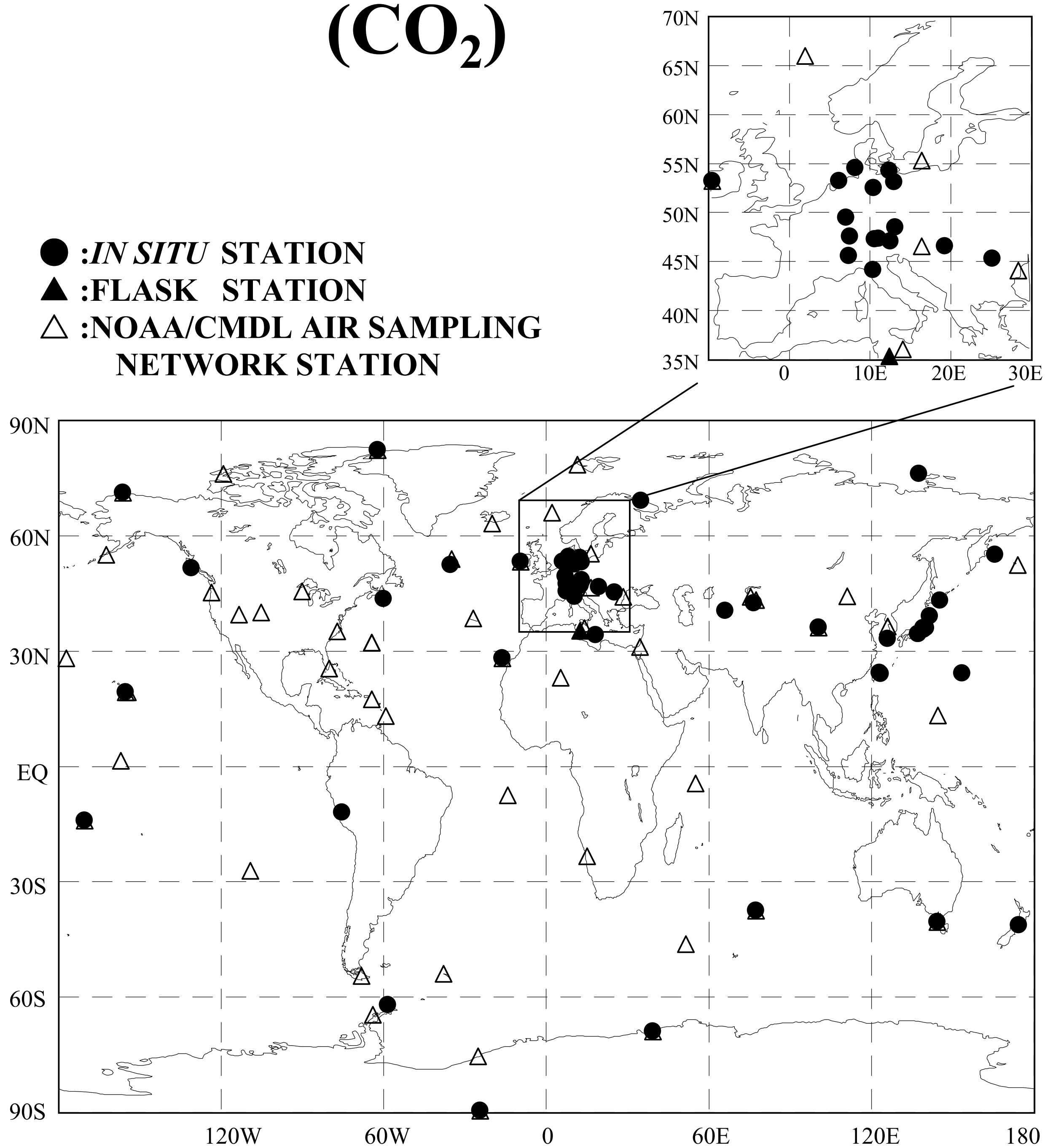
3.
Carbon Dioxide
(CO_2)



3. Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) is a significant greenhouse gas that is the largest contributor to global warming. Before the 18th century (pre-industrial times), the concentration of carbon dioxide in the atmosphere was about 280 ppm based on ice core studies, while in 1999 the concentration was about 368 ppm at Mauna Loa (NOAA/CMDL, 2001). More than half of the direct radiative forcing from the increase in long-lived greenhouse gases is attributed to that of carbon dioxide (IPCC, 2001).

CO_2 is emitted by and absorbed on the Earth's surface in different ways, including respiration and photosynthesis by the terrestrial biosphere, exchange with the oceans and human activity such as fossil fuel combustion and land-use changes. Since the 18th century, the anthropogenic emission of CO_2 has been increasing, and the emitted CO_2 has been distributed into the atmosphere, oceans and terrestrial biosphere, which serve as reservoirs of CO_2 in the global carbon cycle. About half of this amount remains in the atmosphere and the rest is removed by sinks, including forest regrowth and ocean uptake. Carbon isotope studies have successfully demonstrated the significant importance of the terrestrial biosphere and oceans as sources and sinks (Francey *et al.*, 1995; Keeling *et al.*, 1995; and Nakazawa *et al.*, 1993, 1997a), and the importance of carbon isotope data has been increasing.

Large amounts of CO_2 are exchanged among these reservoirs, and the global carbon cycle is coupled with the climate system on seasonal, interannual and decadal time-scales. Accurate understanding of the global carbon cycle is essential for estimating future CO_2 concentrations in the atmosphere.

At the beginning of this chapter, operational observation sites on the ground that have submitted CO_2 concentration data to the WDCGG by November 2001 are shown on a map. They include *in situ* stations measuring continuously and flask-sampling stations such as the ones in the NOAA/CMDL network. In addition to such fixed stations, mobile stations on ships and aircraft, and other stations measuring on a campaign (event data) also report their data to the WDCGG (Appendix: LIST OF OBSERVING STATIONS).

3.1 Analysis of global, hemispheric and zonal mean concentrations

Global, hemispheric and zonal mean concentrations were calculated from data calibrated on the WMO mole fraction scale. The data used for the analysis came from 92 stations that can be considered to be background.

Figure 3.1 shows the monthly mean concentrations and their deseasonalized long-term trend from 1983 to 2000 for the globe and for both hemispheres. Long-term increases in both hemispheres and seasonal variation in the Northern Hemisphere are clearly seen. The annually averaged concentration is 369 ppm in 2000 for the globe. Figure 3.2 shows the growth rates for the same areas as in Figure 3.1. The average growth rate over this period (1983–2000) is 1.6 ppm/year for the globe. In terms of the growth rate for the globe, the maximum is 3.0 ppm/year in the spring of 1998 and the minimum is 0.7 ppm/year in the summer of 1992. High growth rates above 2 ppm/year are seen in 1987/1988 and 1997/1998.

Figure 3.3 shows the monthly mean concentrations and their deseasonalized long-term trend from 1983 to 2000 for each 30-degree latitudinal zone. Deseasonalized concentrations are the highest in northern high or mid-latitudes, suggesting regions with a strong net source in these latitudes.

Figure 3.4 shows the analytical results for the deseasonalized long-term trend and growth rates. Variations of growth rates are seen, and variability in the growth rate is comparatively large in the northern high latitude. Growth rates are high in 1983, 1987/1988, 1994/1995 and 1997/1998, and are low in 1984/1985, 1989/1990, 1992/1993 and 1996/1997. In particular, a negative value was recorded in the northern high latitudes in 1992/1993.

Changes in growth rate are also known to be associated with El Niño-Southern Oscillation (ENSO). El Niño events occurred in 1982/1983, 1986-1988, 1991/1992, 1993 and 1997/1998. Correspondingly, growth rates were high in 1983, 1987/1988, 1994/1995 and 1997/1998, but low in 1992. Carbon isotope (^{13}C) studies are used to clarify how terrestrial and oceanic sinks contribute to such variations (Francey *et al.*, 1995; Ciais *et al.*, 1995; and Keeling *et al.*, 1995). They suggest that changes in the growth rate during El Niño events may reflect two offsetting effects: reduced uptake by the terrestrial biosphere and increased uptake by oceans. The former effect is brought about by a high global temperature through the activated respiration of plants and decomposition of organic matter in soil. Sparse precipitation, particularly in the tropics, also enhances this effect by suppressing plant photosynthesis. The latter is caused by weak upwelling CO_2-rich water in the eastern equatorial Pacific. In normal cases, the former effect surpasses the latter, resulting in increased growth rates (Dettinger *et al.*, 1998). However, the El Niño event in 1991/1992 was an exception. The lower temperature after the eruption of Mt. Pinatubo reduced emission from the northern terrestrial biosphere and increased uptake to the global oceans (Rayner *et al.*, 1999).

An anomalously strong El Niño event occurred in 1997/1998 and high growth rates of atmospheric CO_2 were observed worldwide in 1998. The climate system involving the atmosphere, oceans, land, terrestrial biosphere and so forth largely deviated from normal conditions (JMA, 1999; WMO, 1999b). Anomalously scarce precipitation brought about frequent droughts and forest fires in Southeast Asia in 1997/1998, and the global mean temperature was the highest ever recorded in 1998. Such extreme climate conditions perturbed the global carbon cycle, and accelerated the increase of CO_2 concentrations in the atmosphere.

Figure 3.5 shows a time series of CO_2 growth rates in the tropical area ($<\pm 30^\circ$) and its comparison with the SOI (Southern Oscillation Index), the SST anomaly in Region B (4°N-4°S, 150°W-90°W), which are widely used as the indicators of ENSO and the temperature anomaly on land in the tropics calculated from NCEP reanalysis data. In the figure, the SOI, SST anomaly and the temperature anomaly are processed by a five-month running mean in order to display the seasonal variation. There are high correlations between the growth rate in the tropics and the SOI and SST anomaly with a time lag, and these correlations suggest that the growth rate is highly related with ENSO. In 1992, the correlations were very low, but that with the temperature anomaly was high. The high correlation between the temperature anomaly and the growth rate suggests a strong influence of the tropical vegetation on the tropical CO_2 concentration.

Figure 3.6 draws average seasonal cycles for each 30-degree latitudinal zone. Seasonal variation in CO_2 concentration is basically induced by the activity of the terrestrial biosphere, by which CO_2 is typically absorbed by photosynthesis, emitted by respiration in vegetation and decomposed by microbes in soil (e.g. Nakazawa *et al.*, 1997b). Ocean uptake (Ramonet *et al.*, 1996) and biomass burning (Wittenberg *et al.*, 1998) are also thought to influence the seasonal variation.

Amplitudes of seasonal cycles are clearly large in northern high and mid-latitudes and small in the Southern Hemisphere. The seasonal cycle in the Northern Hemisphere reflects an influence of absorption/emission in the biosphere there. The small amplitudes in the Southern Hemisphere are attributed to small amounts of absolute emission/absorption by the terrestrial biosphere and offset the contributions of oceans and biomass burning. A semiannual cycle is displayed only in southern low latitudes. The direct influence of sources and sinks in the Southern Hemisphere might be partly canceled by diffusion of out-of-phase seasonal variation from the Northern Hemisphere.

The maximum concentration in the seasonal cycle appears in March in northern mid-latitudes, and in northern high and low latitudes, their maximum concentrations are delayed by one or two months. Months of minimum concentration appear in August in northern high and mid-latitudes and in September in northern low latitudes. The reason for the delayed peak in low latitudes is that the higher-latitudes' airmass takes a few months to reach low latitudes (Tanaka *et al.*, 1987). In southern high and mid-latitudes, the maximum concentration in the seasonal cycle appears in austral early spring, and the minimum concentration appears in austral early autumn.

Figure 3.7 shows the latitudinal distributions of CO_2 concentrations in January, April, July and October in 1999. Seasonal variation of the latitudinal gradients is clearly seen corresponding to the seasonal cycle for each latitudinal zone described above.

3.2 Analysis for individual stations

Time-series analysis was made for stations in the global or regional situations: Barrow (Alaska, U.S.A.), Mauna Loa (Hawaii, U.S.A.), Tutuila (Samoa), the South Pole (Antarctica), Monte Cimone (Italy) and Ryori (Japan), which were selected taking into account the data record length and geographical location. Figure 3.8 shows the time series of monthly mean concentrations, deseasonalized long-term trends, growth rates for each year and average seasonal cycles for each of the above stations.

At all stations except Barrow, the highest growth rate was recorded in 1997/1998. The highest increase in 1997/1998 at Mauna Loa was also reported by Bell *et al.* (1999). These high growth rates observed globally were probably caused by the anomalously strong El Niño event in 1997/1998. The lower temperature influenced all of the stations after the eruption of Mt. Pinatubo, and the growth rates decreased with different timing. In the northern high and mid-latitude stations, i.e., Barrow, Monte Cimone and Ryori, the lowest growth rates were recorded from the end of 1991 to the beginning of 1992. In the northern low-latitude and the southern stations, i.e., Mauna Loa, Tutuila and the South Pole, however, the lowest rates were recorded from the end of 1992 to the beginning of 1993.

The amplitude of the seasonal cycle is considerably large at Ryori and Monte Cimone, and further larger amplitudes can be seen at Barrow, because the variation of net CO_2 flux from the terrestrial biosphere is larger in high latitudes.