Quaternary Research **58**, 27–31 (2002)
doi:10.1006/qres.2002.2327

Last Interglacial and Early Glacial ENSO

George J. Kukla[1]

Lamont-Doherty Earth Observatory, Palisades, New York 10964

Amy C. Clement

RSMAS, University of Miami, 4600 Rickenbacker Causeway, Miami, Florida 33149

Mark A. Cane and Joyce E. Gavin

Lamont-Doherty Earth Observatory, Palisades, New York 10964

and

Stephen E. Zebiak

International Research Institute for Climate Prediction, Palisades, New York 10964

Received June 21, 2001

Although the link between insolation and climate is commonly thought to be in the high northern latitudes in summer, our results show that the start of the last glaciation in marine isotope stage (MIS) 5d was associated with a change of insolation during the transitional seasons in the low latitudes. A simplified coupled ocean-atmosphere model shows that changes in the seasonal cycle of insolation could have altered El Niño Southern Oscillation (ENSO) variability so that there were almost twice as many warm ENSO events in the early glacial than in the last interglacial. This indicates that ice buildup in the cooled high latitudes could have been accelerated by a warmed tropical Pacific.

Key Words: **ENSO; insolation; glacial start; equatorial Pacific.**

Since the early 1900s, the link between insolation and climate has been seen in the high latitudes of the Northern Hemisphere where summer insolation varies significantly. Insolation at the top of the atmosphere (TOA) during the summer solstice at 65°N is commonly taken to represent the solar forcing of changing global climate. This is at odds with the results of Berger *et al.* (1981), who correlated the varying monthly TOA insolation at different latitudes of both hemispheres with the marine oxygen isotope record of Hays *et al.* (1976). The highest positive correlation ($p \leq 0.01$) was found not for June but for September, and not in the high latitudes but in the three latitudinal bands representing the tropics (25°N, 5°N, and 15°S). The highest negative correlation, also for $p \leq 0.01$, was found in March for all tested latitudes (85°N, 65°N, 45°N, 25°N, 5°N, 15°S, 35°S, and 75°S).

[1] To whom correspondence should be addressed. E-mail: kukla@ldeo.columbia.edu.

These observations are placed in a new perspective by recent results from a coupled ocean–atmosphere model of the tropical Pacific (Clement *et al.*, 1999). Past orbitally induced changes in solar forcing from Berger (1978) were imposed as heat flux in the Zebiak and Cane (1987) model, which has been used for more than a decade to understand and predict El Niño Southern Oscillation (ENSO) (Cane, 1986). It is an anomaly model, with some aspects of the oceanic and atmospheric physics linearized about the present mean monthly climatology. Its active domain includes only the tropical Pacific. Obviously, the omission of processes in higher latitudes impairs its ability to simulate paleoclimatic variations fully. This limitation, however, permits attribution of the results directly to ocean–atmosphere interactions in the tropical Pacific. Because the model uses the current average climatology, it is best applied to times during which the global climate was similar to that of today, i.e., to interglacials and the interglacial–glacial transitions.

Clement *et al.* (1999) showed that ENSO behavior is strongly controlled by orbitally driven changes in the seasonal cycle of solar forcing at the equator (Fig. 1a). To illustrate how the modeled ENSO could have changed during the last interglacial and early glacial periods, the number of warm and cold events per 500 yr was computed (Fig. 1b). A major warm (or cold) event is defined as an anomaly of mean annual sea-surface temperature (SST) that exceeds 1°C. The area of the anomaly is in the eastern equatorial Pacific between 150°W and 90°W and 5°N and 5°S, known as Niño 3.

The modeled ENSO variation is caused mainly by the modulated seasonal cycle in the eastern equatorial Pacific due to the changed intensity of the solar beam in transitional seasons. The present sun–earth distance during the spring equinox is

0033-5894/02 $35.00

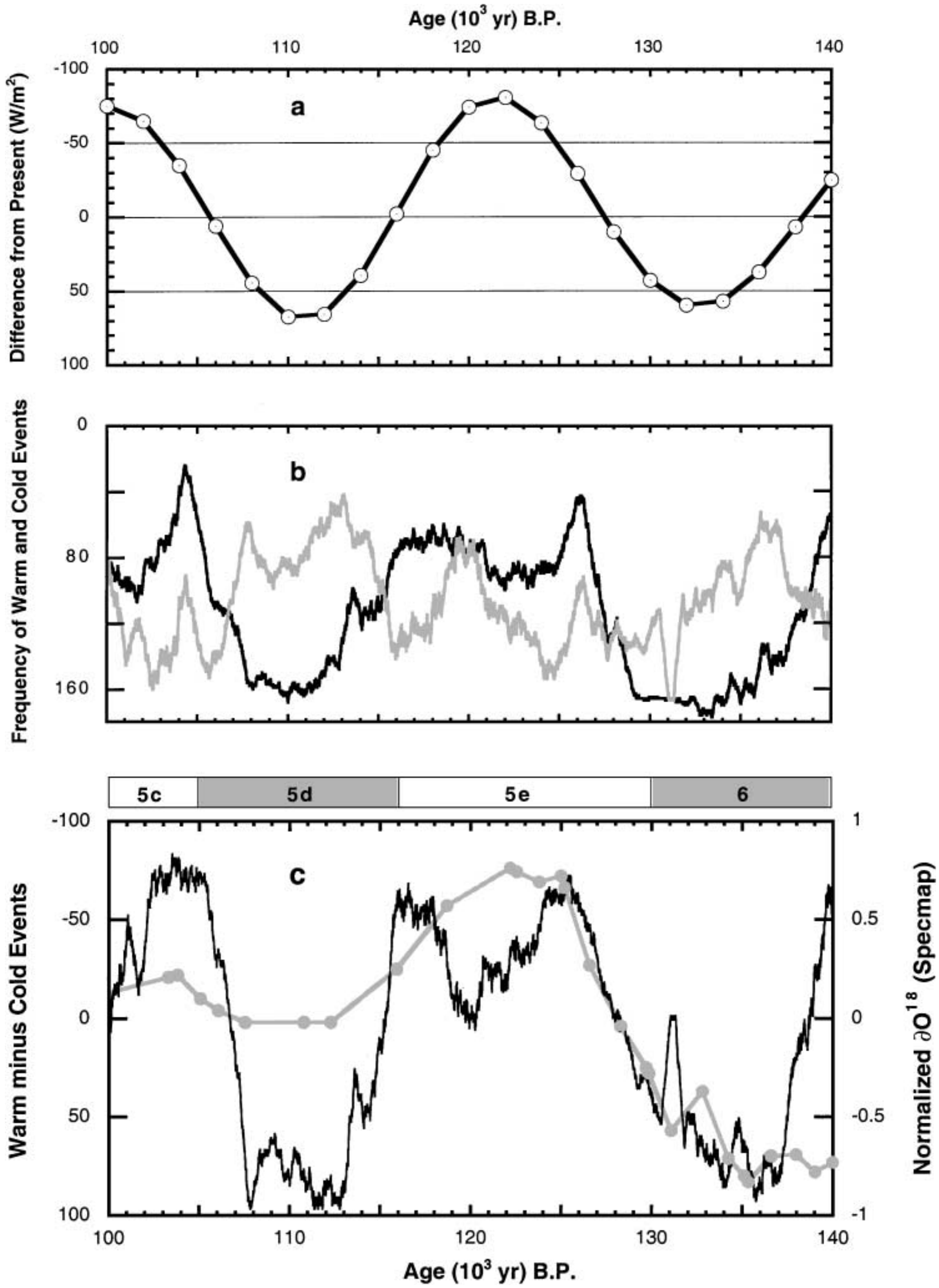

FIG. 1. (a) March minus September insolation (Wm^{-2}) at the equator between 140,000 and 100,000 yr ago as a difference from present. (b) Frequency of cold (gray) and warm (black) events per 500 yr calculated by the model. (c) Comparison of the SPECMAP benthic oxygen-isotope curve, representing the global ice volume (gray), with the difference between the mean frequency of modeled El Niño and La Niña episodes (black).

very similar to the autumn equinox, so that the intensity is approximately equal. However, 111,000 yr ago, the shortest approach of the earth to the sun (perihelion) was reached in March and the farthest (aphelion) in September. Consequently, the intensity of the solar beam was considerably stronger in March than in September (Fig. 1a). The opposite situation occurred 122,000 yr ago.

The seasonal cycle in the equatorial Pacific is amplified when perihelion occurs in boreal spring and aphelion in autumn. This is because the eastern Pacific becomes warmest in April and coldest in late summer and fall. Strengthening the seasonal cycle has been shown to make model simulations of ENSO stronger and more regular (Chang *et al.*, 1994). The difference between the March and September insolation at the top of the atmosphere

(TOA) is a convenient index of the orbital impact on tropical SST.

When the number and intensity of warm anomalies increases and that of cold anomalies decreases, the mean annual character of the tropical Pacific approaches an El Niño-like state. Data from the last 50 yr demonstrate that high SST in the Niño3 region correlates with higher than normal global mean tropospheric temperature (Angell, 2000). The Climate Prediction Center (2002) has designated El Niño and La Niña seasons for individual years from 1950 to present. Using their classification for all cold and warm events, we calculated zonal temperature updated from the original data of Jones (1994) merged with SST data (Parker, 1995). They are shown for autumn and spring of each hemisphere in Fig. 2. During average El Niño conditions in autumn, both the tropics and the globe are warmer, but the high latitudes are colder than normal. The temperature gradient between the low and the high latitudes is higher during the El Niño and lower than normal during La Niña conditions. Autumn in both hemispheres is the season of peak water transfer to high latitudes, and the increased temperature gradient is likely to accelerate this process.

In Figs. 1b and 1c we compare the modeled El Niño and La Niña frequencies with the SPECMAP marine isotope stages of Martinson *et al.* (1987). The latter record is considered to represent a close proxy of global ice volume. It is tuned to astronomic chronology, but within the interval discussed here it is independently tied to the high-precision U/Th ages of emerged coral reefs. During the last interglacial, modeled La Niña events dominated and El Niño events were relatively infrequent. From 127,000 to 115,000 yr ago, the number of major warm events varied between ∼45 and 110 per 500 yr, with an average close to 80. This compares with 82 ± 15 major events (2 SD) in 500 yr computed in the model with modern solar forcing. In the first 10,000 yr of the early glacial period marine isotope stage (MIS 5d), the computed average number of warm events was about 135 per 500 yr, whereas the cold events numbered about 85 per 500 yr. The frequency of warm events was also high in the penultimate glacial stage (MIS 6). At the same time, the number

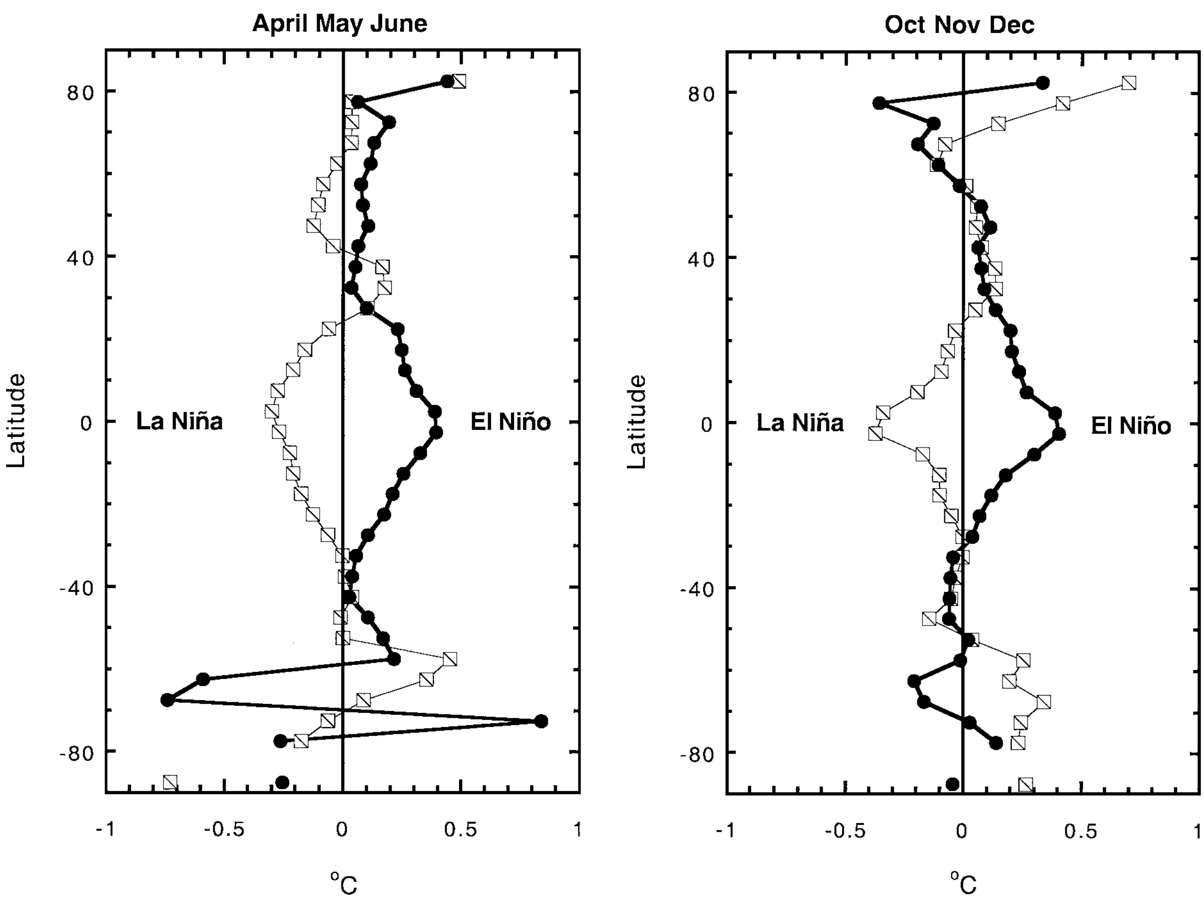

FIG. 2. Zonal mean surface air temperature and sea-surface temperature departures from the 1961–1990 average (Jones *et al.*, 1994; Parker *et al.*, 1995, and updates). Seasonally averaged for April through June and October through December for the El Niño and La Niña years as classified by the Climate Prediction Center (2002) from 1950–1998. Temperature data acquired through the IRI climate server at http://ingrid.ldeo.columbia.edu/SOURCES/.UEA/.CRU/.Jones/.landsea/.April–June season (Cold): 1950, 1955, 1956, 1971, 1974, 1975, 1984, 1985, 1989; (Warm): 1953, 1957, 1958, 1966, 1969, 1972, 1982, 1983, 1987, 1991, 1992, 1993, 1997, 1998; October–December season (Cold) 1950, 1954, 1955, 1956, 1964, 1970, 1971, 1973, 1974, 1975, 1983, 1984, 1988, 1995, 1998; (Warm): 1951, 1957, 1958, 1963, 1965, 1968, 1969, 1972, 1976, 1977, 1982, 1986, 1987, 1990, 1991, 1992, 1993, 1994, 1997.

of computed cold events was low. The relatively fast buildup of ice between about 116,000 and 112,000 yr B.P. corresponds to the relatively fast shift of the insolation intensity from boreal autumn to spring. Dominance of warm over cold anomalies increased equally fast.

Paleoclimatic evidence from the last 20 millennia shows that El Niño was frequent prior to about 15,000 yr ago (Rittenour *et al.*, 2000) and subdued during the warmest part of the Holocene (Sandweiss *et al.*, 1996). Its intensity and frequency has been on the rise again during the last several millennia (Rodbell *et al.* 1999; Tudhope *et al.*, 2001). Because the progression of the precessional cycle during the last interglacial was very similar to that during the Holocene (Kukla and Gavin, 1992), the observations appear to confirm the relative dearth of El Niño events during peak interglacials and their increased frequency in colder times.

Paleoclimatic data from earlier intervals are less clear. According to the observation of Lea *et al.* (2000), the ice buildup is preceded by a relatively cold Pacific for several thousand years. This is in agreement with our model and SPECMAP data, according to which, the fastest increase of El Niño frequency and of global ice volume followed a relatively cold interglacial Pacific by several millennia. More-accurate determination of the delay between the Pacific SSTs and the growth of global ice is difficult, because both the Mg/Ca temperature proxy and the ice volume information were derived from planktonic foraminifera, which are affected by local SST. The sedimentation rates are too low and, consequently, the time resolution too poor in some cores to allow reliable timing between the western and eastern Pacific.

Without doubt, the temperature of tropical waters gradually decreased through the last glacial cycle (Lea *et al.*, 2000). However, the secondary warmings in the tropical belt, accompanied by decreased insolation in high latitudes, could have led to periodic amplification of the equator-to-pole temperature gradient, increased poleward moisture transport, and increased accumulation of ice (Ruddiman and McIntyre, 1979; Cortijo, 1999; Khodri *et al.*, 2001; Sachs *et al.*, 2001; Stenni *et al.*, 2001).

At first glance the implications of our results appear to be counterintuitive, indicating that the early buildup of glacier ice was associated not with the cooling, but with a relative warming of tropical oceans. Recent analogs suggest that it might even have been accompanied by a temporary increase of globally averaged annual mean temperature. If correct, the main trigger of glaciations would not be the expansion of snow fields in subpolar belts, but rather the increase in temperature gradient between the low and the high latitudes.

The temporal link between a relatively warm tropical ocean and the accumulation of ice in the high latitudes at the beginning of a glacial cycle supports the hypothesis of Tyndall (1872). He saw the cause of glaciations in an increased energy supply to the oceans, leading to increased evaporation and intensified transport of water vapor to the cold polar belts.

Although the Zebiak–Cane model is reasonably successful in predicting current El Niño events, and appears to be in qualitative agreement with the variations of ENSO in the Holocene (Tudhope *et al.*, 2001), we cannot be fully certain how ENSO has varied in the past. Nevertheless, the results presented here provide a quantitative demonstration of how solar forcing in low latitudes could have altered tropical SST and contributed to global climate change. This link needs to be investigated further with more complete ocean–atmosphere models.

ACKNOWLEDGMENTS

We thank two anonymous reviewers whose comments helped to greatly improve the paper. This material is partly supported by NSF grant ATM 01-00830 and is a Lamont-Doherty Earth Observatory contribution # 6298.

REFERENCES

Angell, J. K. (2000). Tropospheric temperature variations adjusted for El Niño, 1958–1998. *Journal of Geophysical Research* **105,** 11,841–11,849.

Berger, A. (1978). Long-term variations of daily insolation and Quaternary climate changes. *Journal Atmospheric Science* **35,** 2362–2367.

Berger, A., Guiot, J., Kukla, G., and Pestiaux, P. (1981). Long-term variations of monthly insolation as related to climatic changes. *Geologischen Rundschau* **70,** 748–758.

Cane, M. A. (1986). El Niño. *Annual Review of Earth and Planetary Science* **14,** 43–70.

Climate Prediction Center (2002). Retrieved January 1, 2002, from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.html.

Cortijo, E., Lehman, S., Keigwin, L., Chapman, M., Paillard, D., and Labeyrie, L. (1999). Changes in meridional temperature and salinity gradients in the North Atlantic Ocean (30–72°N) during the last interglacial period. *Paleoceanography* **14,** 23–33.

Chang, P., Wang, B., Li, T., and Ji, L. (1994). Interactions between the seasonal cycle and the Southern Oscillation: Frequency entrainment and chaos in a coupled ocean-atmosphere model. *Geophysical Research Letters* **21,** 2817–2820.

Clement, A., Seager, R., and Cane, M. (1999). Orbital controls on the tropical climate. *Paleoceanography* **14,** 441–456.

Hays, J. D., Imbrie, J., and Shackleton, N. J. (1976). Variations in the Earth's orbit: Pacemaker of the Ice Ages. *Science* **194,** 1121–1132.

Jones, P. D. (1994). Hemispheric surface air temperature variations: A reanalysis and an update to 1993. *Journal of Climate* **7,** 1794–1802. [Updates provided at http://www.cru.uea.ac.uk/cru/data/temperature/]

Khodri, M., LecLainche, Y., Ramstein, G., Braconnot, P., Marti, O., and Cortijo, E. (2001). Simulating the amplification of orbital forcing by ocean feedbacks in the last glaciation. *Nature* **410,** 570–574.

Kukla, G., and Gavin, J. (1992). Insolation regime of the warm to cold transitions. *In* "Start of a Glacial, Proceedings Mallorca NATO ARW, NATO ASI Series I." (G. Kukla and E. Went, Eds.), pp. 307–339. Springer-Verlag, New York.

Lea, D. W., Pak, D. K., and Spero, H. J. (2000). Climate impact of late Quaternary equatorial Pacific sea surface temperature variations. *Science* **289,** 1719–1724.

Martinson, D. G., Pisias, N. G., Hays, J. D., Imbrie, J., Moore, T. C. Jr., and Shackleton, N. J. (1987). Age dating and orbital theory of ice ages: Development of high-resolution 0 to 300,000-year chronostratigraphy. *Quaternary Research* **27,** 1–29.

Parker, D. D., Folland, C. K., and Jackson, M. (1995). Marine surface temperature: observed variations and data requirements. *Climatic Change* **31,** 559–600.

Rittenour, T. M., Brigham-Grette, J., and Mann, M. E. (2000). El Niño-like climate teleconnections in New England during the Late Pleistocene. *Science* **288,** 1039–1042.

Rodbell, D. T., Seltzer, G. O., Anderson, D. M., Abbott, M. B., Enfield, D. B., and Newman, J. H. (1999). An ∼15,000-year record of El Niño-driven alluviation in southwestern Ecuador. *Science* **283,** 516–520.

Ruddiman, W. F., and McIntyre, A. (1979). Warmth of the subpolar North Atlantic Ocean during Northern Hemisphere ice-sheet growth. *Science* **204,** 173–175.

Sachs, J. P., Anderson, R. F., and Lehman, S. J. (2001). Glacial surface temperatures of the southeast Atlantic Ocean. *Science* **293,** 2077–2079.

Sandweiss, D. H., Richardson, J. B. I., Reitz, E. J., Rollins, H. B., and Maasch, K. A. (1996). Geoarchaeological evidence from Peru for a 5000 years B.P. onset of El Niño. *Science* **273,** 1531–1533.

Stenni, B., Masson-Delmotte, V., Johnsen, S., Jouzel, J., Longinelli, A., Monnin, E., Rothlisberger, R., and Selmo, E. (2001). An oceanic cold reversal during the last deglaciation. *Science* **293,** 2074–2077.

Tudhope, A. W., Chilcott, C. P., McCulloch, M. T., Cook, E. R., Chappell, J., Ellam, R. E., Lea, D. W., Lough, J. M., and Shimmield, G. B. (2001). Variability in the El Niño–Southern Oscillation through a glacial–interglacial cycle. *Science* **291,** 1511–1517.

Tyndall, J. (1872). “The Forms of Water.” Appleton and Company, Akron, OH.

Zebiak, S. E., and Cane, M. A. (1987). A model El Niño Southern Oscillation. *Monthly Weather Review* **115,** 2262–2278.