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Letter to the Editor

Seasonal variations and vertical movement of the tropopause in the UTLS region

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Abstract. Based on the tracking of the movement of the tropopause over the whole year, the extent/depth of stratosphere-troposphere exchange (STE) events and their seasonal variations is investigated. It is found that a stratospheric signature can be observed at pressures as high as 400 hPa in a hemisphere during its winter to spring period, while a tropospheric signature can be observed at pressures as low as 190 hPa during the hemispheric summer to autumn months. The major implication for such a pronounced vertical movement is that the downward penetration of air from the stratosphere is likely to deposit elevated levels of O_3 into the upper troposphere. Though the analysis at 250 hPa reveals that the values of the stratosphere-troposphere index are similar all year round, a result which is consistent with other studies, it is found that an intrusion from the stratosphere to the troposphere is more likely to occur during the hemispheric winter to spring period than other seasons.

Key words. Atmospheric composition and structure (pressure, density, and temperature; troposphere–composition and chemistry)

1 Introduction

Tropospheric O_3 is recognized as one of the most important greenhouse gases, along with CO_2, CH_4, and N_2O (Johnson et al., 1999). Hence, it is very important to understand the processes which govern levels of O_3 in the troposphere (e.g. Lelieveld and Dentener, 2000), especially under the context of future climate change in the stratosphere and in the troposphere, and the prospect of an increasing trend in anthropogenic and pyrogenic emissions of O_3 producing precursors, such as NO_x, CO, and hydrocarbons, over the next century.

Essentially, there are two processes which can give rise to elevated ozone in the remote troposphere. First, where transport of O_3 from the stratosphere to the troposphere is the dominating source of O_3 in the troposphere. Second, where tropospheric O_3 is produced in situ via the photoxidation of volatile organic compounds in the presence of NO_x (e.g. see Monks, 2000, and references therein). The quest to understand the variety of sources and their impact on tropospheric O_3 is highlighted by the need to find a consistent explanation of the observed spring O_3 maximum (Monks, 2000).

Transport of O_3 from the stratosphere to the troposphere occurs following air exchange in the lower stratosphere and upper troposphere (e.g. Murphy and Fahey, 1994), and some studies have suggested that STE might be the main contributing factor to the spring ozone maximum (e.g. see reviews in Monks, 2000). Since no preferred occurrence of STE events has been shown in spring compared with any other season, Monks (2000) argued that if the STE process is the main contributing factor for the spring ozone maximum, then it must be the extent or depth associated with the STE events instead of their frequency that would contribute to the ozone maximum.

In light of this insightful observation, the purpose of this paper is to examine the extent or depth of STE events during the year following the seasonal movement of the tropopause. A brief description of the experimental design is described in the next section, followed by a discussion of the results.

2 Tracking the tropopause

A detailed description of the formulation and evaluation of the model used in this study can be found in Wang et al. (2001a, b). In this study, the model uses analyzed winds from the European Center for Medium Range Weather Forecasts (ECMWF), and it contains 19 vertical layers which extend from the surface to about 10 hPa. The definition of the tropopause is taken as: (1) the model PV is 1.6 PVU (1 PVU=10^{-6} m^2 Ks^{-1}kg^{-1}), for latitudes pole-ward 25°, (2) the potential temperature is 380 K, for latitudes between 25° N and 25° S (Hoskins, 1991).

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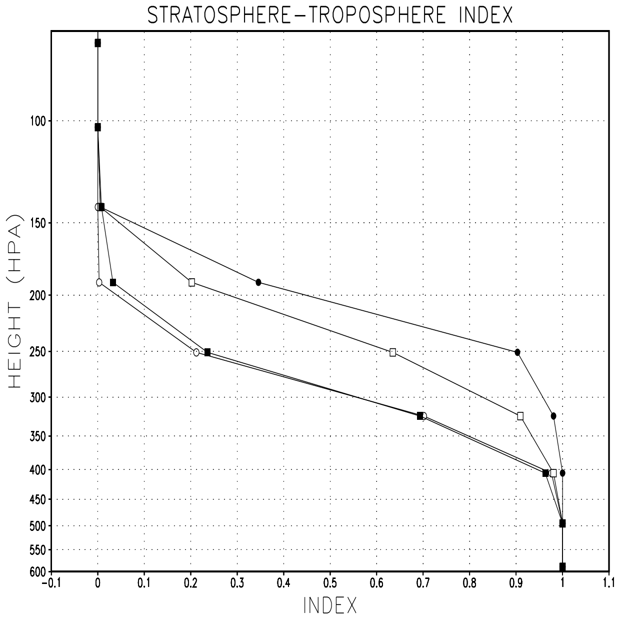

Fig. 1. Seasonal mean vertical index profiles of the stratosphere (denoted as 0), troposphere (denoted as 1), and the transient movement of the tropopause in the UTLS region (denoted as values between 0 and 1) for the NH spring (open circles), summer (solid circles), autumn (open squares), and winter (solid squares) calculated at a location in the NH (40° N, 105° W).

During the model integration, each model box below the tropopause is said to be in the troposphere and is assigned a number 1, while the model box above the tropopause is said to be in the stratosphere and is assigned a number 0. Hence, there is a time-varying distribution of these 3-D 0s and 1s in the upper troposphere and lower stratosphere (UTLS), according to the wave activities in the UTLS region (e.g. Holton et al., 1995, and references therein). A model box always has a value of 1/0 if it stays permanently in the troposphere/stratosphere. However, if a model box stays in the UTLS region, it is exposed to sharp transitions, as air from either the lower stratosphere or upper troposphere dominates; hence, its assigned value will change swiftly between 1 and 0. Notice here that the boxes stand still and the air moves. The frequency of the switch between 1 and 0 depends entirely on the STE frequency (Elbern et al., 1998), while the depth (altitude) where a box with 1 or with 0 can reach depends entirely on the strength and maintenance of the wave instability in the UTLS region. Hence, when a time average of these 3-D model boxes is taken, the distribution of boxes with values which vary between 0 and 1 is clearly seen to appear in the UTLS region.

3 Results

Figure 1 shows the seasonal mean vertical index profiles of the stratosphere (denoted as 0), troposphere (denoted as 1), and the transient movement of the tropopause in the UTLS region calculated at a location in the NH (40° N, 105° W). While the model boxes remain permanently in the stratosphere and troposphere for altitudes above 150 hPa and below 500 hPa, respectively, variations in the index values between 0 and 1 characterize the seasonal movement of the tropopause.

For example, the box at 250 hPa has an index value of 0.2 during winter to spring. This indicates that this model box experiences stratospheric air 80% of the time and tropospheric air only 20% of the time during this period. The index value at this location increases to 0.9 in summer, indicating a complete reversal, where it now experiences tropospheric air 90% of the time and only 10% stratospheric air. Hence, the air with stratospheric/tropospheric characteristics prevails in the UTLS region during the winter/summer period. Intrusion of the tropospheric/stratospheric air into the high/low altitudes is seen as contours with values between 0 and 1, between 150 hPa and 500 hPa. Processes of this kind are often followed by the exchange of the air between the troposphere and the stratosphere (e.g. Vaughan et al., 1994; Holton et al., 1995; Bethan et al., 1996).

Since there is a clear seasonal variation of the stratosphere-troposphere index in the UTLS region, as shown in Fig. 1, an analysis, such as taking a space-time cross section along a longitudinal circle at a specified latitude as a function of altitudes and time, can indicate the temporal and spatial variations of the tropopause annually. Figure 2 shows such analyses (Hovmöller diagrams) for the SH at 45° S. Notice that the light shading in Fig. 2 indicates the influence of the stratosphere, while the dark shading indicates the influence of the troposphere.

At a high altitude of 190 hPa (Fig. 2a), the model is dominated by the stratospheric influence during the SH winter to spring period. Some minor tropospheric penetrations can be seen during the SH summer to autumn period. On the contrary, at the lowest altitude of 450 hPa (Fig. 2d), the model is completely dominated by the troposphere, except for some period of time when patches of stratospheric influence appear during the SH winter to spring period. For the altitudes between 320 hPa (Fig. 2c) and 250 hPa (Figure 2b), stratospheric influence has become more prominent with increasing height during the SH early winter to early spring period, while the tropospheric influence gradually fades away with increasing altitude during the SH summer to autumn period.

Hence, a stratospheric perturbation can penetrate as far down as 400 hPa in the SH during its winter to spring period, while tropospheric perturbation can extend up to 190 hPa during the SH summer to autumn months. The downward deep penetration from stratosphere into the troposphere is likely to deposit elevated levels of O_3 in the upper troposphere. Notice that the analysis at 250 hPa reveals that the distribution of the stratosphere-troposphere index is quite similar year-round. This indicates that there is no preferred season of tropopause excursions, a result which is consistent with other studies (see a review by Monks, 2000). However, the significant point is that stratospheric air is more likely to penetrate to low altitude during the SH winter to spring period than during other seasons.

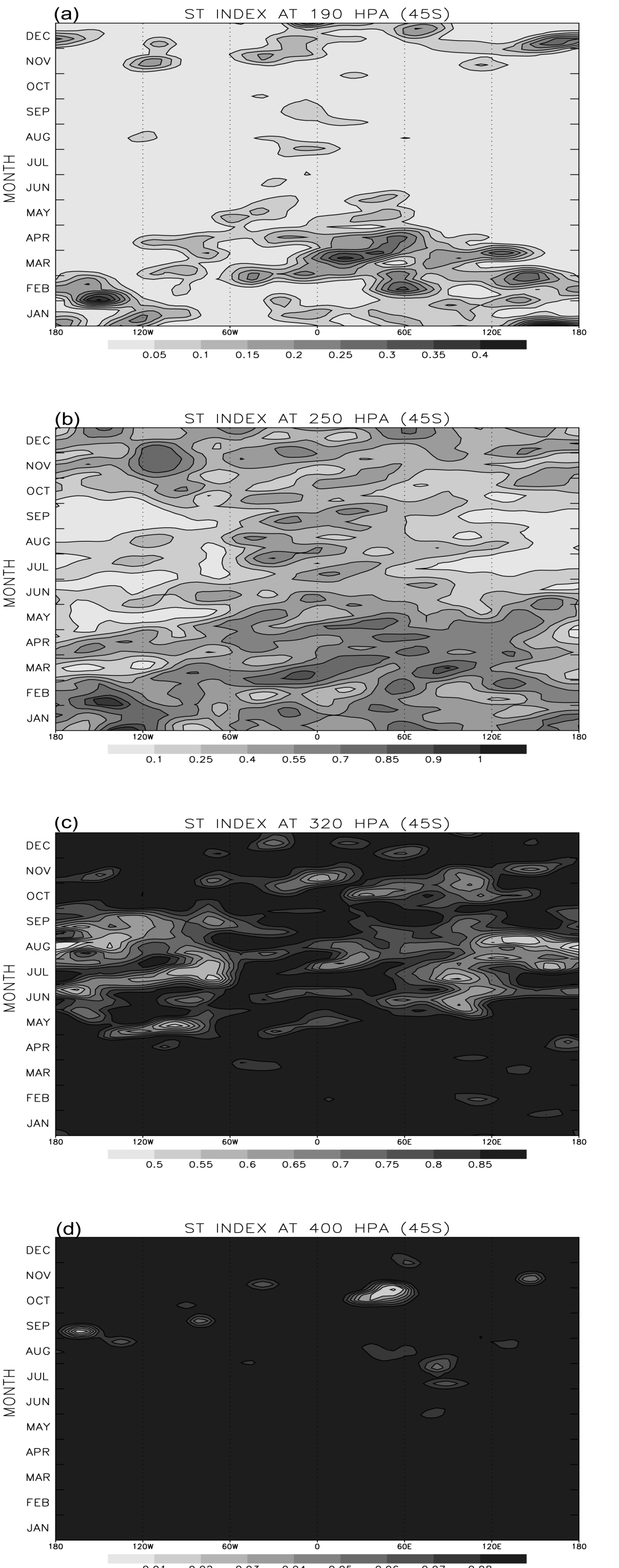

Fig. 2. Hovmöller diagrams of the distribution of the stratosphere-troposphere index along the 45° S latitude at **(a)** 190 hPa, **(b)** 250 hPa, **(c)** 320 hPa, and **(d)** 400 hPa surfaces.

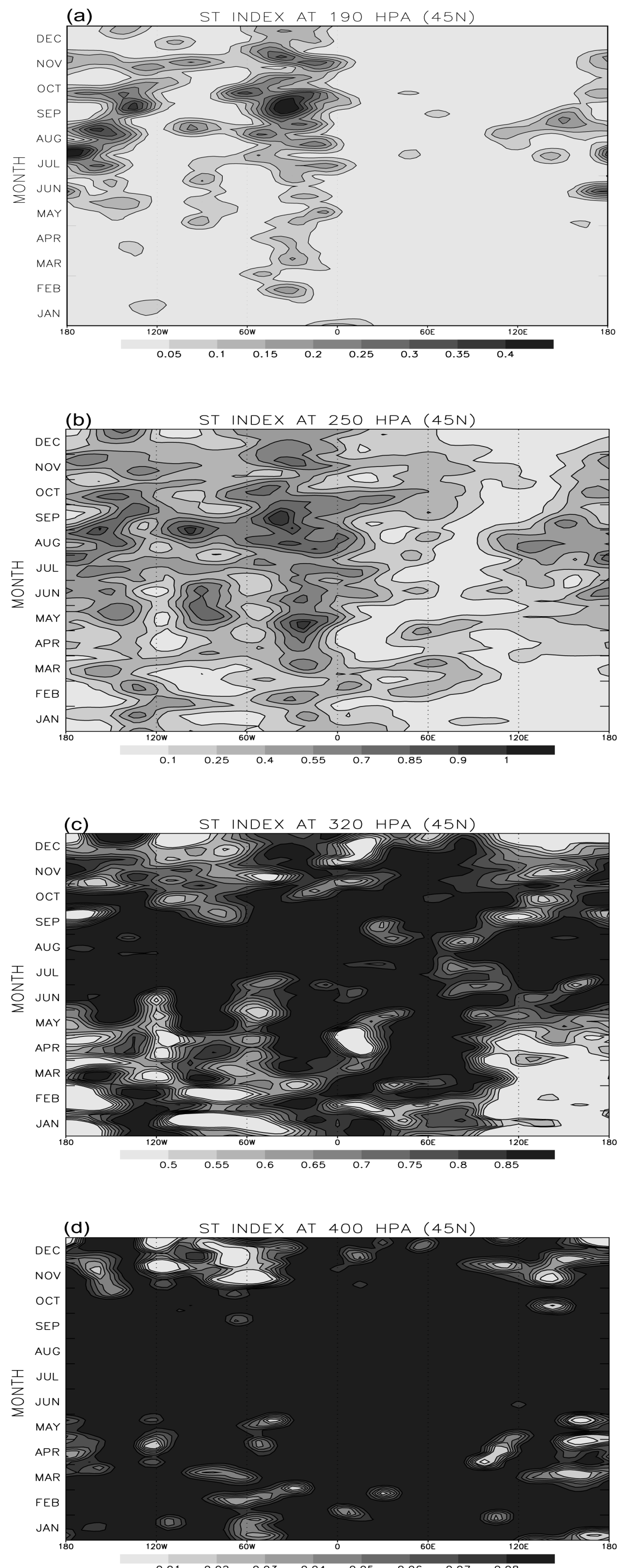

Fig. 3. The same as in Fig. 2 but for latitude at 45° N.

Figure 3 shows a similar analysis but for the NH at 45° N. Identifiable stratospheric air can be seen as low as 400 hPa during the NH winter to spring period, while tropospheric air can appear as high as 190 hPa during the NH summer to autumn months. Distinctive stratospheric influences (with the stratosphere-troposphere index less than 0.5) prevail during the NH winter to spring months.

Notice the distinctive interhemispheric asymmetry patterns, as shown in the distribution of the stratosphere-troposphere index at 320 hPa between the NH and the SH. The most pronounced downward influence from the stratosphere occurs during the NH winter to spring period (Fig. 3c), similar to the SH (Fig. 2c). However, the stratosphere-troposphere index at 320 hPa is generally smaller in the NH during winter to spring than in the SH, suggesting that the stratospheric influence is more pronounced.

4 Summary

Based on the tracking of the tropopause movement over the whole year, the extent or depth of the STE events and their seasonal variations have been investigated. We have found that the stratospheric influence can penetrate as far down as 400 hPa in a hemisphere during its winter to spring period, while the tropospheric influence can extend as high up as 190 hPa during the hemispheric summer to autumn months. The implication for this significant vertical movement is that the downward deep penetration from stratosphere is likely to deposit elevated O_3 with stratospheric origin in the upper troposphere. Though the analysis at 250 hPa shows similar occurrences in the values of the stratosphere-troposphere index year-round, a result which is consistent with other studies, we found that air coming down from the stratosphere to the troposphere is more likely to take place during the hemispheric winter to spring period than during other seasons.

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