented his El Niño prediction and Wyrtki presented his El Niño theory at the October 1974 Eastern Pacific Oceanic Conference in Lake Arrowhead, California. The underlying physical concepts behind the prediction and theory were essentially identical. So, during the conference, Wyrtki and Quinn hatched an idea to test the theory on the assumption that the prediction would prove true. Wyrtki led the writing of a proposal, submitted to the National Science Foundation in late October 1974, to fund an equatorial Pacific "El Niño Watch" expedition aboard the University of Hawaii's R/V *Moana Wave*. The goal was to determine the origin of anomalously warm surface waters appearing in the eastern Pacific during the onset of an El Niño and to ascertain whether the source of

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[2] At the time, Quinn computed the SOI as the pressure difference between Easter Island and Darwin. Easter Island, like Tahiti, is located in the subtropical high pressure zone of the South Pacific.

these waters was consistent with the idea of remote wind forcing from the central Pacific. The proposal was successful and jointly funded by the National Science Foundation and the Office of Naval Research. Two cruises were launched as part of the expedition, the first in February–March 1975 and the second in April–May 1975 (see sidebar).

Data collected during the expedition showed an initial SST warming in February–March 1975 but then a return to normal conditions by May. No El Niño developed in 1975. Wyrtki and collaborators published their findings the following year in a *Science* paper entitled "Predicting and observing El Niño" (Wyrtki et al. 1976). The paper was notable not only for what it documented, including the SOI prediction and a subset of the expedition data, but also in retrospect for what it did not report. Today, it raises several interesting questions that were beyond the capabilities of research scientists of the 1970s to address: What were the large-scale ocean–atmosphere conditions before, during, and after the expedition? What were the ocean dynamics behind the brief warming observed in February–March 1975? Why did this warming not amplify into a full-blown El Niño? The paper also prompts the question of what, in retrospect, we would have predicted in 1975 from 1974 initial conditions using modern El Niño prediction techniques.

Our purpose is to revisit this period to answer the above questions. In the early 1970s, there was no sustained real-time ocean observing system in the tropical Pacific, only a rudimentary understanding of El Niño dynamics, and no proven El Niño forecasting capabilities. Now, from the perspective of 40 more years of experience, we can in hindsight shed light on this first attempt at predicting an El Niño event and observing its evolution. In documenting this historical event with modern analysis and forecasting methods, we can determine not only what happened but why it

THE 1975 EL NIÑO WATCH EXPEDITION

The proposal for an El Niño Watch expedition was funded just six weeks after submission, with joint sponsorship from the National Science Foundation (NSF) and the Office of Naval of Research (ONR). The proposal was successful thanks in part to the strength of the scientific arguments and also to Klaus Wyrtki's reputation as a leading force in El Niño research. Once funded, cruise preparations proceeded with a sense of urgency, given how little lead time there was before the expected onset of the El Niño. In parallel with these preparations, a small working group gathered in La Jolla, California, in mid-December 1974 to reexamine the prediction prior to the launch of the expedition. According to Curt Collins, the NSF program manager who administered the proposal, if updated information indicated that an El Niño might not develop, the cruise would be delayed and reconsidered for the following year. Instead, the prediction was reconfirmed for a weak, late developing El Niño and the expedition was given the green light. Collins shared his notes from that meeting, which included an evocative poem that he penned "ex tempore." It ended with

> The Child will be late this year
>
> but His Presence will be felt
>
> by those who know the sea.

It was appreciated, even before the Rasmusson and Carpenter (1982) composite description of El Niño evolution, that warm SST anomalies would develop first in the far eastern Pacific and then progressively later in the central basin (Hickey 1975). Bjerknes (1966, 1969) emphasized that patterns of weather variability over North America were strongly influenced by these later developing central Pacific SSTs. However, oceanographic interest at the time focused on the far eastern Pacific where the first signs of warming had occurred in previous El Niño events and where the 1972/73 El Niño had caused a collapse of the Peruvian anchovy fishery. Thus, the expedition took place in the region near to and east of the Galapagos Islands.

The expedition consisted of two cruises aboard the R/V *Moana Wave*, the first in February–March 1975 and the second in April–May 1975. Investigators from many institutions were on board the ship to make extensive physical, chemical, and biological oceanographic measurements, as well as surface meteorological measurements and upper air soundings (Patzert 1976). Most of these observations were compiled and described in the El Niño Watch expedition atlas (Patzert et al. 1978). Deep ocean moorings were also deployed on the first cruise. Data from these moorings lead to a second publication in *Science*, in addition to that of Wyrtki et al. (1976), on the first description of Rossby waves in the tropical Pacific Ocean (Harvey and Patzert 1976).

Wyrtki et al. (1976) described the temperature and salinity differences between the two cruises to illustrate the initial warming observed in February–March 1975 and its return to near normal in April–May. They interpreted these changes as an incursion from and later retreat to the north of warm, low salinity water. We present here an analysis of the temperature data from the two cruises (Fig. SB1) to highlight the structure of these changes and how they are consistent with the response to the passage of an intraseasonal Kelvin wave. Note that these data are also included in the ORA-S4 ocean reanalysis used in our study.

Very warm 26°–28°C SSTs and a 40–60-m-deep thermocline were observed near the equator in February–March

(Fig. SB1a). Coastal upwelling at this time was restricted to a narrow nearshore strip south of 5°S. These conditions were very much El Niño like and one can appreciate how exciting these observations would have been at the time. However, conditions returned to near normal during the second cruise, with shallow thermocline and cold SSTs typically associated with robust coastal and equatorial upwelling (Fig. SB1b). The difference between the two cruises (Fig. SB1c) shows the largest 20°C changes concentrated within a few degrees of the equator and along the coast, as would be expected from the passage of an equatorially trapped downwelling Kelvin wave that transferred energy into a downwelling coastally trapped wave. The difference plot also indicates that SSTs were almost 5°C warmer east of the Galapagos during the first cruise than during the second. The depressed thermocline along the equator and coast during the February–March cruise would have reduced the effectiveness of upwelling to cool the surface, since the source waters for the upwelling would have been warmer. Offshore advection from the coast of warmer upwelled water would also have led to anomalous warming south of the equator during the first cruise (e.g., Wyrtki 1977b).

Interestingly, local wind conditions during the cruises were not reported in Wyrtki et al. (1976). However, William Patzert, who served as chief scientist on the first cruise in February–March, observed that "the Southeast Trades were extremely weak north of 10°S" (Patzert 1976, p. 19). These anomalously weak trades are evident in Fig. 3a. Regional weakening of the trade winds may have contributed to the unusually deep thermocline and warm SSTs observed at this time. However, regional trade wind weakening, when it occurs, is generally of secondary importance compared to remote wind forcing in generating thermocline depth and SST anomalies in the eastern equatorial Pacific (e.g., Zhang and McPhaden 2008).

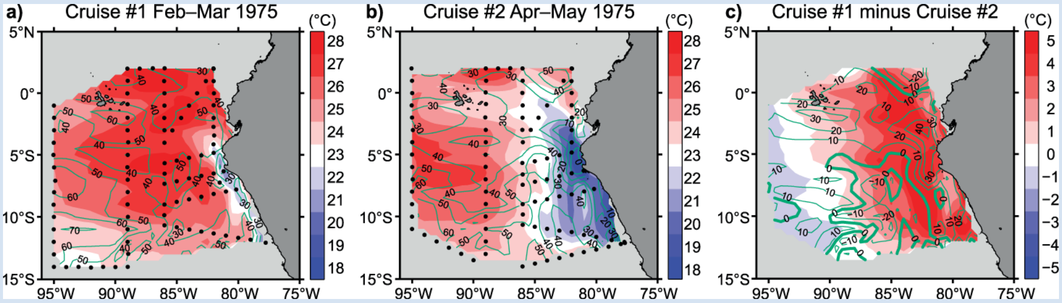

Fig. SB1. SST (shading; °C) and depth of the thermocline as indicated by the 20°C isotherm (contours; m) from El Niño Watch expedition data for (a) the Feb–Mar 1975 cruise, (b) the Apr–May 1975 cruise, and (c) the difference between the two cruises. Dots indicate station locations.

happened. Recounting the events of this period also allows us to highlight progress since the 1970s in our ability to observe, understand, and predict variations associated with ENSO, which is a tribute to early pioneers like Bjerknes, Wyrtki, and Quinn who laid the groundwork for later generations to build upon.

DATA AND METHODS. Today we can generate historical reconstructions of oceanic variability by combining information from ocean models, atmospheric forcing, and ocean observations. These ocean reanalyses provide a more comprehensive perspective on the state of the ocean than was available to Wyrtki and his collaborators at the time of the El Niño Watch expedition. However, data from the tropical Pacific for both the ocean and the atmosphere in the mid-1970s were sparse relative to later decades, so the accuracy of reanalyses from that era are limited by deficiencies in observing systems, as well as by approximations in data assimilation methodologies and model systematic errors.

Bearing these limitations in mind, we use the European Centre for Medium-Range Weather Forecasts (ECMWF) ocean reanalysis system 4 (ORA-S4), which spans the period from 1958 to the present (Balmaseda et al. 2013). ORA-S4 has been produced by forcing an ocean model with atmospheric reanalysis heat, momentum, and freshwater fluxes and combining the output with SST, sea level from satellite altimetry (since 1993), and quality-controlled in situ ocean observations from the EN3 dataset (Ingleby and Huddleston 2007) every 10 days. For the period in question, the in situ observations are mainly ship based: temperatures from expendable bathythermographs (XBTs) corrected for fall rate (Wijffels et al. 2008) and temperature and salinity from conductivity–temperature–depth (CTD) sensors. Sea level data from coastal and island tide gauges were not assimilated.

SST and surface fluxes are from the 40-yr ECMWF Re-Analysis (ERA-40; Uppala et al. 2005). ERA-40 combines the output of an atmospheric model forced by SST with available observations of the atmosphere. In 1974, most of the atmospheric observations were conventional data (e.g., radiosondes and sea level pressure), although infrared data from the Vertical Temperature Profiler Radiometer (VTPR) during 1972–79 were used for the first time in data assimilation as radiances. The SST data used in ERA-40 for 1974/75 are from the presatellite era, provided by the Hadley Centre Sea Ice and Sea Surface Temperature dataset, version 1 (HADISST1; Rayner et al. 2003).

We also use zonal surface winds from Banaba Island (0.9°S, 169.5°E) in the Republic of Kiribati during the 1970s. These wind data were reported by observers using the Beaufort scale and subsequently converted to wind speed (Luther et al. 1983). Island winds in general were not assimilated into the ERA-40 because of concerns about how representative they were of open ocean conditions (Uppala et al. 2005). However, the Banaba and ERA-40 winds are remarkably consistent, as we shall see below.

Retrospective forecasts from various dates in 1974 and 1975 are made using the latest version of the ECMWF seasonal forecast system, known as system 4 (S4), which was implemented operationally in 2010 (Molteni et al. 2011). The forecasts take initial conditions for the ocean and atmosphere from ORA-S4 and ERA-40, respectively. The atmosphere model has a T255 spectral truncation and an 80-km horizontal resolution and 91 levels extending to the lower mesosphere. ENSO SST forecast performance in recent decades is very good (Molteni et al. 2011), but previous tests with a similar model version have shown somewhat lower levels of skill in the 1960s and 1970s. Note that S4 has a moderately good representation of the 30–60-day-period Madden–Julian oscillation (MJO), which has been linked to the triggering of past El Niño events. The S4 system also includes a multi-time-level stochastic physics scheme, designed to represent some of the uncertainty in forecasts due to model error. These two factors ensure that forecasts from S4 have significant spread, which at least in recent years represents well the actual forecast uncertainty.

We also include comparison with the previous ECMWF S3 (Stockdale et al. 2011), for which reforecasts for the 1960s and 1970s are available. S3 was implemented in 2006 and showed fairly good skill during this epoch in terms of its ensemble mean forecasts. However, because of its underrepresentation of uncertainty in the winds, it had a much narrower and less reliable representation of forecast uncertainty in SST. Finally, we include with these state-of-the-art seasonal forecasts a series of retrospective forecasts for 1974 and 1975 from centers that participated in the Development of a European Multimodel Ensemble System for Seasonal-to-Interannual Prediction (DEMETER) project. DEMETER was a European project to develop a multimodel seasonal prediction system (Palmer et al. 2004) including the seasonal forecasting systems available as of 2002. To compare models with different systematic errors, or biases, model correction techniques were applied to each model individually based on their retrospective seasonal forecasts of multiple decades (Palmer et al. 2004; Molteni et al. 2011; Stockdale et al. 2011). This intermodel comparison will provide a context of how

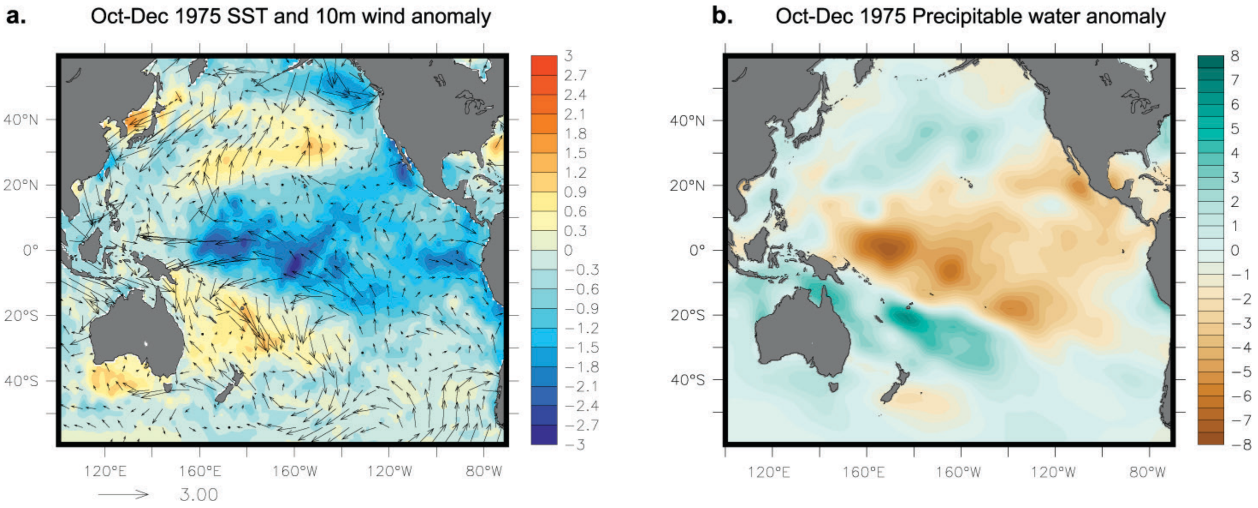

Fig. 2. Seasonal mean anomalies of (a) SST (in °C) from the HADISST1 (Rayner et al. 2003) and 10-m wind (in m s^{-1}) and (b) precipitable water content (in kg m^{-2}) for Oct–Dec 1975 from the National Centers for Environmental Prediction (NCEP) Twentieth Century Reanalysis (Compo et al. 2011).

dynamical seasonal forecasting has progressed over the last decade.

OBSERVED VARIABILITY IN 1974/75. Quinn (1974b) predicted that an El Niño would develop in 1975. It turned out instead that a strong La Niña developed (Figs. 1 and 2). La Niña is characterized by colder than normal SSTs in the equatorial Pacific, stronger than normal trade winds across the basin, and anomalously dry conditions in the central and eastern tropical Pacific. Unusually cold conditions, if mentioned at all in the 1970s, were sometimes referred to as "anti–El Niño" (Barnett 1977). The term "La Niña" had not been coined yet and formal description of the cold side of the ENSO cycle would wait until the strong 1988 La Niña to be recognized as a phenomenon worthy of study in its own right (Philander 1990).

The period from mid-1973 to early 1976 moreover coincided with a stretch of prolonged cold conditions

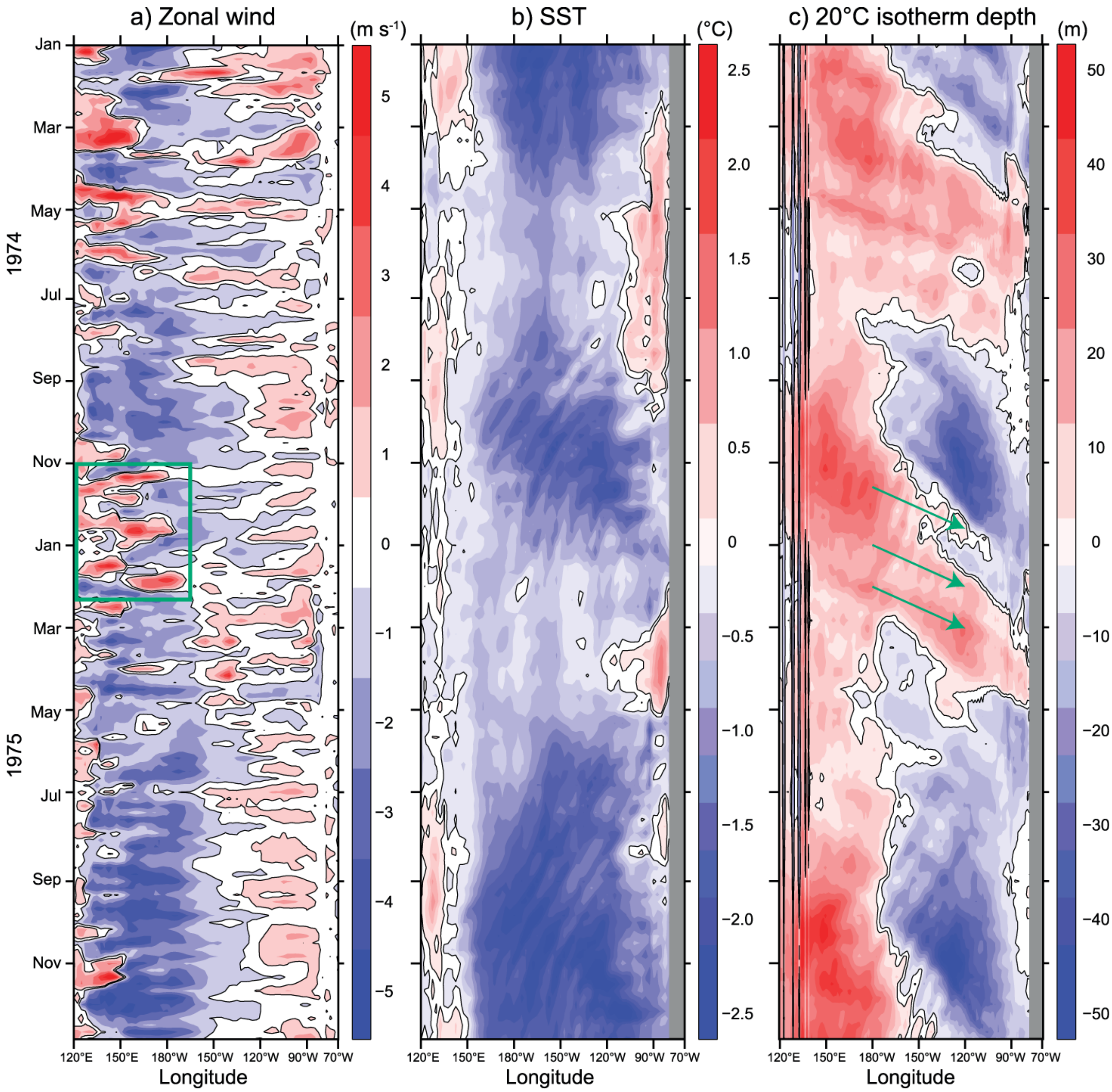

FIG. 3. Anomalies of (a) zonal wind, (b) SST, and (c) depth of the 20°C isotherm from 1 Jan 1974 to 31 Dec 1975 for the equatorial Pacific (2.5°S–2.5°N; pentad averages). Zonal winds are from ERA-40; SSTs and subsurface temperatures are from ORA-S4. The 1961–90 climatology is subtracted from each field. Three westerly wind bursts are enclosed by the green box in (a). Arrows in (c) indicate three downwelling Kelvin waves (first baroclinic mode; 2.5 m s^{-1} phase speed) evident in the 20°C isotherm depth.

in the tropical Pacific (Fig. 1). It has recently been recognized that La Niña conditions often persist and reemerge over two or more consecutive yearlong periods, in contrast to El Niño events, which generally decay in boreal spring following their peak (McPhaden and Zhang 2009). Reemergent La Niña conditions were evident not only in 1973–75 but also in 1954–56, 1983–85, 1998–2001, 2007–09, and 2010–12 (Fig. 1). The reason for this asymmetry in the ENSO cycle is still a matter of debate, but it may relate to remote influences from the Indian Ocean on deep convection over the Pacific (Okumura and Deser 2010) or more localized and nonlinear ocean–atmosphere feedbacks (e.g., DiNezio and Deser 2014). In retrospect, the possibility of La Niña conditions persisting into 1975 would not have been an unreasonable forecast to make in 1974, given the analogous development of other cold periods in the record.

Evolution of conditions along the equator in 1974/75 shows that unusually strong and persistent trade winds in the central and western Pacific were interrupted by three brief periods of westerly wind anomalies in the western Pacific between November 1974 and January 1975 (Fig. 3). These weakened trade winds in ERA-40 were also observed at Banaba Island with similar timing and amplitude (Fig. 4). The wind bursts occurred during a brief lull in the otherwise high SOI values observed during mid-1973 to early 1976 (Fig. 1). Periods of episodic westerly winds lasting several days to weeks and their connection to El Niño were first described in the early 1980s (Keen 1982; Luther et al. 1983). They are often referred to as westerly wind bursts (WWBs) and develop in association with the MJO (McPhaden 1999; Hendon et al. 2007), cold air outbreaks from higher latitudes (Yu and Rienecker 1998), tropical cyclones (Keen 1982), and/or random weather events (Harrison and Vecchi 1997). They can occur at any time of year, though seasonally they are most frequently observed during November–January (Harrison and Vecchi 1997). On interannual time scales, WWBs occur most frequently in association with El Niño events (Luther et al. 1983; McPhaden 2004).

One immediate consequence of a WWB is the excitation of a downwelling equatorial Kelvin wave that propagates eastward along the equator. Kelvin waves in response to the WWBs in late 1974 and early 1975 are evident in the eastward progression of the 20°C isotherm, which is an index of thermocline depth in the tropical Pacific (Fig. 3c). The phase speed of these waves is about 2.5 m s^{-1}, which is in the range expected for a first baroclinic Kelvin wave, based on the mean density stratification of the central Pacific (Kessler et al. 1995; Roundy and Kiladis 2006; Shinoda et al. 2008).

Only the third of these Kelvin waves, the one in response to the January 1975 WWB, reached the eastern boundary (Fig. 3), perhaps because of the countervailing effects of easterly wind anomalies on upwelling and mixing in the central Pacific during November–December 1974. The phase speed of this wave decreased east of approximately 100°E, consistent with the shoaling of the mean thermocline and its effects on baroclinic wave speeds (Giese and Harrison 1990). It is this WWB-induced downwelling equatorial Kelvin wave that led to the depressed thermocline and brief SST warming detected on the first El Niño Watch expedition cruise east of the Galapagos in February–March 1975 (Figs. 3b, 5, and SB1). Note that the Kelvin wave depressed the thermocline all across the basin (Fig. 5), but it translated into surface warming only in the far eastern Pacific, where the mean thermocline is shallowest and SST is sensitive to small changes in thermocline depth. Unusually strong trade winds associated with cold La Niña conditions limited the region over which SST warmed, but the timing and areal extent of this SST warming just happened to coincide with the timing of and the area sampled by the El Niño Watch expedition (Fig. 5).

Tropical Pacific changes in thermocline depth are mirrored in sea level because when the thermocline is deep, a greater volume of warm, low density water above it elevates surface heights; and when the thermocline is shallow, there is a smaller proportion of warm, low density water and thus lower surface heights. So the Kelvin waves evident in depressed 20°C (Fig. 3c) are also evident in elevated sea level in early 1975 at Kanton Island and later at Baltra in the Galapagos Islands further to the east (Fig. 4).

Equatorial Kelvin waves in 1975 were a theoretical construct for oceanographers (Hurlburt et al. 1976; McCreary 1976; Moore and Philander 1977) and one had never been observed in the ocean at this time. In retrospect, Kelvin waves evident in the tide gauge data from Baltra and Kanton Island in late 1974–early 1975 (Fig. 4) combined with data from the El Niño Watch expedition (see sidebar) would have provided the first evidence for the existence of these waves. However, at that time the lack of basin-scale observations made it virtually impossible to link the observations to equatorial wave theory. The first clear demonstration of the existence of Kelvin waves would await the work of Knox and Halpern (1982), who observed the signature of a Kelvin pulse in April–May 1980 from mooring velocity data at 152°W and subsequently in Galapagos sea level data. Later, Eriksen et al. (1983) rationalized variability observed in island tide gauge

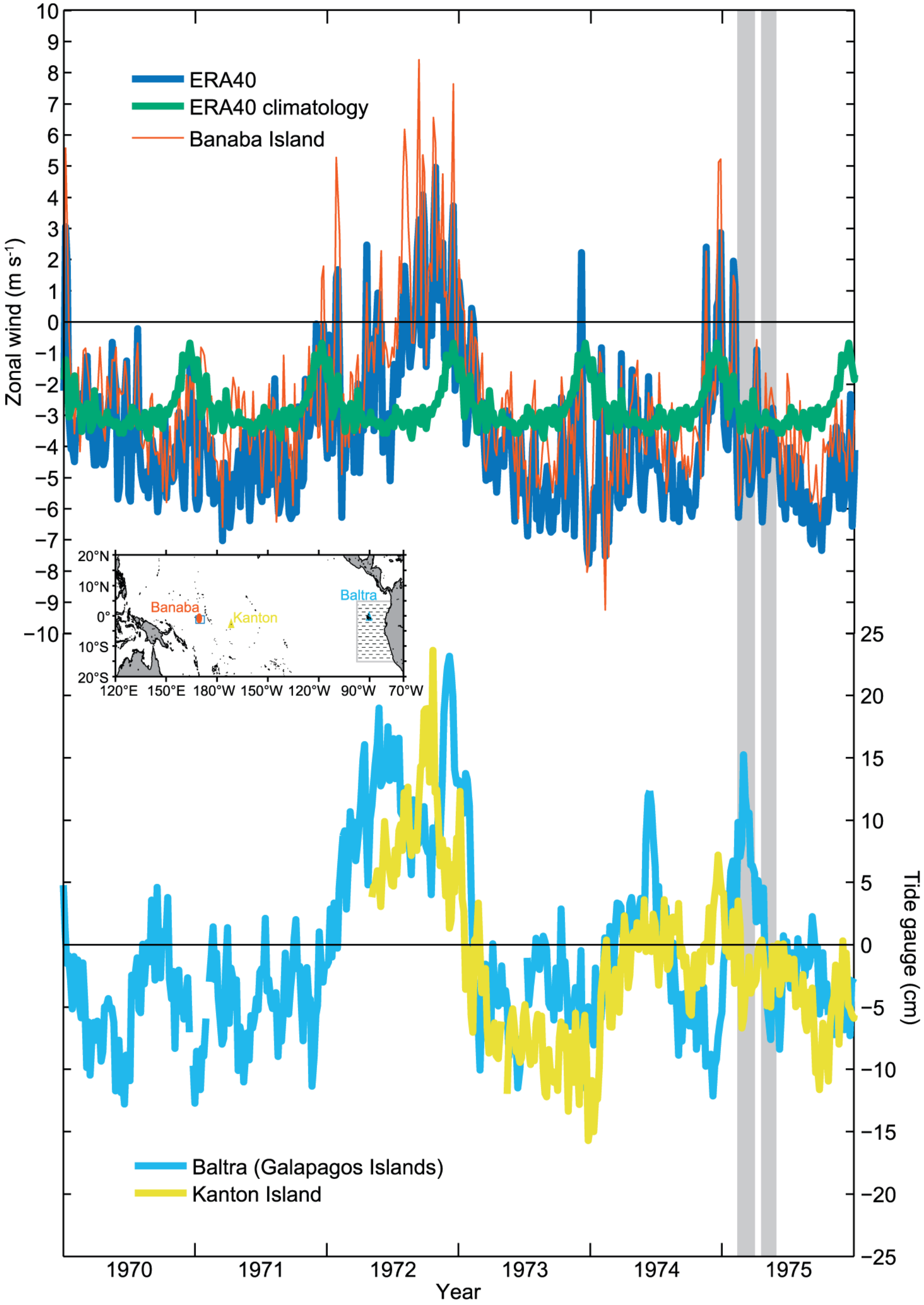

Fig. 4. (top) Zonal winds and (bottom) tide gauge anomalies from 1 Jan 1970 to 31 Dec 1975 for several stations in the equatorial Pacific. Island zonal winds (red, pentad mean of 6-hourly records) are compared to ERA-40 (blue, pentad mean; green, 1961–90 pentad climatology). For sea level, time series are relative to the long-term annual signal at each station (cf. Wyrtki 1977a, their Fig. 6). Station locations, reanalysis grid, and domain of the Wyrtki cruises are shown in the insert (Banaba Island, 0.9°S, 169.5°E; Kanton Island, 2.8°S, 171.7°W; Baltra, Galapagos Islands, 0.4°S, 90.3°W; ERA-40, 2.5°S–0°N, 167.5°–172.5°E; and cruises, 15°S–5°N, 97.5°–75°W). Times of the two El Niño Watch expedition cruises are highlighted (11 Feb–31 Mar and 17 Apr–27 May 1975).

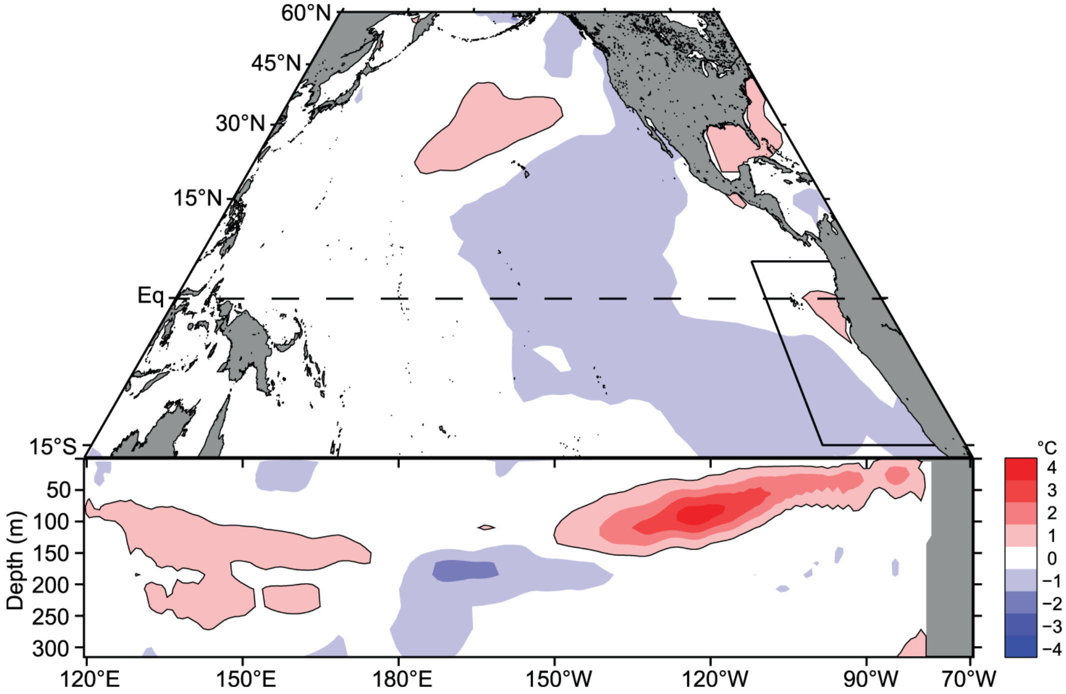

Fig. 5. Surface (HadISST) and subsurface (ORA-S4) ocean temperature anomalies during Mar 1975 with respect to the 1961–90 climatology. Anomalies on the vertical plane are an average over 2.5°S–2.5°N. Warm and cool anomalies exceeding ±0.5°C are shaded in color. El Niño Watch expedition cruises took place in the area enclosed by the box.

measurements throughout the equatorial Pacific in terms of wind forcing and equatorial wave dynamics. WWB-forced intraseasonal Kelvin waves and their effects on SST are now regularly observed in the equatorial Pacific by virtue of today's modern ocean observing system (e.g., Kessler et al. 1995; McPhaden 1999). Interestingly, Wyrtki (1977a) published the same sea level data shown in Fig. 4 in a study whose major focus was the 1972/73 El Niño, evident in the sustained reversal of the trade winds and rise in Pacific sea level in late 1972. He made passing reference to the sea level pulse in early 1975 at the Galapagos as a Kelvin wave, but did not discuss its eastward progression from Kanton to the Galapagos and the implied zonal phase speed in the context of equatorial wave theory.

If large-scale oceanic conditions are just right, WWBs can initiate an El Niño event. This facilitating role of WWBs in the evolution of El Niño was initially a controversial notion when first introduced in the early 1980s but has since gained wide acceptance. WWBs can cause warming along the equator both by exciting eastward-propagating downwelling Kelvin waves and by generating anomalous eastward surface currents that advect warm water accumulated in the western Pacific toward the east (Kessler et al. 1995; Kessler and Kleeman 2000). Initial WWB-induced warming can then stimulate positive Bjerknes SST–wind stress feedbacks, leading to further warming and the growth of large-scale SST anomalies. These anomalies in turn generate enhanced convection and disturbed weather over the ocean that favors further WWB development (Lengaigne et al. 2004; Eisenman et al. 2005; Vecchi et al. 2006). WWB-forced downwelling Kelvin waves are a prominent feature of virtually all El Niño events (Kessler et al. 1995; Zhang and Gottschalck 2002), with the first clear demonstration of their connection to El Niño reported for the 1982/83 El Niño (Lukas et al. 1984; Roundy and Kiladis 2007).

However, the effects of some WWB-forced Kelvin waves are short lived. After their generation, the ocean can quickly return to normal as was the case for example for the 1980 Kelvin wave detected in the seminal paper by Knox and Halpern (1982). Similarly, in 1975, the second El Niño Watch expedition cruise captured the return to normal conditions in April–May following three WWBs, such that there was little if any impact on the low-frequency evolution of the Pacific ocean–atmosphere system. Part of the reason was that the ocean was already so unusually cold in 1974 because of prevailing La Niña conditions (Fig. 3b) that it was difficult for short-duration downwelling Kelvin pulses to initiate a positive feedback that would lead to surface warming. There is a suggestion that the cold anomalies along the equator weakened in response to these Kelvin pulses in early 1975 (Fig. 3b); however, except for the region east of the Galapagos, no actual warm SST anomalies appeared.

Wyrtki himself provided a conceptual framework to understand why some WWBs can impact the evolution of El Niño and not others, albeit 10 years after the 1975 expedition. He hypothesized (Wyrtki 1985) that a necessary precondition for El Niño onset is the buildup of excess heat content integrated across the basin near the equator several seasons prior to an event. Once underway, this excess heat is purged to higher latitudes by oceanic processes, which terminates the event. This idea was shown to apply in the framework of early experimental computer model forecasts of El Niño (Cane et al. 1986) and subsequently formalized in a theory for ENSO known as the recharge oscillator (Jin 1997).

Wyrtki (1985) developed an index for heat content, referred to as warm water volume (WWV), equivalent to the volume of water above the 20°C isotherm. Meinen and McPhaden (2000) computed WWV from observations over 1980–99, verifying that heat content along the equator typically led Niño-3.4 SSTs by two to three seasons. This lead time has shortened to only about one season in the twenty-first century as the frequency of the ENSO cycle has increased (McPhaden 2012).

Despite some small differences, the ORA-S4 ocean reanalysis faithfully reproduces the time history of WWV when compared to the purely observational analyses of Meinen and McPhaden (2000) and McPhaden (2012) (Fig. 6a). This result is not surprising since many of the same observations are common to both analyses. Thus, we have some confidence in using the ORA-S4 reanalysis prior to 1980 for the purposes of this study. Note that a buildup in WWV equal to or exceeding 1×10^{14} m^3 preceded every El Niño in the record going back to 1961, with the exception of 1994/95. In the period 1960–79, the lead times were typically two to three seasons as for 1980–99 (Fig. 6b). Focusing in on the early 1970s, we can see that a buildup of $\sim 2 \times 10^{14}$ m^3 preceded the onset of the strong 1972/73 El Niño.

In this context, it is evident now that the necessary precondition for an El Niño to occur in 1975—namely, excess heat content along the equator in late 1974 and early 1975—was not met. Values of WWV at this time, though weakly positive, never reached the typical El Niño threshold of 1×10^{14} m^3. Thus, the large-scale conditions were not favorable for El Niño development even in the presence of potential WWB triggers.

RETROSPECTIVE FORECASTS FOR 1975.

Forty years after Quinn's first El Niño prediction, we can ask whether present-day state-of-the-art El Niño prediction models would have been capable of correctly forecasting conditions in 1975 when initialized for the period leading up to and including the time of the El Niño Watch expedition. Quinn issued his forecast in October 1974 based on trends in the SOI from preceding months and Wyrtki submitted his proposal to the National Science Foundation (NSF) in October 1974, motivated by that forecast. Effectively, they were making a two-season prediction for the purpose of staging cruises in early 1975. February 1975 would have been the last possible time to call off the expedition, which was over by the end of May.

Here we present the results of retrospective Niño-3.4 SST anomaly forecasts for models initialized every 3 months during August 1974– May 1975 at lead times up to 6 months using five different forecast models. The models are ECMWF S4, ECMWF S3, and three models of early 2000s vintage from the DEMETER project: Météo-France, the Met Office (UKMO), and ECMWF (Fig. 7). There are 9 ensemble members for each DEMETER model and 15 members for both ECMWF S3 and S4. For the multimodel ensemble (Fig. 7a) only the first 9 S3 and S4 ensemble members were included, so that the total number of forecasts in the ensemble is 45, with all models evenly weighted.

The multimodel ensemble mean and spread (±1 standard deviation) indicate that most of the forecasts in this period would have predicted the likelihood of either ENSO-neutral conditions or, for forecasts initialized in August 1974, weak La Niña conditions (Fig. 7a). The November 1974 forecasts all showed warming trends, particularly for S4, perhaps because the November 1974 initial conditions included the observed WWB that month (Figs. 3 and 4). However, warming trends in almost all the November forecast ensemble members did not translate in Niño-3.4 SST anomalies in excess of 0.5°C, the threshold for the onset of El Niño (Figs. 7b–d). Multimodel forecasts from February 1975 also showed warming trends, primarily in the S4 forecasting system (Fig. 7b). However, the multimodel ensemble mean would have predicted ENSO-neutral conditions, with only a slight probability for a weak El Niño developing in mid-1975.

Neither the February nor the May ensemble mean forecasts captured the significant cooling trend in mid-1975 associated with the observed La Niña (Fig. 2). Forecast skill from these start times might be expected to be lower than at other times of the year because of the "spring predictability barrier" (Webster and Yang 1992; Goddard et al. 2001). The S4 forecasting system, which has a better representation of forecast uncertainty (Molteni et al. 2011), captures the possibility of significant cooling (Fig. 7b). Even so, La Niña would have been a low-probability event based on these forecasts.

In summary, using state-of-the-art seasonal forecasting techniques, we would have predicted ENSO-neutral conditions as the most likely outcome for 1975, with lower probabilities for an El Niño, which did not occur, and a La Niña, which did. It is possible that if we had today's observing system as well as today's forecasting systems, the forecasts might have been better, with some indications of SST cooling by mid-1975.

PERSPECTIVES. Wyrtki et al. (1976) concluded that "the year 1975 will not enter oceanographic history as a year of a large El Niño" (p. 191). They went on to say that, "however, as predicted, an El Niño situation began to develop" (p. 191). Wyrtki (1977a) later asserted that 1975 was a "minor El Niño event" and Quinn et al. (1978) classified it as a "very weak" El Niño. The implication was that the forecast for El Niño had in fact been verified by the observations.

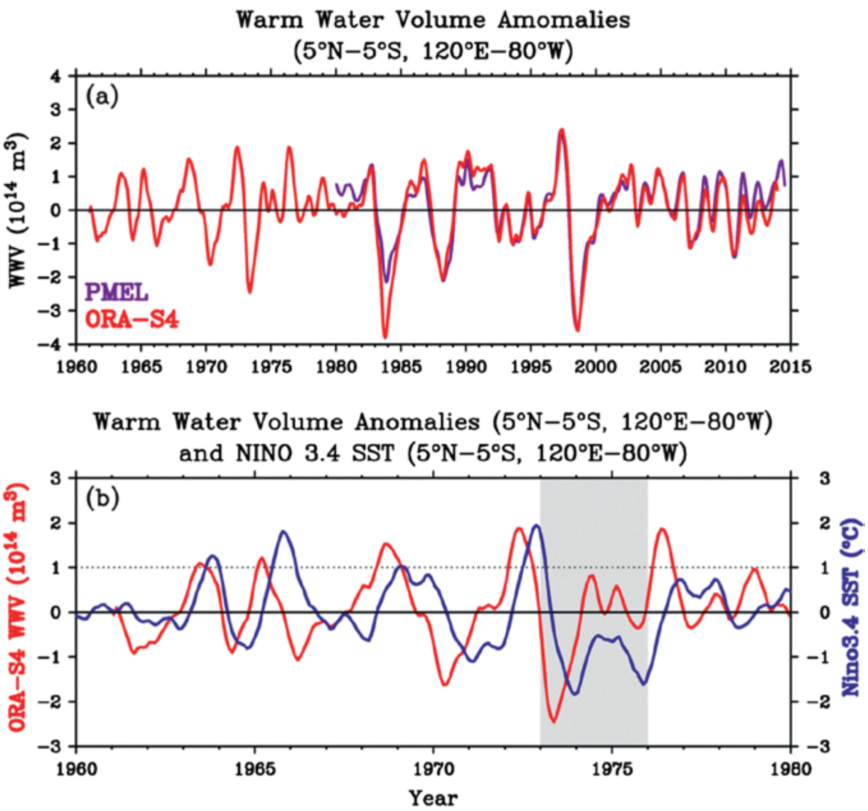

Fig. 6. (a) WWV anomalies from ORA-S4 from 1961 to present, with Pacific Marine Environmental Laboratory (PMEL) WWV anomalies from 1980 onward overplotted. (b) WWV and Niño-3.4 SST anomalies from ORA-S4 for 1960–80. WWV is the volume of water above the 20°C isotherm integrated across the Pacific basin over 5°N–5°S, 80°W–120°E. Gray shading indicates the period 1973–75. Dotted line in (b) indicates the WWV threshold above which El Niño onset is favored. ORA-S4 WWV anomalies have been detrended using a quadratic in time to account for drift in the early part of the record.

However, in the 1970s, there was no agreed upon definition for El Niño and it was not until 1983 that the Scientific Committee for Ocean Research (SCOR) Working Group 55 proposed the first formal definition: "El Niño is the appearance of anomalously warm water along the coast of Ecuador and Peru as far south as Lima…exceeding one standard deviation for at least four (4) consecutive months" (SCOR 1983, p. 48). Wyrtki was a member of SCOR Working Group 55, which developed this definition, according to which 1975 would not have been classified as an El Niño because warming lasted only 2 months.

The SCOR definition did not gain acceptance because it was too narrowly focused on the South American coast. Most global impacts on weather related to the ENSO cycle are more strongly correlated with large-scale warming in the eastern and central Pacific (Barnston et al. 1997), so that indices for El Niño and La Niña that concentrate on areal SST averages in these regions are now most commonly invoked to characterize ENSO variability (e.g., Fig. 1). These indices stipulate both a temperature anomaly threshold of 0.4°–0.5°C and a duration of 3–5 months that should be met for an event to be classified as an El Niño or, on the cold side, as a La Niña (Trenberth 1997; www.nws.noaa.gov/ost/climate/STIP/ElNinoDef.htm). By these definitions, a La Niña event rather than an El Niño event occurred in 1975 (Fig. 2).

Wyrtki et al.'s timing was off by one year: an El Niño did not develop in 1975, but one did in 1976 (see Fig. 1), with widespread impacts on weather in the United States and elsewhere (Canby 1977; Palmer and Mansfield 1984). Quinn's forecast for 1975 is recognized today as a failure, but at the time it succeeded in highlighting the potential predictability of El Niño and the need to develop reliable methods of making seasonal forecasts. It also emphasized the need for continuous basin-scale observations of evolving climatic conditions in the tropical Pacific, which added impetus to Wyrtki's efforts to establish a sea level network of island tide gauges for El Niño studies (Wyrtki 1979a,b). Finally, it helped to spur on 1970s research programs, like NORPAX and the related National Oceanic and Atmospheric Administration (NOAA) Equatorial Pacific Ocean Climate Studies (EPOCS) program (Halpern 1996), designed to provide a more complete understanding of the underlying mechanisms that give rise to El Niño.

Nature is full of surprises and, as 1975 was fading from memory, the scientific community was completely caught off guard by the 1982/83 El Niño (Rasmusson and Wallace 1983). This El Niño was the largest of the century up to that time, with spectacular impacts that rattled many parts of the globe (Canby 1984). It was, however, neither predicted nor even detected until nearly at its peak. Ironically, while attending a U.S. planning meeting at Princeton University in October 1982 for an international program to study El Niño [which would later become known as the Tropical Ocean Global Atmosphere (TOGA) program], Wyrtki famously exclaimed that "to call this El Niño would be child abuse!" (Anderson 2010, p. 2). The 1982/83 experience was a perfect storm of inadequate data to describe what was happening as the event unfolded, overly simplistic notions about how El Niño evolved, and a lack of reliable seasonal climate forecast models (McPhaden et al. 1998). Failure to adequately observe and predict the 1982/83 El Niño fundamentally influenced the design of the 10-year (1985–94) TOGA program that led to a quantum leap in our ability to observe, understand, and predict ENSO (McPhaden et al. 2010). TOGA fostered the development of a basin-scale real-time observing system, new comprehensive theories of ENSO variability, and a hierarchy of statistical and dynamical model techniques for

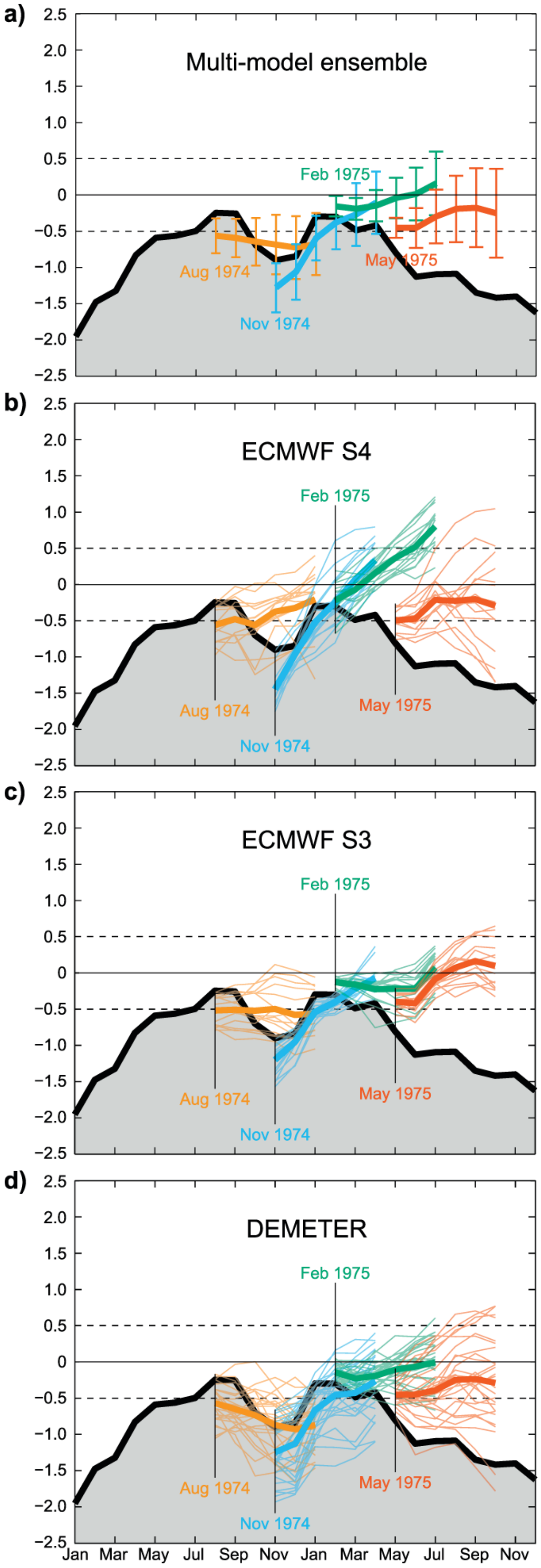

Fig. 7. Retrospective forecasts of Niño-3.4 SST anomalies (°C) for models initialized every 3 months during Aug 1974–May 1975 (colors) and HadISST observations for Jan–Dec 1974/75 (black). Forecast leads extend 6 months. (a) Multimodel mean (five models) and intermodel spread (±1 standard deviation) for 45 ensemble members (9 for each model). (b)–(d) Hindcast means (thick) and ensemble (thin) from (b) ECMWF S4, (c) ECMWF S3, and (d) DEMETER. ECMWF S4 and S3 have 15 members and DEMETER has three models (Météo-France, UKMO, and ECMWF) with 9 members each. The 1961–90 climatology is subtracted from each field. Dashed lines indicate the neutral zone for El Niño/La Niña conditions (±0.5°C).

seasonal forecasting. TOGA scientists also played a central role in designing and implementing the first retrospective model-based oceanic and atmospheric reanalyses, the most recent generation of which from ECMWF we use in this study. In addition, TOGA paved the way for the application of ENSO analysis and forecast products to problems of practical importance to society (Kovats et al. 2003; Falcon et al. 2004; Schroeder et al. 2012).

Despite all that we have learned in the past 40 years, El Niño still continues to surprise us. We have detected, for example, the emergence of decadal variations in ENSO, one aspect of which is the more frequent occurrence over the last 30 years of El Niño events that exhibit their largest SST anomalies in the central equatorial Pacific rather than in the eastern Pacific (Ashok et al. 2007; Larkin and Harrison 2005; Kao and Yu 2009; Kug et al. 2009; Lee and McPhaden 2010; Capotondi et al. 2015). Central Pacific versus eastern Pacific El Niño events can have very different climate impacts both in the Pacific basin and globally (McPhaden 2004; Larkin and Harrison 2005; Weng et al. 2007; Kim et al. 2009; Yu et al. 2012) because of the different spatial structures of warm SST anomalies along the equator and how they affect tropical convection. It is likely that this recent change in El Niño characteristics represents a natural variation of the climate system (Newman et al. 2011; Yeh et al. 2011; McPhaden et al. 2011) rather than a response to greenhouse gas forcing (Yeh et al. 2009). However, precisely why El Niño's center of action has shifted from the eastern to central equatorial Pacific is an unanswered question.

The past 10–15 years in the tropical Pacific have also witnessed a shift to an unprecedented cold phase of the Pacific decadal oscillation (PDO) (England et al. 2014), during which mean Pacific trade winds have increased and eastern Pacific SSTs have decreased. These conditions have led to a threefold increase in the rate of sea level rise in the western tropical Pacific compared to the global mean rate (Timmermann et al. 2010) and to prolonged severe drought conditions in parts of the southern United States (Kosaka and Xie 2013). Moreover, this decadal SST cooling trend in the eastern equatorial Pacific has been identified as a contributor to the recent hiatus in global warming, during which globally averaged surface air temperatures have not risen (Kosaka and Xie 2013; England et al. 2014). It is hypothesized that the unusually cold tropical Pacific has been absorbing heat from the atmosphere at a faster rate than in previous decades, such that there is less residual heating from greenhouse gas forcing to elevate global atmospheric temperatures. The period coincident with these cold phase PDO conditions and the global warming hiatus has been characterized by more frequent, stronger, and prolonged La Niña events and generally weaker central Pacific type El Niño events (Fig. 1). Whether changes in decadal mean conditions in the tropical Pacific are a cause or a consequence of changes in ENSO statistics is a matter of continuing debate (Rodgers et al. 2004; Choi et al. 2011) as is the influence of different El Niño types on global average temperatures (Banholzer and Donner 2014).

There is also the curious case of the widely anticipated strong El Niño that failed to materialize in 2014, only to be followed by an unforeseen major event that is developing in 2015 (McPhaden 2015). A series of WWBs in early 2014 excited large-amplitude downwelling Kelvin waves comparable in strength to those observed in early 1997 at the beginning of the strongest El Niño on record. Given an initial SST warming in the eastern basin in response to these waves and a large ensemble of forecast models that consistently predicted El Niño onset for midyear, both the scientific community and the public were abuzz with the possibility that a major event might develop (e.g., Carrington et al. 2014). However, as time went on, the initial SST anomalies faded such that by late 2014 only weak warming was evident. Forecasts then called for a return to normal conditions in boreal spring 2015 (www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_disc_jan2015/) but El Niño came roaring back instead with a strong event now underway (www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_disc_jul2015/).

There have been other recent El Niño surprises as well. For example, many seasonal forecasting centers predicted an El Niño for 2012 (www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_disc_aug2012/ensodisc.html). However, for unknown reasons the initial warming seen in mid-2012 did not blossom into a full-fledged El Niño event. Overall, it appears that the predictability of ENSO has decreased in the twenty-first century relative to the 1980s and 1990s (Barnston et al. 2012) perhaps because of the unusually strong cold phase PDO conditions and/or the prevalence of weak central Pacific El Niños since 2000.

Seasonal forecasting techniques today are far more advanced than they were 40 years ago, thanks to the development of complex coupled ocean–atmosphere–land numerical models, modern statistical forecasting tools, sophisticated data assimilation systems, and global observing systems providing real-time data streams for forecast initialization. Computers are also vastly more powerful, enabling ensembles of seasonal forecast simulations with state-of-the-art climate models that produce a probability distribution of possible outcomes at various lead times for slightly different initial conditions (as in Fig. 7). The forecast ensemble mean and spread take into account the predictable signal from ocean initial conditions as well as the unpredictable, chaotic elements of the climate system. Multimodel ensembles like DEMETER, composed of forecasts from independent models, can further enhance forecast skill by diluting the effects of model systematic errors from poorly performing models (Palmer et al. 2004). Nonetheless, for all the advances in seasonal forecasting over the past 40 years, the fundamental problem of skillfully predicting the development of ENSO events and their consequences still challenges the scientific community.

In conclusion, it is easier to write history knowing what has happened than it is to chart the future in a highly dynamic system. Global warming is altering the mean climate of Earth with potential impacts on the ENSO cycle that we are only beginning to fathom (e.g., Yeh et al. 2009; Collins et al. 2010; Power et al. 2013; Bellenger et al. 2014; Cai et al. 2014). Thus, for all that we have learned about ENSO so far, more surprises await us. As Wyrtki stated in accepting the Maurice Ewing Medal from the American Geophysical Union in 1989 (AGU 1990), "I am always a little glad if theories and predictions do not turn out to be totally correct, because it convinces me that mother nature knows more than we do" (p. 261). He understood that the way to advance science was to confront theory with observations and to be prepared for the unexpected. We owe much to the early pioneers in ENSO research like Klaus Wyrtki who, through vision, intellect, and tenacity, laid the scientific foundations for a now-burgeoning field of study in climate dynamics.

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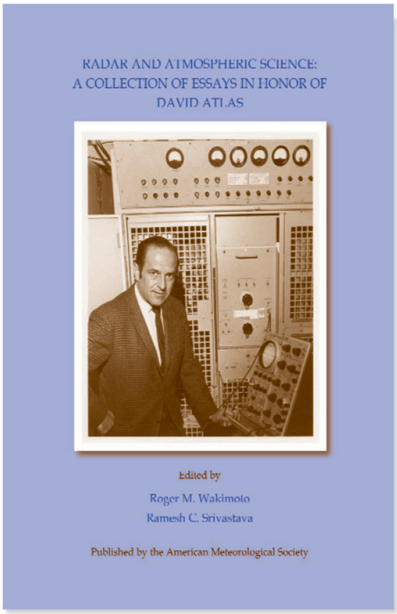

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