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GENERATION OF LAYERING IN THE UPPER ARCTIC TROPOSPHERE AWAY FROM THE JET STREAM

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Abstract. Ozone sounding databases for two stations, Sodankylä (67°N, 27°E) and Ny-Ålesund (79°N, 12°E) were used in order to investigate the generation of layering in the upper and middle troposphere of the Arctic. We concentrated on dry, ozone-rich and stable layers observed below the thermal tropopause under light wind conditions. Selection criteria for ozone, humidity and stability anomalies of the tropopause fold detection algorithm were used here to pick out for detailed studies the most pronounced examples of laminae. We found that layers could be classified in two groups. Laminae of the first group were observed equatorward of the jet stream and those of second group were observed poleward of the jet. Back trajectory analyses showed that these layers originated in the vicinity of the polar jet stream. We suppose that laminae-like structures in the troposphere were caused, in both groups, by equatorward (poleward) advection of the stratospheric (tropospheric) air together with differential vertical shear.

Introduction

It is widely recognised that stratosphere-troposphere exchange (STE) in the extratropics occurs mainly through mesoscale, temporarily isolated processes such as tropopause fold development. (Shapiro, 1980). Since the upper troposphere and the lower stratosphere differ significantly in their chemical composition and dynamical properties, STE processes can considerably modify both regions. The extreme dryness, significantly larger ozone concentration and higher potential vorticity (PV) values of stratospheric air provide the elements for distinguishing it from tropospheric air using the vertical profiles of one or all of these parameters. Layering of stratospheric air within the middle and upper troposphere is usually observed in the vicinity of a jet stream (Shapiro, 1980). This phenomenon is known as a tropopause fold. It should be mentioned here that a tropopause fold on its own does not lead to irreversible mass transfer between stratosphere and troposphere, and the main part of the stratospheric air then returns to the stratosphere. There are evidences that not all layers near the tropopause could be referred to as a tropopause fold (Zachariasse et al., 2000), however this phenomenon was not studied enough. This is especially true for the Arctic, since only a few observational studies connected to STE have been performed yet (e.g. Shapiro et al., 1986). The main goal of this investigation is to establish the connection between the layering of stratospheric air in the upper and middle troposphere away from the jet stream and the dynamical processes involved. In this paper, both case studies and a statistical approach are presented to describe layering generation in the Arctic troposphere.

Ozone sounding data sets for period since 1989 from two Arctic stations Sodankylä, (67.4°N, 26.7°E) and Ny-Ålesund (78.9°N, 12.0°E) were used in this investigation. Fields of meteorological variables have been retrieved from the European Centre for Medium Range Weather Forecasts (ECMWF) T213-analyses. Isentropic trajectories of air particles were constructed using HYSPLIT 4 (HYbrid Single-Particle Lagrangian Integrated Trajectory Model, 1997; web address: http://www.arl.noaa.gov/ready/hysplit4.html, NOAA Air Resources Laboratory, Silver Spring, MD).

To pick out layering events from the complete ozonesonde data sets we used the automatic algorithm developed by Van Haver et al. (1996) for tropopause fold detection. This algorithm allows the detection of a stratospheric intrusion from profiles of ozone, temperature, pressure, humidity and wind. In order to exclude the tropopause fold events, all cases observed in the jet stream were rejected.

Generation of layering resulting from an equatorward Rossby wave breaking event

We start with a case observed on November 10, 1993 at Sodankylä. Balloon-borne observations made at 12 UTC on that day are presented in Fig. 1a. An ozone maximum of 115 ppb is located between 7 and 9 km, corresponding to a potential temperature range of 305-320K. Geopotential heights and wind vectors on the 300 hPa pressure surface for November 10 are depicted in Fig. 1b. The jet stream is seen to propagate far northwards, with the station positioned on its equatorward side. Using succesive isentropic PV maps and back trajectories (not shown) we connected ozone layer observed at 8 km with a passage of a stratospheric streamer which developed from a tropopause fold over North Atlantic three days before. The evolution of the streamer shows all the features of the equatorward Rossby wave breaking (Appenzeller et. al, 1996). We refer to this case as an example of layering resulting from equatorward

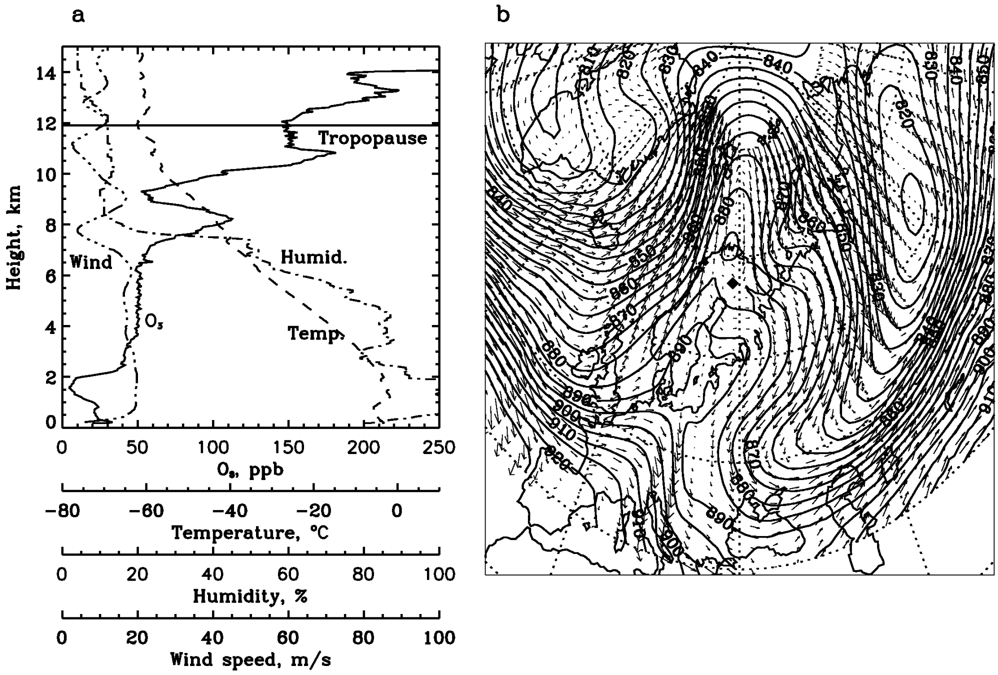

Figure 1. (a) Sodankylä profiles of ozone, relative humidity, temperature and wind speed at 12 UTC on November 10, 1993 and (b) 300 hPa geopotential height (decameters) at 12 UTC on November 10, 1993. Superimposed are wind vectors. Sodankylä is marked with a diamond.

breaking, because observation of the layering was made southward of the jet stream in the anticyclonic large-scale flow shear. Such a far northward penetration of the jet stream is not part of the day-to day weather system development in high latitudes; Sodankylä is usually located north of the polar front. Therefore, it would be expected that poleward Rossby wave breaking plays a more important role in layering generation in the Arctic. We now proceed with a case study of layering observed on the northward side of the jet stream.

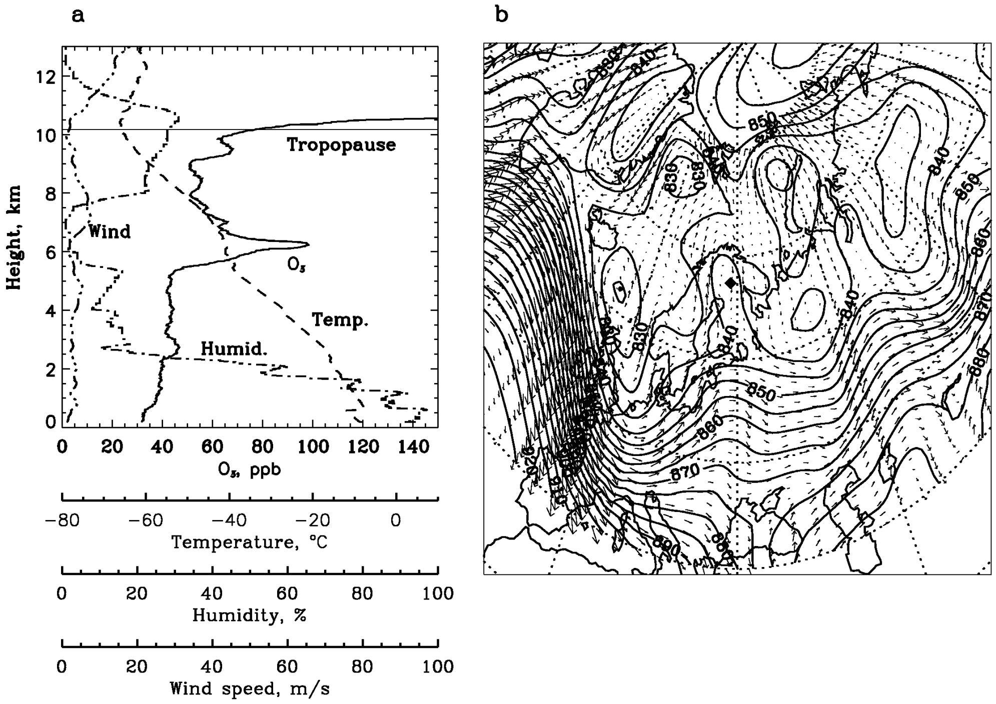

Figure 2. Same as in Fig.1 but at 12 UTC on February 16, 2000.

Generation of layering resulted from a poleward Rossby wave breaking event

The event presented here was observed on two successive ozone soundings on February 16-17, 2000 at Sodankylä. The sounding performed at 12 UTC on February 16 revealed a dry, stable and ozone-rich layer between 5.5-6.6 km with maximum ozone of about 100 ppb at 6.2 km (Fig. 2a). This layer appeared on the sounding at 12 UTC on the following day (not shown) between 6.1-6.6 km with maximum ozone of about 90 ppb at 6.4 km. Such light winds observed at the station are in good agreement with the ECMWF wind and geopotential heights analysis (Fig. 2b). From this Figure it is seen that the jet stream on the 300 hPa surface was positioned far south of the station at 12 UTC on February 16.

Investigation of ECMWF isentropic PV charts for the 295 K surface, which corresponds to ozone layer at about 6 km, has shown that stratospheric air passed over the station on February 16-18. According to trajectory analysis, this air originated from tropopause fold developed over Greenland on February 14. Consider now the isentropic level of 310 K, which is higher than the height of the ozone-rich layer but below the thermal tropopause positioned over Sodankylä at the 317 K level. Figure 3a shows the PV distribution on the 310 K level for 12 UTC on February 16. The most remarkable feature is a thin elongated tropospheric streamer stretching from the European part of Russia to Northern Scandinavia representing a poleward Rossby wave breaking. A bulb of tropospheric air at the tip of the streamer is located just above the station. The line on Fig. 3a marks the direction of the cross-section of PV (Fig.3b). It can be seen that the tropospheric air is located above the stratospheric intrusion. The PV distribution above the station is in good agreement with the ozone vertical profile presented in Fig.2a. High PV values are found in the ozone-rich layer on the 295 K level, while the low PV layer above the stratospheric intrusion corresponds to tropospheric values of ozone. As in the previous example, we conclude that the generation of layering in this case resulted from shear-induced differential horizontal advection. Air from the ozone-rich layer at the 295 K level was advected from the Arctic stratosphere, while air within the ozone minimum at the 310 K level originated from the mid-latitude troposphere. However, in this case it was a mid-latitude tropospheric streamer that propagated north of the jet stream.

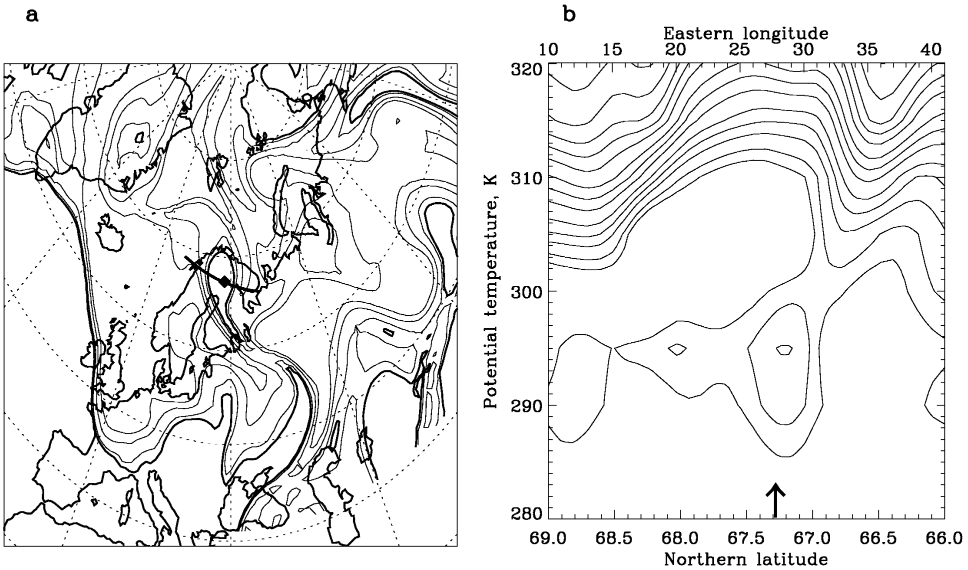

Figure 3. (a) PV chart for 310 K at 12 UTC on February 16. Sodankylä is marked with a diamond. Only PV>1.6 PVU is coloured (b) Cross-section of PV along the black line from (a) across the tropospheric filament. The station is marked with an arrow.

Statistics of layering observation in troposphere

We now consider the statistics of layers of stratospheric origin in the upper and middle troposphere obtained from Sodankylä and Ny-Ålesund data sets over the period 1989-2000. We used the criteria for stability, ozone and humidity described by Van Haver et al. (1996) in order to pick out all cases when stratospheric layers were observed in the troposphere. All the tropopause fold cases were rejected from the final statistics. The remaining cases were regarded as layers of stratospheric air in the troposphere resulting from the shear-induced differential horizontal advection or, shortly, filaments. It turned out that only 2% of all observations for Sodankylä and 3% for Ny-Ålesund fitted the criteria. Analysis of the synoptic situations as well as the isentropic PV charts for the cases showed that only a minor fraction of them could be attributed to equatorward Rossby wave breaking. A large case-to-case variability in the synoptic situations was observed for the second group of stratospheric laminae that were detected north of the jet stream. Nevertheless, in about half of all the cases, streamers of tropospheric air were found in the vicinity of the stations on isentropic surfaces just above the stratospheric layers detected. It should be kept in mind that the criteria used in our investigation were developed for tropopause fold detection. Stratospheric air injected within a tropopause fold into the troposphere interacts with tropospheric air for a shorter time than the aged layers investigated here. A different frequency of the filaments would be obtained if we were to take into account the fact that, during the advection following the initialization of the intrusion, the air parcels could have lost some of their stratospheric characteristics through diabatic processes. Taking into account the model results of Forster et al. (2000) and assuming an exponential rate of decay we relaxed our criteria for stability, ozone and humidity by 30 % each. These modifications in the criteria resulted in an increase in the fraction of filaments to 6% for Sodankylä and to 7% for Ny-Ålesund. Presented statistical results depend on criteria used for their derivation, and so should be taken with some care. For example, relaxing criteria for stability, ozone and humidity by 50% each would result in an increase in the fraction of filaments to 8% for Sodankylä and to 9% for Ny-Ålesund, whereas relaxing by only 10% would result in fraction of about 3% for both stations. More important is to stress that, according to our results, laminae in the mid- and upper troposphere are common in the Arctic. Their occurrence is not confined to the Arctic jet streams, which were earlier investigated by Shapiro et. al, (1986). Rather, they are ubiquitous elsewhere because of quasi-horizontal transport due to the breaking of Rossby-waves.

Conclusions

Stratospheric laminae in the troposphere are of great interest in stratosphere-troposphere exchange. This paper presents detailed study of stratospheric layers observed in the Arctic troposphere. Since layering near the Arctic jet stream associated with vertical tilting of the stratospheric air in the tropopause fold has been studied before (Shapiro et. al., 1986), we concentrated here on the layers resulted from horizontal transport away from the jet stream, which we refer to as filaments. It is known that shear-induced differential advection can cause tracer surfaces to stretch, leading to quasi-horizontal laminae-like tracer structures (see Appenzeller and Holton, 1997, Figure 1). The formation of both stratospheric and tropospheric streamers and their propagation that can be seen on isentropic PV charts, represent an example of shear-induced differential advection. Differential vertical shear at the streamer boundaries converts horizontal ozone gradient into vertical one, which is observed in the vertical soundings as a laminated structure.

The importance of the streamers as STE agents was discussed, in detail, by Appenzeller et al (1996). Break up of the streamer into separate vortices on the isentropic surface points to the irreversibility of the process. Horizontal stretching and lamination, studied in the present paper, substantially enhance the potential for the mixing due to an increase of the surface area of the intrusion. In general, assuming the lifetime of the filaments of 3 days, we found signs of stratospheric intrusions away from the jet stream in about 6-7% of all soundings at both stations in the period 1989-2000. These estimations suffer, to some extent, from uncertainties in the quantitative definition of filaments. Nevertheless, we believe that layering in the upper troposphere generated by Rossby wave breaking, represents an important mechanism in stratosphere-troposphere exchange in the Arctic.

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