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Lagrangian transport experiments in the MLT region

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In order to evaluate material transports in the upper mesosphere and lower thermosphere (MLT) region, Lagrangian transport experiments are performed using wind fields simulated by the Kyushu University middle atmosphere general circulation model (Miyahara and Miyoshi, 1997; Miyahara *et al.*, 1993). The Lagrangian mean meridional circulation is different from the residual mean circulation defined by the Transformed Eulerian Mean equation system, which is thought to be approximately equal to the Lagrangian mean meridional circulation in the middle atmosphere in case of weak dissipation and transience (Andrews and McIntyre, 1978; Andrews *et al.*, 1987). It is considered that the diffusivity caused by the transience and dissipation of various wave motions in the MLT region has significant effects on the material transport in this region, and makes them different from each other.

1. Introduction

Material transport processes in the MLT region are highly complicated. They are influenced not only by diurnal tides and semidiurnal tides those are both dominant wave motions in this region, but also by prevailing zonal and meridional mean winds and by other waves, such as planetary waves and gravity waves.

Some discussions on the material transport in this region were done based on the Eulerian approach, and some of them focused on dynamical influences of diurnal migrating tides on $O(^1S)$ nightglow. For example, Forbes *et al.* (1993) discussed the nightglow based on numerical simulations using photochemical coupling GCM, Shepherd *et al.* (1997) discussed it based on WINDII observations, and Roble and Shepherd (1997) discussed it based on both the WINDII observations and the TIME-GCM simulation.

It is of interest to study the material transport in the region from a different viewpoint that is the Lagrangian viewpoint. In case of weak dissipation and transience, the residual mean circulation in the Transformed Eulerian Mean (TEM) equation system,

$$(\overline{v}^*,\ \overline{w}^*) \equiv (\overline{v} - \rho_0^{-1}(\rho_0\,\overline{v'\theta'}/\overline{\theta}_z)_z\,,\quad \overline{w} + (a\cos\phi)^{-1}(\cos\phi\,\overline{v'\theta'}/\overline{\theta}_z)_\phi\,)$$

is thought to be approximately equal to the Lagrangian mean meridional circulation (Andrews and McIntyre, 1978; Andrews *et al.*, 1987). It is, however, not clear how accurately the TEM residual mean circulation approximates the actual Lagrangian mean circulation under effects of significant dissipation and transience, those are not negligible in the MLT region.

In this paper, off-line Lagrangian transport experiments under perpetual September equinox conditions are done to study the Lagrangian transport in the MLT region. The wind data simulated by the Kyushu University middle atmosphere general circulation model are used, that covers the atmospheric layers from the ground through the lower thermosphere.

An outline of the Lagrangian transport experiment is presented in Section 2. In Section 3, we focus our attention on the Lagrangian mean transport over 10 days. The Lagrangian mean meridional circulation is compared with the TEM residual mean circulation. Section 4 is devoted to conclusions and remarks.

2. Description of the Lagrangian Transport Experiment

Off-line transport experiments are performed as follows. The hourly sampled output wind data for the last 10 days of T21L55 version of Kyushu University middle atmosphere general circulation model under perpetual September equinox conditions are used for the experiments, because tidal motions are analyzed and it is confirmed that both the migrating and non-migrating tides are dominant in this data set (Miyahara and Miyoshi, 1997). The model has horizontal resolution truncated at zonal wavenumber 21, and in the vertical from the ground to 150 km are covered by 55 layers. Model descriptions are found in Miyahara and Miyoshi (1997), and Miyahara *et al.* (1993). In this GCM both upward propagating tides from below and *in situ* tides in the lower thermosphere are generated through the diurnal cycle of solar radiation processes. In order to focus on the transport due to long time scale motions, the output data are low-pass filtered to eliminate effects of motions which have shorter time scale than 12 hours. A spherical pressure coordinate system is used for the trajectory calculation, because the original GCM data are given on the coordinate system.

Initially, parcels are located on some isobaric surfaces which are laid between 86 km and 114 km heights with intervals of about 2 km. 360 parcels are initialized at equispaced

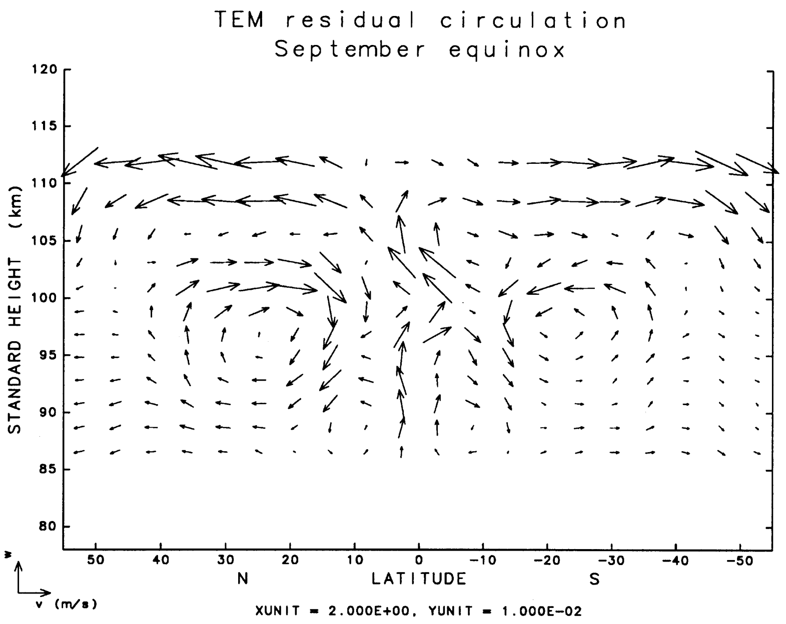

Fig. 1. TEM residual mean circulation averaged over 10 days. Unit arrows show 2.0 m s^{-1} in horizontal and 10 mm s^{-1} in vertical.

longitudinal grid positions on each latitude circle having interval of 2.7 degree in latitude. The Eulerian velocity of the GCM output is linearly interpolated to positions of parcels at each trajectory integration time step from eight neighboring GCM grid points to obtain the wind data for the time integration. The fourth-order Runge-Kutta scheme is used for the time integration of the parcel positions. The time step of the integration is taken to be 12 minutes. To check errors in the time integration, time integrations with time steps of 3, 6, 10, 12, 15, 20, and 30 minutes are conducted. Mean positions of parcels after 10 days projected on the meridional plane concentrate in the circle with 0.5 degree $\times$ 0.25 km in cases of time integrations with time steps between 3 minutes and 15 minutes.

After the trajectory calculation, the advected part of Lagrangian mean meridional circulation is calculated from the mean distribution of the transported parcels obtained by the forward and backward transport experiments introduced by Kida (1983) to compare with the TEM residual mean circulation. This method is used to remove the apparent Lagrangian mean velocity which arises from the diffusive motion of parcels on the meridional plane, which tend to violate mass conservation. The advected part of Lagrangian velocity field is, however, still not necessary to keep mass conservation, because this method is based on not the continuity equation but the kinematical relation.

3. Zonal Mean Transport

Figure 1 shows the TEM residual mean circulation averaged over the 10 days. This is calculated using the same low-pass filtered data set for the Lagrangian transport experiments mentioned in Section 2. A pair of equatorward wind centered at 100 km height and two pairs of poleward wind centered at 113 km and 90–95 km height are seen. Associated with these meridional winds, an upward wind is seen at 90–110 km height over the equator, downward winds are seen at 15°N and S, and upward winds are seen at 35°N and S. These wind distributions are qualitatively similar to the Eulerian mean velocity field obtained by the WINDII data set (Fauliot *et al.*, 1997).

The Eulerian mean meridional circulation of the present model (not shown) shows basically same distribution as the TEM residual mean circulation, although the magnitude of the circulation of the Eulerian mean is somewhat larger than that of the TEM. This result seems to allows us to consider the Lagrangian mean meridional transport in this height region using the Eulerian mean circulation at least in qualitative meaning.

However, it is not clear that the TEM residual mean circulation actually represents the Lagrangian mean meridional circulation, because effects of dissipation and transience are thought to be important in this height region. We attempt to compare the TEM residual mean circulation with the Lagrangian mean meridional circulation which is obtained from the present data set.

3.1 Lagrangian mean transport by diurnal tides in 24 hours

Figure 2 shows the result of a Lagrangian transport experiment using the modified data set from which components other than the zonal wavenumber $s = 1$ diurnal tidal component are filtered out to show the Lagrangian mean meridional transport (the Stokes drift) only by the diurnal tide which is the most dominant wave component in the MLT region of the present numerical simulation (Miyahara and Miyoshi, 1997). Initially, 360 parcels are lined up along each of latitudinal circles at locations designated by '$\otimes$' in the figure, and they are moved by the first 24 hours of wind data. Parcel positions after 24 hours are projected on a meridional plane, and those are represented by dots.

Downward movements over the equator, upward move-

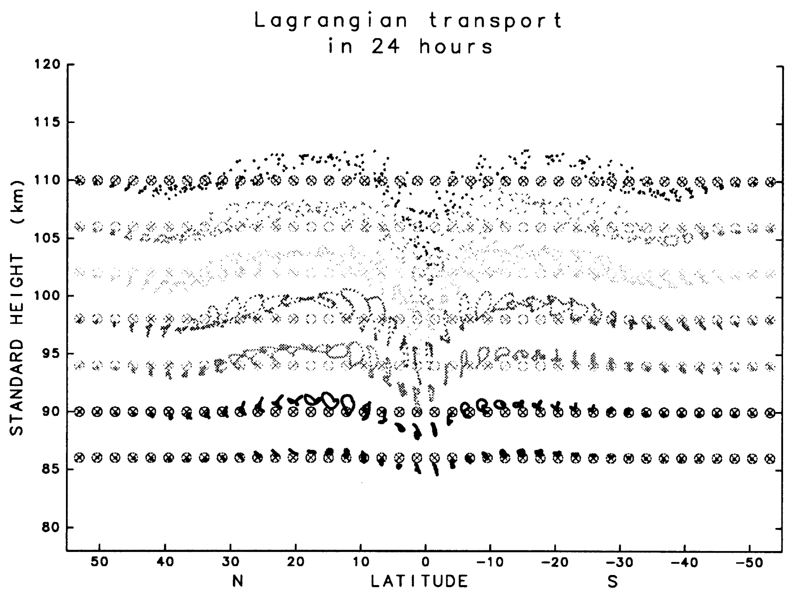

Fig. 2. Lagrangian transport (Stokes drift) in 24 hours due to the zonal wavenumber $s = 1$ diurnal tide. Initial positions of parcels are designated by '⊗'.

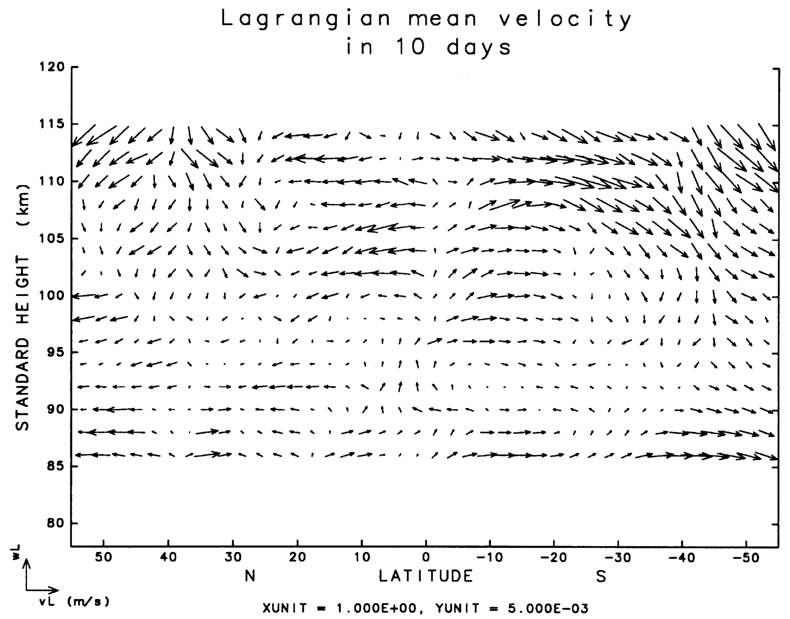

Fig. 3. Advected part of Lagrangian mean meridional circulation using the 10 days data including all components having longer than 12 hours. Unit arrows show 1.0 m s^{-1} in horizontal and 5.0 mm s^{-1} in vertical.

ments between 10° and 30°N and S, and weak downward movements in higher latitudes are seen as a result of the net transport (the Stokes drift) by the diurnal migrating tides in 24 hours. It is noteworthy that the parcels move opposite direction to the TEM residual mean circulation mentioned above (Fig. 1).

However, it is not surprising, because the Lagrangian transport shown in Fig. 2 is only due to the diurnal tide itself (the Stokes drift), and the transport due to the Eulerian mean meridional circulation is not included. It is known that the Lagrangian mean meridional circulation consists of both the Eulerian mean meridional circulation and the Stokes drift (e.g., Andrews *et al.*, 1987). The result shown in Fig. 2 is only due to the Stokes drift by the diurnal tide, while the TEM residual mean circulation shown in Fig. 1 includes both the Eulerian mean and Stokes drift effects.

3.2 Lagrangian mean transport over 10 days

Figure 3 shows the advected part of Lagrangian mean circulation calculated from the Lagrangian transport experiment based on Kida's method (Kida, 1983) using the 10 days data in which all components having longer than 12 hours (including the steady component) are included. Thus, in con-

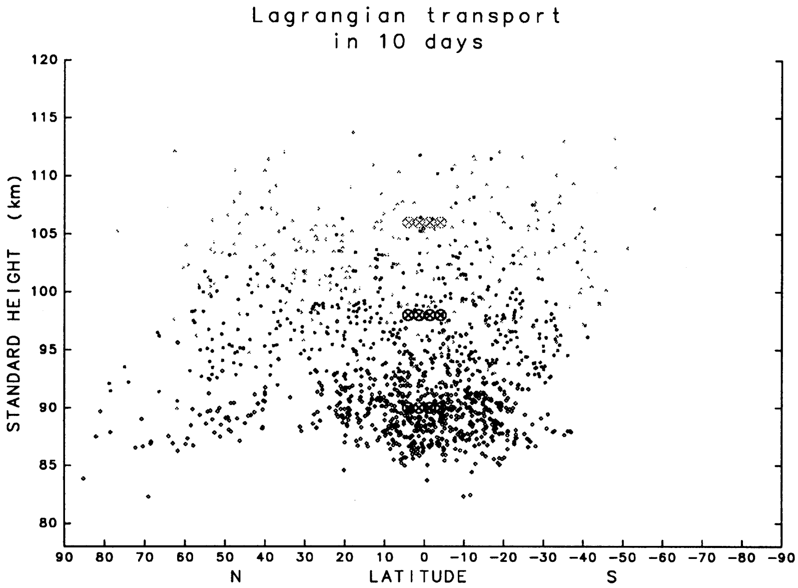

Fig. 4. Parcel positions after 10 days initially located at locations designated by '⊗'.

trast to the former experiment, effects of the Eulerian mean meridional circulation are included in the present experiment. Poleward symmetric meridional transports, an upward transport near the equator, and downward transports in both hemispheres are seen. The maximum of the upward transport around 100 km altitude is 1.0 mm s^{-1} near the equator, the downward transports around 100 km height in the middle to high latitudes are -2.0 mm s^{-1}. The magnitudes of the Lagrangian mean meridional circulation are about a half of the TEM residual mean circulation shown in Fig. 1. Comparing to the TEM residual mean circulation (Fig. 1), the pair of circulation centered at 97 km height and 25°N and S is not seen in the Lagrangian mean circulation, and only a circulation rising over the equator and moving poleward is seen.

The present results show that the TEM residual mean circulation is not necessarily a good approximation of the advected part of Lagrangian mean meridional transport in the MLT region. In this region effects of dissipative and transient waves are important, and the transport of parcels is extremely diffusive as shown in Fig. 4 which shows the parcel positions after 10 days initially located at locations designated by '⊗'. It is shown that the transported parcels after 10 days are strongly diffused in the meridional plane, and move poleward.

In addition, it should be pointed out that for this Lagrangian mean velocity field (Fig. 3), as mentioned in Section 2, mass conservation seems to be violated in some regions such as around (8°S, 98 km) and (5°N, 95 km), and above 105 km height. This is mainly due to the fact that the diffusion is strong and highly dependent on spatial position in the lower thermosphere. Thus, the diffusive effect does not act in the same manner for the forward and the backward transport experiments, and the effect does not cancel out in contrast to the stratospheric case studied by Kida (1983).

Corresponding to above result, recent analyses of the original GCM data set used in this transport experiment show that diurnal tides are dominant around 100 km height, and that dissipation of the diurnal tides and variability of the diurnal non-migrating tides are both large in that height region (Miyahara *et al.*, 1999). They also show that semidiurnal tides are dominant above 105 km height and dissipation of them are large in that height region.

In order to see the transient feature of the Lagrangian transport, we conducted some Lagrangian transport experiments in 24 hours. Figures 5(a)–5(e) show day-to-day variations of the 24 hours Lagrangian mean meridional circulation of the 1, 3, 5, 7 and 9 days. It is noteworthy that none of them resemble not only the TEM residual mean circulation averaged over 10 days (Fig. 1), but also the 10-day Lagrangian mean meridional circulation (Fig. 3). Because of the large day-to-day variation, it seems to be difficult to obtain a typical picture of the Lagrangian mean transport in 24 hours, even if 10 day mean of the 24 hours experiments is constructed (Fig. 5(f)). And again it does not resemble the TEM residual mean circulation averaged over 10 days (Fig. 1), too.

From the above results, we should be careful when we discuss the material transport in the MLT region using whether the Eulerian mean or the TEM residual mean circulation obtained from WINDII data set (e.g., Fauliot *et al.*, 1997) which represents the steady circulation averaged over some months.

4. Conclusions and Remarks

In order to evaluate the material transport in the MLT region, Lagrangian transport experiments using wind data simulated by the Kyushu University GCM are performed. From comparison between the TEM residual mean circulation and the advected part of Lagrangian mean circulation, we conclude as follows.

- The TEM residual mean circulation obtained by the present data set resemble the Eulerian mean circulation obtained by the WINDII data set (Fauliot *et al.*,

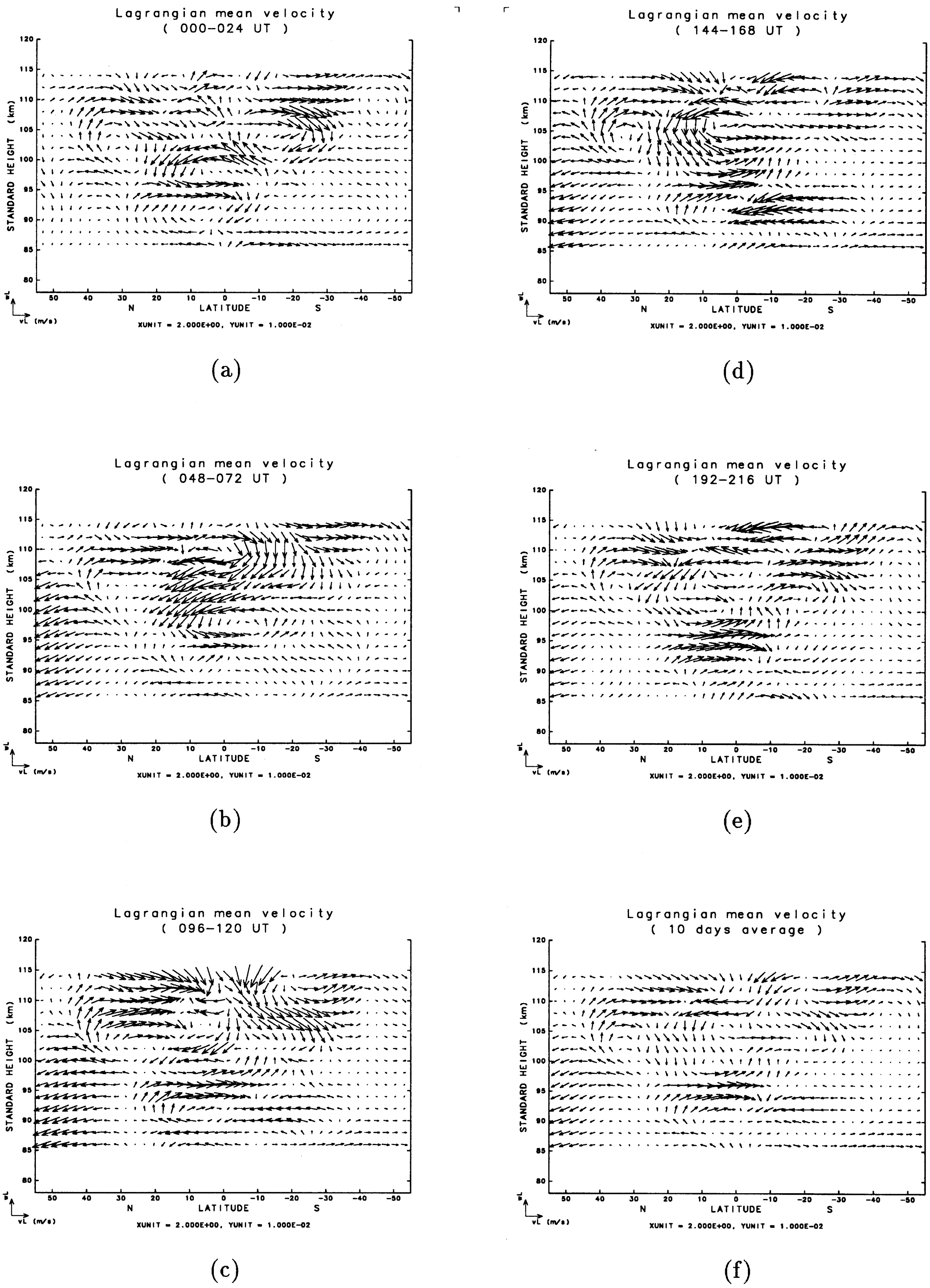

Fig. 5. Advected part of Lagrangian mean meridional circulation of (a): day = 1, (b): day = 3, (c): day = 5, (d): day = 7, and (e): day = 9. (f) shows 10 days average of Lagrangian mean meridional circulation. Unit arrows show 2.0 m s^{-1} in horizontal and 10 mm s^{-1} in vertical.

1997). However, the TEM residual mean circulation do not agree with the advected part of Lagrangian mean circulation in the MLT region for this study.

The TEM residual mean circulation is not necessarily a good approximation of the Lagrangian mean circulation in the MLT region, because of the transient and dissipative structure of waves. However, it is difficult to quantify the effects of transience and dissipation from the present results. Because the GCM wind field is rather complicated, and a similar Lagrangian transport experiment using output data of more simple wave model should be suitable for this problem.

In the present transport experiments, effects of local vertical eddy diffusion due to local convective instabilities associated with large amplitude wave disturbances which occur frequently in the present GCM simulation, are not taken into account. In addition, gravity waves which have periods shorter than 12 hours are filtered out, and waves which have horizontal scales smaller than T21 truncation are also neglected. These effects would make the transport more diffusive than the present results, and the results would be quite different.

The mesopause is analogous to the tropopause in that the static stability of the zonal mean state sharply changes with height. However, as shown in the present experiments, the mesopause is not as important a barrier for the material transport between the mesosphere and lower thermosphere, because of the strong vertical mixing by various wave motions.

Further Lagrangian transport studies with finer resolution data in space and time are needed to reveal Lagrangian transport in the MLT region.

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