CLIMATE CHANGE MONITORING REPORT
2016

October 2017
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JAPAN METEOROLOGICAL AGENCY
Cover: Annual mean temperature anomalies 2016
The circles indicate temperature anomalies from 1981-2010 baseline averaged in 5° x 5° grid boxes.
Preface

The Japan Meteorological Agency (JMA) has published annual assessments under the title of *Climate Change Monitoring Report* since 1996 to highlight the outcomes of its activities (including monitoring and analysis of atmospheric, oceanic and global environmental conditions) and provide up-to-date information on climate change in Japan and around the world.

In 2016, the formation of the first tropical cyclone (TC) over the western North Pacific basin was the second-latest ever recorded. In August, the front line and successive typhoons (including the first recorded landing from the Tohoku Pacific Ocean side of Japan) brought heavy rainfall and caused serious damage to northern Japan. Elsewhere, major disasters were caused by record rainfall in the Chang Yangtze River basin (April to July), droughts in Southeast Asia (January to May), heatwave conditions in India (March to May) and a hurricane in Haiti (October). The remarkable El Niño phenomenon that prevailed from 2014 to the spring of 2016 continued to affect weather in Japan and around the world, contributing to the third consecutive record-high annual global average temperature. In this way, extreme weather and climatic phenomena adversely affected society and economic activity in various places in 2016.

The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) suggests that changes in the characteristics of many extreme weather and climate events have been observed since around 1950. The report specifies a high likelihood that extreme phenomena such as very high temperatures will last longer and be more frequent, and that heavy precipitation events will be more intense and more frequent in numerous regions. In response to such climate change impacts, the Paris Agreement (a new related countermeasure framework) went into effect in November 2016. Japan’s government formulated the National Plan for Adaptation to the Impacts of Climate Change in November 2015 ahead of the Paris Agreement. In line with this plan, national and local governments are currently taking steps to address climate change.

This report summarizes post-El Niño impacts and associated remarkable climate phenomena, and presents recent JMA scientific data, information and findings. It is intended to provide a scientific basis for better implementation of measures relating to climate change and to raise awareness of global environmental issues.

Sincere appreciation goes to JMA's Advisory Group of the Council for Climate Issues and its chair, Dr. Hiroki Kondo, for their pertinent comments and guidance on this report.

Toshihiko Hashida
Director-General
Japan Meteorological Agency
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Topics

I  Post-El Niño

The annual anomaly of the global average surface temperature in 2016 was +0.45°C above the 1981 – 2010 average, which was the highest since 1891. The mean surface temperature in Japan for 2016 is estimated to have been +0.88°C above the 1981 – 2010 average, which is the highest since 1898. The high temperatures observed in 2016 are considered to be partially attributable to the high temperature of the troposphere in association with the El Niño event.

I.1  Global temperature for 2016 was the highest since 1891

The annual anomaly of the global average surface temperature for the year 2016 (i.e., the combined average of the near-surface air temperature over land and the sea surface temperature (SST)) is estimated at +0.45°C above the 1981 – 2010 average, which was the highest since 1891.

Positive temperature anomalies were seen over many regions of the world, especially Eurasia, North America, the Indian Ocean and the Tropical Pacific, while negative temperature anomalies were seen over parts of the North Atlantic and the North Pacific (Figure I.1-1). The monthly anomalies of the global average surface temperatures for January, February, March, April, June and July, and the seasonal anomalies of the global average surface temperatures for the boreal winter, spring and summer were also the highest since 1891.

Figure I.1-1  Annual mean temperature anomalies 2016

Circles indicate temperature anomalies from the 1981 – 2010 baseline averaged in 5° x 5° grid boxes.

1 Monthly, seasonal and annual estimates of average temperatures around the globe and around Japan are published on JMA’s website.
http://ds.data.jma.go.jp/tcc/tcc/products/gwp/gwp.html (English)
The mean surface temperature in Japan for 2016 is estimated to have been +0.88ºC above the 1981 – 2010 average, which is the highest since 1898.

In an El Niño event, atmospheric air temperatures generally increase on a global scale first at low latitudes and then at mid-to-high latitudes. Warm sea water in the eastern part of the Indian Ocean extended to the western part in association with a change in winds over the tropical Indian Ocean from relatively weak westerlies to easterlies2 (Section 1.3). SSTs in the Indian Ocean then increase around three months after the evolution of an El Niño event. Thus, it is known that the global mean temperature increases after an El Niño event.

The high global average surface temperature observed in 2016 is attributed to high SSTs in the tropical Pacific and the tropical Indian Ocean in association with the El Niño event that continued from boreal summer 2014 to boreal spring 2016, as well as to global warming and the high temperature of the troposphere. The high temperatures observed over Japan in 2016 are attributed to warm-air inflow over Japan throughout boreal winter to spring in relation to strong high-pressure systems to the south and east of the country in association with the El Niño event, as well as to global warming and the high temperature of the troposphere.

On a longer time scale, it is virtually certain that the global average surface temperature has risen at a rate of about 0.72ºC per century, and it is virtually certain that the annual mean surface temperature over Japan has risen at a rate of about 1.19ºC per century.

Table I.1-1  The 10 highest annual average surface temperature anomalies globally and in Japan

<table>
<thead>
<tr>
<th>Global</th>
<th>Year</th>
<th>Anomalies (ºC)</th>
<th>Japan</th>
<th>Year</th>
<th>Anomalies (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>2016</td>
<td>+0.45</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>2016</td>
<td>+0.88</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>2015</td>
<td>+0.42</td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>1990</td>
<td>+0.78</td>
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<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>2014</td>
<td>+0.27</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>2004</td>
<td>+0.77</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt;</td>
<td>1998</td>
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<td>4&lt;sup&gt;th&lt;/sup&gt;</td>
<td>1998</td>
<td>+0.75</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt;</td>
<td>2013</td>
<td>+0.20</td>
<td>5&lt;sup&gt;th&lt;/sup&gt;</td>
<td>2015</td>
<td>+0.69</td>
</tr>
<tr>
<td>2010</td>
<td>+0.20</td>
<td>6&lt;sup&gt;th&lt;/sup&gt;</td>
<td>2010</td>
<td>+0.61</td>
<td></td>
</tr>
<tr>
<td>7&lt;sup&gt;th&lt;/sup&gt;</td>
<td>2005</td>
<td>+0.17</td>
<td>2007</td>
<td>+0.61</td>
<td></td>
</tr>
<tr>
<td>8&lt;sup&gt;th&lt;/sup&gt;</td>
<td>2009</td>
<td>+0.16</td>
<td>8&lt;sup&gt;th&lt;/sup&gt;</td>
<td>1994</td>
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</tr>
<tr>
<td>2006</td>
<td>+0.16</td>
<td>9&lt;sup&gt;th&lt;/sup&gt;</td>
<td>1999</td>
<td>+0.49</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>+0.16</td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>2013</td>
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<td></td>
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<tr>
<td>2002</td>
<td>+0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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2 http://www.data.jma.go.jp/gmd/cpd/data/elnino/learning/faq/whatiselnino2.html (Japanese)
I.2 Influences from the termination of the El Niño event on the global climate

The El Niño event that emerged in summer 2014 peaked in winter 2015/2016 and ended in spring 2016. This section highlights the characteristics of atmospheric circulation observed after its termination and related impacts on the global climate, including extremely heavy precipitation in the Yangtze River basin and delayed formation of the first TC in the western North Pacific.

(1) Heavy precipitation in the Yangtze River basin

Areas along the middle and lower reaches of the Yangtze River experienced above-normal precipitation from April to July 2016. Cumulative precipitation from April 1 averaged over the stations in the basin was the highest since 1997 (Figure I.2-1). Amounts soared from late June onward in particular, with the highest cumulative 30-day precipitation among the stations for June 21 to July 20 exceeding 900 mm (Figure I.2-2). More than 200 fatalities were reported in relation to heavy rainfall and landslides from late June to early July according to the government of China.

Such an extended period of extremely heavy precipitation was caused by a strong convergence of moist air flow from the South China Sea over the Yangtze River (Figure I.2-4). This was induced by anticyclonic circulation anomalies over the western tropical North Pacific (Figure I.2-3) associated with high SSTs in the Indian Ocean in the wake of the El Niño event (see Section 1.3).

Figure I.2-1 Cumulative precipitation averaged over the stations in the middle and lower Yangtze River basin
Observation stations are shown on the inset map. The red, blue and green lines indicate cumulative precipitation for the periods starting on April 1 of 2016, 1998 and 1999, respectively, and the grey lines indicate the same periods for all other years since 1997. The dashed black line indicates the average over the 19 years from 1997 to 2015.
Figure I.2-2  30-day precipitation in the middle and lower reaches of the Yangtze River basin
The map indicates 30-day precipitation for June 21 to July 20 2016, when particularly heavy rainfall was recorded. Red dots denote stations recording the three highest precipitation amounts for the 30-day period (Anqing, Wuhan and Macheng) and the highest amount for April 1 to July 24 (Huangshan).

Figure I.2-3  Anomalies of outgoing longwave radiation (shading) and sea level pressure anomalies (contours; unit: hPa) for April to June 2016
Warm and cool colors indicate suppressed and enhanced convective activity, respectively. H denotes anticyclonic anomalies.
(2) Delayed formation of the season’s first tropical cyclone
The first tropical cyclone (TC) of 2016 over the western North Pacific basin formed on July 3 (TC definition: a tropical low-pressure system with wind speeds of 17.2 m/s or higher). This was the second-latest since 1951, being slightly earlier than the July 9 date recorded in 1998 (Table I.2-1). The top four records in Table I.2-1 coincide with TC seasons subsequent to a winter when an El Niño event reached its peak and sea surface temperatures in the Indian Ocean remained high. During all these TC seasons, pronounced anticyclonic circulation anomalies developed in the lower troposphere and convection activity was suppressed over the western tropical North Pacific as per the pattern seen in Figure I.2-3.

In summary, suppressed convective activity and enhanced anticyclonic circulation over the western North Pacific in association with high SSTs in the Indian Ocean in the wake of the El Niño event were a factor behind the heavy precipitation observed in the Yangtze River basin from April to July 2016 and the delayed first TC formation of 2016.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Year</th>
<th>Date of first TC formation (UTC)</th>
<th>Rank</th>
<th>Year</th>
<th>Date of first TC formation (UTC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1998</td>
<td>06Z, July 9</td>
<td>6</td>
<td>1984</td>
<td>06Z, June 9</td>
</tr>
<tr>
<td>2</td>
<td>2016</td>
<td>00Z, July 3</td>
<td>7</td>
<td>1964</td>
<td>06Z, May 15</td>
</tr>
<tr>
<td>3</td>
<td>1973</td>
<td>18Z, July 1</td>
<td>8</td>
<td>2001</td>
<td>00Z, May 11</td>
</tr>
<tr>
<td>4</td>
<td>1983</td>
<td>06Z, June 25</td>
<td>9</td>
<td>2006</td>
<td>12Z, May 9</td>
</tr>
<tr>
<td>5</td>
<td>1952</td>
<td>18Z, June 9</td>
<td>10</td>
<td>2011</td>
<td>12Z, May 7</td>
</tr>
</tbody>
</table>
II Extreme climate conditions in Japan in August 2016

- In August 2016, western Japan experienced hot summer conditions, and sea surface temperatures in the area were much higher than normal.
- Due to rainfall from tropical cyclones, fronts and moist air inflow, monthly precipitation was the highest on record in northern Japan and caused serious damage.

II.1 Surface climate and sea surface temperature

(1) Surface climate conditions
In mid-to-late August, four tropical cyclones (Chanthu (T07), Mindulle (T09), Lionrock (T10) and Kompasu (T11)) made landfall on northern and eastern Japan in rapid succession. This was the joint-highest number of monthly TC (tropical cyclone) landfalls on the country since records began in 1951, tying with August 1962 and September 1954. The Hokkaido region was affected by Conson (T06), which passed the area’s Nemuro Peninsula. Lionrock (T10) was the first TC to make landfall on the Tohoku region from the Pacific Ocean side since 1951, and caused heavy precipitation there. Due to rainfall from the TC, fronts and moist air inflow, monthly precipitation amounts were significantly above normal in northern Japan and were the highest (at 231% of the normal) since 1946 on the Pacific side of northern Japan. Meanwhile, sunshine durations in northern Japan were also significantly above normal in association with high-pressure systems that frequently covered the area during the first half of the month.

Western Japan experienced hot and dry conditions from late July to August. In western Japan, monthly mean temperatures were +0.9°C above the normal and the 10-day mean temperature for mid-August was the second highest since 1961 at +1.6°C above the normal. Monthly sunshine durations on the Sea of Japan side and the Pacific side of western Japan were 131% (the second-highest since 1946) and 126% (the third-highest since 1946) of the normal, respectively.

![Figure II.1-1 Temperature anomalies, precipitation ratios and sunshine duration ratios for August 2016](image_url)
(2) Sea surface temperature
As with the hot conditions observed in western Japan, sea surface temperatures (SSTs) were much higher than normal in August in the seas around western Japan and the Okinawa Islands. In contrast, SSTs were much lower than normal in the seas around Minamitorishima and in seas east of Japan affected by TCs.

In the northern part of the East China Sea, areas with SSTs exceeding 31°C were seen in mid-August (Figure II.1-2). The 10-day mean SST in mid-August was 29.9°C, which was the highest since 1982.

Figure II.1-2  10-day mean sea surface temperatures (top) and related anomalies (bottom) for 11 – 20 August 2016
Sea surface temperatures (unit: °C) are based on the MGDSST dataset. The aqua rectangle indicates the northern part of the East China Sea (30 – 35°N, 120 – 130°E).
II.2 Atmospheric conditions (Figure II.2-2)

(1) Record precipitation in northern Japan

Convective activity was enhanced from the area around the Philippines to the southeast of Japan from late July. The westerly jet stream meandered northward around the Kamchatka Peninsula and a blocking high developed (Figure II.2-1(a)). Meanwhile, the jet stream meandered southward over the central Pacific and a trough formed there.

Cyclonic eddies separated from the trough over the mid-latitude central Pacific and moved westward, contributing to the enhanced convective activity over the seas to the southeast of Japan. In association with this enhancement, major cyclonic circulation was seen to the south of Japan and a greater number of tropical cyclones than normal formed (Figure II.2-1(b)). Southerly winds prevailed in the upper troposphere to the east of Japan due to the meandering of the westerly jet stream. The Pacific High was weaker than normal over the seas to the south of Japan and extended toward the south of the Kamchatka Peninsula. Due to these large-scale circulation anomalies, tropical cyclones moved northward over the seas to the east of Japan along the Pacific High and approached or hit the north of the country following southerly winds in the upper troposphere. Lionrock (T10) followed a peculiar path: after moving southwest over the seas to the south of the Kanto region, it made a U-turn over the Pacific Ocean and then moved northwest in association with the meandering westerly jet stream. It was the first TC make landfall on the Tohoku region from the Pacific Ocean side since 1951. These TCs brought a series of heavy precipitation events and serious damage to northern Japan, especially on the Pacific side.

(2) Hot summer conditions in western Japan

Divergent flow in the upper troposphere from the area around the Philippines was clearly seen in association with enhanced convective activity there (Figure II.2-1(b)). The jet stream meandered northward over northeastern China, and the Tibetan High was stronger than normal in its northeastern part (Figure II.2-1(a)). The flows converged over the area from eastern China to western Japan, and downward flows were seen in the mid-troposphere. Vertical advection and greater amounts of solar radiation than normal were seen as factors behind the hot and dry summer conditions in western Japan. The sea surface temperature around western Japan was much higher than normal in association with the enhanced solar radiation and weak surface wind.
Figure II.2-1  (a) Wind (arrows) and height anomalies (shading) at 200 hPa (height: approx. 12,000 m), (b) outgoing longwave radiation (shading) and sea level pressure (contours) in August 2016
(a) Long arrows indicate the jet stream, and Hs denote the blocking high (east) and the extended Tibetan High (west).
(b) Blue shading indicates the active convection area, and H and L denote the center of the Pacific High and the cyclonic circulation system, respectively.

Figure II.2-2  Characteristics of atmospheric circulation associated with extreme climate conditions in Japan in August 2016

(a) Wind (arrows) and height anomalies (shading) at 200 hPa (height: approx. 12,000 m), (b) outgoing longwave radiation (shading) and sea level pressure (contours) in August 2016
(a) Long arrows indicate the jet stream, and Hs denote the blocking high (east) and the extended Tibetan High (west).
(b) Blue shading indicates the active convection area, and H and L denote the center of the Pacific High and the cyclonic circulation system, respectively.
III  Sea surface temperature (SST) product based on geostationary Himawari-8 satellite data

- JMA has provided SST products since 1946 to support monitoring of oceanic variations, coastal disaster prevention, the shipping and fishing industry, marine tourism and other areas. In 2016, two new SST products were developed using data from the Himawari 8 geostationary satellite.

III.1  Sea Surface Temperature Composite Images Based on Himawari Data

The functions and specifications of the imager on board Himawari-8, which entered operation in July 2015, are notably superior to those of imagers on board previous geostationary satellites. The high-resolution, high-accuracy SST data produced by the satellite is used to provide a new product called Sea Surface Temperature Composite Images Based on Himawari Data. The product provides composite images made from hourly Himawari SST data, and is issued twice a day with a horizontal resolution of 0.02 degrees in both longitude and latitude. There are fewer areas where SST data cannot be retrieved due to cloud cover in this product as compared to a 12-hour snapshot, giving users a clearer picture of sea conditions.

Figure III.1-1 shows a sample of the product for 17th March 2016. It can be seen that sharp fronts lie between the Oyashio cold water distributed widely southeast of Hokkaido and the Kuroshio warm water extending east of Honshu. SST distribution and ocean current status can be monitored from this product in areas with no cloud or sea ice.

Figure III.1-1  Sea Surface Temperature Composite Image Based on Himawari Data (17th Mar 2016)
III.2 High-resolution Merged Satellite and in-situ Data Sea Surface Temperature (HIMSST)

HIMSST analysis is based on SSTs from the Himawari-8 geostationary satellite, polar-orbiting satellites and in-situ platforms (buoys and ships). With the addition of Himawari SST data and method improvement, HIMSST data now offer higher resolution and better analysis accuracy than data from conventional analysis. The improvement enables consideration of small-scale and short-period variations determined from Himawari SST data and NOAA/AVHRR high-resolution data. The HIMSST area of coverage is limited to the western north Pacific to ensure the validity of verification of Himawari-8 observation data. Table III.2-1 shows verification of HIMSST and conventional analysis compared to in-situ data. HIMSST accuracy is higher than that of conventional analysis with both bias and RMSE, and the data are more sensitive to SST variations.

III.3 Sea Surface Temperature (SST) product specifications

Table III.3-1 shows the specifications of JMA’s current SST products. The Sea Surface Temperature Composite Images Based on Himawari Data product has been provided since May 2016, and HIMSST has been provided since November 2016. Both are uploaded to JMA’s Marine Diagnosis Report web page (Japanese only).
IV Interannual variability in carbon dioxide concentrations and related causes

- Carbon dioxide (CO$_2$) atmospheric concentration growth rate exhibits interannual variability strongly associated with terrestrial biosphere uptake and emission.
- The net uptake of CO$_2$ by the terrestrial biosphere in 2015$^3$ was lower than the average for the previous decade. This was due to high temperatures and droughts in tropical regions and elsewhere associated with the recent El Niño event, which enhanced CO$_2$ emissions from plant respiration, decomposition of organic matter in soil, and wildfires.

Carbon dioxide (CO$_2$) is the most influential contributor to global warming. Its atmospheric concentration increases at a rate of around 2 ppm/year, corresponding to 4 GtC/year in units of carbon mass, with seasonal cycles. The growth rate of CO$_2$ concentration is not necessarily constant, exhibiting significant interannual variations. The 2015 growth rate was the second-highest since 1985 (Figure IV-1).

The interannual variability observed is primarily associated with natural sources and sinks of CO$_2$. Accordingly, it is important to clarify the causes of this variability in order to better understand the global carbon cycle, which will eventually provide scientific pointers for the effective reduction of greenhouse gas concentrations.

Figure IV-1  Time-series representation showing monthly averages of global atmospheric CO$_2$ concentration (blue dots) and its annual growth rate (gray bars) from 1985 to 2015

The analysis was performed using data archived by the World Data Centre for Greenhouse Gases (WDCGG). The annual growth rate is defined as the average of concentrations in December of one year and January of the next year minus the corresponding average for previous years. Conversion from ppm to carbon mass per year is based on a factor of 2.12 GtC/ppm (IPCC, 2013).

As shown in Figure IV-2, once CO$_2$ is emitted into the atmosphere as a result of anthropogenic activity, it is exchanged with reservoirs formed by oceans and the terrestrial biosphere. As a result, roughly half of all anthropogenic emissions remain in the atmosphere, with the remainder being captured in these reservoirs. The terrestrial biosphere plays the most significant role in interannual variations of the CO$_2$ concentration growth rate.

$^3$ The latest available data (up to 2015) are referenced here.
The method for estimating net CO$_2$ uptake by the terrestrial biosphere here is that of Le Quéré et al. (2016), with the atmospheric concentration growth rate and oceanic uptake subtracted from anthropogenic emissions. Figure IV-3 illustrates the resulting net CO$_2$ uptake by the terrestrial biosphere as a function of years. A rate of $2.6 \pm 0.8$ GtC/year on average is seen for the period 1990 – 2015. The annual net CO$_2$ uptake in 2015 was $2.2 \pm 0.9$ GtC/year, which is lower than the average of $3.2 \pm 0.9$ GtC/year for the previous decade (2006 – 2015).

El Niño events usually induce high temperatures and droughts, particularly in the tropics, and such anomalies enhance CO$_2$ emissions from the terrestrial biosphere. Plant respiration and decomposition of organic matter in soil are promoted as a result, while plant photosynthesis is diminished (Keeling et al., 1995; see also Section 3.1.1). In addition, frequent wildfires contribute to higher CO$_2$ emissions. The low net CO$_2$ uptake by the terrestrial biosphere in 2015 can be attributed to the 2014 – 2016 El Niño event (WMO, 2016). Similar suppressions of net CO$_2$ uptake by the terrestrial biosphere were also observed with rough correspondence to the El Niño events of 1997/1998, 2002/2003 and 2009/2010. In particular, 1998 exhibited the highest growth rate of atmospheric CO$_2$ concentration for three decades and the lowest net uptake by the terrestrial biosphere. An exception was the period 1991 – 1992, when net CO$_2$ uptake by the terrestrial biosphere was large despite the corresponding El Niño event. This may be attributable to the eruption of Mt. Pinatubo, which caused negative temperature anomalies worldwide and inhibited CO$_2$ emissions from the decomposition of organic matter in soil (Keeling et al., 1996; Rayner et al., 1999).

Net uptake of CO$_2$ by the terrestrial biosphere exhibited no discernible long-term trend in the period 1990 – 2015 due to large interannual variations. It is possible, however, that the progress of global warming will suppress the uptake of CO$_2$ by the terrestrial biosphere and accelerate the increase in atmospheric CO$_2$ concentrations (IPCC, 2013). Hence, it is necessary to continuously monitor the long-term trend of CO$_2$ exchanges among the atmosphere, the oceans and the terrestrial biosphere.
Figure IV-3  Time-series representation of annual net CO$_2$ uptake by the terrestrial biosphere from 1990 to 2015

Net CO$_2$ uptake is estimated by subtracting the growth rate of atmospheric concentration (Figure IV-1) and oceanic uptake (Iida et al., 2015; see also Section 3.1.1) from anthropogenic emissions mainly caused by fossil fuel combustion and land-use changes (Le Quéré et al., 2016). Oceanic uptake incorporates a natural CO$_2$ efflux of 0.7 GtC/year (IPCC, 2013) associated with river input into oceans. Positive/negative values indicate CO$_2$ uptakes/ emissions, respectively. Error bars represent a 68% confidence level. El Niño and La Niña periods are shaded in red and blue, respectively.
Chapter 1  Climate in 2016

1.1  Global climate summary

- Extremely high temperatures were frequently observed in many regions of the world, and in particular continued for most of the year in various places at low latitudes.
- Droughts in Southeast Asia (January – May), heatwaves in India (March – May), heavy rains in China (April – July) and hurricane Matthew striking Haiti (October) caused immense damage.

Major extreme climate events and weather-related disasters occurring in 2016 are shown in Figure 1.1-1 and Table 1.1-1.

Extremely high temperatures were frequently observed in many regions of the world ((4), (5), (8), (12), (15), (16), (17), (18), (19), (21), (22), (24), (25), (26), (27), (28), (30) in Figure 1.1-1). In particular, extremely high temperatures continued for most of the year in various places at low latitudes. At one weather station in the Svalbard Islands of northern Norway, the monthly mean temperature for February was -5.6°C (8.0°C higher than the normal)

4

6

4

°C higher than the normal), while the monthly mean for March at Makkah in western Saudi Arabia was 31.5°C (4.1°C higher than the normal). The seven-month mean for February – August at Barra do Corda in eastern Brazil was 28.1°C (2.3°C higher than the normal).

Extremely low precipitation amounts were observed from southwestern France to northeastern Spain and in eastern Brazil ((14) and (25) in Figure 1.1-1). The total precipitation amount for July – August in France was the lowest since 1959 (Meteo France), and precipitation for these two months at Gourdon in southwestern France was just 13 mm (10% of the normal). The four-month total for February – May at Vitoria da Conquista in eastern Brazil was 32 mm (9% of the normal).

Extremely high precipitation amounts were observed in southeastern Europe, from the Midwest to the southern USA and in southeastern Australia ((13), (20) and (29) in Figure 1.1-1). Precipitation for October at Bucharest in Romania was 128 mm (259% of the normal), while monthly precipitation for April at San Antonio in the state of Texas in the USA was 157 mm (295% of the normal). Nationwide average precipitation in Australia for June was the second highest for the month since 1900 (Bureau of Meteorology, Australia), and precipitation for the month at Canberra in Australia was 144 mm (333% of the normal).

Torrential rains frequently hit China (especially southeastern to southern parts) from April through July, causing more than 490 fatalities ((3) in Figure 1.1-1). Two-month precipitation at Wuhan in Hubei Province was 1,036 mm (225% of the normal). Hurricane Matthew brought significant damage and loss of life to Haiti (more than 540 fatalities) and the southeastern USA (more than 40 fatalities) in October.

Toroidal mean temperatures were above normal in many parts of the world and below normal in the southwestern part of Eastern Siberia and in northern Argentina (Figure 1.1-2).

Annual precipitation amounts were above normal in eastern China, Mongolia, Central Asia, southeastern Europe, Indonesia and southern Argentina, and were below normal in...
eastern Brazil and southern Chile (Figure 1.1-3).

The El Niño event that prevailed until spring and subsequent warming in the Indian Ocean are considered responsible for the frequent heavy rains observed in southern China from April through July, for the Southeast Asian drought that continued until May, and for the high temperatures observed at low latitudes.
<table>
<thead>
<tr>
<th>No.</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Heavy rain: the northeastern part of the Korean peninsula (August – September)</td>
</tr>
<tr>
<td>2.</td>
<td>Cold: in and around eastern Mongolia (January, October – November)</td>
</tr>
<tr>
<td>3.</td>
<td>Heavy rain: China (April – July)</td>
</tr>
<tr>
<td>4.</td>
<td>Warm: southern Kyushu region in Japan to southeastern China (April – June, October, December)</td>
</tr>
<tr>
<td>5.</td>
<td>Warm: Southeast Asia (January – May, July – November)</td>
</tr>
<tr>
<td>6.</td>
<td>Drought: Southeast Asia (January – May)</td>
</tr>
<tr>
<td>7.</td>
<td>Tropical storm: Sri Lanka, northeastern India and Bangladesh (May)</td>
</tr>
<tr>
<td>8.</td>
<td>Warm: southern India to Sri Lanka (January – April, July – August, October, December)</td>
</tr>
<tr>
<td>9.</td>
<td>Heat wave (March – May) and Heavy Rain (July – October): India</td>
</tr>
<tr>
<td>10.</td>
<td>Heavy rain: Pakistan (July – August)</td>
</tr>
<tr>
<td>11.</td>
<td>Heavy rain: northern Pakistan to Afghanistan (March – April)</td>
</tr>
<tr>
<td>12.</td>
<td>Warm: the northern part of Central Siberia to the Svalbard Islands (February, April – July, September)</td>
</tr>
<tr>
<td>13.</td>
<td>Wet: southeastern Europe (February – March, May – June, October)</td>
</tr>
<tr>
<td>14.</td>
<td>Dry: southwestern France to northeastern Spain (July – August, October, December)</td>
</tr>
<tr>
<td>15.</td>
<td>Warm: in and around northern Algeria (January – February, October)</td>
</tr>
<tr>
<td>16.</td>
<td>Warm: northeastern Saudi Arabia to the southern coast of the Red Sea (March, May – July)</td>
</tr>
<tr>
<td>17.</td>
<td>Warm: in the western part of Western Africa to the northwestern part of Central Africa (April – June, August – December)</td>
</tr>
<tr>
<td>18.</td>
<td>Warm: Seychelles to the northeastern part of South Africa (January – April, October)</td>
</tr>
<tr>
<td>19.</td>
<td>Warm: the eastern part of Eastern Siberia to the western coast of Canada (April – August, October)</td>
</tr>
<tr>
<td>20.</td>
<td>Wet: the Midwest to the southern USA (March – April, July – August)</td>
</tr>
<tr>
<td>21.</td>
<td>Warm: the eastern to the southern USA (March, June – October)</td>
</tr>
<tr>
<td>22.</td>
<td>Warm: the southwestern USA to northwestern Mexico (February – March, October – December)</td>
</tr>
<tr>
<td>23.</td>
<td>Hurricane: Haiti and the southeastern USA (October)</td>
</tr>
<tr>
<td>24.</td>
<td>Warm: southern Mexico to Colombia (January – August, October)</td>
</tr>
<tr>
<td>25.</td>
<td>Warm (February – August) and Dry (February – May): eastern Brazil</td>
</tr>
<tr>
<td>26.</td>
<td>Warm: in and around central Chile (January – February, August – September, November)</td>
</tr>
<tr>
<td>27.</td>
<td>Warm: Micronesia (March – April, June, August)</td>
</tr>
<tr>
<td>28.</td>
<td>Warm: northern to southeastern Australia (March – July, September, November)</td>
</tr>
<tr>
<td>29.</td>
<td>Wet: southeastern Australia (January, June, September)</td>
</tr>
<tr>
<td>30.</td>
<td>Warm: in and around New Zealand (February, May, September)</td>
</tr>
</tbody>
</table>

Data and information on disasters are based on official reports of the United Nations and national governments and databases of research institutes (EM-DAT).
Figure 1.1-2 Annual mean temperature anomalies in 2016
Categories are defined by the annual mean temperature anomaly against the normal divided by its standard deviation and averaged in 5° × 5° grid boxes. Red/blue marks indicate values above/below the normal calculated for the period from 1981 to 2010. The thresholds of each category are −1.28, −0.44, 0, +0.44 and +1.28. Areas over land without graphical marks are those where observation data are insufficient or normal data are unavailable.

Figure 1.1-3 Annual total precipitation amount ratios in 2016
Categories are defined by the annual precipitation ratio to the normal averaged in 5° × 5° grid boxes. Green/yellow marks indicate values above/below the thresholds. The thresholds of each category are 70, 100 and 120% of the normal calculated for the period from 1981 to 2010. Areas over land without graphical marks are those where observation data are insufficient or normal data are unavailable.

5 In normal distribution, values of 1.28 and 0.44 correspond to occurrence probabilities of less than 10 and 33.3%, respectively.
1.2 Climate in Japan

- In 2016, temperatures were generally above normal all over Japan, except for autumn in northern Japan. Annual mean temperatures were significantly above normal almost nationwide. In particular, the temperature for eastern Japan tied with 2004 as the highest since 1946 (+1.0°C above the normal).
- Four tropical cyclones made landfall on northern Japan in August, bringing record heavy rainfall with storms in northern Japan.
- In autumn, seasonal precipitation amounts were significantly above normal and seasonal sunshine durations were significantly below normal in western Japan due to the influences of low-pressure systems, fronts, and tropical cyclones.

1.2.1 Annual characteristics (Figure 1.2-1)

- Annual mean temperatures were significantly above normal almost nationwide.
- Annual precipitation amounts were significantly above normal on the Pacific side of northern Japan, in western Japan and Okinawa/Amami, above normal on the Sea of Japan side of northern Japan, near normal in eastern Japan.
- Annual sunshine durations were above normal in northern Japan and on the Sea of Japan side of eastern Japan, below normal in western Japan, and near normal on the Pacific side of eastern Japan and in Okinawa/Amami.

Figure 1.2-1  Annual climate anomaly/ratio for Japan in 2016
The base period for the normal is 1981 – 2010.

6 The term significantly above normal is used for cases in which observed mean temperatures or precipitation amounts exceed the 90th percentile for the base period (1981 – 2010), and significantly below normal is used when the corresponding figures fall below the 10th percentile.
1.2.2 Seasonal characteristics (Figure 1.2-2, Figure 1.2-3, Table 1.2-1)

(1) Winter (December 2015 – February 2016) (Figure 1.2-3 (a))

- Mean temperatures were above normal in nationwide, especially in eastern and western Japan.
- Precipitation amounts were above normal in nationwide, especially in western Japan and Okinawa/Amami.
- Sunshine durations were significantly below normal in Okinawa/Amami, below normal on the Sea of Japan side of northern and western Japan and near normal on the Pacific side of northern and western Japan and in eastern Japan.

In association with a weak winter monsoon, seasonal temperatures were above normal all over Japan, especially in eastern and western Japan. Seasonal snowfall amounts for the Sea of Japan side were generally below normal, and significantly above normal in Northern Kyushu, due to considerably cold air outbreaks at the end of January. Due to the significant influences of low-pressure systems and fronts, seasonal precipitation amounts were above normal all over Japan, with Okinawa/Amami experiencing record highs (188% of the normal) for winter since 1946/47.

(2) Spring (March – May 2016) (Figure 1.2-3 (b))

- Mean temperatures were significantly above normal in nationwide.
- Precipitation amounts were significantly below normal on the Sea of Japan side of eastern Japan, below normal on the Pacific side of northern Japan, above normal on the Pacific side of western Japan and in Okinawa/Amami, and near normal in other regions.
Seasonal mean temperatures were significantly above normal due to warm southerly winds, associated with dominant high-pressure systems over eastern Japan and the development of the subtropical high in southern Japan. Seasonal sunshine durations were significantly above normal on the Sea of Japan side of eastern Japan, and above normal in northern and western Japan, due to significant influences from high-pressure systems. Seasonal precipitation amounts were significantly below normal on the Sea of Japan side of eastern Japan, and below normal on the Pacific side of northern Japan. Meanwhile, seasonal precipitation amounts were above normal on the Pacific side of western Japan and Okinawa/Amami due to the influences of the low-pressure systems and fronts in April.

(3) Summer (June – August 2016) (Figure 1.2-3 (c))

- Mean temperatures were significantly above normal in Okinawa/Amami, above normal in northern, eastern and western Japan.
- Precipitation amounts were significantly above normal in northern Japan, above normal on the Pacific side of western Japan, below normal in Okinawa/Amami, and near normal in eastern Japan and on the Sea of Japan side of western Japan.
- Sunshine durations were above normal almost nationwide.

Seasonal mean temperatures and sunshine durations were above normal all over Japan. In Okinawa/Amami, the seasonal mean temperature was the highest on record for summer since 1946 (+1.1°C above the normal), in association with strong solar radiations accompanying high sunshine durations. Meanwhile, in northern Japan, seasonal precipitation amounts were significantly above normal. On the Pacific side of northern Japan, the figure was 163% of the normal (the highest on record for summer since 1946), in association with the frequent passage of cyclones around northern Japan in June and the approach of numerous tropical cyclones around northern Japan in August.

Four tropical cyclones made landfall on the Hokkaido region and Iwate Prefecture, bringing significant rainfall with storms. Hokkaido and Iwate Prefecture experienced record heavy rainfall, which caused serious damage including river overflows and landslides.

(4) Autumn (September – November 2016) (Figure 1.2-3 (d))

- Mean temperatures were significantly above normal in western Japan and Okinawa/Amami, above normal in eastern Japan, and below normal in northern Japan.
- Precipitation amounts were significantly above normal in western Japan, above normal on the Sea of Japan side of eastern Japan and in Okinawa/Amami, below normal in northern Japan, near normal on the Sea of Japan side of eastern Japan.
- Sunshine durations were below normal in nationwide especially on the Sea of Japan side of northern Japan, on the Pacific side of eastern Japan and in western Japan.

Western Japan and Okinawa/Amami experienced record seasonal mean temperatures (+1.3 and +1.2°C above the normal, respectively) for autumn since 1946 due to warm southerly winds. In association with significant influences from low-pressure systems and fronts, western Japan experienced significantly above-normal seasonal precipitation amounts.
and below-normal seasonal sunshine durations. Seasonal precipitation was 173% of the normal on the Sea of Japan side of western Japan (the highest on record for autumn since 1946), while seasonal sunshine durations were 74% of the normal on the Sea of Japan side of western Japan and 82% of the normal on the Pacific side of the region (both with the lowest on record for autumn since 1946). Seasonal sunshine durations were also below normal in other regions. In northern Japan, seasonal mean temperatures were below normal for the first time since 2002, even with the high temperatures recorded in September, and temperatures remained low after October.

(5) Early Winter (December 2016)

In conjunction with a weaker-than-normal winter monsoon pattern, low-pressure systems frequently passed over the area around Japan and above-normal temperatures continued all over the country. Monthly mean temperatures were significantly above normal nationwide except in northern Japan, and snowfall amounts were below normal on the Sea of Japan side. In Okinawa/Amami, the monthly mean temperature was the highest on record for December since 1946. Monthly precipitation amounts were above normal on the Pacific side of northern Japan, and significantly above normal on Pacific side of eastern Japan and in western Japan.
Figure 1.2-3  Seasonal anomalies/ratios for Japan in 2016
(a) Winter (December 2015 to February 2016), (b) spring (March to May 2016), (c) summer (June to August 2016), (d) autumn (September to November 2016). The base period for the normal is 1981 – 2010.
Table 1.2-1  Number of observatories reporting record monthly and annual mean temperatures, precipitation amounts and sunshine durations (2016)
From 154 surface meteorological stations across Japan.

<table>
<thead>
<tr>
<th></th>
<th>Temperature</th>
<th>Precipitation amount</th>
<th>Sunshine duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Highest</td>
<td>Lowest</td>
<td>Heaviest</td>
</tr>
<tr>
<td>January</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>February</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>March</td>
<td>3</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>25</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>1</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>August</td>
<td>3</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>September</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>October</td>
<td>40</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>November</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>December</td>
<td>5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>year</td>
<td>16</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
(Chapter 1 Climate in 2016)

1.3 Atmospheric circulation and oceanographic conditions

- The El Niño episode that emerged in summer 2014 peaked in November – December 2015 and ended in spring 2016. Sea surface temperatures over the Indian Ocean remained above normal from winter 2015/2016 to spring 2016. Tropical circulation was presumed to be influenced by these temperature anomalies.
- In August 2016, convective activity was enhanced in the 20°-30°N latitude band over the western Pacific, and cyclonic circulation anomalies formed to the southeast of Japan. In association, a series of tropical cyclones formed and approached or made landfall on Japan.
- In autumn 2016, warm air often flowed over the Arctic due to a pressure anomaly pattern around the North Pole, thereby delaying the expansion of sea ice.

Monitoring of atmospheric and oceanographic conditions (e.g., upper air flow, tropical convective activity and sea surface temperatures (SSTs)) is key to understanding the causes of extreme weather events. This section briefly outlines the characteristics of atmospheric circulation and oceanographic conditions seen in 2016.

1.3.1 Characteristics of individual seasons

(1) Winter (December 2015 – February 2016)

The El Niño episode that emerged in summer 2014 peaked in November – December 2015. SSTs were higher than normal along the equator over the central – eastern Pacific (Figure 1.3-1) and most of the Indian Ocean. In association with these anomalies, convective activity was enhanced over the central – eastern Pacific and suppressed from the Maritime Continent to the western Pacific (Figure 1.3-2).

Positive anomalies in the 500-hPa height field were clearly seen over Western – Central Siberia and over the seas east of Japan (Figure 1.3-3). Positive sea level pressure (SLP) anomalies were seen over the seas east of Japan and negative values were seen over the northeastern part of the North Pacific, indicating that the Aleutian Low was located southeast of its normal position (Figure 1.3-4). This anomaly pattern tends to be observed during El Niño events. Although winter precipitation in the southwestern USA tends to be greater than normal in El Niño conditions, the amount was lower than normal in winter 2015/2016 due to positive SLP anomalies along the western coast of the USA, prolonging the drought that began in 2013. SLP anomalies over Western – Central Siberia were positive in winter 2015/2016, partly because of the significantly developed Siberian High in January of 2016.

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7 See the Glossary for terms relating to El Niño phenomena, monsoons and Arctic Oscillation.
8 The main charts used for monitoring of atmospheric circulation and oceanographic conditions are: sea surface temperature (SST) maps representing SST distribution for monitoring of oceanographic variability elements such as El Niño/La Niña phenomena; outgoing longwave radiation (OLR) maps representing the strength of longwave radiation from the earth’s surface under clear sky conditions into space or from the top of clouds under cloudy conditions into space for monitoring of convective activity; 500-hPa height maps representing air flow at a height of approximately 5,000 meters for monitoring of atmospheric circulation variability elements such as westerly jet streams and the Arctic Oscillation; and sea level pressure maps representing air flow and pressure systems on the earth’s surface for monitoring of the Pacific High, the Siberian High, the Arctic Oscillation and other phenomena.
9 JMA publishes Monthly Highlights on the Climate System including information on the characteristics of climatic anomalies and extreme events around the world, atmospheric circulation and oceanographic conditions. It can be found at http://ds.data.jma.go.jp/tcc/tcc/products/clisys/highlights/index.html.
(2) Spring (March – May 2016)\(^{10}\)
Positive SST anomalies in the central – eastern Pacific weakened and the El Niño event ended, while SSTs over most of the Indian Ocean remained higher than normal (Figure 1.3-5). Convective activity was enhanced in the central Pacific, where SSTs remained above normal (Figure 1.3-6). Meanwhile, SSTs were suppressed from the Bay of Bengal to the seas east of the Philippines, and the first tropical cyclone formation of 2016 was the second-latest since 1951 in the western North Pacific. These anomaly patterns (i.e., positive SSTs in the Indian Ocean and suppressed convection with enhanced high-pressure systems over the western North Pacific) tend to appear after El Niño event peaks.

Positive anomalies in the 500-hPa height field were observed widely, especially over the Arctic, around Japan and over the western USA, reflecting the rise of global temperatures (Figure 1.3-7). Positive and negative SLP anomalies were seen to the seas east of Japan and over the northeastern North Pacific, respectively (Figure 1.3-8). This anomaly pattern brought warm air to Japan and northwestern North America, causing significantly warm conditions there.

(3) Summer (June – August 2016)\(^{11}\)
SSTs over the central – eastern equatorial Pacific began to exhibit negative anomalies (Figure 1.3-9). Positive SST anomalies over the Indian Ocean weakened and negative anomalies were seen in some areas of the western Indian Ocean. SSTs were above normal from the Maritime Continent to the seas south of Japan. Convective activity was enhanced from the eastern Indian Ocean to the Maritime Continent and suppressed over the western Indian Ocean and the equatorial Pacific (Figure 1.3-10). In the western North Pacific, enhanced convection areas were observed over the 20° – 30°N latitude band.

Positive anomalies in the 500-hPa height field were seen over large areas as in spring, especially over Western Siberia and the northern North Pacific (Figure 1.3-11). Negative SLP anomalies were observed over the subtropical area of the North Pacific and around Japan (Figure 1.3-12). These low-pressure anomalies and the above-mentioned enhanced convection observed over the 20° – 30°N area of the western Pacific were considered to be associated with tropical cyclones in August, which formed repeatedly and approached or made landfall on Japan.

(4) Autumn (September – November 2016)
Negative SST anomalies over the central – eastern equatorial Pacific were clearer than in summer, and SSTs in the western Pacific remained above normal (Figure 1.3-13). SSTs in many parts of the Indian Ocean began to exhibit negative anomalies. Convective activity was enhanced around the Maritime Continent and over the Intertropical Convergence Zone of the Pacific, and was suppressed over the western – central Indian Ocean (Figure 1.3-14).

Positive anomalies in the 500-hPa height field were pronounced over the Arctic coast of Siberia (Figure 1.3-15), and negative height anomalies zonally extended from the mid-latitudes of the Eurasian continent to the northern North Pacific. Positive SLP anomalies

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\(^{10}\) See Topics I.2 (2) for details of delayed formation of the first tropical cyclone.

\(^{11}\) See Topics II for details of extreme climate condition in Japan for August 2016.
were seen over the Arctic coast from Europe to Central Siberia, and negative anomalies were observed over the Western Hemisphere side of the Arctic Sea (Figure 1.3-16). This SLP pattern brought warm air to the Arctic, and the expansion of sea ice was delayed. The Subtropical High was stronger than normal and negative SLP anomalies were observed over the southern Eurasian continent, bringing warm air to the area stretching from western Japan to Okinawa/Amami.
(Chapter 1 Climate in 2016)

Figure 1.3-1 Three-month mean sea surface temperature (SST) anomaly (December 2015 – February 2016)
The contour interval is 0.5°C. Sea ice coverage areas are shaded in gray. The base period for the normal is 1981 – 2010.

Figure 1.3-2 Three-month mean outgoing longwave radiation (OLR) anomaly (December 2015 – February 2016)
The contour interval is 10 W per m². The base period for the normal is 1981 – 2010. Negative (cold color) and positive (warm color) OLR anomalies show enhanced and suppressed convection, respectively, compared to the normal.

Figure 1.3-3 Three-month mean 500-hPa height and anomaly in the Northern Hemisphere (December 2015 – February 2016)
Contours show 500-hPa height at intervals of 60 m, and shading indicates height anomalies. The base period for the normal is 1981 – 2010. “H” and “L” denote high- and low-pressure systems, respectively. Westerly winds flow along the contours. Dense (sparse) contour intervals denote high (low) wind speed.

Figure 1.3-4 Three-month mean sea level pressure and anomaly in the Northern Hemisphere (December 2015 – February 2016)
Contours show sea level pressure at intervals of 4 hPa, and shading indicates sea level pressure anomalies. The base period for the normal is 1981 – 2010. “H” and “L” denote high- and low-pressure systems, respectively.
Figure 1.3-5  Three-month mean sea surface temperature (SST) anomaly (March – May 2016)
As per Figure 1.3-1, but for March – May 2016

Figure 1.3-6 Three-month mean outgoing longwave radiation (OLR) anomaly (March – May 2016)
As per Figure 1.3-2, but for March – May 2016

Figure 1.3-7 Three-month mean 500-hPa height and anomaly in the Northern Hemisphere (March – May 2016)
As per Figure 1.3-3, but for March – May 2016

Figure 1.3-8 Three-month mean sea level pressure and anomaly in the Northern Hemisphere (March – May 2016)
As per Figure 1.3-4, but for March – May 2016
(Chapter 1 Climate in 2016)

Figure 1.3-9 Three-month mean sea surface temperature (SST) anomaly (June – August 2016)
As per Figure 1.3-1, but for June – August 2016

Figure 1.3-10 Three-month mean outgoing longwave radiation (OLR) anomaly (June – August 2016)
As per Figure 1.3-2, but for June – August 2016

Figure 1.3-11 Three-month mean 500-hPa height and anomaly in the Northern Hemisphere (June – August 2016)
As per Figure 1.3-3, but for June – August 2016

Figure 1.3-12 Three-month mean sea level pressure and anomaly in the Northern Hemisphere (June – August 2016)
As per Figure 1.3-4, but for June – August 2016
Figure 1.3-13 Three-month mean sea surface temperature (SST) anomaly (September – November 2016)
As per Figure 1.3-1, but for September – November 2016

Figure 1.3-14 Three-month mean outgoing longwave radiation (OLR) anomaly (September – November 2016)
As per Figure 1.3-2, but for September – November 2016

Figure 1.3-15 Three-month mean 500-hPa height and anomaly in the Northern Hemisphere (September – November 2016)
As per Figure 1.3-3, but for September – November 2016

Figure 1.3-16 Three-month mean sea level pressure and anomaly in the Northern Hemisphere (September – November 2016)
As per Figure 1.3-4, but for September – November 2016
Chapter 2  Climate Change

2.1 Changes in temperature

- The annual anomaly of the global average surface temperature in 2016 was the highest since 1891, and the annual anomaly of the average temperature over Japan was also the highest since 1898.
- On a longer time scale, it is virtually certain that the annual global average surface temperature and the annual average temperature over Japan have risen at rates of about 0.72 and 1.19ºC per century, respectively.
- It is virtually certain that the frequency of extremely high monthly temperature events has increased, while the frequency of extremely low monthly temperature events has decreased.
- It is virtually certain that the annual number of days with minimum temperatures below 0ºC \((T_{\text{min}} < 0ºC)\) has decreased, while the annual number of days with minimum temperatures of 25ºC or higher \((T_{\text{min}} \geq 25ºC)\) has increased. The annual number of days with maximum temperatures of 30 ºC or higher \((T_{\text{max}} \geq 30ºC)\) is very likely to have increased, and that with maximum temperatures of 35 ºC or higher \((T_{\text{max}} \geq 35ºC)\) is virtually certain to have increased.

2.1.1 Global surface temperature

The annual anomaly of the global average surface temperature in 2016 (i.e., the combined average of the near-surface air temperature over land and the SST) was +0.45ºC above the 1981 – 2010 average. This was the highest since 1891 and the third consecutive annual record. The surface temperature anomalies over the Northern Hemisphere and the Southern Hemisphere were +0.59ºC (the highest) and +0.31ºC (the highest), respectively (Figure 2.1-1). The global average temperature fluctuates on different time scales ranging from years to decades. On a longer time scale, it is virtually certain that the global average surface temperature has risen at a rate of about 0.72ºC per century \(^{(13)}\) (statistically significant at a confidence level of 99%). Similarly, it is virtually certain that average surface temperatures over the Northern Hemisphere and the Southern Hemisphere have risen at rates of about 0.77 and 0.68ºC per century, respectively (both statistically significant at a confidence level of 99%). Linear temperature trends for 5° x 5° latitude/longitude grid boxes indicate that most areas of the world have experienced long-term warming (Figure 2.1-2 top) and that the rates of warming observed over approximately the last four decades have been greater than those of earlier decades (Figure 2.1-2 bottom). These long-term trends in annual average temperatures can be largely attributed to global warming caused by increased concentrations of greenhouse gases such as \(\text{CO}_2\). On a shorter time scale, temperatures fluctuate due to the influence of

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12 Monthly, seasonal and annual estimates of average temperatures around the globe and around Japan are published on JMA’s website.
http://ds.data.jma.go.jp/tcc/tcc/products/gwp/gwp.html (English)

13 According to IPCC AR5, the global average surface temperature has risen about 0.85ºC (The 90% uncertainty interval is 0.65 to 1.06ºC) over the period 1880 to 2012. The values given in IPCC AR5 and those in this report are considered to show no remarkable difference that have risen on a longer time scale and are higher since the mid-1990s, although they do not correspond exactly because of differences in dataset calculation methods and the statistical period examined.

14 For evaluation and clarification of the significance statistics used here, see “Explanatory note on detection of statistical significance in long-term trends” at the end of the report.
natural climate dynamics over different time scales ranging from years to decades. The high temperatures observed in 2016 are considered partially attributable to the El Niño event that persisted from boreal summer 2014 to spring 2016 (Topic I and Section 2.5.1).

Figure 2.1-1  Annual anomalies in surface temperature (i.e., the combined average of the near-surface air temperature over land and the SST) from 1891 to 2016 for the globe (top left), for the Northern Hemisphere (top right) and for the Southern Hemisphere (bottom). Anomalies are deviations from the baseline (the 1981 – 2010 average). The thin black line with dots indicates surface temperature anomalies for each year. The blue line indicates the five-year running mean, and the red line indicates the long-term linear trend.

Figure 2.1-2  Linear temperature trends for 5° × 5° latitude/longitude grid boxes for the period of 1891 to 2016 (top), and 1979 to 2016 (bottom). The grid boxes with gray circles have no statistically significant trend.
2.1.2 Surface temperature over Japan

Long-term changes in the surface temperature over Japan are analyzed using observational records dating back to 1898. Table 2.1-1 lists the meteorological stations whose data are used to derive annual mean surface temperatures.

Table 2.1-1 Observation stations whose data are used to calculate surface temperature anomalies over Japan

<table>
<thead>
<tr>
<th>Element</th>
<th>Observation stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Abashiri, Nemuro, Suttsu, Yamagata, Ishinomaki, Fushiki, Iida, Choshi, Sakai, Hamada, Hikone, Miyazaki, Tadotsu, Naze, Ishigakijima</td>
</tr>
</tbody>
</table>

The mean surface temperature in Japan for 2016 is estimated to have been 0.88°C above the 1981–2010 average, which is the highest since 1898 (Figure 2.1-3). The surface temperature fluctuates on different time scales ranging from years to decades. On a longer time scale, it is virtually certain that the annual mean surface temperature over Japan has risen at a rate of about 1.19°C per century (statistically significant at a confidence level of 99%). Similarly, it is virtually certain that the seasonal mean temperatures for winter, spring, summer and autumn have risen at rates of about 1.11, 1.38, 1.08 and 1.20°C per century, respectively (all statistically significant at a confidence level of 99%).

It is noticeable from Figure 2.1-3 that the annual mean temperature remained relatively low before the 1940s, started to rise and reached a local peak around 1960, entered a cooler era through to the mid-1980s and then began to show a rapid warming trend in the late 1980s. The warmest years on record have all been observed since the 1990s.

The high temperatures seen in recent years have been influenced by fluctuations over different time scales ranging from years to decades, as well as by global warming resulting from increased concentrations of greenhouse gases such as CO2. This trend is similar to that of worldwide temperatures, as described in Section 2.1.1.

Figure 2.1-3 Annual surface temperature anomalies from 1898 to 2016 in Japan. Anomalies are deviations from the baseline (the 1981–2010 average). The thin black line indicates the surface temperature anomaly for each year. The blue line indicates the five-year running mean, and the red line indicates the long-term linear trend.
2.1.3 **Long-term trends of extreme temperature events in Japan**

This section describes long-term trends of extremely high/low-temperature events in Japan, as derived from analysis of temperature records from the 15 observation stations. Though monthly mean temperatures of the stations in Miyazaki and Iida have been adjusted to eliminate the influence of their relocation, records from these two stations are not used for analysis of daily temperatures due to the difficulty of adjustment in regard to the relocation.

(1) **Long-term trends of monthly extreme temperatures**

It is virtually certain that the frequency of extremely high monthly temperatures has increased, while that of extremely low monthly temperatures has decreased (both statistically significant at the confidence level of 99%) (Figure 2.1-4). These trends are consistent with the rising annual mean temperatures discussed in Section 2.1.2.

![Figure 2.1-4 Annual number of extremely high/low monthly mean temperature occurrences](image)

The graphs show the annual number of occurrences of the highest/lowest first-to-forth values for each month during the period from 1901 to 2016. The green bars indicate annual occurrences of extremely high/low monthly mean temperatures divided by the total number of monthly observation data sets available for the year (i.e., the average occurrence per station). The blue line indicates the five-year running mean, and the straight red line indicates the long-term linear trend.

(2) **Annual number of days with maximum temperatures of ≥30°C and ≥35°C**

The annual number of days with maximum temperatures \(T_{\text{max}}\) of ≥30°C is very likely to have increased (statistically significant at a confidence level of 90%) and with \(T_{\text{max}}\) ≥ 35°C is virtually certain to have increased (statistically significant at a confidence level of 99%) (Figure 2.1-5).

---

15 Here, judgment of extremely high/low temperatures is based on the fourth-highest/lowest monthly values on records over the 116-year period from 1901 to 2016. The frequency of occurrence of the highest/lowest to the fourth-highest/lowest values over this period is once every 29 years, which is close to JMA’s definition of extreme climate events as those occurring once every 30 years or longer (See the Glossary for terms relating to Extreme climate event).
Figure 2.1-5  Annual number of days with maximum temperatures of $\geq 30^\circ$C and $\geq 35^\circ$C
The graphs show the annual number of days per station, with the green bars indicating the values for each year during the period from 1931 to 2016. The blue line indicates the five-year running mean, and the straight red line indicates the long-term linear trend.

(3) Annual number of days with minimum temperatures of $< 0^\circ$C and $\geq 25^\circ$C
It is virtually certain that the annual number of days with minimum temperatures ($T_{\text{min}}$) of $< 0^\circ$C has decreased, while the annual number of days with $T_{\text{min}} \geq 25^\circ$C has increased (both statistically significant at a confidence level of 99%) (Figure 2.1-6).

Figure 2.1-6  Annual number of days with minimum temperatures of $< 0^\circ$C and $\geq 25^\circ$C
As per Figure 2.1-5.
2.1.4 Urban heat island effect at urban stations in Japan

The long-term trends of annual average temperatures are more pronounced for urban observation stations whose data are homogeneous over a long period (Sapporo, Sendai, Nagoya, Tokyo, Yokohama, Kyoto, Hiroshima, Osaka, Fukuoka, Kagoshima) than for the average of the 15 rural observation stations (Table 2.1-2).

Table 2.1-2 Long-term trends of annual and seasonal average temperatures at urban stations in Japan

These figures are based on data from 1931 to 2016. The trend of the 15 rural station averages (Table 2.1-1) is also listed. Values shown in italics are not statistically significant at a confidence level of 90%. For stations with asterisks (among the 15 rural stations, Iida and Miyazaki), trends are calculated after adjustment to eliminate the influence of relocation.

<table>
<thead>
<tr>
<th>Station</th>
<th>Long-term temperature trend (°C/century)</th>
<th></th>
<th>Daily maximum</th>
<th></th>
<th>Daily minimum</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ann</td>
<td>Win</td>
<td>Spr</td>
<td>Sum</td>
<td>Aut</td>
<td>Ann</td>
</tr>
<tr>
<td>Sapporo</td>
<td>2.7</td>
<td>3.4</td>
<td>2.9</td>
<td>1.9</td>
<td>2.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Sendai</td>
<td>2.4</td>
<td>3.0</td>
<td>2.8</td>
<td>1.4</td>
<td>2.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Nagoya</td>
<td>2.9</td>
<td>3.0</td>
<td>3.2</td>
<td>2.2</td>
<td>3.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Tokyo*</td>
<td>3.3</td>
<td>4.4</td>
<td>3.3</td>
<td>2.0</td>
<td>3.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Yokohama</td>
<td>2.8</td>
<td>3.5</td>
<td>3.1</td>
<td>1.8</td>
<td>2.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Kyoto</td>
<td>2.7</td>
<td>2.6</td>
<td>3.0</td>
<td>2.3</td>
<td>2.8</td>
<td>1.1</td>
</tr>
<tr>
<td>Hiroshima*</td>
<td>2.0</td>
<td>1.6</td>
<td>2.4</td>
<td>1.6</td>
<td>2.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Osaka*</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.2</td>
<td>3.1</td>
<td>2.2</td>
</tr>
<tr>
<td>Fukuoka</td>
<td>3.1</td>
<td>2.9</td>
<td>3.4</td>
<td>2.2</td>
<td>3.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Kagoshima*</td>
<td>2.8</td>
<td>2.7</td>
<td>3.2</td>
<td>2.3</td>
<td>3.1</td>
<td>1.3</td>
</tr>
<tr>
<td>15 stations*</td>
<td>1.5</td>
<td>1.6</td>
<td>1.9</td>
<td>1.2</td>
<td>1.5</td>
<td>1.1</td>
</tr>
</tbody>
</table>

As it can be assumed that the long-term trends averaged over the 15 rural stations reflect large-scale climate change, the differences in the long-term trends of urban stations from the average of the 15 stations largely represent the influence of urbanization.

Detailed observation reveals that the long-term trends are more significant in winter, spring and autumn than in summer and more pronounced for minimum temperatures than for maximum temperatures at every urban observation station.

Records from urban stations whose data are not affected by relocation are used to determine long-term trends for the annual number of days with minimum temperatures of < 0°C and ≥ 25°C and maximum temperatures of ≥ 30°C and ≥ 35°C. The number of days with T_{min} < 0°C has decreased with statistical significance at all urban stations, and the number with T_{min} ≥ 25°C has increased with statistical significance at most stations except Sapporo. Also the number of days with T_{max} ≥ 30°C and ≥ 35°C has increased with statistical significance at most stations except Sapporo (Table 2.1-3).
Table 2.1-3  Long-term trends for the annual number of days with minimum temperatures of < 0°C and ≥ 25°C and maximum temperatures of ≥ 30°C and ≥ 35°C.

These figures are based on data from 1931 to 2016 (1961 to 2016 for maximum temperatures of ≥35°C). The trend of the 13 rural station averages (Table 2.1-1, excluding Iida and Miyazaki) is also listed. Values shown in italics are not statistically significant at a confidence level of 90%.

<table>
<thead>
<tr>
<th>Station</th>
<th>Annual number of days</th>
<th>Trend (days/decade)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T$_{\text{min}}$ &lt; 0°C</td>
<td>T$_{\text{min}}$ ≥ 25°C</td>
<td>T$_{\text{max}}$ ≥ 30°C</td>
<td>T$_{\text{max}}$ ≥ 35°C</td>
</tr>
<tr>
<td>Sapporo</td>
<td>-4.6</td>
<td>0.0</td>
<td>0.1</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Sendai</td>
<td>-5.8</td>
<td>0.3</td>
<td>1.0</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Nagoya</td>
<td>-7.1</td>
<td>3.7</td>
<td>1.1</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>Yokohama</td>
<td>-6.4</td>
<td>3.0</td>
<td>2.1</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Kyoto</td>
<td>-7.5</td>
<td>3.6</td>
<td>1.2</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Fukuoka</td>
<td>-5.1</td>
<td>4.7</td>
<td>1.1</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>13 Stations</td>
<td>-2.1</td>
<td>1.7</td>
<td>0.6</td>
<td>0.4</td>
<td></td>
</tr>
</tbody>
</table>
2.2 Changes in precipitation

- The annual anomaly of global precipitation (for land areas only) in 2016 was +2 mm.
- The annual anomaly of precipitation in 2016 was +212 mm in Japan.
- The annual number of days with precipitation of $\geq 100$ mm is virtually certain to have increased, and that with precipitation of $\geq 200$ mm is extremely likely to have increased. The annual number of days with precipitation of $\geq 1.0$ mm is virtually certain to have decreased.

2.2.1 Global precipitation over land

Annual precipitation (for land areas only) in 2016 was +2 mm above the 1981 – 2010 average (Figure 2.2-1), and the figure has fluctuated periodically since 1901. In the Northern Hemisphere, records show large amounts of rainfall around 1930 and in the 1950s. Long-term trends are not analyzed because the necessary precipitation data for sea areas are not available.

![Annual Global Precipitation](image1)

![Annual Northern Precipitation](image2)

![Annual Southern Precipitation](image3)

Figure 2.2-1 Annual anomalies in precipitation (over land areas only) from 1901 to 2016 for the globe (top left), for the Northern Hemisphere (top right) and for the Southern Hemisphere (bottom). Anomalies are deviations from the baseline (the 1981 – 2010 average). The bars indicate the precipitation anomaly for each year, and the blue line indicates the five-year running mean.

2.2.2 Precipitation over Japan

This section describes long-term trends in precipitation over Japan as derived from analysis of precipitation records from 51 observation stations (Table 2.2-1).

Annual precipitation in 2016 was +212.3 mm above the 1981 – 2010 average. Japan experienced relatively large amounts of rainfall until the mid-1920s and around the 1950s. The annual figure has become more variable since the 1970s (Figure 2.2-2).

---

16 Data on annual precipitation around the world and in Japan are published on JMA’s website.

Table 2.2-1  List of 51 observation stations whose data are used to calculate precipitation anomalies and long-term trends in Japan

<table>
<thead>
<tr>
<th>Element</th>
<th>Observation stations</th>
</tr>
</thead>
</table>

Figure 2.2-2  Annual anomalies in precipitation from 1898 to 2016 in Japan. Anomalies are deviations from the baseline (the 1981 – 2010 average).

The bars indicate the precipitation anomaly for each year, and the blue line indicates the five-year running mean.

2.2.3  Snow depth in Japan

Long-term trends in the annual maximum snow depth (represented in terms of a ratio against the 1981 – 2010 average) in Japan since 1962 are analyzed using observational records from stations located on the Sea of Japan coast (Table 2.2-2).

Table 2.2-2  Observation stations whose data are used to calculate snow depth ratios in Japan

<table>
<thead>
<tr>
<th>Region</th>
<th>Observation stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea of Japan side of northern Japan</td>
<td>Wakkanai, Rumoi, Asahikawa, Sapporo, Iwamizawa, Suttsu, Esashi, Kutchan, Wakamatsu, Aomori, Akita, Yamagata</td>
</tr>
<tr>
<td>Sea of Japan side of eastern Japan</td>
<td>Wajima, Aikawa, Niigata, Toyama, Takada, Fukui, Tsuruga</td>
</tr>
<tr>
<td>Sea of Japan side of western Japan</td>
<td>Saigo, Matsue, Yonago, Tottori, Toyooka, Hikone, Shimonoseki, Fukuoka, Oita, Nagasaki, Kumamoto</td>
</tr>
</tbody>
</table>

The annual maximum snow depth ratio in 2016 was 82% relative to the 1981 – 2010 average for the Sea of Japan side of northern Japan, 96% for the same side of eastern Japan, and 153% for the same side of western Japan (Figure 2.2-3). The annual maximum snow depth reached a local peak in the early 1980s followed by a sharp decline until around the early 1990s. The decline was particularly striking on the Sea of Japan side of eastern and western Japan.

On a longer time scale, the annual maximum snow depth ratio from 1962 onward on the Sea of Japan side of eastern Japan is virtually certain to have decreased at rates of about 12.3% per decade (statistically significant at a confidence level of 99%), and that on the Sea of Japan side of western Japan is extremely likely to have decreased at rates of about 14.6% per decade (statistically significant at a confidence level of 95%). The annual maximum snow depth ratio on the Sea of Japan side of northern Japan shows no discernible trend.
Figure 2.2-3  Annual maximum snow depth ratio from 1962 to 2016 on the Sea of Japan side for northern Japan (top left), eastern Japan (top right) and western Japan (bottom). Annual averages are presented as ratios against the baseline (the 1981 – 2010 average).

The bars indicate the snow depth ratio for each year. The blue line indicates the five-year running mean, and the red line indicates the long-term linear trend.

2.2.4  Long-term trends of extreme precipitation events in Japan

This section describes long-term trends in frequencies of extremely wet/dry months and heavy daily precipitation events in Japan based on analysis of precipitation data from 51 observation stations.
(Chapter 2 Climate Change)

(1) Extremely wet/dry months

It is virtually certain that the frequency of extremely dry months increased during the period from 1901 to 2016 (statistically significant at a confidence level of 99%) (Figure 2.2-4 left). There has been no discernible trend in the frequency of extremely wet months (Figure 2.2-4 right).

Figure 2.2-4 Annual number of extremely wet/dry months

The graphs show the annual number of occurrences of the first-to-fourth heaviest/lightest precipitation values for each month during the period from 1901 to 2016. The green bars indicate annual occurrences of extremely heavy/light monthly precipitation divided by the total number of monthly observation data sets available for the year (i.e., the average occurrence per station). The blue line indicates the five-year running mean, and the straight red line indicates the long-term linear trend.

(2) Annual number of days with precipitation of $\geq 100$ mm, $\geq 200$ mm and $\geq 1.0$ mm

The annual number of days with precipitation of $\geq 100$ mm is virtually certain to have increased (statistically significant at a confidence level of 99%) and that with precipitation of $\geq 200$ mm is extremely likely to have increased (statistically significant at a confidence level of 95%) during the period from 1901 to 2016 (Figure 2.2-5). The annual number of days with precipitation of $\geq 1.0$ mm (Figure 2.2-6) is virtually certain to have decreased over the same period (statistically significant at a confidence level of 99%). These results suggest decrease in the annual number of wet days including light precipitation and in contrast, an increase in extremely wet days.

---

17 Here, judgment of extremely heavy/light precipitation is based on the fourth–highest/lowest monthly values on record over the 116-year period from 1901 to 2016. The frequency of occurrence of the highest/lowest to the fourth–highest/lowest values over this period is once every 29 years, which is close to JMA’s definition of extreme climate events as those occurring once every 30 years or longer (See the Glossary for terms relating to Extreme climate event).
Figure 2.2-5  Annual number of days with precipitation ≥ 100 mm and ≥ 200 mm
The graphs show the annual number of days per station, with the green bars indicating the values for each year during the period from 1901 to 2016. The blue line indicates the five-year running mean, and the straight red line indicates the long-term linear trend.

Figure 2.2-6  Annual number of days with precipitation of ≥ 1.0 mm
As per figure 2.2-5.

2.2.5  Long-term trends of heavy rainfall analyzed using AMeDAS data
JMA operationally observes precipitation at about 1,300 unmanned regional meteorological observation stations all over Japan (collectively known as the Automated Meteorological Data Acquisition System, or AMeDAS). Observation was started in the latter part of the 1970s at many points, and observation data covering the 41-year period through to 2016 are available. Although the period covered by AMeDAS observation records is shorter than that of Local Meteorological Observatories or Weather Stations (which have observation records for the past 100 years or so), there are around eight times as many AMeDAS stations as Local Meteorological Observatories and Weather Stations combined. Hence, AMeDAS is better equipped to capture heavy precipitation events that take place on a limited spatial scale.

Here, trends in annual number of events with extreme precipitation of ≥ 50 mm/80 mm per hour (every-hour-on-the-hour observations) (Figure 2.2-7) and ≥ 200 mm/400 mm per day (Figure 2.2-8) are described based on AMeDAS observation data\(^\text{18}\).

It is virtually certain that the annual numbers of events with precipitation of ≥ 50 mm per hour and ≥ 80 mm per hour have increased (statistically significant at a confidence level of 99%). The annual number of days with precipitation of ≥ 200 mm shows no statistically significant trend, while the corresponding figure for days with precipitation of ≥ 400 mm is very likely to have increased (statistically significant at a confidence level of 90%).

\(^{18}\) The number of AMeDAS station was about 800 in 1976, and had gradually increased to about 1,300 by 2016. To account for these numerical differences, the annual number of precipitation events needs to be converted to a per-1,000-station basis. Data from wireless robot precipitation observation stations previously deployed in mountainous areas are also excluded.
(Chapter 2 Climate Change)

As the annual number of extreme precipitation events is subject to large annual variations and the period covered by observation records is still relatively short, the addition of future observations to the data series is expected to increase the reliability of statistical trend detection.

Figure 2.2-7 Annual number of events with precipitation of ≥ 50 mm and ≥ 80 mm per hour (per 1,000 AMeDAS stations)
The graphs show the annual number of events per 1,000 AMeDAS stations, with the green bars indicating the values for each year during the period from 1976 to 2016. The blue line indicates the five-year running mean, and the straight red line indicates the long-term linear trend.

Figure 2.2-8 Annual number of days with precipitation of ≥ 200 mm and ≥ 400 mm (per 1,000 AMeDAS stations)
The graphs show the annual number of days per 1,000 AMeDAS stations, with the green bars indicating the values for each year during the period from 1976 to 2016. The blue line indicates the five-year running mean, and the straight red line indicates the long-term linear trend.
2.3 Changes in the phenology of cherry blossoms and acer leaves in Japan

- It is virtually certain that cherry blossoms have been flowering earlier.
- It is virtually certain that acer leaves have been changing color later.

JMA implements phenological observation to research the impact of meteorological conditions on plants and animals, and eventually to monitor the progress of seasons as well as geographical variations and long-term changes in relation to the climate. Observation covers the first/full flowering and leaf color change of several plants and the first reported appearance/song of insects, birds and animals.

As part of its phenological monitoring, JMA observes cherry blossoms at 58 stations and acer leaves at 51 stations. Figure 2.3-1 shows interannual changes in the first reported dates of cherry blossom flowering and acer leaf color change between 1953 and 2016. The former exhibits a long-term advancing trend at a rate of 1.0 days per decade, while the latter shows a delaying trend at a rate of 2.9 days per decade (99% level of confidence for both cases). Table 2.3-1 compares climatological normals (based on 30-year averages) of the first reported date of cherry blossom flowering between 1961 – 1990 and 1981 – 2010 at stations in major Japanese cities. These phenomena are closely related to the surface mean temperature in the period before the event, and long-term warming is considered to be a major factor behind the trends observed.

![Figure 2.3-1](image)

The black lines show annual anomalies of the first reported date averaged over all observation stations nationwide based on the normals for 1981 – 2010, and the blue lines indicate five-year running means. The red lines show the linear trend (cherry blossoms: −1.0 days per decade; acer leaves: +2.9 days per decade).

Table 2.3-1 Comparison of first reported dates of cherry blossom flowering

<table>
<thead>
<tr>
<th>Station</th>
<th>1961-1990 average</th>
<th>1981-2010 average</th>
<th>Difference (days)</th>
<th>Station</th>
<th>1961-1990 average</th>
<th>1981-2010 average</th>
<th>Difference (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kushiro</td>
<td>May 19</td>
<td>May 17</td>
<td>-2</td>
<td>Osaka</td>
<td>Apr 1</td>
<td>Mar 28</td>
<td>-4</td>
</tr>
<tr>
<td>Sapporo</td>
<td>May 5</td>
<td>May 3</td>
<td>-2</td>
<td>Hiroshima</td>
<td>Mar 31</td>
<td>Mar 27</td>
<td>-4</td>
</tr>
<tr>
<td>Aomori</td>
<td>Apr 27</td>
<td>Apr 24</td>
<td>-3</td>
<td>Takamatsu</td>
<td>Mar 31</td>
<td>Mar 28</td>
<td>-3</td>
</tr>
<tr>
<td>Sendai</td>
<td>Apr 14</td>
<td>Apr 11</td>
<td>-3</td>
<td>Fukuoka</td>
<td>Mar 28</td>
<td>Mar 23</td>
<td>-5</td>
</tr>
<tr>
<td>Niigata</td>
<td>Apr 13</td>
<td>Apr 9</td>
<td>-4</td>
<td>Kagoshima</td>
<td>Mar 27</td>
<td>Mar 26</td>
<td>-1</td>
</tr>
<tr>
<td>Tokyo</td>
<td>Mar 29</td>
<td>Mar 26</td>
<td>-3</td>
<td>Naha</td>
<td>Jan 16</td>
<td>Jan 18</td>
<td>+2</td>
</tr>
<tr>
<td>Nagoya</td>
<td>Mar 30</td>
<td>Mar 26</td>
<td>-4</td>
<td>Ishigakijima</td>
<td>Jan 15</td>
<td>Jan 16</td>
<td>+1</td>
</tr>
</tbody>
</table>

Table 45
2.4 Tropical cyclones

- A total of 26 tropical cyclones (TCs) with maximum wind speeds of 17.2 m/s or higher formed in 2016, which was near normal.
- The numbers of formations show no significant long-term trend.

In 2016, 26 tropical cyclones (TCs) with maximum wind speeds of 17.2 m/s or higher formed over the western North Pacific (Figure 2.4-1), which was near the normal (i.e., the 1981 – 2010 average) of 25.6. The numbers of formations show no discernible long-term trend during the analysis period from 1951 to 2016, but have often been lower since the latter half of the 1990s than in previous years.

Figure 2.4-2 shows the numbers and rates of tropical cyclones with maximum wind speeds of 33 m/s or higher to those with maximum wind speeds of 17.2 m/s or higher from 1977 (the year in which the collection of complete data on maximum wind speeds near TC centers began). The numbers of tropical cyclones with maximum wind speeds of 33 m/s or higher show no discernible trend.

---

Figure 2.4-1  Time-series of the numbers of tropical cyclones with maximum winds of 17.2 m/s or higher forming in the western North Pacific.

The thin and thick lines represent annual and five-year running means, respectively.

Figure 2.4-2  Time-series of the numbers of strong tropical cyclones (blue) and rates of the strong tropical cyclones to the total tropical cyclones (red) forming in the western North Pacific. The strong tropical cyclones are those with maximum winds of 33 m/s or higher.

The thin and thick lines represent annual and five-year running means, respectively.
2.5 Sea surface temperature

- The annual mean global average sea surface temperature (SST) in 2016 was 0.33°C above the 1981 – 2010 average, which was the highest since 1891.
- The global average SST has risen at a rate of about +0.53°C per century.
- Annual average SSTs around Japan have risen by +1.09°C per century.

2.5.1 Global sea surface temperature

The annual mean global average SST in 2016 was 0.33°C above the 1981 – 2010 average. This was higher than the previous highest value of +0.30°C observed in 2015, and was the highest since 1891. The linear trend from 1891 to 2016 shows an increase of +0.53°C per century (Figure 2.5-1). Both global average SST and global average surface temperature (Section 2.1) are affected by natural climate variability on interannual to interdecadal time scales as well as by global warming. In particular, the global average SST shows an association with the NINO.3 SST anomaly with a time lag of several months (Trenberth et al., 2002). Accordingly, 2016’s record-high temperatures may have been caused by the El Niño event that persisted from summer 2014 to spring 2016 (Section 1.3). Although magnitudes of the long-term SST trend vary by area, SSTs are extremely likely to have increased in many parts of the world’s oceans (Figure 2.5-2).

On a multi-year time scale, the global average SST showed a warming trend from the middle of the 1970s to around 2000 and remained at the same level to the early 2010s (blue line in Figure 2.5-1). This is partly because internal decadal to multi-decadal variations in the climate system overlap with the rising trends. It is important to estimate the contribution of these internal variations in order to properly understand global warming. In the next section, the Pacific Decadal Oscillation (PDO) is presented as a typical example of decadal variability observed in SSTs.

![Figure 2.5-1 Time-series representation of global average sea surface temperature anomalies from 1891 to 2016](image1)

- The black, blue and red lines indicate annual anomalies, the five-year running mean and the long-term linear trend, respectively. Anomalies are deviations from the 1981 – 2010 average.

![Figure 2.5-2 Linear trend of annual mean sea surface temperature during the period from 1891 to 2016 (°C per century)](image2)

- Plus signs indicate statistically significant trends with a confidence level of 95%.

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19 The results of analysis regarding tendencies of SSTs worldwide and around Japan are published on JMA’s website. http://www.data.jma.go.jp/gmd/kaiyou/english/long_term_sst_global/glb_warm_e.html
2.5.2  Sea surface temperature (around Japan)

Figure 2.5-3 shows increase rates of area-averaged annual mean SSTs for 13 areas around Japan. The average SST of all areas around Japan has risen by +1.09°C per century, which is higher than the corresponding value for the North Pacific (+0.50°C per century).

It is virtually certain (statistically significant at a confidence level of 99%) that SSTs have risen by between +0.75 and +1.70°C per century in the Yellow Sea, the East China Sea, the sea around the Sakishima Islands, central and southwestern parts of the Sea of Japan, the southern part of the sea off Kanto, the sea off Shikoku and Tokai, the sea off Kushiro, and the sea east of Okinawa (areas I-VI, VII, X, XII, and XIII). It is extremely likely (statistically significant at a confidence level of 95%) that SSTs in the sea off Sanriku, and the eastern part of the sea off Kanto (areas VIII and IX) have risen by +0.68°C and +0.70°C per century, respectively. SSTs in the northeastern part of the Sea of Japan (Area XI) exhibit no statistical long-term trend.

<table>
<thead>
<tr>
<th>Area number</th>
<th>Area name</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Yellow Sea</td>
</tr>
<tr>
<td>II</td>
<td>Northern part of the East China Sea</td>
</tr>
<tr>
<td>III</td>
<td>Southern part of the East China Sea</td>
</tr>
<tr>
<td>IV</td>
<td>Sea around the Sakishima Islands</td>
</tr>
<tr>
<td>V</td>
<td>Sea off Shikoku and Tokai</td>
</tr>
<tr>
<td>VI</td>
<td>East of Okinawa</td>
</tr>
<tr>
<td>VII</td>
<td>Sea off Kushiro</td>
</tr>
<tr>
<td>VIII</td>
<td>Sea off Sanriku</td>
</tr>
<tr>
<td>IX</td>
<td>Eastern part of the sea off Kanto</td>
</tr>
<tr>
<td>X</td>
<td>Southern part of the sea off Kanto</td>
</tr>
<tr>
<td>XI</td>
<td>Northeastern part of the Sea of Japan</td>
</tr>
<tr>
<td>XII</td>
<td>Central part of the Sea of Japan</td>
</tr>
<tr>
<td>XIII</td>
<td>Southwestern part of the Sea of Japan</td>
</tr>
</tbody>
</table>

Figure 2.5-3  Increase rates of area-averaged annual mean SSTs around Japan from 1900 to 2016 (°C per century)
Areas with no symbol and those marked with [*] have statistical significant trend at confidence levels of 99% and 95%, respectively. Areas marked with [#] are those where no discernible trend is seen due to large SST variability factors such as decadal oscillation.
2.6 El Niño/La Niña and PDO (Pacific Decadal Oscillation)

- An El Niño event that began in summer 2014 passed on its mature stage in November–December 2015 and ended in spring 2016.
- Although negative PDO index values were generally observed from around 2000 to the early 2010s, the positive annual mean values have been recorded consecutively since 2014.

2.6.1 El Niño/La Niña
An El Niño event is a phenomenon in which sea surface temperatures (SSTs) are higher than normal across a wide area from the center of the equatorial Pacific to the region off the coast of Peru for a period of between half a year and 1.5 years. In contrast, a La Niña event is a phenomenon in which SSTs are lower than normal in the same area. Both occur once every few years, causing changes in global atmospheric conditions and abnormal weather conditions worldwide. In Japan, cooler summers and warmer winters tend to appear during El Niño events, while hotter summers and colder winters tend to appear during La Niña events. El Niño/La Niña events also tend to cause SST changes in the tropical Indian Ocean with a delay of approximately three months from changes in the El Niño monitoring region. Such changes in the tropical Indian Ocean are considered to cause abnormal weather conditions worldwide.

Figure 2.6-1 shows a time-series representation of SST deviations from the climatological mean based on a sliding 30-year period for the El Niño monitoring region (5°N – 5°S, 150°W – 90°W) and the tropical Indian Ocean (20°N – 20°S, 40°E – 100°E) since 2006. An El Niño event that began in summer 2014 passed on its mature stage in November–December 2015 and ended in spring 2016. In the tropical Indian Ocean, the five-month running mean of SST deviations (from the climatological mean based on a sliding 30-year period) peaked in February–March 2016 and turned negative in summer 2016. Influences of this El Niño event and high SSTs in the tropical Indian Ocean on the global climate are described in Topics I.

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2.6.2 Pacific Decadal Oscillation

SST variability is also observed on time scales ranging from one to several decades in addition to El Niño/La Niña events, whose time scale is several years, and long-term trends associated with global warming. Among these, the atmosphere and oceans tend to co-vary with a period of more than ten years in the North Pacific in a phenomenon known as the Pacific Decadal Oscillation (PDO). When SSTs are lower than their normals in the central part of the North Pacific, those in its eastern part and in the equatorial Pacific are both likely to be higher than their normals. This seesaw pattern changes slowly, and appears repeatedly with a period of more than ten years. The PDO index, which is defined by the SST anomaly pattern in the North Pacific, is used as a measure of phase and strength of the oscillation. Both the PDO index and SST anomaly patterns associated with PDO include relatively short-timescale variabilities such as El Niño/La Niña events in addition to decadal to multi-decadal components.

When the PDO index is positive (negative), SSTs in the central part of the North Pacific are likely to be lower (higher) than their normals (Figure 2.6-2), and sea level pressures (SLPs) in the high latitudes of the North Pacific are likely to be lower (higher) than their normals. This indicates that the Aleutian Low is stronger (weaker) than its normal in winter and spring (Figure 2.6-3). These atmospheric variations affect meteorological conditions mainly in North America. When the PDO index is positive, winter temperatures tend to be high in the northwestern part of North America and the northern part of South America, and low in the southeastern part of the USA and in parts of China (Mantua and Hare, 2002).

The PDO index was generally positive from the late 1920s to the early 1940s and from the late 1970s to around 2000, and generally negative from the late 1940s to 1970s and from around 2000 to the early 2010s. The annual mean PDO index value has been positive consecutively since 2014 and was +1.3 in 2016 (Figure 2.6-4).
Figure 2.6-2  Typical SST anomaly patterns in the positive phase of the PDO

Figure 2.6-3  Typical SLP anomaly patterns in the positive phase of the PDO

Figure 2.6-4  Time-series of the PDO index
  The red line represents annual mean values for the PDO index, the blue line represents five-year running mean values, and the gray bars represent monthly values.
Oceans have a significant impact on the global climate because they cover about 70% of the earth’s surface and have high heat capacity. According to the Intergovernmental Panel on Climate Change Fifth Assessment report (IPCC, 2013), more than 60% of the net energy increase in the climate system from 1971 to 2010 is stored in the upper ocean (0 – 700 m), and about 30% is stored below 700 m. Oceanic warming results in sea level rises due to thermal expansion.

It is virtually certain that globally integrated upper ocean (0 – 700 m) heat content (OHC) rose between 1950 and 2016 at a rate of $2.22 \times 10^{22}$ J per decade as a long-term trend with interannual variations (statistically significant at a confidence level of 99%) (Figure 2.7-1). This OHC increasing trend corresponds to a rise of 0.023°C per decade in the globally averaged upper ocean (0 – 700 m) temperature. OHC exhibited marked increases from the mid-1990s to the early 2000s and slight increases for the next several years, as seen with the global mean surface temperature and the sea surface temperature. Since the mid-2000s OHC has increased again significantly. These long-term trends can be attributed to global warming caused by increased concentrations of anthropogenic greenhouse gases such as CO₂ as well as natural variability.

![Time-series representation of the globally integrated upper ocean (0 – 700 m) heat content anomaly](http://www.data.jma.go.jp/gmd/kaiyou/english/ohc/ohc_global_en.html)
2.8 Sea levels around Japan

- A trend of sea level rise has been seen in Japanese coastal areas since the 1980s.
- No clear trend of sea level rise was seen in Japanese coastal areas for the period from 1906 to 2016.

The IPCC Fifth Assessment Report 2013 (AR5) concluded that the global mean sea level had risen due mainly to 1) oceanic thermal expansion, 2) changes in mountain glaciers, the Greenland ice sheet and the Antarctic ice sheet, and 3) changes in land water storage. The report also said it is very likely that the mean rate of global average sea level rise was 1.7 [1.5 to 1.9] mm/year between 1901 and 2010, 2.0 [1.7 to 2.3] mm/year between 1971 and 2010, and 3.2 [2.8 to 3.6] mm/year between 1993 and 2010, where the values in square brackets show the 90% uncertainty range.

Sea levels in Japanese coastal areas exhibited no significant rise from 1906 to 2016 (Figure 2.8-1), but have shown a rising trend since the 1980s. Recent rates of rise around the country have been 1.1 [0.6 to 1.6] mm/year from 1971 to 2010 and 2.8 [1.3 to 4.3] mm/year from 1993 to 2010. These are comparable to the global average figures provided in AR5.

In Japanese coastal areas, variations with 10- to 20-year periods were between 1906 and 2016, with the maximum sea level appearing around 1950. The major factor behind sea level variations with 10- to 20-year periods is the variability of atmospheric circulation over the North Pacific. Westerlies in the mid-latitudes of the Northern Hemisphere are strengthened in boreal winter, and the consequent decadal variations in turn cause sea level variations in the central North Pacific. These propagate westward due to the earth’s rotation, causing sea level rise around Japan.

The extent to which global warming has contributed to sea level change around Japan remains unclear due to the involvement of various other factors such as variations with 10- to 20-year periods as mentioned above. Continuous monitoring is needed to clarify the long-term trend of sea level rise caused by global warming.

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23 Sea levels around Japan are published on the JMA’s website.
http://www.data.jma.go.jp/gmd/kaiyou/english/sl_trend/sea_level_around_japan.html
Figure 2.8-1  Time-series representation of annual mean sea levels (1906 – 2016) and locations of tide gauge stations

Tide gauge stations assessed as being affected to a lesser extent by crustal movement are selected. The four stations shown on the map on the left are used for the period from 1906 to 1959, and the sixteen shown on the right are used for the period since 1960. From 1906 to 1959, a time-series representation of mean annual mean sea level anomalies for the selected stations is shown. For the period since 1960, cluster analysis was first applied to sea level observation data for the selected stations along the Japanese coast. The nation’s islands were then divided into four regions based on sea level variation characteristics, annual mean sea level anomalies were averaged for each of the regions, and the variations were plotted in the figure. The four regions are I: from Hokkaido to Tohoku district; II: from Kanto to Tokai district; III: from the Pacific coast of Kinki to that of Kyushu district; and IV: from Hokuriku to East China Sea coast of Kyushu district. Sea level variations are plotted on the chart as a time-series representation of annual mean sea level anomalies for each year, obtained using the 1981 to 2010 average as the normal. The solid blue line represents the five-year running mean of annual sea level anomalies averaged among the four stations shown in the lower left map, while the solid red line represents that averaged among the four divided regions in the lower right map. The dashed blue line represents the value averaged among the four stations shown in the lower left map for the same period shown by the solid red line (after 1960) for reference. The coefficient of correlation between the solid red line and the dashed blue line from 1962 to 2014 is as high as 0.98. Accordingly, the extent to which changing the tide gauge stations used in the monitoring affects the analysis of variance of sea level anomalies can be regarded as small. Among the tide gauge stations, those at Oshoro, Kashiwazaki, Wajima and Hosojima belong to the Geospatial Information Authority of Japan. Sea level data for the Tokyo station are available from 1968 onward. Sea level data for the period from 2011 to 2016 from Hakodate, Fukaura, Kashiwazaki, Tokyo and Hachinohe were not used due to possible influences from the 2011 off the Pacific coast of Tohoku Earthquake.
2.9 Sea ice

- The sea ice extent in the Arctic Ocean shows a decreasing trend. In 2016, the annual minimum sea ice extent in the Arctic Ocean was $4.10 \times 10^6$ km$^2$, and the annual maximum was $14.74 \times 10^6$ km$^2$, which were both the second-smallest values recorded since 1979.
- The sea ice extent in the Antarctic Ocean shows an increasing trend. In 2016, however, the annual mean sea ice extent in the Antarctic Ocean was $11.61 \times 10^6$ km$^2$, which was the fourth-smallest value recorded since 1979.
- The maximum sea ice extent in the Sea of Okhotsk shows a decreasing trend of $0.067 \times 10^6$ km$^2$ per decade.

2.9.1 Sea ice in Arctic and Antarctic areas (Figure 2.9-1)

Sea ice is formed when sea water in the Arctic and Antarctic freezes. As the albedo (reflection coefficient) of sea ice is greater than that of the ocean surface, sea ice extent reductions caused by global warming result in more solar energy absorption at the surface, which in turn accelerates global warming. Sea ice also affects deep-ocean circulation because the expelled salt as it forms increases the salinity (and therefore the density) of the water below it causing the water to sink.

It is virtually certain that there has been a long-term trend of decrease in sea ice extent in the Arctic Ocean since 1979 when continuous monitoring of sea ice using satellite sensors with similar properties started (statistically significant at a confidence level of 99%). In particular, the reduction in the annual minimum extent is notable. The rate of decrease in the annual

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24 Information on sea ice in the Arctic/Antarctic, and in the Sea of Okhotsk are published on JMA’s website.
http://www.data.jma.go.jp/gmd/kaiyou/english/seaice_global/series_global_e.html (Arctic/Antarctic)
http://www.data.jma.go.jp/gmd/kaiyou/english/seaice_okhotsk/series_okhotsk_e.html (Sea of Okhotsk)
minimum up to 2016 was $0.092 \times 10^6$ km$^2$ per year and the annual minimum was $4.10 \times 10^6$ km$^2$, which was the second-lowest record since 1979. The annual maximum sea ice extent in the Arctic Ocean was $14.74 \times 10^6$ km$^2$, which was also the second-lowest record since 1979. Meanwhile, it is virtually certain that there has been an increase at a rate of $0.025 \times 10^6$ km$^2$ per year in the annual mean sea ice extent in the Antarctic Ocean (statistically significant at the confidence level of 99%). However, the value for 2016 was $11.61 \times 10^6$ km$^2$, which was the fourth-lowest record since 1979.

2.9.2 Sea ice in the Sea of Okhotsk (Figure 2.9-2)

The Sea of Okhotsk is the southernmost sea in the Northern Hemisphere where sea ice is observed across a wide area. The variation of the sea ice in the Sea of Okhotsk has effect on climate in coastal area facing the Sea of Okhotsk in Hokkaido and water quality of Oyashio.

The maximum$^{25}$ sea ice extent in the Sea of Okhotsk shows large interannual variations. However, it is virtually certain that it exhibited a long-term trend of decrease for the period from 1971 to 2016 (statistically significant at the confidence level of 99%). The maximum extent has decreased by $0.067 \times 10^6$ km$^2$ per decade (corresponding to 4.3% of the Sea of Okhotsk’s total area).

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25 The maximum sea ice extent: It shows sea ice extent that sea ice was the most expanding of every five days in the course of the year.
2.10 Snow cover in the Northern Hemisphere

- A decreasing trend is observed in the interannual variability of the total snow cover extent in the Northern Hemisphere for May, June and the period from September to December.
- In winter 2015/2016, there were fewer days of snow cover than normal in many parts of the Northern Hemisphere.

The albedo of snow-covered ground (i.e., the ratio of solar radiation reflected by the surface) is higher than that of snow-free ground. The variability of snow cover has an impact on the earth’s surface energy budget and radiation balance, and therefore on the climate. In addition, snow absorbs heat from its surroundings and melts, thereby providing soil moisture and related effects on the climate system. The variability of atmospheric circulation and oceanographic conditions affects the amount of snow cover, which exhibits a close and mutual association with climatic conditions. JMA monitors snow-cover variations in the Northern Hemisphere using analysis data derived from observations conducted by the Special Sensor Microwave/Imager (SSM/I) and the Special Sensor Microwave Imager Sounder (SSMIS) on board the Defense Meteorological Satellite Program (DMSP) polar-orbiting satellites of the USA based on an algorithm developed by JMA.

In the Northern Hemisphere (north of 30°N), there was a decreasing trend (statistically significant at a confidence level of 95%) in the interannual variability of the total snow cover extent over the 29-year period from 1988 to 2016 for May, June and the period from September to December (Figure 2.10-1 bottom-left), while no trend is seen for the period from January to April (Figure 2.10-1 top-left). In winter (December – February) 2015/2016, there were fewer days of snow cover than normal in many parts of the Northern Hemisphere. In February, significantly fewer-than-normal snow cover days were observed in western Eurasia (Figure 2.10-1, top right), and the snow cover extent in the Northern Hemisphere was the smallest since 1988. In November 2016, there were more days of snow cover than normal around Central Asia and in northeastern China, and fewer in western China and North America (Figure 2.10-1, bottom right).
Figure 2.10-1  Interannual variations in the total area of monthly snow cover (km$^2$) in the Northern Hemisphere (north of 30°N) over the period from 1988 to 2016 for February and November (left), and anomalies in the number of days with snow cover for February 2016 and November 2016 (right).

Left: the blue lines indicate the total snow cover area for each year, and the black lines show linear trends (statistically significant at a confidence level of 95%).

Right: statistics on the number of days with snow cover are derived using data from the Special Sensor Microwave Imager (SSMI) and the Special Sensor Microwave Imager Sounder (SSMIS) on board the US Defense Meteorological Satellite Program (DMSP) satellites based on an algorithm developed by the Japan Meteorological Agency. The base period for the normal is 1989 – 2010.
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>
<th>Lifetime (in years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-industrial level around 1750</td>
<td>Global mean for 2015</td>
<td>Relative increase from pre-industrial level</td>
<td>Absolute increase from previous year</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>About 278 ppm</td>
<td>400.0 ppm</td>
<td>+ 44 %</td>
<td>+2.3 ppm</td>
</tr>
<tr>
<td>Methane</td>
<td>About 722 ppb</td>
<td>1,845 ppb</td>
<td>+156 %</td>
<td>+11 ppb</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>About 270 ppb</td>
<td>328.0 ppb</td>
<td>+ 21 %</td>
<td>+1.0 ppb</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 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). 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 CO$_2$ concentrations is ascribed to the presence of major 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 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.
(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).
(3) Oceanic carbon dioxide

Figure 3.1-5 shows annual changes in oceanic and atmospheric CO$_2$ concentrations averaged between 7°N and 33°N along 137°E for winter (January and February). The mean growth rates of oceanic and atmospheric CO$_2$ 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 CO$_2$ in the ocean is lower than that in the atmosphere, meaning that the ocean acts as a CO$_2$ sink in winter.

![Figure 3.1-5](image)

JMA conducts in situ observations of CO$_2$ 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 CO$_2$ concentrations and other oceanographic parameters such as sea surface temperature (SST), salinity and chlorophyll-a concentration, which differ by region. Global oceanic CO$_2$ concentrations were estimated using datasets of such parameters based on these relationships, and CO$_2$ exchanges between the atmosphere and the ocean were calculated (Iida *et al.*, 2015). It was found that the ocean releases CO$_2$ into the atmosphere in equatorial regions and the northern Indian Ocean, where seawater with a high CO$_2$ concentration upwells and absorbs CO$_2$ in other regions (Figure 3.1-6 (a)). Lower SSTs in winter and biological CO$_2$ consumption in spring/autumn result in lower surface ocean CO$_2$ concentrations and therefore higher CO$_2$ uptake, especially in the mid-to-high latitudes. Figure 3.1-6 (b) and (c) show monthly and annual variations in global ocean CO$_2$ uptake, respectively. Considering natural CO$_2$ efflux of 0.7 GtC per year (IPCC, 2013), which results from riverine input to the oceans, the amount of oceanic CO$_2$ uptake corresponds to 30% of all anthropogenic CO$_2$ emission, which IPCC (2013) estimates to be 9 GtC per year. Global ocean CO$_2$ 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.

Figure 3.1-6 Distribution of global ocean CO$_2$ uptake/release for 2015 (a) and time-series representations of monthly (b) and annual (c) CO$_2$ uptake from 1990 to 2015

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.
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 $p$CO$_2$ 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 CO₂ concentrations on the route from Atsugi Base (35.45°N, 139.45°E) to Minamitorishima (24.28°N, 153.98°E) with support from the Japan Ministry of Defense to support aircraft operation (Tsuboi et al., 2013; Niwa et al., 2014). The flight altitude is approximately 6 km. CO₂ 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 CO₂ and other greenhouse gases at altitudes of around 10 km using commercial passenger aircraft since 1993 under the Comprehensive Observation Network for TRace gases by AIrLiner (CONTRAIL) project (Matsueda et al., 2015; Machida et al., 2008). Figure 3.1-13 shows CO₂ 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

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29 The results of upper-troposphere monitoring of carbon dioxide are now based on the Comprehensive Observation Network for TRace gases by AIrLiner (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.

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).
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).

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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)).

![Figure 3.1-16](image_url)
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).

![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).

![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).

![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.

31 Information on the ozone layer and ultraviolet radiation is published on JMA’s website.
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.
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.

![Time-series representation of global-averaged total ozone deviations shown as percentages](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.
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 1979–2016. The green line indicates the overall area of the Antarctic (1.39 × 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 28, 2016, 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 mid-1990s, 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 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).

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.
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)

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.

Information on aerosols and Kosa is published on JMA’s website.

36 The atmospheric turbidity coefficient indicates the ratio of the atmospheric optical depth affected by aerosols, water vapor and gases in the atmosphere to that unfluenced 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.

37 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.

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 radiation38 at five stations in Japan (Sapporo, Tsukuba, Fukuoka, Ishigakijima and Minamitorishima) (Figure 3.3-4).

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
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

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

(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/m$^2$ 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\(^ {39} \) stations worldwide (+0.3 W/m$^2$ 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

\(^ {39} \) 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).
Explanatory note on detection of statistical significance in long-term trends

Meteorological observation data, including those relating to temperature and precipitation, are subject to large amplitude fluctuations due to the influence of atmospheric and oceanic dynamics on a broad spectrum of spatial and temporal scales. To examine the possible presence of long-term climate system trends associated with global warming in consideration of natural variability, raw climate data need to be converted into suitable statistical time-series representations and subjected to statistical testing in order to highlight the likelihood of systematic temporal trends that cannot be explained by random variability alone. When the results of such testing allow reasonable conclusion that random variability is unlikely to be the sole factor at work, a change is described as statistically significant.

In this report, the likelihood of a systematic long-term change existing in a time-series representation is based on the results of statistical significance testing performed at confidence levels of 99, 95 and 90%. The following terminology summary describes each level:

<table>
<thead>
<tr>
<th>Level of confidence</th>
<th>Term</th>
</tr>
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<tbody>
<tr>
<td>≥ 99%</td>
<td>Virtually certain to have increased/decreased (statistically significant at a confidence level of 99%)</td>
</tr>
<tr>
<td>≥ 95%</td>
<td>Extremely likely to have increased/decreased (statistically significant at a confidence level of 95%)</td>
</tr>
<tr>
<td>≥ 90%</td>
<td>Very likely to have increased/decreased (statistically significant at a confidence level of 90%)</td>
</tr>
<tr>
<td>&lt; 90%</td>
<td>No discernible trend</td>
</tr>
</tbody>
</table>

The following statistical methods are applied for the data used in this report:

i) For statistical variables whose annual fluctuation component can be assumed to follow normal distribution
   For temperature anomalies, trend-removed annual variability data are expected to approximately follow normal distribution. T-testing is performed for statistical variables assumed to be normally distributed using a coefficient of correlation between years and values.

ii) For statistical variables whose annual fluctuation component cannot be assumed to follow normal distribution
   The assumption of normality may not be applicable to frequency statistics regarding weather conditions, including those for extremely warm days, tropical nights and hourly precipitation amounts exceeding 50 mm. Accordingly, non-parametric testing, which does not depend on underlying assumptions about distribution, is applied to such variables.

It should be noted that statistical tests are in theory inevitably susceptible to the establishment of false conclusions even if the results indicate a statistically significant trend. Even outcomes indicating statistical significance at confidence levels of 90, 95 or 99% imply that there are small inherent probabilities of up to 10, 5 and 1%, respectively, of the significance being erroneously detected when in fact the observed long-term change occurred
by mere random chance. Conversely, when a systematic long-term change actually exists, statistical testing may fail to detect the significance correctly. In general, test results are not considered highly stable if they are based on observation records that are temporally limited, influenced by large annual fluctuations/rare events or subject to change when new observations are added to a data sequence. Readers are encouraged to interpret the analytical results presented in the report appropriately with due note of these considerations.
Glossary

**Aerosols**
Aerosols are airborne solids or liquids in fine particle form. Their many types include particles of natural origin blown up from land/sea surfaces, anthropogenic particles and secondary aerosols formed from anthropogenic and biogenic precursors. In addition to absorbing and scattering sunlight, they also provide condensation nuclei for clouds. Particulate matter 2.5 (PM2.5) is the name given to aerosol particles measuring 2.5 micrometers or less in diameter (about 30 times thinner than a human hair), and is considered to have possible adverse effects on human health when inhaled.

**Anthropogenic**
Resulting from or produced by human activities.

**Arctic Oscillation**
The Arctic Oscillation (AO) is a major atmospheric circulation variation exhibiting an annular pattern of sea-level pressure anomalies in a seesaw fashion with one sign over the Arctic region and the opposite sign over the mid-latitudes. Its negative phase, which is characterized by positive and negative sea-level pressure anomalies over the Arctic region and the mid-latitudes, respectively, helps cold Arctic air move into the mid-latitudes. The positive phase, whose sea-level pressure anomaly pattern is reversed, keeps Arctic air over the Arctic region.

**Erythemal UV radiation**
Erythema is sunburn – a reddening of the skin resulting from continuous exposure to ultraviolet (UV) rays present in solar radiation. It is known that excessive erythema and long-term exposure to the sun can cause human health problems such as a high incidence of skin cancer and cataracts. Erythemal UV radiation is widely used as a scale of UV radiation for evaluation of its effects on the human body, and is calculated in consideration of various influences depending on wavelength.

**Extreme climate event**
In general, an extreme climate event is recognized as an unusually severe or rare climate event creating disaster conditions or exerting significant socio-economic influence. The definition includes severe weather conditions covering periods ranging from only a few hours (such as heavy rain or strong wind) to several months (such as drought or cold summer conditions). JMA defines extreme climate events as those occurring once every 30 years or longer.

**IPCC (Intergovernmental Panel on Climate Change)**
The Intergovernmental Panel on Climate Change (IPCC) is an international organization established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988. It reviews and assesses scientific, technical and socio-economic information on climate change, the potential impacts of such change and related vulnerability, and options for adaptation and mitigation, in collaboration with scientists and experts on an international basis. The Panel’s reports highlight common understanding of such information to support political matters such as treaty negotiations on global warming.
**Kosa (Aeolian dust)**

Kosa (Aeolian dust) is a meteorological phenomenon in which fine dust is blown up to an altitude of several thousand meters by cyclonic or other wind systems from deserts or cropland in semi-arid areas of the Asian continent, and is transported over long distances by westerly winds, resulting in haze or dustfall in downstream areas. It is often observed between March and June in Japan and makes the sky yellow and hazy. Heavy Kosa can affect transportation by obstructing visibility.

**Monsoon**

The term *monsoon* primarily refers to seasonally reversing winds, and by extension includes related seasonal rainfall change with wet and dry phases. Monsoon climate regions where seasonal winds prevail are found in numerous places around the world, with a major one located over a broad area from the Asian continent to northern Australia.

**Normals**

Normals represent climatic conditions at meteorological stations, and are used as a base to evaluate meteorological variables (e.g., temperature, precipitation and sunshine duration) and produce generalizations (e.g., cool summer, warm winter and dry/wet months) for particular periods. JMA uses averages for the most recent three decades (currently 1981 – 2010) as normals, which are updated every decade in line with WMO Technical Regulations.

**Terms relating to El Niño/La Niña events**

*El Niño/La Niña events:* In an El Niño event, sea surface temperatures (SSTs) are higher than normal across a wide region from near the date line to the area off the coast of South America in the equatorial Pacific for about a year. In a La Niña event, SSTs are lower than normal in the same area. Both occur every few years, and are associated with frequent extreme climate conditions worldwide.

JMA recognizes the occurrence of an El Niño event when the five-month running mean of SST deviations from the climatological mean (based on a sliding 30-year period averaged over the NINO.3 El Niño Monitoring Region (5°N – 5°S, 150°W – 90°W; Figure A)) remains above +0.5°C for a period of six months or more. Similarly, a La Niña event is recognized when the corresponding figure is below −0.5°C for the same area/period.

Figure B shows typical SST deviations from the normal during El Niño and La Niña events. The dark red and blue shading seen from the date line to the coast of South America indicates large deviations.
Southern Oscillation: El Niño and La Niña events are closely related to trade winds (easterlies blowing around the tropical Pacific), which tend to be weak during the former and strong during the latter. The strength of such winds is closely related to the sea level pressure difference between eastern and western parts of the Pacific. This pressure difference varies in a phenomenon known as Southern Oscillation. El Niño/La Niña events and Southern Oscillation are not independent of each other; they are different manifestations of the same phenomenon involving atmospheric and oceanic interaction, and are referred to as ENSO (El Niño – Southern Oscillation) for short.

Terms relating to the greenhouse effect

Greenhouse effect: Greenhouse gases (trace gases present in the earth’s atmosphere) absorb and re-radiate infrared rays. The earth’s infrared radiation consists of thermal emissions from its surface, which is warmed by solar radiation. Significant amounts of these emissions are absorbed into the atmosphere, reflected back and re-absorbed by the earth’s surface in a phenomenon known as the greenhouse effect. According to estimates, the average temperature of the earth’s surface would be ~19 °C without this effect; with it, the actual value is calculated as 14 °C. Increased presence of greenhouse gases (whose major species include carbon dioxide, methane and nitrous oxide) in the atmosphere enhances the greenhouse effect, making the earth warmer. Water vapor has the largest overall greenhouse effect in the present atmosphere, but is generally not included among anthropogenic greenhouse gases in discussions of global warming issues.

Carbon dioxide: Of all greenhouse gases, carbon dioxide (CO₂) is the most significant contributor to global warming. Since the start of the industrial era in the mid-18th century, its atmospheric concentration has increased as a result of emissions from various human activities such as fossil fuel combustion, cement production and deforestation. Around half of all cumulative anthropogenic CO₂ emissions have remained in the atmosphere. The rest was removed from the atmosphere and stored in natural terrestrial ecosystems and oceans (IPCC, 2013).
**Methane:** Methane (CH$_4$) is the second most significant greenhouse gas after CO$_2$, and is emitted into the atmosphere from various sources including wetlands, rice paddy fields, ruminant animals, natural gas production and biomass combustion (WMO, 2016). It is primarily removed from the atmosphere via photochemical reaction with reactive and unstable hydroxyl (OH) radicals.

**Nitrous oxide:** Nitrous oxide (N$_2$O) is a significant greenhouse gas because of its large radiative effect per unit mass (about 300 times greater than that of CO$_2$) and its long lifetime (about 121 years) in the atmosphere. It is emitted into the atmosphere by elements of nature such as soil and the ocean, and as a result of human activities such as the use of nitrate fertilizers and various industrial processes. It is photodissociated in the stratosphere by ultraviolet radiation.

**ppm, ppb, ppt:** Concentrations of greenhouse gases are indicated with mole fractions as parts per million (ppm), parts per billion (ppb) and parts per trillion (ppt).

**Terms relating to the ozone layer**

**Total ozone:** Total ozone at any location on the globe is defined as the sum of all ozone in the atmosphere directly above that location, and is often reported in m atm-cm or Dobson units. The unit of m atm-cm (read as “milli-atmosphere centimeters”) indicates the columnar density of a trace gas (ozone) in the earth’s atmosphere. A value of 1 m atm-cm represents a layer of gas that would be 10 μm thick under standard temperature and pressure conditions. For example, 300 m atm-cm of ozone brought down to the earth’s surface at 0°C would occupy a layer 3 mm thick. Typical values of total ozone vary between 200 and 500 m atm-cm over the globe, and the global mean is about 300 m atm-cm.

**Ozone-depleting substances:** Ozone-depleting substances (ODSs) are those that deplete the ozone layer as listed in the Montreal Protocol, which bans their production. Major ODS species include chlorofluorocarbons (CFC-11, CFC-12 and CFC-113 among others), carbon tetrachloride, hydrochlorofluorocarbons (HCFCs), 1,1,1-trichloroethane, chloromethane, halons and bromomethane. These are also powerful greenhouse gases that trap heat in the atmosphere and contribute to global warming.

**Ozone hole:** The phenomenon referred to as the ozone hole is a reduction in the concentration of ozone high above the earth in the stratosphere over the Antarctica. For simplicity, it is often regarded as the area in which the total ozone amount is equal to or less than 220 m atm-cm to the south of the southern latitude of 45 degrees. The hole has steadily grown in size and annual length of presence (from August to December) over the last two decades of the last century.

**Montreal Protocol:** The Montreal Protocol on Substances that Deplete the Ozone Layer (a protocol to the Vienna Convention for the Protection of the Ozone Layer) is an international treaty designed to protect the ozone layer by phasing out the production of numerous substances believed to be responsible for ozone depletion. The treaty was opened for signatures in 1987 and came into force in 1989. Since then, it has undergone several revisions. Japan ratified the protocol in 1988.

**Terms relating to marine observation**

**Cooperative Study of the Kuroshio and Adjacent Regions (CSK):** A cooperative international undertaking under the auspices of the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), involving the main aim of clarifying the vertical and horizontal structure of the Kuroshio current and its spatial/temporal variability and the roles of heat, salt, chemical/biological elements and other influences. Contributors: 10 countries and territories including Japan, the USA and the USSR.
World Ocean Circulation Experiment (WOCE): An initiative conducted under the World Climate Research Programme (WCRP) to clarify the roles of the world’s oceans in the earth’s climate system. A major element is a ship-based program operated to monitor global fields of temperature, salinity, nutrition, oxygen and other variables.

Global Ocean Ship-based Hydrographic Investigation Program (GO-SHIP): Established in 2007, the program has resulted in a recommendation for the development of a sustained repeat hydrography initiative.

North Pacific Subtropical Mode Water (NPSTMW) area: A thermostad between the seasonal and main thermoclines. The NPSTMW area is considered to form in the surface mixed layer just south of the Kuroshio Extension as a result of huge heat loss in winter. It is defined as an area of 16–18-degree water at depths of 100 to 400 m at around 20 to 30°N along the 137°E line.

North Pacific Tropical Water (NPTW) area: A water mass characterized by a surface ocean salinity maximum. The NPTW area forms at the sea surface in subtropical areas where evaporation exceeds precipitation. It is defined as water with a salinity level of 34.9 or more at depths about 150 m at around 10 to 30°N along the 137°E line.

North Pacific Intermediate Water (NPIW) area: The NPIW area forms in the mixed region between the Kuroshio Extension and the Oyashio front. It is defined as water with a salinity level of 34.0 or less at a depth of around 800 m at around 20 to 30°N along the 137°E line.
Map 1 Names of world regions

Map 2 Names of Japan’s island areas (left figure) and Names of Japanese regions used in this report (right figure)
Map 3  Distribution of surface meteorological observation stations in Japan
References

Topics


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Chapter 1


Chapter 2


Chapter 3


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