El Niño-Like Pattern in Ice Age Tropical Pacific Sea Surface Temperature
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Atmospheric CO₂ and N₂O

The most compelling argument for an El Niño–
stadial link may be the atmospheric CO₂, CH₄, and N₂O records from ice cores (34–35). The atmospheric concentration of each of these gas species increased during stadials, although the variations were small. The primary source of preindustrial atmospheric N₂O, CH₄, and CO₂ is from the tropics. Upwelling in the tropical Pacific is the largest atmospheric source of CO₂ and a major source of N₂O (32). Tropical soils constitute the other primary source of N₂O, and these are major sources of CH₄. El Niño events disrupt the flux of CO₂ and N₂O to the atmosphere as upwelling in the eastern equatorial Pacific is reduced or shut down. Similarly, shifts in precipitation from land to ocean, as occurs during El Niño, can have a profound effect on tropical soils, as witnessed by the severe droughts over Indonesia and failure of the monsoon. We submit that the El Niño–stadial association provides a plausible explanation for the lower atmospheric CO₂, CH₄, and N₂O observed in ice core records.

We conclude that the strongest case can be made for an El Niño–stadial linkage during the last 70 kyr. At times of cooling at high latitudes, the tropical Pacific was experiencing either less-frequent or less-persistent El Niños. The notion that El Niño would have been the dominant state during a glacial contrasts sharply with previous modeling and low-resolution observational studies that have predicted stronger trade winds and a larger tropical thermocline tilt.

References and Notes

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36. We thank the NSF for supporting this research. We acknowledge the careful analytical assistance of M. Rincon.

Supporting Online Material

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Materials and Methods

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Reports

El Niño–Like Pattern in Ice Age Tropical Pacific Sea Surface Temperature

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Sea surface temperatures (SSTs) in the cold tongue of the eastern equatorial Pacific exert powerful controls on global atmospheric circulation patterns. We examined climate variability in this region from the Last Glacial Maximum (LGM) to the present, using a SST record reconstructed from magnesium/calcium ratios in foraminifera from sea-floor sediments near the Galápagos Islands. Cold-tongue SST varied coherently with precession-induced changes in seasonality during the past 30,000 years. Observed LGM cooling of just 1.2°C implies a relaxation of tropical temperature gradients, weakened Hadley and Walker circulation, southward shift of the Intertropical Convergence Zone, and a persistent El Niño–like pattern in the tropical Pacific. This is contrasted with mid-Holocene cooling suggestive of a La Niña–like pattern with enhanced SST gradients and strengthened trade winds. Our results support a potent role for altered tropical Pacific SST gradients in global climate variations.

Studies of El Niño–Southern Oscillation (ENSO) dynamics and impacts demonstrate that the tropical Pacific ocean-atmosphere system influences global climate on interannual to decadal time scales (1). Models suggest that this system is sensitive to orbital forcing, dominated by precession in the tropics, which modulates the annual insolation cycle and affects the seasonal strength of winds and intensity of upwelling (2). Orbital perturbations of the seasonal cycle are believed to be critical determinants of the long-term behavior of ENSO (2). Proxy hydrographic records from the tropical Pacific document significant spectral power at precessional periods (19 to 23 thousand years (ky)) (3, 4), but the specific mechanisms by which precession affects basin-scale ocean-atmosphere dynamics and their interaction with global climate remain elusive. Paleoclimatic evidence bearing on these questions is scant because of a lack of detailed, well-dated climate records from this region. In this study, we focus on the cold tongue of the eastern equatorial Pacific (EEP), where the

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largest ENSO signal occurs. We present a
\(^{14}C\)-dated Mg/Ca record of SST from near
the Galápagos Islands and use it to evaluate
changes in tropical Pacific SST patterns over
the past 30 ky.

Cold-tongue SSTs are sensitive to chang-
es in local wind patterns because of the pres-
ence of a shallow thermocline, which allows
large SST anomalies to be induced by mod-
erate changes in winds (5). This is evident in
the large seasonal and interannual SST am-
plitudes in the cold tongue (5° to 10°C) com-
pared with minimal changes in the western
Pacific warm pool (1°C), where the thermoe-
cline is much deeper. The cold tongue itself is
best developed south of the equator (5). Mean
annual SST increases to the north, reaching a
maximum at 10°N, the mean position of the
Intertropical Convergence Zone (ITCZ) (Fig.
1). The cross-equatorial oceanographic gradi-
ent north of the Galápagos Islands is sharpest
during seasonal upwelling events (August to
September), when the cold tongue is fully
developed, and relaxes in the warm season
(February to March) and during El Niño,
when the upwelling diminishes. To minimize
the complicating influence of this gradient,
we have selected for study a site south of the
equator and near the core of the upwelling
system.

Core V21-30 (1°13′S, 89°41′W, 617 m
water depth) was raised just north of Es-
pañola Island in the Galápagos Archipelago
(Fig. 1). The shallow depth and unusually
high sedimentation rates at this site (an aver-
age of 13 cm/ky over the past 30 ky) mini-
mize postdepositional alteration problems
associated with carbonate dissolution and
bioturbation, and its position south of the
equator makes it optimal for monitoring cold-
tongue hydrographic properties. Sediment
samples, each averaging ~50 to 100 years of
deposition, were taken at 5-cm intervals or a
mean temporal resolution of 450 years. We
measured the oxygen isotope ratios (\(^{18}O\)) of
the planktonic foraminifer Globigerinoides
sacculifer (Fig. 2B), a species inhabiting the
surface mixed layer, because of its associa-
tion with photosynthetic symbionts (6). Al-
though this species is believed to accrete up
to 30% of its shell mass near the thermocline
(7), observed core-top \(^{18}O\) values in V21-30
are consistent with annual mean temperature
and salinity at the surface (6). This result
indicates that the overall ecologic preference
of G. sacculifer at this site renders it a useful
recorder of surface hydrography, with only
minor subsurface influence. In order to obtain
explicit estimates of SST variations at this
site, we applied Mg/Ca paleothermometry to
this species. Uptake of Mg by planktonic
foraminifera increases exponentially with
ambient water temperature, as shown by
core-top and culture calibration studies (6).
Our results from V21-30 (table S1) are shown
in Fig. 2C. The amplitude of reconstructed
SST variations over the past 30 ky is about
2°C. Average SST during the Last Glacial
Maximum (LGM) [23 to 19 ky before the
present (B.P.)] is estimated from Mg/Ca to be
1.2° ± 0.3°C less than the average SST dur-
ing the late Holocene (4.5 to 0 ky B.P.) (Fig.
2C). This estimate is supported by the \(^{18}O\)
of G. sacculifer (Fig. 2B), which records a
mean late Holocene–LGM change of 1.2 ±
0.15 per mil (%). After correcting for an
ice-volume effect of 1.0% (8), the implied
mean LGM SST was 1° ± 0.7°C less than
late Holocene values, assuming no change in
seawater \(^{18}O\) associated with salinity ef-
facts. An independent estimate of LGM SST
at this site from alkenone paleothermometry
similarly indicates that temperatures were
cooler by 1.2°C (9). The convergence of three
independent proxies suggests that they are
capturing the true amplitude of glacial-inter-
glacial SST change at this site, averaging
1.2°C. This result is further supported by
additional oxygen isotope data from neigh-
boring cold-tongue sites (table S2). This find-
ing is incongruous with recent reconstruc-
tions using radiolarian and foraminiferal
transfer functions (10, 11), which suggest that
LGM cold-tongue temperatures were lower
by 3° to 5°C. Because these methods are
complicated by no-analog problems and, in
the case of foraminifera, selective species
removal by dissolution, we believe that a
geochemical approach based on multiple
proxies is better suited to this region.

Mg/Ca evidence from sites north of the
Galápagos Islands (3) indicates that mean
LGM SSTs were 2.5° to 3.0°C less than in the
late Holocene, exceeding our estimate from
V21-30 by at least a factor of 2. The emerg-
ing north-south pattern of LGM SST anom-
aliest from these records indicates a reduction
of the eastern Pacific cross-equatorial gradi-
ent. At present, a reduced gradient occurs
seasonally in boreal winter and interannually
during El Niño. It is accompanied by a south-
ward shift of the ITCZ and contraction of the
cold tongue as the northeast trades intensify
and southeast trades weaken. We propose
that, in analogous manner, the ITCZ was
displaced southward during the LGM. Such a
shift is consistent with evidence indicating
wetter climate in the Bolivian Altiplano (12),
drier climate in northern South America (13),
and a southward shift of the Atlantic ITCZ
(14, 15). A reduction of the cross-equatorial
(meridional) gradient in the EEP would tend
to weaken the intensity of the Hadley cell
(16). Weaker LGM Hadley circulation has
been inferred from a pattern of drier tropics-
wetter subtropics indicated by paleo-
levels (>17°) (17) and dust concentrations in
Amazonian ice cores (18).

We test the alternative hypothesis that the
LGM SST structure in the tropical Pacific resembled a La Niña–like pattern, with an
enhanced east-west (zonal) gradient (3) and
a stronger thermocline tilt. This hypothesis calls
for intensified upwelling in the cold tongue
due to stronger trade winds caused by the
overall increase of the equator-to-pole temper-
ature gradient. However, as the lower limb
of the Hadley cell, trade wind circulation is
more sensitive to the low-latitude gradient
(16), which we find was reduced. Further, a
southward shift of the ITCZ may have coun-
teracted any increase in winds by shifting the
zone of diminished wind strength closer to
the equator, suppressing an upwelling re-
response. We evaluated the zonal gradient in
the equatorial Pacific by comparing our cool-
ing estimate from V21-30 with estimates from
the western Pacific. Records from the
warm pool (3) and adjacent marginal basins
such as the South China Sea (SCS) (19, 20)
indicate a range of LGM cooling from 2.5° to
4°C, which exceeds our estimate of 1°
to 1.5°C for the cold tongue. This implies a
reduced east-west gradient and therefore
weaker Walker circulation and trade winds.
Hence, we propose that the LGM temperature
pattern in the tropical Pacific was more El
Niño–like, with reduced zonal and meridion-
al low-latitude gradients and a cooler back-
ground level. Possible mechanisms for this
pattern include weaker atmospheric convect-
on over the warm pool and ITCZ due to
ocean cooling and reduced tropospheric
 greenhouse heating due to lower water vapor
and CO₂ levels.

Lea et al. (3) showed that Pleistocene SST
variations in the EEP consistently led chang-
es in ice volume as reflected in δ18O. How-
ever, a precise chronology of the last degra-
ciation in the cold-tongue region has been
lacking. Our 14C-dated record confirms a
lead of Mg/Ca SST over δ18O by several
millennia (Fig. 2B, C and D) and indicates that
post-LGM warming occurred between 20 and
17 ky B.P., during a maximum in equatorial
seasonality (Fig. 2C). Experiment with a
model of the tropical Pacific show that in-
creased seasonality (reduced insolation in the
upwelling season, August to September) fa-
vors the growth of El Niño events by weak-
ening the trades and results in warmer mean
cold-tongue temperatures (2). The modeled
response of ENSO to orbital forcing predicts
a sharp increase in warm (El Niño) events
between 21 and 17 ky B.P. (2), matching the
timing of warming in V21-30. The midpoint
of observed warming at ~19 ky B.P. (Fig.
2C) coincides with the initial pulse of sea
level rise after the LGM low stand, also dated
to 19 ky B.P. (21). This indicates that cold-
tongue dynamics were influential in halting
global ice growth and initiating ice decay at
the end of the LGM. Comparison with Ant-
arcctic climate as recorded in the Byrd ice core
(Fig. 2E) shows synchronous cold-tongue
warming and deglacial inception in Antarc-
tica. This synchrony may result from dynami-
cal coupling of the type observed presently
during ENSO events (22) as an avenue for
transmitting orbitally induced tropical SST
anomalies to the Antarctic region. Further,
advection of subantarctic water masses via
the Equatorial Undercurrent (23) may have
provided a positive climatic feedback be-
tween the two regions.

The period between 15 and 10 ky B.P. is
marked by large high-frequency SST varia-
tions in V21-30 (Fig. 2C). The pattern of
variability at this time suggests an inverse
relation with Greenland temperature (Fig.
2A), most clearly seen at the onset of the
rapid Bolling warming 14.8 ky B.P., when
V21-30 reflects cooling by 1°C. Subsequent
short-lived SST fluctuations persist until ~10
ky B.P. but cannot be definitively matched to
the Greenland Ice Sheet Project Two (GISP2)
ice-core record because of 14C dating uncer-
tainties. To further explore the nature of this
variability and its effect on the equatorial
Pacific zonal gradient, we compared our
V21-30 SST record with the alkenone-based
SST record from SCS core 18287-3 [obtained
by Kienast et al. (20)] (Fig. 3). The SCS
experienced abrupt warming in phase with
Greenland at ~14.8 ky B.P., whereas temper-
ature in the cold tongue dropped. This pattern
implies an abrupt increase of the zonal gra-
dient by ~2°C and a shift toward more La
Niña–like conditions at the time of the Bolling warming. During the Younger Dryas the gradient decreased, primarily because of cooling in the SCS, then increased to near-present values by ∼11 ky B.P. Overall, the observed pattern suggests a link between millennial-scale Greenland warming and establishment of a strong zonal gradient in the tropics. Pacific and between cooling and a weak zonal gradient. Improvements in resolution, dating, and spatial coverage of tropical climate records are required to more accurately describe the millennial-scale climate pattern in the Pacific and its links with high latitudes.

Holocene variability in the cold tongue is of special interest because of mounting evidence for changing ENSO behavior during this time, in response to forcing by precession. A gradual decline in seasonality after 15 ky B.P. reached a broad minimum in the mid-Holocene (5 to 8 ky B.P.), which is mirrored by a broad SST minimum in V21-30 (Fig. 2C). Reduced or absent El Niño activity during this time is inferred from western Pacific corals (24), pollen evidence from Australia (25), and a lake record from Ecuador (26). A modeling study found reduced mid-Holocene SSTs in the EEP, because of strengthened zonal winds and enhanced upwelling, in response to precession (27). In accord with these studies, our data indicate that cooler and relatively stable SSTs prevailed in the cold tongue during this period. The zonal SST gradient in the equatorial Pacific was enhanced by ∼0.5°C (Fig. 3), consistent with stronger trades and more vigorous Walker circulation. Some authors have inferred mid-Holocene warming in coastal northern Peru on the basis of geoarchaeologic evidence (28, 29), in discord with our finding of cooling. This disagreement may indicate that either (i) coastal Peru sites do not faithfully capture long-term SST trends in the cold tongue or (ii) their evidence requires a more complex interpretation.

Our record offers potential insights into the Holocene history of atmospheric methane concentrations. The mid-Holocene decrease in methane (Fig. 2D) has been attributed in part to weaker tropical wetland sources (30), despite evidence for intensified monsoon circulation (31) with wetter conditions and expanded vegetation cover in northern Africa, India, and Australia (25, 32). This decrease seems to require that the bulk of the reduction in tropical methane sources occurred in South America, consistent with pollen evidence for the expansion of savanna at the expense of Amazonian rainforest in Bolivia (33). The methane decline over the first half of the Holocene is correlative with reduced SST in V21-30 (Fig. 2C). We suggest that persistent cold-tongue upwelling, inactive ENSO, and reduced seasonality in the mid-Holocene limited the ability of the ITCZ to penetrate southward during austral summer, depriving the southern margin of Amazonia of moisture. As cold-tongue temperatures rose in the late Holocene, ENSO became more active (26), Amazonian rainforests expanded (32), and atmospheric methane increased (Fig. 2D). Pre-Holocene methane variations do not appear directly related to V21-30 SST, which we attribute to the more complex pattern of global source variations during deglaciation. Our data demonstrate that cold-tongue SST varied with the modulation of seasonality by precession during the past 30 ky, confirming the sensitivity of this system to insolation forcing (2). Despite their small amplitude, the timing of observed variations supports a central role for tropical Pacific dynamics in the global climate progression from the LGM to the late Holocene. Our finding of altered SST gradients in the past allows for large global impacts in accord with models (34) and supports the notion that sustained changes in tropical SSTs and their spatial patterns have profound long-term effects on global climate.

**Fig. 3.** Comparison of eastern and western equatorial Pacific SST history during the last deglaciation and Holocene. Mg/Ca SST data from V21-30 (blue line) are used as reference for the cold tongue, and alkenone (Uk’/Uk

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**References and Notes**
Two-Dimensional X-ray Waveguides and Point Sources

F. Pfeiffer, C. David, M. Burghammer, C. Riekel, T. Salditt

We show that resonant coupling of synchrotron beams into suitable nanostructures can be used for the generation of coherent x-ray point sources. A two-dimensionally confining x-ray waveguide structure has been fabricated by e-beam lithography. By shining a parallel undulator beam onto the structure, a discrete set of resonant modes can be excited in the dielectric cavity, depending on the two orthogonal coupling angles between the beam and the waveguide interfaces. The resonant excitation of the modes is evidenced from the characteristic set of coupling angles as well as the observed far-field pattern. The x-ray nanostructure may be used as coherent x-ray point sources with a beam cross section in the nanometer range.

X-ray scattering has had a tremendous impact as an experimental technique for studying the atomic structure of condensed matter. However, the technique is usually limited by two important constraints. First, it is characterized by two extremely opposed (separated) length scales: the microscopic x-ray wavelength $\lambda \approx 0.1 \text{ nm}$ and the macroscopic cross section $D$ of the beam or, equivalently, the spot size on the sample. The sample therefore must be homogeneous over the entire length $D$, and the technique probes its ensemble-averaged structure. Second, the technique is restricted to static structural information owing to the elastic nature of the scattering events. X-ray scattering is insensitive to the dynamic nature of structural assemblies.

While synchrotron-based inelastic x-ray scattering and photon correlation spectroscopy address the second constraint, microbeam techniques challenge the first ($1$, $2$). If both constraints are to be circumvented simultaneously, small, intense, and fully coherent x-ray beams are needed. Micrometer-sized pinholes are currently used in photon correlation spectroscopy ($3$), but smaller coherent beams of $D \approx 100 \text{ nm}$ cannot be achieved by pinholes. Even if hypothetical pinholes of such size were available, the flux throughput would be insufficient. Spot sizes of $\sim 90 \text{ nm}$ have been obtained in the range of 5 to 8 keV by glass capillary optics ($4$), but these optics do not preserve coherence. Focused spot sizes of coherent beams can be achieved in the range of tens of nanometers for soft x-rays ($4$) by using diffractive lenses (Fresnel zone plates). However, because of the strong decrease of the absorption and phase shift with increasing photon energy, it becomes increasingly difficult to obtain small spot sizes at photon energies of 8 keV and above, and to our knowledge, no coherently focused spot sizes of less than several 100 nm have been reported to date ($5$).

X-ray waveguide structures present an approach for producing a coherent and divergent x-ray beam with precisely defined properties concerning shape and coherence ($6$), based on the principle of resonant beam coupling. The size of the beam at the exit of the waveguide is smaller than the thickness $d$ of the waveguiding layer, which may reach down to $d = 10 \text{ nm}$ ($7$). The flux is efficiently increased by internal resonant field enhancement due to the generation of modes. Lensless projection phase contrast microscopy ($8$), as well as x-ray diffraction with sub-micrometer spatial resolution, has been demonstrated ($9$). The samples can be positioned outside the x-ray waveguide in the exiting beam or can be directly incorporated in the device. Macromolecular films ($10$) and colloidal suspensions ($11$) have already been investigated inside the resonantly enhanced field of a waveguide structure, making up its guiding layer.

To date, x-ray waveguide optics have been exclusively one-dimensional ($1D$), whereas most nanobeam applications would require two-dimensional ($2D$) point beams instead of $1D$ line beams. We present a proof of principle that the concept of resonant beam coupling can be generalized to two dimensions. To this end, we fabricated a rectangular x-ray waveguide by e-beam lithography, which compresses hard x-ray beams in two dimensions.

Visible light and infrared waveguides used in integrated optics are made of a rectangular dielectric core material, typically with an index of refraction in the range between 1.3 and 1.6, embedded in a dielectric cladding of a lower index to allow for guided mode propagation. The principal geometry of a rectangular waveguide is shown in Fig. 1, with width $w$ and height $h$ in the micrometer range. Contrarily, the index of refraction for hard x-rays $n = 1 - \delta + \iota \beta$ is always slightly smaller than 1, in proportion to the electron density of the material ($12$). The core material must therefore have a low electron density and yet also have a low absorption coefficient, and the cladding material with a comparably high electron density must provide a sufficiently high potential wall for the formation of guided modes. Apart from the optical constants, an important constraint is given by the condition that the chosen materials must be compatible with currently available lithography techniques to reach $w$ and $h$ values in the range of 100 nm and below. Considering these requirements, a combination of poly(methyl methacrylate) (PMMA) as a core material with a Cr cladding was chosen.

In order to analytically analyze the guiding characteristics of an x-ray waveguide and to optimize the design parameters, one has to solve the scalar wave equation

$$\nabla^2 \Psi(x,z) + n^2(x,z) k^2 \Psi(x,z) = 0$$

for the electromagnetic field $\Psi(x,z)$, where

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2}, \quad k = 2\pi / \lambda,$$

and $n(x,z)$ is the profile of the refractive index given by the geometry of the guide ($13$). An exact