Seasonal variation of global stratosphere-troposphere mass exchange*

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Abstract By Wei formula in pressure coordinate, the stratosphere-troposphere mass exchange (STME) is diagnosed globally for 44 years from 1958 to 2001 using the European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis datasets. Regions of mass flux into the stratosphere are found over Indonesia, bay of Bangladesh and the mid-west coast of South Africa. Compensating mass outflow from the stratosphere appears mainly over mid-latitudes near large-scale troughs. Upward and downward transport of mass at the middle and high latitudes accompany with each other. Mass flux into troposphere is stronger in autumn and winter than in spring and summer. Strong downward mass flux into the troposphere occurs in eastern Asia the whole year with nearly stable sites. Although the area of eastern Asia accounts for only 5.6% of that of the northern hemisphere (NH), its net mass exchange reaches 15.83% of that of the NH, which means that research on STME of eastern Asia is greatly important to that of the NH and even the global areas. Air across the tropopause enters more from stratosphere to troposphere than that from troposphere to stratosphere, which is possibly related with systematic bias of the assimilated datasets and with persistent rise of the tropopause height. Contributions of the mass exchange and the mass flux exchange in the NH and southern hemisphere (SH) on their latitudes increase from equator to pole, with larger contributions in the NH. Mass exchange and mass flux exchange per areas at high latitudes are larger than that at low latitudes, which means greater mass exchange efficiency at high latitudes.

Keywords: stratosphere, troposphere, mass exchange, seasonal variation.

Air mass and trace constituents exchange between the stratosphere and the troposphere has long been a crucial problem in meteorology, climatology, and atmospheric chemistry. Since stratospheric air has high potential vorticity (PV), rich ozone and low water vapor and chlorofluorocarbons (CFC) compared with the troposphere, transport and mixing between the stratosphere and troposphere can lead to changes in the chemical and dynamical characteristics of the atmosphere[1,2]. Understanding stratosphere-troposphere exchange (STE) is critical for understanding the spatial and temporal distribution of trace constituent such as ozone, water vapor, nitrous oxide (N_2O), methane (CH_4), and aerosols. Lelieveld[3] thought that ozone in upper troposphere is greatly influenced by STE. In the opinion of Davies and Schuepbach[4], air with rich ozone from stratosphere can be transported to the mid and low troposphere or even to the ground. Otherwise, such violent phenomena scarcely occur in some places with multifarious cycles and tropopause folds, such as northeast North America[5] and near Japan Sea[6].

It is now widely known that air primarily enters the stratosphere in the tropics and sinks back into the troposphere at extratropical latitudes as part of the Brewer-Dobson circulation, which was deduced from analysis of water vapor and ozone observations in the stratosphere by extending the circulation below the tropopause[7—9]. Much of our current knowledge of the global budget is derived from Reiter[10], who attempted to assimilate the findings from case studies with large-scale analyses of the zonally averaged mass circulation. Researches of Spaete et al.[11] and Lamarque et al.[12] were concentrated on cases, which cannot reveal long-term cross tropopause flux of the NH and the globe. Hoerling et al.[13] and Siegmund et al.[14] discussed the NH, but only limited to one month in winter. Schoeberl et al.[15] computed the global mid-latitude STME and pointed out that STME at mid-latitude was mainly determined by air between the tropopause and 380 K isentropic surface.

As important mechanisms of STME in the extratropics, tropopause foldings, associated with plane-

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tary- and synoptic-scale Rossby wave breaking[16—21], cutoff lows[22—25] and storm[11], have been widely studied in observations and models. Subtropical jet stream[26] can also result in STME. Some other researches focus on the annual cycle of transport between the stratosphere and the troposphere[27,28], and the seasonal and spatial variations of the cross-tropopause exchange (CTE)[13—15,29—33].

Methods to estimate STME involve Eulerian analysis including mass budget calculations[12,13,27,28,34,35], semi-Lagrangian transport model[29], combination of the two in the tracer transport budget calculation[36], and Lagrangian analysis[31,37,38].

From the above, we can see that previous work basically focused on regional phenomenon studies or short-term studies or case studies. However, large-scale and long-term calculations of STME are absolutely essential in order to understand global STME in seasonal, interannual and even decadal timescales.

The purpose of the current study is to diagnose the global and regional distributions of the time-averaged STME. The roles of individual processes are examined, including horizontal movement of air at the tropopause, vertical movement of air at the tropopause, and the shift of the tropopause itself.

1 Data and methodology

ECMWF reanalysis data from 1958 to 2001 was used, with a $2.5^{\circ}\times 2.5^{\circ}$ horizontal resolution, 23 levels in the vertical and an interval of 6 hours each day.

In the present study, Wei formula[39] was used to calculate cross-tropopause flux (CTF) in pressure coordinate

$$F(\rho) = -g^{-1}\left(\frac{DP}{Dt} - \frac{\partial P_{tp}}{\partial t} - \boldsymbol{V}\cdot\nabla P_{tp}\right)$$
$$= \left(\frac{1}{g}(\boldsymbol{V}\cdot\nabla P)_{tp} - \frac{\omega}{g}\right) + \frac{1}{g}\frac{\partial P_{tp}}{\partial t}$$
$$= F_{AM} + F_{TM} \tag{1}$$

where $\omega = DP/Dt$ is the vertical velocity, $\boldsymbol{V}$ the vector horizontal velocity, P_{tp} the tropopause pressure, F_{AM} the mass exchange caused by air movement, and F_{TM} the mass exchange by tropopause movement.

Two definitions of the tropopause were used to evaluate STME. A thermal method[9] was used which defines the tropopause as 380 K isentropic surface. A dynamical method[40] based on potential vorticity (PV) was also used, which used 3.5 PVU (1 PVU $= 10^{-6}\ m^2\cdot K\cdot kg^{-1}\cdot s^{-1}$) to define the tropopause. We thus produced a "blended" analysis that uses the dynamical definition poleward of 30° latitude and the thermal definition equatorward of 10° latitude. The analysis in subtropics was based on a weighted average[13] of dynamically and thermally derived tropopause pressure according to

$$P = WP_{\text{dynamical}} + (1 - W)P_{380\,K} \tag{2}$$

where the weights W are defined by

$$W = A\,\text{sech}\,\Phi + B\Phi^2 + C \tag{3}$$

The coefficients in (3) are empirically derived such that $W=1$ at $\Phi=30^{\circ}$, $W=0$ at $\Phi=10^{\circ}$ and $W=0.5$ at $\Phi=20^{\circ}$.

2 Seasonal variation of global stratosphere-troposphere mass exchange

In order to present large-scale features of seasonal variations of STME, the filtering methods used by Schaack[41] were utilized. First, Fourier transformation was used to filter waves with wavenumber larger than 5 at the longitude, then low-pass filtering method was used at the latitude to perform 4-time (2, 3, 2) transformation and 1-time (−1, 5, −1) inverse transformation.

The global upward and downward cross-tropopause mass flux (CTMF) was computed at a 6-hour interval with space filtering and time average. Fig. 1 shows the result.

2.1 The tropics

Fig. 1 shows that, for March-April-March (MAM), downward mass flux appears over mid- and east-tropical Pacific, southeast America, northwest and southeast coast of Atlantic, north Australia and central and northern Africa, with a peak -2×10^{-4} $kg\cdot m^{-2}\cdot s^{-1}$ over southeast coast of America. On the other hand, upward transport from the troposphere into the stratosphere is concentrated over bay of Bangl, Indo-China Peninsula, mid- and west-coast of Africa, mid- and west- coast of south America, with a peak 2×10^{-4} $kg\cdot m^{-2}\cdot s^{-1}$ over bay of Bangl.

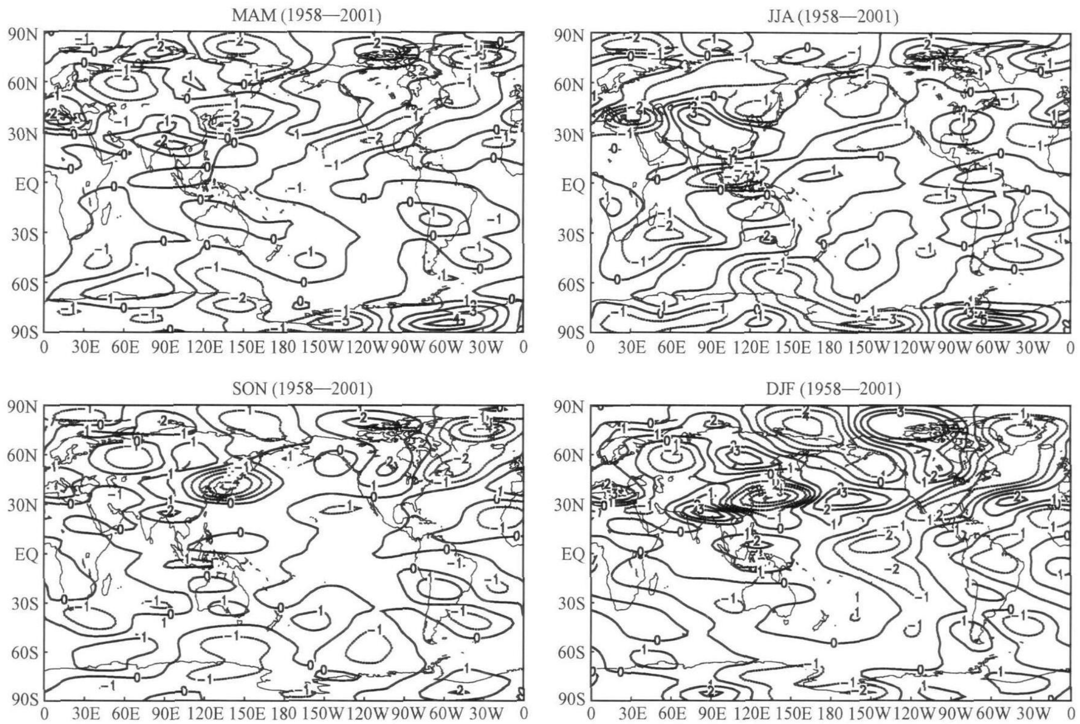

Fig. 1. Seasonal stratosphere-troposphere mass flux exchange for (a) spring (MAM); (b) summer (JJA); (c) autumn (SON); and (d) winter (DJF). Positive (negative) values indicate a time-mean mass flux from the troposphere (stratosphere) into the stratosphere (troposphere) (Contour interval: 10^{-4} kg·m^{-2}·s^{-1}).

The June-July-August (JJA) climatology for downward flux presents nearly the same peak areas. The primary peak over mid- and east-tropical Pacific is a bit weaker than the counterparts for the MAM case, while the peak over Indonesia extends a little and strengthens to -3×10^{-4} kg·m^{-2}·s^{-1}. Upward transport peaks over northwest/southeast coast of Africa and mid- and central-coast of south America are strengthened and a new peak occurs over southeast of America.

In September-October-November (SON), the negative peak over Indonesia is replaced by a positive one, while the peak over Indo-China Peninsula bates to 2×10^{-4} kg·m^{-2}·s^{-1}. Additionally, downward peak over northwest of Africa and upward peaks over mid- and west-Africa/south America scarcely change.

As far as December-January-February (DJF) is concerned, upward flux over Indo-China Peninsula, Philippines and Indonesia strengthen to their maxima, with peaks 3×10^{-4} kg·m^{-2}·s^{-1} and 2×10^{-4} kg·m^{-2}·s^{-1}, respectively, while downward flux over tropical mid-Pacific, northwest Africa and northern South America strengthen a little, with peaks -3×10^{-4} kg·m^{-2}·s^{-1} and -3×10^{-4} kg·m^{-2}·s^{-1} over tropical mid-Pacific and northeast South America.

2.2 Mid- and high-latitudes

Upward and downward mass flux appears alternatively at mid- and high-latitudes, with prominent "+−+−" distribution. Downward transport mainly appears near the large-scale troughs, stronger in autumn and winter than in spring and summer.

During MAM, downward mass flux appears over eastern Asia, southeastern part of North America, and central Europe, which correspond to the regions of the highest occurrence of Rossby wave-breaking events, and over Greenland and the northeastern Russia, with a peak -3×10^{-4} kg·m^{-2}·s^{-1} in eastern Asia and Greenland. Downward exchange regions are well correlated with the NH storm tracks, whose activity is greatest at the tropopause level. This indicates the significance of baroclinic activity in mass exchange across the tropopause.

JJA climatology for downward flux gives nearly the same peak areas with a little weakening. The primary peaks over eastern Asia, central Europe, northeastern Russia and Greenland are a bit weaker than the counterparts for the MAM case, while a new peak -4×10^{-4} kg·m^{-2}·s^{-1} occurs over the Mediterranean.

As for SON, peaks over eastern Asia, southeastern part of North America and Greenland strengthen and extend much, with new peaks -4×10^{-4} kg·m^{-2}·s^{-1}, -2×10^{-4} kg·m^{-2}·s^{-1} and -4×10^{-4} kg·m^{-2}·s^{-1} respectively, among which the former two are consistent with the deepening of the troughs. Additionally, the peak over northeastern Russia extends much and keeps the same extent. It is worth noticing that a new downward flux peak appears again over central Europe, and the downward flux over Mediterranean vanishes, replacing with the upward flux.

Finally, more attention should be paid to STE in DJF, during which peaks of the downward transport over eastern Asia, southeastern part of North America, central Europe, Greenland and the northeastern Russia are almost the strongest all over the year, with the maximum -7×10^{-4} kg·m^{-2}·s^{-1} over eastern Asia. In mid-latitudes, the most prominent feature is the intense outflow from the stratosphere over eastern Asia, the southeastern United States and the central Europe. These centers lie within the base of the Asian, North American, and European trough axes. A transport of mass to the stratosphere is generally found downstream of the mid-latitude outflow regions. The pattern is particularly well defined over the North Pacific, northern North America and the central Eurasia. The results in Fig. 1 imply that the time-mean effect of air-mass migrations downstream of the stationary troughs is to transport mass of low-latitude origin poleward and upward across the high-latitude tropopause.

In addition, the ingress to the stratosphere over the northern Canada and its poleward areas is as intense as that occurring over tropics and mid-latitudes all the year, especially in winter, a feature of the global budget different from previous work, which is worthy of being further investigated.

As far as the SH is concerned, it shows a simple STME pattern with the peaks centered on the Antarctic land along 80°S, and upward (downward) centers over the south (east) coast of Australia and the southwest (southeast) coast of South America. The magnitude of STME in mid-latitude is small and less well organized than the NH case due to the greater zonal symmetry in storm tracks in the SH than in the NH, while it is contrary in high latitude especially on the Antarctic continent which is not mentioned in previous works. Therefore, much attention should be paid to the STME study on the Antarctic continent.

In autumn of the SH (corresponding to spring in the NH), at high-latitude, upward (downward) transport appears over east (west) of 110°W, south (east) coast of Australia, southwest (southeast) of south America, and southwest (southeast) coast of Africa. In winter, STME presents "$-+-+$" pattern along 80°S from west to east centered in 40°E, 130°E, 140°W and 60°W with the positive (negative) center over south coast of Australia (southeast coast of Africa) strengthened to 2×10^{-4} kg·m^{-2}·s^{-1} (-2×10^{-4} kg·m^{-2}·s^{-1}), while the peaks over southwest coast of Africa, southwest and southeast coast of south America keep the same. Compared with winter, the "$-+-+$" pattern still exists but the peaks bate a little in spring, with the centers 130°E, 140°W and 60°W moving to 110°E, 170°W and 40°W at the same time. Additionally, at mid-latitude, the pattern shows similar to winter except for a bit weakening of the negative center over south coast of Africa. In summer, the "$-+-+$" pattern on the Antarctic continent is similar with that of the spring except for a little strengthening, while the pattern at mid-latitude keeps similar except for a bit weakening.

For the most part, the results in Fig. 1 indicate a preference for stratospheric mass outflow at low latitude of extratropics near quasi-stationary troughs, and a return mass flow to the stratosphere at high latitudes of extratropics near quasi-stationary ridges, which is consistent with the result of Hoerling et al.[13]. However, STME patterns at high latitude are different from that of Hoerling's, which is probably caused by the data lengths and the methods to compute STME. Additionally, our results in NH present similar patterns as that of Yang and Lu[33] over most parts of the NH. Nevertheless, different patterns appear in some places such as the northern North America and the northern Europe in autumn, and tropical middle and eastern Pacific in spring, summer and winter, which may be induced by different datasets (NCEP reanalysis datasets used by Yang and Lu, while ECMWF reanalysis datasets by us) and the filtering methods.

2.3 Eastern Asia

As is known to all, STME at mid-latitude is accomplished in two ways: one is the adiabatic process through isentropes fulfilled by the eddy motion such as the tropopause folds, cut-off lows and upper troughs, and the other is the diabatic process through isentropes which are mainly the small-scale mixture and turbulence processes.

Eastern Asia (30°—60°N, 100°—150°E) lies in the east of the largest continent (the Eurasian continent), with the largest ocean (the Pacific Ocean) to its east and Qinghai-Tibetan Plateau in its west. Thermal difference between land and sea, and dynamical and thermal roles of the plateau make it significant to the STME in this region, therefore it is greatly important to understand the mechanisms of STME at mid-latitudes.

STME over eastern Asia is shown in Fig. 1. Strong mass flux from the stratosphere into the troposphere occurs over a steady area all the year, with a maximum in winter and a minimum in summer. Mass transported from the troposphere (stratosphere) to the stratosphere (troposphere) is 11.2998×10^{17} kg (-12.1701×10^{17} kg) for the NH during the 44 years from 1958 to 2001, and 0.8598×10^{17} kg (-0.9987×10^{17} kg) for eastern Asia which accounts for 7.61% (8.20%) of that of the NH. What really attracts us is that the cross-tropopause net mass exchange in the NH and eastern Asia is -0.8704×10^{17} kg and -0.1388×10^{17} kg respectively, with the latter accounting for 15.83% of the former (Table 1), while the area of eastern Asia is only 5.6% of that of the NH. Therefore, STME of eastern Asia plays an important role in that of the NH and even the globe.

Table 1. Averaged cross tropopause mass exchange of 44 years (unit: 10^{17} kg)

	Net exchange	Troposphere to stratosphere	Stratosphere to troposphere
Globe	−1.5391	20.3028	−21.8419
NH	−0.8704	11.2998	−12.1701
SH	−0.6688	9.0030	−9.6718
Eastern Asia (EA)	−0.1388	0.8598	−0.9987
Percentage of EA in NH	15.83	7.61	8.20

Percentage of the annual CTMF in eastern Asia in that of the NH shows about a 20-year period (Fig. 2), with the above-average in the 1960s and 1980s and under-average in the 1970s and 1990s, which are closely correlated with semi-tropical summer monsoon index from Shi[42]. In addition, the above percentage changed in the late 1970s, which probably indicates that CTMF change in the late 1970s in eastern Asia is closely associated with the abrupt change of the general circulation of atmosphere between the late 1970s and early 1980s in the northern hemisphere.

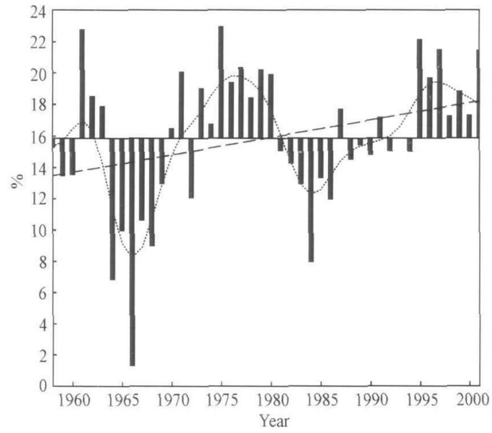

Fig. 2. Ratio of annual cross-tropopause mass exchange in eastern Asia to that of the NH (column bar). The dot dash line is the Gauss 9-point filter curve of the ratio; long dashed line indicates the tendency of the ratio.

2.4 Seasonal variation of monthly- and zonal-averaged mass flux

The seasonal variation of monthly- and zonal-averaged mass flux is shown in Fig. 3.

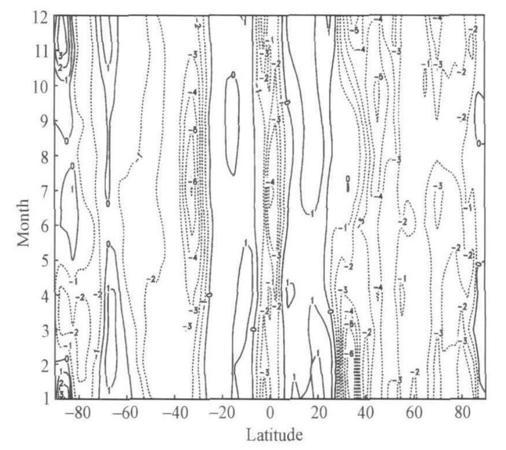

Fig. 3. Seasonal variation of monthly mean and zonal mean cross-tropopause mass flux. Positive (negative) values indicate a time-mean mass flux from the troposphere (stratosphere) into the stratosphere (troposphere). Contour interval: 10^{-4} kg·m^{-2}·s^{-1}. Positive (negative) values in abscissa present northern (southern) latitude, 0 is the equator.

It tells us that regions of mass outflow across the tropopause are between 5°—25°N, 5°—25°S and the neighborhood of the North and the South Pole. Areas of the upward mass flux extend wider longitudinally in the tropics than in the polar regions, with the maxima concentrated between 10° and 20° in both hemispheres, which spans widest in summer. Additionally, it is worth noticing that downward mass flux appears between 5°S and 5°N, which is possibly brought about by the weakening of the equatorial convergence zone.

At mid-latitude, the net STME is almost the inflow from the stratosphere. In the NH, the peaks of the downward mass flux move from south to north from winter to summer with the peak centered at 45°N in autumn, then switch back to south from autumn to winter with the peak concentrated at 35°N. The strongest downward mass flux is in winter (February) with a maximum -6×10^{-4} kg·m^{-2}·s^{-1}. While in the SH, the downward flux peaks are mainly along 30°S with a maximum -6×10^{-4} kg·m^{-2}·s^{-1} in July.

At high latitude, transport of mass to the stratosphere is generally found over northward of 80°N, 60°—70°S and southward of 80°S with a maximum occurring in summer in the South Pole. While, transport of mass to the troposphere is over northward of 60°—85°N and 75°—85°S, with a maximum -3×10^{-4} kg·m^{-2}·s^{-1} in January in the NH and a maximum -2×10^{-4} kg·m^{-2}·s^{-1} in March in the SH.

2.5 Contributions of different parts in Wei formula to CTMF

According to (1), the cross-tropopause mass flux is determined by three processes: The role of horizontal movement of air (HMA) at the tropopause, the role of vertical movement of air (VMA) at the tropopause, and the role of the movement of the tropopause (TM) itself. Fig. 4 shows seasonal- and zonal-averaged cross-tropopause mass flux and the co-

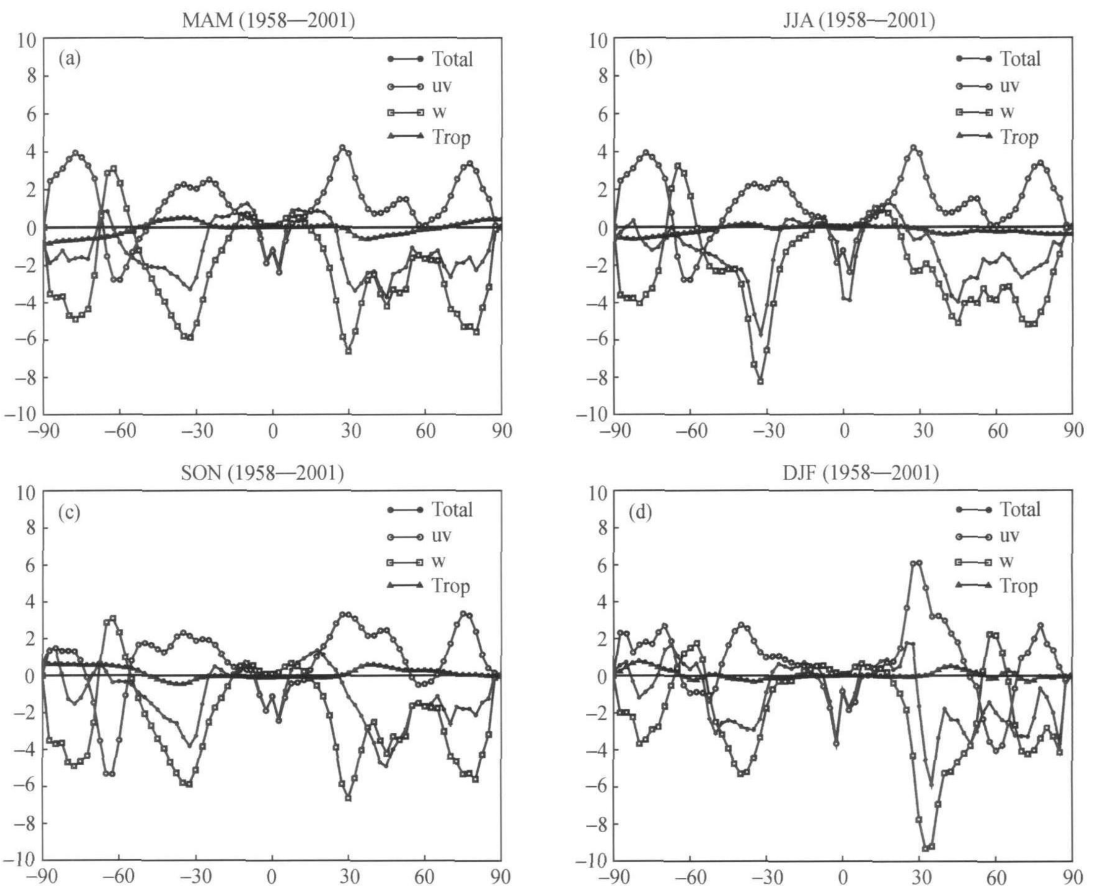

Fig. 4. Seasonal mean and zonal mean cross-tropopause mass flux exchange (total) and that caused by the horizontal movement of air (uv), vertical movement of air (w), and the movement of the tropopause itself (trop) for (a) spring (MAM); (b) summer (JJA); (c) autumn (SON); and (d) winter (DJF). Positive (negative) values indicate a time-mean mass flux from the troposphere (stratosphere) into the stratosphere (troposphere). Contour interval: 10^{-4} kg·m^{-2}·s^{-1}. Positive (negative) values in abscissa present northern (southern) latitude, 0 is the equator.

unterpart caused by its three different parts. We can see clearly that HMA and VMA count more to STME while TM counts less, especially in the tropics. The contribution of HMA is the largest between 5°S and 5°N probably as a result of the weakening of the equatorial convergence zone, while VMA is the biggest poleward of 10° in the tropics in both hemispheres where the diabatic process is the primary mechanism leading to STME. CTMF at middle and high latitude is the difference between HMA and VMA, the two of which have opposite phase but nearly the same order of magnitudes. According to conservation of mass, convergence and divergence caused by horizontal movement are closely related with vertical ascent and descent. Air at mid- and high-latitudes has an obvious baroclinic character, and quasi-geostrophic movement in baroclinic air is not a pure horizontal movement, accompanied with the vertical circulation above the quasi-geostrophic horizontal movement; during the destruction from advection to geostrophic balance, vertical circulation plays a role of compensation. In addition, it is worth noticing that CTMF around 60°N, 50°S and 70°S is close to zero, which is possibly correlated with strong wind shears around polar-front jets and is to be further investigated.

3 Averaged cross-tropopause mass exchange of 44 years

Global cross-tropopause mass exchange (CTME) was computed annually from 1958 to 2001 (Table abridged), and then we got its average (Table 1). It is shown that the annual net mass exchange is all negative in both NH and SH, which does not agree with the reality in such a long time period.

For the reason of the bias, CTME anomalies in NH, SH (Fig. 5) and the globe (Figure abridged) were evaluated. In addition, balance between the total transport from upward and downward and 44-year averaged transportation were computed, then the percentage of the balance to 44-year averaged transportation was given (Fig. 6).

Fig. 5 shows that from the 1970s, in both NH and SH, cross tropopause net mass exchange, upward exchange and downward exchange have an obvious increase especially in the SH, which discovers more active weather systems in the SH during the latest 30 years. While, it is worth noticing that CTME decreased from the 1990s in the NH, which indicates that weather systems in the NH become stable. Eastern Asia has a similar change with that of the NH.

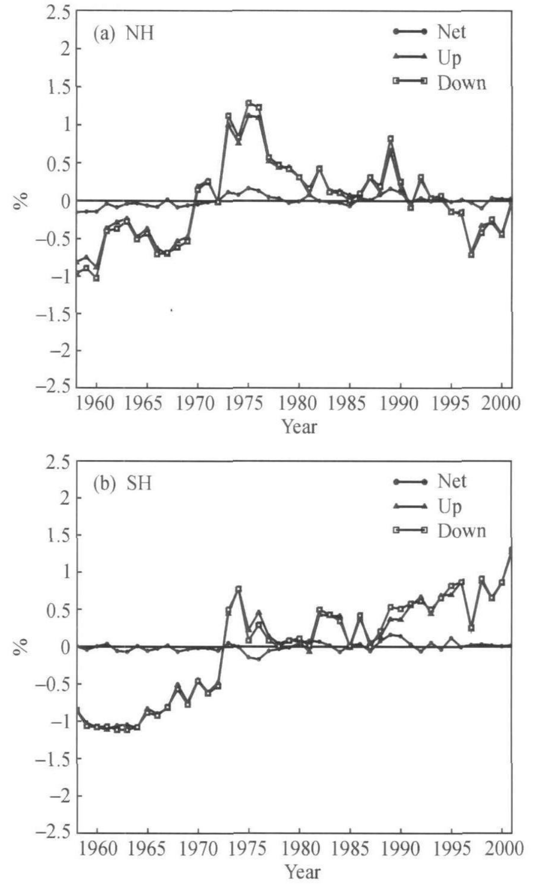

Fig. 5. Annual cross tropopause mass exchange anomaly in NH (a) and SH (b). Dot solid line indicates net exchange, and triangle-solid (square) line is the exchange from the troposphere (stratosphere) into the stratosphere (troposphere)) (unit: 10^{17} kg).

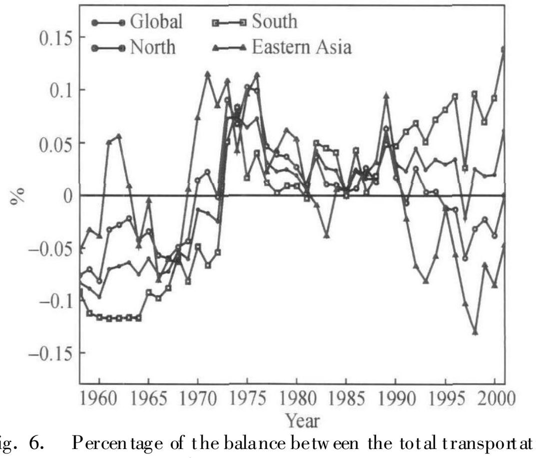

Fig. 6. Percentage of the balance between the total transportation (upward and downward) and 44-year averaged transportation in 44-year averaged transportation.

Fig. 6 indicates that STME is weak before the early 1970s in both hemispheres, while stronger from the mid-1970s to the early 1990s, which is possibly associated with global climate abrupt change in the late 1970s and early 1980s. Furthermore, STME shows opposite character in the NH and SH, which indicates more active STME in the SH than that in the NH from the 1990s.

In addition, seasonal and yearly-averaged tropopause heights from 1958 to 2001 were computed (Figures are abridged). We found that in both NH and SH, tropopause heights showed a prominent ascent during the 44 years, which suggests more advantageous transportation from stratosphere to troposphere and partly explains the negative net STME during the 44 years.

4 Latitudinal ratios of the net mass flux exchange and the net mass exchange to their areas

Fig.7 implies that contribution of the net mass flux to its latitudes is larger at high latitudes than at low latitudes although the areas at high latitudes are smaller than that at low latitudes, which indicates that the net STMF per area is larger at high latitudes. That is to say, the STMF efficiency at high latitudes is greater than that of the low latitudes, resulting from lower tropopause heights at high latitudes than at low latitudes, which is more advantageous to STME.

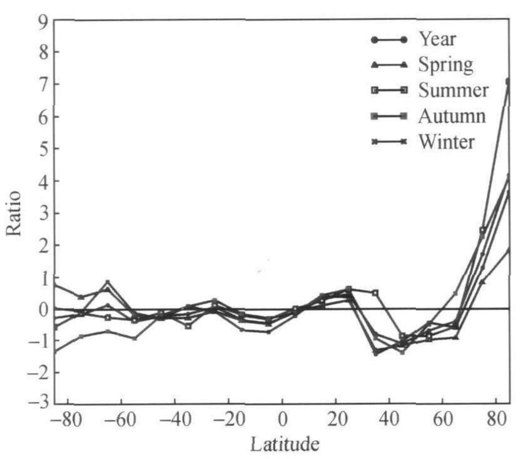

Fig. 7. Latitudinal ratio of the net mass flux exchange to theri areas (unit: 10^{-16} kg·m^{-2}·s^{-1}). Positive (negative) values in abscissa represent northern (southern) latitude; 0 is the equator.

From Fig. 8, we can see that contribution of the net mass exchange to its latitudes is larger in the NH than in the SH, which implies that there are more multifarious, violent and complicated weather conditions in the NH than in the SH especially at about 25°N, 45°N and 75°N.

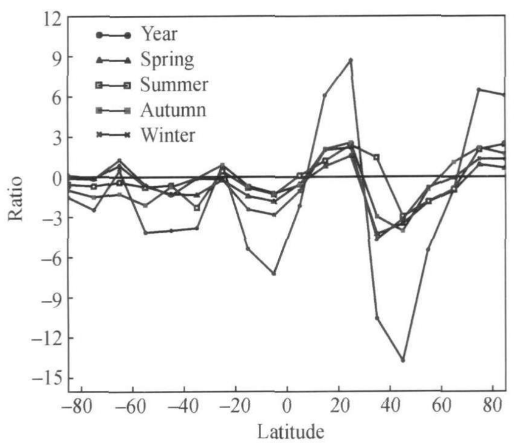

Fig. 8. Latitudinal ratio of the net mass exchange to their areas (10^3 kg·m^{-2}). Positive (negative) values in abscissa represent northern (southern) latitude; 0 is the equator.

5 Summary and discussion

Indonesia, bay of Bangl and the mid-west coast of the South Africa are the main channels of the upward mass flux into the stratosphere. Upward and downward transport of mass at the middle and high latitude accompany with each other. Downward transport from the stratosphere to the troposphere mainly appears near the large-scale troughs, while transport of mass to the stratosphere generally occurs downstream and poleward of the midlatitude outflow regions. Mass transport into troposphere is stronger in autumn and winter than in spring and summer.

Strong downward cross-tropopause mass flux appears in eastern Asia. Although the area of eastern Asia accounts to only 5.6% of that of the NH, its net mass exchange reaches 15.83% of that of the NH, which means that STME in eastern Asia is highly important to that of the NH and even the globe.

Contribution of HMA is the largest between 5°S and 5°N, while VMA is the biggest poleward of 10° in the tropics in both hemispheres. CTMF at middle and high latitude is the difference between HMA and VMA with opposite phase but nearly the same order of magnitudes.

It is noted by Gettelman[28] that it is essential for accuracy of the prognosticated data and the assimilated data in order to use Wei method. Biases from data may lead to obvious deviation from the results. From our analysis, net CTME is from stratosphere to troposphere, which is probably caused by systematic errors of the assimilated data and the persistent ascent of the tropopause height. STME negatives in the equator may be due to the persistent cooling on equipotential temperature surface in the assimilated data.

Net STME has a similar trend both in 5°S—5°N and the globe (Figs. are abridged), which indicates that the former is indicative to the latter, which is to be further studied.

Contributions of the mass exchange and the mass flux exchange in NH and SH to their latitudes increase from equator to pole, with larger contributions in the NH. Mass exchange and mass flux exchange per area are larger at high latitudes than at low latitudes, which implies greater mass exchange efficiency at high latitudes.

Previous work on STME is more concentrated on the tropics and extra-tropics than on the polar regions. Otherwise, with more complexity of the polar weather and climate and with the acquisition of the polar data, it should have become a very critical issue for the study on STME in the polar regions. Also, the relationship between STME and ozone on the Antarctica continent is worth to be noticed and studied.

Additionally, owing to the peculiar geographic situations and general circulation characteristics of eastern Asia and Qinghai-Tibetan Plateau, it is worth researching on STME of the two regions especially on the correlated mechanisms.

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