NOTES AND CORRESPONDENCE

The Statistical Analysis of Long-term Trajectory Calculation Based on the Observed Data

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Abstract

The behavior of air parcel transport between hemispheres and between the troposphere and stratosphere is studied by directly calculating 180-day trajectories based on observed data. It is shown that air parcels from the extra-tropical troposphere of one hemisphere are transported to the other hemisphere through the upper troposphere. The estimated inter-hemispheric exchange time is about one year. The main pathway from the troposphere to the stratosphere is the tropical tropopause. The flow from the equatorial lower stratosphere branches off in two directions, *i.e.*, one is the return flow to the troposphere through the sub-tropical tropopause gaps and the other is the poleward flow in the lower stratosphere.

1. Introduction

The subject of the following short note is to show how air parcels are transported globally by the large-scale atmospheric flow. Many tracer experiments have been made by using 3-D winds from the GCM and solving the tracer continuity equation (Mahlman and Moxim, 1978; Mahlman *et al.*, 1980; Mahlman *et al.*, 1986; Tans *et al.*, 1990). Kida (1983a, 1983b) made a pioneering work in which many long-term trajectories of air parcels were calculated, making use of 3-D wind data which were simulated by a simple hemispheric GCM. His works have elucidated the Brewer-Dobson circulation in the lower stratosphere and the dispersive behavior of transport in the troposphere. However, since his works were based on the hemispheric GCM, the interhemispheric transport was not investigated. Noda (1988) extended the Generalized Lagrangian-Mean (GLM) theory and obtained the GLM meridional circulation in the troposphere for January from the simulation of the MRI-GCM. However, the GLM circulation contains a large divergent component and it is difficult to understand the global transport intuitively. Recently, Iwasaki (1989, 1990 and 1992) devised the pressure-isentrope hybrid coordinate (p_+) and studied the transformed

Eulerian-mean (TEM) in that coordinate, which is a kind of extension of the conventional transformed Eulerian-mean in pressure coordinates (Andrews and McIntyre, 1976). This formulation solved finite-amplitude and lower boundary problems in the conventional TEM. The diagnosis of the NCAR community climate model was performed by Iwasaki (1992).

All the works mentioned above are based on GCMs. Therefore they are unavoidable from model's biases. On the other hand, Yamazaki (1986, 1987 and 1989) studied the global transport by calculating many 10-day trajectories using the US NMC (National Meteorological Center) objective analysis data. When the objective analysis data are used the problem of model bias is largely reduced, though problems of estimating the vertical velocity and the sampling time arise.

One aim of this study is to clarify to what extent the observed global distribution of anthropogenic trace gases such as carbon dioxide (CO₂) and chlorofluorocarbons (CFCs) is explained by atmospheric transport alone. For instance, the observed meridional distributions of CO₂ or CFCs show the large meridional gradient near the equator. In the vertical, the density of CFCs is rather uniform in the troposphere and it rapidly decreases with altitude in the stratosphere. In the southern troposphere, the

Fig. 1. Latitude-height distributions of air parcels which were located initially between 30°N and 85°N, 850 hPa and 300 hPa (rectangles in the figures) after (a) 10, (b) 30, (c) 60 and (d) 180 days. The initial time is 12UTC of January 11, 1987.

annual-mean density of CO₂ increases with altitude, while it decreases in the northern hemisphere (Pearman and Garratt, 1973, Nakazawa *et al.*, 1991). Some of these features are brought about by atmospheric transport. In this short note, the statistical analysis of the long-term trajectories based on the NMC data is briefly reported.

2. Data and method

The data used in this study are the twice-daily objective analysis data made by the US NMC (National Meteorological Center). Its horizontal resolution is 2.5° in longitude and 2.5° in latitude and it has 12 standard levels (1000, 850, 700, 500, 400, 300, 250, 150, 100, 70 and 50 hPa). The used variables are horizontal wind and geopotential. Also, the topography data of the same horizontal resolution are used to estimate the surface pressure from the geopotential height data. The vertical velocity is estimated from the divergence of horizontal wind using the continuity equation with the boundary condition of no vertical velocity at 30 hPa. No adjustments of the vertical velocity are made at the lower boundary except for setting it to be zero below the ground. The calculated vertical velocity has a three-cell structure in the zonal mean and this seems to be reasonable. In the monthly mean fields of February, the maximum zonal-mean upward velocity is -30 hPa/day at 300 hPa, 7.5°S and the maximum downward velocity is 27 hPa/day at 700 hPa, 15°N.

Horizontally, the regions of the strong upward velocity accord with the convectively active regions, *i.e.*, over equatorial Africa, over New Guinea and over the central and western equatorial Pacific. The February-mean maximum upward velocity at 500 hPa in the tropics is found at 142.5°E, 12.5°S and its value is -145 hPa/day.

Initially, air parcels are placed globally at 1° interval in longitude and 5° interval in latitude and at 11 standard levels from 850 hPa to 50 hPa. In total, 138,600 (360 × 35 × 11) trajectories are calculated with a time step of 20 minutes. The 3-D wind at the position of the parcel at each time step is calculated from winds at surrounding grid points by a temporally and spatially linear interpolation. The initial time is 12UTC of January 11, 1987 and the ending time is 12UTC of July 6, 1987. The period is 6 months (180 days). In this calculation, subgrid-scale motion is ignored.

3. Results

3.1 Transport from the northern troposphere

In this sub-section, the transport of air parcels from the northern troposphere is studied. Figure 1 shows the meridional distributions of air parcels which were located initially between 30°N and 85°N, 850 hPa and 300 hPa after 10, 30, 60 and 180 days. After 10 days, parcels spread equatorward through the lower troposphere. Some of the parcels reach the equator and start to ascend. After 30 days, there

Table 1. The distribution of the number of air parcels which were located initially between 85°N and 30°N, 850 hPa and 300 hPa after 180 days.

LAT	hPa											TOTAL
	100	200	300	400	500	600	700	800	900	1000		
-90- -80	2	13	11	8	8	5	4	3	1	1	0	56
-80- -70	5	35	39	23	14	18	22	6	3	10	0	175
-70- -60	11	42	47	59	30	31	20	21	17	44	1	323
-60- -50	19	64	80	71	42	62	30	30	29	49	15	491
-50- -40	32	74	115	114	81	82	64	82	61	56	17	778
-40- -30	32	98	125	126	122	126	123	117	83	88	23	1063
-30- -20	38	124	142	169	173	168	176	148	111	113	12	1374
-20- -10	76	185	181	185	160	157	165	169	135	112	32	1557
-10- 0	83	177	192	207	173	169	177	143	144	156	28	1649
0- 10	99	186	237	243	223	233	185	183	208	194	41	2032
10- 20	82	205	223	211	196	191	212	256	248	270	32	2126
20- 30	73	179	192	218	215	176	280	236	296	253	28	2146
30- 40	45	118	175	185	223	255	282	200	235	231	33	1982
40- 50	26	87	124	208	220	239	238	238	234	199	88	1901
50- 60	17	62	118	189	162	166	177	189	171	345	32	1628
60- 70	6	23	76	120	126	157	140	168	165	402	7	1390
70- 80	8	16	59	71	75	82	99	103	76	86	13	688
80- 90	1	8	16	31	28	29	38	27	27	25	11	241

are many parcels at the equatorial lower troposphere and parcels spread upward at the upward branch of the Hadley cell (0°–10°S). Some of parcels reach the lower stratosphere. Also a sparse region is found in the middle and upper troposphere at about 30°N where the downward branch of the Hadley cell is located. The origin of this sparse region will be discussed in Section 3.3. Transport into the southern hemisphere occurs through the upper troposphere. After 60 days (March 10), parcels spread throughout the whole tropical troposphere and southern mid-latitude troposphere. After 180 days (July 9), parcels spread throughout the whole troposphere and lower stratosphere, though the densities in the Arctic and Antarctic stratospheres are low.

In the meridional plane of Fig. 1d (day 180), the number of parcels is counted within each meridional box with 100 hPa and 10° intervals (Table 1). Taking into account the sphericity of the earth, the number is divided by a *cosine* of latitude (hereafter referred as density) and the density is shown in Fig. 2 for the lower troposphere (below 700 hPa). In the lower troposphere, the meridional gradient is large around 10°N and the density is large between 60°N and 70°N. In the southern hemisphere, the density is nearly flat in the low-latitudes and it gradually decreases southward in the extra-tropics. The large meridional gradient near the equator can be understood by considering trajectories of air parcels from the northern extra-tropics. To the north of the upward branch of the Hadley cell (near the equator), parcels can be transported with a short time directly from the northern extra-tropics. On the other hand, to the south of it, parcels take a much longer time

Fig. 2. The meridional distribution of density of air parcels below 700 hPa after 180 days (see text in detail).

to reach the lower troposphere through the pathway of the southern Hadley cell. Therefore, a large meridional gradient is formed near the upward branch of the Hadley cell.

The vertical distributions of the density in the northern and southern extra-tropics (30°N/S–60°N/S) are shown in Fig. 3 for Day 180. In the northern hemisphere, the density tends to decrease with altitude. Above 300 hPa, it decreases rapidly

Fig. 3. Vertical profiles of density of air parcels in the northern extra-tropics (30°N – 60°N ; closed circles) and in the southern extra-tropics (30°S – 60°S ; open circles) after 180 days (see text in detail).

with altitude. In the troposphere of the southern hemisphere, the density is about one-third of that in the northern hemisphere. It is intriguing to note that the density in the southern hemisphere increases with altitude up to 300 hPa, which is opposite to the northern hemisphere. The GCM simulation of the advective transport of passive tracers from various northern hemispheric sources (Yamazaki and Chiba, 1992) produced the similar vertical distribution in the southern hemisphere. The observed annual-mean vertical profile of CO_2 in the southern hemisphere is just like this profile (Pearman and Garratt, 1973, Nakazawa *et al.*, 1991). It suggests that the atmospheric transport contributes to the observed distribution of CO_2 in the southern hemisphere, in addition to the CO_2 sink over the ocean (Tans *et al.*, 1990). The air parcels from the northern hemisphere is lifted at the upward branch of the Hadley cell and transported into the southern hemisphere through the upper troposphere. This transport process causes the vertical profile of air parcel density in the southern hemisphere as shown in Fig. 3.

In the stratosphere above 300 hPa, the difference between the hemispheres is small and it is almost negligible above 100 hPa (Fig. 3), though there were parcels initially up to the 300 hPa level in the northern hemisphere. This result can be explained by the fact that most parcels in the stratosphere passed the tropical tropopause and little parcels were transported directly from the extra-tropical troposphere.

Fig. 4. Same as in Fig. 1 except for the initial positions are in the southern hemisphere and for (a) day 30 and (b) day 180.

3.2 Transport from the southern troposphere

Figure 4 shows the meridional distributions of air parcels which were located initially between 30°S and 85°S , 850 hPa and 300 hPa after 30 and 180 days. These are almost mirror images of Fig. 1 about the equator. On Day 30, the center of upward motion is located at about 10°S where the upward branch of the Hadley cell in boreal Winter is situated. The features of the vertical and meridional distributions after 180 days are similar to the northern source case, though the high-latitude peak in the lower troposphere does not exist.

3.3 Transport from the equatorial region

Figure 5 shows the meridional distributions of air parcels which were located initially between 10°S and 10°N , 850 hPa and 300 hPa after 30 and 180 days. The diffusivity is very large and the Hadley circulation is obscured. The dispersive characteristics in the tropics accord with the results of Plumb and Mahlman (1987). This example is also similar to the Amazonian source case of Yamazaki and Chiba (1992).

Figure 6 shows the meridional distribution of air parcels which were located initially in the equatorial lower stratosphere (between 10°S and 10°N , 50 hPa and 100 hPa) after 60 days. Many parcels return to the troposphere, passing the tropopause gaps at about 30°N and 30°S . Because the season is late Winter and the counterclockwise Winter Hadley cell

Fig. 5. Same as in Fig. 4 except for the initial positions are between 10°N and 10°S, 850 hPa and 300 hPa.

is dominant in the tropics, the number of parcels in the northern troposphere is larger than in the southern troposphere. Many parcels are also transported into the polar regions in the lower stratosphere. Parcels seem to branch off in two directions at around 30°N, 200 hPa. This feature is similar to Fig. 8 in Iwasaki (1989).

By comparing Figs. 1 and 6, it is seen that stratospheric air is transported into the sparse region in Fig. 1b. It is suggested the sub-tropical troposphere is the region where the mixing of tropospheric air and stratospheric air takes place. This transport should be observed in the meridional distribution of stratospheric-origin gases such as ozone. In fact, the ozone observations (Gerhardt *et al.*, 1989; Matsubara *et al.*, 1991) show the pattern which can be interpreted as the intrusion of ozone through the tropopause gap into the sub-tropical troposphere.

In the polar stratospheres, the density in the southern hemisphere is slightly larger than that in the northern hemisphere. During this season (austral late Summer), the mean zonal wind is very weak in the lower stratosphere of the southern hemisphere and planetary waves still exist below 50 hPa. This provide a preferable situation for meridional mixing in the lower and extra-tropical stratosphere of the southern hemisphere (Yamazaki, 1989). Plumb and Mahlman (1987) also showed the large meridional component of diffusivity near the zero-wind line (see

Fig. 6. Same as in Fig. 4 except for the initial positions are between 10°N and 10°S, 50 hPa and 100 hPa and for day 60.

their Figs. 5–8).

4. Summary and discussion

The behavior of air parcel transport between hemispheres and between the troposphere and stratosphere was presented by directly calculating long-term trajectories based on observational data. It was shown that air parcels from the extra-tropical troposphere of one hemisphere are transported equatorward through the near-surface layer, lifted near the equator and transported into the other hemisphere through the upper troposphere. The inter-hemisphere exchange time (τ) can be estimated by the following results using a simple two-box diffusion model:

$$\frac{dx_S}{dt} = -\frac{x_S}{\tau} + \frac{x_N}{\tau} \quad (1)$$

$$\frac{dx_N}{dt} = \frac{x_S}{\tau} - \frac{x_N}{\tau} \quad (2)$$

where x_N is the average tracer density in the northern hemisphere and x_S is the average tracer density in the southern hemisphere. The solution is as follows for the case in which the tracer is located initially in the northern hemisphere:

$$\frac{x_S}{x_N} = \tanh(t/\tau) \quad (3)$$

The estimated τ from Eq. (3) and the distribution on Day 180 is about 1.0 year for the northern initial case and 0.9 year for the southern initial case. This difference comes from the fact that the initial position of the upward branch of the Hadley cell is in the southern hemisphere in this experiment. For example, the parcels initially located at 5°S can be easily advected into the northern hemisphere. In any case, the obtained inter-hemispheric exchange time of about one year is a reasonable estimate (Tans *et al.*, 1990).

As for transport into the stratosphere from the troposphere, the main pathway is the upward transport through the tropical tropopause. The fast

return flow from the equatorial lower stratosphere to the troposphere occurs mainly through the subtropical tropopause gaps. The behavior of transport mentioned above produces the meridional and vertical distribution of air parcels shown in Figs. 2 and 3. A picture of global transport obtained in this study is similar to Fig. 8 in Iwasaki (1989). The results in this study will help to interpret the observed distribution of tracer gases such as ozone, CO₂ or CFCs.

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References

- Andrews, D.G. and M.E. McIntyre, 1976: Planetary waves in horizontal and vertical shear: The generalized Eliassen-Palm relation and the mean zonal acceleration. *J. Atmos. Sci.*, **33**, 2031–2048.
- Gerhardt, Ph., D. Poppe and A. Marenco, 1989: Ozone, CO and NO_x distribution in the troposphere during STRATOZ III. *Ozone in the Atmosphere. Proceedings of the Quadrennial Ozone Symposium 1988 and Tropospheric Ozone Workshop*, (ed. R.D. Bojkov and P. Fabian). Deepak, 467–470.
- Iwasaki, T., 1989: A diagnostic formulation for wave-mean flow interactions and Lagrangian-mean circulation with a hybrid vertical coordinate of pressure and isentropes. *J. Meteor. Soc. Japan*, **67**, 293–312.
- Iwasaki, T., 1990: Lagrangian-mean circulation and wave-mean flow interactions of Eady's baroclinic instability waves. *J. Meteor. Soc. Japan*, **68**, 347–356.
- Iwasaki, T., 1992: General circulation diagnosis in the pressure-isentrope hybrid vertical coordinate. *J. Meteor. Soc. Japan*, **70**, 673–687.
- Kida, H., 1983a: General circulation of air parcels and transport characteristics derived from a hemispheric GCM. Part 1. A determination of advective mass flow in the lower stratosphere. *J. Meteor. Soc. Japan*, **61**, 171–187.
- Kida, H., 1983b: General circulation of air parcels and transport characteristics derived from a hemispheric GCM. Part 2. Very long-term motions of air parcels in the troposphere and stratosphere. *J. Meteor. Soc. Japan*, **61**, 510–523.
- Mahlman, J. D. and W. J. Moxim, 1978: Tracer simulation using a global general circulation model: Results from a midlatitude instantaneous source experiment. *J. Atmos. Sci.*, **35**, 1340–1374.
- Mahlman, J.D., H. Leovy, II. and W.J. Moxim, 1980: Three-dimensional tracer structure and behavior as simulated in two ozone precursor experiments. *J. Atmos. Sci.*, **37**, 655–685.
- Mahlman, J.D., H. Leovy, II. and W.J. Moxim, 1986: Three-dimensional simulations of stratospheric N₂O: predictions for other trace constituents. *J. Geophys. Res.*, **91**, 2687–2707.
- Matsubara, K., M. Doi, T. Uekubo, K. Okada, S. Aoki and S. Kawaguchi, 1991: Results of ozone observation from the equatorial region to Antarctica. *Proc. NIPR Symp. Polar Meteorol. Glaciol.*, **4**, 1–11.
- Nakazawa, T., K. Miyashita, S. Aoki and M. Tanaka, 1991: Temporal and spatial variations of upper tropospheric and lower stratospheric carbon dioxide. *Tellus*, **43B**, 106–117.
- Noda, A., 1988: Generalized Lagrangian-Mean (GLM) meridional motions in the troposphere. *J. Meteor. Soc. Japan*, **66**, 201–226.
- Pearman, G.I. and J.R. Garratt, 1973: Space and time variations of tropospheric carbon dioxide in the southern hemisphere. *Tellus*, **25**, 309–311.
- Plumb, R.A. and J.D. Mahlman, 1987: The zonally-averaged transport characteristics of the GFDL general circulation/transport model. *J. Atmos. Sci.*, **44**, 298–327.
- Tanaka, T., Nakazawa, T. and Aoki, S., 1987. Seasonal and meridional variations of atmospheric carbon dioxide in the lower troposphere of the northern and southern hemispheres. *Tellus* **39B**, 29–41.
- Tans, P.P., I.Y. Fung and T. Takahashi, 1990. Observational constraints on the global atmospheric CO₂ budget. *Science*, **247**, 1431–1438.
- Yamazaki, K., 1986: Preliminary calculation of trajectory analysis in the lower stratosphere of the southern hemisphere. *Geophys. Res. Lett.*, **12**, 1312–1315.
- Yamazaki, K., 1987: Transport characteristics in the troposphere and lower stratosphere of the southern hemisphere. *Proc. NIPR Symp. Polar Meteorol. Glaciol.*, **1**, 39–53.
- Yamazaki, K., 1987: Diffusion coefficients derived from the Lagrangian statistics. *Proc. NIPR Symp. Polar Meteorol. Glaciol.*, **2**, 16–24.
- Yamazaki, K. and Chiba, M., 1992. Transport simulation of passive tracers from the northern hemisphere to the southern hemisphere. *Proc. NIPR Polar Meteorol. Glaciol.*, **5**, 9–23.

観測データによる長期間トラジェクトリーの統計解析

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半球間や成層圏と対流圏の間の空気塊の輸送の様子を観測データに基づく180日間のトラジェクトリー計算によって調べた。一方の半球から他の半球への輸送は上部対流圏を通して行われることがわかった。半球間の交換時間は約1年と推定された。対流圏から成層圏への輸送は主に熱帯対流圏界面を通して行われる。熱帯下部成層圏からの流れは2つに分かれる。一つは亜熱帯のトロポポーズギャップから対流圏にもどる流れであり、他方は下部成層圏を極方向に向かう流れである。