Geology

Evidence for active El Niño Southern Oscillation variability in the Late Miocene greenhouse climate

Simone Galeotti, Anna von der Heydt, Matthew Huber, David Bice, Henk Dijkstra, Tom Jilbert, Luca Lanci and Gert-Jan Reichart

Geology 2010;38;419-422
doi: 10.1130/G30629.1

Notes

Evidence for active El Niño Southern Oscillation variability in the Late Miocene greenhouse climate

Simone Galeotti[1], Anna von der Heydt[2], Matthew Huber[3], David Bice[4], Henk Dijkstra[2], Tom Jilbert[5], Luca Lanci[1], and Gert-Jan Reichart[5,6]

[1]Dipartimento GeoTeCA, Università degli Studi di Urbino, Campus Scientifico, 61029 Urbino, Italy

[2]Institute for Marine and Atmospheric Research Utrecht, Department of Physics and Astronomy, Utrecht University, Princetonplein 5, 3584 CC Utrecht, Netherlands

[3]Department of Earth and Atmospheric Sciences, and Purdue Climate Change Research Center, Purdue University, West Lafayette, Indiana 47907, USA

[4]Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania 16802, USA

[5]Faculty of Geosciences, Earth Science Department, Utrecht University, 3508 TA Utrecht, Netherlands

[6]Alfred Wegener Institut for Polar and Marine Research, BioGeoScience, Bremerhaven, Germany

ABSTRACT

An evaporite varve thickness record from the Late Miocene Mediterranean reveals significant signals of interannual variability, the frequency and persistence of which are compared with climatic oscillations affecting the region today. Sustained variability in the 2–7 yr band resembles the modern spectrum of the El Niño Southern Oscillation (ENSO) and contrasts with that of the North Atlantic Oscillation (NAO), the cyclicity of which is less stationary in frequency and less sustained in duration. Fully coupled climate model simulations demonstrate not only that ENSO variability persisted during the Late Miocene, but also that its teleconnections may have extended further than today, as high-latitude climate modes weakened due to a reduced meridional temperature gradient. ENSO appears to have exerted a stronger influence on the evaporative balance of the Mediterranean in the Late Miocene than it does today. This evidence suggests that the Pacific prior to the Northern Hemisphere glaciation was characterized by ongoing interannual variability.

INTRODUCTION

It has been hypothesized that the current climate system resides near a threshold, whereby a slight temperature increase may trigger the oscillating tropical ocean-atmosphere system to collapse into a permanent El Niño state (Fedorov et al., 2006; Ravelo et al., 2006; Wara et al., 2005), with profound implications for global climate. Yet, the low resolution of the paleorecords used in these studies compromises their ability to describe interannual variability, making the reliability of such conclusions questionable (Haywood et al., 2007; Rosenthal and Broccoli, 2004). The relationship between El Niño Southern Oscillation (ENSO) variability and the longer term mean climatic state is of crucial importance to future climate predictions and remains controversial (Collins et al., 2005; Seager et al., 2007; Trenberth and Otto-Bliesner, 2003). Short of waiting for hypothesized collapses to occur, a promising approach to test these predictions is to compare annually resolved paleoclimate records from warmer episodes in Earth history with global climate models capable of simulating potential ENSO variability. In the tropics, suitable records for many time slices are scarce. However, since ENSO exerts teleconnections to higher latitude regions, records from these areas provide a possible alternative if accompanied by evidence that such teleconnections existed at the time in question.

Here we present an evaporite varve (halovarve) thickness record of Late Miocene age (ca. 5.6 Ma) from the Mediterranean. The Late Miocene was characterized by elevated global mean temperatures and weaker than modern meridional temperature gradients (Crowley and Zachos, 2000), though atmospheric CO_2 concentrations were similar to today (Pagani et al., 2005). The modern Mediterranean region has complex interannual climate variability, with a weak but significant ENSO teleconnection (Bronnimann et al., 2007) competing with local oscillatory modes such as the North Atlantic Oscillation (NAO) (Luterbacher, 2006) for influence over temperature and precipitation. We compare the evolutionary power spectrum of the Miocene halovarve thickness record with those of the modern ENSO and NAO, and run a fully coupled climate model simulation to investigate the extent of Miocene ENSO teleconnections relative to today.

MATERIALS AND METHODS

The halovarves comes from the Gesso balatino facies of the Gessoso Solfifera formation, deposited during the Lower Evaporites phase of the Messinian salinity crisis (5.96–5.32 Ma) (Krijgsman et al., 1999). The balatino is a laminar alternation of gypsum and shales considered to result from primary deep-water sedimentation during annual rhythms (Ogniben, 1957). More recent work suggests that most of the balatino gypsum represents the fine-grained product of low- to high-density gravity flows (Manzi et al., 2005). Here we focus on balatino facies showing a grass-like growth structure of the gypsum, which suggests a primary nature of the halovarves. Thin sections of the halovarves were analyzed by laser-ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS) scanning and optical microscopy to establish the geochemical and sedimentological characteristics of the sequence. The varves consist of millimeter-scale layers of intergrown gypsum crystals in which thin horizons of fine-grained detrital material are embedded (Fig. 1). Couplet thickness varies from ~0.5 to ~1.5 mm and is dictated by gypsum layer thickness, which accounts for >90% of the total material. By calculating the gypsum precipitation rate in a hypothetical isolated basin in the modern Mediterranean, we show that the couplets most likely were deposited annually (see GSA Data Repository[1]). Assuming the detrital inputs to occur at the same stage of each annual cycle, the amount of gypsum accumulated between detrital horizons represents the severity of evaporative conditions during the year. Accordingly, we digitally analyzed a thin-section photomicrograph to construct a 250 yr varve thickness record from halovarves exposed near the village of Portonovo in the Mezzavalle beach area (43°34′9.57″N, 13°34′29″E) on the Adriatic coast of Italy. Digital records, obtained using ImageJ software, were compared to manual counting of the couplets confirming image analyses data. We then performed an evolutionary spectral analysis on this record, using a series of Matlab algorithms modified from Muller and MacDonald (2000), to investigate periodic components in thickness variability. The same analysis was performed on instrumental records of ENSO and NAO indices.

[1]GSA Data Repository item 2010116, methods, model description, supplemental data, and supplemental figures and tables, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

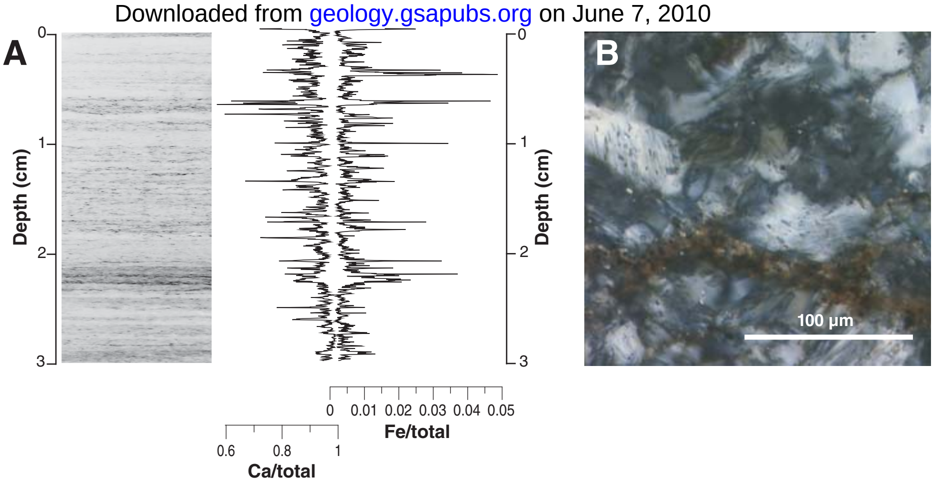

Figure 1. A: Laser-ablation inductively coupled plasma–mass spectrometry profiles of Ca, representing gypsum, and Fe, representing detrital material, in halovarve section. Elements are reported as proportion of total ion counts of all measured elements (S, O, and H were among elements not measured, thus Ca/total value of 1 indicates pure gypsum, $CaSO_4.2H_2O$). B: Close-up of structure of evaporite, showing detrital laminations embedded in matrix of intergrown gypsum crystals.

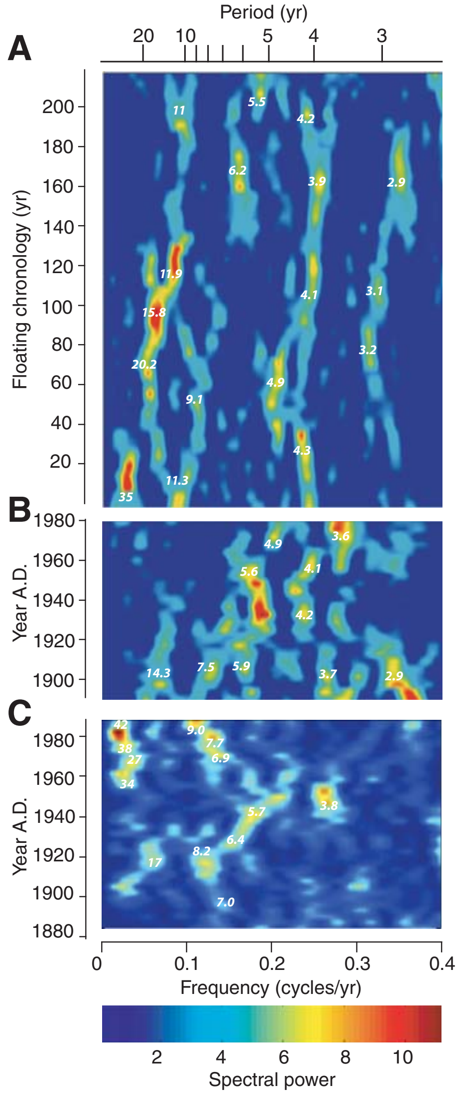

Figure 2. A: Evolutionary spectra of halovarve thickness record obtained from 250 yr series from Mezzavalle after subtraction of noise (95% confidence level) simulated by Monte Carlo routine. B: Equivalent analysis of modern NINO3 index (from National Oceanic and Atmospheric Administration Climate Prediction Center: www.cpc.ncep.noaa.gov/data/indices/sstoi.indices). C: Equivalent analysis of modern December-January-February North Atlantic Oscillation index (from J. Hurrell's 1864–2003 instrumental data: www.cgd.ucar.edu/cas/jhurrell/).

Model simulations were performed using the Community Climate System Model (CCSM 1.4) of the National Center for Atmospheric Research. The CCSM is a fully coupled global ocean–atmosphere–land–sea ice general circulation model, simulating the evolution of climate under external forcing conditions without the use of flux corrections (Blackmon et al., 2001). The model faithfully reproduces modern ENSO variability and teleconnections (Blackmon et al., 2001; Kang et al., 2002; Otto-Bliesner and Brady, 2001). A full spinup simulation was performed with idealized Miocene boundary conditions (see the Data Repository). After the spinup, the model was synchronously integrated for 395 yr; we analyzed the past 200 yr. This simulation is an extension of the runs described by von der Heydt and Dijkstra (2005, 2006).

RESULTS AND DISCUSSION

The LA-ICP-MS data show that the light-dark oscillations visible in the halovarve sequence mirror variable elemental chemistry (Fig. 1), which in turn reflects changes in the severity of evaporation and/or precipitation (see the Data Repository). Evolutive spectral analysis of the halovarve thickness record shows a subdecadal band characterized by elevated power at a frequency of ~0.25 (period ~4 yr). Intermittent elevated power is also observed at other frequencies within the 2–7 yr band (Fig. 2). Hence, it appears that the evaporation-precipitation balance of the Mediterranean region during the Late Miocene was characterized by more stationary and sustained interannual frequencies than observed today (Luterbacher, 2006). The spectrum bears a close resemblance to that of modern ENSO, which shows peaks in the subdecadal band sustained for several decades. In contrast, peaks in the modern NAO spectrum are neither sustained nor stationary, and power develops intermittently and migrates across frequencies.

The CCSM 1.4 simulation was then used to investigate whether the proto-Mediterranean was indeed teleconnected to Pacific ENSO variability during the Miocene. Mean extratropical sea-surface temperatures (SSTs) in the Miocene simulation are 4–10 °C warmer than in a simulation of the present day (Selten et al. 2004; von der Heydt and Dijkstra, 2006), whereas tropical temperatures are only slightly warmer. The mean SST difference between the east and west tropical Pacific is about the same as in modern simulations (Zelle et al., 2005), but the location of the cold tongue in the eastern tropical Pacific is slightly shifted in the Miocene simulation. This may be due to higher mean temperatures, as suggested by Nnafie et al. (2009, personal commun.). Temporally, marked tropical Pacific SST variability is observed in the Miocene simulation (Fig. 3A) with spectral peaks at 2.4–3.3 and 4.1–8.3 yr (Fig. 3B). An empirical orthogonal function (EOF) analysis of the SST field yields an ENSO-like SST pattern, slightly wider meridionally than in present-day climate simulations, possibly due to the larger Pacific basin and the open Central American Seaway of the Miocene (see the Data Repository).

Cross-correlation maps of the modeled Miocene NINO3.4 index and precipitation reveal a large area of positive correlation in the Mediterranean region that is greater than that observed in modern simulations (Fig. 4). Within this area, we chose a region of high correlation close to the site of the halovarves (green box in Fig. 4B) to define a mean Mediterranean precipitation index (MPI) for the Late Miocene. Spectral analysis of the modeled MPI time series shows statistically significant bands at 1.6, 2–3.3, and 4 yr that are coherent with the modeled NINO3.4 frequencies at the 99% significance level (Fig. 5). These results suggest that the relative strength of the ENSO teleconnection to the Mediterranean was greater in the Miocene than today. This is consistent with the argument that tropical climate variability should grow in importance as a factor in global (extratropical) variability in a warmer world, because high-latitude modes of variability should scale approximately with the meridional temperature (and hence pressure) gradients, which are generally considered to be reduced in past greenhouse climates (Huber and Caballero, 2003). Our Miocene simulation shows

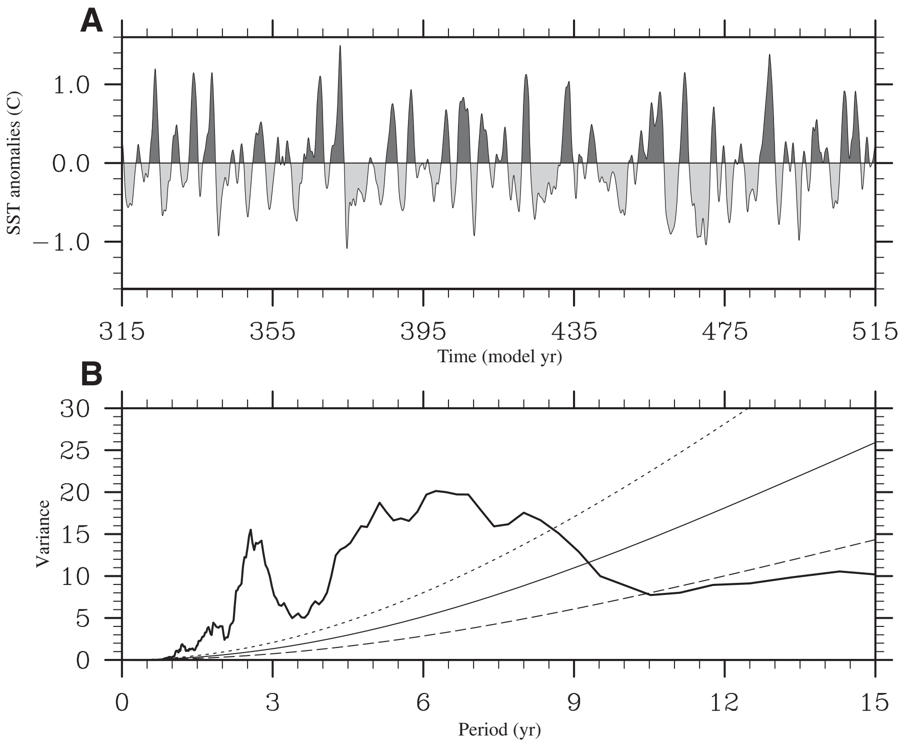

Figure 3. A: Miocene NINO3.4 index (sea-surface temperature, SST averaged over 190°E–240°E and 5°S–5°N) over past 200 model years. B: Power spectrum of NINO3.4 index. Annual cycle is removed, and monthly time series is filtered with 11 mo. Trenberth filter before calculating spectrum. Continuous line indicates theoretical Markov spectrum and dotted lines correspond to lower and upper confidence limits.

atmospheric variability similar to the present NAO, but not on the time scales in question. The simulated Miocene NAO shows a broad, almost white spectrum and the correlation to Mediterranean precipitation is weak. A stronger relative influence of ENSO on Mediterranean climate potentially explains the interannual variability observed in other high-resolution Pliocene and Miocene records (corals, lake varves, tree rings) from the proto-Mediterranean (Brachert et al., 2006; Muñoz et al., 2002; Mertz-Kraus et al., 2009) and northern Europe (Kurths et al., 1993).

However, geochemical records from the Equatorial Pacific suggest a reduced zonal SST gradient and thermocline tilt in warmer climatic periods such as the Pliocene (e.g., Chaisson and Ravelo, 2000; Ravelo et al., 2006; Wara et al., 2005) interpreted to represent a permanent El Niño state. This is difficult to reconcile with our results from the Late Miocene, which suggest both a sustained zonal SST gradient and ongoing ENSO variability. Earlier results, however, rely on the fact that the mean SST pattern, including the position of the cold tongue in the tropical Pacific, is the same as today. Model studies have suggested that this may not be the case, in particular for the Miocene Epoch, when the Central American Seaway was open (Nnafie et al., 2009, personal commun.). Therefore, the solution to this discrepancy could lie either in a difference between Pliocene and Miocene geometry, or an incorrect understanding of the processes controlling the mean-state thermocline or of the relationships between mean state and ENSO variability.

CONCLUSIONS

We have shown that the characteristics of interannual variability in a Miocene halovarve thickness record bear a closer resemblance to the modern ENSO spectrum than to the NAO. Model simulations provide evidence that the ENSO teleconnection to the Mediterranean was

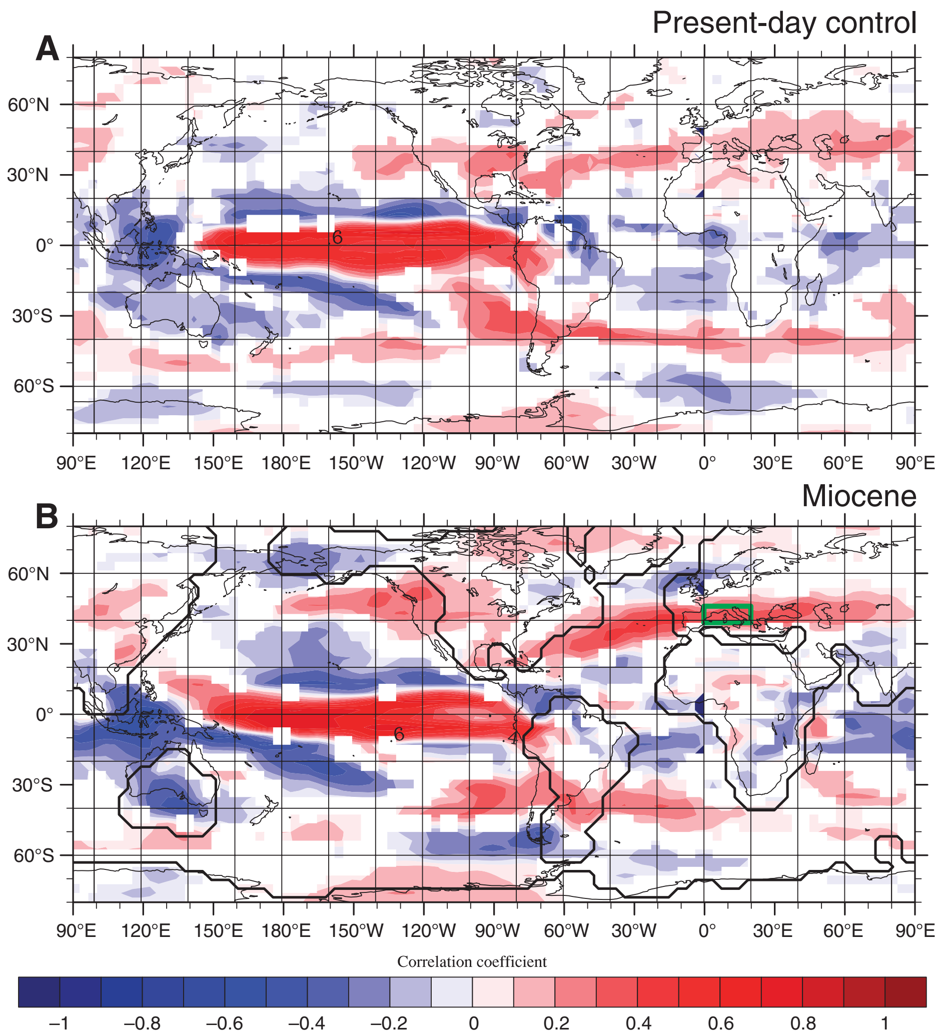

Figure 4. Cross-correlation map between NINO3.4 index and precipitation in simulations. A: Present-day control run as described in von der Heydt and Dijkstra (2006). B: Miocene simulation. Thick black lines show model geometry for simulation, thin lines show modern continents. Green box indicates area where Mediterranean precipitation index is defined.

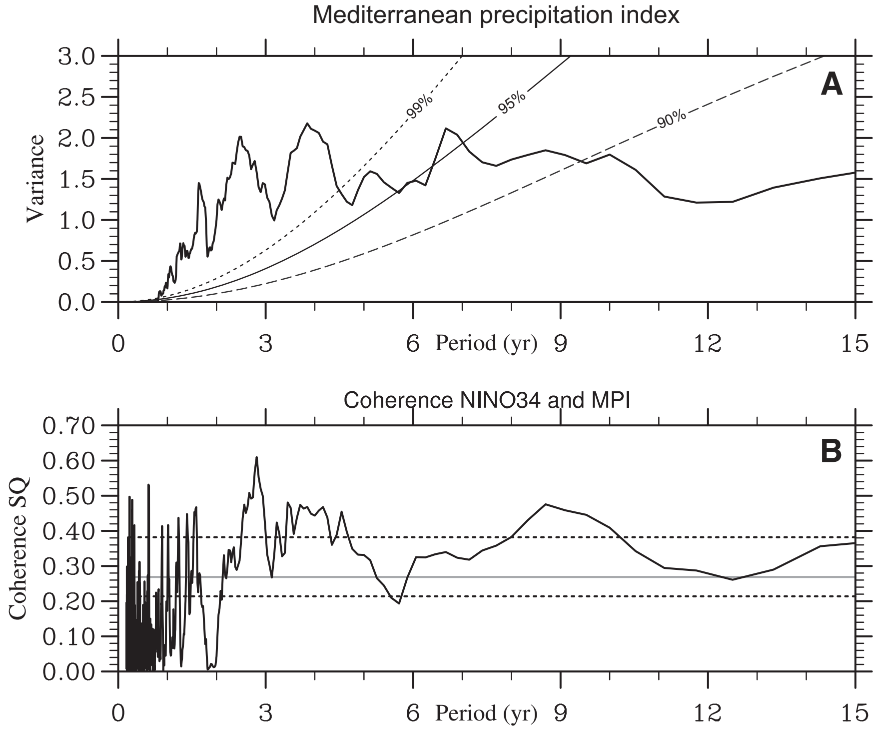

Figure 5. A: Power spectrum of Mediterranean precipitation index (MPI). Annual cycle is removed and monthly time series is filtered with 11 mo. Trenberth filter before calculating spectrum. Gray line indicates theoretical Markov spectrum, and dashed lines correspond to lower and upper confidence limits, respectively. B: Coherence of MPI with simulated NINO3.4 index. Dashed lines indicate 90%, 95%, and 99% confidence levels.

indeed enhanced during the Late Miocene relative to the present day. This could result from the weakening of high-latitude oscillatory behavior in response to reduced meridional temperature gradients in the warmer climate of this period.

ACKNOWLEDGMENTS

Von der Heydt acknowledges personal support through a Veni grant by the Netherlands Organization for Scientific Research (NWO). Computer resources were funded under project SC-192 by the National Computing Facilities Foundation (NCF) with financial support from NWO.

REFERENCES CITED

Blackmon, M., and 25 others, 2001, The Community Climate System Model: American Meteorological Society Bulletin, v. 82, p. 2357–2376, doi: 10.1175/1520-0477(2001)082<2357:TCCSM>2.3.CO;2.

Brachert, T.C., Reuter, M., Felis, T., Kroeger, K.F., Lohmann, G., Micheels, A., and Fassoulas, C., 2006, Porites corals from Crete (Greece) open a window into Late Miocene (10Ma) seasonal and interannual climate variability: Earth and Planetary Science Letters, v. 245, p. 81–94, doi: 10.1016/j.epsl.2006.03.005.

Bronnimann, S., Xoplaki, E., Casty, C., Pauling, A., and Luterbacher, J., 2007, ENSO influence on Europe during the last centuries: Climate Dynamics, v. 28, p. 181–197, doi: 10.1007/s00382-006-0175-z.

Chaisson, W.P., and Ravelo, A.C., 2000, Pliocene development of the east-west hydrographic gradient in the equatorial Pacific: Paleoceanography, v. 15, p. 497–505, doi: 10.1029/1999PA000442.

Collins, M, and The CMIP Modelling Groups, 2005, El Niño or La Niña climate change?: Climate Dynamics, v. 24, p. 89–104, doi: 10.1007/s00382-004-0478-x.

Crowley, T.J., and Zachos, J.C., 2000, Comparison of zonal temperature profiles for past warm time periods, *in* Huber, B., et al., eds., Warm climates in Earth history: Cambridge, UK, Cambridge University Press, p. 50–76.

Fedorov, A.V., Dekens, P.S., McCarthy, M., Ravelo, A.C., deMenocal, P.B., Barreiro, M., Pacanowski, R.C., and Philander, S.G., 2006, The Pliocene paradox (mechanisms for a permanent El Nino): Science, v. 312, p. 1485–1489, doi: 10.1126/science.1122666.

Haywood, A.M., Valdes, P.J., and Peck, V.L., 2007, A permanent El Nino–like state during the Pliocene?: Paleoceanography, v. 22, PA1213, doi: 10.1029/2006PA001323.

Huber, M., and Caballero, R., 2003, Eocene El Nino: Evidence for robust tropical dynamics in the "hothouse": Science, v. 299, p. 877–881, doi: 10.1126/science.1078766.

Kang, I.S., and 16 others, 2002, Intercomparison of atmospheric GCM simulated anomalies associated with the 1997/98 El Nino: Journal of Climate, v. 15, p. 2791–2805, doi: 10.1175/1520-0442(2002)015<2791:IOAGSA>2.0.CO;2.

Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J., and Wilson, D.S., 1999, Chronology, causes and progression of the Messinian salinity crisis: Nature, v. 400, p. 652–655, doi: 10.1038/23231.

Kurths, J., Spiering, C., Mullerstoll, W., and Striegler, U., 1993, Search for solar periodicities in Miocene tree-ring widths: Terra Nova, v. 5, p. 359–363.

Luterbacher, J., 2006, Mediterranean climate variability over the last centuries: A review, *in* Lionello, P., et al., eds., Mediterranean climate variability: Amsterdam, Elsevier, p. 27–148.

Manzi, V., Lugli, S., Ricci Lucchi, F., and Roveri, M., 2005, Deep-water clastic evaporites deposition in the Messinian Adriatic foredeep (northern Apennines, Italy): Did the Mediterranean ever dry out?: Sedimentology, v. 52, p. 875–902, doi: 10.1111/j.1365-3091.2005.00722.x.

Mertz-Kraus, R., Brachert, T.C., Reuter, M., Galer, S.J.G., Fassoulas, C., and Iliopoulos, G., 2009, Late Miocene sea surface salinity variability and paleoclimate conditions in the Eastern Mediterranean inferred from coral aragonite $\delta^{18}O$: Chemical Geology, v. 262, p. 202–216, doi: 10.1016/j.chemgeo.2009.01.010.

Muller, R.A., and MacDonald, G.J., 2000, Ice ages and astronomical causes; data, spectral analysis and mechanisms: Chichester, UK, Praxis Publishing, 318 p.

Muñoz, A., Ojeda, J., and Sanchez-Valverde, B., 2002, Sunspot-like and ENSO/NAO-like periodicities in lacustrine laminated sediments of the Pliocene Villarroya Basin (La Rioja, Spain): Journal of Paleolimnology, v. 27, p. 453–463, doi: 10.1023/A:1020319923164.

Ogniben, L., 1957, Petrografia della serie Solfifera Siciliana e considerazioni geologiche relative: Memorie Descrittive della Carta Geologica d'Italia v. 33, 275 p.

Otto-Bliesner, B.L., and Brady, E.C., 2001, Tropical Pacific variability in the NCAR Climate System Model: Journal of Climate, v. 14, p. 3587–3607, doi: 10.1175/1520-0442(2001)014<3587:TPVITN>2.0.CO;2.

Pagani, M., Zachos, J.C., Freeman, K.H., Tipple, B., and Bohaty, S., 2005, Marked decline in atmospheric carbon dioxide concentrations during the Paleogene: Science, v. 309, p. 600–603, doi: 10.1126/science.1110063.

Ravelo, A.C., Dekens, P.S., and McCarthy, M., 2006, Evidence for El Niño–like conditions during the Pliocene: GSA Today, v. 16, p. 4–11, doi: 10.1130/1052-5173(2006)016[0008:E]2.0.CO;2.

Rosenthal, Y., and Broccoli, A.J., 2004, In search of paleo-ENSO: Science, v. 304, p. 219–221, doi: 10.1126/science.1095435.

Seager, R., and 12 others, 2007, Model projections of an imminent transition to a more arid climate in southwestern North America: Science, v. 316, p. 1181–1184, doi: 10.1126/science.1139601.

Selten, F.M., Branstator, G.W., Dijkstra, H.A., and Kliphuis, M., 2004, Tropical origins for recent and future Northern Hemisphere climate change: Geophysical Research Letters, v. 31, L21205, doi: 10.1029/2004GL020739.

Trenberth, K.E., and Otto-Bliesner, B.L., 2003, Toward integrated reconstruction of past climates: Science, v. 300, p. 589–591, doi: 10.1126/science.1083122.

Von der Heydt, A., and Dijkstra, H.A., 2005, Flow reorganizations in the Panama Seaway: A cause for the demise of Miocene corals?: Geophysical Research Letters, v. 32, L02609, doi: 10.1029/2004GL020990.

Von der Heydt, A., and Dijkstra, H.A., 2006, Effect of ocean gateways on the global ocean circulation in the late Oligocene and early Miocene: Paleoceanography, v. 21, PA1011, doi: 10.1029/2005PA001149.

Wara, M.W., Ravelo, A.C., and Delaney, M.L., 2005, Permanent El Nino–like conditions during the Pliocene warm period: Science, v. 309, p. 758–761, doi: 10.1126/science.1112596.

Zelle, H., Van Oldenborgh, G.J., Burgers, G., and Dijkstra, H., 2005, El Nino and Greenhouse warming: Results from ensemble simulations with the NCAR CCSM: Journal of Climate, v. 18, p. 4669–4683, doi: 10.1175/JCLI3574.1.

Manuscript received 21 August 2009
Revised manuscript received 26 November 2009
Manuscript accepted 2 December 2009

Printed in USA