Technical Note:

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

Ellis Remsberg
Science Directorate, NASA Langley Research Center, 21 Langley Blvd.,
Mail Stop 401B, Hampton, Virginia, 23681, USA
Correspondence: Ellis Remsberg (ellis.e.remsberg@nasa.gov)

October, 2023

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 positive and large in the shallow branch following the eruption of Pinatubo, but they then decreased and agreed with tropospheric trends in the late 1990s and early 2000s. CH_4 decreased in the upper part of the deep branch from 1992 to 1997 or following the eruption of Pinatubo. CH_4 continued to decrease in the deep branch in the late 1990s but then increased in the early 2000s, although the changes were small compared with the seasonal and interannual variations of CH_4. Those multi-year changes were 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 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. 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°) than before to provide more representative sampling, especially at ±45° from 2000 to 2005 when the samples from HALOE were more 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 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 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 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

https://doi.org/10.5194/egusphere-2023-2211
Preprint. Discussion started: 9 October 2023

eruption of Pinatubo. The 5-yr changes from 1996 to 2001 are less negative and they become positive during 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 distinct differences in the 5-yr changes in CH_4 for the three successive time spans.

Figures 3-5 show the distributions of linear terms (% change / 5-yr) from the zonally averaged CH_4 data for 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 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 from July 1992 to June 1997 or following the Pinatubo eruption of June 1991. The changes were larger at middle latitudes in the northern than the southern hemisphere, indicating that ascent within the deep branch of the BDC occurred mainly in the northern subtropics immediately following the eruption. Separate, zonal mean cross sections of HALOE CH_4 also show 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 events accelerate the deep branch of the BDC and lead to a mixing of middle latitude and polar air. That mixing tends to flatten contours of zonal average CH_4 mixing ratio. However, there were no sudden stratospheric warming (SSW) events in the northern hemisphere during 1992 to 1997 (Choi et al., 2019).

Methane is not a perfect tracer, as it has a chemical lifetime as short as only a few months at 45 km (~1.5 hPa) but 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 near-zero, linear change for CH_4 near 15°S and 2 hPa in Fig. 3 indicates that there was a slow, steady transport of CH_4 to that region from the tropics after July 1992. There was also an accumulation of CH_4 at middle latitudes at ~20 to 30 hPa in 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 tropical trend of 4 % at 20 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 CH_4 at low and middle latitudes indicate an acceleration of the BDC, 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 and positive AOA implies a deceleration of the BDC. Diallo et al. (2017) reported that AOA decreased during the first six months due to tropical upwelling following the eruption of Pinatubo. But then they found that 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 meridional mixing tendency and a slowdown of the residual circulation. The 5-yr changes in Fig. 3 for the lower stratosphere also indicate a reduced tropical upwelling and an accumulation of CH_4 at middle latitudes, due to mixing and a slowdown of the BDC. The negative changes in CH_4 in upper regions of Fig. 3 imply 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 of SSW events during the mid-1990s.

(b) July 2996 to June 2001

Figure 4 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 in the upper stratosphere and a broadening of the region of decreasing trends. SSW events also led to greater ascent of CH_4 in the tropical upper stratosphere, where the chemical conversion of CH_4 was most effective and the negative changes in Fig. 4 were enhanced compared to Fig. 3. 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 trends occurred at a level of the stratosphere, where the conversion of CH_4 to H_2O and H_2 is not efficient.

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 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 northern hemisphere.

The 1997-1998 warm ENSO event occurred near solar minimum, for which Calvo and Marsh (2011) 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 support the present finding of increases in CH_4 in the extratropics near 10 hPa in Fig. 4. More focused analyses of the relative roles of SSWs and ENSO on the results of Fig. 4 and beyond the scope of the present exploratory study.

(c) 2000 to 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 includes the net effect of those episodic SSW events. 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 the stratopause region (~1 hPa) the changes are from negative to positive from Fig. 4 to Fig. 5 and are rather uniform across latitude. On the other hand, the changes near 10 hPa are weaker now than in Fig. 4 at middle latitudes of the northern hemisphere. Fig. 1(a) indicates that this change may be a consequence, in part, of large 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 to Fig. 5 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 is also no clear separation of the shallow and deep branches of the BDC from Fig. 5 for the southern hemisphere.

Figure 6 provides a clearer picture of what was occurring from 2000 to 2005. Fig. 6(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 in 2001, and they may influence the overall analyzed trend for that time span. On the other

https://doi.org/10.5194/egusphere-2023-2211
Preprint. Discussion started: 9 October 2023

hand, there is little indication of a change in CH_4 at the time of the anomalous SSW event of September 2002. Fig. 6(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, Fig. 6(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 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 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 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 the shallow branch and deceleration in 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 deceleration of the BDC in the shallow branch and acceleration in the deep branch during 2000 to 2005. The implied BDC also differed markedly in the two hemispheres over that 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.

Acknowledgements. The author carried out this work while serving as a Distinguished Research Associate of the Science Directorate at NASA Langley.

References

Barriopedro, D., and Calvo, N.: On the Relationship between ENSO, Stratospheric Sudden Warmings, and Blocking, J. Climate, 27, 4704-4720, https://doi.org/10.1175/JCLI-D-1300770.1, 2014.

Bönisch, H., Engel, A., Birner, T., Hoor, P., Tarasick, D. W., and Ray, E. A.: On the structural changes in the Brewer-Dobson circulation after 2000, Atmos. Chem. Phys., 11, 3937–3948, https://doi.org/10.5194/acp-11-3937-2011, 2011.

Brasseur, G. and Solomon, S.: *Aeronomy of the Middle Atmosphere: Chemistry and Physics of the Stratosphere and Mesosphere*, Dordrecht: Springer, 3rd Edition, 2005.

Butchart, N.: The Brewer-Dobson Circulation, Rev. Geophys., 52, 157-184, https://doi.org/10.1002/2013RG000448, 2014.

Calvo, N., and Marsh, D. R.: The combined effects of ENSO and the 11-year solar cycle on the Northern Hemisphere polar stratosphere, J. Geophys. Res., 116, D23112, https://doi.org/10.1029/2010JD015226 . 2011.

Calvo, N., Garcia, R. R., Randel, W. J., and Marsh, D. R.: Dynamical Mechanism for the Increase in Tropical Upwelling in the Lowermost Tropical Stratosphere during Warm ENSO Events, J. Atmos. Sci., 67, 2331-2340, https://doi.org/10.1175/2010JAS3433.1, 2010.

Choi, H., Kim, B-M., and Choi, W.: Type Classification of Sudden Stratospheric Warming Based on Pre- and Postwarming Periods, J. Climate, 32, 2349-2367, https://doi.org/10.1175/JCLI-D-18-0223.1, 2019.

Diallo, M., Konopka, P., Santee, M. L., Mu¨ller, R., Tao, M., Walker, K. A., Legras, B., Riese, M., Ern, M., and Ploeger, F.: Structural changes in the shallow and transition branch of the Brewer–Dobson circulation induced by El Niño, Atmos. Chem. Phys., 19, 425–446, https://doi.org/10.5194/acp-19-425-2019, 2019.

Diallo, M., Ploeger, F., Konopka, P., Birner, T., Mu¨ller, R., Riese, M., Garny, H., Legras, B., Ray, E., Berthet, G., and Jegou, F.: Significant contributions of volcanic aerosols to decadal changes in the stratospheric circulation, Geophys. Res. Lett., 12, 10780–10791, https://doi.org/10.1002/2017GL074662, 2017.

Dlugokencky, E. J., Bruhwiler, L., White, J. W. C., Emmons, L. K., Novelli, P. C., Montzka, S. A., Masarie, K. A., Lang, P. M., Crotwell, A. M., Miller, J. B., and Gatti, L. V.: Observational constraints on recent increases in the atmospheric CH_4 burden, Geophys. Res. Lett., 36, L18803, https://doi.org/10.1029/2009GL039780, 2009.

Newman, P. A., and Nash, E. R.: The Unusual Southern Hemisphere Stratosphere Winter of 2002, J. Atmos. Sci., 62, 614-628, https://doi.org/10.1175/JAS-3323.1, 2005.

Randel, W. J., Garcia, R. R., Calvo, N., and Marsh, D. R.: ENSO influence on zonal mean temperature and ozone in the tropical lower stratosphere, Geophys. Res. Lett., 36, L15822, https://doi.org/10.1029/2009GL039343, 2009.

Remsberg, E.: Methane as a diagnostic tracer of changes in the Brewer-Dobson circulation of the stratosphere, Atmos. Chem. Phys., 15, 3739–3754, https://doi.org/10.5194/acp-15-3739-2015, 2015.

Russell III, J. M., et al.: UARS Halogen Occultation Experiment (HALOE) Level 2 V019, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC) [data set], https://disc.gsfc.nasa.gov/datacollection/UARHA2FN_019.html (last access: 23 August 2023), 1999.

Tao, M., Konopka, P., Ploeger, F., Grooß, J.-U., Mu¨ller, R., Volk, C., Walker, K., and Riese, M.: Impact of the 2009 major stratospheric sudden warming on the composition of the stratosphere, Atmos. Chem. Phys., pp. 8695–8715, https://doi.org/10.5194/acp-15-8695-2015 , 2015.

https://doi.org/10.5194/egusphere-2023-2211
Preprint. Discussion started: 9 October 2023

Figures

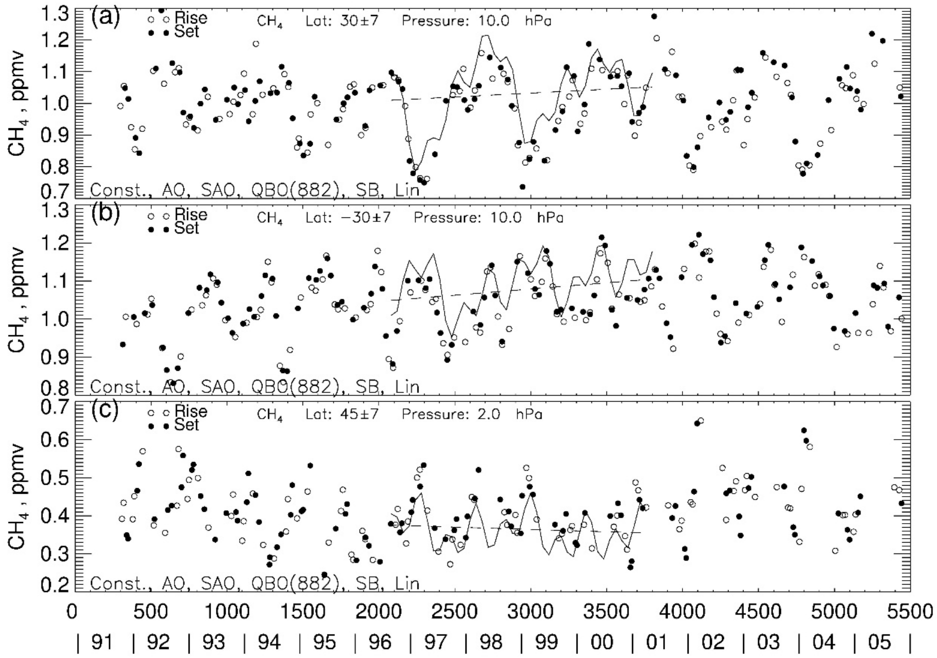

Figure 1—Time series of HALOE CH$_4$ (a) 30°N and 10 hPa, (b) 30°S and 10 hPa, and (c) 45°N and 2 hPa. MLR fit for July 1996 through June 2001 is the solid curve, and its linear trend is the dashed line. Day numbers on the abscissa are from 1 January 1991. Model terms are listed at bottom left.

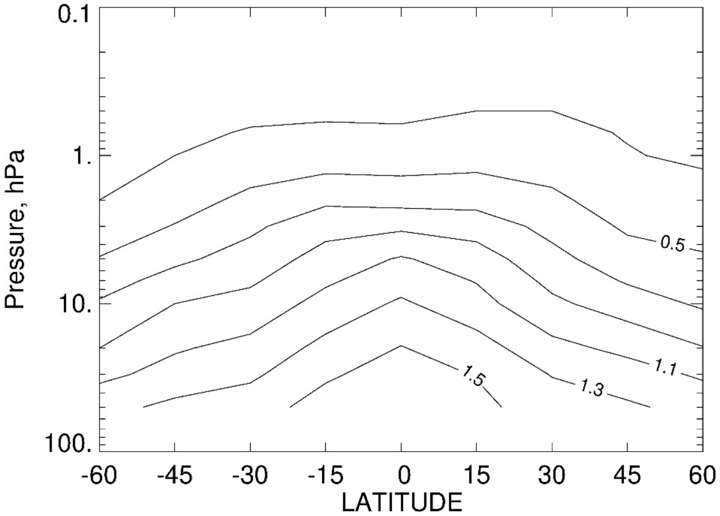

Figure 2—Average CH_4 for July 1996 through June 2001; contour interval is 0.2 ppmv.

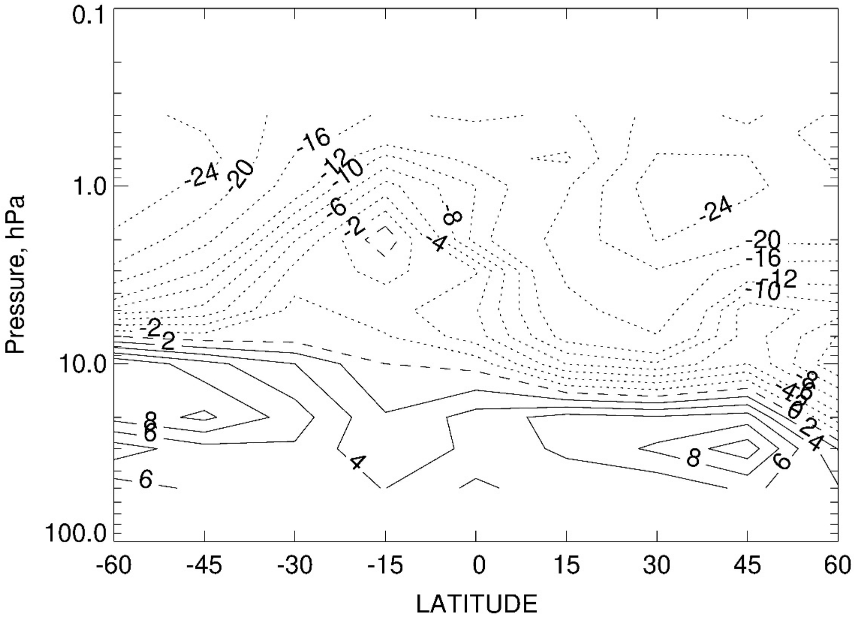

Figure 3—Changes in CH_4 for July 1992 through June 1997 (in % / 5-yr); positive changes are solid, negative changes are dotted, and zero is dashed. Contour interval is 2 % within ±12 % but 4 % outside that range.

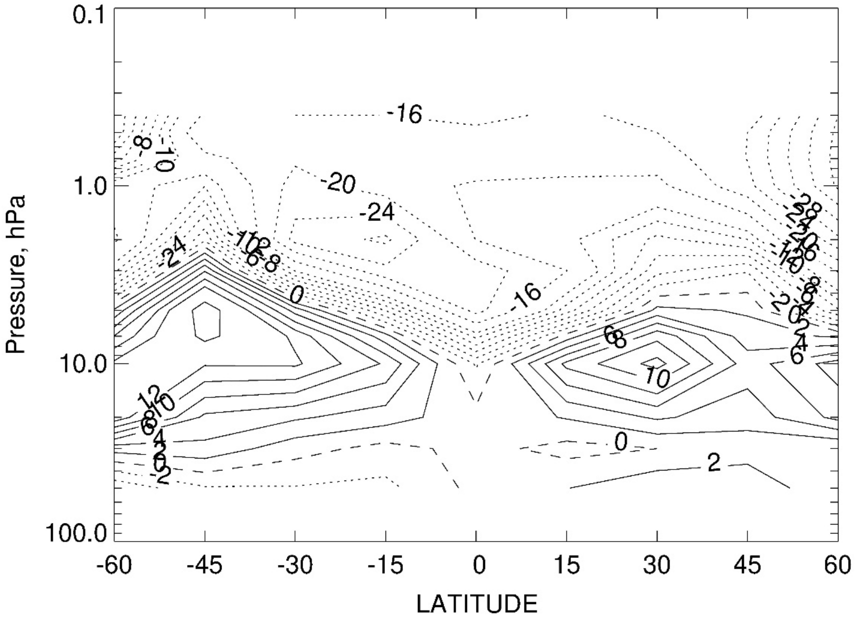

Figure 4—As in Fig. 3, but for July 1996 through June 2001.

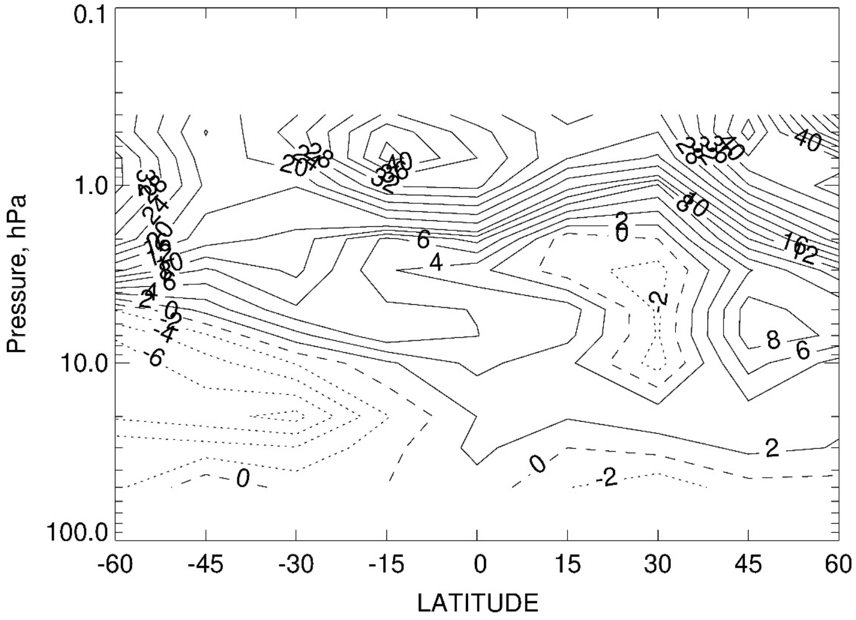

Figure 5—As in Fig. 3, but for July 2000 through June 2005.

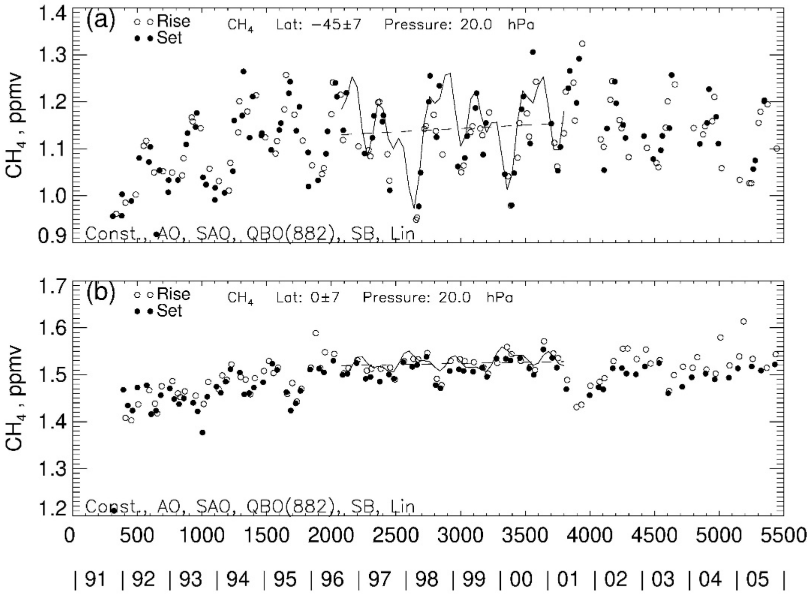

Figure 6—As in Fig. 1, but 6(a) is for 45°S and 20 hPa, and 6(b) is for Eq and 20 hPa.