Chapter 3  Atmospheric and Marine Environment Monitoring

3.1 Monitoring of greenhouse gases

- The global concentration of carbon dioxide (CO$_2$) has shown a long-term increase in the atmosphere and oceans.
- The global mean atmospheric concentration of methane (CH$_4$) has shown a long-term increase with a plateau period from 1999 to 2006.
- The concentration of nitrous oxide (N$_2$O) has shown a long-term increase in the global atmosphere.

JMA operates the World Data Centre for Greenhouse Gases (WDCGG) as part of the WMO/GAW Programme to collect, maintain and provide data on global greenhouse gases. Analysis of data reported to the WDCGG shows that global mean concentrations of major greenhouse gases, which are chemically stable and have long-term impacts on climate change, have shown a continuous increase (Table 3.1-1).

In Japan, JMA monitors atmospheric concentrations of greenhouse gases at three surface stations in Ryori (Ofunato City, Iwate), Minamitorishima (Ogasawara Islands) and Yonagunijima (Nansei Islands). JMA observes oceanic and atmospheric CO$_2$ in the seas around Japan and the western North Pacific using research vessels. In 2011, the Agency began monitoring middle-tropospheric greenhouse gas concentrations over the western North Pacific using cargo aircraft (Figure 3.1-1).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Atmospheric mole fraction</th>
<th>Absolute increase from pre-industrial level</th>
<th>Relative increase from previous year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-industrial level around 1750</td>
<td>Global mean for 2015</td>
<td>+44%</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>About 278 ppm</td>
<td>400.0 ppm</td>
<td>44%</td>
</tr>
<tr>
<td>Methane</td>
<td>About 722 ppb</td>
<td>1,845 ppb</td>
<td>156%</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>About 270 ppb</td>
<td>328.0 ppb</td>
<td>21%</td>
</tr>
</tbody>
</table>

Table 3.1-1  Global mean mole fractions of greenhouse gases (2015)

26 Information on greenhouse gas monitoring is published on JMA's website.
http://www.data.jma.go.jp/ghg/info_ghg_e.html (Atmospheric greenhouse gases)
http://www.data.jma.go.jp/gmd/kaiyou/english/oceanic_carbon_cycle_index.html
27 See the WDCGG website for more information:
http://ds.data.jma.go.jp/gmd/wdcgg/wdcgg.html
28 Pre-industrial levels and lifetimes are from IPCC (2013). Increases from previous year are from WMO (2016). Increases from pre-industrial level are calculated from the differences between pre-industrial and 2015 levels. Response time (which is needed to reduce the influence of a temporary increase) is adopted as lifetime (IPCC, 2013).
3.1.1 Global and domestic atmospheric carbon dioxide concentrations

(1) Global atmospheric carbon dioxide concentrations

Global atmospheric \( \text{CO}_2 \) concentrations show a continuous increase with a seasonal cycle (Figure 3.1-2). The seasonal variation observed (characterized by a decrease from spring to summer and an increase from summer to spring) is mainly due to terrestrial biospheric activity (i.e., photosynthesis and decomposition of organic matter in soil). \( \text{CO}_2 \) concentrations are high in the mid- and high-latitudes of the Northern Hemisphere, and decline going southward (Figure 3.1-3). This latitudinal distribution of \( \text{CO}_2 \) concentrations is ascribed to the presence of major \( \text{CO}_2 \) sources in the Northern Hemisphere. The amplitude of seasonal variations is larger in the mid- and high-latitudes of the Northern Hemisphere and smaller in the Southern Hemisphere, where there is much less land (Keeling et al., 1989). WDCGG analysis shows that the global mean concentration of \( \text{CO}_2 \) increased by 2.3 ppm from 2014 to 2015, reaching as high as 400.0 ppm (Table 3.1-1). The average annual growth rate over the last 10 years has been 2.1 ppm/year, which exceeds the 1.5 ppm/year value seen in the 1990s.
Figure 3.1-3 Monthly variations in zonally averaged atmospheric CO$_2$ concentrations

This analysis was performed using data archived in the WDCGG based on WMO (2009). The data contributors were listed in WMO (2017).

(2) Carbon dioxide concentrations in Japan

Atmospheric CO$_2$ concentrations at domestic stations also show a continuous increase with seasonal cycles affected by biospheric activity (Figure 3.1-4 (a)). The amplitude of seasonal cycles at Ryori is larger than those at Minamitorishima and Yonagunijima because its latitude is the most northerly of the three stations (see Figure 3.1-1) and CO$_2$ concentrations are more subject to terrestrial biosphere conditions. CO$_2$ concentrations are generally higher with a larger range of seasonal variation at Yonagunijima than at Minamitorishima despite their similar latitudes. This reflects Yonagunijima’s location in the vicinity of the Asian continent where anthropogenic emissions as well as wintertime biospheric respiration and decomposition of organic matter in soil are dominant. Annual mean CO$_2$ concentrations in 2016 were 407.2 ppm at Ryori, 404.9 ppm at Minamitorishima and 407.1 ppm at Yonagunijima, representing an increase on the previous year, and were the highest on record (based on preliminary estimations).

The periods in which a high growth rate of CO$_2$ concentration was seen roughly correspond to those of El Niño events. The relationship can be explained as follows: During El Niño events, anomalous climatic phenomena such as unusually high temperatures inhibit photosynthesis, enhance plant respiration and promote organic soil decomposition, thereby increasing the amount of CO$_2$ released from the terrestrial biosphere (Keeling et al., 1995; Dettinger and Ghil, 1998). A sharp increase in CO$_2$ concentrations was recently observed at all domestic stations in response to the El Niño event seen from 2014 to 2016 (Figure 3.1-4 (b)). A similar increase was also observed in the global average (WMO, 2016).
(Chapter 3 Atmospheric and Marine Environment Monitoring)

(3) Oceanic carbon dioxide

Figure 3.1-5 shows annual changes in oceanic and atmospheric CO₂ concentrations averaged between 7°N and 33°N along 137°E for winter (January and February). The mean growth rates of oceanic and atmospheric CO₂ concentrations from 1984 to 2016 were 1.7 ppm per year and 1.8 ppm per year, respectively (both significant at a confidence level of 99%). In this region, the concentration of CO₂ in the ocean is lower than that in the atmosphere, meaning that the ocean acts as a CO₂ sink in winter.

![Figure 3.1-5](image)

JMA conducts *in situ* observations of CO₂ in surface seawater and the air in the western North Pacific, which covers subarctic to equatorial regions, using automated monitoring systems installed on the research vessels *Ryofu Maru* and *Keifu Maru*. Air and surface seawater samples are collected with a pump and are continuously analyzed using automated apparatus in on-board laboratories.

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 3.1-6 (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 3.1-6 (b) and (c) show monthly and annual variations in global ocean CO₂ uptake, respectively. 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 3.1-6 (b)). The estimated annual global ocean CO$_2$ uptake has increased since 2000.

The blue/red area in the map on the left (a) indicates ocean uptake/release of CO$_2$ from/into the atmosphere. The grey area shows the border of the region analyzed. The dotted line in graph (c) shows the 1.7 GtC average for the period from 1990 to 2015.

The column inventory of oceanic CO$_2$ was estimated using long-term time-series data on dissolved inorganic carbon from 1990s (Figure 3.1-7). 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 – 13 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.

Figure 3.1-7  Changes in oceanic CO$_2$ between the sea surface and 27.5 $\sigma_0$ (about 1,200 – 1,400 m in depth) along 137°E and 165°E. Error bars denote a 95% confidence level
(4) Ocean acidification

The ocean acts as a large sink for CO$_2$ emitted as a result of human activities, 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 activities 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 of 0.016 per decade in surface seawater pH for the whole Pacific (Figure 3.1-8), 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 3.1-9 and 3.1-10). Ocean interior pH along these lines also shows decreasing trends of 0.003 to 0.036 per decade (Figure 3.1-11) with higher rates in the northern than the southern subtropics due to greater accumulation of anthropogenic CO$_2$ in the former.
Figure 3.1-8  Long-term trend of surface seawater pH (left) and pH distribution in 1990 and 2015 (right) in the Pacific

Left: Rate of pH change in the Pacific. The solid line is a time-series representation of the pH anomaly from the normal (average from 1990 to 2010) in the Pacific. The shaded area and dotted line represent the standard deviation range (±1 σ) and the long-term trend, respectively. The ‘±’ symbol indicates a 95% confidence interval.

Right: Lower pH values are represented as warmer colors.
Figure 3.1-9  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 3.1-10  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) Middle- and upper-troposphere monitoring of carbon dioxide
Since 2011, JMA has monitored middle-troposphere CO\textsubscript{2} concentrations on 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 to support aircraft operation (Tsuboi et al., 2013; Niwa et al., 2014). The flight altitude is approximately 6 km. CO\textsubscript{2} concentrations in the middle troposphere show a continuous increase with seasonal cycles. The trend is similar to those observed at the Minamitorishima surface station. Aircraft observation values recorded from winter to spring tend to be lower than those at Minamitorishima (Figure 3.1-12).

The National Institute for Environmental Studies and the Meteorological Research Institute have monitored CO\textsubscript{2} and other greenhouse gases at altitudes of around 10 km using commercial passenger aircraft since 1993 under the Comprehensive Observation Network for TRrace gases by ArLiner (CONTRAIL) project\textsuperscript{29} (Matsueda et al., 2015; Machida et al., 2008). Figure 3.1-13 shows CO\textsubscript{2} concentrations at altitudes from 8 to 13 km for the 25°–30°N and 20°–25°S latitudinal zones on the flight route between Japan and Australia. The signature seasonal cycle is also observed in the upper troposphere, reflecting surface seasonal cycles of

\textsuperscript{29} The results of upper-troposphere monitoring of carbon dioxide are now based on the Comprehensive Observation Network for TRrace gases by ArLiner (CONTRAIL) project run by the National Institute for Environmental Studies (NIES), the Meteorological Research Institute (MRI), Japan Airlines (JAL), JAMCO Tokyo and JAL Foundation (JALF). The project has been financially supported by the Ministry of the Environment (MOE) since 2006. Observation was first performed in 1993 as part of a joint project run by MRI, JAL, JALF and the Ministry of Transport.
CO₂ fluxes. The seasonal amplitude in the upper air is smaller than that of surface observations in the Northern Hemisphere. Variations in CO₂ concentrations in the Southern Hemisphere are more complicated than those in the Northern Hemisphere, and include double-peak seasonality in some cases. These characteristics are attributed to small seasonal variations of surface CO₂ concentration in the Southern Hemisphere and the interhemispheric transport of CO₂ in the upper troposphere (Sawa et al., 2012).

![Figure 3.1-12 Time-series representation of monthly mean CO₂ concentrations as observed at Minamitorishima surface station (red) and by aircraft (blue). Black circles represent individual observation values obtained on level flights (altitude: approx. 6 km) between Atsugi Base and Minamitorishima.](image1)

![Figure 3.1-13 Time-series representation of CO₂ concentrations in upper troposphere from April 1993 to December 2015. The data used in this analysis were collected from commercial flights between Japan and Australia under the CONTRAIL project. The black dots show concentrations and the blue lines show deseasonalized trends averaged from 25°N to 30°N (left) and from 20°S to 25°S (right), the red ones show annual growth rates of concentrations. The method of calculating deseasonalized trends is described in WMO (2009).](image2)
3.1.2 *Global and domestic atmospheric methane concentrations*

(1) Global atmospheric methane concentration

Surface-air concentration of CH$_4$ has shown an increasing trend since global instrumental measurement began in the 1980s, with a stationary phase from 1999 to 2006 (see the red line in Figure 3.1-14). The cause of this low growth rate remains unclear, although various scenarios have been proposed (IPCC, 2013). The increase after 2007 is attributed to anthropogenic emissions in the tropical and mid-latitude Northern Hemisphere (WMO, 2016). WDCGG global analysis indicates that the global mean concentration of CH$_4$ in 2015 was 1,845 ppb, which is the highest on record since 1984 (Table 3.1-1).

![Figure 3.1-14 Time-series representation of global atmospheric monthly-averaged CH$_4$ concentration (blue circles) and its deseasonalized trend (red line) (WMO, 2016)](image)

The analysis was performed using data archived by the WDCGG. The deseasonalized trend calculation was based on WMO (2009). The data contributors were listed in WMO (2017).

Concentrations show a sharp decline southward from the mid- and high-latitudes of the Northern Hemisphere to the Southern Hemisphere. This is because land areas in the Northern Hemisphere are home to major sources of CH$_4$, which reacts with OH radicals$^{30}$ and is transported to the Southern Hemisphere. Seasonal variations with a summer decrease are also apparent because large amounts of CH$_4$ are removed through chemical reaction with OH radicals, whose presence increases in summer due to the effects of intensified ultraviolet radiation (Figure 3.1-15).

![Figure 3.1-15 Monthly variations in zonally averaged atmospheric CH$_4$ concentrations](image)

This analysis was performed using data archived by the WDCGG. The calculation was based on WMO (2009). The data contributors were listed in WMO (2017).

$^{30}$ OH radical is a highly reactive chemical generated by the reaction of the oxygen atom and water vapor contained in air, where the oxygen atom is derived from ozone by ultraviolet photolysis. In low latitudes, it is abundant produced by plenty of ultraviolet radiation and water vapor.
Atmospheric CH$_4$ concentration has shown a significant increase (+156 %) since the industrial era at a rate much higher than that of atmospheric CO$_2$ (+44 %) (Table 3.1-1). This is attributable to larger anthropogenic emissions than those from natural sources as compared to the situation for CO$_2$. The characteristics of CH$_4$ variability have not yet been fully elucidated in quantitative terms because it is complicated by emissions from human activities, natural emissions from wetlands, and atmospheric chemical removal. To enhance understanding of the situation, the global CH$_4$ observation network needs to be improved.

(2) Methane concentrations in Japan
Observational data revealing atmospheric CH$_4$ concentrations at three JMA stations indicate increasing tendencies with a seasonal cycle characterized by a decrease in summer and an increase in winter, and show a latitudinal dependency by which concentrations are higher northward (Figure 3.1-16 (a)). This tendency is also common to hemispheric characteristics. CH$_4$ concentration at Ryori is the highest of the three stations because chemical reaction with OH radicals there is the weakest due to its higher latitude and its relative proximity to major CH$_4$ sources on the Asian continent. Concentrations at Yonagunijima and Minamitorishima, whose latitudes are similar, decrease by the same level in summer. OH radical-rich summer conditions contribute to lower concentrations at these two stations because the maritime air mass is dominant at lower latitudes. In winter, the concentration at Yonagunijima is higher than at Minamitorishima. Due to continental air mass expansion in winter, Yonagunijima is significantly influenced by CH$_4$ sources from the Asian continent. Since 2010, winter CH$_4$ concentrations at Yonagunijima have almost reached those observed at Ryori in some years. Annual mean CH$_4$ concentrations in 2016 were 1,929 ppb at Ryori, 1,875 ppb at Minamitorishima and 1,896 ppb at Yonagunijima, representing increases on the previous year, and were the highest on record (values are preliminary estimations).

Atmospheric CH$_4$ concentration growth rates show interannual variations that differ significantly for each station (Figure 3.1-16 (b)).
3.1.3 Global and domestic atmospheric nitrous oxide concentrations

Concentration of atmospheric N\textsubscript{2}O shows an increase on a global scale (Figure 3.1-17). WDCGG analysis indicates that the global mean value in 2015 was 328.0 ppb, which is 21% higher than the pre-industrial level of 270 ppb observed around 1750 (Table 3.1-1). The seasonal cycle of N\textsubscript{2}O concentration is not as significant as that of CO\textsubscript{2} or CH\textsubscript{4}. Although the deseasonalized trend does not exhibit a large difference between the Northern and Southern Hemispheres (unlike CO\textsubscript{2} and CH\textsubscript{4}), N\textsubscript{2}O concentrations are on average a few ppb higher in the Northern Hemisphere than in the Southern Hemisphere (Figure 3.1-18) because the former is more subject to anthropogenic and soil emissions.

Figure 3.1-19 shows a time-series representation of monthly mean N\textsubscript{2}O concentrations in the atmosphere as observed at Ryori. No clear seasonal variability is seen, and the plot shows a continuous increasing trend. The annual mean N\textsubscript{2}O concentration was 330.2 ppb in 2016 (preliminary estimation).

![Figure 3.1-17 Time-series representation of global atmospheric monthly-averaged N\textsubscript{2}O concentration (WMO, 2016)](image)

The analysis was performed using data archived by the WDCGG. The calculation was based on WMO (2009). The data contributors were listed in WMO (2017).

![Figure 3.1-18 Monthly variations in zonally averaged atmospheric N\textsubscript{2}O concentrations](image)

This analysis was performed using data archived by the WDCGG. The calculation was based on WMO (2009). The data contributors were listed in WMO (2017).

![Figure 3.1-19 Time-series representation of monthly mean atmospheric N\textsubscript{2}O concentrations at Ryori](image)

The replacement of the observation system at the beginning of 2004 improved monitoring precision and reduced the scale of fluctuations in observed values.
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.
- Increasing trends in annual cumulative daily erythemal UV radiation have been observed at all three domestic sites (Sapporo, Tsukuba and Naha) 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

3.2.1 Ozone layer

1. Global ozone layer

The globally averaged total ozone amount decreased considerably in the 1980s and the early 1990s (Figure 3.2-2). Although no change or a slightly increasing trend is observed after the mid-1990s, total ozone has remained low compared to that seen before the 1980s. Global mean total ozone over the last five years with enough data points for statistical analysis (2011 – 2015) 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

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32 Law No. 53 of May 20, 1988, Article 22: Observation and monitoring

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.
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 (JMA, 2011). 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 (2011–2015), 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 annual maximum ozone hole area in 2016 was very similar to the decadal mean area for 2006–2015 (Figures 3.2-3 and 3.2-4).

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).

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33 See the Glossary for terms relating to Ozone hole.
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 – 2016. 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 3.2-5 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 mid-1990s, slightly increasing trends are observed at all four sites.

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 at Sapporo and Tsukuba are virtually certain to have increased for the whole of the observational period by ratios of 3.5% and 4.8% per decade, respectively (Figure 3.2-6). It is also extremely likely that those at Naha have increased for the whole of the observation period by a ratio of 2.2% per decade (Figure 3.2-6). At Sapporo, UV radiation levels increased from the mid-1990s to the 2000s. At Tsukuba, no remarkable increase has been observed since the maximum recorded in 2011. 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 and 95% for Naha).

3.2.3 Global and domestic observation 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$_2$ 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$_2$.

(1) Global concentrations of ozone-depleting substances

Global concentrations of atmospheric CFCs increased rapidly until the 1980s. However, since the 1990s, falling rates of increase or a decreasing tendency have been dominant (Figure 3.2-7) due to the effect of the Montreal Protocol. CFC-11 concentrations peaked from 1992 to 1994,

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34 See the Glossary for terms relating to erythemal UV radiation.
and have shown a decreasing tendency since then. CFC-12 concentrations increased until around 2005, and have also shown a decreasing tendency since then. The trend for CFC-113 concentration is almost the same as that for CFC-11, peaking around 1993 – 1994 in the Northern Hemisphere and around 1997 in the Southern Hemisphere. Differences in the concentrations of these gases between the Northern Hemisphere (where most emission sources are located) and the Southern Hemisphere (which has significantly fewer sources) tended to be smaller in the 2000s than in the 1980s and 1990s. These results show the gradual appearance of a positive effect from CFC emission control efforts in readings of atmospheric CFC concentrations.

Figure 3.2-7  Time series of the monthly mean concentrations of CFCs
CFC-11 (upper left), CFC-12 (upper right) and CFC-113 (lower left). These figures were produced using data archived in the WDCGG. The data contributors were listed in WMO (2017).

(2) Ozone-depleting substances in Japan
In line with global observations, concentrations of CFC-11, CFC-12 and CFC-113 at Ryori have all decreased since reaching peaks in different periods (Figure 3.2-8). The concentration of CFC-11 peaked at about 270 ppt in 1993 – 1994, and has decreased since then. CFC-11 showed a distinct maximum of concentrations when temperatures were high during the summer of 2011, which may be attributable to effective leakage from damaged polyurethane insulation foam related to the Tohoku earthquake and tsunami of 11 March 2011 (Saito et al., 2015). CFC-12 concentration increased rapidly until 1995 and continued to rise slowly until 2005, but has shown a gradual decrease since then. The concentration of CFC-113 showed no clear trend until 2001 and decreased gradually thereafter.
Figure 3.2-8  Time-series representations of monthly mean concentrations of atmospheric CFC-11 (top), CFC-12 (middle) and CFC-113 (bottom) at Ryori

The replacement of the observation system in September 2003 improved monitoring precision and reduced the scale of fluctuations in observed values.
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 11 in 2016, and the total number of stations reporting its occurrence during the year was 96.

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 SO₂ 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.

![Figure 3.3-1 Time-series representation of annual mean atmospheric turbidity coefficients (1960 – 2016)](image)

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.

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35 See the Glossary for terms relating to aerosols.
37 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.
38 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 2016) 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 11 in 2016 (Figure 3.3-2), and the total number of stations reporting its occurrence during the year was 96 (Figure 3.3-3).

Although the number of days on which Kosa is observed and the annual total number of stations reporting the occurrence of the phenomenon show increasing trends in the period from 1967 to 2016, their annual variations are so large that the long-term trend is not clear. Sustained observation is expected to enable the identification of certain long-term trends.

![Figure 3.3-2 Number of days when any station in Japan observed Kosa (1967 – 2016) 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 – 2016) 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\(^{38}\) 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).

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\(^{38}\) 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.

![Figure 3.3-5](image)

Figure 3.3-5  Time-series representations of annual and five-year-running means of global solar radiation at five stations in Japan (Sapporo, Tsukuba, Fukuoka, Ishigakijima and Minamitorishima)

(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 2016 (Figure 3.3-6). This is consistent with the trend seen in the results of analysis using data from 20 BSRN\textsuperscript{39} stations worldwide (+0.3 W/m² per year during the period from 1992 to 2009) (WCRP, 2010).

Figure 3.3-6  Time-series representations of annual and five-year-running means of downward infrared radiation at Tsukuba

\textsuperscript{39} 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).