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Atmospheric Chemistry and Physics Discussions

Interactive comment on "The governing processes and timescales of stratosphere-to-troposphere transport and its contribution to ozone in the Arctic troposphere" *by* Q. Liang et al.

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We thank the anonymous reviewer for the comments.

Major concerns 1) and 3).

The term "diabatic descent" does not refer to any specific transport mechanism, but rather the general descending motion of an air parcel that is accompanied by diabatic cooling. We agree with the reviewer that STT is mostly associated with episodic mesoscale perturbations of the tropopause. But these perturbations can occur both adiabatically along isentropes and diabatically. Holton et al. (1995) suggested that for STE, "what is significant is the irreversible transport across the tropopause, more precisely, across some representative mean position of the tropopause, that may be asso-

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ciated, for instance, with the synoptic-scale baroclinic eddies or with smaller-scale processes or with global-scale diabatic ascent or descent" (Page 405). Figure 3 in Holton et al. (1995) summarizes the dynamic aspects of STE and "is useful to distinguish between transport along isentropic surfaces, which may occur adiabatically, and on the other hand transport across isentropic surfaces, which may require diabatic heating, including small-scale three-dimensionally turbulent processes" (page 407). Holton et al. 1995 also pointed out that "the wavy arrows (adiabatic transport by eddy motions) are not meant to suggest the complete picture (of STE transport), even for transport along isentropes". For stratospheric air to be transported into the troposphere, in particular the mid and lower troposphere, diabatic descent across the isentropes has to occur as the troposphere in general has lower potential temperatures than the lower stratosphere. The paper referenced by the reviewer, Stohl et al. (2003), also stated that "transport from the overworld to the troposphere is slow because air must cross isentropic surfaces, which requires diabatic cooling" (page 1-2). The reviewer stated that through his/her review of literature, he/she could think of no examples of slow diabatic downward transport of stratospheric ozone across the tropopause and STT transport is almost entirely associated with episodic transport along isentropes. In fact, many examples in the literature show that STE is comprised of an adiabatic and a diabatic component and numerous modeling studies have been conducted to quantify the relative contribution of adiabatic and diabatic STE mass fluxes (e.g. Dethof et al. 2000; Yang and Tung, 1996; Schoeberl et al., 2004; Olsen et al., 2004). The diabatic descent is particularly important for STT into the Arctic troposphere. Since, in a typical two-dimensional picture, isentropes do not intersect with the tropopause in the Arctic, diabatic descent is required for air of stratospheric origin to enter the Arctic troposphere.

The purpose of this paper is to use CFC-12 and dynamic tracers and their seasonal cycles as diagnostics to understand the timescale of stratosphere-to-troposphere transport. Several previous studies have used long-lived tracers, e.g. CFCs and N2O, as a diagnostic to track diabatic descent in the polar region (e.g. Rosenfield et al.,1994;

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Strahan et al.,1994). Propagation of a periodic tracer, such as CFC-12, is adequate in estimating transport age (Waugh and Hall, 2002). Unlike artificial particles or dynamic tracers, the use of CFC-12 makes it possible to compare with the observations, which provides a crucial observational constraint on model-simulated transport time. The fact that our simulated seasonal minimum in the lower stratosphere and at the surface (the minimum at the surface lags the minimum in the LS by 3 months) agrees well with the observations suggests that the model reproduces well STE/STT, which occurs slowly during a 3-month period. This is explained in the manuscript (section 1 and 3.2). Three papers that were referenced by the reviewer (James et al., 2003; Stohl et al., 2003; Stohl, 2006) found very similar transport times, 1 month from the lower stratosphere to the upper tropopause and 3 months from the lower stratosphere to the surface in the Arctic, lending more confidence to our model results. More specifically, James et al. (2003) and Stohl et al. (2003) showed that STT tracers (PV $>$ 2) with an age of 0-20 days account for only 18.3% of air in the troposphere, while tracers with age 20-90 days and $>$90 days account for 37.5% and 44.1%, respectively. Mixing ratios of STT tracers with young age of air (0-20 days) maximize at about 5-8 km in the Arctic troposphere, and those with age 20-90 days and $>$ 90 days maximize at 3 km and surface, respectively. This implies vertical transport times of 1 month to the upper troposphere and $>=$ 3 months to the surface. Stohl [2006] found that the average age in the lower troposphere in the Arctic since a particle left the stratosphere is on the order of 100 days.

While many STE studies are interested in understanding the episodic processes that contribute to STE, the main focus of this study is to understand the accumulated impact of stratosphere-to-troposphere transport and how that affects the seasonal cycle of ozone in the Arctic troposphere, using monthly-averaged CFC-12 and dynamic tracers. The identification of the actual synoptic-scale processes is beyond the scope of this study. Holton et al. (1995) explained that while “the quasi-isentropic transport of air out the lower-most stratosphere initiated by tropopause folding could in principle occur in the absence of the global-scale diabatic circulation”, in fact, “the global-scale diabatic

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circulation is required to transport stratospheric constituents such as ozone downward from the over world to the lowermost stratosphere. The average rate at which such a species can be transported into the troposphere is thus ultimately determined by the rate at which the dynamically controlled global-scale circulation transports mass from the overworld into the lowermost stratosphere. The details of mesoscale tropopause-folding events may not be important for determining the global flux of ozone and other tracers from the stratosphere" (page 422). In addition, Haynes et al. (1991) stated that "the rate at which stratospheric material becomes available for descent into the extratropical troposphere after descending across the 350 K isentropic surface is controlled exclusively by eddy dissipation on isentropic surfaces lying above the 350 K surface, whatever the rate of tropopause folding, cutoff cyclone formation, or other aspects of eddy motion, below that surface" (page 652-653).

Although we disagree with the reviewer on several points as discussed above, we have taken serious consideration of the reviewer's comments and revised our manuscript accordingly for a clear explanation of the processes contributed to STE and STT.

2) Figure 5 seems to imply that 20-25% of the air that is transported downwards across the tropopause in the polar regions remains in the polar regions over 3 months as it descends into the lower tropopsphere, as if there exists some type of quasi-permanent Arctic tropospheric vortex. This seems very unlikely given the transport patterns across the Arctic. Stohl [2006] provides a very nice analysis of transport patterns and lifetimes in the Arctic, for tracers of stratospheric air and for anthropogenic pollutants. He conň-cludes that the average age of an air parcel north of 80 N is 1-2 weeks at the surface and much less at higher altitudes, only about 3 days in the upper troposphere. This was clear to the many researchers who visited the Arctic this past spring for the various air pollution studies. Polluted air masses from the mid-latitudes frequently traversed the Arctic leaving little time for air masses to become isolated and well aged. Therefore the stratospheric tracers in the present study that enter the troposphere in the Arctic are quickly advected out of the Arctic and then travel far and wide across the northňern *hemisphere as they descend through the troposphere and become well mixed with stratospheric tracers that entered the troposphere at lower latitudes. A comparison between the present study and Stohl [2006] regarding transport times and STE needs to be included in the manuscript.*

The definition of the age of air in the Arctic in Stohl (2006) is different from the transport time (since the air left the stratosphere) in this study. The age of air in the Arctic in Stohl (2006) refers to the time that an air parcel spend in the Arctic troposphere, which includes both vertical transport from/to the stratosphere and horizontal transport from/to the lower latitudes. The transport time in this study is defined as the time elapsed since an air parcel crosses the tropopause and enters the troposphere. The relatively short age of air (1-2 weeks) in Stohl (2006) is mostly due to efficient exchange of air in the horizontal between different latitudes. This is consistent with our results that the timescale of horizontal air mass transport between the mid latitudes and the polar region is on the order of one month (section 4.3 and 4.4) based on monthly-averaged tracer concentrations. In addition, Stohl (2006) calculated that the average time in the lower troposphere in the Arctic since a particle left the stratosphere is on the order of 100 days (page 6), which agrees well with the results we have shown in this study. The other two papers that the reviewer suggested that are highly relevant to this study, James et al. (2003) and Stohl et al. (2003), concluded that rapid deep STT does not occur frequently. Figure 1 in James et al. (2003) showed that STT tracers (PV $>$ 2) with an age of 0-20 days account for only 18.3% of air in the troposphere, while tracers with age 20-90 days and $>$90 days account for 37.5% and 44.1%, respectively. Mixing ratios of STT tracers with young age of air (0-20 days) maximize at about 5-8 km in the Arctic troposphere, and those with age 20-90 days and $>$ 90 days maximize at 3 km and surface, respectively. This implies vertical transport times of 1 month to the upper troposphere and 3 months to the surface, which also agrees well with our results. The agreement between our analysis and these studies demonstrates the robustness of our model results. We thank the reviewer in pointing out the importance of the above studies, which we have referenced in our revised manuscript.

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4) The authors need to carefully consider and reference the findings in two papers that are highly relevant to the present study. James et al., [2003] used the FLEXPART Lagrangian particle dispersion model to study global STE processes. They discuss 1) the tropospheric distribution of stratospheric tracers with ages varying from 1 to greater than 90 days, 2) the regions most strongly impacted by stratospheric intrusions and 3) the seasonal variation of stratospheric ozone in the mid-latitudes (but with lifetimes less than 30 days).

James, P., A. Stohl, C. Forster, S. Eckhardt, P. Seibert, and A. Frank, A 15-year climaň-tology of stratosphere-troposphere exchange with a Lagrangian particle disňpersion model, 2, Mean climate and seasonal variability, J. Geophys. Res., 108(D12), 8522, doi:10.1029/2002JD002639, 2003.

Another paper (now classic) that is of interest for Arctic STT mechanisms is Shapiro et al. [1987].

SHAPIRO MA, HAMPEL T, KRUEGER AJ, THE ARCTIC TROPOPAUSE FOLD, MONTHLY WEATHER REVIEW Volume: 115 Issue: 2 Pages: 444-454, 1987.

We thank the reviewer for pointing out the relevance of the above papers, in particular James et al. (2003) (see response to major comment 2) and have included these two papers in references.

Specific comments:

1. Introduction: When discussing the cause of the springtime ozone maximum please also reference: Stohl et al. (2003) A NEW PERSPECTIVE OF STRATOňSPHERE-TROPOSPHERE EXCHANGE. Bull. American Met. Society, which concludes that the springtime ozone maximum cannot be sue to STT alone because STT peaks earlier than the ozone maximum. This same Stohl paper is also the first (to the best of my knowledge) to recommended that STE be divided into STT and TST, as was mentioned in the present study on page 19381.

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We have added Stohl et al. (2003) in the references.

2. Section 2, Model description: Please provide the model horizontal and vertical resolution as well as the model time step for both calculations and output.

The horizontal resolution of the simulation is 2° latitude by 2.5° longitude. The original meteorological fields have 55 layers extending from the surface to 0.01 hPa, which have been regridded to 42 layers. There are 20 layers from the surface to the lower stratosphere with about 1 km resolution near the tropopause. The surface and upper level meteorological fields are updated every 3 hours and 6 hours, respectively. Advection and chemistry are computed every 30 minutes and 30-minute output are accumulated to calculate monthly averages. We have added this in the manuscript.

3. page 19383 What is the definition of the tropopause in this paper?

The tropopause is defined using a combination of temperature profiles and potential vorticity as the highest thermal tropopause (defined by temperature lapse rate) below 3PVU. We have added this in the manuscript.

4. page 19384 Does the amplitude of the dynamic tracers range from 50 to 150 ppbv?

The prescribed annual cycle of the dynamic tracers is defined by first averaging CFC-12 in the lower stratosphere between 70-90°N and then normalizing the averaged annual cycle to yield an annual average of 100 ppbv and peak-to-trough amplitude of 100 ppbv. The amplitude of the dynamic tracers ranges from 57 ppbv to 156 ppbv. This is to mimic the seasonal variation of CFC-12 in the extratropical LS for easy comparison. We have clarified this in the manuscript.

5. page 19386 What is the sampling time of the MkIV measurements?

When referring to "sampling time", did the reviewer mean sampling frequency? The time when the MkIV balloon measurements were taken was included in the original manuscript. In terms of sampling frequency, the MkIV measurements were reported at 1km vertical interval and extended from the upper troposphere/lower stratosphere

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(ranging from 7 to12 km for individual profile) to 35 km altitude level. We have added this in the manuscript.

6. page 19387 Please indicate the sampling frequency of ACE and the spatial coverage

The satellite has a 74° inclined orbit at an altitude of 650 km, providing up to 15 sunrise and 15 sunset solar occultations per day. This orbit provides spatial coverage in the tropics, midlatitudes and polar region, with a sampling frequency that is highest in the Arctic and Antarctic. We have added the sampling frequency and spatial coverage of ACE in the manuscript.

7. page 19389 use STT instead of STE.

We disagree with the reviewer's suggestion to replace STT with STE. As we have explained in the manuscript (introduction), for the purpose of this study, we use STE to refer to the process of mass exchange at the tropopause, and expand the traditional definition of STT to include stratosphere-to-troposphere transport and the subsequent transport within the troposphere.

8. page 19389, lines 22-24 Here the text gives the impression that the only transport pathway back to high latitudes is via warm and cold conveyor belts, whereas pole-ward quasi-isentropic transport commonly occurs outside of these airstreams. Actually the CCB probably isn't that important for transporting air from low latitudes to high latitudes as it originates poleward of the warm front which is already in the mid-latitudes, whereas the WCB originates in the sub-tropics.

Yes, the reviewer is right. Although air streams associated with cyclones are most efficient in transport air back to high latitudes, transport can also occur outside these air streams, such as large-scale advection, flow around high pressure systems. We have clarified this in the text. We disagree with the reviewer on the importance of CCB in transporting air of stratospheric origin from mid to high latitudes. WCB has received

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much more attention in the past decades due to its efficiency in ventilating boundary layer pollution and long-range transport of anthropogenic pollutants. However, for transport of air of stratospheric origin into the Arctic, there is no reason to expect that the CCB should not be as equally important as the WCB. While vertical lifting in CCB is not as vigorous as WCB, it plays an important role in poleward transport in the horizontal. In addition, CCB originates in the mid-latitudes. This suggests that it may be more efficient in transporting air of stratospheric origin to the Arctic as stratospheric flux occurs predominantly in the mid-latitudes.

9. page 19390 lines10-15 I am not convinced by the argument that STT of DTfix is delayed by one month in the poles as compared to the mid-latitudes. To me it seems that STT in the polar regions is much less than in the mid-latitudes, and the one month delay in the maximum occurring at high latitudes could just be the integrated effect of the time required to transport intrusions from the mid-latitudes to the high latitudes. Testing this hypothesis requires separate DTfix tracers for high latitudes and mid-latitudes

We have tested the hypothesis suggested by the reviewer by separating DTfix tracers for mid and high latitudes. The result indicates that both factors contribute to the one month delay in the maximum at high latitudes. The maximum STT of DTfix in the high latitudes occurs in March, one month behind that in the mid latitudes (February), and the transport of intrusions from the mid-latitudes to the high latitudes takes one month. We have revised the text accordingly.

10. page 19390 lines 21-22 If the seasonal variation of the 4-month and 6-month tracers are similar, doesn't this imply that 4 months is the maximum amount of time that is required for a STT tracer to become well-mixed throughout the troposphere?

Yes, this suggests that it takes about or less than 4 months for a STT tracer to become well-mixed throughout the troposphere.

11. page 19391 lines 26-28 The transport process described here seems like the main process the paper should focus on.

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See response to major concerns 1) & 3).

12. page 19392 line 1-5 The text makes it sound like the CFC-12S tracer takes an addiňtional cyclonic pathway that is not followed by the DT6-month tracer. But both take the same pathway, it's just that the lag in the seasonal minimum of the CFC-12S tracer is due to the lag in the lower stratosphere.

We apologize for the confusion that might have risen due to phrasing. Yes, the CFC-12S tracer and the DT6-month tracer take the same pathway. However, while both tracers started with the same seasonal peak (maximum of DT6-month and minimum of CFC-12S) in the lower stratosphere, the minimum of CFC-12S lags the maximum of DT6-month by 1-2 months in the troposphere. This is because the seasonality of CFC-12S is predominantly determined by STE flux in the high latitudes and this recirculation of the high-latitude influx result in a delay in its seasonal minimum. We have rewritten this part of the text for clarification.

13. page 19394 lines 6-10 and Figure 8 Are the mixing ratios shown just due to transport from the stratosphere or do they also re64258;ect tropospheric sources?

The mixing ratios include both tropospheric sources and that transported from the stratosphere.

14. page 19395, first paragraph: Does the model account for ozone destruction in the lower troposphere due to halogen chemistry?

The GMI model does not include halogen chemistry in the lower troposphere. We have clarified this in model description. However, we do not expect this to affect the results of this paper.

15. page 19395 line 21 change concentrations to mixing ratios

Changed.

16. Figure 10b I don't understand this figure. It seems to show that there is a net flux

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of NOy from the troposphere to the stratosphere in Feb-March. But isn't this the time when DTfix shows maximum transport to the troposphere?

The net STE flux of a tracer is determined by both air mass flux and its gradient in mixing ratios across the troposphere. Due to the influx of NOy from mid-latitudes in February-March, the mixing ratios of NOy in the Arctic upper troposphere slightly exceed that in the lower stratosphere and the net STE flux of NOy is from the troposphere to the stratosphere. In contrast, DTfix shows maximum transport to the troposphere as mixing ratios of DTfix in the lower stratosphere greatly exceed that in the upper troposphere. This is consistent with the definition of DTfix, which is used to track transport from the stratosphere to the troposphere.

17. Figure 3 The mass flux peaks in the upper trop. in winter. But Stohl's [2003] review of Appenzeller et al [1996] puts it at late spring. Why the discrepancy?

The net mass flux of air across the tropopause peaks in late spring as shown by Appenzeller et al (1996) as well as the two papers referenced by the reviewer, James et al. (2003) and Stohl et al. (2003). The gross STT flux maximizes in later winter (James et al. 2003; Stohl et al., 2003; Olsen et al., 2004). The net mass flux of a tracer is different from the mass flux of air, because it is determined by both air mass flux and its gradient in mixing ratios across the tropopause. Since the mixing ratios of DTfix in the lower stratosphere greatly exceeds that in the troposphere, the seasonality of its net STE flux is dominated by stratosphere-to-troposphere transport. Therefore its seasonality closely follows that of gross STT air mass flux and peaks in late winter.

18. Figure 4 I don't follow the convention of changing the sign of the CFC-12 anomalies.

We plot the negative of the CFC-12 anomalies for an easy comparison with the dynamic tracers, O3 and NOy when discussing their seasonal maximum in STE.

References:

Dethof, A., O'Neill, A., and Slingo, J.: Quantification of the isentropic mass transport

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across the dynamical tropopause, J. Geophys. Res., 105, 12,279-12,293, 2000.

Haynes, P. H., Marks, C. J., McIntyre, M. E., Sheperd, T. G., and Shine, K. P.: On the “downward control” of extratropical diabatic circulations by eddy-induced mean zonal forces, J. Atmos. Sci., 48, 651-678, 1991.

Holton, J. R., Haynes, P. H., McIntyre, M. E., Douglass, A. R., Rood, R. B., and Pfister, L.: Stratosphere-troposphere exchange, Rev. Geophys., 33, 403-439, 1995.

James, P., A. Stohl, C. Forster, S. Eckhardt, P. Seibert, and A. Frank, A 15-year climatology of stratosphere-troposphere exchange with a Lagrangian particle dispersion model, 2, Mean climate and seasonal variability, J. Geophys. Res., 108(D12), 8522, doi:10.1029/2002JD002639, 2003.

Olsen, M. A., Schoeberl, M. R., and Douglass, A. R.: Stratosphere-troposphere exchange of mass and ozone, J. Geophys. Res., 109, D24114, doi:10.1029/2004JD005186, 2004.

Rosenfield, J. E., Newman, P. A., and Schoeberl, M. R.: Computations of diabatic descent in the stratospheric polar vortex, J. Geophys. Res., 99, D8, 16,677-16,689, 1994.

Schoeberl, M. R.: Extratropical stratosphere-troposphere mass exchange, J. Geophys. Research, 109, D13303, doi:10.1029/2004JD004525, 2004.

Stohl, A., Characteristics of atmospheric transport into the Arctic troposphere, J. Geophys. Res., 111, D11306, doi:10.1029/2005JD006888, 2006.

Stohl, A., Wernli, H., James, P., Bourqui, M., Forster, C., Liniger M. A., Seibert, P., and Sprenger, M.: A new perspective of stratosphere-troposphere exchange, Bull. American Met. Society, 84(11), 1565-1573, 2003.

Strahan, S.E., and Mahlman, J.D. : Evaluation of the SKYHI general circulation model using aircraft N2O measurements: 2. Tracer variability and diabatic meridional circulation, J. Geophys. Res., 99, D5, 10,319-10,332, 1994.

Waugh, D. W., and Hall, T. M.: Age of stratospheric air: Theory, observations, and models, Rev. Geophys., 40(4), 1010, doi:10.1029/2000RG000101, 2002.

Yang, H., and Tung, K. K.: Cross-isentropic stratosphere-troposphere exchange of mass and water vapor, J. Geophys. Res., 101, 9413-9423, 1996.

Interactive comment on Atmos. Chem. Phys. Discuss., 8, 19377, 2008.