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On the relation between atmospheric CO_2 and equatorial sea-surface temperature

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ABSTRACT

Associations between the sea-surface temperature (SST) in the eastern equatorial Pacific (0°–10°S, 180°–80°W) and changes in atmospheric CO_2 concentration have been examined. The CO_2 records at Mauna Loa and the South Pole of the Scripps Institution of Oceanography, and the shorter records of the Geophysical Monitoring for Climatic Change program at Barrow, Samoa, the South Pole and Mauna Loa, were used after the annual cycles and the growth due to fossil fuel emissions had been removed.

We find that warmer than average SST precedes above-average increases in CO_2 by about one season at Mauna Loa and two seasons at the South Pole. The shorter records at Samoa and Barrow support longer lags - 2 to 3 seasons at Samoa and 3 to 5 seasons at Barrow. The correlations and their lags change with time, however, there being periods of relatively high correlation associated with El Niño events and periods of lower correlation when El Niño is not present. Furthermore, there is a seasonal preference for these high correlations. At Mauna Loa, the change of CO_2 from (NH) fall to spring is better correlated with antecedent SST than the changes from spring to fall. At the South Pole, a similar pattern is found with a one-season shift.

1. Introduction

The characteristics of the growth of carbon dioxide (CO_2) concentration in the atmosphere are well-known. The record maintained by Scripps Institution of Oceanography (SIO) since 1958 at Mauna Loa Observatory shows a steady increase in concentration from a value of about 315 parts per million by volume (ppm) to a current value of about 345 ppm. Superimposed on this growth is an annual cycle with a maximum in spring and minimum in fall. The general rise and the shape of the annual cycle have been confirmed at other locations. The range of the annual cycle appears greatest in the north, roughly between 50° and 60°N latitude, and diminishes toward the south. In the southern hemisphere the range is much smaller and the phase reverses so that at the South Pole the maximum is in the southern hemisphere spring and the minimum in fall.

The upward trend in mean annual concentration is mainly caused by the emissions of CO_2 from fossil fuel burning. The annual cycle is usually ascribed to the annual cycles of photosynthesis and respiration in the biosphere. Most of the biosphere is in the northern hemisphere so the annual cycle would be expected to be larger there than in the southern hemisphere, as is observed. It is also possible that there is an annual cycle in the exchange of CO_2 between ocean and atmosphere that may affect the annual cycle in the atmosphere.

When the CO_2 concentration record is adjusted to remove the annual cycle and the growth due to fossil fuel emissions, there remain variations in time to be explained. Bacastow (1976) was the first to note a relation between CO_2 records so treated and the southern oscillation. The southern oscillation is a recurrent phenomenon that does not appear to be periodic, and which has substantial effects on atmospheric and oceanic circulations, the El Niño phenomenon in the eastern equatorial Pacific being one manifestation.

Newell and Weare (1977) and Machta et al. (1977) pointed out that the changes in CO_2

concentrations were also related to changes in sea surface temperature of the tropical Pacific. There are a number of ways this temperature could influence the concentration of atmospheric CO_2. The solubility of CO_2 in seawater is a function of water temperature, increasing with decreasing temperature. The equilibrium constants that affect the bicarbonate-carbonate chemistry of ocean waters have a temperature dependence. Hyson and Pearman (1980) note, however, that the expected effects of temperature on CO_2 partial pressure are not sufficient to account for all of the observed CO_2 signal. Changes in temperature may also reflect changes in the vertical circulation of the ocean (e.g., upwelling) that in turn can affect the uptake of CO_2 by phytoplankton and its subsequent removal from the surface waters. Newell et al. (1978) discuss these in more detail.

In addition, changes in water temperature may be associated with large-scale changes in atmospheric circulation such as changes in the strength and location of the Hadley cells. This could affect CO_2 amounts by producing changes in the cross-equatorial exchange of air, since almost all fossil fuel combustion takes places north of about 20° N (Marland et al., 1985). Ocean temperature changes may be associated with very large scale interannual changes in growing conditions such that the global cycles of photosynthesis and respiration are altered.

We will show a number of correlations between sea-surface temperatures in the region 0°–10° S, 180°–80° W and seasonal changes in CO_2. In this paper we use SST to designate the sea-surface temperature in this region alone. It has been shown by Angell (1981) that there is a correlation of about 0.7 between this SST and the southern oscillation Index (SOI) defined as the normalized pressure differences between Tahiti and Darwin. This region is, of course, where El Niño phenomena are produced and surface temperatures in the eastern equatorial Pacific are sometimes used as an index of the southern oscillation. Correlations between CO_2 changes and the SOI, however, were slightly poorer than correlations with the SST. For this reason we focus our attention on the SST relationships. The material presented will be largely descriptive, showing relationships in time and space among the CO_2 records. We will concentrate on the records from Scripps Institution of Oceanography (SIO) because they are longer, using the shorter records from NOAA's Geophysical Monitoring for Climatic Change (GMCC) to test or expand some of the conclusions.

Section 2 describes the CO_2 data in more detail, and our treatment of them.

2. The data

The basic CO_2 concentration data were compiled by SIO at the Mauna Loa Observatory and the South Pole Observatory, and by GMCC at Mauna Loa, the South Pole, Barrow Observatory and Samoa Observatory. Table 1 gives the locations of these sites and the lengths of the CO_2 records used. With the exception of the SIO record at the south pole, all the concentrations were measured with non-dispersive infra-red gas analyzers in place at the observatories. The south pole SIO data are from flasks of air samples collected at the south pole and analyzed at SIO. The standard calibration gases used in the analyses of both groups were traceable to the set of standards maintained at SIO.

Each group examines its raw data to eliminate periods of equipment malfunction and to select data representative of "background" conditions. The selection criteria of the two groups are similar but not identical. The groups each form monthly mean values of background concentrations. We formed seasonal averages from these records by grouping the DJF, MAM, JJA and SON data.

The data sets are subject to revisions as more is learned about the individual instruments and the basic calibration systems, as well as refinements in the procedures for choosing background data. Thus, each data set is to be considered provisional. This is particularly true of the 1983–84 data because recalibration of the reference gases, which is performed after the data collection period, sometimes results in small changes in the reported concentrations. Data were occasionally missing for particular months due to instrument problems. In some of these cases flask-sample data were substituted by the particular group. In a few cases where data were missing we interpolated monthly values to maintain continuity; otherwise we have used the data as reported by the two groups.

Table 1. *Carbon dioxide observation sites used in this study, and length of the CO_2 records used, where SIO is the Scripps Institute of Oceanography and GMCC the Geophysical Monitoring for Climatic Change group of NOAA*

Station	Organization	Lat.	Long.	Elevation (m)	Length of record
Mauna Loa	SIO	19.5°N	155.6°W	3397	Apr 1958–May 1984
Mauna Loa	GMCC	19.5°N	155.6°W	3397	May 1974–Feb 1985
south pole	SIO	90°S		2810	Jan 1965–Jan 1979
south pole	GMCC	90°S		2810	Jan 1976–Jan 1985
Barrow	GMCC	71.3°N	156.6°W	11	Jan 1973–Feb 1985
Samoa	GMCC	14.3°S	170.6°W	30	Jan 1976–Feb 1985

Fig. 1 shows the seasonal CO_2 concentrations plotted for each of the six records. The curves show the familiar features of CO_2 records: the upward trend in concentration and the relatively larger annual amplitude in the north decreasing southward and with a phase reversal at the South Pole. There is practically no annual cycle discernible at Samoa, which presumably is in the region where the phase changes.

South Pole CO_2 data were available from SIO only through January 1979. To extend the record through 1983, we formed a composite south pole

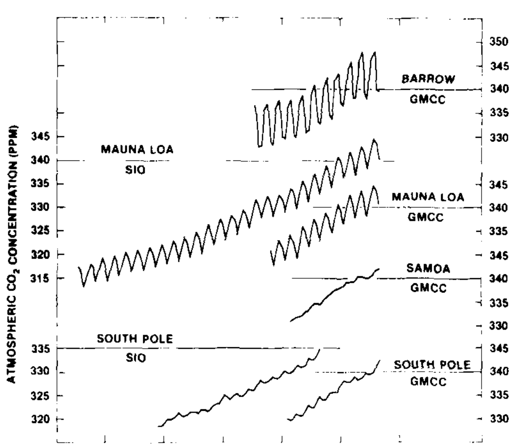

Fig. 1. Seasonal values of atmospheric CO_2 concentration (parts per million by volume) at given sites through 1983. Values obtained by the Scripps Institute of Oceanography (SIO) are indicated at left, values obtained by the Geophysical Monitoring for Climatic Change (GMCC) group of NOAA at right. Abscissa tick marks are in the northern summer (JJA).

record by adding to the SIO data the observed seasonal changes from the GMCC south pole data after 1978. This means that our south pole record is not homogeneous. As can be seen from Fig. 1, the SIO and GMCC data are quite similar when they overlap, both at Mauna Loa and the south pole, but there are small differences. We calculated statistical quantities (described below) for the south pole record from the beginning of the record to 1979 (during which the record is homogeneous) and through 1983 for the composite. The conclusions drawn were the same for the two records. We furthermore made a similar composite record using GMCC data substituted for SIO data at Mauna Loa since 1979 and compared the statistics of the homogeneous record and the composite record; they were quite similar although the composite record showed a bit more scatter and somewhat lower correlation coefficients (about 5%–10% less). This increased our confidence that augmenting SIO records with GMCC data does not produce substantially different statistical values, and qualitative deductions should be the same. We feel our results will not be altered when the south pole SIO record through 1983 is available.

We will concentrate later on adjusted season-to-season changes in CO_2. The observed changes have been plotted in Fig. 2 for the SIO record at Mauna Loa and composite record at the south pole. Because the fossil fuel combustion has almost doubled since 1958, we would expect to find a rising trend in each of the records, as indeed is the case for some of them. The SON to DJF and DJF to MAM changes at Mauna Loa do display this, as do the DJF to MAM and

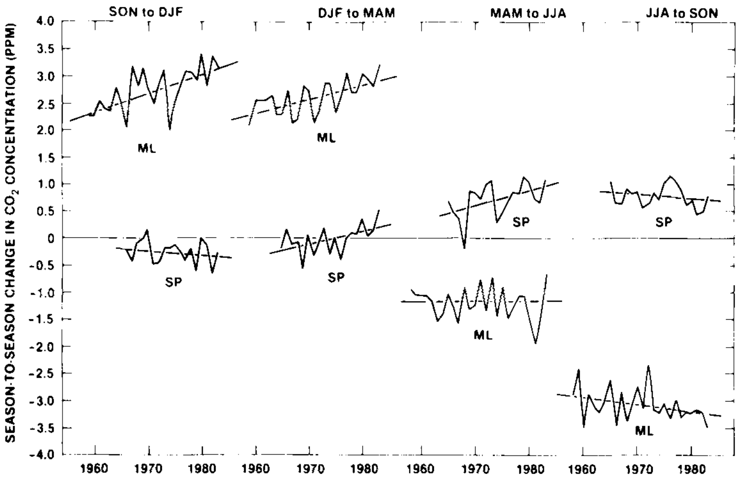

Fig. 2. Variation in season-to-season changes of CO_2 through 1983, based on SIO data at Mauna Loa (ML) and SIO and GMCC data at the South Pole (SP). The straight lines are linear regression lines.

MAM to JJA changes at the south pole. But a rise is less clear, if it exists, for other differences, and the trend in JJA to SON is clearly downward at Mauna Loa. Bacastow et al. (1985) have discerned an increase in annual amplitude at Mauna Loa, and such an increase could lead to some of the features in Fig. 2.

We have used the deviations from seasonal means of the SST data rather than the values themselves. This is also true of the CO_2 data where we formed data sets for each of the records in the following steps.

(1) We found the individual changes from one season to the next by subtracting the concentration in DJF from the concentration in MAM, etc.
(2) We than averaged each of these seasonal changes from the first full year of record through 1982.
(3) We than subtracted these mean changes from each individual change.

Part of the mean CO_2 increase from fall to spring must include a component due to fossil fuel addition, and the drop from spring to fall must have been reduced by the additions from fossil fuel. The resulting sets of values in step 3 therefore represent the season-to-season changes with both the mean annual cycle and the effect of the mean fossil-fuel emission (and any other net emissions) removed.

Because there has been a trend in fossil-fuel emissions, we made another adjustment.

(4) For each record we calculated the mean fossil fuel emission (Marland and Rotty, 1984) during the appropriate length of record.
(5) For each year, we subtracted the mean emission from the actual emission, converted the value to ppm of CO_2, multiplied the result by 0.57 (the average amount of fossil fuel CO_2 retained in the air; see, e.g., Elliott et al., 1985) and divided this annual correction by four (to estimate seasonal emission).
(6) We finally subtracted the result from the deviations of season-to-season change as calculated in step 3.

This final data set then represents the deviations from the mean season-to-season change corrected for fossil-fuel emissions. We refer to these values as dCO_2.

We constructed another set of values that consists of the cumulative sums of these corrected seasonal deviations; that is,

$$(\text{cumulative } dCO_2)_N = \sum_{n=1}^{N} (dCO_2)_n,$$

where N is the number of seasons since the beginning of the record. This set of values represents the concentration record with the fossil-fuel emissions and the annual cycle removed. We also constructed a set of values of the season-to-season change in SST deviations—effectively the derivative of the SST deviation record and designated as dSST. Thus for each of the CO_2 concentration records we have a set of season-to-season change-in-concentration deviations and the cumulative sum of these deviations, with both the mean annual cycle and the fossil-fuel emissions effects removed. We also have the deviations of the water temperature from the seasonal means and the season-to-season change of this quantity. It is the associations among these four sets of quantities that we will examine in the rest of this paper.

For ease in seeing the important features of the record, we have found it helpful to smooth the data sets using a 1–2–1 binomial smoothing applied several times. The first and last points of the smoothed records are the simple means of the first and last pairs of values, respectively. We will make use of linear correlations in discussing the records but the correlations were calculated with unsmoothed values.

3. Relations between CO_2 and SST

3.1. *Mauna Loa and the South Pole*

Fig. 3. shows the departures of the seasonal CO_2 changes from their means (dCO_2), as well as SST departures, as functions of time. (We also show the curves for Barrow and Samoa which we will discuss later.) The CO_2 records have been smoothed four times and the SST record twice to bring out the large scale features. One has the

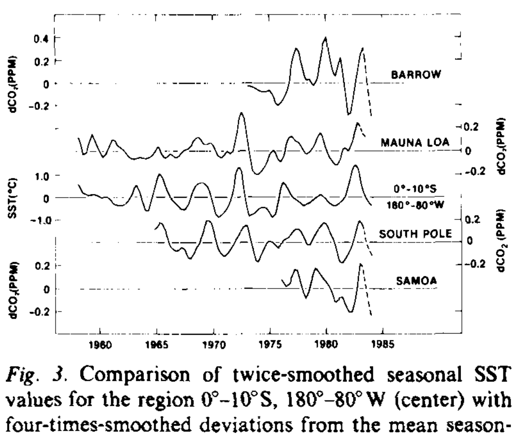

Fig. 3. Comparison of twice-smoothed seasonal SST values for the region 0°–10°S, 180°–80°W (center) with four-times-smoothed deviations from the mean season-to-season change in carbon dioxide (dCO_2) at given sites. The latter curves are dashed in 1984 because of the provisional nature of the data. Abscissa tick marks are in the northern summer (JJA).

impression that the peaks and troughs in the CO_2 records might be responses to a common "cause". Also one can surmise that SST could be part of this cause, or at least responding to the same events. There are several other features of these curves worth noting. The SST curve shows two relatively high peaks corresponding to El Niño events of 1972–73 and 1982–83; other lesser El Niño's are also apparent. While the Mauna Loa response (if indeed it is that) is greater with greater SST deviation, the south pole record seems almost indifferent to the size of the SST deviation. The Mauna Loa record does not show a particularly good correlation with SST prior to the late 1960's.

Fig. 4 is similar to Fig. 3 except that we show the cumulative dCO_2 curves (smoothed twice) for the records as well as repeating the SST curve. The cumulative dCO_2 curves are similar to the dCO_2 curves except that the peaks and troughs occur about two seasons later. There is an apparent trend in this quantity, particularly after about 1976, which we will discuss later. As was the case with dCO_2 curves, the apparent relationship with SST is better at Mauna Loa after the late 1960's than before. El Niño's of 1972–73 and 1982–83 stand out in the CO_2 record at Mauna Loa, but at the south pole are no more pronounced than other apparent responses to SST.

To explore the relationships further, and to establish the lags between SST and changes in CO_2, we cross correlated the SST records with the CO_2 records whose smoothed versions are shown in Figs. 3 and 4. The results at different lags are shown in Fig. 5, for the full record lengths (solid lines) and the 1970–83 records (dash-dot lines). The top curves show the correlation between SST and dCO_2. We adopted the convention that a change from season n to season $n+1$ would be assigned to season $n+1$ so that the top curves suggest that an above-average SST in, say, the northern hemisphere fall (SON) would be accompanied by an above average change in CO_2 from SON to DJF at Mauna Loa and an above average change from DJF to MAM at the south pole. We will refer to these as one and two season lags respectively, although the asymmetry of the curves suggests the Mauna Loa response could be a bit greater than one season, and the south pole a bit less than two seasons, after the SST.

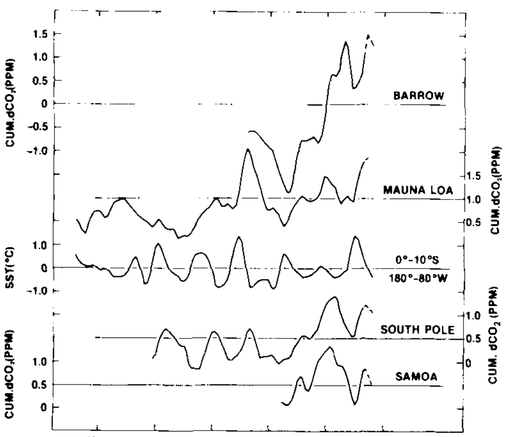

Fig. 4. Comparison of twice-smoothed seasonal SST values for the region 0°–10°S, 180°–80° W (center) with twice-smoothed values of cumulative dCO_2 at given sites. Otherwise see Fig. 3 legend.

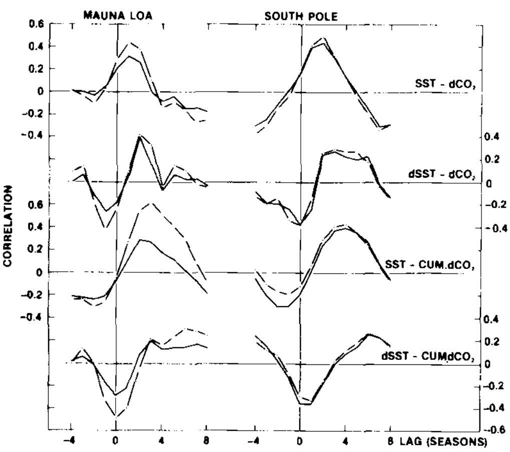

Fig. 5. Lag correlations between SST in the region 0°–10°S, 180°–80°W or its season-to-season change (dSST), and season-to-season change in carbon dioxide (dCO_2) or cumulative dCO_2. Solid lines are for the total length of the records at Mauna Loa and South Pole (through 1983), dashed lines for records from 1970 through 1983. Positive correlations at a positive lag signify that CO_2 variations have followed SST variations.

The other curves in this figure represent correlations among the other quantities as defined previously. These correlations reflect other aspects of the primary correlations between SST and CO_2. The second pair shows the relationship between dSST and dCO_2. Here the CO_2 change lags the SST change by 2 seasons at Mauna Loa and about 3 seasons at south pole. That is, if the SST change from, say, JJA to SON was above average, then the CO_2 change from DJF to MAM would be above average at Mauna Loa and above average from MAM to JJA at south pole. The third pair is the correlation between SST and the cumulative dCO_2. It suggests that a high value of SST would precede a high value of CO_2 by two to three seasons at Mauna Loa and three to four at south pole. Finally, the last pair shows the correlations between dSST and cumulative CO_2. The interesting feature here is the negative correlation close to zero lag. This suggests that, if there is a decrease of SST from, say, SON to DJF the CO_2 concentration during DJF is above average at Mauna Loa and during MAM at south pole, although the differences between the two stations may not be as great as a full season.

Except for the correlations between dSST and dCO_2, the peak values for the correlations are higher at the south pole than at Mauna Loa. A similar result was found by both Bacastow (1976) and Newell and Weare (1977). To test how sensitive these correlations are to the particular time period, we computed the same correlations beginning both records in 1970. This year was chosen to avoid the period (1964–69) where Keeling et al. (1982) point out some possible problems with the Mauna Loa data record. The dash-dot lines in Fig. 5 show that the shorter south pole record is not substantially different from the full record which is about 5 years longer. At Mauna Loa there are, however, some differences, the shorter record generally providing larger correlations, particularly between SST and cumulative dCO_2.

Table 2 summarizes some of the correlations between SST and dCO_2 at Mauna Loa and south pole. We also give the correlations for the full records of Barrow and Samoa which will be discussed in the next subsection. Table 2 shows that the correlations at the south pole using the homogeneous record from SIO (1965–78) are not notably different from those of the composite record (1965–83), which lends credence to our combination. The Table also shows that from 1958 through 1969 there was almost no correlation between SST and dCO_2 at Mauna Loa. When comparing south pole and Mauna Loa correlations after 1970, there is only a small difference.

Table. 2. *Maximum correlations (r) between the deviations from the mean season-to-season changes in CO_2 concentration (dCO_2) and SST in the region 0°–10° S, 180°–80° W*

Site	Period	r (lag)	5% level
Mauna Loa	1958–83	0.32 (1)	0.19
	1958–69	0.08 (1)	0.30
	1970–83	0.44 (1)	0.27
south pole	1965–83	0.43 (2)	0.24
	1965–78	0.43 (2)	0.27
	1970–83	0.49 (2)	0.27
Barrow	1973–83	0.27 (5)	0.31
Samoa	1976–83	0.38 (3)	0.37

The lag of maximum correlation in seasons is given in parentheses, dCO_2 following SST. The 5% significance level is also given.

The lags are consistent, also, except for the 1958–69 period at Mauna Loa where there was little correlation at all. We cross-correlated the dCO_2 records at Mauna Loa and south pole to confirm the lag. Indeed, the best correlations were found with south pole following Mauna Loa by one season as would be anticipated from Table 2.

We investigated further the relationships between some of these quantities by asking whether the relationship deduced from Fig 5 are stable over the lengths of record at the stations, or whether the overall correlations are brought about by different patterns during different time periods. To do this we calculated cross correlation coefficients for 21-season intervals, starting from the beginning of the records and then continually dropping the first season while adding a new season until the end of the record. We plotted these 5-year correlation coefficients at the mid points of the interval and drew isopleths of the correlations coefficients. Fig. 6 shows the patterns for the correlations between SST and dCO_2 for both Mauna Loa and south pole.

Several features are clear. At both locations the maximum correlation does change with time. There is very little correlation between SST and dCO_2 at Mauna Loa before the late 1960's. The highest correlations at both locations begin near the time of the 1972–73 El Niño and continue until the late 1970's when they drop markedly. The correlations increase again in association with the 1982–83 El Niño. If the 1972–73 event proves to be a model we would expect the correlation to be relatively high for several more years.

The lag of maximum correlation seems to be relatively stable at the south pole, being about 2 seasons behind the SST but possibly a bit longer in the early 1970's. At Mauna Loa the lag is somewhat more variable, ranging between 1 and 2 seasons. One also has the impression that the maximum correlation at the south pole remains higher for a longer period of time than at Mauna Loa; an exception being the period centered about 1976–77. Mauna Loa concentrations seem to have responded more to the warm SST of 1976–77 than the south pole concentrations.

We also asked whether there were preferred seasons for high correlations. We correlated the value of dCO_2 for a particular season with the values of SST at that season, one season earlier, etc. Doing this for each season might reveal particular seasons when the SST is more effective in producing later CO_2 changes. Conversely, it could reveal seasons whose dCO_2 is particularly sensitive to antecedent conditions. Table 3 shows the results of such calculations for both Mauna Loa and the south pole for the period 1970–83, when the overall correlations were the highest.

There do seem to be preferred seasons for dCO_2 to be correlated with SST. At Mauna Loa, for instance, the Table shows that the DJF to MAM change in CO_2 is well correlated with the SST both one season earlier (DJF) and two seasons earlier (SON). The changes from SON to DJF also appear sensitive to the SST one-or-two seasons earlier. At the south pole we also see two sensitive seasonal changes, DJF to MAM and MAM to JJA. While the sensitive seasons at Mauna Loa are those seasons where the CO_2 concentration is normally increasing, this is not the case at the south pole. The south pole seems to follow Mauna Loa by about one season, as we inferred from the overall correlations.

Because of the small number of pairs available for these seasonal correlations, some of the differences shown in Table 3 may not be significant. The differences between the minimum correlations at Mauna Loa in the SON–DJF and DJF–MAM changes are significantly different (5% levels using the Z-statistic, Panofsky and Brier,

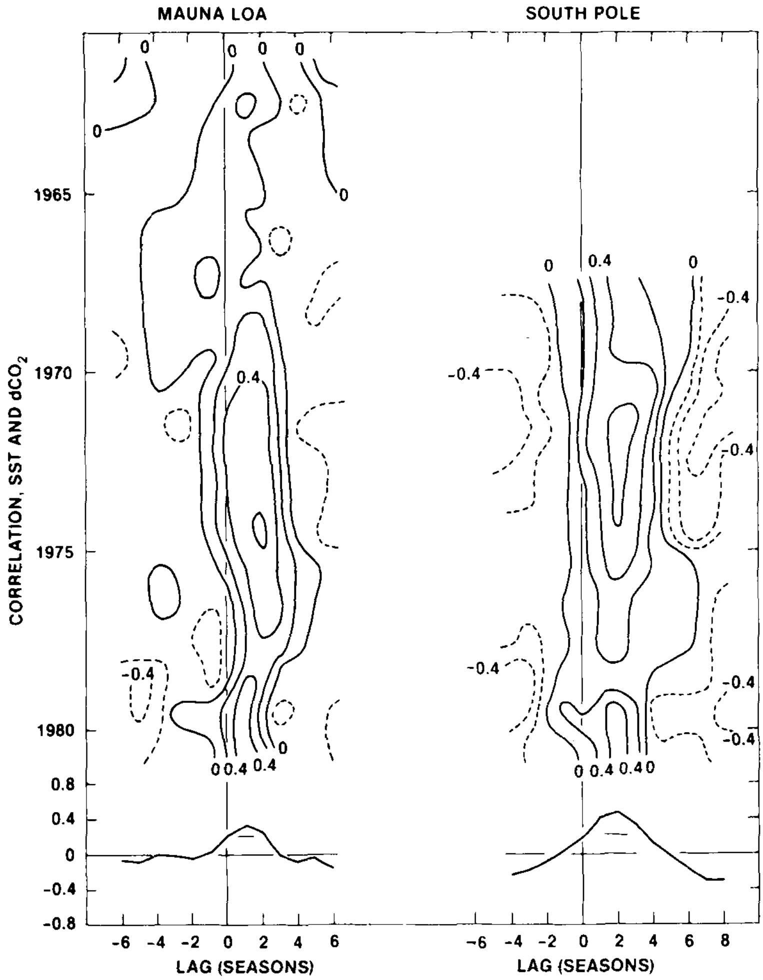

Fig. 6. Variation in lag correlation between SST and dCO_2 at Mauna Loa and South Pole. The lag correlation for the total record is shown at bottom, the horizontal bar denoting a zero-lag correlation significant at the 5% level taking into account the serial correlation. Positive correlations at a positive lag signify that CO_2 variations have followed SST variations.

1958, page 93), from the maximum correlations JJA–SON, but we cannot say whether the MAM–JJA maximum correlations are different from the others – either higher or lower. For the south pole the maximum DJF–MAM and MAM–JJA are different from the SON–DJF and JJA–SON maxima. More data will be needed to see if the seasonal differences implied by Table 3 stand up in the future.

3.2. Samoa and Barrow

At Samoa and Barrow we see some unexpected results. From Table 2, dCO_2 at Samoa lags SST by three seasons even though Samoa is almost in the part of the ocean where we are measuring SST. The Samoa record is the shortest of the group and the early part of the record was troubled by various malfunctions. Attempts have been made to identify poor data and replace them with interpolated values but it is possible that this has distorted the relationships. If subsequent data confirm that this surprising lag is indeed correct, however, an explanation needs to be sought. Such an explantation could be in the geographical position of Samoa. There is evidence that northern hemisphere air alternates with southern

Table. 3. *Correlations between the deviations from the mean season-to-season changes in carbon dioxide (dCO_2) at Mauna Loa and the south pole, and SST in the region 0°–10° S, 180°–80° W the given number of seasons earlier, based on data for the interval 1970–83*

	SST *N* seasons earlier				
dCO_2	0	1	2	3	4
Mauna Loa					
SON to DJF	0.61	0.62	0.50	−0.20	−0.51
DJF to MAM	0.48	0.63	0.66	0.50	0.22
MAM to JJA	−0.14	0.32	0.43	0.38	0.34
JJA to SON	0.20	0.19	0.01	−0.13	−0.24
south pole					
SON to DJF	0.22	0.18	0.19	0.32	0.04
DJF to MAM	0.69	0.81	0.75	0.50	−0.02
MAM to JJA	0.27	0.51	0.64	0.58	0.53
JJA to SON	−0.23	−0.02	0.06	0.08	0.10

hemisphere air during the year at Samoa (Halter, personal communication). The CO_2 characteristics and the interannual changes in growth rate could be influenced by the timing of these events more than by the SST characteristics in the immediate vicinity.

The Barrow record also exhibits some surprises. First, of course, is the long lag, about five seasons, between the dCO_2 and SST. The low values of the correlation coefficients may suggest that there really is little relationship between SST (in the eastern tropical Pacific) and the dCO_2 at Barrow. One possible reason for the low values could be in this long lag. As seen in Fig. 3, the post-El Niño drop in dCO_2 had not begun at Barrow at the end of 1983. When we added 1984 data, whose tentative nature cautions us not to over interpret them, the lag of maximum correlation shifted from five seasons to four seasons but the correlation remained about the same. These changes make it difficult to specify the lag at Barrow with any confidence. It is certainly possible that the characteristics of Barrow's CO_2 record reflect its proximity to an extensive biome with a large seasonal photosynthesis cycle.

When 1984 data are added to the Samoa record, the lag is shortened to two seasons but the correlation coefficients decrease. These two examples show the importance of record length. If large El Niños are the major source of the correlations, then the shorter GMCC records have only felt the effects of one such event. Furthermore, the period from 1976 to 1981 was a time of relatively low correlations between SST and dCO_2 at both Mauna Loa and south pole, and this is the period of most of the observations at Barrow, and especially Samoa.

4. CO_2 variations, 1976–81

A notable feature of the curves of Fig. 4 is the apparent increase in the cumulative CO_2 concentration that occurred from about 1976 to 1981. The rate of increase during this six-year period was between 0.2 and 0.3 ppm/yr at Mauna Loa and Samoa, between 0.4 and 0.5 ppm/year at the south pole and a bit greater than 0.5 ppm/yr at Barrow. The rate of increase at Mauna Loa during the comparable period from 1967 to 1973 was about the same (0.25 ppm/yr) but there was no contemporary rise at south pole. The 1967–73 rise is clearly associated with SST events whereas that is not so obviously the case during 1976–81.

What caused this apparent 6-year increase in CO_2? Our method of treating the data eliminates fossil-fuel use as the cause unless there is a substantial error in the Marland and Rotty (1984) estimates during this period. This error would have to be much larger than their estimate of 10% error in the data and it would have to be systematic. We doubt this is the cause of the rise.

The data from the two separate laboratories share the same features at each of their stations so any instrumental cause of the increase could only lie in an undetected drift in the underlying SIO calibration system. We cannot eliminate this possibility but the change seems so large that it is unlikely such a drift would have escaped notice.

It is possible that some additional sources of atmospheric carbon operated during these few years. Perhaps the interplay of photosynthesis and respiration resulted in a substantial net emission from the biosphere then. An additional source on the order of one GT of carbon per year for the period would be sufficient to account for the rise, assuming roughly half that emission was transferred to the ocean. It is also possible that some normally operating sink either in the oceans or the biosphere failed to operate at its usual strength during those years.

Although the SST did not increase during this period (if anything the trend is downward), some of the CO_2 increase is very likely associated with the 1976–77 El Niño. Although the timing seems a bit anomalous, the initial increase in CO_2 may be nothing more than one would expect. What could be anomalous is the failure to return to lower values after the event was over. There is a tendency for CO_2 to rise more quickly than it falls during El Niño cycles. The behavior of the CO_2 records from 1976 to 1981 could be the result of two successive El Niño-like events with too little time between them to recover.

The 1979–80 warming of the ocean was very small and is not considered by most experts to have shown El Niño properties in the Eastern Pacific. The apparent reaction to this slight warming (if indeed the growth was a reaction to it) seems much larger than the rest of the record would lead one to anticipate. In this connection, however, Donguy et al. (1982) have pointed out that some meteorological and oceanographic quantities exhibited El Niño-like conditions in the Western Pacific despite the near absence of such indicators in the Eastern Pacific. To this list of El Niño-like phenomena in 1979–80 can be added the behavior of atmospheric CO_2.

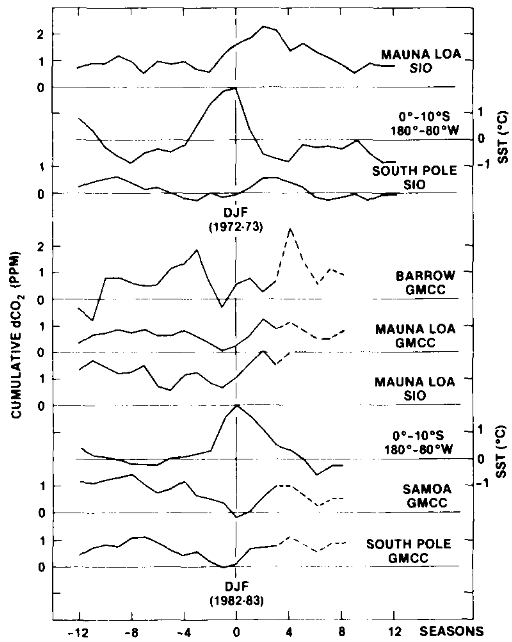

Fig. 7. Comparison of SST in the given equatorial region and cumulative dCO_2 at given sites during the pronounced El Niño of 1972–73 (top three curves) and 1982–83 (bottom six curves). The unsmoothed seasonal values are centered on the northern winter (DJF) of these years.

5. El Niños of 1972–73 and 1982–83

Fig. 7 shows unsmoothed traces of records to isolate the two most prominent El Nino events in the record, those of 1972–73 and 1982–83. Here we use for the 1982–83 event the GMCC south pole record and we also show the GMCC Mauna Loa record as a separate curve. The purpose is to see if these events do have more in common other than the obvious post-warming increase in CO_2. One sees first that the SST cycles were somewhat different. In the 1972–73 event the SST increased relatively slowly to its maximum and then fell quickly. In the 1982–83 event the opposite is true —a rather rapid rise to the maximum and then a slow fall. It is well known that the 1982–83 event was different from the 1972–73 event in a number of ways (Cane, 1983), and these differences may well be the reason it is difficult to arrive at a composite for the behavior of the CO_2 concentration during El Niño. Caution should be exercised in extending any interpretation of the 82–83 event to other El Niños.

Fig. 7 shows that in 1982–83 at the southern hemisphere stations there was a minimum in the CO_2 concentration almost coinciding with the SST maximum. In the northern hemisphere, however, the minimum occurred about 1 season prior to the maximum SST. The two records available during the 1972–73 event provide little evidence for a minimum prior to the maximum SST. If the picture gained from these stations is representative of the globe, however, we can say that there was more CO_2 in the air a few seasons after the maximum SST than a few seasons before. It further appears that this relative build up of CO_2 lasts for at least several seasons after the SST has returned to normal.

6. Discussion

We tested whether our method of analyzing the data would reveal a sensitive feature found by others with more sophisticated statistical treatment. Trends in the amplitude of the annual cycle of CO_2 concentrations at Mauna Loa, south pole and Barrow have been detected by others (e.g., Cleveland et al., 1983; Bacastow et al., 1985; and Peterson et al., 1986) and are suggested by Fig. 2. At Mauna Loa the corrected change from SON to MAM (the period when the concentration is normally increasing) does appear to be increasing, while the change from MAM to SON is becoming more negative. Over the full Mauna Loa record, these changes implied an increase in the peak-to-trough annual values of 0.039 ppm/yr, a figure quite close to the 0.036 ppm/yr found by Bacastow et al. (1985). For the Barrow record we found an increase of 0.11 ppm/yr between 1973 and 1983 but this was not statistically significant.

There is a tendency for the fall-to-spring change at Mauna Loa to be increasing more rapidly than the spring-to-fall change has been declining since the middle 1970's but this is a short time period and we are not convinced this is an established feature.

At the south pole we also found evidence of an increasing amplitude but only until the late 1970's. The south pole record from GMCC indicates a slight, and certainly not statistically significant, decrease in amplitude since about 1976, a result reported by Komhyr et al. (1985). Furthermore, as shown in Fig. 2, the SON to DJF change decreases and the MAM to JJA change increases as would be expected in the southern hemisphere. But the DJF and MAM change increases and JJA to SON change decreases, as found at Mauna Loa. It is as if the northern hemisphere pattern had been shifted one season. A northern hemisphere signal arriving with a one-season delay would not be in phase with the southern hemisphere signal and could act to decrease the amplitude at the south pole. The question is certainly open.

The changes in SST precede the changes in CO_2 and one is tempted to infer that these SST changes are to some extent a cause of changes in CO_2. We calculated linear regression coefficients for the relationships between both dCO_2 and cumulative dCO_2 and SST. At Mauna Loa the results implied that, for the period 1970–1983, the season-to-season change would be about 0.2 ppm higher for a $+1\,^{\circ}C$ deviation in the temperature of the eastern equatorial Pacific. A slightly lower figure, 0.15 ppm/°C, was found at the south pole (for the full record length) and about 0.35 ppm/°C at Barrow for its full record. These numbers were all calculated at the lag of maximum correlation. For the cumulative dCO_2 we found a $1\,^{\circ}C$ deviation would produce about 0.4 ppm change at Mauna Loa, 0.3 ppm at the south pole and 0.8 ppm at Barrow at the appropriate lags of maximum correlation. (The Samoa record was considered too short to produce a meaningful relation.) Those latter values for Barrow and Mauna Loa are comparable to those presented by Schnell et al. (1981) using sea-surface temperatures from different regions of the Pacific. Nevertheless, we cannot say for certain whether these SST changes bring about changes in air-sea gas exchange, whether they reflect other changes in the water that could affect CO_2 transfer, or whether the SST and CO_2 changes are both caused by some other mechanism.

Some of the results of this analysis raise other questions. The long lag between SST changes and CO_2 changes at Barrow and the low correlation between them requires some explanation. It is possible that the more remote a station is from the northern hemisphere land masses the more its annual cycle variation would be influenced by SST deviations. This could explain the generally higher correlations with SST found at the south pole despite its greater distance from the SST region.

The increase in cumulative CO_2 concentration between 1976 and 1981 was mentioned above. Why it occurred, not apparently correlated with SST in the eastern Pacific, is a puzzle. Another side of this question is the apparent large CO_2 response to the relatively trivial warming in 1979. This period 1976–81 was also a period of poor correlation between SST and dCO_2 (as well as between SST and SOI). The pattern suggests that El Niños, particularly 1972–73 and 1982–83 but also including the 1976–77 event, are responsible for the bulk of the correlation between SST and CO_2.

The reasons behind the apparent preference for high correlations between SST and dCO_2 at specific seasons are obscure. The (northern hemisphere) fall-to-spring change in CO_2 at Mauna Loa seems more sensitive to SST than the spring-to-fall change. Is this tied in some way either to the terrestrial or marine biosphere? The south pole shows a similar two-season preference displaced from Mauna Loa by only one season. If the preference were tied to the southern hemisphere biosphere, we might expect a two-season lag between the south pole and Mauna Loa, unless the hypothetical biosphere influence is in the northern hemisphere or tropics and propagated southward.

7. Summary

The CO_2 concentration records of Mauna Loa, south pole, Barrow and Samoa were adjusted to remove the annual cycle and eliminate the effects of fossil fuel combustion and any other mean source of CO_2. The seasonal data so adjusted were then compared with a record of the deviations of seasonal sea surface temperatures from their seasonal mean in the region bounded by the equator and 10°S latitude and 80° and 180°W longitude.

We found, as have others, that warming of this region is usually followed by an above-average increase in CO_2 concentration. At Mauna Loa this increase follows the SST by about one season and at the south pole by about two seasons. At Samoa there is a tendency for a two or three season lag and a three to five season lag at Barrow. Because of the relative shortness of these latter records these statements have less certainty. The adjusted CO_2 concentration, as opposed to the season-to-season change in concentration, lags the SST by an additional two seasons.

The correlations between these variables are not constant with time nor is the lag of maximum correlation. Highest correlations between the season-to-season change in CO_2 and SST were found from about 1970 to 1976 at both Mauna Loa and the south pole, and again apparently beginning in about 1981. These periods of high correlation include the periods of exceptionally strong El Niño conditions in 1972–73 and 1982–83. Relatively low correlations were found between about 1976 and 1981—which was also a period of relatively poor correlation between the SST and the southern oscillation. A similar period of poor correlation was found prior to 1970 at Mauna Loa.

There are certain seasonal changes that are better correlated with SST than others. At Mauna Loa the CO_2 changes from SON to DJF and DJF to MAM were considerably better correlated with the SST one and two seasons earlier than were the CO_2 changes from MAM to JJA and JJA to SON. That is, deviations during normally rising CO_2 concentrations were better correlated with SST than deviations during normally falling concentrations. At the south pole the best correlations were with the CO_2 changes from DJF to MAM and MAM to JJA.

There was an apparent rise in CO_2 concentration between about 1976 and 1981 that was in addition to the fossil-fuel source and is not clearly related to the SST.

Some of the results and speculations above are based on short data records and may prove transitory and not withstand the addition of more data. The recent expansion of the flask-sampling programs (Komhyr et al., 1985) and the accumulation of high quality data from the southern hemisphere by the Australian group (Fraser et al, 1983) will contribute substantially to illuminate this.

Finally, that we are able to find consistent features in these CO_2 data after removing the annual cycle and fossil fuel effects, is a tribute to the skill of the scientists at SIO and GMCC who produced them.

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