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Ground-based observations of the slowdown in ozone decline and onset of ozone increase

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[1] This paper presents the evidence for a slowdown in ozone decline and subsequent ozone increase using ground-based data, i.e., Dobson, Brewer, and Russian filter ozonometer total-ozone data and Umkehr and ozonesonde-derived layer-ozone data. The impacts of quasi-biennial oscillation (QBO) and 11-year solar cycle were minimized by determining 5-year trends based on 11-year running means. On the basis of 50–60 total-ozone stations, the global trends vary from a maximum negative value of $-2.1 \pm 0.6\%$/decade in 1988 to a value of $0.7 \pm 0.5\%$/decade at the end of the record in 2000, where the confidence intervals are 2 standard deviations of the mean of the individual station trends. Because of the use of 5-year trends and 11-year running means, the actual year of slowdown in total-ozone decline may be up to 7 years later than the year of maximum negative trend in our analysis, or close to the 1993–1995 peak in ozone-depleting substances (ODS) in the atmosphere. Umkehr and ozonesonde-derived layer-ozone trends were determined for 32- to 53-, 24- to 32-, 19- to 24-, 10- to 19-, and 0- to 10-km layers of the north temperate zone. On the basis of four Umkehr stations and about five ozonesonde stations, the integrated layer-weighted Umkehr trends vary from a maximum negative value of $-3.8 \pm 0.3\%$/decade in 1989 to a value of $1.2 \pm 2.1\%$/decade in 2000, while the integrated sonde trends vary from a maximum negative value of $-4.8 \pm 1.6\%$/decade in 1989 to a value of 1.8 ± 2.1/decade in 2000. Both Umkehr and sonde data show that nearly half of the increase in north temperate total-ozone trend between 1989 and 2000 is due to trend increase in the low-stratospheric 10- to 19-km layer, with the troposphere contributing only about 5%.

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1. Introduction

[2] The World Meteorological Organization/U.N. Environment Programme (WMO/UNEP) report “Scientific Assessment of Ozone Depletion: 2006” finds that “global ozone levels are no longer declining as they were from the late 1970s to the mid 1990s.” This reflects the success of the Montreal Protocol in controlling the production of ozone-depleting substances (ODS), *Froidevaux et al.* [2006] showing in their Figure 1 that tropospheric total chlorine peaked in about 1993, and *Wallace and Livingston* [2007] showing in their Figure 1 that column hydrogen chloride peaked in about 1995. Even before publication of this evidence for a recent decrease in ODS there was discussion of when and where a slowdown of ozone decline and subsequent ozone increase (turnaround) might first be observed. *Hofmann et al.* [1997] proposed that the first signs of ozone recovery would be in about 2008 and involve the change in vertical profile of ozone within the Antarctic Ozone Hole. *Weatherhead et al.* [2000] opined that statistically significant evidence of full ozone recovery would be observed between 2015 and 2045 and be noted first in the midlatitudes of the Southern Hemisphere. *Reinsel et al.* [2002] expanded on the matter of statistical detection, and estimated that in midlatitudes detection of ozone turnaround would be observed in 2009 or 2010 and full ozone recovery in 2017 to 2027. However, since the stratosphere at full ozone recovery will be different than it is now, for example cooler, it is not obvious what “full ozone recovery” means [*WMO*, 2007].

[3] Turning to observations, *Reinsel* [2002] found, on the basis of 35- to 45-km ozone data from the north temperate Umkehr stations of Arosa, Boulder and Tateno, a 0.2% per year positive ozone trend for the 5-year period after 1996. *Newchurch et al.* [2003] followed with evidence from SAGE and HALOE satellite data for a slowdown in 35- to 45-km ozone losses after 1997, stating that it “constituted the first stage of ozone recovery.” However, *Steinbrecht et al.* [2004a] argued that the diminished downward trend of 35- to 45-km ozone after 1997, which they also observed using lidar measurements at Hohenpeissenberg, was due to the ozone increase associated with the 2001 sunspot maximum. *Cunnold et al.* [2004] questioned the Steinbrecht et al. procedure for identifying the solar cycle in ozone data, responded to by *Steinbrecht et al.* [2004b], but the discussion ended with

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Steinbrecht et al. [2004b] acknowledging in their conclusion, "we are probably seeing a beginning recovery of upper stratospheric ozone." A recent reevaluation and update of the Arosa Umkehr record [*Zanis et al.*, 2006] shows that ozone trends were negative from 1970 to 1995, but became positive during 1996–2004 both above 33 km and below 24 km. *Miller et al.* [2006] also found a significant change in trend in the north midlatitude ozonesonde data between 13 and 18 km, and around 35 km, in the timeframe of 1996.

[4] Recent papers on this topic differ with respect to their estimate of the time and extent of ozone recovery. Taking into account the influence of the solar cycle, *Reinsel et al.* [2005] find, for latitudes 40° and above in both hemispheres, positive ozone trends since 1996. *Weatherhead and Andersen* [2006] are more circumspect, stating that "although recent data suggest that column ozone abundances have at least not decreased over the past 8 years for most of the world, it is still uncertain whether this improvement is actually attributable to the observed decline of ozone-depleting substances in the earth's atmosphere." *Yang et al.* [2006] are more assertive, stating that "Multiple satellite and ground-based observations provide consistent evidence that the thickness of earth's protective ozone layer has stopped declining since 1997, close to the time of peak stratospheric halogen loading." A very recent review article by *Fioletov* [2008] shows total-ozone deviations for 60°N–60°S, with seasonal, solar, QBO and volcanic effects removed. He finds the ozone time series too noisy to pick a year of turnaround. His article makes for an interesting comparison with ours.

[5] The present work differs from that referred to above in the use of 11-year running means rather than regression as a means of minimizing the impact of 11-year solar cycle and quasi-biennial oscillation or QBO (tropical oscillation of stratospheric east-west winds with a period of 26–30 months) on ozone variability. It adds to previous work by using all three ground-based ozone measurement systems (total ozone, Umkehr and sonde).

2. Procedures

[6] The annual Dobson-Brewer and Russian filter total-ozone values, and annual Umkehr and ozonesonde-derived layer-ozone values, used in this analysis were obtained from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC), and may be obtained from their web site: www.woudc.org. With the proviso that at least 2 months of data be available for a seasonal value, and all four seasons for an annual value, the analysis procedure involved the following steps for each station (see Table 1 for a station listing).

[7] 1. The considerable impact of volcanic eruptions on ozone variability [*Mader et al.*, 2007, Figure 4] has been minimized by linearly interpolating annual ozone values between year of eruption and 3 years thereafter for Agung (1963), El Chichon (1982) and Pinatubo (1991) volcanic eruptions. Almost all volcanic influence on ozone amount is for these two intervening years [e.g., *Angell*, 1997, 1998].

[8] 2. The impact of the 11-year solar cycle and QBO on ozone variability has been minimized by application of 11-year running means to the annual ozone values. Most of the papers cited in section 1 used regression for this purpose, but regression can introduce errors if the time evolution of the solar or QBO signal is not known accurately. In particular, because the two solar maxima before 2000 were close in time to the volcanic eruptions of Pinatubo and El Chichon, the effects of the solar cycle can be confused with those of the eruptions [*Weatherhead and Andersen*, 2006], the small number of cycles available for regression making it especially difficult to accurately determine the solar signal. Unlike regression, our approach assumes only that the solar signal has a period of about 11 years.

[9] 3. On the basis of the 11-year running means of annual ozone values, overlapping 5-year trends were determined by means of linear regression, thereby placing the ozone data in a context useful for visualizing the slowdown in ozone decline and beginning of ozone increase.

[10] 4. On the basis of the 5-year trends at individual stations, confidence intervals extending 2 standard deviations of the mean both sides of the average trend were determined for north temperate regions and climate zones. Global averages were obtained by weighting the station ozone trends by the cosine of station latitude. Confidence intervals for global means were obtained from the standard deviation calculated using cosine weighting of the deviations of the station trends from the global mean.

[11] 5. Because of the use of 5-year overlapping trend based on 11-year running means, the year of maximum negative trend is easily determinable. However, also because of this heavy smoothing, the year of maximum negative trend may not be the year of slowdown in ozone decline, but rather a time as much as 7 years earlier (5 years due to the 11-year running means and an additional 2 years due to the 5-year trends). Thus, the procedure used here cannot specify the year of slowdown in ozone decline with precision.

3. Global Total-Ozone Trends

[12] Figure 1 shows the variation with time of overlapping 5-year total-ozone trends, together with their 2-standard-deviation-of-the-mean confidence intervals (vertical bars), for North America, Europe and Asia, and, at the bottom of Figure 1 with a twofold difference in ordinate scale, for the north temperate zone as a whole. All the total-ozone trends are positive at the end of the record in 2000, but only Asia and the north temperate zone are indicated to be significantly so (confidence intervals not intersecting the zero-trend axis). The representativeness of the Asian data is suspect, both because until 1973 Asia was represented only by Japanese data and because north of 43°N there are no Asian Dobson and Brewer total-ozone data during the entire record. The nonoverlapping confidence intervals during the last 10 years of the north temperate record strongly suggest a significant increase in north temperate total ozone trend during that period.

[13] Figure 2 shows the variation with time of overlapping 5-year total-ozone trends for north polar, north temperate, tropical, south temperate and south polar climate zones (climate-zone boundaries at 30° and 60° north and south), and at the bottom of Figure 2 with a twofold difference in ordinate scale, for the globe. In addition to the north temperate zone, the north polar zone and tropics, as well as globe, also have positive ozone trends at the end of the record, but the south temperate and south polar zones do not. The south

Table 1. List of the Total Ozone, Umkehr, and Ozonesonde Stations Used in This Analysis[a]

Station	Name	Latitude	Longitude	Dates	Country
		Total Ozone Stations			
North America					
19	Bismarck	47°N	101°W	1958–2006	USA
67	Boulder	40°N	105°W	1964–2007	USA
20	Caribou	47°N	68°W	1963–2006	USA
79	Churchill	59°N	94°W	1965–2006	Canada
21	Edmonton	54°N	114°W	1958–2006	Canada
76	Goose Bay	53°N	60°W	1962–2006	Canada
341	Hanford/Fresno	36°N	120°W	1984–2006	USA
106	Nashville	36°N	87°W	1963–2006	USA
65	Toronto	44°N	79°W	1960–2006	Canada
107	Wallops Island	38°N	75°W	1970–2006	USA
Europe					
35	Arosa	47°N	10°E	1958–2007	Switzerland
68	Belsk	52°N	21°E	1964–2007	Poland
100	Budapest	47°N	19°E	1967–2007	Hungary
36	Cambourne/Bracknell	50°N	5°W	1958–2003	UK
40	Haute Provence	44°N	6°E	1984–2005	France
99	Hohenpeissenberg	48°N	11°E	1968–2007	Germany
96	Hradec Kralove	50°N	16°E	1961–2007	Czech Republic
43	Lerwick	60°N	1°W	1958–2007	UK
50	Potsdam/Lindenburg	52°N	13°E	1964–2007	Germany
305	Rome/Vigne	42°N	13°E	1958–2006	Italy
53	Uccle	51°N	4°E	1972–2007	Belgium
261	Thessalonika	41°N	30°E	1983–2005	Greece
Asia					
3	Alma-Ata	43°N	77°E	1974–2003	Kazakhstan
112	Bolshaya	47°N	143°E	1974–2003	Russia
35	Irkutsk	52°N	104°E	1975–2002	Russia
7	Kagoshima	32°N	131°E	1954–2004	Japan
118	Nagaevo	60°N	151°E	1981–2003	Russia
120	Omsk	55°N	73°E	1977–2002	Russia
12	Sapporo	43°N	141°E	1959–2007	Japan
252	Seoul	38°N	127°E	1985–2007	Korea
42	St. Petersburg	60°N	30°E	1973–2003	Russia
14	Tateno	36°N	140°E	1958–2007	Japan
208	Xianghe	40°N	116°E	1979–2007	China
016	Vladivostok	43°N	132°E	1973–2001	Russia
116	Moscow	56°N	38°E	1973–2004	Russia
122	Ekaterinburg	57°N	61°E	1973–2001	Russia
North Polar					
24	Resolute	75°N	95°W	1958–1999	Canada
262	Sodankyla	67°N	27°E	1989–2007	Finland
199	Barrow	71°N	157°W	1974–2006	USA
Tropical					
245	Aswan	24°N	32°E	1985–2007	Egypt
216	Bangkok	14°N	101°E	1980–2007	Thailand
152	Cairo	30°N	31°E	1968–2007	Egypt
84	Darwin	12°S	131°E	1991–2007	Australia
8	Kodaikanal	10°N	77°E	1958–2004	India
209	Kunming	25°N	107°E	1980–2006	China
31	Mauna Loa	20°N	156°W	1964–2007	USA
190	Naha	26°N	128°E	1975–2007	Japan
10	Delhi	29°N	77°E	1958–2007	India
11	Quetta	30°N	67°E	1969–2007	Pakistan
191	Samoa	14°S	171°E	1976–2006	American Samoa
74	Varanasi	25°N	83°E	1964–2007	India
187	Poona	19°N	24°E	1974–2007	India
200	Cachoeira P.	23°S	45°W	1975–2005	Brazil
South Temperate					
27	Brisbane	27°S	153°E	1958–2007	Australia
91	Buenos Aires	27°S	153°E	1958–2007	Argentina
256	Lauder/Invercargill	45°S	170°E	1970–2007	New Zealand
29	Macquarie Island	55°S	159°E	1964–2007	Australia
253	Melbourne/Aspendale	38°S	145°E	1958–2007	Australia
159	Perth	32°S	116°E	1970–2007	Australia
South Polar					
111	Amundsen Scott	90°S		1962–2006	USA
268	McMurdo	78°S	167°E	1989–2007	New Zealand
101	Syowa	69°S	40°E	1982–2007	Japan

Table 1. (continued)

Station	Name	Latitude	Longitude	Dates	Country
		Umkehr Stations			
35	Arosa	47°N	10°E	1968–2007	Switzerland
67	Boulder	40°N	105°W	1968–2004	USA
40	Haute Provence	44°N	6°E	1984–2005	France
14	Tateno	36°N	140°E	1968–2000	Japan
		Ozonesonde Stations			
7	Kagoshima	32°N	131°E	1969–2004	Japan
12	Sapporo	43°N	141°E	1969–2007	Japan
21	Edmonton	54°N	114°W	1973–2006	Canada
76	Goose Bay	53°N	60°W	1970–2006	Canada
77	Churchill	59°N	94°W	1970–2006	Canada
99	Hohenpeissenberg	48°N	11°E	1968–2007	Germany
107	Wallops Island	38°N	78°W	1971–2006	USA
174	Lindenberg	52°N	14°E	1975–2007	Germany
221	Legionowo	52°N	21°E	1979–2007	Poland

[a]Included is the station name and number as well as the country in which it is located, its latitude and longitude, and its period of record. The choice of stations is based on length of record and the availability of data in recent years.

temperate trace also differs from the others in having a positive (though not significant) trend in 1989, or near the time of maximum negative trend in the other climate zones. Indeed, the south temperate and tropical trends tend to be out of phase during most of the record. The representativeness of the south temperate trace is open to question because the trends are based on only five stations. As in the case of the north temperate zone, the nonoverlapping confidence intervals during the last decade of the global record strongly suggest a significant increase in global total-ozone trend during that period.

[14] Table 2 summarizes the salient features of Figures 1 and 2. On the basis of the three north temperate regions, five climate zones and globe, the median year of maximum negative trend is 1988, well before the 1995 peak in ODS. However, because of the use of 5-year trends based on 11-year running means, the slowdown in ozone decline can follow the maximum negative trend by as much as 7 years (see procedure 5), raising the possibility that the slowdown in total-ozone decline did indeed occur near the time of peak ODS. The average magnitude of the maximum negative trend for the nine areas is -3.6 ± 1.1%/decade, compared to the value of 0.9 ± 0.8%/decade at end of record.

4. North Temperate Umkehr and Ozonesonde Layer-Ozone Trends

[15] Most of the Umkehr and ozonesonde stations with recent layer-ozone data are in the north temperate zone, and accordingly this is the only climate zone analyzed in detail using these data. The matter of the quality of these data has been discussed by *Bojkov et al.* [2002] and more recently by *Fioletov et al.* [2006], who estimate ozone variability and instrument uncertainties from Umkehr and ozonesonde measurements as well as satellite measurements. This follows earlier detailed analyses of ozonesonde data by *Logan* [1994] and of Umkehr data by *Petropavlovskikh et al.* [2001, 2005a]. The Umkehr stations used here are among those considered acceptable in quality by *Bojkov et al.* [2002].

[16] This analysis uses the new (2004) algorithm [*Petropavlovskikh et al.*, 2005b] developed specifically for trend analysis and which, unlike the previous 1992 algorithm, does not use a priori profiles that depend on column ozone. Figure 3 presents at left Umkehr-derived layer-ozone trends for 32- to 53-, 24- to 32-, 19- to 24-, 10- to 19- and 0- to 10-km layers, and at right sonde-derived trends for the same layers with the omission of the 32- to 53-km layer. These layers were chosen to represent, respectively, the high stratosphere, middle stratosphere, ozone peak, low stratosphere, and troposphere. Figure 3 shows that there is only modest agreement between Umkehr and sonde data regarding the variation of layer-ozone trends with time. Thus, the Umkehr data show a rapid decrease in negative trend (rapid slowdown in ozone decline) in 1989 and 1988 in 10- to 19- and 19- to 24-km layers, respectively, whereas the sonde data show such a rapid slowdown in 1989 only in the 10- to 19-km layer. In the 0- to 10-km layer the Umkehr data show a continuation of small negative trends after 1990 whereas the sonde data indicate a progression toward positive trends. Neither Umkehr nor sonde traces show much evidence of a slowdown around 1990 in the 24- to 32-km layer, while the sonde data indicate a positive trend at end of record and the Umkehr data do not. The 32- to 53-km Umkehr trace basically shows only a transition from strong negative trends to modest positive trends [see also *Steinbrecht et al.*, 2006].

[17] Weighting the trend in each layer of Figure 3 by the fraction of the column ozone in that layer, and then summing the results, integrated layer-weighted trends are obtained which can be compared to the total-ozone trends to judge the consistency of the ground-based observations. On the basis of the long-term north temperate Umkehr station of Arosa, the fraction of the column ozone in each of the layers 32–53 km, 24–32 km, 19–24 km, 10–19 km and 0–10 km is, respectively, 0.06, 0.32, 0.31, 0.25 and 0.06. On the basis of the long-term north temperate ozonesonde station of Hohenpeissenberg, the fraction of the column ozone in the bottom four layers is, respectively, 0.34, 0.33, 0.27 and 0.06. Figure 4 shows the comparison of the integrated layer-weighted Umkehr and sonde trends with the north temperate total-ozone trend. Interestingly, while the Umkehr and sonde layer-ozone trends may disagree, the integrated values shown in Figure 4 are in fairly good agreement, both Umkehr and sonde data indicating a maximum negative trend in 1989, and

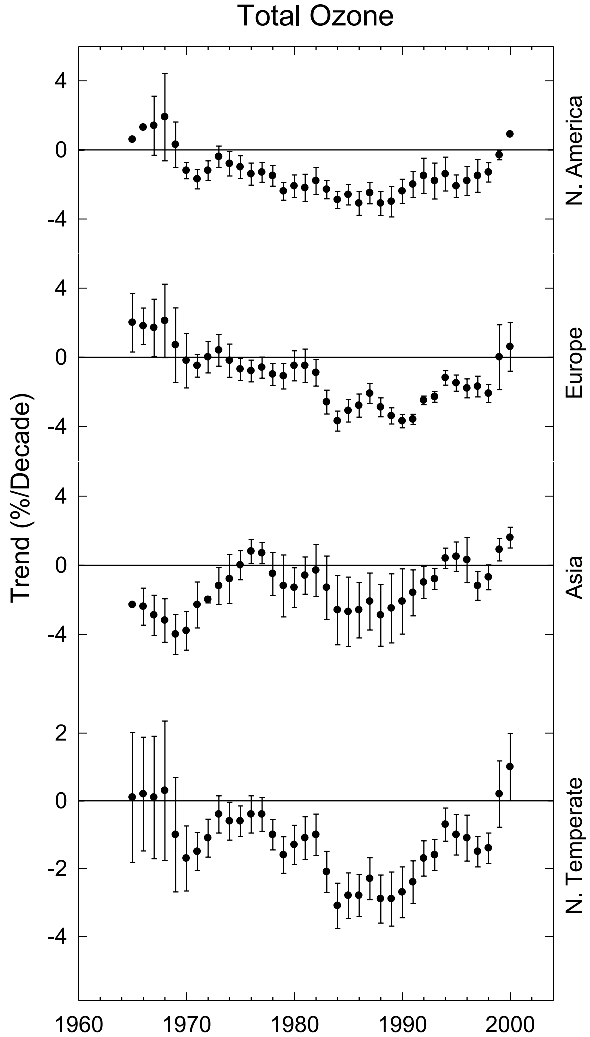

Figure 1. On the basis of 11-year running means of annual total-ozone anomalies, the variation with time of overlapping 5-year trends (shown as percent per decade) for North America, Europe, Asia, and, with a twofold difference in ordinate scale, the north temperate zone as a whole. Confidence intervals extend 2 standard deviations of the mean both sides of the average trends, as determined from the individual station trends within each region. The absence of confidence intervals means that data were available for only one station.

positive trends during the last 2 years of the record. However, it is also apparent that the increase in trend between maximum negative trend and end of record is considerably larger for the sonde data than for the Umkehr and total-ozone data. The disagreement between integrated sonde and total-ozone trends was discussed by *Randel et al.* [1999], as well as in various WMO assessments. Even more obvious is the greater size of the sonde confidence intervals than Umkehr confidence intervals after about 1990. Figure 5 shows that one of the reasons for this is the much greater variation with time of the ozonesonde trends at individual stations so that if the station trends are not in phase the standard deviation of the trend values can become large. Another

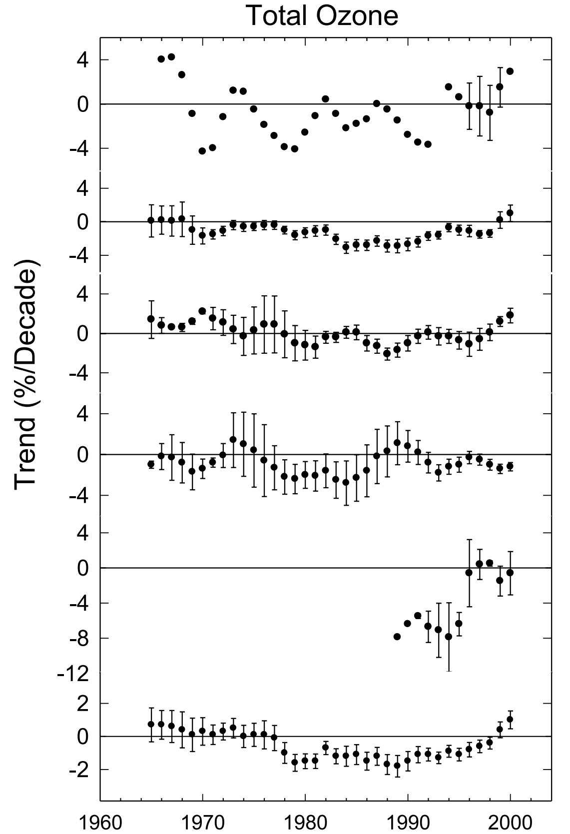

Figure 2. As in Figure 1, but for north polar, north temperate, tropical, south temperate, south polar climate zones and, with a twofold difference in ordinate scale, the globe as a whole. Global averages and confidence intervals are based on station data weighted by the cosine of station latitude.

contributor to the difference in station value could be the difference between ECC and BM sondes [*Terao and Logan*, 2007].

[18] Table 3 summarizes the salient features of Figures 3 and 4. There are positive ozone trends at the end of the record

Table 2. On the Basis of Overlapping 5-Year Trends Determined From 11-Year Running Means, the Year and Magnitude of Maximum Negative Total-Ozone Trend and the End-of-Record (2000) Total-Ozone Trend for North Temperate Regions, Climate Zones, and Globe[a]

	Maximum Negative Trend		End-of-Record Trend
North America	1986, 1988	−3.1%/decade	0.9%/decade
Europe	1984, 1990	−3.7	0.6
Asia	1988	−2.9	1.6
North Polar	1970	−4.3	2.9
North temperate	1984	−3.1	1.0
Tropics	1988	−2.1	1.8
South temperate	1984	−2.8	−1.2
South Polar	1989, 1994	−7.9	−0.6
Globe	1988	−2.1	0.7

[a]The year of slowdown in ozone decline may be up to 7 years later than the year of maximum negative trend.

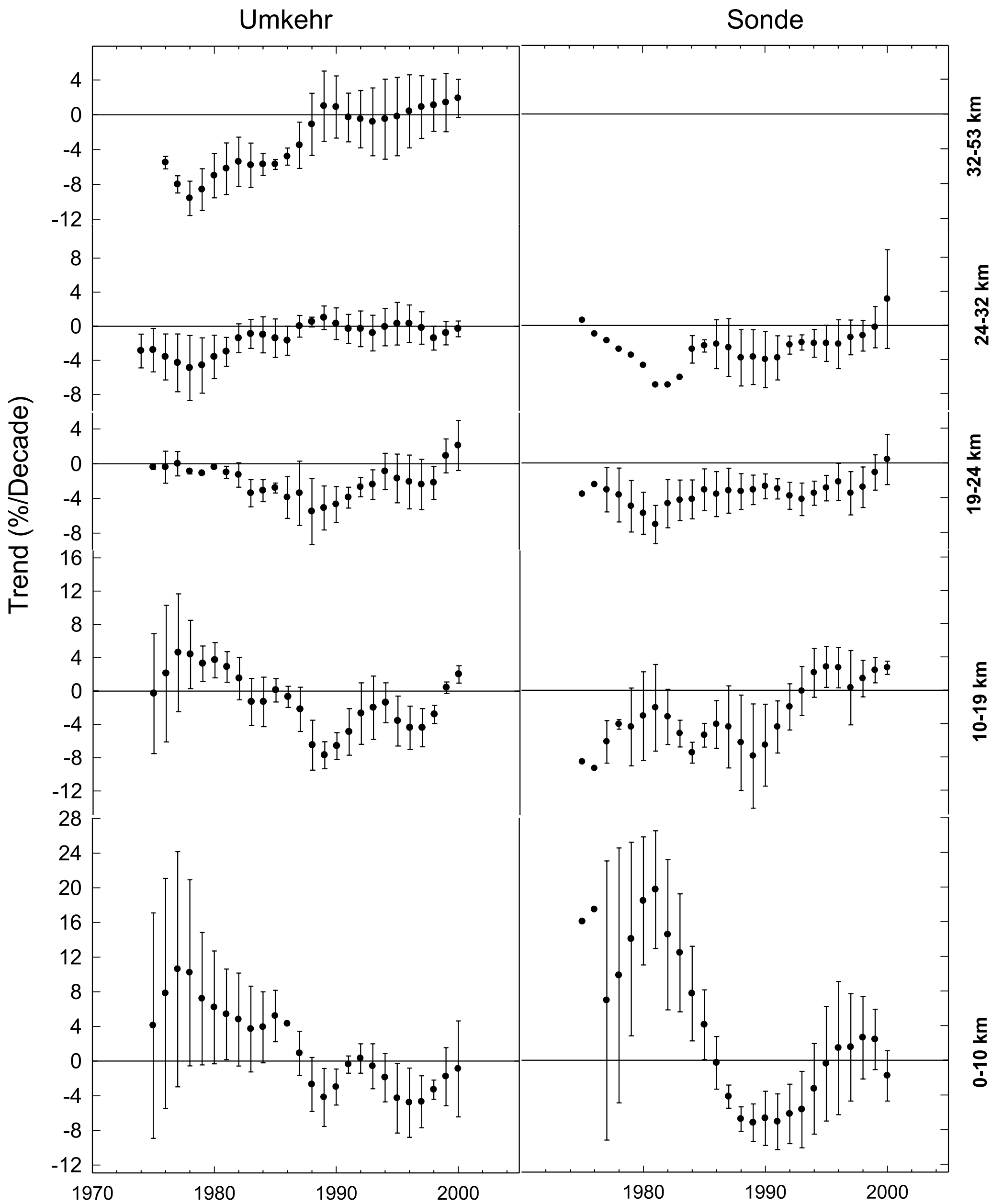

Figure 3. Variation of layer-ozone trend with time for height layers of the north temperate zone, as determined by Umkehr and ozonesonde observations. The 32- to 53-, 24- to 32-, 19- to 24-, 10- to 19-, and 0- to 10-km layer-ozone trends are based, respectively, on ozone data for Umkehr layers 7, 8, 9, and 10, Umkehr layers 5 and 6 and sonde pressure surfaces 20 and 10 mb, Umkehr layer 4 and sonde pressure surfaces 70, 50, and 30 mb, Umkehr layers 2 and 3 and sonde pressure surfaces 200, 150, and 100 mb, and Umkehr layers 0 and 1 and sonde pressure surfaces 700, 500, and 300 mb.

for 32- to 53-, 19- to 24- and 10- to 19-km Umkehr layers and integrated layer value, and 24- to 32-, 19- to 24- and 10- to 19-km sonde layers and integrated layer value. Only 24- to 32- and 0- to 10-km Umkehr layers, and 0- to 10-km sonde layer, do not have a positive trend at end of record. The median year of maximum negative trend for the six Umkehr layers and five sonde layers is 1988, the same year as for the total-ozone trends (Table 2). The average magnitude of the maximum negative trend for the six Umkehr values is -6.0 ± 1.6%/decade and for the five sonde values is -7.1 ± 1.3%/decade, compared to Umkehr and sonde values of 1.0 ± 1.0%/decade and 1.2 ± 1.6%/decade, respectively, at end of record.

5. Contribution of North Temperate Layers to the Increase in Total-Ozone Trend

[19] The contribution of individual ozone layers to the increase in north temperate total-ozone trend is estimated by multiplying the increase in layer-ozone trend between 1989

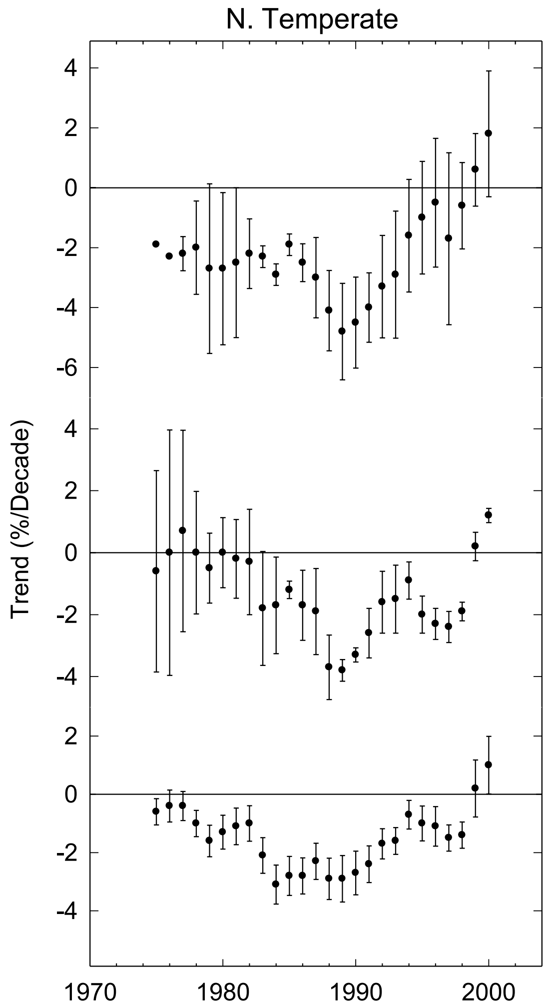

Figure 4. Comparison of north temperate total-ozone trends with integrated north temperate Umkehr and sonde-derived trends obtained by weighting the Umkehr and sonde trends in each layer by the fraction of the column ozone in that layer (see Table 4) and then summing.

and 2000 by the fraction of the column ozone in each layer (parenthetical numbers in Table 4). The year 1989 was chosen because it is the year of maximum negative trend for the integrated Umkehr and sonde trends in Figure 4 (see also bottom row of Table 3). The Umkehr data indicate that about half of the increase in north temperate total-ozone trend is due to trend increases in the low-stratospheric 10- to 19-km layer and about half to trend increase in the 19- to 24-km (ozone peak) layer, with essentially no contribution from the other layers. This supports the contention of *Hadjinicolaou et al.* [2005] that transport changes have had a role in the recent ozone increases, at least in the north temperate zone. The sonde data show a different variation of trend increase with height, with about half as much contribution from the ozone-peak layer as from the low-stratosphere and middle-stratosphere layer above the ozone peak. Both data sets indicate only about a 5% contribution from the tropospheric layer. If one chooses to average the Umkehr and sonde results, the troposphere has contributed 5%, the low stratosphere 48%, the ozone-peak layer 34%, the middle stratosphere 12% and the high stratosphere 1% to the increase in total-ozone trend between 1989 and 2000.

6. Summary and Conclusion

[20] Following are the main findings regarding the year and amount of maximum negative trend, and trend at end of record, in the total ozone and Umkehr and ozonesonde layer ozone records.

[21] 1. On the basis of this approach, there are positive total-ozone trends at the end of the record (the year 2000)

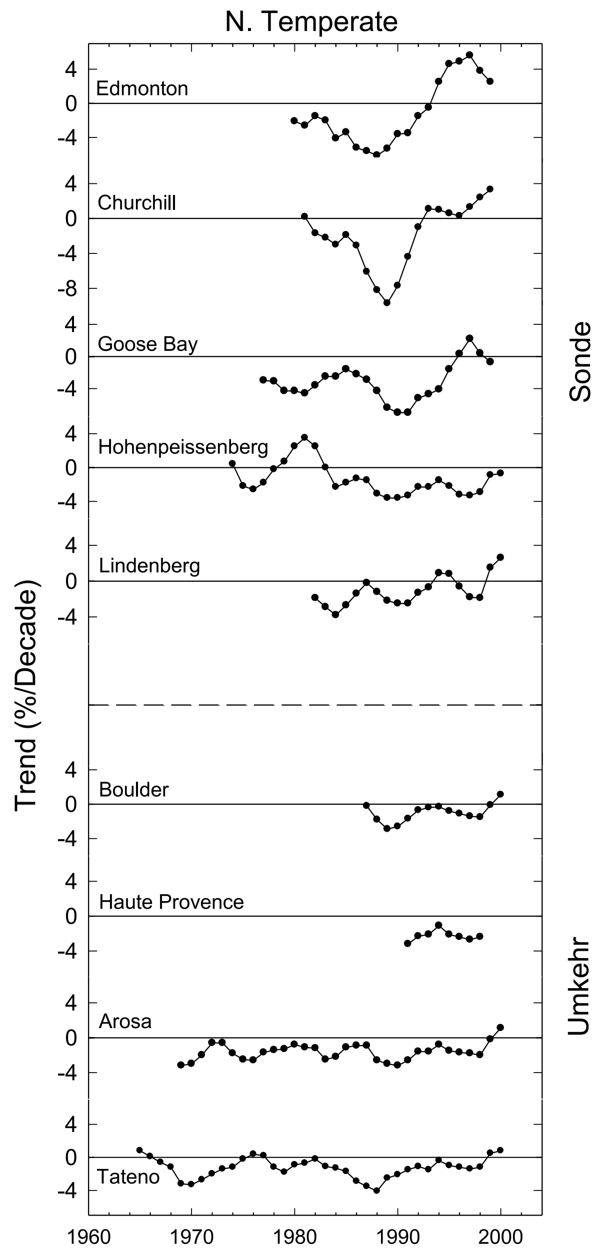

Figure 5. Variation with time of integrated Umkehr and sonde values of ozone trend for individual stations in the north temperate zone. Ozonesonde stations with fewer than 5 years of usable trend data are not included here.

Table 3. As in Table 2 but for Year and Magnitude of Maximum Negative Layer-Ozone Trend and Integrated Value and the End-of-Record Layer-Ozone Trend and Integrated Value, Based on Umkehr and Ozonesonde Observations

	Maximum Negative Trend				End-of-Record Trend	
	Umkehr		Sonde		Umkehr	Sonde
32–53 km	1978	−9.6%/decade			−1.9%/decade	
24–32 km	1978	−4.9	1982	−7.0%/decade	−0.3	−3.1%/decade
19–24 km	1988	−5.5	1981	−7.1	2.1	0.4
10–19 km	1989	−7.7	1976	−9.4	2.0	2.7
0–10 km	1996	−4.8	1989	−7.2	−0.9	−1.8
Integrated	1989	−3.8	1989	−4.8	1.2	1.8

for North American, European and Asian north temperate regions, north polar, north temperate and tropical climate zones, and globe.

[22] 2. On the basis of the three north temperate regions, five climate zones, and globe, the median year of maximum negative total-ozone trend is 1988. Because the slowdown in total-ozone decline can follow the year of maximum negative trend by as much as 7 years, the slowdown may be related to the 1995 peak in ODS.

[23] 3. There are positive ozone trends at the end of the record in 2000 for 32- to 53-, 19- to 24- and 10- to 19-km Umkehr layers and integrated layer value, and 24- to 32-, 19- to 24- and 10- to 19-km sonde layers and integrated layer value.

[24] 4. The median year of maximum negative trend for the six Umkehr layers and five sonde layers is 1988, the same year as the median year for the total-ozone trends.

[25] 5. The integrated layer-weighted Umkehr and sonde data are similar in having a maximum negative trend in 1989 and positive ozone trends for the last 2 years of record. The larger confidence intervals for the sonde data result partly from the greater variability with time of the station values of ozonesonde trends.

[26] 6. Averaging the Umkehr and sonde results, the troposphere has contributed 5%, the low stratosphere 48%, the ozone-peak layer 34%, the middle stratosphere 12% and the high stratosphere 1% to the increase in north temperate total-ozone trend between 1989 and 2000.

[27] In conclusion, it is hoped that this paper has provided a more visual presentation of the change in ozone trend from fairly large downward values in the late 1980s to no trend or even positive trend in recent years, complementing previous statistical studies. The procedures used here may be useful for future monitoring of ozone, especially with regard to how the north temperate total-ozone trend recovery is distributed among the various atmospheric layers.

Table 4. Percentage Contribution of North Temperate Height Layers to the Increase in North Temperate Total-Ozone Trend Between 1989 and End of Record, as Estimated From Umkehr and Sonde Observations[a]

Height Layer	Umkehr	Sonde
32–53 km	(0.06) 1%	
24–32 km	(0.32) −9%	(0.34) 34%
19–24 km	(0.31) 51%	(0.33) 18%
10–19 km	(0.25) 53%	(0.27) 43%
0–10 km	(0.06) 4%	(0.06) 5%

[a]The fraction of column ozone in each layer for Umkehr and sonde observations, based on long-term Arosa Umkehr data and long-term Hohenpeissenberg ozonesonde data, is given in parentheses.

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