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Science **314**, 1740 (2006);
DOI: 10.1126/science.1132588

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published weekly, except the last week in December, by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005.

ENSO as an Integrating Concept in Earth Science

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The El Niño–Southern Oscillation (ENSO) cycle of alternating warm El Niño and cold La Niña events is the dominant year-to-year climate signal on Earth. ENSO originates in the tropical Pacific through interactions between the ocean and the atmosphere, but its environmental and socioeconomic impacts are felt worldwide. Spurred on by the powerful 1997–1998 El Niño, efforts to understand the causes and consequences of ENSO have greatly expanded in the past few years. These efforts reveal the breadth of ENSO's influence on the Earth system and the potential to exploit its predictability for societal benefit. However, many intertwined issues regarding ENSO dynamics, impacts, forecasting, and applications remain unresolved. Research to address these issues will not only lead to progress across a broad range of scientific disciplines but also provide an opportunity to educate the public and policy makers about the importance of climate variability and change in the modern world.

The El Niño–Southern Oscillation (ENSO) cycle, a fluctuation between unusually warm (El Niño) and cold (La Niña) conditions in the tropical Pacific, is the most prominent year-to-year climate variation on Earth. El Niño and La Niña typically recur every 2 to 7 years and develop in association with swings in the Southern Oscillation, an atmospheric pressure pattern spanning the tropical Indian and Pacific Oceans that is intimately related to the strength of the Pacific trade winds. ENSO is unique among climate phenomena in its strength, predictability, and global influence, projecting beyond the tropical Pacific through atmospheric teleconnections that affect patterns of weather variability worldwide.

Major advances in ENSO research from the early 1980s to the mid-1990s included development of the ENSO observing system (*1*), theoretical understanding of the mechanisms responsible for the ENSO cycle and its global teleconnections (*2*, *3*), seasonal climate forecast models (*4*), and an elucidation of ENSO's human dimensions (*5*). Then, the extraordinary 1997–1998 El Niño focused worldwide attention on the ENSO cycle, its global impacts, and its socioeconomic consequences (*6*). Spurred by the enormity of this event, by some measures the strongest of the 20th century (*7*), interest in ENSO exploded in both the research community and the general public (*8*).

ENSO, with its cat's cradle of interconnected scientific and societal issues, has long been fertile ground for interdisciplinary research. Study of its causes and consequences takes on even greater importance today in view of efforts to develop informed policies for sustainable development and responsible stewardship of the environment. This article provides perspectives on recent advances, current trends, and present challenges in ENSO research and applications.

ENSO Physics

A key feature of ocean-atmosphere interactions in the tropical Pacific is the positive feedback between trade wind intensity and zonal sea surface temperature (SST) contrasts referred to as the Bjerknes feedback (*9*). The trade winds normally pile up warm surface water in the western Pacific while upwelling colder water in the east from below the surface along the equator and off the west coast of South America. The resulting east-west surface temperature contrast reinforces an east-west air pressure difference across the basin that in turn drives the trades.

During El Niño, the trade winds weaken along the equator as atmospheric pressure rises in the western Pacific and falls in the eastern Pacific. Anomalous warming in the central and eastern Pacific ensues as warm water in the western Pacific migrates eastward and upwelling is reduced (Fig. 1). The Bjerknes feedback now runs in reverse, with weakened trade winds and SST warming tendencies along the equator reinforcing one another as El Niño develops.

Weakened trade winds at the onset of El Niño generate basin-scale waves in sea level, upper ocean currents, and temperatures that rapidly propagate eastward and westward along the equator. These waves initially support the growth of anomalously warm SSTs. However, after transiting the basin and reflecting off the eastern and western boundaries, they act in concert with upwelling favorable waves generated by wind forcing at the height of El Niño to eventually shut off the warming (*2*). Equatorial wave-induced cooling thus represents a delayed negative feedback that brings about the demise of El Niño and, if strong enough, the initiation of La Niña. The combination of Bjerknes and equatorial wave feedbacks controls the magnitude and duration of individual ENSO events and the interval between them. The mean seasonal cycle also acts as a pacemaker for ENSO, with the largest SST anomalies typically occurring near the end of the calendar year.

This basic conceptual framework for understanding ENSO does not imply that it is a purely cyclic phenomenon. The fluctuation between warm and cold events exhibits considerable irregularity in amplitude, duration, temporal evolution, and spatial structure. This irregularity has been interpreted as resulting from either nonlinear chaotic dynamics of the ocean-atmosphere system or from stochastic forcing by weather noise, including episodic "westerly wind bursts" and other forms of intraseasonal atmospheric variability (*2*).

The life cycles of El Niño and La Niña differ in important details (*10*), one of which is that nonlinear processes favor stronger El Niños than La Niñas (*11*). These differences may account in part for the skewed distribution of ENSO SST anomalies toward larger extreme warm vis-à-vis cold values (Fig. 2). The tendency for more and stronger El Niños than La Niñas from the mid-1970s to the late 1990s has also been cited as evidence for a decadal modulation of ENSO. Interaction with the Pacific decadal oscillation (PDO) (*12*) is one possible explanation, although it could also be simply that the ENSO cycle varies randomly on decadal time scales (*13*, *14*).

There is considerable debate at present about what causes the trade winds to relax at the onset of El Niño. One perspective is that ENSO freely oscillates between warm and cold phases as part of a continuum in which weakening of the trades at the onset of the warm phase results from large-scale deterministic processes operating during previous phases (*15*). Another perspective is that the ocean and atmosphere in the tropical Pacific tend to stably reside in a preferred state that is cold in the east and warm in the west and that El Niños occur only when the system is energized by high-frequency stochastic forcing (*16*). Arguments have been marshaled to support both perspectives, and there is evidence to suggest that the system may alternate between multidecadal epochs of more stable versus freely oscillating dynamics (*13*). This issue has considerable implications not only for our understanding of ENSO but also for our ability to improve ENSO forecast models, because predicting the onset of warm and cold events and their ultimate magnitude while still in the early stages of development may depend on accurate representation of both seasonal and shorter time scale dynamical processes in the ocean and the atmosphere (*17*).

Climate Impacts

Shifts in tropical Pacific precipitation patterns in response to El Niño warming in the central

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and eastern Pacific typically bring drought to Australia, Indonesia, and neighboring countries, whereas the island states of the central Pacific and the west coast of South America are often inundated with heavy rains. Changes in the location and intensity of this rainfall and associated latent heat release into the atmosphere also lead to widespread changes in atmospheric circulation and weather patterns outside the tropical Pacific referred to as teleconnections (*3*). The remote effects of ENSO are felt in the North and South Pacific (Fig. 1), in all other ocean basins, on all seven continents (*3*, *18*, *19*), and in the stratosphere (*20*). Strong events like those in 1982–1983 and 1997–1998 have dramatic worldwide consequences, whereas weak events like the one in 2004–2005 (Fig. 2) may have impacts that are muted or even undetectable above the background weather noise of the atmosphere (*21*). La Niña often produces climate impacts that are roughly opposite to those of El Niño, although asymmetries in convective heating of the tropical atmosphere due to warm and cold SST anomalies favor larger atmospheric responses to strong El Niños than to strong La Niñas (*22*).

El Niño and La Niña affect the frequency, intensity, and spatial distribution of tropical storms. In the Atlantic, for example, hurricanes tend to be reduced in number and intensity during moderate to strong El Niño events but stronger and more numerous during La Niña events. These year-to-year changes translate into a 3-to-1 greater likelihood of a major Atlantic hurricane striking the United States during La Niña versus El Niño years, with correspondingly higher economic losses during La Niña years (*23*).

Geographically, the impacts of El Niño and La Niña are most consistent from event to event in the tropical Pacific and bordering areas where the atmosphere responds directly to SST forcing (*3*). Impacts are prominent but less consistent at higher latitudes and in other ocean basins remote from the Pacific because of interference from weather noise or other regional modes of climate variability. Teleconnections may also vary with time because of long-term changes in the structure and amplitude of ENSO SST anomalies or because of changes in atmospheric circulation that affect far-field responses to tropical Pacific SST forcing (*24*, *25*). Thus, although El Niño and La Niña often lead to systematic seasonal shifts in regional weather patterns that favor drought, flood, heat waves, and extreme events, actual impacts may vary from those expected for any given ENSO episode.

Ecosystems

The altered environmental conditions that result from El Niño and La Niña influence global patterns of primary production (the fixation of carbon by plants) (*26*), with effects that ripple through higher levels of the food chain in both marine and terrestrial ecosystems. During El Niño, primary production in the tropical Pacific, which accounts for 10% of the total in the world ocean, significantly decreases in response to weakened upwelling (*27*). This reduced productivity affects the mortality, fecundity, and geographic distribution of marine mammals, sea birds, and commercially valuable fish species (*28*). El Niño's impact on Pacific ecosystems extends from the open ocean to the west coasts of North and South America and involves benthic as well as pelagic communities (*29*). Moreover, atmospheric teleconnections can influence marine ecosystems remote from the tropical Pacific, such as in the Southern Ocean where ENSO affects the abundance and distribution of krill, a keystone species in the Antarctic marine ecosystem (*30*).

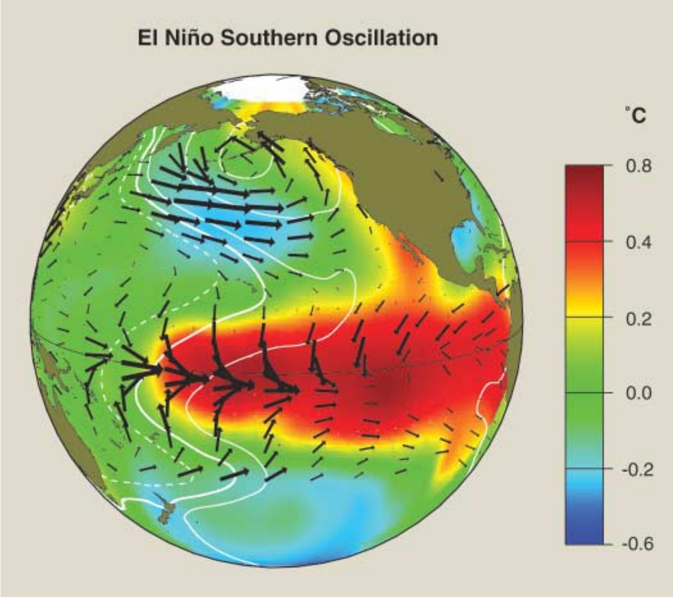

Fig. 1. El Niño anomalies in SST (color shading and scale in °C), surface atmospheric pressure (contours), and surface wind stress (vectors) in the Pacific basin. Pressure contour interval is 0.5 mb, with solid contours positive and dashed contours negative. Wind stress vectors indicate direction and intensity, with the longest vector equivalent to ~1 N m^{-2}. The patterns in this graphic are derived from a linear regression against SST anomalies averaged over 6°N–6°S, 90°W–180° in the eastern and central equatorial Pacific. All quantities scale up or down with the intensity of anomalies in this index region, that is, higher for strong El Niños and lower for weak El Niños. Anomalies of opposite sign apply to La Niña events, although there are some differences in the spatial patterns of El Niño and La Niña that this linear analysis does not capture (*10*, *11*).

Populations decimated by El Niño, particularly at higher trophic levels, may require several years to fully rebound. The collapse of the Peruvian anchovy fishery during the 1972–1973 El Niño is a classic example. The fishery was the largest in the world, with harvests of over 12 million metric tons in the early 1970s. However, a decade of overfishing had reduced the resilience of the anchovy stocks to withstand major environmental disturbances. This set the stage for a catastrophic shift in the ecosystem when sea temperatures warmed and the food chain was disrupted. Anchovy harvests during the subsequent 20 years were reduced by an order of magnitude, a reduction reinforced by a decadal shift toward warmer tropical Pacific temperatures in the mid-1970s (*31*).

Elevated temperatures associated with strong El Niño events lead to bleaching of tropical corals. The most massive and widespread episode of bleaching occurred during the 1997–1998 El Niño, when 16% of the world's reef-building coral died (*32*). Decadal warming trends in tropical ocean temperatures, possibly related to global warming, contributed to this bleaching by elevating background temperatures on which El Niño SST anomalies were superimposed.

ENSO influences terrestrial ecosystems primarily by altering patterns of rainfall, surface temperature, and sunlight availability, which affect primary productivity, plant and animal mortality, and species-specific reproductive strategies. Effects of El Niño and La Niña have been documented in such diverse environments as tropical rainforests, mangrove swamps, boreal forests, deserts, and semiarid shrub lands (*28*, *33*). In the Galapagos Islands, for example, seasons of unusually heavy rainfall associated with El Niños lead to the greening and flowering of an otherwise arid landscape. Sharp increases in the population of Darwin's finches result from the increased availability of seeds and insects, with some species faring better than others depending on body and beak size. Many broods of a reproductively successful finch species can hatch over the course of a strong El Niño event, so the forces of natural selection act to produce evolutionary changes in key physical traits that are passed from one generation to the next. These adaptations provide a unique demonstration of Darwin's theory of evolution (*34*).

Species may respond in unexpected ways to ENSO forcing as a result of biotic interactions involving competition and predator-

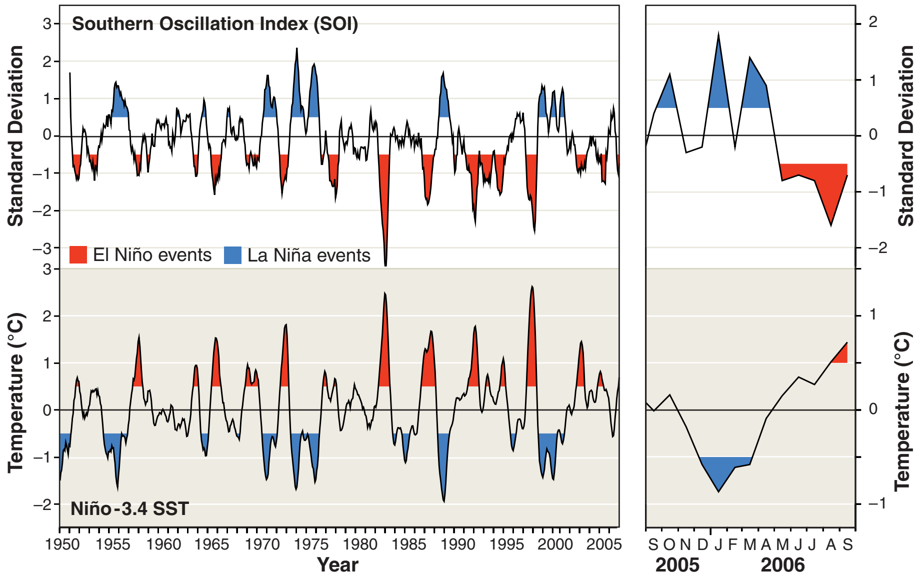

Fig. 2. The Southern Oscillation index (SOI) and Niño-3.4 SST index for January 1950 to September 2006. This plot illustrates the coupled interactions between the ocean and the atmosphere that give rise to ENSO variations. Low SOI values are associated with weaker trade winds and warm sea temperatures (El Niño), whereas high SOI values are associated with stronger trade winds and cold sea temperatures (La Niña). The Niño-3.4 index is computed from monthly SST anomalies in the region 5°N–5°S, 120°–170°W. Positive anomalies >0.5°C indicate El Niño events, and negative anomalies 0.5 are shaded to emphasize the relationship with El Niño and La Niña. In the left panel, values have been smoothed with a 5-month running mean for clarity. The right panel shows the last 13 months of the record (unsmoothed) to highlight developing El Niño conditions in late 2006. Note the different scales for Niño-3.4 SST and SOI in the two panels.

prey relationships (*28*). ENSO impacts may also be exaggerated by land-use practices (*35*) and in some cases may catalyze shifts in ecosystems that persist stably for decades (*33*). Forest fires, like those that burned out of control over large drought-affected regions of Central America, the Amazon, and Indonesia during the 1997–1998 El Niño, result in catastrophic changes in ecosystem structure and function as habitat is destroyed and endemic populations are decimated. Local extinctions that affect biodiversity are also possible as in the case of fig wasps in Borneo, which disappeared as a result of extreme drought associated with the 1997–1998 El Niño (*36*).

Global Carbon Cycle

Year-to-year variability in global atmospheric carbon concentrations is dominated by the ENSO cycle (*37*). The equatorial Pacific is the largest natural oceanic source of carbon to the atmosphere, outgassing about 1 billion metric tons of carbon in the form of CO_2 per year. The source of this carbon is equatorial upwelling, which brings water rich in inorganic carbon from the interior ocean to the surface. During El Niño, equatorial upwelling is suppressed in the eastern and central Pacific, significantly reducing the supply of CO_2 to the surface (*38*). As a result, the global increase in atmospheric CO_2, which is primarily driven by anthropogenic sources, noticeably slows down during the early stages of an El Niño. However, during the later stages of an El Niño, global CO_2 concentrations rise sharply, reflecting the delayed response of the terrestrial biosphere to El Niño–induced changes in weather patterns. Widespread droughts and elevated temperatures in the tropics contribute to an increase in the number and extent of forest fires and to modification of the balance between respiration and photosynthetic uptake of CO_2 in land plants. These processes, which were particularly pronounced during the severe 1982–1983 and 1997–1998 El Niños (*39*), result in an anomalous increase in the supply of CO_2 to the atmosphere sufficient to override the reduction in CO_2 from decreased equatorial upwelling. Forest fires in Indonesia during the 1997–1998 El Niño, because of their scale and duration, released unprecedented amounts of CO_2 into the atmosphere, producing the largest annual increase in concentrations since record-keeping began in 1957 (*40*).

Forecasting ENSO and Its Impacts

Except for the regular progression of the seasons, ENSO is the most predictable climate fluctuation on the planet. Its predictability is based on wind-driven seasonal variations in the amount of heat stored in the upper few hundred meters of the tropical Pacific Ocean. These variations affect sea surface temperatures, which in turn influence the global atmospheric circulation. The ability to predict ENSO was first demonstrated in the mid-1980s using simple dynamical and statistical models (*4*). This was followed by the development of several other forecast systems of increasing sophistication, with skill (a quantitative measure of forecast accuracy) expected for lead times of up to a year. Surprisingly however, weak to moderate strength ENSO-related fluctuations of the early to mid-1990s were not well predicted. Forecast models also failed to predict the onset, rapid growth, ultimate magnitude, and sudden demise of the giant 1997–1998 El Nino with uniform reliability (*41*).

Despite considerable efforts in model and forecast system development, progress in improving prediction skill has been very modest in recent years. Dynamical methods offer the most promise for further improvement in the long term, but they are not at present systematically better than statistical methods (*42*). Virtually all coupled climate models exhibit significant bias errors in the simulation of ENSO variations and the mean tropical Pacific climate (*43*). Coupled model forecasts are also prone to experience "initialization shock," a rapid unphysical adjustment toward the model climatology that can interfere with the ability to correctly evolve real climate signals. Moreover, few if any 3 of these models realistically represent variability associated with westerly wind bursts and other tropical intraseasonal time-scale fluctuations.

In parallel with efforts to reduce model biases, minimize initialization shock, and improve overall model performance, ensemble forecast methods have recently been developed to enhance forecast skill. These methods involve averaging over several individual forecasts from a single model or averaging over the forecasts from several different models (*44*). One such ensemble illustrates SST predictions for the development of an El Niño this year (Fig. 3). Warming is already under way (Fig. 2), although there is uncertainty in the ultimate strength of the event given the spread of the forecasts, which range from weak to moderate in amplitude. It is noteworthy that this ensemble of models did not predict significantly enhanced probabilities of El Nino development until July 2006, more or less coincident with the occurrence of westerly wind bursts in the western Pacific and observed warming in the central Pacific.

From a societal perspective, it is important to predict not only ENSO-related ocean temperature fluctuations but also seasonal climate anomalies throughout the world. Statistical and dynamical modeling approaches are both presently used for this purpose (*45*), and they indicate the likely development of typical El Niño temperature and precipitation anomalies for the 2006–2007 boreal fall and winter season (*46*). However, as with the ultimate magnitude of the event, there is considerable uncertainty at present in the expected severity of its impacts.

Promising methods to improve forecasting of seasonal climate anomalies in the future are under development, including those that combine information from an ensemble of dynamical global climate models weighted according to their relative reliability (*47*).

Practical Applications

ENSO variability affects agriculture, power generation, fresh water resources, public health and safety, forestry, fisheries, transportation, tourism, financial markets, and many other spheres of climate-sensitive human endeavor (*48*). To cite a few specific examples, ENSO-related changes in temperature and precipitation create conditions favorable for the spread of zoonotic, insect-borne, and water-borne diseases such as hantavirus, malaria, dengue fever, and cholera (*49*). As a measure of impact, many of the 22,000 lives lost during the 1997–1998 El Niño were related to disease outbreaks in the developing world (*6*). The unprecedented scale of the Indonesian forest fires (*35*) and the resulting veil of haze and smog throughout Southeast Asia during 1997–1998 also led to widespread respiratory illness (*50*).

Drought as well as flooding can adversely affect both subsistence agriculture and the production of cash crops. ENSO-related shifts in precipitation patterns have affected the production of wheat, rice, maize, sugar cane, and other important crops in far-flung corners of the globe (*48*, *51*, *52*). Historically, drought-related crop failures due to El Niño were a major contributor to famine that would periodically devastate vulnerable populations (*53*).

Current ENSO climate forecasts have modest skill at two- to three-season lead times, although for specific seasons and locations performance is much better (*45*). Thus, even in view of their limitations, ENSO forecasts can provide valuable input to the development of risk-management strategies for many climate-sensitive activities. In addition, although forecasting the precise onset of warm and cold events is problematic, it is known that ENSO SST anomalies during the second half of the calendar year tend to persist for about two seasons. Therefore, once an event is under way, simply being able to observe and describe its evolution can provide valuable information for decision makers.

The predictability of ENSO has prompted many efforts to make practical use of climate analysis and forecast information (*54*). Examples include input to management strategies for public health (*50*, *55*), agriculture and food security (*51*, *52*), fresh water resources (*56*), and fisheries (*57*). ENSO's impacts on storm-generated surface waves and coastal ocean circulation, which affect geological processes such as shoreline erosion and accretion, have been factored into land development and coastal zone management plans at local governmental levels (*58*).

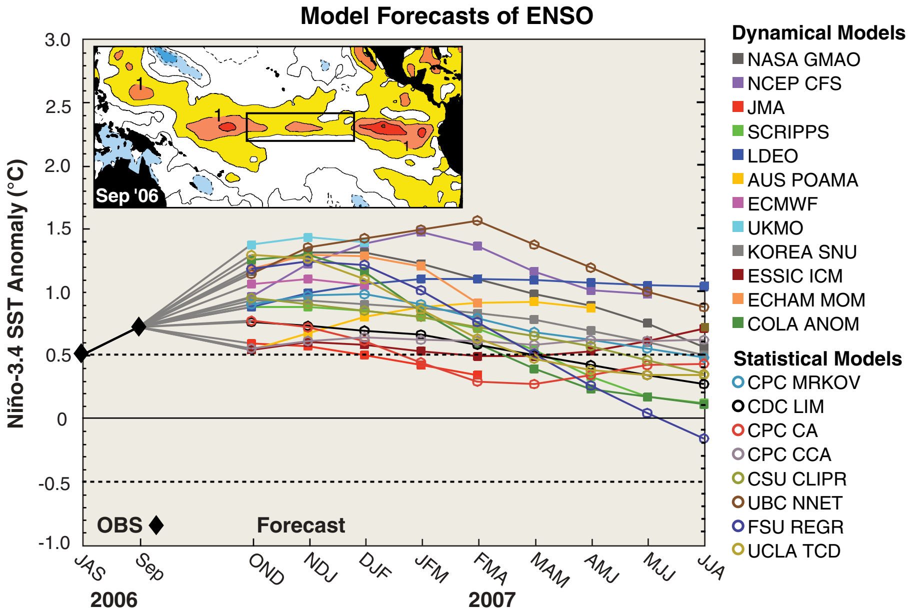

Fig. 3. Statistical and dynamical model forecasts for SST in the Niño-3.4 region (5°N–5°S, 120°–170°W). Forecasts in most cases are from September 2006 initial conditions and are for seasonal averages from October-November-December (OND) 2006 through June-July-August (JJA) 2007 seasonal averages. Most models predict significant warm anomalies (>0.5°C anomaly), indicating the likelihood of a weak to moderate strength El Niño lasting at least into boreal spring 2007. The forecasts represent ensemble means or, for most statistical models, a single deterministic forecast. Institutions involved in issuing the forecasts are indicated by different symbols and listed at right (*80*). Area between the dashed lines at ±0.5°C indicates neutral conditions. Observed values (OBS) for July-August-September (JAS) 2006 and for September 2006 alone are shown as black diamonds. The inset shows observed SST anomalies averaged over 3 to 30 September 2006, with the Niño-3.4 region outlined. Contour interval in the inset is 0.5°C, with warm anomalies in yellow to red colors and cold anomalies in blue. See http://iri.columbia.edu/climate/ENSO/currentinfo/SST_table.html for a description of the various models and the methods by which the forecasts are compiled.

To be of value, seasonal forecasts need to be delivered with sufficient accuracy, timeliness, and detail. Communicating the probabilistic nature of the forecasts and their uncertainties is also essential (*52*) because forecasts are not 100% perfect and outcomes sometimes are at odds with expectations. Despite these challenges, though, prudent use of ENSO forecasts can pay dividends. California, for instance, saved US $1 billion in 1997–1998 as a result of actions taken by individuals, businesses, and government in response to advance warning of El Niño's impending impacts (*59*).

Most efforts to make use of ENSO forecast information have focused on preparing for El Niño events because in the past 25 years they have tended to be more frequent, stronger, and dramatic in terms of impacts than La Niña events. However, predictability can be exploited advantageously for both phases of the ENSO cycle (*60*). Also, it is often the adverse impacts of ENSO variations that receive the most publicity, whereas the benefits, at least for some regions of the globe, are much less understood and appreciated. It is estimated, for example, that the 1997–1998 El Niño resulted in a net benefit of $20 billion to the U.S. economy because of the reduced number of land-falling hurricanes and the unusually warm winter in the Midwest (*59*).

ENSO Past and Future

Evidence from natural climate archives such as corals and lake sediments indicates that ENSO varied significantly in strength in the geologic past. For example, changes in the Earth's radiation balance due to major volcanic eruptions, variations in solar output, and the precession of the Earth about its axis have all affected the ENSO cycle over the past 130,000 years (*9*, *61*, *62*). Further back in time, permanent El Niño–like conditions developed in the tropical Pacific during the warm Pliocene ~3 to 5 million years ago when atmospheric CO_2 levels were comparable to those of today (*63*). Also, evidence suggests a more energetic ENSO cycle during the Eocene "hothouse" ~35 to 55 million years ago when atmospheric CO_2 concentrations approached levels that were twice the pre-industrial values (*64*).

Past climates are not exact analogs for the modern world, but it is reasonable to assume that changes in the radiative balance of the earth due to anthropogenic greenhouse gas emissions could affect climatic conditions in the tropical Pacific. Using this logic, some investigators have interpreted the tendency for stronger and more frequent El Niños than La Niñas since the mid-1970s (Fig. 2) as a manifestation of global warming. This recent behavior is, however, most likely not outside the range expected for natural climate variability (*62*, *65*). Competing hypotheses, such as random fluctuations or interaction with the PDO, are equally plausible (*13*). Thus, there is no definitive evidence from the instrumental record at present for changes in ENSO behavior in response to greenhouse gas forcing.

How future global warming may affect ENSO is open to debate. The consensus outlook from the current generation of global climate models suggests no significant change in ENSO characteristics under various greenhouse gas emission scenarios that presume a doubling of atmospheric CO_2 from preindustrial levels over the next 100 years (*66*). Similarly, there is no clear indication of a significant shift toward either permanent El Niño–like or permanent La Niña–like background conditions in response to doubled CO_2 concentrations (*9*, *66*). However, climate models have known flaws that compromise the reliability of future projections in the tropical Pacific (*67*).

Therefore, we cannot say with confidence at present how global warming will affect either ENSO variability or the background state on which it is superimposed (*9*). Nonetheless, substantial long-term changes in the tropical Pacific, if they were to occur, could amplify global warming (*63*, *68*) and leave regional-scale fingerprints on it by shifting the probability distribution of ENSO-related teleconnections. These changes would affect marine and terrestrial ecosystems, in some cases counterintuitively because of species interactions or other nonlinear biological processes (*33*). Systematic changes in the tropical Pacific would feed back to the global carbon cycle by modifying the balance of carbon sources and sinks in the ocean and on land (*38*). Altered climatic conditions in the tropical Pacific would likewise introduce a wild card into the effects of global warming on hurricane frequency and intensity, currently a topic of hot debate (*69*).

Concluding Remarks

The first years of the 21st century have witnessed a burgeoning interest in the ENSO cycle, its impacts on the Earth system, and its socioeconomic consequences. This interest was stimulated by the powerful 1997–1998 El Niño and enabled by research advances over the previous two decades. ENSO is the strongest and most predictable natural variation of Earth's climate on year-to-year time scales, affecting physical, biological, chemical, and geological processes in the oceans, in the atmosphere, and on land. As a key piece of Earth's complex climate puzzle, it provides a conceptual framework within which to coherently interpret seemingly disconnected events in widely separated parts of the globe. By virtue of their recurrence every few years and their distinctive global pattern of environmental impacts, El Niño and La Niña also provide a unique context for developing testable hypotheses about how various components of the Earth system respond to climate forcing. Knowledge about the ENSO cycle and the ability to forecast its variations, however limited at present, supply valuable information for economic development, public welfare, and responsible stewardship of Earth's limited natural resources. From a broad perspective, therefore, ENSO represents an integrating concept across a range of disciplines in the Earth and related social sciences. Moreover, as a fascinating scientific problem with real-time climate impacts and tangible socioeconomic consequences, ENSO offers an opportunity to educate the public and policy makers about natural climate variability and, by extension, climate change.

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81. We acknowledge funding from NOAA's Climate Program Office (M. J. M. and S. E. Z.) and the National Science Foundation (M. H. G.). Special thanks to T. Barnston, S. Tudhope, M. Holmgren, and R. Feely for helpful suggestions and to S. Hare for permission to reproduce Fig. 1. This is PMEL publication 2969.

17 July 2006; accepted 31 October 2006
10.1126/science.1132588