QBO and QTO of atmospheric methane

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Abstract

The 12-month running means of methane (CH$_4$) concentrations at the surface/lower troposphere averaged for latitude groups 1–8 (1, 82–63°N; 2, 56–53°N; 3, 47–36°N; 4, 32–26°N; 5, 20–13°N; 6, 5–14°S; 7, 41°S only; 8, 65–90°S) showed oscillations but the peak spacings were similar to that of 30 mb wind (~30 months) only for groups 3, 4 and 7. A cross-correlation with 30 mb wind showed maximum good correlations (+0.7) with a phase lag of about 6 months for CH$_4$ in group 7 (in agreement with Camp et al. [2001. The sensitivity of tropospheric CH$_4$ to the interannual variability in stratospheric ozone. Chemosphere-Global Change Science 3, 147–156]) and about 12 months for CH$_4$ in groups 6 (+0.7). A spectral analysis indicated for 30 mb wind, a prominent Quasi-biennial oscillation (QBO) at 2.34 years and a minor peak at 2.06 years. For Southern Oscillation Index (SOI) (T–D), there was a prominent Quasi-triennial oscillation (QTO) peak at 3.6 years, but there was also a less prominent but significant QBO at 2.54 years. All CH$_4$ groups showed significant QBOs in the range 2.22–2.58 years but also showed more prominent QTOs in the range 3.2–4.1 years, and barely significant peaks in the range 1.6–1.9 years (19–22 months). To test the ozone mechanism proposed by Hamilton and Fan [2000. Effects of the stratospheric QBO on long-lived greenhouse gases in the troposphere. Journal of Geophysical Research 105, 20581–20587] (stratospheric wind QBO affecting stratospheric ozone, in turn affecting the filtered UV, the tropospheric OH radical, and finally tropospheric CH$_4$), TOMS-SBUV data were analyzed. Many CH$_4$ and ozone groups showed QBOs in the range 2.22–2.77 years, and lower periodicities in the range 1.60–1.91 years (19–22 months [Tung, K.K., Yang, H., 1994. Global QBO in circulation and ozone. Part I. Reexamination of observational evidence. Journal of Atmospheric Science 51, 2699–2707]), confirming that the ozone mechanism was operative. A disconcerting feature is the QTO of ~3.5 years, which was present in CH$_4$ in all latitude groups, but in ozone, only in groups 3, 6, 7.

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1. Introduction

The Climate Monitoring and Diagnostics Laboratory (CMDL) of the National Oceanic and Atmospheric Administration (NOAA), Air Resources Laboratory, Boulder, CO, USA, has been making meticulous measurements of several trace elements such as carbon dioxide, carbon monoxide, methane (CH$_4$), ozone, nitrous oxide and halocarbons. The CH$_4$ concentration at each location is a result of sources, sinks and atmospheric transport, integrated over various temporal and spatial scales. Tung and Yang (1994) and Yang and Tung (1994) illustrated that whereas the low latitude ozone had a Quasi-biennial oscillation (QBO) similar to the stratospheric wind QBO of a periodicity of ~30 months, the ozone in extra-tropical latitudes had...
additional periodicities at 20 and 8.6 months (further finer details of latitude dependence given in Kane, Sahai and Casiccia (1998)).

In an earlier communication (Kane, 1994), it was shown that the time series of some trace elements showed interannual variations, roughly in the QBO (2–3 years) and/or quasi-triennial oscillation (QTO, 3–4 years) ranges. However, for some elements, the data available were only annual means and for only a few (about 6) years. In Kane (2000), CH$_4$ data used were for 1983–1992 only. In the present communication, the data for CH$_4$ measurements (surface/lower stratosphere) are examined for longer intervals, mainly with a view to compare with the QBO known to exist in stratospheric low-latitude zonal winds (Reed et al., 1961; Veryard and Ebdon, 1961) and with the QBO and QTO of El Niño/Southern Oscillation (ENSO, Rasmussen et al., 1990). A comparison with TOMS ozone values is also made.

2. Data

The data used are monthly values of CH$_4$ (air samples collected at several sampling sites and analyzed at a central laboratory in Boulder, CO, USA) obtained by the NOAA/CMDL, and available at the website <ftp://ftp.cmdl.noaa.gov/ccg/ch4/flask/month/>.

3. Plots

To suppress the seasonal variation and to bring out the interannual variability, running means (12 m) were evaluated over 12 successive months. These are shown in Fig. 1. The following may be noted:

(1) The top plots in Fig. 1(a) are for the 12-month running means of the 30 mb low-latitude stratospheric zonal wind (positive, westerly; negative, easterly), and Southern Oscillation Index (SOI) represented by Tahiti (T)—Darwin (D) atmospheric pressure difference (T–D). El Niño occurrences (S, strong; M, moderate; W, weak) are shown black. The numbers are spacings (in months) between successive peaks. (b) Percentage CH$_4$ for latitude Groups 1–8; (c) percentage 12-month running means minus 3-year running means (12–36 months) of CH$_4$, for latitude Groups 1–8, for northern (NH) and southern (SH) hemisphere, and for the whole globe (GLOBAL). The bottommost plot is for Growth Rate (from Dlugokencky et al., 2001, Fig. 2).

Fig. 1. The 12-month running means of: (a) 30 mb low-latitude zonal wind (positive, westerly; negative, easterly) and Southern Oscillation Index (SOI) obtained as Tahiti (T)—Darwin (D) pressure difference (T–D). El Niño occurrences (S, strong; M, moderate; W, weak) are shown black. The numbers are spacings (in months) between successive peaks. (b) Percentage CH$_4$ for latitude Groups 1–8; (c) percentage 12-month running means minus 3-year running means (12–36 months) of CH$_4$, for latitude Groups 1–8, for northern (NH) and southern (SH) hemisphere, and for the whole globe (GLOBAL). The bottommost plot is for Growth Rate (from Dlugokencky et al., 2001, Fig. 2).
malized to a value of 100 for 1996. Data for different latitude belts were obtained by averaging data from individual locations as follows:

Group 1: ALT Alert, N.W.T. 82°N
1985(11)–2001(12)
BRW Barrow, Alaska 71°N
1983(09)–2001(12)
STM Ocean Station M, Norway 66°N
1983(09)–2001(12)
ICE Vestmannaeyjar, Iceland 63°N
1993(03)–2001(12)

Group 2: BAL Baltic Sea, Poland 56°N
1993(01)–2001(12)
CBA Cold Bay, Alaska 55°N
1983(10)–2001(12)
MHD Mace Head, Ireland 53°N
1991(11)–2001(12)
SHM Shemya Island, Alaska 53°N
1986(02)–2001(12)

Group 3: HUN Hegyhatsal, Hungary 47°N
1993(08)–2001(12)
UUM Ulaan Uul, Mongolia 44°N
1992(06)–2001(12)
NWR Niwot Ridge, Colorado 40°N
1983(11)–2001(12)
UTA Wendover, Utah 40°N
1993(10)–2001(12)
TAP Tae-ahn Peninsula, Korea 37°N
1991(08)–2001(12)
WLG Mt. Waliguan, China 36°N
1991(10)–2001(12)

Group 4: BME St. David’s Head, Bermuda 32°N
1989(07)–2001(12)
BMW Southhampton, Bermuda 32°N
1989(10)–2001(12)
IZO Tenerife, Canary Islands 28°N
1992(04)–2001(12)
MID Sand Island, Midway 28°N
1986(01)–2001(12)
KEY Key Biscayne, Florida 26°N
1984(03)–2001(12)

Group 5: MLO Mauna Loa, Hawaii 20°N
1983(10)–2001(12)
KUM Cape Kumukahi, Hawaii 20°N
1983(09)–2001(12)
GMI Guam, Mariana Islands 13°N
1983(10)–2001(12)

Group 6: SEY Seychelles, Mahe Island 5°S
1983(10)–2001(12)
ASC Ascension Island 8°S
1983(10)–2001(12)
SMO Tutuila, American Samoa 14°S
1983(09)–2001(12)

Group 7: CGO Cape Grim, Tasmania 41°S
1983(06)–2001(12)
SYO Syowa, Antarctica 69°S
1988(07)–2001(12)
SPO South Pole, Antarctica 90°S
1983(07)–2001(12)

Fig. 1(b) shows the plots. As can be seen, after the seasonal changes are eliminated in the 12-month running means, the major CH$_4$ changes now are the long-term increases, almost monotonic, but rapid during 1984–1991 (~5% in 8 years) and slower thereafter (1991–2000, ~2% in 9 years). However, there are small wiggles superposed. To bring these out clearly, the long-term trend has to be eliminated. The trend was evaluated as 3-year running averages (36 m) and subtracted from the 12-month running averages (12 m). The residues (12–36 m) are shown in Fig. 1(c). The oscillations have a much smaller range (less than 0.3%, peak to trough), but there are distinct peaks, with peak spacings as indicated by the numbers (in months). The average spacings in months for the various groups were: 1, 31; 2, 30; 3, 28; 4, 33; 5, 36; 6, 28; 7, 28; 8, 30, showing wide differences (28–36 months) from one group to another. Some average spacings are near the average spacing (~29 months) of 30 mb winds. In the hemispheric averages, average spacing were larger, 45 months for NH and 37 months for SH, with a large spacing (45 months) for the global average also. Obviously QBO characteristics are different in different latitudes (but with no systematic latitude dependence) and smaller spacings are obliterated in broad latitude bands (NH and SH), leaving only spacings of ~40 months.

A parameter often mentioned in literature is the ‘Growth Rate’, namely, a change from a particular month (or season) of 1 year to the same month (or season) of the next year (Dlugokencky et al., 1994a, b). We calculated the same by using the
12 m values centered 3 months apart, thus yielding four values per year of the Growth Rate, centered 3 months apart. The bottom plot in Fig. 1(c) is for the CH₄ Growth Rate. Here, the average spacing was much smaller (28 months), similar to that of 30 mb winds. However, as pointed out in Dlugokencky et al. (2001), the major features of the Growth Rate interannual variability are in 1991–1992 and in 1997–1998, coincident with El Niños and attributed to wetland CH₄ emissions. The QBO seems to be a superposed oscillation of smaller magnitudes (<0.3%) as compared to the long-term trend (several percent) and the major El Niño effect (~0.5%).

4. Correlation analysis

To obtain quantitative estimates of the interrelationships between the various plots in Fig. 1(a) and (c), a correlation analysis was conducted. The following was noted:

(1) In the CH₄ groups, only the nearby latitudes are well correlated (correlations exceeding +0.6), indicating that the characteristics at different latitudes were different.

(2) The correlations of the 30 mb wind with all the CH₄ groups were low (<0.45). To check whether the correlation might have been affected by phase shifts, a cross-correlation analysis was carried out between 30 mb wind and CH₄ of groups 3, 6 and 7, as only these groups had average spacings of 28 months, comparable to that of 30 mb wind of 29 months. For CH₄ group 3, the correlations were small (<0.3). For CH₄ group 6, the correlation was good (0.7) for a phase difference of four seasons (12 months). For CH₄ group 7 the correlation was good (0.7) for a phase difference of two seasons (6 months). Since group 7 consists of one station only (Cape Grim), these results are directly comparable to those of Camp et al. (2001) who report a QBO (Wind) signal for CH₄ at Cape Grim with a lag of about 6 months.

5. Spectral analysis

To obtain quantitative estimates of the spectral characteristics of the inter-annual variability, the series in Fig. 1(c) (about 60 data points of 3-monthly values) were subjected to spectral analysis by maximum entropy method (MEM, Burg, 1967; Ulrych and Bishop, 1975), which locates peaks much more accurately than the conventional BT (Blackman and Tukey, 1958) method. However, the amplitude (Power) estimates in MEM are not reliable (Kane, 1977, 1979; Kane and Trivedi, 1982). Hence, MEM was used only for detecting all the possible peaks $T_k (k = 1–n)$, using length of the prediction error filter (LPEF) as 50% of the data length. These $T_k$ were then used in the expression:

$$f(t) = A_0 + \sum_{k=1}^{n} [a_k \sin(2\pi t/T_k) + b_k \cos(2\pi t/T_k)] + E = A_0 + \sum_{k=1}^{n} r_k \sin(2\pi t/T_k + \phi_k) + E,$$

where $f(t)$ is the observed series and $E$ the error factor. A multiple regression analysis (MRA, Bevington, 1969) was then carried out to estimate $A_0 (a_k, b_k)$, and their standard errors (by a least-square fit). From these, amplitudes $r_k$ and their standard error $\sigma_k$ (common for all $r_k$ in this methodology, which assumes white noise) were calculated. Any $r_k$ exceeding $2\sigma$ is significant at a 95% (a priori) confidence level.

There are, of course, more sophisticated methods (Ghil et al., 2002) which can be used, for allowing for the possibility that the periodicities may be generated by non-linear processes and cross-testing may be needed. MEM is a technique that is designed to pick up sharp resonances and may not be necessary for the CH₄ series. But in the present case, we are handicapped here with the smallness of the signal and very limited length of the CH₄ series (9 years, further reduced to 6 years, as running means of 36 months are used). However, for the stratospheric winds and ENSO, MEM is still useful, as is illustrated in the text, and compared with CH₄ also. Since some periodicities of winds and ENSO are very near each other, values are calculated to two decimal places. Some workers feel that the moving average methodology can generate artifacts that can cause distortions and may affect the accuracy of the final conclusions. Our previous experience shows that this fear is not justified, but in any case, the present results should be considered as only approximate, to be checked later in future when longer data series may be available, and MEM may be adequate for this limited purpose. More elaborate methods and confirming the robustness of the results by introducing random noise may not be
necessary as the sample is short and only approximate results are expected.

Since the 30 mb wind and (T–D) series do not have long-term trends (Fig. 1(a)), their spectra were obtained for (12 months) values only. For CH₄, spectral analysis was carried out for the (12–36 months) series and the Growth Rate series. The results are shown in Fig. 2. The following may be noted:

1. The top plot is the spectrum (amplitude versus periodicities) for 12 month values of 30 mb wind and shows one prominent periodicity of 2.34 years (28 months, in the QBO region) and a minor periodicity of 2.06 years (25 months, also in the QBO region), which should be responsible for the scatter of spacings (24–33 months) in Fig. 1(a).

2. The second plot is the spectrum for the 12 months values for SOI (T–D) and shows a prominent peak at 3.60 years (43 months, QTO) but also a slightly smaller peak at 2.54 years (30 months, QBO).

3. The other plots show spectra for CH₄ (12–36 months) (full lines) and indicate periodicities in the QBO and QTO regions, some QBOs tallying with 30 mb wind QBO and other QBOs tallying with the (T–D) QBO. The QTOs vary in a wide range 3.2–4.3 years and some are near the 3.6 years of (T–D).

4. The full lines are for (12–36 months) and the dashed lines are for the Growth rates. The periodicities are almost similar, though the amplitudes of (12–36 months) are slightly lesser. Whereas the QTO has larger amplitudes as compared to QBO for most of the CH₄ groups, CH₄ group 6 seems to have a QBO larger than its QTO, but the periodicity of the CH₄ QBO (2.52 years) is almost the same as of (T–D) QBO (2.54 years) and not the same as of wind QBO (2.34 years). On the other hand, the QBO of CH₄ groups 1 and 3 (2.23 and 2.22 years) is more similar to the wind QBO (2.34 years) than to (T–D) QBO (2.54 years).

5. An interesting feature is the presence of periodicities of ~1.6–1.9 years (19–23 months) which are barely (or non-) significant but appear in all CH₄ groups. These are discussed later.

From this comparison of periodicities, one would conclude that firstly, CH₄ has a strong, significant ENSO signal in the QTO region (~3.5 years) and secondly, that in the QBO region, some CH₄ groups (2, 5, 6, 7, 8) have a signal similar to ENSO QBO while some others (1, 3) have a signal similar to stratospheric wind QBO. However, this depends crucially upon whether the wind QBO at 2.34 years is considered as different from the ENSO QBO at 2.54 years. The MEM methodology is certainly good enough to see this difference with good confidence, but there is another aspect which is more bothersome, as follows.

When the QBO in stratospheric wind was discovered in early 1960s, it was considered as ‘biennial’, as anything else was unimaginable at that time. However, it was soon realized that the signal was definitely longer than 24 months and was soon ascertained to be ~26 months. In due course, the
signal was reported to have increased to ~28 months (Naujokat, 1986) and has increased further to ~30 months in recent years (Kane, 1998). Thus, the value 2.34 years (28 months) for the 30 mb QBO may not be fully representative of the present epoch, and might have been caused to be lesser due to the one short spacings of 24 months during 1997–1999. Incidentally, this peculiar feature of wind QBO, namely, the two successive short spacings of 27 and 24 months during 1996–1999, could be used for a direct comparison with different CH4 groups. As can be seen in Fig. 1, this feature appears in CH4 group 6 exactly, in CH4 group 7 in a reverse order (24, 27), and in CH4 group 8 in an obscure way (the middle peak not clear). In all other CH4 groups, this feature does not exist even approximately. Thus, by this criterion, CH4 groups 6 and 7 (and perhaps 8) have a good association with stratospheric wind QBO while other CH4 groups do not have such a good association, in particular, CH4 group 3, which has a large contribution from ENSO at 3.8-year periodicity.

6. Relationship with column ozone

Among the two mechanisms suggested for a connection between stratospheric wind and CH4, one involves column ozone (mostly stratospheric). Camp et al. (2001) examined the CH4 measurements at Cape Grim, which is the (only) station in our CH4 group 7 (41°S). Here, a similar analysis is extended to the other CH4 groups. TOMS-SBUV ozone monthly values were obtained from the website http://code916.gsfc.nasa.gov/Public/Analysis/merged/data/toms_sbuv.v3.78-02.za.txt. The ozone levels changed considerably and unevenly from 1985 to 1999. However, in a spectral analysis by MEM, the long-term trends do not alter the short-term periodicities (Kane and Trivedi, 1986). Hence, the 12-month running means of ozone centered 3 months apart (four values per year) were subjected to MEM-MRA. It should be remembered that volcanic eruptions can affect ozone and temperature in the lower stratosphere for several months, e.g., Mt. Pinatubo during June 1991–September 1993. This can distort the spectra, but it is difficult to access how much the distortion would be. Since volcanic eruptions have occurred with spacings of more than 5 years, distortions of periodicities exceeding 5 years can be expected, but these are not in the QBO, QTO ranges. The spectra (amplitudes versus periodicities detected by MEM) are shown in Fig. 3. The top plot (A) is for 30 mb wind, with one major peak at 2.34 years and a minor peak at 2.06 years (same as the top plot in Fig. 2). The next plot (B) is for (T–D), with two almost comparable major peaks at 2.54 and 3.60 years (same as the second plot in Fig. 2). The third plot (C) is for TOMS ozone amplitudes for latitudes corresponding to CH4 group 1 (63–82°N). It shows barely significant peaks at 1.72 and 2.42 years, a significant peak at 5.1 years, and a very prominent peak at ~10 years, which could be a solar cycle peak or a representation of the long-term ozone trend. As can be seen, the QBO is small in magnitude and the periodicity 2.42 years is in between the periodicity 2.34 years of wind and 2.54 years of (T–D). For comparison, the CH4 periodicities of group 1 of

![Fig. 3. Spectra (amplitudes versus periodicities T detected by MEM) for 1985–1999, for (A) 30 mb wind, and (B) Southern Oscillation Index (T–D). Plot (C) is for TOMS ozone for latitude Group 1. The numbers indicate periodicities in years. For comparison with methane, the numbers in parentheses indicate periodicities for methane for Group 1 (same as in Fig. 2, third plot). The plots (D–J) are for ozone and methane (numbers in parentheses) for the other latitude Groups 2–8. The hatched portion shows the 2σ limits and lines protruding above this limit are significant at a better than 95% confidence level. (Note that the abscissa scale is logarithm of periodicity T.)](http://code916.gsfc.nasa.gov/Public/Analysis/merged/data/toms_sbuv.v3.78-02.za.txt)
Fig. 2 are shown here in parantheses. The 1.74-year peak of CH$_4$ tallies with the 1.72-year peak of ozone. The 2.23-year peak of CH$_4$ almost tallies with the 2.42-year peak of ozone, but the ~3.8-year peak of CH$_4$ is not seen in ozone, and the 5.1-year peak in ozone is not seen in CH$_4$.

In the fourth plot (D) for latitude group 2 (53–56°N) also, the QBOs tally (1.95 with 1.92; 2.53 with 2.70), but CH$_4$ has a peak at 4.1 years, not seen in ozone. Same is true for the sixth plot F and the seventh plot G (latitude group 4, 26–32°N; latitude group 5, 13–20°N), where CH$_4$ has QTO peaks not seen in ozone.

In plots (E), (H), (I) for latitude groups 3, 6, 7, the situation is very different. The QBOs as well QTOs tally fairly well. Thus, for these groups, ozone also has a QTO. If interpreted as an ENSO effect (similarity with T–D), it would indicate that besides the effect of stratospheric QBO, the ozone in these groups has a significant contribution from the terrestrial El Niño phenomena. The UV connection (ozone–UV–OH–CH$_4$) may still be there, but not because of stratospheric QBO. The question would then arise, how did the ENSO effect reach the ozone in the stratosphere? In this connection, the following scenario is relevant. During El Niño and La Niña events, anomalous wave trains propagate poleward in the winter hemisphere of the troposphere. Present in those wave trains are planetary-scale waves that are able to propagate vertically into the stratosphere (Horel and Wallace, 1981). Such waves could be playing an important role in conveying ENSO effects from the troposphere to the stratosphere.

7. Conclusions and discussion

An analysis of methane (CH$_4$) concentrations at the surface/lower troposphere showed considerable seasonal variations. As the purpose of the present investigation was to examine quasi-biennial and quasi-triennial oscillations (QBO and QTO), 12-month running means (12 m) were evaluated. (These would eliminate periodicities of 12 months or less.) CH$_4$ concentrations were also dominated by long-term trends, which were camouflaging short-time fluctuations. The trends were estimated by calculating 36-month running means (36 months) and these were subtracted from the 12-month running means to give the time series (12–36 months) devoid of long-term trends. Data at various locations during 1983–2001 were expressed as percentages of their means and averaged in latitude groups 1: 63–82°N; 2: 53–56°N; 3: 36–47°N; 4: 26–32°N; 5: 13–20°N; 6: 5–14°S; 7: 41°S; 8: 65–90°S, and four values per year centered 3 months apart were used for plots and other analyses. The following was noted:

(1) The plot of (12 m) of 30 mb wind had no long-term trends and showed smooth oscillations with peak spacings in the range 24–33 months (average ~29 months). The (12 months) of SOI Tahiti (T)–Darwin (D) atmospheric pressure difference (T–D) also had no long-term trends and showed large depressions during El Niño events only (spaced 4–5 years apart). The series (12–36 months) of all the CH$_4$ groups showed oscillations but the peak spacings were similar to that of 30 mb wind only for groups 3, 6, 7. In the 30 mb wind, there were two successive small spacings (27 and 24 months) during 1996–1999. This feature was seen only in CH$_4$ groups 6 and 7, indicating that a good association of 30 mb wind with CH$_4$ existed only in latitudes 5–41°S (in agreement with the results of Camp et al. (2001), for Cape Grim, 41°S).

(2) A cross-correlation with 30 mb wind showed maximum good correlations (+0.7) with a phase lag of about 6 months for CH$_4$ group 7 (in agreement with Camp et al. (2001)) and about 12 months for CH$_4$ groups 6 (+0.7).

(3) For 30 mb wind, a spectral analysis indicated a prominent QBO at 2.34 years and a minor peak at 2.06 years. For (T–D), there was a prominent QTO peak at 3.6 years, but there was also a less prominent but significant QBO at 2.54 years. All CH$_4$ groups showed significant QBOs in the range 2.22–2.58 years but also showed more prominent QTOs in the range 3.2–4.1 years (only CH$_4$ group 6, 5–14°S, had QBO more prominent than QTO). Also, there were (barely significant) peaks in the range 1.6–1.9 years (19–22 months).

(4) Hamilton and Fan (2000) suggested two mechanisms for association of stratospheric wind QBO with CH$_4$, first, through changes in STE (stratosphere–troposphere exchange, transport mechanism), and second, through stratospheric ozone (stratospheric wind QBO affecting stratospheric ozone, in turn affecting the filtered UV,
the tropospheric OH radical, and finally tropospheric CH$_4$, ozone mechanism). To test the ozone mechanism, we analyzed TOMS-SBUV data by the same procedure as for the CH$_4$ data, in similar latitude groups. Almost all CH$_4$ and ozone groups showed QBOs in the range 2.22–2.77 years, and lower frequencies in the range 1.60–1.91 years (19–22 months). The periodicity of ~20 months in ozone has been explained by Tung and Yang (1994) as a beat frequency between the annual wave (12 months) and the QBO (30 months), (1/12 + 1/30~1/8.6 and 1/12 – 1/30~1/20, only 20 months seen here as 8.6 months would be wiped out in 12-month running means), and is mentioned as an extra-tropical feature. However, here it was observed in all ozone groups. The periodicities are not exactly alike for ozone and CH$_4$, but the existence of both the QBO and the ~20 months periodicity in both ozone and CH$_4$ does substantiate the ozone mechanism.

(5) A disconcerting feature is the QTO of ~3.5 years, which was present in CH$_4$ in all latitude groups, but in ozone only in groups 3, 6, 7. Since QTO is not present in stratospheric wind, its presence in ozone at least for some latitudes indicates a tropospheric ENSO effect extending to stratosphere (STE, stratosphere–troposphere exchange, probably via planetary-scale waves), and its simultaneous occurrence in tropospheric CH$_4$ could still be by the ozone mechanism, but unrelated to stratospheric wind QBO.

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