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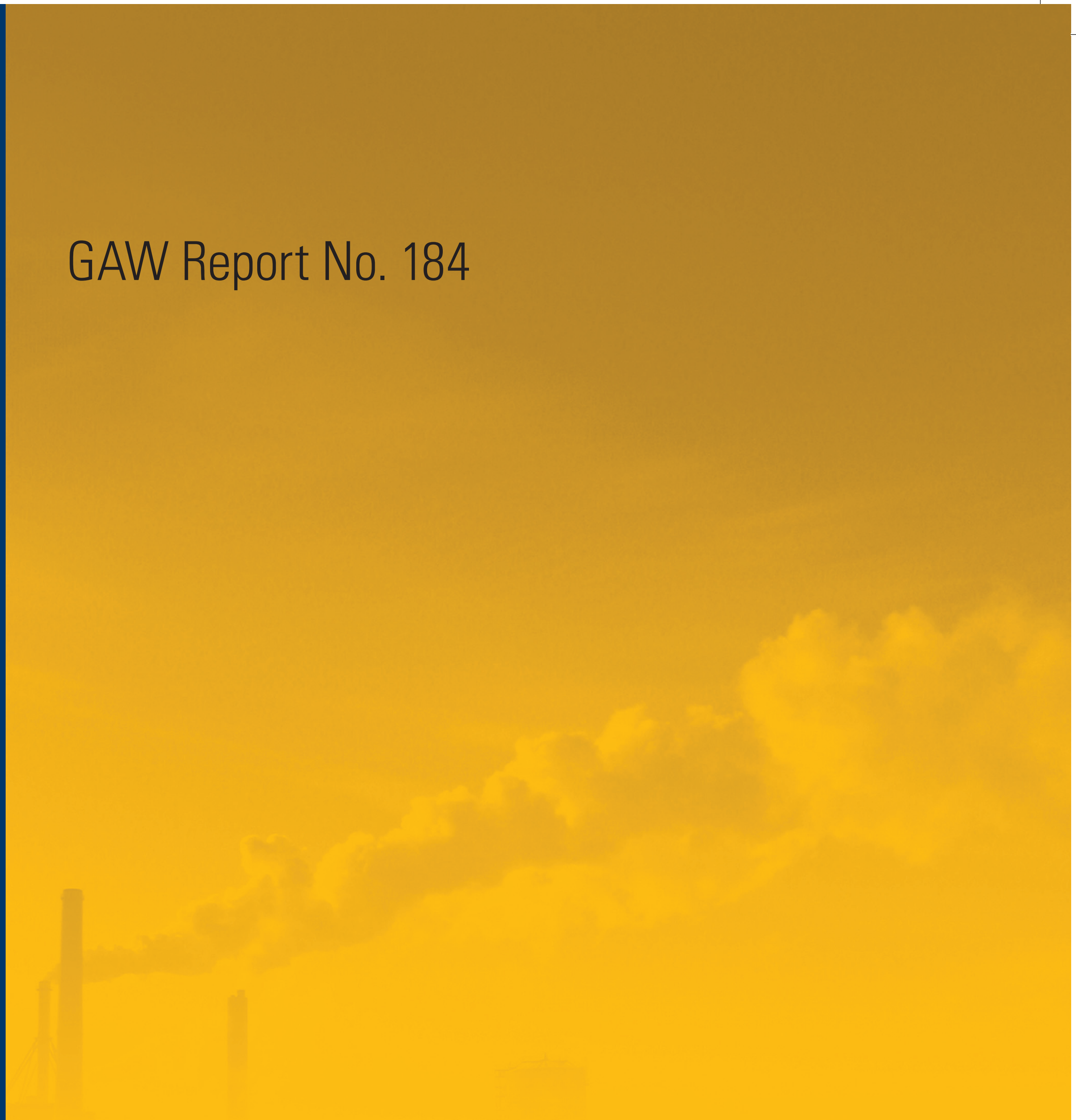

GAW Report No. 184

Technical Report of Global Analysis Method for Major Greenhouse Gases by the World Data Center for Greenhouse Gases

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WORLD METEOROLOGICAL ORGANIZATION
GLOBAL ATMOSPHERE WATCH

Technical Report of Global Analysis Method for Major Greenhouse Gases by the World Data Center for Greenhouse Gases

Yukitomo Tsutsumi, Kazumasa Mori, Takatoshi Hirahara, Masaaki Ikegami and Thomas J. Conway

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ABSTRACT

Since 1989 the World Meteorological Organization（WMO）has organized the Global Atmosphere Watch (GAW) programme to monitor the global atmospheric environment. At present, the GAW network is officially recognized as supplying the CO_2 and CH_4 data of the Global Climate Observing System (GCOS) which supports research and systematic observations under the United Nations Framework Convention on Climate Change (UNFCCC). The World Data Center for Greenhouse Gases (WDCGG), which is operated by the Atmospheric Environment Division (AED) of the Japan Meteorological Agency (JMA) under the framework of the GAW, gathers data about greenhouse gases and related tracer measurements from observation stations, archives and disseminates these data, and performs global analyses such as calculations of global mean mole fractions. Some of these results are included in the WMO Annual Greenhouse Gas Bulletin. For consistent global analyses using observation data from various stations conducted by different laboratories and organizations, a synchronized dataset is practical, with a common reference scale and no gaps in the observation period. We have presented a global analysis method, including production of a synchronized dataset by the WDCGG. The U. S. National Oceanic and Atmospheric Administration (NOAA) also publishes global greenhouse gas analyses using their observation network, which constitutes a major part of the GAW network. We compared the CO_2 global mean mole fractions calculated by the WDCGG with those from NOAA. Averagely, the WDCGG's CO_2 global mean mole fractions are greater than NOAA's by 0.35 ppm. The major cause of the difference was the use of different stations in the analyses.

1. INTRODUCTION

Long-lived greenhouse gases including CO_2 contribute greatly to global warming. An accurate understanding of their state that includes sources and sinks is fundamental for developing mitigation and adaptation policies through the Kyoto protocol under the UNFCCC. An accurate determination of global sources and sinks of greenhouse gases thus requires worldwide long-term observational data, which have a common reference standard and are of uniform quality.

In 1968, the Carbon Cycle Group in the Climate Monitoring and Diagnostics Laboratory (CMDL) of the NOAA, in what is now part of NOAA's Earth System Research Laboratory (ESRL) Global Monitoring Division (GMD), established a global observation network [Komhyr *et al.*, 1985] and began measuring CO_2 from flask samples. The observations expanded to include CH_4 in 1983 [Dlugokencky *et al.*, 1994]. The sampling stations in the NOAA network are globally distributed in cooperation with overseas organizations, and located mainly in oceanic or coastal areas that represent well mixed tropospheric air [Conway et al., 1994].

The WMO initiated the GAW programme in 1989 to monitor the atmospheric environment [WMO, 1992]. The global observation network for greenhouse gases, in which many international organizations participate, including NOAA, has been incorporated into the GAW programme. At present, the GAW observation network for greenhouse gases (CO_2 and CH_4) (Figure 1) is recognized as the atmospheric chemistry component of GCOS that supports research and systematic observations under the UNFCCC.

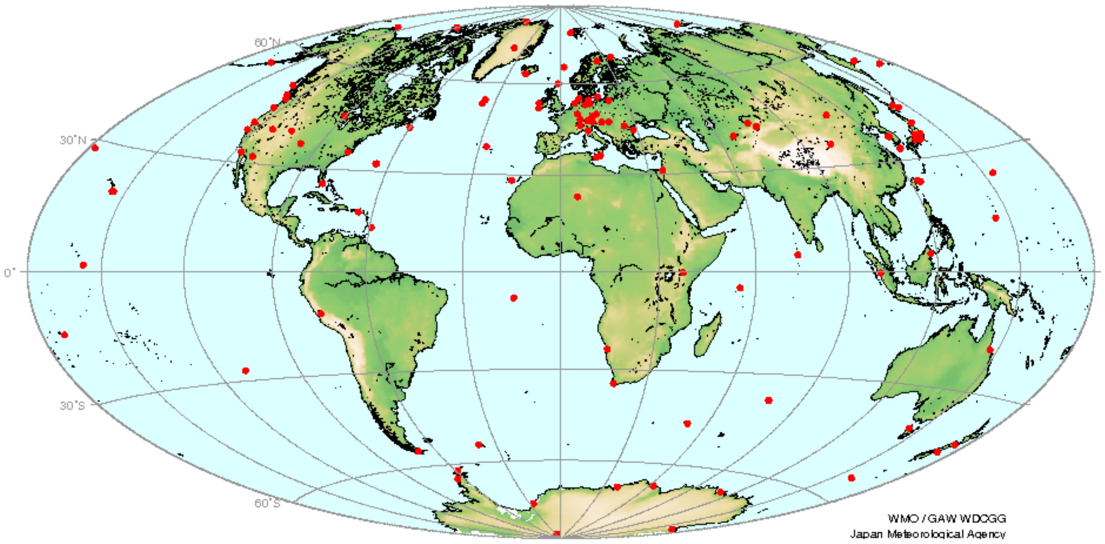

Figure 1. Global locations of GAW observation stations for the main greenhouse gases. These stations comprise the atmospheric chemistry component of the comprehensive GCOS network

In WMO/GAW, Scientific Advisory Groups (SAGs) provide scientific and technical guidance for the observation network. Furthermore, GAW supports observations by coordinating central facilities, such as the Central Calibration Laboratories (CCLs), which manage or maintain the reference scales; the Quality Assurance/Scientific Activity Centers (QA/SACs), which identify or support observation techniques; the World Calibration Centers (WCCs), which improve data quality and ensure traceability; and the World Data Centers (WDCs), which gather and disseminate data and other relevant information. For assessment of measurement traceability for uniformity of data quality, inter-comparisons of standard gases (Round Robin experiments) are conducted in the programme [Masarie *et al*, 2001; WMO, 2006; http://gaw.kishou.go.jp/wcc/ch4/comparison.html].

According to the GAW Strategic Plan [WMO, 2007a], these activities harmonize and promote:

- Standardized quality-related processes and procedures
- Traceable measurement scales
- Known data quality
- Easy access to observational data.

The above coordination by the GAW programme fosters consistent and systematic global atmospheric environment observations. For example, the Data Quality Objectives (DQO) for CO_2 are ±0.1 ppm in the Northern Hemisphere, and ±0.05 ppm in the Southern Hemisphere, whereas the DQOs for CH_4 and N_2O are ±2 ppb and ±0.1 ppb, respectively [WMO, 2006]. Within the GAW, observational data on greenhouse gases are gathered, their formats are standardized, and these standardized data are archived and disseminated to scientists and the public by the WDCGG. The archived data can be accessed on the WDCGG website. In 2007, the WDCGG published the Data Submission and Dissemination Guide [WMO, 2007b] to promote the use of archived data. Since 2006, the WMO has published an annual Greenhouse Gas Bulletin summarizing measurement of greenhouse gases. (http://www.wmo.int/pages/prog/arep/gaw/ghg/ghgbull06_en.html#ghgbulletins). The Bulletin includes the global mean mole fractions and growth rates of CO_2, CH_4, and N_2O, which are derived by the WDCGG using the analysis method presented in this paper.

Currently, global information on greenhouse gases, such as global mean CO_2 mole fraction, is obtained using precise measurements at ground-based stations. Several different global mean CO_2 values have been published. Besides the WMO Greenhouse Gas Bulletin, IPCC [2007] reported the global mean CO_2 mole fraction in 2005 using both the Scripps Institution of Oceanography (SIO) sites and the NOAA network. The Global Monitoring Division (GMD) in the NOAA Earth System Research Laboratory (ESRL) calculates the global mole fractions obtained from data gathered at their network sites and the method of Conway *et al.* [1994](http://www.esrl.noaa.gov/gmd/ccgg/trends/).

For global analyses of greenhouse gases using observational data from multiple measurement programmes, following two problems need to be considered. First, the measurements have to be on the same measurement scale derived from a common reference standard (otherwise, they cannot be compared). Second, measurement data from all stations have to be synchronized for the observation period. However, the observation period for each station, particularly the beginning of observations, is usually different. Furthermore, many stations have gaps in their observation time series due to instrument malfunctions or other reasons. If global analyses are performed without considering these problems, the results may be biased by the particular stations used and the availability of data. In contrast, if only stations that have long observation periods are selected, data from many stations in recent years would not be included in global analyses. For global analyses, it is practical to prepare a dataset of uniform quality that includes recently established stations without gaps and that is not biased by variation in station and data number.

NOAA/ESRL/GMD produces an internally-consistent synchronized dataset without gaps using the method of Masarie and Tans [1995]. They announce global mean mole fraction values by this method using the marine surface stations (http://www.esrl.noaa.gov/gmd/ccgg/trends/). On the other hand, the GAW observation network includes many inland regional stations, which are relatively close to sources and sinks of greenhouse gases, in addition to the NOAA network stations. The WDCGG uses as many stations as possible from the GAW network that it considers are contributive to global analyses. As a result, the mole fractions dealt by the WDCGG should cover a wider range than those from the NOAA network.

The JMA operates the WDCGG that supports scientific research, assessments, and corresponding policy for environmental issues such as global warming, ultimately to contribute towards reducing societal environmental risks, and to meet the requirements of related environmental conventions (WMO, 2007b). As a result, the WDCGG, together with the SAG for Greenhouse Gases, is charged with producing reliable global analyses using GAW network data. The aim of this paper is to clarify the scientific rationale of the WDCGG global analysis method, and to illustrate the results. The steps required to produce a synchronized dataset and to obtain global results are shown in Section 2. A discussion of the global analysis method, including comparison with NOAA’s results, is presented in Section 3.

2. THE WDCGG GLOBAL ANALYSIS METHOD

2.1 Outline of the WDCGG global analysis method

The WDCGG produces a synchronized and uniform quality dataset that has no gaps and is traceable to the WMO standard scale. Subsequently, the WDCGG performs global analyses using this dataset. The steps of the procedure are described below. The dataset is produced using monthly mean mole fractions for stations that have reported data for at least one year.

Step 1: Station selection based on traceability to the WMO standard scale
Step 2: Integration of parallel data from the same station

Step 3: Selection of stations suitable for global analysis

Step 4: Abstraction of a station’s average seasonal variation expressed by the Fourier polynomial

Step 5: Interpolation for data gaps

Step 6: Extrapolation for synchronization of data period

Step 7: Calculation of the zonal and global mean mole fractions, trends, and growth rates.

The details of these steps are explained in the following sections.

2.2 Station selection based on traceability to WMO standard scale

The WDCGG confirms the consistency of measurement scales using the latest submitted metadata (observation relevant information). For global CO_2 analysis, the WDCGG uses only data traceable to the WMO standard scale or the SIO scale, the former WMO standard scale. For global CH_4 analysis, since NOAA established the WMO standard scale in 2005 [Dlugokencky *et al.*, 2005], the WDCGG selects data that are traceable to the WMO standard scale. However, this scale is not yet employed worldwide. Therefore, the WDCGG also selects data that disclose the differences between the observation scales and the WMO standard scale, and use data after conversion to the WMO standard scale (see Appendix of WMO, [2007c]). For global N_2O analysis, WDCGG selects data that are traceable to the WMO standard scale [Hall *et al.*, 2007] or that are obtained by the Advanced Global Atmospheric Gases Experiment (AGAGE) group. Although the AGAGE group employs its own scale, it compares these results with those of the NOAA. Based on the results of these comparisons, the WDCGG converts the AGAGE data to the WMO standard scale.

2.3 Integration of parallel data from the same station

Some stations perform continuous (at a frequency of every hour) and flask sampling measurements (at a frequency of about once per week). If data maintenance for background condition is adequate, continuous measurements are usually thought to be better for representation. Therefore, when both continuous and flask sampling data exist at a station, the WDCGG first uses the continuous measurement data, with data gaps filled with flask sampling data (Figure 2). At the NOAA stations, the monthly mean flask and continuous CO_2 data were estimated to agree within ±0.16~0.35 ppm [Tans *et al.*, 1990].

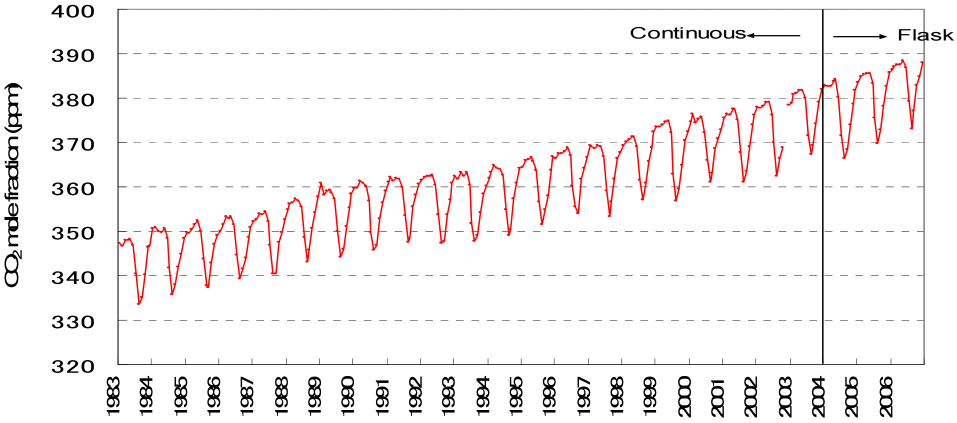

Figure 2. Example of unified CO_2 data from continuous measurement and flask sampling. Data were unified in January 2004 (Barrow, Alaska, USA)

2.4 Selection of stations for global analyses

The WDCGG accepts observational data not only targeted for background condition but also for other purposes. Therefore the WDCGG selects stations suitable for global analysis based on a reasonable latitudinal scatter range. A latitudinal smoothing value is determined from a "loess" model that uses nearest-neighbour local-quadratic regression [Cleveland and Devlin 1988; Masarie and Tans, 1995] using all station data normalized against the South Pole. The normalized station data are averaged for the whole observation period. Similar to the method of Tans *et al*. [1990], stations with normalized values exceeding ±3σ from the fitted curve are excluded (Figure 3). This process is repeated until all remaining normalized station data are within ±3σ of the fitted curve.

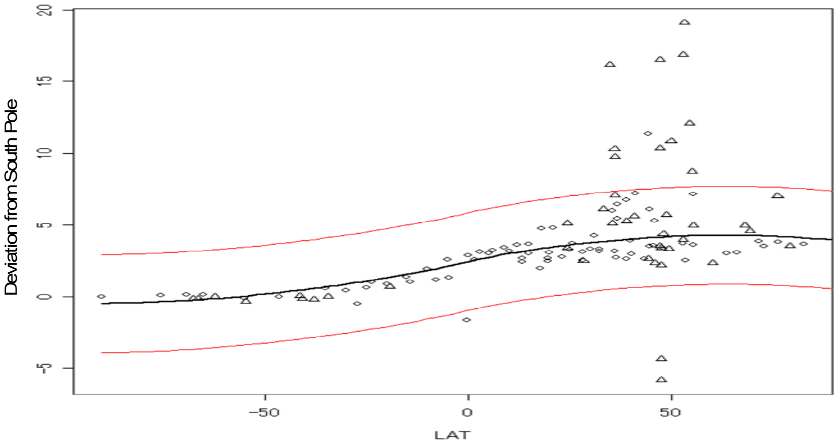

Figure 3. Latitudinal distribution of the averaged CO_2 mole fractions (ppm) normalized with respect to the South Pole. The thick line is the fitted LOESS model curve, and the thin lines are ±3σ from the fitted curve. Stations outside the thin lines are excluded and thin lines (±3σ) are recalculated

The numbers of stations (station indexes) selected using steps 1-3 in the WMO GHG Bulletin No.3 are shown in Figure 4. The stations and contributors whose data were used in that bulletin are posted on the WDCGG website (http://gaw.kishou.go.jp/wdcgg/products/bulletin.html).

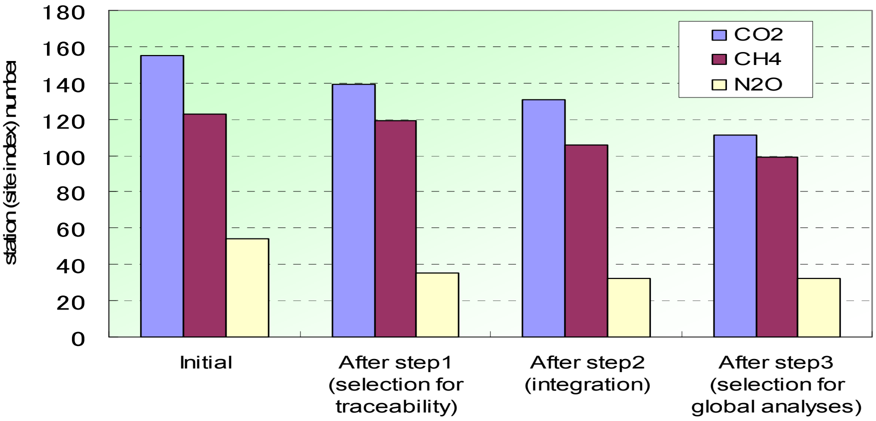

Figure 4. Selected station (site index) numbers in steps 1 (selection for traceability), 2 (integration), and 3 (selection for global analyses) in the WMO Greenhouse Gas Bulletin No.3

2.5 Abstraction of a station’s average seasonal variation expressed by the Fourier polynomial

Observation data from each station can be decomposed into a long-term trend and an average seasonal variation. Using the longest continuous segment of data, a station’s average seasonal variation is derived using the Fourier polynomial:

(a) A linear trend *T(t)* is derived from the original observational data *F(t)* using a least square method.

(b) The detrended data (*F(t)*-*T(t)*) are expressed in the Fourier harmonics to derive an average seasonal cycle *S(t)* (Figure 5), using the equation:

,

$$S(t)=\sum_{i=1}^{3}\left[A_i\sin(2\pi i t)+B_i\cos(2\pi i t)\right]$$

where, A_i and B_i are fitted parameters, *t* (in months) denotes the time from the beginning of the observation, and *i* denotes the harmonic number. In our analysis, three harmonics are used to fully express the seasonal variation at all stations (Nakazawa et al., 1991).

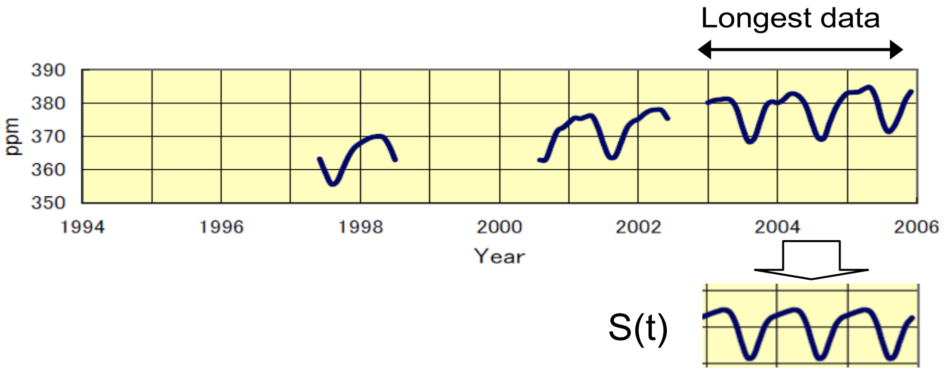

Figure 5. Example of CO_2 observation data with gaps and average CO_2 seasonal cycle S(t) derived using the longest continuous data

(c) The original data *F(t)* are deseasonalized by subtracting *S(t)*. Subsequently, a long-term trend is obtained by applying a Lanczos filter (a cut-off frequency of 0.48 cycle/year) [Duchon, 1979] to the deseasonalized data.

(d) The detrended data are obtained by subtracting the long-term trend from the original data *F(t)*, yielding an average temporary seasonal variation, as shown in (b) above.

(e) Steps (c) and (d) are repeated until neither the long-term trend nor the average seasonal cycle changes.

(f) Finally, the average seasonal variation is determined (Figure 6).

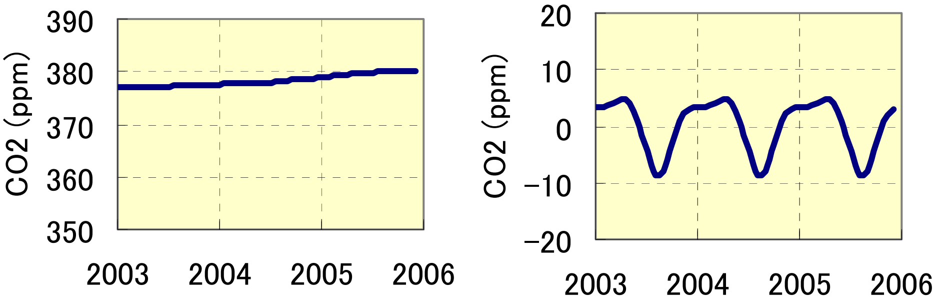

Figure 6. **Examples of CO_2 long-term trend (left) and average seasonal variation (right)**

2.6 Interpolation for data gaps

To fill in gaps in the observations, a linear interpolation is performed for gaps in the long-term trend from which the seasonal variation has been subtracted. Subsequently, the time series without any gaps is obtained by adding the average seasonal variation to the interpolated periods (Figure 7).

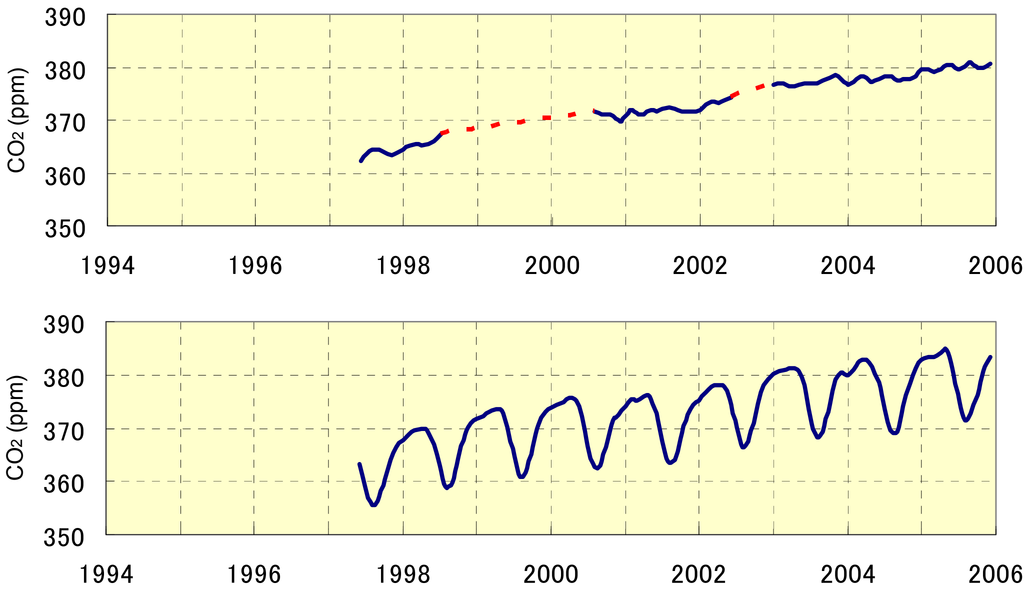

Figure 7. **Examples of a long-term CO_2 trend (top) whose gaps are linearly interpolated (dashed line) and a retrieved long-term CO_2 variation (bottom) calculated by adding the average seasonal variation**

2.7 Extrapolation for synchronization of data period

The WDCGG extrapolates to synchronize the data periods of all selected stations. Each latitudinal band (every 30°) contains several long-running stations that cover the synchronization period (e.g. from 1983 for CO_2). Therefore, to synchronize the data period of the other stations, the long-term trend is extrapolated back to the beginning of the synchronizing period following the zonal mean growth rate that was calculated from the data obtained from long-running stations in the same latitudinal band. Finally, synchronized data are obtained by adding the average seasonal variation (Figure 8) to the extrapolated long-term trend. These processes are applied to all selected stations that do not have data for the entire period.

The result is a synchronized, continuous dataset that is traceable to the WMO standard scale (Figure 9). The WDCGG performs global analyses using this synchronized dataset.

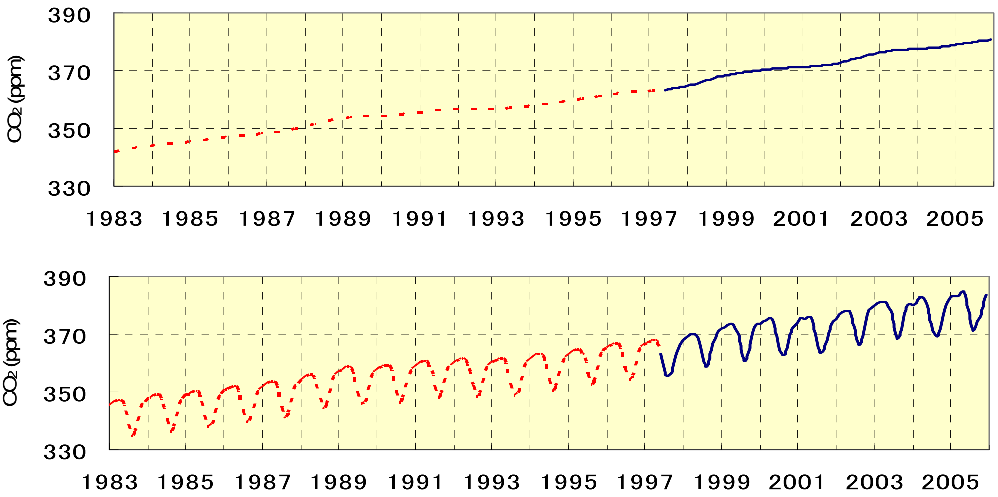

Figure 8. Examples of a long-term CO_2 trend (top) and a long-term CO_2 variation (bottom) extrapolated for data synchronization (dashed line)

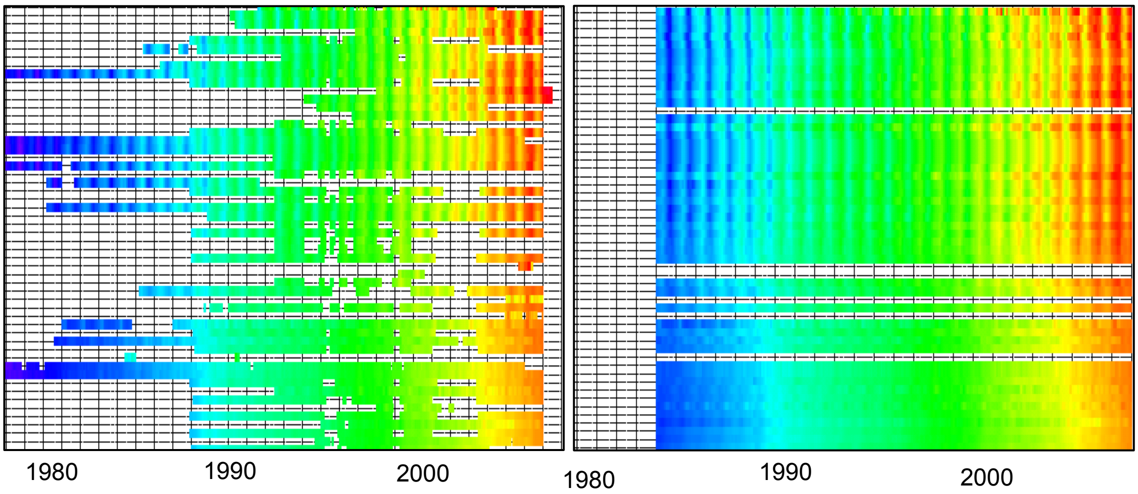

Figure 9. Original (left) and synchronized (right) monthly mean CO_2 mole fractions of stations used for global analysis illustrated in colours that change with mole fractions. Stations are arranged from north to south

2.8 Calculation of the zonal and global mean mole fractions, trends, and growth rates

Zonal means of mole fractions (every 30°) are calculated using synchronized data (Section 2.7) from stations located in each latitudinal band. Global and hemispheric means are calculated by averaging the zonal means, taking into consideration the area ratio of each latitudinal band. Deseasonalized long-term trends for the globe, both hemispheres and each latitudinal band are calculated by removing the seasonal cycle as described in Section 2.5. Growth rates for the globe, both hemispheres and each latitudinal band are the time derivatives of the long-term trends.

To derive long-term trends for the entire period, we provisionally applied a linear trend for CO_2 and N_2O and a quadratic trend for CH_4 over the synchronizing period. Therefore, the analyzed trends and growth rates at both ends of the record (about a half year) could depart from actuality.

3. DISCUSSION

3.1 Comparison with results from NOAA

NOAA/ESRL/GMD operates a global observation network and also contributes to the GAW programme. NOAA/ESRL/GMD produces an internally consistent synchronized dataset using the method of Masarie and Tans [1995] to calculate zonal and global results. The major differences from our method are the selected stations (the GAW observation network includes stations not included in the NOAA network) and the methods of interpolation and extrapolation for gaps in observations. Most of the NOAA stations employed for global means are located in coastal areas and usually sample marine boundary layer air. Furthermore, NOAA employs the Latitude Reference Method [Masarie and Tans, 1995] for interpolation and extrapolation; this method determines mole fractions at a station by fitting a latitudinal smoothing curve each week to the marine boundary layer stations.

Figure 10 shows the differences (NOAA-WDCGG) in CO_2 global mean monthly mole fraction, as determined by NOAA and the WDCGG. In this Figure, NOAA's values are referenced from the Carbon Cycle Group website in NOAA/ESRL/GMD. The WDCGG global mean was, on average, 0.35±0.31 ppm larger than that of the NOAA. Seasonally, WDCGG summer values were usually smaller than those of NOAA, but the WDCGG values were larger during other seasons, particularly the winter. Two potential causes for these discrepancies are the different stations used and the difference in global analysis method. Although the WDCGG exclude station whose weight is smaller before the global mean calculation (see Section 2.4), the stations used by WDCGG include inland stations that are closer to sinks and sources than NOAA's. As a result, the summer decrease caused by plant photosynthesis and the winter increase caused by plant respirations and rise of fossil fuel combustion, are expected to be greater than that of the NOAA marine boundary layer stations. In order to study the cause of the global mean difference between NOAA and WDCGG, we calculated the global mean mole fractions by the WDCGG method using monthly mean data at the NOAA marine boundary layer stations (see Masarie and Tans [1995]) that are archived in the

WDCGG. By comparison, the difference between the WDCGG and NOAA global means was 0.13 ppm, which indicates that the effect of using the different stations (0.22 ppm) is greater than the effect of using a different method.

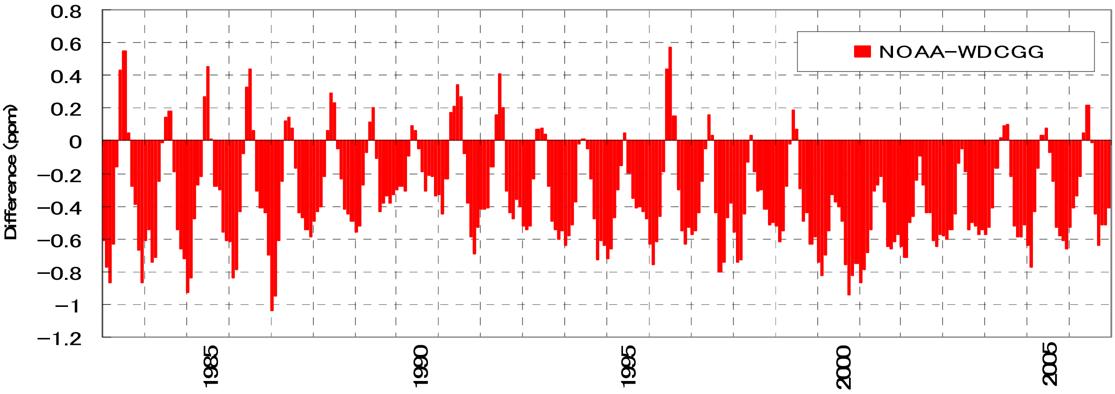

Figure 10. Difference between the WDCGG and NOAA globally-averaged CO_2 monthly mole fractions

3.2 Examples of global analyses

Figure 11 shows three-dimensional representations of the latitudinal distributions of atmospheric CO_2 mole fractions (top) and growth rates (bottom) derived from the synchronized dataset. These figures are convenient to easily understand the global CO_2 increase with seasonal variation and variable global growth rates.

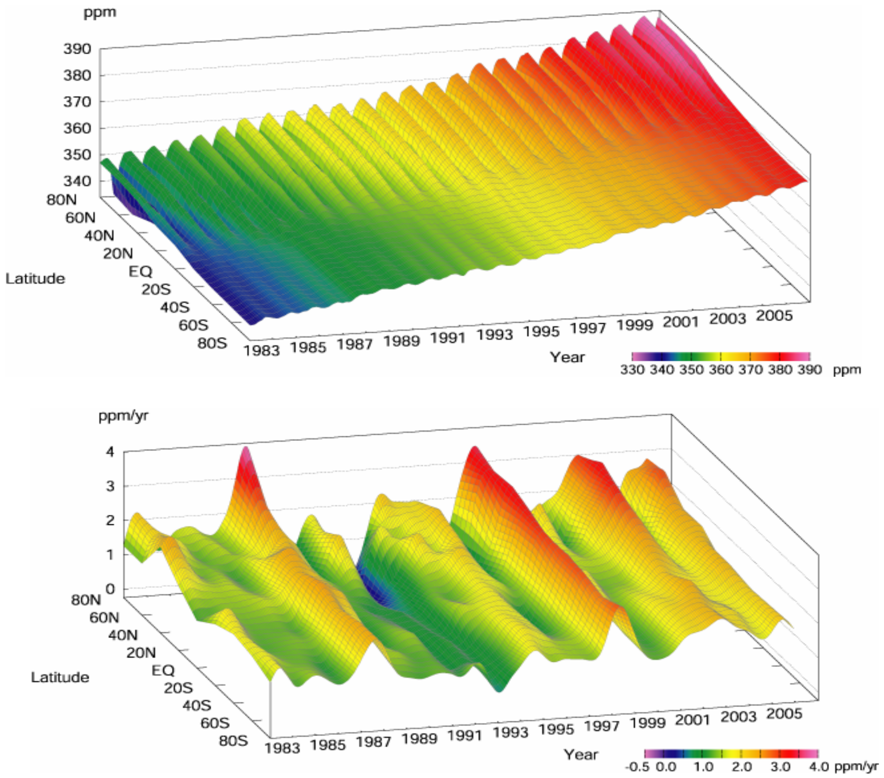

Figure 11. Three-dimensional representations of the monthly variations of zonally-averaged atmospheric CO_2 distribution (mole fractions (top) and growth rates (bottom)). The latest version is reported in the WMO WDCGG Data Summary

The growth rate of CO_2 is closely related to global temperature and drought that affect CO_2 emission from the land biosphere [e.g. Keeling *et al.*, 1995]. Figure 12 shows the relationship of CO_2 rate of incerase in the tropics (30°N-30°S) with temperature anomaly (5 months running mean) on land in the tropics from a 24 year average determined using JRA-25 reanalysis data [Onogi *et al.*, 2007]. The rate of CO_2 increase and the temperature anomaly correlate well, except for 1991-1992, due to the effect of the Mt. Pinatubo volcanic eruption. The correlation coefficient for the entire period (1983-2006) was 0.70. Notably, at tropical latitudes, both the temperature anomaly on land and the growth rate of CO_2 remained high after 2001. However, the global increase in CO_2 observed after 2001 may be due to an increase in anthropogenic CO_2 emissions [Canadell *et al.*, 2007].

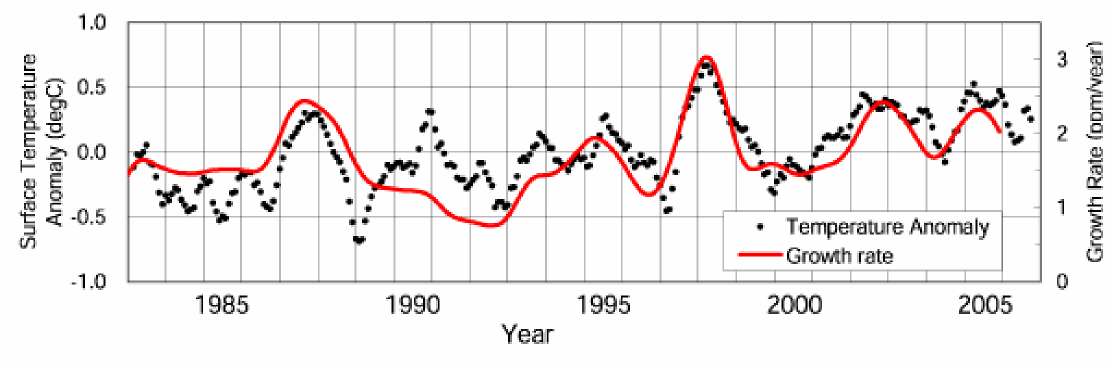

Figure 12. Time series of CO_2 growth rates in the tropics (30°N-30°S) and temperature anomaly (5 months running mean) on land in the tropics calculated from the JRA-25 reanalysis data. The temperature anomaly is the difference from the mean of the entire period (1983-2006). The latest version is reported in the WMO WDCGG Data Summary

4. SUMMARY

A synchronized dataset with no gaps in the observation period that is traceable to the WMO standard scale is practical for global analyses of greenhouse gases. The WDCGG produces such a dataset using data from the GAW global observation network and following procedures:

- Station selection based on traceability to the WMO standard scale
- Integration of parallel data from the same station
- Selection of stations suitable for global analyses
- Interpolation of data gaps
- Extrapolation of data for synchronization throughout the observation period.

Using the synchronized dataset, the WDCGG calculates monthly means, long-term trends and growth rates for each latitudinal band. Subsequently, the global mean and other global statistics are calculated using latitudinal values weighted according to area. NOAA also publishes global mean mole fractions using their own observation network, which is also part of the GAW network. The difference between the NOAA and WDCGG global mean mole fractions from 1983 to 2006 averaged 0.33±0.31 ppm, primarily because different stations are used in each analysis.

The WMO has organized the GAW programme to monitor the global atmospheric environment. The GAW network is officially recognized as supplying the CO_2 and CH_4 data of the GCOS which supports research and systematic observations under the UNFCCC. The WDCGG gathers, archives, and disseminates data about greenhouse gases and related tracer measurements from observation stations, and also performs global analyses such as calculations of global mean mole fractions. Through these activities, the WDCGG will contribute to global warming prevention in the future.

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167. The German Contribution to the WMO Global Atmosphere Watch Programme upon the 225th Anniversary of GAW Hohenpeissenberg Observatory (edited by L.A. Barrie, W. Fricke and R. Schleyer (WMO TD No. 1336).

168. 13th WMO/IAEA Meeting of Experts on Carbon Dioxide Concentration and Related Tracers Measurement Techniques (Boulder, Colorado, USA, 19-22 September 2005) (edited by J.B. Miller) (WMO TD No. 1359).

169. Chemical Data Assimilation for the Observation of the Earth's Atmosphere – ACCENT/WMO Expert Workshop in support of IGACO (edited by L.A. Barrie, J.P. Burrows, P. Monks and P. Borrell) (WMO TD No. 1360).

170. WMO/GAW Expert Workshop on the Quality and Applications of European GAW Measurements (Tutzing, Germany, 2-5 November 2004) (WMO TD No. 1367).

171. A WMO/GAW Expert Workshop on Global Long-Term Measurements of Volatile Organic Compounds (VOCs) (Geneva, Switzerland, 30 January – 1 February 2006) (WMO TD No. 1373).

172. WMO Global Atmosphere Watch (GAW) Strategic Plan: 2008 – 2015 (WMO TD No. 1384).

173. Report of the CAS Joint Scientific Steering Committee on Environmental Pollution and Atmospheric Chemistry (Geneva, Switzerland, 11-12 April 2007) (WMO TD No.1410).

174. World Data Center for Greenhouse Gases Data Submission and Dissemination Guide (WMO TD No. 1416).

175. The Ninth Biennial WMO Consultation on Brewer Ozone and UV Spectrophotometer Operation, Calibration and Data Reporting (Delft, Netherlands, 31-May – 3 June 2005) (WMO TD No. 1419).

176. The Tenth Biennial WMO Consultation on Brewer Ozone and UV Spectrophotometer Operation, Calibration and Data Reporting (Northwich, United Kingdom, 4-8 June 2007) (WMO TD No. 1420).

177. Joint Report of COST Action 728 and GURME – Overview of Existing Integrated (off-line and on-line) Mesoscale Meteorological and Chemical Transport Modelling in Europe (ISBN 978-1-905313-56-3) (WMO TD No. 1427).

178. Plan for the implementation of the GAW Aerosol Lidar Observation Network GALION, (Hamburg, Germany, 27 - 29 March 2007) (WMO TD No. 1443).

179. Intercomparison of Global UV Index from Multiband Radiometers: Harmonization of Global UVI and Spectral Irradiance (WMO TD No. 1454).

180. Towards a Better Knowledge of Umkehr Measurements: A Detailed Study of Data from Thirteen Dobson Intercomparisons (WMO TD No. 1456).

181. Joint Report of COST Action 728 and GURME – Overview of Tools and Methods for Meteorological and Air Pollution Mesoscale Model Evaluation and User Training (WMO TD No. 1457).

182. IGACO-Ozone and UV Radiation Implementation Plan (WMO TD No. 1465).

183. Operations Handbook – Ozone Observations with a Dobson Spectrophotometer (WMO TD No. 1469).