SOURCES AND SINKS OF CARBON DIOXIDE

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ABSTRACT

The conventional representation of the impact on the atmosphere of the use of fossil fuels is to state that the annual increases in concentration of CO_2 come from fossil fuels and the balance of some 50% of fossil fuel CO_2 is absorbed in the oceans or on land by physical and chemical processes.

An examination of the data from:

i) measurements of the fractionation of CO_2 by way of Carbon-12 and Carbon-13 isotopes,
ii) the seasonal variations of the concentration of CO_2 in the Northern Hemisphere and
iii) the time delay between Northern and Southern Hemisphere variations in CO_2,

raises questions about the conventional explanation of the source of increased atmospheric CO_2.

The results suggest that El Nino and the Southern Oscillation events produce major changes in the carbon isotope ratio in the atmosphere. This does not favour the continuous increase of CO_2 from the use of fossil fuels as the source of isotope ratio changes. The constancy of seasonal variations in CO_2 and the lack of time delays between the hemispheres suggest that fossil fuel derived CO_2 is almost totally absorbed locally in the year it is emitted. This implies that natural variability of the climate is the prime cause of increasing CO_2, not the emissions of CO_2 from the use of fossil fuels.

1 INTRODUCTION

The conventional representation of the impact on the atmosphere of the use of fossil fuels is to state that the annual increases in concentration of atmospheric CO_2 come from fossil fuel emissions and the balance of some 50% of emissions is absorbed in the oceans or on land by chemical or biogenic interactions[1]. The annual changes at Mauna Loa[2] are shown in Figures 1A and 1B along with the estimated production of CO_2 from fossil fuels[3]. Note that the absorption shown in Figure 1B is simply found by subtraction of the atmospheric increase from the calculated emissions of CO_2 shown in Figure 1A.

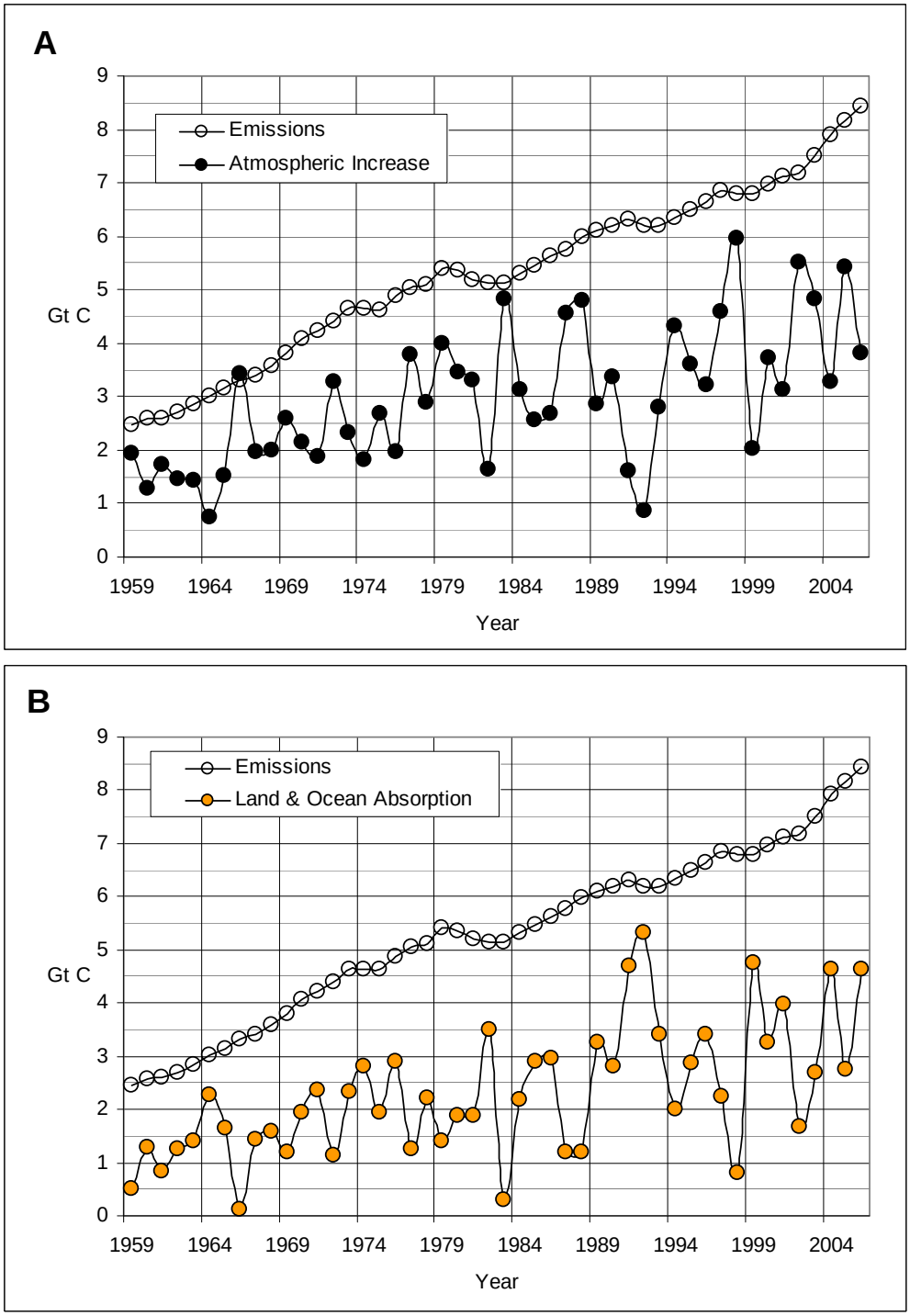

Figure 1 A) *Estimated emissions from worldwide fossil fuel use and the annual increase in atmospheric CO_2 sourced from http://cdiac.ornl.gov/trends/co2/contents.htm .* ***B)*** *Estimated emissions from worldwide fossil fuel use and the estimated amount of CO2 absorbed by land and ocean, calculated by subtraction of the atmospheric CO2 increase from the estimated emissions from fossil fuels.*

The justification for this conclusion is supported by measurements of the falling proportion of ^{13}C in the atmosphere which is taken to signal the appearance of CO_2 from fossil fuel emissions.

The fundamental assumption of the anthropogenic source of increasing CO_2 is the basis for all climate change policy development. It has deep historical roots given fresh force from measurements started in the late 1950's. Extended time series data have become available and it is well worth reviewing the data to check that original assumptions remain valid.

Carbon has two stable isotopes, Carbon-12 (^{12}C) and Carbon-13 (^{13}C). In general ^{12}C is 99% of natural carbon and ^{13}C 1%. However the rates at which chemical reactions and physical processes take place vary due to the masses of the isotopes present. For carbon the result is fractionation of the isotopes so that carbon found in coal or oil is 1.083% ^{13}C while carbon in the atmosphere is 1.103% ^{13}C.

Results are given as $\boldsymbol{\delta}^{13}C$, a measure of the isotope ratio of $^{13}C/^{12}C$ defined as:

$$\boldsymbol{\delta} = 1000 \times ((^{13}C/^{12}C)_{sample} / (^{13}C/^{12}C)_{standard} - 1)$$

The standard ratio is an international standard of comparison and is the zero point for δ [4].

δ for CO_2 coming from biogenic sources has an approximate value of -26[5], the fossil fuel value is -29, (estimated from US energy use[6] from a range of -20 to -44) and CO_2 from the ocean is given values ranging from -7 to 1.5[7]. The atmospheric values are found to vary from -7 to -8. If there are two sources of CO_2, the ocean and a biogenic or fossil fuel source then the average implies that some 4% to 33% of atmospheric CO_2 has been derived from biogenic or fossil fuel sources[8].

One of the great unknowns is the variability of the oceans that have multi-year cycles that cause temperature variations such as El Nino and the Southern Oscillation events. It is not clear whether there are other climate effects from the oceans and from the land and ocean based sources of biogenic CO_2. However the size of these reservoirs and the annual exchanges with the atmosphere are estimated to be at least a factor of 20 times the annual production of CO_2 from fossil fuel[9]. There are substantial uncertainties in reservoir size and exchanges.

This paper provides an analysis of the changes in CO_2 and ^{13}C in the atmosphere using the extensive measurements made by the SIO[10] and the CSIRO[11] spanning many years. All the data are available on the website http://cdiac.ornl.gov/trends/co2/contents.htm with CO_2 concentrations and ^{13}C /^{12}C isotope ratios in monthly and yearly form[12,14]. The development of this extensive set of measurements has been reviewed recently by Beck[13].

Three approaches have been adopted, first looking directly at the variations of ^{13}C in the atmosphere, second, looking at the seasonal variations of CO_2 through the annual summer-winter cycles and finally examining timing differences of the Northern and Southern Hemisphere changes in CO_2.

2 CARBON-13 IN THE ATMOSPHERE

Variations in the amount of ^{13}C in CO_2 are shown in Figures 2 and 3 with data from the Scripps Institute of Oceanography (SIO) for Mauna Loa and also the South Pole[14].

Variations in ^{13}C have a strong cyclic pattern in the Northern Hemisphere with a biogenic variation in ^{13}C as plant growth preferentially favours the lighter isotope, ^{12}C.

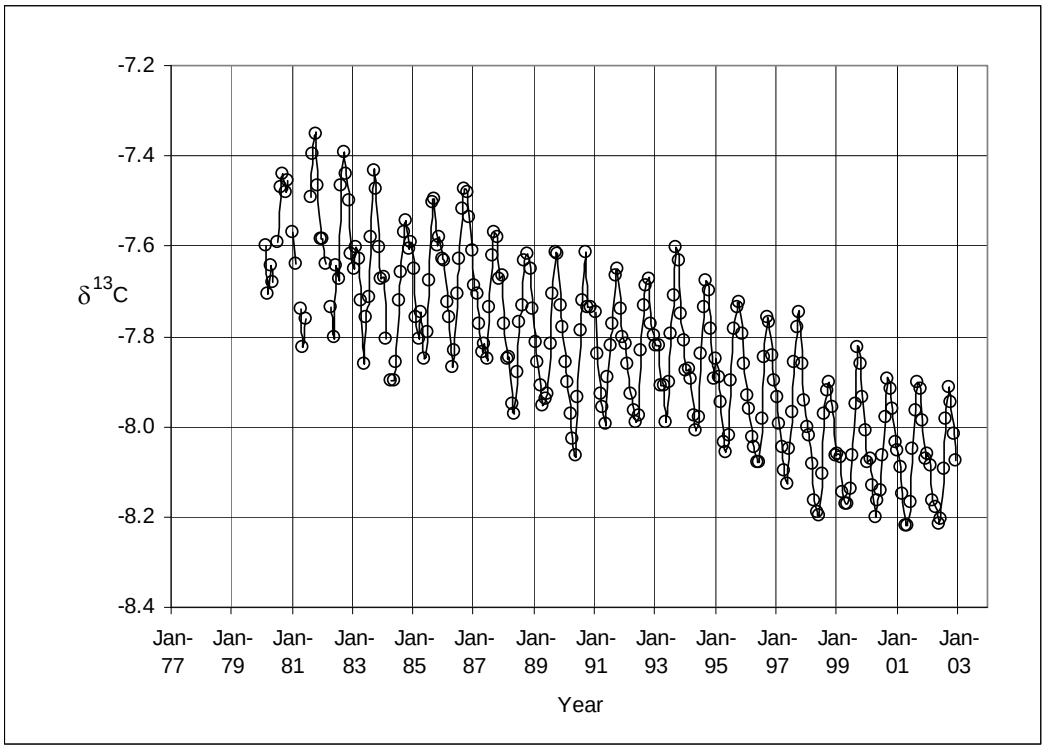

Figure 2 *Monthly variations in $\delta^{13}C$ at Mauna Loa from SIO[14]*

However at the South Pole this variation is muted and it is possible to see trends outside of the annual variations.

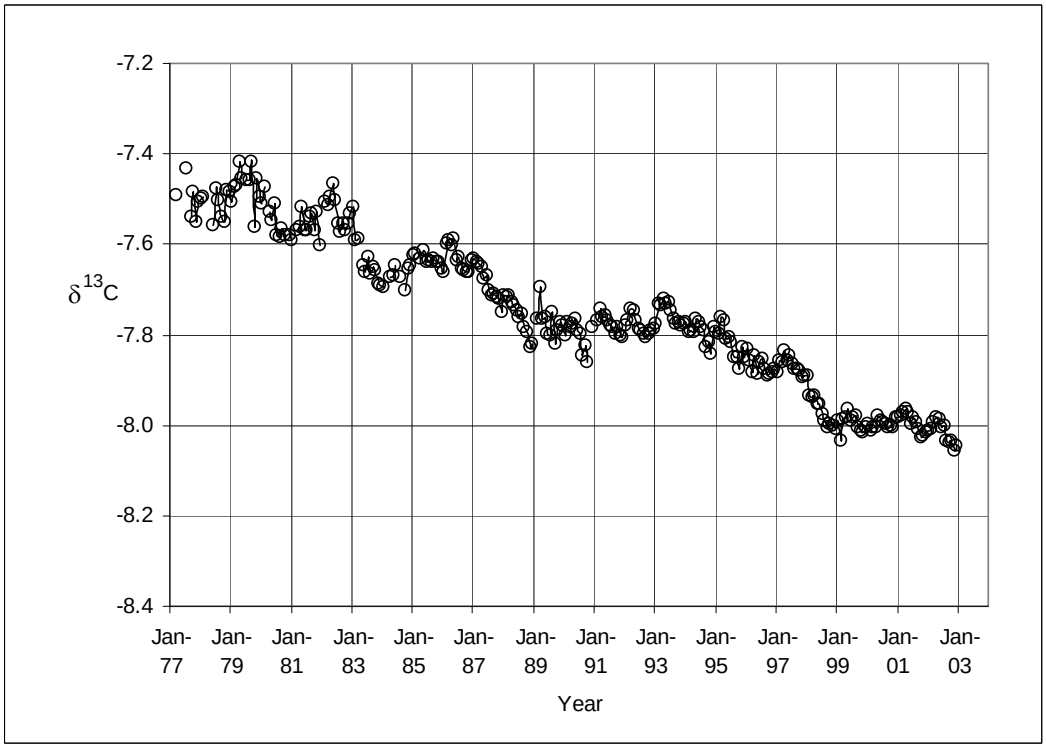

Figure 3 *Monthly variations in $\delta^{13}C$ at the South Pole from SIO[14]*

The measurements show a cascade of values with the atmosphere showing a decrease in ^{13}C. In fact the fall in ^{13}C appears as a series of steps. This behaviour is better displayed by looking at annual changes. Figure 4 shows these changes for SIO measurements from Mauna Loa and the South Pole. The annual differences in $\delta^{13}C$ are calculated from three month averages of year on year differences

of the monthly measured values in order to remove the regular seasonal cycle and to expose departures from that cycle.

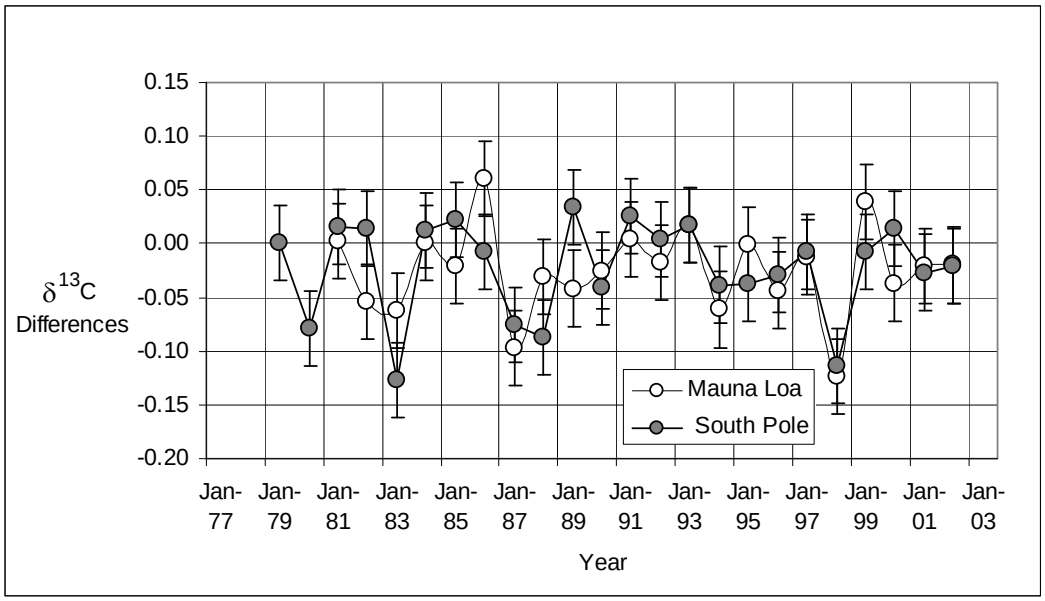

Figure 4 *Three Month averages of year on year differences of the monthly measured $\delta^{13}C$ for Mauna Loa and the South Pole[14].*

A natural question to ask is whether these steps are associated with other variations in the atmosphere. The annual increase in CO_2 is shown in Figure 5 taking one-year differences from each location time series thus again removing a regular seasonal cycle to expose departures from that cycle.

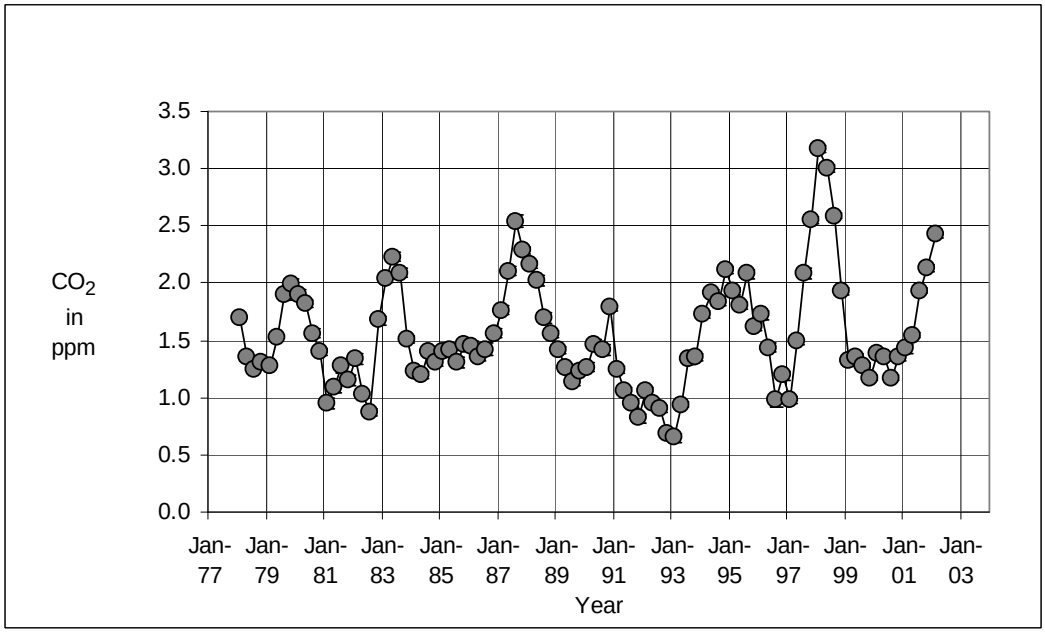

Figure 5 *Three Month averages of year on year differences of the monthly measured CO2 atmospheric concentrations for Mauna Loa and the South Pole[2] .*

Following the pattern shown in Figures 4 and 5, all 15 available data sets of ^{13}C measurements have been analysed. These extend from 82^0N at Alert to 90^0S at the South Pole. The results are shown in Figure 6. The same differencing procedure discussed above has been applied to the changes in ^{13}C

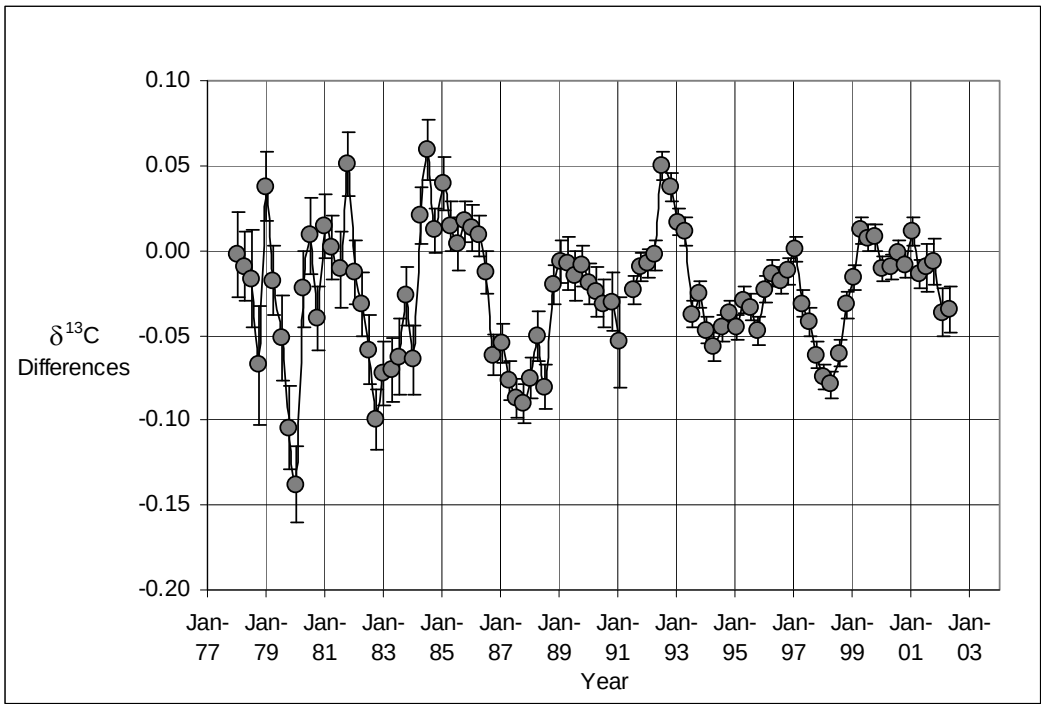

Figure 6 *Three Month averages of year on year differences of the monthly measured $\delta^{13}C$ from SIO[14] and CSIRO[12] data for 15 locations from Alert to the South Pole. Error bars are errors of the mean.*

The location data sets have been combined on the assumption that variations in ^{13}C are simultaneous throughout the atmosphere within the accuracy of the data.

There is a discontinuity in the SIO data at the start of 1991[15]. The step in the SIO data and its difference to the CSIRO data is shown in Figure 7. In Figure 6 and all subsequent analysis the SIO data for 1991 has not been used.

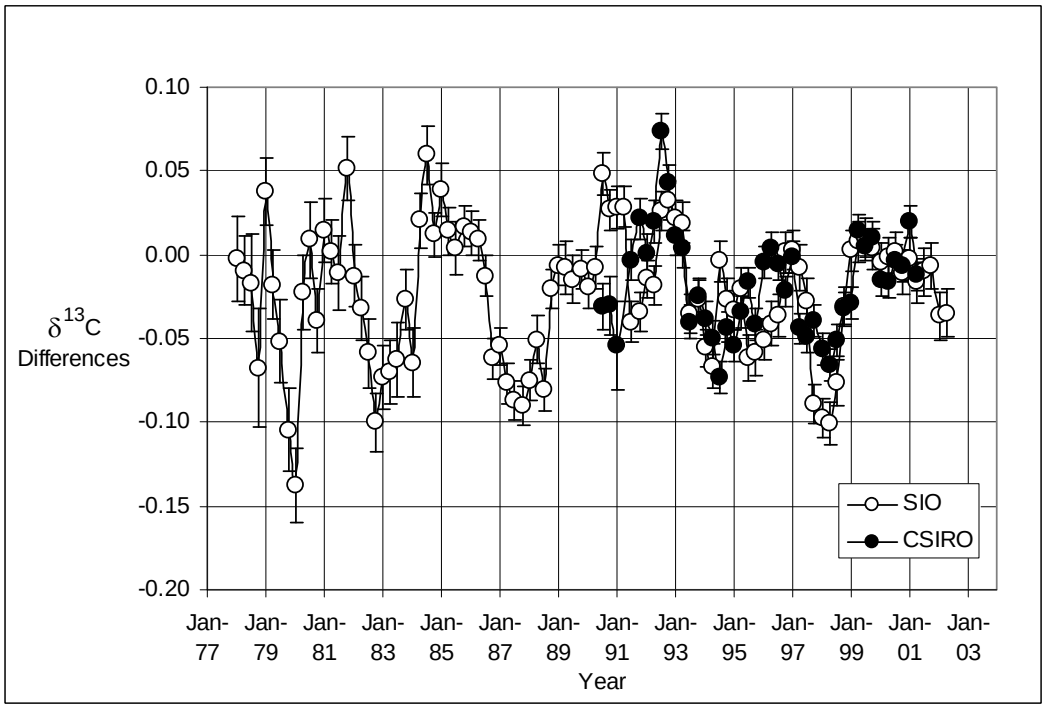

Figure 7 *Separate SIO and CSIRO data series. Three Month averages of year on year differences of the monthly measured $\delta^{13}C$ from SIO[14] and CSIRO[12] data for 15 locations from Alert to the South Pole. Error bars are errors of the mean.*

The measuring errors combined with any time spread have been estimated by looking at the spread of measurements at each time point with from 1 to 15 locational data points. The standard deviation is found to be overall 0.050 for $\delta^{13}C$ with 0.050 for the SIO data and 0.046 for the CSIRO data. The errors plotted are the errors on the mean. Some 2,000 data points have been used in the analysis and a small number, less than 30, were rejected as being more than 4 standard deviations from the mean. This was a particular problem in the 1991-92 period where 22 SIO data points were rejected.

The correlation of CO_2 concentration with $\delta^{13}C$ gives a correlation coefficient of -0.60. Figure 8 illustrates this correlation where the $\delta^{13}C$ difference values have been plotted along with the annual changes in CO_2 concentration.

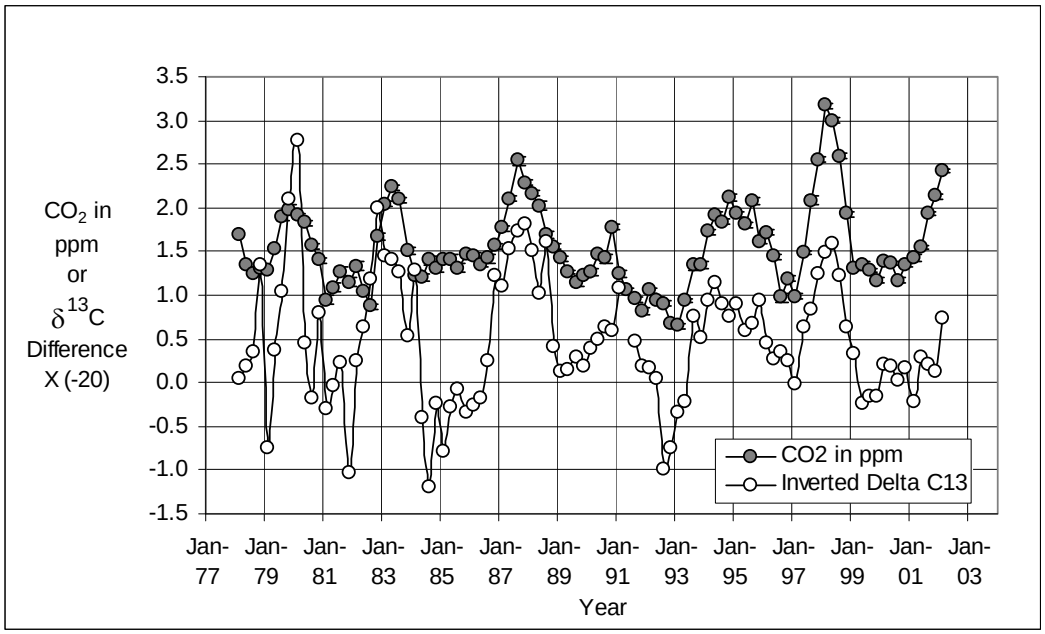

Figure 8 *Correlation of CO2 annual increases and $\delta^{13}C$ differences. The $\delta^{13}C$ differences have been inverted and scaled. Three Month averages of year on year differences of the monthly measured CO_2 concentrations for Mauna Loa and the South Pole[2] and $\delta^{13}C$ from SIO[14] and CSIRO[12] data for 15 locations from Alert to the South Pole.*

The peaks in the CO_2 concentration appear to correlate with ENSO[16] events of Figure 9.

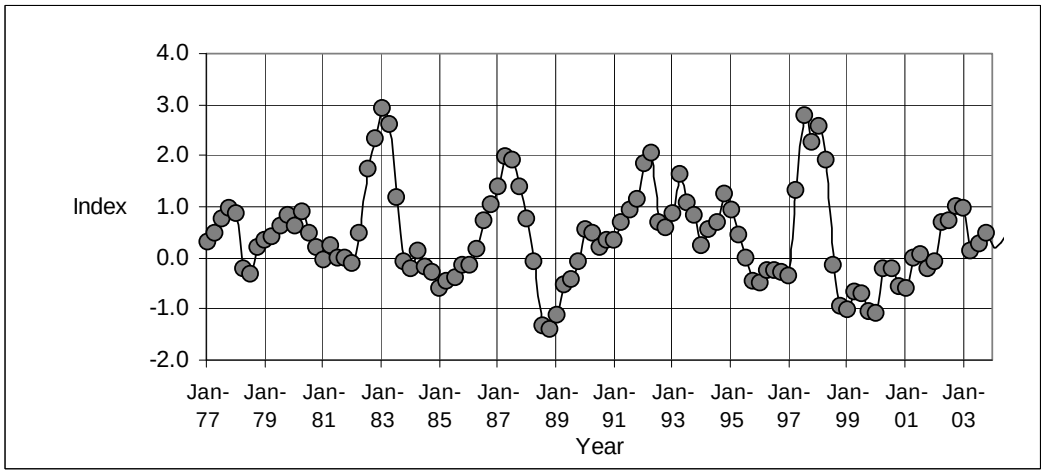

Figure 9 *Multivariate ENSO Index compiled by K Walter[16]*

So this would suggest that the change in $\delta^{13}C$ might be driven from the same source responsible for ENSO events.

3 ILLUSTRATION OF CARBON-13 CASCADE

In order to illustrate the working of the analysis, a simple set of straight lines have been matched to the South Pole data points as shown in Figure 10. The alternative of a constant addition of fossil fuel CO_2 would give a steady decrease in $\delta^{13}C$. The yearly differences (Figure 11) show the mapping of the $\delta^{13}C$ cascade.

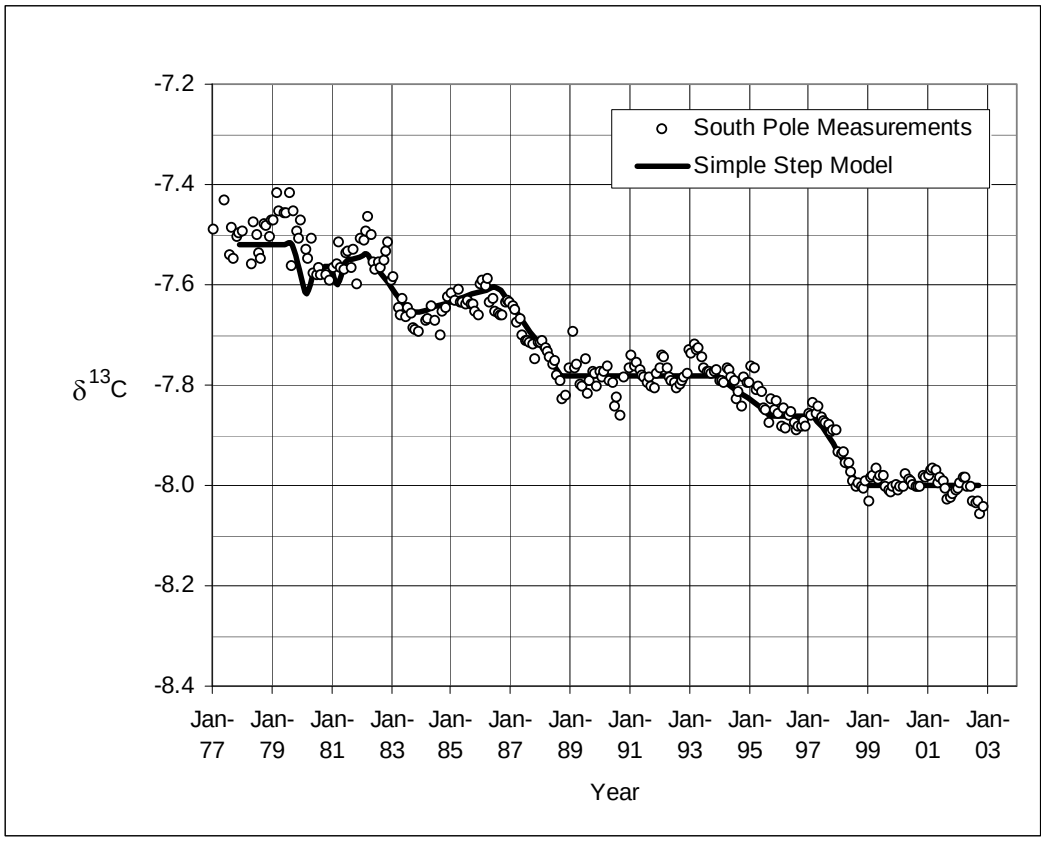

Figure 10 *A simple step model of the changes in $\delta^{13}C$ at the South Pole compared to the SIO measurements.*

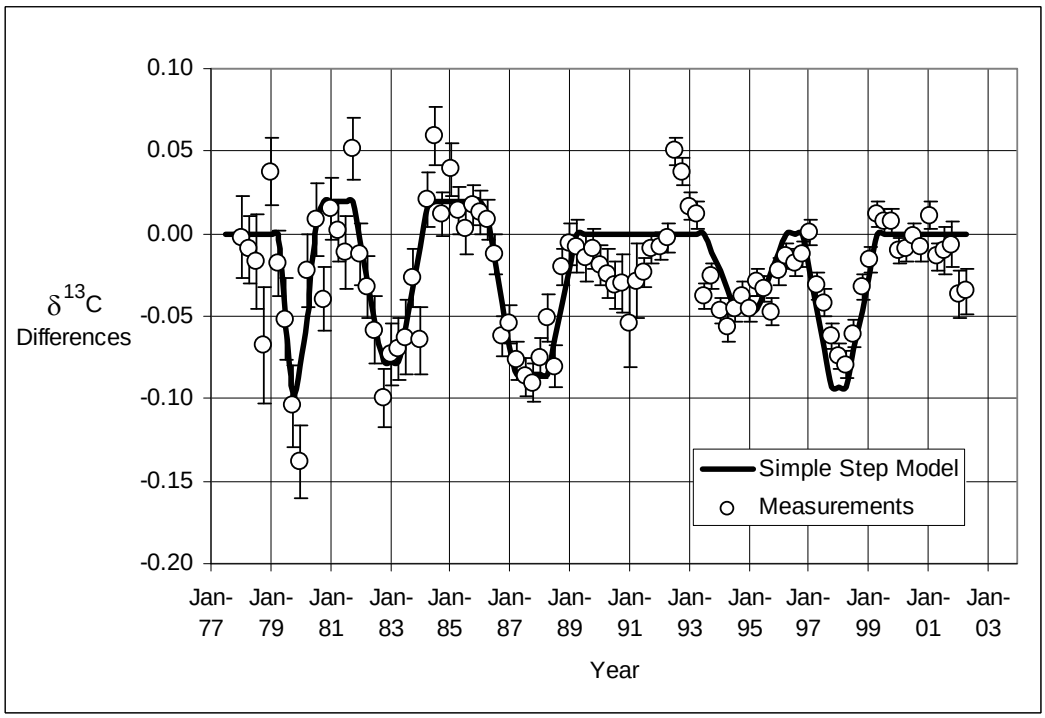

Figure 11 *A simple step model of the changes in $\delta^{13}C$ at the South Pole along with the SIO measurements showing annual differences in $\delta^{13}C$.*

The correlation of changes in $\delta^{13}C$ with ENSO events and the comparison with a simple model of a series of cascades suggest that the changes in $\delta^{13}C$ in the atmosphere have little to do with the input of CO_2 emissions from the continuous use of fossil fuels.

4 SEASONAL VARIATIONS OF ATMOSPHEREIC CARBON DIOXIDE

The increase of CO_2 in the atmosphere is modulated by seasonal variations. These are understood to be a reflection of biogenic and chemical interactions from plants, the soil and the oceans. There is a remarkable regularity in this as can be seen in Figure 12 for the monthly measurements at Mauna Loa.

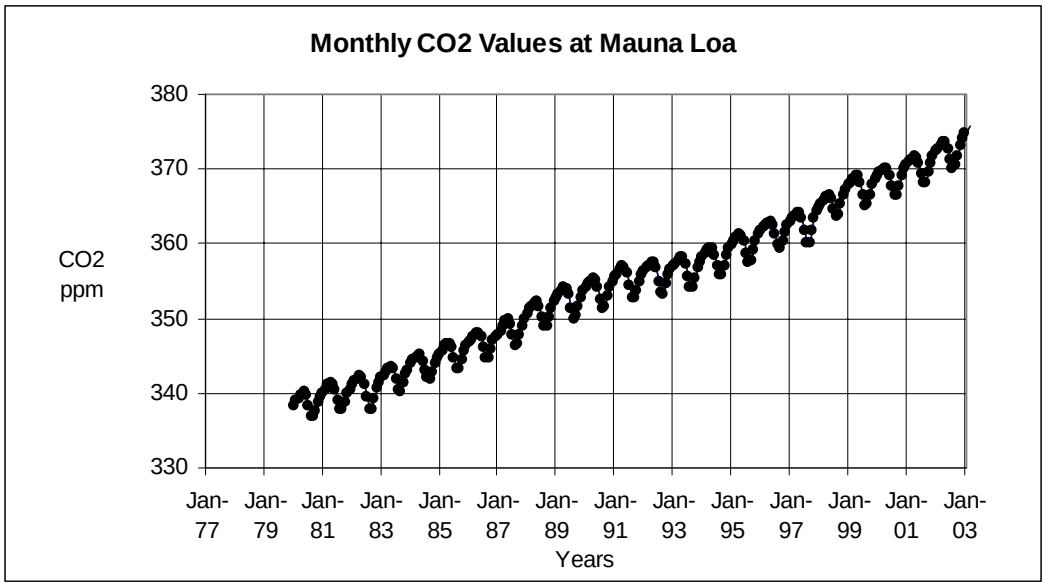

Figure 12 *Monthly variations of CO2 concentration at Mauna Loa*[2].

The variations of CO_2 in the atmosphere over the last twenty-five years are best summarised in the following figures 13, 14 and 15 with the results listed in the Attachment. The data is from the extensive SIO and CSIRO measurements of CO_2 and from one UBA site, Schauinsland in Germany[17].

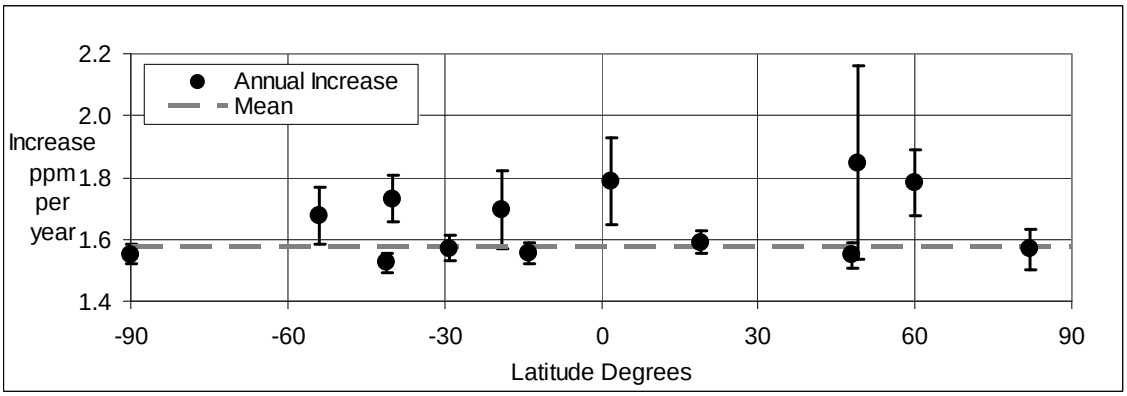

Figure 13 *Annual increases in CO_2 concentration at different locations. The time span ranges from 7 to 22 years.*

The annual increase of CO_2 in the atmosphere is in sharp contrast with the annual change in the seasonal variations. The mean values are:

Annual CO_2 increase	**1.572 ± 0.013 ppm per year**
Seasonal CO_2 increase	**-0.001 ± 0.013 ppm per year**

There is a difference, within errors, of a factor of 100 in annual increases.

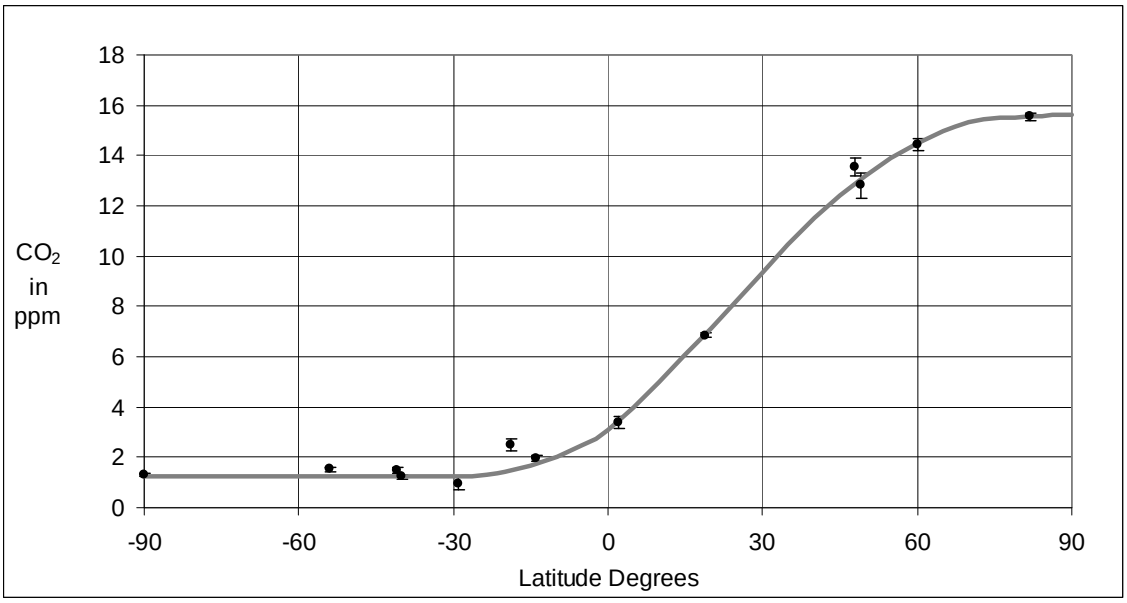

Figure 14 *Seasonal variations of CO_2 concentration at different locations. The time span ranges from 7 to 22 years.*

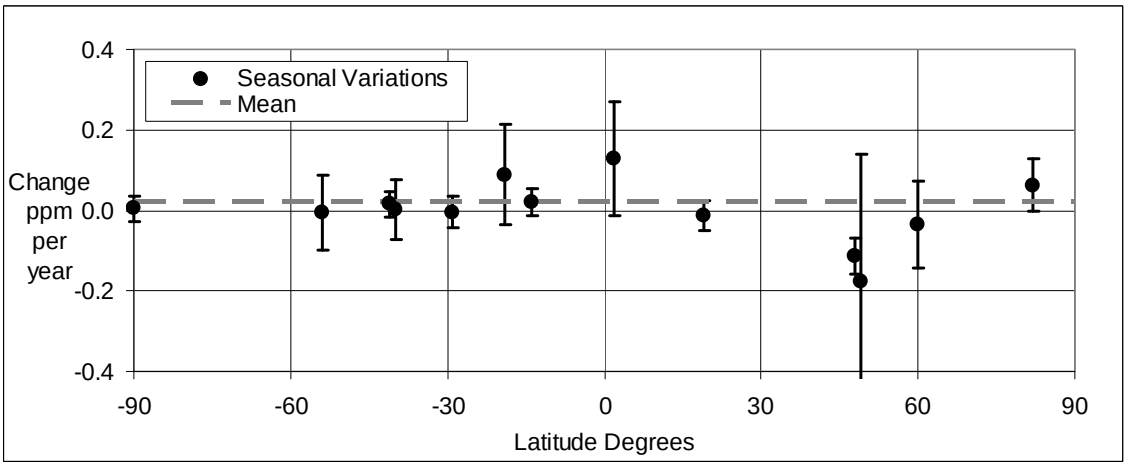

Figure 15 *Annual changes in the seasonal variation of CO_2 concentration at different locations. The time span ranges from 7 to 22 years.*

Over the last 20 years substantial amounts of CO_2 derived from fossil fuel have been released into the atmosphere. This has moved from 5.0 Gt of carbon in 1980 to 6.2 GtC in 1990 to 7.0 GtC in 2000. Figure 16 shows the distribution of fossil fuel CO_2 by latitude[18].

Over 95% of this CO_2 has been released in the Northern Hemisphere.

To put this in context, the total carbon in CO_2 in that region of the atmosphere is some 400 GtC with seasonal net variations of 10 GtC. (This can be seen in Figure 14 where the mean seasonal net variation is 9 ppm for a total 380 ppm CO_2 concentration.)

The remarkable feature of this behaviour is that despite the accumulation in the atmosphere of fossil fuel emissions from 1980 to 2000 at the rate 3 GtC per year, there has been virtually no change in the seasonal variations.

If the rise in CO_2 concentration is understood to be from fossil fuel CO_2 but the balance of emissions is taken up by sinks of CO_2 then it follows that there is an increase in the capacity of the

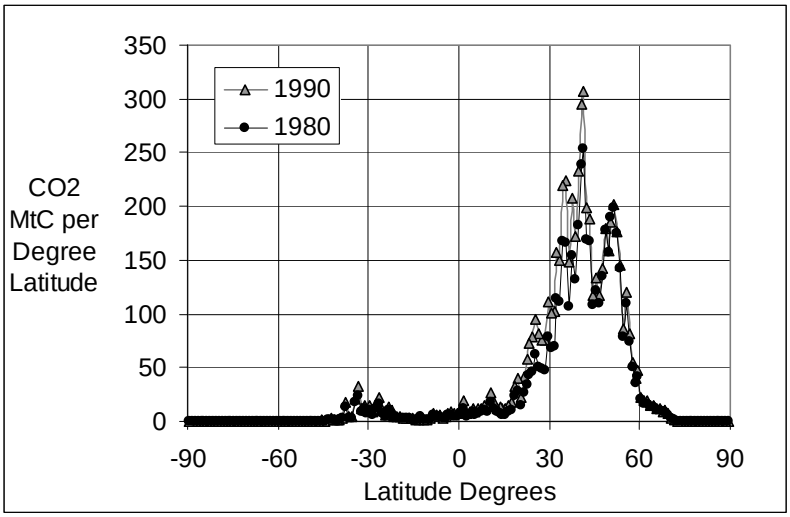

Figure 16 *Estimated Atmospheric CO2 from fossil fuels. Source CDIAC*[18].

sinks to absorb CO_2. If this is the case then one might expect changes in the seasonal variations in proportion to the expansion of the land-based or biogenic sinks of CO_2.

The estimate of the effects of added CO_2 is shown for the Northern Hemisphere in Table 1. The carbon cycle data is taken from the 3rd IPCC Report[19].

Carbon Cycle			Atmosphere		CO_2 from Fossil Fuel	
			1980	2000	1980	2000
Global						
Atmospheric Concentration of CO_2	ppm		350	381		
Increase per year	ppm	1.572				
Amount of CO_2 in Atmosphere Tonnes	GtC		750.0	816.4		
Total Atmosphere CO_2 Exchanges	GtC	28%	210.0	228.6		
Atmosphere-Land CO_2 Exchanges	GtC	16%	120.0	130.6		
Increase per year	GtC/year		3.4	3.4	5.30	7.00
Northern Hemisphere						
Atmosphere Fraction		50%				
Amount of CO_2 Tonnes	GtC		375.0	408.2		
Atmosphere-Land CO_2 Exchanges	GtC	22%	80.6	87.8		
Net Seasonal Variations	ppm		9.4	9.4		
~12% of land exchanges	GtC		10.1	10.1		
Fossil Fuel CO_2 Emitted	GtC	100%			5.30	7.00
Land source/sink						
Emitted CO_2 absorbed by land sink	GtC	30%			1.59	2.10
Increase to Seasonal Variations	GtC				0.20	0.24
~12% of additional absorbed CO_2						
Estimated Increase per year	**ppm**				**0.185**	**0.225**
Seasonal Variations						
Measured Increase per year						
Seasonal Variations	ppm				0.013	0.013
(-0.001+/- 0.013)						

Table 1 *Estimate of expected increase in seasonal variations for CO2 in the Northern Hemisphere. The third column shows the seasonal variations for 1980 and 2000. The fourth column shows the estimated contribution from the continuous production of fossil fuel CO_2 for 1980 and 2000. The CO_2 from fossil fuel is assumed to be distributed 50% to the atmosphere, 20%, to the ocean and 30% to biogenic sinks. In the Northern Hemisphere the land exchange has been increased as there is 40% land cover compared to 20% for the Southern Hemisphere.*

The calculations in the tables are order of magnitude estimates of the variations that might be expected if 30% of the fossil fuel sourced CO_2 was taken up in biogenic sinks.

In addition there is a 10% seasonal variation in CO_2 from fossil fuel use in North America and a similar behaviour might be expected in Europe. These variations have not been considered.

The estimates indicate limits to the variations that are substantially larger than the measured values. This assumes that the measured value is independent of latitude.

It is remarkable that emitted CO_2 is thought to be partially absorbed by CO_2 sinks but yet leaves no hint of expected biogenic variation. Increasing CO_2 might be expected to encourage plant growth. A simple conclusion that might be drawn from this is that the fossil fuel derived CO_2 is almost totally absorbed locally in the year that it is emitted. An alternative explanation would require the ocean to be the sink for CO_2. The absence of change remains a puzzle.

5 NORTH-SOUTH HEMISPHERE TIMING DIFFERENCES

Another interesting approach is to see if there are timing differences between the Northern and Southern Hemispheres (NH and SH) with the emission of CO_2.

A tracer for CO_2 transport from the NH to the SH was provided by. ^{14}C created by nuclear weapons testing in the 1950's and 1960's.The analysis of ^{14}C in atmospheric CO_2[20],[21] shows in Figure 17 that it took some years for exchanges of CO_2 between the hemispheres before the ^{14}C was uniformly distributed.

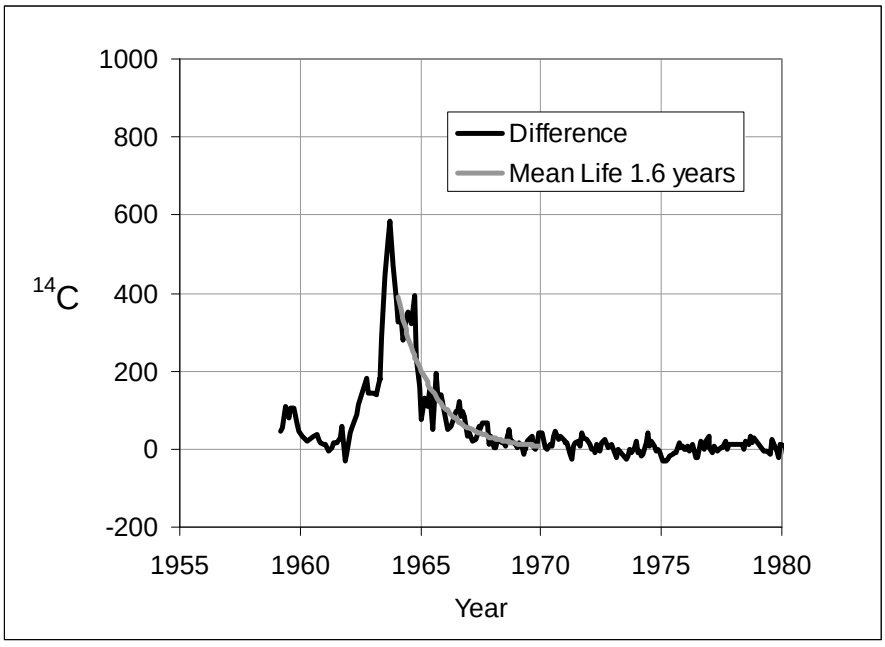

Figure 17 *Timing differences of Northern and Southern Hemisphere carbon pulse. A number of massive weapons were detonated in the Arctic circle just before the Partial Test Ban Treaty came into force in October 1963. The measurements were made in New Zealand[20] and Germany[21].*

If 75% of CO_2 from fossil fuel is emitted north of latitude 30 then some time lag might be expected due to the sharp year-to-year variations in the estimated amounts left in the atmosphere. A simple model, following the example of the ^{14}C data with a one year mixing time, would suggest a delay of

6 months for CO_2 changes in concentration in the Northern Hemisphere to appear in the Southern Hemisphere.

A correlation plot of SIO year on year differences of monthly measurements at Mauna Loa against those at the South Pole is shown in Figure 18. The time difference is positive when the South Pole data leads the Mauna Loa data. Any negative bias (asymmetry in the plot) would indicate a delayed arrival of CO_2 in the Southern Hemisphere.

There does not appear to be any time difference between the hemispheres. This suggests that the annual increases may be coming from a global or equatorial source.

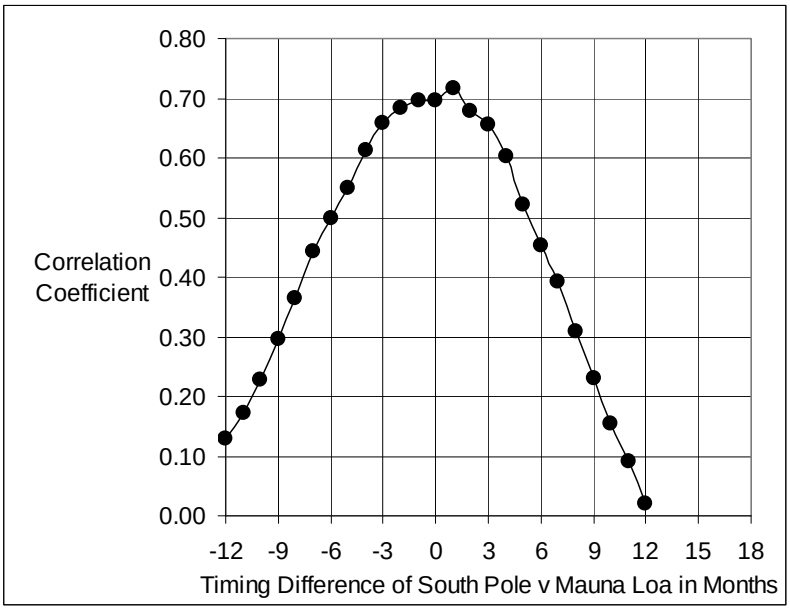

Figure 18 *Variation in the correlation coefficient between year on year differences in measured monthly CO2 concentrations at Mauna Loa and the South Pole as the times series are separated. A negative timing bias would indicate the delayed arrival of CO_2 in the Southern Hemisphere.*

A similar comparison has been made for the variations of $\delta^{13}C$ shown in Figure 19. The data has been analysed as 3-month averages. The result is not straightforward and suggests possible variations in the two hemispheres with time delays in both directions.

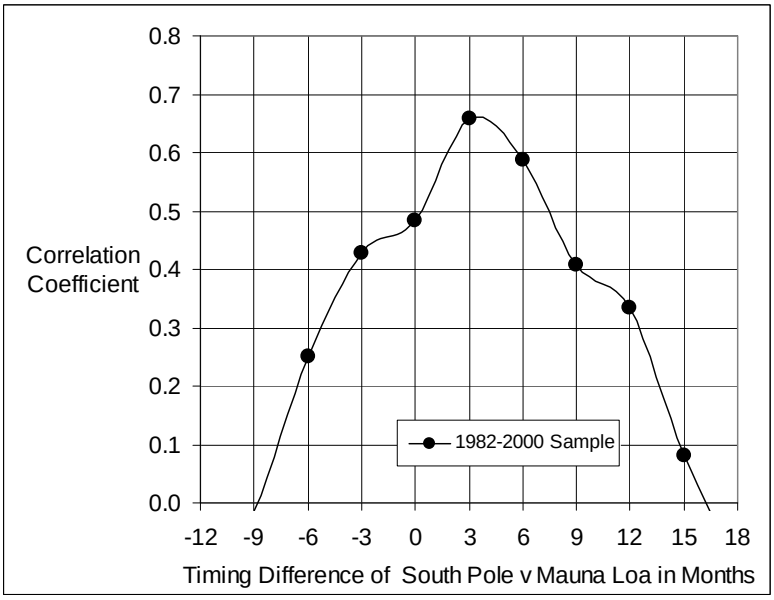

Figure 19 *Variation in the correlation coefficient between year on year differences of three monthly average $\delta^{13}C$ measurements at Mauna Loa and the South Pole as the times series are separated. A positive timing bias indicates the delayed arrival of CO_2 in the Northern Hemisphere.*

If the increases in atmospheric CO2 are being driven by fossil fuel emissions then changes in the isotope ratio would be expected to occur first in the Northern Hemisphere and then move to the Southern Hemisphere. The result suggests that the changes in the isotope ratio start in the Southern Hemisphere. This suggests an equatorial or Southern source of CO_2 emission.

6 CONCLUSION

During the 1977 to 2001 time period analysed:

Changes in the isotope ratio are discontinuous. The temporal peaks in ^{13}C appear to correlate with the CO_2 concentration changes. Further the temporal peaks in ^{13}C and the CO_2 peaks correlate with ENSO events.

The yearly increases of atmospheric CO_2 concentrations have been nearly two orders of magnitude greater than the change to seasonal variation which implies that the fossil fuel derived CO_2 is almost totally absorbed locally in the year that it is emitted.

A time comparison of the SIO measurements of CO_2 at Mauna Loa with the South Pole shows a lack of time delay for CO2 variations between the hemispheres that suggests a global or equatorial source of increasing CO_2. The time comparison of ^{13}C measurements suggest the Southern Hemisphere is the source. This does not favour the fossil fuel emissions of the Northern Hemisphere being responsible for ther observed increases.

All three approaches suggest that the increase of CO_2 in the atmosphere may not be from the CO_2 derived from fossil fuels. The ^{13}C data is the most striking result and the other two approaches simply support the conclusion of the first approach.

It is not obvious that the pulsed contributions of CO2 are related to continuous fossil fuel emissions given the seasonal data and the lack of a time delay in the Southern Hemisphere. Could it be a biogenic signal? After all the Northern Hemisphere has seasonal fluctuations of up to 15 ppm so could a 2 ppm pulse be related to changing conditions in tropical lands as a result of El Nino's?

The conclusion is that CO_2 emissions from fossil fuels do not make it to the "well mixed" atmosphere but are probably fixed locally. The increase in CO_2 is driven by other processes related to the natural variability of the climate. Some of this CO_2 variability is correlated with and may be related to ENSO events.

Acknowledgements

The author wishes to thank W. Kininmonth, R. Carter and G. Paltridge for many extensive tutorials. In addition T. Segalstad and J. McLean have supplied valuable references and help on particular sections of the paper.

Attachment: Table of Data used in Figures 13 to 15

Location and Latitude		No. of Years	Annual Increase of CO_2 ppm per year		Seasonal Variations of CO_2 ppm		Annual Change of Seasonal Variations ppm per year	
			Value	Error	Value	Error	Value	Error
South Pole	**-90**	22	1.551	0.031	1.32	0.05	0.005	0.031
Macquarie Island	**-54**	9	1.676	0.093	1.52	0.09	-0.006	0.093
Baring Head	**-41**	27	1.524	0.031	1.46	0.12	0.015	0.031
Cape Grim	**-40**	9	1.731	0.075	1.23	0.08	0.003	0.075
Kermadec	**-29**	22	1.571	0.040	0.97	0.26	-0.005	0.040
Cape Ferguson	**-19**	10	1.696	0.124	2.49	0.22	0.089	0.124
American Samoa	**-14**	22	1.557	0.034	1.96	0.10	0.020	0.034
Christmas Island	**2**	9	1.788	0.140	3.38	0.23	0.128	0.140
Mauna Loa	**19**	22	1.591	0.037	6.85	0.07	-0.013	0.037
Schauinsland	**48**	20	1.548	0.042	13.57	0.36	-0.113	0.046
Point Estevan	**49**	7	1.848	0.314	12.81	0.50	-0.175	0.314
Shetland Islands	**60**	9	1.783	0.106	14.45	0.23	-0.035	0.106
Alert	**82**	19	1.569	0.065	15.54	0.15	0.062	0.065
Mean Values			**1.572**	**0.013**			**-0.001**	**0.013**

Table *Results of straight line fits to quantities derived from monthly measurements of CO2 concentrations from SIO[2] and CSIRO[8] data sources.*

References

[1] See for instance IPCC Climate Change 2007, Synthesis Report, Summary for Policymakers

[2] Keeling, C.D. and T.P. Whorf. 2005. Atmospheric CO_2 records from sites in the SIO air sampling network. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

[3] Marland, G., T.A. Boden, and R. J. Andres. 2007. Global, Regional, and National CO_2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

[4] Kenneth E. Peters, Clifford C. Walters, J. Michael Moldowan 2005. The Biomarker Guide, Cambridge University Press, page 137

[5] Hoefs, J. (1980): *Stable isotope geochemistry, 2nd ed. Minerals and Rocks, 9.* Springer-Verlag, 208 pp

[6] Blasing, T.J., C.T. Broniak, and G. Marland, 2004. Estimates of monthly carbon dioxide emissions and associated $\delta^{13}C$ values from fossil-fuel consumption in the U.S.A. In Trends: A Compendium of Data on Global Change, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A.

[7] Ohmoto, H. (1986): Stable isotope geochemistry of ore deposits. *Reviews in Mineralogy 16,*491-559 and a recent measurement example:-Feely R. A., C. L. Sabine, F. J. Millero, A. G. Dickson , R. A. Fine, C. A. Carlson, J. Toole,T. M. Joyce, W. M. Smethie, A. P. McNichol, and R. M. Key. 2008. Carbon Dioxide, Hydrographic, and Chemical Data Obtained During the R/V *Knorr* Repeat Hydrography Cruise in the Atlantic Ocean: CLIVAR CO_2 Sections A20_2003 (22 September–20 October 2003) and A22_2003 (23 October–13 November, 2003). Ed. A. Kozyr. ORNL/CDIAC-154, NDP-089. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee.

[8] Segalstad, T.V. (1992): The amount of non-fossil-fuel CO_2 in the atmosphere. *American Geophysical Union, Chapman Conference on Climate, Volcanism, and Global Change, March 23-27, 1992, Hilo, Hawaii. Abstracts,* 25.

[9] 3rd IPCC Report http://www.grida.no/climate/ipcc_tar/wg1/097.htm#fig31

[10] Keeling, C.D. and T.P. Whorf. 2004. Atmospheric CO_2 concentrations derived from flask air samples at sites in the SIO network. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A.

[11] Steele, L. P., P. B. Krummel and R. L. Langenfelds. 2007. Atmospheric CO_2 concentrations from sites in the CSIRO Atmospheric Research GASLAB air sampling network (August 2007 version). In Trends: A Compendium of Data on Global Change, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A.

[12] Allison, C.E., R.J. Francey and P.B. Krummel. $\delta^{13}C$ in CO_2 from sites in the CSIRO Atmospheric Research GASLAB air sampling network, (April 2003 version). In Trends: A Compendium of Data on Global Change, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A.

[13] Beck, E.G., 2008. 50 Years of Continuous Measurement of CO_2 on Mauna Loa, Energy & Environment 19, 7.pp. 1017-1028.

[14] Keeling, C.D, A.F. Bollenbacher, and T.P. Whorf. 2005. Monthly atmospheric $^{13}C/^{12}C$ isotopic ratios for 10 SIO stations. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

[15] Segalstad, T.V., Private communication

[16] http://www.cdc.noaa.gov/people/klaus.wolter/MEI/

[17] Uhse, K., M. Schmidt and I. Levin. 1998. Atmospheric CO_2 records from sites in the UBA air sampling network. In Trends: A Compendium of Data on Global Change. Carbon Dioxide

Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

[18] http://cdiac.ornl.gov/ftp/ndp058/LAT.TAB

[19] 3rd IPCC Report http://www.grida.no/climate/ipcc_tar/wg1/097.htm#fig31

[20] Manning, M.R., and W.H. Melhuish. 1994. Atmospheric $\delta^{14}C$ record from Wellington. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

[21] Levin, I., B. Kromer, H. Schoch-Fischer, M. Bruns, M. Münnich, D. Berdau, J.C. Vogel, and K.O. Münnich, 1994. $\delta^{14}CO_2$ record from Vermunt. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.