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Trends in positive and negative ozone laminae in the Northern Hemisphere

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[1] The measured ozone profile is often not a smooth curve with a maximum in the stratosphere. It exhibits narrow layers of enhanced ozone concentration (positive laminae) and of depleted ozone (negative laminae). Here we deal with the trends in ozone laminae characteristics. All sufficiently long data series of ozonesonde soundings from the Northern Hemisphere poleward of 30°N are analyzed separately for Europe, northern America, Japan, and the Arctic. The trends in ozone laminae are quite strong, much stronger than those in total ozone at middle latitudes. A reversal in trends in the ozone laminae characteristics, mainly in the overall ozone content (deficit) in positive (negative) laminae per profile and the number of laminae per profile, is found to have occurred in the mid-1990s. Whereas a negative trend was observed before the mid-1990s, a positive trend was observed after about 1995. We assume this change in the ozone laminae trend to be caused predominantly by a change in the trends in circulation in the middle atmosphere.

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1. Introduction

[2] The ozone profiles measured by ozonesondes, particularly those observed in late winter and early spring, do not display a smooth shape below the maximum of the ozone layer. Very often we may observe the occurrence of weak undulations and/or relatively narrow layers of substantially increased or depleted ozone concentration. These layers are called laminae, positive laminae in the former (enhanced ozone concentration) and negative laminae in the latter case. The laminar structure of ozone profiles was first described by *Dobson* [1973] on the basis of ozonesonde data. Laminae occur also in lidar and satellite ozone profiles [e.g., *Appenzeller and Holton*, 1997; *Manney et al.*, 2000, 2001; *Randall et al.*, 2003] but with poorer height resolution (satellites about 1 km at best) and with much shorter data series than ozonesonde data available at middle latitudes since the 1960s or early 1970s. We are interested in long-term trends and therefore hereafter we deal with ozonesonde data only. On the other hand, satellites provide global coverage and more frequent measurements (sondes typically no more than 2–3 times per week at best). The first tracer lamina climatology based on satellite data was published by *Appenzeller and Holton* [1997]. However, that climatology is based on calculations of where laminae are expected to occur from horizontal gradients in the poor vertical resolution Microwave Limb Sounder data, rather than from direct observations of laminae. *Kar et al.* [2002] used satellite data from Stratospheric Aerosol and Gas Experiment (SAGE) II (version 6.0). They were interested in layers with depths of 3 to 6 km, and they claimed that they had investigated layers broader than laminae.

[3] Why do we study ozone laminae? First, in no other parameter in the midlatitude middle atmosphere can we find such a strong negative trend as in positive laminae over the period of the late 1960s to early 1990s [e.g., *Lastovicka*, 2002]. Second, despite the small amount of ozone in the individual laminae, the observed strong trends in laminae could contribute to the observed trends in total ozone at middle latitudes, particularly in late winter–early spring [e.g., *Lastovicka*, 2001]. Third, the trends in laminae seem to be, to some extent, related to long-term changes in circulation/transport [e.g., *Mlch and Lastovicka*, 1997].

[4] We deal with ozone number density profiles and laminae expressed in terms of ozone partial pressure, not with mixing ratio profiles. Strong laminae in terms of ozone partial pressure occur only below the maximum of the ozone profile, whereas strong laminae in terms of the ozone mixing ratio also occur in the upper stratosphere.

[5] Laminae are observed most prominently during the winter and spring in extratropics [*Reid and Vaughan*, 1991]. At middle latitudes in Europe the seasonal variation of the lamina occurrence frequency is larger than a factor of five with a maximum in late winter–early spring [*Mlch and Lastovicka*, 1996]. There are many profiles, particularly in late summer and early autumn, which exhibit no stronger lamina. On the other hand, in late winter and early spring we can often observe profiles with more than one lamina, as that shown in Figure 1.

[6] Laminae occur most frequently at heights around 14 km according to *Reid and Vaughan* [1991], which is

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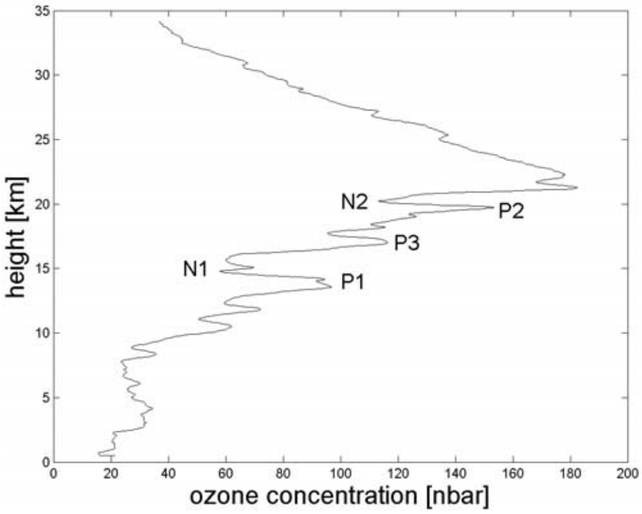

Figure 1. Ozone profile measured at Payerne on 11 February 2000. P1, P2, P3, positive laminae; N1, N2, negative laminae.

consistent with our result [*Lastovicka*, 2002] that more than 40% of the overall ozone content in laminae is located between 100 and 200 hPa. Other results [*Bird et al.*, 1997; *Pierce and Grant*, 1998; *Orsolini et al.*, 2001] put the maximum occurrence of laminae at potential temperatures of 375–400 K, i.e., about 14–16 km, which agrees with the above results. *Manney et al.* [2000] found for laminae in the lower stratosphere in November 1994 a pronounced longitudinal dependence with minimum occurrence at 30–90°E and maximums at 90–150°E and 210–270°E.

[7] The laminae at high and middle latitudes are predominantly associated with the exchange processes in the vicinity of the vortex edge and therefore with the transport of polar air in the form of oblique filaments toward the midlatitudes [e.g., *Mlch and Lastovicka*, 1996; *Reid et al.*, 1994, 1998]. The filamentary structures are a part of tracer (for instance ozone) sheets, vertically tilted in the shear zone in the vicinity of the polar jet. Thin laminar structures (positive or negative laminae) in the tracer vertical profiles appear as the result of isentropic wrapping and vertical shearing of such tracer sheets [*Orsolini et al.*, 1995; *Orsolini*, 1995]. High-resolution modeling confirms that tilted ozone sheets, peeled off near the vortex edge, result in the formation of laminae in the ozone profile [*Orsolini et al.*, 1997]. Balloon-borne measurements confirm well-resolved laminations near the vortex edge [*Orsolini et al.*, 1998]. *Manney et al.* [2001] attributes multisatellite observed laminae in early November 1994 to the protovortex. At high latitudes inside the polar vortex there are two other mechanisms of lamina formation, intrusions into the vortex, and differential advection of local ozone anomalies (possibly resulting from chemical loss) [*Manney et al.*, 1998]. The poleward motion of filaments can create positive "superlaminae" inside the Antarctic ozone hole as observed by *Moustaoui et al.* [2003]. Complex measurements at Shigaraki (35°N) in April 1998 identified a well-developed lamina caused by differential advection due to the vertical shear associated with the subtropical westerly jet and the stationary Rossby wave embedded therein [*Tomikawa et al.*, 2002]. Intrusions of ozone-poor tropical air into higher latitudes can create negative laminae there [e.g., *Manney et al.*, 2000]. Some smaller undulations of the ozone profile and weaker layers of enhanced or depleted ozone concentration may be caused by gravity waves, particularly at middle latitudes [e.g., *Reid et al.*, 1994; *Pierce and Grant*, 1998]. Therefore we consider only sufficiently strong laminae (see section 2), which may be assumed to originate very predominantly at the polar vortex edge.

[8] Since we are interested in trends in ozone laminae, recent reviews on trends in related stratospheric parameters, namely in the total ozone [*Staehelin et al.*, 2001] and stratospheric temperatures [*Ramaswamy et al.*, 2001], should be mentioned. *Logan et al.* [1999] have broadly studied the trends in ozone profiles.

[9] Our previous investigations, based on the ozonesonde data from the late 1960s to the early 1990s [*Mlch and Lastovicka*, 1996, 1997; *Lastovicka*, 2001, 2002], yielded the following main conclusions about laminae:

[10] 1. There is a very strong negative trend in the overall ozone content in laminae per profile at middle and high latitudes of the Northern Hemisphere. A typical decrease is about 50% over 20–25 years.

[11] 2. This strong negative trend does not exhibit a pronounced dependence on latitude down to about 36–37°N (Tateno) despite the large decrease of the overall ozone content in laminae per profile with decreasing latitude.

[12] There are various indications that long-term trends in some parameters of the middle atmosphere at middle latitudes of the Northern Hemisphere changed in the 1990s [*Lastovicka and Krizan*, 2005]. The change of trends in laminae in the Northern Hemisphere is the main topic of the paper. The change of trends in the positive laminae was first mentioned by *Krizan* [2003] for Hohenpeissenberg and Sodankylä in Europe. Such a change for the negative laminae follows from the data presented by *Tarasick et al.* [2004, Figure 3] for a few northern American stations.

[13] Section 2 deals with the lamina determination. Section 3 briefly describes the data we have used. The trends in both positive and negative laminae over Europe, northern America, Japan and the Arctic are treated separately for each region in section 4. The results are discussed in section 5. Paper ends with section 6, conclusions.

2. Determination of Laminae

[14] Figure 1 shows an example of the measured ozone vertical profile that clearly illustrates the main problem of lamina calculation. It is the determination of a reference profile, the ozone profile as it would be in the absence of laminae, with respect to which the laminae are computed. Various authors have used various approaches to the reference profile determination, which is one of the reasons for some differences between their results. It should be noted that ozone profiles, which are "wilder" than that in Figure 1, are not rare.

[15] In this paper we use a method similar to that used by *Pierce and Grant* [1998]. Its basic idea is to obtain the reference profile by smoothing the observed profile. This can be done by splines. We use a simpler 1-2-1 smoothing applied repeatedly until the profile between the tropopause

and the ozone profile maximum (= region of strong lamina occurrence) becomes uniform. The approach is as follows:

[16] There are n measured data points $a_0 \ldots a_n$ along the profile. The value of the smoothed ith point, pa_i, is ($i \neq 0$ and $i \neq n$):

$$pa_i = (a_{i-1} + 2\, a_i + a_{i+1})/4 \qquad (1)$$

The value of the first point, pa_0:

$$pa_0 = (2a_0 + a_1)/3 \qquad (2)$$

The value of the last point, pa_n:

$$Pa_n = (2a_n + a_{n-1})/3 \qquad (3)$$

This procedure is repeated until the reference profile between the tropopause and ozone concentration maximum) becomes uniform. Such a reference profile is shown in Figure 1. Our method of smoothing reduces slightly the ozone profile maximum and can create some problems at both ends of the profile, but none of these three regions is the lamina occurrence region, where the reference ozone profile seems to be correct. On the other hand, no method yields a reference profile, which is quite certainly correct. Some degree of uncertainty always remains.

[17] Once we have the reference ozone profile, we can compute the intersection points of this profile with the measured ozone profile. There is a local extreme of the observed profile between two consecutive intersection points. If the extreme is a maximum, we have three points: the first intersection point, the maximum and the second intersection point. Designate H1(2) the height of the first (second) intersection point in meters, O1(2) the ozone concentration at the first (second) intersection point, and Omax the ozone concentration in the maximum. If these three points match the following criteria, they form a positive ozone lamina:

$$500 < (\mathrm{H2} - \mathrm{H1}) < 3500 \qquad (4)$$

$$\mathrm{Omax} - 0.5(\mathrm{O1} + \mathrm{O2}) > \mathrm{sl}, \mathrm{sl} - \text{minimum size of lamina} \qquad (5)$$

$$\mathrm{Omax} - \mathrm{O1} > \mathrm{sl}/2, \mathrm{Omax} - \mathrm{O2} > \mathrm{sl}/2 \qquad (6)$$

The two intersection points and the local minimum of ozone concentration form in a similar way a negative ozone lamina.

[18] Some smaller undulations of the ozone profile and weaker layers of enhanced or depleted ozone concentration may be caused by gravity waves, particularly at moderate latitudes [e.g., *Reid et al.*, 1994; *Pierce and Grant*, 1998]. To exclude them, we consider only sufficiently strong laminae, usually those larger than 40 nbar, i.e., sl = 40 nbar in (5). When we applied this criterion to Figure 1, where no extreme is larger than 40 nbar, we found no strong lamina for this particular day.

[19] We calculate three parameters characterizing the laminae in ozone profiles: (1) the occurrence frequency of laminae per profile, (2) the ozone content (deficit) per positive (negative) lamina, and (3) the overall ozone content in positive laminae (or deficit in negative laminae) per profile. The third parameter is analyzed in the paper more broadly than the first two, because it is the most relevant for estimating the contribution of trends in laminae to the total ozone trends.

[20] Different methods of lamina determination and definition have some impact on the results of lamina studies. In previous investigations we used three different methods for lamina calculation. Prior to the method described above two other methods assuming all laminae to be positive (i.e., in Figure 1 the positive laminae P1, P2 and P3 began in the maximums of negative laminae N1 and N2) and the observed profile as a reference profile, and different constrains of the type of equation (6). The older method used before 2001 was described by *Halenka and Mlch* [1996], and the second method by *Krizan and Lastovicka* [2004].

[21] *Krizan and Lastovicka* [2004] compared the results obtained by those three methods for nearby stations Payerne (Switzerland) and Hohenpeissenberg (southern Germany). Even though the absolute values of the overall ozone content in positive laminae per profile were substantially different, the relative trends (in percentage) were very close to each other. The strong trends appear to be quite robust and method-independent. As for condition (4), lamina thickness between 0.5 and 3.5 km, Figure 2 (computed with the second method described by *Krizan and Lastovicka* [2004]) reveals the independence of the trend on lamina thickness in spite of a principal difference in the value of the overall ozone content in laminae as a function of lamina thickness. Figure 2 shows that thin laminae (upper limit of thickness of 1.5 km) almost do not contribute to the overall ozone content in strong laminae (sl > 40 nbar). The lower limit of 0.5 km was selected with respect to the ozone sounding vertical resolution of about 150 m [*Harris et al.*, 1998], but anyway very thin laminae do not play a role in the overall ozone content in laminae, as Figure 2 indicates. The trend might depend on the parameter sl (5); however, *Krizan and Lastovicka* [2004] found that the trends for sl = 40 and 70 nbar are very similar, and *Lastovicka* [2002] observed a similarity of trends for sl = 40 and 20 nbar. This means that the trends are almost independent of the lower limit of lamina size, sl.

3. Data

[22] As mentioned above, we use ozonesonde data with a sufficiently long period of observations from four regions at middle and high latitudes of the Northern Hemisphere over the period 1970–2003: (1) European midlatitude stations, Payerne (46.49°N, 6.57°E, 1970–2002), Hoheinpeissenberg (47.8°N, 11.02°E, 1970–2002), Lindenberg (52.21°N, 14.12°E, 1975–2003), Legionowo (52.4°N, 20.97°E, 1979–2003), Prague-Libus (50.02°N, 14.45°E, 1979–2003, only January–April), Uccle (50.8°N, 4.35°E, 1970–2001); (2) northern American stations, Goose Bay (53.32°N, 60.3°W, 1970–2003), Edmonton (53.55°N, 114.01°W, 1973–2003), Churchill (58.75°N, 94.07°W, 1974–2003), Wallops Island (37.93°N, 75.48°W, 1970–1998); (3) Japanese stations, Tateno (36.05°N, 140.1°E, 1970–2003), Sapporo (43.05°N, 141.33°E, 1970–2003)

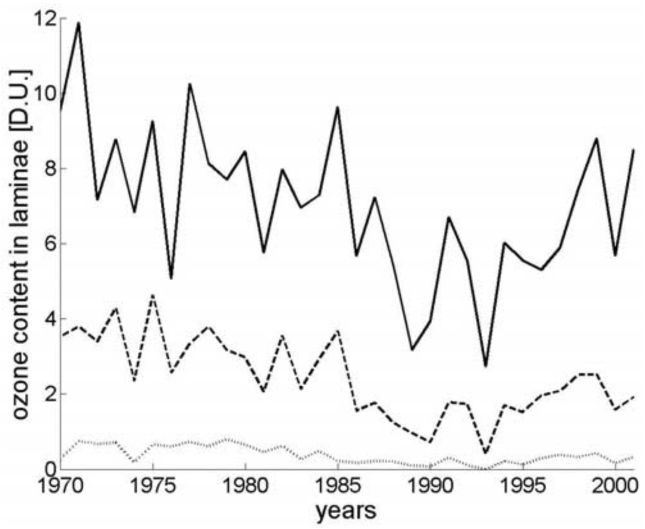

Figure 2. Overall ozone content in positive laminae per profile at Payerne in the period 1970–2001 for laminae larger than 40 nbar with the upper limit of lamina thickness 3.5 km (standard, top curve), 2.5 km (middle curve), and 1.5 km (bottom curve). After *Krizan and Lastovicka* [2004].

and Kagoshima (31.63°N, 130.6°E, 1970–2003); and (4) Arctic stations, Sodankylä (67.39°N, 26.65°E, 1989–2003), Ny Aalesund (78.93°N, 11.88°E, 1991–2003), Resolute Bay (74.72°N, 94.98°W, 1970–2003), Alert (82.5°N, 62.3°W, 1988–2003). Ozonesonde data for these stations were taken from the international ozone database in Toronto: http://www.msc-smc.ec.gc.ca/woudc. We use only data for January–May, the period of the highest occurrence frequency of laminae. In September–October, the number of laminae is less than 20% of that in February–April.

[23] There are large differences in the number of observations at these stations. The following stations have the largest number of observations: Payerne, Hoheinpeissenberg, and Uccle. The Arctic stations except for Resolute Bay have shorter periods of observations. In the paper we report the results for stations of the Northern Hemisphere. The analysis of the ozone laminae characteristics in the Southern Hemisphere is under way and will be published in a separate paper.

[24] The intervals between data points in measured ozone profiles could vary from station to station and with time as measurements were improved. This can affect the results. The January–May averaged intervals between data points in profiles at "lamina" heights are summarized in Table 1 for each station and each year. The smallest intervals, i.e., the best data, are provided by Payerne, Uccle and Sodankylä. The most recent data are best. Legionovo in 1986 and Wallops till 1976 have average intervals larger than 1 km. However, Figure 2 shows that laminae thinner than 1.5 km contribute very little to the overall ozone content in laminae per profile for the laminae studied (>40 nbar). Therefore the varying intervals between data points in profiles probably do not affect significantly the results. This conclusion concerns particularly the long-term trends and it is supported by similarity of trend patterns at various stations, as shown in section 4. On the other hand, year-to-year variations may be affected to some extent.

[25] Another factor, the variable seasonal distribution of measurements, can affect the results due to a very strong seasonal variation of laminae. For example, *Sofieva et al.* [2004, Table 1] show distribution of monthly numbers of ozone sonde profiles for Sodankylä, 1989–1999. First, the yearly average number of profiles varies substantially, between 41 (1999) and 83 (1995), which may but need not affect the results. Second, and much more important, the seasonal distribution of soundings varies considerably from year to year, which can remarkably contribute to some large year-to-year changes observed at Sodankyla (see section 4, Figures 9 and 10). This is primarily problem of stations with smaller number of soundings. Stations with larger number and more regular soundings, like Payerne or Hohenpeissenberg, display smaller year-to-year changes (Figures 3 and 4).

[26] The third potential problem arises with differences in ozone sonde preparation and data processing between different countries, even different stations, and different types of sondes. This was a problem particularly in early years of measurements. Various intercomparisons, standardization, partial sonde unification, and data homogenization made this problem much less important in recent years [*Harris et al.*, 1998]. This may affect remarkably the differences in year-to-year variations among various stations, particularly in the 1970s, but it does not seem to affect significantly the observed trends, because they are similar at various stations, as shown in section 4.

[27] The discussion in the two previous paragraphs shows that the gross features and strong long-term trends appear to be reliable, but fine details and year-to-year changes must be considered with great caution, and we do not consider many of them reliable.

4. Trends in Laminae

[28] Figures 3 and 4 display the trend in the overall ozone deficit (content) in negative (positive) laminae per profile for six European middle latitude stations. Figures 3 and 4 look very busy and not very readable. However, this is to some extent our intention. Owing to the discussion at the end of section 3, only gross features, i.e., primarily the overall long-term trend of the whole data set, appear to be reliable, while year-to-year changes of individual curves are of very questionable reliability. We ask readers do not try to follow details, which might be incorrect and misleading, consider only the general character of long-term trends. The same is valid for all Figures 3–10.

[29] A principal change in the trend occurred in the mid-1990s. A strong negative trend (reduction of ozone content in positive laminae and reduction of ozone deficit in negative laminae) was observed before 1993–1995 (the minimum in 1993 might be the effect of the Mount Pinatubo volcanic eruption). In more recent years the trend is positive, i.e., an increase of ozone content in positive laminae and ozone deficit in negative laminae. This change in trend in the overall ozone content in laminae per profile in the mid-1990s occurred both in the case of positive and negative laminae, and for all six individual stations. The negative trend in Figure 4 represents a laminar ozone content reduction by more than 50% from 1970 to the mid-1990s for Payerne, Hohenpeissenberg, and Uccle and a

Table 1. January–May Average Values of the Interval Between Data Points in Profiles at Heights 10–25 km for All Stations and All Years[a]

Year	Pa	Hoh	Lind	Leg	Prg	Ucc	Sod	Ny	Res	Ale	Goos	Edm	Chur	Wal	Sap	Tat	Kag
1970	165	385	0	0	0	133	0	0	536	0	609	0	0	954	684	749	865
1971	171	381	0	0	0	139	0	0	609	0	620	0	0	1103	673	717	882
1972	168	407	0	0	0	116	0	0	703	0	668	0	0	1247	688	702	864
1973	177	438	0	0	0	120	0	0	630	0	671	591	0	1311	658	722	805
1974	194	451	0	0	0	162	0	0	749	0	717	681	722	1111	646	572	831
1975	184	427	636	0	0	176	0	0	853	0	805	769	815	1180	603	756	893
1976	192	437	728	0	0	163	0	0	697	0	729	690	717	1138	698	1105	0
1977	211	408	598	0	0	116	0	0	550	0	626	574	629	817	0	1246	0
1978	228	409	670	0	0	128	0	0	633	0	648	598	628	793	553	824	759
1979	218	366	666	765	619	138	0	0	609	0	646	580	655	637	609	642	748
1980	232	345	664	882	681	140	0	0	610	0	623	545	603	551	710	752	1125
1981	209	353	704	754	639	153	0	0	645	0	642	591	636	581	639	744	989
1982	120	354	606	775	700	141	0	0	570	0	592	552	606	626	709	751	1041
1983	116	367	555	793	701	115	0	0	581	0	587	577	582	0	678	734	1019
1984	113	356	579	792	830	118	0	0	659	0	610	550	622	555	617	722	934
1985	115	361	573	683	690	111	0	0	627	0	549	603	580	578	597	702	901
1986	119	404	576	1069	689	107	0	0	573	0	577	550	543	577	673	687	867
1987	135	384	645	723	770	120	0	0	400	0	399	367	377	522	664	720	851
1988	137	386	781	857	545	112	0	0	368	342	386	361	366	537	714	732	909
1989	139	384	867	777	631	120	52	0	354	330	367	349	336	594	678	726	886
1990	28	404	742	651	605	83	50	387	405	373	401	395	407	556	673	744	891
1991	25	379	661	633	633	89	63	128	310	296	370	320	317	524	651	710	901
1992	25	385	602	678	536	86	303	79	322	332	381	325	356	560	676	714	957
1993	21	385	560	262	508	84	53	293	433	406	391	379	392	560	707	797	928
1994	21	359	437	188	474	84	50	52	345	382	275	267	322	524	690	768	897
1995	20	367	466	62	489	79	51	54	287	298	260	301	337	561	687	733	878
1996	22	427	453	54	508	74	46	52	250	320	314	311	301	527	655	753	858
1997	21	350	408	52	499	77	12	54	270	40	279	355	294	494	625	700	820
1998	22	330	438	52	467	82	12	59	251	263	296	316	279	501	559	678	750
1999	20	359	423	53	454	82	11	61	262	260	306	316	261	0	599	721	816
2000	21	342	450	49	53	85	10	62	36	40	48	41	48	0	407	417	545
2001	34	356	440	50	53	89	11	58	39	40	49	37	46	0	378	447	533
2002	35	342	467	50	54	83	9	55	43	41	47	39	45	0	415	454	522
2003	32	356	438	48	54	83	9	55	41	41	45	39	42	0	57	58	62

[a] In meters. The 0 means no measurements. Pa, Payerne; Hoh, Hohenpeissenberg; Lind, Lindenberg; Leg, Legionovo; Prg, Prague-Libus; Ucc, Uccle; Sod, Sodankylä; Ny, Ny Aalesund; Res, Resolute Bay; Ale, Alert; Goos, Goose Bay; Edm, Edmonton; Chur, Churchill; Wal, Wallops Island; Sap, Sapporo; Tat, Tateno; Kag, Kagoshima.

rapid trend reversal after the mid-1990s. Station Prague-Libus provides larger values of both positive and negative laminae because measurements were run only in January–April each year, when the average number of laminae is higher than in May. The comparison of Figures 3 and 4 reveals the ratio of the ozone deficit in negative laminae to the ozone surplus in positive laminae to be about 2:3 or a little lower with good correlation (but not one-to-one correspondence) of the positive and negative laminae variations.

[30] Canadian midlatitude stations (Figures 5 and 6) display a trend pattern very similar to that for European stations, a strong negative trend before the mid-1990s with a minimum in 1995–1996 followed by a rapid trend reversal. The Wallops Island data series terminated in the late 1990s. Nevertheless, Wallops Island provides a similar trend pattern for the positive laminae, whereas for the high-scatter negative laminae data no evident trend can be detected. The Wallops Island values of ozone in laminae are generally somewhat smaller compared with Canadian stations due to lower latitude. The ozone deficit to ozone surplus ratio seems to be slightly smaller for the Canadian stations than for the European stations.

[31] It is more difficult to draw a conclusion about trends in the ozone content in laminae per profile for the Japanese stations (Figures 7 and 8), because the number of observa-

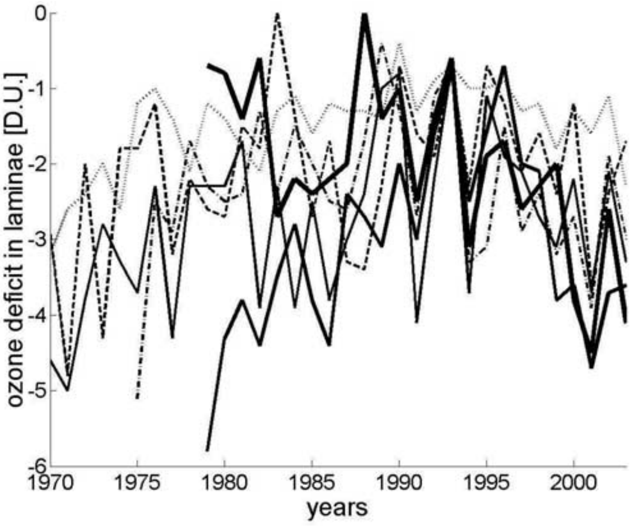

Figure 3. Overall ozone deficit in negative laminae per profile for the European middle latitude stations Hohenpeissenberg (dotted line), Legionovo (heavy solid line), Lindenberg (dash-dotted line), Praha-Libus (medium solid line), Payerne (thin solid line), and Uccle (dashed line), 1970–2003.

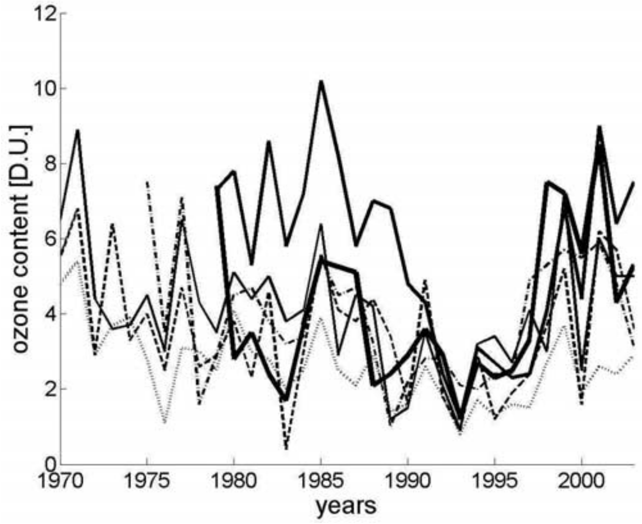

Figure 4. Overall ozone content in positive laminae per profile for the European middle latitude stations Hohenpeissenberg (dotted line), Legionovo (heavy solid line), Lindenberg (dash-dotted line), Praha-Libus (medium solid line), Payerne (thin solid line), and Uccle (dashed line), 1970–2003.

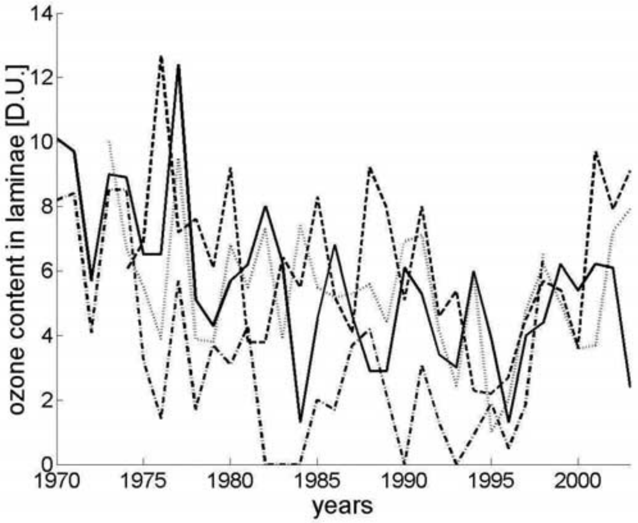

Figure 6. Overall ozone content in positive laminae per profile for the northern American middle latitude stations Churchill (dashed line), Edmonton (dotted line), Goose Bay (solid line), and Wallops Island (dash-dotted line), 1970–2003.

tions is small in the 1970s and 1980s, and the overall ozone content in laminae per profile is lower than that in Europe due to the lower latitudes of the Japanese stations. This influences the results and is also, but not only, responsible for the appearance of an outlier in Tateno in 1978. The ozone content in the laminae at Kagoshima is very low, because Kagoshima is the lowest-latitude station, which seems to be basically out of reach of the laminae of polar vortex edge origin. Nevertheless, we can say that there was again a substantial negative trend (Sapporo and Tateno) before the mid-1990 with a minimum around 1996, and an evident tendency to trend reversal after this year, although not as rapid as in Europe.

[32] The Arctic stations (Figures 9 and 10) display a similar change in the trend of the overall ozone content in positive laminae as well as ozone deficit in negative laminae as the midlatitude stations with a minimum in 1995–1997. However, except for Resolute Bay all stations have provided data only since the very late 1980s. The negative trend followed by rapid trend reversal for positive laminae at Resolute Bay is similar to that for the above midlatitude stations. The overall ozone content in laminae per profile for high-latitude stations is higher than that for middle latitudes, which is in line with the idea of the dominant polar vortex

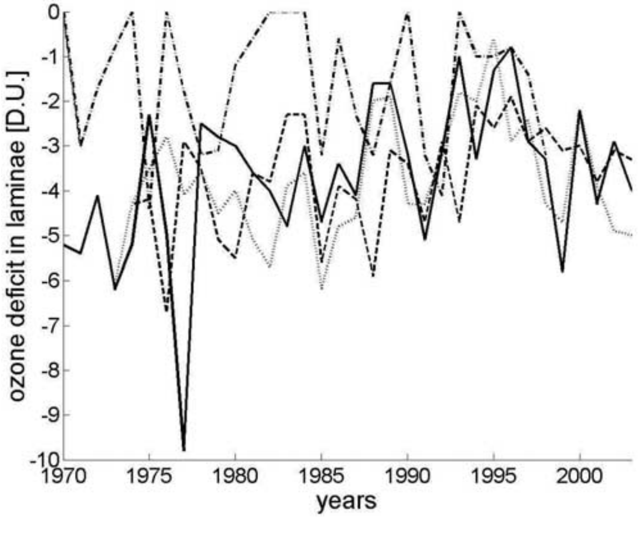

Figure 5. Overall ozone deficit in negative laminae per profile for the northern American middle latitude stations Churchill (dashed line), Edmonton (dotted line), Goose Bay (solid line), and Wallops Island (dash-dotted line), 1970–2003.

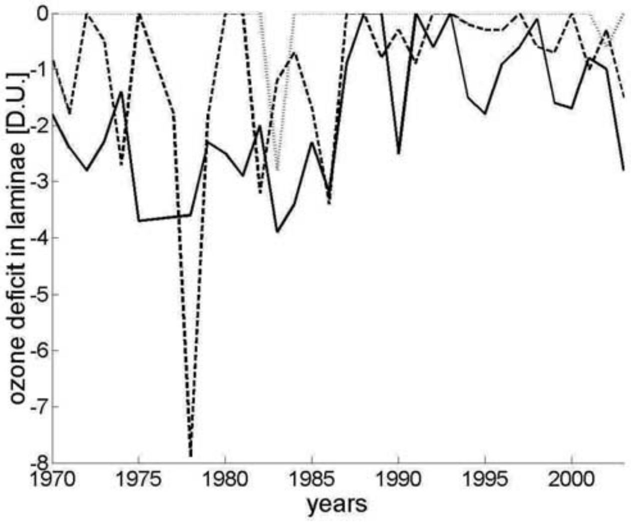

Figure 7. Overall ozone deficit in negative laminae per profile for the Japanese stations Kagoshima (dotted line), Sapporo (solid line), and Tateno (dashed line), 1970–2003.

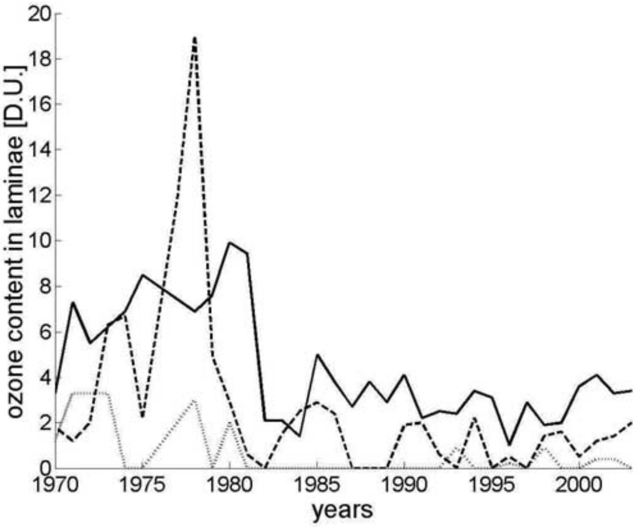

Figure 8. Overall ozone content in positive laminae per profile for the Japanese stations Kagoshima (dotted line), Sapporo (solid line), and Tateno (dashed line), 1970–2003.

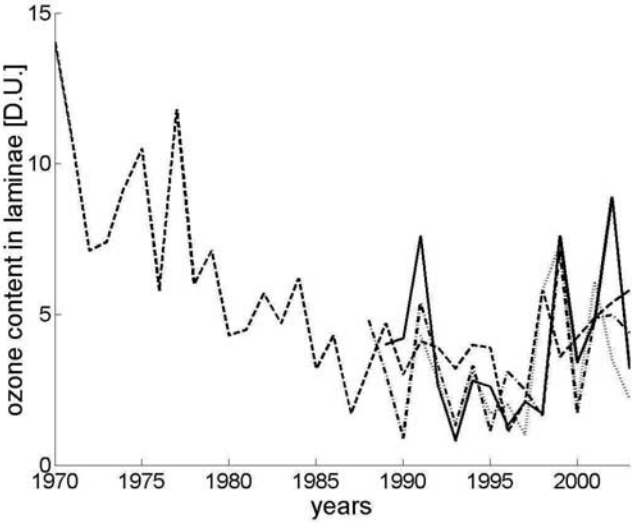

Figure 10. Overall ozone content in positive laminae per profile for the Arctic stations Alert (dash-dotted line), Ny Aalesund (dotted line), Resolute Bay (dashed line), and Sodankylä (solid line), 1970–2003.

edge origin of laminae. High-latitude stations are often situated inside the polar vortex. The ozone deficit to ozone surplus ratio seems to be around 0.6 for the Arctic stations.

[33] The trend in the number of ozone laminae per profile is similar to that in the overall ozone content in laminae per profile, as shown in Figure 11 for the positive laminae and the representative stations of all four regions. The station with the largest amount of data, Payerne in Europe, reveals trends in terms of percentage change, which are very close to those in the overall ozone content in laminae per profile both for the positive and negative laminae. It is more difficult to make such a quantitative comparison of trends for other regions due to outliers and higher year-to-year variability, mainly because of the lower number of measurements and their unstable seasonal distribution. Nevertheless, it is evident from the comparison of Figures 11 and 12 with Figures 4, 6, 8, and 10 that there is not much difference between the trends in the number of laminae per profile and the overall ozone content in laminae per profile for any of the regions under study. In Japan, Sapporo and Tateno display an evident trend in the number of laminae per profile. Kagoshima (not shown here) located at lower latitude than Sapporo and Tateno does not reveal a detectable trend, but there are very few strong laminae at Kagoshima. The ratio of the number of negative laminae (not shown here) to positive laminae is approximately 2:3,

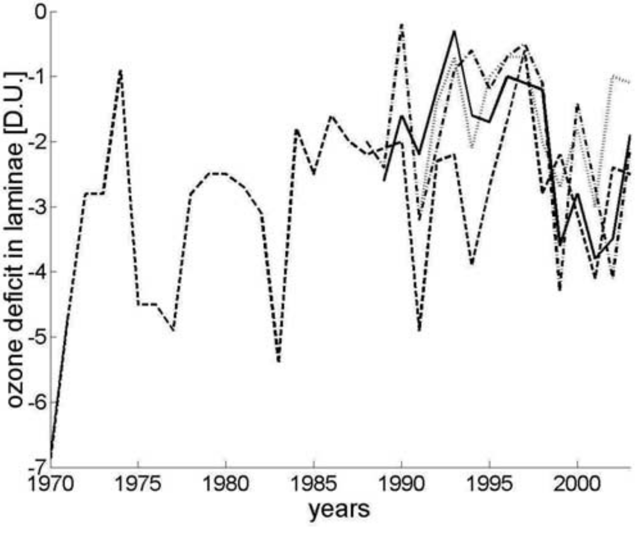

Figure 9. Overall ozone deficit in negative laminae per profile for the Arctic stations Alert (dash-dotted line), Ny Aalesund (dotted line), Resolute Bay (dashed line), and Sodankylä (solid line), 1970–2003.

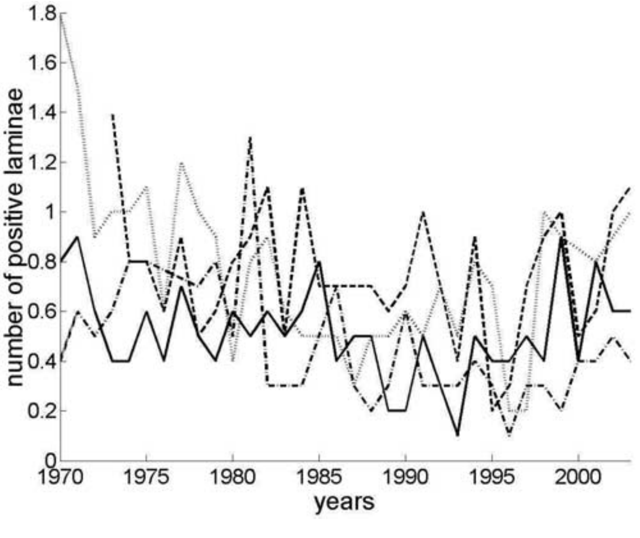

Figure 11. Number of positive laminae per profile for the four representative stations Payerne (Europe, solid line), Edmonton (northern America, dashed line), Sapporo (Japan, dash-dotted line), and Resolute Bay (Arctic, dotted line), 1970–2003.

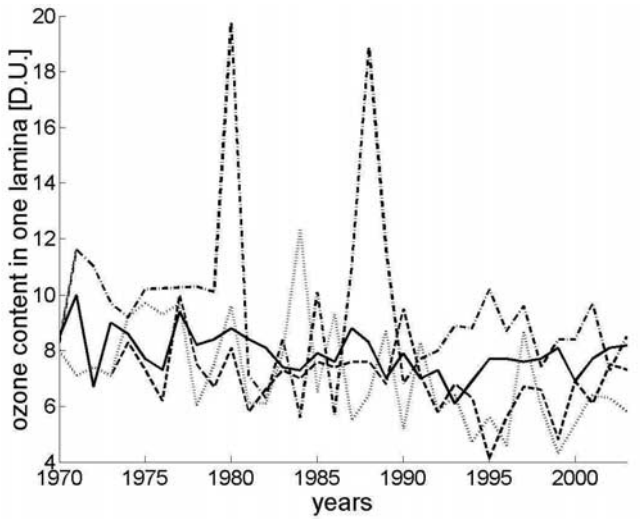

Figure 12. Ozone content per positive lamina for the four representative stations Payerne (Europe, solid line), Edmonton (northern America, dashed line), Sapporo (Japan, dash-dotted line), and Resolute Bay (Arctic, dotted line), 1970–2003.

i.e., similar to that for the overall ozone content in laminae per profile.

[34] The third lamina parameter is the ozone content (or deficit) per one positive (negative) lamina, shown for the representative stations of all four regions in Figure 12 for positive laminae. This parameter displays a quite different pattern of trends. Payerne and Sapporo show a very weak negative trend without detectable reversal, whereas the middle and high-latitude stations in the American sector, Edmonton and Resolute Bay, exhibit an evident negative trend with a tendency to leveling off (Resolute) or even slight reversal (Edmonton) of the trend in the mid-1990s. On the other hand, there is no evident and statistically significant trend for the negative laminae in any of the four regions (not shown here). However, no detectable trend may include the existence of a weak trend. Weak trends may be masked by the problems with data uncertainty (instrumental effects) mentioned at the end of section 3. In general, the trends in the ozone content per lamina are less reliable than trends in the other lamina parameters. The behavior of the other stations in Europe and northern America, and Tateno in Japan, is consistent with the behavior of the selected representative stations Payerne, Edmonton and Sapporo. The ozone deficit (not shown here) to ozone surplus (positive laminae) ratio seems to be about 5:7, but its estimate is very uncertain. The outliers for Sapporo occur due to the smaller number of measurements and their year-to-year unstable seasonal distribution.

5. Discussion

[35] The trends observed in the overall ozone content (or deficit) in laminae per ozone profile are quite strong in all four regions, Europe, northern America, Japan (middle latitudes), and Arctic (high latitudes) down to about 35°N, which means that the observed trend is a global characteristic of the Northern Hemisphere at higher middle and high latitudes. The decrease of the overall ozone content in positive laminae per profile from 1970 to the mid-1990s is more than 50%. The overall ozone content (deficit) in laminae per profile is created by two parameters, by the number of laminae per profile and the ozone content (deficit) per lamina. In Europe and Japan, the trend is almost entirely caused by the trend in the number of laminae per profile. On the other hand, in the American sector this only applies to the negative laminae, whereas for the positive laminae the contribution of the trend in the ozone content per lamina is significant, even though it is not dominant. Such a difference in the origin of trends in the American sector versus Europe and Japan was reported first by *Mlch and Lastovicka* [1997] for positive laminae over the period from the late 1960s to the early 1990s. They found some difference in the trends in circulation indices in the lower stratosphere, which could be at least partly responsible for some difference in the origin of trends in the overall ozone content in laminae per profile in the American sector versus Europe and Japan.

[36] All stations in the Northern Hemisphere, except for the lowest-latitude Kagoshima, show a reversal in the trend in the overall ozone content in positive laminae per profile in the mid-1990s. We assume that this reversal of the trend is of dynamical origin, because it appeared too early for chemical origin of the reversal (consequence of the Montreal Protocol process). Such a reversal of trends has been observed simultaneously in the total ozone content both in satellite and ground-based (Arosa, Switzerland) data in the middle latitudes of the Northern Hemisphere [*Appenzeller et al.*, 2001; *Fioletov et al.*, 2002; *Fioletov*, 2004]; however, no such trend reversal has been observed in the Southern Hemisphere. There are also indications of a change of trends in the zonal wind in the upper middle atmosphere in the 1990s [*Jacobi et al.*, 2003]. *Appenzeller et al.* [2001] reported a tendency of the North Atlantic Oscillation (NAO) from the 1970s to the mid-1990s to a more negative phase, which was replaced by a tendency to a more positive phase after 1995–1996. The ozone trends in the lower stratosphere over Payerne at altitudes below 20 km were found to be caused, to a substantial extent, by dynamical changes [*Weiss et al.*, 2001]. All these observations suggest rather a dynamical origin of the ozone laminae trend reversal in the mid-1990s. There are various possible dynamical contributors to the long-term trend in total ozone, as discussed, e.g., by *Staehelin et al.* [2002] and *Hudson et al.* [2003]. Our first multiple regression investigations for Payerne, March average values, and a set of dynamical a solar parameters, reveal only four parameters, which are responsible for more than 5% of the total variance each: NAO (36%), potential vorticity (15%), QBO (at 50 hPa – 9%), Eliassen-Palm flux (5%). Any other parameter, including El Niño–Southern Oscillation (ENSO), contributed less than by 5%. However, for other regions we expect different roles of dynamical parameters, for example for Japan the role of ENSO must be larger and that of NAO smaller. A more detailed investigation of the origin of the trend reversal will be a topic of a separate paper after obtaining information on laminae trends in the Southern Hemisphere, which very likely establish some constrains on the possible interpretation and origin/mechanism of the observed trend reversal.

Table 2. Coefficients of Correlation Between the Characteristics of Positive and Negative Laminae for All Ozonesonde Stations Except Low-Latitude Kagoshima

Stations	Number of Laminae	Ozone in Laminae per Profile	Ozone per One Lamina
Payerne	0.68	−0.66	−0.29
Hoheinpeissenberg	0.62	−0.79	0.08
Lindenberg	0.64	−0.64	−0.11
Legionowo	0.65	−0.48	−0.09
Praha	0.84	−0.81	0
Uccle	0.85	−0.83	−0.26
Sodankyla	0.84	−0.80	−0.55
Ny Aalesund	0.94	−0.80	−0.18
Resolute Bay	0.51	−0.60	0.09
Alert	0.80	−0.84	−0.34
Goos Bay	0.76	−0.77	−0.29
Edmonton	0.52	−0.63	−0.34
Churchill	0.39	−0.65	0.26
Wallops Island	0.33	−0.14	−0.29
Sapporo	0.36	−0.46	0.13
Tateno	0.85	−0.76	−0.09

[37] There might be some indications of a true "chemical" reversal, or rather leveling off of the trends in ozone in recent years since about 1997–1998, but in the upper stratosphere, as reported by *Newchurch et al.* [2003]. However, *Steinbrecht et al.* [2004a] questioned the interpretation of the leveling off of the ozone trends in the upper stratosphere as evidence of "chemical" reversal. They attributed the observed changes rather to the solar cycle effect. The most recent paper by *Steinbrecht et al.* [2004b] mentions both possibilities and shows that measurements in the next few years (solar cycle minimum period) should resolve the problem.

[38] The results presented in section 4 indicate good correlations between the trends in positive and negative laminae parameters. Table 2 quantifies those correlations. We can see good correlation between the number of positive and negative laminae per profile; the correlation coefficient varies between 0.33 (Wallops Island) and 0.94 (Ny Aalesund). A good negative correlation is observed between the overall ozone in positive laminae per profile and the ozone deficit in negative laminae per profile, which is related to the good correlation between the number of positive and negative laminae. On the other hand, correlations between the ozone content per positive lamina and the ozone deficit per negative lamina are weak and mostly quite insignificant. This difference in correlations is understandable, if the main reason for correlations is the good correspondence between trends, because the trend observed in the ozone content per lamina is much smaller than in the other two parameters. However, some contribution to the observed correlations may be introduced by the method of lamina determination, namely by the smoothing used in constructing the reference ozone profile, which might result in a tendency to produce pairs of related positive and negative laminae therefore the results on the correlations between the positive and negative laminae characteristics must be considered to some degree as uncertain. Fortunately, as shown by *Krizan and Lastovicka* [2004] and mentioned in section 2, only the values of ozone content, not the trends in positive laminae characteristics are significantly influenced by the applied method of lamina determination.

[39] *Lastovicka* [2002] estimated the contribution of the trends in laminae to the total columnar ozone trends at middle latitudes in Europe to be as much as one third of the overall trend in the late winter/early spring, and negligible in early autumn. However, this result was obtained with another method of lamina determination, which computed only positive laminae and with more ozone than the method we are using now. In other words, that estimate may be considered to be the upper limit of the effect of trends in laminae on trends in total ozone. The net ozone depletion caused by the difference between the overall ozone content versus deficit in laminae per profile (Figures 4 and 3) between 1970 and the mid-1990s is about 5–7% of the total ozone depletion for yearly average values. Since we use only January–May data, and with respect to the method of lamina determination used in this paper, which rather underestimates the laminae contribution due to the connection between the positive and negative laminae, the estimate of 5–7% may be considered to be the lower limit of the effects of laminae on trends in total ozone in the late winter/early spring. Thus the contribution of laminae to the trends in total ozone is in no way dominant, but it cannot be neglected in European region, and similarly elsewhere at middle latitudes. The observation that the trends in total ozone at northern middle latitudes reveal a well-pronounced reversal in the mid-1990s in the late winter/early spring, but much weaker change in fall, is in line with the nonnegligible role of laminae in trends in total ozone.

6. Conclusions

[40] The data of all the Northern Hemisphere ozone sounding stations at latitudes $\varphi > 30^\circ$N with sufficiently long data series were analyzed for the long-term trends in laminae in ozone profiles in the lower stratosphere over the period 1970–2001. The analysis was complemented with several shorter data series, particularly from Arctic. The data were analyzed separately for four regions: Europe, northern America, Japan and the Arctic. As mentioned in section 1, the change of trends in laminae in the Northern Hemisphere was the main topic of the paper. Such a change in trends in the overall ozone content in positive laminae and the overall ozone deficit in negative laminae per profile was observed in the mid-1990s in the form of a trend reversal. The main results may be summarized as follows:

[41] 1. There was a strong trend of reduction of the overall ozone content in positive laminae, as well as the overall ozone deficit in negative laminae per ozone profile and in the number of both positive and negative laminae per profile from 1970 to the mid-1990s in all four regions. The reduction reached more than 50% for the overall ozone content in positive laminae.

[42] 2. After the mid-1990s the trend in both parameters and both positive and negative laminae reversed from negative to positive in all four regions.

[43] 3. The trends in the number of laminae are very similar to those in the overall ozone content (or deficit) in positive (negative) laminae.

[44] 4. There is no detectable trend in the ozone amount per positive lamina except for the American sector, where a weaker negative trend with a tendency to reversal or

leveling off in the mid-1990s was observed, and no detectable trend in the ozone deficit per negative lamina.

[45] 5. There are some indications that the observed reversal of trends in laminae is of dynamical rather than chemical origin, i.e., unfortunately it probably is not a consequence of the Montreal Protocol and its amendments.

[46] Only large laminae, in terms of partial ozone pressure larger than 40 nbar, were analyzed. However, as mentioned in section 2, the trends appear to be almost independent of the size of laminae.

[47] Future work will be focused on two problems: (1) to obtain information about the trends in laminae in the Southern Hemisphere and (2) to find the origin of the observed reversal of laminae trends in the mid-1990s. Task 1 is a necessary condition for fulfilling task 2 because the behavior of trends in total ozone at middle latitudes of the Northern and Southern Hemisphere differs. Therefore the trends in laminae in the Southern Hemisphere can provide some constrains for the origin/mechanism of the trend reversal. To fulfill task 2, we have to find optimal proxies, mainly dynamical proxies, which influence the behavior of laminae. Such proxies must have global influence, because the reversal of trends in the ozone laminae characteristics has been observed in the whole Northern Hemisphere poleward of about 35°N. We shall focus our effort on the positive laminae behavior, because the negative laminae behave in a similar way as for the long-term trends.

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