

Global climate models: Past, present, and future

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Global climate is a result of the complex interactions between the atmosphere, cryosphere (ice), hydrosphere (oceans), lithosphere (land), and biosphere (life), fueled by the nonuniform spatial distribution of incoming solar radiation. We know from climate reconstructions using recorders such as ice cores, ocean and lake sediment cores, tree rings, corals, cave deposits, and ground water that the Earth's climate has seen major changes over its history. An analysis of the temperature variations patched together from all these data reveals that climate change occurs in cycles with characteristic periods, for example 200 million, 100,000, or 4–7 years. For some of these cycles, particular mechanisms have been identified, for example forcing by changes in the Earth's orbital parameters or internal oscillations of the coupled ocean-atmosphere system. However, major uncertainties remain in our understanding of the interplay of the components of the climate system. Paleoclimate reconstructions, in particular from ice cores (1) also have shown that climate can change (e.g., $\Delta T = 5^\circ\text{C}$) over extremely short periods of time such as a few years. Over the last century, humans have altered the Earth's surface and the composition of its atmosphere to the extent that these factors measurably affect current climate conditions. There is concern that perhaps during one human generation we will gradually change climate conditions or even trigger a rapid and much more dramatic shift. We might be "poking an angry beast" (2).

Major progress in our understanding of climate processes in the past, present, and future has been made by the development of numerical models that simulate climate at an increasing level of detail. Recent breakthroughs in spatial coverage and temporal resolutions of systems recording today's climate (3) and high-resolution reconstructions of past climate conditions from diverse archives using new proxies make it possible to validate climate models and thus improve their reliability for future predictions.

Global Climate Models

Global climate models or general circulation models are based on the general principles of fluid dynamics and thermodynamics. They had their origin in numerical weather prediction and describe the dynamics of the atmosphere and ocean in an explicit way. The models provide a laboratory for numerical experiments of climate transitions during the past, present, and future. The identification of resonances and thresholds in the system allows an estimate of possible future climate shifts.

One focus of these models is the global ocean circulation. Paleoclimatic evidence suggests that some past climate shifts such as the glacial-interglacial cycles were associated with changes in North Atlantic deep-water formation. This circulation imposes strong northward heat transport, making the northern North Atlantic about 4°C warmer than corresponding latitudes in the Pacific. Variations in ocean circulation therefore have the potential to cause significant large-scale climate change.

The Younger Dryas cold spell at the end of the last ice age is the most recent and best documented abrupt climate change in

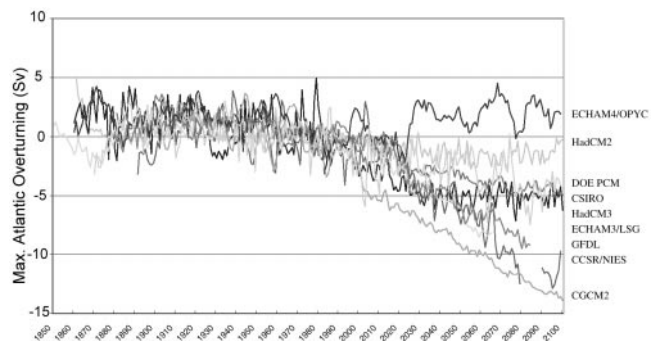


Fig. 1. Change in ocean circulation strength ($1 \text{ Sv} = 10^6 \text{ m}^3\text{s}^{-1}$). The simulations have been performed by several research institutes using different coupled atmosphere-ocean models, but common forcing scenarios (compiled by Cubasch and Fischer-Bruns.).^{††}

the past (4). Various modeling studies indicate that meltwater of dying continental ice masses might have led to the cessation of North Atlantic deep water formation, slowed down circulation, and cooled northern hemisphere climate. However, paleoclimatic records show that deglacial meltwater has entered the Atlantic Ocean during a warm period (Bølling) preceding the Younger Dryas. This apparent paradox was recently resolved by a scenario supported by paleoceanographic data and model simulations that water crossing the Greenland-Scotland Ridge inhibited a breakdown of the ocean circulation (5). This stabilization mechanism helped to maintain mild climate conditions in Europe during the Bølling warm period, despite the massive meltwater input.

Understanding these processes is essential, because increased levels of greenhouse gases also can affect fresh water supply and temperature distribution over the North Atlantic region. Most models predict an increase in precipitation in high latitudes and a decrease in the strength of the deep-water formation (Fig. 1) due to increased atmospheric greenhouse gases. The considerable differences in model simulations can be attributed to uncertainties in the parameterization of subgrid-scale processes such as vertical mixing and the representation of clouds and oceanic overflow (7), and a possible interaction between the El Niño/Southern Oscillation phenomenon and Atlantic deep-water formation (8).

Recently, Earth system models are an attempt to integrate even more components of the climate system, such as the

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^{††}Cubasch, U. & Fischer-Bruns, I., Regional Climate Spring Meeting, May 8–9, 2001, Jevnaker Torbjørnrad, Norway, pp. 13–28.

biosphere and cryosphere (9) with the ultimate goal to represent the climate in all of its facets.

El Niño

El Niño has become a common term in much of the world (only one of ≈ 80 participants in the German-American Frontiers of Science Symposium in June 2000 confessed to having not heard of El Niño before). This has not always been the case. Global recognition of this phenomenon is the result of two decades of a widely coordinated international effort to observe, model, and predict El Niño events. The 1997–1998 El Niño, one of the largest events on record, was predicted almost 6 months in advance, and monitored in great detail with an array of *in situ* instruments (moorings, buoys, and satellites, ref. 3). This was in contrast to the other great El Niño event that occurred in 1982–1983 when the international community of scientists was not aware that the event was occurring until it was well underway. Near global datasets from a variety of sources now reveal that El Niño is the largest mode of variability of the climate system on longer than seasonal time scales. El Niño is the warm phase of what has come to be known as the El Niño/Southern Oscillation; La Niña is the cold phase and these events recur on a roughly 2- to 7-year time scale.

A simplified view of how this oscillation works is provided by the delay oscillation model with low-frequency ocean waves providing the memory for the delay (Fig. 2). Two types of waves are important for the oscillation: Kelvin waves, special gravity waves confined to the equator, propagate eastward with a speed of $\approx 2\text{--}3\text{ ms}^{-1}$; and Rossby waves, which are driven by the variation of the Coriolis force with latitude, that propagate westward at about $0.6\text{--}0.8\text{ ms}^{-1}$. The interaction between these waves moving across the Pacific basin, and the atmospheric response they generate give rise to an oscillation on a time scale of several years (Fig. 2). This mechanism, which arises in simple models of the tropical Pacific ocean-atmosphere system, is generally consistent with the observations and has been borne out in coupled general circulation models as well (11). Because of the memory provided by the ocean, there is some predictability to the system. Now that there is an observational network in place in the tropical Pacific, which can provide a sufficiently complete set of initial conditions, predictions are made on an operational basis at a number of institutes worldwide (12).

A wide range of proxy records that provide clues about how El Niño has behaved in the past also are becoming available. These come from such disparate sources as corals living in the warm tropical oceans (13) to archeological records (14), ice caps from the high Andes (15), and tree rings (16). Some of these records indicate that El Niño has been increasing in intensity from about 7,000 years ago (17). This poses a challenge, which is currently at the frontier of climate research: can we explain and attribute these past changes in El Niño seen in the paleoclimate

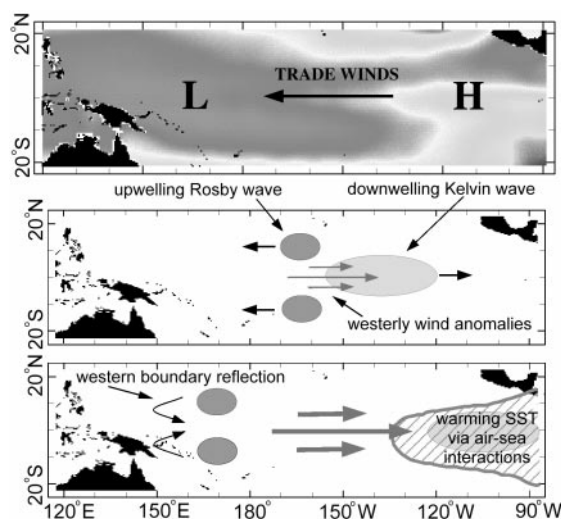


Fig. 2. The delayed oscillator mechanism for the El Niño/Southern Oscillation. (Top) The “normal” state of the tropical Pacific Ocean. Sea surface temperatures are warmer (gray scale) in the western than in the eastern Pacific, and trade winds blow from east (high atmospheric pressure) to west (low pressure) across the basin. This situation changes with the El Niño/Southern Oscillation, which is shown schematically (Middle and Bottom). Trade winds weaken in the central equatorial Pacific (Middle), generating an eastward propagating Kelvin wave carrying a warming signal and a westward propagating Rossby wave carrying a cooling signal. (Bottom) As the Kelvin wave reaches the eastern boundary, air-sea interactions amplify the signal and an El Niño event occurs. The cooling Rossby wave is reflected off the western boundary and then propagates eastward as a cooling Kelvin wave. The signal takes about 6 months to cross the Pacific and when it arrives in the east will terminate the El Niño event and initiate a La Niña event (10).

record? Some initial attempts have been made to apply what we have learned from modern observations and modeling to this problem (18, 19). The merging of these fields—geochemistry, archaeology, climate modeling—present a rich opportunity for extending our understanding of El Niño back in time and address the more general question of how El Niño operates under different climate states. An even more pressing question is how will El Niño behavior change in the future, as greenhouse gas levels in the atmosphere increase? We can again turn our models to this problem, but results are as yet inconclusive (6).

There is much progress to be made in improving our understanding of the Earth’s climate system, which opens another new frontier. The community of earth scientists and social scientists are beginning to address the question of whether forecasts may be useful in helping certain populations manage climate variability, an extremely complex problem.

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