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ON THE TRANSPORT OF TRACE GASES BY EXTRA-TROPICAL CYCLONES

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ABSTRACT

Extratropical cyclones are able to transport trace gases through the whole troposphere and lower stratosphere. At mid-latitudes most of the ozone transport from the lower stratosphere down into the troposphere is accomplished by depressions. The changing the total ozone contents, associated with the variable tropopause heights, are shown to be clearly visible in satellite ozone data.

1. INTRODUCTION

The transport of trace gases in the atmosphere takes place on different spatial and time scales. It ranges from small scale transport by turbulent diffusion to large scale organised transport in the migrating cyclones and baroclinic waves. At midlatitudes one of the most important contributors to transport are depressions. Large cyclones extends from the surface upto the lower stratosphere. Cyclones are effective and rapid both for vertical and horizontal transport. The outer scales are thousands of kilometers while the inner scales go down to hunderds of meters in the instabilities in the depression. Moreover, the vertical transport is largest in the small horizontal scales.

In this paper an analytical model of a cyclone (Heijboer and Kelder, 1991) is used to get an impression of the exchange between the stratosphere and troposphere and to understand the corresponding changes of the tropopause height.

The exchange between the troposphere and the stratosphere takes place in the tropopause foldings which are partly irreversible. The tropopause is pushed up ahead of the depression and torn down behind it. This causes high total ozone values at the reverse of the depression and low values in front of the depression. This was already known for more than forty years (Reed, 1950). Here, one event is studied in detail to demonstrate this picture.

2. AN ANALYTICAL MODEL OF A CYCLONE AND THE CORRESPONDING FLOW REGIMES

An analytic conceptual model of an extratropical cyclone was developed recently (Heijboer and Kelder, 1991). It consists of a highly truncated solution of the quasi-geostrophic or semi-geostrophic equations. The simple model reveals the main characteristics of the cyclone as is shown in figure 1. Several different flow regimes can be distinguished. Ahead of the depression a warm moist conveyor belt is transporting boundary layer air upto the upper troposphere. The ascending movement is accelerated by the release of latent heat. The cold moist conveyor belt is ascending upto the middle troposphere

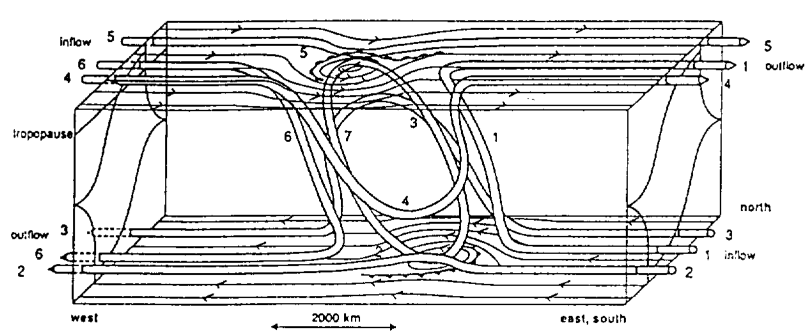

Fig. 1. Relative trajectories within and around a standard moving extratropical cyclone.

1. Warm moist conveyor belt
2. Low tropospheric flow of the environment
3. Cold moist conveyor belt
4. Descending stratospheric air overrunning the warm moist conveyor belt
5. Stratospheric flow of the environment
6. Descending stratospheric air into the troposphere
7. Circulating air in the centre of the depression moving with the speed of the depression

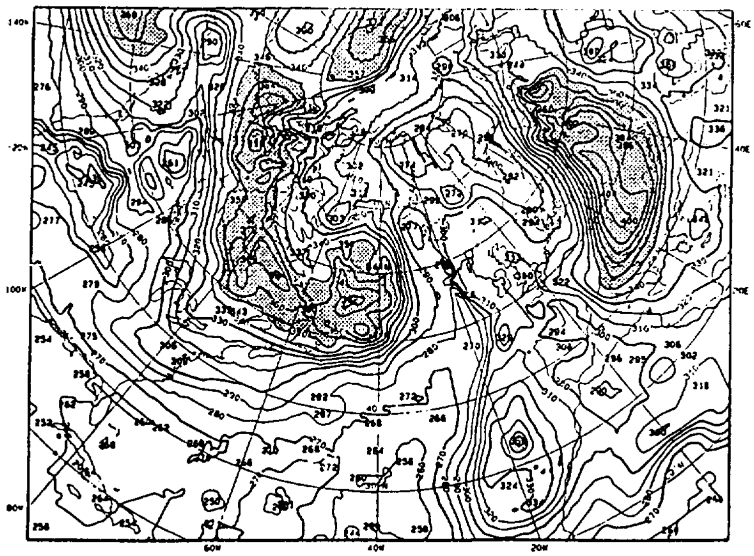

Fig. 2. The TOVS total ozone values for the Northern Hemisphere valid for 6 December, 1991. Areas with total ozone values over 350 Dobson units are shaded.

and is turning around the core of the depression before descending. Both conveyor belts are characterised by clouds and precipitation. Away from the depression the tropospheric flow is only little affected by the depression. At the back partly irreversible downward movement of lower stratospheric air takes place in channel 6. The downward movement in channel 4 of lower stratospheric air to the middle troposphere and back is in principle reversible. But this air is overrunning the warm moist conveyor belt and through shear and convective instabilities strong mixing takes place between these flows. The flow in the lower stratosphere and upper troposphere away from the depression is nearly undisturbed. In the core air of stratospheric and tropospheric origin is thoroughly mixed.

3. ESTIMATION OF THE TRANSPORT OF TRACE GASES

The analytical model suggests that the downward fluxes of trace gases takes place in three ways.

In channel 6 the air is transported from the lower stratosphere into the lower troposphere. The dimensions of the channel of a characteristic cyclone are about 800 km width and about 1.5 km thickness and the velocity with respect to the cyclone is assumed to be of the order of 10 m/s. If a concentration of n mol/m^3 is assumed, then per second n x 1.2 x 10^{10} molecules are transported downwards. The lifecycle of a cyclone is four to five days of which during about two days effective downward transport takes place. The total transport for one cyclone amounts to n x 2.1 x 10^{15} molecules.

In channel 4 lower stratospheric air descends to the middle troposphere and back. The ascending air overruns the moist conveyor belt and convective and shear instabilities are causing strong mixing of the air in both channels. It is assumed that about half of the air from stratospheric origin remains by mixing in the troposphere and this contributes to n x 1.3 x 10^{15} molecules.

Mixing in the core of stratospheric and tropospheric air is a third way of exchange. If the cyclone is dying out the deformed tropopause in the core will be restored and is closing above the core. If the core has a radius of 500 km and the stratospheric part a thickness of about 1.5 km per depression n x 1.2 x 10^{15} molecules are transported in this way. One cyclone amounts to n x 4.6 x 10^{15} molecules.

Assuming 4 separate depressions per 4 days in the midlatitudes of the Northern Hemisphere leads to a total of n x 1.7 x 10^{18} molecules per year. For ozone at 300 hPa, 50^0 N the concentration is about 3 x 10^{18} mol/m^3 and the mean downward flux becomes 5.0 x 10^{36} molecules ozone per year. The mean vertical flux for the Northern Hemisphere becomes 6.2 x 10^{14} molecules m^{-2} s^{-1}. This is in the range of other estimates (e.g. Ebel et al., 1991).

In the same way upward fluxes can be determined. In channel 1, the warm moist conveyor belt, air is transported from the boundary layer air into the upper troposphere and lower stratosphere. This air, containing gases with residence times of hours to days like NO_x, SO_2, HNO_3 etc., is taking part in the chemistry of the upper troposphere. The air is processed in ascending by clouds, precipitation and mixing with dry air from stratospheric origin. In the midlatitudes above the Atlantic Ocean in the belt of 40^0 N to 60^0 N upper tropospheric air is replaced intermittently by marine boundary layer air (Ehhalt et al., 1991).

4. CHANGES IN TROPOPAUSE HEIGHT AND TOTAL OZONE

Strong interrelation exists between midlatitude cyclones and total ozone.

1. In midlatitude cyclones ozone is transported from stratosphere into the troposphere.
2. The (column) total ozone-content can be a useful tool to unravel the structure of midlatitude cyclones.

Ozone trapped in a tropopause fold will of course show up on the total ozone picture. This ozone will eventually mix trough the troposphere and break down by chemical destruction or by deposition in the boundary layer.

Figure 2 shows the TOVS total ozone values for December 6, 1991; Figure 3 shows the tropopause pressures for the same date. Steep gradients indicate tropopause folds.

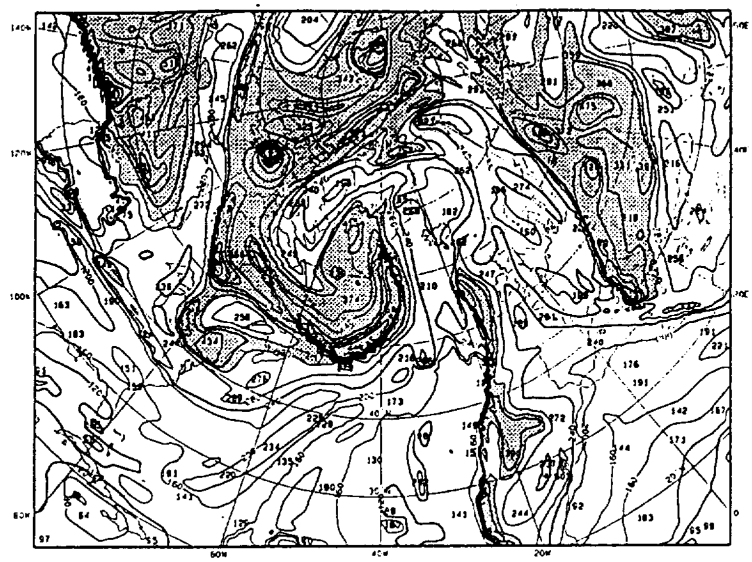

Fig. 3. Tropopause pressures valid for 6 December, 1991. Areas with tropopause pressures over 320 hPa are shaded.

5. SUMMARY AND DISCUSSION

In the paper it was argued that cyclones have a large impact on the transport of trace gases at midlatitudes. Most of the downward ozone transport from the stratosphere to the troposphere is accomplished by cyclones. With a simple model of a depression a conceptual view of the main flow regimes in and around a depression was obtained. The importance of the transport by cyclones for the budgets of total ozone was discussed.

The conclusion is that part of the short term fluctuations in total ozone is due to migrating cyclones. This idea was already formulated more than 40 years ago (Reed, 1950) but with the analyses of the ECMWF model and the satellite observations of total ozone now, it is possible to quantify his idea more accurately.

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