The Total Ozone Field Separated into Meteorological Regimes. Part I: Defining the Regimes

ROBERT D. HUDSON, ALEXANDER D. FROLOV, MARCOS F. ANDRADE, AND MELANIE B. FOLLETTE

Department of Meteorology, University of Maryland, College Park, College Park, Maryland

(Manuscript received 9 July 2002, in final form 10 February 2003)

ABSTRACT

Traditionally, studies in the stratosphere using column ozone amount, ozone profiles, and dynamical variables at midlatitudes have centered on zonal averages of these quantities made over specific latitude bands. This is in sharp contrast to the studies made within the polar vortices where the average is made within regions defined by potential vorticity, a meteorological parameter. An analysis of the ozone field in the Northern Hemisphere outside of the polar vortex is presented in which it is shown that this field can also be separated into meteorological regimes. These regimes are defined as 1) the tropical regime, between the equator and the subtropical front; 2) the midlatitude regime, between the subtropical and polar fronts; 3) the polar regime, between the polar front and the polar vortex; and 4) the arctic regime, within the polar vortex. Within each regime the zonal daily mean total ozone value is relatively constant, with a clearly separate value for each regime. At the same time, the stratospheric ozone profiles are clearly distinguishable between regimes, each regime having a unique tropopause height. A midlatitude zonal average, whether of ozone profiles, total ozone, or dynamical variables, will depend on the relative mix of the respective values within each regime over the latitude range of the average. Because each regime has its own distinctive characteristic, these averages may not have physical significance.

1. Introduction

Dobson et al. (1927) reported ground-based measurements of the total column ozone using a spectrometer that observed the solar ultraviolet irradiance. They noted that when an upper-tropospheric front passed over the instrument, the total ozone value either dropped or rose sharply. Shalamyanskiy and Romanshkina (1980) and later Karol et al. (1987) divided ground-based total ozone measurements into three regions, separated by the polar and subtropical jet streams. They found that total ozone and temperature profiles had small variability within each region but changed sharply at the polar and subtropical fronts. The same change in ozone across a frontal boundary can be seen in the data from the Total Ozone Mapping Spectrometer (TOMS; McPeters et al. 1996). Figure 1 shows an image of the total ozone measurements for the Northern Hemisphere, taken on 11 March 1990. Three distinct regions can be identified—one dark blue, one green/yellow, and the other red—separated by two boundaries in the total ozone field. These boundaries are shown as solid blue and yellow lines in Fig. 1, and it will later be shown that these lines correspond to the upper-tropospheric subtropical and polar fronts, respectively. The solid red line marks the position of the sharp gradient in the isentropic potential vorticity (IPV) contours on the 450-K isentropic surface, which traditionally is assumed to mark the edge of the polar vortex (Nash et al. 1996; Traub et al. 1995; Schoeberl et al. 1992). These three lines divide the total ozone field into four meteorological regimes, which we define as 1) the arctic regime, within the polar vortex; 2) the polar regime, between the polar front and the polar vortex; 3) the midlatitude regime, between the subtropical and polar fronts; and 4) the tropical regime, between the equator and the subtropical front.

The total ozone archived dataset used in this paper is the TOMS level-3 hierarchical data format product (for details of this dataset see McPeters et al. 1996), which is made up of 1° latitude by 1.25° longitude pixels. In all cases the mean total ozone shown in this paper is an area-weighted mean. Figure 2a shows the zonally averaged (over 1° latitude bands) total ozone amount for all of the data (open circles) and the same average within each of the four regimes. It should be noted that every pixel was used in this analysis. The average for all of the data slowly increases with latitude until the polar vortex is reached. On the other hand, the average for the tropical, midlatitude, and polar regimes are relatively constant over a wide range of overlapping latitudes. There is also a clear difference between the average total ozone amounts for each of these regimes. If

Corresponding author address: Dr. Robert D. Hudson, Dept. of Meteorology, University of Maryland, College Park, College Park, MD 20742-2425.
E-mail: hudson@atmos.umd.edu

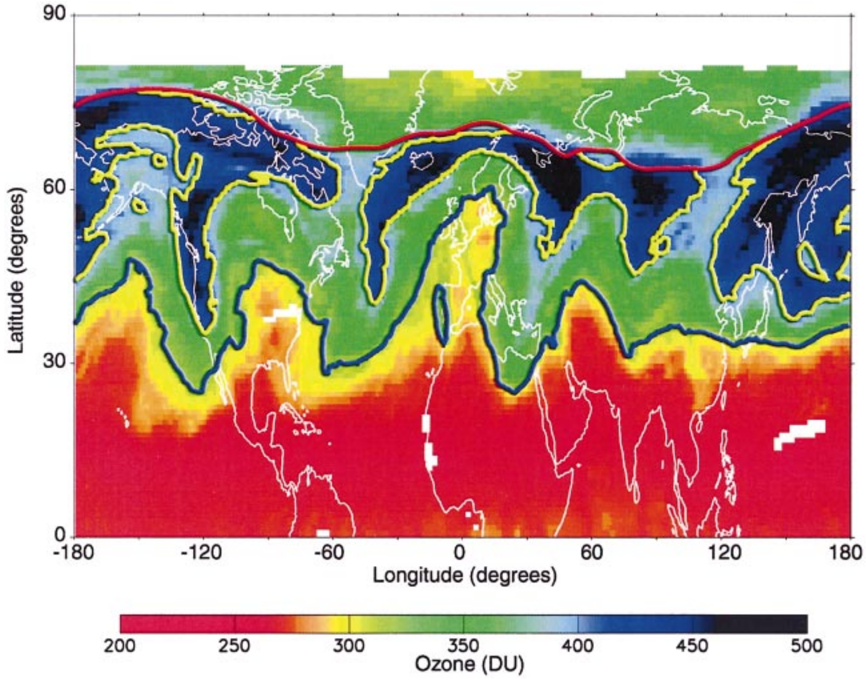

FIG. 1. Total ozone image taken by TOMS on 11 Mar 1990. The solid yellow and blue lines represent boundaries in the total ozone field, corresponding to the polar and subtropical upper-tropospheric fronts, respectively. The red line indicates the edge of the polar vortex derived from the sharp gradient in PV contours on the 450-K isentropic surface.

those total ozone values close to and at the boundaries are excluded from the average, then the range of values within each regime, except for the Arctic regime, becomes narrower, as shown in Fig. 2b. The important point to be noticed in both Figs. 2a and 2b is that each regime, except for the Arctic regime, has a distinct range of ozone values, which do not overlap with the other regimes. The Arctic regime is only present in the winter months, and for the remainder of this paper the analysis will be restricted to the other three.

This paper is divided into six sections. In section 2, the method used to define the ozone boundaries of the regimes is explained. The meteorological significance of these boundaries is discussed in section 3. In sections 4 and 5 the ozonesonde and temperature profiles within each regime are analyzed. The summary and conclusions of the paper are given in section 6.

2. Derivation of the total ozone boundaries

Shalamyanskiy and Romanshkina (1980) and Karol et al. (1987) used the geopotential height on the 200-hPa level of the maximum wind speed in the subtropical jet to obtain the position of the subtropical front, and on the 300-hPa level for the polar front. They then used these boundaries to separate ground-based total ozone measurements into three regimes on a daily basis. They observed that over the course of a month the value of the geopotential height of these boundaries differed by less than 80 m. Similarly, when they analyzed the ozone value at the position of the boundary, they found that, over the course of a month the total ozone was constant to within a few Dobson units (1000 DU = 1 atm cm). This monthly mean varied little over the 7 yr of the study. The asterisks in Fig. 3 are the mean boundary values that they obtained. These boundary values will be referred to as the Karol data in the remainder of this paper. Under the assumption of small variability of total ozone within each regime, a simple schematic of the ozone field as a function of latitude can be drawn (Fig. 4). In this picture, the ozone value for the boundary of the front is defined as being numerically equal to the average of the ozone values on either side of the front. This definition of the boundary has been adopted in this paper.

In order to obtain objective values of the total ozone at the boundaries as a function of time, the following procedure has been developed. First, the Karol boundaries were used to generate an initial mask for each day. This mask delineates the fronts and identifies those pixels that are within each regime. Figure 5 shows the mask generated for 11 March 1990. The positions of the subtropical and polar fronts were obtained by using a contour program on the TOMS level-3 dataset. The position of the polar vortex was derived from the position of the 31.5–potential vorticity (PV) unit contour [1PV unit (PVU) = 10^{-6} K m^2 kg^{-1} s^{-1}] on the 450-K potential temperature surface obtained from the National Centers

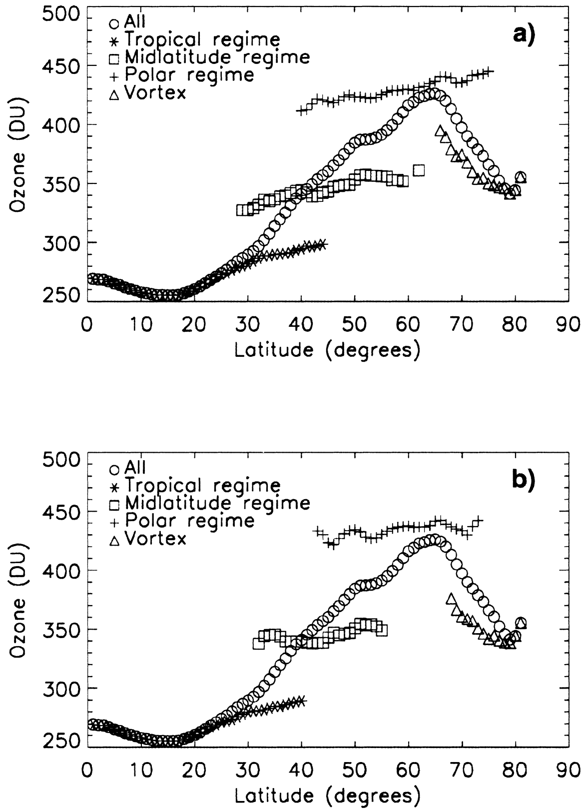

FIG. 2. (a) Zonally averaged total ozone values over 1° latitude bands. The average of all the data is shown as circles. The average for the tropical regime is shown as asterisks the midlatitude as squares, the polar as pluses, and the Arctic as triangles. (b) Similar to (a), but using the same mask broadened by ±2° in both latitude and longitude.

for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996; Kistler et al. 2001).

Second, total ozone data close to the boundaries, where the value is changing from one regime to another, were excluded. This was done by enlarging the initial

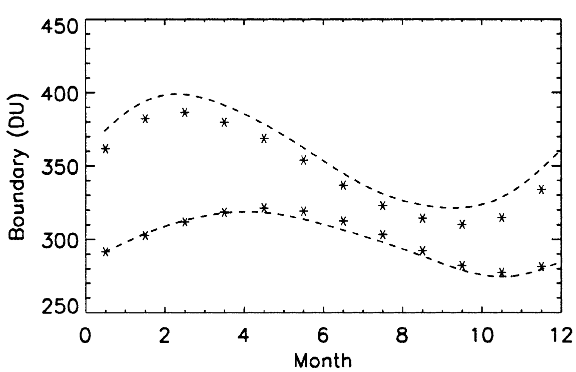

FIG. 3. Monthly total ozone values for the boundary of the subtropical front (bottom curve) and the polar front (top curve). The asterisks are taken from the Karol data, and the dashed lines from the analysis presented in this paper.

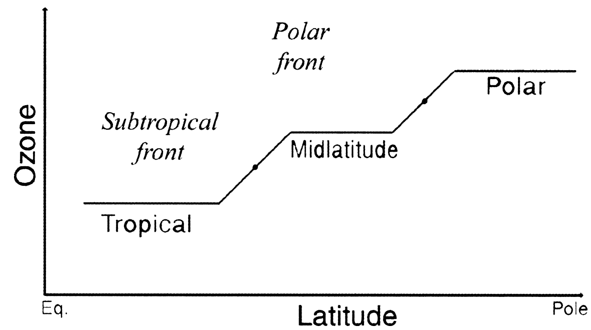

FIG. 4. Schematic showing total ozone as a function of latitude, including the subtropical and polar fronts.

mask boundaries such that pixels within ±2° latitude and longitude of the central pixel were now included in the boundaries. The daily mean total ozone was then obtained for each regime. New boundary values were obtained from these mean values and then used to derive new masks, and the procedure repeated until convergence was obtained. The average seasonal component of the midpoints for the period from 1980 to 1992, obtained using TOMS level-3 data, are shown in Fig. 3 as dashed lines. There is good agreement between the Karol results and the new analysis for the polar and subtropical fronts. In practice, these average seasonal boundaries are not used in the analysis of the total ozone data, instead a 30-day running mean of the daily boundaries is used. The yellow and blue solid lines in Fig. 1 are those mean daily boundaries for 11 March 1990.

Figure 6a shows the boundaries for the subtropical front, polar front, and polar vortex plotted on the total ozone map for 11 March 1990 along with the potential vorticity contours on the 330-K isentropic surface taken from the NCEP–NCAR reanalysis. Figure 6b shows a similar plot to Fig. 6a for PV values on the 315-K isentropic surface. It is important to point out that the TOMS image shown in Figs. 6a and 6b is taken over a

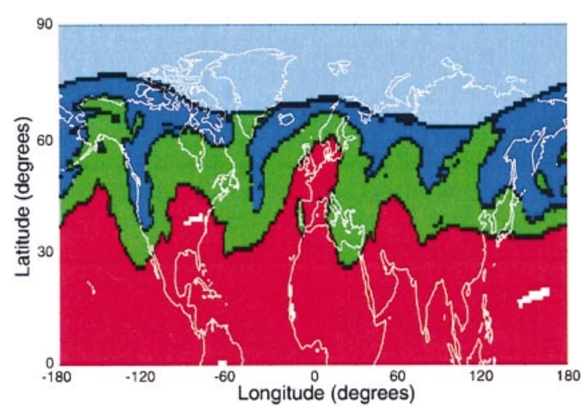

FIG. 5. Mask created for 11 Mar 1990 using the Karol data for the boundaries of the subtropical and polar fronts. The position of the arctic front was obtained from the 31.5-PVU level on the 450-K isentropic surface from NCEP–NCAR. Each black pixel represents a 1° latitude by 1.25° longitude area.

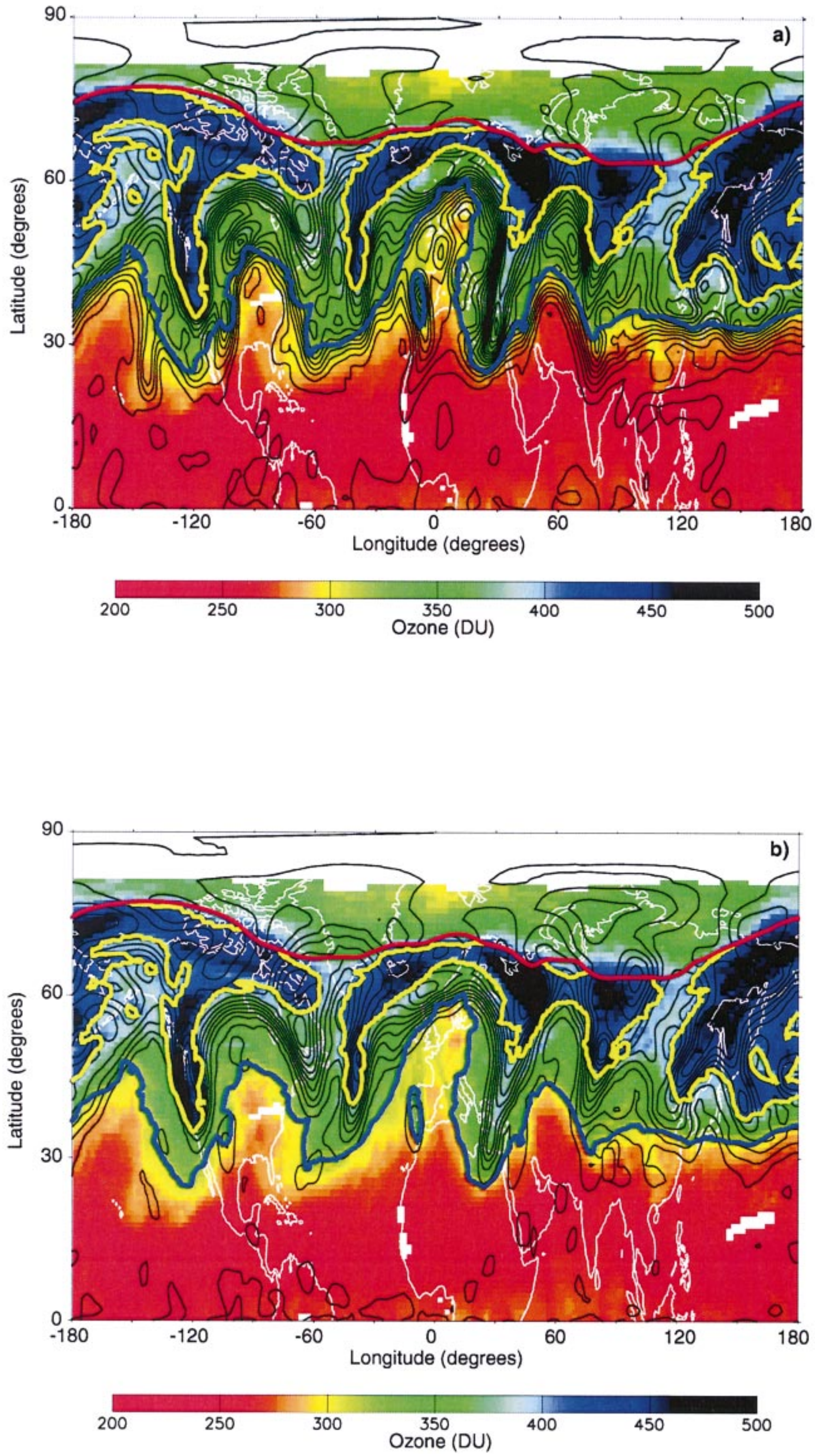

FIG. 6. (a) Potential vorticity contours on the 330-K isentropic surface, at intervals of 0.5 PVU, superimposed on the total ozone field for 11 Mar 1990. (b) Similar plot, but for the 315-K isentropic surface.

period of 24-h, the right-hand edge corresponding to the international date line (0000 UTC), the left-hand edge to 0000 UTC for the next day. However, the dynamical fields given in the NCEP–NCAR dataset are synoptic, and are produced at four specific times per day, 0000, 0600, 1200, and 1800 UTC. In the comparisons shown in Figs. 6a and 6b, and in those that follow, the NCEP–NCAR dataset has been interpolated with time across the TOMS image. When this is done there is a close agreement between the positions of the fronts outlined by both the total ozone and the gradient in the meteorological data, as shown in Figs. 6a and 6b.

Nash et al. (1996) determined the position of the polar vortex by calculating the maximum slope of the equivalent latitude for PV on the 450-K potential temperature surface, which is always within the stratosphere. This technique however is not accurate for the 330- and 315-K surface as, at their respective fronts, these isentropic surfaces move from the stratosphere to the troposphere, where the PV value becomes small and noisy. Karol et al. (1987) found that although the geopotential height at the center of the front was constant over a month, it had a seasonal dependence. It is quite likely therefore that either the value of the potential temperature, the associated value for the PV, or both at the center of the front will be a function of season. In addition to the seasonal dependence, the total ozone boundary values are also found to decline between 1978 and 1992. It is likely that the isentropic surface and PV values will also change with time. The choice of the 330- and 315-K isentropes for Figs. 6a and 6b is subjective. The choice was made principally because these are two of the potential temperatures for which PV is given in the NCEP–NCAR dataset, and these surfaces move across the subtropical and polar fronts (Shapiro et al. 1987).

A closer look at Fig. 1 shows that the ozone boundary is not necessarily sharp. The yellow color, at around 280 DU, corresponds closely to the transition zone between the tropical and midlatitude regimes. The width of this color band is therefore a good indication of the sharpness of the boundary. The width of the boundary at 10°E longitude is narrow, indicating a sharp boundary, while the boundary around 60°W is wide, indicating a more diffuse boundary. Figures 6a and 6b show the same diffuseness for the PV boundaries, indicating that the variability in the total ozone field is a good surrogate for dynamical variability.

It should be noted that the NCEP–NCAR dataset is obtained from the NCEP global spectral model that has been constrained using data assimilation techniques. As with any optimal estimation scheme, whenever the restraining measurements become sparse, the output of the assimilation scheme will revert to the initial guess. Kistler et al. (2001) note that, ''while the NCEP analysis system efficiently assimilates upper air observations, it is only marginally influenced by surface observations.'' They note further, in a discussion of the use of the reanalysis data for trend estimates, ''in the absence of rawinsondes, the re-analysis results are not reliable, even if there are plenty of surface observations.'' The latter statement is significant considering that the bulk of the rawinsonde measurements are restricted to the continents.

As noted above, in general, the agreement between the position of the front determined by PV and ozone is good. However, the agreement is not exact, and in some regions can differ significantly. The ozone boundary is determined directly from the total ozone data using an objective technique. In addition, the total ozone values have a high precision (McPeters et al. 1996). On the other hand, the data from the NCEP–NCAR analysis is model dependent, especially in regions of sparse rawinsonde measurements. More importantly there seems to be no objective way to determine the exact isentropic temperature surfaces and PV values that correspond to the subtropical and polar frontal boundaries. For these reasons, the analysis presented in the remainder of this paper will rely largely on the determination of the frontal boundaries from the total ozone data.

There is one caveat to the last statement. It should be noted that the method described above for determining the boundaries from the ozone data, basically assumes that the tropospheric contribution to the total column ozone is constant over the regime. However, this is not true during the summer months when strong pollution events can occur. Over most of the year the difference in total ozone across a boundary is greater than 50 DU, but in the summer months, for example July, this difference for the subtropical front becomes as small as 30 DU. In general, when the tropospheric ozone does not deviate from the background level, the boundary can be delineated accurately. However, when the tropospheric ozone is much higher then the background, then the boundary becomes distorted. In these cases, geopotential height on the 200-hPa pressure surface from the NCEP–NCAR analysis has been used to define the subtropical front.

Figure 7 shows a histogram of the total ozone values for 19 July 1999 within the tropical regime, using the geopotential boundary for the subtropical front. The overall distribution shown in Fig. 7 (solid line) can be fit with two Gaussian functions displayed as dotted and dashed lines, with peak values of 280 and 310 DU, respectively. Hudson and Thompson (1998) determined from an analysis of TOMS and ozonesonde measurements that the background tropospheric level for column ozone in the tropical regime was constant throughout the year at a value of 24 ± 5 DU. However, when local area pollution occurred this value could be as large as 60 DU. The difference between the background and polluted values is about 30 DU, that is, the same as the difference between the two peaks in Fig. 7, and as large as the difference between the tropical and midlatitude mean values in July.

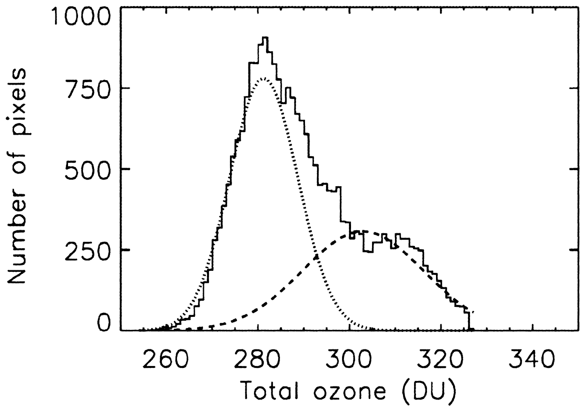

FIG. 7. Histogram of the tropical total ozone distribution for 19 Jul 1999. This histogram can be fitted with two Gaussian functions. The dotted curve, centered at 280 DU, is the nominal distribution. The dashed curve, centered at 310 DU, is ascribed to local ozone pollution.

3. Meteorological significance of the total ozone boundaries

Several groups (Danielsen 1968; Shapiro 1978; Shalamyanskiy and Romanshkina 1980; Shapiro et al. 1987; Uccellini et al. 1985) have used aircraft measurements of ozone concentration, and total ozone measurements to study the upper-tropospheric fronts. Both Shapiro et al. (1987), and Uccellini et al. (1985), found a strong coincidence between large gradients in the total ozone measurements from TOMS and upper-level jet streams/frontal zone tropopause foldings. Shapiro et al. (1987), identified three fronts—the subtropical, polar, and arctic—each with an associated jet stream. It should be noted that the arctic front defined by Shapiro et al. is a tropopause phenomena and need not necessarily correspond to the polar vortex, which is a stratospheric phenomena. During the spring, summer, and fall seasons the arctic front is either weak or not formed.

Figure 8 shows a total ozone image over North America taken on 11 March 1990 for the latitude range 25°–60°N. Also shown in Fig. 8 are the positions of rawinsonde measurements for that day marked as white circles. The frontal boundaries derived from the ozone data are shown as continuous blue and yellow lines for the subtropical and polar fronts, respectively. The dotted lines correspond to 2.0 and 1.8 PVU on the 330- and 315-K potential surfaces, respectively. The white circles filled with red crosses are those measurements identified as being clearly within the tropical regime, green crosses are in the midlatitude regime, and blue crosses are in the polar regime. The white circles without a cross are measurements that fall within ±2° latitude and longitude

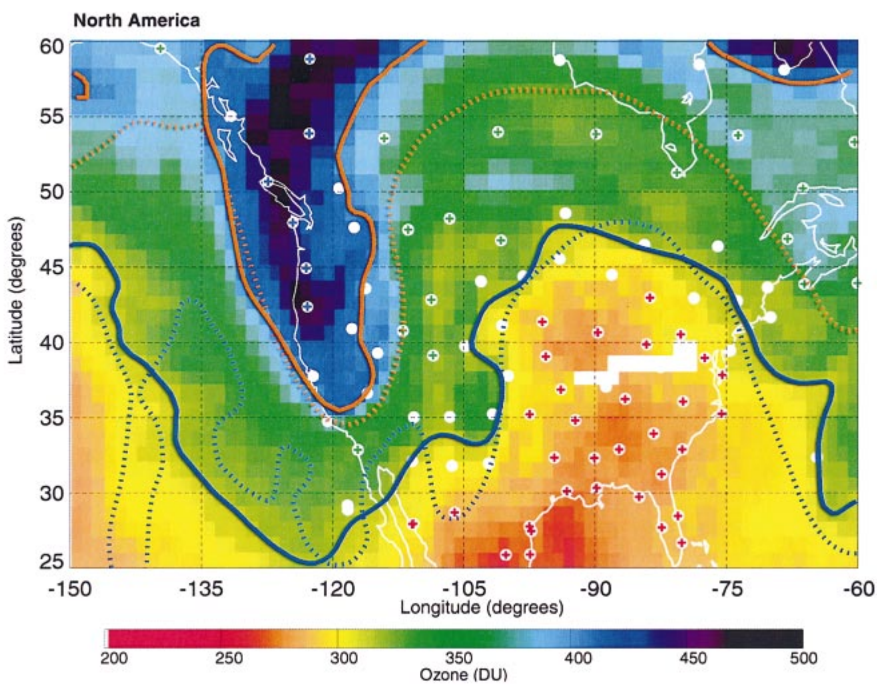

FIG. 8. Total ozone image taken over North America on 11 Mar 1990, between 25° and 60°N. The yellow and blue solid lines represent the positions of the polar and subtropical front, respectively. The dotted lines correspond to 2.0 and 1.8 PVU on the 330- and 315-K potential surfaces, respectively. The white circles indicate the positions of rawinsonde measurements. Crosses in the white circles identify a measurement as within a particular regime: red crosses are tropical, green crosses are midlatitude, and blue crosses are polar. The white circles without crosses are rawinsonde measurements that fell within ±2° latitude and longitude of the frontal boundaries and were not used in the analysis.

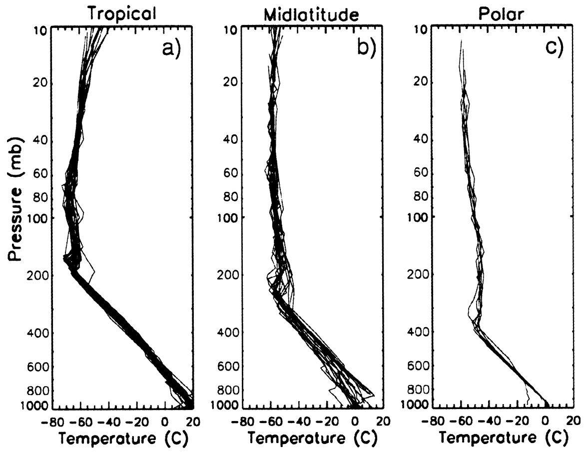

FIG. 9. Temperature profiles from the rawinsonde measurements for the filled circles shown in Fig. 8. They are (a) tropical, (b) midlatitude, and (c) polar.

of the frontal boundaries and were not used in this analysis. In Fig. 9, the temperature as a function of pressure altitude is plotted for each of the rawinsondes selected by regime.

The most significant point shown in Fig. 9 is that each temperature profile within a total ozone regime has the same, distinctive tropopause height. This supports the conclusion of Shalamyanskiy and Romanshkina (1980) and Shapiro et al. (1987), that the ozone boundary and the meteorological boundary are one and the same, a picture consistent with total ozone acting as a surrogate dynamical tracer.

4. Ozonesonde and rawinsonde profiles within the boundaries

As noted in section 1, the total ozone values have small variability within each regime. This should restrict the values that the ozone profile can assume (Bojkov 1969). To test this hypothesis the ozonesonde profiles were separated by regime using broad masks (±2° latitude and longitude of the central pixel). In order to get enough profiles to obtain a reasonable statistical sample, all ozonesonde measurements in the Northern Hemisphere for the period from 1985 to 1990 were used. The stations that were used are listed in Table 1, and the total number of profiles within a regime that were selected within each month is given in Table 2. The data for each ozonesonde was obtained from the World Ozone and Ultraviolet Data Center (WOUDC). Figure 10 shows 20 profiles for each of the regimes, taken at random from the selected March profiles. As was the case for the rawinsonde measurements, the ozone profiles within a regime have a distinct tropopause height. Figure 11 compares the mean ozone and temperature profiles obtained for each regime averaged over the month of March (the mean profiles for the temperature are for March 1990 only). Also shown are the standard deviations of the profiles about the mean. From comparisons with mean ozone profiles from the Stratospheric Aerosol and Gas Experiment (SAGE) instrument, the increase in the standard deviation of the ozone profiles between 100 and 200 hPa represents atmospheric variability and not instrumental error.

The mean values for the tropopause height for each temperature measurement can be derived using the method described by the World Meteorological Organization (WMO 1957). The mean values obtained were 126 ± 26 hPa (480 profiles) for the tropical regime, 229 ± 46 hPa (660 profiles) for the midlatitude regime,

TABLE 1. Inventory of ozonesonde stations.

WMO ID no.	Latitude	Longitude	Station name
007	31.60	130.60	Kagoshima
012	43.05	141.33	Sapporo
018	82.50	−62.30	Alert
021	53.55	−114.10	Edmonton
024	74.72	−94.98	Resolute
040	43.93	5.70	Haute Provence
053	50.80	4.35	Uccle
067	40.03	−105.25	Boulder
076	53.32	−60.30	Goose
077	58.75	−94.07	Churchill
089	78.93	11.88	Ny Alesund
099	47.80	11.02	Hohenpeissenberg
109	19.72	−155.07	Hilo
156	46.82	6.95	Payerne
190	26.20	127.68	Naha
260	36.05	140.10	Tskuba
297	44.65	11.62	S. Pietro Capofiume
315	44.65	−85.93	Eureka

TABLE 2. Number of ozonesonde measurements classified by regime.

Regime	Mar	Jun	Sep	Dec
Tropical	33	39	130	66
Midlatitude	144	76	19	56
Polar	137	123	31	43

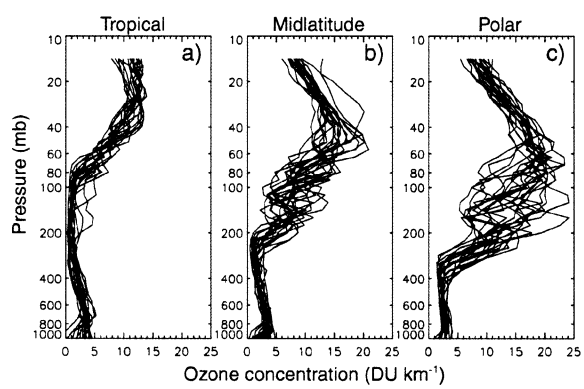

FIG. 10. Twenty March ozonesonde ozone profiles for each regime taken at random from the period 1985 to 1990. The regimes are (a) tropical, (b) midlatitude, and (c) polar.

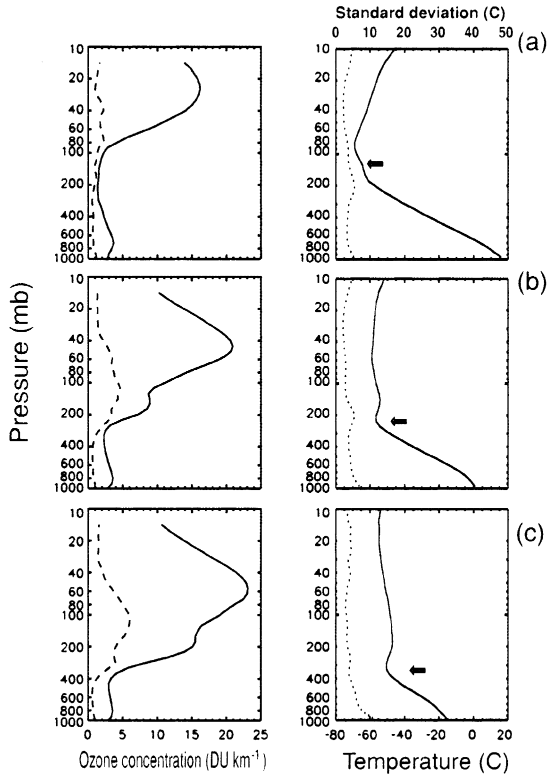

FIG. 11. (left) Mean ozone and (right) temperature profiles (solid) and the standard deviation from the mean (dashed), for Mar; (a) tropical, (b) midlatitude, and (c) polar regimes.

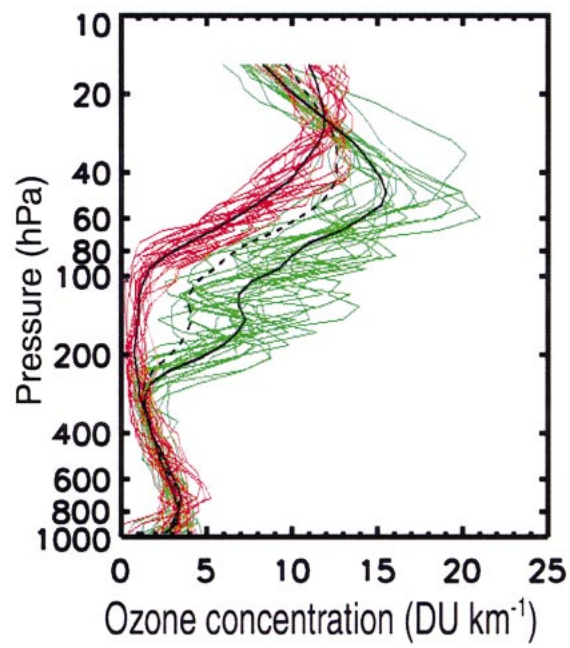

FIG. 12. Twenty March ozonesonde ozone profiles for both the midlatitude and tropical regimes. The average profile within each regime is shown as a solid line, whereas the overall average of all 40 profiles is shown as a dashed line. Red is tropical; green is midlatitude.

and 338 ± 39 hPa (133 profiles) for the polar regime. These values are displayed in Fig. 11. It should be noted that, for each regime, the tropopause heights for both the temperature and ozone profiles are similar. These measurements, then, also lead to the conclusion that the stratospheric ozone field is divided into distinct regimes bounded by the upper-tropospheric meteorological fronts.

Many intercomparisons between ozone profile measurements from different instruments have been made using zonal averages (Harris et al. 1998). But, as shown above, the profile shape depends not only on latitude but also on regime. Figure 12 compares the profiles shown in Fig. 11, for the tropical and midlatitude regimes. Also plotted in Fig. 12 are the mean profiles for the 20 tropical and 20 midlatitude profiles and the mean profile of all 40 profiles. To be considered a physical quantity, the mean of a set of data must be a viable member of that dataset. The mean profiles obtained for the tropical and midlatitude regimes meet this criterion. The overall mean profile does not, and therefore is not a physical quantity. In addition, the average profiles obtained over a given latitude range will be a function of the relative mix of the regimes corresponding to each individual measurement, and will depend strongly on the area sampling for each instrument.

5. Total ozone values within the boundaries

In Fig. 13, the daily mean total ozone value for each regime is plotted for 1990. In general, the values vary quite smoothly from day to day, and even when there is a large variability, that is, in the polar regime from December to March, the mean value varies slowly with time, and variability is obviously not noise. The number of values included in the daily averages shown in Fig. 13 is at least 1000. The standard deviation (in percent of the total ozone value) for the points is also plotted in Fig. 13. These values can range from 1% up to 8%. However, the error of the mean is at least a factor of 30 less than these values, and this is reflected in the smoothness of the values from day to day.

The seasonal dependence of the daily mean is different for each regime. Total ozone in the tropical regime reaches a maximum in July and a minimum in December. The midlatitude regime reaches a maximum in April and a minimum in October; the polar regime reaches a maximum in February and a minimum in September. The seasonal dependence for a zonal average, such as was obtained by Dobson (1968), is a mix of the seasonal dependencies of the three regimes, and will depend on the relative number of total ozone values from each regime that are included in the overall average.

6. Discussion and conclusions

Clear evidence has been presented showing that the Northern Hemisphere total ozone field can be separated

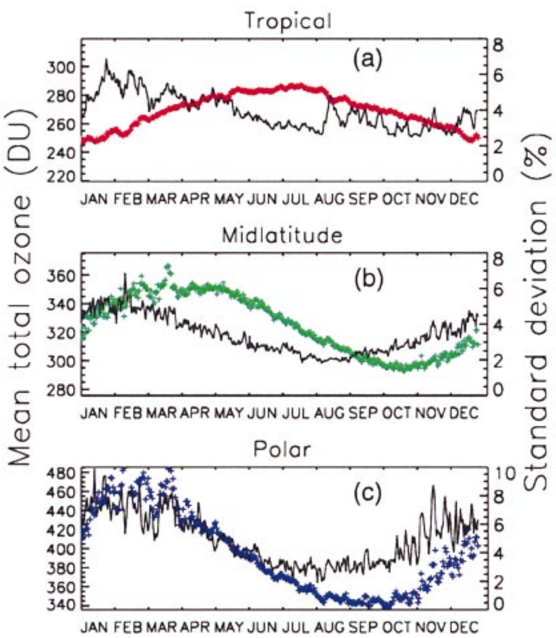

FIG. 13. The 1990 daily mean total ozone values for the (a) tropical, (b) midlatitude, and (c) polar regimes (in color). The standard deviations (in %) are shown in black for each regime.

into distinct regimes, the boundaries of which are the subtropical and polar upper-tropospheric fronts, and, in the winter, the polar vortex. It has been shown, both from rawinsonde and ozonesonde measurements, that the tropical, midlatitude, and polar regimes are identified with a distinct tropopause height. The standard deviations about the daily mean total ozone value are less than 8% indicating that a unique total ozone value can be assigned to each of the three regimes. Each regime also has a distinct seasonal dependence.

As was noted in the abstract, studies of the variability of total ozone, ozone profiles, and dynamical variables in the lower stratosphere have been centered on zonal averages over specific latitude bands (Harris et al. 1998; World Meteorological Society 1999; Staehelin et al. 2001). However, the boundaries of the ozone regimes are the upper-tropospheric meteorological fronts. These fronts follow the Rossby waves in the atmosphere, and, on any day, can meander over a wide range of latitudes (see, e.g., Fig. 1). Thus, the midlatitude zonal average, whether ozone profile, total ozone, or dynamical variable, will depend on the relative mix of the respective values within each regime over the latitude range of the average. Furthermore, because each regime has such distinctive characteristics, these averages may not have physical significance.

Acknowledgments. The early part of this work was funded by the Orbital Sciences Corporation as part of a subcontract (1995–1998). This subcontract was in support of a design study for the OMPS instrument sponsored by the Intergovernmental Program Office of the National Polar Orbiting Environmental Satellite System. The ACMAP program of NASA has sponsored the work since August 2001. We would also like to thank the reviewers for their many helpful comments.

REFERENCES

Bojkov, R., 1969: Computing the vertical ozone distribution from its relationship with total ozone amount. *J. Appl. Meteor.,* **8,** 284–292.

Danielsen, E., 1968: Stratospheric–tropospheric exchange based on radioactivity, ozone and potential vorticity. *J. Atmos. Sci.,* **25,** 502–518.

Dobson, G. M. B., 1968: *Exploring the Atmosphere.* Clarendon Press, 188 pp.

——, D. N. Harrison, and J. Lawrence, 1927: Measurements of the amount of ozone in the Earth's atmosphere and its relation to other geophysical conditions—Part II. *Proc. Roy. Soc. London,* **A114,** 521–541.

Harris, N., R. Hudson, and C. Phillips, Eds., 1998: WMO, SPARC/IOC/GAW Assessment of trends in the vertical distribution of ozone. SPARC Rep. 1, World Meteorological Organization Global Ozone Research and Monitoring Project Rep. 43, Geneva, Switzerland, 407 pp.

Hudson, R. D., and A. M. Thompson, 1998: Tropical tropospheric ozone from total ozone mapping spectrometer by a modified residual method. *J. Geophys. Res.,* **103,** 22 129–22 145.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Karol, I. L., L. P. Klyagina, A. D. Frolov, and A. M. Shalamyansky, 1987: Fields of ozone and temperature within the boundaries of air masses. *Meteor. Gidrol.,* **10,** 47–52.

Kistler, R., and Coauthors, 2001: The NCEP–NCAR 50-Year Reanalysis: Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.,* **82,** 247–267.

McPeters, R. D., and Coauthors, 1996: *Nimbus-7* Total Ozone Mapping Spectrometer (TOMS) data products user's guide. NASA Reference Publ. 1384, 67 pp.

Nash, E. R., P. A. Newman, J. E. Rosenfield, and M. R. Schoeberl, 1996: An objective determination of the polar vortex using Ertel's potential vorticity. *J. Geophys. Res.,* **101,** 9471–9478.

Schoeberl, M. R., L. R. Lait, P. A. Newman, and J. E. Rosenfield, 1992: The structure of the polar vortex. *J. Geophys. Res.,* **97,** 7859–7882.

Shalamyanskiy, A. M., and A. K. Romashkina, 1980: Distribution and variation in the total ozone concentration in various air masses. *Izv. Atmos. Oceanic Phys.,* **16,** 931–937.

Shapiro, M. A., 1978: Further evidence of the mesoscale and turbulent structure of upper level jet stream–frontal zone systems. *Mon. Wea. Rev.,* **106,** 1100–1111.

——, T. Hampel, and A. J. Krueger, 1987: The Artic tropopause fold. *Mon. Wea. Rev.,* **115,** 444–454.

Staehelin, J., N. R. P. Harris, C. Appenzeller, and J. Eberhard, 2001: Ozone trends: A review. *Rev. Geophys.,* **39,** 231–290.

Traub, W. A., K. W. Jucks, D. G. Johnson, and K. V. Chance, 1995: Subsidence of the Arctic stratosphere determined from thermal emission of hydrogen fluoride. *J. Geophys. Res.,* **100,** 11 261–11 267.

Uccellini, L. W., D. Keyser, K. F. Brill, and C. H. Wash, 1985: The Presidents' Day Cyclone of 18–19 February 1979: Influence of upstream trough amplification and associated tropopause folding on rapid cyclogenesis. *Mon. Wea. Rev.,* **113,** 962–988.

World Meteorological Organization, 1957: Definition of the thermal tropopause. *WMO Bull.,* **6,** 136.

——, 1999: Scientific assessment of ozone depletion: 1998. Global Ozone Research and Monitoring Project Rep. 44, 496 pp.