

Atmospheric carbon dioxide measurements in the Australian region: data from surface observatories

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ABSTRACT

Observations of the atmospheric carbon dioxide (CO_2) concentration made at surface locations in the Australian and Antarctic regions are presented for the period 1976–1984. These observations complement those already reported which were based on samples collected from aircraft throughout the troposphere and lower stratosphere in the same region.

Data are presented for 4 sites, Cape Grim ($40^\circ 41' \text{S}$; $144^\circ 41' \text{E}$), Mawson ($67^\circ 37' \text{S}$; $62^\circ 52' \text{E}$), Macquarie Island ($54^\circ 29' \text{S}$; $158^\circ 58' \text{E}$) and Wilbinga ($31^\circ 25' \text{S}$; $115^\circ 33' \text{E}$) and for air samples collected on board ships traversing the Southern Ocean. By far the most comprehensive monitoring program described is that for the Cape Grim Observatory, where continuous in situ observations have been made since 1976.

Methods are considered for the selection of data to represent the baseline or background concentration and a description is given of the natural variability of CO_2 concentration, including within-hour and diurnal variability, seasonal cycles, interannual and secular trends. The average rate of concentration increase over the period represented by the data was 1.5 ppmv yr^{-1} .

A comparison is made between the selected data from these programs and similar data sets collected at Amsterdam Island and in New Zealand by other international projects.

1. Introduction

The observations reported in this paper were made as part of a comprehensive monitoring program which was commenced by our laboratory in 1972. The objective was to describe the temporal and spatial variability of the atmospheric carbon dioxide (CO_2) concentration in the Australian region and, in conjunction with data collected by other laboratories in a comparable way, to describe the CO_2 distribution on a hemispheric and global scale. The data were required for identification and estimation of large-scale carbon fluxes and thus the elucidation of details of the global carbon cycle.

Data based on measurements of the CO_2 concentration in air samples collected by aircraft have been presented previously (Pearman and

Beardsmore, 1984). The present paper deals with those CO_2 observations made at the four surface stations shown in Fig. 1 (Mawson, Macquarie Island, Wilbinga and Cape Grim) and on ships crossing the Southern Ocean between Australia and Antarctica.

It aims to describe the measurement programs at these surface stations and interpret the major features of the data. Applications of the data to global studies can be seen in papers such as those of Fraser et al. (1983), Pearman et al. (1983b) and Pearman and Hyson (1986).

2. The measurement program

2.1. Sampling sites and techniques

Detailed descriptions of the sites and tech-

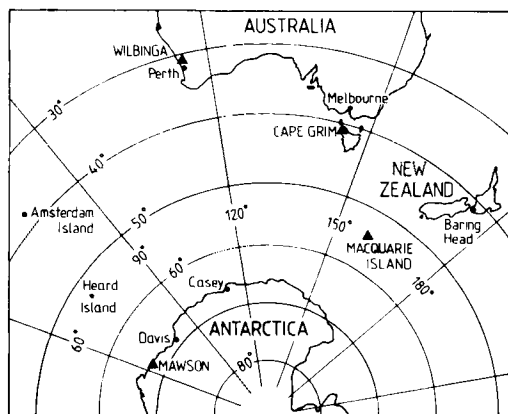


Fig. 1. A map of the location of the observatory sites used in the CSIRO surface monitoring program for atmospheric carbon dioxide.

niques used in collecting the CO₂ data published in this paper, are given elsewhere in a technical report (Beardsmore et al., 1984). They can, however, be summarized as follows.

2.1.1. Cape Grim (40°41'S; 144°41'E). The Australian Baseline Atmospheric Observatory at Cape Grim is part of the Australian contribution to the UNEP/WMO Background Air Pollution Network. It is a station which undertakes a comprehensive program of observations of the constituents of the background atmosphere for the purposes of (a) identifying trends in constituents that may be of climatic significance (b) describing the distribution of constituents both temporally and spatially, in conjunction with other stations of the network, for the purpose of improving understanding of biogeochemical cycles, and (c) using the data in studies of large-scale atmospheric dynamics (Pearman, 1982).

The observatory is located near the top of a 95 m promontory on the western side of the northwestern tip of Tasmania. In this situation it is well sited to sample southwesterly air of maritime origin which has suffered no recent modification due to terrestrial-biospheric or anthropogenic activities. Investigations indicate that the monthly frequency of winds from this quadrant (180°–270°) can exceed 50% with a greater proportion usually being experienced in summer than in winter (see Baseline, 1981). When monitoring activities commenced in April 1976, the analysis equipment was temporarily housed in a large caravan situated near the cliff-top. With the

completion of a permanent station building in 1981, a new set of equipment was built and installed and, after an interval of comparison of the two systems, the old equipment was dismantled and used as back-up instrumentation in the new laboratory. In this paper we refer to the temporary installation as Mark I and that in the permanent laboratory as Mark II.

The primary CO₂ analysis system at Cape Grim is based on an in situ nondispersive infrared (NDIR) gas analyser, sample air being pumped to it from an inlet approximately 3 m above the highest part of the cape in the case of the temporary system and in the permanent laboratory, from a main air intake whose inlet is 10 m above the roof of the building. Since the inception of the program, all gases have been dried either chemically or cryogenically before entry into the analyser. The possibility of small errors due to chemical drying is discussed later in Subsection 3.4.4. The response of the analyser to the CO₂ concentration in the dried sample is compared to that for two Tertiary Standard (span) gases which are automatically supplied to the instrument at regular (usually hourly) intervals. As the span gas CO₂ concentrations are known, the CO₂ in the sample can then be interpolated. By ensuring that the analyser responses of the two span gases are respectively higher and lower than that of the sample air, and that the spans differ by no more than about 10–12 ppmv (parts per million by volume) of CO₂ from each other, we estimate that the mean hourly CO₂ concentration of the sample can be found by this method to a precision of 0.1–0.2 ppmv (Beardsmore et al., 1978; Pearman et al., 1983a). In the course of the program at Cape Grim four different NDIR gas analysers have been used. The details of these instruments are included in Table 1.

Throughout the program a separate pump unit incorporating a chemical drying system, has been used at intervals to collect air samples in ½ l glass flasks similar to those used in the Australian CO₂ sampling program from aircraft (see Beardsmore et al., 1978; Pearman et al., 1983a for details). These types of pumps and chemical drying systems have also been used to fill the ½ l glass flasks collected in the Mawson, Wilbinga and ship-board programs (see later). A separate air intake at the same height as that of the in situ equip-

Table 1. *Details of the non-dispersive infra-red carbon dioxide gas analysers used in the surface CO₂ monitoring program*

Make and model	Serial no.	Detector type	Period of use	Carrier gas correction factor
Cape Grim				
UNOR 5B	5-0599	Series	01.04.76–24.06.76	0.9808 + 0.37E-5C
UNOR 2	631478	Series	13.09.76–26.09.77	0.9854 + 0.28E-5C
			07.12.79–14.04.80	
			23.04.80–02.05.80	
URAS 2T	30107275	Parallel	29.09.77–07.12.79	1.0130 + 1.16E-5C
			14.04.80–23.04.80	
			02.05.80–30.11.81	
			13.07.83–30.11.83	
			21.09.84–	
URAS 2T	30827270	Parallel	04.06.81–13.07.83	1.0125 – 0.23E-5C
			30.11.83–21.09.84	
Macquarie Island				
ADC	2020	Parallel	April '79–	1.0106 + 0.77E-5C

Carrier gas correction factor is the factor by which apparent concentrations must be multiplied to obtain true concentrations when the analyser is calibrated with CO₂/N₂ standards. It takes the form $a + bC$, where C is the apparent atmospheric CO₂ concentration.

ment was used for flask filling in the temporary installation whereas, in the permanent laboratory, both the flask filling pump and the in situ analyser draw air from the same main intake. The flasks are analysed for CO₂ at our central laboratory (Aspendale, Melbourne) using the equipment and techniques employed in the aircraft monitoring program.

2.1.2. Mawson (67°37'S; 62°52'E). In late 1977, a CO₂ sampling program was initiated at Mawson, one of the three permanent research stations operated by the Antarctic Division of the Australian Department of Science and Technology (DST) on the Antarctic continent. Mawson is located on a narrow rocky area between the head of a small, deep-water harbour and the edge of the continental ice sheet. Strong southeasterly katabatic winds from the ice plateau prevail most of the year (Betts, 1981). Single or pairs of samples in $\frac{1}{2}$ l glass flasks are collected once or twice a month from locations at the upwind edge of the station so that no anthropogenic contamination is likely. Originally the observer collected the samples outdoors with a portable unit but, since March 1980, the pump has been permanently located in one of the buildings and the

samples collected through a fixed inlet about 0.5 m above the roof level. The sample flasks are stored in wooden cases until they can be returned to the laboratory at Aspendale on the annual supply ships for analysis.

2.1.3 Macquarie Island (54°29'S; 158°58'E). Macquarie Island is located in the sub-Antarctic westerly wind belt of the Southern Ocean. The research station operated by the Antarctic Division of DST is located on a low, narrow isthmus at the northern end of the island (Betts, 1981). Early in 1979 a CO₂ monitoring program based on an in situ NDIR analyser, was commenced. Owing to the difficulties of supplying the large quantities of calibration gases required for continuous operation, the system is only activated for up to 30 h on 3 or 4 days each month. These periods are selected to be when an oceanic wind fetch is anticipated at the station in an endeavour to avoid biospheric effects which may be introduced by the flourishing flora on the island. The Macquarie Island CO₂ measurement system is a simpler version of that used at Cape Grim. Sample air is pumped from an intake about 3 m above the ground and chemically dried before being passed to the NDIR analyser, calibrations

with two span gases being automatically performed at hourly intervals. The analyser outputs are recorded by a potentiometric chart recorder from which the data are extracted and hourly mean CO₂ concentrations computed manually. Concurrent meteorological information is readily available as regular observations are made at the station by personnel of the Australian Bureau of Meteorology. Details of the NDIR analyser used at Macquarie Island are included in Table 1.

2.1.4. Southern ocean ships. During each summer season the Australian Antarctic research stations are remanned and supplied by ships chartered by the Antarctic Division of DST (Betts, 1981). On some of these voyages, expedition personnel collect air samples in flasks at intervals across the Southern Ocean between Australia and Antarctica using the type of equipment described earlier and return them to Australia for analysis. Details of the ship's position and meteorological data are recorded at each sampling point.

2.1.5. Wilbinga (31°25'S; 115°33'E). A minor CO₂ measurement program was carried out between 1979 and 1981 at Wilbinga, on the Australian west coast about 75 km north of Perth in cooperation with the Western Australian Department of Conservation and the Environment. The sampling site was on the coastal dunes approximately 100 m inland from the Indian Ocean. Land elevation rarely exceeds 100 m for more than 30 km from the site and vegetation in the vicinity is restricted to a sparse cover of grass and low shrubs. A group of six $\frac{1}{2}$ l flasks of dried air was collected at approximately monthly intervals through an inlet about 3 m above ground level and returned to the CSIRO laboratory at Aspendale for analysis.

2.2. Calibration and carrier-gas corrections

The NDIR CO₂ analysers used in all of these surface monitoring programs were calibrated using locally-manufactured Tertiary Standards which had themselves been calibrated against Secondary Standards obtained from the WMO CO₂ Central Laboratory (Scripps Institution of Oceanography, La Jolla, California). The Tertiary Standards and methods used for determining CO₂ concentrations in flask samples from

Cape Grim, Mawson, Wilbinga and the ships are identical to those described for the aircraft monitoring program (Pearman et al., 1983a; Pearman and Beardsmore, 1984). The logistics involved in supplying the Tertiary Standards used to calibrate the in situ NDIR analysers at Cape Grim and Macquarie Island precluded regular check calibrations against Secondary Standards during their period of use. The gases were therefore carefully calibrated at our laboratory before and after usage. In most cases concentration drifts of <0.4 ppmv were recorded in periods between calibrations (up to 29 months at Macquarie Island) implying an error of $<\pm 0.2$ ppmv during use if linear drift with time is assumed. Complete data on these drifts are to be found in Beardsmore et al. (1984). With the installation in December 1983 of a suite of four stable, well-calibrated "surveillance" gas mixtures, drift rates in the concentrations of any of the Tertiary Standards used at the Cape Grim observatory can now be monitored.

For most of the period of data collection described in this paper, Secondary and Tertiary Standards were mixtures of CO₂ in dry nitrogen (CO₂/N₂) contained in high pressure steel or aluminium tanks. The use of these CO₂/N₂ standards led to all the CO₂ data being in error due to the so-called carrier-gas effect (see e.g. Pearman, 1977; Griffith, 1982). Carrier-gas errors for each NDIR analyser used in the programs described in this paper have been determined by the procedures given in Pearman et al. (1983a) and the appropriate corrections applied to the data sets presented. In November, 1982, in accordance with decisions taken at the WMO meeting of experts on CO₂ measurement (WMO, 1981), Secondary and Tertiary Standards for all CO₂ monitoring programs at our laboratory and at the Cape Grim observatory were changed to CO₂/air mixtures, thus eliminating the problem of carrier-gas errors. The change to CO₂/air calibration gases at Macquarie Island was delayed until supplies were available in mid-October 1983.

The data we present in the paper are published with only a limited number of the Secondary Standards having been recalibrated against the Primary Standards after their periods of usage. We do not believe this will make any significant difference to the data because (a) the calibrations did not use any Secondary Standard which has

shown any systematic drift with respect to the majority of the Secondary Standards we had available during regular intercomparisons and (b) each Tertiary has been calibrated against several Secondary Standards and the combined error of a group of gases is smaller than that for a single tank. All CO₂ data in this paper are presented in the WMO 1981 CO₂ Calibration Scale as defined by the WMO CO₂ Central Laboratory (Bacastow et al., 1982). As all of the Secondary Standards used in the calibration of CO₂ concentrations recorded in this paper were supplied before or soon after 1981, any errors due to the subsequent drifts in Primary Standards at the CO₂ Central Laboratory will be less than 0.1 ppmv for individual tanks and thus insignificant in their effects on the calibration using several tanks of different ages. A preliminary assessment indicates that the data presented here should be increased by ~0.03 ppmv to be comparable with the WMO 1985 CO₂ Calibration Scale.

2.3. The data sets

Complete listings of daily averages of all data obtained at the Cape Grim Observatory to the end of 1982 in the programs described, are given in Beardsmore et al. (1984) along with all "baseline" values from Cape Grim as defined by the selection criteria discussed later in this paper. All flask data from the stations and in situ data for Macquarie Island are given in that same publication. Hourly averages of the Cape Grim selected data set are also available on magnetic tape from the National Climatic Data Center, Asheville, North Carolina and both the total and selected data from the Carbon Data Information Center, Oak Ridge, Tennessee.

3. Cape Grim observations

3.1. Hourly variability

Data collected with the Mark II equipment is stored on magnetic tape as 1-minute averages. Thus for each hour, after allowing for calibration periods and analyser equilibration following gas changes, there are 48 individual estimates of the CO₂ concentration. From these, hourly mean concentrations and standard deviations (σ_m) are calculated. Under conditions where we appear to be measuring concentrations uninfluenced by local surface exchanges (see below), we find that σ_m

is generally <0.1 ppmv. For example, 299 h of such data collected in the winter month of August 1983 showed the average value of σ_m to be 0.054 (standard deviation of $\sigma_m = 0.028$) whilst in January of the same year (summer) 316 h of data yielded an average σ_m of 0.023 ppmv (standard deviation of $\sigma_m = 0.015$). The difference in the precision for these two months actually reflects the fact that the analyser in operation at the station was changed in July 1983 (see Table 1) and instrument 30107275 has a higher inherent noise level than instrument 30827270. These results and experience with the analysers during extensive calibration periods in the laboratory suggest that the precision of the existing CO₂ analyses over time periods of up to one hour is better than 0.1 ppmv.

An initial inspection of data shows that the CO₂ concentration at Cape Grim is variable. To demonstrate this, we have chosen to consider the observations from two months (March and May of 1982; Fig. 2) during which the meteorology was quite different. In March there was a series of frontal passages with the wind tending to persist either from the east or the southwest whereas in May the winds were more consistently from the west and southwest. In both months, however, it is clear that there appears to be a "preferred" CO₂ concentration which often persists for many hours at a time, but about which fluctuations occur. It is also obvious that the "preferred" concentration is generally measured during periods of certain wind directions. This is demonstrated in Fig. 2c where the same data as in Fig. 2b are replotted after exclusion of data collected during conditions of all wind directions other than 190°–280°. In both months the remaining data are seen to represent a rather well-defined concentration level. The importance of wind direction is further illustrated by observing the mean concentration for selected seasons in data aggregated on the basis of wind direction (Fig. 3). The figure clearly shows that higher concentrations are, on average, associated with wind directions over the land. However, it is equally true that these same conditions can represent times of greatest lowering of concentration during daylight hours. Fig. 2b shows periods of steady concentration followed by several days during which nocturnal build-up and daytime draw-down of concentration occurs. The obvious

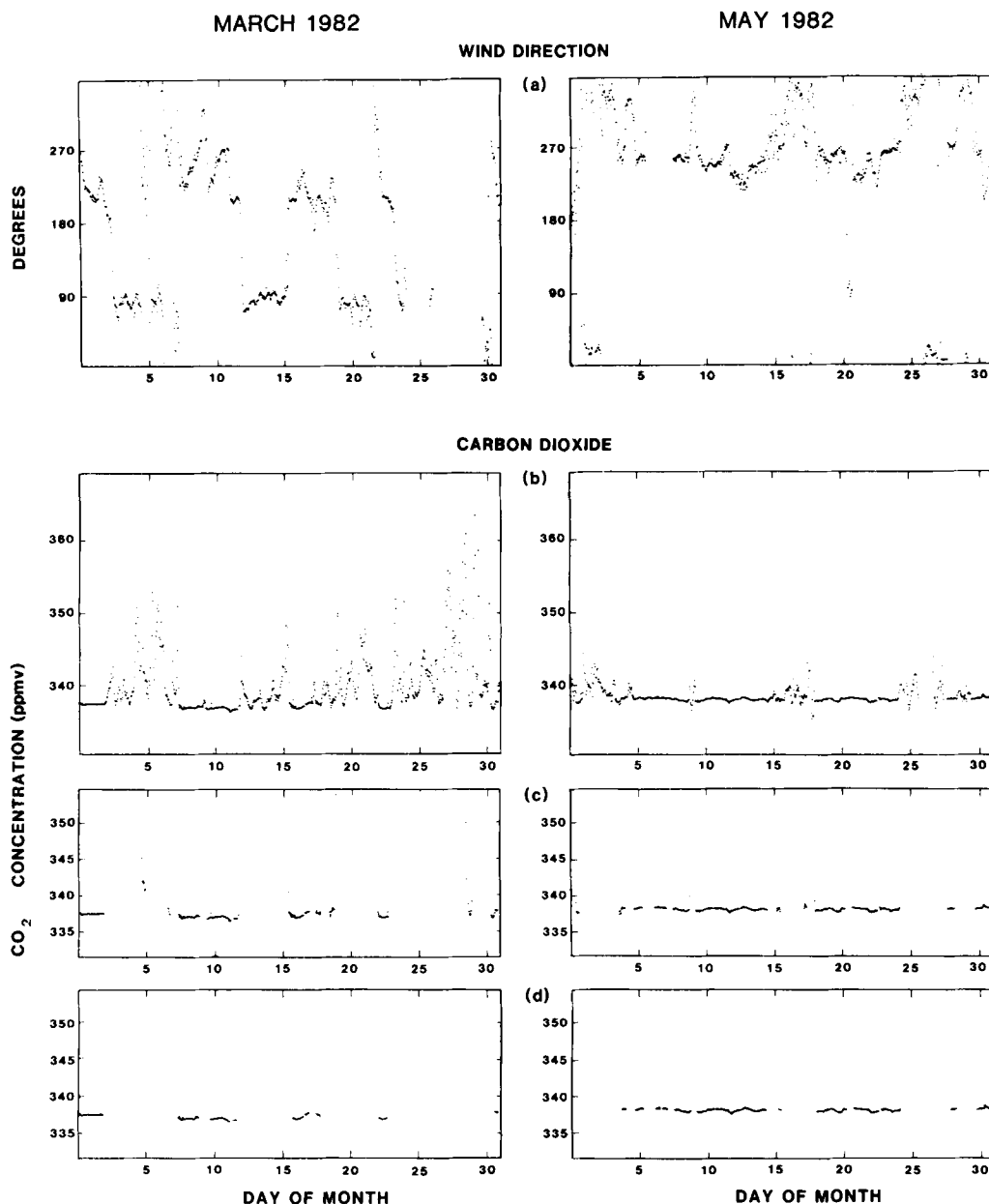


Fig. 2. Hourly mean carbon dioxide concentration and wind direction at the Cape Grim Observatory for two selected months (March, May) in 1982. (a) Wind direction data. (b) The CO₂ data. (c) The CO₂ data selected for wind directions between 190° and 280°. (d) Selected as for (c) and also on the basis of individual hourly values being part of a period of 5 hours during which the concentration deviated by ± 0.3 ppmv.

explanation for such behaviour during periods when the air mass passes over land to the south-east of Cape Grim, is the influence of nocturnal respiratory CO₂ loss and daytime photosynthetic

uptake by the Tasmanian terrestrial vegetation. This has been confirmed by the observation of coincident isotopic variations during such episodes (see Francey, 1985). In addition, Fig. 2b

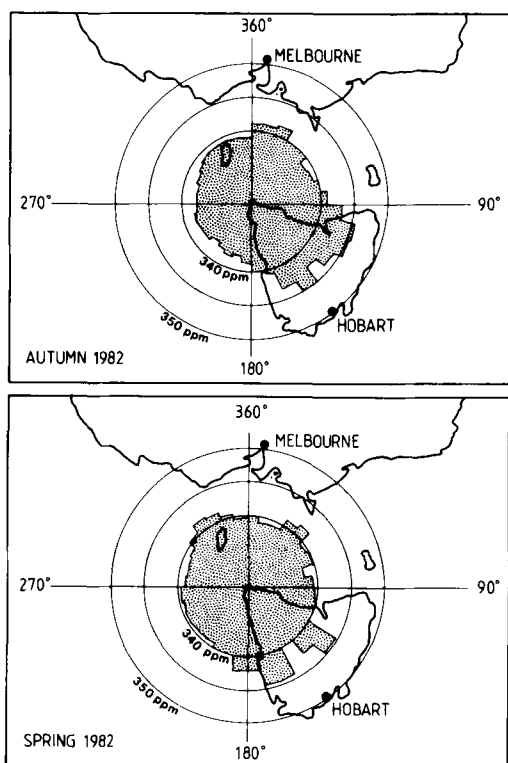


Fig. 3. Seasonally averaged CO_2 concentrations observed at the Cape Grim Observatory, plotted as a function of wind direction, showing the influence of land trajectories on the mean concentration.

illustrates that variability of concentration also occurs during conditions where the winds, as shown in Fig. 2a, are from the north. This probably reflects the influence of the Australian mainland vegetation which has been shown from aircraft observations to influence concentrations through the planetary boundary layer (Pearman and Beardsmore, 1984).

In Fig. 4 we have considered further subsets of the 1982 Mark II data. In this case we have used 2 months of data from each of the two seasons summer (January and February) and winter (July and August), respectively, to contrast the analyses with comparable Mark I data from 1980. Fig. 4b shows that under conditions of southwest winds, there is no discernable diurnal variation in the 1982 data. Indeed the hourly averages for both the summer and winter periods deviate by less than ± 0.2 ppmv. The standard deviations on the individual hourly means are about 0.2 ppmv.

We will show below that the seasonal variation of concentration at Cape Grim is about ± 0.6 ppmv and therefore part of this small variability might even be explained in terms of real inter-monthly changes. Thus, as would be expected in data truly representative of a large air mass, there is consistency of concentration with no evidence of diurnal effects. The data for southwest wind conditions collected in 1980, however, show a distinct diurnal variation of amplitude of about 1.0 ppmv particularly in the winter months. This phenomenon appears to have been present throughout the period when we were using the lower (3 m) air intake. In recent years we have had evidence of the Cape Grim cliff establishing a small standing eddy to a height of about 5 m at the position of the air intake when winds are from the southwest. The short residence time of the air over vegetation on the cliff top in this eddy may be sufficient to effect the CO_2 concentration in the manner observed. Alternatively, coincident with the move to the present facility, some other factor (e.g., temperature stability within the analysis system) may have been changed that influenced the instrument response to ambient air (see below). During 1986 we will be commencing a more detailed study of this phenomenon.

Figs. 4c and 4d show the diurnal variation of data collected during the winter months of same years, but for those periods when the winds were from the southeast, over Tasmania, or from the north. These data illustrate the magnitude of diurnal variations encountered when active terrestrial vegetation exchanges are influencing the CO_2 concentration in the lower layers of the atmosphere as is the case when the winds are from the southeast. Several comments can be made about these data. First, it is clear that the variability of the data collected with winds in these directions is considerably larger than for southwest winds. Second, in both the 1980 and 1982 data, there appears to be some diurnal variability, the daytime concentrations being lower than those at night by approximately 2 ppmv whilst for north winds (Figs. 4c and 4d), the degree of variability even suggests that there are concentration maxima at dawn and dusk. Data for the summer months (not presented here) also show these effects. Third, the average concentration in air from the southeast or north is elevated with respect to that from the southwest

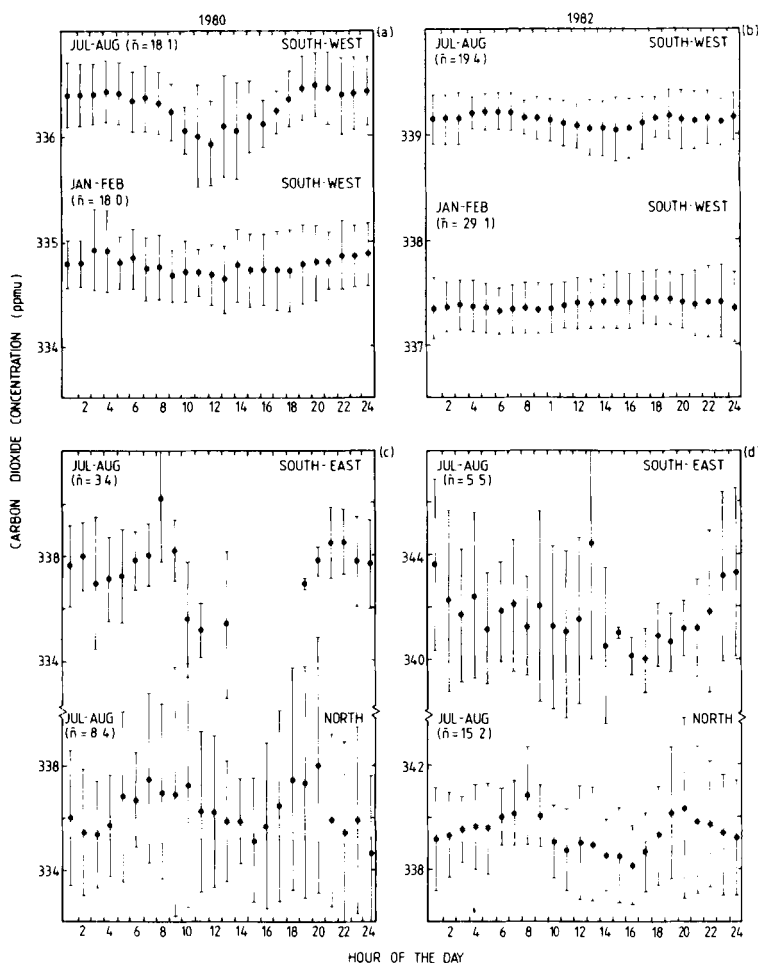


Fig. 4. The diurnal variation of CO₂ concentration at the Cape Grim Observatory averaged for the months of January/February and July/August. (a) For those occasions in 1980 where data were selected as being uninfluenced by local surface exchanges. (b) As for (a) in 1982. (c) For those conditions in 1980 where the wind directions were from either the south-east or the north. (d) As for (c) in 1982. $\bar{n}$ indicates the average number of hourly mean values used to obtain the averages over the two-month periods and the vertical bars indicate the standard deviation of the individual hourly means that make-up the averages.

at the same time of the year by approximately 2.0 and 0.5 ppmv respectively in the winter and 4.0 and 1.5 ppmv respectively in the summer. It is the contribution of these effects, weighted by the relative frequency of the winds from the various directions that leads to monthly average concentrations for all data being in the order of 1.0 ppmv greater than those measured in the south-westerly sector alone (see full data sets in Beardsmore et al., 1984). For example in 1982 the mean concentration for all months for all data was 1.2

(± 0.7) ppmv higher than that for selected data alone.

3.2. Selection criteria

We have referred above to a "preferred" CO₂ concentration that is apparent in the data from continuously recording stations provided that a sufficient period (days to weeks) is inspected. It is reasonable to assume that these periods of concentration constancy reflect the fact that the station is recording a concentration characteristic

of large space scales. This will be considered further in the Discussion. We regard the identification of this concentration as the prime purpose of the CO₂ monitoring program and call such observations, baseline observations, and the conditions under which they are observed, baseline conditions.

The selection of the baseline observations from the total data set is a problem which we have taken very seriously. As pointed out elsewhere (Fraser et al., 1983), because of the magnitude of local vegetation effects at almost all observatories, these have to be removed very carefully so that residual contamination of data will not influence the baseline concentration by more than 0.1–0.2 ppmv. The latter errors in defining the baseline concentration must be regarded as the maximum acceptable for the small meridional gradients in the atmosphere which these observational programs are attempting to define.

Given the obvious relationship between wind direction and persistence of concentration, this appears to be an important method for data selection. To find what range of wind directions might best define Cape Grim baseline conditions, we did an analysis of 1982 data, the first year in which values were available for more than 90% of the time. For that year, Table 2 shows the mean and standard deviations of hourly CO₂ concentrations (σ_h) associated with 10° intervals of wind direction for Autumn (March, April, May) and Spring (September, October, November), the seasons which usually have the least rate of change of CO₂ concentration. When grouped into 90° quadrants (9 sectors) the average standard deviations of the groups of data are lowest in the 190°–280° quadrant for both the seasons suggesting that this might be a satisfactory criterion to use in the identification of baseline data. However, an inspection of Fig. 2c, where concentration is plotted for these directions only, reveals that large deviations sometimes still occur, particularly at the beginning of such periods. Experience suggests that these are occasions when either nocturnal land breezes are followed by daytime ocean winds, several hours being needed before air of high CO₂ concentration is swept away or mixed vertically or the wind speed is sufficiently low for eddies produced by the topography to carry contamination from local sources to the air intake. Irrespective of the cause, further

selection criteria are required to eliminate these events from the data set. One possible method is to set a minimum wind speed above which vertical mixing of the lower atmosphere will be sufficiently intense for the effect of the contaminating events to be minimal. Another way is to insist that the hourly mean CO₂ value remains within a given concentration range for a certain minimum number of hours. Table 3 contains statistics of the hourly mean CO₂ concentration at Cape Grim for the months of March and May 1982 using various combinations of the selection criteria discussed above.

Inspection of the figures in Table 3 shows that (i) for the baseline wind directions previously determined, the CO₂ data variability is, at times, quite large (e.g. $\sigma_h = 1.8$ ppmv for March 1982 where σ_h is the standard deviation of the hourly means) indicating that all non-baseline data are not filtered out; (ii) wind speed criteria alone are of little use as no filtering of land trajectory effects is accomplished and the statistics (mean and σ_h) differ only slightly from those of the total data set; (iii) consistency criteria alone, while decreasing the σ_h somewhat, still do not eliminate the possibility of including data influenced by land trajectories. There is a substantial increase in the standard deviation of the data (especially, for example, in March 1982), by increasing the magnitude of the "window" from ± 0.3 to ± 0.5 ppmv. Doubling the time during which the concentration is required to be consistent decreases the data variability to some extent but the quantity is significantly reduced (again this effect is best seen in the March 1982 example); (iv) combinations of selection criteria, as suggested earlier, appear to minimize σ_h whilst retaining a sufficient amount of data. Wind speed and direction combine to produce a data set in which the standard deviation is 0.4 and 0.2 ppmv for the two example months respectively; (v) when all 3 selection parameters are combined the CO₂ variability is about 0.1–0.3 ppmv. No improvement in standard deviation seems to be attained by using a consistency time of 10 h whereas about 20% of the usable data set is lost; (vi) no appreciable deterioration occurs when only wind direction and consistency are combined and there is a slight increase in the size of the data set. Another advantage in this combination is that it requires only one instrumentally derived parameter

Table 2. *Hourly mean carbon dioxide concentration at the Cape Grim Observatory for the autumn and spring of 1982, and the influence of wind direction*

Wind direction (degrees)	Mean carbon dioxide concentration (σ_n ; no. hours) (ppmv)			
	Autumn (M,A,M)		Spring (S,O,N)	
10-20	341.0 (2.0; 38)	340.7 (3.5; 525)	339.1 (2.1; 46)	340.0 (2.7; 331)
20-30	341.6 (3.9; 34)		339.3 (1.3; 58)	
30-40	340.1 (3.5; 23)		341.6 (4.7; 15)	
40-50	340.1 (2.5; 20)		342.0 (4.7; 17)	
50-60	339.1 (2.9; 39)		339.8 (1.6; 14)	
60-70	339.5 (3.0; 55)		340.0 (2.3; 27)	
70-80	340.1 (3.3; 84)		338.6 (1.7; 36)	
80-90	341.3 (4.4; 113)		339.8 (3.4; 47)	
90-100	343.5 (5.7; 77)		339.8 (2.5; 48)	
100-110	346.0 (5.6; 27)	343.1 (4.6; 181)	340.4 (3.4; 61)	342.6 (4.2; 195)
110-120	345.7 (5.6; 15)		340.2 (4.3; 63)	
120-130	344.2 (4.4; 11)		345.0 (6.6; 23)	
130-140	342.6 (3.9; 10)		343.1 (3.7; 5)	
140-150	345.3 (5.0; 6)		340.4 (1.5; 6)	
150-160	343.5 (6.6; 12)		344.8 (5.5; 8)	
160-170	341.4 (4.0; 18)		344.8 (5.9; 11)	
170-180	340.8 (3.8; 39)		342.5 (3.6; 4)	
180-190	338.9 (2.8; 43)		342.5 (3.0; 14)	
190-200	338.2 (2.4; 97)	338.1 (1.4; 950)	340.3 (0.9; 22)	339.7 (1.3; 780)
200-210	338.6 (2.4; 63)		340.4 (3.1; 27)	
210-220	338.0 (2.5; 58)		339.7 (0.7; 51)	
220-230	337.7 (0.7; 79)		339.7 (1.1; 121)	
230-240	338.0 (0.7; 84)		339.6 (0.3; 108)	
240-250	338.1 (1.6; 98)		339.7 (1.8; 121)	
250-260	338.2 (1.3; 167)		339.4 (0.7; 109)	
260-270	337.9 (0.4; 220)		339.6 (2.0; 95)	
270-280	337.9 (0.5; 84)		338.7 (0.9; 126)	
280-290	337.8 (0.8; 45)	339.0 (1.7; 320)	338.4 (1.6; 275)	339.9 (3.1; 673)
290-300	338.1 (0.8; 25)		338.7 (2.1; 154)	
300-310	338.5 (1.3; 26)		338.9 (2.7; 92)	
310-320	338.7 (1.5; 29)		340.3 (3.7; 58)	
320-330	339.2 (2.3; 43)		341.4 (4.4; 28)	
330-340	339.2 (1.1; 64)		341.0 (3.6; 14)	
340-350	339.4 (1.8; 36)		340.5 (3.9; 34)	
350-360	339.1 (2.1; 52)		339.7 (1.8; 18)	
360-370	341.2 (3.8; 42)		340.5 (4.2; 23)	

thus eliminating the possibility of data losses during periods of anemometer breakdown or maintenance.

Where these combined selection criteria are applied, the mean concentration is lowered from

that obtained using all data by about 3.0 and 0.5 pmv for the March and May examples respectively. In both cases the use of only the wind direction selection criterion reduces the mean concentration by about $\frac{1}{3}$ of this difference (using

Table 3. *The influence of various selection criteria applied to hourly mean carbon dioxide data from the Cape Grim Observatory of the months of March and May, 1982*

Selection criteria	Mean carbon dioxide concentration (σ_h ; no. hours; no. days) (ppmv)	
	March 1982	May 1982
Total data	340.12 (2.87; 726; 31)	338.52 (0.71; 700; 31)
Wind direction 190°–280°	337.92 (1.76; 235; 17)	338.06 (0.15; 391; 26)
Wind speed > 5 ms ⁻¹	340.39 (3.60; 592; 31)	338.55 (0.75; 648; 31)
Consistency:		
5 hr; < ± 0.3 ppmv	337.50 (0.59; 227; 19)	338.14 (0.32; 489; 28)
5 hr; < ± 0.5 ppmv	337.98 (1.16; 298; 25)	338.23 (0.51; 533; 29)
5 hr; < ± 1.0 ppmv	338.37 (1.33; 457; 29)	338.30 (0.68; 589; 31)
10 hr; < ± 0.3 ppmv	337.31 (0.45; 157; 12)	338.04 (0.15; 421; 25)
10 hr; < ± 0.5 ppmv	337.47 (0.58; 191; 15)	338.07 (0.19; 473; 26)
10 hr; < ± 1.0 ppmv	338.02 (1.24; 316; 24)	338.18 (0.34; 533; 28)
W/D : 190°–280°	337.34 (0.42; 205; 14)	338.07 (0.15; 375; 25)
W/S : > 5 ms ⁻¹		
W/D : 190°–280°	337.19 (0.32; 172; 12)	338.05 (0.14; 358; 25)
W/S : > 5 ms ⁻¹		
Cons.: 5 h; < ± 0.3 ppmv		
W/D : 190°–280°	337.12 (0.24; 123; 8)	338.03 (0.14; 299; 22)
W/S : > 5 ms ⁻¹		
Cons.: 10 h; < ± 0.3 ppmv		
W/D : 190°–280°	337.22 (0.36; 180; 13)	338.03 (0.16; 371; 20)
Cons.: 5 h; < ± 0.3 ppmv		
W/D : 190°–280°	337.12 (0.24; 123; 8)	338.03 (0.14; 307; 22)
Cons.: 10 h; < ± 0.3 ppmv		

32 and 56% of the data respectively). Consistency (5 h; < 0.3 ppmv) reduces the March mean from 340.12 to 337.50 ppmv while together with wind direction the mean is reduced to 337.22 ppmv. For both months, the various sets of combined selection criteria produce monthly means that differ by no more than approximately 0.1 ppmv.

3.3. Selected data set

All tentative in situ CO₂ baseline sets of data from Cape Grim which have been published to date, have been selected using the combination of wind direction 190°–280° and wind speed > 5 m s⁻¹. In the light of the foregoing analysis however, the selection criteria defining in situ baseline conditions have been amended to wind direction 190°–280° and the individual hourly mean to be part of a sequence of 5 consecutive hours

during which the CO₂ concentration varies by < ± 0.3 ppmv. The filtering efficiency of these criteria is demonstrated when the final data for March and May 1982 in Fig. 2d are compared with the wind direction filter only in Fig. 2c. The hourly mean data are in the process of being resubmitted to the archiving agencies with the baseline data selected in this way. The monthly mean baseline CO₂ concentrations selected on the basis of these new criteria are presented in Table 4.

The complementary air samples in flasks described previously, were not always collected on days when baseline conditions prevailed. Since CO₂ consistency can not be used in these instances, wind direction 190°–280° and wind speed > 5 m s⁻¹ have been retained as the selection criteria to define baseline conditions for these

Table 4. *Monthly mean baseline carbon dioxide concentration at the Cape Grim Observatory*

(a) From Mark I in situ equipment in the temporary laboratory corrected as described in the text after September 1978
 (b) From Mark II in situ equipment in the new permanent laboratory (c) From flasks collected on the Mark I sampling equipment in the temporary laboratory and analysed at CSIRO, Aspendale; and (d) From flasks collected on the Mark II sampling equipment in the permanent laboratory and analysed at CSIRO, Aspendale

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
(a)												
1976	—	—	—	329.4 0.1; 5	328.9 0.1; 7	328.9 0.4; 8	—	—	330.9 0.3; 5	—	331.0 0.4; 12	330.6 0.3; 14
1977	330.9 0.5; 17	330.7 0.5; 11	331.0 0.1; 3	330.8 0.2; 12	—	331.7 0.1; 10	332.0 0.3; 7	—	—	332.9 0.3; 15	332.9 0.2; 20	332.3 0.3; 19
1978	332.1 0.5; 20	332.2 0.2; 7	332.5 0.3; 11	332.2 0.1; 3	332.7 0.2; 2	—	—	334.1 0.7; 8	333.8 0.5; 9	334.0 0.6; 18	334.0 1.1; 2	333.2 0.3; 16
1979	333.2 0.4; 17	333.3 0.5; 13	333.6 0.5; 16	333.4 0.3; 13	333.5 0.2; 19	333.7 0.1; 4	334.8 0.2; 8	334.8 0.1; 8	—	—	335.1 0.2; 10	334.8 0.3; 11
1980	334.8 0.4; 20	334.9 0.3; 11	335.1 0.2; 22	335.0 0.1; 6	335.2 0.4; 12	335.6 0.5; 10	336.2 0.4; 18	336.4 0.2; 23	336.5 0.3; 24	336.5 0.2; 21	336.4 0.3; 18	336.3 0.4; 17
1981	336.6 0.6; 17	336.5 0.4; 11	336.5 0.1; 14	336.6 0.1; 10	336.8 0.1; 5	337.2 0.2; 8	—	337.7 0.3; 16	337.8 0.3; 9	—	—	—
(b)												
1981	—	—	—	—	—	—	337.8 0.4; 8	337.4 0.4; 11	337.4 0.2; 23	337.3 0.4; 22	337.6 0.3; 10	337.5 0.3; 27
1982	337.5 0.2; 24	337.3 0.3; 19	337.4 0.4; 13	337.7 0.5; 18	338.2 0.2; 26	338.4 0.2; 9	339.0 0.3; 12	339.1 0.2; 23	339.5 0.3; 17	339.6 0.2; 18	339.4 0.1; 9	339.0 0.2; 16
1983	339.0 0.2; 23	339.5 0.8; 11	339.5 0.2; 14	340.1 0.5; 5	340.0 0.1; 15	340.2 0.1; 12	340.9 0.2; 2	341.3 0.2; 22	341.4 0.2; 23	341.3 0.4; 21	341.4 0.2; 17	341.4 0.1; 19
1984	341.4 0.1; 8	341.3 0.1; 21	341.3 0.2; 17	341.2 0.5; 22	341.4 0.1; 12	341.8 0.5; 12	342.0 0.4; 15	342.4 0.2; 14	342.5 0.3; 17	342.4 0.4; 16	342.5 0.2; 14	342.3 0.1; 16
(c)												
1976	—	—	—	—	—	328.0 0.4; 4	—	—	331.8 0; 2	—	330.8 1.1; 13	—
1977	—	—	—	—	331.3 0.1; 3	331.2 0.1; 3	331.1 0.3; 7	331.2 0.1; 3	332.0 0.4; 8	332.4 0.9; 5	—	332.5 0.2; 3
1978	—	332.3 1.0; 4	332.4 0.2; 5	—	—	—	333.4 0.7; 7	333.6 0.3; 8	333.8 0.5; 6	333.2 0.6; 12	333.5 0.8; 12	333.6 0.3; 12
1979	333.2 0.6; 12	333.1 0.8; 9	334.0 0.1; 2	333.5 0.6; 7	334.4 0.5; 12	334.4 0.7; 8	334.3 0.6; 14	334.8 0.7; 12	335.3 0.6; 9	334.1 0.6; 10	334.4 0.9; 11	334.7 0.8; 12
1980	334.4 0; 2	335.6 1.0; 7	335.3 0.2; 3	335.1 0.1; 3	—	—	335.9 0.3; 6	336.5 0.4; 11	336.2 0.3; 12	336.3 0.9; 12	336.0 0.6; 9	336.0 0.6; 12
1981	337.7 0.8; 11	336.6 0.8; 9	336.5 0.3; 7	336.6 0.2; 6	336.5 0.3; 7	336.4 0.1; 3	336.9 0.2; 4	337.6 1.0; 6	337.7 0.4; 6	337.4 0.5; 8	336.5 1.1; 6	—
(d)												
1983	—	—	—	—	—	—	—	—	341.4 0.5; 10	341.3 0.3; 14	341.5 0.3; 10	341.6 0.1; 9
1984	341.2 0.3; 12	341.1 0.2; 9	341.2 0.1; 14	341.5 0.2; 11	341.4 0.2; 6	342.0 0.2; 8	342.7 0.6; 13	—	343.0 0.2; 10	342.7 0.2; 9	342.7 0.2; 10	342.6 0.2; 6

Also listed for each month are the standard deviation of the daily average data used in each mean together with the number of days in the case of the in situ data and the number of flasks in the case of the flask data. All concentrations are expressed in the 1981 WMO CO₂ Calibration Scale with all appropriate corrections applied.

samples. Mean monthly baseline CO₂ concentrations as determined from the flask data, are also given in Table 4.

3.4. Data integrity

Although the data set from Cape Grim has been selected to give what we consider to be the best estimate of the regional baseline CO₂ concentration, several factors have been noted in the course of the station's operations which could, at times, have affected the accuracy and precision of the final concentration values. Most have been discussed in Beardsmore et al. (1984) and their possible effects will therefore only be summarized here.

3.4.1. Carrier gas corrections. The fact that we have found two markedly different systems (in situ and flask sampling), using different gas analysers give CO₂ values which, on average, agree to within 0.2 ppmv supports our confidence that the method of correction of the carrier gas errors which we use, is accurate to ± 0.1 – 0.2 ppmv for each analyser.

3.4.2. Analyser characteristics. All of the data collected on the Mark I system at Cape Grim are derived by assuming a linear response of the instrument to changing CO₂ concentration. We consider that this assumption introduces errors of <0.1 ppmv provided the range between calibration (span) gases is kept to 10–12 ppmv (Beardsmore et al., 1978). It should be noted however, that for concentrations greater than 5 ppmv outside the span gas range (e.g., non-baseline conditions or badly selected span concentrations), larger errors can occur. We have found that the output balance point of the URAS 2T analyser normally used in the Cape Grim Mark II monitoring system is prone to drift into a range of significantly non-linear behaviour if care is not taken. Thus, on occasions between July 1982 and July 1983, when we used reference gases whose concentrations were too high, the instrument became excessively non-linear and introduced errors in the computed CO₂ values. On the basis of instrument calibrations before and after this period and checks derived from the instrument's decrease in sensitivity as its output became less linear, a series of corrections have been applied to the Mark II data for 1982 and 1983. The errors

thus incurred were $<\pm 0.3$ ppmv. From the beginning of 1984 regular check calibrations have been performed using the "surveillance" gas mixtures. From these, quadratic analyser characteristics have been derived enabling corrections for curvature to be applied when the concentrations are computed.

3.4.3. Systematic error. For the period September 1978 through November 1981, a correction was necessary to compensate for a sudden unexplained increase in the Mark I results in September 1978. A series of experiments failed to determine the cause of this discontinuity but did prove that it was unrelated to the carrier-gas effects. As both aircraft and Cape Grim flask data sets showed no such sudden increases at this time, and their trends were consistent with one another, a time dependent linear correction factor was derived for the in situ data based on its displacement from the Cape Grim flask data (see Beardsmore et al., 1984 for further details). Because of the uncertainties introduced by the discontinuity and subsequent corrections, we estimate the accuracy of the Cape Grim in situ data over this period to be ± 0.5 ppmv.

Since the Mark II flask sampling system became operational, the CO₂ concentrations derived from 223 flasks have been, on average, 0.2 ± 0.2 ppmv higher than those measured by the in situ system at the time of the sample collections.

3.4.4 Other errors. Two other possible sources of error have been identified in the course of CO₂ monitoring at Cape Grim. Firstly we have found that the drying efficiency of the magnesium perchlorate diminishes with time and significant reductions of efficiency may occur even though there are no visible signs of it being spent (i.e., coagulation of the granules). This could be a problem as the URAS 2T analysers are sensitive to the presence of water vapour and inefficiencies in drying could result in inaccuracies in the final results. Additionally, we have determined experimentally that the CO₂ concentration can be depressed by as much as 0.6 ppmv when the air stream is passed through a spent drying column (90 mm out of 200 mm of the chemical visibility coagulated), although such extreme conditions have never been allowed to occur during actual

monitoring activities. Thus errors of 0.1 to 0.2 ppmv may have occurred due to these effects early in our monitoring program when we were much more dependent on chemical drying. Since the development of an efficient cryogenic drying system in the Mark II equipment, the problem no longer exists.

The other possible source of error relates to the diurnal cycle of up to 1 ppmv that has been observed on occasions in the baseline CO₂ data from the Mark I system (see earlier). Whatever the cause of this cycle, its magnitude is reduced to <0.1 ppmv in the Mark II system, with its 10 m high intake. It is difficult to estimate what effect the cycle had on the CO₂ data as the relationship between the true baseline value and the extremes of the cycle is not known. If, as seems likely, the baseline value falls between the two, the maximum error of a monthly mean concentration, would probably be in the order of ± 0.3 ppmv. A difference of about this size does, in fact, occur between the concentrations measured by the Mark I and Mark II systems in August and September, 1981 (see Table 4).

3.5. Annual and secular variability

Fig. 5 shows a plot of the monthly mean CO₂ concentration observed at the Cape Grim Observatory after selection to represent baseline conditions. Both the Mark I and Mark II data sets are shown together with the data set collected from aircraft sampling in the mid troposphere over southeast Australia (Pearman and Beardsmore,

1984). The annual variations in the Cape Grim and aircraft data sets were removed using a technique based on complex demodulation. The data were then filtered using a low-pass digital filter to examine the variability of concentration on time-scales longer than one year (techniques described by Thompson et al., 1986). Fig. 6 shows the derivative of the fitted trend which indicates that while, on average, the mean rate of CO₂ concentration increase over the period April 1976 to December 1984 at Cape Grim was 1.49 ppmv yr⁻¹, there is a strong interannual variation in this rate of increase which is also observed in the aircraft data and elsewhere globally (see Thompson et al., 1986).

Fig. 7a shows the mean annual variation of CO₂ observed at Cape Grim using both the in situ and flask data.

4. Antarctic observations

4.1. Mawson

Table 5 contains the monthly mean CO₂ concentrations derived from the flask samples collected at Mawson. As the flasks were only filled with air in conditions when no contamination from the station activities was likely, all samples are considered to be of "baseline" concentrations and no other selection criteria have been applied. Occasional samples which have been contaminated due to failure of components of the intake line in the building, have been discarded. All samples

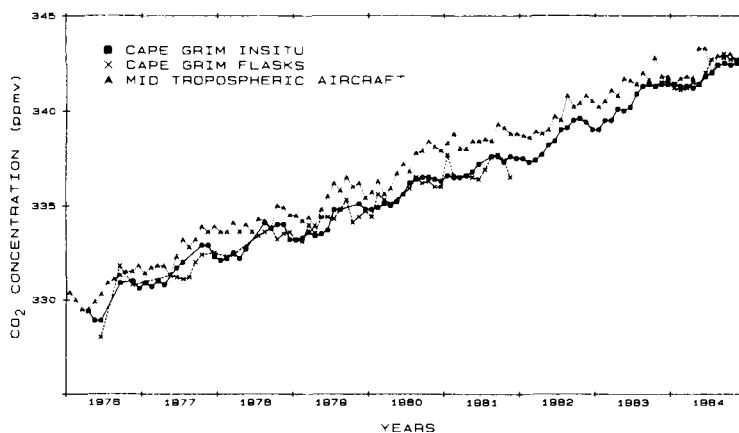


Fig. 5. The monthly mean baseline CO₂ concentration at the Cape Grim Observatory since monitoring commenced. Data from the mid-troposphere are shown for comparison from Pearman and Beardsmore (1984).

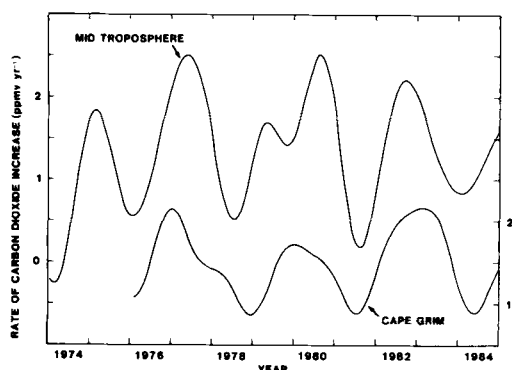


Fig. 6. The rate of carbon dioxide concentration increase observed at the Cape Grim Observatory and in the mid-troposphere over southeastern Australia.

were chemically dried either when collected or before analysis except for a small batch from March/April 1978. In this latter case, small errors could be incurred even though a correction for the volumetric effect of water vapour on the UNOR type analyser was made (see Pearman, 1975) as experiments, described in Pearman et al. (1983), indicate that a correction in excess of the purely volumetric one may be required.

4.2. Macquarie Island

Unlike Mawson, Macquarie Island has a flora consisting of grasses and succulent species of sufficient density to influence the CO_2 values in its vicinity. This is illustrated in Fig. 8 where the

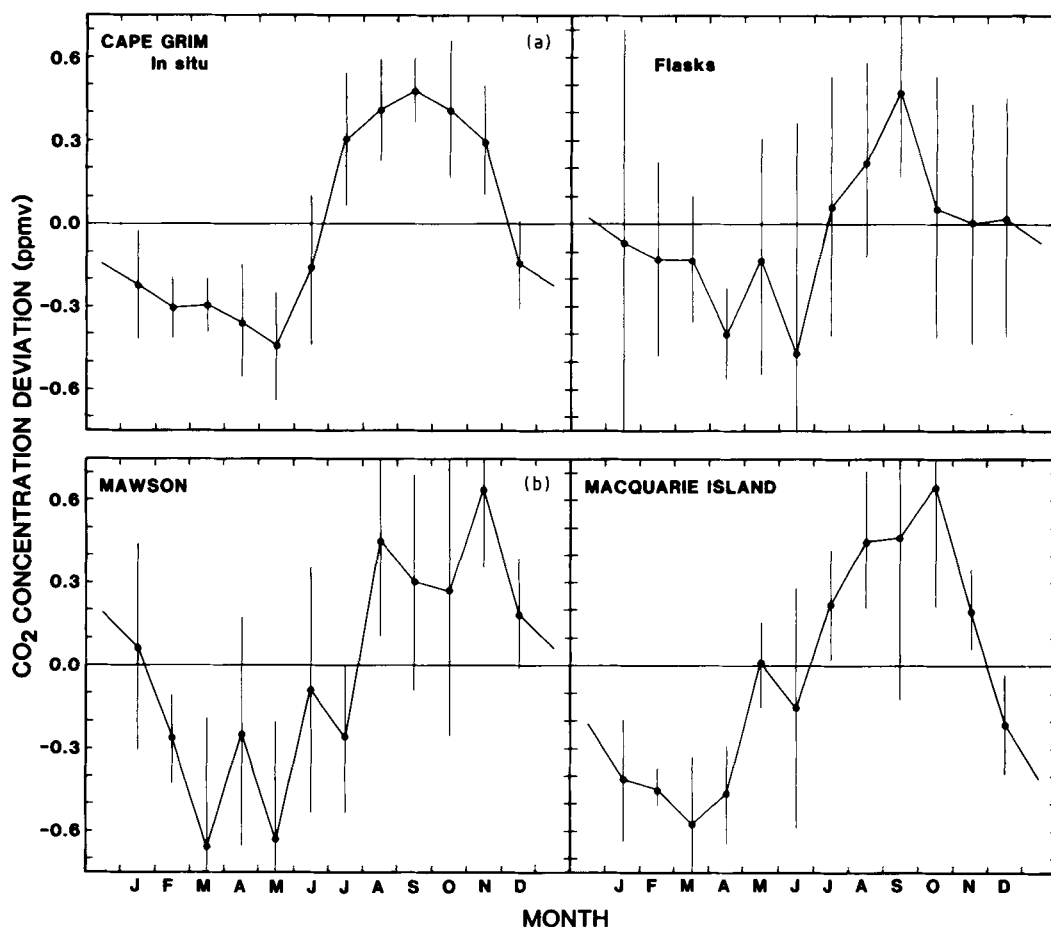


Fig. 7. The average annual variation of CO_2 concentration at (a) the Cape Grim Observatory since monitoring commenced based on in situ measurements and flask samples. (b) Mawson and Macquarie Island. Vertical bars represent one standard deviation of the annual estimation of monthly deviations from the appropriate computed trend.

Table 5. *Monthly mean baseline carbon dioxide concentration at Mawson (Antarctic), Macquarie Island, and Wilbinga*

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
(a) Mawson Flasks												
1977	—	—	—	—	—	—	—	—	—	—	—	332.8 0.1; 2
1978	332.4 0.1; 2	332.4 0.1; 2	332.0 0.1; 2	332.7 0; 1	332.8 0.4; 2	333.0 0; 1	333.5 0; 1	334.6 0; 1	334.6 0; 1	334.6 0; 1	334.6 0; 1	—
1979	334.2 0; 1	334.0 0.1; 2	333.0 0.1; 2	334.2 0; 1	334.2 0; 1	334.0 0.1; 2	334.6 0; 2	335.0 0.1; 2	335.8 0.1; 2	335.9 0; 2	336.3 0; 1	335.5 0.4; 3
1980	335.4 0.4; 2	335.1 0; 1	334.8 0.2; 2	334.6 0.4; 2	—	335.4 0.1; 2	—	335.9 0; 1	336.2 0.2; 2	—	337.0 0.3; 4	336.8 0.3; 2
1981	337.4 0.2; 2	—	336.4 0.2; 2	—	335.5 0; 1	—	336.4 0.6; 2	—	337.4 0.1; 2	337.7 0; 2	338.2 0.1; 2	338.8 0; 2
1982	338.3 0.2; 6	338.4 0.2; 2	339.2 0.7; 3	339.8 0.4; 4	339.4 0; 1	340.0 0.4; 4	339.9 0; 1	340.4 0.3; 2	339.6 0.2; 2	339.5 0; 2	340.9 0.3; 2	340.1 0.7; 2
1983	—	—	—	—	—	—	—	—	—	—	—	—
1984	—	—	—	—	—	—	—	—	—	—	—	342.5 0; 2
(b) Macquarie Island in situ												
1979	—	—	—	333.7 0.2; 31	334.4 0; 4	335.0 0.4; 23	335.0 0; 3	—	—	336.0 0.1; 3	336.4 0.2; 9	—
1980	335.2 0.2; 27	335.6 0.2; 25	335.4 0.2; 19	336.2 0.2; 10	336.8 0.2; 10	337.2 0.1; 2	336.9 0.2; 16	337.5 0.6; 32	338.1 0.3; 13	338.7 0.4; 14	337.9 0.2; 32	337.7 0.5; 61
1981	337.4 0.3; 18	337.4 0.9; 39	337.4 0.5; 26	337.3 0.2; 22	337.6 0.4; 31	—	338.2 0.3; 27	338.6 0.4; 32	338.7 0.3; 8	338.5 0.8; 21	—	—
1982	—	—	339.1 0.1; 6	339.1 0.4; 17	339.7 0.4; 8	339.7 0.2; 10	340.2 0.4; 24	339.9 0.5; 24	341.0 0.2; 11	—	—	339.7 0.2; 8
1983	339.8 0.5; 11	339.8 0.1; 13	339.8 0.2; 13	—	340.7 0.2; 73	340.2 0.4; 7	341.6 0.3; 16	342.1 0.1; 14	342.2 0.3; 26	342.1 0.2; 20	342.2 0.4; 47	341.7 0.3; 23
1984	341.8 0.3; 9	341.7 0.3; 28	341.4 0.4; 37	341.4 0.3; 42	342.4 0.4; 40	341.8 0.7; 26	342.6 0.2; 35	343.2 0.2; 6	342.0 0.9; 36	344.0 0.4; 49	343.2 0.3; 19	342.6 0.3; 14
(c) Wilbinga flasks												
1979	—	—	337.2 0.4; 4	—	—	—	335.8 0.3; 6	335.2 0.5; 5	335.4 0.1; 2	335.5 0.1; 5	335.6 0.1; 6	335.9 0.2; 5
1980	338.0 0.1; 5	338.9 0.4; 5	335.9 0.1; 5	—	—	—	—	—	338.2 0.5; 6	—	338.7 0.4; 6	—
1981	—	—	338.2 1.0; 3	341.1 0.4; 5	—	—	—	—	—	—	—	—

Also listed for each month are the standard deviation of the daily average data used in each mean together with the number of hours in the case of the in situ data and number of flasks in the case of the flask data. All concentrations are expressed in the 1981 WMO CO₂ Calibration Scale with all appropriate corrections applied.

effects of plant respiration raise the CO₂ concentration by several ppmv when the air mass traverses up to 6 km of land and intertidal zone before reaching the sampling point. From the sampling point an oceanic fetch could be obtained from either the north-west or the south-east.

Even from these directions however, contamination could still be detected at the station in eddies from the higher plateau regions at low wind speeds. The following baseline criteria were therefore devised to minimize these effects:

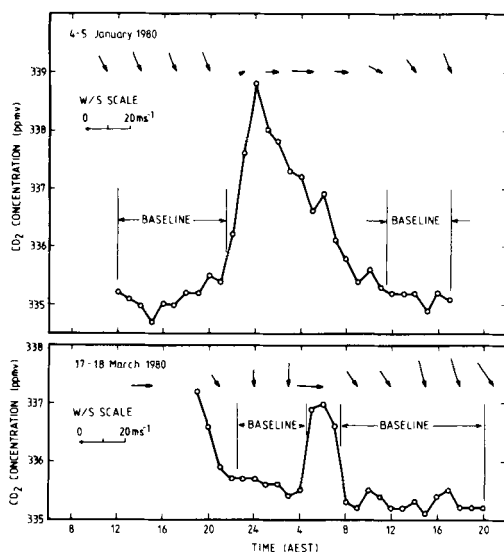


Fig. 8. Hourly mean CO_2 concentrations measured at Macquarie Island illustrating the magnitude of changes which can occur with changes between baseline and non-baseline conditions. Arrows indicate the wind directions and speed (w/s) at 3-hourly intervals.

- (1) wind direction: 110° – 180° or 290° – 360° ;
- (2) wind speed: $> 7 \text{ m s}^{-1}$;
- (3) consistency: hourly mean concentration to be 0.3 ppmv or less from either adjacent valid hour.

The mean monthly baseline CO_2 concentrations from Macquarie Island as determined by these criteria, are listed in Table 5. Fig. 7b shows the mean annual variability of CO_2 concentration at both Macquarie Island and Mawson.

4.3. Ships

In spite of the sampling point being kept as far upwind as possible, the flasks from ships in the southern ocean have been filled in close proximity to sources of CO_2 . There is therefore a higher-than-normal risk of minor contamination, although no definite evidence of its occurrence has been noted to date. Where pairs of flasks have been filled, their variability has been no more than that seen in other flask sampling programs. Samples with major contamination due to damaged equipment have been discarded from the data set. Table 6 lists the mean monthly CO_2 concentrations that have been measured in various bands of latitude across the southern ocean.

4.4. Comparison

The monthly mean selected baseline concentration at both Mawson and Macquarie Island are plotted in Fig. 9. The mean trend at Mawson between 1978 and 1982 is found to be $1.53 (\pm 0.07) \text{ ppmv yr}^{-1}$ whilst that at Macquarie Island is $1.42 (\pm 0.05) \text{ ppmv yr}^{-1}$ between 1980 and 1984. These

Table 6. Monthly mean carbon dioxide measured in air from flask samples collected from ships in the Southern Ocean

Month	Latitude(s)					
	40–44°59'	45–49°59'	50–54°59'	55–59°59'	60–64°59'	65–69°59'
Dec 1977	—	332.00 (1)	332.90 (2)	—	333.10 (1)	332.60 (1)
Nov 1979	—	—	336.00 (1)	336.50 (1)	337.30 (1)	—
Jan 1980	—	335.55 (2)	335.15 (2)	—	335.40 (2)	—
Jan 1981	336.30 (1)	—	337.20 (2)	336.80 (2)	336.80 (1)	336.80 (1)
Feb 1981	—	336.75 (2)	336.45 (2)	—	336.68 (4)	336.35 (2)
Mar 1981	—	—	337.67 (3)	—	337.93 (3)	—
Nov 1981	—	339.05 (2)	338.80 (1)	339.80 (2)	339.40 (1)	—
Jan 1982	—	338.30 (2)	338.43 (3)	—	—	—
Feb 1982	—	—	338.80 (2)	338.90 (1)	338.30 (1)	—
Feb 1983	—	339.83 (3)	340.90 (1)	—	—	—
Mar 1983	339.50 (1)	—	—	339.50 (1)	339.30 (1)	339.60 (1)
Jan 1984	—	340.77 (1)	—	340.66 (2)	341.00 (3)	—
Apr 1984	—	341.43 (1)	—	341.53 (1)	340.72 (1)	—

Numbers in parenthesis indicate the number samples used to produce the monthly mean.

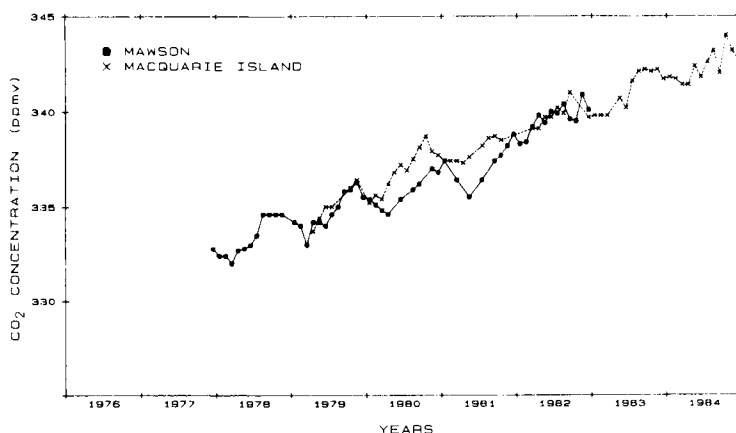


Fig. 9. The monthly mean baseline CO₂ concentration at Mawson and Macquarie Island.

values are in good agreement with each other and with other stations when one takes into account the interannual variability of concentration and the dissimilar averaging periods. Unfortunately almost two years of data were lost at Mawson in 1983–84 due to a leak in the air intake allowing contamination of the samples by laboratory air.

Where possible, a direct comparison of the monthly mean data from land stations with those from ships in the comparable latitude band, is of interest. At the latitude of Macquarie Island the mean difference for six such months gives the land station a higher concentration by $0.19 (\pm 0.43)$ ppmv. The small mean difference is gratifying when one considers that several factors could contribute to a difference. These include the fact that there is an in situ analyser on the island whereas the ship samples are collected in flasks and analysed at Aspendale. During much of the period under study, CO₂/N₂ calibration gases were in use necessitating the application of estimated carrier-gas correction to both systems. The positions at which sampling occurred would also have ranged over distances up to 1500 km.

Unfortunately, ship samples have only been collected on two occasions in the latitude band comparable with Cape Grim (40–45°S). The mean difference in these meagre data however is well within the limits of precision of the system, Cape Grim having a $0.14 (\pm 0.20)$ ppmv higher concentration. The possibilities for error are similar to those for Macquarie Island although the shipboard samples are unlikely to have been collected more than 500 km from Cape Grim.

The two direct comparisons of ship samples in the latitude band of Mawson (65–70°S) show Mawson's mean concentration to be higher by $0.4 (\pm 0.3)$ ppmv. Also, when all four available months of ship data in the 65–70°S latitude band are compared with the corresponding Cape Grim data, the ship values are, on average, $0.1 (\pm 0.2)$ ppmv higher whereas a mean variation of $0.7 (\pm 0.4)$ ppmv exists between Mawson and Cape Grim values for eight of the months when ship traverses occurred. All these comparisons tend to suggest that CO₂ concentration data collected at Mawson differ from those collected from ships in the same latitudes. As both Mawson and ship samples are collected and analysed in a similar manner, there should be no experimentally induced difference between them. An explanation of the differences may be that the two programs are sampling different air masses. Mawson air samples usually originate in the katabatic flow from the Antarctic continent whereas the ship samples would be of Southern Ocean origin.

An inspection of the data listed in Table 6 indicates a possible systematic variation in CO₂ concentration across the Southern Ocean with a maximum between 55° and 65°S. A CO₂ source at these latitudes has also been suggested by Komhyr et al. (1985). To test this, the appropriate Cape Grim monthly mean value was subtracted from each ship monthly mean. Data from Cape Grim and Macquarie Island were included in the mean values of the 40–45°S and 50–55°S bands respectively but Mawson data were not used due to doubts about their oceanic origin. The mean

concentration deviation was then related to the central points of the latitude bands by the least-squares derived regression:

$$\Delta C = -13.42 + 0.51 (L) - 4.54 \times 10^{-3} (L)^2$$

where ΔC is the mean concentration deviation from the appropriate Cape Grim values over the 6 months from November to April and L , the latitude. From the derivative of the above equation the latitude of the maximum CO_2 deviation is calculated to be approximately 56°S . This is slightly south of the Antarctic convergence in the region south of Australia.

5. Wilbinga

The once monthly sample collection at Wilbinga took no account of the meteorological conditions at the time and local and regional biological activity probably affected the CO_2 concentrations at times when the wind was from the landward direction. A tentative selection criterion of wind direction in the on-shore sector of 150° – 330° , has therefore been applied and the resulting "base-line" data set is given in Table 5.

6. Discussion

The CO_2 concentration observed at a fixed location such as the Cape Grim Observatory, might be expected to vary depending on the space-scales over which the air mass under consideration can be considered to be homogeneous. For CO_2 , we now have ample evidence that in the mid-latitudes of the southern hemisphere CO_2 concentration variations through the depth of the troposphere, excluding the boundary layer, are of the order of $0.04 \text{ ppmv km}^{-1}$ (Pearman and Beardsmore, 1984). In the northern hemisphere these gradients are about an order of magnitude greater (Bolin and Bischof, 1970), due to the influence of seasonal exchanges of CO_2 by the terrestrial biosphere. Horizontally, variations of less than $0.001 \text{ ppmv km}^{-1}$ have been observed in both hemispheres (Bolin and Bischof, 1970; Pearman and Beardsmore, 1984) in the middle and upper troposphere. Clearly, therefore, an observatory which is actually measuring the free tropospheric CO_2 concentration would expect to experience variations of much less than 1.0 ppmv on

time scales of order one day. These variations presumably relate to the large-scale transport of air masses over long distances where the surface exchanges have been different or mixing within the air mass has been more or less intense. At a hypothetical observatory located in the middle troposphere the averaging of data should lead to a time averaged concentration which defines the mean concentration with a precision of order 0.1 ppmv or better. Indeed, such precision can probably be obtained on a monthly time-scale using aircraft measuring at about weekly intervals. However, at a surface station, even if it is on a mountain top, the situation is complicated by the combined effects of surface exchanges and boundary-layer stability. The result is that over terrestrial sources or sinks, where surface fluxes may be of order $10^{-8} \text{ kg m}^{-2} \text{ s}^{-1}$ (in units of carbon) averaged over 24 h, surface concentrations (say at about 10 m) can be as much as 5 ppmv different to those in the lower levels of the free troposphere. This is discussed theoretically by Garratt and Pearman (1973) and Pearman et al. (1983b) and, in light of observed vertical profiles through the boundary layer, by Pearman and Beardsmore (1984). Thus air which has traversed terrestrial vegetation might be expected to show concentration variation in a day of this magnitude as the strength and direction of the surface exchange varies diurnally. This, associated with changes in the intensity of the vertical mixing, will affect the degree of agreement between what concentration is observed near the surface and that of the free troposphere. Most existing CO_2 monitoring stations are influenced to some extent by these effects, even when the station is located on a mountain such as at the Mauna Loa Observatory in Hawaii. Indeed, this is the reason that there has been an attempt to locate many of the observatories near the coast where much of the time the air being observed has resided over water for many days. The magnitude of net exchanges of CO_2 with oceanic surfaces is probably about two orders of magnitude smaller than those with terrestrial vegetation. Further, in general, conditions of very strong stability are unusual over the ocean. Thus surface CO_2 concentrations more closely approximate those of the overlying free troposphere. But at almost any coastal station, land breezes do occur under some circumstances so that variability of concentration is affected. In the establishment of the selection

criteria used in the present paper, we have kept these factors in mind. However, the criteria still remain somewhat arbitrary. We can never be sure that when we exclude data because there has been a small variation in concentration (>0.3 ppmv) over a few hours, whether that variation was due to terrestrial effects that were probably confined to the boundary layer, or to differences between large air masses representing perhaps vastly different origins and effective latitudes.

Despite this it is reassuring that when the measurements selected for any one month as representing baseline conditions are compared, even though they may represent several separate periods broken by unselected data, the variance of the combined data is marginally greater than the day-to-day measurement precision of the equipment. After all, on time-scales of a month, even the secular trend and seasonal variation will be contributing in part to this residual variability. At this time it is not possible to assess to what extent this variability relates to instrumentation, ineffective removal of local or terrestrial effects, or contributions from events of longer time-scales.

We have seen above that the precision (defined here as one standard deviation of individual values in a data set) of the Cape Grim instruments over a one hour period is 0.02 and 0.05 ppmv depending on the instrument. This precision probably represents the limit due to electronic instabilities in the power supplies and signal amplification but may also reflect high frequency variability of atmospheric pressure. In principle, given that we calibrate the instrument hourly, one might expect that our ability to define the mean concentration will be improved by the addition of successive hours of data. The fact that the variance of hourly mean data is considerably larger than that for within-hour measurements suggests either there are real between-hour variations of order 0.1–0.2 ppmv, and/or the accuracy with which the hourly calibration is performed is a greater limitation than the stability of the instrument. There are several potential influences on the accuracy of calibration. These include differences in flow rate and hence measurement cell pressure between sample and calibration measurement periods, temperature differences and gas fractionation effects. It is not intended to discuss these factors in this paper, but we point out that it is in this area of instrumentation technology where limits to the

overall precision of our present data set appear to exist.

While a precision of 0.1–0.2 ppmv may be regarded as satisfactory, it is important that this also represents the accuracy with respect to the international standard gases. A comparison of the monthly mean CO₂ concentration selected as being representative of baseline conditions at Cape Grim and at Macquarie Island with measurements made at Amsterdam Island (Ascencio-Parvey et al., 1984; Komhyr et al., 1985), Baring Head (WMO, 1983, 1984) and the mid-troposphere of S.E. Australia (Pearman et al., 1983a) is given in Table 7 and reveals that differences in concentrations have exceeded 1.0 ppmv in the past. The question arises, are these differences reflecting real atmospheric differences or are they indicative of a lack of interstation comparability?

The Table shows that during the period 1981 through 1983, baseline concentrations at Cape Grim have been less than those observed by the other southern hemisphere programs at similar latitudes and that the magnitude of this difference has changed markedly over this period. It is unlikely that all of this change reflects atmospheric conditions.

The good agreement between Amsterdam Island (CNRS) and Baring Head CO₂ concentrations on average is suggestive that these stations have been measuring background concentrations which are zonally representative and that the Cape Grim data are consistently low. Measurements at Amsterdam Island by the National Oceanic and Atmospheric Administration (NOAA; Komhyr et al., 1985) indicated concentrations a further ppmv higher during 1981. Early in 1982 however, both sets of observations at Amsterdam Island were ~ 2 ppmv higher than Cape Grim and this difference slowly decreased until it was close to 0.5 ppmv from mid 1982 onwards. There is some evidence of a reduced difference between Cape Grim and Baring Head measurements over the same period although the changes were less distinctive.

The closer agreement between Cape Grim and our aircraft observations in 1983 tends to support the argument that earlier Cape Grim data, particularly 1980–81, may have been systematically low. While the aircraft data were, on average, slightly less than 1.0 ppmv higher than those at Cape Grim during 1976–79, the difference was clearly greater than 1.0 ppmv through 1980–82.

Table 7. *A comparison of the monthly mean carbon dioxide concentration observed in situ at the Cape Grim Observatory during 1981–83 with that observed at Baring Head (WMO, 1983,84) and Amsterdam Island (Ascencio-Parvy et al., 1984; Komhyr et al., 1985), stations at similar latitudes in the southern hemisphere*

Month	Amsterdam Is. (38°S; 78°E)		Carbon dioxide concentration (ppmv)			Cape Grim (41°S; 145°E)	
	CNRS	NOAA	Baring Head (41°S; 175°E)	Mid-troposphere (S.E. Australia)	Macquarie Is. (55°S; 159°E)	Flasks	in situ
1981							
Jan	338.1 (+1.5)	338.5 (+1.9)	337.6 (+1.0)	338.3 (+1.7)	337.4 (+0.8)	337.7 (+1.1)	336.6*
Feb	338.3 (+1.8)	338.5 (+2.0)	337.5 (+1.0)	338.8 (+2.3)	337.4 (+0.9)	336.6 (+0.1)	336.5*
Mar	338.2 (+1.7)	338.7 (+2.2)	337.4 (+0.9)	338.0 (+1.5)	337.4 (+0.9)	336.5 (+0.0)	336.5*
Apr	338.1 (+1.5)	338.9 (+2.3)	337.9 (+1.3)	338.0 (+1.4)	337.3 (+0.7)	336.6 (+0.0)	336.6*
May	338.3 (+1.5)	339.2 (+2.4)	337.8 (+1.0)	338.4 (+1.6)	337.6 (+0.8)	336.5 (−0.3)	336.8*
Jun	338.0 (+0.8)	339.5 (+2.3)	338.1 (+0.9)	338.4 (+1.2)	—	336.4 (−0.8)	337.2*
Jul	338.2 (+0.4)	339.6 (+1.8)	338.6 (+0.8)	338.5 (+0.7)	338.2 (+0.4)	336.9 (−0.9)	337.8
Aug	338.7 (+1.3)	339.7 (+2.3)	338.5 (+1.1)	338.4 (+1.0)	338.6 (+1.2)	337.6 (+0.2)	337.4
Sep	338.4 (+1.0)	339.7 (+2.3)	339.0 (+1.6)	339.3 (+1.9)	338.7 (+1.3)	337.7 (+0.3)	337.4
Oct	338.6 (+1.3)	339.7 (+2.4)	338.8 (+1.5)	339.1 (+1.8)	338.5 (+1.2)	337.4 (+0.1)	337.3
Nov	338.8 (+1.2)	339.8 (+2.2)	338.5 (+0.9)	338.8 (+1.2)	—	336.5 (−1.1)	337.6
Dec	338.9 (+1.4)	339.7 (+2.2)	338.9 (+1.4)	338.8 (+1.3)	—	—	337.5
Ave	338.4 (+1.3)	339.3 (+2.2)	338.2 (+1.1)	338.6 (+1.5)	337.9 (+0.9)†	336.9 (−0.1)†	337.1
1982							
Jan	339.3 (+1.8)	339.5 (+2.0)	338.6 (+1.1)	338.7 (+1.2)	—	—	337.5
Feb	339.5 (+2.2)	339.1 (+1.8)	339.0 (+1.7)	338.6 (+1.3)	—	—	337.3
Mar	339.3 (+1.9)	338.8 (+1.4)	338.8 (+1.4)	338.9 (+1.5)	339.1 (+1.7)	—	337.4
Apr	339.0 (+1.3)	338.8 (+1.1)	338.9 (+1.2)	338.8 (+1.1)	339.1 (+1.4)	—	337.7
May	338.9 (+0.7)	338.9 (+0.7)	339.1 (+0.9)	339.0 (+0.8)	339.7 (+1.5)	—	338.2
Jun	339.0 (+0.6)	339.1 (+0.7)	339.1 (+0.7)	339.7 (+1.3)	339.7 (+1.3)	—	338.4
Jul	339.1 (+0.1)	339.4 (+0.4)	339.4 (+0.4)	339.5 (+0.5)	340.2 (+1.2)	—	339.0
Aug	339.8 (+0.7)	339.7 (+0.6)	340.0 (+0.9)	340.8 (+1.7)	339.9 (+0.8)	—	339.1
Sep	339.7 (+0.2)	339.8 (+0.3)	340.0 (+0.5)	340.2 (+1.7)	341.0 (+1.5)	—	339.5
Oct	339.5 (−0.1)	339.8 (+0.2)	340.1 (+0.5)	340.4 (+0.8)	—	—	339.6
Nov	339.5 (+0.1)	339.7 (+0.3)	340.1 (+0.7)	340.8 (+1.4)	—	—	339.4
Dec	339.5 (+0.5)	339.9 (+0.9)	339.7 (+0.7)	340.5 (+1.5)	339.7 (+0.7)	—	339.0
Ave	339.3 (+0.8)	339.4 (+0.9)	339.4 (+0.9)	339.7 (+1.2)	339.8 (+1.3)†	—	338.5
1983							
Jan	339.8 (+0.8)	—	—	340.2 (+1.2)	339.8 (+0.8)	—	339.0
Feb	340.1 (+0.6)	—	—	340.5 (+1.0)	339.8 (+0.3)	—	339.5
Mar	340.2 (+0.7)	—	—	341.1 (+1.6)	339.8 (+0.3)	—	339.5
Apr	340.5 (+0.4)	—	—	340.8 (+0.7)	—	—	340.1
May	340.5 (+0.5)	—	—	341.7 (+1.7)	340.7 (+0.7)	—	340.0
Jun	341.0 (+0.8)	—	—	341.6 (+1.4)	340.2 (+0.0)	—	340.2
Jul	341.7 (+0.8)	—	—	341.4 (+0.5)	341.6 (+0.7)	—	340.9
Aug	341.7 (+0.4)	—	—	342.0 (+0.7)	342.1 (+0.8)	—	341.3
Sep	341.7 (+0.3)	—	—	341.6 (+0.2)	342.2 (+0.8)	341.4 (+0.0)	341.4
Oct	341.6 (+0.3)	—	—	342.8 (+1.5)	342.1 (+0.8)	341.3 (+0.0)	341.3
Nov	341.6 (+0.2)	—	—	341.8 (+0.4)	342.2 (+0.8)	341.5 (+0.1)	341.4
Dec	—	—	—	341.8 (+0.4)	341.7 (+0.3)	341.6 (+0.2)	341.4
Ave	340.9 (+0.5)†	—	—	341.4 (+0.9)	341.1 (+0.6)†	341.5 (+0.1)†	340.4

Also for comparison are included data for Macquarie Island (from Table 5) Cape Grim flasks (from Table 4) and the mid-troposphere over south-eastern Australia (Pearman and Beardsmore, 1984). Figures in brackets show differences from Cape Grim in situ concentration. *denotes the value has been obtained from Mark I equipment. All other Cape Grim values are from the Mark II installation. † indicates that the annual average has been computed from less than 12 monthly means.

Modelling studies (Pearman and Hyson, 1986) lead us to expect a higher CO₂ concentration in the mid-troposphere than at the surface at these southern latitudes because of both the spatial distribution of sources and sinks and the mode of transport of northern hemisphere air into the higher latitudes of the southern hemisphere. This is confirmed by an observed vertical concentration gradient of 0.04 ppmv km⁻¹ over south-eastern Australia (Pearman and Beardsmore, 1984). Considering the less effective vertical transport in the lower troposphere these studies combine to indicate a difference of 0.5–1.0 ppmv between mid-tropospheric and Cape Grim concentrations. The average difference of 1.5 ppmv observed during 1981 therefore appears to be unreasonably large.

Care needs to be taken in comparing these two data sets as the interpretation is complicated by the fact that the amplitudes of the interannual variation observed (Fig. 6) are clearly not the same. This implies that, on time scales of about 2 years, 40–80% of the vertical difference in concentration can possibly be accounted for by interannual variation. The smaller difference in 1983 therefore may well have been influenced by the phases of the interannual variation as well as other factors.

Some uncertainty is expected in all data sets prior to and including parts of 1982 at stations where CO₂/N₂ calibration standards were used. Corrections of about $\pm 1\%$ (Pearman, 1977) would have been applied to account for the effect of the carrier-gas errors. Cape Grim did not change to CO₂/air standards until November, 1982 at which time the concentration difference had already decreased to <0.5 ppmv on average compared to Amsterdam Island and slightly higher with Baring Head. Given the extensive effort of our laboratory to ascertain the carrier-gas errors (Pearman et al., 1983a) and lack of correlation between the magnitude of the interstation differences and changes to CO₂/air standards, we are convinced that they are not related.

Considerable effort has been put into testing the validity of the Cape Grim in situ data set. In Subsection 4.4, it was shown that on two occasions (1981 and 1983) when flask samples were collected from ships at similar latitudes to Cape Grim, both concentrations agreed to within 0.3 ppmv with those observed at Cape Grim. Similarly the flask concentrations at Cape Grim during 1981 indicate

that the lower concentrations actually occurred. In both of the above instances the measurement systems were entirely independent. Recent analyses of several archived air samples collected at Cape Grim also tend to confirm the low values recorded during 1981–82.

Modelling studies (Pearman and Hyson, 1986) suggest that CO₂ concentrations at stations located at southern latitudes similar to Cape Grim should be, on average, as low as anywhere in the background troposphere. This is because of the inter-hemispheric gradient of annual mean concentrations established by the major sources and sinks and the mode of transport. The 1.0 ppmv higher average concentrations at Macquarie Island and in the mid-troposphere is in qualitative agreement with this. Quantitative agreement would not be expected as the ship-board data are suggesting a minor maximum of concentration over the southern ocean, presumably due to properties of the oceanic exchange near the Antarctic convergence, which is not represented in the modelling. However, if such a concentration gradient exists in the region of this geophysical feature, it will contribute to the variability of concentrations observed at a single latitude as well as the differences between stations. The fact that Baring Head and Amsterdam Island data are selected for conditions of meridional transport might lead these stations to record concentrations somewhat higher than those recorded at Cape Grim where data are selected for conditions of predominantly zonal flow.

Since 1984, CO₂ measurements have been made on flask samples collected by 2 sampling systems at Cape Grim for NOAA, Geophysical Monitoring for Climatic Change Laboratory, Boulder, Colorado. Preliminary data from that laboratory show an interlaboratory precision which presently appears to be 0.2 ppmv or better (personal communications—Dr. P. Tans). We will continue to participate in this and other comparison experiments to provide a clearer and on-going check on the interstation comparability.

Concerning the interstation comparability, we may therefore draw the general conclusions that: (a) During 1981 and possibly earlier, inter-comparability between Cape Grim and other programs in the Southern Hemisphere was no better than $\sim \pm 1.0$ ppmv. One contributing factor may have been the uncertainty of the correction to

the Mark I in situ values (see Section 3.4.3) although the same trend is indicated in the Mark II data late in 1981. (b) For the same period, ship samples, archived air and the Cape Grim flask data confirmed the low in situ concentrations. Unfortunately, the fact that the flask program was inoperative for most of 1982–83 limits our ability to assess whether differences in average concentrations between Cape Grim and stations at similar latitude are valid or are due to errors at one or other of the stations. (c) A comparison of recent observations (1983) suggests that comparability has improved to a point where existing differences may now reflect real atmospheric variations, although some lack of interstation comparability may still exist.

The seasonal cycle of CO_2 concentration (Fig. 7a) is well defined by the Cape Grim baseline in situ data. The minimum concentration occurs in May and the maximum in September with the amplitude (defined as the difference in average concentration for these two months) being 0.92 ppmv. The precision with which the annual cycle is defined is limited by interannual variability. The latter, represented by the standard deviation of the annual estimates of monthly deviations from the computed trend is, on average for all months, 0.19 ppmv. This variability presumably results from measurement errors and real interannual variations of the annual cycle. While the amplitude and months of maximum and minimum concentration are the same for the Cape Grim flask data, the cycle is less clearly defined primarily because of the method used to detrend the data. Given the major loss of flask data during the period 1982–83, the detrending was performed using a linear regression instead of the digital filtering procedures applied to the in situ data. The detrended data thus contains variability associated with both the seasonal and interannual cycles.

Pearman and Beardsmore (1984) showed that the amplitude of the annual cycle appeared to increase with altitude. The present surface data support this conclusion as the Cape Grim amplitude of 0.92 ppmv compares with a mid-troposphere amplitude of 1.23 ppmv. The aircraft data also suggested a phase lag in the cycle at lower altitudes. There is no convincing evidence of further consistent lag of the cycle in the surface data however as the minimum at Cape Grim is a

month later than in the mid-troposphere, and the maximum, a month earlier. It is not surprising that evidence of a simple phase shift and amplitude attenuation is unclear, first because of the difficulty of defining phase shifts, in particular in such a noisy record and second because one might expect that the cycle is influenced both by transport and surface exchanges. Pearman and Hyson (1986) showed that qualitatively an increasing amplitude of the annual cycle with altitude was in part due to large-scale transport of seasonality from low latitudes. They did, however, have little success in describing the seasonality of the higher latitudes quantitatively. More recently, the same authors (unpublished work) have constrained their model with both isotopic and concentration data and in doing so established an hypothesis explaining the major features of seasonality in this region. The key difference in the newer study is that oceanic pCO_2 decreases in summer, presumably representing the effects of marine-biospheric activity in contrast to increasing due to the direct effect of temperature on the carbonate equilibrium. In general the agreement between modelled and observed seasonal variations is good, being consistent with the greater amplitudes of the measured cycles at Macquarie Island the Mawson, of 1.24 and 1.31 ppmv, respectively.

The secular increase of CO_2 concentration described by the low frequency filtering of the Cape Grim in situ data gave an average rate of increase of $1.49 \text{ ppmv yr}^{-1}$ for the period April 1976 through December 1984. This compares with an average rate of increase of $1.47 \text{ ppmv yr}^{-1}$ over the same period estimated from the mid-tropospheric aircraft data of Pearman and Beardsmore (1984). The latter gave a slightly lower rate of increase of $1.30 \text{ ppmv yr}^{-1}$ over the full period of that data set March 1972 through December 1984 using the same smoothing technique. The increases observed at Macquarie Island (1980–1984) and Mawson (1978–1982 linear regression estimate) were 1.42 and 1.53 ppmv yr^{-1} respectively. These data therefore indicate an average rate of concentration increase over the past decade of very close to 1.5 ppmv yr^{-1} .

The objective of the present paper has been to provide a description of the observational programs operated by our laboratory for CO_2 in the surface layers of the background atmosphere. We formally present the data and a description of

methods of measurement, calibration and data selection. It has not been possible to do this without some consideration of the ultimate data needs and applications. We have therefore included some discussion on the interpretation of the results. This serves to highlight the limitations of past and present data sets and establish goals for achievement in CO₂ monitoring for the coming years. More detailed data interpretation and application will be pursued elsewhere.

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