Study on Ozone Change over the Tibetan Plateau

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ABSTRACT

This paper reviewed the main results with respect to the discovery of low center of total column ozone (TCO) over the Tibetan Plateau (TP) in summer, and its formation mechanism. Some important advances are summarized as follows: The fact is discovered that there is a TCO low center over the TP in summer, and the features of the background circulation over the TP are analyzed; it is confirmed that the TP is a pathway of mass exchange between the troposphere and stratosphere, and it influences the TCO low center over the TP in summer; models reproduce the TCO low center over the TP in summer, and the formation mechanism is explored; in addition, the analyses and diagnoses of the observation data indicate that not only there is the TCO low center over the TP in summer, but also TCO decrease trend over the TP is one of the strong centers of TCO decrease trend in the same latitude; finally, the model predicts the future TCO change over the TP.

Key words: the Tibetan Plateau (TP), the TP ozone valley, pathway, total column ozone (TCO) decrease trend

1. Introduction

Ozone is an important trace gas in the atmosphere, and is paid more attention due to the discovery of the Antarctic "ozone hole". In addition, tropospheric ozone and the effects of ozone on human being, ecosphere, and climate are also drawn more attention. In the last decade, facts are confirmed by many observations that anthropogenic activities result in the significant ozone changes in the stratosphere and troposphere (Bojkov, 1994). In China, Wei et al. (1994) analyzed the total column ozone (TCO) in Beijing and Kunming from DOBSON instruments since 1979, and their results showed that the TCO in both sites continuously decreases, and the decrease became more obvious after 1991. In order to realize roundly ozone changes over China during the last decade, we focused the above issues, and paid special attention to the TP. In this paper, we review the results with respect to the ozone over the TP.

2. The TCO low center over the TP in summer

The TCO from TOMS (Total Ozone Meteorological Satellite) over Nimbus satellite is widely used to research ozone changes and its spatiotemporal distribution. When Reiter and Gao (1982) researched the South High movement and heating field over the TP, they used the TOMS data from March to April in 1979 and gave some figures related to weather process. These figures showed that there occurs low TCO over the TP as the South High moves to the TP in the middle April.

By using TOMS data from 1979 to 1991, Zhou et al. (1995) gave the distribution of monthly mean ozone over China. Figure 1 shows the TCO distribution in January, whose isolines roughly parallels with latitude. But in June there appears an obvious TCO low center over the TP, which maintains until

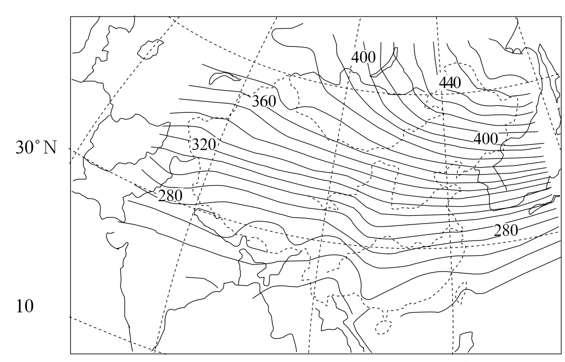

Fig.1. Distribution of monthly averaged total column ozone in January (1979-1991) (unit: DU).

September (Fig.2). Meanwhile, there is a TCO high center over Northeast China. The TCO low center over the TP disappears after October. Compared the TCO over the TP with the counterpart over East China at the same latitude, it is found that the TCO difference between both sites is less than 3% in winter and spring, but about 10% in summer with maximum of 11% in June (Fig.3). Therefore, some physical and chemical processes result in the TCO fall over the TP in summer. The TCO fall is less than Antarctic "ozone hole". The TCO low center over the TP in summer is called "TP ozone valley".

By using the same TOMS data, Zou (1996) and Zou et al. (1998) gave the global climate average of the TCO in different seasons, which further confirmed that the ozone valley not only occurs over the TP (compared with the TCO of the same latitude, it lowers more than 30 DU) but also over the Rocky Mountains (lowers by about 20 DU).

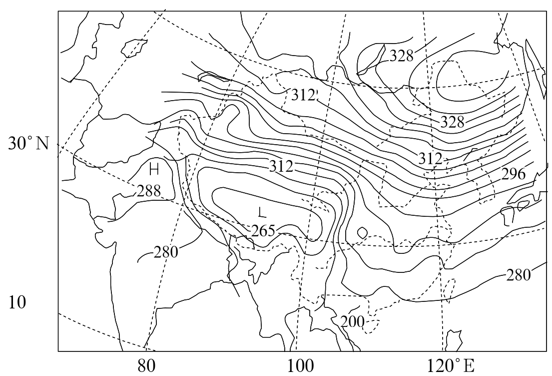

Fig.2. Distribution of monthly averaged total column ozone in July (1979-1991) (unit: DU).

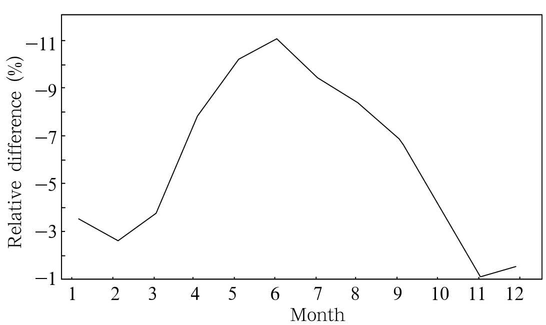

Fig.3. Difference of total column ozone between the Tibetan Plateau and east part of China at the same latitude.

3. Role of seasonal variations of wind field on the ozone over the TP and its surroundings

Zhou et al. (1995) presumed that based on previous researches on the meteorology over the TP, South Asian high caused by thermodynamic role controls atmosphere from 500 to 100 hPa over the TP, in which convective activities occur largely. Synthesis meteorology experiments over the TP indicated that the TP is mostly a convergence area in summer. They speculated that the TP is an important pathway in summer by which the air in low troposphere can be transported into the stratosphere. The pollutants from the TP surroundings of several hundreds kilometers may be converged to the TP in summer, and transported into the stratosphere, then diverged to the surroundings. Thus, low content ozone and high content pollutants from the troposphere are transported into the stratosphere so that they bring about abnormal TCO fall by some physical and chemical process. In order to verify the above presumption, Bian et al. (1997) analyzed seasonal characters of wind field over the TP and its surroundings with ECMWF reanalysis data of 7 levels from 1980 to 1989 and sounding data of 1995 over the southeast of TP. The results showed that in winter horizontal wind field is a shallow cold high near surface over the TP (Fig.4), and western wind in the middle and high troposphere. During the transit period from winter to summer, southern wind component over the TP expands upward and northward with seasonal variations. The convergence from the TP surroundings to the TP also expands upward and northward. In July and August, the low and middle troposphere over the TP becomes a strong convergence area.

In winter, the vertical wind field over the TP is mostly falling except the northwest part of the TP (Fig.5). In spring (April), the ascending flow occurred first in low troposphere over the southeast part of the TP, then gradually expands upward and to its surroundings. In summer, there becomes the ascending flow in the whole troposphere over the TP, and the TP and Bay of Bengal together form a large region of strong ascending flow that is upward part of monsoon vertical circulation. Since May the currents from south, east, and north began to flow to the TP.

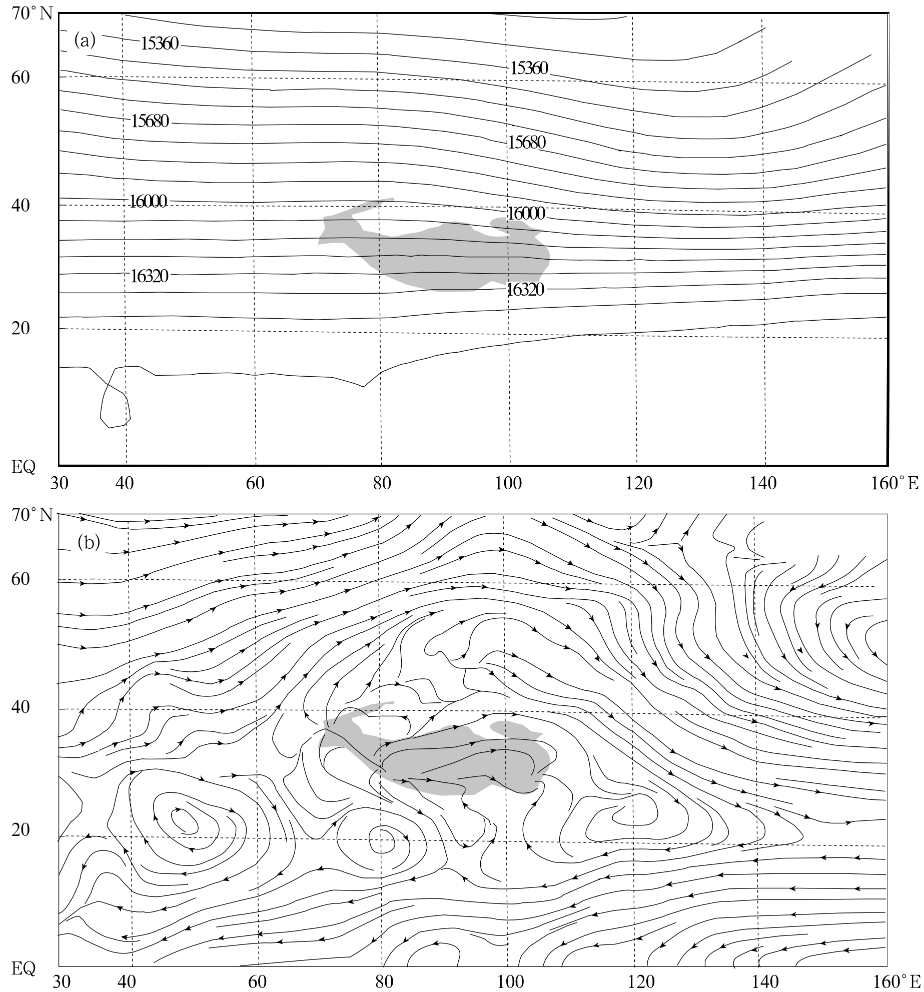

Fig.4. Averaged geopotential height at 100 hPa (a) and streamline field at 850 hPa (b) in January (1980-1989).

In June, the strong ascending flow occurred over the west part of TP (Fig.6). The ascending flow is the strongest in July and August, with the maximum to 100 hPa. This is because the TP is a heating source in summer.

This is also confirmed by results of 2-D global dynamical-radiative-chemical coupled model by Fu et al. (1997, figure omitted). The model result showed that the upward flow of latitudinal circulation over the TP and its surroundings could reach 20 km.

In a word, there becomes the ascending flow in the whole troposphere over the TP in summer, which climbs up the TP from TP surroundings, and reaches the upper troposphere and lower stratosphere where the strong South High controls, then diverges into the surroundings. In addition, convections over the TP are also active in summer. These features of benefit to the convergence of mass and pollutants from the TP surroundings, which reach lower stratosphere over the TP and diverge into the surroundings. This is a favorable circulation background under the condition of which the TP ozone valley occurs.

4. Mass exchange between stratosphere and troposphere over the TP and its surroundings

Based on the favorable circulation background, Zhou et al. (1995) proposed that the TP is an important pathway in summer by which the air in low troposphere can be transported into the stratosphere. In order to verify this view, Cong et al. (2001)

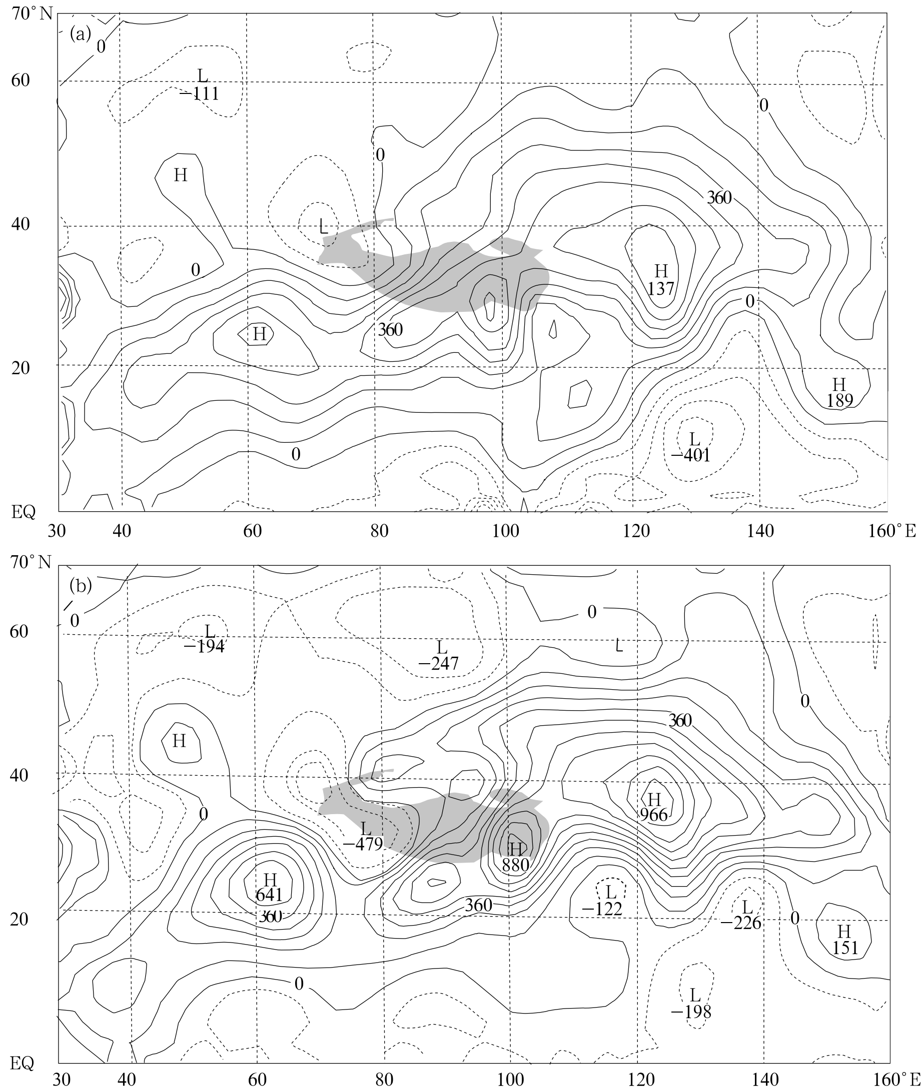

Fig.5. Averaged ω at 300 hPa (a) and 500 hPa (b) in January (1980-1989) (unit: 10^{-6} hPa s^{-1}).

calculated mass exchange cross the tropopause over the TP and its surroundings by Wei (1987)'s way with NCEP reanalysis daily data (1978-1996). The results indicated that in summer strong mass exchanges from troposphere to stratosphere occur over the TP, its southeast part and the north part of Bay of Bengal.

4.1 *Nineteen-yr mean seasonal variation feature of the cross-tropopause mass exchange (CTME) over the TP and its surroundings*

The distribution of the monthly mean CTME over the TP and its surroundings are shown in Fig.7a. From Fig.7a, it is found that in January except for the weak mass transport from troposphere to stratosphere (TTS) in the northwest part of the TP, the Hanshui valley and the Poyang Lake, the transport from stratosphere to troposphere (TST) appears in the south and east of the TP with a large value center, where there is descending flow center. The TST weakens during March and April. In May, the TTS is found in the southeast of the TP. Until June, the TTS in the east of TP becomes stronger and moves northward to the north of the TP when it becomes quite stable. The cross-tropospause mass exchange in summer is very different from that in winter. In summer (Fig.7b), the area of south of 40°N in Asia is covered by the TTS

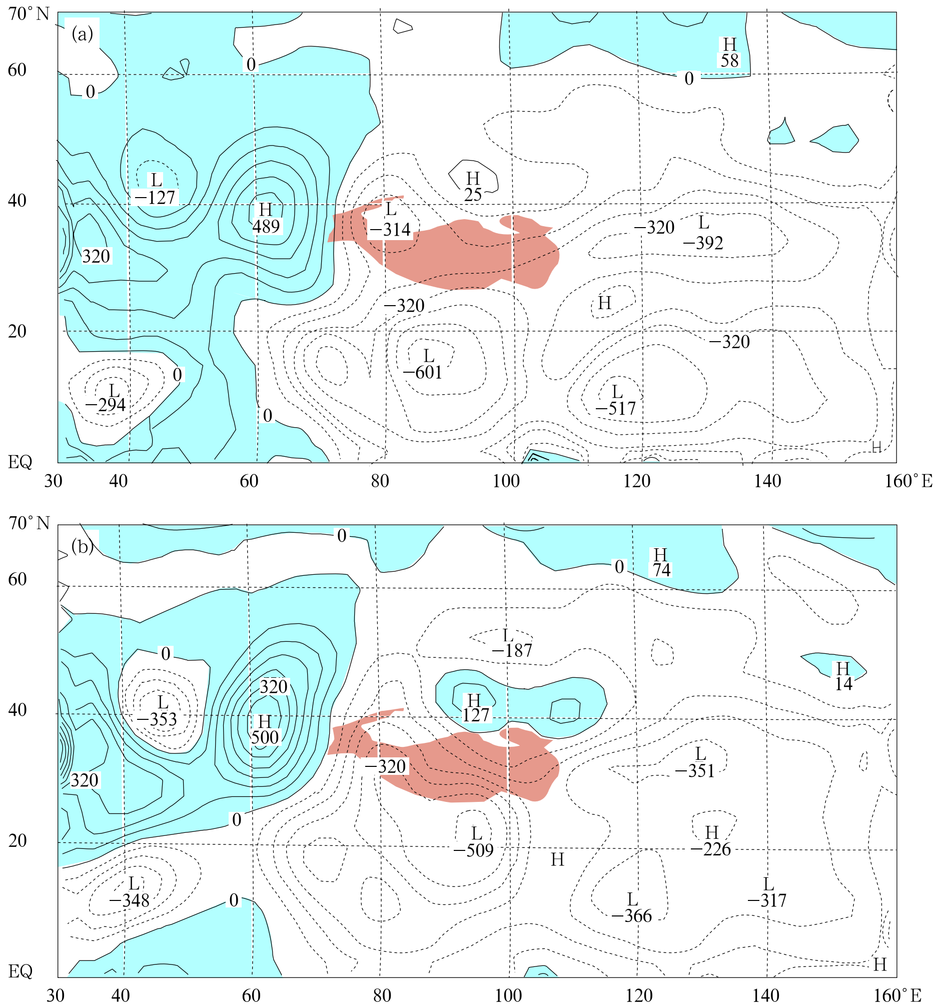

Fig.6. Averaged ω at 300 hPa (a) and 500 hPa (b) in July (1980-1989) (unit: 10^{-6} hPa s^{-1}).

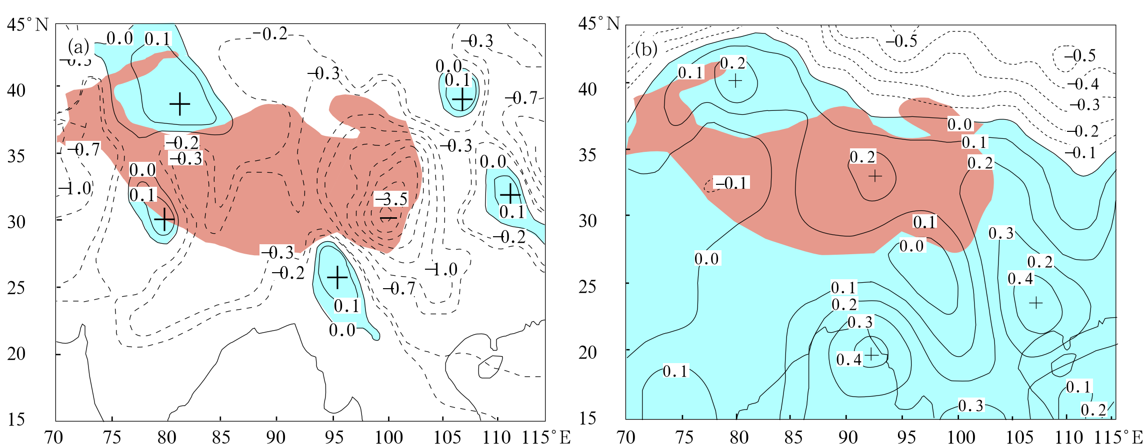

Fig.7. Nineteen-yr averaged mass exchange flux across the tropopause in winter (a) and summer (b) (unit: 10^{-3} kg m^{-2}s^{-1}).

with two high centers located at the north of Bay of Bengal and southeast of TP.

4.2 *Nineteen-yr mean seasonal variation feature of net mass exchange flux across tropopause over the TP and its surroundings*

The monthly variation feature of the mass budget across tropopause over the TP and its surroundings (15°-40°N, 80°-110°E) is shown in Fig.8. The TST weakens step by step from January to April. In May, the TST and TTS reach the balance basically. From June the net cross-tropopause mass exchange appears, and the net TTS gradually becomes stronger. Until mid-summer (July and August) the net TTS reaches the maximum. In September the TTS becomes weaker, and the TST and TTS reach the balance again in October. The net TST occurs into the troposphere in November and December.

4.3 *The relationship between aerosol, ozone of 100 hPa, and the cross-tropopause mass over the TP and its surroundings*

In the study of the aerosol distribution, Li and Yu (2001) pointed out that the maximal aerosol appears at 100 hPa over the TP in summer. This level is approximately the height of the tropopause. Cong et al. (2001) found that the aerosol maximum also occurs in Bay of Bengal and southeast of the TP in July. And they calculated the annual variation of area average aerosol and ozone at 100 hPa and the correlation between aerosol, ozone, and the cross-tropopause mass. The results indicated that there was a positive correlation between the cross-tropopause mass and the aerosol concentration of 100 hPa; and there was a negative correlation between the cross-tropopause mass and ozone. The correlation coefficients are 0.563 and -0.333 with passing significance test of 99% reliability, respectively. A negative correlation is found between the aerosol and ozone of 100 hPa, and passes significance test with correlation coefficient of -0.238 and 95% confidence. Cong et al. (2001) also calculated the annual variation of the cross-tropopause mass, ozone, and aerosol of 100 hPa over the TP and its surroundings from 1993 to 1998. Although the period is short, it is found that the trend of correlation exists.

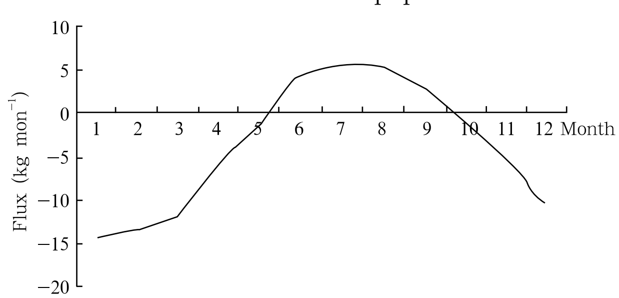

Fig.8. Monthly variation of 19-yr averaged mass exchange flux across the tropopause over a region (15°-40° N, 80°-115°E) (unit: kg month^{-1}).

The above works confirmed that the circulation background over the TP and its surroundings is of benefit to the mass and pollutants from the TP surroundings to converge to the TP and is transported into the stratosphere. The data diagnoses and analyses indicate that in summer mass from the troposphere crosses the tropopause to the stratosphere. Meanwhile, it is shown that in summer Bay of Bengal and the TP are pathways by which mass in the lower troposphere be transported into the upper troposphere and lower stratosphere (UTLS). The correlations between the cross-tropopause mass and aerosol concentration of 100 hPa, and the cross-tropopause mass and ozone volume of 100 hPa suggest that the aerosols in the middle and lower troposphere be transported into UTLS, and under fitting conditions ozone over the TP decreases by some reactions to facilitate the TP ozone valley.

5. Simulation of the TP ozone valley in summer

5.1 *Simulation with 2-D global dynamical-radiative-chemical coupled model*

Ozone change is related to complicated interaction among dynamical, radiative, and photochemical processes. How does the TP ozone valley in summer form and evolve? Fu et al. (1997) explored the causes of formation of the TP ozone valley in summer.

a. *Model description*

This model consists of three parts: dynamical module involves heating process due to coagulation,

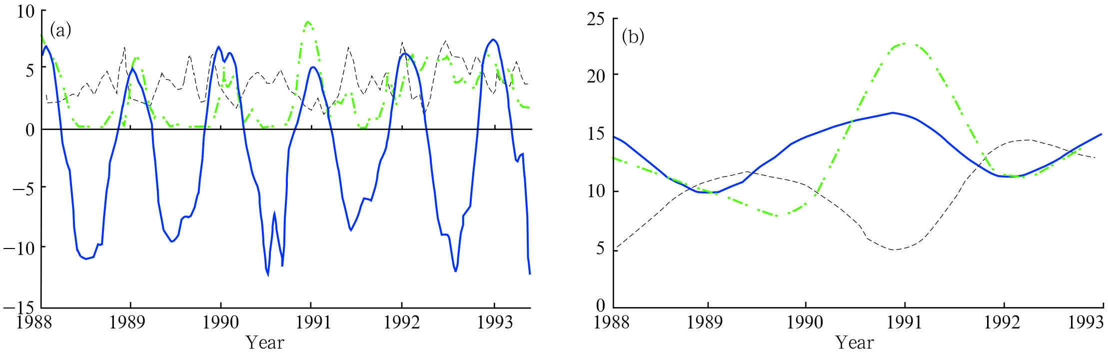

Fig.9. Variation of mass exchange flux across the tropopause in the Tibetan Plateau and its surroundings (solid line, unit: 10^{18} kg month^{-1}), concentration aerosol at 100 hPa (dashed line, unit:10^{-3} km^{-3}), and ozone concentration at 100 hPa (dotted line, unit: 10^{-1} μL L^{-1}) monthly averaged from July 1988 to December 1993 (a), summer averaged from 1988 to 1993 (b).

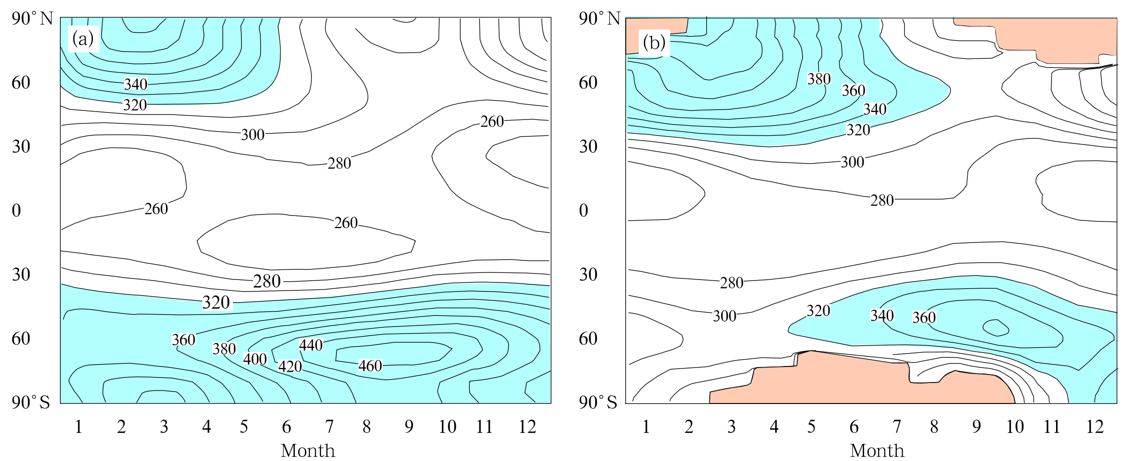

Fig.10. Seasonal variation of total column ozone along latitude. (a) Model result under control run, and (b) averaged TOMS (1979-1991).

eddy process parameterization, and air-surface latent and heating exchange process except radiative process. The vertical coordinate is σ-coordinate with 16 levels from surface to strapopause. Radiative module is the narrow band mode developed by Wang and Ryan (1983). Chemical module is the mode developed by Ren et al. (1997) with the vertical range from surface to 50 km, which includes 48 micro components and 89 reactions in gas phase, 35 photolysis reactions and 3 heterogeneous reactions on aerosol surface. Split operator method is used to calculate transport and chemical process respectively, and the predict-correct method is used in chemical process.

b. *Experiment design*

Three experiments all run for 24 months, and the results of latter 12 months are analyzed. Experiment A is that the terrain is zonal mean, which is a reference test; Experiment B adds monthly mean heat source along 90°E estimated by Yanai et al. (1991); Experiment C is that the terrain is along 90°E, and heat source is the same as Experiment B.

c. *Results*

(1) Reference test: Figure 10a depicts that model TCO varies with season in the reference test. Figure 10b shows averaged TCO of TOMS data from 1979 to 1991. From the comparison of the two figures, it is found that main features of the modeled TCO seasonal variation are very similar to counterparts of the observation. But there are two shortages: 1) TCO maximum in the South Hemisphere is excessively more than

the observation, and 2) Antarctic ozone hole does not occur in the simulation because the model does not involve heterogeneous reactions about PSCs.

(2) Effect of the TP heat source on the TP ozone valley in summer: Figure 11 shows TCO difference between Experiments B and A, which represents that the heat source along 90°E influences the TCO. From the figure, it is found that TCO at 30°N, which is the concerned TP, decreases from May to September with the maximum of 15 DU in July and August. Figure 12 shows averaged TCO difference between the value along 90°E and the zonal mean with TOMS data from 1979 to 1991 (version 6). The comparison of Figs.11 and 12 indicates that the simulation reproduces better TP ozone valley from May to September. But the modeled intensity of TP ozone valley is about 50% less than the observation, which indicates that the role of the heat source on the TP ozone valley is only part of the formation of TP ozone valley. In addition, the maximum appears later than the observation because the seasonal variation of modeled TCO is later than the observation.

(3) Together effects of terrain and heat source on the TP ozone valley: Figure 13 shows TCO difference between Experiments C and A. By comparing Fig.13 with Fig.12, we found that the feature of TCO difference around 30°N is in good agreement with the observation with the maximum of 30 DU. But the maximum appears in July which is later than the observation

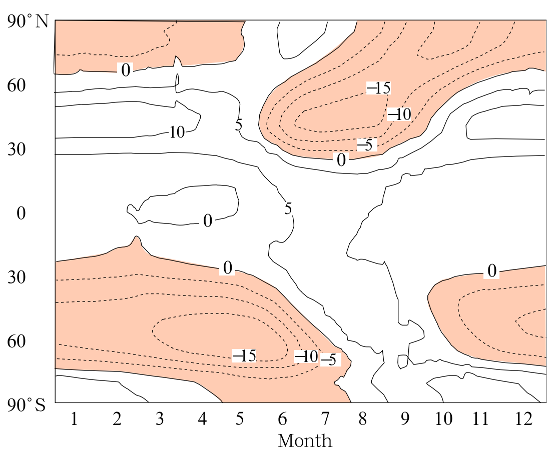

Fig.11. Seasonal variation of the difference of total column ozone between Experiments B and A.

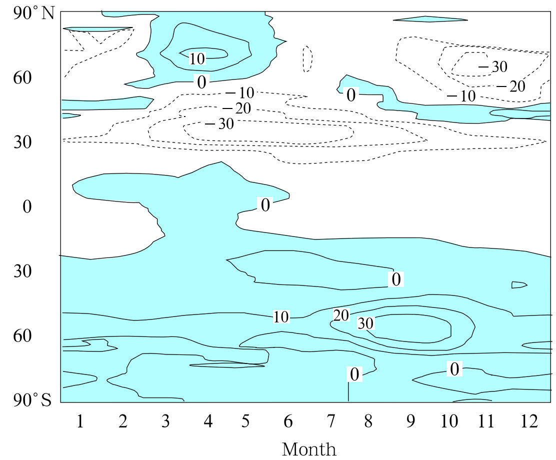

Fig.12. Seasonal variation of the difference of total column ozone from TOMS between the value along 90°E and zonal average.

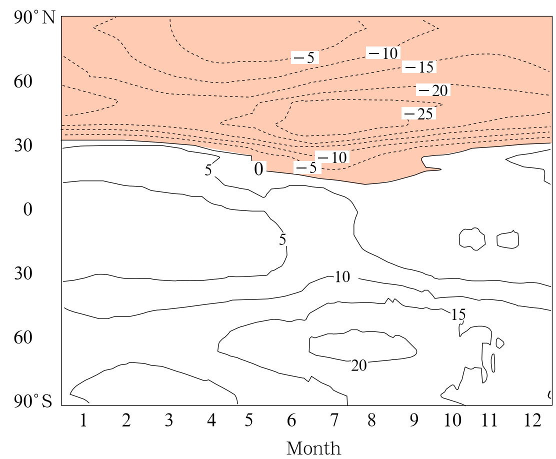

Fig.13. Seasonal variation of the difference of total column ozone between Experiments C and A.

in May. In a word, the model results indicate the dynamic roles due to terrain and heat source over the TP are main reasons for the formation of the TP ozone valley in summer.

(4) Effect of chemical process: In order to analyze the roles of transport and chemical process, the sum of horizontal transport and diffusion, and vertical transport and diffusion are defined as dynamical role; and net budget of chemical production and loss are defined as chemical role. Therefore, the sum of both roles presents net change. Figure 14 shows ozone change caused by the dynamical and chemical role with height at 30°N on 31 July. From this figure it is found that the dynamical role results in ozone

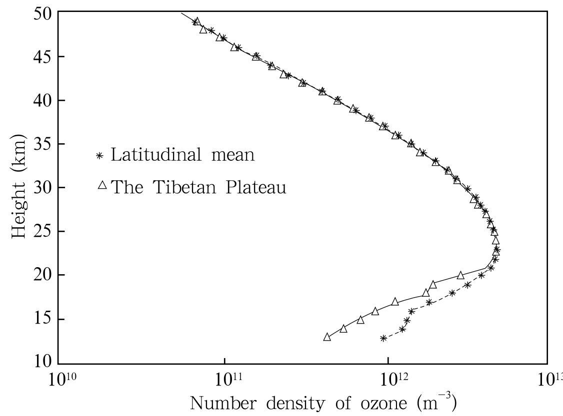

Fig.14. Vertical distribution of ozone from SAGE II on May 16, 1986.

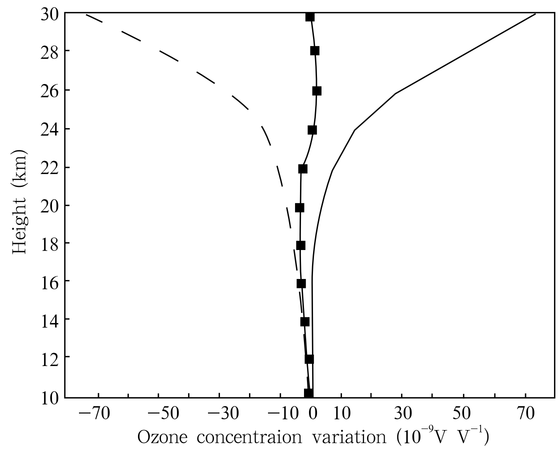

Fig.15. Vertical distribution of dynamical role (dashed line), chemical role (solid line) and net on ozone (square) in Experiment C on July 31.

decrease, the chemical role brings about ozone increase, and the net change is negative below 22 km while it is positive above 22 km. This illustrates that the extreme of ozone decrease at 15-20 km resulted from net change of the dynamical and chemical role. Namely, the transport role is greater than the chemical role on the ozone change. The height of modeled ozone decrease is well agreeable with SAGE data from NASA on May 16, 1986. Figure 15 shows that ozone decrease mainly occurs in 10-20 km during the TP ozone valley in summer.

5.2 *Simulation with 3-D global chemical transport model*

The above 2-D global dynamical-radiative-chemical coupled model is used to simulate the TP ozone valley in summer. However, there are still two questions in the above work: one is that although it is known that dynamical and thermo-dynamical role together play the main roles, we do not know which dynamical process plays more important role; the other is that the role of chemical process still need to be explored further. In addition, the 2-D model has its own shortage that it cannot exhibit longitudinal effect. By using a 3-D chemical transport model, Liu et al. (2003) simulated the TP ozone valley, and analyzed the role of each process.

5.2.1 *Description of the model*

OSLO CTM2 is an off-line chemical transport/tracer model (CTM), which uses pre-calculated transport and physical fields to simulate chemical turnover and distribution in the atmosphere. The model is valid for the 3-D global troposphere with the model domain from the ground up to 10 hPa for the current data set. The model horizontal resolution is determined by the input data. The data set used in this study is ECMWF T21 forecast data (5.625°×5.625°) in 1996. The vertical resolution of the model is determined by the input data and we use 19 levels from the surface up to 10 hPa. Except for heterogeneous reaction, the model involves 48 species, e.g., O_x, NO_y, OH_x, NMHC, etc., 85 reactions and 16 photolysis reactions. Split operator method is adopted to solve Eq.(1).

$$\begin{aligned}\frac{\partial\varphi}{\partial t} &= \left(\frac{\partial\varphi}{\partial t}\right)_{\text{dynamic}} + \left(\frac{\partial\varphi}{\partial t}\right)_{\text{chemistry}} \cdot \left(\frac{\partial\varphi}{\partial t}\right)_{\text{dynamic}} \\ &= \left(\frac{\partial\varphi}{\partial t}\right)_{\text{adv.}} + \left(\frac{\partial\varphi}{\partial t}\right)_{\text{conv.}} + \left(\frac{\partial\varphi}{\partial t}\right)_{\text{B.L.}},\end{aligned} \tag{1}$$

where φ represents trace gas concentration; t: time; the footnote "dynamic": dynamic process; "chemistry": chemical process; adv.: advective process; conv.: convective process; and B.L.: effect of boundary layer. The detailed introduction about OSLO CTM2 is in Sundet (1997), Wild et al. (2000), and Müller (1992). The model runs for 15 months, and the results of the latter 9 months are analyzed.

5.2.2 *Results and analyses*

It is mainly attributed to the ozone reduction at

15-20 km where the TP ozone valley in summer is produced. OSLO CTM2 domain is from the ground to 10 hPa, therefore, the model is able to simulate the seasonal variation of the TP ozone valley. Figure 16 displays the difference between TCO at 90°E and zonal mean TCO. Figure 17 depicts the difference between TCO of TOMS along 90°E and zonal mean TCO. The comparison of the two figures manifests that modeled TP ozone valley in summer is in excellent agreement with TOMS observation, but modeled intensity of TP ozone valley is less than that of TOMS data, namely, modeled difference of TCO is 25 DU, but observed difference is 30 DU. Figure 18 shows the modeled height-time variation of the ozone difference between the TP (31°N, 90°E) and zonal mean. Compared with Fig.15, the model results very well revealed that the formation of the TP ozone valley in summer is primarily ascribed to ozone reduction from 120 to 40 hPa (equivalent to 14-23 km).

In order to analyze the effects of transport and chemical processes on the formation of the TP ozone valley in summer, the grid (31°N, 90°E; 100 hPa) over

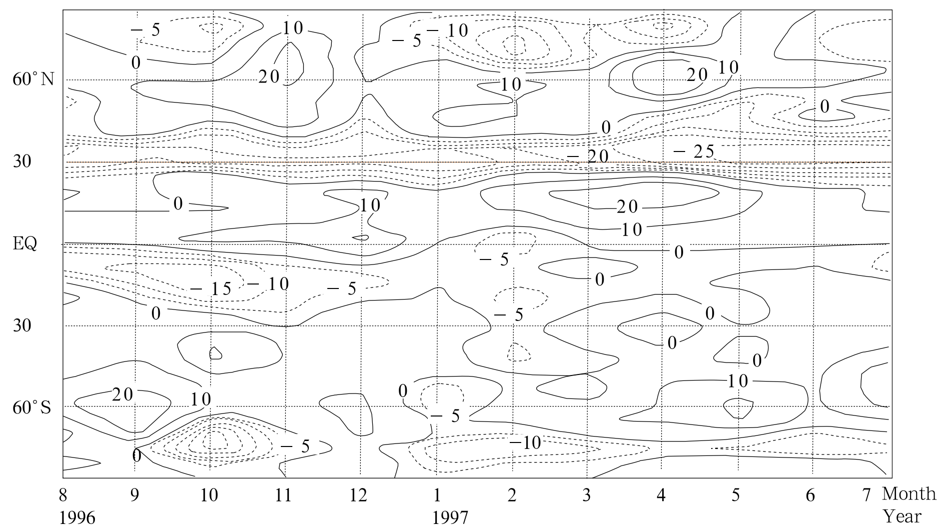

Fig.16. Seasonal variation of the difference of simulated total column ozone between along 90°E and zonal average (unit: DU).

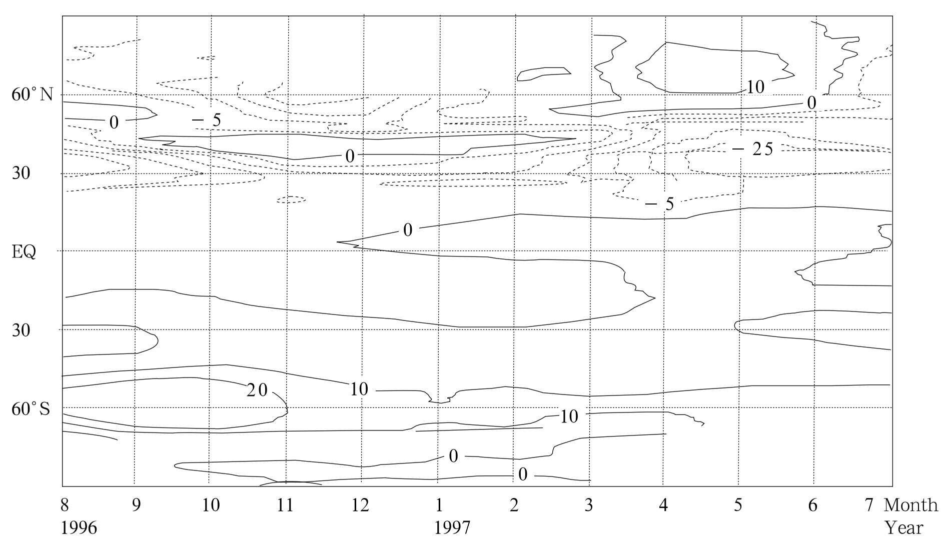

Fig.17. Seasonal variation of the difference of total column ozone from TOMS between along 90°E and zonal average (unit: DU).

the TP is selected to do analyses of ozone budgets. Generally, statistic of material budget is the sum of every process from an o'clock to another o'clock. However, when the changes of trace concentration are analyzed the averaged concentration usually is used, e.g., in the above results, monthly averaged concentrations are used. Therefore, in order to be consistent with averaged concentration, a method is used as follows:

$$\begin{aligned}
x_1 &= x_0 + \sum_j p_{j1} \\
x_2 &= x_1 + \sum_j p_{j2} = x_0 + \sum_j \Big(p_{j1} + p_{j2}\Big) \\
x_i &= x_{i-1} + \sum_j p_{ji} \\
&= x_0 + \sum_j \Big(p_{j1} + p_{j2} + \ldots + p_{ji}\Big) \\
\bar{x} &= x_0 + \sum_j \Big(p_{j1} + \frac{m-1}{m} p_{j2} + \\
&\quad \frac{m-2}{m} p_{j3} + \ldots + \frac{1}{m} p_{jm}\Big),
\end{aligned} \tag{2}$$

in which x_i represents trace concentration at ith o'clock; p_{ji} is the effects of jth process at ith o'clock; and $\bar{x}$ is averaged concentration. The sum in the bracket is the effect of jth process on averaged concentration. By comparing the effect of every process at different period, the reason for averaged concentration change is explored. From Eq.(2) it is known that the changes of averaged concentration of different periods which started at the same o'clock are ascribed to changes of the effect of every process. Table 1 shows the changes of averaged concentration, the effect of every process, and the differences of every process between different periods.

From Table 1, it is found that the averaged concentrations in the four periods decrease gradually, i.e., the monthly averaged concentration deceases gradually from April to July. Compared with the results of April and of April-May, it can be seen that the ozone reduction is attributed to horizontal and vertical transport, and the effect of horizontal transport is greater than that of vertical advection. In the horizontal transport, the effect of latitudinal transport reduces ozone by -753.0 ppbv, but that of longitudinal transport increases ozone by 717.9 ppbv. The magnitude of latitudinal and longitudinal transport is much bigger than that of net horizontal and vertical transport. The dynamic transport makes ozone decrease by 38.6 ppbv; but the effect of chemical process is opposite to that of dynamic process, which leads ozone to increase by 14.8 ppbv. The sum of all effects is ozone reduction of 23.2 ppbv. Because the magnitude of chemical process effect is equivalent with that of the net effect, the chemical effect cannot be neglected.

Table 1. Ozone budget (unit: ppbv)

	Apr. 1 to Apr. 30	Apr. 1 to May 31	Apr. 1 to Jun. 30	Apr. 1 to Jul. 31
Averaged concentration	241.333	214.098 (-27.2)	199.341 (-14.8)	189.590 (-9.8)
Longitudinal transport	1480.288	2208.212 (717.9)	2648.866 (440.6)	2864.468 (211.6)
Latitudinal transport	-1440.558	-2193.613 (-753.0)	-2551.049 (-357.4)	-2616.951(-65.9)
Horizontal transport	39.730	14.599 (-25.1)	97.817 (83.2)	247.517 (149.7)
Vertical advection	38.525	25.192 (-13.3)	-94.464 (-119.7)	-288.096 (-183.6)
Convective activities	0.000	-0.169 (-0.169)	-1.759 (-1.6)	-9.164 (-7.4)
Dynamic process	78.255	39.622 (-38.633)	1.594 (-38.032)	-49.743 (-51.337)
Chemical process	6.560	21.363 (14.8)	44.774 (23.4)	87.732 (43.0)
Sum	80.377	57.140 (-23.2)	41.539 (-15.6)	31.649 (-9.9)

Notes: The bracket is the difference between current and last period.

Similar to the changes between April and April-May, the averaged concentration (199.3 ppbv) in April-June is less than that in April-May. The table indicates that the ozone reduction in June is mostly ascribable to the vertical transport, and the effect of convective activities is small. Meanwhile, the horizontal transport and chemical process result in ozone increase. The changes of the horizontal transport are because the ozone increases induced by the longitudinal transport are more than the ozone reduction resulted from the latitudinal transport. The net sum of ozone changes is the ozone reduction of 15.6 ppbv. Like the ozone changes in April-June, the effect of every process on ozone becomes stronger in April-July than that in June.

From the above analyses of April-May, April-June, and April-July, it is found that in May, i.e., early period of the TP ozone valley, the horizontal transport is the main part of the dynamic process that results in the TP ozone valley. However, in June and July the vertical transport becomes main part of dynamic process.

The effect of the gaseous chemical process brings about ozone increases that are more than the net changes sometimes, thus the chemical effect is also important.

5.3 *Cause for formation of the TP ozone valley in summer*

From the above analyses, it can been seen that when the ozone valley occurs and develops, the transport process of ozone plays the main role, and the chemical process partly compensates the ozone reduction by the transport process. In the dynamic transport process of ozone, the horizontal transport process plays a chief role of the ozone reduction in May. The vertical transport process gradually plays a main role of the ozone reduction in June and July. Effect of convective activities rises little by little so that this effect cannot be overlooked in July. Synthesized analyses of model results and weather, we further depict the dynamic and chemical process in the formation and development of the TP ozone valley. In May, early period of the TP ozone valley, the formation of the TP ozone valley is primary because South Asian high moves northwestward to bring ozone of lower concentration from low latitudes. Then, while South Asian high moves over the TP and its intensity strengthens, ozone of low concentration from low troposphere around the TP is transported into the upper troposphere and lower stratosphere over the TP. Consequently, the vertical transport plays a main role of the TP ozone valley, but the horizontal transport compensates partly the effect of the vertical advection. At the same time, the effect of chemical process plays an important role, and can not be overlooked.

6. The deepening of the TP ozone valley and prediction of the TP TCO trend

Zhou et al. (1995) discovered that there is the TP

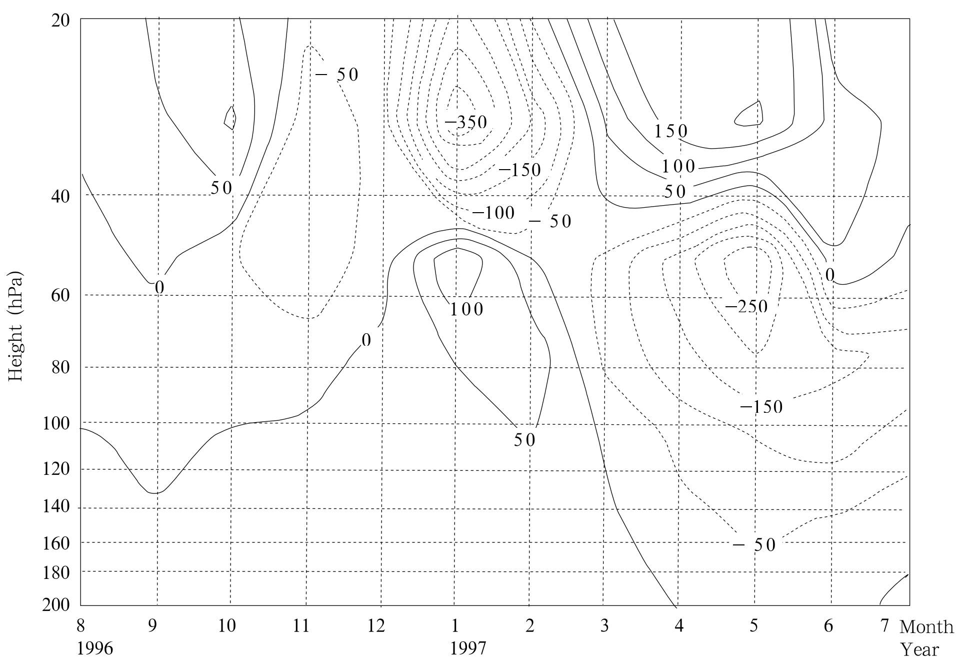

Fig.18. Seasonal variation of the difference between a site (31°N, 90°E) and its zonal average with height (unit:10^{-9} V V^{-1}).

ozone valley in summer, and TCO decrease trend in Lasha is quicker than that over East China of the same latitude. Since Lasha is located in the area of TP ozone valley, we wonder what is the trend of TCO over the TP? Based on TOMS data from 1979 to 1992 (version 7), Liu and Li (2001) calculated global TCO trend and verified their reliability after the TOMS data is handled by moving average.

Figure 19 depicts TCO trend over China, which is based on TOMS data handled by moving average to filter QBO, seasonal variation, etc., and inspects with the 95% reliability, where the shadow area represents that the reliability is lower than 95%. From this figure, it is found that the TCO decreases over most of China except for Hainan Island, and their reliability is more than 95%. TCO decrease trends increase with latitude increasement. The maximum of the decrease trend appears in Northeast China, which is also a large center of TCO decrease trend with more than 0.5% per year. Meanwhile, the figure shows that there is a large center of TCO decrease trend over the TP with more than 0.3% per year, but the TCO decrease trend is about 0.2% per year over East China.

Because the site (32.5°N, 88°E) is a center of TCO decrease trend in June, the sites (32.5°N, 88°E; 32.5°N, 120°E) are selected to represent the TP and East China respectively. Table 2 exhibits TCO trends at these sites, the trends of both TCO difference, and their reliability, in which "×" represents that the reliability is less than 95%, the other represent that the reliability is more than 95%. From the table, it is seen that in January and June the reliability of the trend of TCO and TCO difference between the two sites is more than 95%. Because the TP ozone valley exists in June and solar radiation is strong in this time, the TP ozone valley in June is given more attention. From Fig. 20, it is found that there is a large center of TCO decrease trend over the TP in June, which is 0.3% per year. And the TCO difference between the TP and East China increase with more than 95% confidence. Therefore, there is a deepening trend of TP ozone valley. Figure 20 shows that the area of the deepening trend is from 78° to 94°E and from 29° to 33°N (about 450 000 km^2). Compared with TCO trend over other area of the same latitude, the trend over the TP is one of strong centers of TCO decrease trend.

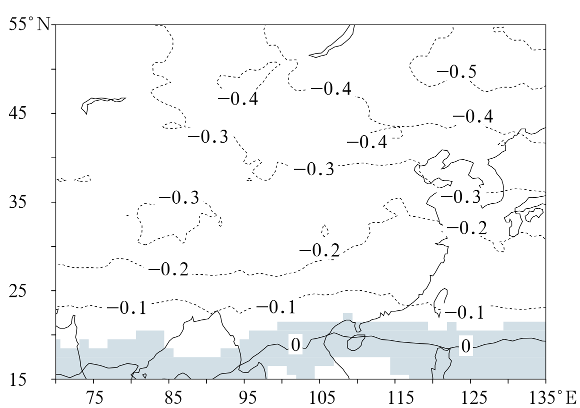

Fig.19. Trend of total column ozone (unit: % yr^{-1}) .

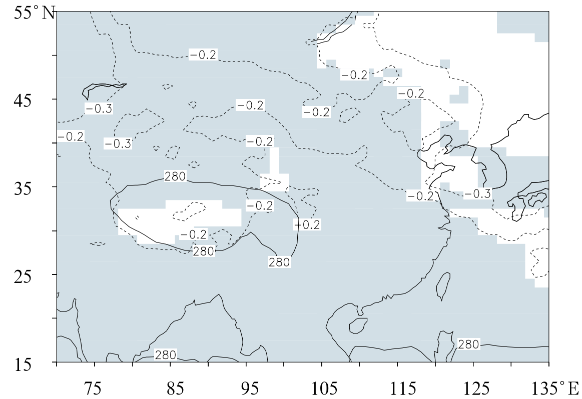

Fig.20. Area of deep ozone valley in June over the Tibetan Plateau. (Solid line is 280 DU of ozone, dashed line represents ozone decrease rate, and shaded area represents that it does not reach 95 % confidence.)

The TP covers a quarter of the whole China. Because there is TP ozone valley in summer and it deepens, it will lead to solar UV radiation increases, and influence Tibetan human beings, ecosystem, and environment strongly. Therefore, future TCO trend over the TP is given close attention. Liu et al. (2001) explored TCO trend over the TP with a 2-D global chemical model.

Figure 21 shows the pattern of TCO change over the TP: TCO decreases from 1980 to 1993; it reaches low extremum in 1993; it recovers rapidly from 1993

Table 2. Trend of TCO at (32.5°N, 88°E) and (32.5°N, 120°E) and their difference

	Jan.	Feb.	March	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
88°E	-0.58	-0.26	-0.57	-0.37	-0.36	-0.34	-0.16	-0.08	-0.10	-0.19	-0.36	-0.11
REL		×					×	×	×	×	×	
120°E	-0.38	-0.29	-0.26	-0.10	-0.37	-0.19	-0.00	0.02	-0.02	-0.06	-0.32	-0.16
REL				×		×	×	×	×	×		×
DIF	3.75	-0.92	4.21	2.35	-0.45	0.917	1.38	0.947	0.812	1.85	0.655	-1.00
REL		×	×	×	×			×	×		×	×

Notes: REL represents reliability; DIF represents difference; and "×" represents the confidence lower than 95%.

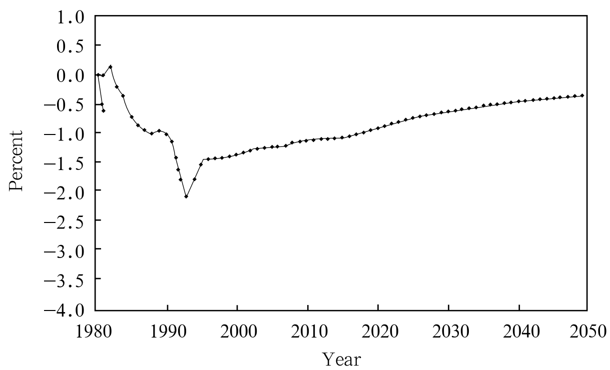

Fig.21. Trend of modeled total column ozone over the Tibetan Plateau.

to 1995; then it recovers gradually, but until 2050 it does not reach that of 1980. Under the condition of TP special circulation, TCO recovers faster than under zonal mean condition. It illustrates that the TP special circulation is not the main reason that the strong center of TCO decrease trend forms over the TP.

7. Summary

This paper reviewed the main results in the last decade with respect to the discovery of low center of TCO over the TP in summer, and its formation mechanism. Some important advances are summarized as follows: The fact is discovered that there is the TP ozone valley in summer, and the features of the background circulation over the TP are analyzed; it is confirmed that the TP is a pathway of mass exchange between troposphere and stratosphere, and it influences the TP ozone valley; models reproduce the TP ozone valley, and the formation mechanism are explored; in addition, the analyses and diagnoses of the observation data indicated that not only there is the TP ozone valley, but also TCO decrease trend over the TP is one of strong centers of TCO decrease trend in the same latitude; finally, the model predicts future TCO change over the TP.

Because under the condition of TP special circulation ozone change over the TP results from net role of dynamical, physical, and chemical processes which involve many natural and anthropogenic effects, it is difficult to understand them definitely now, such as the TCO decrease trend over the TP, dynamical and thermo-dynamical role cannot explain this phenomenon, this should be ascribed to other reasons. Maybe, heterogeneous reaction and clouds over the TP are related to that, which is a nonlinear result of dynamical, physical, and chemical processes. Because the TP is a special and important region that could influence climate and environment of East Asia and globe, we hope to have opportunities to further explore the above issues.

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