Time Series Analysis for the ACE-FTS and MIPAS CFC-11 and CFC-12 Data Products

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1. Motivation

To progress from monitoring atmospheric composition to investigating and quantifying atmospheric changes, well-characterized measurements over many years are required. The long lifetime of the Atmospheric Chemistry Experiment (ACE) has provided more than a decade of composition measurements that contribute to our understanding of ozone recovery, climate change and pollutant emissions. To enable the generation of climate data records using multiple data sets, characterization of the differences between data sets is required. This study analyzes and compares the time series of chlorofluorocarbon (CFC) measurements from two infrared satellite sensors, the ACE-Fourier Transform Spectrometer (ACE-FTS) (Bernath et al., 2005) and the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) (Fischer et al., 2008). The long-term trend as well as annual, semi-annual and quasi-biennial oscillation (QBO) terms derived from each data set are compared for different altitude and latitude regions.

2. ACE-FTS and MIPAS CFCs data sets

The ACE-FTS v3.5/v3.6 and MIPAS IMK-IAA (Institut für Meteorologie und Klimaforschung at the Karlsruhe Institute of Technology and Instituto de Astrofisica de Andalucía) version 5 CCl_3F (CFC-11) and CCl_2F_2 (CFC-12) coincident data from 2005 to 2012 are used in this study. For examining the sampling effect, the entire ACE-FTS data set is also used. The coincidence criteria used are ±5° in latitude, ±10° in longitude, and ±12 hours in time. The data quality control of ACE-FTS data follows the criteria given by Sheese et al. (2015). Time series are built by collecting data points within latitude bands at regular altitude grid points. From these, monthly mean values are calculated and used for the regression analysis. Five latitude bands are defined as 90°S – 60°S, 60°S – 30°S, 30°S – 30°N, 30°N - 60°N, and 60°N - 90°N and the altitude grid is at regular 1 km interval.

3. Regression Analysis

The ACE-FTS and MIPAS CFCs monthly mean time series, obtained from the coincident data set from 2005 to 2012 at five latitude bands and at each altitude grid point, are decomposed into several composites containing linear, QBO, annual cycle, semi-annual cycle components and other overtones of 3, 4, 8, 9, and 18 months using a method similar to Stiller et al. (2012), Kellmann et al. (2012), and Eckert et al. (2016). The theoretical background can be found in von Clarmann et al. (2010). Similar regression analysis is also applied to the entire ACE-FTS data set for the same period. The example plot displayed in Fig. 1 illustrates some details.

The coefficients derived from these regression analyses are compared. Error estimates for the regression coefficients are also calculated based on the residual errors between the measurement and the model and are represented in terms of 95% confidence level. The standard errors for amplitude and phase are calculated following the law of propagation of uncertainties.

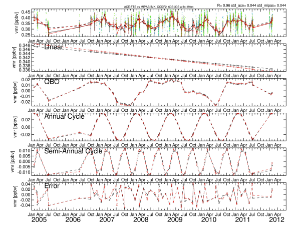

Fig. 1 An example of decomposing the ACE-FTS and MIPAS coincident data time series. Top panel shows the original data points (blue for ACE-FTS, yellow for MIPAS) with solid black line for ACE-FTS monthly mean time series, solid red line for MIPAS monthly mean time series, and dashed black line for modelled ACE-FTS time series, dashed red lines for modelled MIPAS time series. The 2nd, 3rd, 4th, and 5th panels are the composites for linear, QBO, annual cycle, and semi-annual cycle components, the bottom panel the errors between the measurement and modelled values, black for ACE-FTS and red for MIPAS.

4. Results

4.1 Initial offset and linear trend components

Fig. 2 (a) and (b) show the vertical profiles of the initial offsets for CFC-11 and CFC-12 for the five latitude bands. The initial offset represents the state at the beginning of the time series, i.e., Jan. 1, 2005 which is largely dominated by the mean state. The offset profiles all have very narrow error bars, demonstrating the results are very reliable. Both ACE-FTS and MIPAS agree very well, with a slight low bias for ACE-FTS across the latitudes. This instrument difference was also pointed out by Eckert et al. (2016). The offsets show a well mixed state below the tropopause. Variations of CFCs distribution with respect to the altitude and latitude are largely attributed to the Brewer-Dobson Circulation.

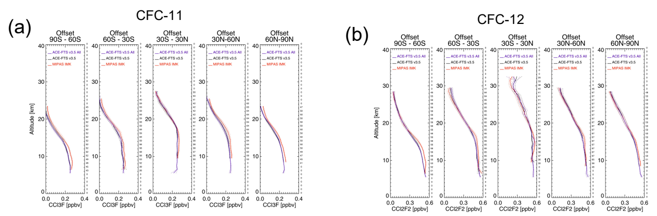

Fig. 2 Vertical profiles of initial offsets for CFC-11 (a) and CFC-12 (b) for five latitude bands derived from the regression analyses. The black and red solid lines represent the offsets obtained from the ACE-FTS and MIPAS coincident time series, respectively, and blues lines from the entire ACE-FTS data. Their respective errors are represented in terms of 95% confidence level by dotted lines with respective colors. Numbers besides the right vertical axes are the numbers of the monthly mean time series at the altitudes.

The derived linear trend profiles for CFC-11 and CFC-12 are shown in Fig. 3a and Fig. 3b, respectively. The linear trends and their 95% confidence levels show variations with altitude and latitude. To further determine whether a linear trend is significant or not, it is necessary to see whether the high and low 95% confidence levels have the same sign. In general, at lower altitudes where CFCs have the largest concentration, the 95% confidence levels have narrower widths, and the estimated linear trends appear to be significant. The overall linear trends for both CFC-11 and CFC-12, except in some regions, are negative. This is a manifestation of the success of the Montreal Protocol 1987 and subsequent amendments, which prohibit the anthropogenic emission of those ODS (Ozone Depletion Substances) such as CFCs.

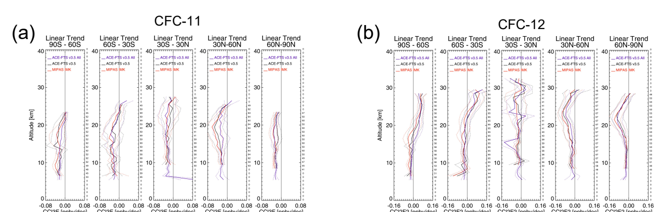

Fig. 3 Similar to Fig. 2 but for the linear trends and their 95% confidence levels for CFC-11 (a) and CFC-12 (b).

4.2 Annual cycle components

Annual cycle is one major atmospheric variation mode in the stratosphere and is strongly associated with the Brewer-Dobson Circulation. The derived annual cycle components for CFC-11 (Fig. 4a for amplitude and Fig. 4c for phase) and CFC-12 (Fig. 4b for amplitude and Fig. 4d for phase) show clearly that annual cycle is a significant component with large amplitudes at high latitudes. The phase of an annual cycle is defined as the month of the minimum value within a period. A phase shift of six months is seen between the northern and southern hemisphere. The slant slopes of the phase profiles at high latitudes are the result from descending air masses associated with the descending branch of the Brewer-Dobson Circulation.

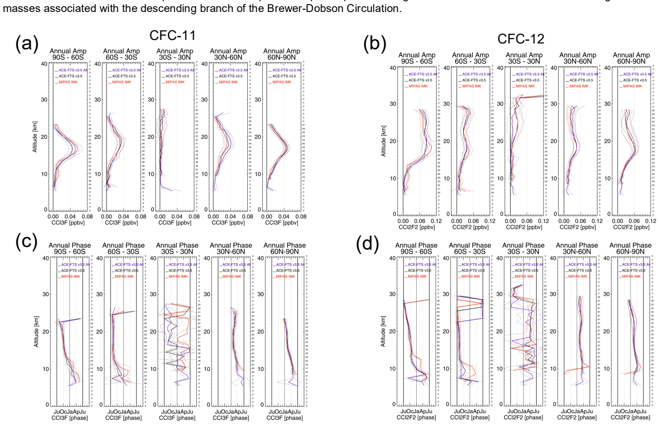

Fig. 4 The annual cycle amplitude profiles for CFC-11 (a) and CFC-12 (b), as well as the phase profiles for CFC-11 (c) and CFC-12 (d) derived from ACE-FTS and MIPAS coincident data and from the entire ACE-FTS data for the period 2005-2012. They are represented by the solid lines with respective color (black and red colors for ACE-FTS and MIPAS coincident data, blue for the entire ACE-FTS data set). The 95% confidence levels are represented by dotted lines with respective colors.

Fig. 5 shows the reconstructed annual cycle components for CFC-12 derived from the ACE-FTS and MIPAS coincident data as an altitude/time section along 60°S – 30°S, which is a latitude band where ACE-FTS sampling results in monthly mean values that are more evenly distributed than for other bands. Both ACE-FTS and MIPAS show strikingly similar features – downward propagation of signals in the descending branch of the Brewer-Dobson Circulation.

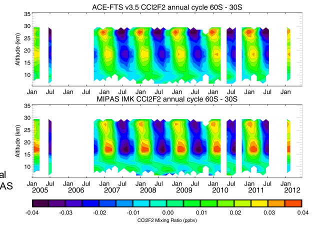

Fig. 5 Reconstructed altitude/time sections of the annual cycle components for ACE-FTS (upper panel) and MIPAS (bottom panel) at the latitude band 60°S – 30°S.

4.3 Semi-annual cycle components

The semi-annual oscillation (SAO) is the strongest natural variability mode in the tropical upper stratosphere (above 30km). The SAO components extracted from both CFC-11 and CFC-12 data show large amplitudes in the tropics above ~20km with significant confidence levels (Fig. 6a and Fig. 6b). The phase profiles in the same region (Fig. 6c and Fig. 6d) show consistency across the altitudes with the 95% significance levels within half of the period.

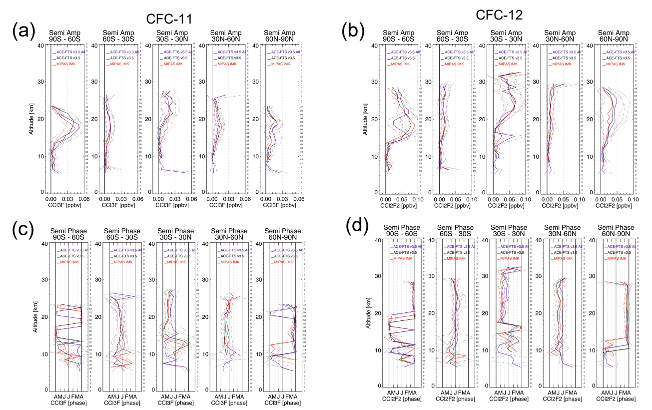

Fig. 6 Similar to Fig. 4 but for the semi-annual components.

4.3 QBO components

The QBO is a primary mode of the equatorial mean wind in the stratosphere, and is characterized by the downward propagating easterly and westerly winds alternating approximately every two years. Because of the Earth's rotation, the horizontal wind change induces vertical motion which causes variations in the stratospheric CFCs because of their layered distribution. The influence of the QBO can extend to the entire latitudes.

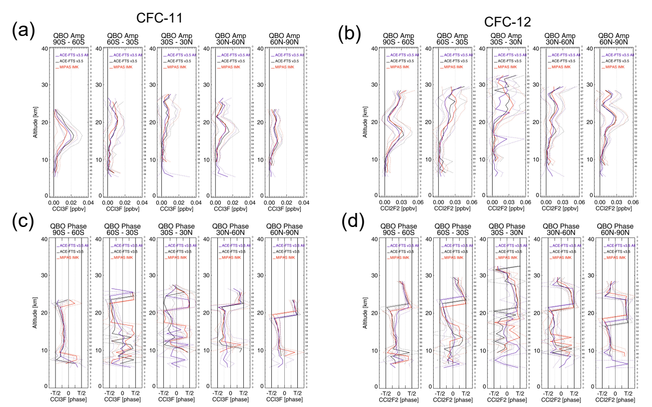

Fig. 7 Similar to Fig. 4 but for the QBO components.

The QBO amplitude profiles for CFC-11 (Fig. 7a) and CFC-12 (Fig. 7b) display significant signals in the stratosphere across all latitudes, although the magnitudes are just a few percent of their mean values. Because they are small values, the low 95% confidence levels in some regions are below zero, where the extracted components are regarded as insignificant. The phase profiles (Fig. 7c and Fig. 7d) show some regions with vertical slant lines, such as the CFC-12 phase profile between 20 km and 30 km at 60°S – 30°S, which is the example shown in Fig. 8. Fig. 8 is the reconstructed QBO components in altitude/time section derived from the ACE-FTS and MIPAS CFC-12 coincident data between 60°S and 30°S. Both plots show excellent agreement and typical QBO features such as the alternation of phase between 30 km and 20 km and the downward propagation of the signals with a period of about two years.

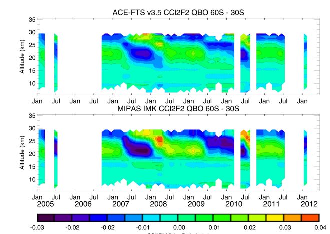

Fig. 8 Reconstructed altitude/time sections of the QBO components for ACE-FTS (upper panel) and MIPAS (bottom panel) at the latitude band 60°S – 30°S.

5. Conclusions

In this study, regression analyses are applied to coincident ACE-FTS and MIPAS CFC-11 and CFC-12 data (2005-2012) as well as to the entire ACE-FTS data set for the same period. The temporal composites extracted from these three data sets show excellent overall agreement, demonstrating the high quality of the CFC measurements from the two independent instruments even for those small variation composites. It should be pointed out that those regression functions such as sine and cosine functions are not a perfect model for the cyclic signals, but they are nevertheless capable of capturing the major features. The error estimates established based on residual errors help identify regions whether the extracted composites are significant.

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