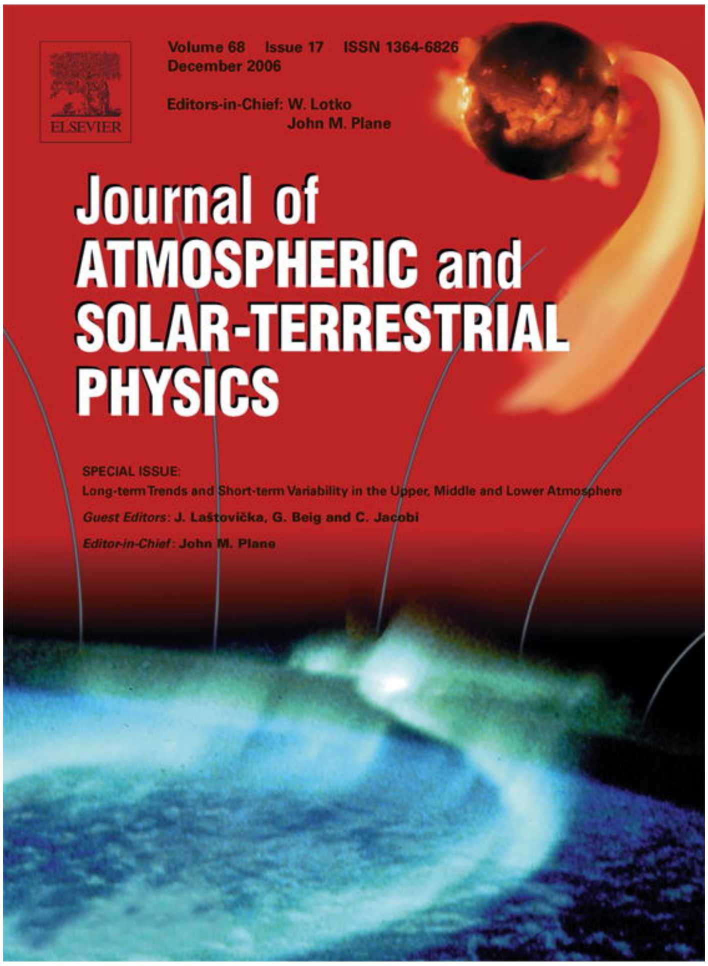
Volume 68 Issue 17 ISSN 1364-6826
December 2006
Editors-in-Chief: W. Lotko
John M. Plane
ELSEVIER
Journal of
ATMOSPHERIC and
SOLAR-TERRESTRIAL
PHYSICS
SPECIAL ISSUE:
Long-term Trends and Short-term Variability in the Upper, Middle and Lower Atmosphere
Guest Editors: J. Laštovička, G. Beig and C. Jacobi
Editor-in-Chief: John M. Plane

ELSEVIER

Journal of Atmospheric and Solar-Terrestrial Physics 68 (2006) 1962–1972

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

Ozone laminae: Comparison of the Southern and Northern Hemisphere, and tentative explanation of trends

Peter Križan, Jan Laštovička*

Institute of Atmospheric Physics, Acad. Sci. Czech Rep., Bocni II, 14131 Prague, Czech Republic

Available online 13 June 2006

Abstract

The measured ozone profiles often exhibit narrow layers of enhanced ozone concentration (positive laminae) or depleted ozone (negative laminae). Here we deal with the ozone laminae characteristics in the Southern Hemisphere in comparison with earlier studied laminae characteristics in the Northern Hemisphere. There are large differences between the ozone laminae characteristics in the Northern and Southern Hemisphere. The overall ozone content (deficit) in the positive (negative) laminae per profile and the number of laminae is much smaller in the Southern Hemisphere compared with the Northern Hemisphere. No detectable trend in these two lamina characteristics was found in the Southern Hemisphere contrary to a strong negative trend with a reversal to strong positive trend in the mid-1990s in the Northern Hemisphere. Pattern of trends in the ozone content in one lamina is quite different; no trend except for a slight negative trend in the Northern American sector. Some dynamical factors, mainly the degree of stability of the polar vortex, are suggested as contributing (or not) to the long-term behavior of lamina characteristics.

Keywords: Atmospheric ozone; Ozone laminae; Long-term trends

1. Introduction

The ozone profiles are measured with high resolution by ozonesondes. Particularly the profiles observed in late winter and early spring do not display a smooth shape below the maximum of the ozone layer. Often we may observe the occurrence of relatively narrow layers of substantially increased or depleted ozone concentration, called laminae, positive laminae for the enhanced ozone concentration and negative laminae in the latter case. The laminar structure of ozone profiles was first described by Dobson (1973). Laminae occur also in lidar and satellite ozone profiles (e.g., Appenzeller and Holton, 1997; Manney et al., 2000, 2001) but with poorer height resolution 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. The first indirect tracer lamina climatology based on satellite data was published by Appenzeller and Holton (1997).

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

*Corresponding author. Tel.: +420 2 67103055; fax: +420 2 72763745.
E-mail addresses: krizan@ufa.cas.cz (P. Križan), jla@ufa.cas.cz (J. Laštovička).

1364-6826/$ - see front matter
doi:10.1016/j.jastp.2006.04.003

frequency is larger than a factor of five with a maximum in late winter–early spring (Mlch and Laštovička, 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 Fig. 1.

There are some indications that the reversal of trends in laminae in the Northern Hemisphere in the mid-1990s might be of predominantly dynamical origin (e.g., Križan and Laštovička, 2005 and references herein). For searching of explanation of the trend reversal, particularly for possible dynamical explanation, it would be useful to determine observational constraints on the mechanism responsible for the reversal of trends in laminae. One of such constraints may be behavior of trends in laminae in the Southern Hemisphere, which is studied in the paper.

The Northern Hemisphere positive laminae seem to be predominantly formed at/near the edge of the polar vortex as filaments of air "escaping" from the vortex due to horizontal transport, at least as concerns strong laminae studied here. The horizontal transport is differential in vertical layers, which makes filaments oblique and, therefore, thin in vertical direction, thus producing relatively narrow laminae observed in vertical ozone soundings. Since the Southern Hemisphere polar vortex is much stable and the southern circulation more zonal than the northern circulation, we can expect less laminae and their partly different behavior in the Southern Hemisphere. The strong negative laminae, studied in the paper, may be the consequences of differential horizontal transport of tongues of ozone-poor air from low latitudes, or of ozone-depleted (chemical depletion) air from high latitudes. The Southern Hemisphere laminae have been much less (almost not at all) studied than the Northern Hemisphere laminae.

Section 2 deals with the lamina determination methods and briefly describes the data we have used. The differences in the ozone laminae characteristics in positive and negative laminae in the high and middle latitudes of the Southern Hemisphere in comparison with the Northern Hemisphere are treated in Section 3. The explanation of trend reversal is discussed in Section 4. Paper ends with Section 5, concluding remarks.

2. Determination of laminae and data description

Fig. 1 shows an example of the measured ozone vertical profile with positive and negative ozone

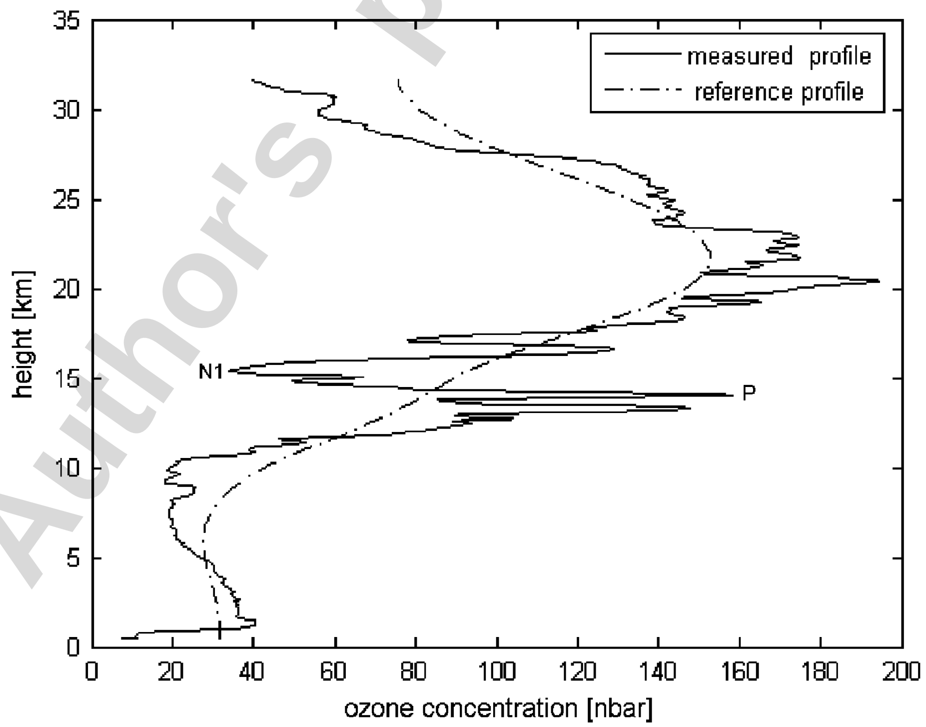

Fig. 1. The ozone profile measured at Payerne on 3 February 1997. P—positive lamina; N—negative lamina. Dashed smooth curve—reference profile.

laminae. It is evident that it is not easy to establish a reference "undisturbed" profile to evaluate the laminae with respect to. Various authors use different ways of definition and determination of laminae, which could affect results. Various ways how to determine laminae and their characteristics were carefully discussed by Križan and Laštovička (2004, 2005) and Laštovička and Križan (2006) with conclusion that various methods provide laminae with significantly different ozone content (or deficit for negative laminae), but the long-term trends in laminae appear to be robust and almost method-independent. We deal with ozone number density profiles and laminae expressed in terms of ozone partial pressure, not with mixing ratio profiles. Strong laminae defined in such a way occur in ozonesonde profiles only below the main ozone maximum, as illustrated by Fig. 1. We consider only sufficiently strong laminae, here those larger than 40 nbar, to avoid smaller undulations of the ozone profile and weaker layers caused by gravity waves (e.g., Reid et al., 1994; Pierce and Grant, 1998). More detailed description of lamina determination used here may be found, e.g., in Križan and Laštovička (2005). The lamina parameters we are working with here are the overall ozone content in positive laminae (or deficit in negative laminae) per profile and the number of laminae per profile.

The following ozonesonde data with long data series from the Southern Hemisphere are used:

High latitudes: Syowa (69°S, 39.58°E, 1970–2003), Neumayer (70.65°S, 8.26°W, 1992–2003).
Middle latitudes: Laverton (37.87°S, 144.75°E, 1983–98), Lauder (45.04°S, 169.68°E, 1986–2003).

For comparison the following Northern Hemisphere ozonesonde data are used:

High latitudes: Sodankylä (67.39°N, 26.65°E, 1989–2003), Resolute Bay (74.72°N, 94.98°W, 1970–2003).
Middle latitudes: Payerne (46.49°N, 6.57°E, 1970–2003), Sapporo (43.05°N, 141.33°E, 1970–2003)—comparable latitudes with the Southern Hemisphere stations.

Ozonesonde data were taken from the international ozone database in Toronto: http://www.msc-smc.ec.gc.ca/woudc. Only data from July–November in the Southern Hemisphere and January–May in the Northern Hemisphere (winter and spring) are considered. In summer and autumn, the number of laminae is several times lower and, therefore, trend results become less reliable.

The number of ozonesonde stations is very small in the Southern Hemisphere compared to that in the Northern Hemisphere. There are no more Southern Hemisphere stations with sufficiently long and quasi-continuous data series for trend calculations than those listed above. The list of the Northern Hemisphere stations is broader, but they all reveal very similar trends for Europe, North America, Japan and Arctic down to latitudes of about 35°N (Križan and Laštovička, 2005). Therefore, the use of the above four representative stations is sufficient for comparison.

3. Ozone laminae characteristics in the Southern Hemisphere compared with the Northern Hemisphere

Figs. 2 (4) and 3 (5) display the number of positive (negative) laminae per ozone profile at high latitudes and middle latitudes of both the hemispheres. The large difference in the number of laminae in the Southern Hemisphere versus the Northern Hemisphere, which is confirmed also by data in Table 1, is the dominant feature. Ozone laminae are much more frequent in the Northern Hemisphere than in the Southern Hemisphere. This difference maximizes at high latitudes (eight times for positive laminae in average). There are almost no negative laminae at southern high latitudes. The hemispheric difference is somewhat smaller but still large at middle latitudes, particularly for negative laminae.

The long-term behavior of the number of laminae for positive and negative laminae is similar. No detectable long-term trend in the number of laminae per profile is observed in the Southern Hemisphere. However, only strong trends in laminae could be detected due to small number of laminae in the Southern Hemisphere. Contrary to that, the long-term trends are strong and well pronounced in the Northern Hemisphere. A principal change in trend in the Northern Hemisphere is observed in the mid-1990s. The negative trend reverses to the positive trend, both being pronounced and strong. No such reversal is visible in the Southern Hemisphere. The Southern Hemisphere exhibits much less laminae than the Northern Hemisphere. Nevertheless, such strong trends with the well-pronounced trend

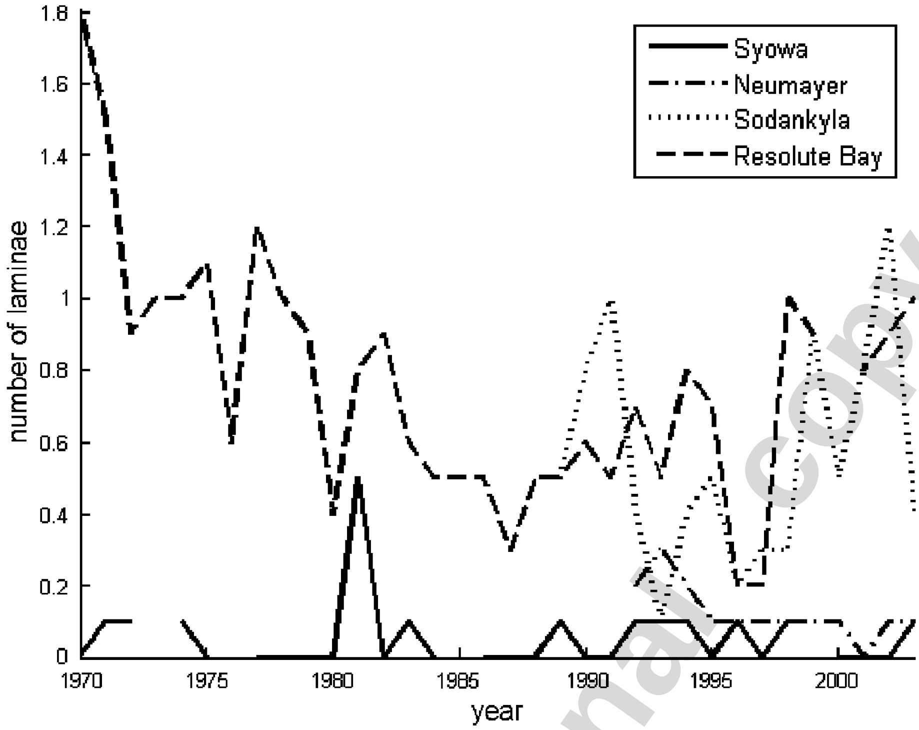

Fig. 2. The number of positive laminae per profile at high latitudes of the Southern and Northern Hemisphere.

reversal should be detectable in the Southern Hemisphere, if they exist.

The negative trends over the period 1970–95 at northern stations Resolute Bay, Payerne and Sapporo are statistically significant at the 95% level for the positive laminae and at 95% level or a little bit less for the negative laminae. The statistical significance of the northern stations positive trends over much shorter period 1996–2003 is lower due to shorter interval, but for all stations significant at least at the 90% level (except for Payerne) as calculated with routine approach. We do not want to discuss to which extent is the calculated significance based on eight-yearly data points reliable. The statistical significance for negative laminae trends is slightly lower due to smaller number of negative laminae but it is generally not less than 90%. Since there are no detectable trends at southern stations, their significance is not calculated. The statistical significance would be higher for European stations Payerne and Sodankyla if we consider the year 1993 as the turnover point, but the minimum in 1993 is very probably consequence of the Mt. Pinatubo volcanic eruption. The statistical significance was computed by a commercial MATLAB computer code that provided the statistical significance as a product of calculation of trend by the linear regression method.

Table 1 presents for each station and each year the number of ozone soundings, of positive laminae and negative laminae (only 5 months of each year are analyzed). Table 1 makes possible better estimate of reliability of the results and better interpretation of Figs. 2–7. For example, some 0.0 values in Fig. 2 for Syowa are years of no measurements and the outlier in 1981 (Syowa) is a consequence of only two measurements in that year with a lamina in one of them.

Križan and Laštovička (2005) estimated the ratio of negative to positive laminae for the Northern Hemisphere. This cannot be done for the Southern Hemisphere due to much smaller and, thus, less reliable number of laminae, but it is evident (e.g., Table 1) that more positive than negative laminae occur for strong laminae ($>$ 40 nbar) studied in the paper.

Figs. 6 and 7 show the overall ozone content in laminae per profile for positive laminae at high and middle latitudes of both hemispheres. The pattern of trends in the overall ozone content in laminae per profile is similar to that in the number of laminae per profile; a strong negative trend until the mid-1990s (a decrease by 50% over 20–25 years) and

Table 1

Year	Resolute	Sodankyla	Payerne	Sapporo	Laverton	Lauder	Neumayer	Syowa
1970	17/30/20	0	38/29/25	15/6/5	0	0	0	10/0/1
1971	19/27/13	0	44/39/25	16/10/4	0	0	0	17/2/0
1972	20/18/11	0	17/11/9	12/6/4	0	0	0	8/1/0
1973	22/24/11	0	35/14/15	11/7/5	0	0	0	0
1974	17/17/5	0	30/13/13	8/6/2	0	0	0	10/1/0
1975	23/25/17	0	31/18/14	6/5/2	0	0	0	5/0/0
1976	16/11/8	0	56/23/18	0	0	0	0	0
1977	18/22/16	0	52/36/23	0	0	0	0	2/0/0
1978	14/14/6	0	52/27/18	3/2/1	0	0	0	1/0/0
1979	17/16/9	0	99/41/33	4/3/1	0	0	0	2/0/0
1980	18/8/11	0	48/28/13	4/2/1	0	0	0	3/0/0
1981	12/9/4	0	40/21/8	3/4/1	0	0	0	2/1/0
1982	14/13/7	0	54/33/25	3/1/1	0	0	0	2/0/0
1983	15/9/15	0	43/22/14	4/1/2	0	0	0	10/1/0
1984	8/4/4	0	57/32/32	4/1/2	8/1/0	0	0	6/0/0
1985	10/5/4	0	53/43/20	4/2/1	0	0	0	0
1986	13/6/4	0	45/17/21	3/2/1	5/1/1	25/1/4	0	4/0/0
1987	23/7/9	0	49/25/21	4/1/1	6/0/0	36/6/2	0	18/0/0
1988	26/13/11	0	53/27/17	5/1/0	3/0/0	39/6/1	0	17/0/0
1989	28/16/11	22/12/8	48/8/6	4/1/0	17/2/1	34/5/2	0	12/1/0
1990	19/12/9	27/22/9	26/5/3	5/3/1	13/2/3	34/4/1	0	23/0/0
1991	20/13/18	25/26/12	48/24/25	7/2/0	0	38/13/8	0	15/0/0
1992	33/23/15	51/18/10	56/16/20	13/4/1	9/0/1	41/9/4	33/9/1	17/1/0
1993	10/5/4	36/5/2	35/5/4	15/4/0	20/0/0	35/4/2	33/10/3	28/4/0
1994	13/11/9	39/14/9	56/26/25	21/8/3	13/1/0	35/6/2	32/7/1	25/3/2
1995	20/14/9	57/26/19	64/28/10	20/6/4	18/2/2	36/12/7	41/4/1	20/1/0
1996	13/4/4	34/7/5	68/24/15	18/2/3	19/2/1	29/3/4	43/4/0	31/2/0
1997	21/5/2	65/19/13	67/36/19	20/6/1	14/1/0	35/6/3	53/6/2	39/2/1
1998	21/20/9	38/11/10	61/24/25	20/5/1	20/2/2	22/5/1	46/3/2	30/2/1
1999	20/17/10	33/29/17	67/60/28	17/4/4	0	23/6/1	46/3/2	0
2000	0	43/23/19	66/24/18	14/6/3	0	22/1/1	40/6/2	39/1/1
2001	17/13/12	24/19/15	64/50/23	19/8/3	0	23/6/1	33/1/0	32/0/0
2002	7/6/5	23/28/12	69/43/20	22/10/3	0	33/14/3	35/4/0	30/1/0
2003	20/20/9	47/18/13	65/40/28	20/8/6	0	0	51/4/0	48/4/1

then reversal to a positive trend in the Northern Hemisphere contrary to essentially no detectable trend in the Southern Hemisphere and evidently no principal reversal of trends in the mid-1990s. The same holds for negative laminae, which are not shown here. Statistical significance of the observed trends is similar to that for the number of laminae. The ozone content in laminae per profile is much larger in the Northern Hemisphere than in the Southern Hemisphere. The overall ozone content in positive laminae is remarkably larger than the overall ozone deficit in negative laminae due to remarkably larger number of positive laminae. The difference between the Southern and Northern Hemisphere is similar to that in the number of laminae.

Contrary to the large hemispheric difference for the number of laminae and the overall ozone content in laminae per profile, the ozone content (deficit) per one lamina (not shown here) appears to be quite comparable at both hemispheres. This is partly influenced by selecting only laminae larger than a fixed limit of 40 nbar. We observe weak and barely significant at the 95% level negative trend without any visible reversal for the northern high latitude station Resolute Bay (American sector). Other stations do not reveal any trend in this parameter and, therefore, also no trend reversal. Typical values of the ozone content per one positive lamina larger than 40 nbar are about 6–8 D.U., almost independent on hemisphere, latitude and time. The larger variance of values of the ozone content in one lamina in the Southern Hemisphere may be caused by much smaller number of laminae per profile and smaller number of soundings in the Southern Hemisphere (Table 1).

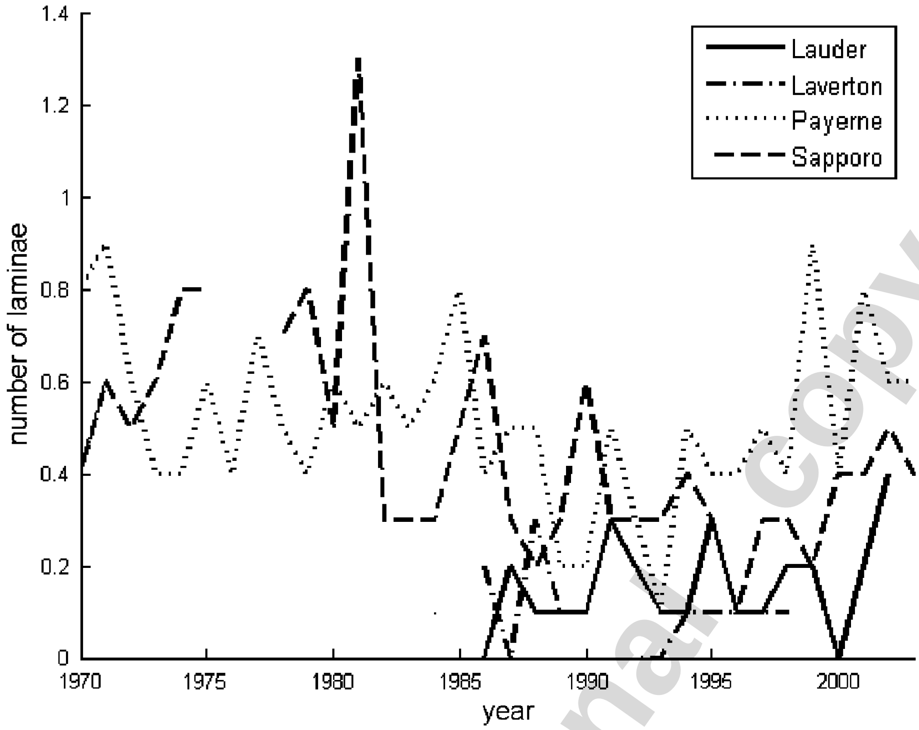

Fig. 3. The number of positive laminae per profile at middle latitudes of the Southern and Northern Hemisphere.

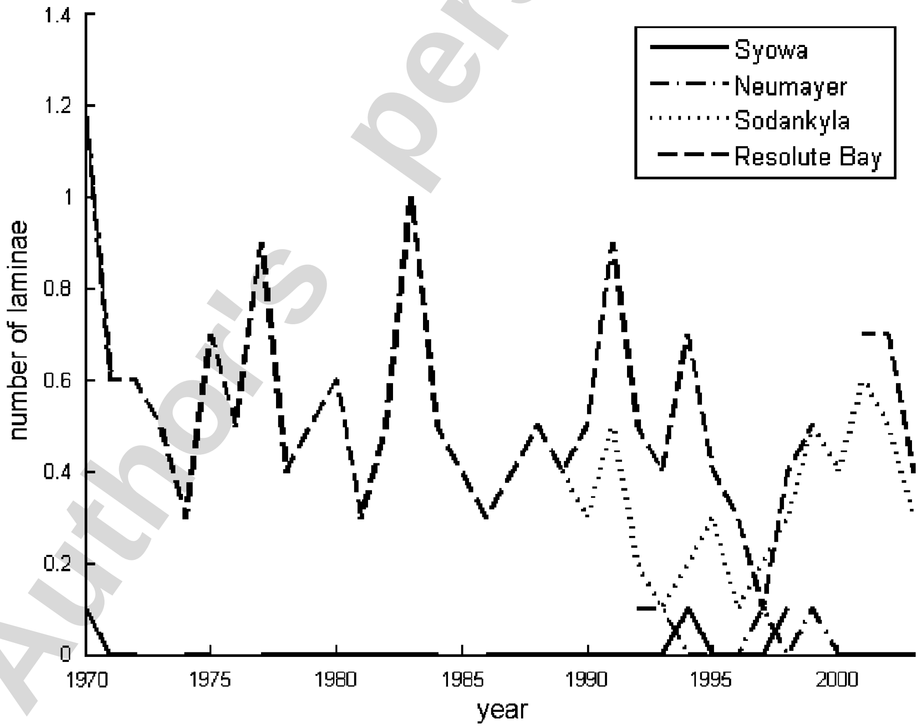

Fig. 4. The number of negative laminae per profile at high latitudes of the Southern and Northern Hemisphere.

Thus the quite different behavior of laminae in the Northern and Southern Hemisphere creates a constraint on possible mechanisms for explanation of the Northern Hemisphere laminae trends and their reversal in the mid-1990s.

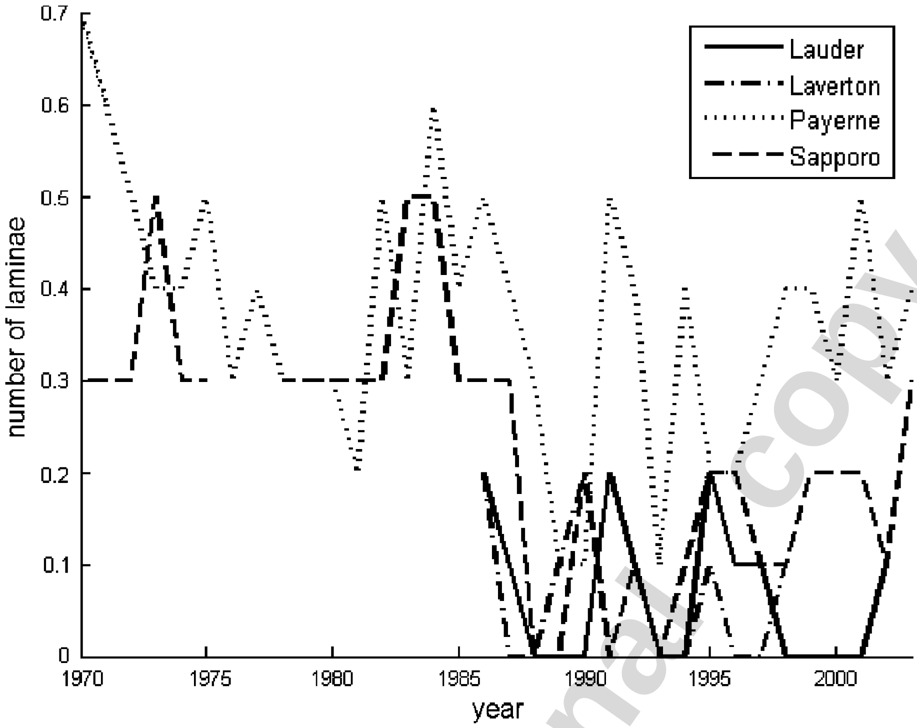

Fig. 5. The number of negative laminae per profile at middle latitudes of the Southern and Northern Hemisphere.

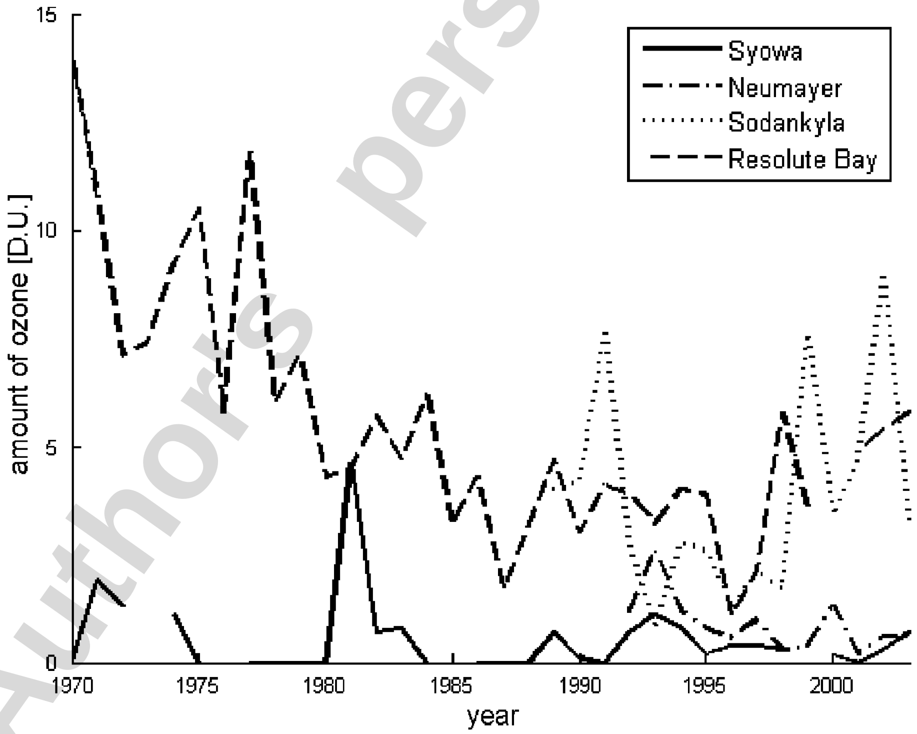

Fig. 6. The overall ozone content in positive laminae per profile at high latitudes of the Southern and Northern Hemisphere.

Our data are not from the area of expected highest lamination rate near 60°N/S (Appenzeller and Holton, 1997), but the Northern–Southern Hemisphere difference is so large that it cannot be the main factor responsible for the hemispheric difference.

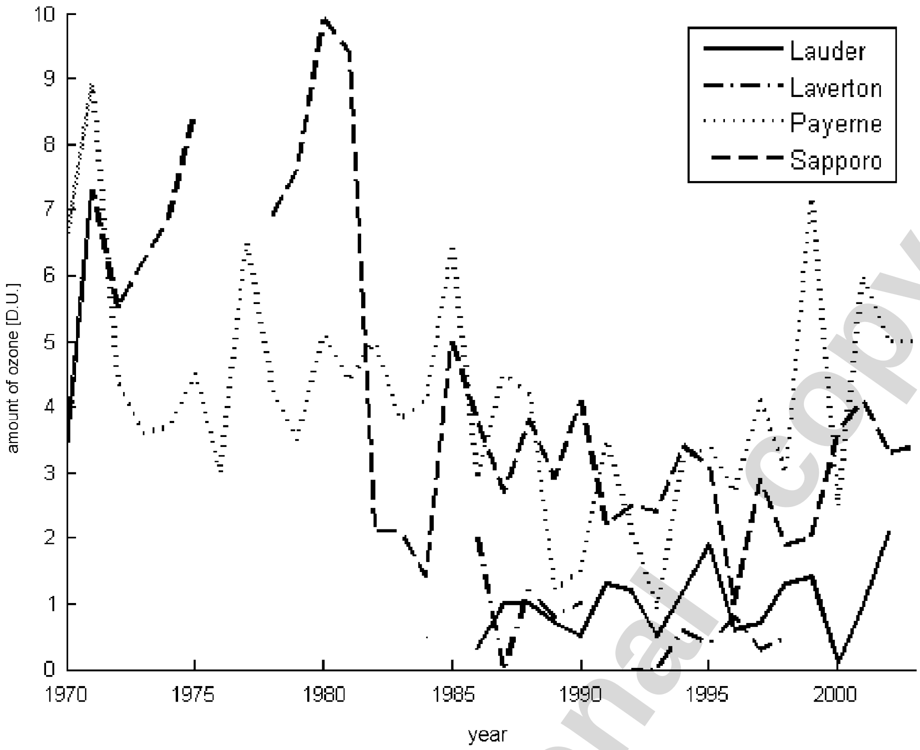

Fig. 7. The overall ozone content in positive laminae per profile at middle latitudes of the Southern and Northern Hemisphere.

4. Why the Northern Hemisphere laminae trends reversed in the mid-1990s?

Let us first look for observational constraints and other findings, which either limit possible explanations, or can serve as hints for possible explanation:

(1) The main driver of the reversal cannot be chemistry. First, it occurred too early for chemistry, because the tropospheric concentration of the effective equivalent chlorine peaked in 1993–94 (e.g., Elkins et al., 2005) and, therefore, its concentration in the lower stratosphere was still slightly rising in the time interval of the laminae trend reversal. Moreover, the strong reversal occurred only in the Northern Hemisphere, not in the Southern Hemisphere where the role of chemistry in ozone behavior is even more important than in the Northern Hemisphere.

(2) The trend in the NH midlatitude total ozone reversed in the mid-1990s, as well. 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, only a slowdown of ozone loss was reported (Malanca et al., 2005). This coincides with the trend reversal pattern in laminae.

(3) There was a tendency of the North Atlantic Oscillation (NAO) to change from the 1970s to the mid-1990s to a more negative phase, which was replaced by a tendency to a more positive phase after 1995–96, which appears to coincide with the time development of trends in the Northern Hemisphere midlatitude total ozone (Appenzeller et al., 2001) and in laminae. 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).

(4) Ozonesonde measurements of ozone profiles over Canada in 1980–2001 reveal a negative overall ozone trend in the lower stratosphere with a strong negative trend in 1980–90 but a positive trend in 1991–2001 below 63 hPa with reversal in about the mid-1990s, which is not caused by changes in the tropopause height (Tarasick et al., 2005). This is consistent with the trend reversal in laminae both in time and altitudinal range as large majority of laminae

occur below 63 hPa. Tarasick et al. (2005) suggest changes in circulation to be the main cause of the observed trend reversal. The ozone trends in the lower stratosphere over Payerne at altitudes below 20 km were found to be, to a substantial extent, of dynamical origin (Weiss et al., 2001).

All the above observational findings/constraints point to changes in atmospheric dynamics, not in chemistry, as the main driver of the observed change of trends in ozone laminae in the mid-1990s. But which changes in dynamics?

The main reason for the difference in ozone laminae characteristics between the Northern and Southern Hemisphere is expected to be different circulation at high latitudes and the much more stable southern polar vortex compared to the northern polar vortex. In the Northern Hemisphere, the variability of vortex and circulation is larger than in the Southern Hemisphere, especially in winter and early spring. During Arctic winter, the major midwinter stratospheric warmings occur and the polar vortex is in general less strong, less regular and less stable. The major warmings have not been observed at high latitudes of the Southern Hemisphere except for the year 2002. The Northern Hemisphere positive laminae seem to be predominantly formed at/near the edge of polar vortex as filaments. They are transported from the vortex boundary by vertically differential meridional wind. Balloon-borne measurements confirm well-resolved laminations near the vortex edge (Orsolini et al., 1998). When the vortex is more stable (Southern Hemisphere), the number of ozone laminae is smaller than in the case of unstable vortex (Northern Hemisphere). Ozone laminae are transported from the boundary of polar vortex to middle latitudes, but the southern circulation is more zonal than the northern circulation. These two factors can qualitatively explain much smaller number of laminae in the Southern Hemisphere.

Thus the behavior of polar winters in Arctic appears to be of primary importance for laminae in northern high and middle latitudes. How the polar winters varied during the period of laminae investigations, 1970–2003? Winters 1964/65–1971/72 were unusually warm. They were followed by a "normal period" with close to average polar stratospheric temperatures and distribution of cold and warm winters. Then a period of very cold winters occurred in the early and mid-1990s (Manney et al., 2005). The colder winter, the more stable polar vortex. This means lower release of strong laminae from the polar vortex edge area. The observed 1970–mid-1990s cooling of vortex area and related decrease of release of strong laminae is qualitatively consistent with the observed negative trend in northern laminae. On the other hand, winters 1997/98–2003/2004 were again unusually warm in the Arctic stratosphere (Manney et al., 2005). This warming results in more laminae, i.e. a positive trend in laminae as observed. Thus the general behavior of the winter Arctic polar vortex seems to be of high importance for the behavior of the Northern Hemisphere laminae.

Another parameter, which affects ozone behavior, is changes in the tropopause height. The average tropopause height above the Canadian ozonesounding stations has changed neither over the period 1980–2001, not 1990–2001, which means that trends in laminae, lower stratospheric ozone and total ozone amount, and their change in the mid-1990s, do not appear to be related to changes in the tropopause height over Canada (Tarasick et al., 2005). On the other hand, at Hohenpeissenberg the tropopause height had been slightly increasing and then since the mid-1990s has been approximately stable (Claude et al., 2004), which means that a contribution of the tropopause height variation to trends in ozone including laminae is possible but not principal in European sector.

5. Conclusions

The data of all four Southern Hemisphere ozone sounding stations at latitudes $\phi > 30°S$, which have sufficiently long data series were analyzed for the long-term trends in laminae in ozone profiles in the lower stratosphere over the period 1970–2003. The analysis was complemented by comparison with the results for four representative ozonesounding stations in the Northern Hemisphere. The analysis was made for that part of the year, when the occurrence frequency peaks, i.e. for July–November in the Southern Hemisphere and January–May in the Northern Hemisphere. The main results on the trends in the Southern Hemisphere laminae in comparison with the Northern hemisphere are as follows:

(1) The overall ozone content (deficit) in positive (negative) laminae per profile is much larger in the Northern Hemisphere than in the Southern

Hemisphere, especially at high latitudes. Laminae are much more frequent in the Northern Hemisphere.

(2) A strong negative trend in the number of ozone laminae and in the overall ozone content (deficit) in positive (negative) laminae per profile in the Northern Hemisphere reversed in the mid-1990s to a positive trend. No strong trend and no remarkable trend reversal similar to that in the Northern Hemisphere were observed in those ozone lamina characteristics in the Southern Hemisphere.

(3) There is no detectable trend in the ozone content per one lamina in both hemispheres except for Resolute Bay in the American sector, where a slight negative trend is observed. Typical value of the ozone content in lamina is 6–8 D.U.; this value is almost independent of hemisphere, latitude and time.

The other purpose of the paper is to suggest possible explanation of the observed reversal of trends in the Northern Hemisphere laminae in the mid-1990s. The results may be summarized as follows:

(1) The main driver of the trend reversal cannot be chemistry. First, it occurred too early for chemistry (impact of the Montreal Protocol with amendments on the effective equivalent stratospheric chlorine). Second, the strong reversal occurred only in the Northern Hemisphere, not in the Southern Hemisphere.

(2) The long-term behavior of the Arctic polar vortex strength and polar lower stratosphere temperatures is qualitatively consistent with the long-term trends in laminae in the Northern Hemisphere including their reversal in the mid-1990s.

(3) The NAO seems to play some role in trends in laminae. The role of tropopause height changes is rather minor, if any.

Acknowledgments

This work has been supported by the European Commission under Contract no. EVK2-CT-2001-00133, and by the Academy of Sciences of the Czech Republic under Project no. AVOZ30420517.

References

Appenzeller, C., Holton, J.R., 1997. Tracer lamination in the stratosphere: a global climatology. Journal of Geophysical Research 102, 13555–13569.

Appenzeller, C., Weiss, A.K., Staehelin, J., 2001. Ozonschwund und Klimaschaukel in Europa. Spektr. Wissenschaft (March), 12–14 (in German).

Claude, H., Köhler, U., Steinbrecht, W., 2004. Evaluation of ozone and temperature trends at Hohenpeissenberg (Germany). In: Zerefos, C.S. (Ed.), Proceedings of the XX Quadrennial Ozone Symposium. University of Athens, Athens, pp. 314–315.

Dobson, G.M.B., 1973. The laminated structure of the ozone in the atmosphere. Quarterly Journal of the Royal Meteorological Society 99, 599–607.

Elkins, J.W., Moore, F.L., Dutton, G.S., Hurst, D.F., Ray, E.A., Montzka, S.A., Butler, J.H., Fahey, D.W., Hall, B.H., Atlas, E., Wofsy, S.C., Romashkin, P.A., 2005. Trace gas trends in the stratosphere. Paper A53B-05, Spring AGU Meeting, abstracts on CD-ROM, New Orleans.

Fioletov, V.E., 2004. Total ozone variations over midlatitudes and on the global scale. In: Zerefos, C.S. (Ed.), Proceedings of the XX Quadrennial Ozone Symposium. University of Athens, Athens, pp. 25–26.

Fioletov, V.E., Bodeker, G.E., Miller, A.J., McPeters, R.D., Stolarski, R., 2002. Global and zonal total ozone variations estimated from ground based and satellite measurements. Journal of Geophysical Research 107, 4647.

Hudson, R.D., Frolov, A.D., Andrade, M.F., Follette, M.B., 2003. The total ozone field separated into meteorological regimes. Part I. Defining the regimes. Journal of Atmospheric Sciences 60, 1664–1677.

Križan, P., Laštovička, J., 2004. Definition and determination of ozone laminae in ozone profiles. Studia Geophysica et Geodaetica 48, 777–789.

Križan, P., Laštovička, J., 2005. Trends in positive and negative ozone laminae in the Northern Hemisphere. Journal of Geophysical Research 110, D10107, doi:10.1029/2004JD005477.

Laštovička, J., Križan, P., 2006. Trends in laminae in ozone profiles in relation to trends in some other middle atmospheric parameters. Physics and Chemistry of the Earth 31, 46–53.

Malanca, F.E., Canziani, P.O., Argüello, G.A., 2005. Trends evolution of ozone between 1980 and 2000 at midlatitudes over the Southern Hemisphere: decadal differences in trends. Journal of Geophysical Research 110 (D5), D05102.

Manney, G.L., Michelsen, H.A., Irion, F.W., Toon, G.C., Gunson, M.R., Roche, A.E., 2000. Lamination and polar vortex development in fall from ATMOS long-lived trace gases observed during November 1994. Journal of Geophysical Research 105, 29023–29038.

Manney, G.L., Michelson, H.A., Bevilacqua, R.M., Gunson, M.R., Irion, F.W., Livesey, N.J., Oberheide, J., Riese, M., Russell III, J.M., Toon, G.C., Zawodny, J.M., 2001. Comparison of satellite ozone observations in coincident air masses in early November 1994. Journal of Geophysical Research 106, 9923–9943.

Manney, G.L., Krüger, K., Sabutis, J.L., Sena, S.A., Rawson, S., 2005. The remarkable 2003–2004 winter and other recent warm winters in the Arctic stratosphere since the late 1990s. Journal of Geophysical Research 110, D04107.

Mlch, P., Laštovička, J., 1996. Analysis of laminated structure in ozone vertical profiles in Central Europe. Annales Geophysicae 14, 744–752.

Orsolini, Y., Manney, G.L., Engel, A., Ovarlez, J., Claud, Ch., Coy, L., 1998. Layering in stratospheric profiles of long-lived trace species: balloon-borne observations and modeling. Journal of Geophysical Research 103, 5815–5825.

Pierce, R.B., Grant, W.B., 1998. Seasonal evolution of Rossby and gravity wave induced laminae in ozone data obtained at Wallops Island, Virginia. Geophysical Research Letters 25, 1859–1862.

Reid, S.J., Vaughan, G., 1991. Lamination in ozone profiles in the lower stratosphere. Quarterly Journal of the Royal Meteorological Society 117, 825–844.

Reid, S.J., Vaughan, G., Mitchell, N.J., Prichard, I.T., Smith, H.J., Jorgensen, T.S., Varotsos, C., de Backer, H., 1994. Distribution of ozone laminae during EASOE and the possible influence of inertia-gravity waves. Geophysical Research Letters 21, 1479–1482.

Staehelin, J., Mäder, J., Weiss, A.K., Appenzeller, C., 2002. Long-term ozone trends in Northern mid-latitudes with special emphasis on the contribution of changes in dynamics. Physics and Chemistry of the Earth 27 (6–8), 461–469.

Tarasick, D.W., Fioletov, V.E., Wardle, D.I., Kerr, J.B., Davies, J., 2005. Changes in the vertical distribution of ozone over Canada from ozonesondes: 1980–2001. Journal of Geophysical Research 110 (D2), D02304.

Weiss, A., Staehelin, J., Appenzeller, C., Harris, N.R.P., 2001. Chemical and dynamical contributions to ozone profile trends at the Payerne (Switzerland) balloon soundings. Journal of Geophysical Research 106, 22685–22694.