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INTERANNUAL CHANGE OF EXTRA-TROPICAL METHANE INDUCED BY THE QUASI-BIENNIAL OSCILLATION OF TROPICAL WIND AND ITS FORMATION MECHANISM

BI Yun (毕　云), CHEN Yue-juan (陈月娟), ZHOU Ren-jun (周任君), CAI Hong-ke (蔡宏珂)

(School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026 China)

Abstract: Researchers have paid much attention to the influence of the tropical zonal wind quasi-biennial oscillation (QBO) on tropical methane, while generally ignoring the change in extra-tropical methane. The present study analyzed the interannual changes in the methane mixing ratio in extra-tropics of both the Southern Hemisphere (SH) and Northern Hemisphere (NH) using Halogen Occultation Experiment (HALOE) satellite data. The results show that interannual changes in extra-tropical methane exhibit QBO features in both hemispheres that are obviously different from those in the tropics. The extra-tropical methane QBO perturbations usually occur in two layers and are longitudinally asymmetrical about the equator. The amplitude of the methane QBO disturbance in the extra-tropics is smaller than that in the tropics from 10 to 1 hPa but much larger in the layer from 30 to 10 hPa. The interannual relative changes in the methane mixing ratio are similar in both the NH extra-tropics and the tropics in the middle and upper stratosphere. Using the National Center for Atmospheric Research two-dimensional, interactive chemical dynamical radiative model (SOCRATES), simulation was conducted to investigate the mechanism of the extra-tropical methane QBO. The results indicate that the tropical stratospheric zonal wind QBO results in the QBO of the induced residual circulation. It is the transport of methane by the induced residual circulation that causes the methane QBO in the extra-tropics. The induced residual circulations in the middle and upper stratosphere are not always longitudinally symmetrical about the equator, resulting in different distribution of the methane QBO in the SH and NH extra-tropics.

Key words: HALOE data; QBO; methane; NCAR numerical model; tropical wind

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1 INTRODUCTION

Methane (CH_4) is one of the most important greenhouse gases in the atmosphere and it is emitted either by natural processes or human activity. The Intergovernmental Panel on Climate Change (IPCC)[1] reported that the atmospheric methane concentration (hereafter AMC in mixing ratio) has increased rapidly since the industrial era began. Over the past 25 years, AMC has increased by 30%. The radiative forcing associated with the increase of AMC is 0.48 ± 0.05 W m^{-2}, making methane the second highest among the long-lived greenhouse gases, following CO_2. Although global AMC has shown zero annual growth since 2000, its interannual change is significant. Stratospheric methane comes from the troposphere. In comparison with the homogeneous distributions of the AMC in the troposphere, the AMC decreases rapidly with altitude in the stratosphere, and the AMC at low latitudes is greater than that at high latitudes. This pattern reflects the role of chemical and dynamical processes in methane distribution[2]. Although the AMC in the stratosphere is much less than that in the troposphere, methane is a very active component in photochemical processes in the stratosphere, where it influences the concentration of stratospheric water vapor and O_3, thereby influencing the stratospheric temperature. Simulation results have shown that when the AMC is increased by 10%, the annual mean temperature will decrease by 0.2 K in the upper stratosphere, and the middle stratospheric cooling will exceed 0.05 K at mid- and high-latitudes[3]. Hence the change in stratospheric AMC should be studied closely. An analysis of Halogen Occultation Experiment (HALOE) data showed no obvious long-term trend in methane from 1992 to 2004 in the middle stratosphere, although clear interannual change was found[4]. The

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Corresponding author: BI Yun, e-mail: biyun@ustc.edu.cn

photochemical life of methane is longer than 100 days in the lower stratosphere and on the order of 1 month in the middle and upper stratosphere. Hence methane is a good tracer for stratospheric transport processes, and dynamical changes will inevitably affect the methane distribution there.

The zonal wind has a QBO feature in the tropical stratosphere. Early studies found that the period of the stratospheric QBO is basically 2 years. The oscillations propagate downward from 30 km with unchanged amplitude until 23 km, whereas the amplitude decreases rapidly below 23 km. The oscillations are symmetric about the equator, with propagation rates of about 1 km per month. However, more recent studies have shown that the QBO phenomenon still exists in the upper stratosphere with large amplitude. For example, Randel et al.[5] analyzed United Kingdom Meteorological Office stratospheric assimilation data and noted that the QBO amplitude of averaged zonal wind in the tropics was largest in the 20 to 35 km altitude range. They also found that the QBO still existed from 45 to 50 km, although the QBO amplitude decreased and the QBO phase was opposite to that at 30 km. Their study also indicated that the wind QBO amplitude was largest in the tropics.

Plumb and Bell[6] reported that the wind QBO affects the distribution of chemical species, such as N_2O, CH_4, H_2O, and aerosols, in the tropical lower stratosphere through the mean meridional circulation. By analyzing the total ozone amount over the tropics, Funk and Garnham[7] and Ramanathan[8] revealed the QBO of ozone and its relation to the QBO of upper winds over the low latitudes. In recent years, researchers have performed many studies of the QBO of stratospheric O_3, HCl, NO_X, and H_2O[9-12]. Such studies have improved our understanding of the QBO of stratospheric trace gases and its formation mechanisms. These studies have shown that all stratospheric trace gases have QBO characteristics but differ in their QBO features. These differences are related mainly to the distribution of each kind of gas. The stratospheric wind QBO perturbation is the main reason for the formation of trace gas QBOs, but not the only reason. Compared to studies on other trace gases, fewer studies have focused on the methane QBO. Moreover, previous studies mainly focused on the tropics using short time series of data[13-15]. In addition, the interannual change in methane and its formation mechanism in the extra-tropics have never been studied. Herein, we analyze the interannual change in methane in extra-tropical regions based on the HALOE satellite data and investigate the formation mechanisms using the simulation from the Chemistry, Radiation, and Transport of Environmentally Important Species (SOCRATES) model of the U.S. National Center for Atmospheric Research (NCAR).

2 DATA ANALYSIS

2.1 *HALOE observation data*

HALOE is an instrument onboard the Upper Air Research Satellite (UARS), which uses the solar occultation approach to measure the vertical distribution of H_2O, O_3, CH_4, HF, HCl, NO, NO_2, temperature profiles, and the extinction coefficients of aerosols. HALOE data have been widely used since they were published in 1991[2-4, 9-15] and hence are not further described here. As the HALOE dataset supplies a variety of trace gases data with high accuracy, it has been regarded as one of the most important datasets by the Stratospheric Processes and Their Role in Climate (SPARC) research group of the World Climate Research Program (WCRP) of World Meteorological Organization. The AMC used here was downloaded for the period of January 1992–June 2004. For more convenient use, the data were interpolated to 5° × 5° grid points for each season, which shows good agreement with the HALOE observational data.

2.2 *QBO characteristics of stratospheric methane in the extra-tropics*

To highlight the interannual change characteristics of methane in the extra-tropics, AMC anomalies were calculated. Fig. 1a shows a height-time cross-section of methane mixing ratio anomalies averaged over 30–50° N. As can be seen, the interannual changes of AMC are mainly associated with QBO over the extra-tropics of the NH, with a period of about 27 months. The QBO occurs in three layers: 5–1 hPa, 30–10 hPa, and 100–30 hPa. The signs of the QBO perturbation in the three layers are generally "+, -, +" or "-, +, -" from the higher level to the lower level. The perturbation amplitude at 5–1 hPa and 30–10 hPa is larger than that at 100–30 hPa. Fig. 1b presents the height-time cross-section of methane mixing ratio anomalies averaged over 30–50° S. The figure shows that the interannual changes in the methane mixing ratio are also featured as QBO in the SH, with a period of approximately 27 months. The QBO in the SH is located at 5–1 hPa and 30–10 hPa, and the phases of the QBO in the two layers are opposite. The methane QBO features in the SH become more obvious after performing band-pass filtering (figure omitted). There are some similarities in Figs. 1a-1b: the QBO perturbations dominate at 30–10 hPa and 5–1 hPa, the perturbation amplitudes are similar, and the signs of perturbation are opposite in the upper and lower layers. In addition, in both the NH and SH, the extra-tropical methane QBO seems to propagate upward above 30 hPa. However, there are also some differences between the hemispheres: the methane QBO is not symmetric about the equator in the SH and NH extra-tropics at the same altitude, with significant differences in phase and amplitude. Upward propagations occurring in extra-tropical methane QBO are also shown in the QBOs of tropical water vapor and NO_2. Shi et al.[11] pointed out that the QBO in tropical water vapor propagates upward from 100 hPa to 30 hPa. Similarly, the analysis by Zheng et al. [16] showed that the QBO in tropical NO_2 propagates upward from 6 hPa to 1 hPa.

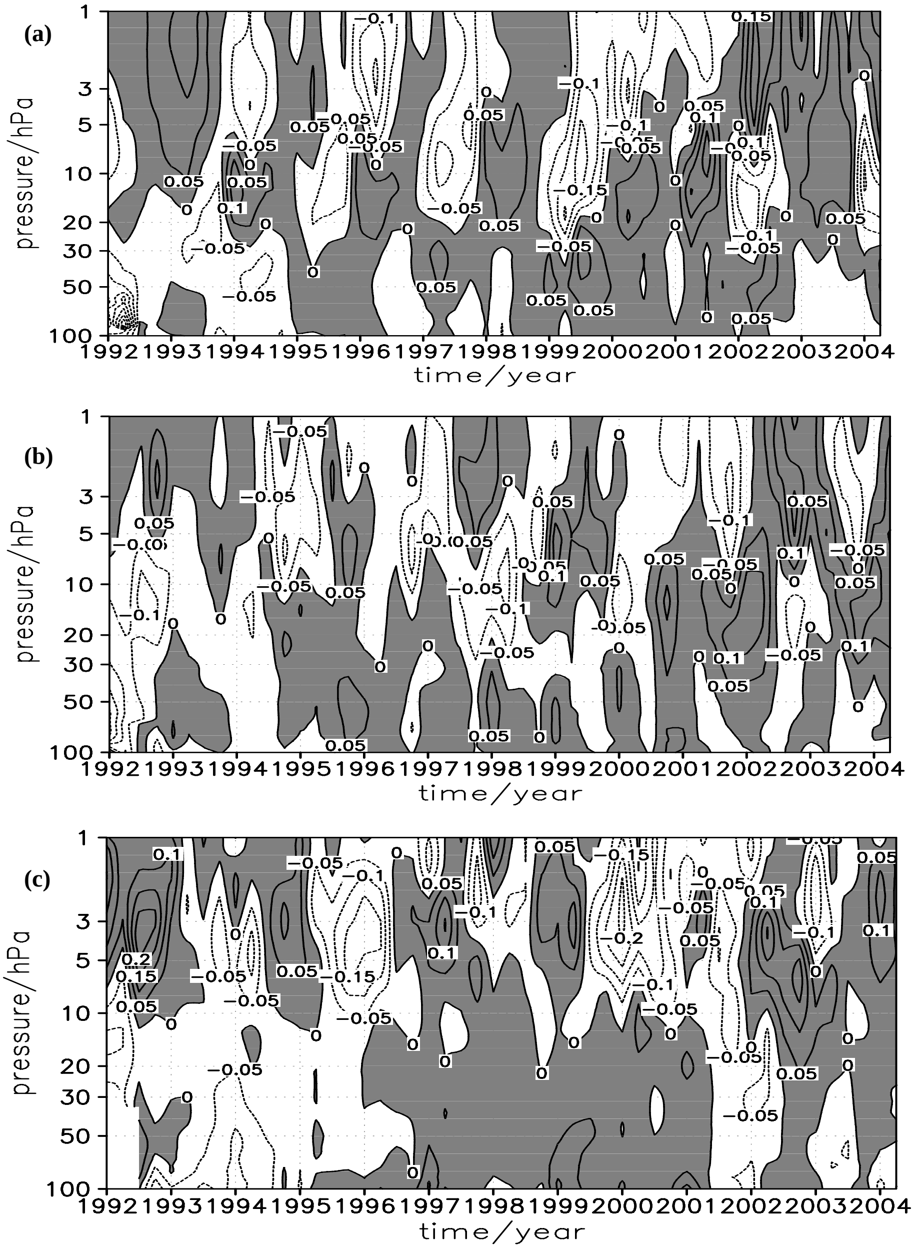


Fig. 1. Height-time cross-section of zonally averaged AMC anomalies (units: ppmv) a: 30° –50° N, b: 30° –50° S, c: equator.

To compare the methane QBO over the extra-tropics with that over the equator, the height-time cross-section of methane anomalies averaged over the equator was plotted (Fig. 1c). It shows that the methane QBO in the tropics is significantly different from that in the extra-tropics. Although the period of the QBO is also about 27 months in the tropics, the equatorial QBO disturbance is mainly at 10–1 hPa and is very weak at 30–10 hPa. The QBO amplitude in the tropics is significantly larger than that in the extra-tropics at 10–1 hPa, but much smaller than that in the extra-tropics at 30–10 hPa. Further statistical analysis of the QBO perturbation percentage (QBO perturbation divided by the methane mixing ratio; figures omitted) shows that QBO perturbation usually accounts for up to 10–15% of the methane concentration at 10–1 hPa in the tropics, but very small below 10 hPa. The QBO perturbation usually reaches 10–15% of the AMC at 5–1 hPa and 5–10% at 30–10 hPa over the NH extra-tropics, and 5–10% at 5–1 hPa and 5% at 30–10 hPa over the SH extra-tropics. At 30–10 hPa, the interannual change in the methane mixing ratio in the extra-tropics is much larger than that in the tropics. In the middle and upper stratosphere, the interannual relative changes in methane over the NH extra-tropics are no less than those in the tropics. To verify the period of interannual change in methane, a power spectrum analysis was conducted (figure omitted). The results show that the methane mixing ratios in both the SH and NH extra-tropics have a main period of about 27 months, in comparison with the main period of 12 months (followed by a period of 27 months) in the tropics.

As an environmentally important trace gas, methane has a double-edged role in affecting the earth's atmosphere. The main negative impact of methane is that it can increase the greenhouse effect. As a positive impact, methane can protect the ozone layer by removing the Chlorine atom (Cl) in the stratosphere. Numerical simulations have shown that if the methane mixing ratio increases by 10% in the stratosphere, the O_3 mixing ratio will increase by 0–0.5% in most of the stratosphere and perhaps by more than 0.5% in some regions of the SH[3]. The interannual change in methane in the extra-tropics will affect the interannual change in O_3 in the stratosphere, particularly in the middle stratosphere, which should not be ignored.

3 MODEL AND SIMULATION RESULTS

3.1 *Brief description of the SOCRATES model*

We used the NCAR 2-D model SOCRATES for our numerical experiment. This model has been used for simulating the middle stratosphere[3, 9-12, 16-20]. The model domain extends from the surface to 120 km with 1-km vertical resolution, and from -85° to 85° latitude with 5° latitudinal resolution. The lower boundary of circulation and temperature is fixed at 2 km. The chemistry component of the model includes 76 chemical species and more than 160 chemical reactions. In the radiation part, both solar radiative heating and infrared radiative heating are considered. Deformation Eulerian equations are used in the dynamical frame of the model. The residual velocity is used for the analysis of tracer transport by residual circulation. A wind QBO forcing may be added selectively to the momentum equation using a parameterized method to simulate the QBO of temperature and circulation.

According to observations in the tropics, the tropical wind QBO can be expressed with the following formulation in the model:

$$\overline{u}_{QBO} = -\overline{u}_{\max}\exp\left[-\left(\frac{\varphi}{\varphi_w}\right)^2\right]\cos\left(\frac{\pi}{2}\cdot\frac{\varphi}{\varphi_w}\right)\cos\left(\frac{z-z_{\max}}{h_{QBO}}\pi\right)\cos\left(2\pi\frac{t-1}{t_{QBO}}+2\pi\frac{z-z_{\max}}{z_{hfwd}}\right) \tag{1}$$

where h_{QBO} is the QBO vertical extent of 24 km, t the model time (in units of days), and t_{QBO} is the QBO period (about 27 months). The maximum zonal wind QBO perturbation ($u_{\max}$) is 25 m/s and is centered over the equator. The QBO perturbation decays exponentially in latitude with a Gaussian latitude width of 15°. φ_w is the width of Gaussian latitude (15 degrees). The perturbation varies sinusoidally in altitude, between 16 km and 40 km, with a maximum vertical amplitude at $z_{\max}$ (28 km); z_{hfwd} is a half width of 27 km.

3.2 *Simulated quasi-biennial oscillation of methane*

The atmospheric conditions in the early 1990s were used as the initial field in this experiment. A set of ideal comparative runs with 10-year model integration was designed, with and without the stratospheric zonal wind QBO forcing considered separately. Figs. 2a-2b show the simulated AMC perturbation induced by the wind QBO forcing in the SH and NH extra-tropics (the AMCs simulated with the wind QBO minus those without the wind QBO). Fig. 2a shows that the methane QBO in the NH extra-tropics has a period of about 27 months. The AMC disturbance tends to change stably from the fifth model year and shows an obvious two-layer structure at 5–1 hPa and 30–10 hPa in the NH extra-tropics. The QBO phases are opposite in the two layers, which is basically consistent with the analysis of HALOE data. The initial value of the AMC in the model is basically consistent with the HALOE data in the same period. However, the simulated QBO amplitude of the AMC appears to be smaller than the observed value. Fig. 2b consistently shows that the methane QBO in the SH extra-tropics has a period of about 27 months. In addition, the simulation indicates a clear two-layer structure between 5 and 1 hPa and between 30 and 10 hPa from the first model year to the fourth model year, and their phases are also reversed. After the fifth model year, the boundary of the two layers shifts upward slightly to near 3 hPa. The simulation results basically reproduce the observed QBO features of methane in the SH extra-tropics, and the QBO amplitude approaches that of the observations. The simulation results show that the methane QBO in the NH extra-tropics also propagates upward from 5 hPa to 1 hPa in the first and third model years. However, neither upward nor downward propagations are obvious between 5 hPa and 1 hPa in the other model years. The downward propagation is significant below 5 hPa. In the SH extra-tropics, the methane QBO also propagates upward from 5 hPa to 1 hPa in the 1st-3th, 8-9th model years. Although the upward propagation in methane QBO can be simulated by SOCRATES, it usually occurs between 5 hPa and 1 hPa. However, upward propagation occurs above 30 hPa in observational data, implying some deficiency in the QBO scheme in SOCRATES.

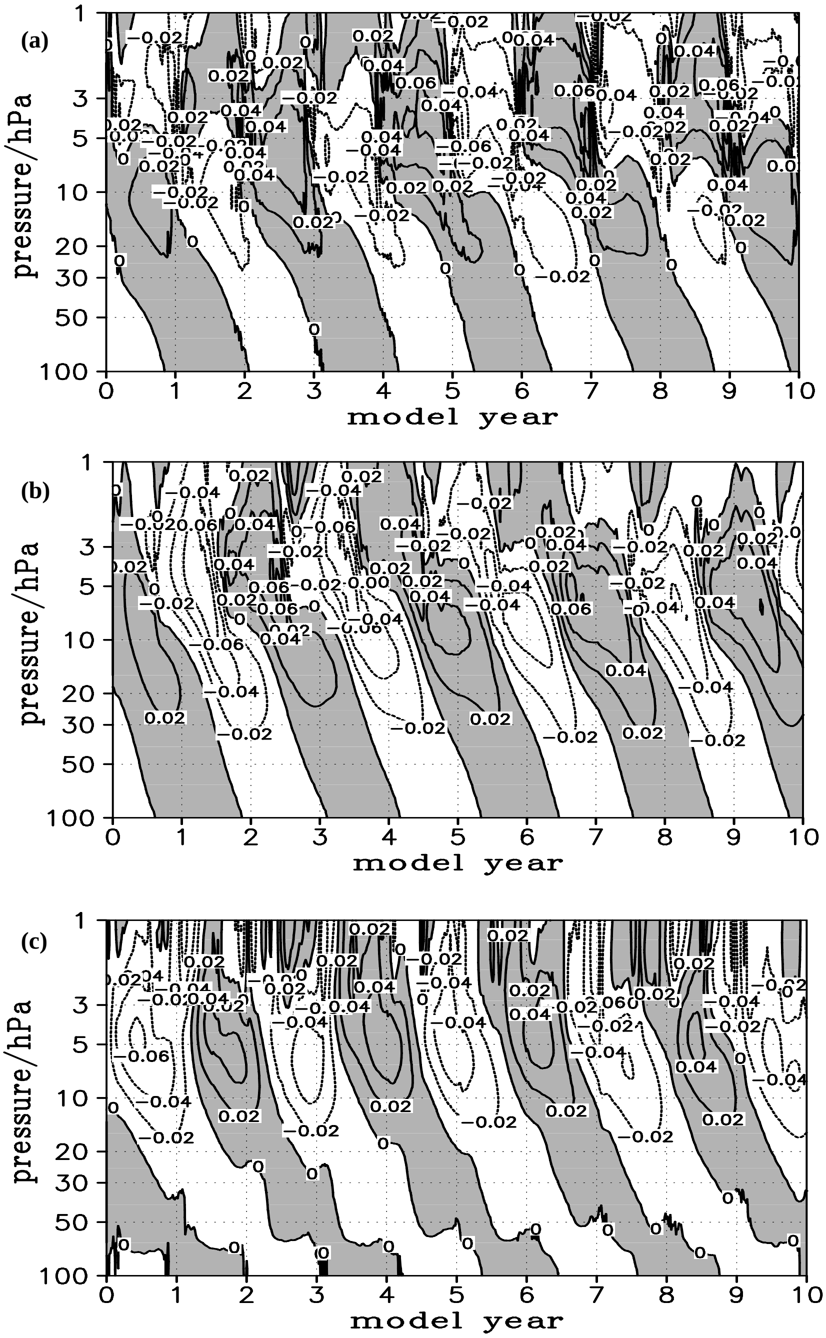


Fig. 2. Simulated AMC perturbation (units: ppmv) induced by the zonal wind QBO forcing (values simulated with wind QBO minus those without wind QBO). a: 30–50 ° N, b: 30–50 ° S, c: Equator.

Figure 2c shows the simulated equatorial methane mixing ratio perturbation induced by the wind QBO forcing (the values simulated with the wind QBO minus those without the wind QBO). This result is very similar to the observations, except that the simulated QBO amplitude is smaller than the observational value and the height of the maximum is slightly lower than that observed. The simulation is better in the tropics than in the extra-tropics.

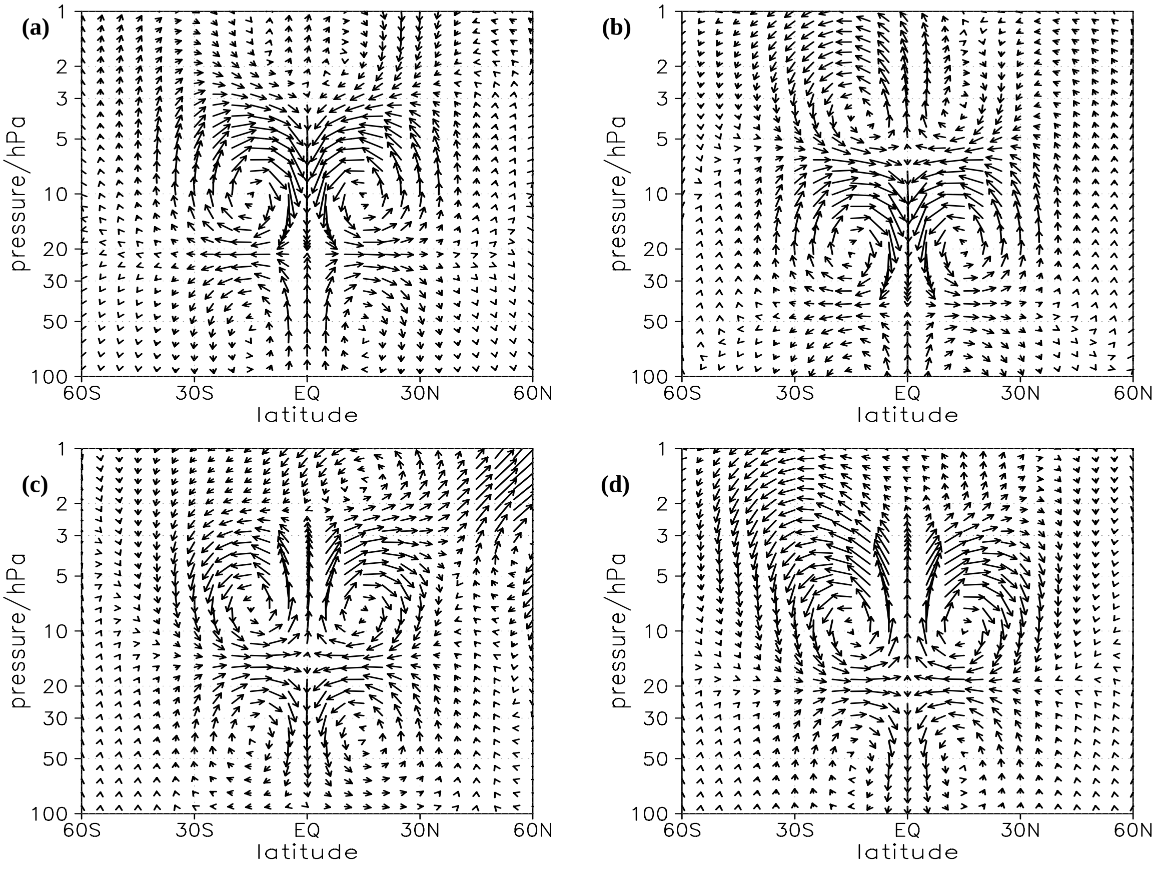
4 FORMATION MECHANISM OF THE METHANE QBO IN THE EXTRA-TROPICS

4.1 *Formation of the QBO in induced residual*

circulation

The analysis of Fig. 2 indicates that the tropical stratospheric zonal wind QBO not only causes the tropical but also the extra-tropical methane QBO. Moreover, the extra-tropical methane QBO perturbation is not less than that over the equator. We further analyzed the mechanism of how the wind QBO influences the methane QBO.

Figure 3 shows the difference in residual circulation between simulations with and without wind QBO forcing from April of the first model year to March of the second model year (corresponding to the westerly phase) and from May of the second model year to May of the third model year (corresponding to the easterly phase). The residual vertical velocity has been magnified 500 times in the plot. The westerly phase refers to the period in which the stratospheric wind near 10 hPa over the equator is westerly; otherwise, it is in the easterly phase. As can be seen in Fig. 3, the tropical zonal wind QBO forcing can induce a meridional secondary vertical circulation, which we refer to as the induced residual circulation due to the wind QBO. In April of the first model year (Fig. 3a) when the westerly phase appeared and started to increase in intensity, the induced residual circulation consisted of three pairs of cells aligned vertically in the low latitude stratosphere. These cells were located at 100–20 hPa, 20–3 hPa, and 3–1 hPa, respectively. The flow moved downward over the equator and separated to the south and the north near 20 hPa, turning upward near 30° N(S) and moving back to the equator at about 3 hPa. The cells above 3 hPa and below 20 hPa moved in the opposite direction from the cells at 20–3 hPa. The induced residual circulations caused by the wind QBO were particularly evident at lower latitudes but relatively weak at middle to high latitudes. Although the middle and lower cells were longitudinally symmetric about the equator, the upper cells were asymmetric. With an increase in simulation time, the three pairs of cells moved gradually downward. In September and October of the first model year (Fig. 3b) when the westerly phase was in its strongest days, the cells moved to the layers below 30 hPa, 30–5 hPa, and above 5 hPa, respectively. At this time, the upper cells are evidently strengthened in the SH. In March of the second model year (Fig. 3c) when the westerly had been very weak, the lower cells moved to near 100 hPa, gradually weakening, and the middle cells moved to the levels below 10 hPa and gradually replaced the lower cells. The cells staying originally above moved to 10–2 hPa and became symmetric about the equator. The induced residual circulations above 2 hPa appeared to be asymmetric about the equator and were stronger in the NH. The ascent movement was clearly strengthened in the middle and upper stratosphere over the NH extra-tropics.



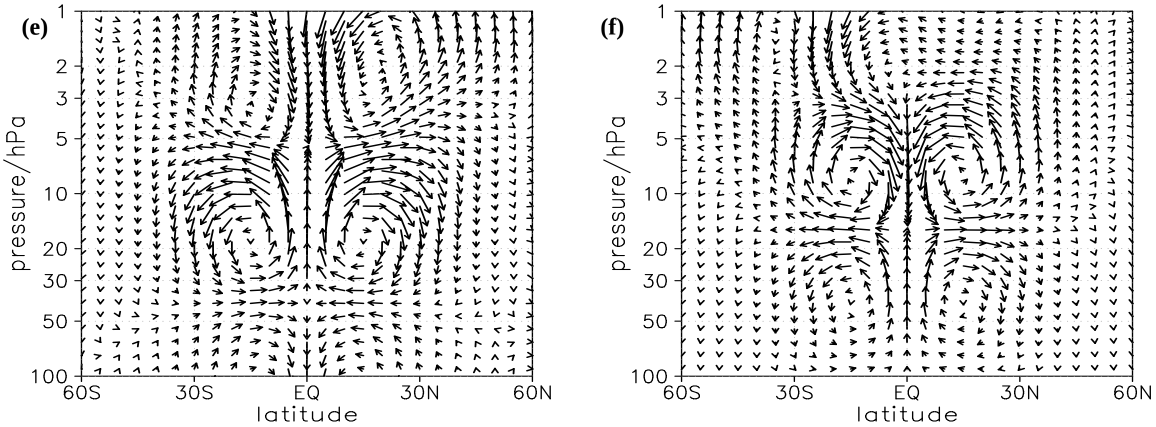


Fig. 3. Simulated induced residual circulation due to the wind QBO (difference of the values between the simulation with wind QBO and without wind QBO; panels a, b, c are in the westerly phase and panels g, d, e, f are in the easterly phase. a: April, first model year, b: September and October, first model year, c: March, second model year, d: May, second model year, e: October and November, second model year, f: May, third model year.

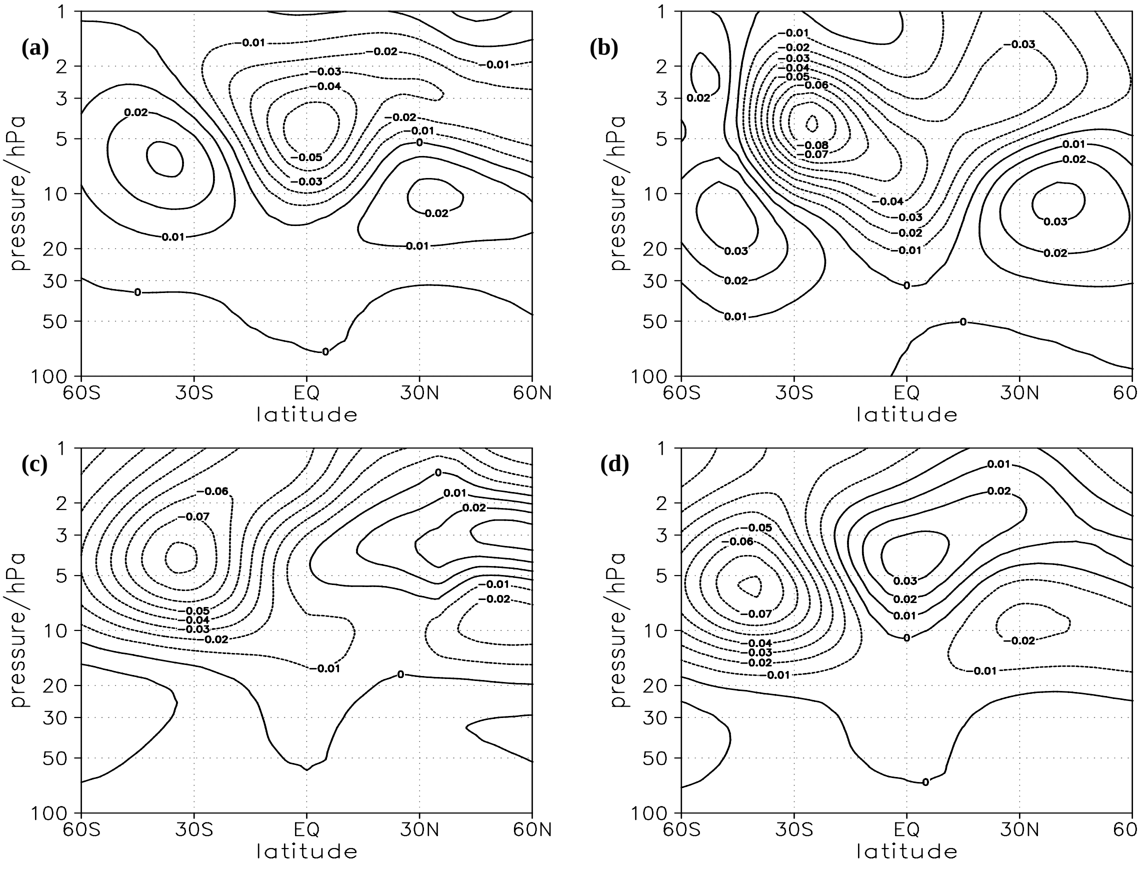
In May of the second model year (Fig. 3d) when the easterly phase appeared and started to increase in intensity, the cells continued moving down. Their locations in the middle and lower cells were the same as those in April of the first model year, except that the directions of the cells were reversed. The circulation had strengthened above 3 hPa in the SH extra-tropics. With further increase of the simulation time, the cells continued to move down, and changes in both the position and intensity duplicated the situation in the westerly phase. In October and November of the second model year (Fig. 3e), when the easterly phase was strongest, the locations of the cells were basically consistent with those in September and October of the first model year, except that the directions were reversed. At the same time, the upper cells were evidently reinforced in the NH, resulting in an asymmetry of the induced residual circulations over the SH and NH extra-tropics in the middle and high stratosphere. When the simulations reached May of the third model year (Fig. 3f) with a very weak easterly, the positions of the cells were consistent with those in March of the second model year, but their directions were reversed. At this time, the induced residual circulation in the SH was stronger than that in the NH in the upper stratosphere. Subsequently, the cells changed constantly in the easterly and westerly phases showing the QBO features.

The cells in the middle (upper) layers were continuously weakened (strengthened) during their downward motion. The upper cells were asymmetrical about the equator initially and then became symmetric. Moreover, they were often longitudinally asymmetric about the equator over the extra-tropics in the middle and upper stratosphere, and there were some differences in strength and phase. The circulations in the extra-tropics were stronger in the upper stratosphere than in the middle and lower stratosphere.

4.2 *Formation of the methane QBO in the extra-tropics*

The QBO of the induced residual circulation led to the methane QBO through transport of methane. Fig. 4a shows the AMC perturbation induced by transport of the induced residual circulation (AMC simulated with the wind QBO minus that without the wind QBO) in April of the first model year. Fig. 4a shows that the methane AMC obviously decreased at the equator above 10 hPa but changed little below 10 hPa. The AMC increased significantly in the layer between 30 and 2 hPa over the SH extra-tropics. In the NH extra-tropics the AMC increased at the 30–5 hPa layer and decreased at the 5–2 hPa layer, appearing as a two-layer structure; the signs of the perturbations were opposite in the upper and lower layers. At the same time, the upper cells also led to asymmetry in the variation of AMC in the SH and NH extra-tropics. The transport of methane by the induced residual circulation includes the vertical transport and meridional transport. The net transport amount is relevant to both the induced residual circulation and the vertical and meridional gradients in the methane mixing ratio. As shown in Fig. 4a, although the induced residual circulations at lower latitudes were much stronger than those at middle and higher latitudes, the resulting AMC perturbations at lower latitudes were not definitely larger than those in the extra-tropics. In September and October of the first model year (Fig. 4b), with the cells moving down, both the negative perturbation center of the AMC over the equator and the positive perturbation center over the SH and NH extra-tropics moved downward. Because the poleward and downward flow significantly strengthened over the SH extra-tropics in the upper stratosphere, it caused a clear decrease of AMC in 10–1 hPa. At the same time, the methane perturbations appeared as a two-layer structure, the signs of the perturbations were opposite in the upper and lower layers, and the upper perturbations were stronger. The locations and intensities of the perturbation centers were different in the SH and NH. In March of the second model year (Fig. 4c), the perturbation center of the AMC continued to move downward in both the tropics and the extra-tropics. The positive methane mixing ratio perturbations occurred over the NH extra-tropics in the upper stratosphere; at the same time, the methane perturbations can be divided into three layers, with the main layers being 20–5 hPa and 5–1 hPa. In the tropics, the negative perturbation weakened. The methane mixing ratio perturbations in the SH extra-tropics still occurred in two layers (10–1 hPa and below 10 hPa) and the negative perturbations strengthened. In May of the second model year (Fig. 4d), the methane mixing perturbations were contrary to those in Fig. 4a. The positive perturbations occurred in 10–1 hPa over the tropics; the negative perturbations of the methane mixing ratio continued to move downward in the SH extra-tropics and the two-layer structure occurred at 20–1 hPa and below 20 hPa. The two-layer structure (20–5 hPa and 5–1 hPa) and intensities of the perturbation remained in the NH extra-tropics. In October and November of the second model year (Fig. 4e), the perturbation centers of the AMC continued to move downward in the extra-tropics and tropics. In May of the third model year (Fig. 4f), the perturbations in the SH extra-tropics were basically contrary to those in Fig. 4c; the perturbations of the methane mixing ratio continued to move downward in the NH extra-tropics and the negative perturbations occurred in the upper stratosphere. Subsequently, the negative perturbations continued to move downward and the perturbation patterns were different from those in Fig. 4c for the NH extra-tropics. With an increase in the simulation time, the AMC perturbations in both the tropics and extra-tropics duplicated the variation regularity in the westerly and easterly phases showing the QBO features.

The location and intensity of the residual circulation induced by the wind QBO in both the tropics and extra-tropics changed with the westerly and easterly phase, which caused the QBO of the AMC in these regions. The amplitudes and phases of the methane QBO were different in the SH and the NH extra-tropics because the upper cells and extra-tropical cells were incompletely symmetrical in the two hemispheres. The two-layer structure with stronger AMC perturbations in the upper layer over the extra-tropics agrees with the observational data. Although the simulated induced residual circulations at lower latitudes were stronger than those at middle or high latitudes, the methane QBO induced by them was similar. However, the observations show that the methane QBO in the tropics is stronger than that in the extra-tropics. This reflects the fact that the methane QBO in the tropics or extra-tropics is also affected by other factors.



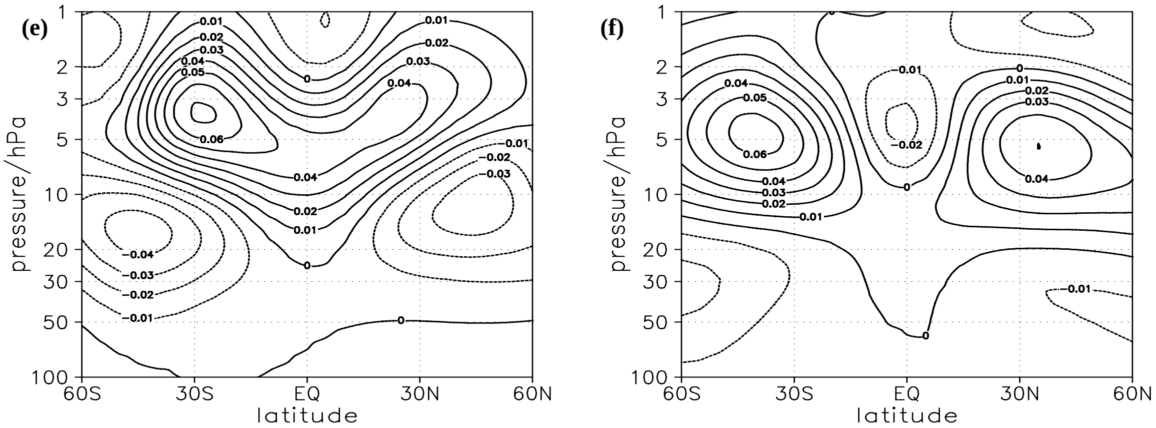


Fig. 4. Simulated differences of AMC due to the wind QBO between the simulation with wind QBO and without wind QBO (a: April, first model year, b: September and October, first model year, c: March, second model year, d: May, second model year, e: October and November, second model year, f: May, third model year; panels a, b, c are for the westerly phase; panels d, e, f are for the easterly phase. Units: ppmv).

The correlation analysis using HALOE and European Center for Medium-Range Weather Forecasts (ECMWF) 40-year reanalysis (ERA-40) data shows that there are obviously negative correlations between methane and temperature over the equator at the 30–2 hPa layer, especially at the 5–3 hPa layer. There are positive correlations in the NH extra-tropical upper stratosphere. The correlation coefficient is very small in the SH. The chemical reaction induces the depletion of methane mainly in the middle and upper stratosphere ($CH_4+OH \rightarrow CH_3+H_2O$, $CH_4+O(^1D) \rightarrow CH_3+OH$), where the changes in temperature lead to the changes in photochemical velocity relating to OH and O(^{1}D), thus affecting the methane. In this sense, the tropical methane QBO is related to temperature change (by altering the photochemical velocity) and residual circulation. As the photochemical lifetime of methane is of the same magnitude as the transport time of mean zonal wind in the stratosphere, the effect of the dynamical process on methane becomes very significant. The extra-tropical methane QBO results mainly from the dynamical process and is basically not relevant to temperature. A change in methane can also affect temperature; however, the effect is small as it is mainly derived from ozone and water vapor through the chemical process. Both the ERA-40 data and simulation results show that the temperature QBOs propagate downward in the tropics and extra-tropics, thus the upward propagation in the methane QBO should not be induced by the temperature QBO. We further calculated the stratospheric residual circulation[21] and its transport for methane using the Japanese 25-year reanalysis (JRA-25) data provided by the Japan Meteorological Agency (JMA) and Central Research Institute of Electric Power Industry (CRIEPI). The methane transports by the residual vertical velocity and residual meridional velocity show the obvious QBO features propagating downward; however, the vertical and the meridional transport usually counteract each other. As a result, the methane QBO propagates upward in the NH extra-tropics, which accounts for the nonexistence of methane QBO over the equator and SH extra-tropics. It seems that, although the QBO scheme in SOCRATES has some deficiencies, the simulation results are better than those calculated from reanalysis data.

5 CONCLUSIONS AND DISCUSSION

The interannual changes in AMC were analyzed in the SN and NH extra-tropics using HALOE satellite data and compared to those in the tropics. The formation mechanism of the methane QBO in the extra-tropics was then examined through a set of ideal comparative experiments with and without the wind QBO using the NCAR SOCRATES 2-D model. The main results are summarized as follows.

The analyses using the HALOE observational data indicated that the interannual change of methane in the extra-tropics is featured as QBO with a period of about 27 months. There are distinct differences in the amplitudes and phases of the methane QBO in the SH and NH extra-tropics. The methane QBO in the NH extra-tropics is located at 5–1 hPa, 30–10 hPa, and 100–30 hPa, with the upper two layers being primary, and the signs of methane QBO perturbation continuously change with altitude. The methane QBO in the SH extra-tropics occurs at 5–1 hPa and 30–10 hPa, and the signs of QBO perturbation are opposite in the layers.

The methane QBO in the extra-tropics is different from that in the tropics. The methane QBO in the tropics mainly appears at 10–1 hPa. The QBO perturbation amplitude is larger than that in the extra-tropics from 10 to 1 hPa. The QBO amplitudes of extra-tropical methane are much larger than those in the tropics at 30–10 hPa. Moreover, the interannual relative change in extra-tropical methane in the NH is no less than that in the tropics in the middle and upper stratosphere.

Numerical simulations show that the tropical stratospheric zonal wind QBO induces the secondary meridional vertical circulation, or an induced residual circulation. With the transition of easterly and westerly phases in the tropics, the locations and intensities of the induced residual circulations in the tropics and extra-tropics are featured as QBO. The transport of methane by the induced residual circulation leads to a methane QBO in the tropics and extra-tropics. Although the induced residual circulations at middle and higher latitudes were much weaker than those at lower latitudes, the resulting AMC perturbations at middle and higher latitudes were not definitely less than those at lower latitudes. The induced residual circulations in the NH and SH middle and upper stratosphere are not always longitudinally symmetric about the equator and show some differences in strength and phase. This leads to the differences in the amplitudes and phases of the methane QBO over the SH and NH extra-tropics.

The simulations also show that the amplitude of the methane QBO in the extra-tropics is similar to that in the tropics. However, observational data indicate that the QBO amplitude in the tropics is obviously larger than that in the extra-tropical middle and upper stratosphere. This indicates that the interannual changes in methane over the tropics or extra-tropics are also influenced by other factors. Because the photochemical reactions of methane are active in the middle and upper stratosphere, the temperature QBO can influence the methane QBO by altering the photochemical velocity. Analyses also show that the influence of temperature is more obvious in the tropics. The observational data show that the extra-tropical methane QBO propagates upward in some periods, in consistency with the simulation. Analyses indicate that the induced residual circulation and the transport of methane by both the residual vertical velocity and meridional velocity propagate downward together. However, the vertical transport and meridional transport usually counteract each other, with the final effect of creating a false upward propagation of the methane QBO.

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