NOTES AND CORRESPONDENCE

Variability in Total Ozone Associated with Baroclinic Waves

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1. Introduction

Lim and Wallace (1991, hereafter LW) have demonstrated the efficacy of one-point regression maps for investigating the three-dimensional structure of baroclinic waves. They regressed gridded data for the wind, temperature, and geopotential height fields at standard pressure levels against a high-pass-filtered time series of data at a single point (usually 500 mb height at a grid point centered on an oceanic stormtrack). This technique yields patterns that may be viewed as composite maps of the perturbations associated with baroclinic waves. In addition to the aforementioned fields, regression analysis can be used for derived dynamical fields such as potential vorticity (PV) and for trace constituent fields such as ozone.

It is well known (e.g., Hoskins et al. 1985) that baroclinic waves are characterized by PV anomalies near the tropopause, which depress the tropopause height in regions of cyclonic vorticity and raise it in regions of anticyclonic vorticity. Since the three-dimensional motion field can be deduced from the distribution of PV, knowledge of the PV anomaly field defines most aspects of the structure of a synoptic disturbance.

It is also well known (Reed and Danielsen 1959; Danielsen 1968; Shapiro 1987) that the high frequency variability of PV and ozone are strongly correlated near the tropopause. Since concentrations of ozone are much higher in the lower stratosphere than in the upper troposphere, any process that depresses the height of the tropopause will tend to replace ozone-poor tropospheric air by ozone-rich stratospheric air, and the total column ozone amount will increase; this relationship has been noted, for example, by Reed (1950) and by Schubert and Munteanu (1988). Thus, troughs of baroclinic disturbances should be associated with elevated amounts of total ozone. Since total ozone, unlike PV, is routinely observed on a global basis by satellite, it would be useful to establish whether the high frequency varying part of the total ozone field can be used as a proxy for the upper-level PV distribution of baroclinic disturbances in data-poor regions, particularly the oceanic stormtracks and to make a quantitative estimate of the amplitude of the fluctuations in ozone associated with baroclinic waves. Schoebel and Krueger (1983), in a case study, showed that satellite observations of total ozone reveal the Southern Hemisphere pentagonal wave.

2. Data source and analysis procedure

Ozone data were provided by the Total Ozone Mapping Spectrometer (TOMS) aboard the Nimbus-7 Satellite, which began collecting data in November 1978. Seven winters were used, November through April, from 1980/81 through 1986/87.

The gridded TOMS data tapes contain daily data reported for cells of dimensions 1.0° latitude by 1.25° longitude for the region between 50°S and 50°N. The longitudinal spacing increases to 2.5° between 50° and 70° latitude. In order to simplify the calculations, these original cells were averaged into 2.0° latitude by 2.5° longitude bins. Time series were formed for each winter at each bin point and gaps filled by linear interpolation.

Since the polar night precludes the collection of data north of 67° for a substantial portion of the time series, the data used were limited to the range of 10°–66°N.

The fluctuations in total ozone due to baroclinic waves are small in comparison to the low-frequency variability. Thus, to study the impact of baroclinic waves on ozone, we removed the low-frequency variability by forming a bandpass-filtered reference time series \( x(t) \) of geopotential height, following LW. For each winter, filtered, normalized, nondimensional time series of 500 mb height were formed at the reference points PAC (41°N, 178°E) and ATL (45°N, 41°W). The filter had half-power points at frequencies corresponding to about 6 days and 2 days. Height data were available for the entire period of record of the ozone measurements at the PAC reference point, but only through calendar year 1984 for ATL. Calculations were performed on a latitude–longitude grid, then interpolated onto the 1977-point NMC octagonal grid for plotting.

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Because the Nimbus-7 passes over a given area at approximately noon local time, the data are not synoptic. Temporally interpolating the ozone data from daily measurements to find synoptic maps of ozone proved to be both inaccurate and cumbersome, so a more efficient method was devised. For each grid longitude, a shifted time series was formed by considering the geopotential height at the reference grid point, but linearly interpolated to the time each day when the satellite passed over that grid longitude. For example, at longitude 90°W, local noon is 1800 UTC, so each day’s reference height corresponding to 90°W can be estimated by averaging that day’s 1200 UTC value and the next day’s 0000 UTC value. To assure that the standard deviation of the reference time series is unity, the normalization was done after the temporal shift. This method exploits the higher temporal resolution of the reference series (twice daily) and more accurately captures the phase relationship between ozone and height. The price of this improvement is some loss of resolution in the reference time series, and hence some of the magnitude of the correlation between ozone and height.

Covariances between the ozone field and the normalized value of the 500-mb geopotential height were calculated using the equation

\[ c_i = \frac{1}{N} \sum_{t=1}^{N} y_i(t)x_i(t) \]

where \( y_i(t) \) is the time series at grid point \( i \), and \( x_i(t) \) is the reference time series at the longitude of grid point \( i \). The sum is performed over all days for which ozone data can be found at grid point \( i \), and \( x_i(t) \) is renormalized for these available days.

The values thus found can be treated as a two-dimensional field and plotted on a grid; this is the one-point regression map. Additionally, time-lagged maps can be produced by replacing the \( t \) in \( y_i(t) \) by \( t + \Delta t \), where \( \Delta t \) is a time lag in days. We averaged the regression coefficients \( c_i \) over the available winters. As LW note, bandpass filtering the reference time series is sufficient to eliminate the contribution of the low-frequency variability to the regression pattern.

3. Results

Figure 1 shows a one-point regression map formed in the manner described in the previous section when total ozone is regressed on bandpass-filtered 500 mb height at the grid point in the Pacific stormtrack (PAC). The pattern of alternating positive and negative values extends over nearly 180° longitude, and there appear to be three complete waves, of wavelength 50° longitude. For reasons that are not clear to us, the wavelength appears to be longer over the western Pacific than over the eastern Pacific; this cannot be attributed solely to the changing tilt of the waves as they mature (see, for instance, Fig. 1a of LW). Downstream of the reference point the anomaly patterns take on a bowed shape, while upstream they tend to be more isotropic, except for a broad, flat region between about 150° and 160°E, which is partly responsible for the lengthened wavelengths there.

The amplitude of the bandpass-filtered ozone anomaly field is about 11 Dobson Units (DU) near the reference point, or about 3% of its seasonally averaged value. This is consistent with a 500 m anomaly in tropopause height, using Reed’s (1950) estimate that a 1 km displacement in the lower stratosphere would produce a 24 DU ozone anomaly. Note that anomalies in tropopause height cannot be equated with anomalies in the heights of pressure surfaces.

It would be instructive to compare these maps for ozone with maps for potential vorticity. Unfortunately, LW do not show regression maps for PV, but their Fig. 11 shows a regression map for relative vorticity (\( \Phi \)); in view of the rather short zonal wavelength of baroclinic waves, we should expect the distributions of \( \Phi \) and PV to be very similar. Indeed, the regression patterns for
total ozone and $\zeta$ are similar in sign and shape, but two differences warrant comment. First, the zonal wavelength of the ozone pattern appears to be somewhat longer than that for vorticity (and for the other fields in LW). Since Wallace et al. (1988) have shown that the details of the filter are unlikely to influence the deduced wavelength of baroclinic waves, it seems more plausible that the ozone field responds with larger amplitude to the longer waves in the spectrum of baroclinic waves, which are better able to penetrate into the stratosphere. Second, the regression maximum appears to be located just to the north of the base grid point on the ozone maps and just to the south of the base grid point in the vorticity map. It is possible that this difference is attributable to different meridional gradients in ozone and vorticity, but it might also be related to the contribution of the thermal field to the relative vorticity.

The winter-to-winter variations of the pattern are slight. For a typical winter such as 1986/87 (Fig. 2), the high and low centers are close to their positions in the average plot (Fig. 1).

A comparison with the pattern formed by allowing the reference time series to lead or lag the ozone data shows the time evolution of the pattern (see Fig. 3). The dominant features progress eastward at a rate of about 15 degrees per day, implying a period of 4 days, and remain largely unchanged in shape. The patterns at day +1 and day −1 are almost exactly out of phase, and both display remarkable behavior in the region of 150° to 160°E, mentioned above. Individual low or high centers seem almost to jump as they cross this region. It is also curious that the pattern is generally stronger downstream, even at lag −2; in fact, the low center at about 160°W is deeper at day −2 than at day +2. One possible explanation is that presence of the climatological mean trough and corresponding wintertime ozone maximum located at about 60°N, 140°E somehow suppresses ozone response in this region.

A similar analysis with the Atlantic reference point (Fig. 4) reveals a similar wave pattern, although it is coherent over a much shorter range of longitudes. Again, the ozone minimum is located slightly to the west of the reference point, and the wavelength is about 50°. The wavelike pattern damps out and splits only one wavelength downstream of the reference point, where the waves move over the Eurasian continent.

4. Conclusions

An analysis of one-point regression maps of total ozone formed by regressing the time series of bandpass-

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**Fig. 3.** As in Fig. 1, but with a lag (in days) of (a) −2, (b) −1, (c) 0, (d) 1, and (e) 2. A lag of 2 days means the ozone value on day $n + 2$ is regressed on the height value on day $n$. 
filtered geopotential height data against the gridded TOMS data reveals a strong signature of baroclinic waves in the ozone variability. The regressed patterns are similar in extent and behavior to the relative vorticity patterns reported by LW. They appear to propagate eastward at about 15° longitude per day and have wavelengths of order 50° longitude (wavenumber 6 or 7). A coherent pattern at least three wavelengths long can be identified in the Pacific region, which extends across much of the North American continent. The Atlantic pattern, by contrast, breaks down when the waves reach Europe. We believe that this behavior reflects the fact that the subtropical jetstream and baroclinic wave guide have a relatively small meridional range in the Pacific and over North America, while not only is there large latitudinal variability in the jet location in the European sector, but the flow frequently splits into separate jets over northern Europe and the Mediterranean. As a result the composite patterns formed by the regression analysis are far more effective at defining baroclinic waves over North America than over Europe. Features of the wintertime mean ozone field may influence the response to tropospheric waves.

Shapiro et al. (1982) show that the TOMS instrument can be used to locate the jet stream. The results presented above show that TOMS data also provide statistical information on the amplitudes and phases of baroclinic waves. Whether these relationships are dependable enough to be of practical use in four-dimensional data assimilation schemes remains to be seen.

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REFERENCES


