Orbitally driven changes in ENSO over the Holocene and possible abrupt change

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In this paper, we present results from a simplified coupled ocean-atmosphere model of the tropical Pacific which demonstrate the potential influence of orbitally driven changes in the seasonal cycle of solar radiation on ENSO behavior. We impose orbitally induced changes in solar forcing as an anomalous heat flux on the Zebiak-Cane coupled ocean-atmosphere model (Zebiak and Cane 1987). This model has been used for more than a decade to understand and predict the El Niño/Southern Oscillation (ENSO) (Cane 1986). It is an anomaly model, with some aspects of the oceanic and atmospheric physics linearized about the mean monthly climatology of the present. The model's active domain includes only the tropical Pacific.

Figure 1 shows the the frequency and amplitude of warm ENSO events within 500 year overlapping windows for multiple runs with different initial conditions for the last 14 kyr. A large event is defined to occur when the mean Dec-Feb NINO3 index (the average SST anomaly over the region 150^oW to 90^oW and 5^oS to 5^oN) exceeds 3^oC. The model results show a distinct increase in both the frequency and amplitude of warm ENSO events over the mid- to late-Holocene.

Since the model is forced only by orbital changes, with no change in mean state, the explanation for the change in the behavior of the model ENSO lies in the change in the seasonal cycle. The orbital configuration in the mid-Holocene, a time of greater heating in the boreal summer, and less heating in boreal winter, alters the seasonal cycle of the coupled system such that the development of warm events was suppressed. The system continued to oscillate throughout the Holocene, though large warm events occurred less frequently and were smaller in magnitude in the mid-Holocene (see Clement et al. 2001 for more complete explanation of the mechanism). These results are consistent with a number of recent studies that have interpreted paleoproxy data to describe the state of the tropical Pacific and changes in ENSO over the Holocene (McGlone et al. 1992, Shulmeister and Lees 1995, Sandweiss et al. 1996, Rodbell et al. 1999). We also note a peak in the frequency and amplitude of warm events around 1-2 kyr which is consistent with a recent study of geoarcheological data from the Peruvian coast by Sandweiss et al. (2001).

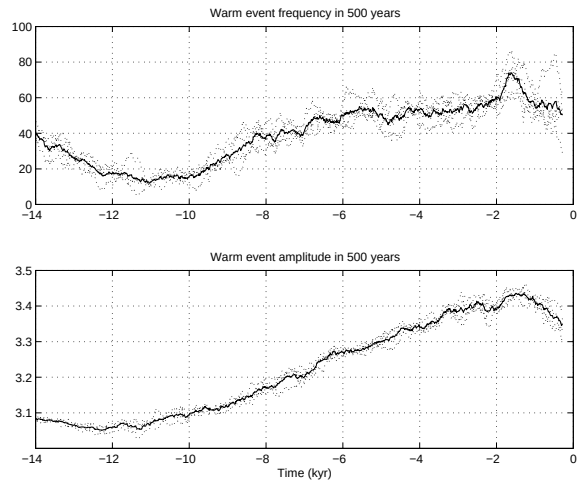

Figure 1: (a) The number of occurences of events in 500 year overlapping windows (overlapping every 10 years) as a function of kyr BP. (b) The mean amplitude in the same overlapping 500 year windows of the events exceeding 3 K (in ^{o}C). Dotted lines are from six runs of the model with slightly different initial conditions. The solid line is the mean over these runs.

In addition to the gradual changes over the Holocene, we also find that the model ENSO is capable of abrupt change in response to the smoothly varying solar forcing. Under particular orbital configurations, ENSO variability "flickers" on and off, abruptly locking to the seasonal cycle for several centuries. Figure 2a shows an example of one such period that occurs at approximately 12 kyr, a time which coincides with the Younger Dryas. There is a mean SST change associated with this shut down in ENSO (Figure 2b) which has an increased zonal gradient, similar to that of La Niña event.

These abrupt events are paced by the solar forcing and recur approximately every 11 kyr (Figure 3). During the periods 450-400 and 50-0 kyr ENSO shut downs last for several centuries. At these times the orbital configuration is similar because of the 400 kyr cycle in eccentricity.

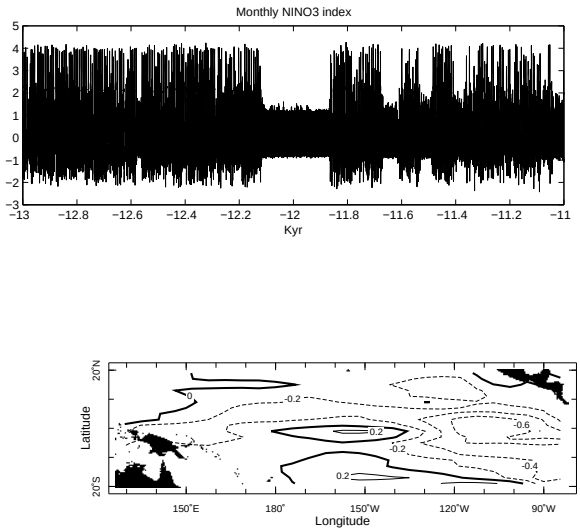

Figure 2: (a) Monthly NINO3 index (^{o}C) from the Zebiak-Cane coupled model with imposed orbital forcing for the period between 13 and 11 kyr. (b) Annual mean SST change (^{o}C) relative to the control run for 12 kyr when ENSO is shut down.

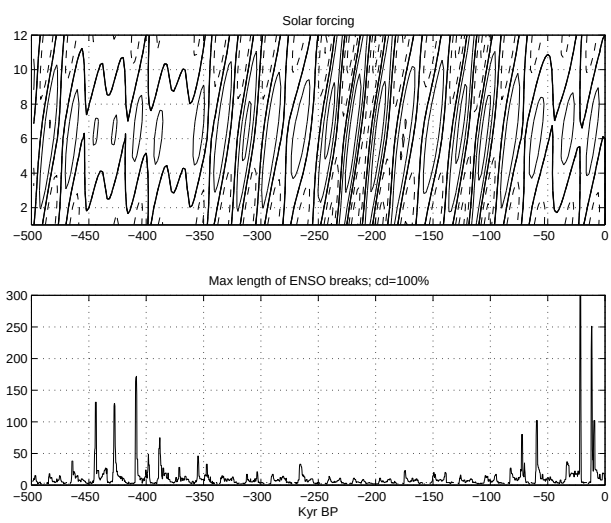

Figure 3: (a) Solar forcing on the equator imposed as an anomalous heat flux into the ocean in the Zebiak-Cane coupled model for the last 500 kyr as a function of kyr BP (x-axis) and month of the year (y-axis). The contour interval is 20 Wm^{-2}. Solid lines indicate heat flux into the ocean and dashed lines indicate heat flux out of the ocean. (b) Maximum length of shut downs of ENSO (years) in 1000 year overlapping windows. A shut down is defined to occur when the annual mean NINO3 does not exceed 0.5 ^{o}C for longer than 5 years.

Both the smooth response in the model ENSO to the orbital forcing over the Holocene, and the abrupt response at 11 kyr intervals have associated mean changes in SST. We suggest that a persistent ENSO-like SST change would have some pattern of climate change associated with it that could be compared with the paleoclimate indicators, in particular from ENSO sensitive regions of South America.

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