

## CHAPTER 4

### *Data for Carbon Cycle Model Testing*

In order to have a common data set available for testing and validation of carbon cycle models the most relevant data for these purposes have been brought together in this chapter. It is recommended that these data are used rather than earlier compilations in order to permit as close a comparison between different models as possible. As more data become available these will naturally also be used, but the present data set might serve as a starting point for a more careful comparison than has been the case before.

### *Atmospheric Carbon Dioxide Concentration and the Observed Airborne Fraction.*

R.B. BACASTOW and C.D. KEELING

The increase per year in carbon dioxide concentration in the atmosphere is one of the important observations in understanding the global carbon cycle. In a discipline where firm numbers are not easy to come by, it is probably also one of the better determined observations.

The average increase per year, together with data on production of fossil fuel CO<sub>2</sub>, permits calculation of the observed airborne fraction. If a linear model of the reservoirs involved in the carbon cycle is at steady state when an exponential fossil fuel input is started, the airborne fraction approaches a constant after a time of several exponential time constants (Bacastow and Keeling, 1979). The airborne fraction is a useful concept because it will remain constant as long as the model remains linear and the input exponential.

However, the biosphere, during the last century, may have been a large source of CO<sub>2</sub> to the atmosphere. If so, the observed airborne fraction will be less than the airborne fraction that should be associated with models without a biota source during the last century (see Bacastow and Keeling, chapter 5).

## MAUNA LOA AND SOUTH POLE DATA

Monthly averages of the concentration of atmospheric CO<sub>2</sub> at Mauna Loa Observatory (figure 1) have been obtained from a continuously operated infrared gas analyzer at 3397 meters above sea level on the shoulder of Mauna Loa on the island of Hawaii. The analyzer has been operated in collaboration with the United States National Oceanic and Atmospheric Administration (NOAA). Tabulated values of the CO<sub>2</sub> concentration (Table 1) are in mole fraction, relative to dry air, and are corrected for reference gas system drift, use of nitrogen standards to measure air, and infrared analyzer nonlinearity (1974 manometric calibration). The best value to use for reference system drift, after 1974, will not be known until the calibration is repeated; this could introduce a systematic error, approximately the same at all stations, of a few tenths ppm by 1978. This error would be proportional to time after 1974.

We are presently studying the 20 year record for systematic errors such as, for example, arise from contamination of air intake lines. Some problems have been discovered, but we do not expect the monthly averages to be changed more than a few tenths ppm as a result of this study.

Similar data for the South Pole have been obtained principally from 5 liter evacuated flasks, three of which, in recent years, were filled twice monthly by NOAA personnel and returned to Scripps Institution for analysis. The tabulated values (table 4) are also in mole fraction with the same corrections as for Mauna Loa. However, the twice monthly data has all been adjusted to the 15th of each month. These data sets, and the manometric calibration of the standard gases, are discussed in a series of publications by Keeling and coworkers (Keeling *et al.*, 1976a and 1976b).

The data for both Mauna Loa and the South Pole have been fit to a trend, represented by a spline (figures 2 and 4, tables 2 and 5) and an average seasonal effect, calculated by averaging the differences between the data and the spline trend for each month of the year (tables 3 and 6). Since the starting point of the fitting procedure for the Mauna Loa data is monthly averages, the seasonal effect (table 3) is not quite as large in amplitude as if all daily averages were adjusted to the 15th of the month, as was done for the South Pole data. However, the trends are not significantly effected by this difference in analysis.

## OBSERVED AIRBORNE FRACTION

We define the observed airborne fraction to be the observed CO<sub>2</sub> increase at a particular station divided by the increase which would have occurred if the atmosphere were well mixed and if all the carbon in fossil fuel produced during the period of the observed CO<sub>2</sub> increase were converted to CO<sub>2</sub> and this CO<sub>2</sub> stayed in the atmosphere. Consequently, the observed airborne fraction depends on the location and period of observation.

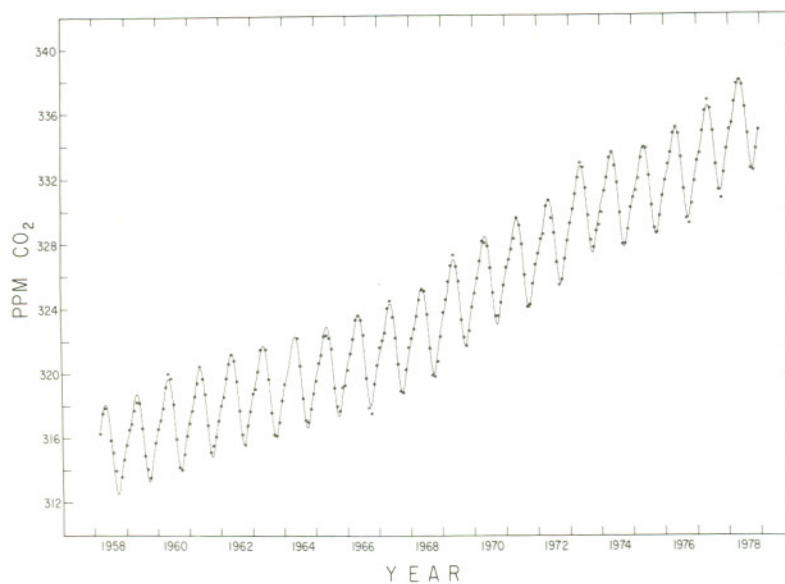


Figure 1: Concentration of atmospheric CO<sub>2</sub> at Mauna Loa Observatory, Hawaii, 19.5°N, 155.6°W. Dots indicate monthly averages based on continuous measurements.

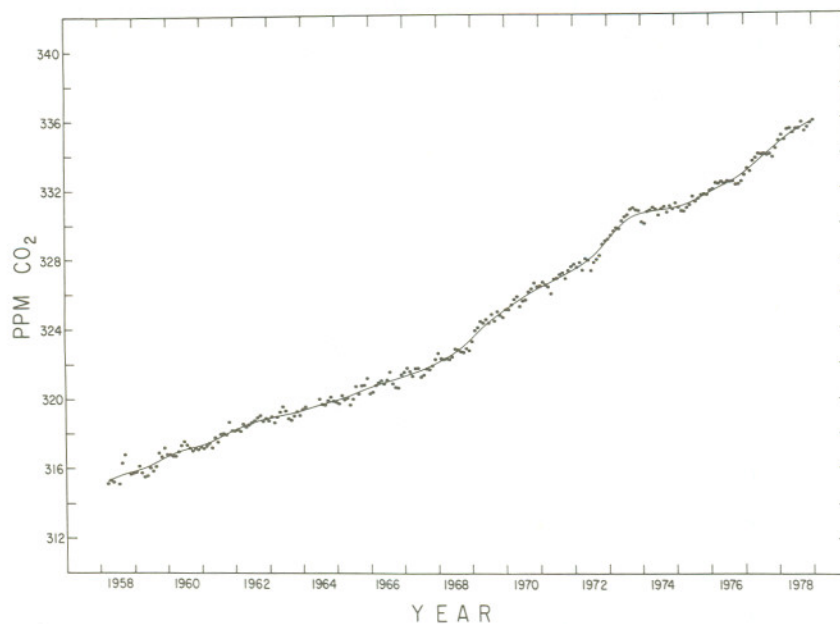


Figure 2: Concentration of atmospheric CO<sub>2</sub> at Mauna Loa Observatory, Hawaii, with seasonal effect removed. Dots are seasonally adjusted monthly averages. The smooth curve is a spline fit to the dots.

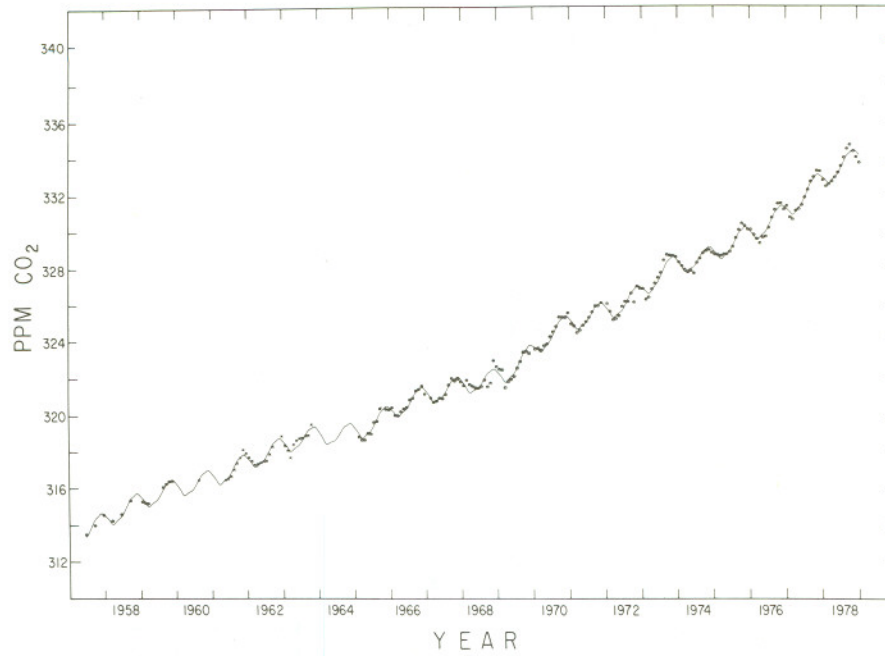


Figure 3: Concentration of atmospheric CO<sub>2</sub> at the South Pole. Dots indicate averages of flask measurements adjusted to the 15th of each month.

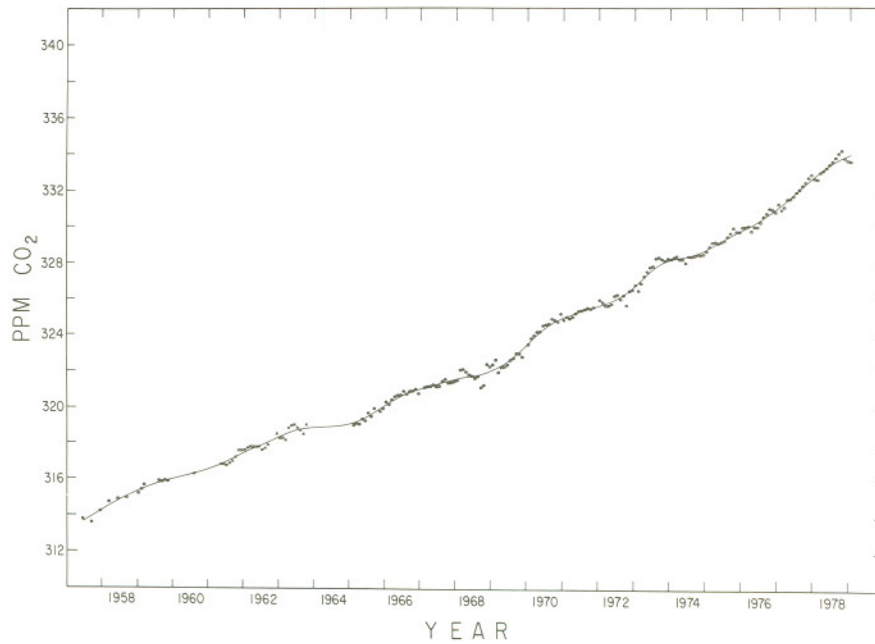


Figure 4: Concentration of atmospheric CO<sub>2</sub> at the South Pole with seasonal effect removed. Dots are seasonally adjusted points from Figure 3. The smooth curve is a spline fit to the dots.

The CO<sub>2</sub> increase each year, however, is not uniform; it is much larger in some years than in other years (Machta, Hansen and Keeling, 1977). Some aspect of the Southern Oscillation appears to be responsible for part of this variation (Bacastow, 1976). However, other factors, such as perhaps volcanic explosions, also apparently influence the data (Bacastow, 1979). As the record grows longer, the effect on the observed airborne fraction of these irregularities is reduced. To some extent, one may lessen the influence of the Southern Oscillation by calculating the airborne fraction between approximately equivalent phases of the Southern Oscillation.

The observed airborne fractions between Jan. 1, 1959, and Jan. 1, 1978, are 0.548 at Mauna Loa and 0.505 at the South Pole (table 7). Both these dates are approximately one year after minima in a Southern Oscillation index (Bacastow, *et al.*, 1980).

The carbon production from fossil fuel during this period is as compiled by Rotty (this volume). If a correction is made for apparently erroneous values for coal production in China during 1958, 59, and 60, as was done by Keeling (1973) and called the "Trend A" correction, total carbon production during these years is reduced by 38, 79, and 132 million metric tons, respectively. The observed airborne fractions are then negligibly changed (table 7).

The difference between the observed airborne fractions at Mauna Loa and the South Pole is consistent with a model in which most of the fossil fuel is consumed in the Northern Hemisphere and there is a delay in mixing between hemispheres (Bacastow and Keeling, this volume).

See authors additional note on page 112.

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Table 1. Monthly average concentration of atmospheric CO<sub>2</sub> at Mauna Loa Observatory, Hawaii, mole fraction (ppm).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1958			316.33	317.59	317.93		315.92	315.15	314.02		313.64	314.71
1959	315.62	316.59	316.94	317.77	318.29	318.24	316.67	314.96	314.12	313.58	315.14	315.77
1960	316.62	317.16	317.90	319.21	320.02	319.74	318.15	316.00	314.23	314.07	315.04	316.19
1961	316.97	317.74	318.63	319.43	320.47	319.71	318.78	316.84	315.16	315.56	316.14	317.13
1962	318.06	318.59	319.74	320.63	321.21	320.83	319.55	317.75	316.27	315.62	316.84	317.70
1963	318.80	319.08	320.15	321.49	322.25	321.50	319.67	317.61	316.25	316.17	317.01	318.36
1964	319.37					322.19	320.49	318.48	317.13	317.02	317.84	318.78
1965	319.55	320.65	321.15	322.31	322.35	322.19	321.53	319.13	317.99	317.70	319.15	319.27
1966	320.22	321.23	322.13	323.30	323.57	323.29	322.36	319.71	317.89	317.54	319.36	320.51
1967	321.60	322.03	322.50	324.00	324.46	323.46	322.19	320.57	318.91	318.81	320.24	321.59
1968	322.15	322.73	323.50	324.52	325.11	325.06	323.62	321.55	319.89	319.80	320.73	322.25
1969	323.73	324.53	325.62	326.58	327.24	326.53	325.63	323.28	322.21	321.67	322.61	324.07
1976	324.91	325.81	326.85	328.07	327.97	327.77	326.44	324.92	323.49	323.50	324.34	325.39
1971	326.46	326.93	327.56	328.23	329.51	329.04	327.87	326.00	324.06	324.20	325.48	326.62
1972	327.30	328.20	328.50	330.22	330.58	329.48	328.56	326.77	325.39	325.72	326.97	328.09
1973	329.16	330.02	330.95	331.95	332.85	332.58	331.30	329.64	328.12	327.67	328.69	329.05
1974	329.82	331.13	331.94	333.16	333.51	332.67	331.64	329.79	327.86	327.90	328.79	330.13
1975	330.74	331.16	331.88	333.14	333.76	333.74	332.06	330.26	328.85	328.57	329.60	330.84
1976	331.77	332.77	333.46	334.64	334.98	334.61	333.19	331.25	329.44	329.15	330.36	331.73
1977	332.97	333.43	334.76	335.99	336.67	336.13	334.77	332.73	331.18	330.68	332.24	333.69
1978	334.85	335.23	336.54	337.65	337.86	337.57	336.20	334.59	332.48	332.37	333.66	334.82

Table 2. Smoothed monthly averages at Mauna Loa with seasonal effect removed, mole fraction (ppm).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1958			315.25	315.32	315.39	315.46	315.52	315.58	315.64	315.69	315.74	315.78
1959	315.82	315.87	315.92	315.98	316.04	316.12	316.20	316.29	316.38	316.47	316.55	316.63
1960	316.71	316.78	316.84	316.91	316.96	317.01	317.06	317.10	317.14	317.18	317.22	317.27
1961	317.32	317.38	317.44	317.52	317.59	317.68	317.76	317.84	317.93	318.01	318.09	318.16
1962	318.23	318.30	318.37	318.43	318.50	318.56	318.61	318.66	318.71	318.75	318.80	318.83
1963	318.87	318.91	318.94	318.98	319.01	319.04	319.08	319.11	319.15	319.19	319.24	319.29
1964	319.34	319.39	319.44	319.50	319.55	319.60	319.64	319.69	319.74	319.78	319.83	319.87
1965	319.92	319.97	320.02	320.08	320.14	320.21	320.28	320.35	320.42	320.49	320.55	320.61
1966	320.67	320.73	320.78	320.83	320.88	320.94	320.98	321.03	321.09	321.14	321.20	321.25
1967	321.31	321.37	321.42	321.48	321.53	321.60	321.66	321.73	321.81	321.88	321.97	322.05
1968	322.13	322.22	322.31	322.40	322.50	322.61	322.73	322.85	322.99	323.12	323.28	323.43
1969	323.59	323.75	323.89	324.05	324.19	324.33	324.46	324.59	324.71	324.83	324.95	325.06
1970	325.17	325.29	325.39	325.50	325.61	325.71	325.81	325.92	326.02	326.11	326.20	326.28
1971	326.36	326.44	326.52	326.60	326.68	326.76	326.85	326.94	327.03	327.11	327.21	327.30
1972	327.40	327.50	327.60	327.72	327.84	327.98	328.12	328.29	328.47	328.65	328.84	329.03
1973	329.22	329.41	329.57	329.74	329.90	330.04	330.16	330.27	330.36	330.43	330.49	330.54
1974	330.57	330.61	330.64	330.66	330.69	330.71	330.73	330.75	330.78	330.80	330.83	330.87
1975	330.91	330.95	331.00	331.07	331.14	331.21	331.29	331.38	331.47	331.56	331.65	331.74
1976	331.83	331.92	332.00	332.09	332.17	332.25	332.34	332.43	332.53	332.63	332.75	332.87
1977	333.00	333.14	333.27	333.41	333.55	333.69	333.83	333.97	334.11	334.25	334.39	334.53
1978	334.66	334.80	334.91	335.03	335.14	335.24	335.34	335.44	335.53	335.62	335.71	335.80

Table 3. Average seasonal effect at Mauna Loa, mole fraction (ppm)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	-0.12	0.51	1.25	2.31	2.76	2.25	0.86	-1.11	-2.72	-3.04	-1.98	-0.98



Table 5. Smoothed monthly data at South Pole adjusted to 15th of month, mole fraction (ppm).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1957						313.71	313.81	313.91	314.01	314.10	314.21	314.31
1958	314.41	314.51	314.60	314.69	314.78	314.87	314.96	315.04	315.12	315.20	315.28	315.35
1959	315.43	315.50	315.56	315.63	315.69	315.75	315.81	315.86	315.91	315.96	316.00	316.05
1960	316.09	316.13	316.17	316.21	316.25	316.30	316.34	316.38	316.43	316.48	316.53	316.58
1961	316.63	316.69	316.75	316.81	316.88	316.96	317.03	317.11	317.20	317.29	317.37	317.46
1962	317.54	317.62	317.68	317.76	317.82	317.89	317.96	318.03	318.11	318.18	318.26	318.34
1963	318.42	318.49	318.56	318.63	318.69	318.74	318.78	318.82	318.85	318.88	318.90	318.91
1964	318.93	318.94	318.95	318.96	318.96	318.97	318.99	319.00	319.02	319.04	319.07	319.11
1965	319.15	319.20	319.25	319.32	319.40	319.48	319.57	319.67	319.78	319.88	319.99	320.09
1966	320.20	320.31	320.40	320.50	320.59	320.68	320.75	320.82	320.89	320.94	321.00	321.05
1967	321.10	321.15	321.19	321.24	321.28	321.33	321.37	321.42	321.46	321.51	321.55	321.59
1968	321.63	321.67	321.70	321.73	321.75	321.77	321.80	321.83	321.87	321.92	321.98	322.04
1969	322.11	322.19	322.27	322.36	322.45	322.56	322.68	322.81	322.95	323.09	323.26	323.40
1970	323.57	323.73	323.88	324.04	324.19	324.33	324.45	324.57	324.68	324.77	324.86	324.94
1971	325.01	325.07	325.13	325.19	325.25	325.30	325.36	325.41	325.46	325.51	325.57	325.62
1972	325.67	325.72	325.77	325.84	325.90	325.98	326.06	326.15	326.25	326.36	326.49	326.63
1973	326.77	326.93	327.07	327.24	327.39	327.54	327.68	327.81	327.92	328.01	328.09	328.15
1974	328.20	328.24	328.27	328.30	328.33	328.36	328.40	328.44	328.49	328.55	328.61	328.69
1975	328.77	328.86	328.94	329.04	329.13	329.22	329.32	329.41	329.50	329.59	329.68	329.76
1976	329.84	329.92	330.00	330.08	330.17	330.27	330.37	330.48	330.60	330.71	330.83	330.95
1977	331.07	331.20	331.33	331.47	331.61	331.76	331.90	332.05	332.21	332.35	332.50	332.63
1978	332.77	332.90	333.02	333.15	333.27	333.39	333.49	333.59	333.69	333.77	333.84	333.91
1979	333.98											

Table 6. Average seasonal effect at South Pole, mole fraction (ppm).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	0.07	-0.22	-0.49	-0.44	-0.37	-0.30	-0.10	0.15	0.39	0.45	0.53	0.33

Table 7. Calculation of Airborne Fraction at Mauna Loa and the South Pole.

	Mauna Loa	South Pole
Jan. 1, 1978* (ppm)	334.60	332.70
Jan. 1, 1959* (ppm)	315.80	315.39
Difference (ppm)	18.80	17.31
Fossil fuel production (g)		$72784 \cdot 10^{12}$
Increase if all produced CO <sub>2</sub> stayed in atm. (ppm)		34.29
Airborne fraction	0.548	0.505
Fossil fuel production with "Trend A,, correction (g)		$72573 \cdot 10^{12}$
Increase if all produced CO <sub>2</sub> stayed in atm. (ppm)		34.19
Airborne fraction	0.550	0.506

\*Calculated by averaging Dec. 15 and Jan. 15 values in Tables 2 and 5.

Authors additional note:

A new calibration of infrared analyzer response, completed in december 1980, establishes a change in rate of drift in the system of primary standards since 1974 from the rate assumed previously. The new drift rate varies with concentration. The data of tables 1, 2, 4, and 5 can be approximately corrected by adding to each entry after 1 July, 1974:

$$\Delta = -0.00023 (X - 345.74) M$$

where X is the mole fraction in ppm listed in the table and M is the number of months since 1 July, 1974.