The Role of Fronts on the Vertical Transport of Atmospheric Pollutants (2-D model)

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A quantitative study of the amount of air transported between the boundary layer and the free atmosphere is important for understanding air quality and upper tropospheric ozone, which is a greenhouse gas. Frontal systems are known to be an effective mechanism for the vertical transport of pollutants. Numerical experiments have been performed with a simple two-dimensional front model to simulate vertical transport of trace gases within developing cold fronts. Three different trace gases experiments have been done numerically according to the different initial fields of trace gases such as aerosol, ozone and H_2O_2.

Trace gas field tilts to the east while the front tilts to the west. Aerosol simulation shows that pollutants can be transported out of the boundary to altitudes of about 10 km. The stratospheric ozone is brought downwards in a tropopause fold behind of the frontal surface. The meridional gradient in trace gas (H_2O_2) can cause a complicate structure in the trace field by the meridional advection.

Keywords: front, trace gas, pollutant, vertical transport

1. Introduction

Most pollutants are emitted into the atmospheric at the ground. Under stagnant meteorological conditions, these pollutants accumulate in the boundary layer and react to form secondary pollutants such as ozone and peroxy acyl nitrate, resulting in poor air quality. Under more active meteorological condition, pollutants will be effectively transported to the free atmosphere, where they are long-lived. We thus have a situation where the extent of transport of air between the boundary layer and the free troposphere governs whether pollutant emissions result in poor air quality or contribution to climate change.

A quantitative study of the amount of air transported between the boundary layer and the free atmosphere is important for understanding air quality and upper tropospheric ozone, which is a greenhouse gas. Frontal systems are known to be an effective mechanism for the vertical transport of pollutants. Fronts associated with growing baroclinic waves develop due to patterns of horizontal deformation and vertical shear flow [3, 7]. Banic[1] has shown the distribution of pollutants near a frontal surface by field experiment and numerical modelling.

In this study, a two-dimensional primitive equation model has been used to simulate growing frontal systems and to investigate the transport of trace gases in a developing front

2. Model description

This model configurations are based on many previous researches[3, 5, 7]. The model is a Boussinesq primitive equation model in which the grid is a staggered both in horizontal and vertical

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resolution in the boundary layer to investigate the role of surface processes in producing vertical transport. A front is generated by imposing small amplitude Eady wave onto a background flow with a meridional temperature gradient(corresponding to a vertical wind shear). All dependent variables are assumed to be independent of y, except for the constant meridional potential temperature gradient.

A small amplitude Eady wave perturbation is added which grows into a front by taking energy from the meridional temperature gradient. A free-slip and a no-slip boundary condition are used at the upper and lower boundaries respectively. The lateral boundary conditions are periodic.

Vertical viscosities are calculated as dependent on the Richardson number and horizontal viscosities are dependent on the horizontal wind shear. The original model was developed by Cooper[2]. The advection and diffusion of a trace gas, G, have been included in the model according to equation (1).

$$\frac{\partial G}{\partial t}+u\frac{\partial G}{\partial x}+v\frac{\partial \overline{G}}{\partial y}+w\frac{\partial G}{\partial z}=\frac{\partial}{\partial x}\left(K_x\frac{\partial G}{\partial x}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial G}{\partial z}\right) \quad (1)$$

3. Discussion of results

3.1. SIMULATION OF FRONT

The results of numerical integration of the front forced by the meridional temperature gradient are shown in Fig. 1. It shows the isotachs of cross-front wind(u), along-front wind(v), vertical velocity(w), and the isentropes of potential temperature after 4 days in the simulation.

The cross-frontal flow(Fig. 1a) shows a region of enhanced PBL convergence at around 2000 km due to frictional effects. The along-front wind field(Fig. 1b) tilts to the west with height. There are northward transport of warm air to the east and southward transport of cold air to the west of the cold front. The strong low-level meridional jet, which is generated by the effect of the no-slip in the lower boundary, can be seen near the ground.

Vertical velocity field(Fig. 1c) shows the warm air rising ahead of the front and cold air sinking behind of it. It can be seen the several convection features formed by the convective instability behind of the front. The temperature field(Fig. 1d) shows the strong convective instability behind of the front in the boundary layer.

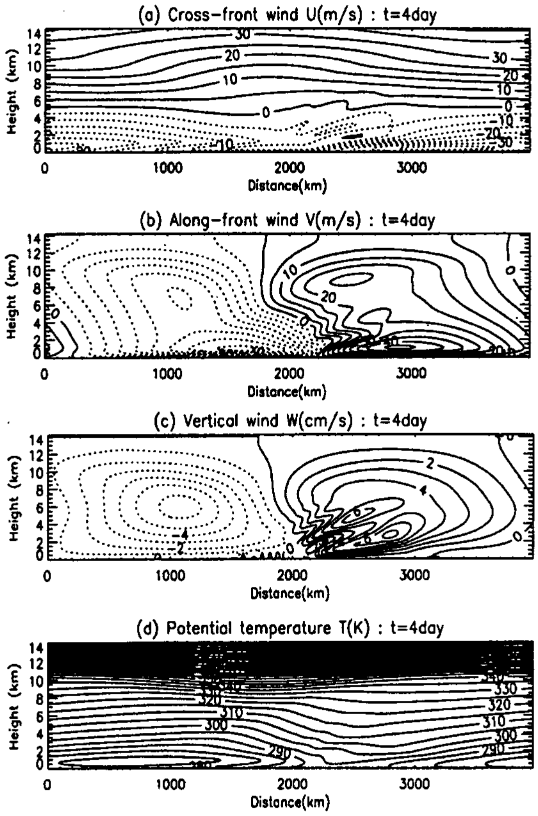

Fig. 1. (a) cross-front wind, (b) along-front wind, (c) vertical velocity, and (d) potential temperature calculated by the model 4days in the simulation.

3.2. TRACE GASES SIMULATION

Three different trace gas experiments have been done numerically according to the different initial fields of trace gas such as Gaussian profile, vertical increasing profile, and constant everywhere. The aerosol number density profile is similar to the Gaussian profile in the troposphere. The ozone profile is given as vertical increasing profile which increases linearly with height from 40 ppbv at the ground to 100 ppbv at the tropopause and to 200 ppbv at the lower stratosphere(14km). The hydrogenperoxide(H_2O_2) field is constant at 1000 pptv everywhere and has a meridional gradient of -45 pptv per latitude [4].

Fig. 2 shows the distribution of trace concentration calculated by the model after 4 days into the simulation. The aerosol simulation(Fig. 2a) shows that pollutants can be transported out of the boundary layer to altitudes about 10km. Also, in the east of cold front trace gas ascends to the east. The ozone field(Fig. 2b) reveals that stratospheric air is brought downward in a tropopause fold. The hydrogenperoxide(H_2O_2) simulation(Fig. 2c) displays that the higher concentration appears near tropopause in the east of the front and the lower concentration appears at the lower troposphere in the west of the front because of the meridional advection of trace gas.

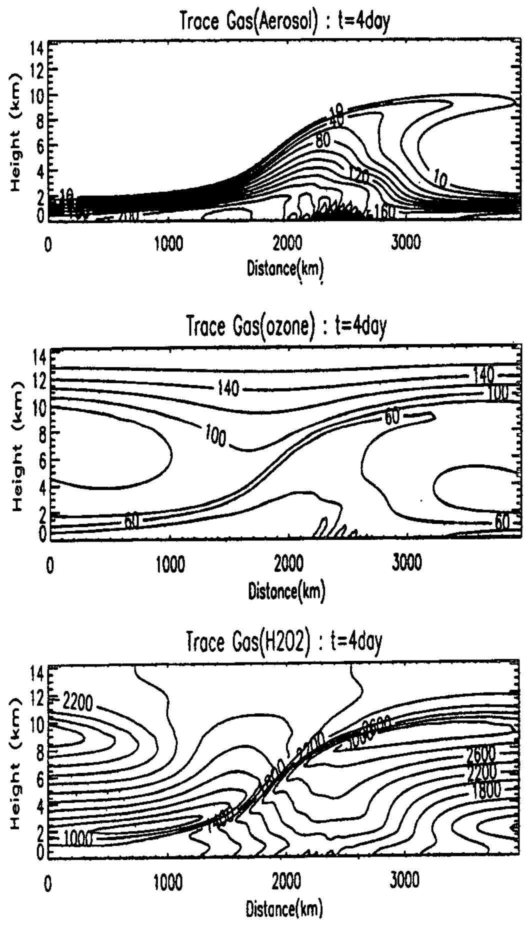

Fig. 2. Distribution of trace gases concentration such as (a) aerosol, (b) ozone, and (c) hydrogenperoxide (H_2O_2) after 4days in the simulation.

4. Vertical transport of pollutants

4.1. VERTICAL TRANSPORT

Fig. 3a shows time variation of the mean boundary layer height in the model domain. The boundary layer height gradually increases from 500 m at the initial time to 706 m at 1 day and around 1200 m at 2 days. Fig. 3b shows how much tracer is transported from boundary layer, where heights are decided by the Richardson number(solid line) and fixed 1 km height(dashed line), to the free atmosphere. The tracer in the free atmosphere transported from the boundary layer quickly increases to 35.6% around 20 hours and very slightly decrease due to the increasing boundary layer height in the simulation.

Fig. 4a is the time variation of the tropopause height decided by the potential vorticity(PV=1.5 unit). The tropopause height increases very slightly with time in the simulation. Fig. 4b shows the time variation of the amount of ozone in the troposphere according to different tropopause height which are decided by the PV(1.5 unit; solid line) and fixed height(10 km; dashed line). In this figure, we know the vertical exchanging of ozone though the tropopause occurs very slowly by the tropopause folding.

5. Conclusion

Numerical experiments have been performed with a simple two-dimensional front model to simulate vertical transport of trace gases within a developing cold front. The model includes high resolution in the boundary layer. The front is forced by a meridional temperature gradient into the model.

The trace gas field tilts to the east while the front tilts to the west. When the front is forced by the vertical shear flow the trace ascends to the east. Aerosol simulation shows that pollutants can be transported out of the boundary layer to altitudes of about 10 km. Ozone simulation shows that stratospheric air is brought downwards in a tropopause fold behind of the frontal surface. The meridional gradient in trace gas(H_2O_2) can cause a complicate structure in the trace field by the meridional advection.

This study will be continued as more realistic one by including chemical transformation, cloud formation, and the comparison between calculated and measurement.

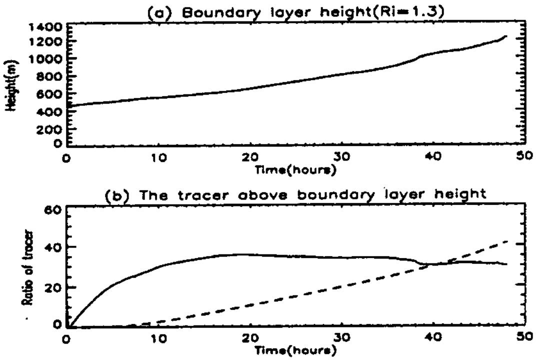

Fig. 3. Time variation of boundary layer height (a) and trace gas amount above boundary layer height (b) according to Ri=1.3 (solid line) and 1 km (dashed line) in the simulation

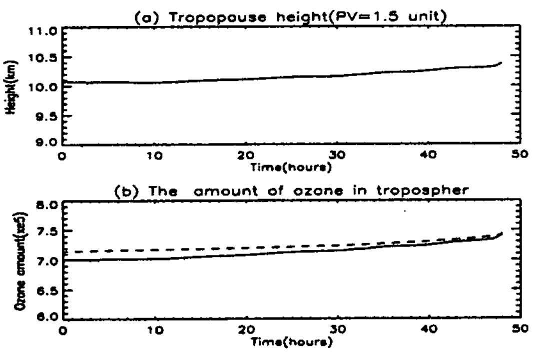

Fig. 4. Time variation of tropopause height (a) and ozone amounts in the troposphere(b) according to PV=1.5unit (solid line) and 10 km (dashed line) in the simulation.

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