ANALYSIS OF GASP CARBON MONOXIDE DATA

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1. INTRODUCTION

This report summarizes an analysis of carbon monoxide data from the Global Atmospheric Sampling Program (GASP). The objective of this study, as described in the original proposal, is to try to improve our understanding of the cycle of this trace species in the atmosphere. To date, the sources, sinks, and transports of CO are still not yet fully identified and understood. While some of the previous figures and/or ideas on its production are under revision, new thoughts are being proposed. For example, Crutzen et al. (1979) have recently suggested that the burning of biomass is another possible source. The high values of CO found over Africa during October 1977 PAN AM round-the-world flight were first explained by Newell and Gauntner (1979) as the result of interhemispheric transport, but Pratt and Falconer (1979) attribute them as originating from vegetation in the tropical regions. A good summary of our current understanding of the carbon monoxide budget has been given recently by Marenco and Delaunay (1980). This report provides more information about the distribution and variation of CO and presents our new findings.
2. DATA

2.1 General Description

All carbon monoxide data used in the analysis are from GASP measurements. GASP was a multiyear program beginning in 1972 to measure atmospheric ozone, carbon monoxide, water vapor, condensation nuclei, and clouds, and related meteorological parameters with instruments aboard four commercial airlines (a United Airlines B-747, two Pan American World Airways B-747's, a Qantas Airways of Australia B-747) and the NASA CV-990 research aircraft. The in situ CO measurement is made with an infrared absorption analyzer using dual isotope fluorescence as described by Dudzinski (1979). For each flight, data acquisition begins on ascent through the 6 km altitude flight level, and terminates at descent through 6 km, with most observations taken between 10- and 12-km altitude. A complete GASP sampling cycle is 1 hour, divided into twelve 5-minute sampling segments. Six of these segments were data segments during which measurements were made. Interspersed between these data segments were six 5-minute calibration segments during which the systems are under checking and adjustment. Details on instrumentation, routes, and other information can be found in data reports by Holdeman et al. (1978, 1979, 1980) and Briehl et al. (1980).

2.2 Availability

The CO data are stored on tapes VL0009 through VL0020, which cover the period March 1977 through October 1978; the content of each tape is described in the above mentioned "Data Reports." A summary of carbon
monoxide observations and flights is given in Tables 2.1 and 2.2. Although data are taken in all flights above 6 km altitude, the bulk of observations fall between about 9 km and 12.5 km. Furthermore, the data are scattered unevenly over the globe. Beside the GASP data, the tapes also contain the tropopause heights (both in pressure and in meters) obtained from time and space interpolation of National Meteorological Center (NMC) archived data for the dates of the flights.

2.3 Data Check

All CO data used in the analysis were checked for obvious errors. Unexplained anomalies, such as very high values (reaching to 200 ppbv) in the stratosphere, were not included in the climatological presentation of carbon monoxide distribution over the globe. Other checks, including zero shift, variability, tagged values, extremely low and high readings, were carried out for all flights made by all aircraft for the period March 1977 through October 1978. If the zero is shifting rapidly, as indicated by inspection and by the number of values tagged "C," an indicator used to denote zero shifts of more than 100 mv but less than 200 mv between successive zero reading, then the data is classified as poor. Also, if the data is tagged "F," an indicator used to denote full scale data readings (COV = 5000 mv), then the data is classified as poor. Likewise, negative readings, again an indication of zero setting problems, would receive this classification. A method by which CO concentration is computed from the instrument voltage is outlined in "Data Reports" mentioned previously. A good guide to possible zero setting problems seems to be available in the mean stratospheric concentrations. If these are close to 50 ppbv
as found earlier by Seiler (1974), then, in general, the remainder of the data in a given file seems to be problem free. This cannot be an absolute rule, otherwise we would be producing a prejudiced climatology, but it is a good guide that seems to fit in with other tests. Several measurements of very low CO (10-20 ppbv) did appear in the stratosphere and these were retained in the analysis, when the mean values were close to 50 ppbv. In fact, each of the observations has been scanned visually by both the author and Professor Newell. After some experience, it is possible to pick out anomalies rather easily. Almost all the very low CO values are characteristic of the stratosphere and are associated with high ozone. Sometimes these values are found below the nominal tropopause; more examples are given later. A more sophisticated approach could be devised to divide the data between troposphere and stratosphere now that this experience has been gained, but for the present report the division is based on the nominal height of the tropopause as given in the data tapes.

Very high point-to-point variability can also sometimes be used as an indicator that the instrument is not working properly, particularly if this occurs throughout the tape. Some studies of the autocorrelation distance (not included here) based on data we considered excellent by other criteria yielded values of several hundred kilometers. Occasionally, sizeable patches of very high or very low CO will occur and these could be studied further as we suggest by trajectory analysis. At this time they are thought to be real.

The quality of each tape or the performance by individual aircraft is rated based on the above mentioned check items, and indicated
in Table 2.1 with a short explanation in the remarks. Consequently, 
tape 10, tape 18, file 2 of tape 19, files 1 and 2 of tape 20, the first 
1.5 hours of measurements by QANTAS contained in tape 11, and the winter 
CO data in file 1 of tape 14 are omitted in the final composite presenta-
tions on an aircraft basis. Some of the data are treated separately for 
a comparison purpose. Note that the full scale data readings (COV = 
5000 mv) identified with an "F" were also discarded. A substantial 
amount of data had already been removed before the tapes were made 
available by means of the criteria that the zero shift between readings 
exceeded 200 mv.
### TABLE 2.1. Summary of GASP Carbon Monoxide Data

<table>
<thead>
<tr>
<th>Tape no.</th>
<th>Aircraft</th>
<th>File</th>
<th>Dates</th>
<th>Total flights</th>
<th>Quality</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>PAN AM-N533 PA</td>
<td>1-4</td>
<td>10/28-31/77</td>
<td>4</td>
<td>Very good</td>
<td>Round-the-world</td>
</tr>
<tr>
<td>10</td>
<td>PAN AM-N533 PA</td>
<td>1</td>
<td>01/21/77-04/03/77</td>
<td>66</td>
<td>--</td>
<td>No CO data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>04/06/77-05/31/77</td>
<td>99</td>
<td>Poor</td>
<td>High variability, suspect zero drift, therefore, not included in the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>06/01/77-06/02/77</td>
<td>2</td>
<td>Poor</td>
<td>analysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>06/03/77-08/12/77</td>
<td>96</td>
<td>Poor</td>
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<tr>
<td></td>
<td></td>
<td>5</td>
<td>08/13/77-10/04/77</td>
<td>73</td>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>QANTAS VH-EBE</td>
<td>1</td>
<td>01/10/77-02/28/77</td>
<td>127</td>
<td>--</td>
<td>No CO data</td>
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<tr>
<td></td>
<td></td>
<td>2</td>
<td>03/15/77-04/23/77</td>
<td>120</td>
<td>OK</td>
<td>Low readings of CO occur often during the first 1- to 2-hour flights</td>
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<tr>
<td></td>
<td></td>
<td>3</td>
<td>04/24/77-06/18/77</td>
<td>144</td>
<td>OK</td>
<td>owing to the water vapor contamination effect on the desiccator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>06/18/77-08/12/77</td>
<td>131</td>
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<tr>
<td></td>
<td></td>
<td>5</td>
<td>08/15/77-10/02/77</td>
<td>124</td>
<td>OK</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>UAL-N4711U</td>
<td>1</td>
<td>01/03/77-03/25/77</td>
<td>49</td>
<td>--</td>
<td>No CO data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>03/26/77-06/13/77</td>
<td>102</td>
<td>OK</td>
<td>Flight route is limited between 21°N-46°N and 74°W-157°W</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>06/14/77-07/26/77</td>
<td>93</td>
<td>OK</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>07/27/77-09/20/77</td>
<td>110</td>
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<td></td>
</tr>
<tr>
<td>13</td>
<td>PAN AM-N655 PA</td>
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<td>02/22/77-04/09/77</td>
<td>84</td>
<td>--</td>
<td>No CO data</td>
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<tr>
<td></td>
<td></td>
<td>2</td>
<td>04/15/77-06/14/77</td>
<td>126</td>
<td>OK</td>
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<tr>
<td></td>
<td></td>
<td>3-5</td>
<td>06/01/77-10/05/77</td>
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<tr>
<td>14</td>
<td>PAN AM-N533 PA</td>
<td>1</td>
<td>10/04/77-01/03/78</td>
<td>109</td>
<td>Fair</td>
<td>CO values are OK in fall, but too high in winter</td>
</tr>
<tr>
<td></td>
<td>UAL-N4711U</td>
<td>2</td>
<td>11/06/77-01/05/78</td>
<td>138</td>
<td>OK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PAN AM-N655 PA</td>
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<td>10/05/77-12/18/78</td>
<td>99</td>
<td>OK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>QANTAS VH-EBE</td>
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<td>10/03/77-11/19/77</td>
<td>96</td>
<td>OK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>QANTAS VH-EBE</td>
<td>5</td>
<td>11/20/77-04/04/78</td>
<td>120</td>
<td>OK</td>
<td>CO values are too high in winter stratosphere</td>
</tr>
<tr>
<td>Tape no.</td>
<td>Aircraft</td>
<td>File</td>
<td>Dates</td>
<td>Total flights</td>
<td>Quality</td>
<td>Remarks</td>
</tr>
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<td>-------------------</td>
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<td>---------</td>
<td>----------------------------------------------</td>
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<tr>
<td>15</td>
<td>PAN AM-N533 PA</td>
<td>1</td>
<td>01/08/78-03/01/78</td>
<td>81</td>
<td>Excellent</td>
<td>Good for case studies</td>
</tr>
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<td></td>
<td></td>
<td>2</td>
<td>03/02/78-05/03/78</td>
<td>81</td>
<td>Excellent</td>
<td></td>
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<td></td>
<td>3</td>
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<td>84</td>
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<td>No CO data</td>
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<tr>
<td>16</td>
<td>PAN AM-N533 PA</td>
<td>1</td>
<td>06/22/78-08/14/78</td>
<td>111</td>
<td>Good O3</td>
<td>No CO data</td>
</tr>
<tr>
<td></td>
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<td>08/01/78-10/05/78</td>
<td>102</td>
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<td></td>
</tr>
<tr>
<td>17</td>
<td>UAL-N4711U</td>
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<td>01/05/78-03/20/78</td>
<td>160</td>
<td>Good</td>
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<td></td>
<td>2</td>
<td>03/22/78-05/08/78</td>
<td>79</td>
<td>Good</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>3</td>
<td>05/08/78-06/23/78</td>
<td>103</td>
<td>Good</td>
<td></td>
</tr>
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<td>18</td>
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<td>06/23/78-08/11/78</td>
<td>123</td>
<td>Poor</td>
<td>Many CO data with tag C; Summer values are unusually high; not included in the analysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>08/11/78-10/06/78</td>
<td>70</td>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>QANTAS VH-EBE</td>
<td>1</td>
<td>01/05/78-03/04/78</td>
<td>70</td>
<td>Poor/fair</td>
<td>Treated separately, high variability</td>
</tr>
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<td></td>
<td>PAN AM-N655 PA</td>
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<td>01/09/78-03/06/78</td>
<td>160</td>
<td>Fair</td>
<td>Treated separately</td>
</tr>
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<td></td>
<td>PAN AM-N655 PA</td>
<td>3</td>
<td>03/06/78-05/02/78</td>
<td>82</td>
<td>Poor</td>
<td>Many CO data with tag F; CO values are too high; not included in the analysis</td>
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<td>PAN AM-N655 PA</td>
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<td>05/16/78-06/12/78</td>
<td>67</td>
<td>Poor</td>
<td>Many CO data with tag F; not included in the analysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>06/13/78-07/27/78</td>
<td>134</td>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>07/28/78-10/09/78</td>
<td>162</td>
<td>OK</td>
<td>Treated separately</td>
</tr>
<tr>
<td>Aircraft</td>
<td>Period</td>
<td>No. of month</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>PAN AM-N533 PA</td>
<td>04/06/77-10/04/77</td>
<td>15</td>
<td></td>
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<td></td>
</tr>
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<td>10/04/77-12/21/77</td>
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<td>01/08/78-06/21/78</td>
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<tr>
<td>PAN AM-N655 PA</td>
<td>04/14/77-05/07/77</td>
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<td>10/05/77-12/18/78</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>01/09/78-10/09/78</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>UAL-N4711U</td>
<td>03/26/77-07/26/77</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>11/17/77-01/05/78</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>01/05/78-10/06/78</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QANTAS VH-EBE</td>
<td>03/22/77-10/02/77</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10/03/77-12/04/77</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>01/05/78-03/04/78</td>
<td></td>
<td></td>
<td></td>
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</tr>
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</table>
3. RESULTS AND DISCUSSIONS

3.1 Analysis Procedures

The analysis procedures involved tabulating and analyzing the CO data on a tape basis first. For those tapes which contain CO measurements by more than one aircraft, we have followed the same processes on a file basis. Finally, the composite results from four airliners, namely, PAN AM-533PA, PAN AM-N655 PA, UAL-N4711U and QUANTAS VH-EBE, are given in tabular as well as in graphical forms. In the presentations, mean values of CO and their standard deviations have been summarized on a 10° latitude by 20° longitude grid basis with subdivision into troposphere and stratosphere using reported tropopause heights with a further subdivision into seasons. In the computations of cross correlation coefficients among carbon monoxide, ozone, temperature, and zonal and north-south winds, we require that all the variables must be measured simultaneously and that the ozone data with an "L" tag is excluded. Special treatment of tape 9 has been made. Since all the data are local measurements, they were averaged by one degree in latitude and then used for plotting. However, both local and averaged values were used in the study (see Figures 3.1-2). For the other tapes, we used 128 second average values throughout.

Data were divided into four seasons: December-February, March-May, June-August and September-November. As abbreviations in the figures we have termed these winter (WI), spring (SP), summer (SU) and fall (FA)
even though the basic division is calendar months regardless of hemisphere, and seasons is not an appropriate term for the tropics.

3.2 Distribution and Variations of Carbon Monoxide

3.2.1 On tape and aircraft basis

The distribution and variations of carbon monoxide as a function of latitude and longitude in the troposphere and stratosphere for different seasons are shown in Tables 3.1 through 3.10. Zonal mean values of CO mixing ratio are plotted in Figures 3.3a-d. The purpose of presenting the data based on tape or file is to enable us to make a good comparison among all observations conducted by different aircraft during their flights. Hopefully, we can select a good data set to be used for representation of the CO background values for a significant fraction of the world. Since to date there are no substantial statistics of this gas available, the GASP data can actually be considered as the largest collection in the world, and should provide useful information on the CO climatology. The earlier reports by Seiler (1974,1975) and Dianov-Klokov et al. (1978) in USSR contain far fewer values than the present report.

3.2.2 Composite results on an aircraft basis

After careful study we have selected data from the tapes and constructed four sets of CO climatological pictures based on four aircraft. The key to the data used in each set is shown in Table 3.11 in which Tables 3.12 and 3.13 are mentioned.

Figure 3.4 presents the composite results of zonal mean mixing ratio of carbon monoxide. The UAL flights of the summer of 1978 on tape 18 have been omitted from the overall summary because of zero drift.
problems. But a summary of these data is included in Table 3.8 for information as it illustrates one of the problems arising in the type of analysis. It will be noted that there is a sharp discontinuity at the west coast of the United States with values over the land much higher than values over the ocean. Further examination showed that this came from time variations of the zero setting rather than spacial variations of carbon monoxide. Flights from Chicago to Honolulu and return showed no such discontinuity at the coast.

We should point out the fact that the averaged values of CO mixing ratio for each grid area are derived from four aircraft whose flight routes are irregular in time and space.

3.2.3 Findings

Several findings are noted.

1. Measurements of CO made by different aircraft are generally consistent. Summaries of zonal mean values collected by the four aircraft are shown by season in Table 3.14. Note that for the spring troposphere there is very good agreement between data from three aircraft. For the fall and winter troposphere agreements is not so good and we use the stratosphere data as a guide at this time. Values in the general range of CO of 50-70 ppbv are considered acceptable. On this basis all three aircraft provide good data in the spring, while the UAL data in the summer is suspect. Inspection of the individual QANTAS results for the fall showed many cases of high ozone and CO values in the 50-70 ppbv range, hence these data were accepted. PAN AM-655 data is suspect in the fall. Both PAN AM-655 and QANTAS data are suspect in the
winter as they appear too high. Present climatology may be obtained from PAN AM-533 data with the addition of PAN AM-655 plus UAL in the spring, with QANTAS and UAL in the fall, and with UAL in the winter. Having this experience with the data set it would now be possible to go back and devise a different set of criteria for data selection; however, funds are exhausted so this is not possible.

2. The overall acceptable results shown in Table 3.14 indicate that northern hemisphere values are higher than those in the southern hemisphere and troposphere values are larger than those in the stratosphere, as found by Seiler (1974).

3. A new item is tentative evidence of a seasonal cycle with northern hemisphere spring values exceeding those of summer and fall. This finding confirms the conclusion of Dianov-Klokov et al. (1978) based on measurements of total CO in the atmospheric column.

4. There is no reliable data to evaluate the seasonal cycle in the southern hemisphere. Further work with this data set on this topic is recommended.

3.3 Relationship of Carbon Monoxide with Ozone, Temperature and Winds

3.3.1 On tape or aircraft basis

We first computed linear bivariate correlation coefficients among five variables: carbon monoxide (CO), ozone (O₃), air temperature (T), zonal wind (U) and north-south wind (V) on a tape or aircraft basis using the same division as in section 3.2. We anticipate that CO should correlate negatively with O₃ in the vicinity of the tropopause. The agreement is based on the fact that O₃ is mainly produced in the stratosphere, while CO has its source on the ground and, therefore, the
vertical gradients are oppositely directed. An upward motion will bring more CO and less O₃ to the tropopause region. A downward motion would act in an opposite way.

In view of the difference in the production rates of CO and O₃ over an annual cycle, we have divided the data into seasons. A special treatment of tape 9 has been made. The correlation coefficients (R's) were computed separately for individual flights, for the troposphere and stratosphere and for the averaged values over 1° latitude. The results are presented in Table 3.15a-c. The R's for other tapes are given in Tables 3.16-3.22. It is noted that the data on tape 9 have been studied by Holdeman et al. (1978), Gauntner et al. (1979), Newell and Gauntner (1979,1980), and Pratt and Falconer (1979).

3.3.2 Composite results on an aircraft basis

Computations of correlation coefficients (R's) were performed on an aircraft basis (see Table 3.11 and Tables 3.23-3.26). In view of the dramatic decrease in CO mixing ratio in the stratosphere, which suggests that the chemical reactions of CO with other minor species become active in that region, and since the ozone mixing ratio shows almost constant and low values in the upper troposphere within about 20 degrees in either side of the equator from all observations (see Fig. A.1), we further divide the data into four categories, namely, troposphere, stratosphere, regions below and above 20° latitude. The R-values calculated in this arrangement are presented in Tables 3.23-3.26. Note that part of these correlations is contributed by the overall variation of carbon monoxide and other variables as a function of position and
it would be desirable to eliminate this contribution to the variance. However, limited funds and time did not permit this differentiation.

3.3.3. Findings

1. On individual tape basis

Except the data on tape 11 which yield very low values of correlation coefficient between CO and O₃, \( R(\text{CO}, O₃) \), possibly due to water vapor contamination on the instruments, the other 9 tapes provide us with 23 \( R(\text{CO}, O₃) \)'s of which 21 cases show minus signs and 2 show positive signs. Using a student-t test, we have found that none of the positive \( R(\text{CO}, O₃) \)'s are significant. For negative \( R(\text{CO}, O₃) \)'s, 19 out of 21 are significant at the 1% level or higher.

2. On aircraft basis

a. Above 20° latitude

Twenty-two \( R(\text{CO}, O₃) \) values have been obtained. All of them indicate the anticorrelation between CO and O₃. Three \( R(\text{CO}, O₃) \)'s are insignificant with the rest, 19 values of R, having significant levels higher than 1%.

b. Below 20° latitude

There are only seven R values. Interestingly enough, all but one have positive signs. However, most of them are insignificant; only one has significance at the 1% level and two at about the 3% level. In general, the lowest correlations occur for aircraft and season which were rejected in our consideration of Table 3.14.
3.4 Case Studies

We have made several case studies examining how the CO mixing ratio changes in response to the variations of $O_3$ concentrations. Records of flight level, tropopause altitude, air temperature, ozone and carbon monoxide mixing ratios are plotted in Figure 3.5 through Figure 3.11. It is seen clearly in these figures that in the stratosphere the $O_3$ mixing ratio and the air temperature are high and the CO mixing ratio is low, and that the picture is reversed when the aircraft is flying in the troposphere. However, two interesting points are worthy of note.

1. At times when the aircraft was supposed to be in the troposphere according to the tropopause altitude indication, occasionally one finds that the mixing ratio of CO decreases sharply and the $O_3$ and $T$ increase at the same time. Such incidences can be found in Figure 3.5 (by the arrow at 0115 GMT) and Figure 3.9 (by the arrow at 1050 GMT).

2. On the other hand, when the aircraft was indicated as flying in the stratosphere, the instruments suddenly recorded high CO, low $O_3$ and $T$ values as shown in Figure 3.8 by the arrow at 1245 GMT and in Figure 3.10 by the arrow at 1900 GMT.

The former cases can be explained by the downward motion of the stratospheric air into the troposphere at those times, while the latter cases are thought to be due to an upward intrusion of the tropospheric air into the stratosphere. These examples lead us to suggest that the $O_3$ concentrations, the air temperature and the CO mixing ratio should be analyzed simultaneously and that the numerical height of the
tropopause is not always a good indicator to be used for dividing the CO values. This approach could be used in future analysis.

3.5 Ozone Data

In view of the relationships found in section 3.3.3 between ozone and carbon monoxide, we include a summary of the ozone data itself in Appendix A. It may be seen from Figure A.1 that ozone in the upper tropical troposphere has an almost constant and low mixing ratio (~20 ppbv). These values are similar to those reported by Routhier et al. (1980) in the GAMETAG experiment. The negative correlation between the two species at high latitudes can no doubt be explained by vertical motion processes as illustrated in section 3.4. The positive correlation at low latitudes may partly arise from photochemical interactions between the species as have been described recently by Fishman et al. (1980). There may also be a contribution to the positive correlation from the process of advection. Northern hemisphere middle latitude air moving into the tropics will be traveling down the gradient of both ozone and carbon monoxide, as may be seen from a comparison of Figure 3.4 and Figure A.1.

There are some unexplained very low ozone concentrations (16-30 ppbv) in the middle latitudes as may be seen from Table A.9. These originate from the tape 20 record for May 1978. The instrument measured up to 600 ppbv when the aircraft was definitely in the stratosphere so these measurements are not evident instrument problems.

(text continues on page 113)
FIGURE 3.1. Flight path of the PAN AM B-747SP aircraft, 28-31 October 1977. F1 is from San Francisco (SFO) to London (LHR); F2 is from LHR to Capetown (CPT); F3 is from CPT to Auckland (AKL); F4 is from AKL to SFO. The other routes indicated by 1 through 6 are the paths of the PAN AM-N655 aircraft.
FIGURE 3.2a. Carbon monoxide, ozone and air temperature (T) on the PAN AM flights from north pole to south pole.
FIGURE 3.2b. Similar to Figure 3.2a, but from south pole to north pole.
FIGURE 3.3a. Zonal means of carbon monoxide mixing ratio. SP, SU, FA and WI stand for spring, summer, fall and winter, while subscripts T and S are for troposphere and stratosphere, respectively.
FIGURE 3.3b. Similar to Figure 3.3a except that the data are taken from different tapes or obtained by different aircraft.
FIGURE 3.3c. Similar to Figure 3.3b.
FIGURE 3.3d. Similar to Figure 3.3b.
FIGURE 3.4. Composite results of zonal mean mixing ratio of CO derived from four airlines. SP, SU, FA and WI stand for spring, summer, fall and winter, while subscripts T and S are for troposphere and stratosphere, respectively.
FIGURE 3.5. Measurements of ozone ($O_3$) and carbon monoxide (CO) mixing ratios and temperature ($T$) during the flight of the PAN AM-N533PA from San Francisco to Hong Kong 1 February 1978.
FIGURE 3.6. Measurements of ozone ($O_3$) and carbon monoxide (CO) mixing ratios and temperature (T) during the flight of the PAN AM-N533PA from JFK (40.67$^\circ$N, 73.78$^\circ$W) to HND (35.53$^\circ$N, 139.71$^\circ$E) on 24 February 1978.
FIGURE 3.7. Similar to Figure 3.5 but from HND to JFK and on 4 March 1978.
FIGURE 3.8. Similar to Figure 3.5 but from HND to JFK and on 13 March 1978.
FIGURE 3.9. Similar to Figure 3.5 but from HND (35.53°N, 139.71°E) to LAX (33.86°N, 118.34°W) and on 15 March 1978.
FIGURE 3.10. Similar to Figure 3.5 but on 1 April 1978.
FIGURE 3.11. Similar to Figure 3.5 but from HND (35.53°N, 139.71°E) to LAX (33.86°N, 118.34°W) and on 23 April 1978.
TABLE 3.1a. Fall tropospheric CO data taken from tape 9 as a function of latitude and longitude. The mean mixing ratio (ppbv) and standard deviation for each grid are given at the left and right corner, and the number of points is indicated at the bottom of the box. The zonal mean and the total observations are shown at the right-hand column.
TABLE 3.1b. Similar to Table 3.1a but for the stratosphere.
TABLE 3.2a. Spring tropospheric CO data taken from tape 11 as a function of latitude and longitude. The plotting code is the same as described in Table 3.1a. The first one and one-half hours of each flight data are excluded.
TABLE 3.2b. Similar to Table 3.2a but for the stratosphere.
TABLE 3.2c. Similar to Table 3.2a but for summer troposphere.
TABLE 3.2d. Similar to Table 3.2c but for the stratosphere.
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**TABLE 3.2e.** Similar to Table 3.2a but for fall troposphere.
TABLE 3.2f. Similar to Table 3.2e but for the stratosphere.
TABLE 3.3. CO data taken from tape 12 as a function of latitude and longitude. The plotting code is the same as described in Table 3.1a.
TABLE 3.4a. Spring tropospheric CO data taken from tape 13 as a function of latitude and longitude. The plotting code is the same as described in Table 3.1a.
TABLE 3.4b. Similar to Table 3.4a but for the stratosphere.
TABLE 3.5a. Fall tropospheric CO data taken from tape 14, file 1. The plotting code is the same as described in Table 3.1a except that the zonal mean values are shown at top row of the table.
TABLE 3.5a. Continued.
TABLE 3.5b. Similar to Table 3.5a but for the stratosphere.
TABLE 3.5b. Continued.
TABLE 3.5c. Similar to Table 3.5a but for winter troposphere.
TABLE 3.5d. Similar to Table 3.5c but for the stratosphere.
TABLE 3.5d. Continued.
TABLE 3.5e. Fall tropospheric (left) and stratospheric (right) CO data taken from tape 14, file 2. The plotting code is the same as described in Table 3.1a.
TABLE 3.5f. Similar to Table 3.5e but for winter.
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TABLE 3.5g. Fall tropospheric CO data taken from tape 14, file 3. The plotting code is the same as described in Table 3.1a.
TABLE 3.5g. Continued.
TABLE 3.5h. Similar to Table 3.5g but for the stratosphere.
TABLE 3.5i. Similar to Table 3.5g but for winter troposphere.
TABLE 3.5j. Similar to Table 3.5i but for the stratosphere.

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TABLE 3.5k. Fall tropospheric CO data taken from tape 14, files 4 and 5. The plotting code is the same as described in Table 3.1a.
TABLE 3.5k. Continued.
TABLE 3.51. Similar to Table 3.5k but for winter troposphere.
TABLE 3.5m. Similar to Tables 3.5k and 3.5l but for fall stratosphere (top) and winter stratosphere (bottom).
Table 3.6a. Winter tropospheric CO data taken from tape 15 as a function of latitude and longitude. The plotting code is the same as described in Table 3.1a.
TABLE 3.6b. Similar to Table 3.6a but for the stratosphere.
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TABLE 3.6d. Similar to Table 3.6c but for the stratosphere.
### Table 3.7a

Winter tropospheric (left) and stratospheric (right) CO data taken from tape 17 as a function of latitude and longitude. The plotting code is the same as described in Table 3.1a.

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*Note: The table shows the data values for each latitude and longitude combination.*
TABLE 3.7b. Similar to Table 3.7a but for spring 1978.
TABLE 3.7c. Similar to Table 3.7a but for summer 1978.
TABLE 3.8a. Summer tropospheric (left) and stratospheric (right) CO data taken from tape 18 as a function of latitude and longitude. The plotting code is the same as described in Table 3.1a.
TABLE 3.8b. Similar to Table 3.8a but for fall 1978.
TABLE 3.9a. Winter tropospheric CO data taken from tape 19, file 1. The plotting code is the same as described in Table 3.1a.
TABLE 3.9b. Winter tropospheric CO data taken from tape 19, file 2.
TABLE 3.9c. Similar to Table 3.9b but for the stratosphere.
TABLE 3.10a. Summer tropospheric CO data taken from tape 20, file 3.
TABLE 3.10a. Continued.
TABLE 3.10b. Similar to Table 3.10a but for the stratosphere.
TABLE 3.10b. Continued.
TABLE 3.10c. Similar to Table 3.10a but for fall troposphere.
TABLE 3.10c. Continued.
TABLE 3.10d. Similar to Table 3.10c but for the stratosphere.
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**TABLE 3.12a.** Composite results of carbon monoxide measurements made by United Airlines B-747 aircraft. The data are taken from tape 12, tape 14 (file 2 only) and tape 17. The plotting code is the same as described in Table 3.1a. (a) Spring troposphere. (b) Spring stratosphere. (c) Summer troposphere. (d) Summer stratosphere.
TABLE 3.12b. Similar to Table 3.12a but (a) for fall troposphere, (b) for fall stratosphere, (c) for winter troposphere, and (d) for winter stratosphere.
TABLE 3.13a. Composite results of carbon monoxide measurements made by QANTAS Airways during winter (December 1977-February 1978) in the troposphere. The data are taken from tape 14 (files 4 and 5) and tape 19 (file 1 only). The plotting code is the same as described in Table 3.1a.
TABLE 3.13a. Continued.
TABLE 3.13b. Similar to Table 3.13a but for winter stratosphere.
TABLE 3.13b. Continued.
### TABLE 3.14a. Summary of Zonal Mean Mixing Ratios of CO for the Troposphere

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* indicates that the data are not included in the calculations of the means.
Number of observations in parentheses.
No data in southern hemisphere.
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<th>FLIGHT 2 (2523)</th>
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<td>$T$</td>
<td>$U$</td>
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**TABLE 3.15a.** Linear bivariate correlation coefficients among five variables. CO = carbon monoxide; $O_3$ = ozone; $T$ = air temperature; $U$ = zonal wind, $V$ = N-S wind. Number of data pairs in parenthesis.
TABLE 3.15b. Similar to Table 3.15a except that the data are grouped based on whether they are obtained in the troposphere or stratosphere instead of on flight basis.

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<tr>
<td>U</td>
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<tr>
<td>V</td>
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<tr>
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<tr>
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TABLE 3.15c. Similar to Table 3.15a but using averaged values of CO, O₃ and T over 1° latitude.
TAPE 11 FALL (350)

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<tr>
<td>T</td>
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TAPE 11 SUMMER (1171)

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TABLE 3.16. Similar to Table 3.15a but for tape 11 and on seasonal basis.
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TABLE 3.17. Similar to Table 3.16 but for tape 12.
TABLE 3.18. Similar to Table 3.16 but for tape 14, file 1 and file 3 only.
TABLE 3.19. Similar to Table 3.16 but for tape 14 (file 4 and 5) and for tape 15.
<table>
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<table>
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**TABLE 3.20.** Similar to Table 3.16 but for tape 17.
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**TABLE 3.21.** Similar to Table 3.16 but for tape 18 and tape 19 (file 2).
TABLE 3.22. Similar to Table 3.16 but for tape 20 (file 3).
**WINTER TROPOSPHERE**

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**WINTER STRATOSPHERE**

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**TABLE 3.23a.** Similar to Table 3.15 except that the data are grouped based on latitude and the region below and above the tropopause. The data used in the computations were collected by PAN AM-N533 aircraft.
TABLE 3.23b. Similar to Table 3.23a but for spring season.
### FALL TROPOSPHERE

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### FALL STRATOSPHERE

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<tr>
<td>U</td>
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<tr>
<td>V</td>
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**TABLE 3.23c.** Similar to Table 3.23a but for fall season.
### Winter Troposphere

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>O$_3$</th>
<th>T</th>
<th>U</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
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<td>0.352</td>
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<td>0.083</td>
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<tr>
<td>O$_3$</td>
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<td>0.253</td>
<td>-0.089</td>
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<tr>
<td>T</td>
<td>0.184</td>
<td>-0.083</td>
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<tr>
<td>V</td>
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<td>0.019</td>
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### Winter Stratosphere

<table>
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<tr>
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<th>O$_3$</th>
<th>T</th>
<th>U</th>
<th>V</th>
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</thead>
<tbody>
<tr>
<td>CO</td>
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<tr>
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<td>T</td>
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<td>-0.068</td>
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**TABLE 3.24a.** Similar to Table 3.23a except that the data used in the computations were obtained by PAN AM-N655 aircraft.
### SPRING TROPOSPHERE

<table>
<thead>
<tr>
<th>&gt; 20° LATITUDE (89)</th>
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<th>T</th>
<th>U</th>
<th>V</th>
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</thead>
<tbody>
<tr>
<td>CO</td>
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<tr>
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<tr>
<td>T</td>
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<td>-0.036</td>
<td>-0.199</td>
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<tr>
<td>U</td>
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<td>-0.080</td>
<td>0.567</td>
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<tr>
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<table>
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<tr>
<th>&lt; 20° LATITUDE (22)</th>
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### < 20° LATITUDE (0)

<table>
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<th>U</th>
<th>V</th>
</tr>
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<tr>
<td>CO</td>
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**TABLE 3.24b.** Similar to Table 3.24a but for spring season.
### FALL TROPOSPHERE

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>O₃</th>
<th>T</th>
<th>U</th>
<th>V</th>
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</thead>
<tbody>
<tr>
<td>CO</td>
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<tr>
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<td>V</td>
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### FALL STRATOSPHERE

<table>
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<th>T</th>
<th>U</th>
<th>V</th>
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</thead>
<tbody>
<tr>
<td>CO</td>
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<tr>
<td>O₃</td>
<td>-0.404</td>
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<tr>
<td>T</td>
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<td>0.539</td>
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<td>U</td>
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<td>0.399</td>
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**TABLE 3.24c.** Similar to Table 3.24a but for fall season.
<table>
<thead>
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<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WINTER TROPOSPHERE</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>&gt; 20° LATITUDE (86)</td>
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</tr>
<tr>
<td>CO</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>O₃</td>
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<td>T</td>
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<td></td>
<td></td>
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<td></td>
</tr>
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<td>0.322</td>
<td>0.299</td>
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</tbody>
</table>

**TABLE 3.25a.** Similar to Table 3.23a except that the data used in the computations were obtained by United Airlines B-747 aircraft.
TABLE 3.25b. Similar to Table 3.25a but for spring season.

### SPRING TROPOSPHERE

<table>
<thead>
<tr>
<th></th>
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<th>O₃</th>
<th>T</th>
<th>U</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>O₃</td>
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<td></td>
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<tr>
<td>T</td>
<td>0.048</td>
<td>-0.055</td>
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</tr>
<tr>
<td>U</td>
<td>-0.064</td>
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<td>-0.140</td>
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<tr>
<td>V</td>
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<td>0.058</td>
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### SPRING STRATOSPHERE

<table>
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<tr>
<th></th>
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<th>T</th>
<th>U</th>
<th>V</th>
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</thead>
<tbody>
<tr>
<td>CO</td>
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<td></td>
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<tr>
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<tr>
<td>T</td>
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<td>0.689</td>
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</tr>
<tr>
<td>U</td>
<td>-0.079</td>
<td>-0.067</td>
<td>-0.029</td>
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<td>V</td>
<td>-0.056</td>
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<td>0.205</td>
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TABLE 3.25c. Similar to Table 3.25a but for summer season.
TABLE 3.26a. Similar to Table 3.23a except that the data used in the computations were obtained by QANTAS Airways VH-EBE aircraft.
### Fall Troposphere

<table>
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<th></th>
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<th>U</th>
<th>V</th>
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<tr>
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<tr>
<td>O&lt;sub&gt;3&lt;/sub&gt;</td>
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<tr>
<td>T</td>
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<td>0.025</td>
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<tr>
<td>U</td>
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### Fall Stratosphere

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<th>U</th>
<th>V</th>
</tr>
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<tr>
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<td></td>
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<td></td>
<td></td>
</tr>
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<td></td>
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**TABLE 3.26b.** Similar to Table 3.26a but for fall season.
4. SUMMARY AND CONCLUDING REMARKS

The GASP observations of carbon monoxide are plentiful and can be claimed as the largest collection in the world. Our studies reported in this document can only represent an overall look at this material; much remains to be investigated in more detail. Unfortunately, due to instrumental problems, about one-half or more of the data has been found questionable. Hence, great care was exercised when we examined these data. We believe that the final results presented in this report are reasonably good and can be used by modelers in validating their theoretical calculations. The following conclusions are reached.

1. Based on the final data recommended in Table 3.14, we note that carbon monoxide is higher in middle latitudes of both hemispheres than in low latitudes with the largest values in the northern hemisphere.

2. Also, based on the data of Table 3.14, there is preliminary evidence of a seasonal cycle in the northern hemisphere with maximum values in the spring season. Because so much of the data from the southern hemisphere was discarded, it is not possible to establish a seasonal cycle there.

3. Carbon monoxide and ozone are negatively correlated for latitude polewards of 20°, a circumstance we ascribe to vertical motion. Ozone-rich carbon monoxide poor air descends from higher levels in the stratosphere often through the tropopause while ozone poor carbon monoxide rich air ascends from lower levels in the troposphere to flight levels.
4. Carbon monoxide and ozone are positively correlated for latitudes equatorwards of 20°, a circumstance that may be related to photochemical interactions between the gases as observed by Fishman et al. (1980).

5. Variability of CO in the stratosphere is small. Because we used the stratosphere as a calibration device we partly forced this conclusions. But as long as the instrument was able to measure down to about 50 ppbv and simultaneously registered high ozone (> = 120 ppbv) the data was accepted. There were a few measurements of very low carbon monoxide (= 10-20 ppbv) whose origin is unknown. Again, they could be examined by trajectory analysis.
REFERENCES


APPENDIX

Summary of GASP ozone data as a function of latitude and longitude for the period March 1977 to December 1978. In each box the value at the upper left corner represents the mean value of ozone mixing ratio (ppbv) for that grid area, the figure at the upper right corner is the standard deviation, and the number of observations is indicated at the bottom. The zonal mean and the corresponding total data points for the latitudinal belt are given at the top row in each table. The data are taken from tapes 11 through 20. Note that the ozone data with an "L" tag are not included in the statistics and that the 128 second average ozone values are used only.
FIGURE A-1. Composite results of zonal mean ozone mixing ratio derived from all available data taken from tapes 11 through 20. SP, SU, FA and WI stand for spring, summer, fall and winter, while subscripts T and S are for troposphere and stratosphere.
TABLE A.1: March, April, May 1977 in troposphere. See appendix.
TABLE A.1. Continued.
TABLE A.2. Continued.
### Table A.3

June, July, August 1977 in troposphere. See appendix.

<table>
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<th>MEAN</th>
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<tbody>
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**Notes:**
- MEAN: Values in bold indicate the mean for each longitude and latitude combination.
- See appendix for detailed explanation and methodology.
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| Mean | 9 | 32 | 37 | 43 | 123 | 181 | 618 | 1153 | 1401 | 599 | 110 |
|------|--|--|--|--|--|--|--|--|--|--|--|--|
| 0    | 102 | 12 | 7 | 15 | 15 | 100 | 35 | 119 | 27 | 31 | 6 |
| 20   | 71 | 17 | 68 | 20 |
| 40   | 50 | 15 | 70 | 17 |
| 60   | 4 | 38 |
| 80   | 38 | 6 | 52 | 6 |
| 100  | 18 | 17 |
| 120  | 25 | 8 | 28 | 11 | 48 | 25 |
| 140  | 77 | 113 | 35 |
| 160  | 39 | -- |
| 180  | 150 | 150 | 12 | 4 | 44 | 16 | 122 | 98 | 100 | 79 | 122 | 66 |

Atmospheric carbon monoxide in the upper troposphere and lower stratosphere for the period March 1977 through October 1978 was analyzed. This trace constituent was measured as part of the Global Atmospheric Sampling Program (GASP) by the four Boeing 747 aircraft. This report summarizes the CO data and presents the distribution and variations in space and time of this gas. The data show that the CO mixing ratios are higher in the troposphere than in the stratosphere. In the northern hemisphere the highest value of CO mixing ratio occurs in spring, although more data are needed to verify these findings. Correlation coefficients among CO, O₃, air temperature (T) and winds were calculated for different regions under different seasons. It has been found that the CO correlates negatively with O₃ above 20 degrees latitude and positively below that latitude. Case studies using the data of CO, O₃, and T measured simultaneously were performed. Discussions and suggestions are made. A summary of ozone data on seasonal basis is given in an appendix.