An Analysis of Tropopause Pressure and Total Ozone Correlations

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ABSTRACT

The relationship between total ozone and tropopause pressure is analyzed using 4 years (1979–82) of Nimbus-7 total ozone data and NMC global analyses of tropopause on a 5° by 5° grid. The fields are separated into medium (synoptic) and large spatial scales via a spherical harmonic expansion. The global distribution of variability and correlation are presented for each season. The large-scale analysis is based primarily on data from 1979 due to pronounced temporal inhomogeneities in the tropical tropopause data.

The synoptic scales show strong correlations (≥0.6) in the middle latitudes of both hemispheres with a rapid equatorward drop and a more gradual poleward decline; a similar dependence on latitude is found using tropopause values derived directly from station data. Within a season, the areas of highest correlation tend to be associated with the regions of maximum variance of the storm track regions. In contrast, the seasonal dependence is such that the summer hemispheres tend to have the most extensive regions of high correlation while the more energetic winter seasons have the smallest. A frequency analysis (limited to time scales longer than 3 days) of selected regions indicates that in middle latitudes synoptic-scale fluctuations of total ozone and tropopause pressure exhibit generally similar distributions in power and no significant phase differences; equatorward the coherence drops rapidly at all frequencies.

Nonseasonal fluctuations of the large-scale fields generally show weak correlations (<0.6) everywhere. A major exception is the springtime middle latitude South Pacific. The strongest correspondence between large-scale ozone and tropopause pressure fields involves long period (seasonal) fluctuations in high latitudes. Over Antarctica the coupling is strongest in middle and late spring in association with the spring warming while the decrease in total ozone in early spring shows no apparent relation to tropopause variations.

1. Introduction

The nature of day-to-day total ozone fluctuations has been of considerable interest for many years. Early studies based on a limited number of ground station reports (e.g., Dobson et al., 1946; Reed, 1950) helped to establish a firm meteorological basis for the observed daily variations. The Reed study, in particular, helped to elucidate the roles of vertical motion and horizontal advection in producing low ozone values in upper tropospheric ridges and high ozone values in upper tropospheric troughs. Ohring and Muench (1960) performed a more detailed analysis of the relationship between ozone and various meteorological quantities (temperature, height, north–south wind at 100 mb) using 2 years of observations from the European ozone network. They found no regular seasonal variation in the correlations while some evidence was found for a maximum in the correlations near 50°N.

With the advent of satellite measurements of ozone, more detailed analyses of ozone variability have become possible. For example, the study by Schoeberl and Krueger (1983) successfully modeled observed total ozone changes in the Southern Hemisphere (SH) and further suggested that, in general, atmospheric disturbances which are vertically trapped near the tropopause and have little vertical phase shift will tend to produce the strongest correlation with total ozone. Recently the record of satellite observations of total ozone has become sufficiently long to allow, for the first time, nearly spatially complete estimates of the climatology of total ozone (Bowman and Krueger, 1985).

In conjunction with the availability of global distributions of total ozone a number of case studies have been performed which demonstrate that total ozone may provide, otherwise difficult to obtain, information about various parameters of meteorological interest. For example, Rodgers et al. (1986) used total ozone to monitor the interactions between tropical storms and their environment. Sechrist et al. (1986) demonstrated the ability to identify secondary circulation features associated with a middle latitude jet. In a more indirect application, tropopause information gained from total ozone have shown potential for improving temperature retrievals. Feasibility studies by Munteanu (1983) show

* Dr. Marie-Jeanne Munteanu passed away after the completion of this study. This work is published as a memorial to her.

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that stratification schemes based on statistically-derived total ozone–tropopause relationships produce significant improvements to microwave retrievals.

The purpose of this work is to provide a better foundation for using ozone information in meteorological studies by providing an estimate of the global distribution and seasonal variation of the correlation between total ozone and tropopause pressure. Section 2 describes the method of analysis and examines the quality of the tropopause information. Section 3 presents the global distribution of the variances and correlation for the synoptic scales together with a frequency analysis of selected regions. Section 4 presents the results for the large scales. The discussion and conclusions are given in section 5.

2. Data analysis

The ozone data consists of Nimbus-7 total ozone measurements area-averaged onto a 5° by 5° grid. The data quality and area averaging from higher resolution data are discussed in Bowman and Krueger (1985). The tropopause pressure data consists of twice daily 2.5° by 2.5° global analyses performed at the National Meteorological Center (NMC). The tropopause data is converted to daily values (average of 0000 and 1200 UTC) and the appropriate 5° by 5° subset is selected for processing with the ozone data; no interpolation in time is performed on the ozone or tropopause data. The following analysis makes use of data covering the time period beginning 1 January 1979 and ending 30 September 1982. In addition, a limited sample of 12z radiosonde observations is used to obtain tropopause values for March–May (MAM) of 1979.

The global fields are decomposed into spherical harmonics with a triangular truncation using the method of least squares to allow for missing data. The field $z$ is expanded in spherical harmonics ($Y^m_n$) as

$$Z(\lambda, \phi) = \sum_{n=1}^{5} \sum_{m=1}^{5} d^m_n Y^m_n(\lambda, \phi) + \epsilon(\lambda, \phi) \quad (1a)$$

where $n$ is the total wavenumber and $m$ the zonal wavenumber. We define the large-scales by the first term on the right hand side (rhs) of (1a) and the medium scales by the second term on the rhs of (1a). The solution for the coefficients ($d^m_n$) is determined from minimizing

$$\int_0^{2\pi} \int_{-\pi/2}^{\pi/2} \epsilon^2(\lambda, \phi) \cos \phi d\phi d\lambda. \quad (1b)$$

The choice of $n = 5$ as a cutoff for the large scales was somewhat arbitrary, however, it was found that the estimates of the high wavenumber modes (total wavenumber $n > 5$) are sensitive to the data in the polar regions. Since the nature of the Toms measurements (backscattered solar) do not allow observations during the polar nights this leads to individual high wavenumber harmonics which are not unique and have little physical meaning.

The NMC tropopause data is the product of an inhomogeneous analysis procedure due to numerous changes which occurred in the NMC model and analysis method during the 4-year period. The most significant changes (concerning the tropopause) occurred in May 1980 and February 1982. Prior to May 1980 the tropopause was treated explicitly as a material surface in a 9-layer grid point model (McPherson et al., 1979). Subsequently the model was changed to a spectral formulation without a material surface tropopause. The tropopause was determined during post processing from an isentropic analysis which classified the tropopause into polar, middle and subtropical types (Gustafson, 1965). As discussed below this algorithm produced a serious positive bias in the tropical tropopause pressure. This was not remedied until early 1982 when a new algorithm was implemented. This scheme determines the tropopause by finding the lowest level (above 550 mb) at which the lapse-rate decreases to 2.0°C km$^{-1}$ or less; the same method was used to obtain the tropopause pressure from the radiosonde station data.

The spatial distribution of the tropopause pressure bias is shown in Fig. 1a in terms of a t-value given by

$$U = \frac{(m + n - 2)^{1/2}(x_m - y_n)}{(1/m + 1/n)^{1/2}(s_x^2 + s_y^2)^{1/2}} \quad (2)$$

which results from a two-sided t-test for equality of the 1979 and 1981 means. Here $s_x^2$ and $s_y^2$ are the centered sums of squares, $x$ and $y$ the sample means and $m$ and $n$ the number of data points at each gridpoint for 1979 and 1981, respectively. The extremely large values in the tropics suggest the bias is not the result of natural atmospheric variability. Note that even if one assumes only 30 effective degrees of freedom the 1% t-value is 2.75. The bias disappears for the most part (Fig. 1b) when the large-scale field is removed.

Other less dramatic jumps (possibly linked to model changes) can be found in traces of the large-scale tropical tropopause which make it difficult to correct for the bias. As a result, the analysis of the large scales was confined to 1979; during this time the large-scale tropopause values seem to be reasonable and one has the benefit of increased data coverage provided by the FGGE observing system. The t-test (Fig. 1b) suggests the synoptic-scale tropopause was not strongly influenced by the model changes. In addition, a comparison of the variances and correlations between individual years suggests the synoptic scale fluctuations are reasonable.

3. Correlation and variance for the synoptic scales

In this section we present first the correlations and variances for the medium scales stratified by season and based on the entire 4 years of data. Prior to com-
Fig. 1. (a) The t-value from a test which compares the 1979 and 1980 means of tropopause pressure. (b) As in (a), except with the large-scale field removed. For (b) absolute values greater than 2.75 are shaded. See text for details. Contour intervals are 0, ±2.75, ±10, ±20, ±30 . . . Negative values have dashed contours. Boxes in (1b) correspond to area-averages analyzed in section 3.
puting the statistics a least-squares quadratic polynomial is removed from the data for each season of each year and at every gridpoint. A simple pointwise test for the significance of the correlations using Fisher’s Z transform (e.g., Pearson and Hartley, 1970, Chap. 7) and assuming 25 degrees of freedom shows values greater than 0.4 are significant at the 95% level. Using this as a guide and for clarity only contour levels with absolute value greater than 0.4 and the 0 contour are actually plotted. In section 3b we present the results of a frequency analysis for selected regions along the Greenwich meridian.

a. Global distribution

Figure 2a shows the Northern Hemisphere (NH) springtime (MAM) correlation field. The field shows a well defined latitudinal dependence with maximum correlations occurring in the middle latitudes of both hemispheres and a rapid drop in the correlations away from these regions. Correlations greater than 0.6 occur over a majority of the latitude band 30°–70°N while values greater than 0.5 are found between 30°–60°S. Correlations greater than 0.7 occur over the major regions of storm activity over the North Atlantic, Europe and the east coast of Asia. These regions are accompanied by maxima in the rms of the tropopause pressure and ozone (Figs. 2b and 2c). In both hemispheres the Pacific sector tends to produce weaker correlations.

For comparison Table 1 shows the average correlations for MAM of 1979 in various latitude bands between 30°W, 30°E. Here 1200 UTC radiosonde station data is used to determine the tropopause pressure values. The method for obtaining the tropopause is outlined in section 2. The mean values presented in column 2 of Table 1 are obtained by computing the correlations for the individual stations and then averaging over all stations within the appropriate latitude band which have more than 15 reports. The third column is the standard deviation between stations of the correlation and the fourth column shows the number of stations used in the averages. The general latitude dependence found for the medium scales (which dominate the variance) is reproduced very well in the station data. There seems to be some tendency for the station data to give somewhat smaller correlations. Note also that very few stations contribute to the tropical and SH results.

Table 1. The correlations between total ozone and tropopause pressure (based on station data between ±30o longitude) for MAM of 1979. Correlations are computed separately for each station with the averages and standard deviations between stations presented below. Stations with less than 15 reports are not included.

<table>
<thead>
<tr>
<th>Latitude band</th>
<th>Average</th>
<th>Std. dev.</th>
<th>Number of stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>40°–70°N</td>
<td>0.60</td>
<td>0.13</td>
<td>94</td>
</tr>
<tr>
<td>20°–40°N</td>
<td>0.36</td>
<td>0.20</td>
<td>18</td>
</tr>
<tr>
<td>20°–20°N</td>
<td>−0.02</td>
<td>0.14</td>
<td>8</td>
</tr>
<tr>
<td>20°–40°S</td>
<td>0.20</td>
<td>0.15</td>
<td>7</td>
</tr>
<tr>
<td>40°–70°S</td>
<td>0.69</td>
<td>0.14</td>
<td>2</td>
</tr>
</tbody>
</table>

maxima displaced to the south of the maximum correlations.

The correlations for SON (Fig. 4a) exhibit a very narrow band of relatively high correlations in the NH with peak values exceeding 0.8 over the eastern North Atlantic. In the SH correlations greater than 0.6 are confined to the middle latitude Atlantic and Indian Oceans. The largest values in the rms pressure pattern (Fig. 4b) also exhibit a very narrow distribution with latitude and coincide with the band of high correlation. In both the SH and NH the largest rms ozone values (Fig. 4c) again appear to be located poleward of the regions of high correlation and rms tropopause pressure.

Figure 5a shows the correlations for DJF. The winter hemisphere correlations show a marked reduction in both amplitude and spatial extent compared to the other seasons. Except for the North Atlantic, the correlations are almost everywhere less than 0.6. In contrast the summer hemisphere shows large areas with correlations greater than 0.7 in the 30° to 60° latitude belt over the Atlantic and extending east to the dateline. The rms fields for both pressure and ozone (Figs. 5b and 5c) show areas of maximum variability which correspond well with areas of maximum correlation.

b. Frequency analysis of regional data

In this section we perform a more detailed analysis of the nonperiodic components of the synoptic-scale fluctuations for selected area averages. Of particular interest is the frequency dependence of the correlations and whether the equatorward drop in correlations is uniform with frequency. The areas chosen (regions 1–5) lie along the Greenwich meridian and are shown in Fig. 1b.

The 3-year time period for this analysis begins 1 July 1979. This period was chosen in order to minimize the number of days without data (approximately 15%). Intervals with missing data are generally only one day in length but in three cases seven consecutive days have no tropopause data. The annual and semiannual cycles and a second-order polynomial were removed, and days with missing values were replaced by a linear in-
Fig. 2. (a) Distribution of the correlation (×100) between total ozone and tropopause pressure for March, April and May for the synoptic scales (1979–82). Contour interval is 10. Only contours with absolute value ≥40 and the zero contour are plotted. Contours with absolute value ≥60 are shaded. (b) As in (a) except for rms of tropopause pressure. Contour interval is 5 mb. Values greater than 30 are shaded. (c) As in (a), except for rms of total ozone. Contour interval is 5 DU. Values greater than 25 are shaded.

Fig. 3. As in Fig. 2, except for June–August.

interpolation in time. In the following, results for periods less than about 3 days are omitted due to an apparent sensitivity of the shorter time-scale results to the missing data.
Figure 6 shows the power spectra for the middle latitude and tropical regions. In middle latitudes (Figs. 6a and 6b) total ozone and tropopause pressure exhibit power distributions with very similar slope suggesting a strong coupling between tropopause and total ozone fluctuations. In the tropics the power is much reduced when compared to the middle latitudes and total ozone shows a much sharper decline in power with increasing frequency than the distribution for tropopause pressure. The subtropical power spectra (not shown) have distributions similar to that of the tropical region.

Figure 7 shows the coherence in the middle latitude
and subtropical regions. The coherence in the tropical region is insignificant at almost all frequencies and is not shown. Figure 7a compares the coherence in the SH and NH middle latitudes. In the NH region one finds a general decrease in coherence with frequency and marginally significant peaks near 5 and 8 days.
The SH region shows surprisingly high coherence (compared to the NH) for periods between 5 days and one month. This suggests that the coherence in the middle latitudes of the SH is not seriously affected by model and data deficiencies. The phase spectra (not shown) show no significant phase differences. The subtropical regions (Figs. 7b and 7c) show a clear reduction in coherence at almost all frequencies. The lower frequencies still show significant coherence while the shorter periods become incoherent, particularly in the NH.

4. Correlation and variance for the large scales (1979)

As discussed in section 2, inhomogeneities in the data restrict the analysis of the large scales to 1979. The problem seems to be mainly confined to the tropics and subtropics. We have also examined statistics of the complete data record and in the following we use the middle and high latitude results to serve as a guide to assess whether the results for 1979 are anomalous. We shall see in this section that non-seasonal fluctuations of the large scales becomes comparable to that of the medium scales during the winter and transition months at high latitudes. We also find a general tendency for total ozone to have a greater fraction of the variance in the large scales than we find for the tropopause pressure.

We present first the correlation and rms fields of the nonseasonal fluctuations, where the seasonal variations are removed by fitting a second-order polynomial as discussed in section 3. Unlike the medium scales, the large-scale fluctuations have a major seasonal component. We show the coupling between the tropopause and ozone on these time scales (part b) by redoing the correlations without removing the second-order polynomial. Caution must be used in interpreting these correlations since, when the seasonal signal dominates, they indicate for the most part how closely the two series follow the same trends.

a. Nonseasonal fluctuations

Figure 8a shows the correlations for MAM. Compared with the medium scales the correlations are generally much smaller showing only a few regions with correlations greater than 0.6. The rms fields for tropopause pressure and ozone (Figs. 8b and 8c) also show a general lack of correspondence. The ozone field shows high variance over North America, Asia and south of Australia. In contrast, the tropopause rms suggests some correspondence with fluctuations in the subtropical highs in the Northern Hemisphere. In Fig. 9a JJA shows a band of relatively high correlation in the winter hemisphere extending from the eastern Pacific across the southern tip of South America and into the higher latitude Indian Ocean. These correlations are in regions of relatively high variance for both tropopause (Fig. 9b) and ozone (Fig. 9c). In the NH relatively high cor-

![Diagram](image-url)

**FIG. 8.** (a) Distribution of the correlation (×100) between total ozone and tropopause pressure for the large scale nonseasonal fluctuations for March, April and May of 1979. Contour interval is 10. Only contours with absolute value ≥40 and the zero contour are plotted. Contours with absolute value ≥60 are shaded. (b) As in (a) except for rms of tropopause pressure. Contour interval is 2 mb. Values greater than 12 are shaded. (c) As in (a), except for rms of total ozone. Contour interval is 2 DU. Values greater than 12 are shaded.
relations exist east of Greenland and extend eastward over northeast Asia: a similar pattern is found in the rms ozone pattern.

The SH spring (SON) shows relatively high correlations throughout the eastern South Pacific Ocean and the Indian Ocean (Fig. 10a). These regions also dominate the rms fields of both the tropopause pressure (Fig. 10b) and total ozone (Fig. 10c). During DJF (Fig. 11) the South Pacific correlations are reduced from their spring values and correlations have increased over
It is difficult to assess the significance of these correlations. Results based on the entire data record (not shown) suggest that the high Pacific correlations during the SH spring, the regions of high correlations during JJA (in both hemispheres), the correlations over the Gulf of Alaska in DJF and possibly the correlations over South America and west of Australia may be real. Certainly some of these regions (e.g., Alaska, South America) suggest an orographic influence, while others such as the high correlations in the high latitude South Pacific are associated with well-known periods of intense storminess.

b. Correlation with the seasonal cycle included

The influence of the seasonal cycle is to sharply increase the correlations (Fig. 12), particularly in high latitudes. While some exceptions occur, the correlations are for the most part positive indicating that as tropopause pressure slowly increases (decreases) the total ozone increases (decreases) as one would expect from simple vertical motion considerations. In general, we find that the high latitude results presented below are similar to those obtained using the entire data record.

For MAM (Fig. 12a) large areas of positive correlation occur over North America and Asia. These are likely associated with the general springtime warming of the large continental regions. In the SH positive correlations occur over the tropical and subtropical Indian Ocean and extend into the middle latitudes of the Pacific Ocean. Comparing this with Fig. 8a we see that the SH correlations are in part due to nonseasonal fluctuations. For JJA (Fig. 12b) the regions of high correlation over North America and Asia have moved poleward and the entire area north of 60° shows correlations which exceed 0.6. In the SH correlations greater than 0.6 occur east of Australia and to the west of southern Africa. Again, comparing this with Fig. 9a we see that the SH correlations are largely due to nonseasonal fluctuations.

During SON (Fig. 12c) the NH correlations are reduced from the summer values and have moved southward off the continents and over the Bering Sea and Gulf of Alaska. A large region of negative correlations occurs in the subtropics, while in the SH high correlations occur over Antarctica extending equatorward over South America. The negative correlations in the NH are partly a reflection of phase differences in the annual cycles of total ozone and tropopause pressure: during SON total ozone is still showing a general decline in these regions while tropopause pressure has begun to increase in response to the decreased solar heating. The Antarctic correlations are discussed in more detail in section 5.

The correlations for DJF (Fig. 12d) show maxima in the NH which have moved further south over western North America and the Gulf of Alaska and weakened when compared to SON. In the SH one finds a
wavey band of high correlations centered at 30° latitude extending around the globe. Comparing this with Fig. 11a we find that a considerable part of the correlation is tied to non-seasonal fluctuations (particularly in the Gulf of Alaska). Antarctica shows everywhere negative correlations: this is the consequence of a general summertime decrease in ozone accompanied by a very weak tropopause increase.

5. Discussion and conclusions

The most striking characteristic of the spatial distribution of the correlations for the synoptic scales is the strong latitudinal gradient with relatively strong correlations (>0.6) in the middle latitudes of both hemispheres, a very rapid decrease in correlations towards the equator and a more gradual decrease towards the poles. The general dependence on latitude was confirmed using station data and does not seem to be strongly influenced by model deficiencies which might produce erroneous tropopause values in data sparse regions. However, in view of the algorithmic changes in the tropopause finder during the period of study and its effect on the tropics, it is possible that our results overestimate the equatorward decline in correlations. Both the poleward and especially the equatorward decline are likely influenced by the difficulty in assigning a unique tropopause in regions characterized by discontinuities in the climatological tropopause (Rodgers, personal communication).

In the NH the position and width of the latitude bands with high correlation show a pronounced seasonal variation. In summer the distribution shows a very broad band of high correlations extending poleward of about 35°N, while the winter season shows
the weakest correlations. In the SH the strength of the band of relatively high correlations also changes with season while the position changes very little. Relatively high correlations are generally found between 30° and 60°S with the highest and most extensive values occurring (as in the NH) during the summer months. Significant longitudinal variations are also found which seem to be tied to the positions of maximum storm activity as inferred from the positions of maximum tropopause variability. However, the nature of the correspondence between high correlation and high ozone variability is not clear. Generally one finds a tendency for the regions of maximum ozone variability to lie slightly poleward of the regions of maximum tropopause variability.

The frequency analysis of synoptic-scale total ozone and tropopause pressure fluctuations shows strong coherence and no phase differences over a wide range of frequencies (periods greater than 3 days) in middle latitudes of both hemispheres, and a general decline in coherence as one moves equatorward. A serious shortcoming of the present analysis is our inability to obtain reliable spectral estimates of shorter period fluctuations. Such estimates should ideally be based on data with higher spatial (2.5° × 2.5°) and temporal (twice daily) resolution together with appropriate averaging in time to colocate the two datasets. Further work also needs to be done to understand the winter/summer differences in correlations. Some preliminary work in which we have computed the spectra separately for the winter and summer months in the NH middle latitude region shows that the largest differences in coherence occur at fairly long periods (near 20 days).

For the large scales the strong dependence on latitude is absent and the correlations are generally much weaker. With the major exceptions of the springtime South Pacific and the summertime NH high latitudes the correlations are almost everywhere less than 0.6. However, the large scale variations have a strong low frequency (seasonal) component which when included in the calculations leads to much stronger correlations particularly in high latitudes. For the most part these correlations are positive and reflect the seasonal cycle in heating in middle and high latitudes.

The general nature of the correlations in the NH high latitudes and the apparently unique behavior over Antarctica becomes somewhat clearer from an inspection of the corresponding time series. Figure 13 shows the tropopause pressure and total ozone time-dependence (no spatial filtering) over a 10° by 10° area covering parts of southern Alaska and the Gulf of Alaska (Fig. 13a) and over Antarctica (Fig. 13b). Over Alaska we see a fairly regular seasonal behavior with a minimum in tropopause pressure and total ozone in late summer and a maximum in both fields during late winter and early spring. Superimposed on this are high frequency fluctuations which have large amplitude in winter and small amplitude in summer. The high frequency fluctuations are primarily due to the medium scales while the slow seasonal variation is dominated by the large scales. Over Antarctica the variation is more complicated. From Fig. 13b it is clear that the strong correlations during spring are the result of the sudden increase in tropopause pressure and ozone which occurs in association with the spring warming in middle and late spring. During the summer months the ozone shows a general decline while the tropopause pressure changes little. The winter seasons show (in contrast to Alaska) a general drop in tropopause pressure, apparently associated with the strong stratospheric cooling and perhaps synoptic-scale horizontal heat transport in the troposphere. Since it is polar night, no total ozone measurements are available. In early spring, when the ozone hole is observed to form (Farman et al., 1985) we see a decrease in total ozone (data starts 25 August) but no corresponding drop in tropopause pressure. This suggests the total ozone decrease over Antarctica during this time of year is not associated with a simple large-scale lifting of the tropopause.

We have not addressed the question of ozone transport in this study. It is certain that high correlation does not guarantee large transport as the winter/summer differences make clear. It is possible that the high summertime correlations are due to fairly barotropic disturbances which primarily cause a lifting and lowering of the tropopause with little horizontal advection. More baroclinic wintertime disturbances extend deeper into the stratosphere producing a complicated mixture of vertical and horizontal advection of ozone. The differences in strength of the correlation between the synoptic and large scales is probably due in part to such differences in vertical structure since the latter are known to propagate strongly into the stratosphere, especially during the winter season. Such problems have been addressed quantitatively for individual cases (Schoeberl and Krueger, 1983) and can be answered more generally by analyzing model simulations such as that performed by Schlesinger and Mintz (1979). Of course, as more complete observations of the vertical distribution of ozone (see Dutsch, 1978, for a summary of recent data) become available the global distribution of fluxes may be obtained directly from the observations.

Returning finally to the main intent of this work, our results suggest that (on the spatial scales resolved in this study) total ozone is not a simple proxy for the circulation in the upper troposphere even in middle latitudes where total ozone explains between 40% and 60% of the variance. The dependence on latitude, season and scale should all be taken into account. Hopefully, as we learn more about ozone transport through modeling and careful observational analyses the combination of total ozone and its vertical distribution will provide both information and a measure of confidence in the information about various circulation parameters of the upper troposphere and lower stratosphere.
FIG. 13. Time series of total ozone and tropopause pressure for unfiltered data for (a) Alaska (10° by 10° box centered on 62.5°N, 152.5°W) and (b) Antarctica (area-average south of 77.5°S). The tropopause is given by the thin solid line. The ozone is denoted by a plus in (a) and by an asterisk in (b).
Acknowledgments. We wish to thank Dr. Kenneth Bowman for providing us with the gridded total ozone data and for his help in developing the spherical harmonic analysis routines. We also benefitted from discussions with Dr. Arlin Krueger. Mr. Dan Iredell provided the expert programming necessary to analyze the station data and Ms. Laura Rumburg helped draft the figures.

REFERENCES


