CLIMATE CHANGE MONITORING REPORT
2011

December 2012
JAPAN METEOROLOGICAL AGENCY
Cover: Three-dimensional representations of monthly variations in zonally averaged atmospheric CO₂ distribution (concentrations (top) and growth rates (bottom)). This analysis was performed using data archived by the WDCGG.
Preface

The frequency of extreme meteorological events such as high temperatures and heavy precipitation is expected to increase as a result of global warming, and concern over how future climate change and extreme weather will impact natural and human systems is growing. Last year, above-normal precipitation amounts were observed throughout the rainy season over the Indochina Peninsula, contributing to disastrous flooding in Thailand. The inundation had a tremendous impact not only in Thailand itself but also internationally, and caused severe damage to many factories in the country, including some run by Japanese companies.

As climate change and extreme weather events affect various social and economic activities, the importance of compiling and providing climate information based on the needs of service users is expected to increase. Against this background, the World Meteorological Organization (WMO) decided to establish the Global Framework for Climate Services (GFCS) and has worked to implement the framework with its partners. The Japan Meteorological Agency (JMA) also accepted the recommendation of the Council of Transport Policy to improve climate information provision and utilization in order to help mitigate the effects of climate change and extreme weather. In line with the recommendation, JMA is currently working on the development of methods to better utilize and disseminate climate information in order to reduce climatic risk in social and economic activities via collaboration and dialogue with related organizations.

Since 1996, JMA has published annual assessments under the title of Climate Change Monitoring Report. The publications present the outcomes of JMA’s activities, including atmospheric, oceanic and environmental monitoring and analysis, and provide up-to-date information on climatic conditions around the world and in Japan. In this issue, the content configuration has been reviewed and descriptions of analysis pertaining to extreme weather events have been enhanced. It also includes the results of long-term monitoring to identify trends in the earliest dates on which cherry blossoms bloom and the color of acer tree leaves changes in Japan as indicators showing the impact of climate change on ecosystems.

I hope this report will help users to develop a better understanding of the latest status of the climate and to take measures to prevent global warming and protect the earth’s environment. We welcome feedback for the improvement of future issues to make climate information easier to understand and more useful. I would like to convey my sincere appreciation to the members of JMA’s Advisory Group of the Council for Climate Issues under the chairmanship of Dr. Hiroki Kondo for their pertinent comments and guidance in our work on this report.

(Mitsuhiko Hatori)
Director-General
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Chapter 1  Climate in 2011

1.1  Global climate summary

- Above-normal precipitation amounts were observed throughout the rainy season over the Indochina Peninsula, contributing to disastrous flooding in the Chao Phraya River and Mekong River basins (July to December), while drought occurred in eastern Africa (January to September).
- Extremely high temperatures (March to September) and extremely light precipitation amounts (January to November) were seen from the southern USA to northern Mexico.
- Weather-related disasters were caused by heavy rains in southeastern Brazil (January), extremely heavy precipitation in southern Pakistan (August to September) and Typhoon Washi (1121) in the Philippines.

Major extreme climate events and weather-related disasters in 2011 are shown in Figure 1.1-1 and Table 1.1-1.

On the Indochina Peninsula, disastrous floods occurred from July to December due to enhanced convective activity associated with an active Asian summer monsoon persisting throughout the rainy season (see 1.3.2 (1)). The extremely warm (March to September) and dry (January to November) conditions seen from the southern USA to northern Mexico seemed to be associated with sea surface temperature anomalies and related convective activity across the tropical Pacific and Atlantic (see 1.3.2 (2)).

Annual mean temperatures were above normal from Siberia to western Europe and from eastern North America to northern Central America, and were below normal from Mongolia to Central Asia, around the Indochina Peninsula, in western North America and in northern Australia (Figure 1.1-2).

Annual precipitation amounts were above normal from the Philippines to the Indochina Peninsula, around southern Pakistan, around the northeastern USA, in northern South America and in Australia, and were below normal in southern China, Saudi Arabia and Europe, from the southern USA to northern Mexico, and in central Polynesia (Figure 1.1-3).
Table 1.1-1  List of extreme events and weather-related disasters in 2011

<table>
<thead>
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<th>No.</th>
<th>Events</th>
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<td>(1)</td>
<td>Light precipitation in southeastern China (January – May)</td>
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<td>(2)</td>
<td>Flooding on the Indochina Peninsula (July – December)</td>
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<td>(8)</td>
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<td>(13)</td>
<td>Light precipitation in central Polynesia (March – October)</td>
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<td>(14)</td>
<td>Low temperatures in northern Australia (January – June)</td>
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</tbody>
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Table 1.1 - List of extreme events and weather related disasters in 2011

1. Light precipitation in southeastern China (January – May)
2. Flooding on the Indochina Peninsula (July – December)
3. Tropical storm in the Philippines (December)
4. Heavy precipitation in southern Pakistan (August – September)
5. Light precipitation in Europe (March – May, September – November)
6. Drought in eastern Africa (January – September)
7. High temperatures from the Seychelles to Mauritius (April – December)
8. Heavy precipitation around the northeastern USA (February – May, August – September)
9. Tornados in southeastern and central parts of the USA (April – May)
10. High temperatures around southern parts of the USA (March – September)
11. Light precipitation from the southern USA to northern Mexico (January – November)
12. Torrential rains in southeastern Brazil (January)
13. Light precipitation in central Polynesia (March – October)
14. Low temperatures in northern Australia (January – June)

Figure 1.1-2 Annual mean temperature anomalies in 2011
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 marks indicate values above the normal calculated from 1981 to 2010, and blue marks indicate values below the normal. 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 where normal data are unavailable.

Figure 1.1-3 Annual total precipitation amount ratios in 2011
Categories are defined by the annual precipitation ratio to the normal averaged in 5° × 5° grid boxes. Green marks indicate values above the normal calculated from 1981 to 2010, and yellow marks indicate values below the normal. The thresholds of each category are 70%, 100% and 120%. Areas over land without graphical marks are those where observation data are insufficient or where normal data are unavailable.
1.2 Climate in Japan

- Below-normal temperatures nationwide in spring, and above-normal temperatures nationwide in summer and autumn.
- Significantly earlier onset and withdrawal of the rainy season in many regions.
- Record-breaking heavy rainfall in the prefectures of Niigata and Fukushima at the end of July
- Record-breaking heavy rainfall due to typhoons Talas and Roke in September.

### 1.2.1 Annual characteristics (Figure 1.2-1)

- Temperatures tended to be below normal nationwide until May due to the effects of cold surges and above normal from June to November. Annual mean temperatures were near normal except in Okinawa/Amami, where they were below normal.
- Annual precipitation amounts were above normal except in Okinawa/Amami and on the Pacific side of northern and eastern Japan. In particular, values were significantly above normal on the Sea of Japan side of northern Japan, which is subject to the effects of low-pressure areas and fronts.
- Annual sunshine durations were above normal on the Pacific side of eastern Japan, below normal in western Japan and significantly below normal in Okinawa/Amami.

![Annual climate anomaly/ratio for Japan in 2011](image)

- The base period for the normal is 1981 – 2010.

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1 Observed mean temperatures or precipitation amounts exceeding the 90th percentile in the base period dataset (1981 – 2010) are deemed to be significantly above normal, while those falling below the 10th percentile are below normal.
1.2 Climate in Japan

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- Annual sunshine durations were above normal on the Pacific side of eastern Japan, below normal in western Japan and significantly below normal in Okinawa/Amami.

1.2.2 Seasonal characteristics

(1) Winter (December 2010 – February 2011) (Figure 1.2-3 (a))

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

Intraseasonal temperature variations were very large nationwide. From the end of December 2010 to the end of January 2011, temperatures were below normal nationwide, and snowfall amounts were above normal in all areas on the Sea of Japan side due to intermittent cold surges. Conversely, in the first half of December and the second half of February, temperatures were above normal nationwide due to the weak winter monsoon.
(Chapter 1 Climate in 2011)

(2) Spring (March – May 2011) (Figure 1.2-3 (b))
- Mean temperatures: below normal all over Japan, and significantly below normal in western Japan and Okinawa/Amami
- Precipitation amounts: significantly above normal on the Sea of Japan side of northern and eastern Japan
- Sunshine durations: significantly below normal in Okinawa/Amami and below normal in northern Japan and on the Sea of Japan side of eastern Japan, and above normal on the Pacific side of eastern and western Japan

Temperatures were below normal nationwide. In the first half of the season, they were significantly below normal in western Japan, while precipitation amounts were below normal and sunshine durations were above normal on the Pacific side due to the strong winter monsoon and anti-cyclones bringing cold air. In the second half of the season, temperatures were below normal in northern Japan due to the presence of cold vortexes.

(3) Summer (June – August 2011) (Figure 1.2-3 (c))
- Mean temperatures: above normal all over Japan
- Precipitation amounts: above normal in western Japan, and below normal in Okinawa/Amami and on the Pacific side of northern Japan
- Sunshine durations: below normal in western Japan

Although seasonal mean temperatures were above normal, intraseasonal temperature variations were very large nationwide. The onset and end of the rainy season were significantly earlier than normal in many regions. At the end of July, record-breaking heavy rainfall caused disaster conditions in the prefectures of Niigata and Fukushima.

(4) Autumn (September – November 2011) (Figure 1.2-3 (d))
- Mean temperatures: above normal all over Japan, and significantly above normal in eastern Japan, western Japan and Okinawa/Amami
- Precipitation amounts: above normal all over Japan, and significantly above normal on the Sea of Japan side of northern Japan and the Pacific side of western Japan
- Sunshine durations: significantly below normal in Okinawa/Amami and below normal in western Japan and on the Sea of Japan side of northern Japan, and significantly above normal on the Sea of Japan side of eastern Japan and above normal on the Pacific side of eastern Japan

As the westerly jet was shifted northward of its normal position, seasonal mean temperatures were above normal nationwide and significantly above normal in eastern and western Japan and Okinawa/Amami. The formation of typhoons and cyclones during the period resulted in above-normal precipitation amounts nationwide. In September, record-breaking heavy rainfall brought by typhoons Talas (1112) and Roke (1115) caused disaster conditions in many areas.

(5) Early winter (December 2011)
As the winter monsoon was intermittently strong, monthly mean temperatures were below normal in northern, eastern and western Japan. Monthly sunshine durations were extremely below normal in Okinawa/Amami due to cold air and low-pressure systems.
(Chapter 1 Climate in 2011)

(2) Spring (March – May 2011) (Figure 1.2-3 (b))

○ Mean temperatures: below normal all over Japan, and significantly below normal in western Japan and Okinawa/Amami

○ Precipitation amounts: significantly above normal on the Sea of Japan side of northern and eastern Japan

○ Sunshine durations: significantly below normal in Okinawa/Amami and below normal in northern Japan and on the Sea of Japan side of eastern Japan, and above normal on the Pacific side of eastern and western Japan

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○ Sunshine durations: below normal in western Japan

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○ Precipitation amounts: above normal all over Japan, and significantly above normal on the Sea of Japan side of northern Japan and the Pacific side of western Japan

○ Sunshine durations: significantly below normal in Okinawa/Amami and below normal in western Japan and on the Sea of Japan side of northern Japan, and significantly above normal on the Sea of Japan side of eastern Japan and above normal on the Pacific side of eastern Japan

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As the winter monsoon was intermittently strong, monthly mean temperatures were below normal in northern, eastern and western Japan. Monthly sunshine durations were extremely below normal in Okinawa/Amami due to cold air and low-pressure systems.

Figure 1.2-3 Seasonal anomalies/ratios for Japan in 2011
(a) Winter (December 2010 to February 2011), (b) spring (March to May), (c) summer (June to August), (d) autumn (September to November). The base period for the normal is 1981 – 2010.
1.3 Atmospheric circulation and oceanographic conditions

- The heavy rainfall observed in the 2011 rainy season over the Indochina Peninsula, which contributed to disastrous flooding in Thailand, seemed to be caused by enhanced convective activity associated with an active Asian summer monsoon persisting throughout the season.
- The extremely warm and dry conditions seen in the southern USA and northern Mexico seemed to be associated with sea surface temperature anomalies and related convective activity across the tropical Pacific and Atlantic.

Monitoring of atmospheric and oceanographic conditions (e.g., upper air flow, tropical convective activity, sea surface temperatures (SSTs)) is important in analyzing the causes of extreme weather events. This section briefly outlines the characteristics of atmospheric circulation and oceanographic conditions for 2011.

1.3.1 Characteristics of individual seasons

(1) Winter (December 2010 – February 2011)

The La Niña event that occurred from summer 2010 to spring 2011 matured in the period from autumn 2010 to winter 2010/2011 (Figure 2.6-1). SSTs in the tropical Pacific were below normal across a wide area east of 150°E and above normal in the area west of 150°E (Figure 1.3-1). Convective activity in the tropics was enhanced over the eastern Indian Ocean, the Philippines and around Australia in association with the La Niña event (Figure 1.3-2). Active convection to the northeast of Australia was shifted slightly westward of that seen in past La Niña events, which contributed to record-breaking rainfall in eastern parts of Australia during December and the first half of January.

In the 500-hPa height and sea level pressure fields, positive and negative anomalies were seen over the high and middle latitudes, respectively (Figures 1.3-3 and 1.3-4). These anomaly patterns indicate a negative phase of the Arctic Oscillation (AO), helping cold Arctic air move into the mid-latitudes. In association with this, Europe, Mongolia, China and the USA experienced below-normal seasonal mean temperatures. The negative AO prevailed in the first half of winter and turned positive in the second half.

In January, both the Siberian High and the Aleutian Low were significantly enhanced, causing a stronger-than-normal winter monsoon around Japan (figure not shown). As a result, the country experienced below-normal temperatures nationwide and heavy snowfall over wide areas on the Sea of Japan side.

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2 See the Glossary for terms relating to El Niño phenomena, monsoons and the Arctic Oscillation.
3 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 top of clouds 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 (AO); 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.
4 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.
(Chapter 1  Climate in 2011)

(2) Spring (March – May 2011)

SSTs remained below normal in central and eastern parts of the tropical Pacific except in the eastern equatorial part and above normal in its western part throughout the season, although the La Niña event decayed in spring 2011 (Figure 1.3-5). In association with this, convective activity was enhanced over the Philippines and around Indonesia, and was suppressed near the equatorial dateline region (Figure 1.3-6).

In the 500-hPa height field, wave trains were observed from Europe to Japan with positive anomalies over the region and negative anomalies over the country, indicating that the westerly jet stream significantly meandered north over the former and south over the latter (Figure 1.3-7). In line with this, Europe experienced light precipitation due to frequent coverage by high-pressure systems (Figure 1.3-8) and a weaker-than-normal influence from low-pressure systems and fronts, while Japan experienced low temperatures nationwide due to cold air flow.

In March, the Siberian High was significantly enhanced, contributing to a strong winter monsoon pattern around Japan (figure not shown). Accordingly, Japan experienced significant low temperatures except in its northern parts.

(3) Summer (June – August 2011)

SSTs in the tropics were near normal across the equatorial Pacific and east of the Philippines, below normal in central and eastern parts of the equatorial region, and above normal in the tropical North Atlantic (Figure 1.3-9).

In association with these SST anomalies, convective activity in the tropics was enhanced over the western Pacific and around the Caribbean Sea and suppressed over the central and eastern Pacific (Figure 1.3-10). It can be inferred that this anomalous convective activity across the Pacific and the Atlantic influenced atmospheric circulation around the USA in association with warm and dry conditions in the southern USA and northern Mexico (see Section 1.3.2 (2) for details).

The Pacific High was generally stronger than normal and extended to Japan (Figure 1.3-12) in association with the anomalous convective activity over the Pacific. In the 2011 warm season, convective activity around the Philippines varied significantly with a period of two to three weeks. It is known that the strength of the Pacific High around Japan is associated with convective activity in the vicinity of the Philippines (e.g., Nitta, 1987). In line with the intraseasonal variability of convective activity near the Philippines, the strength of the Pacific High also varied with a period of a few weeks. Accordingly, temperatures in Japan were above normal nationwide and oscillated substantially.

The westerly jet streams in the extratropics of the Northern Hemisphere generally showed significant meandering during the summer (Figure 1.3-11). In July when pronounced meandering was observed on a hemispheric scale, temperatures were extremely above normal in western Russia and eastern Siberia as well as over northeastern and southern parts of the USA, where northward meandering was seen, and extremely below normal over Europe and western – central Siberia, where southward meandering was seen.
(4) Autumn (September – November 2011)

The SST deviation from the reference value (i.e., the latest sliding 30-year mean SST averaged over the El Niño monitoring region (5ºN – 5ºS, 150ºW – 90ºW)) remained negative throughout autumn, representing La Niña-like conditions (Figure 2.6-1). In autumn during past La Niña events, SSTs in the tropics were above normal in the western Pacific and around Indonesia and below normal in the Indian Ocean, but were near normal in the former areas and above normal in the latter for autumn 2011 (Figure 1.3-13).

Convective activity was near normal or suppressed over the area from Indonesia to the Philippines, where it was enhanced in autumn during past La Niña events, and was substantially enhanced over the western Indian Ocean including the Arabian Sea (Figure 1.3-14). It can be inferred that the differences in these convective activity characteristics from those seen in past events were related to the SST anomalies observed across the Indian Ocean and the Pacific.

Significant meandering of the jet stream was observed from Europe to Japan, with northward meandering seen over the region and the country (Figure 1.3-15). In association with this, Europe experienced light precipitation due to frequent coverage by high-pressure systems (Figure 1.3-16) and a weaker-than-normal influence from low-pressure systems and fronts, while Japan experienced high temperatures nationwide due to warm air flow.
Figure 1.3-1  Three-month mean sea surface temperature (SST) anomaly (December 2010 – February 2011)
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 2010 – February 2011)
The contour interval is 10 W/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 2010 – February 2011)
The contours show 500-hPa height at intervals of 60 m. The shading indicates height anomalies. The base period for the normal is 1981 – 2010. 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 2010 – February 2011)
Figure 1.3-5 Three-month mean sea surface temperature (SST) anomaly (March – May 2011)
As per Figure 1.3-1, but for March – May 2011.

Figure 1.3-6 Three-month mean outgoing longwave radiation (OLR) anomaly (March – May 2011)
As per Figure 1.3-2, but for March – May 2011.

Figure 1.3-7 Three-month mean 500-hPa height and anomaly in the Northern Hemisphere (March – May 2011)
As per Figure 1.3-3, but for March – May 2011.

Figure 1.3-8 Three-month mean sea level pressure and anomaly in the Northern Hemisphere (March – May 2011)
As per Figure 1.3-4, but for March – May 2011.
Figure 1.3-9 Three-month mean sea surface temperature (SST) anomaly (June – August 2011)
As per Figure 1.3-1, but for June – August 2011.

Figure 1.3-10 Three-month mean outgoing longwave radiation (OLR) anomaly (June – August 2011)
As per Figure 1.3-2, but for June – August 2011.

Figure 1.3-11 Three-month mean 500-hPa height and anomaly in the Northern Hemisphere (June – August 2011)
As per Figure 1.3-3, but for June – August 2011.

Figure 1.3-12 Three-month mean sea level pressure and anomaly in the Northern Hemisphere (June – August 2011)
As per Figure 1.3-4, but for June – August 2011.
1.3.2 Analysis of specific events in 2011

(1) Heavy rainfall in the rainy season over the Indochina Peninsula

In general, the rainy season over the Indochina Peninsula associated with the Asian summer monsoon lasts from around May to around October. In 2011, precipitation over the peninsula remained above normal throughout the season (Figure 1.3-17). Four-month precipitation totals from June to September 2011 were 120% – 180% of the normal for most meteorological
observation stations over the peninsula. The figures were 921 mm (134% of the normal) for Chiang Mai in northern Thailand, 1,251 mm (140%) for Bangkok (the capital of Thailand) and 1,641 mm (144%) for Vientiane (the capital of Laos). The rainfall total for the 2011 rainy season (May – September) in Thailand was the third highest since 1951 after 1970 and 1956 (source: Thai Meteorological Department, 2011).

A striking characteristic of the monsoon rainfall for the Indochina Peninsula is that above-normal amounts continued throughout the rainy season over the whole of the Chao Phraya River and Mekong River basins (Figure 1.3-18). This was associated with enhanced convective activity accompanying the Asian summer monsoon (Figure 1.3-19).

This heavier-than-normal rainfall contributed to flooding over a wide area in these two basins. The floods caused serious damage on the Indochina Peninsula – especially in Thailand. It was reported that many factories, including some run by Japanese companies in and around Ayutthaya in Thailand, were flooded and forced to stop operations, affecting industry both in Thailand and in Japan.

Figure 1.3-17 Spatial distribution of the four-month (June – September 2011) precipitation ratio compared to the normal (center), and time-series representations of monthly precipitation at Chiang Mai, Bangkok (Thailand), Vientiane (Laos), and Phnom-Penh (Cambodia).

The base period for the normal is 1981 – 2010. Spaces marked with “×” in the bar graphs are months for which no data were reported.
(Chapter 1  Climate in 2011)

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A striking characteristic of the monsoon rainfall for the Indochina Peninsula is that above-normal amounts continued throughout the rainy season over the whole of the Chao Phraya River and Mekong River basins (Figure 1.3-18). This was associated with enhanced convective activity accompanying the Asian summer monsoon (Figure 1.3-19).

This heavier-than-normal rainfall contributed to flooding over a wide area in these two basins. The floods caused serious damage on the Indochina Peninsula – especially in Thailand. It was reported that many factories, including some run by Japanese companies in and around Ayutthaya in Thailand, were flooded and forced to stop operations, affecting industry both in Thailand and in Japan.

Figure 1.3-17 Spatial distribution of monthly precipitation ratios (%) compared to the normal for June – September 2011
The base period for the normal is 1981 – 2010.

Figure 1.3-18 Spatial distribution of monthly precipitation ratios (%) compared to the normal for June – September 2011
The base period for the normal is 1981 – 2010.

(2) Extremely warm and dry conditions in the southern USA and northern Mexico

Temperatures in southern parts of the USA and northern parts of Mexico remained substantially above normal from spring to summer 2011. Texas and the states surrounding it saw record-breaking high temperatures in the summer (Figure 1.3-20). Dallas/Fort Worth had 40 consecutive days (2 July – 10 August) of maximum temperatures reaching 100°F (37.8°C) or higher (Figure 1.3-21). Significantly lighter-than-normal precipitation persisted from autumn 2010 to autumn 2011 in these areas (Figures 1.3-22 and 1.3-23), leading to extreme drought. These hot dry conditions caused damage to crop yields and livestock, and contributed to wildfires that affected wide areas and destroyed many homes.

In the tropical Pacific, the La Niña event persisted until spring 2011, and La Niña-like SST anomalies persisted during summer and autumn (Figures 1.3-5, 1.3-9 and 1.3-13). In the tropical North Atlantic, SSTs remained above normal during the period from spring to autumn. In association with these SST anomalies, convective activity was enhanced over the area from the western coast of Central America to the Caribbean Sea and suppressed across the central – eastern Pacific (Figures 1.3-6, 1.3-10 and 1.3-14).
In response to these tropical conditions, the westerly jet stream over the area from the southern USA to northern Mexico tended to be shifted northward of its normal position. In association with this, a tendency by which high-frequency eddy activity weakened and warm air flowed was observed there, contributing to the warm and dry conditions.

Figure 1.3-20 Three-month mean temperature anomalies normalized by their standard deviations (June – August 2011)
The base period for the normal is 1981 – 2010.

Figure 1.3-21 Time-series representations of daily maximum (red line), daily mean (yellow line) and daily minimum (blue line) temperatures (left axis, unit: °C) and daily total precipitation (green bars, right axis, unit: mm) in Dallas/Fort Worth (32°54’N, 97°02’W) (1 April – 31 October, 2011)

Figure 1.3-22 14-month total ratio (%) of precipitation to the normal (October 2010 – November 2011)
The base period for the normal is 1981 – 2010.

Figure 1.3-23 Time-series representation of monthly precipitation amounts in Midland, TX, USA (September 2010 – November 2011)
The light-blue bars show monthly precipitation amounts (unit: mm), and the unfilled black-framed bars indicate normal values. The base period for the normal is 1981 – 2010.
Chapter 2  Climate Change

2.1 Changes in temperature

- The annual anomaly of the global average surface temperature in 2011 was the 12th highest since 1891, and the annual anomaly of the average temperature over Japan was the 17th 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 0.68 and 1.15ºC per century, respectively.
- It is virtually certain that the frequency of extremely high-temperature events has increased, while the frequency of extremely low-temperature events has decreased.
- It is virtually certain that the annual number of days with minimum temperatures below 0ºC (Tmin < 0ºC) has decreased, while the annual number of days with minimum temperatures of 25ºC or higher (Tmin ≥ 25ºC) has increased. The annual number of days with Tmax ≥ 35ºC is very likely to have increased.

2.1.1 Global surface temperature

The annual anomaly of the global average surface temperature in 2011 (i.e., the combined average of the near-surface air temperature over land and the SST) was +0.07ºC above the 1981–2010 average, which was the 12th highest since 1891. The surface temperature anomalies over the Northern Hemisphere and the Southern Hemisphere were +0.12ºC (the 11th highest) and +0.02ºC (the 12th 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 0.68ºC per century (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 0.71 and 0.66ºC per century, respectively (both statistically significant at a confidence level of 99%). These long-term trends can be attributed to global warming caused by increased concentrations of greenhouse gases such as CO2. On a shorter time scale, the La Niña conditions seen in the equatorial Pacific contributed to a reduction of the 2011 global temperature in relation to that of the previous year.

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5 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)

6 According to IPCC AR4, the 100-year linear trend of the global average temperature was 0.74ºC for the period from 1906 to 2005. The values given in IPCC AR4 and those in this report are considered to show no remarkable difference, although they do not correspond exactly because of differences in calculation methods and the statistical period examined.

7 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.
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. To calculate long-term temperature trends on a regional scale, JMA selected 17 stations considered to have been affected to a lesser extent by local urbanization that have continuous records covering the period from 1898 onward. Miyazaki and Iida were relocated in May 2000 and May 2002, respectively, and their temperatures have been adjusted to eliminate the influence of the relocation.

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

The mean surface temperature in Japan for 2011 is estimated to have been 0.15°C above the 1981 – 2010 average, which is the 17th warmest on record since 1898 (Figure 2.1-2). The surface temperature fluctuates on different time scales ranging from a few years to several 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 1.15°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 1.19, 1.30, 1.00 and 1.14°C per century, respectively (all statistically significant at a confidence level of 99%).

It is noticeable from Figure 2.1-2 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
warmed 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 several years to several 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 2.1-2 Annual surface temperature anomalies from 1898 to 2011 in Japan. 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/lowlow-temperature events in Japan as derived from analysis of temperature records from the 17 observation stations. 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 a confidence level of 99%) (Figure 2.1-3). These trends are consistent with the rising annual mean temperatures discussed in Section 2.1.2.

Figure 2.1-3 Annual number of extremely high/lowlow monthly mean temperature occurrences

The graphs show the annual number of occurrences of the highest/lowest first-to-fourth values for each month during the period from 1901 to 2011. The green bars indicate annual occurrences of extremely high/lowlow 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.

8 Here, judgment of extremely high/lowlow temperatures is based on the fourth-highest/lowest monthly values on record over the 111-year period from 1901 to 2011. The frequency of occurrence of the highest/lowest to the fourth-highest/lowest values over this period is approximately once every 28 years, which is close to JMA’s definition of extreme climate events as those occurring once every 30 years or longer (see Glossary).
(2) Annual number of days with maximum temperatures of $\geq 30^\circ C$ and $\geq 35^\circ C$

The annual number of days with maximum temperatures ($T_{\text{max}}$) of $\geq 30^\circ C$ shows no discernible trend in the period from 1931 to 2011. Meanwhile, the annual number of days with $T_{\text{max}} \geq 35^\circ C$ is very likely to have increased (statistically significant at a confidence level of 90%) (Figure 2.1-4).

![Figure 2.1-4](image)

**Figure 2.1-4**  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. 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 2.1-5).

![Figure 2.1-5](image)

**Figure 2.1-5**  Annual numbers of days with minimum temperatures of $< 0^\circ C$ and $\geq 25^\circ C$

As per Figure 2.1-4

2.1.4 *Urban heat island* effect at urban stations in Japan

The long-term trends of annual average temperatures are more pronounced for 11 urban observation stations (Sapporo, Sendai, Tokyo, Yokohama, Niigata, Nagoya, Kyoto, Osaka, Hiroshima, Fukuoka, Kagoshima) than for the average of 17 rural observation stations (Table 2.1-2).

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*A urban heat island is a city area where temperatures are higher than those in the surrounding rural areas. The term comes from the shape of the characteristic high-temperature distribution pattern, which resembles an island. JMA annually publishes the Japanese-language Urban Heat Island Monitoring Report, which contains analysis of observation data and numerical simulation experiments on the urban heat island effect.*

The annual number of days with maximum temperatures (Tmax) of ≥ 30ºC shows no discernible trend in the period from 1931 to 2011. Meanwhile, the annual number of days with Tmax ≥ 35ºC is very likely to have increased (statistically significant at a confidence level of 90%) (Figure 2.1-4).

Figure 2.1-4 Annual number of days with maximum temperatures of ≥ 30ºC and ≥ 35ºC

The graphs show the annual number of days per station, with the green bars indicating the values for each year. The blue line indicates the five-year running mean, and the straight red line indicates the long-term linear trend.

It is virtually certain that the annual number of days with minimum temperatures (Tmin) of < 0ºC has decreased, while the annual number of days with Tmin ≥ 25ºC has increased (both statistically significant at a confidence level of 99%) (Figure 2.1-5).

Figure 2.1-5 Annual numbers of days with minimum temperatures of < 0ºC and ≥ 25ºC

The long-term trends of annual average temperatures are more pronounced for 11 urban observation stations (Sapporo, Sendai, Tokyo, Yokohama, Niigata, Nagoya, Kyoto, Osaka, Hiroshima, Fukuoka, Kagoshima) than for the average of 17 rural observation stations (Table 2.1-2).

Table 2.1-2 Long-term trends of annual average temperatures, monthly average temperatures for January and August, and annual averages for daily maximum and minimum temperatures at urban stations in Japan

These figures are based on data from 1931 to 2011. The trend of 17 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 marked “*” (for the 17 rural stations, Iida and Miyazaki), trends are calculated after adjustment to eliminate the influence of relocation.

<table>
<thead>
<tr>
<th>Stations</th>
<th>Temperature</th>
<th>Long-term trend (ºC/century)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average temperature</td>
<td>Daily maximum</td>
<td>Daily minimum</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>January</td>
<td>August</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sapporo</td>
<td>2.7</td>
<td>3.8</td>
<td>1.3</td>
<td>0.9</td>
<td>4.5</td>
</tr>
<tr>
<td>Sendai</td>
<td>2.3</td>
<td>3.1</td>
<td>0.7</td>
<td>1.0</td>
<td>3.2</td>
</tr>
<tr>
<td>Tokyo</td>
<td>3.2</td>
<td>4.7</td>
<td>1.7</td>
<td>1.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Yokohama</td>
<td>2.8</td>
<td>3.7</td>
<td>1.5</td>
<td>2.3</td>
<td>3.6</td>
</tr>
<tr>
<td>Niigata*</td>
<td>2.1</td>
<td>2.6</td>
<td>1.4</td>
<td>1.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Nagoya</td>
<td>2.9</td>
<td>3.2</td>
<td>2.4</td>
<td>1.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Kyoto</td>
<td>2.7</td>
<td>2.8</td>
<td>2.4</td>
<td>0.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Osaka*</td>
<td>2.8</td>
<td>2.7</td>
<td>2.5</td>
<td>2.3</td>
<td>3.8</td>
</tr>
<tr>
<td>Hiroshima*</td>
<td>2.1</td>
<td>1.9</td>
<td>1.6</td>
<td>1.0</td>
<td>3.2</td>
</tr>
<tr>
<td>Fukuoka</td>
<td>3.1</td>
<td>3.0</td>
<td>2.4</td>
<td>1.6</td>
<td>5.2</td>
</tr>
<tr>
<td>Kagoshima*</td>
<td>2.9</td>
<td>3.0</td>
<td>2.7</td>
<td>1.3</td>
<td>4.2</td>
</tr>
<tr>
<td>17 rural stations*</td>
<td>1.5</td>
<td>1.7</td>
<td>1.0</td>
<td>1.0</td>
<td>1.9</td>
</tr>
</tbody>
</table>

As it can be assumed that the long-term trends averaged over the 17 rural stations are only minimally affected by the local urban heat island effect and reflect large-scale climate change, the differences in the long-term trends of urban stations from the average of the 17 stations largely represent the influence of urbanization.

In greater detail, the long-term trends are larger in January than in August and larger for minimum temperatures than for maximum temperatures at every urban observation station. It should be noted that while the annual number of days with Tmin ≥ 25ºC for Sapporo does not show a statistically significant trend, the annual number with Tmin < 0ºC has decreased at all urban stations. This is consistent with the theoretical understanding that temperature differences between urban and non-urban areas are larger in winter than in summer and larger at nighttime than during the daytime, suggesting that the temperature increase observed at the urban stations shown here is at least partly caused by the urban heat island effect.
Table 2.1-3  Long-term trends of the annual number of days with minimum temperatures of < 0 °C and ≥ 25 °C and the annual number of days with minimum temperatures of < 0 °C and ≥ 25 °C in 2011

These figures are based on data from 1931 to 2011. The trend of 15 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%. Values in parentheses indicate the deviation from normal. For stations marked with “*”, the rates of change were not calculated because of station relocation.

<table>
<thead>
<tr>
<th>Station</th>
<th>Annual number of days</th>
<th>Trend (days/decade)</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T&lt;sub&gt;min&lt;/sub&gt; ≥ 25°C</td>
<td>T&lt;sub&gt;min&lt;/sub&gt; &lt; 0°C</td>
</tr>
<tr>
<td>Sapporo</td>
<td></td>
<td>0.0</td>
<td>−4.8</td>
</tr>
<tr>
<td>Sendai</td>
<td></td>
<td>0.3</td>
<td>−6.1</td>
</tr>
<tr>
<td>Tokyo</td>
<td></td>
<td>3.8</td>
<td>−8.6</td>
</tr>
<tr>
<td>Yokohama</td>
<td></td>
<td>2.9</td>
<td>−6.7</td>
</tr>
<tr>
<td>Niigata *</td>
<td></td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Nagoya</td>
<td></td>
<td>3.7</td>
<td>−7.5</td>
</tr>
<tr>
<td>Kyoto</td>
<td></td>
<td>3.6</td>
<td>−8.0</td>
</tr>
<tr>
<td>Osaka *</td>
<td></td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Hiroshima *</td>
<td></td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Fukuoka</td>
<td></td>
<td>4.8</td>
<td>−5.4</td>
</tr>
<tr>
<td>Kagoshima *</td>
<td></td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>15 rural stations</td>
<td></td>
<td>1.4</td>
<td>−2.3</td>
</tr>
</tbody>
</table>
### Long-term trends of relative humidity in urban areas

Table 2.1-4 shows the long-term trends of annual average relative humidity and water vapor pressure recorded at 7 urban observation stations, along with the average over 15 rural stations for comparison, during the period from 1931 to 2011. Relative humidity at the former has decreased faster than the latter. However, the discrepancy in long-term trends between the urban and rural stations is less remarkable for water vapor pressure, with no statistical significance detected except for Tokyo, Nagoya and Kyoto. The long-term trends of monthly mean relative humidity and water vapor pressure for January and August show characteristics similar to those of the annual averages. The declining trend in relative humidity may therefore be attributable primarily to the higher saturation water vapor pressures associated with higher temperatures.¹⁰

Table 2.1-4 Long-term trends of annual average relative humidity and water vapor pressure at urban stations in Japan

These figures are based on data from 1931 to 2011. The trend of 15 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>Relative humidity</th>
<th>Water vapor pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long-term trend (%/century)</td>
<td>Long-term trend (hPa/century)</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>January</td>
</tr>
<tr>
<td>Sapporo</td>
<td>−13.4</td>
<td>−10.7</td>
</tr>
<tr>
<td>Sendai</td>
<td>−9.4</td>
<td>−11.0</td>
</tr>
<tr>
<td>Tokyo</td>
<td>−18.2</td>
<td>−23.3</td>
</tr>
<tr>
<td>Yokohama</td>
<td>−14.3</td>
<td>−18.7</td>
</tr>
<tr>
<td>Nagoya</td>
<td>−18.7</td>
<td>−18.2</td>
</tr>
<tr>
<td>Kyoto</td>
<td>−16.7</td>
<td>−15.6</td>
</tr>
<tr>
<td>Fukuoka</td>
<td>−17.0</td>
<td>−14.3</td>
</tr>
<tr>
<td>15 rural stations</td>
<td>−7.1</td>
<td>−6.3</td>
</tr>
</tbody>
</table>

### Precipitation¹¹

- The annual anomaly of global precipitation (for land areas only) in 2011 was +55 mm.
- The annual anomaly of precipitation in 2011 was +172 mm in Japan.
- The annual numbers of days with daily precipitation of ≥ 100 mm and ≥ 200 mm are extremely likely to have increased.

#### Global precipitation over land

Annual precipitation (for land areas only) in 2011 was +55 mm above the 1981 – 2010 average (Figure 2.2-1), and the figure has fluctuated periodically since 1880. In the Northern Hemisphere, records show large amounts of rainfall around 1930 and in the 1950s. Long-term trends are not

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¹⁰ Relative humidity (RH) is calculated using the following formula:

\[ RH(\%) = \frac{\text{WVP}}{\text{SWVP}} \times 100 \]

Water vapor pressure (WVP) is the pressure of water vapor present in a unit mass of the atmosphere. Saturation water vapor pressure (SWVP) is the maximum pressure above which water vapor condenses to form liquid water, and increases by 6% with a 1°C increase in temperature. Accordingly, RH can fall when SWVP increases even if WVP is constant.

¹¹ Data on annual precipitation around the world and in Japan are published on JMA's website.

analyzed because the necessary precipitation data for sea areas are not available.

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 2011 was +172 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).

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>

2.2.3 Snow depth in Japan

Figure 2.2-1 Annual anomalies in precipitation (over land areas only) from 1880 to 2011 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.

Figure 2.2-2 Annual anomalies in precipitation from 1898 to 2011 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.
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, Hamada, Hikone, Shimonoseki, Fukuoka, Oita, Nagasaki, Kumamoto</td>
</tr>
</tbody>
</table>

The annual maximum snow depth ratio in 2011 was 110% above the 1981 – 2010 average for the Sea of Japan side of northern Japan, 127% for the same side of eastern Japan, and 175% for the same side of western Japan. 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 northern and western Japan is extremely likely to have decreased at rates of about 4.4%/decade and 14.3%/decade, respectively (both statistically significant at a confidence level of 95%). It is virtually certain that the annual maximum snow depth ratio on the Sea of Japan side of eastern Japan has been decreasing at a rate of about 12.3%/decade (statistically significant at a confidence level of 99%).

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.

(1) Extremely wet/dry months

It is virtually certain that the frequency of extremely dry months increased during the period from 1901 to 2011 (statistically significant at a confidence level of 99%) (Figure 2.2-4). There has been no discernible trend in the frequency of extremely wet months.

![Figure 2.2-4](image)

**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 2011. 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 numbers of days with precipitation of $\geq 100$ mm and $\geq 200$ mm

The annual number of days with precipitation of $\geq 100$ mm is extremely likely to have increased in the period from 1901 to 2011 (statistically significant at a confidence level of 95%). The annual number of days with daily precipitation $\geq 200$ mm is also extremely likely to have increased (statistically significant at a confidence level of 95%) (Figure 2.2-5).

![Figure 2.2-5](image)

**Figure 2.2-5 Annual numbers of days with precipitation of $\geq 100$ mm and $\geq 200$ mm**

As per Figure 2.2-4

### 2.2.5 Long-term trends of heavy rainfall analyzed using AMeDAS data

The Japan Meteorological Agency operationally observes precipitation at about 1,300

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12 Here, judgment of extremely heavy/light precipitation is based on the fourth-highest/lowest monthly values on record over the 111-year period from 1901 to 2011. The frequency of occurrence of the highest/lowest to the fourth-highest/lowest values over this period is approximately once every 28 years, which is close to JMA’s definition of extreme climate events as those occurring once every 30 years or longer (see Glossary).
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 periods of close to 35 years 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 numbers of events with extreme precipitation exceeding 50 mm/80 mm per hour (every-hour-on-the-hour observations) (Figure 2.2-6) and 200 mm/400 mm per day (Figure 2.2-7) are described based on AMeDAS observation data.13

The annual number of events with precipitation exceeding 50 mm/hour is extremely likely to have increased (statistically significant at a confidence level of 95%), and the corresponding figure for events with precipitation exceeding 80 mm/hour is also very likely to have increased (statistically significant at a confidence level of 90%). The annual number of events with precipitation exceeding 200 mm/day shows no statistically significant trend, while the corresponding figure for events with precipitation exceeding 400 mm per day is extremely likely to have increased (statistically significant at a confidence level of 95%).

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.

13 The number of AMeDAS stations was about 800 in 1976, and had gradually increased to about 1,300 by 2011. 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.
Figure 2.2-6 Annual numbers of events with precipitation exceeding 50 and 80 mm/hour from 1976 to 2011 (per 1,000 AMeDAS points)

Figure 2.2-7 Annual number of events with precipitation exceeding 200 and 400 mm/day from 1976 to 2011 (per 1,000 AMeDAS points)
2.3 Change in earliest dates of cherry blossom flowering and acer leaf color change in Japan

- A significant long-term trend toward earlier cherry blossom flowering is observed.
- A significant long-term trend toward later acer leaf color change is observed.

JMA implements phenological observation to research the impact of meteorological conditions and climatic change on plants and animals. Observation is conducted for the first/full bloom and leaf tint dates of several typical plants and for the first recorded song of insects, birds and animals.

Seasonal phenomena relating to plants in particular are affected by surface temperatures. JMA observes cherry blossoms at 59 observation stations and acer trees at 52 observation stations. Figure 2.3-1 shows interannual variations in the mean dates of the first cherry blossom flowering and the first autumn acer leaf observation dating back to 1953. A significant long-term trend toward earlier flowering at a rate of 4.8 days every 50 years is observed (statistically significant at a confidence level of 95%), while a significant long-term trend toward later acer color change at a rate of 16.1 days every 50 years is seen (with the same level of statistical significance). As the phenomena discussed here are closely related to surface temperatures, these long-term trends are considered to stem from long-term warming.

![Figure 2.3-1](image)

The blue line shows the anomaly of the first cherry blossom flowering dates and that of acer leaf color change based on data from all observation stations. The red line shows the long-term linear trend (cherry blossoms: −4.8 days/50 years; acers: +16.1 days/50 years).

2.4 Tropical cyclones

- A total of 21 tropical cyclones (TCs) with maximum wind speeds of 17.2 m/s or higher formed in 2011. This was the fourth-lowest number since 1951.
- The numbers of formations show no significant long-term trend.

In 2011, 21 tropical cyclones (TCs) with maximum wind speeds of 17.2 m/s or higher formed over the western North Pacific (Figure 2.4-1). This number was the fourth lowest since 1951 and the same as that for 2003. The normal (i.e., the 1981 – 2010 averages) is 25.6. The numbers of formations show no significant long-term trend, but have been lower than normal in recent years.

Figure 2.4-2 shows the numbers and ratios of tropical cyclones with maximum winds of 33 m/s or higher to those with maximum winds 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 and ratios for tropical cyclones with maximum winds of 33 m/s or higher show no discernible trend.
2.5 Sea surface temperature

- The annual mean of the global average sea surface temperature (SST) in 2011 was 0.04°C above the 1981 – 2010 average, which was the 11th highest since 1891.
- The global average sea surface temperature has risen at a rate of about 0.51°C per century.
- It is virtually certain that sea surface temperatures (SSTs) have risen by between +0.71 and +1.73°C over the last 100 years in the Yellow Sea, the East China Sea, the sea around the Sakishima Islands, the central and southern part of the Sea of Japan, the southern part of the sea off Kanto and the seas south of Japan.

2.5.1 Global sea surface temperature

The annual mean of the global average sea surface temperature in 2011 was 0.04°C above the 1981 – 2010 average, which was the 11th highest since 1891. The global average has risen at a rate of about 0.51°C per century (Figure 2.5-1) (statistically significant at a confidence level of 99%). The rate of mean rise in the average sea surface temperature for each ocean basin has varied from 0.42 to 0.72°C per century (Figure 2.5-2) (statistically significant at a confidence level of 99%).

A phenomenon known as Pacific Decadal Oscillation (PDO) in which sea surface temperatures vary on a decadal time scale is seen in the North Pacific, and is thought to affect meteorological conditions in the region (see column). The PDO index, which is used to evaluate the phase and strength of this oscillation, was −1.3 in winter 2010/2011.

\[14\] The results of analysis regarding tendencies of SSTs worldwide and around Japan are published on JMA’s website. http://www.data.kishou.go.jp/kaiyou/english/long_term_sst_global/glb_warm_e.html

Figure 2.4-1 Numbers of tropical cyclones with maximum winds of 17.2 m/s or higher forming in the western North Pacific. The solid, thick and dashed lines represent annual/five-year running means and normal values (i.e., the 1981 – 2010 average), respectively.

Figure 2.4-2 Numbers (blue) and ratios (red) of tropical cyclone formations with maximum winds of 33 m/s or higher. The thin and thick lines represent annual and five-year running means, respectively.
Figure 2.4 - 1
Numbers of tropical cyclones with maximum winds of 17.2 m/s or higher forming in the western North Pacific. The solid, thick and dashed lines represent annual/five-year running means and normal values (i.e., the 1981–2010 average), respectively.

Figure 2.4 - 2
Numbers (blue) and ratios (red) of tropical cyclone formations with maximum winds of 33 m/s or higher. The thin and thick lines represent annual and five-year running means, respectively.

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http://www.data.kishou.go.jp/kaiyou/english/long_term_sst_global/glb_warm_e.html

2.5.2 Sea surface temperature (around Japan)

Figure 2.5-3 shows rates of area-averaged SST increase around Japan (area numbers: I–XIII) from 1900 to 2011 (unit: °C/century). It is virtually certain that SSTs have risen by between +0.71 and +1.73°C over the last 100 years in the Yellow Sea, the East China Sea, the sea around the Sakishima Islands, the central and southern part of the Sea of Japan, the southern part of the sea off Kanto and the seas south of Japan (I, II, III, IV, V, VI, X, XII and XIII) (statistically significant at a confidence level of 99%). It is extremely likely that SSTs have risen by between +0.61 and +0.94°C over the last 100 years in the sea off Kushiro, the sea off Sanriku and the eastern part of the sea off Kanto (VII, VIII and IX) (statistically significant at a confidence level of 90%). The rates of SST increase in the seas around Japan are higher than the rate for the North Pacific (+0.45°C/century, Figure 2.5-2).
Figure 2.5-3 Rates of mean SST increase from 1900 to 2011 (°C/century)

Values with no symbol and those marked with [**] have statistical significance at confidence levels of 99% and 90%, respectively. Areas marked with [#] are those where no discernible trend is seen due to large SST variability factors such as decadal oscillation.
It is known that sea surface temperatures (SSTs) vary on time scales from one to several decades, ENSO varies on a time scale of several years, and long-term trends associated with global warming are observed. In the North Pacific, the atmosphere and ocean tend to co-vary with periods of more than 10 years. This variability is called 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 10 years. The PDO index, which is defined by a score based on the first mode of the empirical-orthogonal-function of SSTs in the North Pacific, is used to evaluate the phase and strength of the oscillation.

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 2.5-4), and sea level pressure (SLP) values for 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 2.5-5). These atmospheric variations affect meteorological conditions around North America. When the PDO index is positive, winter precipitation tends to be low in Alaska and from the southwestern part of Canada to the area around the Great Lakes, and tends to be high in the northwestern part of the USA. Winter temperatures also tend to be high in the southwestern part of North America and low in the southeastern part of the USA (Mantua and Hare, 2002). The PDO also affects sea level variations near Japan (Yasuda and Sakurai, 2006).

Focusing on the long-term variability of the PDO index, its values varied from positive to negative during the 1940s and from negative to positive during the 1970s, and were generally positive until the 1980s (positive values correspond to a pattern in which SSTs in the central part of the North Pacific are lower than their normals). After 1990, the values repeatedly varied from positive to negative with a period of several years with no distinct trend, while negative values have mostly been observed in recent years (Figure 2.5-6).

15 PDO index time series data are published on JMA’s website.
2.6 El Niño/La Niña\(^{16}\)

- The La Niña event that appeared in summer 2010 decayed in spring 2011.

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.

The panel on the left of 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) since 1950. In recent years, El Niño conditions were observed from summer 2009 to spring 2010, and La Niña conditions were observed from summer 2010 to spring 2011 (see Chapter 1.3).

The panel on the right of Figure 2.6-1 shows a time-series representation of Southern Oscillation Index (SOI) values, which indicate the difference between sea level pressure anomalies at Tahiti and Darwin, since 1950. SOI data highlight atmospheric changes in relation to El Niño/La Niña events, and indicate the strength of trade winds over the Equatorial Pacific. SOI values turned positive with the onset of the La Niña event in spring 2010 and have remained positive since it ended in spring 2011.

Figure 2.6-1 Time-series representations of SST deviations from the climatological mean based on a sliding 30-year period for the El Niño monitoring region (left) and SOI (right)

Thin lines indicate monthly means, and smoothed thick curves indicate the five-month running mean. Left: Red shading denotes El Niño periods, and blue shading denotes La Niña periods. Right: Red shading denotes positive periods, and blue shading denotes negative periods.

\(^{16}\) See the Glossary for terms relating to El Niño phenomena. Monthly diagnosis reports, ENSO monitoring products, ENSO indices and El Niño outlooks are published on JMA’s website.
2.7 Global upper-ocean heat content

An increase in globally integrated upper-ocean heat content was observed from 1950 to 2011 with a linear trend of $1.94 \times 10^{22}$ J/decade.

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 Fourth Assessment report (IPCC, 2007), the increase in ocean heat content accounts for more than 80% of the possible increase in heat content of the Earth system from 1961 to 2003, and two thirds of this heat is absorbed between the surface and a depth of 700 m. Oceanic warming results in sea level rise due to thermal expansion.

It is virtually certain that globally integrated upper-ocean (0 – 700 m) heat content (OHC) rose between 1950 and 2011 at a rate of $1.94 \times 10^{22}$ J/decade as a long-term trend with interannual variations (statistically significant at a confidence level of 99%) (Figure 2.7-1). Oceans exhibited marked warming from the mid-1990s to the early 2000s, and the warmest conditions on record have been maintained since then. A rise of 0.020°C/decade in the globally averaged upper-ocean (0 – 700 m) temperature accompanied the OHC increase. These long-term trends can be attributed to global warming caused by increased concentrations of anthropogenic greenhouse gases such as CO$_2$ as well as natural variability.

2.8 Sea levels around Japan

No clear long-term trend in sea levels along the Japanese coast is observed.

Unlike the global average, no clear long-term trend in sea levels along the Japanese coast since 1906 is observed, as shown in Figure 2.8-1. The maximum sea level appeared around 1950, and bidecadal variation is dominant. Sea levels around the country have shown a clear rise since 1960 when the current observation system became operational, and rose at an average rate of 1.0 mm/year from 1960 to 2011. It is virtually certain that there has been an increase (statistically significant at a confidence level of 99%).

The annual mean sea level around Japan in 2011 was 42 mm higher than the normal (i.e., the

17 The results of ocean heat content analysis are published on JMA’s website. http://www.data.kishou.go.jp/kaiyou/english/ohc/ohc_global_en.html
18 Sea level data for the area around Japan are published on JMA’s website. http://www.data.kishou.go.jp/kaiyou/english/sl_trend/sea_level_around_japan.html
19 According to the Working Group I contribution to the IPCC Fourth Assessment Report (2007), the global average sea level rose at an average rate of 1.8 [1.3 to 2.3] mm/year from 1961 to 2003. The rate was faster from 1993 to 2003 at about 3.1 [2.4 to 3.8] mm/year. (The values in square brackets show the range of uncertainty at a confidence level of 90%).
mean from 1981 to 2010). Sea levels around Japan have remained higher than the normal since the second half of the 1990s.

Figure 2.8-1  Time-series representation of annual mean sea levels (1906 – 2011) 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 in the middle here 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 in the graph are shown 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, while the solid red line represents this value for the four regions. The dashed blue line represents this value at the four stations 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 2009 is as high as 0.96. Accordingly, the extent to which changing the tide gauge stations used affects the 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 Geographical Survey Institute. Sea level data for the Tokyo station are available from 1968 onward. Sea level data for 2011 from Hakodate, Fukaura, Kashiwazaki and Tokyo were not used due to possible influences from the 2011 off the Pacific coast of Tohoku Earthquake, and data for Hachinohe are missing because the tide gauge was washed away.

2.9  Sea ice

- The sea ice extent in the Arctic Ocean shows a decreasing trend. In 2011, the annual minimum extent in the Arctic Ocean was $440 \times 10^4$ km$^2$, which was the second-lowest value behind 2007 since 1979.
- The sea ice extent in the Antarctic Ocean shows an increasing trend with large interannual variations.
- The accumulated sea ice extent (used as an index representing the potency of sea ice for the year) in the Sea of Okhotsk shows a decreasing trend of $184 \times 10^4$ km$^2$/decade.
2.9.1 Sea ice in Arctic and Antarctic areas

It is virtually certain that there has been a long-term trend of decrease in the extent of sea ice in the Arctic Ocean since 1979 (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 minimum up to 2011 was $8.6 \times 10^4$ km$^2$/year (Figure 2.9-1 (a)) and the annual minimum was $440 \times 10^4$ km$^2$, which was the second-lowest value behind 2007 since 1979. The annual mean sea ice extent in the Arctic Ocean shows a decreasing trend of $5.7 \times 10^4$ km$^2$ per year (Figure 2.9-1 (b)), and value for 2011 was $1,056 \times 10^4$ km$^2$. This was slightly less than the 2007 figure of $1,058 \times 10^4$ km$^2$, which is the lowest on record.

Meanwhile, it is virtually certain that there has been an increase of $2.5 \times 10^4$ km$^2$/year in the annual mean sea ice extent in the Antarctic Ocean (statistically significant at a confidence level of 99%) (Figure 2.9-1 (c)). The minimum sea ice extent in 2011 was $248 \times 10^4$ km$^2$, which is the lowest on record.

![Figure 2.9-1 Time-series representations of minimum and annual mean sea ice extents in the Arctic Ocean (including the Sea of Okhotsk and the Bering Sea) and annual mean sea ice extents in the Antarctic Ocean from 1979 to 2011.](image)

The solid blue lines indicate the sea ice extent (from top left: (a) minimum sea ice extent in the Arctic Ocean, (b) annual mean sea ice extent in the Arctic Ocean, and (c) annual mean sea ice extent in the Antarctic Ocean). The dashed lines indicate the linear trend of each. The sea ice extents are calculated from the brightness temperature data set (prompt report after October 1, 2011) provided by NSIDC (the National Snow and Ice Data Center).
2.9.2 Sea ice in the Sea of Okhotsk

The accumulated\(^{20}\) and maximum\(^{21}\) sea ice extents in the Sea of Okhotsk show large interannual variations. However, it is virtually certain that they exhibited a modest trend of decrease for the period from 1971 to 2011 (statistically significant at a confidence level of 99\%) (Figure 2.9-2). The accumulated sea ice extent (used as an index showing the potency of sea ice for the year) has decreased by \(184 \times 10^4 \text{ km}^2/\text{decade}\), and the maximum extent has decreased by \(6.0 \times 10^4 \text{ km}^2/\text{decade}\) (corresponding to 3.8\% of the Sea of Okhotsk’s total area).

![Figure 2.9-2 Time-series representations of maximum sea ice extent (red) and accumulated sea ice extent (green) for the Sea of Okhotsk from 1971 to 2011. Straight lines indicate the linear trend of each.](image)

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, November and December.
- In spring 2011 (March – May), there were more days of snow cover than normal in North America throughout the season.

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 exerting related

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\(^{20}\) The accumulated sea ice extent is the total extent based on each five-day period from December 5 to May 31. It is used as an index showing the potency of sea ice for the year.

\(^{21}\) The maximum sea ice extent is the largest area of sea ice coverage based on each five-day period throughout the year.
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The accumulated and maximum sea ice extents in the Sea of Okhotsk show large interannual variations. However, it is virtually certain that they exhibited a modest trend of decrease for the period from 1971 to 2011 (statistically significant at a confidence level of 99%) (Figure 2.9-2). The accumulated sea ice extent (used as an index showing the potency of sea ice for the year) has decreased by 184 × 10^4 km^2/decade, and the maximum extent has decreased by 6.0 × 10^4 km^2/decade (corresponding to 3.8% of the Sea of Okhotsk’s total area).

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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 exerting 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 24-year period from 1988 to 2011 for May, November and December, while no trend is seen for the period from January to April (Figure 2.10-1). In winter 2010/2011 (December – February), there were more days of snow cover than normal in the USA and eastern Europe throughout the season. In spring 2011 (March – May), there were more days of snow cover than normal in North America throughout the season. In November 2011, there were more days of snow cover than normal around western Siberia and Central Asia (Figure 2.10-1).

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 2011 for May and November (left), and anomalies in the number of days with snow cover for May 2011 and November 2011 (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 (SSM/I) 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 (CO₂) has shown a long-term increase in the atmosphere and oceans.
- The global mean atmospheric concentration of methane (CH₄) has shown a long-term increase with a plateau period from 1999 to 2006.
- The concentration of nitrous oxide (N₂O) 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 and analyze such data in the WDCGG for worldwide distribution. Analysis of data reported to the WDCGG until 2011 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). In 2010, the Agency enhanced its oceanic and atmospheric CO₂ observation activities by introducing high-precision monitoring in the western North Pacific using research vessels. In February 2011, JMA also started regular aircraft-based monitoring of middle-tropospheric greenhouse gas concentrations over the western North Pacific (Figure 3.1-1).

Table 3.1-1 Global mean concentrations of greenhouse gases (2010) (based on WMO (2011a) and IPCC (2007))

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Atmospheric concentration</th>
<th>Increase from previous year</th>
<th>Lifetime (in years)</th>
</tr>
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<tbody>
<tr>
<td>Carbon dioxide</td>
<td>About 280 ppm</td>
<td>389.0 ppm (+39%)</td>
<td>+2.3 ppm</td>
</tr>
<tr>
<td>Methane</td>
<td>About 715 ppb</td>
<td>1,808 ppb (+153%)</td>
<td>+5 ppb</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>About 270 ppb</td>
<td>323.2 ppb (+20%)</td>
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Information on greenhouse gas monitoring is published on JMA’s website.
http://ds.data.jma.go.jp/ghg/info_ghg_e.html (Atmospheric greenhouse gases)
http://www.data.kishou.go.jp/kaiyou/english/oceanic_carbon_cycle_index.html (Oceanic greenhouse gases)

WDCGG website
http://ds.data.jma.go.jp/gmd/wdcgg/wdcgg.html
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- The concentration of nitrous oxide (N$_2$O) has shown a long-term increase in the global atmosphere.

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</table>

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). The peaks of concentration are in the mid and high latitudes of the Northern Hemisphere, and decline southward. This latitudinal distribution of CO$_2$ concentrations is ascribed to the presence of major CO$_2$ sources in the Northern Hemisphere (Figure 3.1-3). 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). Global concentrations of CO$_2$ in 2010 increased by 2.3 ppm from the previous year (Table 3.1-1). Over the last 10 years, the average annual growth rate has been 2.0 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 the seasonal cycles at Ryori is larger than those at Minamitorishima and Yonagunijima because its latitude is the highest of the three stations (Figure 3.1-1) and the amplitude of biospheric activity there is the most significant. 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 2011 were 394.3 ppm at Ryori$^{24}$, 392.8 ppm at Minamitorishima and 394.4 ppm at Yonagunijima, representing an increase on the previous year, and were the highest on record (values are 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 et al., 1998). A recent increase in CO$_2$ concentrations has been observed following the El Niño event seen from 2009 to 2010 (Figure 3.1-4 (b)). A similar increase is observed with global averaged data.

(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). In this region, the oceanic concentration is lower than the atmospheric concentration, suggesting that the ocean acts as a CO$_2$ sink in winter. The mean growth rates of atmospheric and oceanic CO$_2$ concentrations from 1984 to 2011 were 1.8 and 1.6 ppm/year, respectively (both statistically significant at a confidence level of 99%).

$^{24}$As data for April 2011 at Ryori are missing due to damage caused by the Great East Japan Earthquake, the annual mean concentration for the year at this station was calculated using data from only 11 months.
Atmospheric CO₂ concentrations at domestic stations also show a continuous increase with seasonal cycles affected by biospheric activity (Figure 3.1-4 (a)). The amplitude of the seasonal cycles at Ryori is larger than those at Minamitorishima and Yonagunijima because its latitude is the highest of the three stations (Figure 3.1-1) and the amplitude of biospheric activity there is the most significant. CO₂ 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 CO₂ concentrations in 2011 were 394.3 ppm at Ryori, 392.8 ppm at Minamitorishima and 394.4 ppm at Yonagunijima, representing an increase on the previous year, and were the highest on record (values are preliminary estimations).

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

It is known from observation data analysis that CO₂ concentrations in surface seawater are related to sea surface temperature, salinity and other parameters. We estimated CO₂ exchange in the Pacific using these relationships. The ocean releases CO₂ into the atmosphere in equatorial regions and absorbs it in other regions. The estimated mean annual CO₂ uptake in the Pacific was 0.71 GtC/year for the period from 1985 to 2010, accounting for about 30% of the 2.2 GtC/year total for the global ocean (IPCC, 2007). The estimated annual CO₂ uptake in the Pacific shows variability on interannual and decadal time scales, and follows no discernible trend for this period.

Figure 3.1-5 Annual changes in oceanic (blue squares) and atmospheric (red circles) CO₂ concentrations averaged between 7°N and 33°N along 137°E meridian (the red line in the panel on the right) for winter (January – February) from 1984 to 2011.

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Figure 3.1-6 Distribution of CO₂ exchange in the Pacific for 2010 (left) and time-series representations of monthly (upper right) and annual (lower right) net CO₂ exchange from 1985 to 2010.

Positive values indicate a release of CO₂ from the ocean into the atmosphere, and negative values indicate an uptake of atmospheric CO₂ by the ocean. The gray area on the map to the left shows the border of the region analyzed. The dotted line in the graph on the lower right shows the −0.71 GtC average for the period from 1985 to 2010.
The column inventory of oceanic CO₂ was estimated using ocean column observation data for the period from 1994 to 2011 along the 137°E meridian, with results showing that oceanic CO₂ has increased at levels shallower than 500 m. The column inventory averaged from 10°N to 30°N is approximately 100 tC/km², which is a third of the 300 tC/km² value for anthropogenic CO₂ between pre-industrial times and 1994 in the western North Pacific (Sabine et al., 2004).

Figure 3.1-7 Change in oceanic CO₂ from 1994 to 2011 along the 137°E meridian.
Changes in oceanic CO₂ from 1994 to 2011 (left) and a map of the 137°E line analyzed (right).

(4) Upper-troposphere monitoring of carbon dioxide
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 Observational Network for Trace Gases by Airliner (CONTRAIL) project (Machida et al., 2008). The signature seasonal cycle is observed in the upper troposphere to reflect the surface seasonal cycle (Figure 3.1-8). The amplitude of seasonal cycles in 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 (Matsueda et al., 2008).

Figure 3.1-8 Time-series representations of CO₂ concentrations in upper troposphere from April 1993 to March 2009.
The data used in this analysis were collected from commercial flights between Japan and Australia under the CONTRAIL project supported by Japan’s Ministry of the Environment, Japan Airlines and the JAL Foundation. 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 method of calculating deseasonalized trends is described in WMO (2009).

3.1.2 Global and domestic atmospheric methane concentrations
(1) Global atmospheric methane concentration
The surface air concentration of CH₄ has shown an increasing trend since global instrumental
measurement began, with a stationary phase from 1999 to 2006 (see the red line in Figure 3.1-9). WDCGG global analysis indicates that atmospheric CH$_4$ concentration in 2009 was 1,806 ppb, which is the highest on record since 1984 (Table 3.1-1).

(2) Methane concentration in Japan

Figure 3.1-11 (a) shows that atmospheric CH$_4$ concentration in Japan has increased with seasonal variations very similar to those seen worldwide, characterized by a reduction in summer and an increase in winter. Values for Ryori are higher than those for the other two stations because of its more northerly latitude. From autumn to spring, CH$_4$ concentration is higher at Yonagunijima than at Minamitorishima despite their similar latitudes. This reflects the influence of anthropogenic emissions from the heavily populated Asian continent near Yonagunijima. Annual mean CH$_4$ concentrations in 2011 were 1,884 ppb at Ryori, 1,838 ppb at Minamitorishima and 1,861 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 3.1-11 (b)).
3.1.3 Atmospheric nitrous oxide concentration

Concentration of atmospheric N\textsubscript{2}O shows an increase on a global scale. WDCGG analysis indicates that the global mean concentration in 2010 was 323.2 ppb, which is 20% higher than the 270 ppb value estimated for the period before the 18th century (Table 3.1-1).

Figure 3.1-12 shows a time-series representation of monthly mean N\textsubscript{2}O concentrations in the atmosphere as observed at Ryori. No seasonal variability is seen, and the plot shows a continuous increasing trend. The annual mean N\textsubscript{2}O concentration was 325.1\textsuperscript{24} ppb in 2011 (preliminary estimation).

3.2 Monitoring of the ozone layer and ultraviolet radiation

- Global atmospheric concentrations of chlorofluorocarbons (CFCs) have gradually decreased in recent years.
- Global-averaged total ozone amount decreased significantly in the 1980s and the early 1990s, and remains low today.
- 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.
- It is extremely likely that increasing trends in annual cumulative daily erythemal UV radiation have occurred at Sapporo and Tsukuba since the early 1990s.

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 the surface concentration of CFCs at Ryori.

### 3.2.1 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 less than a millionth of CO$_2$ levels, they contribute considerably to global warming because of their significant radiative effects per unit mass, 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 in the 1980s. However, since the 1990s, falling rates of increase or a decreasing tendency have been dominant (Figure 3.2-1) due to the effects of the Montreal Protocol. Maximum concentrations of CFC-11 were observed from 1992 to 1994, and have shown a decreasing tendency since then. Concentrations of CFC-12 increased until around 2005, and have also shown a decreasing tendency since then. The trend for CFC-113 concentrations and related variations are almost the same as those of CFC-11, peaking around 1993 – 1994 in the Northern Hemisphere and around 1997 in the Southern Hemisphere. Differences in the mole fractions 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 3.2-1](image)

**Figure 3.2-1** Time series of the monthly mean concentrations of CFCs CFC-11 (left), CFC-12 (middle) and CFC-113 (right). These figures were produced using data archived in the WDCGG.

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 3.2-2). The concentration of CFC-11 peaked at about 270 ppt in 1993 – 1994, and has decreased since then. The CFC-12 concentration increased until 1995 and continued to rise slowly until 2005, but has shown a gradual decrease since then. The concentration of CFC-113 had stopped increasing by 2001 and decreased slowly thereafter.

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25 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.
Figure 3.2-2 Time-series representations of monthly mean concentrations of atmospheric CFC-11 (top left), CFC-12 (bottom left) and CFC-113 (top right) at Ryori.

The replacement of the observation system in September 2003 improved monitoring precision and reduced the scale of fluctuations in observed values.

3.2.2 Ozone layer

(1) Global ozone layer

The globally averaged total ozone amount decreased considerably in the 1980s and the early 1990s. Although no change or a slightly increasing trend is found after the mid-1990s, total ozone in the 2000s remains low compared to that before the 1980s. The results of ground-based observation indicate that global-mean total ozone in 2011 was 2.1% lower than that for 1979 (which is regarded as a representative year for the pre-1980 period). As shown in Figure 3.2-1, no change or a slight decrease in globally averaged concentrations of ODSs such as CFCs is observed after the mid-1990s. These results may explain why no reduction in total ozone is seen after the mid-1990s.

Figure 3.2-3 Time-series representation of global-averaged total ozone deviations (in %)

The green line represents deviations of monthly-mean global-area-weighted total ozone from the 1970–1980 mean, the red line represents equivalent effective stratospheric chlorine (EESC\textsuperscript{26}) fitting, 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. In addition, the influences of solar 11-year cycles and quasi-biennial oscillation\textsuperscript{27} are removed from each data set. A total of 63 ground-based stations are used for this calculation (54 in the Northern Hemisphere and 9 in the Southern Hemisphere).

(2) Ozone layer over Japan

Figure 3.2-4 shows time-series representations of annual-mean total ozone observed at Sapporo,

\textsuperscript{26} Equivalent effective stratospheric chlorine (EESC) is designed as one measure of the potential for ozone depletion in the stratosphere that can calculated from atmospheric surface abundances of ODSs and natural chlorine and bromine gases (Newman et al., 2007). This approach was adopted in Scientific Assessment of Ozone Depletion: 2010 (WMO, 2011b).

\textsuperscript{27} Quasi-biennial oscillation (QBO) is a quasi-periodic oscillation of equatorial zonal winds between easterlies and westerlies in the tropical stratosphere with a mean period of 28 to 29 months.
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.

(3) 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 3.2-5). The annual maximum for 2011 (Figure 3.2-6) is similar to the average for the 2000s. 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 ODS in the stratosphere. Although ODS amounts over the Antarctic peaked in the mid 1990s, the ozone layer remains vulnerable because an abundance of these substances is still present in the stratosphere.

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See the Glossary reference for “Ozone hole.”
3.2.3 Solar UV radiation in Japan

Annual cumulative values of daily erythemal UV radiation\(^{29}\) at Sapporo and Tsukuba show an increase (statistically significant at a confidence level of 95\%) for the whole of the observational period (Figure 3.2-7) at rates of 4.4 and 4.6\%/decade, respectively. At Naha, some increase in annual cumulative UV radiation is seen in the 1990s, but no increasing trend is observed after the 2000s. Because Figure 3.2-4 indicates that total ozone showed a small trend of increase after the mid-1990s, the increasing trends of erythemal UV radiation observed at Sapporo and Tsukuba as shown in Figure 3.2-7 cannot be explained solely by ozone depletion. The 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 (WMO, 2011b; JMA, 2011).

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\(^{29}\) See the Glossary reference for “Erythemal UV radiation.”
3.3 Monitoring of aerosols and surface radiation

- In Japan, the atmospheric turbidity coefficient (which depends on amounts of aerosols, water vapor and other constituents in the air) has returned to approximately the level 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.
- Interannual variability is predominant both in terms of the number of days on which Kosa is observed and the annual total number of stations reporting the occurrence of the phenomenon, and no particular long-term trend is evident.

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 – 1985 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.

Analysis of aerosol optical depth (AOD) and aerosol particle size distribution from sunphotometer measurements also reveals long-term aerosol variations (Figure 3.3-2). In Japan, AOD values show seasonal variations reaching a maximum in spring. The maximum values recorded in spring may be attributable to Kosa (Aeolian dust) and air pollutants transported from the Asian continent.

![Figure 3.3-1](image)

**Figure 3.3-1** Time-series representation of annual mean atmospheric turbidity coefficients (1960 – 2011)

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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30 See the Glossary reference for "Aerosols."


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

32 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.

33 The aerosol optical depth (AOD) indicates attenuation of solar irradiance due to absorption and scattering by aerosol particles. The value is larger when the atmosphere contains more aerosols.
Minamitorishima shows lower AOD values than the other two stations throughout the year due to its remoteness from the Asian continent, which is a major source of aerosols originating from land areas. The difference in AOD values between 500 nm and 862 nm is smaller at Minamitorishima than at Ryori and Yonagunijima, suggesting that relatively large amounts of sea salt aerosols are more dominant at Minamitorishima than at the other two stations.

Figure 3.3-2 Time-series representations of monthly mean AOD values at 500 nm and 862 nm observed at Ryori (top), Minamitorishima (middle) and Yonagunijima (bottom) from 1998 to 2010

JMA monitors AOD, which shows the total amount of aerosols between the surface and the top of the atmosphere, and particle size distribution with different wavelengths of sunlight at three stations in Japan (Ryori, Minamitorishima and Yonagunijima) using sunphotometers. The values here were calculated from thrice-daily observations conducted until March 2007 and from continuous observation thereafter. The high AOD values for May of 2003 and spring of 2006 are attributed to smoke from forest fires in Siberia and large-scale Kosa events, respectively.
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In recent years, the monitoring of black carbon aerosols released from biofuels such as coal, diesel and firewood has taken on increased importance because these aerosols accelerate global warming by absorbing solar radiation and emitting infrared radiation into the atmosphere.

In 2010, JMA began monitoring diffuse solar radiation\(^{34}\) in addition to its existing direct solar radiation measurements. An optical property of airborne aerosols known as the single scattering albedo (SSA)\(^{35}\) can be analyzed from direct and diffuse solar radiation data and radiative transfer calculations made using a numerical model. SSA can be used to monitor long-term variations in black carbon presence in the atmosphere because its value decreases when the ratio of black carbon aerosols to all aerosols in the atmosphere increases.

Figure 3.3-3 shows a time-series representation of annual mean aerosol optical depth (AOD) and SSA data collected at the Aerological Observatory in Tsukuba. The results indicate increased SSA values and reduced AOD values after 1990. The reduction of black carbon emissions into the atmosphere can be attributed to tighter environmental regulations (Kudo et al., 2010).

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34 Diffuse solar radiation is the incident solar energy acting on the earth’s surface from all directions in the sky except that of the sun, and is scattered by the atmosphere and clouds. Data on this type of radiation help to clarify amounts of aerosols in the atmosphere because the value increases with greater aerosol concentration.

35 The single scattering albedo is defined as the ratio of the scattering coefficient divided by the extinction coefficient, and has values ranging from 0 to 1. When it is closer to 0, more sunlight is absorbed by particles; when it is closer to 1, more sunlight is scattered.
Aerosol observation using lidar

JMA began monitoring vertical profiles of aerosol concentration using lidar (laser radar) in Ryori in March 2002.

These lidar observations confirmed that aerosol concentrations are usually higher in the troposphere than in the stratosphere over Ryori. It was also found that the concentration increases in spring and decreases in both autumn and winter. In addition, the results highlighted an increase in tropospheric aerosol concentrations attributable to forest fires in Siberia in 2003, and also revealed increased atmospheric concentrations related to the eruption of Mt. Sarychev in 2009. From May 22 to 24, 2003, dense smoke aerosols generated by large forest fires in Siberia moved over to northern Japan, reducing the number of hours of sunshine even when the sky was almost cloudless.

Recently, a space-based lidar sensor was developed and mounted on a satellite, providing data that elucidate vertical profiles of aerosol concentration globally. Based on this development, lidar observation at Ryori was discontinued on 31 December, 2011, and JMA now monitors vertical profiles of global aerosol concentration using satellite lidar data.

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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 61 JMA meteorological stations (as of 1 April, 2012) 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 14 in 2011 (Figure 3.3-5), and the number of stations reporting its occurrence during the year was 220 (Figure 3.3-6).

Although interannual variability in both the number of days on which Kosa is observed and the annual total number of stations reporting the occurrence of the phenomenon is predominant and no particular long-term trend is seen, the numbers have often exceeded 30 and 300, respectively, since 2000, and Kosa seems to have been observed more frequently in recent years.
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The scattering ratio represents aerosol concentration, and is derived from the observed intensity of aerosol backscatter. Higher scattering ratios denote the higher aerosol concentrations.

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3.3.3 Solar radiation and downward infrared radiation

The earth’s radiation budget is a source of energy for climate change, and monitoring of its variations is important. To this end, JMA conducts measurements of direct solar radiation, diffuse solar radiation and downward infrared radiation\(^{36}\) at five stations in Japan (Sapporo, Tsukuba, Fukuoka, Ishigakijima and Minamitorishima).

(1) Global solar radiation

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

In Japan, solar radiation declined rapidly from the late 1970s to 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 3.3-7).

\[^{36}\text{Downward infrared radiation is the incident infrared radiation acting on the earth’s surface from all directions in the sky. It is emitted from clouds and atmospheric constituents such as water vapor and carbon dioxide in line with the fourth power of their temperature, and can be used as an index of global warming.}\]
(2) Downward infrared radiation

Measurements of downward infrared radiation have been conducted since the early 1990s at Tsukuba. A time-series representation of five-year running mean downward infrared radiation until 2010 shows an increasing trend at a rate of about 0.4 W/m² per year (Figure 3.3-8). This is consistent with the trend seen in the results of analysis using data from all BSRN stations worldwide (+0.3 W/m² per year) (WCRP, 2010).

![Figure 3.3-8 Time-series representations of annual and five-year-running means of downward infrared radiation at Tsukuba](image)

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37 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).
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>
</thead>
<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 come with inherent probabilities of up to 10, 5 and 1%, respectively, of the observed long-term change being produced 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.
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**Glossary**

**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.

**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.

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

El Niño/La Niña phenomena: An El Niño event is a phenomenon in which sea surface temperatures (SSTs) are higher than normal across a wide region from the center of the equatorial Pacific to the area off the coast of Peru for a period from half a year to one and a half years. In contrast, a La Niña event is a phenomenon in which 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 (5ºN – 5ºS, 150ºW – 90ºW; 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.

![Figure A](image)
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 main factor determining the strength of such winds is the sea level pressure difference between eastern and western parts of the Pacific. This 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.

Aerosol

Aerosols are airborne solids or liquids in fine particle form. Their many types include particles of natural origin blown up from land/sea surfaces and anthropogenic particles emitted from industrial smoke and the like. In addition to absorbing and scattering sunlight, they also provide condensation nuclei for clouds.

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. 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. The hole has steadily grown in size and annual length of presence (from August to December) over 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 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 degrees Celsius without this effect; with it, the actual value is calculated as 14 degrees Celsius. 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 late 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. Among these activities, the combustion of fossil fuels accounts for about three quarters of all anthropogenic CO₂ emissions (IPCC, 2007).

Methane: Methane (CH₄) is the second most significant greenhouse gas after CO₂, and is emitted into the atmosphere from various sources including wetlands, rice paddy fields, ruminant animals, natural gas production and biomass combustion. It is primarily removed from the atmosphere via photochemical reaction with reactive and unstable hydroxyl (OH) radicals.

Nitrous oxide: Nitrous oxide (N₂O) is a significant greenhouse gas because of its large radiative effect per unit mass (about 300 times greater than that of CO₂) and its long lifetime (about 114 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.

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.

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.

**Normals**

The Japan Meteorological Agency (JMA) calculates climate normals for its meteorological stations using data collected over consecutive periods of 30 years based on World Meteorological Organization (WMO) Technical Regulations. The Agency updates these normals every decade in consideration of climate change, addition/closure of stations and other relevant factors.

**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.

**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.
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Map 3  Distribution of surface meteorological observation stations in Japan
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