# Solar-Cycle Modulations of ENSO: A Possible Source of Climatic Change

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**ABSTRACT**: An association between long-term changes in the solar cycle and the frequency of El Niño events has been identified in historical records of El Niño and sunspot number. Although no known mechanism can explain the apparent relationship, the association is strong. A possible coupling between the sun and the ocean's mixed layer, involving ENSO, is worthy of further study.

## INTRODUCTION

Varved (annually layered) marine sediments off Northern California contain evidence that El Niño circulation regimes have alternated with an anti-El Niño (La Niña) regimes since the late Pleistocene (Anderson et al., 1989 and in press). The sediment record shows that ENSO regimes persist for decades to millennia (Anderson et al., in press). Quinn, Neal, and Antunez de Mayolo (QNA) (1987) observed that the frequency of El Niño events changed systematically over time, and Enfield (1988) noted that the QNA record of El Niño contained a centennial cycle.

A search for an explanation of long-term ENSO cycles in the geologic record prompted a comparison of the record of sunspot number with the historical record of El Niño events compiled by QNA. The comparison revealed what appears to be an extraordinary association between sunspot number and the frequency of occurrence of El Niños. This contribution to the PACLIM Workshop describes the association and briefly considers known mechanisms that might explain the observed association.

## SOLAR/EL NIÑO ASSOCIATION

QNA used ships logs of pirates, privateers, and explorers, as well as other information, to assemble a remarkable record of the occurrence and intensity of El Niño events since 1525. Their qualitative data were numerically transformed and compared with the Southern Oscillation Index (SOI) since 1880 and with the record of sunspot number since 1700. Frequency of occurrence of El Niño events (QNA event-date) was transformed by calculating a symmetrical, linearly weighted moving average (e.g., [a + 2b ...2d + e]) for various moving time intervals (e.g., 5, 11, and 19 years). The same rank was assigned to all events and expressed as number of events per year. More frequent events appear as values above the mean in proportion to the number of events in the assigned moving interval, and length of the interval is not critical (Figure 1).

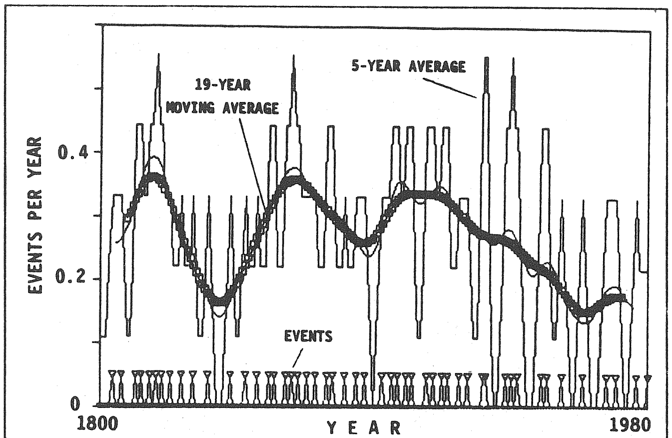


Figure 1. Recurrence of El Niño events (at base) and weighted average for several moving intervals.

The pattern of recurrence was compared to QNA estimates of the strength of El Niño events by assigning a value of 6 to their very strong events, 5 to strong events, etc. and determining the relationship between frequency of occurrence and strength of event. For the historical period after 1880 when data become available, the strength of El Niño events was further estimated by scaling the negative departure from zero of monthly maxima of the SOI in the NOAA Climate Analysis Center Index (Ropelewski and Jones, 1987; e.g., the 1982-83 departure was assigned a value of -2.9).

Comparison of QNA ranking with the SOI revealed inconsistency in ranking the strength of events. Prior to 1800, stronger El Niño events appear to be associated with less frequent El Niños (Quinn et al., 1987). Thereafter, the opposite is the case. Therefore, only the QNA frequency term is used to examine the behavior of El Niño. Comparison of El Niño frequency and sunspot number was done in sets of data organized, younger to older, into four time-series of increasing length but decreasing reliability. The four series include:

- Data for El Niño recurrence and sunspot number from 1880 to 1986 (n = 36), this series also includes the SOI.
- Data for El Niño recurrence and sunspot number from 1800 to 1986 based on the full set of QNA observation (n = 50).

In J.L. Betancourt and A.M. MacKay, editors, 1990. Proceedings of the Sixth Annual Pacific Climate (PACLIM) Workshop, March 5-8, 1989: California Department of Water Resources, Interagency Ecological Studies Program Technical Report 23.

- Data for El Niño recurrence and sunspot number from 1700 to 1986 based on only strong and very strong events (n = 28).
- El Niño recurrence since 1525, also based on only strong and very strong events (n = 47).

Because of the scarcity of data and the subjective nature of the QNA compilation, minimal processing of the transformed data seemed advisable. Associations were identified and further clarified with simple measures of correlation and cross-correlation. In three sets of data for the interval after 1700, when systematic observation of sunspots began, Pearson correlation was used as an estimator of relative association between sunspot number and El Niño recurrence. The solar/El Niño association is observable through only three long solar cycles, and correlation coefficients are used only as a relative measure of association in records of different quality; they are not intended to imply that an association is real.

## El Niño Association with ~90-Year Solar Cycles

Examination of the longest but least reliable time-series (Figure 2) reveals three ~90-year cycles in El Niño recurrence after 1650. Power spectral density in this same record since 1650 confirms a ~90-year cycle. The maxima of the two older cycles correspond, approximately, to the Maunder and Dalton minima in sunspot number. The maximum of the most recent ~90-year cycle in El Niño frequency corresponds to a lesser minimum in sunspot number that centers around the year 1900.

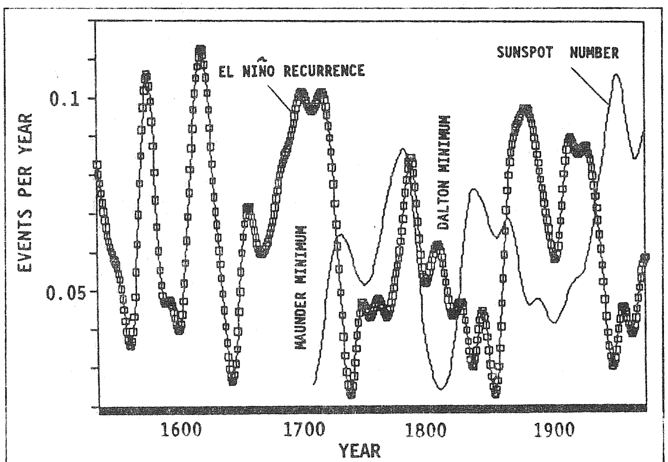


Figure 2. Recurrence of strong and very strong El Niño events since 1525 and sunspot number since 1700. Smoothed time-series. Note that more El Niño events occur during the Maunder Minimum.

The record for strong and very strong events shifts out of phase in the Dalton Minimum. However, a sequence containing more events (Figure 3) confirms a negative association with the Dalton Minimum, and the phase shift in Figure 2 is an artifact of less reliable data. The strongest association and greatest recurrence of El Niño events after 1650 occurs during the Maunder Minimum, an interval of very low sunspot activity (Eddy, 1976; Stuiver and Quay, 1980).

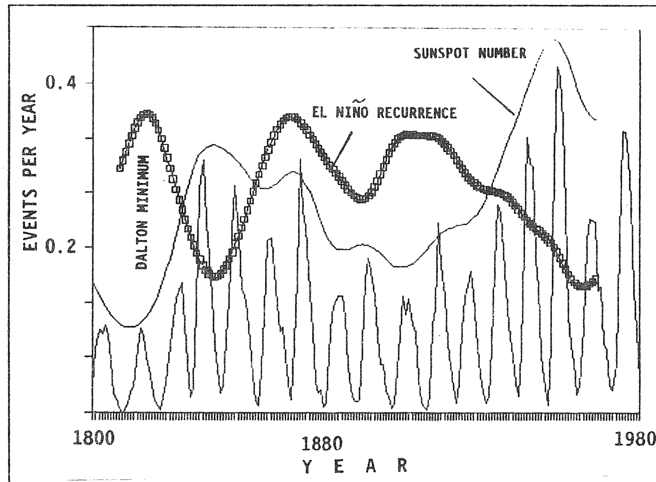


Figure 3. Association between El Niño frequency and sunspot number for all ranks of El Niño events since 1800. Note that the Dalton Minimum has a negative association not apparent in Figure 2 and that fewer El Niño events occur at times of high sunspot number.

The correlation coefficient for El Niño events and sunspot number of an iterated 19-year moving average of the combined record of all El Niño events since 1700 is r = –0.45. The coefficient for the time-series since 1800 (r = –0.59) is increased to r = –0.65 when the El Niño record lags by 4 years. The coefficient for sunspot number and El Niño recurrence since 1880 (see Figure 3) is r = –0.85. Coefficients are lower for 11-year and 5-year moving averages.

A more complete picture of the relationship between sunspot number and El Niño recurrence can be seen in the time-series for all QNA El Niño events after 1800 (Figure 3). The negative association in the Dalton Minimum repeats the stronger effect observed during the Maunder Minimum. A strong 11-year solar cycle after 1930 is accompanied by fewer El Niño events, and the weak 11-year solar cycle between 1880 and 1930 is a time of more frequent El Niños with an equivocal relationship in the transition after the Dalton Minimum. Correlation coefficients, which increase as information improves in newer records, support the visual observation (Figures 2 and 3) that occurrence of El Niños is approximately doubled at times of low sunspot number in ~90-year solar cycles.

## El Niño Association with the 11-year Solar Cycle?

The QNA record since 1800 contains a sufficient number of El Niño events for a 5-year moving average to define the temporal position of groupings of several events (Figures 1 and 4). A detrended 5-year moving average of events after about 1890 shows a cross-correlation with the sunspot record (Figure 4, second half). In contrast, the record before 1890 does not correlate (Figure 4, first half).

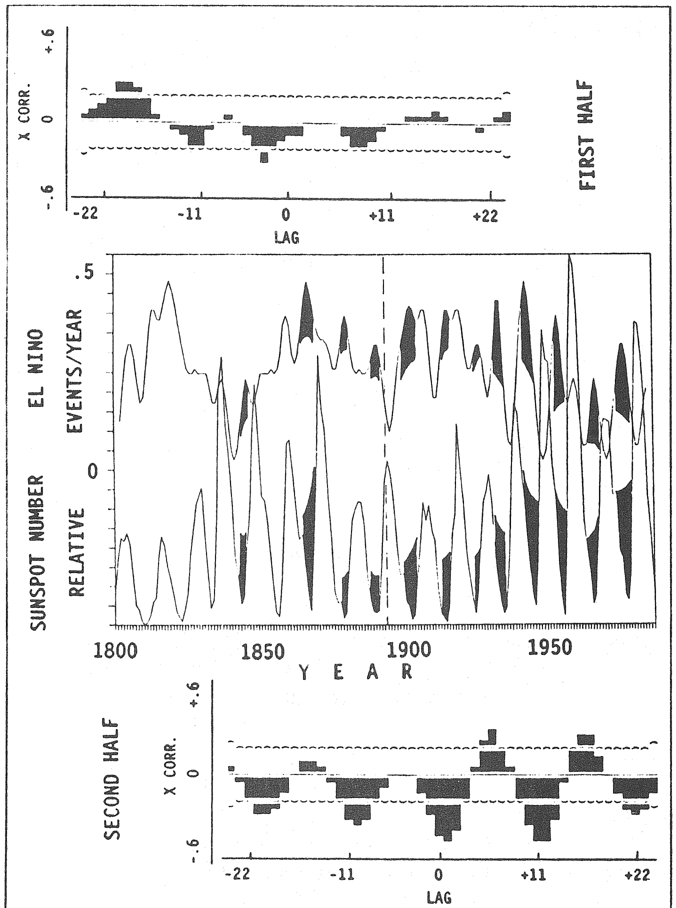


Figure 4. Recurrence of El Niño events and annual sunspot number since 1800 and cross-correlations for first and last half of the record. High coefficients at an 11-year lag in the last half of the record show that El Niño recurrence is aligned with low sunspot number when the 11-year sunspot cycle is strongest.

A stronger correlation in the second half of the record can be attributed to greater alignment between minima of sunspots and maxima in El Niño recurrence. As a test of this supposition, the same number of El Niño events as occur in the second half of the time-series were artificially spaced ~ 11 years apart so that three events occurred within the lowest part of each 11-year sunspot minimum. The coefficient for this contrived association ($r = -0.68$), compared to the coefficient actually observed ($r = -0.51$) confirms that alignment of maxima and minima (negative association between El Niño recurrence and sunspot number) is responsible for the correlation and for the regular 11-year spacing of the lag cycles (Figure 4, second half). The lag of 11 years is largely the result of a strong solar cycle. Nevertheless, the second half of the record, when both the 11-year solar cycle and El Niño recurrence have their greatest amplitude, has a higher correlation coefficient, and more El Niño maxima are visually aligned with sunspot minima (Figure 4).

Changes in the strength of El Niños, as measured by the SOI, appear to have a weak association with sustained changes in sunspot number. For example, before ~ 1930, sunspot number was low when El Niño events were generally stronger (Figure 5). The reverse situation holds after ~ 1930. A correlation of this weak negative association between SOI values and corresponding annual sunspot number for individual events since 1880 is $r = -0.27$ ($n = 53$; $p = 0.05$; extreme outliers from the mean were removed from the detrended series). Reduced amplitude of SOI corresponds to low amplitude variations of sea surface temperature in the quasi-biennial band, which for the same historical period, occur at times of high solar activity (Barnett, 1989).

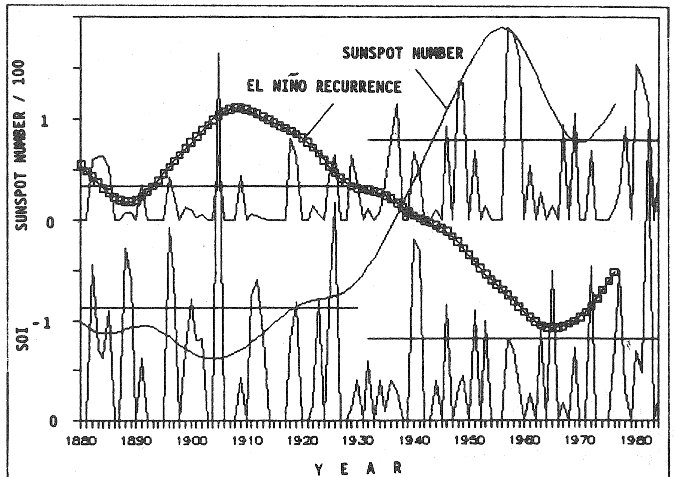


Figure 5. Changes in amplitude of the southern oscillation index (SOI) and corresponding annual sunspot number for all El Niño events after 1880. Shift to lower mean SOI values (straight lines) after 1930 shows that weaker El Niño events occur when the 11-year sunspot cycle is strongest.

## Relationship Between El Niño Strength and Frequency

After 1880, the strength of El Niño events, as measured by the SOI, is reduced when El Niño events are less frequent. The association can be observed visually by comparing the first and second half of the post-1880 SOI and sunspot records (Figure 5). For example, before ~ 1930, SOI values are high when El Niños are generally more frequent. The opposite relationship holds after ~ 1930, suggesting a positive association between higher frequency and strength.

In contrast to the relationship defined by the SOI (more frequent El Niños = stronger El Niños), QNA estimates for the interval before 1880 indicate that El Niño events are weaker when more frequent than the mean frequency. These comparisons show that the relationship between the frequency of recurrence and strength of El Niño events is either unclear or is changeable over time.

In summary, the frequency of occurrence of El Niño events approximately doubles when sunspot number is low. When the 11-year solar cycle is strongest, the spacing between El Niño events increases. The amplitude of El Niño events appears to weaken with a stronger 11-year solar cycle, but the association between frequency and amplitude is equivocal and may change over time.

## MODULATION OF ENSO BY THE SOLAR CYCLE?

The solar/El Niño association described above suggests that unrecognized mechanisms may link ENSO to the solar cycle. However, a specific physical mechanism is required to show that the association is more than a curiosity and to explain why a more active, irradiant sun might be associated with effects that lengthen the period of ENSO and that possibly reduce its amplitude (more sunspots accompany increased irradiance; Kerr, 1987, 1988; Lean, 1989).

ENSO, with an average period of 3 to 4 years for El Niño events, is believed by some observers to be a natural, self-regulating, linear oscillator, with nonlinear effects (Graham and White, 1988). The well understood behavior of linear oscillators indicates that modulation of ENSO by an 11-year solar cycle would lengthen ENSO's period and reduce its amplitude. This heuristic explanation agrees with the observed relationship that El Niño events are less frequent at times of strong 11-year solar cycles. Assuming modulation of a linear oscillator, the historical record suggests that the higher frequency of ENSO would prevail and approach the frequency of the quasi-biennial oscillation when the 11-year solar cycle is weak, as during the Maunder Minimum. The period would lengthen to about 4 years when a strong 11-year solar cycle modulates ENSO. The historical El Niño record is not clear as to whether weaker or stronger El Niños go with more frequent events. However, the SOI record suggests that frequent El Niños are stronger.

Several possible mechanisms for converting solar variability to changes in climate are known (see review in Landscheidt, 1987). A survey of physical processes, however, has failed to identify a mechanism that might explain the solar/El Niño association. Direct transfer of solar energy via heating of the ocean's mixed layer is apparently ruled out by weak changes in solar irradiance that accompany the 11-year solar cycle (about 0.08%; Lean, 1989) and longer solar cycles (about 0.14%; Kerr, 1987).

Without a specific mechanism, the solar/El Niño association described above joins many other earth-based phenomena that have an interesting but unproven relationship to the solar cycle. Is there a chance, however, that the association could be real?

A poor understanding of ENSO and the origin of the oscillation leave open the possibility that the solar/El Niño association may ultimately be explained by as yet unknown mechanisms operating in the larger ocean/atmosphere system. For example, the 11-year solar cycle has been linked through the QBO to upper tropospheric winds and storm tracks and to changes in regional temperature (van Loon and Labitzke, 1988; EOS, 1988). Also, temperature anomalies in the upper troposphere and lower stratosphere contain both a solar and an El Niño signal (Sellers, this volume).

Barnett (1989) apparently has extended the 11-year solar/QBO/atmosphere association identified by van Loon and Labitzke to include an association between the solar cycle and sea surface temperature (SST). The solar/QBO/SST association, in a record that extends to 1884, is strongest after ~1930 when the sun is most active and in the central and eastern equatorial Pacific where El Niño is best developed. In addition, low amplitude variations in the quasi-biennial band coincide with high solar activity, a relationship that matches the solar/El Niño association after 1880 (Figure 5) and the expected response of a linear oscillator.

ENSO and the QBO are closely related, if not part of the same phenomenon, and with the addition of Barnett's (1989) analysis to that of van Loon and Labitzke, a solar/El Niño association in QNA data appears to be a reasonable extension of that relationship, as well as a further indication that solar-related changes occur in the ocean's mixed layer.

## MIXED-LAYER RESPONSE TO ENSO COUPLING

Transforming the historical record of El Niño events (QNA) into a numerical estimate of El Niño frequency has revealed an interesting association with changes in the ocean's mixed layer and with Pacific climate. For example, a record of $\delta^{18}O$ in the planktonic Foraminifera *Globigerina bulloides* reconstructed from the Santa Barbara Basin by Dunbar (1983) shows that isotopic changes in near-surface waters are coincident with the changes in El Niño frequency in cycles of 50 or more years (Figure 6). Changes in $\delta^{18}O$ after 1750 consistently and closely parallel the frequency of occurrence of El Niño events. Dunbar (1983) suggested that $\delta^{18}O$ in *G. bulloides* is an estimator of near-surface temperature, in which case more frequent El Niños occur when the surface layer in the Santa Barbara Basin is cooler.

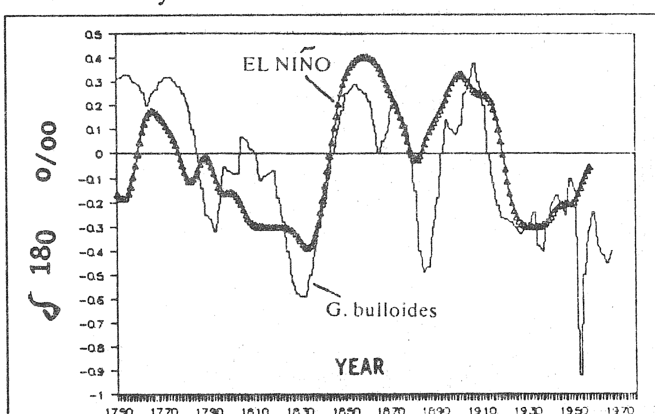


Figure 6. Recurrence of strong and very strong QNA El Niño events and $\delta^{18}O$ in *G. bulloides* after 1750 in Santa Barbara Basin. El Niño record is shifted slightly to adjust for errors in varve chronology.

The validity of *G. bulloides* as an indicator of temperature and the regional extent of a cooler mixed layer must be documented with additional study. However, even without demonstrating the specific nature of the association, the remarkably close agreement between the oxygen isotope and El Niño records in the Santa Barbara

Basin (Figure 6) suggests that a long-term response by the mixed layer is tied to the frequency of El Niño events. If so, the moving-average transformation used to characterize El Niño frequency in historical data is a useful device for examining responses to long-term changes in El Niño. Also, this example suggests that the QNA methodology is reasonably valid and improves prospects that the solar/El Niño association observed in the long historical record is real.

## CONCLUSIONS

The historical record contains an unmistakable association between the solar cycle and the frequency of occurrence of El Niño events, but the record is not long enough to confirm that the association is real. However, evidence is accumulating that the ocean carries the solar signal and that ENSO, along with the QBO, may be part of the mechanism. Potential involvement of the mixed layer suggests that marine paleoclimate records may be an important source of information about the long-term response of El Niño to solar variability and associated changes in climate.

## ACKNOWLEDGMENTS

Supported by National Science Foundation grant ATM8707462. B. Allen, Y. Enzel, S.P. Heustis, L.H. Koopmans, and B.K. Linsley, University of New Mexico, provided critical comments.

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