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A statistical comparison of the CO_2 measurements at Cape St. James and Station "P", Canada

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ABSTRACT

As part of the Canadian CO_2 monitoring program, a CO_2 flask sampling program was initiated at Cape St. James, Canada in May, 1979. The site was to become the replacement station for Ocean Weather Station "P" (located in Gulf of Alaska), which was terminated in June, 1982. In order to compare the Cape St. James data to the Station "P" data, we have examined the statistical properties of the CO_2 measurements taken at these two stations. Both stations show very similar climatological CO_2 seasonal cycle, with an amplitude of about 13 ppmv. Seasonal minimum occurs at the same time at both sites (late August). Furthermore, CO_2 measurements at both locations indicate greater variability in summer than in winter. Cape St. James shows greater variability than Station "P" in winter (statistically significant), while the opposite is true in summer (not statistically significant). Based on the analysis, we have concluded that Cape St. James was a good replacement choice for Station "P".

1. Introduction

In May 1979, as part of the Canadian CO_2 monitoring program, a CO_2 flask sampling program was initiated at Cape St. James (52° N, 130° W) located on the Queen Charlotte Islands off Canada's west coast (see Fig. 1); the site was to become the replacement station for Ocean Weather Station "P" (located in Gulf of Alaska at 50° N, 145° W), which was terminated in June 1982. Cape St. James was located on a rocky island, about 160 km west of British Columbia's mainland. The actual sampling site was surrounded by patches of short grass, with major forested areas to the north of the site. A very stringent sampling protocol allowed sampling only when the winds were clearly blowing from areas away from any major vegetated areas such as to the north and east, in an attempt to sample only the air off the Pacific Ocean. Cape St. James was terminated as a CO_2 grab flask sampling site in August 1992, when the weather station which took the samples was closed as part of a rationalization of the surface observing program. If is of interest to carry out a statistical comparison of the CO_2 data obtained from Cape St. James and Station "P". A brief comparison of these two "Pacific" stations with Alert and Sable Island will also be presented.

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2. Cape St. James data

The sampling protocol at Cape St. James called for flask sampling frequency of once per week, but only when the station surface wind was off the water and its magnitude greater than 5 m s^{-1}. In addition to these constraints, many logistic problems resulted in many missing data at the station, the worst year being 1984 when only 1 measurement appears in the time series. In all, there are 230 accepted measurements in the Cape St. James CO_2 time series from May 1979 to August 1992. These values are given in Table 1. All

Table 1. *Cape St. James CO_2 flask concentrations*

Year	Month	Day	CO_2 (ppm)	Year	Month	Day	CO_2 (ppm)
79	5	10	341.46	82	10	5	337.83
79	5	17	342.55	82	10	27	340.43
79	5	26	341.23	82	11	4	343.31
79	7	20	336.12	82	11	14	341.90
79	8	25	327.81	82	12	3	342.68
79	9	14	330.69	83	1	5	344.70
79	9	21	330.57	83	1	12	344.11
79	10	13	333.17	83	1	27	345.06
79	10	28	336.33	83	2	15	346.86
79	12	9	340.18	83	3	1	345.76
80	2	3	340.00	83	8	2	334.86
80	3	18	341.29	83	8	11	334.20
80	3	28	343.80	83	8	16	332.94
80	5	1	343.52	83	8	19	330.77
80	5	10	343.64	83	8	30	338.10
80	5	23	343.18	83	8	31	335.65
80	5	27	342.21	83	9	13	334.73
80	6	3	340.37	83	9	16	336.19
80	6	18	342.95	83	9	26	338.00
80	7	22	334.06	83	10	8	341.18
80	7	29	334.03	83	10	22	341.14
80	8	21	329.27	83	11	22	345.24
80	8	27	327.74	84	12	22	346.46
80	9	6	331.85	85	3	19	350.41
80	10	8	336.83	85	4	8	350.28
80	10	18	338.74	85	4	23	352.92
80	11	20	341.19	85	5	10	352.14
80	11	27	341.16	85	5	20	351.92
81	1	24	342.75	85	5	29	350.40
81	9	2	333.38	85	6	19	348.72
81	9	11	333.46	85	9	13	340.23
81	9	22	335.15	85	9	24	339.93
81	10	7	338.35	85	10	11	343.87
81	10	14	336.85	85	10	22	345.48
81	10	27	339.82	85	10	30	345.34
81	11	3	340.34	86	1	10	349.26
81	11	11	341.78	86	2	4	349.81
81	11	29	342.65	86	3	1	350.76
81	12	2	342.21	86	3	18	350.23
81	12	10	343.03	86	3	28	351.49
81	12	25	344.46	86	4	8	352.19
82	1	5	344.38	86	4	25	352.41
82	1	6	342.98	86	5	3	351.58
82	1	13	342.33	86	5	13	353.06
82	1	23	344.81	86	6	18	346.95
82	1	29	342.78	86	9	3	341.00
82	2	9	345.20	86	10	21	345.71
82	2	16	344.79	87	8	11	341.96
82	4	9	344.33	87	8	18	341.58
82	4	17	347.07	87	9	22	344.37
82	5	3	347.96	87	9	30	344.57
82	8	31	337.33	87	10	14	346.61
82	9	10	334.29	87	11	10	348.54

Table continued

Table 1—*continued*

Year	Month	Day	CO_2 (ppm)	Year	Month	Day	CO_2 (ppm)
88	1	17	354.17	90	4	22	360.52
88	1	22	353.89	90	4	30	359.91
88	2	1	352.99	90	5	14	359.60
88	2	9	353.78	90	5	14	358.03
88	2	15	354.16	90	6	11	355.36
88	3	2	354.13	90	8	18	348.90
88	3	19	355.12	90	8	28	345.08
88	3	31	353.90	90	9	9	346.56
88	4	13	355.87	90	9	18	349.42
88	4	29	357.28	90	10	1	348.76
88	5	28	355.75	90	10	8	352.44
88	6	6	353.01	90	10	15	352.10
88	7	5	348.44	90	10	22	355.69
88	7	19	351.02	90	11	01	354.86
88	8	13	341.47	90	11	12	355.39
88	10	4	349.11	90	11	19	358.42
88	10	8	351.34	90	11	26	360.63
88	10	19	350.88	90	12	12	359.12
88	10	21	352.55	91	1	7	359.43
88	11	2	353.29	91	1	16	358.86
88	11	7	351.95	91	3	4	361.10
88	11	11	353.07	91	3	14	361.47
88	11	18	354.26	91	3	26	362.02
88	11	28	354.27	91	4	1	361.91
88	12	8	353.54	91	4	16	359.52
88	12	12	354.10	91	4	27	363.02
88	12	19	354.90	91	5	8	362.13
89	1	9	356.05	91	5	15	361.81
89	1	16	356.67	91	6	5	359.21
89	1	26	356.82	91	6	10	357.63
89	1	30	357.49	91	6	18	356.98
89	2	12	356.56	91	7	8	355.52
89	3	22	357.24	91	8	11	347.33
89	3	31	357.34	91	9	13	348.86
89	4	3	358.52	91	10	2	351.40
89	4	10	356.80	91	11	9	356.29
89	4	23	358.20	91	11	13	357.63
89	6	5	357.10	91	11	24	357.17
89	6	18	354.75	91	11	28	359.67
89	6	21	359.96	91	12	4	358.45
89	6	23	351.72	91	12	18	359.04
89	7	7	347.29	91	12	24	358.02
89	7	16	349.63	92	1	9	358.50
89	9	18	347.35	92	1	16	359.50
89	9	29	348.64	92	1	21	360.70
89	10	3	349.80	92	2	19	360.76
89	10	9	352.91	92	2	29	360.99
89	10	17	352.88	92	3	14	359.81
89	11	1	353.24	92	3	17	361.32
89	11	16	352.86	92	3	30	361.28
89	12	2	355.09	92	4	7	360.62
89	12	5	357.24	92	4	15	360.57
89	12	11	355.64	92	4	27	359.09
90	1	25	360.12	92	4	30	362.66
90	2	20	359.05	92	6	17	358.72
90	3	5	357.32	92	6	24	362.14
90	3	5	358.27	92	7	2	354.64
90	3	14	360.34				

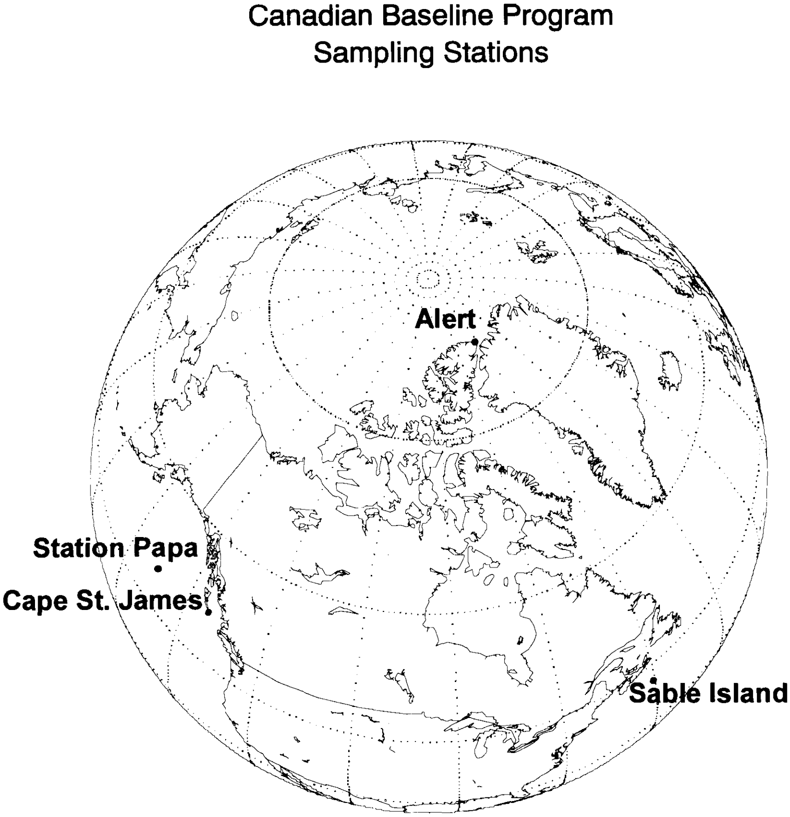

Fig. 1. Location of Cape St. James, off the west coast of Canada, is shown, along with other CO_2 sampling stations of the Canadian Baseline Program.

the CO_2 values in this study are on the WMO 85 Scale. Details concerning equipment, sampling and measurement procedures, and quality control methods used in the Canadian CO_2 BAPMoN Program are given in Trivett et al. (1989), Higuchi et al. (1987), and Wong et al. (1984). A description of Ocean Weather Station "P" (OWSP) as well as a summary of the monthly mean concentrations of atmospheric CO_2 at OWSP are given in Wong et al. (1984).

3. Results and discussion

3.1. Atmospheric circulation in northeastern Pacific

Mean atmospheric circulation in the North Pacific which influenced the air arriving at Cape St. James and OWSP can be seen in Fig. 2 for the astronomical seasons of winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November), respectively. These mean sea level pressure maps, averaged over the 1952–1987 period, were obtained from Power et al. (1990). The atmospheric circulation in the lower troposphere in the North Pacific, represented by the maps in Fig. 2, is characterized by a clear seasonal cycle. During winter, a large cyclonic flow dominates the Pacific Ocean north of 20° N, bringing southerly to westerly winds to the Cape St. James region, as well as to OWSP. During summer, this low system is replaced by a subtropical high, with its centre near 40° N and 150° W, resulting in a dominant northwesterly flow over Cape St. James. On the other hand, a westerly to

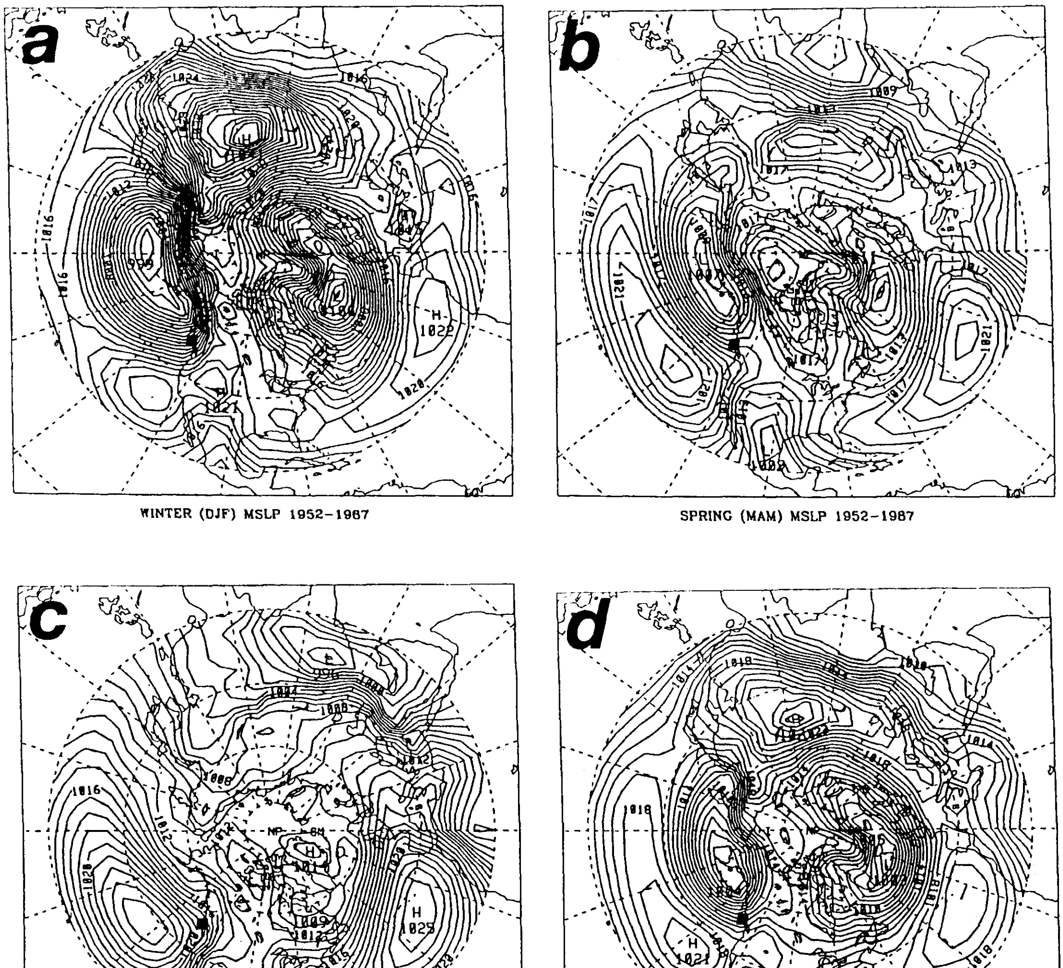

Fig. 2. Northern Hemispheric mean sea-level pressure charts, averaged over the 1952–1987 period, are shown for (a) winter, (b) spring, (c) summer, and (d) autumn. A small solid black square in each frame marks the location of Cape St. James. Obtained from Power et al. (1990).

southwesterly flow influences the OWSP region in the summer. The transitional seasons of spring and autumn are characterized by the northward and southward shifts, respectively, of the low and high systems. Windrose diagrams for Cape St. James and OWSP (not shown) are consistent with the seasonal shifts in the overall mean circulation pattern shown in Fig. 2. It would appear that both Cape St. James and OWSP experienced similar large-scale atmospheric circulation regimes over the northeastern region of the North Pacific.

3.2. Statistical procedure

Measured CO_2 values at Cape St. James are shown in Fig. 3a. Superimposed on the secular upward trend is a very strong seasonal cycle, fitted

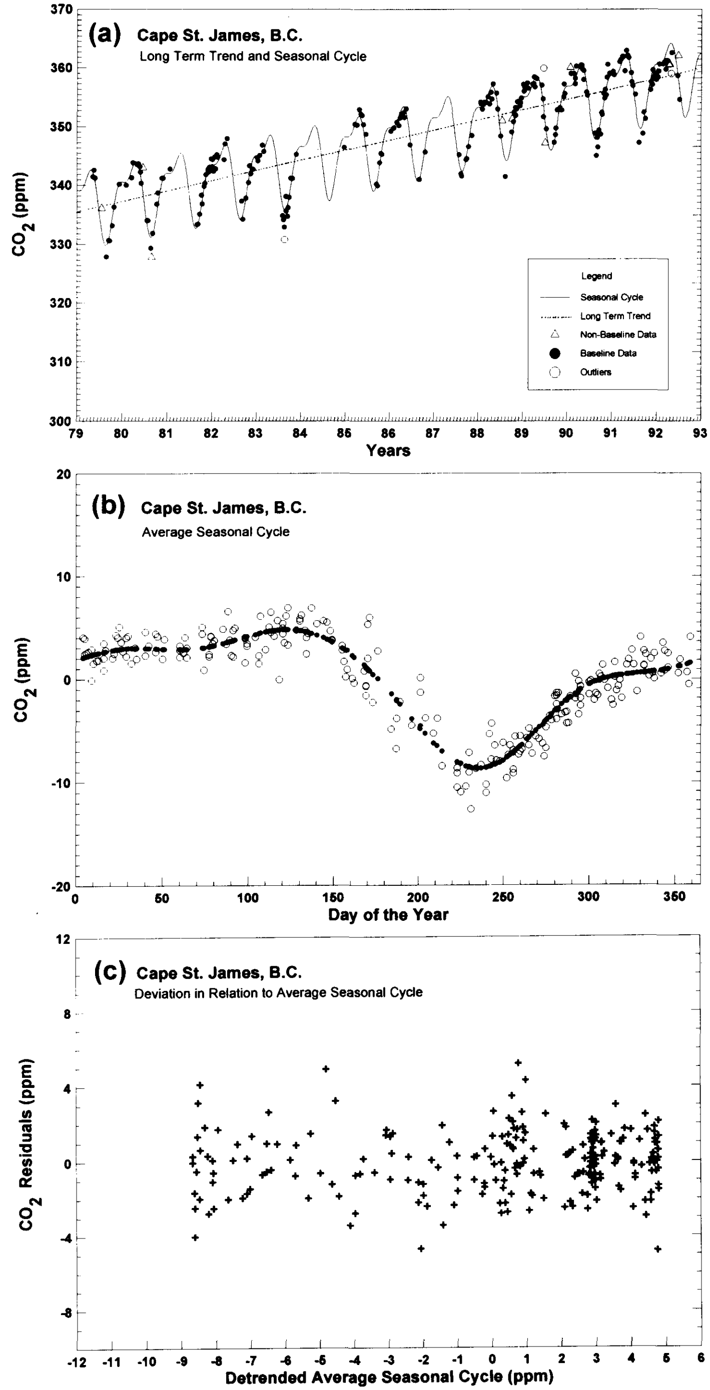

Fig. 3. (a) Carbon dioxide flask values at Cape St. James. The fitted seasonal cycle (solid line) is determined by a forward stepwise harmonic regression technique. The secular rise in the background atmospheric CO_2 concentration is linear from 1979 to 1992. (b) Composite seasonal values (open circles). Average seasonal cycle is shown in solid circles. (c) Deviations from the average seasonal cycle.

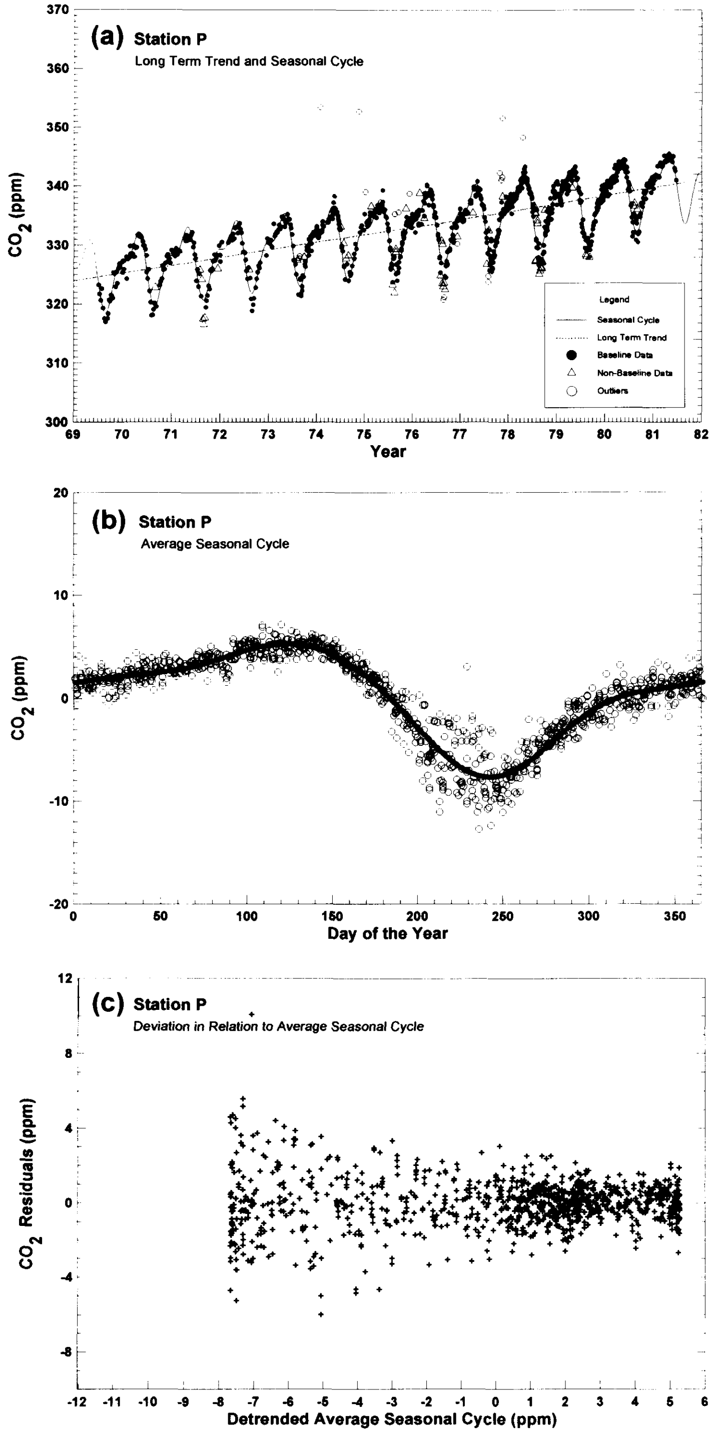

Fig. 4. Same as Fig. 3, but for Ocean Weather Station "P".

to the observation by a forward stepwise harmonic regression (Trivett et al., 1989). An average or climatological CO_2 seasonal cycle at the station is shown in Fig. 3b, where a simple harmonic regression line has been fitted to a detrended composite CO_2 values. A typical seasonal amplitude at Cape St. James is about 13 ppmv, with minimum occurring during the latter half of August and a broad maximum from around late November to early May. A total of 230 residual or deviation values from this average seasonal cycle are displayed in Fig. 3c.

Same statistical analysis applied to Cape St. James data was also employed on the OWSP CO_2 data. There are 966 accepted measurements in the OWSP CO_2 time series from 1961 to 1982. The secular upward trend and a very prominent seasonal cycle observed at Cape St. James is also apparent at OWSP (Fig. 4a). The average seasonal cycle at the station (Fig. 4b) is almost identical to the one at Cape St. James, with similar amplitude of about 13 ppmv. Fig. 4c shows the seasonal dependency of the variability of the CO_2 measurements at OWSP.

A very strict sampling protocol at Cape St. James allowed CO_2 flask sampling only when the station surface wind was off the water and its magnitude greater than $5 \mathrm{~m} \mathrm{~s}^{-1}$. This measurement criteria has built a directional bias into the CO_2 values obtained at Cape St. James. In contrast, such directional or sectorial bias is not present in the data set from OWSP. Thus, in order to determine if this directional bias at Cape St. James has any influence on the statistical comparison between two sites, we constructed another OWSP data set (sectored) by keeping from the original 966 values at OWSP only those values associated with samples taken when winds were blowing from the sector covered by southerly to northwesterly (in clockwise fashion) directions. This procedure made the data sets from both Cape St. James and OWSP statistically more compatible, and reduced the OWSP data sample size to 542.

3.3. *Comparison between Cape St. James and OWSP*

From Figs. 3, 4, it is quite clear that both Cape St. James and OWSP show same secular upward trend at a rate of about 1.4 ppmv/year. This is not surprising since only one (maybe two) good monitoring station is needed in the world to detect the gradual increase in the atmospheric CO_2 concentration. Detrended composite data (Figs. 3b, 4b) of both OWSP data sets (sectored and non-sectored) and Cape St. James show very similar average seasonal cycles with amplitudes of about 13 ppmv. There is essentially no difference between the sectored and non-sectored OWSP data for the fitted seasonal cycle. However, there are slight qualitative differences between the mean seasonal cycles (shown by the harmonically fitted curves) of Cape St. James and OWSP. After reaching a seasonal maximum in early to mid May at both stations, CO_2 concentration at Cape St. James decreases more rapidly than at OWSP, reaching the seasonal minimum about 6 days earlier than OWSP. A more rapid decrease in the atmospheric CO_2 concentration during the early summer at Cape St. James might be indicative of the fact that the station, being closer to vegetated areas, was influenced more strongly by the local and regional seasonal biospheric activities than OWSP. Furthermore, since one cannot obtain more information than that contained in the data by merely curve fitting the observed values, we proceeded to test the significance of the 6-day lag by examining the interannual variability of the timing of the occurrence of the minimum CO_2 actually measured at Cape St. James and OWSP. The results are summarized in Table 2. On average, the seasonal CO_2 minimum at Cape St. James was measured at Julian day of 235.0 (with a standard deviation of 6.6 days), while at OWSP the mean was day 231.0 with s.d. of 8.9 days (non-sectored) and 229.0 with s.d. of 9.2 days (sectored). To test the significance of these differences in

Table 2. *Mean Julian day and associated standard deviation of the occurrence of measured CO_2 minimum at four stations; bracketed values at Station "P" refer to sectored data*

	Mean Julian day	Standard deviation
Ocean weather Station "P"	231 (229)	8.9 (9.2)
Cape St. James	235	6.6
Alert	233	7.2
Sable Island	227	14.1

the occurrences of the seasonal minimum, we employed a Student-t test as given in WMO (1966):

$$t_d = \frac{\overline{x_1} - \overline{x_2} - (\mu_1 - \mu_2)}{\left[\frac{N_1 S_1^2 + N_2 S_2^2}{N_1 + N_2 - 2}\left(\frac{1}{N_1} + \frac{1}{N_2}\right)\right]^{1/2}},$$

where N_1 and N_2 are number of data values in samples 1 and 2, respectively. Sample means are denoted by $\overline{x_1}$ and $\overline{x_2}$, and their corresponding population means are given by μ_1 and μ_2. The variables S_1 and S_2 are standard deviations of samples 1 and 2, respectively. The degrees of freedom are given by $(N_1 + N_2 - 2)$. The results of the test indicate that we cannot, using these flask data, reject at the 95% confidence level the hypothesis that the seasonal minimum in the atmospheric CO_2 concentration occurs at the same time at Cape St. James and OWSP.

The seasonal dependency of the CO_2 variability at Cape St. James and OWSP are graphically displayed in Figs. 3c, 4c, respectively, and the statistical nature of this dependency is summarized in Table 3. Summer in the detrended mean seasonal cycle is defined as the period during which the seasonal cycle is below the reference zero line; the rest of the cycle is defined as winter. Fig. 4c graphically shows that the variability of the CO_2 measurements at OWSP appears to be larger in summer than in winter. The standard deviation in summer is 1.96 ppmv (non-sectored) and 2.01 ppmv (sectored), while in winter it is 0.88 ppmv (non-sectored) and 0.81 ppmv (sectored). Using the standard F test, the difference in the standard deviation between summer and winter at OWSP is shown to be statistically significant at the 95% level for both sectored and non-sectored cases. At Cape St. James the difference between summer and winter variability is barely significant at the 90% level. Thus, both Cape St. James and OWSP appear to show larger variability during summer than winter, although the case for Cape St. James is weaker. It is interesting to note that an analysis of the 500 mb height and 1000–500 mb thickness fields (both correlated with the 1000 mb circulation) from 1946 to 1983 indicates a greater variance in winter than in summer by almost a factor of 2 over the north-eastern Pacific Ocean. This suggests that the high summer variability in the CO_2 measurements at these monitoring sites could result from a biospheric variability in Asia, as well as some contributions from local sources and sinks of CO_2 (particularly at Cape St. James). This is now under investigation. It is also interesting to note that there is no statistically signficant difference in summer variability between Cape St. James and OWSP, but there is (at the 95% level) in winter between these two sites. In winter, Cape St. James experiences a greater variability than OWSP.

Table 3. *Seasonal dependence of the variability of CO_2 measurements at four stations; the values are standard deviation (in ppmv) about the mean seasonal cycle at each station; bracketed values at Station "P" refer to sectored data*

	Summer	Winter	Annual
Ocean weather Station "P"	1.96 (2.01)	0.88 (0.81)	1.39 (1.42)
Cape St. James	1.76	1.53	1.62
Alert	1.37	1.27	1.31
Sable Island	3.11	2.07	2.49

3.4. Comparison with Alert and Sable Island

Some basic statistical characteristics of the detrended CO_2 flask measurements at Cape St. James and OWSP have been presented and discussed above. Both of these "Pacific" sites show similar mean seasonal cycle, with seasonal minimum occuring at the same time. Furthermore, measurements show greater variability during the biospherically active season, even though atmospheric circulation shows greater interannual variability in winter than in summer over the northeastern North Pacific. This point is rather interesting because much of the short-term variability in the atmospheric CO_2 measurements at stations like Alert, Mould Bay, Pt. Barrow in the Arctic and Sable Island off the east coast of Canada has been shown to be related to atmospheric circulation variability (Peterson et al., 1980; Peterson et al., 1982; Halter and Peterson, 1981; Halter and Harris, 1983; Higuchi and Daggupaty, 1985; Higuchi et al., 1987; Chung, 1988; Worthy et al., 1994). It is therefore of interest to briefly compare the nature of the statistical variability at Cape St. James and OWSP with

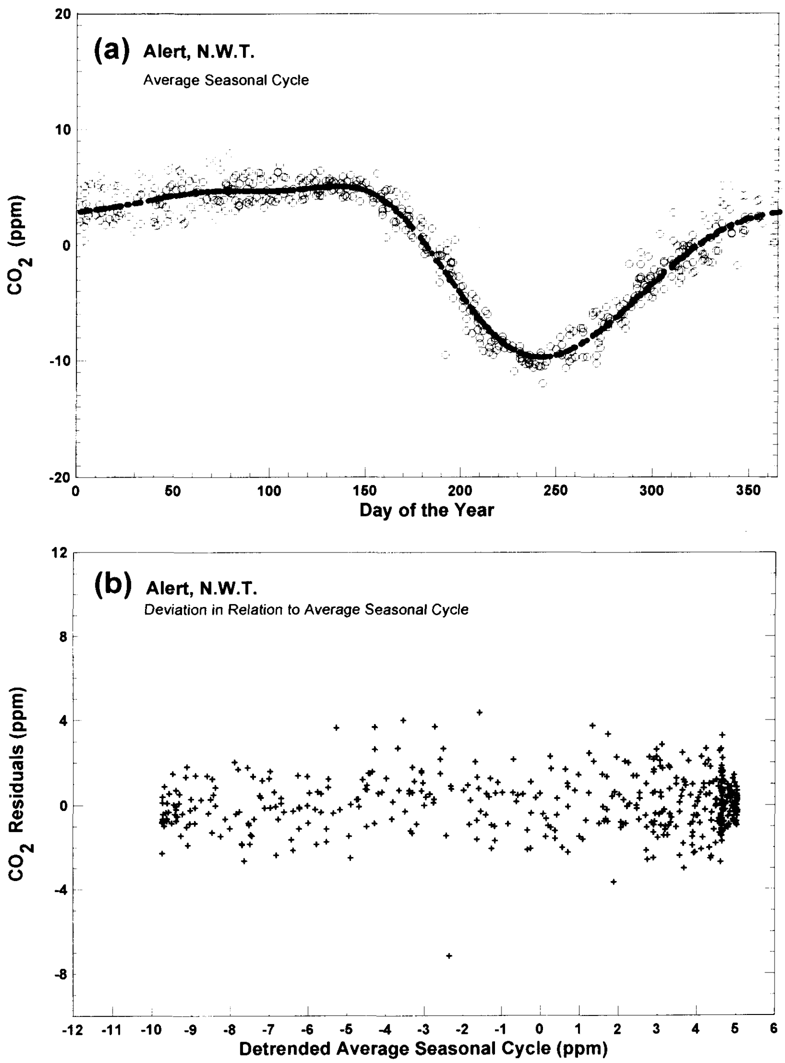

Fig. 5. (a) Same as Fig. 3b, but for Alert. (b) Same as Fig. 3c, but for Alert.

those of Alert and Sable Island. Alert (83° N, 62° W) is located on the northeastern tip of Ellesmere Island within 800 km of the north pole. Sable Island (44° N, 60° W) is located 160 km east of Nova Scotia, Canada. The island is approximately 25 km long and has a maximum width of 1 km (Wong et al., 1984).

Average or climatological CO_2 seasonal cycle and corresponding seasonal dependency of the variability of the CO_2 measurements at Alert are shown in Fig. 5a and 5b, respectively, while those at Sable Island are shown in Fig. 6. Alert and Sable Island residual data sets are composed of 465 values from 1976 to 1993 and 495 values from 1976 to 1991, respectively. Seasonal decline in the atmospheric CO_2 concentration begins in mid April at Sable Island, while at Alert it starts in late May to early June. Decline at the two "Pacific" sites begins around mid May, later than Sable Island but earlier than Alert. The early decline at Sable Island probably reflects its location downwind from the influence of North American

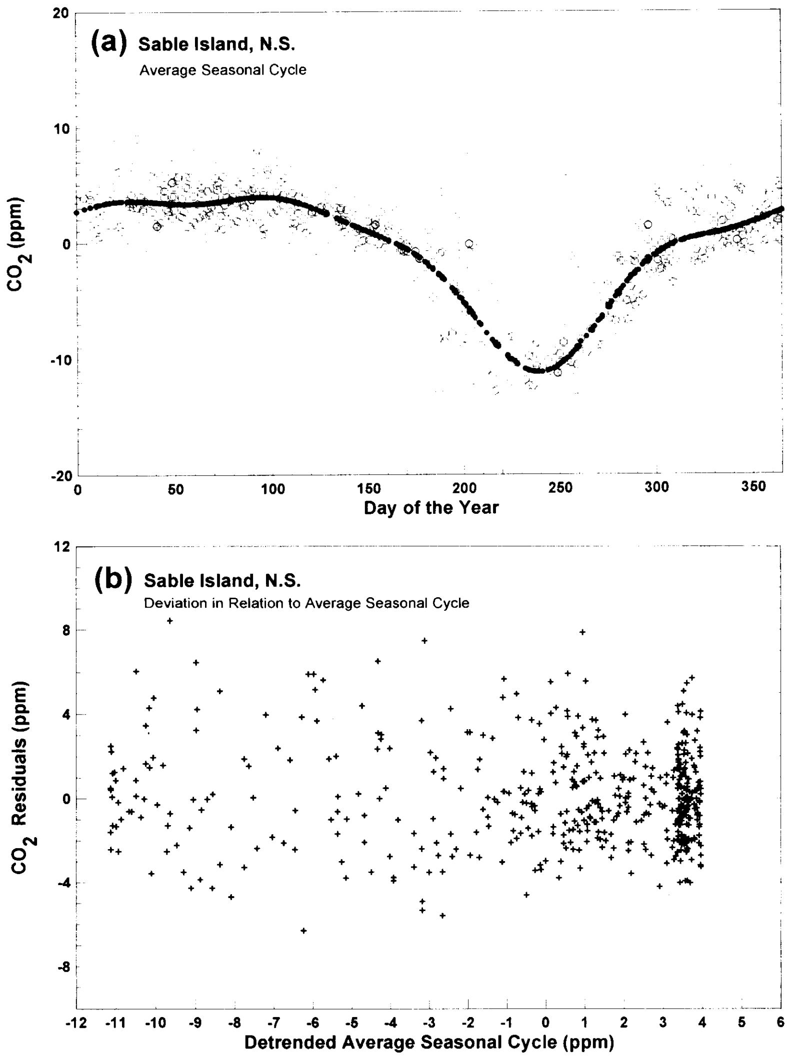

Fig. 6. Same as Fig. 5, but for Sable Island.

continental vegetation. The decline at Alert, on the other hand, is influenced by the thawing of the soil (Coyne and Kelly, 1974) and by its large distance from significant midlatitude photosynthetic uptake (Wong et al., 1984). Using the flask data, the timing of the occurrence of seasonal minimum at Alert and Sable Island (Table 1) cannot be statistically distinguished from those at Cape St. James and OWSP.

Seasonal dependency of the variability of the CO_2 measurements at Alert and Sable Island are summarized in Table 2. Residual values at Sable Island show larger scatter (standard deviation of 3.11 ppmv in summer and 2.07 ppmv in winter) about its seasonal cycle than the other three stations. It is possible that a poor sampling practice at Sable Island is a major contributor to the relatively large variability in its CO_2 measurements. The sampling protocol for Sable Island is to take flask samples on the windward shore to minimize possible "contamination" by the sparse vegetation on the island. Previous to around 1985 the sampling was done from one spot. This might have caused some flask samples to be "contaminated" by the local vegetation, but it is difficult to ascertain the degree of this contamination. Therefore, although summer variability is significantly different at the 95% confidence level from winter variability, its reality is not certain. Variability at Alert is also higher in summer than in winter (Table 2), but the difference is not statistically significant at the 95% level.

4. Conclusion

About 13 years (1979–1992) of CO_2 flask measurements (230 accepted values) taken at Cape St. James on the west coast of Canada have been analysed, and some of its basic statistical characteristics have been compared to those calculated from 966 CO_2 measurements from Ocean Weather Station "P", whose record span the period from 1969 to 1980. It has been found that both of these "Pacific" sites have same climatological CO_2 seasonal cycle, which after reaching a maximum in early to mid May declines, in response to terrestrial photosynthetic uptake, to a seasonal minimum in late August. The amplitude of the seasonal cycle at both stations is approximately 13 ppmv. But there is an interesting qualitative difference in the mean seasonal cycle between these two stations.

The CO_2 concentration at Cape St. James appears to decrease more rapidly than OWSP during early summer, suggestive of the relative proximity of Cape St. James to continental vegetation to the east. In comparison, the decline in the CO_2 concentration begins in mid April at Sable Island and in late May to early June at Alert. Within the context of the flask data we used, the timing of the seasonal minimum at Cape St. James and OWSP is not statistically different.

Both Cape St. James and OWSP show seasonal dependency in the variability of the CO_2 measurements, although this dependency is statistically weak at Cape St. James. At both sites, summer variability exceeds winter variability, although atmospheric circulation variability is greater in winter than summer over the northeastern North Pacific. Sable Island also seems to show variability greater in summer than in winter. Alert is the only station which shows no significant difference in variability between winter and summer. It is interesting to observe that three midlatitude stations which are located closer to large vegetative regions than Alert show increased variability during the period when land biosphere is photosynthetically active.

5. Acknowledgements

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