2. Analysis

2.1 Introduction

Greenhouse gases are emitted to, transformed in, and removed from the atmosphere in various ways. Atmospheric carbon dioxide (CO_2), for example, is emitted by human activities such as combustion of fossil fuels, and exchanged with the terrestrial biosphere by respiration and photosynthesis, and with the ocean. Transformation of CO_2 in the atmosphere is negligible. Methane (CH_4) is emitted from the Earth's surface to the atmosphere mainly by anaerobic processes and anthropogenic sources, and dissociated by oxidation with hydroxyl radicals in the atmosphere. Some substances such as ozone are produced and dissociated in the atmosphere through photochemical processes.

The purpose of greenhouse gas observations is to monitor changes and develop understanding of mechanisms in their emission/production and removal/dissociation, and to provide predictions of their changes (Tans *et al.*, 1989: Keeling *et al.*, 1989). The WDCGG collects, archives, and distributes observation data for concentrations of greenhouse gases, and provides analytical results on collected data.

For the analyses in this publication, only monthly mean concentrations are used. Some stations also report daily and hourly mean concentrations, which may be more appropriate for analyzing variation in various time-scales. But the WDCGG considers it even better to adopt monthly mean data so that the analysis can incorporate more observation sites including a large number of stations in the NOAA flask sampling network.

In this publication, long-term trends and seasonal variations in concentrations of CO_2, CH_4, and carbon monoxide (CO) are derived for global, hemispheric, and zonal averages as well as for several stations representing global or regional situations. For nitrous oxide (N_2O) and halocarbons, time series of monthly mean concentrations are only presented because a small number of stations have so far reported observation data. As far as nitrogen oxides (NO_x) and sulfur dioxide (SO_2) are concerned, annual mean concentrations are displayed on a map of Europe because the WDCGG has received no data from outside of this region as of the end of June 1999.

The method of analysis for CO_2, CH_4, and CO is explained in the following sections. For the other parameters, please refer to the respective chapters.

2.2 Analysis method for CO_2, CH_4, and CO

2.2.1 Analysis for time series of concentrations

A time series of greenhouse gas concentrations, which is often produced by removing local effects with very-short-term variation, is an integration of variation on different time scales. The two major components of variation in CO_2 concentration are a seasonal change and a long-term trend. Many researchers attempted to decompose observation data into these two components by objective curve fitting (Keeling *et al.* 1989), by digital filtering (Thoning *et al.*, 1989: Nakazawa *et al.*, 1991), and by both objective curve-fitting and digital filtering (Conway *et al.*, 1994: Dlugokencky *et al.*, 1994).

The WDCGG formerly adopted running mean to derive long-term trends. In this publication, deseasonalized long-term trend and averaged seasonal cycle are derived by digital filtering for each time series of data by applying the following iterative procedure similar to the one applied by Nakazawa *et al.* (1991):

(1) A linear trend is derived from original observation data.

(2) The detrended data are fitted to the Fourier harmonics,

$$S(t) = \sum_{i=1}^{k} [A_i \sin(2\pi it) + B_i \cos(2\pi it)]$$

to derive an average seasonal cycle. In the harmonics, t is elapsed time (years) relative to the beginning of observation, and value k is set to 3 for all the stations in the both hemispheres so that average seasonal cycles are satisfactorily expressed.

(3) The original data are deseasonalized by subtracting S(t) given in (2). Missing records for less than 2 months are complemented with the linear interpolations. Then the complete time series of deseasonalized concentrations are filtered with the Lanczos filter (Duchon, 1979) with a cut-off frequency of 0.48 cycle/year to obtain a new long-term trend.

(4) The original data are then detrended by subtracting the long-term trend obtained in (3) and fitted again to the harmonics shown in (2) to derive an average seasonal cycle.

(5) The steps (3) and (4) are repeated until neither the long-term trend nor average seasonal cycle is changed. This should be attained after several iterations.

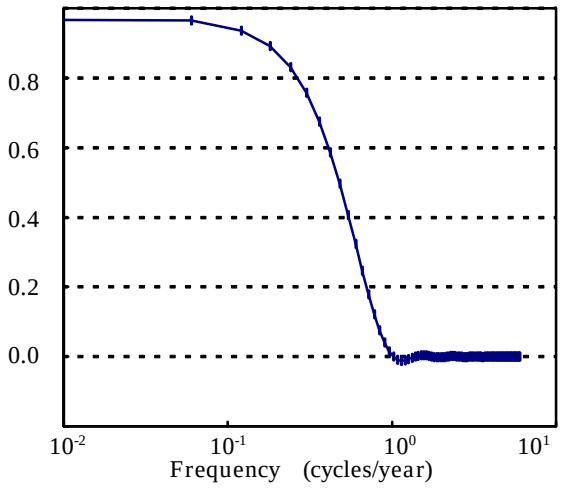

Fig. 2.1 Response function of the Lanczos filter. An input signal with a frequency of 0.48 cycle/year is halved in amplitude after passing this low-pass-filter.

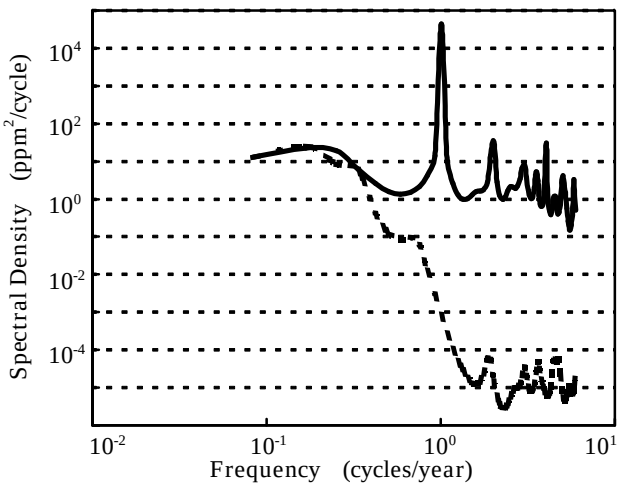

Fig. 2.2 Power spectra of unfiltered monthly mean (solid line) and deseasonalized long-term trend (broken line) of CO_2 concentration at Ryori, derived as described in the text.

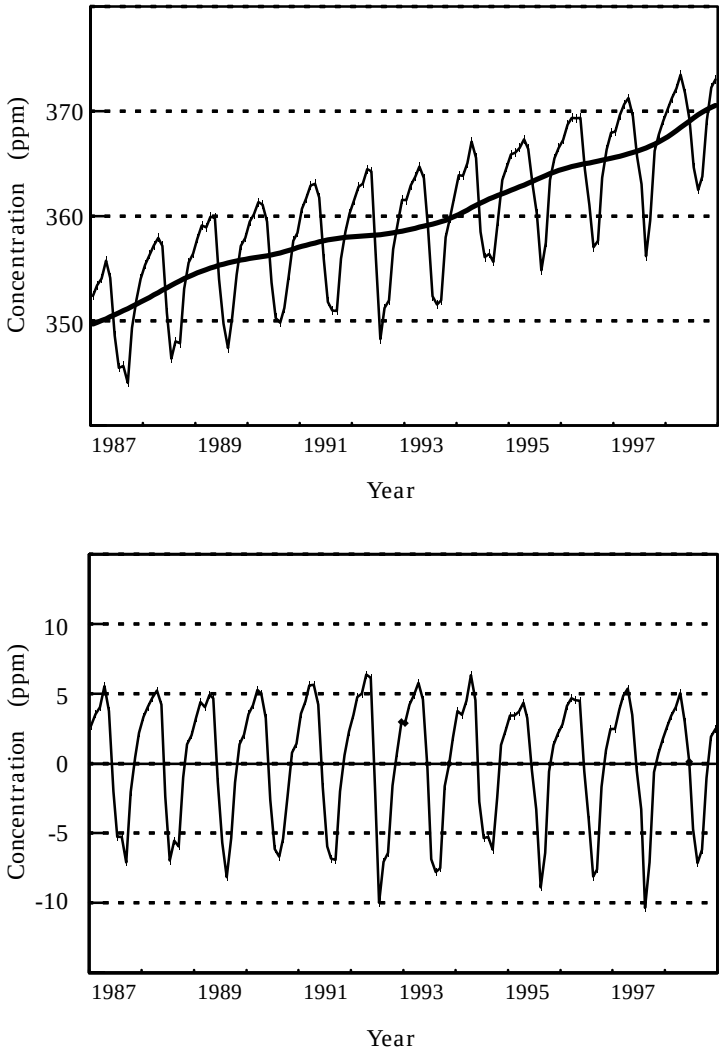

Fig. 2.3 (a) Time series of monthly mean CO_2 concentrations (dots and thin line) and their deseasonalized long-term trend (thick line) at Ryori. (b) Detrended yearly seasonal cycle of CO_2 concentration expressed as deviation of monthly mean concentrations from their deseasonalized long-term trend at Ryori.

Figure 2.1 shows the response function of the Lanczos filter used in the procedure above. An input signal with a frequency of 0.48 cycle/year is halved in amplitude after passing this filter. Figure 2.2 demonstrates how high frequency components of observation data are filtered out by comparing power spectra of unfiltered monthly mean CO_2 concentration at Ryori, Japan and the filtered long-term trend derived from the same data. Figure 2.3(a) shows a time series of monthly mean CO_2 concentrations and their deseasonalized long-term trend. Annual growth rates are calculated as first derivatives of the deseasonalized long-term trend curve. A detrended yearly seasonal cycle, varying year to year, is obtained as deviation from the trend curve as shown in Figure 2.3(b). Amplitude of seasonal cycle is defined as the difference between the maximum and minimum concentrations for each year.

2.2.2 Global, hemispheric, and zonal mean concentrations

The procedure described in the previous section is applied to zonally averaged concentrations of CO_2, CH_4, and CO. Zonal mean concentrations are calculated from data observed in the latitudinal zone by following the procedure mentioned below and global and hemispheric averages are obtained from zonal mean concentrations.

Observation data at 101 stations for CO_2, 83 for CH_4, and 64 for CO are used in total to calculate zonal averages. Observation sites are selected so that they are distributed in not only oceanic but also continental regions, if possible. Zonal averages are taken for the stations in the zone in a weighted manner. The zonal mean concentration C_L for the latitudinal zone L is given

by

$$C_L = \frac{\sum_i c_i \cos(l_i)}{\sum_i \cos(l_i)} .$$

where c_i is the concentration and l_i is the latitude for the observation site *i*.

Global and hemispheric mean concentrations $C_{L1\,L2}$ averaging the values in the latitudinal zones between l_{L1-1} and l_{L2} are similarly obtained as follows, taking into account different covered areas for different zones:

$$C_{L1\ L2} = \frac{\sum_{L_j=L1}^{L2} c_{L_j}\left(\sin(l_{L_j}) - \sin(l_{L_j-1})\right)}{\left(\sin(l_{L2}) - \sin(l_{L1-1})\right)}$$

where c_{Lj} is the zonal mean concentration and l_{Lj} and l_{Lj-1} are the southernmost and northernmost latitudes, respectively, for the zone *j*.

This publication summarizes characteristics of global, hemispheric, and zonal mean concentrations by showing a time series of monthly mean concentrations, a deseasonalized long-term trend curve, a time series of annual growth rates, an average seasonal cycle, and amplitudes of seasonal cycle for each year as defined in the previous section.

2.2.3 Analysis for individual stations

The preceding issues of *Data Summary* covered analytical results for all the reporting stations to the WDCGG. However, the WDCGG has changed its policy to make analyses for only limited stations representing global or regional situations, following a recommendation of the Scientific Advisory Group (SAG) on Greenhouse Gases as mentioned in Chapter 1. This issue covers 6 stations: Point Barrow (Alaska, USA) and the South Pole (Antarctica) as polar stations; Mauna Loa (Hawaii, USA) and a station in Oceania (Baring Head, New Zealand for CO_2 and Cape Grim, Australia, for CH_4 and CO) as oceanic stations; a Japanese station (Minamitorishima for CH_4 and Ryori for CO_2 and CO) and a station in Europe (Schauinsland, Germany for CO_2, Hegyhatsal, Hungary for CH_4, and Hohenpeissenberg, Germany for CO) as continental and near continental stations. Analytical results include a time series of monthly mean concentrations, a deseasonalized long-term trend curve, a time series of annual growth rates, an average seasonal cycle, and amplitudes of seasonal cycle and months with maximum and minimum values for each year.