



Effects of Stationary and Transient Transport of Ozone on the Ozone Valley Over the Tibetan Plateau in Summer

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Specialty section:

This article was submitted to
Atmospheric Science,
a section of the journal
Frontiers in Earth Science

Received: 18 September 2020

Accepted: 10 February 2021

Published: 25 March 2021

Citation:

Xu W, Song Q, Li Y, Shi C, Sun B, Su Y,
Tang Z, Du Y and Guo D (2021) Effects
of Stationary and Transient Transport
of Ozone on the Ozone Valley Over the
Tibetan Plateau in Summer.
Front. Earth Sci. 9:608018.
doi: 10.3389/feart.2021.608018

We studied the effects of the stationary and transient transport of ozone in the upper troposphere and lower stratosphere (UTLS) on the ozone valley over the Tibetan Plateau (OVTP) in summer using the daily ERA-Interim reanalysis dataset for the time period 1979–2016. We used the Lorenz circulation decomposition method to separate the stationary and transient transport of ozone into terms related to either the mean flow or eddies. The decrease in the total ozone concentration in summer is associated with the transport of ozone, which, in turn, reinforces the OVTP. The zonal (meridional) transport of ozone, which combines stationary and transient transport, strengthens (weakens) the ozone valley. The stationary zonal (meridional) transport of ozone strengthens (weakens) the ozone valley. The transient zonal (meridional) transport of ozone weakens (strengthens) the ozone valley, but this effect is weaker than that of stationary transport. The mean flow has the dominant role, especially in the stationary component. The effect of eddies on the zonal transient transport of ozone is as strong as that of the mean flow. For stationary transport, the zonal deviation of ozone transported by the zonal mean flow in the zonal (meridional) direction $C(\overline{O_3^*}[\overline{u}])$ ($C(\overline{O_3^*}[\overline{v}])$) dominates total zonal (meridional) change of ozone $C(\overline{O_3}[\overline{u}])$ ($C(\overline{O_3}[\overline{v}])$), which strengthens (weakens) the ozone valley. The transient transport of the zonal mean ozone by eddies ($C([O_3]'\overline{u}^*)$), the zonal deviation of ozone by the zonal mean flow ($C(O_3^*[\overline{u}'])$) and the zonal deviation of ozone by eddies ($C(O_3^*[\overline{u}']^*)$) all have a strong effect on the ozone valley. By contrast, the transient transport of the zonal mean ozone by eddies in the meridional direction ($C([O_3]'\overline{v}^*)$) has a much weaker and the smallest effect. Both the zonal deviation of ozone by the zonal mean flow and by eddies in the meridional direction ($C(O_3^*[\overline{v}']^*)$ and $C(O_3^*[\overline{v}']^*)$) have major roles in transient meridional transport, but their roles are the opposite of each other. The contributions of stationary and transient transport to zonal transport are consistent, whereas their contributions to meridional transport are the opposite of each other. The influence of transient transport on the formation and maintenance of OVTP is not negligible.

Keywords: Stationary transport, transient transport, ozone valley over the Tibetan Plateau, Lorenz circulation decomposition method, upper troposphere and lower stratosphere

INTRODUCTION

Ozone is an important topic in atmospheric research (Cong et al., 2001). The ozone layer in the stratosphere has an important role in the thermal structure of the atmosphere (Andrews et al., 1987) because it absorbs ultraviolet radiation, modifying the thermal and dynamic structure of the atmosphere (Kerr et al., 1993; Lubin and Jensen, 1995; IPCC, 2007; Chipperfield et al., 2015; Xie et al., 2018). This, in turn, can affect aerodynamic, physical and chemical processes in both the troposphere and stratosphere (Farman et al., 1985; Forster and Shine, 1997; Xie et al., 2008; Shi et al., 2010; Wang et al., 2013).

Since the discovery of the Antarctic ozone hole in 1984 (Farman et al., 1985), the depletion of stratospheric ozone and its impact on the Earth's climate have attracted concern worldwide (Solomon, 1999; Zhou and Zhang, 2005; Crutzen and Oppenheimer, 2008; Tobo et al., 2008; Karpechko et al., 2014; Zhang et al., 2014; Hu et al., 2015; Zhang et al., 2019). The effects of the polar ozone hole on the Earth's climate have been widely studied. (Hartmann et al., 2000; Pienitz and Vincent, 2000; Ungar, 2000; Perlwitz et al., 2008). Outside the polar regions, strong ozone depletion also occurs over the Tibetan Plateau (Reiter and Gao, 1982; Hingane, 1990). The Tibetan Plateau, also known as the third pole (Xu and Chen, 2005), is the highest plateau on Earth, with an average elevation >4,000 m. The unique topography of the Tibetan Plateau means that the dynamic and thermal properties of ozone in this region are different from those in the surrounding atmosphere, which has a significant impact on the Earth's climate (Zhang and Chen, 2005; Wang et al., 2006; Wang et al., 2007). Reiter and Gao (1982) found that a center of relatively low total ozone concentrations appears over the Tibetan Plateau when the South Asian High (SAH) moves over the plateau and is maintained in mid-April.

The accuracy of ozone measurements is constantly improving with developments in satellite technology. Stolarski et al. (2013) investigated the seasonal distribution of ozone at mid-latitudes in the northern hemisphere using data from the Total Ozone Mapping Spectrometer (TOMS) onboard NASA's Earth Probe satellite and found that the trend at 50°N changes from about -0.8% year⁻¹ in winter and early spring to about -0.2% year⁻¹ in summer. Based on more accurate TOMS ozone data, Zhou et al. (1995) found that the total column ozone over the Tibetan Plateau in the half-year of the boreal summer (April–September) is > 5 DU lower than that over eastern China at the same latitude. This center of low ozone concentrations is referred to as the ozone valley over the Tibetan Plateau (OVTP). Zou (1996) confirmed the existence of the OVTP and found that the total column ozone was about 30 DU lower than the zonal mean at the same latitude.

The mechanism of the formation of the summer OVTP was first speculated by Zhou et al. (1995), who suggested that mass transport caused by local ascending motion and the related chemical processes were the main cause of the OVTP. Most

subsequent research has suggested that the dynamic transport associated with large-scale circulation patterns plays a major part in the formation of the OVTP in the upper troposphere and lower stratosphere (UTLS), the role of chemical processes is secondary (Guo and Xu, 1986; Su and Wang, 2000; Liu et al., 2003; Liu et al., 2003; Zhou and Chen, 2005; Wan et al., 2007; Tian et al., 2008; Bian et al., 2011; Guo et al., 2012). Zou (1996) found a significant negative correlation between the surface heat flux and the ozone deficit, which implies a combined effect of the chemical and dynamic processes associated with the surface-air heating over the Tibetan Plateau. The absence of about 4 km of the ozone partial column compared with non-mountainous terrains at the same latitude may contribute to the formation of the OVTP (Tian et al., 2009; Bian et al., 2011; Guo et al., 2016).

The dynamic transport processes associated with the atmospheric circulation are important in the global distribution of ozone (WMO, 1985). The Tibetan Plateau is a geographic high and is an elevated heat source associated with thermally forced circulation patterns. Updraft and convective activities provide a favorable circulation background for the emergence of a center of low ozone concentrations (Ye and Xu, 2003). Liu et al. (2003) simulated the OVTP in summer using a three-dimensional chemical transport model (OSLO CTM2). They found that transport processes have a key role in the formation of the OVTP in summer, whereas chemical processes compensate for the reduction in ozone via transport processes. Zhou et al. (2004), using a chemical transport model, showed that horizontal and vertical transport are the main reasons for the center of low ozone concentrations over the Tibetan Plateau in summer and that the effect of horizontal transport in convective transport is more dominant than that of vertical transport. Guo et al. (2012) studied the dynamic effects of the 150–50 hPa SAH on the OVTP by analyzing the meridional, zonal and vertical transport with the WACCM3 model and found that the seasonal variation of the OVTP changes significantly with the SAH. Dynamic processes have an important effect on the OVTP in summer (WMO, 1985; Ye and Xu, 2003; Liu et al., 2003; Zhou et al., 2004; Zhou and Zhang, 2005; Guo et al., 2012; Guo et al., 2016).

Previous studies of the horizontal transport of ozone have mainly focused on stationary transport in the climatological mean state (Zhou et al., 2004; Guo et al., 2012) and little attention has been paid to the effects of transient transport, which is usually used in the study of synoptic processes. The effect of transient transport is therefore underestimated in the studies of the effect of ozone transport on climate. Mak (1978) and Trenberth (1987) considered that the magnitudes of stationary and transient eddies were almost the same. However, Kraucunas and Hartmann (2005) suggested that the contribution of stationary eddies was smaller than that of transient eddies. An analysis of both stationary and transient transport from the point of view of the mean flow and eddies is therefore important in determining the possible mechanisms of

changes in ozone concentrations over the Tibetan Plateau. Changes in transient transport can be studied better using data with a high spatial and temporal resolution.

This study focuses on the climate characteristics of the two types of ozone transport over the Tibetan Plateau. Lorenz decomposition of the atmospheric circulation is used to help understand the characteristics of ozone transport over the Tibetan Plateau and to explain its impact on the OVTP. This method has been widely applied to the study of transport characteristics (Starr and White, 1951; Ye and Deng, 1956; Newell et al., 1972; Trenberth, 1987; Yi and Tao, 1997; Wang et al., 2007; Egger and Hoinka, 2011; Yang et al., 2014). However, the decomposition used here is more exhaustive than that used in previous studies and is based on both the mean flow and eddies, which are both important in the better study of ozone transport.

This paper is organized as follows. *Materials and Methods Section* describes the ERA-Interim reanalysis dataset and Lorenz decomposition method. The analysis of climate characteristics of stationary and transient transport in summer is presented in *Results Section*. *Conclusions and Discussion Section* provides our conclusions and discussions.

MATERIALS AND METHODS

Data

ERA-Interim Reanalysis Dataset

The ERA-Interim reanalysis dataset from the European Center for Medium-Range Weather Forecasts (ECMWF) is produced using a four-dimensional variational approach and has a high horizontal resolution, good background error constraints, modified variances in the satellite radiation data and improved rapid radiative transfer (Dee et al., 2011). Both the pattern and data assimilation systems have improved since the earlier ERA-40 dataset. The time span has been continuously updated since 1979 and there are 14 atmospheric parameters for 37 standard pressure levels ranging from 1,000 to 1 hPa. The horizontal resolution and the data range of ERA-Interim dataset are optional. Previous studies have shown that the ERA-Interim ozone data compare well with ozone observations from satellites and can be used to analyze changes in the ozone flux (Dragani, 2011; Skerlak et al., 2013). The daily ERA-Interim dataset has a higher resolution than the satellite data, which helps the study of transient transport.

We analyzed the daily ERA-Interim reanalysis data for the ozone concentration and horizontal wind fields from 1979 to 2016 in summer (June–August) at a horizontal resolution of (0.75° × 0.75°).

Methods

Lorenz Decomposition of Atmospheric Circulation

There are three decompositions of the atmospheric circulation: 1) in the time domain; 2) in the space domain; and 3) in the space–time domain. The decomposition of a physical quantity A in the time domain is

$$A = \bar{A} + A' \tag{1}$$

where \bar{A} is the time-averaged component ($\bar{A} = \frac{1}{n} \sum_{i=1}^n A_i$, which does not change with i) and A' is the anomaly component ($A'_i = A_i - \bar{A}$, which varies with i). “ $\bar{}$ ” and “ $'$ ” are time-averaged and time anomaly operators, respectively.

The decomposition in the space domain is

$$A = [A] + A^* \tag{2}$$

where $[A]$ is the zonal-average component ($[A] = \frac{1}{m} \sum_{j=1}^m A_j$, which does not change with j) and A^* is the anomaly component ($A^*_j = A_j - [A]$, which varies with j). “[]” and “ $*$ ” are zonal-average and zonal deviation operators, respectively (Lorenz, 1967; Zhou et al., 2009).

Flux is defined as the physical variable “transport” caused by atmospheric motion per unit time through a unit area perpendicular to the direction of motion. For example, if A represents the physical quantity and u represents the eastward component of the wind, then Au is the eastward transport flux of the physical quantity. The eastward flux is positive and the westward flux is negative.

The time decomposition of time-averaged flux Au yields:

$$\overline{Au} = \overline{(\bar{A} + A')(\bar{u} + u')} = \overline{\bar{A}\bar{u}} + \overline{A'\bar{u}} + \overline{\bar{A}u'} + \overline{A'u'} = \overline{\bar{A}\bar{u}} + \overline{A'u'} \tag{3}$$

where $\overline{\bar{A}\bar{u}}$ and $\overline{A'u'}$ are stationary transport and transient transport of flux, respectively. The time-average component is calculated by averaging the values over all summertime periods (June–August) from 1979 to 2016 ($\bar{A} = \frac{1}{n} \sum_{i=1}^n A_i$, $\bar{u} = \frac{1}{n} \sum_{i=1}^n u_i$, where n is the number of days during the whole time period). Further spatial decomposition gives more detailed components of stationary transport and transient transport flux:

$$\overline{([A] + A^*)([u] + u^*)} = \overline{[A][u]} + \overline{A^*[u]} + \overline{[A]u^*} + \overline{A^*u^*} \tag{4}$$

$$\overline{([A] + A^*)([u] + u^*)} = \overline{[A]'[u]'} + \overline{A^{*'}[u]'} + \overline{[A]'u^{*'}} + \overline{A^{*'}u^{*'}} \tag{5}$$

If we take the ozone zonal transport flux as an example (meridional transport is the same, but for v), we can obtain the following.

Four Items of Stationary Transport

$$\overline{[O_3][u]} (STu1), \text{ the stationary transport of the zonal mean ozone by the zonal mean flow} \tag{6}$$

$$\overline{O_3^*[u]} (STu2), \text{ the stationary transport of the zonal deviation of ozone by the zonal mean flow} \tag{7}$$

$$\overline{[O_3]u^*} (STu3), \text{ the stationary transport of the zonal mean ozone by eddies} \tag{8}$$

$$\overline{O_3^* u^*} (STu4), \text{ the stationary transport of the zonal deviation of ozone by eddies} \quad (9)$$

Four Items of Transient Transport

$$\overline{[O_3]' [u]'} (TTu1), \text{ the transient transport of the zonal mean ozone by the zonal mean flow} \quad (10)$$

$$\overline{O_3^* [u]'} (TTu2), \text{ the transient transport of the zonal deviation of ozone by the zonal mean flow} \quad (11)$$

$$\overline{[O_3]' u^*} (TTu3), \text{ the transient transport of the zonal mean ozone by eddies} \quad (12)$$

$$\overline{O_3^* u^*} (TTu4), \text{ the transient transport of the zonal deviation of ozone by eddies} \quad (13)$$

Local changes in the ozone concentration are caused by individual changes in the ozone concentration, horizontal transport and vertical transport. The individual variations in ozone concentration include both dynamic and chemical impacts. The dynamic effects have the most important roles in the formation of the OVTP in the UTLS region (Liu et al., 2003; Tian et al., 2008; Bian et al., 2011; Guo et al., 2012), whereas chemical processes have more impact on the ozone concentration over the Tibetan Plateau in the stratosphere (Wan et al., 2007; Liu et al., 2011; Zhang et al., 2014; Guo et al., 2015). We therefore focused on the dynamic effects regardless of the chemical influences in the UTLS region. The local change in the ozone concentration can be approximated by the continuity equation:

$$\begin{aligned} \frac{\partial O_3}{\partial t} &\approx -\nabla \cdot (O_3 \vec{V}) \\ &= -\nabla \cdot \left[\overline{O_3 \vec{V}} + (O_3 \vec{V})' \right] \\ &= -\nabla \cdot \left[\overline{O_3 \vec{V}} + \mathcal{O} \left(\overline{O_3 \vec{V}} \right) \right] \\ &= -\nabla \cdot \left(\overline{O_3 \vec{V}} \right) \\ &= - \left[\left(\frac{\partial (\overline{O_3 u})}{\partial x} + \frac{\partial (\overline{O_3 v})}{\partial y} \right) + \frac{\partial (\overline{O_3 \omega})}{\partial z} \right] \\ &= -D \\ &= -(D_H + D_V) \end{aligned} \quad (14)$$

where D is the divergence of the ozone transport flux and $-D$ represents the local change in the concentration of ozone. D_H and D_V are the horizontal and vertical divergence, respectively. Because the vertical divergence is two orders of magnitude smaller than the horizontal divergence, we only discuss the horizontal change:

$$\begin{aligned} -D_H &= -(D_x + D_y) \\ &= -(D_{x-ST} + D_{x-TT} + D_{y-ST} + D_{y-TT}) \end{aligned} \quad (15)$$

where D_x and D_y are zonal and meridional divergence, respectively, D_{x-ST} and D_{x-TT} are the divergence of the stationary and transient transport in the zonal direction, respectively. D_{y-ST} and D_{y-TT} are same as D_{x-ST} and D_{x-TT} , but in the meridional direction.

If we combine Eqs. 6–13, 15, we obtain Eq. 16:

$$-D_H = - \left[\begin{aligned} &\frac{\partial (STu1)}{\partial x} + \frac{\partial (STu2)}{\partial x} + \frac{\partial (STu3)}{\partial x} + \frac{\partial (STu4)}{\partial x} + \frac{\partial (TTu1)}{\partial x} + \frac{\partial (TTu2)}{\partial x} + \frac{\partial (TTu3)}{\partial x} + \frac{\partial (TTu4)}{\partial x} + \frac{\partial (STv1)}{\partial y} \\ &+ \frac{\partial (STv2)}{\partial y} + \frac{\partial (STv3)}{\partial y} + \frac{\partial (STv4)}{\partial y} + \frac{\partial (TTv1)}{\partial y} + \frac{\partial (TTv2)}{\partial y} + \frac{\partial (TTv3)}{\partial y} + \frac{\partial (TTv4)}{\partial y} \end{aligned} \right] \quad (16)$$

Then we define C as the spatial difference of items in Eq. 16, and get Eq. 17:

$$\begin{aligned} -D_H &= (C_{STu1} + C_{STu2} + C_{STu3} + C_{STu4}) + (C_{TTu1} + C_{TTu2} + C_{TTu3} + C_{TTu4}) \\ &\quad + (C_{STv1} + C_{STv2} + C_{STv3} + C_{STv4}) + (C_{TTv1} + C_{TTv2} + C_{TTv3} + C_{TTv4}) \end{aligned} \quad (17)$$

where C_{STu1} , C_{STu2} and other items represents the change of ozone by the spatial difference of items Eqs. 6–13, respectively.

RESULTS

Characteristics of Ozone Transport in the OVTP

The profiles in Figure 1 show the change of ozone caused by zonal stationary ($C(\overline{O_3 u})$, C_{STu}) and transient ($C(\overline{O_3 u}')$, C_{TTu}) transport in the UTLS region in summer. Figure 1A shows the spatial difference of the zonal stationary transport components (C_{STu1} , C_{STu2} , C_{STu3} , and C_{STu4}) and Figure 1B shows the transient transport components (C_{TTu1} , C_{TTu2} , C_{TTu3} , and C_{TTu4}). The black lines in Figures 1A,B represent the total zonal stationary and total zonal transient transport, respectively. The region between the two horizontal lines indicates the approximate vertical scope of the ozone valley.

Figure 1 shows that the stationary transport of zonal ozone reduces the ozone concentration over the Tibetan Plateau and enhances the OVTP. The transient transport of zonal ozone also reduces the ozone concentration, but the effect in strengthening the OVTP is weaker. The divergence of STu1 and TTu1 in Figure 1 is zero. The stationary transport of the zonal deviation of ozone (Figure 1A) by the zonal mean flow (C_{STu2}) strengthens the ozone valley, with the minimum at 70 hPa reaching $-8.0 \times 10^{13} \text{ m}\cdot\text{kg}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}$. The stationary transport of the zonal mean ozone by eddies (C_{STu3}) and the zonal deviation of ozone by eddies (C_{STu4}) are both positive, which slightly weakens the ozone valley. The total zonal stationary transport therefore strengthens the ozone valley. The positive spatial difference of the zonal mean ozone by eddies of zonal transient transport (C_{TTu3}) shown in Figure 1B weakens the ozone valley, with the maximum at about $3.0 \times 10^{14} \text{ m}\cdot\text{kg}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}$. All the other components enhance the ozone valley to different degrees. The zonal

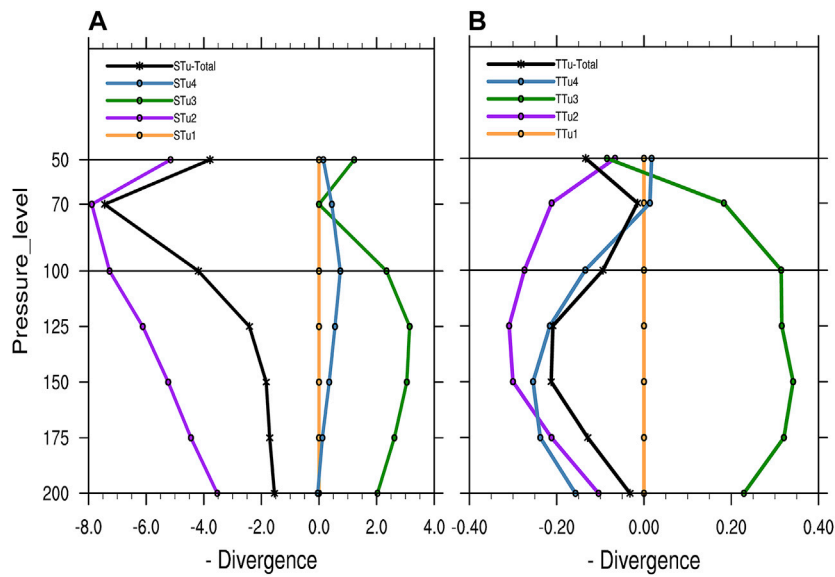


FIGURE 1 | Profiles of the change in zonal ozone transport (negative divergence, $-D_x$) in the UTLS region in summer by **(A)** stationary ($-D_{x_ST}$) and **(B)** transient ($-D_{x_TT}$) transport (units: $10^{13} \text{ m}\cdot\text{kg}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}$). The yellow, purple, green and blue lines indicate the spatial difference of zonal stationary (transient) transport components C_{STu1} (C_{TTu1}), C_{STu2} (C_{TTu2}), C_{STu3} (C_{TTu3}) and C_{STu4} (C_{TTu4}), respectively, and the black lines indicate the total zonal stationary (transient) transport.

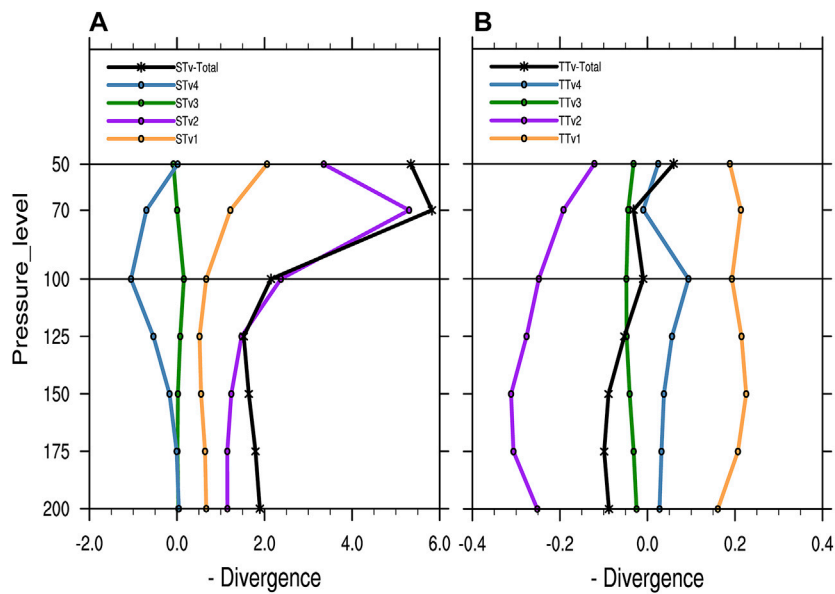
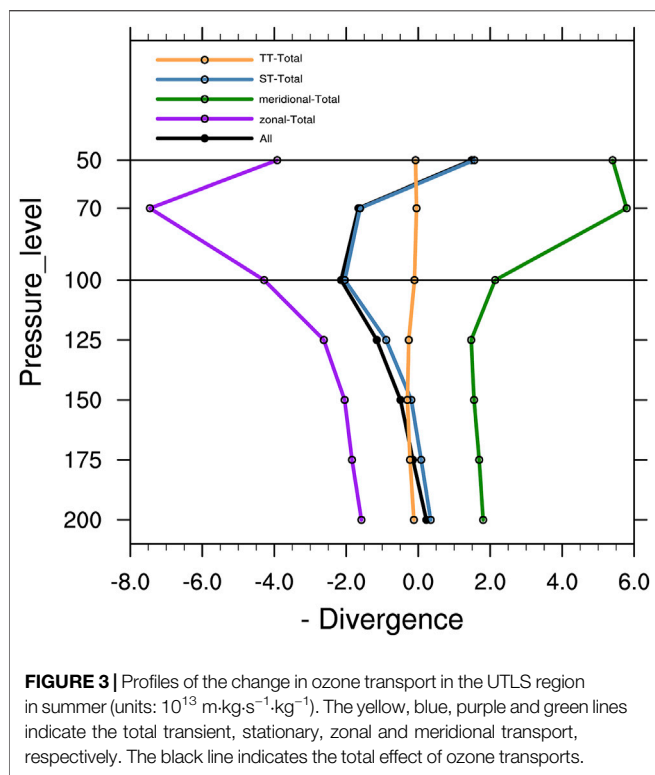


FIGURE 2 | Similar to **Figure 1**, but for meridional ozone transports (v wind).

transient transport therefore strengthens the ozone valley overall, but the effect is weak.

Both stationary and transient transport strengthen the ozone valley in the zonal direction. The mean flow has the dominant role in zonal transport, especially in the stationary part, whereas the eddies have important roles in transient transport, similar to the mean flow in the zonal direction.

Figure 2 shows the profiles of the change of ozone by $C_{STv}(C(\overline{O_3v}))$ and $C_{TTv}(C(\overline{O_3'v'}))$ in the UTLS region in summer. **Figure 2A** shows that stationary transport increases the meridional ozone concentration and weakens the OVTP. The stationary transport of the zonal deviation of ozone by eddies (C_{STv4}) in the meridional direction strengthens the ozone valley, with the minimum at about $-1.0 \times 10^{13} \text{ m}\cdot\text{kg}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}$. The other



components weaken the ozone valley, especially the zonal deviation of ozone by the meridional mean flow (C_{STv2}), which greatly weakens the intensity of the OVTP with the maximum reaching $5.3 \times 10^{13} \text{ m}\cdot\text{kg}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}$. The total meridional stationary transport therefore weakens the ozone valley. **Figure 2B** shows that the transient transport of the zonal mean ozone by the meridional mean flow (C_{TTv1}) weakens the ozone valley to about $2.0 \times 10^{14} \text{ m}\cdot\text{kg}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}$, whereas the zonal deviation of ozone by the meridional mean flow (C_{TTv2}) strengthens the ozone valley, reaching up to $-2.5 \times 10^{14} \text{ m}\cdot\text{kg}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}$. The other the transient transport components by eddies of the zonal mean ozone (C_{TTv3}) and the zonal deviation of ozone (C_{TTv4}) slightly strengthen and weaken the ozone valley, respectively. The total transient transport of meridional ozone therefore slightly strengthens the ozone valley.

The effect of stationary transport on the ozone concentration is more significant than that of transient transport, which weakens the ozone valley in the meridional direction. The impact of the mean flow in the meridional direction is as important as that in the zonal transport component. Eddies also contribute to transient transport.

Figure 3 shows the combination of stationary and transient transport in the zonal and meridional directions. The combined effect of all ozone transport in the UTLS region in summer is to reduce the ozone concentration and enhance the ozone valley. The zonal ozone transport (u-Total) strengthens the ozone valley, whereas the meridional ozone transport (v-Total) weakens it; the impact of u-Total is higher than the impact of v-Total (**Figure 3**). This shows that stationary transport has a major role in altering

the ozone valley, whereas the effect of transient transport is relatively weak. The contribution of the mean flow has the key role in both stationary and transient transport. The effect of eddies is important in transient transport, especially in the zonal direction, where it is as strong as the mean flow (**Figure 1B**).

Climate Characteristics of Stationary Ozone Transport in Summer

To further study the detailed effects of the different stationary transport components, **Figure 4** shows the pressure–latitude cross-section of the change in the zonal ozone stationary transport components C_{STu2} , C_{STu3} and C_{STu4} (C_{STu1} is zero and is ignored here).

Figure 4A shows that $C_{STu2}(C(\overline{O_3}^* [\overline{u}]))$ has the strongest effect on the ozone valley in the UTLS region in summer, resulting in a decrease in ozone concentration and strengthening the ozone valley. The effects of eddies on the $C_{STu3}(C(\overline{[O_3]}^* \overline{u}^*))$ and $C_{STu4}(C(\overline{O_3}^* \overline{u}^*))$ components (**Figures 4B,C**) weaken, resulting in an increase in the ozone concentration and weakening the ozone valley.

Figure 5 shows the change in the meridional ozone stationary transport components C_{STv2} , C_{STv3} , and C_{STv4} . The effect of the $C_{STv2}C(\overline{O_3}^* [\overline{v}])$ component (**Figure 5A**) is the strongest in the UTLS region in summer and increases the ozone concentration and weakens the ozone valley. The $C_{STv3}(C(\overline{[O_3]}^* \overline{v}^*))$ component (**Figure 5B**) weakens the OVTP by increasing the ozone concentration at lower levels, whereas the decreased ozone concentration at upper levels strengthens the OVTP. The $C_{STv4}(C(\overline{O_3}^* \overline{v}^*))$ component (**Figure 5C**) strengthens the ozone valley by reducing the ozone concentration over the Tibetan Plateau.

The magnitude of the mean flow components are significantly larger than the other components in stationary transport, which affects the ozone concentration in the center of the OVTP. The zonal component ($C(\overline{O_3}^* [\overline{u}])$) is stronger than the meridional component ($C(\overline{O_3}^* [\overline{v}])$). The effect of zonal ozone transport by eddies weakens the OVTP, whereas meridional ozone transport by eddies strengthens the OVTP. Because C_{STv3} has the smallest magnitude, the combined effect of C_{STv3} and C_{STu2} strengthens the OVTP.

Climate Characteristics of Transient Ozone Transport in Summer

Figure 6 shows the climate characteristics of the zonal ozone transient transport components C_{TTu2} , C_{TTu3} and C_{TTu4} (C_{TTu1} is zero and is ignored here) in summer in the UTLS region. The $C_{TTu2}(C(\overline{O_3}^* [\overline{u}]^*))$ component (**Figure 6A**) decreases the ozone concentration and enhances the ozone valley. The $C_{TTu3}(C(\overline{[O_3]}^* \overline{u}^*))$ component (**Figure 6B**) weakens the ozone valley by increasing the ozone concentration. The $C_{TTu4}(C(\overline{O_3}^* \overline{u}^*))$ component (**Figure 6C**) reduces the ozone concentration in the lower part of the ozone valley and therefore strengthens this part of the valley. **Figure 7** shows the characteristics of meridional ozone transient transport. The

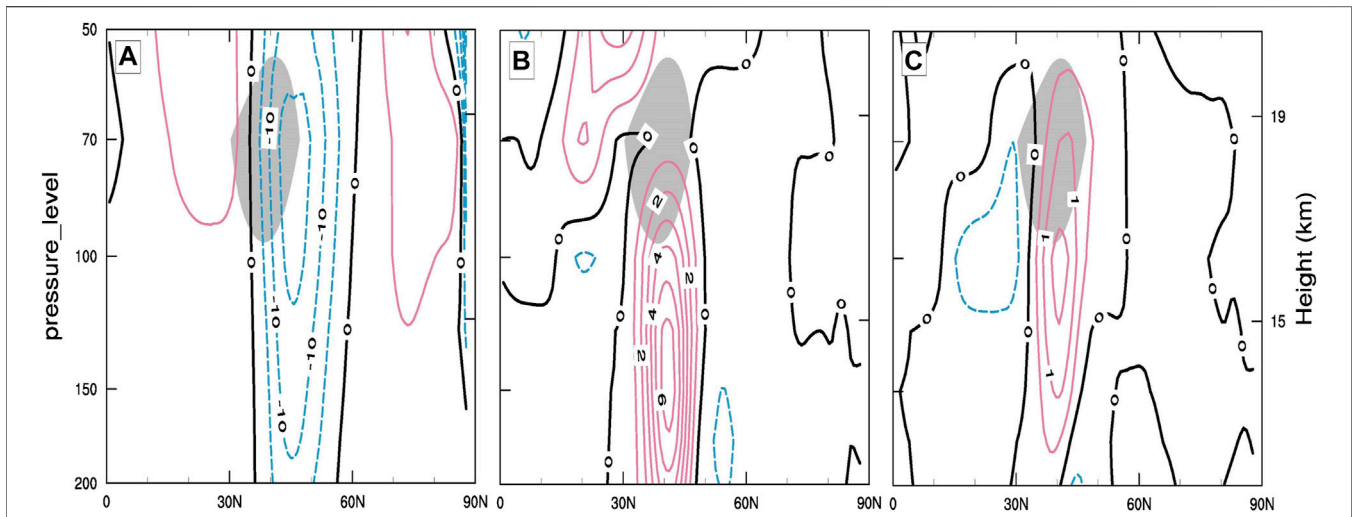


FIGURE 4 | Pressure–latitude cross-section of the change in zonal ozone stationary transport by (A) C_{STu2} , (B) C_{STu3} and (C) C_{STu4} (units: $10^{13} \text{ m}\cdot\text{kg}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}$). The shaded area indicates the OVTP. The blue dashed lines represent decreasing ozone concentrations, the red solid lines represent increasing ozone concentrations and the black bold lines with zero indicate constant ozone concentrations.

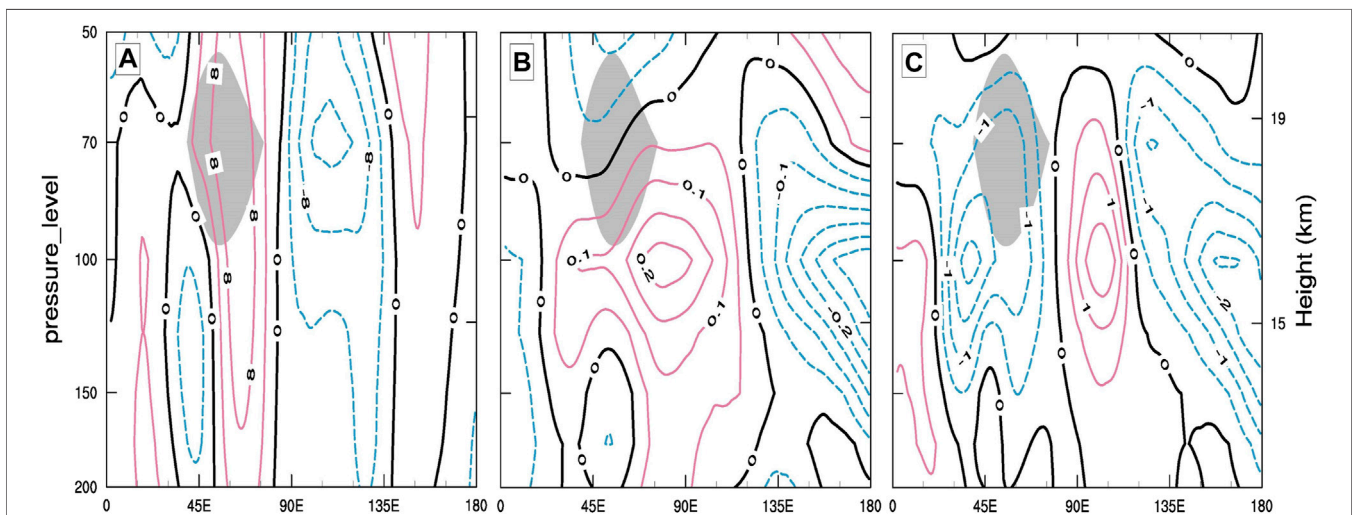


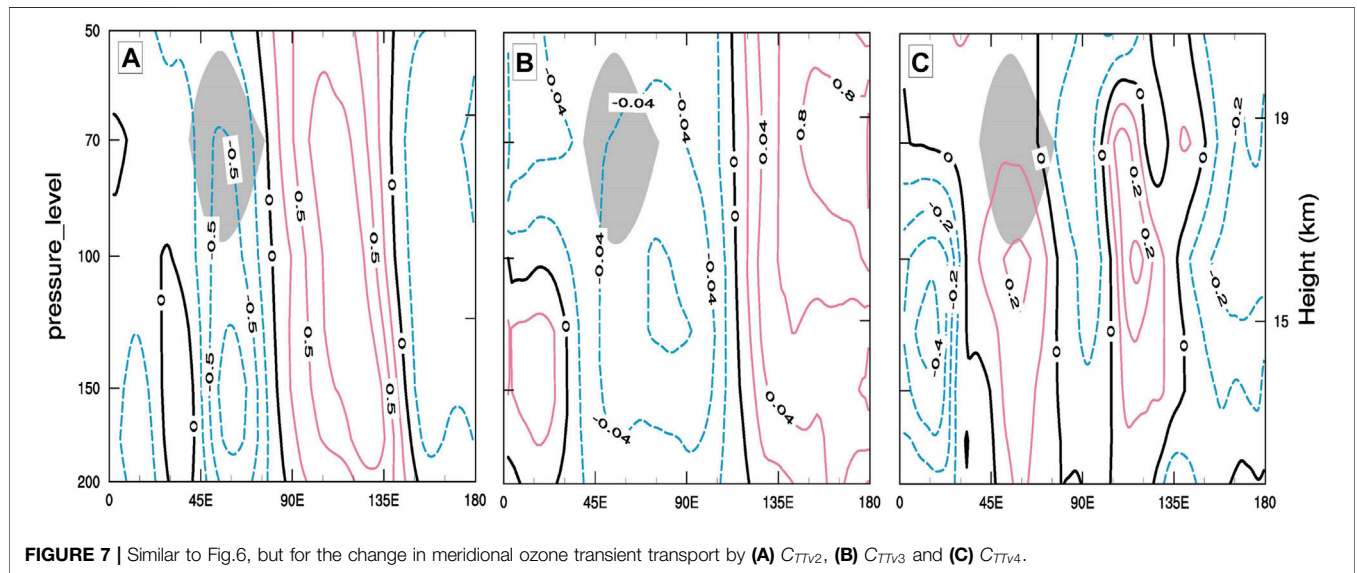
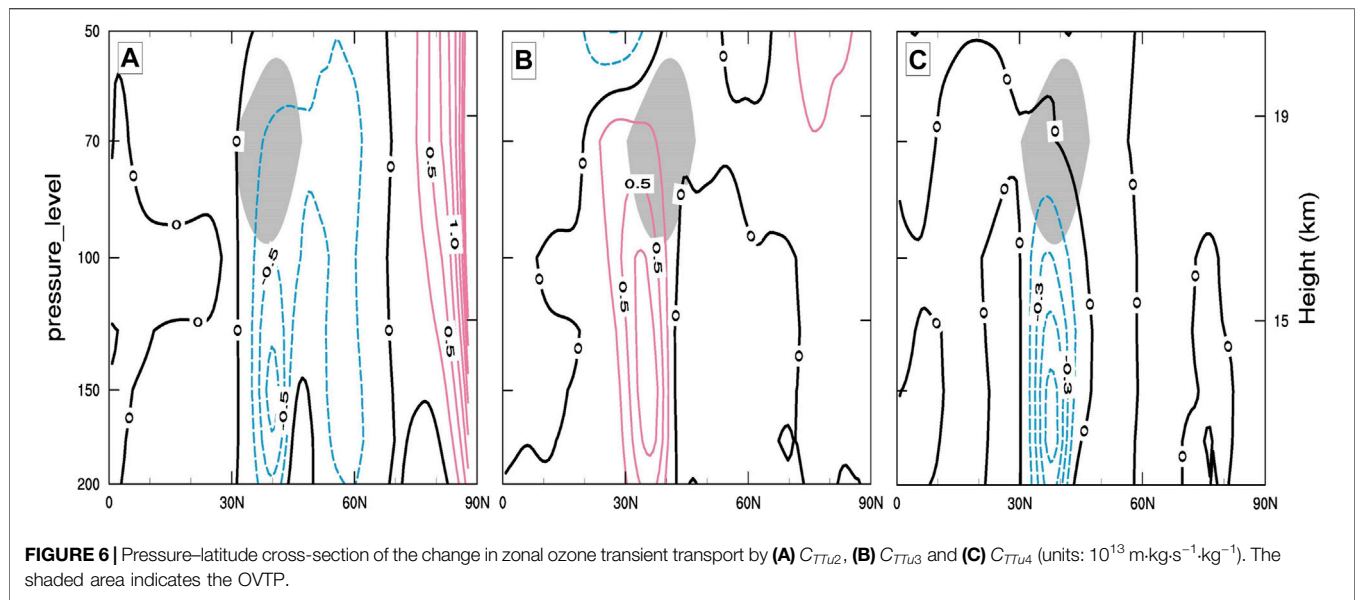
FIGURE 5 | Similar to Fig.4, but for the change in meridional ozone stationary transport by (A) C_{STv2} , (B) C_{STv3} and (C) C_{STv4} .

$C_{TTv3} (C(\overline{[O_3]}'v^{st}))$ component has a minimal effect on transport compared with the $C_{TTv2} (C(\overline{O_3}'[v]'))$ and $C_{TTv4} (C(\overline{O_3}'v^{*'}))$ components. Both the C_{TTv2} and C_{TTv3} components (Figures 7A,B, respectively) enhance the ozone valley with a reduction in the overall ozone concentration. By contrast, the C_{TTv4} component (Figure 7C) weakens the ozone valley. The magnitudes of transient ozone transport by the mean flow and eddies are similar. They have opposite effects in the zonal part, but are consistent in the meridional component. The influence of transient transport is focused in the lower layers.

The contribution of the zonal deviation of ozone by the mean flow is concordant (Figures 4, 6). Both stationary and transient transport reduce the ozone concentration (Figures 4A, 6A). The

effect of eddies on the zonal mean ozone are similar and weaken the OVTP (Figures 4B, 6B). There are a few differences between the C_{STu4} (Figure 4C) and C_{TTu4} (Figure 6C) components, although they have the same influence on the upper OVTP. Stationary and transient transport in the meridional direction (Figures 5, 7) have opposite impacts of the whole layers.

Stationary and transient transport may have different roles in the formation of the ozone valley. They contribute consistently to zonal transport, but inversely to meridional transport, which explains why the effect of the total zonal transport is stronger than the total meridional transport. Different components of transient transport may have different effects—for example, both the zonal and meridional deviations of ozone by the zonal mean flow (C_{TTu2}



and C_{TTV2}) enhance the OVTP and the effect is stronger than that of the other transient components. This shows that the effects of transient transport on the ozone valley obtained by decomposition are non-negligible, especially on the formation and maintenance of the OVTP.

CONCLUSIONS AND DISCUSSION

Conclusions

This study focused on the climate characteristics of the stationary and transient transport of ozone and their effects on the OVTP in the UTLS region in summer using the ERA-Interim dataset and

Lorenz decomposition of the atmospheric circulation. Our main results are as follows.

- 1) The stationary zonal transport of ozone enhances the ozone valley, whereas the stationary meridional transport weakens it. The transient zonal transport of ozone strengthens the ozone valley and the transient meridional transport also slightly strengthens it. The effect of the total stationary transport (zonal or meridional) is much stronger than that of the total transient transport (zonal or meridional) and the mean flow, especially the stationary part, has the dominant role. The effect of eddies on transient transport is as strong as that of the mean flow in zonal transient transport.

- 2) The total ozone transport strengthens the ozone valley, with the total stationary transport playing the major part, whereas the total transient transport slightly weakens the ozone valley in the UTLS region in summer. The total zonal ozone transport combining stationary and transient transport enhances the ozone valley; by contrast, the total meridional ozone transport weakens it.
- 3) Both of the components of the mean flow (C_{STu2} and C_{STv2}) dominate the stationary transport of zonal ozone. The zonal deviation of ozone transported by the zonal mean flow in the zonal direction ($C_{STu2}, C(\overline{O_3^* [u]})$) has the strongest effect on strengthening the ozone valley in the UTLS region in summer, whereas the zonal deviation of ozone transported by the zonal mean flow in the meridional direction ($C_{STv2}, C(\overline{O_3^* [v]})$) weakens the ozone valley. The transient transport component of the zonal deviation of ozone by the zonal mean flow ($C_{TTu2}, C(\overline{O_3^* [u]})$), the zonal mean ozone component by eddies ($C_{TTu3}, C(\overline{[O_3]'} u^{*'})$) and zonal deviation of the ozone component by eddies ($C_{TTu4}, C(\overline{O_3^* u^{*'}})$) in the zonal direction have strong effects on the ozone valley in the UTLS region in summer. By contrast, the transient meridional transport of ozone is much weaker, especially the component $C_{TTv3} (C(\overline{[O_3]'} v^{*'}))$, which has the smallest effect. The $C_{TTv2} (C(\overline{O_3^* [v]})$) and $C_{TTv4} (C(\overline{O_3^* v^{*'}}))$ components have major roles in transient meridional transport, but have the opposite effect.
- 4) The contributions of stationary and transient transport are consistent with the zonal transport, but are opposite to the meridional transport. The impact of transient transport on the formation and maintenance of the OVTP is not negligible.

Discussion

We analyzed the climate characteristics of the stationary and transient transport of ozone and their effects on the OVTP in the UTLS region in summer. The detailed physical mechanisms associated with ozone transport require further study. The stationary and transient transport are separated into terms related to the mean flow or eddies using Lorenz decomposition of the atmospheric circulation. The effect of transient transport is much weaker than stationary transport on the OVTP whereas it is non-negligible, which could have more impacts on the extreme climate. The effects of the mean flow may be caused by the west jet stream.

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Previous research has shown that the SAH is one of the major factors affecting the OVTP of the dynamic process in summer (Su and Wang, 2000; Liu et al., 2003; Tian et al., 2008; Bian et al., 2011; Guo et al., 2012; Qin et al., 2018). We speculate that the SAH may have the key role in the effect of eddies. The stationary and transient transport of ozone by eddies may be influenced by the climatological and abnormal SAH, respectively. The variation in the distribution of ozone concentrations also influences the ozone transport flux.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: <https://apps.ecmwf.int/datasets/>.

AUTHOR CONTRIBUTIONS

DG initiated and coordinated the work. WX provided the calculation and analysis of ozone transport. WX, QS, and YL wrote the manuscript. CS, BS, YS, ZT, and YD gave valuable suggestions for revisions.

FUNDING

This work was jointly supported by the National Natural Science Foundation of China (41675039, 91837311 and 41875048).

ACKNOWLEDGMENTS

We thank ECMWF for the meteorological data (available at <https://apps.ecmwf.int/datasets/>). We are grateful to the High Performance Computing Center of Nanjing University of Information Science and Technology for carrying out the numerical calculations in this paper using its blade cluster system.

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