Analysis of extratropical UTLS structure using a high vertical resolution GCM

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1. Introduction

The thermal and dynamical structure of the extratropical upper troposphere and lower stratosphere (UTLS) has been studied from aircraft and sonde measurements. Strong vertical temperature gradient in the lowermost stratosphere forms an inversion layer just above the extratropical tropopause (e.g., Birner, 2006), while the tropopause mixing layer lies just above the extratropical tropopause, showing a chemical transition layer from the troposphere to stratosphere (e.g., Hoor et al., 2004). Although GCMs are powerful tool analyzing atmospheric structure, current GCMs typically do not fully succeed in simulating these UTLS structures. In this work, we adopted a vertically high resolved GCM to analyze the atmospheric structure and transport/mixing processes in the extratropical tropopause region.

2. Data and analysis method

A high-resolution atmospheric GCM has been developed to study various aspects of small-scale phenomena including gravity waves and their role on the large-scale fields in the middle atmosphere (Watanabe et al., JGR, 2008). The GCM has a T213 truncation in the horizontal and 256 levels in the vertical from the surface to about 85 km with vertical intervals of about 300 m in the upper troposphere and above. Gravity waves re explicitly simulated by the GCM without any gravity wave drag parameterization.

The high vertical resolution GCM allows analyzing

1. fine thermal and dynamical structure of the extratropical UTLS, and
2. roles of variously scaled atmospheric transport processes in the variations of atmospheric compositions

Potential vorticity (PV) fields diagnosed from model outputs with a time interval of 1 hour are analyzed to investigate the extratropical dynamical tropopause and atmospheric transport processes.

PV budget analysis

Zonal mean potential vorticity equation

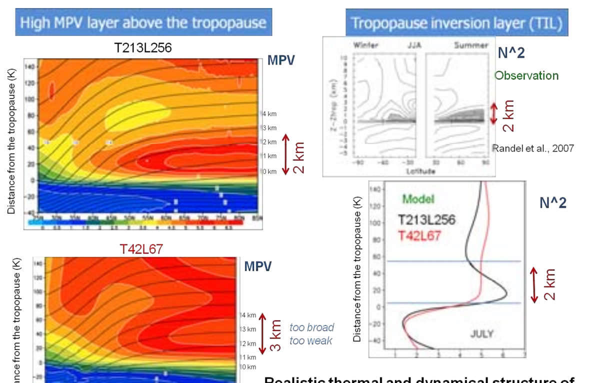
$$\frac{\partial\overline{q^*}}{\partial t} = -\frac{\overline{v^*}}{a}\frac{\partial\overline{r^*}}{\partial\phi} - \overline{Q^*}\frac{\partial\overline{q^*}}{\partial\phi} - \frac{1}{a\cos\phi}\frac{\partial\overline{(r'q')^*\cos\phi}}{\partial\phi} - \frac{1}{\rho_0}\frac{\partial\rho_0\overline{(Q'q')^*}}{\partial\theta}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

where the overbar and asterisk indicate isentropic zonal mean and mass weight, respectively. q: Potential vorticity, Q: Diabatic heating rate

Vertical advection term is

$$\overline{Q^*}\frac{\partial\overline{q^*}}{\partial\phi} = \left(\underbrace{\left(\frac{\partial\overline{\theta^*}}{\partial t}\right)_{p_1}}_{displacement} + \overline{v^*}\frac{\partial\overline{\theta^*}}{\partial a\partial\phi} + \underbrace{\overline{w_1^*}\frac{\partial\overline{\theta^*}}{\partial z}}_{adiabatic\ change}\right)\frac{\partial\overline{q^*}}{\partial\phi}$$

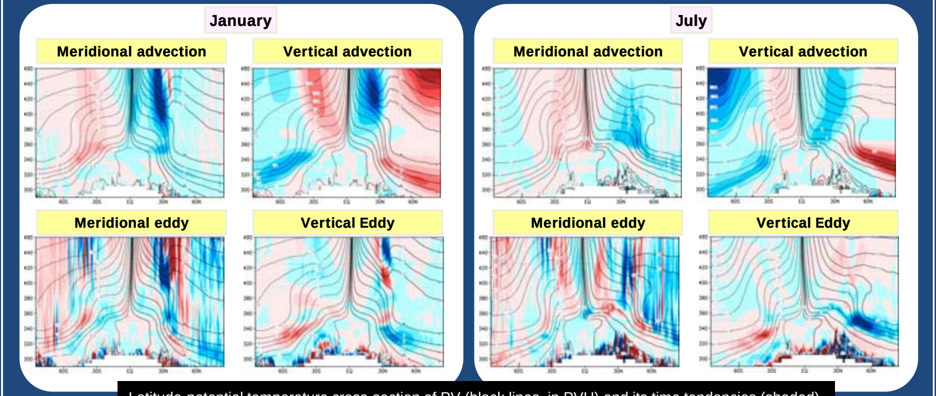
3. Simulation of the extratropical tropopause layer



Realistic thermal and dynamical structure of the extratropical UTLS in a T213L256 GCM

The simulated thermal and dynamic structure of the extratropical UTLS is much better represented by T213L256 GCM compared to a low resolution GCM. T213L256 GCM shows the existence of the tropopause inversion layer (TIL) just above the extratropical tropopause realistically. Within the TIL, temperature strongly increases with height. The thickness of the simulated TIL is about 2 km, and maximum static stability within the TIL lies 40 K above the dynamical tropopause at mid latitudes during winter.

4. PV budget analysis in the UTLS

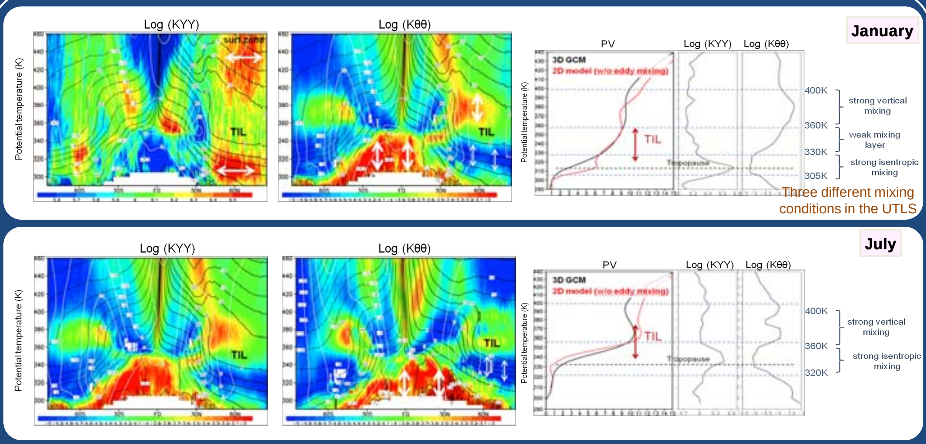


Latitude-potential temperature cross-section of PV (black lines, in PVU) and its time tendencies (shaded).

A large isentropic PV gradient around the extratropical tropopause indicates a barrier for isentropic mixing between the troposphere and stratosphere, whereas the PV gradient is small within the TIL. PV budget analysis demonstrates that:

・Tropospheric eddy motions due to synoptic-scale disturbances increase the PV gradient in the uppermost troposphere and around the tropopause (approximately from 1 to 4 PVU) during winter.

・Stratospheric mean downward motion strongly converges in the lowermost stratosphere, sharpening the PV gradient around the extratropical tropopause (approximately from 2 to 6 PVU) during winter.



Adiabatic and diabatic diffusion coefficients derived from the PV fields show rapid variations in the UTLS.

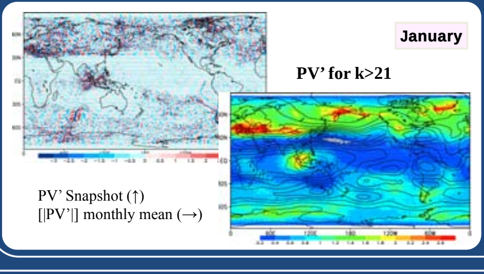
・In the northern extratropics during winter, isentropic mixing is suppressed in the TIL, while active vertical mixing tends to flatten the PV gradient.

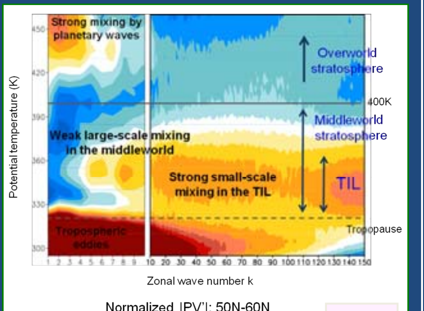
・The subtropical westerly jet stream hinders the isentropic transport of the tropical air into the extratropical TIL.

・Vertical mixing is strongly suppressed near and just above the dynamical tropopause (approximately from 2 to 7 PVU), in association with a very small diabatic diffusion coefficient .

5. TIL mixing

In the upper troposphere (below 330K) and overworld stratosphere (above 400K), planetary-scale and synoptic-scale wave motions cause the strong atmospheric mixing. The TIL (from 330 to 360K) reveals a weaker mixing by large-scale motion, while atmospheric disturbances with horizontal scales less than several thousand kilometers largely contribute to the TIL mixing. The small-scale disturbances are enhanced over mountainous and convective regions, implying that gravity waves are a significant cause of the TIL mixing.





Normalized |PV'|: 50N-60N (deviation from vertical average for each k) January

6. Conclusions

The thermal and dynamical structure of the extratropical tropopause region was studied from a PV budget analysis using a high vertical resolution GCM output. The roles of variously scaled atmospheric transport processes in the PV distribution were investigated. Near the extratropical tropopause, the isentropic PV gradient is increased by the upper tropospheric eddy motions and convergence of the mean downward motion. Vertical mixing is strongly suppressed near and just above the dynamical tropopause. Small-scale disturbance induces the mixing within the TIL probably associated with gravity waves.