The Impact of Meteorology on the Interannual Growth Rate of Atmospheric Methane

N. J. Warwick,[1] S. Bekki,[2] K. S. Law,[1] E. G. Nisbet[3] and J. A. Pyle,[1]

Abstract.

The impact of interannual changes in meteorology on the local and global growth rates of atmospheric methane is assessed in a nineteen year simulation using a tropospheric chemical transport model forced by ECMWF meteorological analyses from 1980 to 1998. A very simple CH_4 chemistry scheme has been implemented, using prescribed OH fields. There are no interannual variations in modeled methane emissions or in the OH fields, so any changes in the modeled growth rate arise from changes in meteorology. The methane simulation shows significant interannual variability at both local and global scales. The local scale variability is comparable in magnitude to the interannual variability found in surface observations and shows some clear correlation with observed changes in growth rates. This suggests that, over relatively short timescales, meteorology could be as important as changes in emissions and sinks in driving the interannual fluctuations of atmospheric methane at the surface.

1. Introduction

Atmospheric methane is of considerable interest due to its role in tropospheric chemistry and its contribution to climate forcing, the object of the Kyoto process. Between 1850 and 2000 the climate forcing due to CH_4, including its indirect effects on stratospheric water vapor and tropospheric ozone, was half as large as that caused by CO_2 or about 40% of the net value for all known forcings [*Hansen et al.*, 2000]. More than half of methane emissions are anthropogenic and its atmospheric lifetime is much shorter than that of CO_2. Therefore emission reductions are possible and would produce observable decreases in CH_4 within a few years.

Although the global CH_4 burden is well constrained by measurements, there are currently large uncertainties in the strengths of many methane sources and how they have varied over the past couple of decades. An improved understanding of the emissions, distribution and trends of atmospheric methane is essential for the successful verification and regulation of emissions.

Over the past couple of decades, relatively large interannual variations in the CH_4 growth rate at the surface have been observed [*Dlugokencky et al.*, 2001]. Possible causes of the observed variability include changes in methane emissions, and changes in methane sinks (e.g. *Reshetnikov et al.* [2000]; *Bekki et al.* [1994]). A third possibility, and the subject of this work, is that changes in meteorology are able to cause interannual variations in the local and global growth rates of methane. Although it is unlikely that meteorology is contributing to long term trends in the growth rate, it could alter growth rates over annual timescales by adjusting convective activity, prevailing winds and transport times from source regions to sink regions.

If meteorological changes are responsible for a significant proportion of the interannual variability in gases such as methane and methyl chloroform, this could have important implications for our understanding of global and hemispheric trends in OH and the oxidizing power of the Earth's atmosphere.

2. Model Description

Model integrations in this study have been carried out using the global three-dimensional chemical transport model, TOMCAT. The model has been used extensively for tropospheric studies. Details about the model and its validation against data can be found in *Law et al.* [1998]; *Stockwell et al.* [1998]; *Wang et al.* [1999].

The horizontal and vertical transport of tracers is based on six-hourly mean meteorological fields, including winds and temperature, derived from European Centre for Medium-Range Weather Forecasts (ECMWF) operational and re-analyses. The spatial resolution applied is 5.5° in the latitudinal and longitudinal directions with 31 vertical levels (from surface to ~30km). The ECMWF analyses used consist of the Reanalysis project (ERA-15) data from 1980 to February 1994 and the Operational Analysis data from March 1994 onwards. It should be noted that the meteorological analyses from 1980-94 were constructed using a single version of the ECMWF model, while the 1994-98 operational analyses were subject to regular improvements and are therefore not necessarily completely consistent. The corresponding meteorological input fields have been used for each year of the model integration. To confirm that the modeled interannual variability was due to changes in transport and not an artifact of model drift, we completed an additional model integration using the meteorological conditions of 1980 for every model year.

The version of TOMCAT used in this work has been modified to include a simple chemistry scheme, which assumes that methane is only removed by the hydroxyl radical, OH. The OH fields are prescribed ten-day means taken from an integration for 1994 of a full chemistry version of TOMCAT [*Law et al.*, 1998]. The lifetimes of methane and methyl chloroform against reaction with OH determined using the model are 9.7 years and 5.6 years respectively, which is in

[1]Centre for Atmospheric Science, Cambridge University, Cambridge, UK.
[2]Service d'Aeronomie du CNRS, Institut Pierre-Simon Laplace, Universite Paris VI, France
[3]Royal Holloway College, University of London, Egham, UK

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good agreement with other estimates [*IPCC*, 2001; *Wuebbles et al.*, 1999]. Table 1 shows the seasonally varying methane emissions (roughly representative of 1990) used in the 1980 to 1998 model simulation. Both the methane emissions and the OH fields are repeated each year, leaving meteorology (winds, temperature) as the only interannual variable in the model integrations. The methane distribution was initialized in TOMCAT using values from the Cambridge 2D model, which were then scaled to match observations on a global network [*Dlugokencky et al*, 1994b]. The influence of the initialization of methane concentrations on the model output was significantly reduced by a 10 year model spin-up using meteorology from the 1990s.

3. Results and Discussion

Figure 1 shows modeled methane concentrations compared with surface observations at Key Biscayne in Florida and Ascension Island for the last 8 years of the integration. Results from these two stations are shown as they are typical of the model's ability to reproduce measurements in the Northern and Southern Hemispheres. The model cannot be expected to faithfully reproduce the trend seen in the observations since the same emissions and OH fields have been used for each model year. Our aim was to reproduce the seasonal cycles in methane concentrations, which has been achieved to a satisfactory level. The seasonal cycle at Key Biscayne is dominated by a sharp summer minimum and a broader winter maximum that the model has reproduced well, although the amplitude of the cycle has been overestimated. In the Southern Hemisphere at Ascension Island, the seasonal cycle is considerably smoother and more regular; this pattern has also been captured by the model.

Figure 2 shows the modeled and observed variations in the atmospheric growth rate for Key Biscayne and Ascension Island from 1983 to 1998. Growth rates are derived from fits to the modeled and observed data, obtained by smoothing short term variations following the method described in *Dlugokencky et al* [1994b]. Monthly mean data are first fitted with a quadratic (representing the long term trend) and a series of four harmonics (representing the average seasonal cycle) using a least square method. Then the residuals [=original data - fit(quadratic + harmonics)] are filtered by conversion into the frequency domain with a fast Fourier transform, smoothing with a low-pass filter and conversion back into the time domain. The cutoff frequency is 0.86 yr^{-1}. This filtering method allows variations occurring on timescales less than 1 year to be removed from the data. CH_4 growth rates are derived directly from the resulting smoothed deseasonalized and detrended time series. The first three model data years are ignored due to larger growth rates resulting from the model still adapting to its initial conditions.

At Key Biscayne, the model is able to reproduce the timing and often the amplitude of most fluctuations monitored (r=0.59). Even during the atmospheric conditions following the eruption of Mt Pinatubo in 1991, there is still a good correlation between the modeled and observed growth rates. At Ascension Island, much of the observed variability is also particularly well captured in the model, again with a very good correlation between the minima/maxima of the modeled and observed growth rates (r=0.68). Methane concentrations at Ascension are influenced by African biomass burning emissions, carried to Ascension by south-easterly trade winds. We would therefore expect observed changes in growth rate to be particularly influenced by changes in transport from biomass burning regions, which are included in the model simulation, as well as interannual changes in biomass burning emissions, which are not included. Table 2 shows the correlation coefficients and regression line gradients for local growth rates at other NOAA measuring stations that have a full CH_4 record between 1984 and 1998. The correlation is generally highest for sites in the tropics, where it ranges from r=0.52 to r=0.68. At these locations the model is reproducing 50% to 99% of the magnitude of the variability. Measuring stations in mid to high northern latitudes show lowest correlation (r¡0.2). In a global mean calculation, local meteorological contributions to methane variability will partly cancel out. Therefore observed global CH_4 trends which are based on a set of surface measurements at a limited number of locations, and not a true global mean, may overestimate interannual variability.

Interannual variations in zonal mean surface CH_4 growth rates have been calculated from deseasonalized and detrended model monthly means for the period 1984 to 1998 and are shown in Figure 3. The modeled zonal average growth rate varies between -13.4 ppbv/yr in 1988 and +7.2 ppbv/yr in 1984, both extremes occurring in the Northern Hemisphere. In both 1988 and 1994, strong minima in modeled growth rates in the Northern Hemisphere coincide with strong maxima in the Southern Hemisphere, which may indicate increased interhemispheric transport of methane. As most of the atmospheric methane burden is in the Northern Hemisphere, enhanced mixing between the two hemispheres would produce a decrease in growth rate in the Northern Hemisphere and an increase in the Southern Hemisphere. However, it should be noted that the model overestimates the interhemispheric gradient of methane by approximately 40% (see Figure 1) and therefore may also overestimate interannual CH_4 variations due to interhemispheric mixing. It is interesting to notice that a certain amount of periodicity is found in both the Northern Hemisphere and tropics. Strong minima in the northern hemispheric growth rate occur about once every three years. Growth rate fluctuations have approximately the same periodicity in the tropics, but are out of phase with those in the Northern Hemisphere, with tropical minima corresponding to northern hemispheric maxima. This indicates that interannual fluctuations in transport between the tropics and extra-tropics could be responsible for much of the variation observed in the modeled local growth rates (see Figure 2, Table 2).

The zonal mean growth rates shown in Figure 3 are deseasonalized and detrended, and as such emphasize interannual variability. The results are therefore not directly comparable with some published growth rates based on observations (see ftp://ftp.cmdl.noaa.gov/ccg/figures/co2_ch4_gr.ps), which include long and short-term trends from changes in emissions and sinks. The observed zonal mean and global growth rates are also based on CH_4 measurements from a selection of stations which are biased to measuring only clean sector air, rather than representing the true zonal means as shown in Figure 3. Nonetheless, the two plots do show some similarities and, more importantly, the zonal mean growth rates shown in Figure 3 are not negligible when compared with the published observed growth rates.

As the majority of methane destruction takes place in tropical regions, where OH radical concentrations are greatest, changes in exchange rates between tropical and extra-tropical regions also have the potential to affect global

growth rates by altering the residence time of methane in regions with different OH levels and consequently the overall removal rate of methane. The average tropospheric detrended modeled growth rate fluctuates between -1.5 and +1 ppbv. The surface average growth rate is somewhat larger (-3 to +2 ppbv/yr), suggesting that surface growth rates are also strongly influenced by vertical re-distribution within the troposphere. These values represent a significant fraction of the surface fluctuations (between zero and +15 ppbv/yr) derived from observations on a global network [*Dlugokencky et al.*, 2001], which also include a long-term trend. The model calculated growth does not account for interannual variations in emissions and therefore will not be able to capture the full extent of the year-to-year variability in the observed growth rates. Nonetheless the results indicate that meteorology may still play a significant role in the CH_4 variations, even on a global scale.

To confirm that the modeled interannual variability was due to changes in transport and not an artifact of model integrations or data processing, we completed an additional integration forcing the model with the 1980 meteorological analyses repeated every year. This perpetual integration was initialized the same way as the varying-meteorology integration described above. The methane growth rates for this perpetual 1980 model integration were found to be very much less than for the variable meteorology integration. There is some variability that is possibly caused by incomplete low-pass filtering, model settling from its initial conditions and, more importantly, the abrupt transition from the meteorology of December 1980 back to that of January 1980 every year. However, in the last half of the experiment, as the model reaches steady state, growth rates at both Key Biscayne and Ascension Island were typically less than ± 0.3 ppbv/yr and show very little variation. In addition, as expected, the small fluctuations in the perpetual integration are not at all correlated with fluctuations in the observed growth rates. We therefore conclude that changes in growth rate simulated in the 1980-98 integration are overwhelmingly driven by changes in transport rather than model drift or the way data are processed. Some components of our modeled trend could possibly arise from discontinuities in the analyses during the late 1990s. Recall, however, that the first 15 years of the analyses are consistent. In both the local and global results there is no significant difference in model performance or the magnitude of methane variability between the two periods.

4. Conclusions

A global 3D model has been used to explore the response of local and global atmospheric surface CH_4 growth rates to varying meteorology. The results suggest that interannual changes in meteorology play a significant role in the interannual fluctuations seen in local surface CH_4 growth rates derived from observations, particularly at locations in the tropics. These fluctuations will be superimposed on the long-term trend, which is likely to be largely driven by changes in emissions and the strength of the OH sink. For example, emissions from the fossil fuel industry are likely to have varied considerably over the last couple of decades [*Reshetnikov et al.*, 2000].

The surface modeled global growth rate varies from -3 to +2 ppbv/yr and is largely influenced by vertical redistribution within the troposphere and the rate at which CH_4 is transported from the middle and high latitudes of the Northern Hemisphere into the tropics, the most effective sink region. It is also likely that changes in transport influence the spatial distribution of OH through changes in the longer lived controlling species, such as O_3 or CO. However, as our OH fields are prescribed this effect is not accounted for in the model.

The results from this work have implications for quantifying the causes of interannual variability in other atmospheric trace gases, for example carbon dioxide and methyl chloroform. Recently, large fluctuations in the hemispheric and global growth rates of methane and methyl chloroform calculated from network surface observations have been used to infer changes in year-to-year emissions or the OH sink [*Krol et al.*, 1998; *Prinn et al.*, 2001]. This work shows that when carrying out these calculations, meteorological variability on both interannual and decadal timescales should be taken into account as it can influence variations in growth rates at the surface from local to global scales.

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N. J. Warwick, K. S. Law, and J. A. Pyle, Centre for Atmospheric Science, Chemistry Department, Cambridge University, Lensfield Road, Cambridge CB2 1EW, UK. (e-mail: nicola.warwick@atm.ch.cam.ac.uk, kathy.law@atm.ch.cam.ac.uk, john.pyle@atm.ch.cam.ac.uk)

S. Bekki, Service d'Aeronomie du CNRS, Institut Pierre-Simon Laplace, Universite Paris VI, Tour 15 Couloir 15-14, 4 Place Jussieu, 75252 Paris Cedex 05, France (e-mail: slimane@aero.jussieu.fr)

E. G. Nisbet, Geology Department, Royal Holloway College, University of London, Egham, Surrey TW20 0EX, UK. (e-mail: nisbet@gl.rhul.ac.uk)

(Received _____.)

Figure 1. Modeled monthly mean CH_4 concentrations (dashed line) and monthly mean measurements (solid line) at (a) Key Biscayne and (b) Ascension Island. Measurements are courtesy of the NOAA Climate Monitoring and Diagnostics Laboratory, Carbon Cycle Greenhouse Gases group.

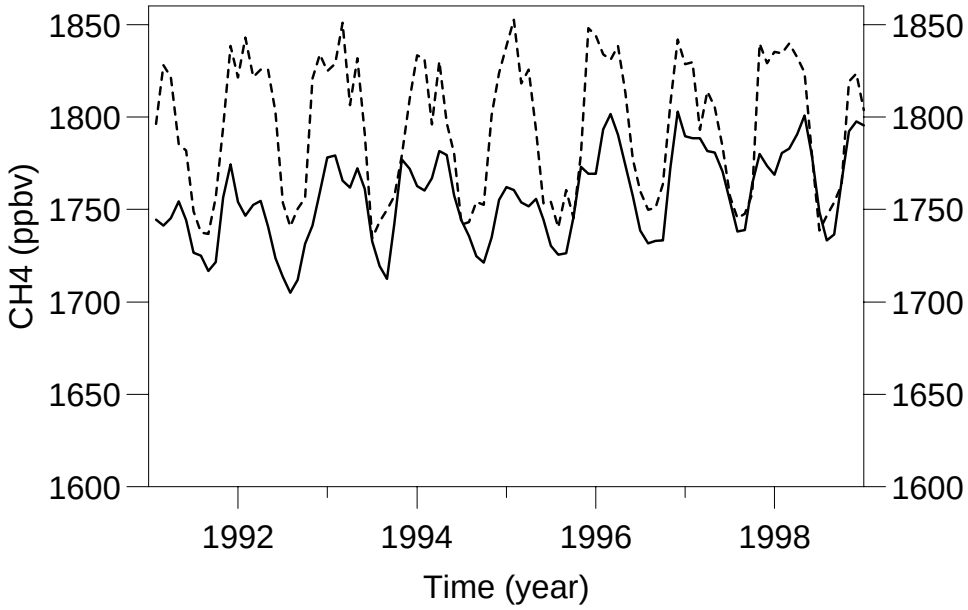
Figure 2. Time series showing the CH_4 growth rate calculated from modeled monthly means in the 1980 to 1998 integration (dashed line) and from monthly mean measurements (solid line) for (a) Key Biscayne and (b) Ascension Island.

Figure 3. Contour plot showing the temporal and spatial variations in the zonal mean growth rate of methane at the surface. The growth rate is calculated from deseasonalized and detrended monthly means.

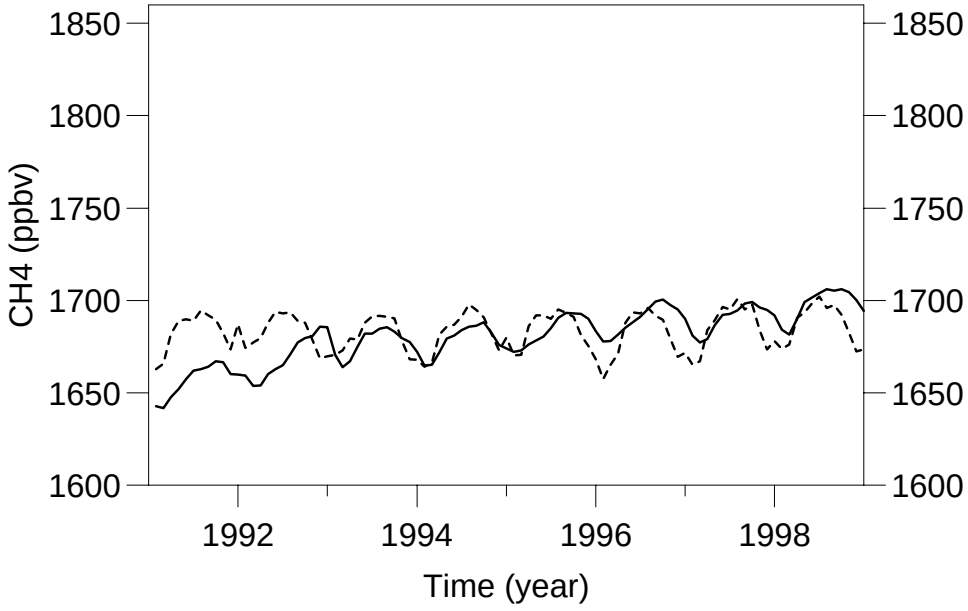
Table 1. Prescribed CH_4 Surface Fluxes.

Table 2. Correlation coefficients (r) and regression line gradients of observed and modeled CH_4 local growth rates for the period 1984 to 1998.

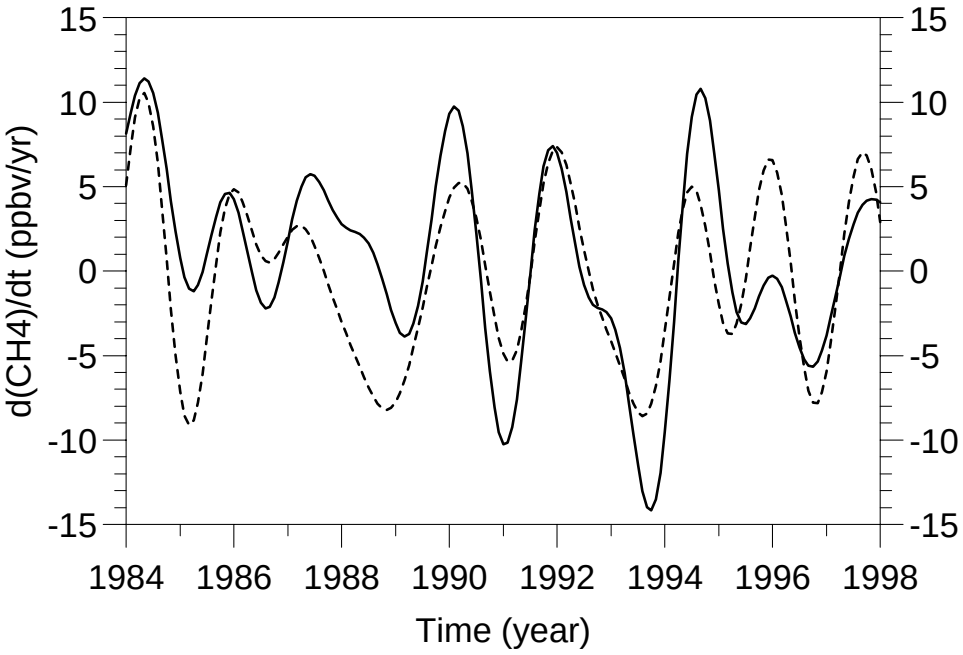
(a) Key Biscayne, Florida (80W, 26N)



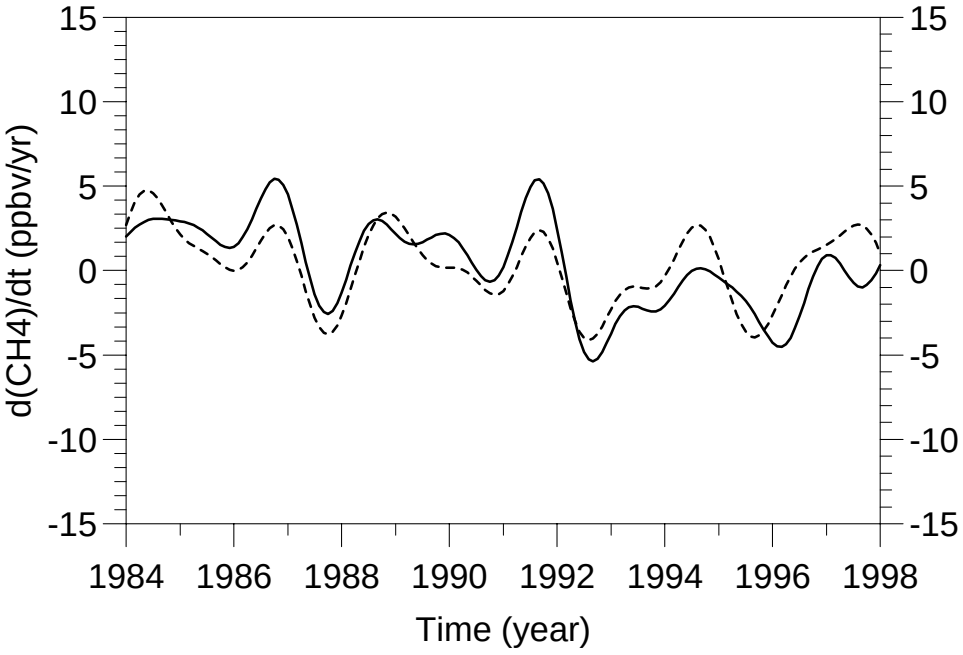
(b) Ascension Island (14W, 8S)

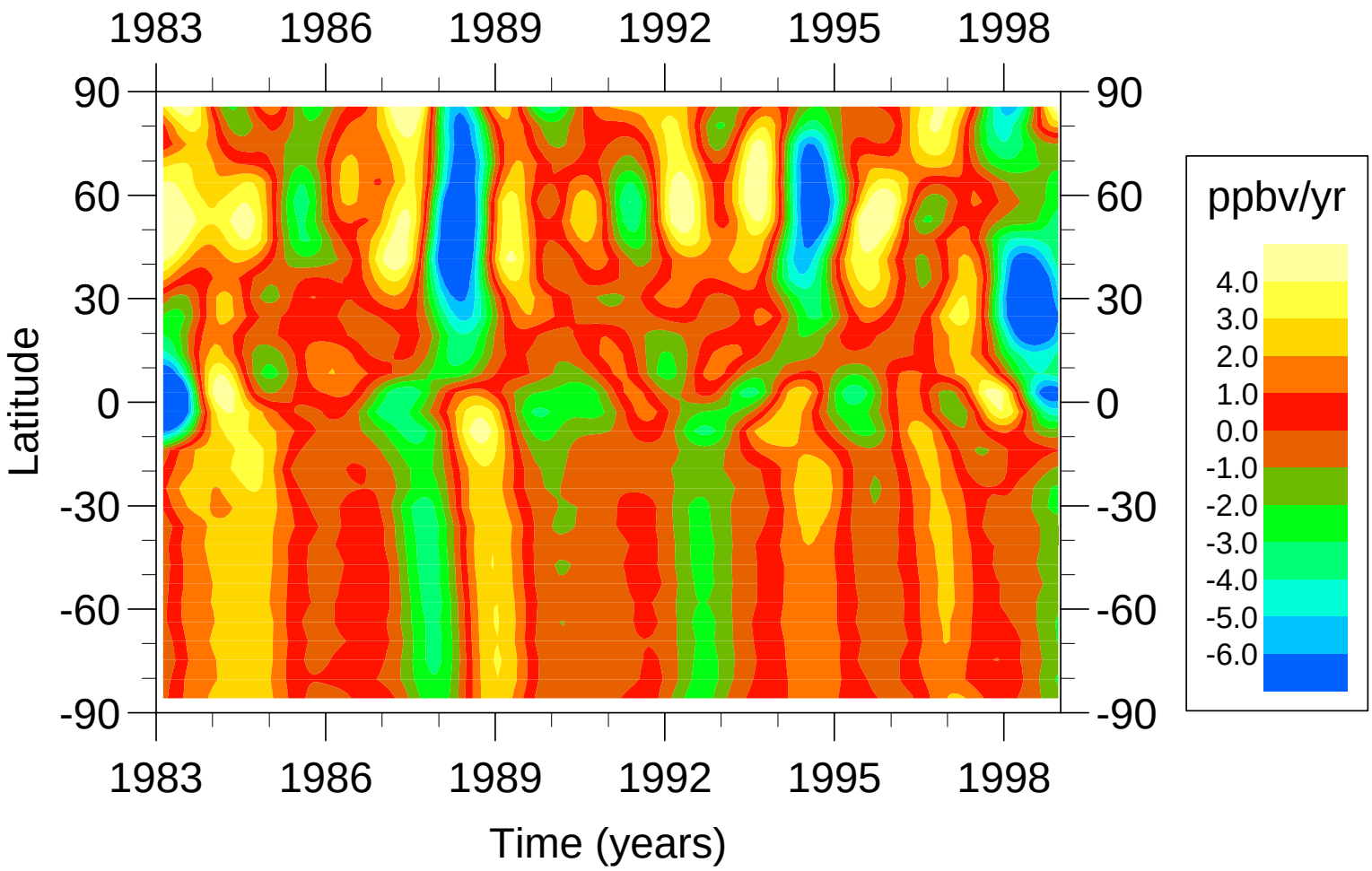


(a) Key Biscayne, Florida (80W, 26N)



(b) Ascension Island (14W, 8S)




1983
1986
1989
1992
1995
1998
90
60
30
0
-30
-60
-90
Latitude
Time (years)
ppbv/yr
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0

Methane Source / Sink	Annual CH_4 Emission ($Tg(CH_4)/yr$)
Animals	105[a]
Termites	20[b]
Gas Hydrates	5[c]
Sewage	35[d]
Landfills	40[d]
Wetlands	115[e]
Rice	80[e]
Natural Gas and Petrol	65[d]
Coal	24[f]
Biomass Burning	54[d]
Ocean	–
Soil Oxidation	−30[g]
TOTAL	512

(e) Aselmann and Crutzen (1989), (a) Lerner et al. (1988), (d) Muller and Brasseur (1995), (f) Muller (1992), (b) Sanderson (1996), (c) Gornitz and Fung (1994), (g) Dörr et al. (1993)

Station	*r*	Gradient
Point Barrow (156 °W, 71 °N)	0.10	0.08
Polar Front (2 °E, 66 °N)	0.18	0.27
Cold Bay (162 °W, 55 °N)	0.09	0.10
Key Biscayne (80 °W, 25 °N)	0.59	0.61
Cape Kumukahi (155 °W, 20 °N)	0.52	0.99
Guam (144 °E, 13 °N)	0.68	0.55
Ascension Island (14 °W, 8 °S)	0.68	0.59
Samoa (170 °W, 14 °S)	0.68	0.73
South Pole (24 °W, 90 °S)	0.45	0.30