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NOTES AND CORRESPONDENCE

Interannual Variation of Growth Rate of Atmospheric Carbon Dioxide Concentration Observed at the JMA's Three Monitoring Stations: Large Increase in Concentration of Atmospheric Carbon Dioxide in 1998

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Abstract

The Japan Meteorological Agency has been monitoring carbon dioxide (CO_2) concentrations in the atmosphere continuously with non-dispersive infrared gas analyzers since January 1987 at Ryori, March 1993 at Minamitorishima, and January 1997 at Yonagunijima. At Ryori with our longest record, a large variation was found in CO_2 growth rate in association with significant global events such as El Niño and the eruption of Mt. Pinatubo, suggesting that global changes in the carbon cycle are closely connected with the climate. The annual growth rates in CO_2 concentration were 3.0 ppm at Ryori, 2.8 ppm at Minamitorishima, and 3.1 ppm at Yonagunijima in 1998. At Ryori and Minamitorishima, they were the largest since the beginning of measurement. It is supposed that this large growth rate is attributed to the strong El Niño event in 1997/98.

1. Introduction

The increased concentration of atmospheric carbon dioxide (CO_2), by enhancing the so-called greenhouse effect, induces global warming and then affects considerably the global ecosystems and human life. CO_2 is distributed among the atmosphere, ocean and terrestrial biosphere, which serve as reservoirs of CO_2 in the global carbon cycle. Large amounts of CO_2 in the reservoirs are exchanged among them and the global carbon cycle is coupled with the climate system on seasonal, interannual, and decadal time-scales. Understanding of the global carbon cycle is essential to estimate future CO_2 concentrations in the atmosphere.

CO_2 fluxes in the ocean and land biosphere fluctuate significantly year to year (Francey et al. 1995; Keeling et al. 1995; Nakazawa et al. 1997a). It is widely known that the growth rate in atmospheric CO_2 concentration is related to the activity of ENSO (El Niño and Southern Oscillation). The CO_2 growth rate at Mauna Loa, Hawaii, is negatively correlated to the Southern Oscillation Index (SOI) with a lag of 5 months (Thoning 1989), and positively to the anomaly in sea surface temperature (SST) in the eastern equatorial Pacific with a lag of one to two seasons (Eliott 1991). However, the El Niño event in 1991/1992 was an exception. It was suggested that the climatic response to the eruption of Mt. Pinatubo in June 1991 had contributed to the increased uptake of CO_2 by the northern terrestrial biosphere and the ocean (Conway et al. 1994; Rayner et al. 1999).

The Japan Meteorological Agency (JMA) has made measurements of atmospheric CO_2 concentrations continuously at its three stations in Japan to monitor not only a long-term trend of CO_2 concentrations, but also its temporal variations in principal climate zones and/or major biomes. These stations

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are part of the worldwide network of the Global Atmospheric Watch (GAW) programme of the World Meteorological Organization (WMO).

This paper reports interannual variations of the growth rate in atmospheric CO_2 concentration, especially an anomalously large increase in 1998, observed at the JMA's three stations. We firstly describe the site environment and measurement method for atmospheric CO_2, secondly present a method of background data selection, thirdly introduce observational results, followed by a conclusion.

2. Measurement of atmospheric carbon dioxide

2.1 Measurement sites

The JMA has monitored atmospheric CO_2 concentrations continuously at Ryori (39°02′N, 141°50′E, 230 m above mean sea level), Minamitorishima (24°18′N, 153°58′E, 8 m above mean sea level), and Yonagunijima (24°28′N, 123°01′E, 30 m above mean sea level) since January 1987, March 1993, and January 1998, respectively (Fig. 1). Since the start of observation, no stations have experienced data missing for more than one month due to a breakdown or maintenance of the instrument. The longest breakdown so far, about one month at Minamitorishima, was caused by a severe typhoon in September 1997.

Ryori is located on the Pacific coast of the Tohoku Region, northeastern Japan. The station is sited on a hill top in an unpopulated peninsula. A road exists but the traffic is scarce. The station is surrounded by a mixture of grassland, cedars, and broad-leaved deciduous trees. The climate is temperate and characterized by four clear seasons. The monthly mean temperatures are below 0°C in January and February and about 21°C in August. The annual average is about 10°C. The precipitation is high from June to September, but low in winter. The annual precipitation is about 1,300 mm. Westerly winds prevail throughout the year, but southerly or easterly winds are also observed in summer.

Minamitorishima is an isolated coral island in the Northwest Pacific about 2,000 km southeast of Tokyo. The island has an area of about 1.4 km^2 and usually a population of about fifty. The island is flat with sparse broad-leaved evergreen trees. The station is situated on the eastern coast. The island has a subhumid tropical climate and an average monthly temperature exceeding 20°C throughout the year. The annual precipitation is about 1,150 mm in normal and early spring is a dry season. As the island is situated on the southern edge of the Pacific high, easterly winds prevail year-round. The average wind speed is about 5 m sec^{-1}.

Yonagunijima is located at the western edge of the Nansei Islands, merely 111 km apart from Taiwan. The station is situated near the northern coast of the island, surrounded by grassland and sugar cane fields. The island is dominated by the continental high in winter and the Pacific high in summer. The monthly average temperatures exceed 25°C from May to October, and about 18°C in January and February. The annual range of temperature is larger than that at Minamitorishima, which is located approximately in the same latitude. The annual precipitation is 2,330 mm. Much of it is generated in winter and/or by the Baiu front and typhoons. Winds from NNE to NE from the continental high prevail in winter and southerly winds from the Pacific high in summer. In winter, the maximum wind speed exceeds 10 m sec^{-1} and cloudy and rainy days are often experienced.

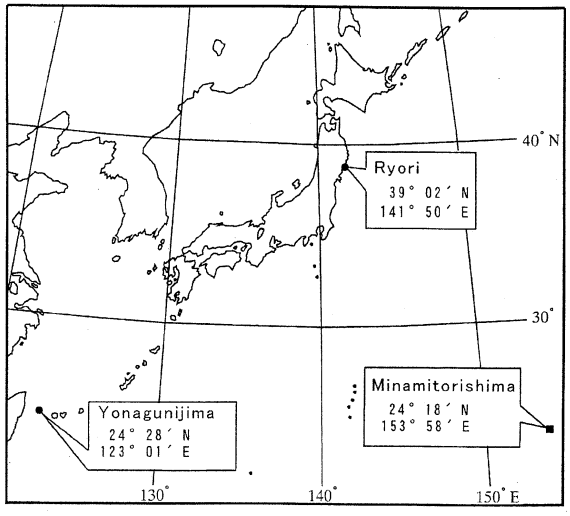

Fig. 1. Monitoring network of the Japan Meteorological Agency for CO_2 continuous measurement.

2.2 Measurement method

Non-dispersive infrared (NDIR) gas analyzers (HORIBA VIA-500R at Ryori and HORIBA VIA-510R at Minamitorishima and Yonagunijima) are used for the continuous measurement of atmospheric CO_2. The basic principle of measurement is almost the same as that at Mauna Loa, Hawaii operated by the National Oceanic and Atmospheric Administration (NOAA) (Komhyr et al. 1989). Air sample is taken from an inlet mounted at a height of 20 meters on a tower in order to minimize effects of human activities and ecosystem around the stations, and then dehumidified step by step to a dew point below −65°C with an electric cooler, a Nafion dryer, and magnesium perchlorate. Four working standards of CO_2-in-natural air mixture, ranging from 340 to 400 ppm as of 1998, are used to calibrate the analyzer every two hours.

The JMA maintains an observation scale with primary, secondary and working standards. All standard gases were CO_2-in-air mixtures prepared volumetrically by Nippon Sanso Corporation, Japan

(Tanaka et al. 1987). The primary standards were calibrated in the WMO scale in 1995 at the Scripps Institution of Oceanography (SIO). A set of four working standards is used at the stations for three to four months. They are calibrated at the headquarters in Tokyo before the shipment and again when they are back to Tokyo six to twelve months later. The objective of the calibration, through the secondary standards, is to determine exactly the concentration and monitor a drift in concentration of working standard gases. The drift is normally within 0.1 ppm. The CO_2 concentrations are calculated on the assumption that the drift proceeds linearly. The secondary standards are calibrated by the primary standards semiannually to check their concentrations.

The analyzer in the measuring system produces voltage signals every second, which are averaged over 30 seconds with an attached data processor. The 30-second-average voltages are converted to CO_2 concentrations and the quality is checked routinely at the Atmospheric Environment Division of the JMA in Tokyo. The conversion from output voltages to CO_2 concentrations is made with a quadratic calibration equation determined every two hours by the least square method between the output voltages and CO_2 concentrations for the four working standards. In order to minimize errors from the response instability of the gas analyzer, concentrations are calculated in a duplicate manner with the two calibration equations determined from bracketing two series of standard gas measurement. The obtained two values are averaged in a time-weighting manner to determine a concentration to be referred to as 30-second-average raw data.

It is supposed that the SIO calibrates the JMA's primary standards against the WMO scale with a precision of 0.1 ppm. The calibration system of the JMA determines the CO_2 concentrations of the working standards with a precision of 0.02 ppm. The precision of the NDIR measurement, estimated from the standard deviation in repeated measurements of the same standard gases, is 0.02 ppm for Minamitorishima and Yonagunijima and 0.06 ppm for Ryori. The overall uncertainty, attributed to the calibrations of primary, secondary, and working standards, drifts of the working standards, measurement errors at site, and so on, is estimated to be 0.1 to 0.2 ppm.

3. Data selection for background values

Raw data obtained as above may represent a local pollution by human and/or biotic activities. Therefore, only those data that represent non-polluted and well-mixed air, must be selected for analysis on a global scale. Such data are referred to as background data. In the JMA, background hourly data are selected when the following criteria are completely met:

a) at least 60 raw data are averaged for an hourly value,

b) the hourly value has a standard deviation of less than the value A mentioned below,

c) neither of the differences from the bracketing hourly values exceeds the value B mentioned below.

The values A and B are determined for each station by finding a condition that the annual or monthly averages become stable as the criterion for the value A or B is tighten gradually, i.e. the value is lessen little by little. In many cases, the calculated annual or monthly averages decrease as the value A or B is lessen. This suggests that data of high concentration mainly due to human sources are removed effectively. For the value A, we have adopted 0.6 ppm for Ryori and Yonagunijima and 0.3 ppm for Minamitorishima. The value B is 0.6 ppm for Ryori and 0.3 ppm for the others.

Figure 2 shows selected background and removed non-background hourly data marked with different symbols at the three stations in 1998. After the selection procedure mentioned above, approximately 40 % of the hourly data remain at Ryori, 80 % at Minamitorishima, and 60 % at Yonagunijima. The percentage of remaining data is constant year-round at Minamitorishima, but seasonally varied at Ryori and Yonagunijima. It is about 20 % in summer and 50 % in the other seasons at Ryori, while at Yonagunijima 40 to 60 % from April to September and 60 to 80 % in the other months. The high percentage at Minamitorishima is due to prevailing easterly winds, location of the site facing the ocean to the east, and sparse anthropogenic CO_2 on the island. At Ryori and Yonagunijima, the percentage is high in the season when well-mixed air masses reach from the continent with the monsoon.

At Minamitorishima, where only sparse vegetation covers the ground, the monthly-mean diurnal changes, defined as the differences between the maximum at night and minimum in the daytime of all raw hourly data, are less than 1 ppm. However, they are about 8 ppm at Ryori and 3 ppm at Yonagunijima in July when photosynthesis is considered to be active. Levin et al. (1995) reported large diurnal changes in July at GAW stations in Germany. They are as high as above 40 ppm at Waldhof (53°N, 11°E, 73 m above mean sea level) in a northern agricultural area and about 20 ppm at Deuselbach (50°N, 7°E, 480 m above mean sea level) in a western hilly terrain. Nakazawa et al. (1997b) also demonstrated a large amplitude of about 40 ppm at a forest station located east of Takayama, central Japan (36°N, 137°E, 1,420 m above mean sea level). These reports suggest that the local vegetation does not influence so much the observations at Ryori and

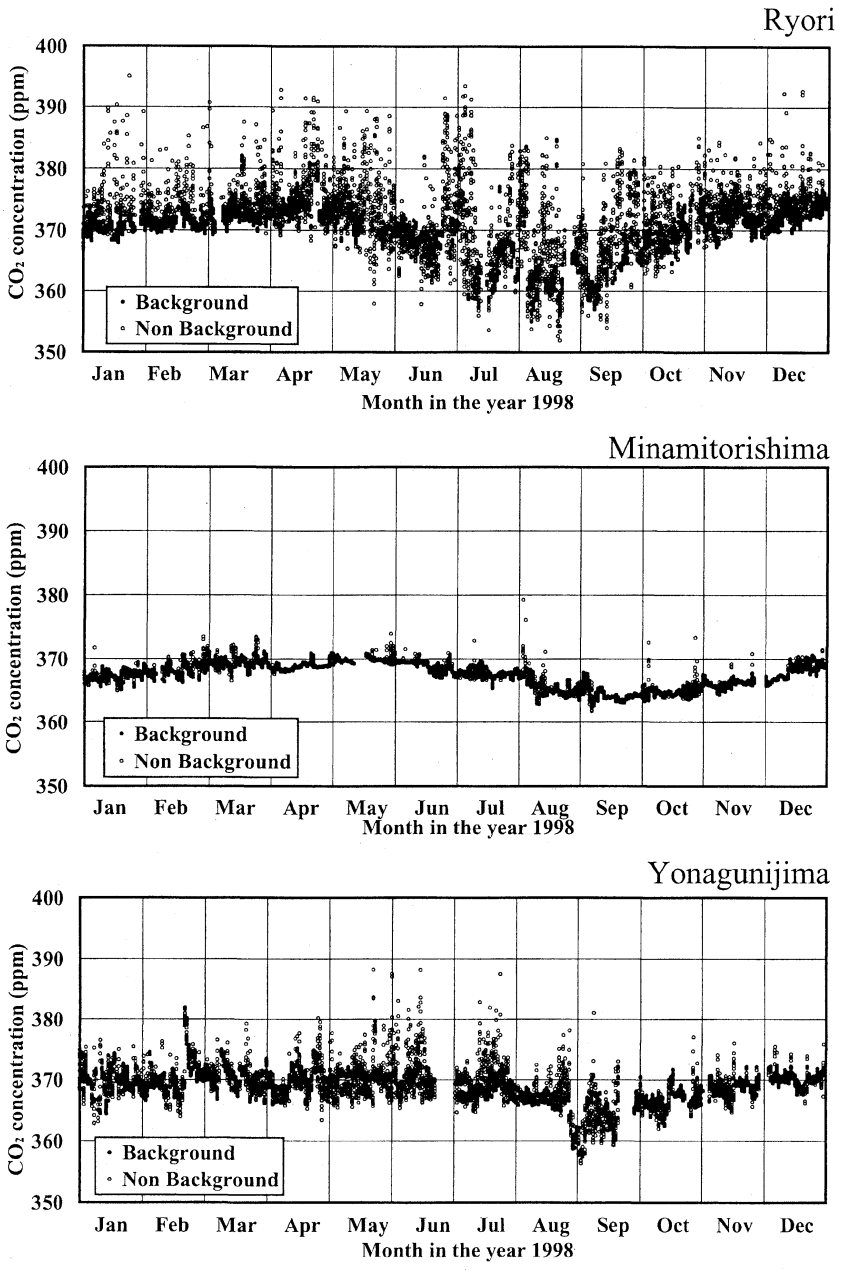

Fig. 2. Hourly data at Ryori, Minamitorishima and Yonagunijima in 1998. Closed and open dots represent background and non-background data, respectively.

Yonagunijima where the diurnal amplitudes calculated from the selected background hourly data are as small as 1 to 2 ppm in summer.

Daily and monthly averages are calculated from background hourly data, and annual ones from monthly data.

4. Observational results and discussions

The observational results and discussions in this section are based on monthly mean concentrations calculated from the background hourly concentrations as written in the previous section. Figure 3 depicts a time series of monthly mean CO_2 concentrations at the three stations of the JMA. For all stations, it is clearly shown that atmospheric CO_2 concentrations vary seasonally with high values in spring and low in summer to early autumn and increase gradually year by year. The seasonal variation is attributed to photosynthesis and respiration in the biosphere (Nakazawa et al. 1997b), and the gradual annual increase to anthropogenic emission. The two subtropical stations, Minamitorishima and

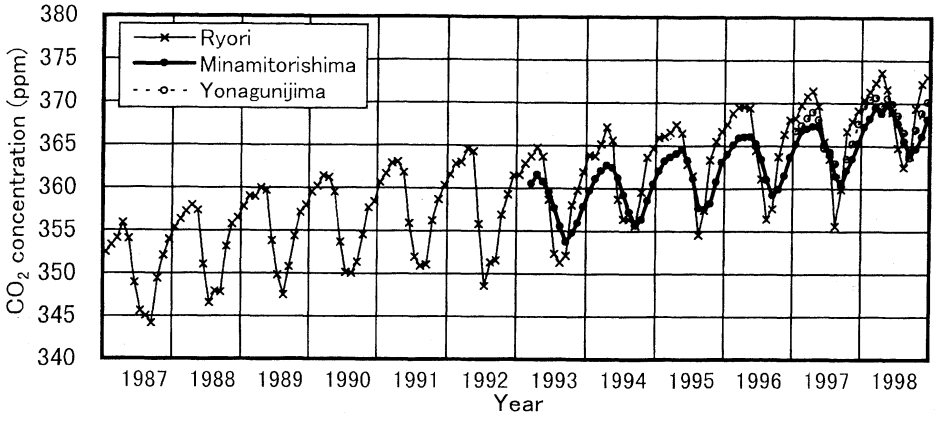

Fig. 3. Time series of monthly mean atmospheric CO_2 concentrations at Ryori, Minamitorishima, and Yonagunijima. Monthly mean values are calculated from hourly data selected as background.

Yonagunijima, are located almost in the same latitude, and the concentrations at both stations are comparable in summer. However, in winter, the concentrations are slightly higher at the latter station. While Minamitorishima receives winds sweeping over the sea throughout the year, Yonagunijima does only in the warm season. In winter, the continental high covering the latter station leads the winds from the continent. This suggests that Yonagunijima, in winter, is susceptible to the Asian continent where CO_2 concentrations are observed to be higher supposedly due to inactive photosynthesis in this season and anthropogenic emission.

Averaged seasonal cycle and a deseasonalized long-term trend are derived from a time series of monthly concentrations by iteratively applying digital filtering, which is similar to the one used by Nakazawa et al. (1991a). The averaged seasonal cycle is expressed as the following Fourier harmonics:

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

where t is elapsed time (years) relative to the beginning of observation, and value k is set to 3 so that average seasonal cycles are satisfactorily expressed. The difference between the present procedure and that of Nakazawa et al. (1991a) is that we used a Lanczos filter (Duchon 1979), as a low-pass digital filter with a cut-off frequency of 0.48 cycle year^{-1} while the latter used the 26th-order Butterworth filter.

Figure 4 shows the averaged seasonal cycle for the JMA's three stations. The amplitudes are about 13 ppm at Ryori, and about 8 ppm at Minamitorishima and Yonagunijima. Nakazawa et al. (1997a) revealed from shipboard flask sampling observations in the western Pacific that the amplitudes of a seasonal cycle were about 15 ppm at 40°N, 9 ppm at 30°N and 7 ppm at 20°N. These results are consistent with our results. The difference in amplitude among the JMA's stations is due to the fact that Ryori is located in a higher latitude than the other two stations, and affected more by seasonally varying activity of land vegetation. The maximum concentration appears in March or April at all stations, while the minimum in August at Ryori and in September at the others. The phases of the seasonal cycle in the western Pacific shown by Nakazawa et al. (1997a) are consistent with those at the JMA's stations.

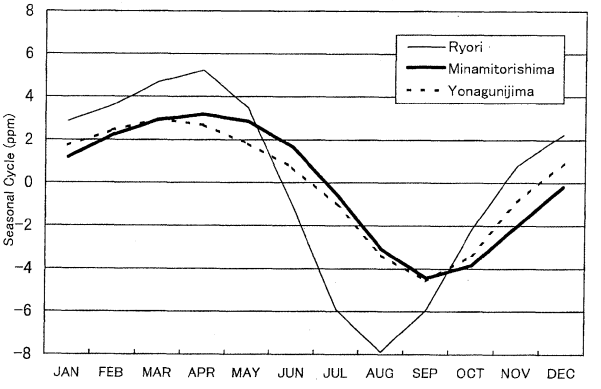

Fig. 4. Averaged seasonal cycles of atmospheric CO_2 concentration at Ryori, Minamitorishima, and Yonagunijima from the beginning of observation to 1998.

Figure 5 shows long-term trends of monthly-mean CO_2 concentrations at Ryori, Minamitorishima, and Mauna Loa. The trend curves of Ryori and Mauna Loa increase almost in parallel. This shows that the CO_2 concentrations at Ryori reflects the variation in the global carbon cycle. Table 1 shows annual mean CO_2 concentrations at the JMA's three stations and Mauna Loa. In 1998, the annual mean CO_2 concentrations were 369.5 ppm, 367.4 ppm, and 368.8 ppm at Ryori, Minamitorishima, and Yonagunijima, re-

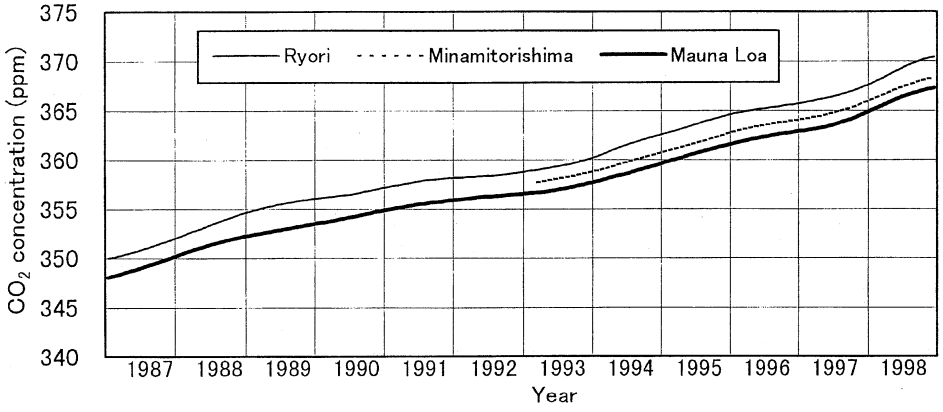

Fig. 5. Long-term trend of atmospheric CO_2 concentrations at Ryori, Minamitorishima, and Mauna Loa. The long-term trend is derived from monthly mean CO_2 concentrations with the iterative procedure written in this literature.

Table 1. Annual mean atmospheric CO_2 concentrations (ppm) at Ryori, Minamitorishima, Yonagunijima, and Mauna Loa. An annual mean concentration is calculated from 12 monthly mean data from January to December. The monthly mean values at Mauna Loa come from the CD-ROM of WMO/WDCGG (World Data Centre for Greenhouse Gases), 1999, for the data between 1987 and 1995, Summary Report of CMDL (NOAA/CMDL 1998) between 1996 to 1997 and a personal communication with P. Tans and K. Thoning at the NOAA/CMDL, Boulder, CO (1999) for the year 1998.

Year	Ryori	Minamitorishima	Yonagunijima	Mauna Loa
1987	350.8	-	-	349.0
1988	353.6	-	-	351.5
1989	355.6	-	-	352.9
1990	356.5	-	-	354.2
1991	358.0	-	-	355.5
1992	358.5	-	-	356.3
1993	359.3	-	-	357.0
1994	361.7	359.7	-	358.6
1995	363.7	361.6	-	360.6
1996	365.2	363.4	-	362.4
1997	366.5	364.6	365.7	363.5
1998	369.5	367.4	368.8	366.5

spectively. The annual increases, defined as the difference of the annual mean concentration in a year from the one in the previous year, were 3.0 ppm, 2.8 ppm, and 3.1 ppm at Ryori, Minamitorishima, and Yonagunijima, respectively.

Figure 6 shows the time series of annual increases at the JMA's three stations. At Ryori, where the average annual increase is 1.7 ppm over the period from 1988 through 1998, the annual increase in 1998 was 1.8 times as large as the average. In the same year, the increases were the largest at Ryori and Minamitorishima since the beginning of measurement. The largest annual increase of 3.0 ppm was also observed in 1998 at Mauna Loa, Hawaii, where measurement began in 1958 (Bell et al. 1999).

Figure 7 displays the growth rates in CO_2 concentration at the JMA's stations expressed as the derivative of the long-term trend curves. The growth rates at Ryori were considerably high in 1988 (2.8 ppm $year^{-1}$ at peak) and 1994 (2.7 ppm $year^{-1}$ at peak), but much higher in 1998 (3.6 ppm $year^{-1}$ at peak). The peak of the growth rate in 1998 was seen firstly at Yonagunijima in February (3.2 ppm $year^{-1}$), secondly at Minamitorishima in March (3.0 ppm $year^{-1}$), and lastly at Ryori in April. Interannual variations in atmospheric CO_2 concentration are considered to be attributed to ENSO events as one of the major affecting factors. Five-month-running-mean anomalies in the sea surface temperature (SST) in the eastern equatorial Pacific (4°N–4°S, 150°W–90°W) are also shown in Fig. 7. SST is analyzed globally for areas of two degrees in latitude and longitude operationally at the Oceanographical Division of the JMA (JMA/Oceanographical Division 1990). SST anomalies are calculated with respect to the 30-year climatologi-

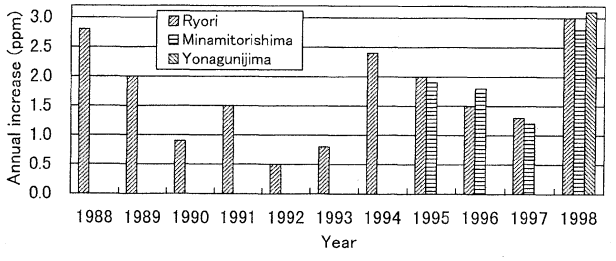

Fig. 6. Time series of annual increases in atmospheric CO_2 concentration at Ryori, Minamitorishima, and Yonagunijima. The annual increase is defined as the difference in annual mean concentration from the corresponding value in the previous year.

cal normals between 1961 and 1990. Averaged SST anomaly in this region is an indicator of ENSO activity used in the JMA.

It is likely that there is a correlation between the growth rates in CO_2 concentration at Ryori and the SST anomalies in the eastern equatorial Pacific with a lag of several months. The correlation coefficient is the highest at 0.87 with a lag of 6 months in the period from April 1993 to November 1998 (Fig. 8). The atmospheric CO_2 changes are positively correlated to the SST changes in the tropics with a lag of 6 to 8 months, in spite of local reverse effects in the eastern equatorial Pacific, where El Niño events suppress upwelling of CO_2-rich deep water resulting in lower CO_2 concentrations in the atmosphere (Dettinger and Ghill 1998). In general, El Niño events bring about extreme meteorological events, in particular high temperature and low precipitation mainly in the tropics (Ropelewski and Halpert 1987; Halpert and Ropelewski 1992). Such abnormal weather events have effects, in many cases, to activate respiration of plants and decomposition of organic matters in soil and inactivate plant photosynthesis, and thus generally lead to increase CO_2 concentrations in the global atmosphere.

In 1997/1998, an anomalously strong El Niño event occurred. The climate system involving the atmosphere, oceans, land, terrestrial biosphere, and so on largely deviated from normal conditions. Anomalously low precipitation brought about frequent droughts and forest fires in southeast Asia in 1997/1998, and the global mean temperature was the highest ever in 1998 (JMA 1999). Such extreme climate conditions perturbed the global carbon cycle, and accelerated the increase of CO_2 concentrations in the atmosphere.

Volcanic eruption is another important factor inducing annual variation in the growth of atmospheric CO_2 concentration. Figure 8 shows that the correlation between the CO_2 growth rates and the SST anomalies in the eastern equatorial Pacific largely deviated in the period from June 1991 to March 1993. Volcanic effects overwhelmed the CO_2 increases expected for 1992 and 1993, following the El Niño event in 1991/92. The lowest growth rate in CO_2 concentration was recorded in 1992 as shown in Fig. 7. Negative values in the growth rate were seen in northern high latitudes in late 1992 (JMA/WMO 2000). It was suggested that the climatic response to the eruption of Mt. Pinatubo in June 1991 had contributed to the increased uptake of CO_2 by the northern terrestrial biosphere and the ocean (Conway et al. 1994; Rayner et al. 1999).

It is noted that there are other factors affecting the CO_2 growth (Nakazawa et al. 1991b). The high growth rate of atmospheric CO_2 concentration in 1995 cannot be attributed to an ENSO event. The second highest global mean temperature recorded in 1995 (JMA 1999) may have brought about the high CO_2 growth in the same year. The relationship between a global high temperature and a high growth rate of atmospheric CO_2 concentration should be discussed in detail, but those are beyond the scope of this article.

5. Conclusion

The Japan Meteorological Agency (JMA) has been monitoring atmospheric CO_2 concentrations continuously since January 1987 at Ryori, March 1993 at Minamitorishima, and January 1997 at Yonagunijima. Observed atmospheric CO_2 concentrations have a clear signal of seasonal change and a long-term increasing trend. In 1998, the annual increases on the basis of the values in the previous year were 3.0 ppm, 2.8 ppm, and 3.1 ppm at Ryori, Minamitorishima, and Yonagunijima, respectively. These were the largest at Ryori and Minamitorishima since the beginning of measurement. The annual increase at Ryori was about 1.8 times as large as the averaged annual increase of 1.7 ppm over the period from 1988 to 1998.

At Ryori where the longest record is kept, the growth rates in atmospheric CO_2 concentration from 1987 to 1998 show a distinct interannual variation. The correlation coefficient between the growth rates and the SST anomalies in the eastern equatorial Pacific (4°N–4°S, 150°W–90°W) is a maximum of 0.87 when the SST anomalies lead the growth rates by 6 months. However, this relationship largely deviated due to a declined growth of CO_2 concentrations following the global cooling after the eruption of Mt. Pinatubo in 1991. These interannual variations of growth rates strongly suggest a close relationship between the global carbon cycle and the global climate.

The large annual increases in atmospheric CO_2 concentration observed in 1998 at the JMA's three stations, Ryori, Minamitorishima, and Yonagunijima, are considered to be a consequence of the

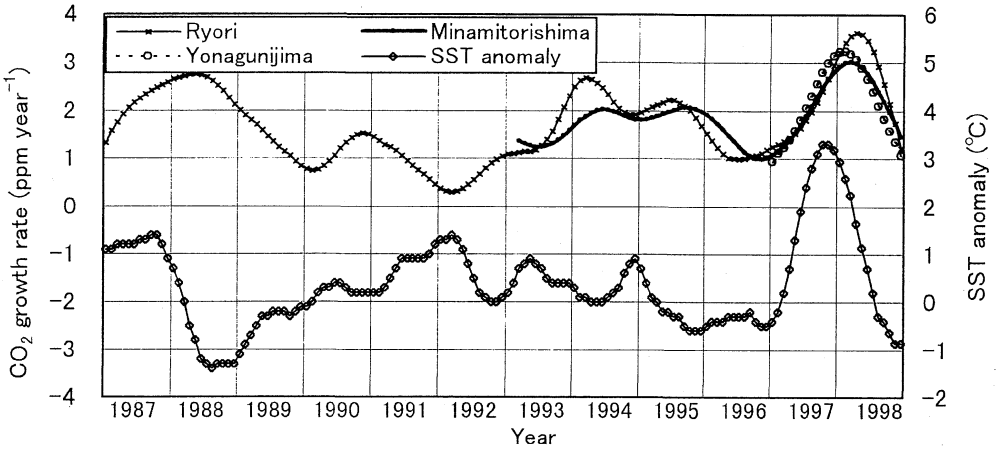

Fig. 7. Growth rates in atmospheric CO_2 concentration at Ryori, Minamitorishima, and Yonagunijima, and 5-month running mean values of the SST anomaly in the eastern equatorial Pacific (4°N–4°S, 150°W–90°W), an indicator of ENSO activity. The growth rate is defined as the derivative of the long-term trend curve and expressed as the equivalent value of annual growth.

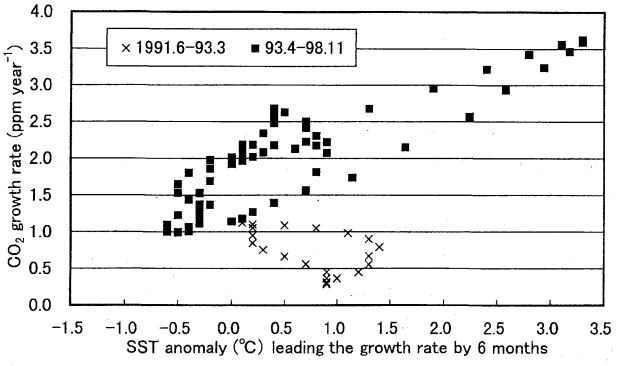

Fig. 8. Relationship between growth rates in atmospheric CO_2 concentration at Ryori and 5-month running mean values of the SST anomaly in the eastern equatorial Pacific (4°N–4°S, 150°W–90°W) leading the growth rates by 6 months. Square dots are used for the period from April 1993 to November 1998, and crosses for the period from June 1991 to March 1993.

anomalously strong El Niño event in 1997/1998. It is important that the continuous monitoring of atmospheric CO_2 concentration should be maintained to clarify further the relationship between the variation of the global climate and that of the global carbon cycle.

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気象庁の3観測地点で観測された大気中の二酸化炭素濃度増加率の年々変動：1998年に見られた大きな大気中の二酸化炭素濃度の増加

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気象庁では1987年1月から綾里、1993年3月から南鳥島、1997年1月からは与那国島において、非分散型赤外線分析計を用い、大気中の二酸化炭素濃度を連続的に測定している。最も観測データが蓄積されている綾里では、エルニーニョ現象やピナトゥボ火山噴火に伴う二酸化炭素濃度増加率の大きな年々変動が見られ、全球的な気候変化と炭素循環の変動が密接に関係していることが示唆される。また、1998年には前年の年平均濃度と比べた年増加量が、綾里では3.0 ppm、南鳥島では2.8 ppm、与那国島では3.1 ppmで、綾里と南鳥島では観測開始以来最大の大きさであった。この大きな年増加量は1997/1998年の大規模なエルニーニョ現象が引き起こしたと考えられる。

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