Remote Sensing of Atmospheric CO and O₃ Anomalies before and after Two Yutian Mₚ7.3 Earthquakes

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Satellite remote sensing data were used to extract concentrations and volume mixing ratios (VMR) of CO and O₃ and Global Data Assimilation System (GDAS) data associated with Yutian Mₛ7.3 earthquakes on March 21, 2008, and February 12, 2014. Difference value and anomaly index methods and the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model were used to simulate gas backward trajectories and analyze the relations between spatial and temporal variations in total columns of CO and O₃ (TotCO and TotO₃) and earthquakes. Then, the causes of abnormal changes were examined. Maximum anomalies in TotCO and TotO₃ occurred one month before the 2008 earthquake and one month after the 2014 earthquake. Anomalies in TotCO and TotO₃ were distributed along or were consistent with the fault zone. Furthermore, during the abnormal period, the coefficient of correlation between CO and O₃ was 0.672 in 2008 and 0.638 in 2014, with both values significant at \( p < 0.05 \). The correlation between TotCO and TotO₃ was also significant. The abnormal phenomena of TotCO and TotO₃ associated with the two earthquakes were attributed to underground gas escape, atmospheric chemical reactions, and atmospheric transportation caused by in situ stress in the generation of earthquakes.

1. Introduction

Understanding earthquake precursory anomalies is a worldwide concern [1]. At present, ground observations based on geophysics and crustal deformation are the typical focus of research [2]. However, it is difficult to obtain large-area dynamic and continuous information on seismic precursory anomalies because of limitations in ground observations, which restrict the ability to predict earthquakes [1]. Satellite hyperspectral technology has the advantages of wide coverage and short observation period and is not affected by the underlying surface [2]. The technology can identify different gases, invert their concentration distributions, and predict earthquakes [3]. With the development of satellite remote sensing technology, using abnormal changes in gas concentrations near epicenters to predict earthquakes has become a focus of research [4, 5]. However, the mechanisms for the abnormal changes remain unclear because of a lack of research. The C–H–O–S system of the earth is rich and includes CO₂, CH₄, H₂, CO, O₃, water vapor, and other gases [6–8]. These gases escape to the atmosphere from seismic fault and rupture zones before and after earthquakes and thus can change atmospheric composition and concentrations [9–12]. After the Gujarat Mₛ7.7 (2001) and Mₛ5.2 (2006) earthquakes, high-altitude O₃-rich air was transported to the epicenter area by the atmosphere, which increased its O₃ concentration [13]. Similarly, before and after two Mₛ > 8.0 earthquakes in Sumatra in 2004 and 2005, abnormal changes were detected in CO and O₃ concentrations, primarily caused by escape of underground gases during the earthquake and chemical reactions between underground and atmospheric gases [14]. Before and after the Wenchuan Mₛ8.0 earthquake in 2008 and the Lushan Mₛ7.0 earthquake in 2013, there were abnormal spatiotemporal changes in CH₄ and CO, and Cui et al. [15] proposed that they were caused by the two major earthquakes and the accompanying fault tectonic activities. Similarly, Singh et al. [16] suggest that abnormal change in CO concentration before the Gujarat
The tail of the large strike-slip Arerjin fault zone, which is an earthquake was 12 km, and the mechanism was a strike-slip type. For spatial distributions, gas concentrations were determined. The average value of a gas was that in a 1° ×1° (480 km from the 2008 Yutian earthquake epicenter). Since the 2008 Yutian earthquake, one was a 6.1 earthquake 2008 Yutian earthquake epicenter area was 36.1°, and the other was a 6.9 earthquake 2014 Yutian earthquake epicenter area was 35.6°. The satellite can cover 85% of the earth twice a day. The 2008 Yutian earthquake occurred in Yutian, Xinjiang, China, at 0633 on March 21, 2008, with a focal depth of 19 km. The earthquake rupture occurred in Yutian, Xinjiang, China, at 0633 on March 21, 2008, with a focal depth of 19 km. The earthquake rupture primarily extensional and strike-slip, and the epicenter was the intersection of the Kangxiwa fault zone and the southwestern end of the Aretjin fault zone in the West Kunlun Mountains. The main seismic zone is the Arerjin fault [17]. Before this earthquake, there were two M 6 ≥ 6 (excluding aftershocks) earthquakes within 500 km of the 2008 Yutian earthquake epicenter. One was a 6.1 earthquake in Rutog County, Tibet, on May 5, 2007 (140 km from the 2008 Yutian earthquake epicenter), and the other was a 6.9 earthquake in Gérê County, Tibet, on January 9, 2008 (480 km from the 2008 Yutian earthquake epicenter). Since then, the extension of the fault zone in the region has increased. On August 12, 2012, another M 6.2 earthquake occurred 90 km from the 2008 Yutian earthquake, resulting in long-term crustal instability and accumulation of strain energy in the region. As a consequence, a M 6.3 earthquake (36.1°N, 82.5°E) occurred at 1719 on February 12, 2014, in Yutian, Xinjiang. The focal depth of the 2014 Yutian earthquake was 12 km, and the mechanism was a strike-slip type. The tail of the large strike-slip Arerjin fault zone, which is an extension zone in the southwestern section of the fault zone, was the epicenter. Atmospheric infrared sounder (AIRS) data were obtained, and the difference and anomaly index methods were used to analyze temporal and spatial variations in O 3 and CO gases before and after two earthquakes. The relations and the differences between the two earthquakes were also examined. Figure 1 shows the faults and seismic history of the research area.

2. Data and Methods

2.1. Data. Column concentration data of CO, O 3, and CH 4 (TotCO, TotO 3, and TotCH 4) and volume mixing ratio data of CO and O 3 (VMR) were all derived from the 8-day data, monthly average standard product deorbit data, and daily data of the AIRS level 3 of the National Aeronautics and Space Administration (NASA). The data were downloaded from NASA’s Goddard Earth Sciences Data and Information Services Center (http://disc.sci.gsfc.nasa.gov/). The 2008 Yutian earthquake epicenter area was 35.6°N, and the average value of a gas was that in a 1° ×1° space at 81.6°E. The 2014 Yutian earthquake epicenter area was 36.1°N, and the average value of a gas was that in a 1° ×1° space at 82.5°E. For spatial distributions, gas concentrations were determined from 33°N to 39°N and 79°E to 85°E. Because AIRX3STD data (AIRS+AMSU) were used in this paper, sensor data were only available to 2016. Therefore, data from 2003 to 2015 were used. The AIRS is a hyperspectral sensor mounted on the Aqua satellite launched by NASA on May 4, 2002. The satellite can cover 85% of the earth twice a day. The AIRS has 2,378 continuous infrared spectral channels, which can provide hyperspectral resolution data in the wavelength range from 3.7 to 15.4 µm with a spatial resolution of 1° ×1°. The spectral resolution was λ/Δλ > 1,200 nominal. It can monitor the physical parameters pressure, temperature, and humidity and the chemicals CH 4, CO, and O 3 [18, 19]. The meteorological data used for backward trajectory were from atmospheric assimilation products and model reanalysis data of the National Centers for Environmental Prediction (NCEP) in the US and were obtained through the GDAS, which assimilates a variety of conventional data and satellite observation data. The data set included air temperature, humidity, near-surface wind speed, and near-surface pressure, with a time resolution of 3 h and a spatial resolution of 1° ×1°. The data were downloaded from the official website of the NCEP of the National Meteorological Administration (https://www.noaa.gov/).

2.2. Methods. Data were extracted by MATLAB, and the abnormal index method and the difference method were used to subtract the average value of the gas background field in nonseismic years and eliminate the influence of seasonal changes. The HYSPLIT model was used to examine transport and diffusion trajectories of O 3.

(1) Extraction of CO, CH 4, and O 3 data. The CO, CH 4, and O 3 concentration data and the VMR data were in NASA standard disk storage format HDF-type (hierarchical data format). MATLAB (2021a) software was used to extract the data, and ArcGIS (10.5) software was used for interpolation processing.

(2) Abnormal index method. This method is similar to the definition of thermal anomaly [21, 22], and the A index (equation (2)) is the ratio of the difference (equation (3)) to the standard deviation (σ(x, y, t)) (equation (1)) [15]. The anomaly index is used to assess the reliability of anomalies. When the A index > 2, the anomaly reliability reaches 95.44%.

(3) Difference method. This method directly reflects the absolute variation in a gas by using the abnormal difference value and highlighting the abnormal degree by which a gas concentration value deviates from the background value. The anomaly difference is the difference between the current gas concentration (G(x, y, t)) and the background gas concentration (G bac (x, y, t)) at one point. The monthly background value G bac was the average value of each month corresponding to the nonearthquake years from 2003 to 2015 and was obtained using equation (4). [15]

\[ \sigma(x, y, t) = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (G_i(x, y, t) - \bar{G}_{\text{bac}}(x, y, t))^2} \],

(1)

\[ A_{\text{index}}(x, y, t) = \frac{A(x, y, t)}{\sigma(x, y, t)}, \]

(2)

\[ A(x, y, t) = G(x, y, t) - \bar{G}_{\text{bac}}(x, y, t), \]

(3)
3. Results

Characteristics of TotCO and TotO₃ anomalies associated with the two Mₛ7.3 earthquakes in Yutian in 2008 and 2014 obtained by difference value and anomaly index methods are shown in Table 1.

3.1. Spatial Anomaly Features. The difference method indicated the anomaly of TotCO before the 2008 Yutian earthquake that occurred primarily in the northwest direction of the epicenter, appearing along the NW (west-northwest) trending the Tekrick fault (Figure 2(a)). The results obtained by the anomaly index method were similar to those obtained by the difference method, and the maximum anomaly index was 2.0σ (Figure 2(b)). The results indicated that it might be associated with the 2008 Yutian earthquake. Figure 3(a) shows that TotO₃ anomalies before the 2008 Yutian earthquake were primarily distributed in a double ring, with the line between the extreme value centers of the two abnormal rings stretching in an EW direction. The distribution of abnormal bands shown in Figure 3(b) was consistent with that in Figure 3(a), and the maximum anomaly index was approximately 2.2σ.

Figure 4(a) shows that the TotCO anomaly was linearly distributed in the NE (northeast) direction along the Arerjin fault-Xiaoerkule-Ashe Cooley fault after the 2014 Yutian earthquake. The CO anomaly distribution in Figure 4(b) was generally consistent with that in Figure 4(a), with a maximum anomaly index of approximately 1.97σ. However, the TotCO anomaly shown in Figure 4(b) was slightly weaker than that in Figure 4(a). Figure 5(a) shows that the anomalous concentration of TotO₃ after the 2014 Yutian earthquake was linear along the Ashkule-Guozhacuo fault zone. Similar results are shown in Figure 5(b), with an anomaly index of approximately 2.0σ. Theoretically, the anomaly centers of TotCO and TotO₃ should be near the epicentral fault zone and overlap each other. However, this expectation was not supported by the results, possibly because of the topographic conditions and the gas distribution height in Yutian County. Yutian County is ox leg-shaped, with the terrain higher in the south and lower in the north, with a height difference of approximately 3,500 m. The Kashash and Kunlun mountains are in the south of Yutian County, and the Taklimakan Desert and the Tarim Basin are in the north. The CO was concentrated primarily near the surface. A downdraft prevails in the basin, and a pressure difference develops between the basin and the alpine region, forming a local atmospheric circulation that moves the CO release point northward to form an abnormal center. O₃ was concentrated primarily at high altitudes, where wind speeds
are high and gas flow is fast. Affected by northerly wind, O₃ moves southward from the original release point to form an abnormal center [26]. Therefore, the TotCO and TotO₃ anomaly centers shifted and did not coincide with one another.

3.2. Temporal Anomaly Characteristics. The maximum anomalies of TotCO and TotO₃ occurred one month before the 2008 Yutian earthquake (Figures 2 and 3). A small-amplitude CO concentration anomaly occurred in December 2007 (Figure 2), which might be associated with the 6.9-magnitude earthquake in Gêrzê County, Tibet, on January 9, 2008 (480 km from the epicenter of the 2008 Yutian earthquake) [27]. Then, the maximum TotCO anomaly appeared in February and gradually recovered to a normal level of variation from March. The timing of anomalous change in TotO₃ (Figure 3) was generally consistent with that of TotCO. As shown in Figure 6(a), TotCO increased sharply from February 8, reached its maximum on February 10, and then decreased gradually. The TotCO also increased from February 28 to March 13, but the change in amplitude was small, consistent with periodic changes. After that increase, the TotCO returned to the level of periodic change. The TotO₃ began to increase from February 8, breaking the cycle of gradual change, but then decreased sharply on February 11 (Figure 6(a)). Then, TotO₃ began to increase sharply on February 23 and reached a maximum on February 27. After the maximum, TotO₃ decreased and returned to a cycle of gradual change. The VMR values of CO and O₃ at 700 hPa from 2003 to February 2015 were extracted

Table 1: Characteristics of atmospheric CO and O₃ anomalies associated with the Yutian Mₛ7.3 earthquakes on March 21, 2008, and February 12, 2014.

<table>
<thead>
<tr>
<th>Method</th>
<th>Time</th>
<th>Spatial</th>
<th>Maximum anomalous amplitude</th>
<th>Time</th>
<th>Spatial</th>
<th>Maximum anomalous amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO anomalous characteristics</td>
<td>A</td>
<td>Feb</td>
<td>Extension along the NWW direction consistent with the fault zone</td>
<td>1.01 x 10¹⁷</td>
<td>Mar</td>
<td>Linear distribution along the NE fault zone</td>
</tr>
<tr>
<td></td>
<td>A_{index}</td>
<td>Feb</td>
<td>Extension along the NWW direction consistent with the fault zone</td>
<td>2.0</td>
<td>Mar</td>
<td>Double annular extremum and stretching along the NE direction</td>
</tr>
<tr>
<td>O₃ anomalous characteristics</td>
<td>A</td>
<td>Feb</td>
<td>Double annular extremum and stretching along the EW direction</td>
<td>22.67</td>
<td>Mar</td>
<td>Linear distribution along the NE fault zone</td>
</tr>
<tr>
<td></td>
<td>A_{index}</td>
<td>Feb</td>
<td>Double annular extremum and stretching along the EW direction</td>
<td>2.2</td>
<td>Mar</td>
<td>Linear distribution along the NE fault zone</td>
</tr>
</tbody>
</table>

Note: A represents the difference method; A_{index} represents the abnormal index method; the unit of the abnormal amplitude of CO is molecules/cm²; the unit of the abnormal amplitude of O₃ is DU.

Figure 2: Spatial distribution of CO concentration anomalies (molecules/cm²) before and after the Yutian earthquake on March 21, 2008. 1—Tekrick fracture; 2—Arerjin fracture; 3—Kangxiwa fracture; 4—Yulong Kashi fracture; 5—Guzhacuo fracture; 6—Tianshen Daban fracture; and 7—Longmucuo-Bangdacuo fracture. Red five-pointed star indicates the epicenter location.
and analyzed, and the values increased sharply at the beginning of February 2008, around February 4 (Figure 7(a)). Maximum values were reached on February 22, 2008. By contrast, in other nonseismic years, the VMR values of CO and \( \text{O}_3 \) did not change significantly. These results indicated that the abnormal changes in TotCO and TotO\(_3\) in February 2008 were not seasonal. Thus, the cause of those changes was most likely associated with the earthquake.

The CO VMR values at 400 to 700 hPa increased significantly from January 5 to February 22 (Figure 8(a)). The CO VMR values increased rapidly above 600 hPa and reached a maximum value on February 22. Then, the values began to decline and returned to normal levels of annual change in April. The CO VMR values at 100 to 300 hPa also increased, but the changes were not obvious because of the height. The \( \text{O}_3 \) VMR values at 300 hPa, 100 hPa, and 150 hPa increased on December 28, 2007 (Figure 9(a)). The \( \text{O}_3 \) VMR value at 300 hPa reached a maximum on March 15, whereas at 100 hPa and 150 hPa, maximum values were reached on January 15. Among the pressure layers, the changes in \( \text{O}_3 \) VMR values were most obvious at 100 hPa and 300 hPa, which may be related to the main distribution height of \( \text{O}_3 \) in the atmosphere. The changes in TotCO and TotO\(_3\) and VMR values were consistent whether they were obtained by the difference method or the abnormal index method.

The TotCO changed slightly in November 2013 (Figure 4), and the TotO\(_3\) changed abnormally in December 2013 (Figure 5), which may be associated with the M\(_{5.6}\) earthquake (36.8°N, 86.7°E) that occurred on November 24, 2013. Afterward, TotCO and TotO\(_3\) increased gradually, and the maximum anomalies appeared in March 2014. As shown in Figure 6(b), TotO\(_3\) increased sharply on March 1, 2014, and reached a maximum on March 5. From March 5 to 11, TotO\(_3\) was higher than that in other months. There

Figure 3: Spatial distribution of \( \text{O}_3 \) concentration anomalies (molecules/cm\(^2\)) before and after the Yutian earthquake on March 21, 2008. 1—Tekrick fracture; 2—Arerjin fracture; 3—Kangxiwa fracture; 4—Yulong Kashi fracture; 5—Guozhacuo fracture; 6—Tianshen Daban fracture; and 7—Longmucuo-Bangdacuo fracture. Red five-pointed star indicates the epicenter location.

Figure 4: Spatial distribution of CO concentration anomalies before and after the Yutian earthquake on February 12, 2014. 1—Peru fracture; 2—Ashe Cooley-Xiaokerule fracture; 3—Kangxiwa fracture; 4—Kuyake fracture; 5—Guozhacuo fracture; 6—Longmucuo-Bangdacuo fracture; 7—Margai Caka fracture; 8—Gongggacuo fracture; and 9—Arerjin fracture. Red five-pointed star indicates the epicenter location.
Figure 5: Spatial distribution of CO concentration anomalies before and after the Yutian earthquake on February 12, 2014. 1—Peru fracture; 2—Ashe Cooley-Xiaoerkule fracture; 3—Kangxiwa fracture; 4—Kuyake fracture; 5—Guozhacuo fracture; 6—Longmucuo-Bangdacuo fracture; 7—Margai Caka fracture; 8—Gonggacuo fracture; and 9—Arerjin fracture. Red five-pointed star indicates the epicenter location.

Figure 6: Changes in CO (molecules/cm²) and O₃ (DU) concentrations in the Yutian earthquake epicenter areas from January to April in 2008 and 2014. Arrows indicate earthquake dates.
were two minimum values of TotCO on March 6 and March 20, which might have been caused by the northward drift of CO from the epicenter. This result indicated that the abnormal change in TotCO might be associated with the 2014 Yutian earthquake. As shown in Figure 7(b), the VMR value of CO began to increase sharply in early March 2014, peaked around March 20, 2014, and then declined and gradually returned to normal at the end of March. The O3 VMR also began to increase sharply in early March 2014 and reached a maximum on March 10, 2014. Then, the values began to decline and gradually returned to normal at the end of March. There were no abnormal changes in CO and O3 VMR values in March in nonseismic years. Thus, the abnormal changes in CO and O3 VMR values in March 2014 were not related to seasonal changes and therefore were likely associated with the 2014 Yutian earthquake. As shown in Figure 8(b), the 850 hPa CO VMR value increased sharply after February 14th, reached a maximum value on March 10–18, and then began to decline. The 400 to 700 hPa CO VMR values also showed upward trends, but the magnitude of increase was small. Maximum values were reached around March 10, which then returned to normal levels in May. These results demonstrated that changes in the 400 to 850 hPa CO VMR values were because of contributions from near the ground. As shown in Figure 9(b), the O3 VMR values at 300 hPa, 100 hPa, and 150 hPa gradually increased after November 18, 2013. The O3 VMR values at 300 hPa began to increase on March 1 and reached a maximum before and after March 25. The O3 VMR values at 100 hPa and 150 hPa reached a maximum around March 1, indicating that the increase in O3 VMR values did not necessarily come from the near surface but might have come from atmospheric chemical reactions and atmospheric transport [28].

4. Discussion

4.1. Relations between TotCO and TotO3 Anomalies and Earthquakes. The TotCO was abnormal three months before the 2008 Yutian earthquake and reached the maximum abnormality in February before that earthquake. The maximum abnormal value of TotCO occurred on February 10, and the degree of abnormality exceeded the background value of $1.011 \times 10^{17}$ molecules/cm$^2$ (Figure 2(a)). Then,
TotCO decreased abnormally and gradually returned to the level of periodic changes. During the abnormal period, the abnormal fluctuation range of TotCO was large at first and then small from the beginning of February 2008. In the month of the 2008 Yutian earthquake, TotCO also fluctuated, but the range of fluctuation was smaller than that in February (Figure 6(a)), which might be related to changes in underground gas emissions caused by changes in ground stress during earthquake buildup. In addition, TotCO showed a slight abnormality three months before the 2014 Yutian earthquake and then returned to normal, which might be associated with an $M_s$ 5.6 earthquake ($36.8^\circ$N, $86.7^\circ$E) that occurred on November 24, 2013. In March 2014, TotCO reached the maximum abnormality, and the maximum abnormal value exceeded the background value of $1.166 \times 10^{17}$ molecules/cm$^2$ during the same period, after which the abnormal degree of TotCO decreased. This result might be related to the release of ground stress during the earthquake in this area, which caused the fault zone to close before the earthquake and then open afterward. As shown in Figure 6(b), there were two extremely low TotCO values on March 6 and March 20. The low values might be because the gas in the epicenter area was evacuated to the northern area far from the epicenter under the influence of atmospheric circulation. This phenomenon was consistent with the results in Figure 4, which further illustrated that abnormal changes in TotCO might be associated with the 2014 Yutian earthquake.

The TotO$_3$ was abnormal one month before the earthquake on March 21, 2008. The maximum abnormal value of TotO$_3$ occurred on February 27, exceeding the background value of 22.67 DU during the same period. Then, the variation in values returned to normal (Figure 3(a)). In addition, TotO$_3$ began to appear abnormal two months before the earthquake on February 12, 2014, and reached the maximum abnormality in March 2014. The maximum abnormal value of TotO$_3$ occurred on March 5, exceeding the background value of 33 DU during the same period (Figure 5(a)), and then, the degree of abnormality decreased. The abnormal values of TotO$_3$ appeared later than those of TotCO, and their duration was longer than that of CO. The spatial correspondence of the two was relatively good, but their intensities were not consistent. The differences might be related to the multiple causes of O$_3$ abnormalities. In addition to underground gas escape and atmospheric chemical reactions, atmospheric transportation might also affect TotO$_3$ abnormalities. Moreover, the spatial distributions of the anomaly centers of TotO$_3$ and TotCO in 2014 did not correspond well (Figures 4 and 5) which might be related to the topography and gas distribution height in Yutian County.

In the past two decades, the strong earthquakes on the Qinghai-Tibet Plateau have generally been distributed on the periphery of the Bayan Har Block [29]. The 2008 Yutian earthquake occurred on the western boundary of the Bayan Har Block. Wan et al. [29] studied the regional structure of the fault zone around the 2008 Yutian earthquake. They found that under the NNE thrust of the Indian Plate against the Eurasian Plate, the Qaidam Basin in the northern margin of the Qinghai-Tibet Plateau moved eastward along the Arejijn fault, whereas the Xingdukush block moved NW along the Karakorum fault as a whole. The epicenter area was between the two blocks, resulting in slow, large-scale strain accumulation in the crust of the epicenter area. The EW-trending tension of the fault zone before the earthquake occurred under the bilateral dynamic interaction, and when
Figure 9: Continued.
the structure was unlocked, the in situ stress was released. The authors speculated that underground gas was released in large quantities, resulting in anomalies. After the earthquake, the structure was locked, and the anomaly gradually decreased. Afterward, the coseismic stress disturbance of the 2008 Yutian earthquake [27] triggered subsequent aftershocks and the $M_{S}6.2$ earthquake (90 km from the 2008 Yutian earthquake epicenter) that occurred on August 12, 2012. As a result, stress increased on the Kunlun fault in the northern segment of the Gonggacuo fault zone [29], such that the southwestern end of the Arerjin fault expanded along the NW tensile structural belt [30], which accelerated the 2014 Yutian earthquake. Because of the tectonic stress caused by the 2008 Yutian earthquake and its triggered aftershocks, the Xiaerkule fault and the Ashe Cooley fault were locked before the earthquake. Therefore, the gas upward flow pores were closed, resulting in a decrease in normal overflow gas in the short term before and after the earthquake and a continuous decline in gas concentration. After the earthquake, the stress in this area was released. The tectonic stress of the Arerjin fault resulted in the SN-trending rupture of the Xiaerkule Basin, which accelerated the sinistral dislocation of the Arerjin fault and formed a series of NE or NNE-trending plume fault systems, including the Ashe Cooley fault and the Guozhacuo fault. The underground

**Table 2:** Coefficients of correlation between CO, $O_3$, and $CH_4$ gas concentrations associated with two $M_{S}7.3$ earthquakes in Yutian.

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<tbody>
<tr>
<td>CO, $O_3$</td>
<td>0.317</td>
<td>0.672</td>
<td>0.017</td>
<td>0.300</td>
<td>0.638</td>
<td>0.359</td>
</tr>
<tr>
<td>$CH_4$, CO</td>
<td>-0.112</td>
<td>-0.731</td>
<td>-0.378</td>
<td>-0.288</td>
<td>-0.370</td>
<td>-0.264</td>
</tr>
<tr>
<td>$CH_4$, $O_3$</td>
<td>-0.394</td>
<td>-0.660</td>
<td>-0.034</td>
<td>-0.342</td>
<td>-0.558</td>
<td>-0.404</td>
</tr>
</tbody>
</table>

**Figure 9:** Changes in CO volume mixing ratio (VMR) values at different heights before and after two $M_{S}7.3$ Yutian earthquakes. Arrows indicate earthquake dates.
gas channels were generally open, and gases were released, resulting in obvious anomalies in March after the earthquake [31].

4.2. Causes of Abnormal TotCO and TotO3. According to previous studies [2, 14, 31], there are currently two primary explanations for the abnormal changes in TotCO and TotO3 in the epicentral area. One explanation is the escape of underground gas along the fault zone, and the other is that the gas dissipating into the atmosphere reacts with original atmospheric gases. However, the contributions of these processes might not be large enough to produce an abrupt increase in total ozone in such a short period [13]. In addition, according to Ganguly [28], atmospheric transportation is also a cause of abnormal changes in TotO3. The causes of abnormal TotCO and TotO3 associated with the two Yutian earthquakes are discussed from these three aspects below.

First, the spatial (Figures 2–5) and temporal (Figures 6, 8, and 9) variations in TotCO and TotO3 anomalies were most likely caused by geological processes in the lithosphere or crustal stress that resulted in the two Yutian M7.3 earthquakes in 2008 and 2014. Many gases remain deep in the earth’s crust, including CO2, CO, CH4, H2, N2, H2O, and H2S [1]. These gases are stored in the earth’s crust at higher than atmospheric pressure, and they tend to migrate upward and penetrate into shallow rock cracks and pores and escape to the atmosphere [15]. During an earthquake, the increase in ground stress causes many cracks, pores, and fissures to form in the fracture zone near the epicenter, and large amounts of carbon-containing gases (e.g., CH4 and CO) escape into the atmosphere through these channels, causing abnormal changes in gas concentrations in the epicenter area [2]. In this study, the spatial distributions of TotCO and TotO3 corresponded well with the fault zone. However, an earthquake is a complex process, and other factors such as topography, weather, and human activities in the epicenter area can also cause abnormal changes in gas concentrations. In this study, calculations were used during the processing of data to eliminate the influences of other factors, and therefore, underground gas emissions might be the largest cause of abnormal changes in TotCO and TotO3 in the epicenter area.

Second, underground gases escape into the atmosphere and chemically react with atmospheric gases. Gas increments affect atmospheric concentrations in an epicenter area, resulting in abnormal changes in TotCO and TotO3. Following escape from underground, CH4 forms the transition products CO and O3 during oxidation, according to the

![Figure 10: Backward trajectories in the 100 hPa pressure layer at the gas anomaly center of the Yutian earthquake in 2008. Red five-pointed star indicates the center point of abnormal gas concentration.](image)
reaction \[ \text{CH}_4 + 4\text{O}_2 + 2\text{hv} \rightarrow \text{H}_2\text{O} + \text{CO} + \text{H}_2 + 2\text{O}_3 \], which increases TotCO and TotO3 [32, 33]. Because of the high background content of atmospheric CH4, the increase in CH4 from underground gas emissions is limited. Nevertheless, the oxidation of CH4 contributes to CO and O3 abnormalities [34–36]. O3 is distributed primarily in the troposphere, and atmospheric photochemical reactions in the troposphere can also cause abnormal O3 concentrations, according to the reaction \[ \text{CO} + 2\text{O}_2 \rightarrow \text{CO}_2 + \text{O}_3 \].

As shown in Table 2, the coefficients of correlation between CO and O3 were 0.672 and 0.638 in 2008 and 2014, respectively, with both correlations significant at \( p < 0.05 \). The correlations between TotCO and TotO3 were relatively weak in 2007, 2009, 2013, and 2015 but were significant in 2008 and 2014, indicating a good correlation between CO and O3 during an earthquake. Sun et al. [14] studied the changes in TotCO and TotO3 before and after two major earthquakes in Sumatra in 2004 and 2005. They found no correlation between TotCO and TotO3 in 2004 to 2005 \( (r = 0.021) \), but the correlation was significant during earthquake activity (December 2004 to March 2005) \( (r = 0.77) \) [14], which is consistent with the results of this study. As shown in Figure 6, the change in TotO3 lagged behind that in TotCO, indicating that the earthquakes caused CO to be oxidized to O3. The coefficients of correlation between CH4 and CO in 2008 and 2014 were \(-0.731\) and \(-0.370\), respectively, with correlations significant at \( p < 0.05 \) and 0.01, respectively. The coefficients of correlation between CH4 and O3 in 2008 and 2014 were \(-0.660\) and \(-0.558\), respectively, with both correlations significant at \( p < 0.05 \), indicating that part of TotCO and TotO3 was also derived from CH4 oxidation. In addition, during an earthquake, low-frequency electromagnetic radiation and ionospheric disturbances promote \( ^{14}\text{N} \) decay to form CO [37, 38], accelerating the production of CO according to the reactions \( ^{14}\text{N}(n, p) \rightarrow ^{14}\text{C} + \text{H} \) and \( 2\text{C} + \text{O}_2 \rightarrow 2\text{CO} \). These reactions are another reason for abnormal changes in TotCO.

Third, atmospheric transmission might also be a cause of abnormal gas concentrations in epicentral areas. The 5-day backward trajectories on the day of the 2008 Yutian earthquake (Figure 10(a)) showed that in the air masses from the NWW direction in the 100 hPa pressure layer, the O3 contribution rate was the largest at 28.57%. In the remaining air masses, the contribution was relatively small. The 5-day backward trajectories of the maximum O3 concentration day (Figure 10(b)) showed that the O3 contribution rate in the air mass from the NWW direction increased to 34.43%. Although the O3 contribution rate in the other air masses also increased, the magnitude of increase was small. The 5-day backward trajectories on the day of the 2014
Yutian earthquake (Figure 11(a)) showed that among the air masses from the SWW direction, the two air masses closest to the south had the largest contributions of O₃, reaching 20.68% and 20.78%. The 5-day backward trajectories of the day with the maximum O₃ concentration (Figure 11(b)) showed that in the air mass from the SWW direction, the maximum contribution rate of O₃ increased to 40.26%. For the source of the air mass, these results were consistent with those obtained by the difference and abnormal index methods, indicating that atmospheric transportation was also a cause of abnormal changes in TotO₃. Ganguly [28] studied the increase in TotO₃ after the Gujarat M₇.7 and M₅.2 earthquakes in 2001 and 2006, respectively, and found that the increase in TotO₃ after the earthquake was due to atmospheric transmission between the upper troposphere and lower stratosphere. The upper O₃-rich air was transported to the epicenter. The results of this study were similar.

5. Conclusions

(1) AIRS hyperspectral remote sensing data were analyzed, and TotCO and TotO₃ changed abnormally before and after two M₇.3 earthquakes in the study area. Abnormal gas concentrations associated with the 2008 Yutian earthquake occurred in February before the earthquake, and those associated with the 2014 Yutian earthquake occurred in March after the earthquake. Before and after the two earthquakes, the anomalies of TotCO and TotO₃ were distributed along the fault zone or the anomaly trend was consistent with the fault zone trend.

(2) The release of ground stress during earthquake buildup and occurrence causes the release of underground gases into the atmosphere along the rupture zone, which might be a cause of the abnormal changes in TotCO and TotO₃. The CO and O₃ released into the atmosphere chemically react with CH₄ and other original atmospheric gases, which may be another cause of the abnormal changes in TotCO and TotO₃. In addition, atmospheric transportation might also contribute to abnormal changes in TotO₃.

(3) The abnormal changes in TotCO and TotO₃ before and after earthquakes may be anomalies that can predict impending earthquakes. The CO and O₃ anomaly indexes of the two Yutian M₇.3 earthquakes obtained by the anomaly index method were 2.0 and 2.2 and 2.0 and 2.2, respectively, and the anomaly reliability exceeded 94%. Thus, satellite hyperspectral remote sensing data can be used to extract reliable seismic-related information from geochemical anomalies.

Data Availability

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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