Guidelines on the Definition and Characterization of Extreme Weather and Climate Events

2023 edition

WEATHER CLIMATE WATER

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PREFACE

The climate is how the atmosphere behaves over a long period of time (typically defined as at least a 30-year period). Descriptions of the climate inform us about the average weather, as well as other aspects of weather patterns and distribution of meteorological parameters – including anomalous, rare and extreme events.

WMO plays a critical role in understanding and monitoring climate variability and change and related extreme events. It is therefore crucial for the Commission for Weather, Climate, Water and Related Environmental Services and Applications (SERCOM) to continuously assist WMO Members by providing guidance on various aspects of extreme events, so that efficient monitoring, forecasting and early warning systems are adequately deployed. This constitutes part of the WMO contribution to building resilient societies able to cope with climate variability and adapt to climate change.

The guidance provided in the present document focuses on generic definitions and methodologies for the characterization of extreme weather and climate events. This guidance has become timely for ensuring consistent exchange of information that underpins the contents of the WMO State of the Climate reports, climate watches, climate change studies and other emerging applications.

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PURPOSE OF THE GUIDELINES

Monitoring and warning of extreme weather and climate events is one of the highest priorities of WMO and its Members. At the national level, National Meteorological and Hydrological Services (NMHSs) design and operate monitoring systems for extreme events, based on local conditions and sectoral applications. The varying needs and the heterogeneous climate from country to country means that the design of these systems, and the underlying definitions and thresholds of events, differ significantly.

At the regional scale, Regional Climate Centres also have a mandate to monitor climate conditions and to issue advisories, such as climate watches, about extreme weather and climate events at timescales beyond weather forecasting. It is therefore very important to use a consistent approach including common generic definitions and characterization of these events.

The purpose of the present guidelines is not to change the practice at the national level. Instead, it provides guidance for generic definitions, which are useful in contributing to WMO State of the Climate reports, climate watches, climate change studies and other emerging applications, including the recently adopted methodology for cataloguing hazardous events (WMO-CHE) (see *World Meteorological Congress: Abridged Final Report of the Eighteenth Session* (WMO-No. 1236), Resolution 12 (Cg-18) – WMO Methodology for Cataloguing Hazardous Weather, Climate, Water and Space Events). These applications require regional and/or international exchange of information on extreme events.

The focus of the present guidelines is on extreme events related to temperature and precipitation, for several reasons:

- They form some of the most challenging events for operational monitoring at the global scale, in all regions. This is due to the varying contexts and needs, making the characterization of these event dependent on local conditions. Many of these extreme events refer to heat and cold waves, heavy precipitation with flooding, and drought.

- Other events such as tropical storms and cyclones already have well-established common definitions, characterization and infrastructure to monitor them at regional scales. It should be highlighted that wider observation and data collection would be required to define other types of weather/climate events, such as hail, lightning, sandstorms and others.

- As temperature and precipitation are the best-observed elements historically in most countries, extreme events related to temperature and precipitation benefit from the best available current and historical data, which allows use of robust statistical methodologies for characterizing these events in a consistent manner.

- Extremes in temperature and precipitation occur in most regions and countries, and as such, monitoring them is of use across all WMO regional centres. Members that have the data and capability to monitor other extremes may still wish to use the concepts and structure promoted in the present guidelines for those extremes.

INTRODUCTION

Examples of extreme weather and climate events include, but are not limited to, heatwaves, cold waves, floods, extreme precipitation, drought, tornadoes and tropical cyclones. Human-induced climate change beyond natural climate variability, including more frequent and intense extreme events, has caused widespread adverse impacts and related losses and damages to nature and people (IPCC, 2022).

It is essential for meteorological communities to improve the understanding and characterization of extreme weather and climate events in time and space with regionally and globally consistent methodologies. Such improvement is based upon their definition and the computation of their thresholds, so that efficient systems for monitoring or even forecasting these events can be deployed as part of building resilient societies able to cope with climate variability and to adapt to climate change. In line with such a concept, the United Nations Office for Disaster Risk Reduction (UNDRR) and International Science Council (ISC) have published the report entitled *Hazard Definition and Classification Review – Technical Report* (UNDRR/ISC, 2020), and its supplement *Hazard Information Profiles* (UNDRR/ISC, 2021). Although the report and its supplement cover wider areas beyond the meteorological and climatological areas, they are useful for risk reduction and resilience-building against the increasingly interconnected, cascading and complex nature of natural and human-induced hazards.

Since climate varies regionally, the definition of an extreme weather or climate event and its threshold will differ from location to location. The definition is also dependent on the infrastructure of individual countries and, in most countries, on the seasonal cycle. In other words, an extreme value of a particular climate element in one location may be within the normal range in a different location. For example, hundreds of people died in northern India due to the shortage of shelters during a cold wave in the northern hemisphere winter of 2011/2012 (WCDMP-No. 80), with temperatures which are considered "normal" spring or autumn conditions in northern Europe. There are also practical reasons, in addition to natural and geographic reasons, for the varying definitions, such as a particular societal sector requiring specific thresholds to take action. This is the case, for example, in defining heatwaves in a heat–health warning system, for which a heatwave is defined specifically according to the potential impacts on human health.

To provide consistent and authoritative guidance to Members on best practices in the domain of weather and climate extremes, the former WMO Commission for Climatology (CCl) Task Team on the Definition of Extreme Weather and Climate Events (TT-DEWCE) reviewed the existing literature on the subject. Initial draft guidelines were produced by the team, providing an approach for defining, characterizing and reporting data on extreme events. In 2019, this work was taken on board by the new Commission for Weather, Climate, Water and Related Environmental Services and Applications (SERCOM), which took over duties undertaken by the CCl, among others.

WMO has adopted Resolution 12 (Cg-18) – WMO Methodology for Cataloguing Hazardous Weather, Climate, Water and Space Weather Events, which is referred to, for simplicity, as the WMO Cataloguing Hazardous Events (WMO-CHE) (*World Meteorological Congress: Abridged Final Report of the Eighteenth Session* (WMO-No. 1236)).

The methodology provides an approach for cataloguing hazardous events using attributes such as Event identifier, Originator, Event start, Event end and Event type. Other attributes provide additional information such as Hazard specification and Description of event. The current guidelines build on the work started by the WMO TT-DEWCE and consider new developments and emerging needs.

The guidelines also provide a template in Annex 2 for providing data required for monitoring extreme events, such as for use in the WMO State of the Climate reports, at both global and regional levels. It is expected that adherence to these guidelines will facilitate attribution of extreme weather and climate events and verification of forecasting and prediction systems.

DEFINITION AND CHARACTERIZATION OF EXTREME EVENTS ASSOCIATED WITH TEMPERATURE AND PRECIPITATION

The former WMO Commission for Climatology Task Team on the Definition of Extreme Weather and Climate Events (TT-DEWCE) issued a survey to WMO Members on existing practices for the definition of heatwave, cold wave, drought and extreme precipitation (hereafter, the WMO Members survey on extreme events). From the results of the survey (see Annex 1), the Task Team concluded that a single standard definition for an extreme event may not be useful for all purposes, and that NMHSs might use different definitions depending on the purpose served at the national level; in some cases, the definition might also vary at sub-national scales for large national territories.

As a general principle, the monitoring of an extreme event should consider the intensity and the temporal and spatial characteristics of the event. Its definition should be impact-independent, with the aim of developing a system that can report consistently on the nature, occurrence and evolution of the event. As a general guidance for characterizing an extreme event, the following properties can be used:

Magnitude. This measures the departure from a baseline or a predefined threshold. It reflects the extremity of the event. The baselines and thresholds should be defined by NMHSs at the national and sub-national scale, according to the local climate conditions and applications. The baselines and thresholds should be maintained in an official database and available for consultation by users.

Duration. At an individual location, the duration is defined as the difference between the time at which the event began (meaning when the threshold is exceeded for the first time) and the time it ended. The overall duration of the event at a wider scale including several locations is defined as the difference between the time at which the event began at a station where it was first recorded and the time it ended at the station where it was last recorded.

Extent. This is defined as the geographical area where stations recorded the event from the start to the end. It can be in the form of a percentage of the number of stations where the event was recorded relative to the whole observing network. However, this method can be considered a reasonable estimate only if the station density is well-distributed in the country or territory. If this is not the case, and the density is poorly distributed, the computation should make use of a suitable gridding method.

Examples of the characterization of extreme events using these properties are provided in Annex 2.

Members may wish to consider using indices in their assessment of extreme events. A set of standard indices for monitoring extreme climate and weather events at the station level has been defined by the former Expert Team on Climate Change Detection and Indices (ETCCDI), and can be used where appropriate. Further details on the use of the ETCCDI indices are available in the *Guidelines on Analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation* (WMO/TD-No. 1500). The definition of the indices, and the software to use in their calculation, can be found, for instance, online (https://etccdi.pacificclimate.org/) as well as via Climpact (https://climpact-sci.org/), which is software developed by WMO experts and which calculates climate indices for use by stakeholders in various socioeconomic sectors.

It is also useful to report information such as the impact associated with the occurrence of an extreme event. In addition to the socioeconomic dimension of extreme events, the collection of impact information in a systematic manner provides crucial data for several applications, such as in impact-based forecasting systems, vulnerability assessment and adaptation strategies, and many others. Therefore, although impact information is not included in the definition of extreme events, it should be part of any extreme event monitoring, to the extent that the information is available.

Temperature

Heatwave

Definition

A heatwave is a pervasive meteorological phenomenon resulting in an increase in many risks, such as health-related or economic risks, including increased human mortality, agricultural losses, wildfires and power shortages, among others. NMHSs are mandated to provide heatwave advisories to help decision makers to minimize these risks and potential damages. Currently, there is no universally accepted definition of heatwave. However, many Members have adopted local criteria for issuing heatwave advisories.

According to the *International Meteorological Vocabulary* (WMO-No. 182), a heatwave is: "Marked warming of the air, or the invasion of very warm air, over a large area; it usually lasts from a few days to a few weeks". The publication *Heatwaves and Health: Guidance on Warning-System Development* (WMO-No. 1142) developed jointly by WMO and the World Health Organization (WHO) provides practical guidance for addressing human health impacts and warnings associated with heatwaves. In the Intergovernmental Panel on Climate Change glossary (IPCC, 2021a), a heatwave is "a period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months".

Even though the WMO and IPCC definitions broadly describe the event, the definitions are not sufficient in guiding NMHSs to develop practical methodologies and tools for a heatwave monitoring system that would allow comparisons across borders. Based on the above literature, the TT-DEWCE recognized that for international exchange of information on heatwaves, it is particularly useful to adopt a simple approach allowing consistent analysis of heatwave information at regional and global levels.

Therefore, a heatwave can be defined as a period of marked and unusually hot weather persisting for at least two consecutive days.

A warm spell, in contrast, refers to a persistent period of abnormally warm weather for the time of year. A warm spell can occur at any time of the year, whereas a heatwave is defined with respect to the highest values observed during the year and is therefore most likely to occur during the warm season in most climates.

Characterization

It is recommended that indices, based on local climatological conditions, be used to objectively characterize a heatwave. The indices can be based simply on one meteorological element (such as minimum temperature (Tmin) or maximum temperature (Tmax)) or computed using a combination of multiple variables such as temperature, humidity and even wind speed. Thresholds can also be defined, departure from which can reflect the abnormally hot conditions and extremity of the event. Examples of metrics and additional information are available in the WMO/WHO joint guidance (*Heatwaves and Health: Guidance on Warning-System Development* (WMO-No. 1142)) and on the Global Heat Health Information Network (GHHIN) website (https://ghhin.org), maintained by the WHO/WMO Joint Office for Climate and Health.

Cold wave

Definition

A cold wave is a meteorological event generally characterized by a sharp drop in air temperature near the Earth's surface, leading to extremely low values that can be associated with hazardous weather, such as frost and icing. A cold wave often causes severe impacts on human health and agriculture, leads to high heating costs, and can even result in mortality for human beings and livestock. IPCC (2007) noted that cold waves continue to be a problem in northern latitudes, where very low temperatures can be reached in a few hours and extend over long periods. However, there is still a lack of a clear and consistent definition for cold wave events globally. Thus, after reviewing the existing definitions in publications and some countries' operational activities, the TT-DEWCE developed the following guidelines for WMO Members for defining and characterizing cold waves.

Typically, a cold wave is associated with invasion of very cold air caused by a polar or high-latitude air mass displacement to lower latitudes. In some cases it is associated with or reinforced by long-wave radiative cooling under a blocking high or other clear sky atmospheric circulation pattern.

According to the *International Meteorological Vocabulary* (WMO-No. 182), a cold wave is “a marked cooling of the air, or the invasion of very cold air, over a large area”. The National Weather Service in the United States of America defines a cold wave as “a rapid fall in temperature within 24 hours to temperatures requiring substantially increased protection to agriculture, industry, commerce and social activities” (AMS, 2022). In China a cold wave is defined as a dramatic cooling weather process, with large-scale cold air from the high latitudes invading the middle and lower latitude regions. Cold waves are also simply defined as persistent extreme low temperature events, sustaining specified temperatures below certain thresholds over a certain minimum number of days (Radinović and Ćurić, 2012; Peterson et al., 2013). The existing terminology helps provide a broad scope for understanding the subject matter of the phenomenon and its underlying physical factors.

The impacts of cold weather may vary by region or by season. As an example, a temperature below 0 °C may have little impact if it occurs in winter but could have very large impacts if it occurs at a critical stage of crop development in spring. Members should consider the impacts of events in deciding which metrics to use for monitoring cold events.

Therefore, a cold wave can be defined as marked and unusually cold weather, which can be associated with a sharp and significant drop of air temperatures near the Earth’s surface and persisting for at least two consecutive days.

A cold spell, in contrast, refers to a persistent period of abnormally cold weather. A cold spell occurs at any time of the year, whereas use of the term “cold wave” is normally reserved for events occurring during the cold season.

Characterization

It is recommended that indices based on local climatological conditions be used to objectively characterize a cold wave. Such indices can be based simply on one meteorological element (such as Tmin or Tmax) or computed using a combination of variables including temperature, wind speed, rate at which temperature has fallen in the last 24 hours, and so forth. Thresholds can also be defined, departure from which can reflect the abnormally cold conditions and extremity of the event.

Precipitation

Extreme precipitation

Definition

Extreme precipitation events often result, either directly or through associated floods, landslides and other phenomena, in fatalities, infrastructure damage and major agricultural and socioeconomic losses. The IPCC Sixth Assessment Report (IPCC, 2021b) reported that the frequency and intensity of heavy precipitation events have likely increased over a majority of land regions with good observational coverage. Heavy precipitation is also expected to become generally more intense and more frequent with additional global warming. Since precipitation patterns differ widely throughout the world, it is not possible to use a single definition of the term "extreme precipitation event" that is suitable for all regions. Extreme precipitation events are also of interest on a wide range of timescales; for example, flash flooding is often driven by rainfall at very short timescales (minutes to hours), while large rivers and reservoirs often respond to rainfall at longer timescales of the order of several days.

It is generally recognized that when a precipitation event is considered extreme, it relates to one of the following two contexts: (1) it exceeds a certain threshold, that is, a fixed threshold, that has a certain associated impact; or (2) it is considered to be extreme due to its rarity, based on either a percentile threshold or its return period. In the case of a percentile-based threshold, the rarity of occurrence tends to take the form of the upper 90th, 95th and 99th percentile of precipitation. Such percentile-based thresholds can be derived from statistical cumulative density functions generated from the observed data or some conceptual distributions for precipitation extremes (such as generalized extreme value (GEV)). When considering the most extreme precipitation events, return period information on the extremely rare events (100 years or more) is important for many engineering applications.

The definition of extreme precipitation from the WMO Members survey on extreme events reflects the key finding that the majority of NMHSs define extreme precipitation with a certain threshold on varying timescales, ranging from 1 hour to several days, taking into account seasonality. In some cases, percentile-based thresholds are also used by Members. Having considered these, the present guidelines propose using a definition of extreme precipitation event that corresponds to the need for the reporting of extreme precipitation at regional and global levels, where data are most consistently available at daily timescales.

Therefore, an extreme precipitation event can be defined as a marked and unusual precipitation event occurring during a period of hours to a longer period of several days, with total precipitation largely exceeding local average conditions of that period.

For reporting extreme precipitation events, hourly totals, daily totals, or totals over the period of the event are recommended.

Characterization

It is recommended that indices, based on local climatological conditions, be used to objectively characterize an extreme precipitation event. Thresholds can also be defined, departure from which can reflect the abnormal precipitation conditions and extremity of the precipitation event.

While fixed thresholds are more easily applicable for many purposes, percentile-based thresholds are more evenly distributed in space and are arguably more meaningful and applicable when sufficient observational data exist. Precipitation can also vary by large amounts over short distances, particularly in complex topography, so percentile-based thresholds are more likely to produce spatially coherent results than absolute thresholds do. The flexibility to define the percentile level for extreme precipitation events also allows the analysis to address very rare events, for instance, those exceeding the 99th percentile. Statistical modelling based on probability distribution of daily or multi-day rainfall could be used for assessing the return period of an extreme precipitation event, which is useful in some applications such as in water resource management and hydrology, as well as in research for assessing the change in extreme event return periods.

On the other hand, the use of percentiles can be of limited value in dry regions in particular (for example, in some arid regions, even the 99th percentile can be zero or close to zero, at least at certain times of the year).

Drought

Definition

Drought, as a natural climatological phenomenon that occurs in all climates, can differ greatly from other extreme events.

Unlike other extreme events that are immediately detectable, droughts typically develop slowly, making it difficult to determine the onset and end in real time. The impacts of drought can be devastating and costly, affecting society, agriculture, infrastructure, the economy and ecosystems. To facilitate communication, management and response, drought can be categorized into four general types: (1) meteorological; (2) agricultural; (3) hydrological; and (4) socioeconomic. Meteorological drought is driven by the atmospheric conditions resulting in the absence or reduction of precipitation over a period of time. Meteorological drought can lead to agricultural drought, identified by precipitation shortages, higher evapotranspiration and soil moisture deficits. Meteorological drought can also lead to hydrological drought, which develops from depleted surface or subsurface water supplies. Socioeconomic drought is the imbalance in supply and demand of water, or the effect of water shortages on the economy (such as crop losses) and society (such as impacts on health). These different types of droughts have one thing in common: they all begin with a deficiency of precipitation (meteorological drought).

While there are substantial regional variations, the IPCC Sixth Assessment Report (IPCC, 2021b) found increases in agricultural drought in a number of regions and decreases only in one region (northern Australia). It is expected that the land area affected by increasing drought frequency and intensity will grow with additional global warming.

Because of the complexity of drought and how it affects many aspects of life and a wide variety of sectors, it is not possible to develop a single definition of drought that can be applied in all circumstances, particularly when data required to support more complex drought indices may not be available in many countries. In order to take initial steps in defining drought for the purpose of the present document, the focus here is solely on meteorological drought and its indices.

From a meteorological perspective, drought is defined in the *International Meteorological Vocabulary* (WMO-No. 182) as a “prolonged absence or marked deficiency of precipitation”. For international exchange of information on drought, it is particularly useful to adopt a common approach that allows consistent analysis of drought at regional and global levels and that aligns with the WMO International Drought Management Programme (IDMP) and the Global Water Programme (GWP).

Therefore, according to the IDMP Glossary (https://www.droughtmanagement.info/find/glossary), a drought can be defined as a: (1) Prolonged absence or marked deficiency of precipitation. (2) Period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance.

Drought should not be confused with aridity, which is a climate characteristic relating to insufficient or inadequate precipitation to maintain vegetation, according to the *International Meteorological Vocabulary* (WMO-No. 182). In other words, drought is a temporary climate phenomenon, while aridity is a permanent climate feature in areas that typically experience low precipitation throughout the year. An example of an arid place is the Sahara, a desert region where the annual precipitation total is often below 25 mm per year. The IDMP recently published *Drought and Water Scarcity* (WMO-No. 1284), which highlights the difference between these phenomena, and the increasing difficulty of separating them, due to climate change.

Characterization

Drought can be numerically characterized using indices that rely on precipitation deficits, often integrated with temperature and other variables that affect evapotranspiration and soil moisture. Several indices in different countries assess drought using solely precipitation deficits in various ways, such as the Standardized Precipitation Index (SPI). Other indices make use of additional variables. For instance, the Palmer Drought Severity Index (developed in the 1960s and still in use today) uses precipitation, temperature and local available water content data to assess soil moisture (Palmer, 1965). From a hydrological perspective, drought is defined as "a period of abnormally dry weather sufficiently prolonged to give rise to a shortage of water as evidenced by below-normal streamflow and lake levels and/or the depletion of soil moisture and a lowering of groundwater levels" (*Technical Regulations* (WMO-No. 49), Volume III).

In December 2009, 44 drought experts from 22 countries met in Lincoln, USA, to discuss the development of standards for drought indices and guidelines for drought early warning systems. One of their recommendations was to encourage the use of the SPI to characterize meteorological droughts, and to provide this information on NMHS websites, in addition to the indices currently used. Another outcome of this meeting was the creation of a comprehensive user manual for the SPI, which provides a description of the index, the computation methods, examples of where it is currently used, its strengths and limitations, mapping capabilities, and how it can be applied. For additional information on the recommendations from the meeting, see *The Lincoln Declaration on Drought Indices: Universal Meteorological Drought Index Recommended* (Hayes et al., 2011).

The suggestion to use the SPI as a drought index is mainly due to its simplicity, as precipitation is the only variable it considers. The SPI helps quantify the precipitation deficit, since it is based on the probability of precipitation for any timescale. The probabilities are standardized, where zero represents the median precipitation amount, a negative index represents dry conditions (less than median precipitation), and a positive index represents wet conditions (greater than median precipitation).

When using the SPI, drought is considered to have started when the SPI value is ≤ -1.0 and to have ended when the SPI value becomes positive. Soil moisture conditions respond to precipitation anomalies on a relatively short timescale. Groundwater, streamflow and reservoir storage reflect the longer-term precipitation anomalies. Therefore, for example, when reporting drought for climate monitoring (monitoring meteorological drought) it may be useful to look at a 1- or 2-month SPI. For agriculture applications (monitoring agricultural drought), anywhere from a 1-month to 6-month SPI may be useful; and for hydrological analyses and applications (monitoring hydrological drought), an SPI in the range of 6 to 24 months or longer may be useful.

For more information on how to compute the SPI, see the *Standardized Precipitation Index User Guide* (WMO-No. 1090), and the *Handbook of Drought Indicators and Indices* (WMO-No. 1173).

Some modifications to the SPI have been developed in recent years to overcome some shortcomings. For WMO Regional Association (RA) VI, a modified version was published by Pietzsch and Bissolli (2011), which applies some corrections to monthly SPI especially in arid regions, where the precipitation distribution differs greatly from a normal distribution. Vicente-Serrano et al. (2009) extended the SPI concept by including evaporation (which requires additional data, especially temperature), resulting in a modified index called SPEI (Standardized Precipitation Evapotranspiration Index). This is also used operationally, for example, in the Global Precipitation Climatology Centre (GPCC) drought index (Ziese et al., 2014).

MONITORING EXTREME EVENTS

The role of National Meteorological and Hydrological Services

A consistent and systematic approach to monitoring extreme events is needed for characterization and reporting. This is particularly important when the monitoring information feeds into regional or international analysis systems. This is the case for monitoring information that supports global assessment of the climate, the WMO annual State of the Climate reports (global and regional) and any climate products on extremes that rely on input from countries and regions. The approach should enable NMHSs to identify and report extreme events routinely, albeit having different operational definitions of the extreme events for local use. Generally speaking, it is beneficial to use gridded data to compute the fundamental physical properties of extreme events, including magnitude, duration and extent. For international exchange, however, station-based data sets may be needed when there is a lack of gridded data. In such cases, the areal extent of an event could be provided in the form of a percentage of stations reporting the event out of the total observing network.

It is also important to report on the geographical location where an event has been recorded. To the extent possible, the reported location should include the geographical position of the centre of the event (such as where the maximum and minimum values were observed, or where the centre of the damage is located), the longitude and latitude of the area affected by the event, and the name of the affected city, region, district, river basin or other geographical area.

In many cases, NMHSs have additional data and information, which are not necessarily available internationally. This can include data and information from additional national station networks, but also from other sources, such as from radars or regional limited-area models with higher resolution, or impact data from local authorities or local media. Therefore, it is highly valuable and desirable that each NMHS set up a regular national extreme event monitoring system, with appropriate documentation, either in national reports or in a database.

The role of WMO Regional Climate Centres

In general, Regional Climate Centres (RCCs) are mandated to provide data, monitoring and forecasting products to enable WMO Members to provide better climate services (Bissolli et al., *WMO Bulletin, 65 (1)*; Bissolli et al., 2020).

At the regional level, RCCs also have a mandate to monitor climate anomalies and extremes occurring in their regions. The role of RCCs in monitoring extremes is critically important, as it provides the larger geographical context necessary to understand the dynamic mechanisms that trigger the extremes, such as the large-scale climate variability modes, including atmospheric and oceanic variation patterns and oscillations. RCCs therefore rely on access to as many high-quality observational data as possible, including long time series, in order to be in a position to apply region-wide approaches for identifying and mapping extremes. In this regard, calculating gridded data for anomalies on common reference time frames and percentiles allows for comparable information across the area under consideration. Such monitoring information is provided on daily up to annual timescales.

Sub-monthly to seasonal information is a critical starting point for issuing climate watch advisories. Combined with (objective) information from sub-seasonal to seasonal forecasts, areas can be identified for which extremes may be expected in a period beyond weather forecasts, typically a couple of weeks to a season ahead. The WMO *Guidelines on Climate Watches* (WMO/TD-No. 1269) are currently under review.

In addition to monitoring current climate conditions, RCCs also provide information for monitoring longer-term climate change.

Another important task of RCCs in extreme event monitoring is collecting national information from NMHSs and other available sources, and summarizing and evaluating the information in relation to large-scale, cross-border phenomena, usually in the form of RCC reports such as monthly, seasonal or annual bulletins, monthly summaries of extreme events or other specialized reports. The operation and maintenance of a regional event database is also highly desirable (see following section).

Database of extreme events

It is important that extreme events information is recorded in a consistent and systematic way so that integration of information from national databases to regional databases (and vice versa) is made with the least transformation and interface software as possible, as these could potentially lead to transmission and conversion errors.

At the NMHS level, such databases can be built as part of a single integrated and administered climate data management system (see *Climate Data Management System Specifications* (WMO-No. 1131)). This would allow optimization of IT equipment and staff resources, with the additional benefit of a single governance and system administration, which are critical for efficient upgrades, security and maintenance of the database.

In addition, there are specific needs for data collection in the context of WMO State of the Climate reports. For the purpose of the present guidelines it is desirable that databases of extreme events contain an appropriate machine readable identifier of the event (for example, Universally Unique Identifiers (UUID)), categories (for example, heatwave, flood, and so forth), start and end date, linkage to large-scale patterns (for example, high-/low-pressure systems), a short description of the event and its related impact, measurement data of the extreme values, ranking in a long-term series, affected area (at least country or subregion, county/province), and the source of information.

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ANNEX 1. RESULTS FROM THE WMO MEMBERS SURVEY ON EXTREME EVENTS

The former WMO Commission for Climatology Task Team on the Definition of Extreme Weather and Climate Events (TT-DEWCE) disseminated a survey to WMO Members, requesting information on the definitions and criteria of extreme weather and climate events that are used operationally in their National Meteorological and Hydrological Services (NMHSs). The survey mainly focused on four types of high-impact extreme events, namely heatwave, cold wave, extreme precipitation and drought. A total of 53 Members responded to the survey. There was very good geographical representation, sampling the major climate zones, including Members with tropical wet and dry climates, arid and semi-arid climates, continental climates and subarctic climates. The number of Members responding to the survey, based on membership of the Regional Associations (RAs), are: 11 from RA I (Africa), 9 from RA II (Asia), 5 from RA III (South America), 5 from RA IV (North America, Central America and the Caribbean), 5 from RA V (South-West Pacific) and 18 from RA VI (Europe).

Among the 53 Members that responded, 7 of them had no criteria to define any of the extreme events. Some Members only had official definitions for a subset of the events. The figure summarizes the number of Members with and without definitions for each extreme event.

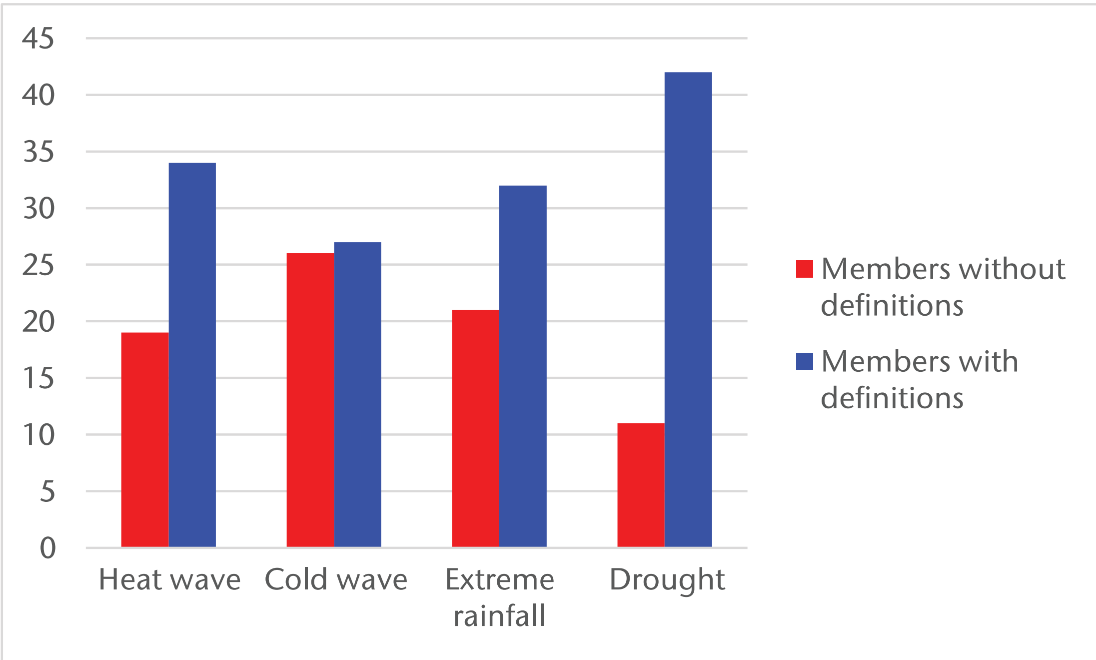

Figure. Number of Members responding to the WMO Members survey on extreme events that have definitions for four types of extreme events

For heatwave and cold wave events, almost all Members having tropical climates responded that they have no definition or criteria for those events, presumably owing to the low seasonal and interannual variability in temperatures in such climates, as well as the limited impacts from those events which do occur. Members located in the higher latitudes or in the Middle East generally have the following criteria for heatwaves: the temperature exceeds a certain threshold (based on absolute value or percentiles) and persists longer than a certain number of consecutive days. Conversely, for cold wave events, the criteria are that the temperature drops to or is less than a certain threshold and persists longer than a certain number of consecutive days. Roughly 65% of the responding Members have criteria for heatwaves, and around 50% have criteria for cold waves. Around 60% of Members that responded as having criteria for heatwaves use absolute values for the threshold and around 30% use percentile-based thresholds. Around 60% of Members having criteria for cold wave events use an absolute value for the threshold while around 25% use a percentile-based threshold.

For drought, around 80% of responding Members indicated that they have criteria and indices for drought. Among those Members that have indices for drought, the majority (around 70%) follow the drought index recommended by WMO: the Standardized Precipitation Index (SPI). Several Members reported using various indices or combinations besides the SPI, such as the Standardized Precipitation and Evapotranspiration Index (SPEI), the Palmer Drought Severity Index (PDSI) and expert assessments; some also reported using hydrological criteria for drought.

For extreme precipitation, around 60% of responding Members indicated that they have criteria and indices for extreme precipitation. Around 70% of those use criteria with an absolute value threshold within a given time interval (hourly, 3 hours, 6 hours or daily). The other criterion commonly used, by roughly 30% of Members, is a percentile-based threshold, for instance the 95th or the 99th percentile. A small number of Members (around 10%) use the return period criterion or base their criteria on other aspects of rainfall distribution for each station.

More details on the types of extreme weather and climate indices used by Members are summarized in the table below.

Table. Summary of the results of the WMO Members survey on extreme events

Event	*Heatwave*	*Cold wave*	*Extreme precipitation*	*Drought*
Number of Members with definitions	34	27	32	42
Absolute value threshold	20	16	23	1
Percentile-based threshold	11	7	9	10
Excess Heat Index (EHI)	5			
Heat–health index	3			
Temperature drop		4		
Return period/distribution-based criteria			3	
SPI				29
SPEI				5
PDSI				3
Water balance and agriculture related				18

Note: Some Members use multiple indicators for a given extreme event type such that the total number of metrics used exceeds the number of respondents for some categories.

The survey asked whether NMHSs require or would benefit from any additional support from WMO on extreme weather and climate events. Members' responses can generally be categorized into two requirements: (1) the need for guidelines for defining extreme events; and (2) the need for capacity building to improve climate monitoring and predictions on extreme events.

ANNEX 2. EXAMPLE REPORTS ON EXTREME EVENTS

A. Example of reporting a heatwave event at the regional scale

Summary: A heatwave occurred in June 2017 in western Europe, making this month about 3 °C warmer than the 1981–2010 long-term average. Due to the heatwave, national heat–health plans across the region were set in motion. During the heatwave, night-time temperatures in France reached an all-time record high on 21 June, with the average reaching 26.4 °C. In Paris, the high temperatures triggered a level three response in France's four-level heatwave plan, as temperatures in the French capital peaked at 37 °C during the week of 19 June. The average monthly June temperature in France was the second warmest on record (after June 2003). In the Netherlands, June 2017 was equal with 1976 as the hottest months of June on record; in Switzerland, June 2017 was the second warmest since 1864, when observations began. In northern areas, the minimum night-time temperatures reached record highs of 24 °C–25 °C. In the United Kingdom of Great Britain and Northern Ireland, the UK Met Office reported that 21 June was the hottest June day in more than 40 years, when temperatures reached 34.5 °C at Heathrow airport. In Spain and Portugal, wildfires forced evacuations, displacing over 1 500 people in Spain and more than 500 people in Portugal, where a forest fire killed at least 64 people and injured 204.
Type of event: Heatwave
Data used: Gridded daily maximum temperature data set
Source of data: In situ observations
Methodology for characterization of the event: Not provided
Description:

Quantitative description	
Thermal index	Warm Spell Duration Index (WSDI)
Threshold	Relative value thresholds in the WSDI are used. The WSDI is defined as the annual or seasonal count of days in a span of 6 consecutive days or longer where the daily maximum temperature exceeds the calendar day 90th percentile of daily maximum temperature, calculated for a 5-day window centred on each calendar day in the 1961–1990 period. This follows the definition in the *Guidelines on Analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation* (WMO/TD-No. 1500).
Temporal information	The heatwave event occurred in June 2017 and lasted 6 days or more in the southern UK, the Netherlands and Belgium, increasing in duration to over 20 days in parts of the Iberian Peninsula.

Event characterization	
Magnitude	The magnitude of the event is illustrated in Figure 1, where the area-averaged daily maximum temperature for the affected area (shown in Figure 2) is calculated and compared against climatological values (based on the 1981–2010 period). Figure 1 shows the heatwave in June, when the area-averaged temperature exceeded 31 °C and was over 6 °C warmer than climatological values. Note: the June 2017 heatwave was preceded by a warm period starting at the end of May.
Duration	The duration of a heatwave is the number of days where temperature values exceed the WSDI threshold. The duration must, according to the WSDI definition, be at least 6 days. The duration of the June 2017 heatwave is shown in Figure 2. Figure 3 shows that the June 2017 heatwave for the area has been the most severe on record, passing the previous record value in June 2003.
Extent	The area impacted by the June 2017 heatwave event is indicated in Figure 2 and relates to the area where the WSDI temperature threshold was exceeded for 6 consecutive days. It includes nearly all of Spain, Portugal, France, Belgium and Switzerland, and parts of many other countries reaching to the Black Sea.

Data requirements	
Data used	E-OBS gridded data set is used (Haylock et al., 2008) based on validated data supplied by National Meteorological and Hydrological Services (NMHSs) in Europe to the Climate Data node of the WMO Regional Climate Centre (RCC) for Regional Association (RA) VI. The spatial and temporal resolution of this data set are, respectively, 0.25° and daily. Data are available from 1950 and are updated monthly.

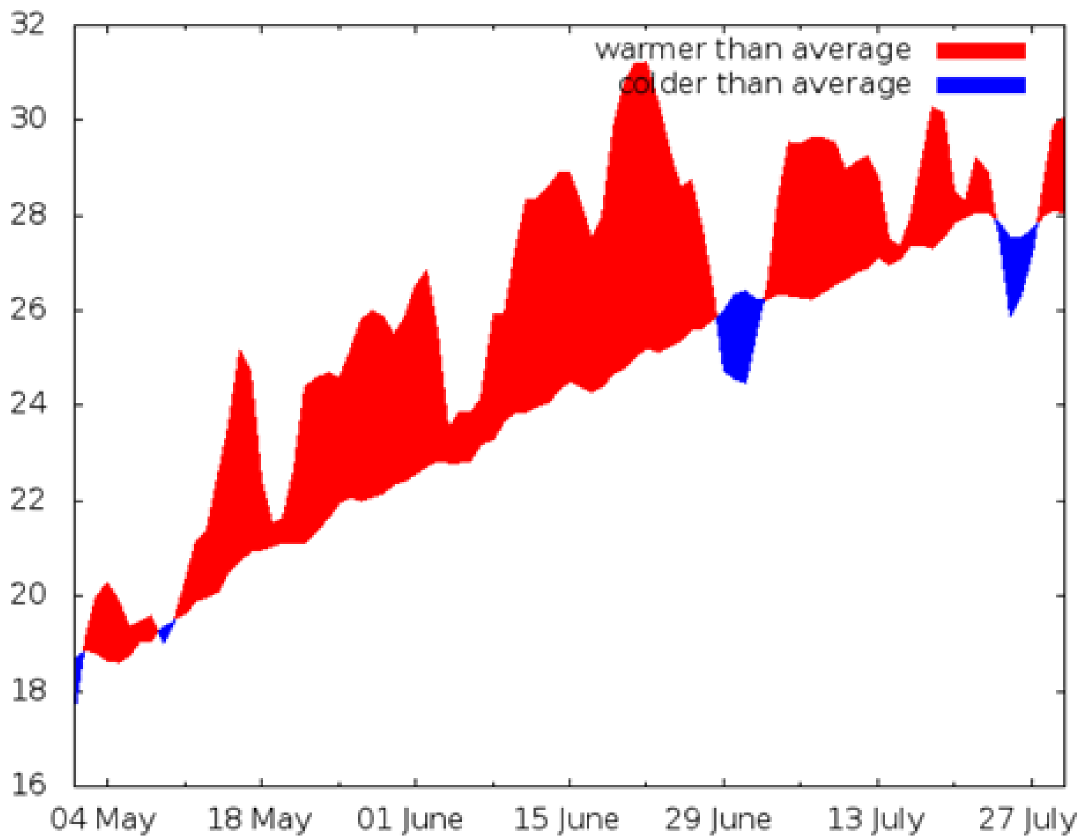

Figure 1. Daily maximum temperature (in degrees Celsius), averaged over the area affected by the heatwave of June 2017 in Europe, characterized as either warmer or colder than average compared to 1981–2010 climatological values. The heatwave in June, with area-averaged temperature exceeding 31 °C (> 6 °C warmer than climatological values from the reference period), stretched from southern Spain to southern UK and the Netherlands, and eastward to the Black Sea.

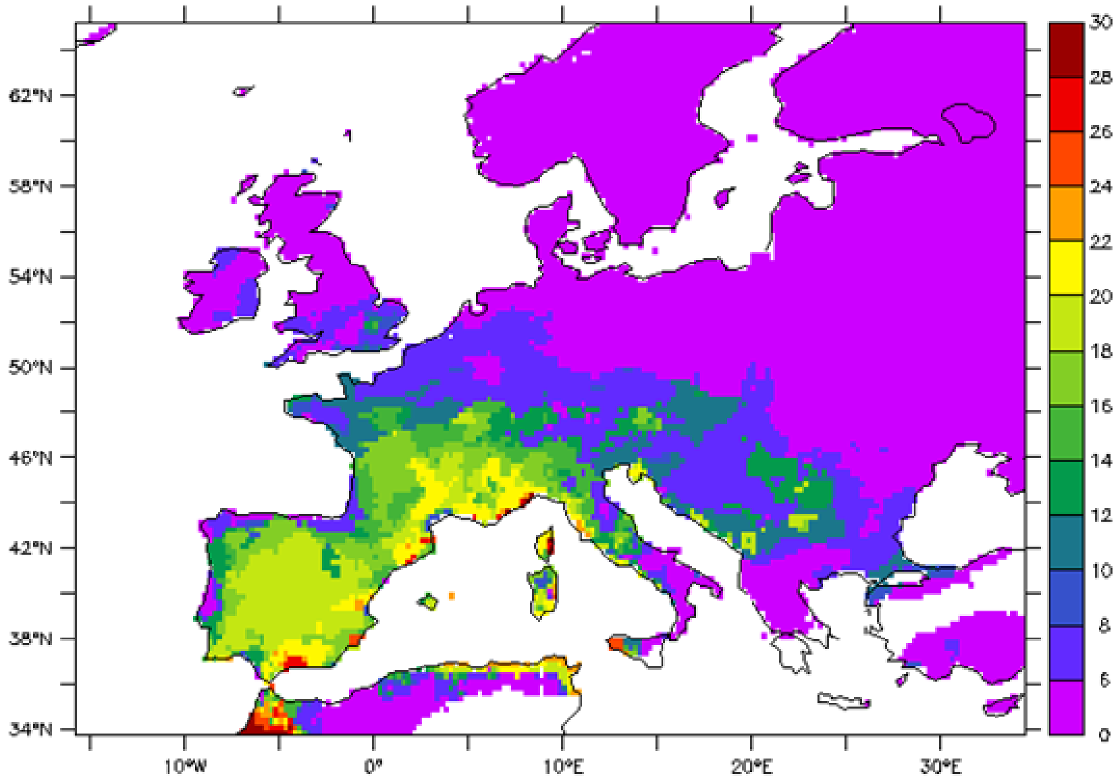

Figure 2. Duration of the June 2017 heatwave event in days, as calculated according to the WSDI

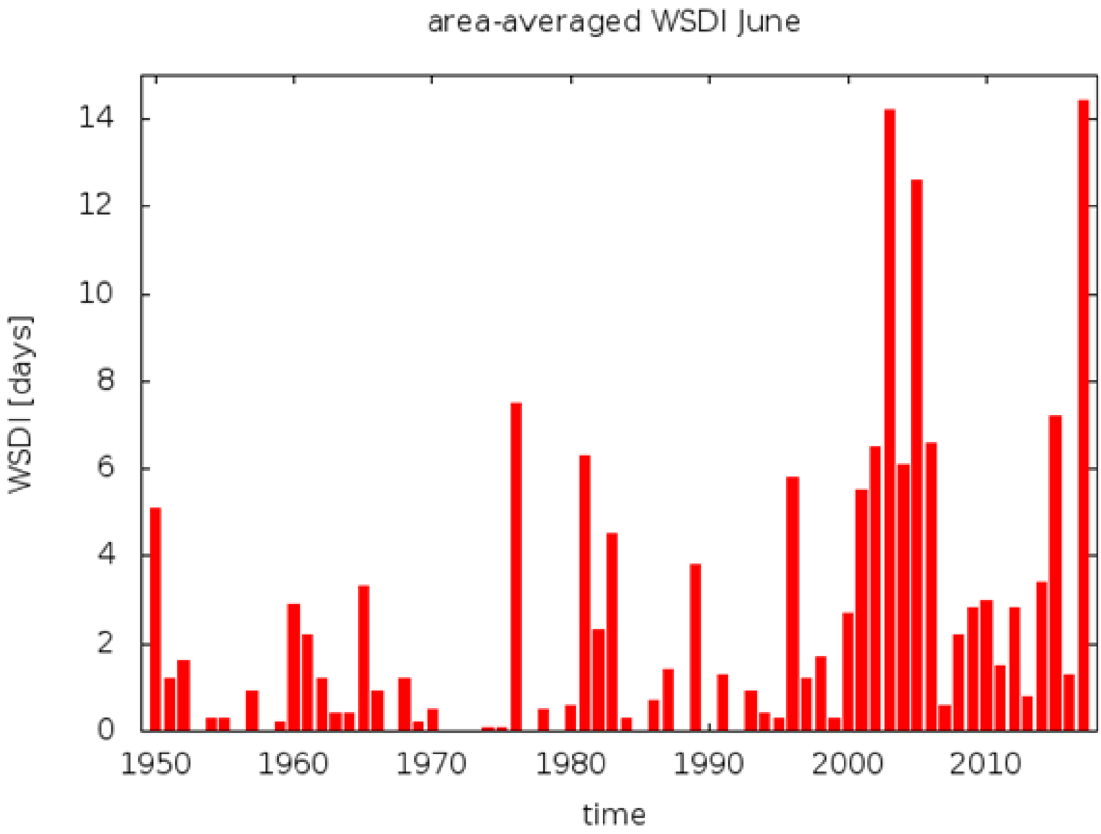

Figure 3. June WSDI values averaged over the countries Portugal, Spain, France, Switzerland and Belgium for 1950 through 2017

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B. Example of reporting a cold wave event at the national scale

Summary: A cold wave event occurred from the middle of December 2005 to the beginning of January 2006 over eastern and western Japan. During that period, there was a cold air invasion from the north-west over Japan on several occasions. This was a result of the strong pressure gradient between the Siberian High and Aleutian Lows. This pattern is typically seen in East Asia during the northern hemisphere winter, and once the gradient becomes strong, it causes cold waves in and around Japan. In addition to the low temperatures, the cold wave events brought heavy snowfall on the Sea of Japan side of the islands.

The Japan Meteorological Agency (JMA) is routinely monitoring extreme events around the world, including in Japan. Extremely cold events are also monitored with temperature anomaly (TA), based on SYNOP/CLIMAT reports. The monitoring results are reported weekly, monthly, seasonally and annually through the Tokyo Climate Center web page (http://ds.data.jma.go.jp/tcc/tcc/products/climate/index.html). In the case of winter 2005/2006, three consecutive weeks in December and one week in January were identified as a cold wave event in weekly monitoring.

Besides monitoring reports, JMA issues warning information on extremely cold temperatures brought about by cold wave events. Forecasts and expected socioeconomic impacts associated with the cold wave are taken into account when making decisions about issuance of warning information. Early warning information on cold conditions is also issued in advance when cold wave events are predicted with medium-range numerical model forecasts.
Type of event: Cold wave
Data used: Conventional surface observation data
Source of data: Surface observation data obtained at SYNOP/CLIMAT stations over Japan
Methodology for characterization of the event: TA is used for monitoring cold wave events based on SYNOP reports. Cold wave events are identified when the criteria are satisfied at observation stations across a wide range of the country, in terms of weekly- to seasonal-average temperature anomalies. The duration of cold events is evaluated as the number of consecutive weeks or months with cold event conditions. The severity is measured simply depending on whether criteria for cold wave events are met or not.
Description:

Quantitative description	
Cold wave index	Temperature anomaly (TA) A cold wave is defined generally in the JMA glossary as a temperature decrease to some extent for a period longer than a few days, due to a cold air invasion. In the monitoring process, averaged TA for each week, month and season is evaluated in terms of statistically derived criteria based on monthly average.
Threshold	For a week: Absolute TA > 3 times the 30-day standard deviation For a month and season: Absolute TA > 1.83 times the monthly standard deviation The 30-day standard deviation is calculated by interpolating the climatological monthly standard deviation. Thresholds that would pick up rare events (defined as once per 30 years) are calculated and adopted.
Temporal information	The cold wave event continued for a total of five weeks, from the middle of December 2005 to the beginning of January 2006, as show in Figure 1.

Event characterization	
Magnitude	The measure of magnitude is related to whether temperature anomalies exceed the threshold or not. The TA value is provided as supplemental information about the magnitude of the event.
Duration	Duration of cold wave events is expressed as the number of consecutive weeks or months that cold wave event conditions persist. The duration of this cold wave is shown in Figure 1.

Extent	The total extent is assessed as the continuous geographical regions where observation data collected at stations meet the criteria for a cold wave event for the duration of the event. Figure 2 illustrates the TA distribution on a map for the duration of the cold wave event. The total extent is estimated at approximately 279 000 km^2 for this event.

Data requirements	
Data used	Surface observation data obtained at SYNOP stations over Japan

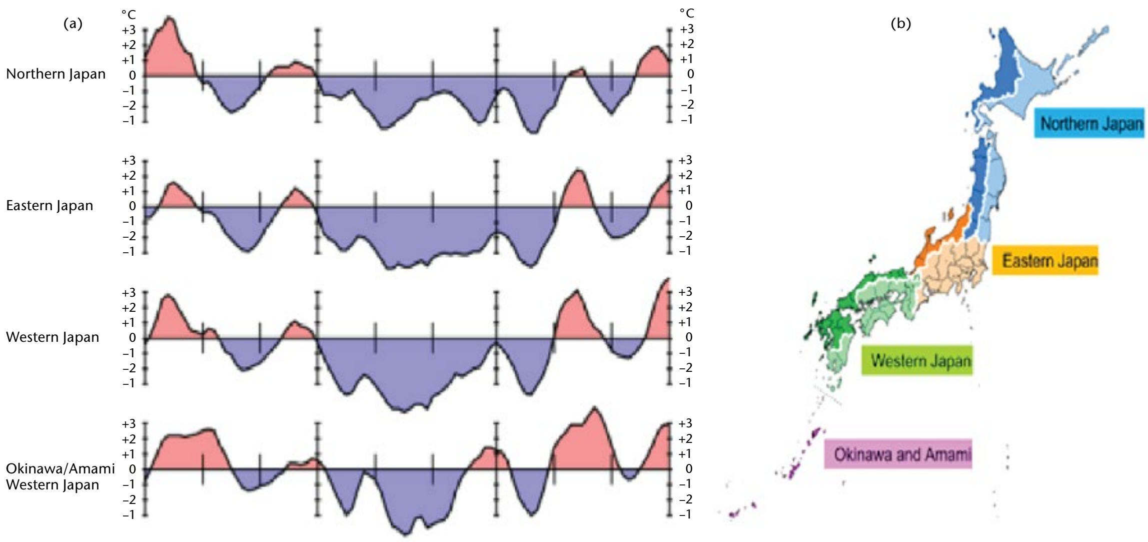

Figure 1. (a) Progression of the cold wave event in the 2005/2006 winter, showing time series of area-averaged TA for each of Japan's four districts (pictured in (b))

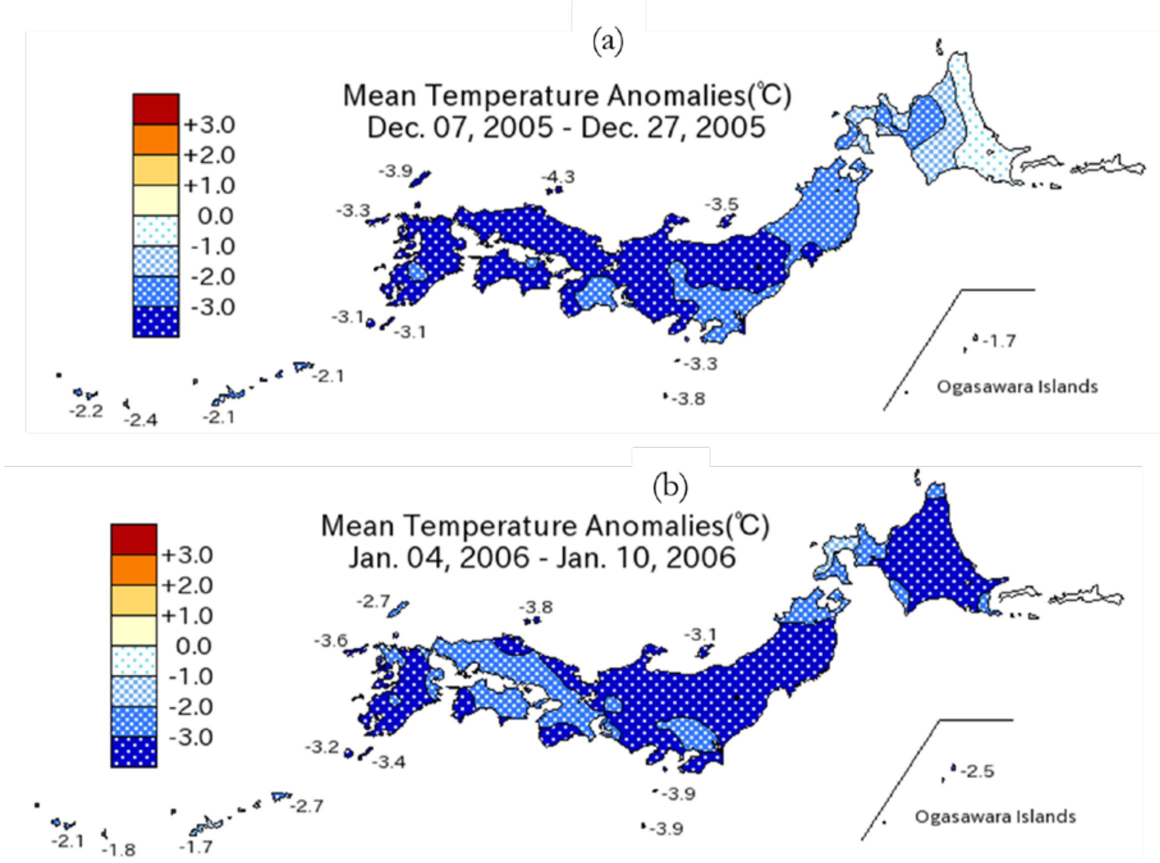

Figure 2. Distributions of TA in two selected periods during the cold wave event, that is, (a) 07–27 December 2005 and (b) 04–10 January 2006

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C. Example of reporting an extreme precipitation event at the national scale

Summary: A persistent extreme precipitation event occurred from 1 to 11 July 1991 in central-eastern China. This extreme precipitation event caused damage to an area of 112 600 km2, with a death toll of 1 800. Approximately 3 million houses were damaged or destroyed, and the economic losses totalled 70 billion Yuan Renminbi (11 billion US dollars).
Type of event: Extreme precipitation
Data used: Station precipitation data set
Source of data: In situ observations
Methodology for characterization of the event: Daily precipitation equal to or greater than 50 mm: (i) is observed by at least three neighbouring stations; and (ii) persists for at least three days at each of those stations. There is at least one overlapping day between neighbouring stations in the duration of the event. The event comes to an end when the above conditions are not satisfied for two consecutive days.
Description:

Quantitative description	
Precipitation index	PI: total precipitation measured for 24 h
Threshold	More than three consecutive days, with daily amount ≥ 50 mm
Temporal information	This extreme precipitation event lasted 11 days, from 1 to 11 July 1991

Event characterization	
Magnitude	PI: Maximum amount of 24 h total precipitation over 50 mm
Duration	Duration (D) of extreme precipitation is the number of consecutive days when daily precipitation exceeds 50 mm in at least three neighbouring stations for a minimum of three consecutive days. The extreme precipitation is allowed to break for at most one day before continuing.
Extent	The area impacted by this persistent extreme precipitation event is 112 600 km^2, as shown in the figure below.

Data requirements	
Data used	Daily precipitation amounts at 756 stations, with detailed metadata provided by the Climate Data Center (CDC) of the National Meteorological Information Center, China Meteorological Administration. The data set provides geographical coverage of China during the period 1951–2010.

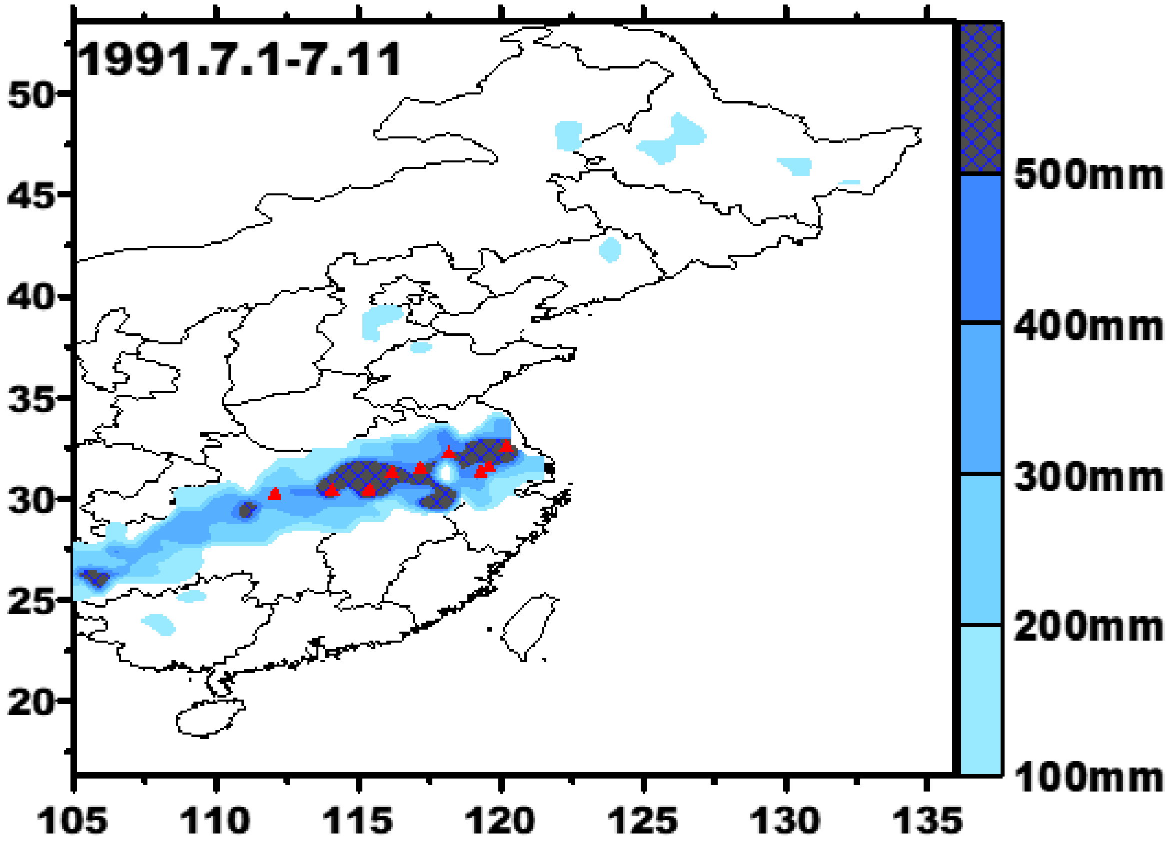

Figure. Persistent precipitation extremes, which occurred from 1 to 11 July 1991. Shadings indicate accumulated precipitation (mm), and red triangles label the stations which experienced at least three consecutive days with extreme precipitation of at least 50 mm per day.

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D. Example of reporting a drought event at the national scale

Summary: A drought event occurred early in 2014 along the eastern coast of Sumatra, Indonesia, which was initiated by a cold surge episode bringing a cold and dry airmass from Siberia. The drought lasted three months, causing problems in the agricultural sector and initiating forest fires.
Type of event: Drought
Data used: Gridded precipitation data set
Source of data: Satellite and in situ observations
Methodology for characterization of the event: Standardized Precipitation Index (SPI) values were calculated based on monthly precipitation data. (The SPI value is the difference between the normalized precipitation value and its median value.) The drought condition was based on an absolute value threshold, and the duration was simply calculated as the number of months with SPI values less than the threshold. The severity was defined as the average of the SPI values over the duration period.
Description:

Quantitative description	
Drought index	Standardized Precipitation Index (SPI)
Threshold	Absolute value threshold, SPI < –1, as defined by McKee et al. (1993)
Temporal information	The drought event lasted three months, from January 2014 through March 2014.

Event characterization		
Magnitude	The categorization of SPI values is based on the definition given by McKee et al. (1993), as follows:	
	2.00 ≤ SPI:	extremely wet
	1.5 < SPI < 2:	severely wet
	1 < SPI < 1.5:	moderately wet
	–1 < SPI < 1:	near normal
	–1.5 < SPI < –1:	moderately dry
	–2 < SPI < –1.5:	severely dry
	SPI ≤ –2:	extremely dry
	The progression of the drought event is shown in Figure 1 from December 2013 (before the onset) until April 2014 (after cessation), and the colour scheme follows the SPI categorization.	
Duration	The duration (D) of a drought in a location is the number of consecutive months with SPI values less than –1. The duration of the drought event is shown in Figure 2.	
Extent	The area impacted by the drought event is 291 000 km^2, as shown in Figure 3.	

Data requirements	
Data used	Operational gridded precipitation data set, obtained by merging in situ and satellite observation data. Temporal resolution in 10-day and monthly timescales, and 0.25° spatial resolution. Data is available for 1998 to the present.

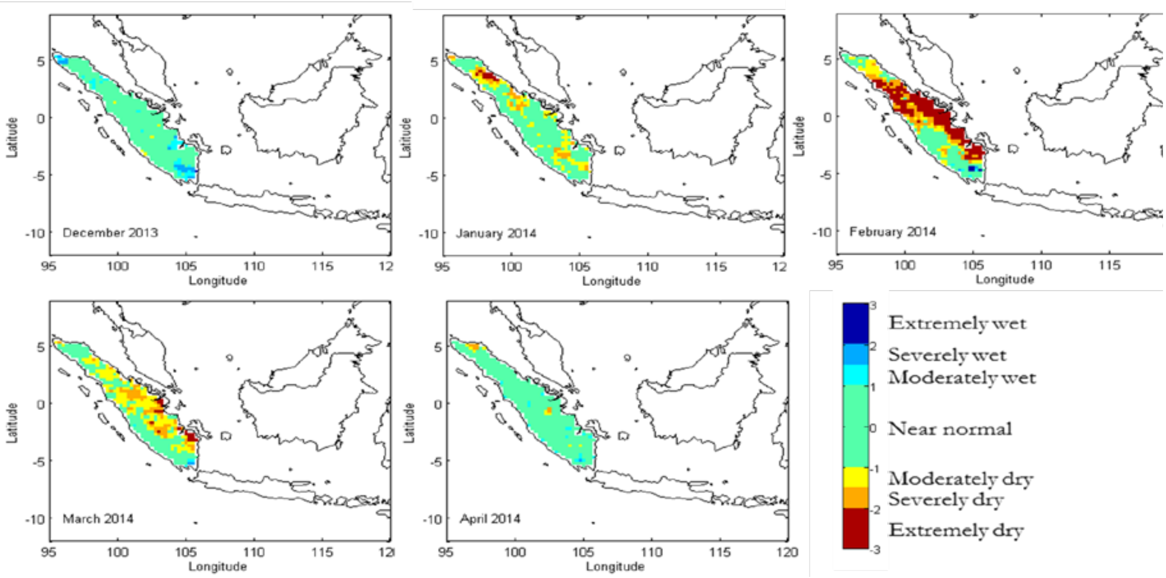

Figure 1. Progression of the drought event from January 2014 through March 2014 on Sumatra Island, Indonesia. The month before the drought (December 2013) and after (April 2014) are also shown. The colour shading represents the SPI categorization according to McKee et al. (1993).

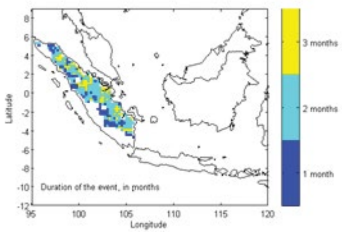

Figure 2. Duration of the event (in months)

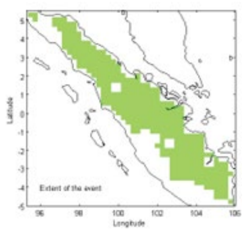

Figure 3. Extent of the event (the impacted area)

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