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Relation of atmospheric CO_2 to tropical sea and air temperatures and precipitation

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ABSTRACT

Associations between the season-to-season changes in CO_2 concentration and the sea-surface temperature in the eastern equatorial Pacific, the tropospheric air temperature, and the precipitation in the tropics are explored. The CO_2 records at Mauna Loa and the South Pole from the Scripps Institution of Oceanography and the GMCC/NOAA program, as well as the GMCC records at Barrow, Alaska and American Samoa were used after the annual cycle and the growth due to fossil fuel emission has been removed. We find that the correlation between CO_2 changes and each of the other variables changes with time. In particular, the period from about 1968 to about 1978 was the period of highest correlation, which was also the period when the climate variables were best correlated with each other. The air temperature and the precipitation were as well correlated with CO_2 changes as was SST. Also, there are individual seasons when the CO_2 changes are much better correlated with the climate variables than at other seasons. Furthermore, El Niño events, while the source of the largest signal in the CO_2 record, are by no means the same from one event to the next. We take these results as further confirmation that the apparent effect of SST on the CO_2 record comes less from changes in the equatorial eastern Pacific Ocean than from climate changes throughout the globe. Climate effects on the terrestrial biosphere seem a likely source of much of the interannual variation in atmospheric CO_2.

1. Introduction

That the carbon dioxide concentration in the atmosphere responds to events in the equatorial Pacific Ocean has been well-known since Bacastow (1976) pointed out a relation between the CO_2 records and the Southern Oscillation. Newell and Weare (1977) and Machta et al. (1977) pointed out that changes in CO_2 concentration were equally well related to changes in Pacific sea-surface temperatures. Angell (1981) also found a strong correlation between the sea-surface temperatures in the eastern equatorial Pacific and the seasonal changes in CO_2 concentration at Mauna Loa and the South Pole. Elliott and Angell (1987, hereafter EA) pursued the topic further, pointing out that the relations were not constant over time and that there were preferred seasons during which the correlations were larger than during other seasons. The present paper is a continuation of that work.

The reasons for the correlation between sea-surface temperatures in the eastern Pacific and changes in CO_2 are not well understood. The association is most easily seen during El Niño events when the surface waters of the eastern equatorial Pacific are unusually warm and the CO_2 concentration rises shortly thereafter. This led to the natural presumption that increased surface temperatures lead to above average release of CO_2 from this region of the ocean, but this explanation was questioned by Hyson and Pearman (1980) who argued that the effect of temperature on the partial pressure of CO_2 in the water was not sufficient to account for the observed signal. Other explanations have been invoked. It is known that upwelling along the equator is reduced during El Niño and this should reduce the uptake of CO_2 by the phytoplankton. At the same time, however, reduced upwelling should reduce the supply of CO_2-enriched water at the surface and thus lead to a diminished concentration.

Siegenthaler and Wenk (personal communication, hereafter SW) addressed this point (at the Hinterzarten meeting) with a model of the response of CO_2 to El Niño events. They argue that the direct effect of warming and the diminished photosynthesis are overwhelmed by the reduced supply of upwelled water and that this would lead to a reduction in atmospheric CO_2. Since this is the opposite of what is observed, it suggests the explanation must lie outside the immediate area of the El Niño.

El Niños are among the largest interannual climate signals, and understanding the effect of these phenomena on the CO_2 signal should help delineate the effects of climate changes on the carbon cycle. We will use the terms warm or cold ENSO event in the subsequent discussions as abnormally cold waters, sometimes called an anti-El Niño, are also important to the CO_2 response, as we shall argue later. These ENSO events have climatic consequences far outside the eastern Pacific. Ropelewski and Halpert (1987) have shown that the ENSO signal can be found in the precipitation patterns in a number of places around the globe, in addition to the well-known association with the Indian monsoon (Rasmusson and Carpenter, 1983). For this reason, we will look at two other measures of climate in the tropics; the temperature of the tropical troposphere and an estimate of precipitation over the land regions of the tropics. The tropical air temperature (TAT) and the tropical precipitation (TRP) can be considered indicators of terrestrial ecosystem respiration and decay, and photosynthesis, respectively, albeit quite crude ones.

In Section 2, we will describe the data sets and their treatment more fully. Following that, the correlations among these quantities will be presented and discussed after which we will look at relations among the variables during specific ENSO events. Finally, we will examine some of the specific seasonal associations among the quantities.

2. The data

2.1. CO_2 data

The CO_2 concentration data were compiled by Scripps Institution of Oceanography (SIO) (Keeling et al., 1989) at Mauna Loa Observatory and the South Pole Observatory and by the Geophysical Monitoring for Climate Change (GMCC) program of NOAA at Mauna Loa (Komhyr et al., 1989), South Pole (Gillette et al., 1987), Barrow, Alaska (Peterson et al., 1986), and Samoa (Waterman et al., 1989). Table 1 gives the location of these sites and the lengths of the records we used. With the exception of the SIO South Pole record all concentrations were measured with non-dispersive infra-red analyzers at the observatories. The South Pole SIO measurements were made on air collected in flasks and sent to SIO. The standard gases used in both programs were traceable to the standards maintained at SIO.

Each program examines their data to eliminate obvious instrument malfunctions and to select

Table 1. *Carbon dioxide observation sites used in this study, and length of the CO_2 records used, where SIO is the Scripps Institution 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–Nov. 1988
Mauna Loa	GMCC	19.5°N	155.6°W	3397	May 1974–Aug. 1989
South Pole	SIO	90°S		2810	Jan. 1965–Nov. 1988
South Pole	GMCC	90°S		2810	Jan. 1976–Nov. 1988
Barrow	GMCC	71.3°N	156.6°W	11	Jan. 1973–Nov. 1988
Samoa	GMCC	14.3°S	170.6°W	30	Jan. 1976–May 1989

data representative of "background" air, i.e., air unaffected by local conditions. The selection criteria of the two groups are similar but not identical. The groups formed monthly mean background values from their data and we formed seasonal mean values by grouping the December, January, February (DJF), etc., values. Data were occasionally missing and we substituted flask sample data when available, otherwise we interpolated for the few remaining missing values. Except for these cases, all the data are those reported by SIO and GMCC.

We used the same data treatment in this paper as in EA. The records here are about 5 years longer; furthermore, the two groups have revised their old data records in light of further refinements of the calibration processes. Thus the data are slightly different from those used in EA even before 1984. It is quite possible that the most recent data, from 1986 onward, will undergo subsequent revisions but our experience with the revised data leads us to be reasonably confident that there will be no qualitative effect on the conclusions, save what could result from an increased record length.

Fig. 1 shows the seasonal CO_2 concentrations for each of the six records. The curves display the familiar features of CO_2 records: the upward trend in the concentrations and the large annual amplitude in the north decreasing southward and reversing phase at the South Pole. The lack of a discernable annual cycle at Samoa reflects the fact that Samoa is influenced by air from both hemispheres at different times of the year (Halter et al., 1988).

The record used in this study, as in EA, is not of the seasonal CO_2 concentrations but rather their change from one season to the next. The data set is formed in the following way.

(1) The individual changes in concentration from one season to the next are found by subtracting the concentration in DJF from that in MAM, etc.

(2) Each of these seasonal changes is averaged from the first full year of the record through 1988.

(3) The average of each season-to-season change is subtracted from each of the individual changes.

The resulting values are the deviations from the mean season-to-season changes with the annual cycle and any mean emissions, including fossil-fuel emissions, removed.

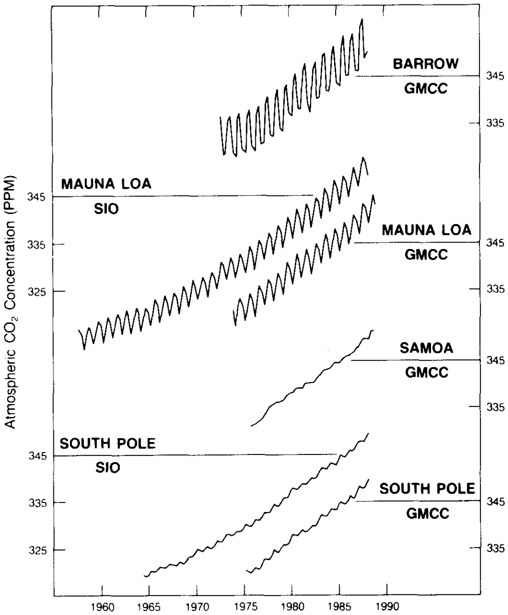

Fig. 1. Time variation in seasonal values of atmospheric CO_2 concentration obtained by Scripps Institution of Oceanography (SIO) and the Geophysical Monitoring for Climate change (GMCC) group of NOAA. Abscissa tick marks are in the northern summer (JJA).

Because the fossil-fuel emission has about doubled since 1958, a further adjustment is made.

(4) The mean fossil-fuel emissions (Marland and Rotty, 1984, updated) were calculated for the appropriate length of record.

(5) For each year the actual emission was subtracted from the mean emission, converted to CO_2 concentration, multiplied by 0.57 (the average fraction of CO_2 retained in the air), and divided by 4 (to estimate the seasonal emission).

(6) The values from step 5 were added to the results of step 3 to form the final data.

This gives a set of deviations from their mean values of season-to-season changes from which the effects of the fossil-fuel emissions have been removed, as well as other mean sources and sinks operating during the time period. We refer to this data set as dCO_2. It is dCO_2 whose relations to the other variables will be examined here.

2.2. Sea-surface temperature (SST) deviations

Our SST values are based on the sea-surface temperatures in the region 2°N to 12°S from 90°W to 180°W, which is the main El Niño region. The values were compiled by H. Diaz of NOAA. They are expressed as seasonal deviations from the mean seasonal values in the period 1950 to 1980. The data set extended from 1950 to 1988; we estimated additional values for the first three seasons of 1989. This is a slightly different set of SST values than that used in EA, where the data were from the Equator to 10°S and from the South American coast to 180°W, but the differences are quite small; the overall correlation between the two data sets is greater than 0.95.

2.3. Tropical air temperature (TAT)

These data are from Angell (1988) and updated by him through the first three seasons of 1989. They represent the mean tropospheric temperature between 850 mb and 300 mb between 30°N and 30°S and are expressed as deviations from the mean seasonal temperatures from 1958 to 1978. They were determined from those stations in the 63-station network described in Angell and Korshover (1983) that are in the tropics. Although the network is sparse, the annual means of the global troposphere temperature are closely correlated with estimates of surface temperature, e.g., the correlation with the surface temperatures of Hansen and Lebedeff (1988) is 0.94 between 1958 and 1987.

2.4. Tropical precipitation (TPR)

These data are from those used by Diaz et al. (1989) and are for the land areas between 25°N and 25°S. They are expressed in percentiles of gamma distributions determined from the 1921–1960 period. For example, a value of 0.40 for a particular season means that the precipitation that season fell in the lowest 40% of the gamma distribution derived from the reference period. Details of the technique can be found in Diaz et al. (1989).

3. Relations among the variables

Fig. 2 shows the departures of the seasonal CO_2 changes from their means (dCO_2) for the six

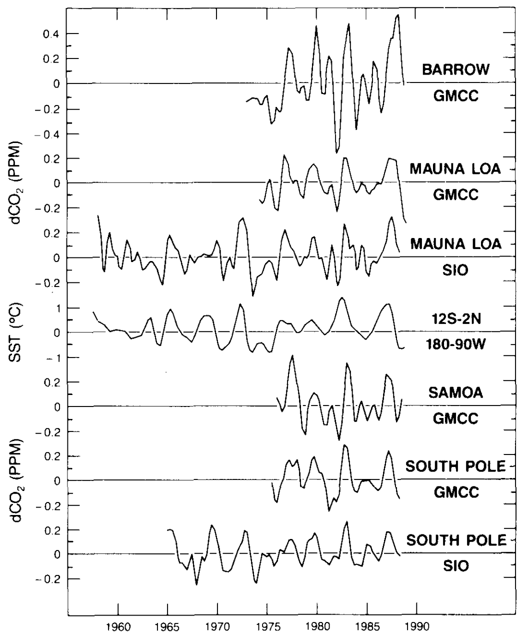

Fig. 2. Comparison of seasonal SST values for the region 12°S–2°N, 180°–90°W (center) with season-to-season changes in CO_2 (dCO_2) at SIO and GMCC sites. All traces have been smoothed by applying a 1-2-1 weighting twice to successive seasonal deviations, and the abscissa tick marks are for JJA.

CO_2 records, and the SST record. The records have been smoothed twice with a 1-2-1 filter to bring out the longer period fluctuations. Forming a series of differences, as has been done here, tends to emphasize any noise in the record. Nevertheless, the major peaks and troughs are seen in each of the records. The peaks in the dCO_2 records generally lag the SST by several seasons. The SIO and GMCC records at both Mauna Loa and the South Pole are in good agreement, as would be hoped, but careful scrutiny does reveal that they are not identical.

There are no significant trends in the dCO_2 records but the Mauna Loa SIO record hints at a decrease from the beginning to about 1975 and a subsequent increase, a pattern that parallels the SST. The SST does show a significant decrease from 1958 to 1975 and a subsequent significant increase to 1988. (Significance of trend, or lack of it, was decided by whether the slope of the linear regression of the variable with time was significantly different from zero at the 5% level.) It is possible to interpret the apparent early decrease and later increase in dCO_2 as indicative of similar changes in non-fossil fuel emissions. On the other hand, there have been changes in atmospheric circulation patterns, particularly over the North Pacific in the last 10 years or so (Trenberth, 1990), and these could be affecting the CO_2 concentrations.

The events in the early 1970s stand out in the SIO Mauna Loa record; they are the most prominent feature. They are also apparent at the South Pole but do not overshadow other events. The El Niño of 1972–73 was preceded and followed by cool periods or cold phases of ENSO. The post-1973 cooling is especially noticeable. These relatively cool periods were accompanied by lower-than-average CO_2 growth, particularly from the end of 1973 to the end of 1976.

A more quantitative estimate of the associations between SST and the long SIO dCO_2 records is given in Table 2 where the maximum linear correlation coefficients and their lag, in seasons, are displayed. In general, Mauna Loa seems to lead the South Pole by a slight bit, but the difference is small and not always consistent. (Table 2 also gives the correlations between dCO_2 and the air temperature and precipitation which will be discussed later.) The values of the correlation coefficients are not large but they are quite significant, mainly at better than the 0.1% level, if one puts aside the fact that maximum values were selected a posteriori.

In this, and in subsequent discussions of correlations, significance was tested using the usual analysis-of-variance techniques. Although the climate variables used here do have serial correlations, dCO_2 has virtually none. Thus, when determining the significance of cross correlation between dCO_2 and the other quantities, no adjustment of the effective number of pairs need be made. As noted above, however, we give significance without reference to the a posteriori selection of the lags, which does reduce the confidence in the correlations.

In EA we noted that there were periods during which the correlations were better than during others. To show this we calculated cross-correlation coefficients between dCO_2 of the Mauna Loa and South Pole records and SST for overlapping 10-year periods starting at the beginning of the records and then continually dropping the first season and adding a new one. These 10-year correlations are shown in Fig. 3 where isopleths of the calculated values have been drawn.

It is clear that the period centered about 1975 produced the largest correlations at both locations. This period includes the warm ENSO event of 1972–73 and the cold events surrounding it. The 1982–83 warm event did not produce the

Table 2. *Correlations between SIO dCO_2 and sea-surface temperature (SST), tropical air temperature (TAT) and tropical precipitation (TPR) for the indicated time periods (TPR correlations to 1986)*

Station	Time	SST	TAT	TPR
Mauna Loa	1958–88	0.35 (2)	0.35 (0)	−0.33 (2)
	1965–88	0.38 (1)	0.39 (0)	−0.34 (1, 2)
South Pole	1965–88	0.47 (2)	0.35 (1)	−0.35 (1)

Numbers in parentheses are lag, in seasons, of maximum correlation, dCO_2 always lagging climate variable.

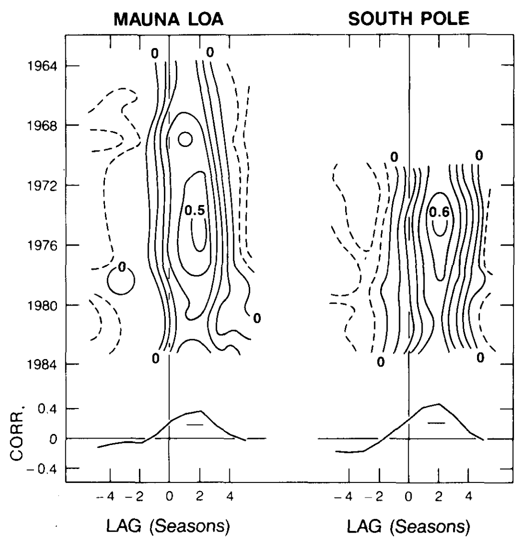

Fig. 3. Variation in lag correlation between SST and dCO_2 at Mauna Loa and South Pole. The lag correlation for the total record is shown at the bottom, the horizontal bar denoting a zero-lag significance at the 5% level. Correlations at a positive lag signify that dCO_2 followed SST variations. The correlations are plotted at the midpoints of moving 10-year intervals.

same degree of correlation, despite its reputation as the greatest such event of the century. There are also two periods of quite low correlations in the Mauna Loa record: the period centered about 1964 and one centered about 1982. The latter period also shows as a minimum at the South Pole.

In EA we had noted this same pattern of correlations. Our data then extended only into the beginning of the 1982–83 warm event but we thought that after it had run its course we might expect the correlations to show an increase much like the 1972–73 event. Such is not the case, however. It is evidently not sufficient to have a large El Niño to produce high correlations. The cold events of the early seventies also appear to be an important factor in producing these correlations.

To investigate further possible effects, we looked at the correlations between dCO_2 and two other climate variables: the tropical air temperature (TAT) and precipitation (TPR), as described in the previous section. These correlations are also given in Table 2. Their values are about the same as those with SST, with positive correlations between dCO_2 and TAT and negative correlations between DCO_2 and TPR. It seems that any of these three variables "explains" about the same amount of variance of dCO_2, with dCO_2 lagging TPR by about 1 to 2 seasons and being in-phase with TAT. Of course, TAT and TPR are themselves correlated with SST and with each other. TAT and SST have a correlation coefficient of about 0.7 with TAT lagging 1–2 seasons and TPR and SST have a coefficient of about -0.6 with no lag. Nevertheless, TAT and TPR do add additional information about dCO_2, particularly since we do not know exactly how the apparent effect is produced.

Fig. 4 shows TAT and TPR plotted against time as well as repeating the curves of SST and dCO_2 from Fig. 2. The ENSO events are reflected in the TAT and TPR, as would be expected. We see that the cold ENSO period in the middle seventies was also a particularly wet and cool period in the tropics. A curious feature is the very dry period associated with the 1982–83 warm event. This event is associated with a subsequent increase in dCO_2 but not so large as one might expect from the dryness and the very warm SST. The TAT also did not respond as strongly as would have been expected given the magnitude of the SST warming. Angell (1988) pointed this out, suggesting it could have been due to the eruption of El Chichón reducing the warming of the air. This effect may account for the somewhat restrained response of dCO_2 if the reduced warming was associated with relatively reduced respiration.

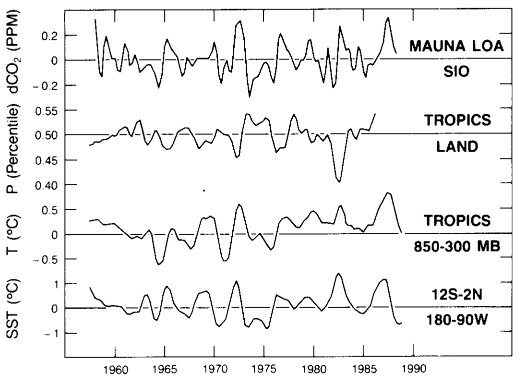

Fig. 4. Comparison of SST (bottom), tropospheric temperature in the tropics (TAT, 2nd from bottom), land precipitation in the tropics (TPR, 3rd from bottom) and dCO_2 at Mauna Loa (top). Otherwise see Fig. 2 legend.

Another features of the curves should be mentioned. From 1958 to about 1964, although dCO_2 displays variability, the SST, TAT and TPR show little interannual variation; a cooling of both the air and water accompanied by an increase in the precipitation being the only features. This is also a time when the correlation between SST and dCO_2 was the poorest, as seen in Fig. 3. Similar results are found when dCO_2 is correlated with TAT and TPR, as in Fig. 3. That is, lower correlations are found in the early parts of the records and maximum correlations are found during periods centered in the late sixties to early seventies. Furthermore, the climate variables are generally best correlated with each other in this period, and least correlated in the early period. (There is also a period in the late seventies when SST and TPR are highly correlated but not with dCO_2.) This suggests that high correlations between dCO_2 and the other quantities arise only during warm and/or cool ENSO events and then usually only when the SST, TAT and TPR are strongly correlated among themselves.

Table 3. *Same as Table 2 for the period 1976–1988 (to 1986 for TPR) for all stations*

Station	SST	TAT	TPR
Mauna Loa (SIO)	0.38 (2)	0.47 (0)	−0.42 (2)
Mauna Loa (GMCC)	0.54 (2)	0.55 (0)	−0.49 (2)
South Pole (SIO)	0.47 (1)	0.38 (1)	−0.42 (1)
South Pole (GMCC)	0.51 (1)	0.38 (1)	−0.32 (1)
Samoa (GMCC)	0.41 (2)	0.30 (2)	−0.33 (2)
Barrow (GMCC)	0.28 (4)	0.32 (2)	−0.27 (3)

Table 3 gives the correlation for all the records from 1976 to 1988 (to 1986 in the case of correlations with TRP). These show about the same things that the longer records indicated. The correlations are usually a bit higher than the longer records because the longer ones include the early period of lower values. All the correlations in the table are significant at the 5% level, and most at the 1% level, except for Barrow and TPR. At Mauna Loa the GMCC record seems a bit better correlated with the variables than the SIO record but we do not attach much significance to this. It does show that the correlations are not arising from some peculiarity in the SIO records. There are some peculiarities in the lags. The South Pole seems to show a more rapid response to SST and TPR in this period than Mauna Loa while it is delayed relative to TAT. Furthermore, Barrow shows a poorer correlation and a longer lag than the other locations, although it is no farther than the South Pole from the SST region. Samoa also shows longer lags than the South Pole even though it is fairly close to the Equator. This is further evidence that it is not simply the events in the tropical ocean that are responsible for the associations.

4. El Niño effects

Fig. 5 gives the specific relations during warm ENSO periods (El Niño). Each of the recognized El Niño events is isolated and dCO_2, SST, TAT, and TPR records are drawn for 6 seasons before and after the DJF season of the event. The data have all been smoothed once. (In 1979 there was a slight SST warming which is usually not considered an El Niño despite an apparent increase in dCO_2.) The top set of curves are the SIO records of dCO_2 at Mauna Loa, with the last 3 points of the 1987–88 event added from the GMCC record. The reader should keep in mind that dCO_2 is a deviation in the change from one season to the next; positive values indicate CO_2 is increasing at an anomalously high rate so that the concentration would be above "normal" for several seasons after the peak dCO_2.

Focusing first on the SST record (bottom set of

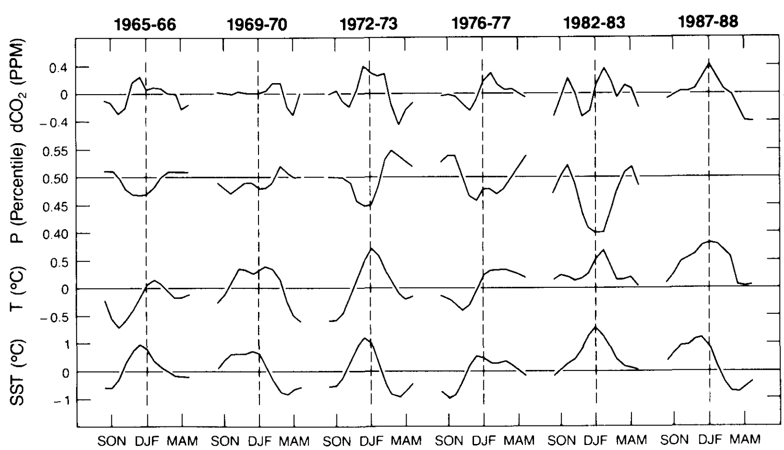

Fig. 5. As in Fig. 4, but only for the El Niño events since 1960, and with a 1-2-1 smoothing applied once.

curves) it is clear that there are differences in the patterns of SST changes with each event, as well as in their magnitudes. Some events are characterized by a slow rise and then a rapid drop in temperature ('69–70, '87–88) while the '65–66 and '76–77 events show a rapid warming and slow cooling. The '82–83 and '72–73 events appear fairly symmetrical, although the '72–73 event cooled more rapidly than it warmed. The TAT curves generally show patterns similar to SST with a one to two season lag. The dCO_2 curves for the '65–66, '69–70, '76–77, and '87–88 events show patterns somewhat similar to the SST curves during these events. It is also noteworthy that the two events characterized by a slow warming ('69–70 and '87–88) do not show a dip in the dCO_2 curve prior to the warming, a feature that the other events show. A possible explanation for this lies in the SW model, which indicates the first response to an El Niño may be a decrease in CO_2 as the upwelling is cut off. A rapid rise in SST may indicate a rapid drop in the upwelling which could account for the dip in the dCO_2, whereas a slow warming suggests a slower decrease in upwelling allowing the other processes that affect CO_2 to overcome the effect of the diminished upwelling.

The two largest events, '72–73 and '82–83, have the most symmetrical SST patterns but are not very similar in the appearance of the dCO_2. The sustained cooling following the '72–73 event seems to be an important feature and may account for the difference between the two. Although TAT generally follows the SST patterns, the fact that the air temperature did not warm so much as expected after the '82–83 event may also contribute to the difference.

The TPR records are more difficult to characterize. Each shows a relatively dry period during the warm events. The very weak drying during the '69–70 event may have contributed to the rather small response of dCO_2 but then one would expect the exceptional drying of '82–83 to have produced a very large increase in CO_2 but that was not the case. A feature of both the '72–73 and '76–77 events was the wet periods associated with the cool events following the El Niños (and preceding the '76–77 event). These cold events are likely as important as the warm events in affecting the CO_2 records as they are in affecting other phenomena.

5. Seasonal preferences

In EA, we noted that there were certain seasons when dCO_2 was much better correlated with SST than others, at least during 1970–1983. Since this is a short period of time we were not sure the result would stand up with more data. We correlated the values of dCO_2 for a particular season with the values of the climate variables for that season, one season earlier, etc. Table 4 shows the results of the calculations, for all three climate variables, for the period 1966–1986, the limits coinciding with the first full year of data at the South Pole and the last year of TPR data. Only those correlation nominally significant at the 5% level are tabulated, to bring out the pattern.

For SST, the results are essentially the same as we found in EA. The change of CO_2 from DJF to MAM is well correlated with antecedent SST at both Mauna Loa and the South Pole, while the change from SON to DJF is sensitive to antecedent SST at Mauna Loa as is the change from MAM to JJA at the South Pole. There do seem to be preferred seasons for the correlation to be high. Note that the correlations during these seasons are a good bit higher than those in Table 2. For TAT the pattern at the South Pole is about the same as that for SST, while only the DJF to MAM dCO_2 at Mauna Loa shows a distinct preference and then only for the DJF and MAM temperatures. TPR relations are less clear but at the South Pole they resemble the other two associations. Note that the JJA to SON changes in CO_2 were not associated with any of the variables for either location.

We carried out similar calculations for the other records available from 1976–1986. This period is so short that the results can only be considered as suggestive, there being only 10 or 11 pairs of data points for correlation. The results for Samoa and Barrow are displayed in Table 5. For Mauna Loa and the South Pole, the results gave the same patterns whether we used the GMCC or the SIO records and were essentially the same as in Table 4, with one exception. That exception is the Mauna Loa/SST correlations. In the short record the significant correlations with SST were for the DJF to MAM and MAM to JJA CO_2 changes rather than the SON to DJF and DJF to MAM changes.

The results for Samoa are somewhat surpris-

Table 4. *Correlation by season between SIO dCO_2 at Mauna Loa and South Pole, and SST, TAT, and TPR for the period 1966–1986*

	Mauna Loa dCO_2				South Pole dCO_2			
	SON–DJF	DJF–MAM	MAM–JJA	JJA–SON	SON–DJF	DJF–MAM	MAM–JJA	JJA–SON
SST								
DJF	0.44	0.55	●	●	●	0.62	0.56	●
MAM	●	0.49	●	●	●	0.44	0.58	●
JJA	0.51	0.44	●	●	●	0.44	●	●
SON	0.50	0.58	●	●	●	0.60	0.58	●
TAT								
DJF	●	0.70	●	●	●	0.50	0.59	●
MAM	●	0.74	●	●	●	0.45	0.69	●
JJA	●	●	●	●	●	●	0.58	●
SON	●	●	●	●	●	●	●	●
TPR								
DJF	●	●	−0.58	●	●	−0.62	−0.44	●
MAM	●	●	−0.59	●	●	−0.54	●	●
JJA	−0.50	●	●	●	●	●	●	●
SON	−0.52	−0.47	●	●	●	●	●	●

Only correlations significant at the 5% level are shown; dCO_2 ends in the season of, or follows, SST, TAT and TPR. For example, the SSTs in SON and DJF are correlated (0.50 and 0.44, respectively) with dCO_2 between SON and DJF; the SSTs in JJA are correlated (0.51) with dCO_2 between the subsequent SON to DJF; the SSTs in MAM are not significantly correlated with subsequent dCO_2 from SON to DJF.

Table 5. *Same as Table 4 for Samoa and Barrow for the period 1976–1986*

	Samoa dCO_2				Barrow dCO_2			
	SON–DJF	DJF–MAM	MAM–JJA	JJA–SON	SON–DJF	DJF–MAM	MAM–JJA	JJA–SON
SST								
DJF	●	●	0.87	●	0.60	●	●	●
MAM	●	●	0.88	●	0.70	●	●	●
JJA	●	●	0.75	●	0.66	●	●	●
SON	●	●	0.78	●	●	●	●	●
TAT								
DJF	●	●	0.85	●	●	●	●	0.63
MAM	●	●	0.75	●	●	●	●	0.66
JJA	●	●	0.64	●	0.64	●	●	●
SON	●	●	●	●	●	●	●	●
TPR								
DJF	●	●	−0.85	●	−0.64	●	●	−0.55
MAM	●	●	−0.91	●	−0.56	●	●	●
JJA	●	●	●	●	●	●	●	●
SON	●	●	●	●	●	●	●	●

ing; only MAM to JJA dCO_2 show an association with antecedent conditions. The correlations are quite high then, while at other times the correlations are usually <0.5. The reason for this behavior may lie in the shifting wind regimes at Samoa (Halter et al., 1988). Barrow also shows a seasonal preference, but this is for the SON to DJF changes with some hint that JJA to SON is also affected by previous TAT and TPR values in DJF and MAM.

We had thought that we might find that the SST in certain seasons would produce a greater apparent effect than others, but rather, we have found certain season to season changes that appear most sensitive to antecedent conditions. Except at Barrow, these seasons tend to be DJF to MAM and MAM to JJA, particularly in the 1976–88 period. As noted above, the CO_2 changes from JJA to SON seem unaffected by any of the climate variables at any of the locations, again with the exception of Barrow. Although not so pronounced, there seems to be a tendency for the TAT and TPR conditions in the early part of the year to be more "effective" than those in the last half. The brevity of the records, particularly at Samoa and Barrow, caution against over-interpretation but the tendency for specific seasons to be affected suggests that the climate variables are influencing some source or sink that has preferred seasons. A prominent candidate for such a source/sink is the terrestrial biosphere.

6. Discussion

That the terrestrial biosphere could be an important source of interannual variability of atmospheric CO_2 is not at all surprising and has been suggested before. For example, Fung et al. (1987) have presented satellite data showing interannual changes in vegetation and discussed their role in CO_2 changes. There is no reason to expect respiration and photosynthesis to balance each other exactly over any particular 12-month period. It is also reasonable to assume that interannual variations in precipitation and temperature affect the growth and decay cycles of the biosphere. The particular climatic variables we have used may not reflect the specific conditions in the biomes that are affecting atmospheric CO_2. The tropical land precipitation (TPR) is a zonal average of the, mainly, continental regions and the tropical troposphere temperature (TAT) is a zonal average of an admittedly sparse network. Nevertheless these two variables are as well correlated with dCO_2 as is SST. Furthermore, the patterns of seasonal correlations, Tables 4 and 5, are not what would be expected if these variables were simply redundant with the SST. Nor is SST simply a surrogate for the other variables. Its changes may indicate changes in other parts of the oceans, in particular, the ocean's biosphere. Each of the variables seems to be "explaining" some separate part of the puzzle.

This observation lends credence to the speculation that the events in the eastern tropical Pacific are not the direct cause of the changes in CO_2, although they may well be the best precursors of changes to come. Another indication that SST events are not the primary cause of CO_2 changes lies in the record at Samoa. This record is brief and there were problems early in the operation but one would expect this location to show a high degree of correlation with SST, given its proximity to the El Niño region. Such is not the case, however; SST is better correlated with dCO_2 at the South Pole than it is with dCO_2 at Samoa and the lag is shorter at the South Pole (see Table 3).

The overall correlations of dCO_2 at Samoa are low because only the MAM to JJA changes are well correlated with the other variables and the same dependence on season is seen at Barrow, although for different seasons. Barrow is very likely influenced by factors other than those represented by our choice of indices. Interannual changes in sea-ice extent suggests itself as something to examine as well as changes in the boreal climates. Along this line, we did look at correlations between dCO_2 at Barrow and other zonal troposphere temperatures, as compiled by Angell (1988), but found lower correlations than with the tropical temperatures.

The warm (El Niño) and cold phases of the ENSO cycle are evidently the events that are associated with large interannual changes in the CO_2 concentrations. However, one of the points we wish to stress is that each event is different in the pattern of CO_2 variation as well as the patterns of SST, TAT and TPR changes. The largest apparent response of CO_2 occurs when these three variables themselves are well correlated as they were in the early and mid 1970s. We also detected a tendency for the dCO_2 to drop initially when the SST warmed rapidly, as modeled by SW, but a drop was not apparent if the SST warmed slowly. Other than these observations, it is difficult to describe a unique dCO_2 response to El Niño; even the maximum SST is not a reliable guide to the CO_2 response.

The data used for TPR are zonal averages of land areas and so if there are specific regions that are especially important for the CO_2 changes, such as the Australasia region, our analysis would not identify them. The averaged data include regions where the precipitation may increase during warm phases (and decrease during cold phases) so it would be useful to examine the precipitation data for selected regions to see if there are areas of particular importance. Similarly, the zonal values of TAT may mask regions where changes are more important than the overall averages indicate. Although our attention was focused on the tropics, and we could find no better relations with tropospheric temperatures at higher latitudes, we would certainly expect climate variations at higher latitudes to have effects on the CO_2 variations.

In EA we showed a record of the cumulative sum of the dCO_2 that suggested a large increase in CO_2 between 1976 and 1981. The revised data and the longer record used here still show this feature but the increase is not so large and it seems to continue to the present. A tendency for the dCO_2 records to display a long term trend, falling from the start of the records to the middle 1970s and rising thereafter was noted earlier (see Fig. 2). Keeling et al. (1989) found a similar trend in their different treatment of the data. While this trend in CO_2 follows the trend in SST, Keeling et al. believe change in the terrestrial biosphere is the more likely cause.

Finally, our results tend to confirm the analysis of Keeling et al., that changes in the carbon assimilation of the terrestrial biosphere are responsible for many of the features in the CO_2 record, certainly on the interannual time scale and possibly the interdecadal time scale.

7. Summary

The CO_2 concentrations at Mauna Loa, South Pole, Samoa, and Barrow were adjusted to remove their annual cycles and eliminate the effects of fossil-fuel combustion, and any other mean emission. Deviations from the mean season-to-season changes of this record (dCO_2) were related to the sea-surface temperature in the eastern Equatorial Pacific (SST), the tropospheric air temperature above the tropics (TAT), and the precipitation over the land areas of the tropics (TPR). The main results are as follows.

(1) The correlation between dCO_2 and each of the other variables changes with time. In particular, the period from about 1968 to about 1978 was the period of highest correlation. This was also the period when the climate variables were best correlated with each other.

(2) The TAT and the TPR were as well correlated with dCO_2 as was SST.

(3) There are individual seasons when the dCO_2 is much better correlated with the climate variables than at other seasons. The particular preferred seasons can be different at the different stations and for different variables, but there was a tendency for changes in CO_2 from DJF to MAM and MAM to JJA to be the most affected by antecedent conditions.

(4) El Niño events, while the source of the largest signal in the dCO_2 record, are by no means the same from one event to the next. The magnitude of the SST change is not even a reliable indicator of the effect on the CO_2 record, although there is a tendency for larger SST changes to be associated with larger dCO_2 values.

Some other results are: there is a tendency for dCO_2 to dip before the main rise if the SST is rising quickly; Barrow's dCO_2 is less well correlated with the tropical variables than either Mauna Loa or the South Pole, and Samoa is not much better than Barrow; there is a large lag between Barrow's CO_2 response and the putative causes.

These results provide further evidence that variations in the respiration and photosynthesis of the tropical terrestrial biosphere are a major source of the interannual variability in the CO_2 records.

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