# Technical Note:

# Multi-year Changes in the Brewer-Dobson Circulation from HALOE Methane

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**Abstract.** This study makes use of Halogen Occultation Experiment (HALOE) methane ($CH_4$) in a search for multi-year changes in the Brewer-Dobson Circulation (BDC). Changes in $CH_4$ are determined for three, successive 5-yr time spans from 1992 to 2005, and there are significant differences in them. There is a clear separation for the changes in the northern hemisphere near 30 hPa or at the transition of the shallow and deep branches of the BDC. The $CH_4$ changes ~~were~~are positive and large in the shallow branch following the eruption of Pinatubo, but they then ~~decreased~~decrease and ~~agreed~~agree with tropospheric trends in the late 1990s and early 2000s. $CH_4$ ~~decreased~~decreases in the upper part of the deep branch from 1992 to 1997 or following the eruption of Pinatubo. $CH_4$ ~~continued~~continues to decrease in the deep branch in the late 1990s but then ~~increased~~increases in the early 2000s, although ~~the~~those changes ~~were~~are small compared with the seasonal and interannual variations of $CH_4$. ~~Those multi~~Multi-year changes ~~were~~are due, in part, to wave forcings during El Nino Southern Oscillation (ENSO) of 1997-1998 and beyond and to episodic, sudden stratospheric warming (SSW) events during both time spans. It is concluded that time series of HALOE $CH_4$ provide effective tracer diagnostics for studies of the nature of the BDC from 1992 to 2005.

## 1. Introduction

Global-scale stratospheric transport is characterized in each hemisphere by a seasonal Brewer-Dobson circulation (BDC), consisting of upward transport in the tropics, poleward transport to higher latitudes, and descent in the polar vortex region (e.g., Butchart, 2014). Model studies indicate that there are also multi-year changes in the BDC in response to increases in the greenhouse gases (GHG) and to dynamical forcings during El Nino/Southern Oscillation (ENSO) events, but where the effects of those forcings may differ within the shallow (lower) and deep (upper) regions of the BDC. Remsberg (2015) reported that the distributions of methane ($CH_4$) from the Halogen Occultation Experiment (HALOE) provide tracer diagnostics for changes in the BDC. The present study is a refinement of his initial analysis and gives some insight on mechanisms for changes in the BDC. Section 2 is a brief description of the methane data and the analysis approach for them. Section 3 presents the results of the analyses in terms of changes in the distribution of $CH_4$ for three successive 5-yr time spans. Qualitative attributions are also ~~provided~~considered for those changes. Section 4 summarizes the findings from this exploratory study.

## 2. Data and Analysis Method

HALOE obtained sunrise (SR) and (SS) occultation measurements across latitude zones throughout its mission of October 1991 to November 2005. The present study considers zonal averages of $CH_4$ for nine latitude zones and at twelve pressure levels (0.4 to 50 hPa), for a total of 108 separate time series. A minimum of 5 profiles gives representative zonal averages for each latitude zone; averages are based on many more profiles in most instances. Figure 1 shows example time series from zonal averages of the SR and SS measurements at specific pressure levels and in three different latitude zones. Figure 1(a) is the time series for the 10 hPa level at 30°N latitude, and there is a clear QBO-signal in the data. Figure 1(b) is for 10 hPa at 30°S, where there is a combination of annual (AO), semi-annual (SAO), and QBO signals. One can also see that seasonal and interannual variations are much larger than the longer-term changes.

Figure 1(c) is for 2 hPa at 45°N, where $CH_4$ decreases gradually in the early to middle 1990s and where it has larger amplitudes in early 2002 and 2004.

The analysis of $CH_4$ for this study is in the manner of Remsberg (2015) with the following modifications. The nine latitude zones are from 60°S to 60°N with a spacing of 15° and no overlap. The latitude bins are a bit ~~wider (15°)~~narrower than before ~~to~~(15° versus 20°) but still provide ~~more~~ representative sampling, ~~especially~~even at ±45° from 2000 to 2005 when the samples from HALOE ~~were more~~are limited. To look for secular trends in the BDC, multiple linear regression (MLR) analysis was applied to the $CH_4$ time series, as separated into three, 5-yr time spans that overlap by one year (July 1992 to June 1997; July 1996 to June 2001; and July 2000 to June 2005). The beginning and end months of July and June, respectively, were selected to avoid large excursions in $CH_4$ at the end points of time series for the northern hemisphere during the dynamically active winter season. Data prior to July 1992 were not used, to avoid issues related to variable solar lock-down procedures for the HALOE sun sensor and because of significant extinction from interfering aerosols following the Pinatubo eruption. The analyses also do not include the period after June 2005, when HALOE operations were limited.

An initial MLR analysis was applied to the 13-yr time span of the HALOE measurements for a range of pressures and latitudes but using only AO and SAO terms. Time series residuals from those runs were analyzed for interannual cycles, yielding significant terms with periods of 882 days (~29-month or QBO-like) and of 690 days (22.6-month or sub-biennial (SB)). Those two terms were highly significant for many of the latitude/pressure time series, so they were included along with the seasonal terms for the MLR model. The 5-yr (or 60 month) time span is equivalent to two complete QBO cycles and avoids biases in the MLR trends due to that periodic term. A biennial (718-dy) term was also indicated for the subtropics, but it was not uniformly present elsewhere and was not retained for the model. A linear term completes the final MLR model; the analyses also correct for lag-1 autoregressive (AR1) effects. The MLR model fit to the data points is shown by the oscillating solid curve for July 1996 to June 2001 in each panel of Fig. 1~~. The~~, and the combination of the constant and linear terms is the dashed line. One can see that the seasonal and interannual variations have large amplitudes compared with the overall 5-yr trend line, such that even minor changes from year to year can affect the linear changes. ~~Figure 1(c) is for 2 hPa and 45°N and indicates that $CH_4$ was decreasing from 1992 to 1997 or following the eruption of Pinatubo. The 5-yr changes from 1996 to 2001 are less negative and they become positive during~~Although the MLR fits and trends are based on analyzed AR1 values for each case, the MLR curves in Fig. 1 are based on AR1 = 0 and give maximum amplitudes for the periodic terms.

The sensitivity of the trend coefficient to the approximate QBO term of the MLR fit was determined for Fig. 1(a) (30°N, 10 hPa), where a QBO cycle shows clearly. Specifically, the length of the QBO cycle was altered (28 months versus 29.5 months) as well as the length of the time span for the MLR analysis (58 months rather than 60 months). The resulting trend coefficients in each case differ by less than 6% from the one of Fig. 1(a). Figure 1(c) focuses on the upper stratosphere, where $CH_4$ decreases from 1992 to 1997 or from one year after the Pinatubo eruption. The 5-yr trend is less negative from 1996 to 2001 and then is positive from 2000 to 2005, punctuated by two winter maximums in early 2002 and 2004.

The distribution of the average $CH_4$ (its constant term) is shown in Figure 2 for the time span of July 1996 to June 2001. Tropical entry-level values extend upward and are transported poleward in each hemisphere. $CH_4$ decreases with altitude and latitude, due to the relatively slow chemical conversion of $CH_4$ to water vapor ($H_2O$) and molecular hydrogen ($H_2$) in the upper stratosphere (Brasseur and Solomon, 2005). That decay of $CH_4$ is nearly symmetric between the two hemispheres. The primary purpose of Fig. 2 is to show the vertical and meridional gradients of $CH_4$ that are acted upon by the BDC. Although the $CH_4$ distributions for the other two 5-yr time spans are like that of Fig. 2, there are small but distinct differences in the 5-yr changes in $CH_4$ for the three successive time spans.

~~Figures 3-5 show the distributions of~~Distributions of the linear terms (% change / 5-yr) from the zonally averaged $CH_4$ data ~~for~~are shown and discussed in Section 3 for each of the three periods of July 1992 to June 1997, July 1996 to June 2001, and July 2000 to June 2005~~, respectively.~~.

Notably, there is good continuity for ~~those changes~~the trends with pressure and latitude~~ and for each time span~~, indicating that each distribution is meaningful and related physically to multi-year changes for the large-scale BDC.~~ Results for the three 5-yr spans are discussed in turn in the next section.~~

## 3. Multi-year changes in $CH_4$

### *(a) July 1992 to June 1997*

Figure 3 shows that $CH_4$ decreased in the upper stratosphere and lower mesosphere from July 1992 to June 1997 or ~~following~~after one year from the Pinatubo eruption of June 1991. The shading indicates where the trends are robust, the dark shading having a confidence interval (CI) of greater than 90% and the light shading having CI between 70 and 90%. Positive changes ~~were~~in $CH_4$ at low and middle latitudes indicate an acceleration of the BDC, and negative changes imply deceleration of the BDC. The negative changes in $CH_4$ in the upper regions of Fig. 3 imply that there was an overall slowdown of the deep branch of the BDC during this time. Changes are larger at middle latitudes ~~in~~of the northern than of the southern hemisphere, indicating that ascent occurred within the deep branch of the BDC ~~occurred mainly~~ in the northern subtropics immediately ~~following~~after the eruption~~.~~ and then there was a decrease from those values. Separate, zonal mean cross sections of HALOE $CH_4$ ~~also show~~(not shown) reveal that the 0.8 ppmv contour of $CH_4$ occurred at ~4 hPa in November 1991 but rose to ~2 hPa by February 1992 in response to the BDC of that winter (e.g., Russell et al. 1999). ~~SSW~~Thereafter, $CH_4$ values that had been lofted to higher altitudes underwent a gradual decline over time. Sudden stratospheric warming (SSW) events tend to accelerate the deep branch of the BDC and ~~lead to a mixing of~~mix middle latitude and polar air~~. That~~; that mixing ~~tends to flatten~~flattens the contours of zonal average $CH_4$ mixing ratio. However, there were no ~~sudden stratospheric warming (SSW)~~SSW events in the northern hemisphere during 1992 to 1997 (Choi et al., 2019).

A more traditional indicator of changes in the BDC is stratospheric age-of-air (AoA), where negative AoA indicates acceleration and positive AoA implies a deceleration of the BDC. Pitari et al. (2016) estimated that AoA decreased in the middle to upper stratosphere by ~0.5 to

0.7 yr during 1991-1992, due mainly to ascent following the eruption of Pinatubo.  Fig. 3 indicates a decline of $CH_4$ (and presumably an increase in AoA) from July 1992 onward. Methane is not a perfect tracer, however, as it has a chemical lifetime as short as only a few months at 45 km (~1.5 hPa) ~~but~~and then lengthening to 6 months and longer at 55 km and above and at 40 km and below (Brasseur and Solomon, 2005).  The relatively short lifetime of $CH_4$ at 1.5 hPa means that even the seasonal variations of $CH_4$ are dampened at that level.  ~~Thus, the~~The near-zero~~, linear change~~ changes for $CH_4$ near 15°S and 2 hPa in Fig. 3 ~~indicates~~may imply that there was ~~a slow, steady~~still some transport of $CH_4$ to that region from the tropics after July 1992.

The 5-yr changes in Fig. ~~There~~3 also indicate that there was ~~also~~ an accumulation of $CH_4$ at ~20 to 30 hPa at middle latitudes ~~at ~20 to 30 hPa in~~of both hemispheres during this period, in reasonable accord with a net poleward transport of tropical $CH_4$ at the top of the shallow branch of the BDC.  ~~In addition, the~~The tropical trend of 3 to 4 % at 20 to 30 hPa is half that at middle latitudes, although it is still larger than the tropospheric trends for $CH_4$ of ~0.3 to 0.4 % / yr (or 1.5 to 2.0 % for the 5-yr period) (Dlugokencky et al., 2009).

~~Positive changes in~~ Figure 4 gives more detail about the effects of the Pinatubo eruption on $CH_4$ ~~at low and middle latitudes indicate~~in the lower stratosphere.  Fig. 4(a) is for 15°N, 50 hPa and shows an ~~acceleration of the BDC~~initial increase in $CH_4$ in 1991 to the middle of 1992, followed by decreasing values through 1993.  HALOE $CH_4$ values are of the order of 1.55 ppmv in 1992, declining to 1.45 ppmv in 1993, and ~~negative changes imply deceleration of the BDC.  However, the more traditional indicator of changes in the BDC is stratospheric age-of-air (AOA), where negative AOA indicates acceleration~~then increasing again.  Independent $CH_4$ measurements at ground level are between 1.70 and ~~positive AOA implies a deceleration of the BDC.~~1.75 ppmv (Dlugokencky et al., 2009).  As an aside, HALOE $CH_4$ values for SR in 4(a) are consistently larger than for SS.  Those differences are likely due to uncorrected detector hysteresis effects for tropical SR measurements just above cloud tops; they decrease at 30 hPa and are negligible at 20 hPa.  Diallo et al. (2017) reported that ~~AOA~~AoA decreased during the first six months ~~due to tropical upwelling~~ following the eruption of Pinatubo~~.  But then they found that AOA~~ due to tropical upwelling.  Then, AoA increased from early 1992 to spring 1993 between 20°S and 30°N and from 20 to 27 km (~50 hPa to 15 hPa), implying a deceleration of the shallow branch of the BDC during ~~1992.  However, they also reported a substantial increase in AOA in northern latitudes that they related to both an increase in~~ that time.  The HALOE SR and SS CH$_4$ variations are in accord with the changes in AoA from 1991 to 1993 in the shallow branch of the BDC.

Figure 4(b) is the HALOE CH$_4$ time series for 45°N, 30 hPa, and it shows a gradual increase of CH$_4$ for 1993 to 1997.  Yet, Diallo et al. (2017) reported increases in AoA for 1993 at tropical and middle latitudes due to meridional mixing ~~tendency and a slowdown of the residual circulation.~~ , followed by decreases in mixing and AoA through 1997.  Fig. ~~The 5-yr changes in Fig.~~ 3 ~~for the lower stratosphere also indicate a reduced tropical upwelling and an~~ suggests that there was an accumulation of CH$_4$ at middle latitudes between ~20 and 30 hPa, due in part to that mixing ~~and a slowdown of the BDC.  The negative changes in CH$_4$ in upper regions of Fig. 3 imply~~trend.  It may also be that there was an overall slowdown ~~of the deep branch of the BDC. CH$_4$ values that had been lofted to higher altitudes by the force of the eruption underwent a gradual decline over time, and meridional mixing was not so effective due to the lack~~in the BDC during this 5-yr period, which was absent of SSW events ~~during the mid-1990s~~and any enhanced descent of CH$_4$-poor, polar air plus its subsequent mixing to middle latitudes.

### *(b) July ~~2996~~1996 to June 2001*

Figure ~~4~~5 shows the 5-yr CH$_4$ changes for 1996 to 2001, when there were several SSW events—on 15 December 1998, 25 February 1999, and 20 March 2000 (Choi et al., 2019).  ~~Their effect on the associated BDC was a transport of CH$_4$ across adjacent latitudes~~The negative trends in the upper stratosphere are smaller in the northern hemisphere and ~~a broadening of~~ larger in the ~~region of decreasing trends.  SSW events also led to greater ascent of CH$_4$ in the~~ southern hemisphere than in Fig. 3, suggesting that there was tropical ~~upper stratosphere,~~ascent but also increased mixing of CH$_4$ to higher latitudes, related in part to SSW activity.  Those changes are also where the chemical ~~conversion~~loss of CH$_4$ ~~was most effective~~to H$_2$O and ~~the negative~~

~~changes in Fig. 4 were enhanced compared to Fig. 3.~~$H_2$ may be a factor.  It is~~ also~~ apparent that there was greater meridional transport of $CH_4$ from the tropics to middle latitudes and an accumulation of $CH_4$ at ~10 hPa in both hemispheres during 1996 to 2001.  Those ~~increasing~~positive trends ~~occurred~~are at a level of the stratosphere~~,~~ where the conversion of $CH_4$ to $H_2O$ and $H_2$ is not ~~efficient~~as effective.

There was a major warm ENSO event in 1997-1998 that altered wave forcing effects on $CH_4$ and for the BDC.  Randel et al. (2009) and Calvo et al. (2010) reported enhanced upwelling in the tropics and an acceleration of the BDC at that time.  Diallo et al. (2019) reported that ENSO leads to the overall strengthening of the shallow branch of the BDC in the extratropics.  It may be that enhanced poleward transport in the shallow branch is why the $CH_4$ changes are more nearly zero in the tropics and agree more closely with tropospheric trends~~ lower during 1996 to 2001~~.  There is a clear separation at ~30 hPa in the sign of the changes in the shallow versus the deep branch of the BDC in the northern hemisphere.

The 1997-1998 warm ENSO event occurred near solar minimum, for which Calvo and Marsh (2011) also found enhanced wave forcing in the middle and upper stratosphere.  That activity leads to acceleration of the BDC and poleward transport of $CH_4$ to the extratropics.  Barriopedro and Calvo (2014) also found connections between ENSO and SSW events, although the exact effects depend on the relative sequence of those events.  Since major SSWs within 1996-2001 occur in December 1998, February 1999 and in March 2000, it is likely that they merely led to further accelerations of the BDC.  As an example, Tao et al. (2015) gave details about how the SSW of 2009 led to an acceleration of the BDC.  Their analyses may support the present finding of increases in $CH_4$ in the extratropics near 10 hPa in Fig. ~~4.  More~~5.  However, more focused ~~analyses~~studies of the relative roles of SSWs and ENSO on the results of Fig. ~~4 and~~5 are beyond the scope of the present exploratory study.

### *(c)  July 2000 to June 2005*

There was even more SSW activity in the northern hemisphere during the 5-yr span from 2000 to 2005 (on 11 February 2001, 2 January 2002, 18 January 2003, and 7 January 2004, according to Choi et al., 2019). The distribution of changes in $CH_4$ in Figure ~~5~~6 includes the net effect of those episodic SSW events. There was an increase in $CH_4$ at upper altitudes, where the effect of SSWs may have also led to greater poleward transport of $CH_4$ to higher latitudes. As before, an SSW event accelerates the deep branch of the BDC, bringing more $CH_4$ to high altitudes and greater meridional transport to higher latitudes. ~~In~~At the stratopause ~~region~~ (~1 hPa) ~~the~~and in the lower mesosphere even small changes in $CH_4$ mixing ratio translate to relatively large percentage changes. Those changes are from negative to positive from Fig. ~~4~~5 to Fig. ~~5~~6 and are rather uniform across latitude. On the other hand, the changes near 10 hPa ~~are weaker now than in Fig. 4~~and at middle latitudes of the northern hemisphere~~.~~ are weaker now than in Fig. 5. Fig. 1(a) indicates that this change may be a consequence, in part, of large seasonal amplitudes for $CH_4$ in early 2001 and in 2005 or near the end points of the 5-yr period from July 2000 to June 2005.

In the southern hemisphere there was an anomalous SSW event on 22 September 2002, leading to a splitting of the polar vortex (Newman and Nash, 2005). The $CH_4$ changes from Fig. ~~4~~5 to Fig. ~~5~~6 at 10 hPa and 30°S were likely altered by that event (c.f., the time series segments in Fig. 1(b) for those two 5-yr periods). ~~There~~Note that there is ~~also~~ no clear separation of the shallow and deep branches of the BDC ~~from Fig. 5~~ for the southern hemisphere in Fig. 6.

Figure ~~6~~7 provides a clearer picture of what ~~was occurring~~occurred from 2000 to 2005. Fig. ~~6~~7(a) is a time series of $CH_4$ at 45°S and 20 hPa, and it shows pronounced annual cycles in $CH_4$. ~~Peak values occur~~A peak seasonal value occurs in 2001, and ~~they~~it may ~~influence~~by influencing the overall analyzed trend for that time span. On the other hand, there is little indication of a change in $CH_4$ at the time of the anomalous SSW event of September 2002. Fig. ~~6~~7(b) shows the corresponding $CH_4$ time series at the Equator and 20 hPa, where ~~the~~ $CH_4$ variations are forced primarily by the QBO. There is a clear decrease in $CH_4$ in 2001 compared to the maximum at 45°S~~. As an aside,~~ in Fig. ~~6~~7(a). Fig. 7(b) also shows that tropical QBO signals are nearly absent in $CH_4$ from 1996 to 2000. Bönisch et al. (2011) reported that tropical upwelling increased after 2000 and accelerated the shallow branch of the BDC. Similar studies based on variations in $CH_4$ may be helpful in determining the nature of the shallow layer of the BDC both prior to and after 2000.

## 4. Summary findings

The present study is an analysis of the distributions of HALOE $CH_4$ for indications of secular changes in the BDC. Linear trends in $CH_4$ were determined for three, successive 5-yr time spans, and there are significant differences between them. There is a clear separation of the deep and shallow branches of the BDC at about 30 hPa in the northern hemisphere in each time span. Although the changes for $CH_4$ in the shallow branch are rather large following the eruption of Pinatubo, they agree well with tropospheric trends ~~in~~for $CH_4$ during the late 1990s and early 2000s. There are decreasing changes in the upper part of the deep branch of the BDC in the early to middle 1990s, indicating a decline of $CH_4$ ~~following~~from one year after the eruption. $CH_4$ changes in the middle and upper stratosphere differ markedly for the early 2000s compared to those of the late 1990s, although those differences are small compared to the seasonal and interannual variations of $CH_4$. In addition, the seasonal changes within the deep branches differ in each hemisphere, perhaps due to episodic SSW events and to wave forcings during ENSO.

In terms of multi-year changes for the BDC, it appears that during the period of 1992 to 1997 there was acceleration ~~in~~of the shallow branch and deceleration ~~in~~of the deep branch. However, those implied changes in the BDC may be anomalous because of the large perturbation to the $CH_4$ distribution in 1991 from the Pinatubo eruption. During 1996 to 2001 the changes in the shallow branch were nearer to zero, while decreasing trends persisted in the deep branch. Yet, it also appears that there was acceleration of the poleward transport and mixing at middle latitudes within the layer from ~30 hPa to ~7 hPa during that 5-yr period. Then, there was a deceleration ~~of the BDC~~ in the shallow branch and acceleration in the deep branch of the BDC during 2000 to 2005. The implied BDC also differed markedly in the two hemispheres over that final 5-yr span. It is concluded that time series of HALOE $CH_4$ provide effective tracer diagnostics for studies of the secular nature of the BDC from 1992 to 2005.

*Data availability*. The HALOE V19 profiles are at the NASA EARTHDATA site of EOSDIS, and its website is https://disc.gsfc.nasa.gov/datacollection/UARHA2FN_019.html (Russell et al., 1999).

*Competing interests*. The author has declared that there are no competing interests.

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## Figures

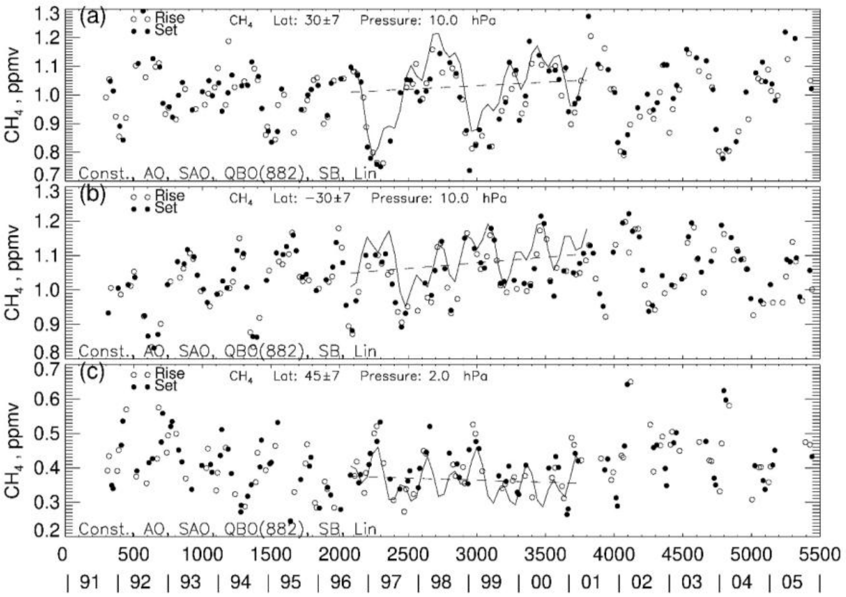


Figure 1—Time series of HALOE $CH_4$ (a) 30°N and 10 hPa, (b) 30°S and 10 hPa, and (c) 45°N and 2 hPa. MLR fit for July 1996 through June 2001 is the solid curve, and its linear trend is the dashed line. Day numbers on the abscissa are from 1 January 1991. Model terms are listed at bottom left.

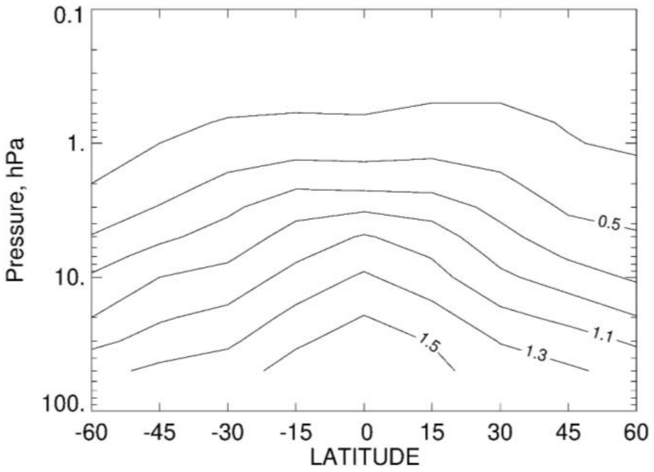
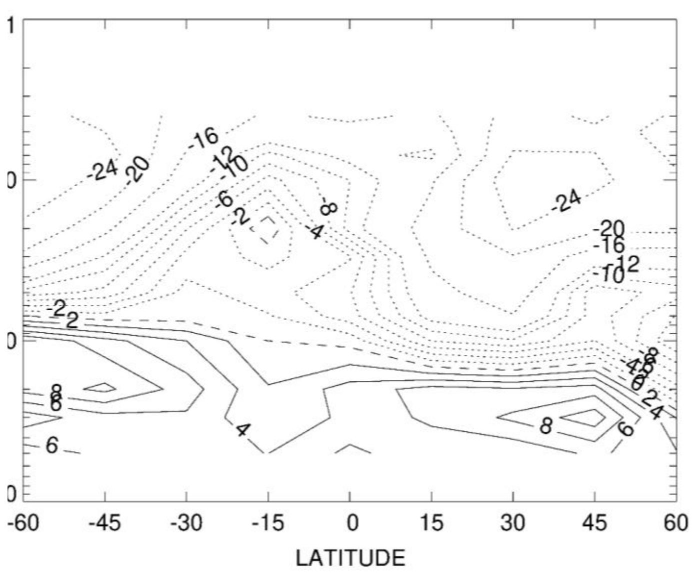


Figure 2—Average $CH_4$ for July 1996 through June 2001; contour interval is 0.2 ppmv.



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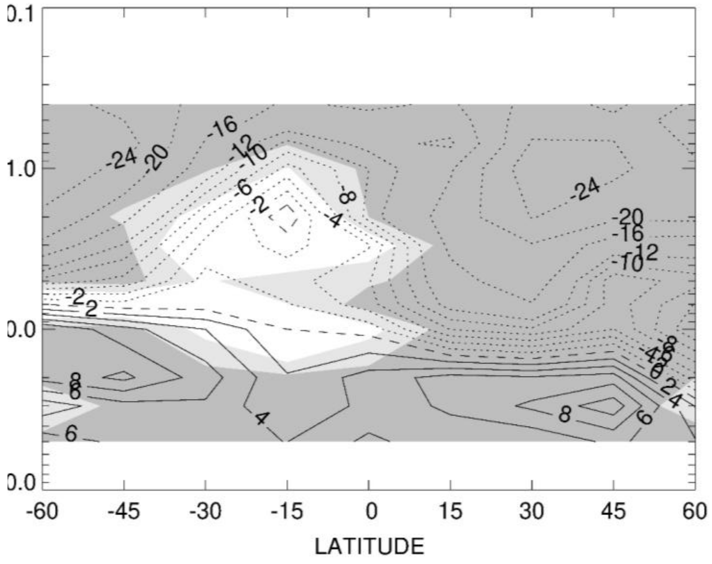

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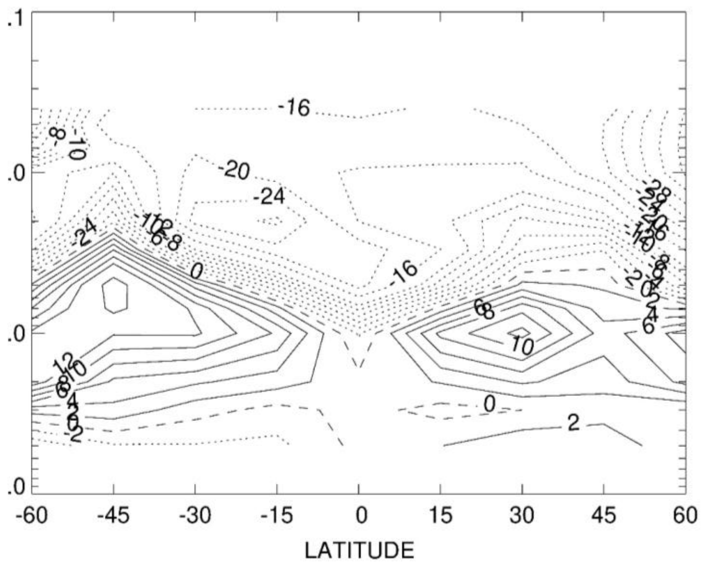
Figure 3—Changes in $CH_4$ for July 1992 through June 1997 (in % / 5-yr); positive changes are solid, negative changes are dotted, and zero is dashed. Contour interval is 2 % within ±12 % but

4 % outside that range. Dark shading shows where the confidence interval (CI) for the trends is greater than 90 %, and light shading shows where CI is between 70 and 90 %.



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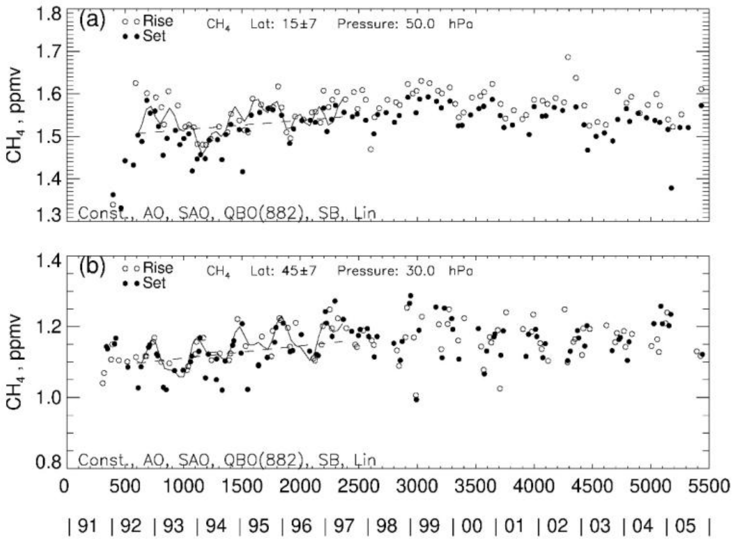

Figure 4—As in Fig. 1, but 4(a) is for 15°N and 50 hPa, and 4(b) is for 45°N and 30 hPa.

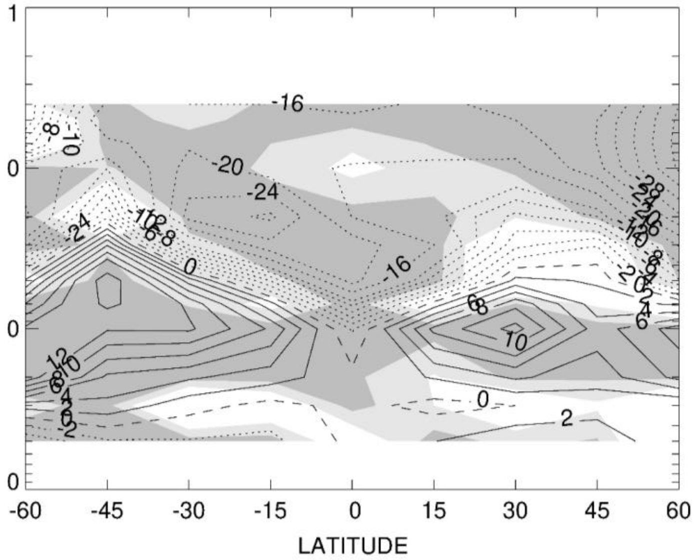

Figure 5—As in Fig. 3, but for July 1996 through June 2001.

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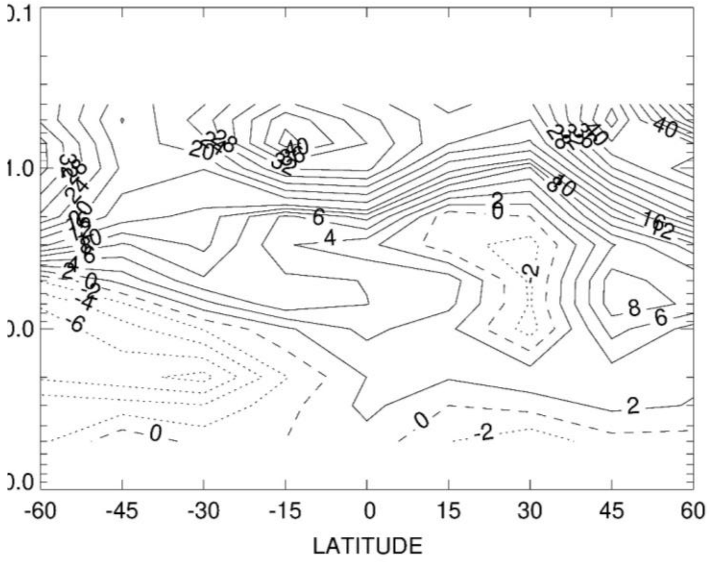

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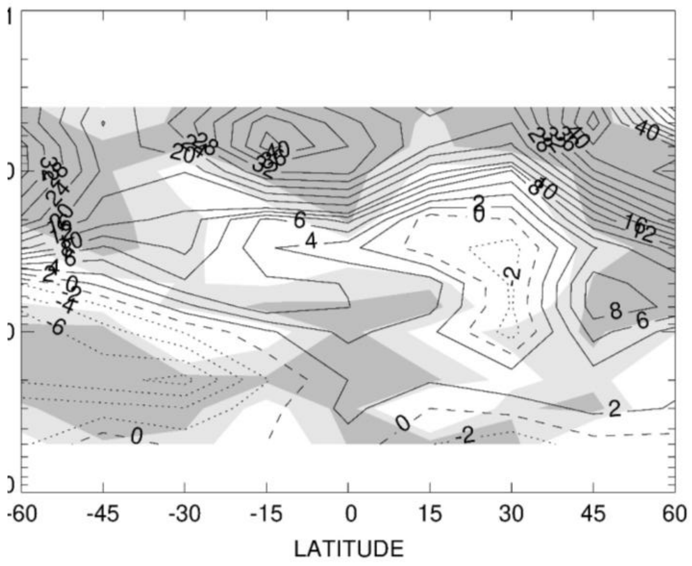

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Figure ~~5~~6—As in Fig. 3, but for July 2000 through June 2005.

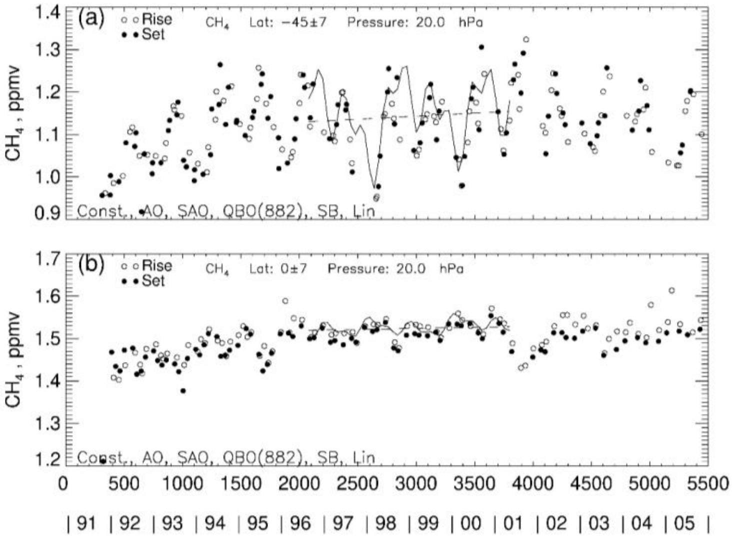

Figure ~~6~~7—As in Fig. 1, but ~~6~~7(a) is for 45°S and 20 hPa, and ~~6~~7(b) is for Eq and 20 hPa.