Chapter 3  Atmospheric and Marine Environment Monitoring

3.1 Monitoring of greenhouse gases

- Concentrations of carbon dioxide both in the air and in oceans are increasing.
- Concentrations of atmospheric methane have shown an ongoing increase (with the exception of a plateau period from 1999 to 2006).
- Concentrations of atmospheric nitrous oxide are increasing.

JMA operates the World Data Centre for Greenhouse Gases (WDCGG) to collect, maintain and provide data on greenhouse gases for related monitoring on a global scale under the WMO/GAW Programme. Analysis of data reported to WDCGG shows that the global mean concentration of greenhouse gases with strong impacts on global warming (in particular, carbon dioxide (CO$_2$), methane (CH$_4$) and nitrous oxide (N$_2$O)) continues to increase (Table 3.1-1).

In Japan, JMA monitors surface-air concentrations of greenhouse gases via three observation stations at Ryori in Ofunato, Minamitorishima in the Ogasawara Islands and Yonagunijima in the Nansei Islands. In the western North Pacific, JMA's research vessels observe oceanic and atmospheric CO$_2$. In addition, sampling of greenhouse gases in upper-air areas using cargo aircraft was commenced in 2011 (Figure 3.1-1).

Table 3.1-1  Atmospheric concentrations of major greenhouse gases (2016)

<table>
<thead>
<tr>
<th>Atmospheric mole fraction</th>
<th>Pre-industrial level around 1750</th>
<th>Global mean in 2016</th>
<th>Relative increase from Pre-industrial level</th>
<th>Absolute increase from 2015</th>
<th>Relative increase from 2015</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>About 278 ppm</td>
<td>403.3 ppm</td>
<td>+ 45 %</td>
<td>+3.3 ppm</td>
<td>+0.83 %</td>
<td>-</td>
</tr>
<tr>
<td>Methane</td>
<td>About 722 ppb</td>
<td>1,853 ppb</td>
<td>+157 %</td>
<td>+9 ppb</td>
<td>+0.49 %</td>
<td>12.4 years</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>About 270 ppb</td>
<td>328.9 ppb</td>
<td>+ 22 %</td>
<td>+0.8 ppb</td>
<td>+0.24 %</td>
<td>121 years</td>
</tr>
</tbody>
</table>

28 Information on greenhouse gas monitoring is published on JMA’s website.
https://www.data.jma.go.jp/ghg/info_ghg_e.html (Atmospheric greenhouse gases)
https://www.data.jma.go.jp/gmd/kaiyou/english/oceanic_carbon_cycle_index.html

29 See the WDCGG website for more information.
https://gaw.kishou.go.jp/

30 Data on the annual mean mole fraction in 2016 and its absolute and relative differences from the previous year are from WMO (2017), while data on pre-industrial levels and lifetime are from IPCC (2013). The lifetime of gas as referred to here describes the time scale over which a local instantaneous increment of gas decays. The increase from pre-industrial levels is calculated from mole fractions for the pre-industrial era and 2016.
3.1.1 Concentration of carbon dioxide

(1) Concentration of global atmospheric carbon dioxide

The global mean concentration of atmospheric CO$_2$ shows a trend of increase with ongoing seasonal variations (Figure 3.1-2), primarily due to influences associated with human activity such as fossil fuel combustion and deforestation. Some anthropogenic CO$_2$ is absorbed by the terrestrial biosphere and the oceans, while the rest remains in the atmosphere. As most major sources of CO$_2$ are located in the Northern Hemisphere, concentrations tend to be higher in the mid- and high latitudes there and lower in the Southern Hemisphere (Figure 3.1-3).

The seasonal variability of CO$_2$ concentration is generally attributable to terrestrial biosphere activity. In summer, active plant photosynthesis consumes masses of CO$_2$, while emissions from plant respiration and organic-matter decomposition become dominant in winter. As a result, the annual maximum concentration is observed from March to April in the Northern Hemisphere and from September to October in the Southern Hemisphere. Seasonal variations exhibit larger amplitudes in the mid- and high latitudes of the Northern Hemisphere than in the Southern Hemisphere because the latter is much less land-rich (Figure 3.1-3). Accordingly, the global mean CO$_2$ concentration usually peaks around April, reflecting the seasonal variations of the Northern Hemisphere.

WDCGG analysis shows that the global mean CO$_2$ concentration increased by 3.3 ppm from 2015 to 2016, reaching as much as 403.3 ppm (Table 3.1-1). This annual increment is the highest since analysis began. The most recent 10-year average annual growth rate is 2.2 ppm/year, as opposed to the corresponding value of 1.5 ppm/year for the 1990s.
The growth rate of CO₂ concentration exhibits significant interannual variations (Figure 3.1-2 (b)). Major increases in concentration often coincide with El Niño events, largely because the terrestrial biosphere emits more CO₂ than usual under such conditions. In particular, El Niño events bring about high temperatures and droughts in tropical areas and elsewhere, thereby promoting plant respiration and organic-matter decomposition in soil and hindering plant photosynthesis (Keeling et al., 1995; Dettinger and Ghil, 1998).

Figure 3.1-4 illustrates net CO₂ uptake by the terrestrial biosphere as estimated using the method of Le Quéré et al. (2016). Here, CO₂ uptake is defined as the amount of anthropogenic emissions minus the increment of atmospheric concentration and the amount of uptake by oceans. The low uptake by the terrestrial biosphere in 2015 is generally attributed to the 2014 – 2016 El Niño event (WMO, 2017). The annual net CO₂ uptake in 2015 was 2.2 ± 1.1 GtC/year, which is lower than the 10-year average of 3.4 ± 1.0 GtC/year for the period 2006 – 2015. Similar suppression of net CO₂ uptake was observed in association with the El Niño events of 1997/1998, 2002/2003 and 2009/2010. In 1998 in particular, the lowest net uptake since 1990 was recorded. An exception was observed from 1991 to 1992, when net CO₂
uptake by the terrestrial biosphere was large despite the presence of an El Niño event. This is attributable to the eruption of Mt. Pinatubo in June 1991, which triggered worldwide low temperatures and inhibited CO₂ emissions from organic-matter decomposition in soil (Keeling et al., 1996; Rayner et al., 1999).

Figure 3.1-4  Annual net CO₂ uptake by the terrestrial biosphere

In this analysis, the net CO₂ uptake is estimated by subtracting the annual increment of atmospheric CO₂ and the amount of uptake by oceans from the amount of anthropogenic emissions. The amount of anthropogenic emissions, stemming from fossil fuel combustion and land-use changes, is based on Le Quéré et al. (2017). The annual increment of atmospheric CO₂ is the annual mean of the monthly means shown in Figure 3.1-2 (b). Oceanic uptake is based on Iida et al. (2015; see also Section 3.1.1 (3)), and incorporates emissions associated with the natural carbon cycle, corresponding to 0.7 GtC/year (IPCC 2013). Error bars indicate 68% confidence levels. El Niño and La Niña periods are shaded in red and blue, respectively. A negative CO₂ uptake equates to an emission.

(2) Concentration of atmospheric carbon dioxide in Japan

Concentration of atmospheric CO₂ at all three of Japan’s observation stations has shown a continuous increase along with seasonal variations (Figure 3.1-5 (a)). The amplitude of these variations is greater at Ryori than at the other stations because Ryori is more readily affected by air from the vegetation-rich northern part of the Asian continent (see Figure 3.1-1). Although Yonagunijima and Minamitorishima have similar latitudes, the former tends to observe higher concentrations and seasonal variations with larger amplitudes because of its greater proximity to the Asian continent, which is characterized by major anthropogenic emissions and an extensive biosphere. The annual mean CO₂ concentration in 2017 was 409.2 ppm at Ryori, 407.7 ppm at Minamitorishima and 409.5 ppm at Yonagunijima. All these figures are the highest on record (based on preliminary estimations).

Figure 3.1-5 (b) shows growth rates of CO₂ concentrations observed at the three observation stations. High rates have been observed in most cases during the periods of El Niño events. As a recent example, a sharp increase in CO₂ concentration was observed in association with the event that ran from summer 2014 to spring 2016.
3. Oceanic carbon dioxide

Based on data collected by JMA's Research Vessels along the 137°E (3°–34°N) and 165°E (5°S–35°N) lines, oceanic and atmospheric pCO₂ concentrations are increasing in the western North Pacific area (Figure 3.1-6, 3.1-7). The growth rates for oceanic and atmospheric pCO₂ along the 137°E line from 1985 to 2017 were 1.3–2.1 and 1.7–1.9 µatm/year, respectively. Those along the 165°E line from 1996 to 2017 were 1.4–3.1 and 1.8–2.0 µatm/year, respectively. Oceanic pCO₂ concentrations exhibit seasonal variations, being higher in summer with higher SSTs and lower in winter with lower SSTs, and the range of variation is more volatile at higher latitudes along both lines. Meanwhile, atmospheric pCO₂ concentrations are constant and higher than oceanic pCO₂ concentrations except in summer. Consequently, the ocean absorbs atmospheric CO₂ emissions overall.
Figure 3.1-7 Time-latitude distribution of oceanic pCO₂ along the 137°E (left) and the 165°E (right) lines. Colors indicate reconstructed monthly oceanic pCO₂ value. The part on the left shows oceanic pCO₂ along the 137°E (3-34°N) since 1985 and the part on the right shows oceanic pCO₂ along the 165°E (5°S-35°N) since 1996.

Analysis of observation data reveals relationships between surface seawater CO₂ concentrations and other oceanographic parameters such as sea surface temperature (SST), salinity and chlorophyll-a concentration, which differ by region. Global oceanic CO₂ concentrations were estimated using datasets of such parameters based on these relationships, and CO₂ exchanges between the atmosphere and the ocean were calculated (Iida et al., 2015). It was found that the ocean releases CO₂ into the atmosphere in equatorial regions and the northern Indian Ocean, where seawater with a high CO₂ concentration upwells and absorbs CO₂ in other regions (Figure 3.1-8 (a)). Lower SSTs in winter and biological CO₂ consumption in spring/autumn result in lower surface ocean CO₂ concentrations and therefore higher CO₂ uptake, especially in the mid-to-high latitudes. Figure 3.1-8 (b) and (c) show monthly and annual variations in global ocean CO₂ uptake, respectively. The estimated mean annual global ocean CO₂ uptake during 1990 to 2016 was 1.8 GtC per year. Considering natural CO₂ efflux of 0.7 GtC per year (IPCC, 2013), which results from riverine input to the oceans, the amount of oceanic CO₂ uptake corresponds to 30 % of all anthropogenic CO₂ emission, which IPCC (2013) estimates to be 9 GtC per year. Global ocean CO₂ uptake is affected by the variability of global SST distribution and biological activity, and decreases/increases in boreal summer/winter (Figure 3.1-8 (b)). The estimated annual global ocean CO₂ uptake has increased since 2000.
The column inventory of oceanic CO$_2$ was estimated using long-term time-series data on dissolved inorganic carbon from 1990s (Figure. 3.1-9). The column inventory rates of oceanic CO$_2$ between the sea surface and 27.5 $\sigma_0$ (1,200 to 1,400 m in depth) along 137°E and 165°E are approximately 4 – 12 and 3 – 12 tC·km$^{-2}$·year$^{-1}$, respectively. The column inventory rates of oceanic CO$_2$ around 20 – 30°N are higher than those at 10°N and 35°N. This is caused by the transport of CO$_2$ from the surface to the ocean interior by water masses known as North Pacific subtropical mode water and North Pacific intermediate water.
(4) Ocean acidification

The ocean acts as a large sink for CO$_2$ emitted as a result of human activity, and the chemical properties of seawater have changed due to the uptake and reserve of anthropogenic CO$_2$. Ocean acidification, known as the decrease in seawater pH (hydrogen ion exponents), is a particular issue of concern because it accelerates global warming by limiting the ocean's capacity of CO$_2$ uptake from the atmosphere and affects marine ecosystems by disturbing plankton growth. The IPCC AR5 (2013) included an estimate that the average global surface seawater pH has decreased by 0.1 due to ocean uptake of atmospheric CO$_2$ emitted as a result of human activity since the beginning of the industrial era (1750). According to numerical model experiments based on future CO$_2$ emission estimates, surface seawater pH will further decrease by 0.065 – 0.31 by the end of 21st century. The CO$_2$ absorbed by the ocean is considered to have been transported into the ocean interior through ocean circulation and biological processes, and to be causing ocean acidification in the interior as well as in the surface layer (Doney et al., 2009).

JMA has long conducted oceanographic observations in the western North Pacific to monitor long-term variability relating to the ocean, such as global warming and ocean acidification. The Agency monitors long-term trends in surface and interior seawater pH along repeat hydrographic lines at 137°E and 165°E, and performs analysis to determine the average decrease in surface seawater pH throughout the Pacific using data on oceanic CO$_2$ concentration and related factors. The results clearly show a decreasing trend in surface seawater pH for the whole Pacific, and 0.013 to 0.021 and 0.011 to 0.033 per decade at individual stations on the 137°E and 165°E lines, respectively (Figures 3.1-10 and 3.1-11). Ocean interior pH along these lines also shows decreasing trends of 0.007 to 0.035 per decade (Figure 3.1-12) with higher rates in the northern than the southern subtropics due to greater accumulation of anthropogenic CO$_2$ in the former.
Figure 3.1-10  Long-term trends of pH at each latitude in JMA’s repeat hydrographic lines at 137°E (left) and 165°E (right). Black plots show pH observation values based on pCO₂ observation data. Solid lines represent monthly pH values reconstructed using the method of Ishii et al. (2011), dashed lines show the long-term trend of pH, and numbers indicate rates of change at each latitude.

Figure 3.1-11  Time-latitude distribution of pH along the 137°E (left) and the 165°E (right) lines. Colors indicate reconstructed monthly pH values. The part on the left shows pH along 137°E (3-34°N) since 1985, and the part on the right shows pH along 165°E (5°S-35°N) since 1996.
(5) Concentration of carbon dioxide in the upper air

Since 2011, JMA has monitored CO$_2$ concentrations at an altitude of approximately 6 km along the route from Atsugi Base (35.45°N, 139.45°E) to Minamitorishima (24.28°N, 153.98°E) with support from Japan Ministry of Defense (Tsuboi et al., 2013; Niwa et al., 2014). The results shown in Figure 3.1-13 indicate an increasing pattern of concentrations with seasonal variations similar to those observed at the Minamitorishima surface station. From winter to spring, however, concentrations tend to be lower in the upper air than on the surface.

The National Institute for Environmental Studies (NIES) and the Meteorological Research Institute (MRI) conduct research on greenhouse gases in the upper air using commercial passenger aircraft under the Comprehensive Observation Network for TRace gases by AirLiner (CONTRAIL) project\(^{31}\) (Matsueda et al., 2015; Machida et al., 2008). Figure 3.1-14, which shows CO$_2$ concentrations observed at altitudes from 8 to 13 km in the 25 – 30°N and 20 – 25°S latitudinal zones on the flight route between Japan and Australia, clearly indicates increasing CO$_2$ concentrations in the upper air. In the Northern Hemisphere, the seasonal variability of concentrations in the upper air clearly reflects those of surface concentrations mainly associated with biospheric activity, although the amplitude of variations is smaller in the upper air. In the Southern Hemisphere, CO$_2$ concentrations exhibit more complicated seasonal variability with a small amplitude. This characteristic involves minor seasonal variations on the surface in the Southern Hemisphere and interhemispheric transport of CO$_2$ via the upper air from the Northern Hemisphere (Sawa et al., 2012).

---

\(^{31}\) The CONTRAIL project is run by NIES, MRI, Japan Airlines (JAL), JAMCO Tokyo and the JAL Foundation (JALF). The initiative has been financially supported by the Ministry of the Environment since 2006. The series of observations originates from a joint project first run in 1993 by MRI, JAL, JALF and the Ministry of Transport.
Figure 3.1-13 Concentrations of atmospheric CO$_2$ at an altitude of approximately 6 km on the flight route between Atsugi Base and Minamitorishima

Black dots represent individual observation values, the blue line shows averages for individual flights, and the red line shows monthly means of observation values at the Minamitorishima surface station.

Figure 3.1-14 Concentrations of atmospheric CO$_2$ on the flight route between Japan and Australia from April 1993 to December 2016

Black dots indicate average concentrations as observed in the 25 to 30°N (left) and 20 to 25°S (right) latitudinal zones. The blue line shows concentrations with seasonal variations removed, and the red line shows the growth rate. Both are calculated using the method of WMO (2009).
3.1.2 Concentration of methane

(1) Concentration of global atmospheric methane

The global mean concentration of atmospheric CH$_4$ has been increasing since at least the 1980s when worldwide monitoring began, except for a stationary phase from 1999 to 2006 (Figure 3.1-15). The mechanism behind the stationary phase remains unclear, but several scenarios have been proposed (IPCC, 2013). The greater concentrations observed since 2007 indicate an increase in CH$_4$ emissions from tropical wetlands and human activity in the mid-latitudes of the Northern Hemisphere (WMO, 2017).

WDCGG analysis shows that the global mean concentration of CH$_4$ in 2016 was 1,853 ppb, which is the highest since records began (Table 3.1-1).

![Figure 3.1-15](image)

Figure 3.1-15 Global mean concentration of atmospheric CH$_4$

The blue dots are monthly values, and the red line represents the corresponding sequence after the removal of seasonal variations. Graph content is based on analysis of observation data reported to WDCGG based on the method of WMO (2009). Data contributors are listed in WMO (2018).

Figure 3.1-16 shows the latitudinal dependence of CH$_4$ concentrations. In the high and mid-latitudes of the Northern Hemisphere, concentrations begin to sharply decrease toward the south. This is because CH$_4$ is mostly emitted from land areas in the Northern Hemisphere, and disappears due to reaction with hydroxyl radicals$^{32}$ over tropical oceans during transportation to the Southern Hemisphere. In summer, more hydroxyl radicals are produced as a result of enhanced ultraviolet radiation, and a larger amount of CH$_4$ is destroyed. This manifests as seasonal variation of CH$_4$ concentrations, as seen in Figures 3.1-15 and 3.1-16.

![Figure 3.1-16](image)

Figure 3.1-16 Latitudinal distribution of atmospheric CH$_4$ concentrations

The data set and analysis method are as per Figure 3.1-15.

---

$^{32}$ Hydroxyl radicals are highly reactive chemicals generated by the reaction of atomic oxygen, which is derived from UV photolysis of ozone, with airborne water vapor. It is particularly abundant at low latitudes, where UV radiation is strong and water vapor is plentiful.
The remarkable increase in the global mean atmospheric concentration of CH$_4$ since the industrial era (+157%) has been much more rapid than that of CO$_2$ (+45%) (Table 3.1-1). This is partly because the amount of anthropogenic emissions of CH$_4$ relative to natural emissions exceeds that of CO$_2$. The long-term trend of CH$_4$ concentration remains to be fully understood due to dependence on various factors, including anthropogenic/natural emissions and chemical reactions. Accordingly, further development of the global CH$_4$ observation network is required.

(2) Concentration of atmospheric methane in Japan
Atmospheric CH$_4$ concentrations at all of Japan’s three observation stations exhibit a trend of increase with seasonal variations in the same way as the global mean concentration (Figure 3.1-17 (a)). Ryori usually observes the highest concentration among the three stations because it is located in the northern part of Japan, where CH$_4$ sources in the Asian continent are more influential and reaction with hydroxyl radicals is less marked. Although Yonagunijima and Minamitorishima are located at similar latitudes, the former tends to record higher concentrations in winter because CH$_4$ sources on the Asian continent have a stronger impact there in winter as a result of continental air mass expansion. In summer, meanwhile, a hydroxyl radical-rich maritime air mass covers both stations, and similarly low concentrations are observed. Since 2010, Yonagunijima has occasionally observed concentrations as high as those of Ryori in winter.

The annual mean CH$_4$ concentration in 2017 was 1,940 ppb at Ryori, 1,889 ppb at Minamitorishima and 1,905 ppb at Yonagunijima, all of which are the highest on record (based on preliminary estimations). The growth rate of atmospheric CH$_4$ concentration exhibits interannual variations that differ significantly from station to station (Figure 3.1-17 (b)).
3.1.3 Concentration of nitrous oxide

Figure 3.1-18 shows that the global mean concentration of atmospheric N₂O has been continuously increasing with no clear seasonal variations, in contrast to the situations with CO₂ and CH₄. The annual mean concentration in 2016 was 328.9 ppb, which was 22% above the pre-industrial level of 270 ppb (Table 3.1-1). The hemispheric mean concentration is several ppb higher in the Northern Hemisphere than in the Southern Hemisphere (Figure 3.1-19) because there are more sources of anthropogenic and soil emissions in the former. This interhemispheric difference is, however, much smaller than those observed with CO₂ and CH₄.

The atmospheric N₂O concentration at Ryori exhibits characteristics similar to those of the global mean (Figure 3.1-20). The annual mean concentration in 2017 at Ryori was 331.9 ppb (based on preliminary estimations).
3.2 Monitoring of the ozone layer and ultraviolet radiation

- Global-averaged total ozone amount decreased significantly in the 1980s and the early 1990s, and remains low today with a slightly increasing trend.
- The annual maximum area of the ozone hole in the Southern Hemisphere increased substantially in the 1980s and 1990s, but no discernible trend was observed in the 2000s. The maximum area in 2017 was the smallest in 29 years because the stratospheric temperature was much higher than the most recent decadal average.
- Increasing trends in annual cumulative daily erythemal UV radiation have been observed at Sapporo and Tsukuba since the early 1990s.
- Global atmospheric concentrations of chlorofluorocarbons (CFCs) have gradually decreased in recent years.

JMA monitors total ozone and/or vertical profiles of ozone at four domestic sites and one Antarctic site (Sapporo, Tsukuba, Naha, Minamitorishima and Syowa Station) under the Act on the Protection of the Ozone Layer through the Control of Specified Substances and Other Measures. It also monitors ultraviolet radiation at the same sites except for Minamitorishima. JMA also monitors the surface concentration of CFCs at Ryori (Figure 3.2-1).

![Figure 3.2-1 JMA's ozone layer and ultraviolet radiation observation network](https://www.data.jma.go.jp/gmd/env/ozonehp/en/diag_o3uv_e.html)

3.2.1 Ozone layer

1. The Director-General of the Meteorological Agency shall observe the state of the ozone layer and the atmospheric concentrations of specified substances and publish the results obtained.

---

33 Information on the ozone layer and ultraviolet radiation is published on JMA's website. [https://www.data.jma.go.jp/gmd/env/ozonehp/en/diag_o3uv_e.html](https://www.data.jma.go.jp/gmd/env/ozonehp/en/diag_o3uv_e.html)

34 Law No. 53 of May 20, 1988, Article 22: Observation and monitoring
2016) was about 1% higher than the 1994 – 2008 mean and 3% lower than the 1970 – 1980 mean, which is a representative value for the period prior to the onset of ozone depletion. A report titled *Scientific Assessment of Ozone Depletion: 2014* (WMO, 2014) stated that total ozone has remained relatively unchanged since 2000 with indications of a small increase in recent years. Concentration of chlorine (an ozone-depleting substance, or ODS) in the stratosphere increased considerably in the 1980s, and then exhibited either no change or a slight decreasing trend after the mid-1990s, as described in Section 3.2.3. It can therefore be inferred that the long-term trend of total ozone may correspond to that of chlorine concentration.

![Figure 3.2-2](image)

**Figure 3.2-2** Time-series representation of global-averaged total ozone deviations shown as percentages

The green line represents deviations of monthly mean global-area-weighted total ozone from the 1994 – 2008 mean, the two red lines represent the 1970 – 1980 mean and the mean over the last five years when there were enough data points for a statistical analysis (2012 – 2016), and the blue dots show NASA TOMS/OMI satellite data averaged at latitudes of 70°S – 70°N. Each data set is deseasonalized with respect to the whole observation period. A total of 65 ground-based stations were used for this calculation (55 in the Northern Hemisphere and 10 in the Southern Hemisphere).

(2) Antarctic ozone hole

The annual maximum area of the ozone hole increased substantially in the 1980s and 1990s, but no discernible trend was observed in the 2000s (Figure 3.2-3). The value for 2017 was the smallest for 29 years (Figures 3.2-3 and 3.2-4) in association with much higher stratospheric temperatures as described in Topics III (The smallest Antarctic ozone hole in 29 years).

The ozone hole area for each year depends on regional climate change with interannual variations, but also shows decadal variation in line with total amounts of ODSs in the stratosphere. Although ODS amounts over the Antarctic peaked in the early 2000s, the ozone layer remains vulnerable because an abundance of these substances is still present in the stratosphere (WMO, 2014).

---

35 See the Glossary for terms relating to Ozone hole.
Figure 3.2-3 Time-series representation of the annual maximum ozone hole area

The ozone hole area is defined as the region over which total ozone south of 45°S is equal to or less than 220 m atm-cm. NASA TOMS/OMI and NOAA-TOVS satellite data are used in calculation of the area for 1979 – 2017. The green line indicates the overall area of the Antarctic ($1.39 \times 10^7$ km$^2$). The left axis shows the ozone hole’s maximum area in units of $10^6$ km$^2$, and the right axis shows its ratio to the area of Antarctica itself.

Figure 3.2-4 Southern Hemisphere distribution of total ozone on September 11, 2017, when the area of the ozone hole reached its maximum for the year

The unit is m atm-cm, and the map is produced using NASA OMI satellite data. The grey shading in the center shows ozone hole areas where the total ozone column value is 220 m atm-cm or less. White regions are domains where no satellite data were available.

(3) Ozone layer over Japan

Figure 3.2-5 shows time-series representations of annual-mean total ozone observed at Sapporo, Tsukuba, Naha and Minamitorishima. A decrease is seen in the 1980s and the early 1990s at Sapporo and Tsukuba. After the 2000, slightly increasing trends are observed at all four sites.

Figure 3.2-5 Time-series representations of annual-mean total ozone at stations in Japan

The stations here are at Sapporo, Tsukuba, Naha and Minamitorishima. JMA began observing ozone concentrations at Tsukuba in 1957 and currently monitors total ozone and/or vertical profiles of ozone at four domestic sites (Sapporo, Tsukuba, Naha, Minamitorishima) and one Antarctic site (Syowa Station).
3.2.2 Solar UV radiation in Japan

Annual cumulative values of daily erythemal UV radiation\textsuperscript{36} at Sapporo and Tsukuba are virtually certain to have increased for the whole of the observational period by ratios of 3.2\% and 4.2\% per decade, respectively (Figure 3.2-6). At Sapporo, UV radiation levels increased from the mid-1990s to the 2000s. At Tsukuba, UV radiation levels increased in 1990s. At Naha, data show no marked changes since the increase observed in the 1990s. This phenomenon may be attributable to a decreasing tendency of aerosol optical extinction, air pollution and/or changes in cloudiness and other meteorological conditions over monitoring sites (UNEP, 2015; JMA, 2011).

![Figure 3.2-6](image)

**Figure 3.2-6** Time-series representations of annual cumulative daily erythemal UV radiation

Observation of erythemal UV at Sapporo, Tsukuba and Naha in Japan started in the early 1990s. Each annual cumulative total is calculated from monthly-mean equivalent values multiplied by the number of days in each month. The monthly-mean equivalent value is based on calculation using daily values from which missing data are excluded. The open circles represent cases of at least one month in which number of days with measurements are less than 20 days. The regression lines cover the whole observation period (statistically significant at a confidence level of 99\% for Sapporo and Tsukuba).

3.2.3 Concentration of ozone-depleting substances

Chlorofluorocarbons (CFCs: CFC-11, CFC-12 and CFC-113), which are compounds of carbon, fluorine and chlorine, and other halogenated gases are classified as ozone-depleting substances (ODSs). They are regulated under the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer and its Amendments and Adjustments. Although ODSs have atmospheric concentrations equivalent to about a millionth of CO\textsubscript{2} levels at most, they contribute considerably to global warming because of their significant radiative effects per unit mass, some of which are several thousand times greater than that of CO\textsubscript{2}.

(1) Global concentration of ozone-depleting substances

Global concentrations of atmospheric CFCs increased rapidly until the 1980s before entering a decreasing trend in the 1990s (Figure 3.2-7). The concentration of CFC-11 peaked in 1992 – 1994, and has since shown a decreasing tendency. The concentration of CFC-12 increased until around 2003, and has also since shown a decreasing tendency. The concentration of CFC-113 has varied in a similar way to that of CFC-11, peaking in around 1993 in the

\textsuperscript{36} See the Glossary for terms relating to erythemal UV radiation.
Northern Hemisphere and around 1996 in the Southern Hemisphere. Differences in the concentrations of these gases between the Northern Hemisphere, where most emissions sources are located, and the Southern Hemisphere, which has significantly fewer sources, have decreased since the 1990s in contrast to the situation of the 1980s. These observations indicate that the CFC emission controls of the Montreal Protocol have been effective.

![Graphs showing monthly mean concentrations of CFC-11, CFC-12, and CFC-113](image)

Figure 3.2-7 Monthly mean concentrations of CFC-11 (upper left), CFC-12 (upper right) and CFC-113 (lower left)

Graph content is based on monthly mean values reported to WDCGG. Dots and circles correspond to observation points in the Northern/Southern Hemisphere, respectively. Data contributors are listed in WMO (2018).

(2) Concentration of ozone-depleting substances in Japan

Concentrations of CFC-11, CFC-12 and CFC-113 at Ryori have shown decreasing tendencies since reaching maxima in various years (Figure 3.2-8). The concentration of CFC-11 peaked at about 270 ppt in 1993 – 1994, and has decreased since then. The distinct peak of concentration observed in the summer of 2011 is probably attributable to high temperatures that caused emissions of gas from polyurethane insulation foam exposed as a result of damage from the Tohoku earthquake and tsunami on March 11, 2011 (Saito et al., 2015). The rate of increase in CFC-12 concentration slowed around 1995, and a gradual decrease has been seen since 2005. There was no clear tendency of increase or decrease in the concentration of CFC-113 until 2001, but a decreasing tendency has been seen since then.
Figure 3.2-8  Monthly mean atmospheric concentrations of CFC-11 (top), CFC-12 (middle) and CFC-113 (bottom) at Ryori

Enhancement of observation equipment in 2003 improved the stability of readings.
3.3 Monitoring of aerosols and surface radiation

In Japan, background atmospheric turbidity coefficient values (which depend on concentrations of aerosols, water vapor and other constituents in the air) have returned to approximate levels seen before the eruption of Mt. Agung in 1963. This is mainly because no large-scale eruptions impacting the global climate have occurred since that of Mt. Pinatubo in 1991.

The number of days when any meteorological station in Japan observed Kosa was 3 in 2017, and the total number of stations reporting its occurrence during the year was 108.

3.3.1 Aerosols

Interannual variations in the atmospheric turbidity coefficient, which is calculated from direct solar radiation measurements taken at five stations in Japan excluding the fluctuation component of the troposphere, clearly shows impacts of stratospheric aerosols resulting from volcanic eruptions (Figure 3.3-1). The increased turbidity coefficients seen for several years after 1963 and the maximum levels observed during the periods of 1982 – 1983 and 1991 – 1993 were caused by the eruptions of Mt. Agung (Indonesia) in 1963, Mt. El Chichón (Mexico) in 1982 and Mt. Pinatubo (Philippines) in 1991, respectively. The increased turbidity stems from the persistent presence of sulfate aerosol in the stratosphere resulting from the huge amounts of SO$_2$ released by the volcanic eruptions. The turbidity coefficient has now returned to approximately the same level as that observed before the eruption of Mt. Agung because no large-scale eruptions have occurred since that of Mt. Pinatubo.

To eliminate the influence of variations in tropospheric aerosols such as water vapor, dust and air pollutants, the annual mean atmospheric turbidity coefficient is calculated using the minimum turbidity coefficient for each month.

Figure 3.3-1  Time-series representation of annual mean atmospheric turbidity coefficients (1960 – 2017)

To eliminate the influence of variations in tropospheric aerosols such as water vapor, dust and air pollutants, the annual mean atmospheric turbidity coefficient is calculated using the minimum turbidity coefficient for each month.

---


38 The atmospheric turbidity coefficient indicates the ratio of the atmospheric optical depth affected by aerosols, water vapor and gases in the atmosphere to that uninfluenced by constituents other than air molecules such as oxygen and nitrogen in the atmosphere. Larger values indicate greater amounts of turbid matter in the air.

39 Direct solar radiation is the incident solar energy acting on the earth’s surface from the sun. The atmospheric turbidity coefficient (also known as the Feussner-Dubois turbidity coefficient) can be calculated from direct solar radiation amounts.
3.3.2 Kosa (Aeolian dust)

Kosa (Aeolian dust) – a kind of aerosol – is fine particulate matter blown up from semi-arid areas of the Asian continent and transported by westerly winds to Japan. A total of 59 JMA meteorological stations (as of 31 December 2017) perform Kosa monitoring. The phenomenon is recorded whenever observed by station staff. The number of days when any meteorological station in Japan observed Kosa was 3 in 2017 (Figure 3.3-2), and the total number of stations reporting its occurrence during the year was 108 (Figure 3.3-3).

The number of days on which Kosa is observed and the annual total number of stations reporting the phenomenon show large interannual variability. As a result, the long-term trend of occurrence remains unclear.

![Figure 3.3-2 Number of days when any station in Japan observed Kosa (1967 – 2017) based on the 59 stations that were active for the whole period](image)

![Figure 3.3-3 Annual total number of stations observing Kosa in Japan (1967 – 2017) based on the 59 stations that were active for the whole period](image)

3.3.3 Solar radiation and downward infrared radiation

The earth’s radiation budget is a source of energy for climate change, and monitoring of its variations is important. To this end, JMA conducts measurements of direct solar radiation, diffuse solar radiation and downward infrared radiation\(^{40}\) at five stations in Japan (Sapporo, Tsukuba, Fukuoka, Ishigakijima and Minamitorishima) (Figure 3.3-4).

![Figure 3.3-4 JMA’s solar radiation and infrared radiation observation network](image)

JMA conducts observation of direct solar, diffuse solar and downward infrared radiation at five stations (Sapporo, Tsukuba, Fukuoka, Ishigakijima and Minamitorishima).

---

\(^{40}\) Downward infrared radiation is the incident infrared radiation acting on the earth’s surface from all directions in the sky. It is emitted from clouds and atmospheric constituents such as water vapor and carbon dioxide in line with the fourth power of their temperature, and can be used as an index of global warming.
(Chapter 3  Atmospheric and Marine Environment Monitoring)

(1) Global solar radiation
Reports indicate that global solar radiation decreased from around 1960 to the late 1980s before increasing rapidly from the late 1980s to around 2000, and no obvious changes have been observed in most regions of the world (Ohmura, 2009).

In Japan, global solar radiation declined rapidly from the late 1970s to around 1990 before increasing rapidly from around 1990 to the early 2000s. Since then, data from measurements at the five observation stations show no obvious changes. These long-term variations are consistent with those reported globally (Figure 3.3-5). Variations are mainly considered to stem from changes in concentrations of anthropogenic aerosols in the atmosphere, and are also partly attributed to changes in cloud cover and cloud characteristics (Wild, 2009). Norris and Wild (2009) quantitatively estimated the cause of the rapid global solar radiation increase observed in Japan from around 1990 to the beginning of the 2000s. According to their estimates, two thirds of the increase was due to reduced anthropogenic aerosols concentrations in the atmosphere and the other third was due to reduced cloud cover. These results imply that the presence of anthropogenic aerosols has a profound effect on solar radiation variations. Results produced by Kudo et al. (2012) indicated that the solar radiation increase was mainly caused by changes in the optical characteristics of aerosols due to changes in the aerosol composition of the atmosphere.

(2) Downward infrared radiation
Atmospheric concentrations of carbon dioxide and other greenhouse gases, which cause global warming, show increasing yearly trends. Observation of downward infrared radiation is effective for the evaluation of global warming because higher values signal the phenomenon more clearly than increased surface temperatures. The results of general circulation model experiments suggest that two decades of downward infrared radiation monitoring should be sufficient to enable the detection of statistically significant increases with a confidence level of 95%, and analysis of in situ observation data covering more than a decade shows an overall increase (Wild and Ohmura, 2004).
In Japan, downward infrared radiation has been monitored since the early 1990s at Tsukuba. Analysis of the data obtained shows an increasing trend at a rate of about 0.3 W/m² per year during the period from 1993 to 2017 (Figure 3.3-6). This is consistent with the trend seen in the results of analysis using data from 20 BSRN\textsuperscript{41} stations worldwide (+0.3 W/m² per year during the period from 1992 to 2009) (WCRP, 2010).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{time_series_representation.png}
\caption{Figure 3.3-6 Time-series representations of annual and five-year-running means of downward infrared radiation at Tsukuba}
\end{figure}

\textsuperscript{41} The BSRN (Baseline Surface Radiation Network) is a global observation network for measuring high-precision surface radiation balance on an ongoing basis. JMA operates five BSRN stations in Japan (Sapporo, Tsukuba, Fukuoka, Ishigakijima and Minamitorishima) and one in Antarctica (Syowa Station).