P3.3S Diagnosis of meridional ozone transport based on mass weighted isentropic zonal means

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1. INTRODUCTION

The meridional transport of minor constituents has been studies using the two-dimensional transport equation based on the transformed Eulerian mean (TEM: Andrews and McIntyre, 1976) in many works. Under the assumption of small amplitude waves and geostrophic balance, the residual mean circulation approximates the Lagrangian mean circulation likely to the Brewer-Dobson circulation. Although the TEM provides a powerful theoretical framework for understanding tracer transport, but there are several problems. First, it is complicated to estimate eddy flux of constituent transport. Second, the TEM cannot express lower boundary condition exactly so that the ozone flux is unrealistic near the ground surface

We have developed a tool for diagnosis of the meridional transport based on mass weighted isentropic zonal means (e.g. Iwasaki 1989; Tanaka et al 2004). This method has mathematical and conceptual advantages to represent eddy transport term compared to the conventional methods. In this study, we apply this diagnosis to quantitative diagnosis the meridional ozone transport in the troposphere and stratosphere. Results are compared with the TEM.

2. ISENTROPIC DIAGNOSIS

We diagnose the mean meridional circulation and ozone transport characteristics (mean and eddy ozone fluxes) based on the mass weighted isentropic zonal means.

Authors have developed a tool for diagnosis of wave mean flow interaction and Lagrangian-mean meridional circulation based on mass weighted isentropic zonal means (e.g. Iwasaki 1989; Tanaka et al 2004). This is equivalent with the TEM under quasi-geostrophic assumptions. The transport equation is described here. (Details of the derivation are described in Miyazaki and Iwasaki (2005)).

Mass weighted isentropic zonal means are defined as

$$\overline{A(\phi,\theta,t)^*} \equiv \frac{1}{2\pi}\int A(\lambda,\phi,\theta,t)\left(\frac{\partial p}{\partial\theta}\Big/\frac{\partial \overline{p}}{\partial\theta}\right)d\lambda.$$

Here, the overbars and asterisk denote isentropic zonal mean and mass weight normalized by its zonal means, repetitively. Eddies are defined as departures from the mass weighted zonal means

$$A' \equiv A - \overline{A^*}.$$

Isentropic zonal mean pressure is used for vertical coordinate

$$p_\dagger \equiv \overline{p}.$$

The log pressure coordinate and the vertical velocities are defined by

$$z_\dagger \equiv -H\log(p_\dagger / p_0), \quad and \quad w_\dagger \equiv \frac{dz_\dagger}{dt},$$

We formulate the transport equation for minor constituents based on mass weighted isentropic zonal means. The zonally symmetric transport equation in a spherical coordinate system can be written by

$$\frac{\partial\overline{r^*}}{\partial t} = -\frac{\overline{v^*}}{a}\frac{\partial\overline{r^*}}{\partial\phi} - \overline{w_\dagger{}^*}\frac{\partial\overline{r^*}}{\partial z_\dagger}$$
$$-\frac{1}{a\cos\phi}\frac{\partial\overline{(r'v')^*}\cos\phi}{\partial\phi} - \frac{1}{\rho_0}\frac{\partial\rho_0\overline{\left(r'w_\dagger{}'\right)^*}}{\partial z_\dagger} + \overline{Q^*}.$$

Time derivative of mass mixing ratio r of minor constituents is composed of mean transport terms, eddy transport terms and net chemical production/loss term Q. Compared with the conventional isentropic formulation (e.g.,Tung 1982), the mass weighted isentropic zonal means of mixing ratio exclude eddy time derivative terms from the transport equation.

The mean and eddy fluxes are defined as

$$F_{mean}(\phi, z_\dagger) = \left[\rho_0\,\overline{r^*}\,\overline{v^*},\ \rho_0\,\overline{r^*}\,\overline{w_\dagger{}^*}\right],$$
$$F_{eddy}(\phi, z_\dagger) = \left[\rho_0\overline{(r'v')^*},\ \rho_0\overline{(r'w_\dagger')^*}\right]$$

Vertical component of eddy transport can be separated into the contributions due to diabatic and adiabatic processes with the aid of thermodynamic equation.

$$\overline{(r'w_\dagger')}^{*} = \frac{\overline{(r'v')}^{*}}{a}\left(\frac{\partial z_\dagger}{\partial \phi}\right)_\theta + \overline{(r'\dot{\theta}')}^{*}\frac{\partial z_\dagger}{\partial \theta}$$

For adiabatic processes, the direction of the eddy becomes

$$\frac{F_{eddy}(z_\dagger)}{F_{eddy}(\phi)} = \frac{1}{a}\left(\frac{\partial z_\dagger}{\partial \phi}\right)_\theta .$$

This infers that the eddy flux is parallel to the local isentropic surface for adiabatic processes.

We describe the lower boundary conditions of the eddy transport fluxes. At the low0er boundary, the mass weighted zonal mean assumes the value at the longitude of minimum surface potential temperature $\lambda(\theta_{s\min})$,

$$\lim_{\theta \to \theta_{s\min}} \overline{A^*} = A(\lambda(\theta_{s\min})).$$

Therefore, the eddy transport fluxes become zero at the lower boundary since the eddy correlations vanish at the lower boundary (Tanaka et al. 2004).

$$\lim_{\theta \to \theta_{s\min}} \overline{(A'B')^*} =$$

$$\lim_{\theta \to \theta_{s\min}} (A(\lambda(\theta_{s\min})) - \overline{A^*})(B(\lambda(\theta_{s\min})) - \overline{B^*}) = 0.$$

In this analysis, we use three-hourly global distributions of ozone and atmospheric fields for 1999-2001, which are obtained with the MRI-JMA ozone reanalysis system (Shibata et al. 2005).

3. CONPARISON WITH THE CONVENTIONAL METHOD

To evaluate the ability of the isentropic method, we compare the mean ozone flux and eddy ozone flux based on mass weighted isentropic zonal means with those of the Eulerian mean and the TEM. Isentropic method has some conceptual and computational advantages, in comparison with the conventional methods.

3.1. Mean transport

Figure 1 shows mean ozone fluxes and mass stream functions based on the Eulerian framework, the TEM and isentropic representation.

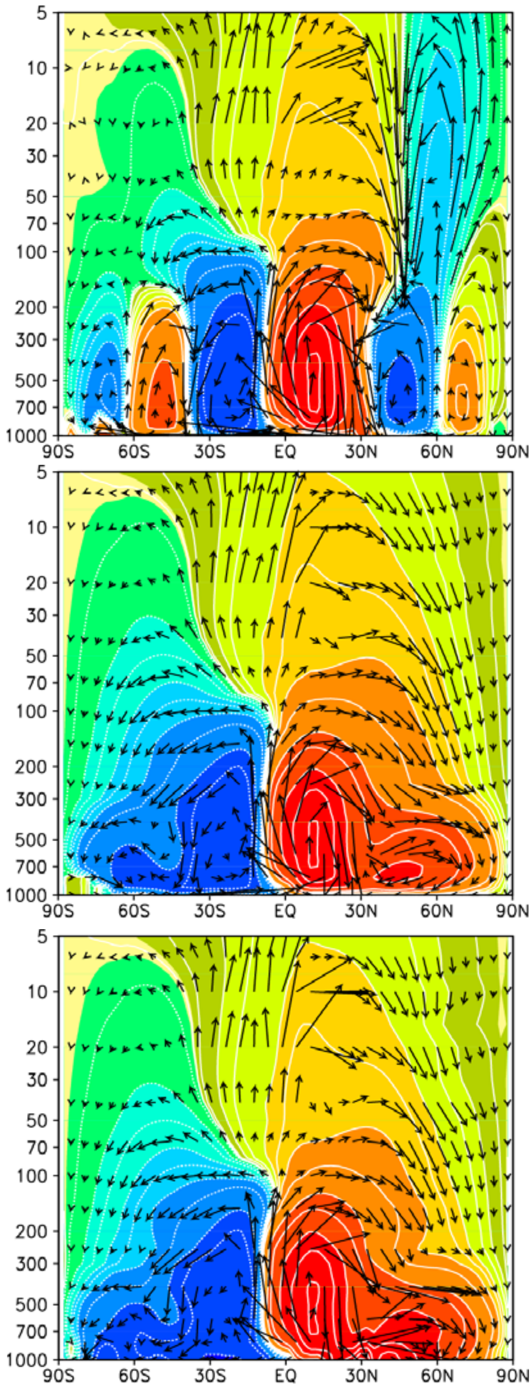

Figure 1. Characteristics of mean ozone transport for northern hemispheric winter (December, January and February) based on the Eulerian mean (upper panel), the TEM (middle panel) and the isentropic diagnosis (lower panel). Mean ozone flux with mass stream function are plotted

The Eulerian mean has equatorward mean ozone flux ad mid-latitude corresponding to the indirect cells. This is inconvenient in the understanding of the meridional transport. Although, in most of the free atmosphere, the mean transport characteristics in the isentropic diagnosis are almost similar to those of the TEM, a significant difference can be found in the vertical mean transport near the Antarctic polar vortex (figures not shown). This is because the isentropic approach follows the displacement of isentropic surfaces, while the TEM represents the mean circulation under the assumption of small-amplitude waves and geostrophic balance for the Stokes correlation. Also, the isentropic approach represents the ozone flux at the lower boundary reasonably. In the extratropics, the isentropic approach shows strong equatorward ozone fluxes near the surface, but the TEM does not, since the stream function intersects the lower boundary.

Figure 2 shows the meridional components of mean ozone flux integrated over the troposphere (from the surface to 100 hPa) and the stratosphere (from 100 hPa to the top) averaging over northern hemispheric winter (DJF), based on the mass weighted isentropic zonal means, the conventional Eulerian mean and the TEM. The integrated ozone fluxes are defined by

$$\int_{Z(100hPa)}^{\infty} F_{mean}(\phi)\cos\phi dz \qquad (stratosphere)$$

$$\int_{0}^{Z(100hPa)} F_{mean}(\phi)\cos\phi dz_{\dagger} \qquad (troposphere)$$

In the stratosphere, there is good agreement between the isentropic method and the TEM. In contrast, large difference can be seen in the troposphere. The TEM estimates the tropospheric poleward transport considerably larger than the isentropic method. This is because the TEM misses the equatorward flux near the lower boundary as mentioned above.

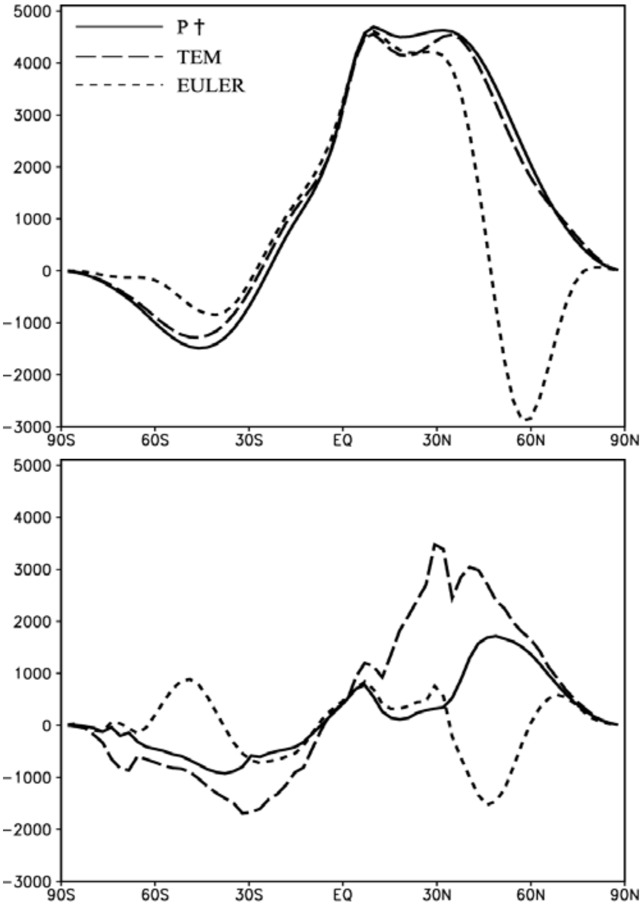

Figure 2. Mean meridional ozone flux integrated from 100 hPa to the top (left) and from the surface to 100 hPa (right), in kgs^{-1}, averaging over DJF, 1999, from Miyazaki and Iwasaki (2005).

3.2. Eddy transport

The eddy ozone fluxes of the Eulerian framework, the TEM and the isentropic representation, with potential temperature are shown in Figure 3. In the conventional Eulerian mean, the eddy flux is defined from isobaric eddies. The eddy ozone flux of the conventional Eulerian mean is larger than the other methods at mid latitudes especially in the winter hemisphere as a result of indirect cells. We estimate eddy transport terms in the TEM with the aid of this eddy flux vector. In comparison with those of the isentropic approach, general properties are similar. However, in the TEM, the eddy flux intersects isentropic surfaces even in the stratosphere where adiabatic processes are dominant. The eddy fluxes of the TEM are more disturbed in the lower stratosphere and upper

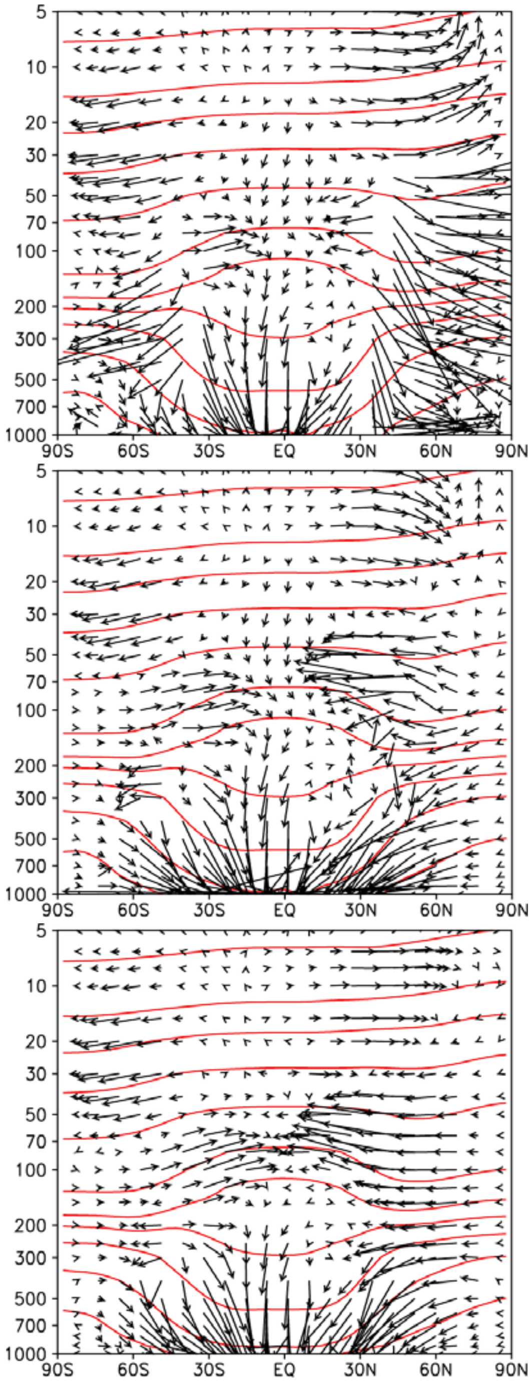

Figure 3. Characteristics of eddy ozone transport for northern hemispheric winter (December, January and February) based on the Eulerian mean (upper panel), the TEM (middle panel) and the isentropic diagnosis (lower panel). Eddy ozone flux with selected potential temperature are plotted

troposphere. In the lower troposphere, the eddy ozone fluxes of the TEM are flatter than the TEM especially in the summer hemisphere. In addition, the amplitude of eddy flux is larger in the TEM than in our method. This result suggests that the small amplitude assumption may be a limitation for the TEM especially in the winter stratosphere associated with planetary wave breaking.

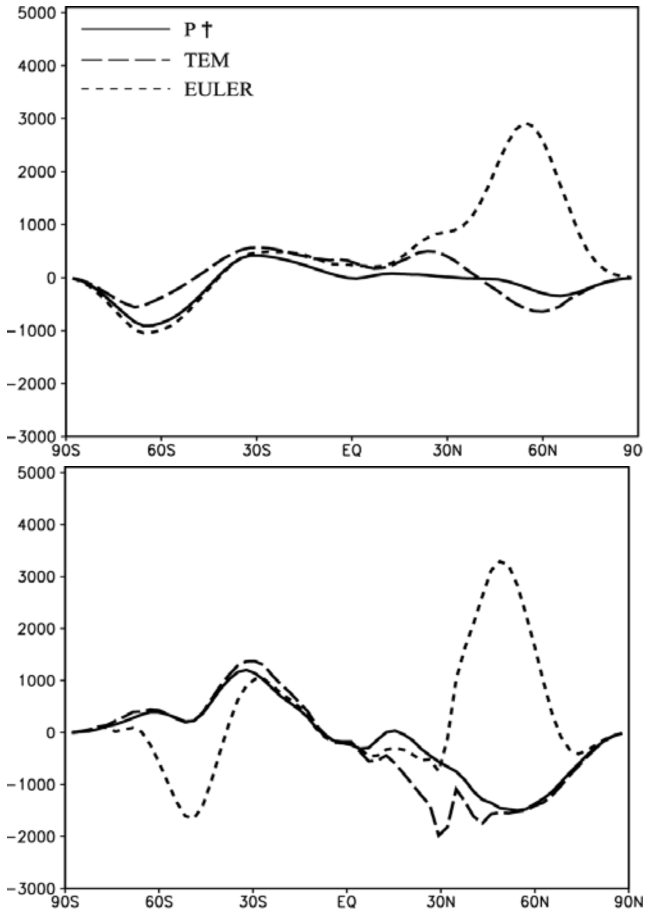

Figure 4. Same as Figure 2, but for the eddy ozone flux, from Miyazaki and Iwasaki (2005)

The meridional components of eddy ozone flux integrated over the troposphere (from the surface to 100 hPa) and the stratosphere (100 hPa to the top) averaging over the northern hemispheric winter (DJF) are shown in Figure 4. We now compare the eddy ozone flux between the TEM and the isentropic method. Significant difference can be found in the winter stratosphere. The amplitude of eddy flux is larger in the TEM than in our method. This result suggests that the small amplitude assumption may be a limitation for the TEM especially in the winter stratosphere associated with planetary wave breaking. In the troposphere, large differences between the two diagnoses are found especially near at latitude 30N. This property also can be found in the comparison of mean ozone flux (cf., Figure 12). It is therefore expected that the TEM has some systematic biases both of mean and eddy ozone fluxes in association with the lower boundary conditions especially at mountainous latitudes.

4. CONCLUSIONS

In this paper, we have diagnosed the ozone transport characteristics in the troposphere and stratosphere by using the two-dimensional transport equation based on mass weighted isentropic zonal means. The mean and eddy ozone fluxes are estimated from global objective analysis, obtained with the MRI ozone reanalysis system.

a. Isentropic method has some conceptual and computational advantages, in comparison with the conventional methods:

(1) Although, in most of the free atmosphere, the mean transport characteristics in the isentropic diagnosis are almost similar to those of the TEM, a significant difference can be found in the vertical mean transport near the Antarctic polar vortex (figures not shown). The isentropic approach follows the Lagrangian-mean meridional circulation, while the TEM approximates it under the assumption of a geostrophic balance for the Stokes correlation.

(2) The isentropic method can reasonably represent the ozone flux in the vicinity of the lower boundary. In the TEM, the stream function intersects the lower boundary, hereby making it difficult to estimate the mean ozone flux near the surface. In contrast, the isentropic diagnosis enables us to perform an accurate tropospheric budget analysis through the exact representation of the strong equatorward mean ozone transport near the surface.

(3) An important advantage is the capability to simply and exactly represent the eddy transport terms. The isentropic mass weighted zonal means of the mixing ratio excludes the eddy time derivative terms from the transport equation. In addition to the mean fluxes, the eddy fluxes also play an important role in the determination ozone concentration, especially in the extratropical troposphere and in the high latitude stratosphere. The eddy flux is parallel to the isentropic surface for adiabatic processes.

b. We can obtain a comprehensive picture of the ozone life cycle (Figure 5) through an exact estimation of mean and eddy transport terms (Figure 1 and Figure 3).

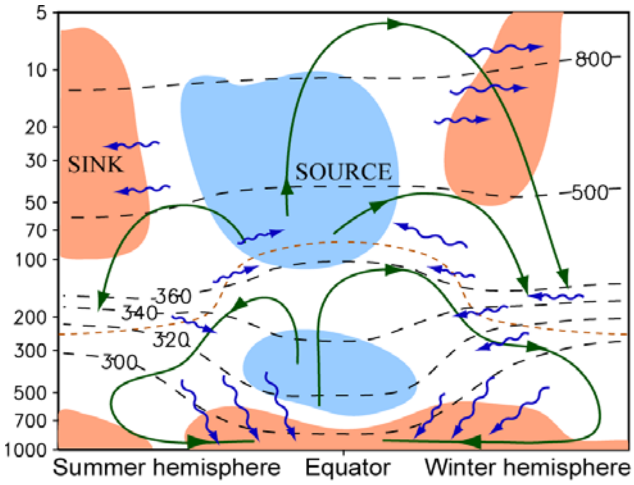

Figure 5. Schematic diagram of the ozone life cycle in the troposphere and stratosphere for the northern winter. Straight arrows show transport due to the mean circulation; wavy arrows show the eddy transport; broken lines show selected isentropic lines; dotted line shows the tropopause. Shaded areas indicate major chemical source and sink, from Miyazaki and Iwasaki (2005)

Ozone produced mainly in the tropical stratosphere is transported to the extratropics by the Brewer-Dobson circulation. In the stratosphere, the mean ozone flux dominates the eddy ozone flux, except at the high latitude. At the high latitude stratosphere of the winter hemisphere, the poleward eddy ozone flux is significantly associated with planetary wave breaking. In the summer hemisphere, the eddy ozone flux increases the ozone rather than the mean ozone flux near the polar region, and compensates for chemical losses. In the extratropical lower stratosphere and upper troposphere, the ozone subsides due to by mean downward motions and is diffused to lower latitudes primarily due to baroclinic waves. These eddy fluxes appear to be separated into two streams along the isentropic surfaces in the mid latitude: equatorward-upward flux in the lower stratosphere (above the isentrope 360 K) and equatorward-downward flux in the upper troposphere (below the isentrope 340 K). The lower tropospheric eddy fluxes deviate from the isentropic surface, reflecting diabatic diffusions. Near the surface, large equatorward transport appears due to strong meridional flows. In the subtropical lower troposphere, the ozone is destroyed by chemical reactions.

Acknowledgments

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