# Guide to Climatological Practices

2023 edition

WEATHER CLIMATE WATER

WORLD
METEOROLOGICAL
ORGANIZATION

WMO-No. 100

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**EDITORIAL NOTE**

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WMO-No. 100



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ISBN 978-92-63-10100-6

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# FOREWORD

One of the purposes of the World Meteorological Organization (WMO), as laid down in the WMO Convention, is to promote the standardization of meteorological and related observations, including those that are applied to climatological studies and practices. With this aim, the World Meteorological Congress adopts, from time to time, Technical Regulations that set out the meteorological practices and procedures to be followed by WMO Members. The Technical Regulations are supplemented by a number of guides that provide more details on the practices, procedures and specifications that Members are expected to follow or implement in establishing and conducting their arrangements in compliance with the Technical Regulations and in otherwise developing their meteorological and climatological services. One of the publications in this series is the *Guide to Climatological Practices* (WMO-No. 100), the purpose of which is to provide, in a convenient form for all concerned with the practice of climatology, information that is of the greatest importance for the successful implementation of their work. This key resource is designed to help WMO Members to provide a seamless stream of crucial information to support National Meteorological and Hydrological Services (NMHSs) with their daily practices and operations. A complete description of the theoretical bases and range of applications of climatological methods and techniques is beyond the scope of the present *Guide*, although references to such documentation are provided where applicable.

The first edition of the *Guide to Climatological Practices* (WMO-No. 100) was published in 1960 using material developed by the Commission for Climatology. It was edited by a special working group, with the assistance of the WMO Secretariat. The second edition of the *Guide* originated at the sixth session of the Commission for Special Applications of Meteorology and Climatology (1973). The Commission instructed the working group responsible for the Guide to make arrangements for a substantially revised edition in light of the progress made in climatology during the preceding decade and in the use of climatological information and knowledge in various areas of meteorology and other disciplines. At its seventh session, the Commission (1978) re-established the working group, which continued to work on the second edition on a chapter-by-chapter basis, producing the version that was ultimately published in 1983. The work on the third edition of the *Guide* started in 1990, when the content and authorship were approved by the advisory working group of the Commission for Climatology at a meeting in Norrköping, Sweden. An editorial board for the *Guide* was subsequently established to supervise individual lead authors and chapter editors. Nevertheless, it was not until 1999 that the lead authors received a draft summary to further develop the text of the *Guide*. At its fourteenth session, in 2005, the Commission re-established an expert team and agreed that some overarching activities would be the responsibility of the Management Group. These included the further development of Part II of the Guide and more work on the review and designation of Regional Climate Centres (RCCs). The text of the third edition of the Guide was approved by the president of the Commission for Climatology shortly before the fifteenth session of the Commission, held in Antalya, Türkiye, in February 2010. At its sixteenth session, held in Heidelberg, Germany, in July 2014, the Commission decided to establish a task team to regularly update the *Guide to Climatological Practices* to ensure that the best scientific knowledge was made available to users as quickly as possible. The work of the Task Team on the Guide to Climatological Practices led to the issuing of the current version of the *Guide*, which was approved by the Commission at its seventeenth session, held in Geneva in April 2018.

With the restructuring of WMO in 2019, the Commission for Weather, Climate, Hydrological, Marine and Related Environmental Services and Applications, also known as the Services Commission (SERCOM), was established to contribute to the development and implementation of globally harmonized weather, climate, water, ocean and environment-related services and applications to enable informed decision-making and realization of socioeconomic benefits by all user communities and society as a whole. Its Standing Committee on Climate Services (SC-CLI) is responsible for the maintaining and updating the Guide. While many fundamentals of climate science and climatological practices have remained constant over time, scientific advances in climatological knowledge and data analysis techniques, changes in technology, computer capabilities and instrumentation, and the growing importance of climate science throughout the world, have made this fourth edition necessary.

I am grateful to the WMO Services Commission for taking the initiative to oversee the process of producing this fourth edition. On behalf of the World Meteorological Organization, I also wish to thank all those who have contributed to the preparation of this publication. Special recognition is due to the Chair of the Standing Committee on Climate Services, Prof. Manola Brunet India (Spain), who guided and supervised the preparation of the text.

This updated version of the *Guide* is published in English and will be gradually translated into the other official languages of WMO to maximize the dissemination of knowledge. As with the previous versions, WMO Members may translate the Guide into their national languages, as appropriate, in coordination with the WMO Secretariat.

(Petteri Taalas)
Secretary-General

# ACKNOWLEDGEMENTS

WMO would like to acknowledge the work of the lead author, Dr Nathaniel Guttman (United States of America). Significant contributions to the writing and editing were provided by Mr Omar Baddour (WMO), Prof. Chris Hewitt (United Kingdom of Great Britain and Northern Ireland), Dr John Kennedy (United Kingdom), Mr Gregor Macara (New Zealand), Mr Denis Stuber (France) and Dr Blair Trewin (Australia). An excellent team of reviewers included Dr Adnan Akyuz (United States), Dr Lisa Alexander (Australia), Mr Amir Delju (WMO), Dr Robert Dunn (United Kingdom), Dr Jose A. Guijarro (Spain), Dr Peer Hechler (WMO), Dr Khadija Kabidi (Morocco), Dr  Stanislava Kliegrova (Czechia), Dr Rupa Kumar Kolli (India), Dr Renata Libonati (Brazil), Ms Charlotte McBride (South Africa), Mr Awatif Mostafa (Egypt), Dr Marisol Osman (Argentina), Dr Ge Peng (United States), Dr Guillermo P. Podestá (United States), Dr. Adam Scaife (United Kingdom), Ms Helen Tseros (Australia) and Dr William Wright (Australia).

# 1. INTRODUCTION

## 1.1 Purpose and content of the Guide

The *Guide to Climatological Practices* (WMO-No. 100) remains the primary governance publication on climatology and is subject to the approval of the WMO Executive Council and Congress. The recommended practices, procedures and specifications that should be followed or implemented to achieve compliance with the *Manual on the High-quality Global Data Management Framework for Climate* (WMO-No. 1238) are described in the Guide, as is the broader field of the provision of climate services. The *Guide* is designed to provide WMO Members with guidance and assistance in developing national activities linked to climate information and services. There have been three previous editions: the original publication, which appeared in 1960, the second edition, published in 1983, and the third edition, published in 2011 and updated in 2018. While many fundamentals of climate science and climatological practices have remained constant over time, a fourth edition is necessary owing to scientific advances in climatological knowledge and data analysis techniques and changes in technology, computer capabilities and instrumentation, and because of the growing importance of climate science throughout the world.

This fourth edition describes essential basic principles and modern practices in the development and implementation of all climate services and outlines current best practices in climatology with a focus on climate services and communication. Rather than attempting to provide all-inclusive guidance, it presents concepts and considerations and provides references to other technical guidance and information sources. The *Guide* is intended to cover newer topics and expand on the topics addressed in older editions to help to develop capacities and allow users to attain and maintain competence in providing climate services and providing clear, trustworthy information to multidisciplinary environmental scientists, decision makers and the general public. The guidance applies to the collection, processing and servicing of data and information relating to the climate system, including atmospheric, hydrologic, oceanic and environmental sciences (see section 1.2.2).

The Guide is supported by other documents, such as the *Manual on the High-quality Global Data Management Framework for Climate* (WMO-No. 1238). As a formal annex to WMO *Technical Regulations* (WMO-No. 49), Volume I, the *Framework* has the status of regulatory material for the management of climate data. Building on existing WMO infrastructure, the *Framework* is a reliable, integrated, underpinning data infrastructure at the global, regional and national levels. The *Framework* establishes standards and recommended practices for sourcing, securing, managing, assessing and cataloguing climate data, and it reflects WMO resolutions for the sharing of data in place as of 2022. The latest edition of the *Framework* also introduces requirements for important climate data-related initiatives, such as the WMO Centennial Stations process and the WMO process for assessing climate extremes. It thus provides a robust data foundation for generating climate products and delivering climate services through the Climate Services Information System of the Global Framework for Climate Services (GFCS).

This first chapter of the present *Guide* includes information on climatology and its scope, WMO climate programmes, global, regional and national climate activities and quality management. The remainder of the *Guide* is broken down into four chapters (on climate data management, data sets and statistics, climate products, and climate services, respectively).

Where possible, the procedures described in the Guide have been taken from decisions on standards and recommended practices and procedures. The main decisions concerning climate practices are contained in the WMO Technical Regulations and Manuals and in the reports of the World Meteorological Congress and the Executive Council. They originate mainly from the recommendations of experts from around the world.

Lists of relevant WMO documents and other publications of particular interest to those providing climate services and communicating environmental information are provided in the reference section at the end of each chapter. Blue text is used for Internet links, which are provided for all United Nations and WMO references, as well as many other documents.

## 1.2 Climatology

Climatology is the study of the Earth's atmosphere, weather patterns and the interactions between the atmosphere on the one hand and the hydrosphere, cryosphere, lithosphere and biosphere on the other over time. The discipline includes the description of long-term variations, extremes, patterns and trends. It also includes the influences of these descriptions on a variety of activities, including water resources, human health, safety and welfare. Climate refers to the set of weather conditions observed at a particular location or region over several decades or longer. One way to describe climate is in terms of statistical descriptions of the central tendencies and variability of relevant elements, such as temperature, precipitation, atmospheric pressure, humidity and winds. Another way is through combinations of elements – such as weather types and weather phenomena – that are typical of a location or region, or of the Earth as a whole, for a particular time period. Beyond being treated as a statistical entity, climate can also be studied as a determinant of, a resource for and a hazard to human activities. Physical climatology embraces a wide range of studies that include the interactive processes of the climate system. Dynamic climatology is closely related to physical climatology, but it is mainly concerned with patterns in the general circulation of the atmosphere. Both involve the description and study of the properties and behaviour of the atmosphere.

Climatology incorporates both climatic variability and change. Climatic variability refers to variations in climate conditions between one time period and another (for example, intraseasonal, inter-annual and inter-decadal variations). In general, climatic variability is connected with variations in the state of atmospheric and ocean circulation and land surface properties (such as soil moisture) at the intraseasonal to inter-decadal timescales. Climate change, by contrast, refers to a systematic change in the statistical properties of climate, such as mean and variance, over prolonged periods (decades to centuries), as manifested in an upward or downward trend in, for example, extreme rainfall values. For most of the Earth's climate history, systematic changes in climate have occurred because of natural causes, such as variations in the nature of the Earth's orbit around the sun, axial tilt or solar output and the changing relationship between the "natural" components that make up the climate system (see section 1.2.2). There is now mounting evidence, however, that humans and their activities are altering the climate system.

### 1.2.1 *History*

In their course on climate and weather training, (Terefe et al., 2022) included a section on the history of climate. The earliest documented sources are found in *On Airs, Waters and Places*, written by Hippocrates in around 400 BC, and *Meteorologica*, written by Aristotle in around 350 BC. To the early Greek philosophers, the word "climate" meant "slope", in reference to the curvature of the Earth's surface. This curvature produces variations in climate at different latitudes due to the changing incidence of the sun's rays. Logical and reliable inferences on climate are found in the work of the Alexandrian philosophers Eratosthenes and Aristarchus.

With the onset of extensive geographical exploration in the fifteenth century, people began to describe the Earth's climates and the related conditions. The invention of meteorological instruments such as the thermometer, invented in 1593 by Galileo Galilei, and the barometer, invented in 1643 by Evangelista Torricelli, gave a greater impulse to the establishment of mathematical and physical relationships between the different characteristics of the atmosphere. This in turn led to the establishment of relationships that could be used to describe the state of the climate at different times and in different places.

The observed pattern of circulation linking the tropics and subtropics, including the trade winds, tropical convection and subtropical deserts, was first interpreted by George Hadley in 1735, and subsequently became known as the Hadley cell. Julius von Hann, who published the first of three volumes of *Handbook of Climatology* (von Hann, 1908) in 1883, wrote the classic work on general and regional climatology, which included data and eyewitness descriptions of weather and climate. In 1918, Wladimir Köppen produced the first detailed classification of world climates based on the vegetative cover of land. This endeavour was followed by more detailed developments in descriptive climatology. The geographer E.E. Fedorov (1927), for example, attempted to describe local climates in terms of daily weather observations. In the first thirty years of the twentieth century, the diligent and combined use of global observations and mathematical theory to describe the atmosphere led to the identification of large-scale atmospheric patterns. Notable contributors to this field included Sir Gilbert Walker (1923), who conducted detailed studies of the Indian monsoon, the Southern Oscillation, the North Atlantic Oscillation and the North Pacific Oscillation.

Other major twentieth-century works on climatology included an article by TorBergeron (1939) on dynamic climatology and a climatology handbook, first published in 1936 by Wladimir Köppen and Rudolf Geiger (1936). Geiger had first described the concept of microclimatology in some detail in 1927, but further developments in this field did not occur until the Second World War. During the war, it became necessary, for planning purposes, to use probabilities to forecast weather data months or even years ahead. C.W. Thornthwait (1948) established a climate classification based on a water budget and evapotranspiration. In the decades that followed, major progress was made in the development of theories on climatology.

In September 1929, the Conference of Directors of the International Meteorological Organization, meeting in Copenhagen, agreed to set up a technical commission for climatology "for the study of all questions relating to this branch of science". The creation of WMO in 1950 (as the successor to International Meteorological Organization, founded in 1873) established a system of data collection and led to the systematic analysis of climate. Based on the analysis, conclusions were drawn about the nature of climate. As concern about climate change increased during the final decades of the twentieth century, it became clear that climate needed to be understood as a major part of a global system of interacting processes involving all the Earth's major domains (see 1.2.2). Climate change is defined as a statistically significant alteration in either the average state of the climate or in its variability that persists for an extended period, typically decades or longer. The alteration may be caused by natural internal processes, external forcing or persistent anthropogenic changes in the composition of the atmosphere or land use (Terefe et al., 2022) Considerable national and international efforts are being directed towards other aspects of climatology as well. These efforts include improved measurement and monitoring of climate, an increased understanding of the causes and patterns of natural variability, more reliable methods of predicting climate over seasons and years ahead, and a better understanding of the linkages between climate and a range of social and economic activities and ecological changes.

Climate-related activities at the end of the twentieth century and in the first decade of the twenty-first century were strongly influenced by three world climate conferences organized by WMO in collaboration with other United Nations agencies and programmes. At the First World Climate Conference, in 1979, it was recognized that the problem of possible human influence on climate was a matter of special importance. At the Second World Climate Conference, in 1990, it was recognized that there was an urgent need to acquire comprehensive information on the properties and evolution of the Earth's climate system in order to detect climate change, support climatological applications for economic development and develop climate science and predictions. The Third World Climate Conference, in 2009, was held with a vision for "an international framework for climate services that links science-based climate predictions and information with the management of climate-related risks and opportunities in support of adaptation to climate variability and change in both developed and developing countries"

Extreme weather events, from heat waves to destructive storms, had made it clear to government entities that climate change was a risk of concern. Countries worldwide signed the Paris Agreement on climate change in 2015 but failed to significantly reduce their greenhouse emissions. As evidence of climate change mounted, climate scientists became more vocal in advocating action.

Research was expanded to include the effects of climate on all aspects of human activity. The research, projections and warnings are summarized in the recurring reports of the Intergovernmental Panel on Climate Change (IPCC). Recent and older reports and activities, news, and other information related to climate change are shared on the IPCC website.

### 1.2.2 *The climate system*

The climate system (Figure 1.1) is a complex and interactive system consisting of the atmosphere, land surface, snow and ice, oceans and other bodies of water, and living organisms. The atmosphere is the gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen and oxygen, but also contains small quantities of argon, helium, carbon dioxide, ozone, methane and many other trace gases. The atmosphere also contains water vapour, condensed water droplets in the form of clouds and aerosols. The hydrosphere is the part of the Earth's climate system comprising liquid water distributed on and beneath the Earth's surface in oceans, seas, rivers, freshwater lakes, underground reservoirs and other water bodies. The cryosphere collectively describes elements of the Earth system containing water in its frozen state and includes all snow and ice (sea ice, lake and river ice, snow cover, solid precipitation, glaciers, ice caps, ice sheets, permafrost and seasonally frozen ground). The surface lithosphere is the upper layer of the solid Earth, including both the continental crust and the ocean floor. The biosphere comprises all ecosystems and living organisms in the atmosphere, on land (terrestrial biosphere) and in the oceans (marine biosphere), including derived dead organic matter, such as litter, soil organic matter and oceanic detritus.

Influenced by solar radiation and the radiative properties of the Earth's surface, the climate of the Earth is determined by interactions among the components of the climate system. The interaction of the atmosphere with the other components plays a dominant role in shaping the climate. The atmosphere obtains energy directly from incident solar radiation or indirectly via processes involving the Earth's surface. This energy is continuously redistributed vertically and horizontally through thermodynamic processes or large-scale motions with the unattainable aim of achieving a stable and balanced state of the system. Water vapour plays a significant role in the vertical and horizontal redistribution of heat in the atmosphere through condensation and latent heat transport. The ocean, with its vast heat capacity, limits the rate of temperature change in the atmosphere and supplies it with water vapour and heat. The distribution of the continents affects oceanic currents, and mountains redirect atmospheric motions. Polar, mountain and sea ice reflect solar radiation into space. At high latitudes, sea ice acts as an insulator and protects the ocean from rapid energy loss to the much colder atmosphere. The biosphere, including its human activities, affects atmospheric components such as carbon dioxide and features of the Earth's surface such as soil moisture and albedo.

Interactions among the components occur at all spatial and temporal scales (Figures 1.2 and 1.3). Spatially, the microscale encompasses climate characteristics over small areas, such as individual buildings, plants and fields. A change in microclimate can be of major importance when the physical characteristics of an area change. For example, new buildings may increase windiness, reduce ventilation, cause excessive run-off of rainwater and increase pollution and heat. Natural variations in microclimate, such as changes in shelter, exposure, sunshine and shade, are also important, since they can determine, for example, which plants will prosper in a particular location and whether provisions are needed for safe operational work and leisure activities.

The mesoscale encompasses the climate of a region of a limited extent, such as a river catchment area, valley, conurbation or forest. Mesoscale variations are important in applications such as land use, irrigation and damming, the location of natural energy facilities and resort location.

The macroscale encompasses the climate of large geographical areas, continents and the globe. It determines national resources and constraints in agricultural production and water management, and is thus linked to the nature and scope of the health and welfare of the biosphere. It also defines and determines the impact of major features of the global circulation, such as the El Niño-Southern Oscillation, the monsoons and the North Atlantic Oscillation.

Understanding the characteristics of an environmental element over a period of one hour is important for certain activities. In agriculture, for example, it is important for operations such as pesticide control and the monitoring of energy usage for heating and cooling. The characteristics of an element over a day might determine the human activities that can be safely pursued. The climate over months or years will determine, for example, the crops that can be grown or the

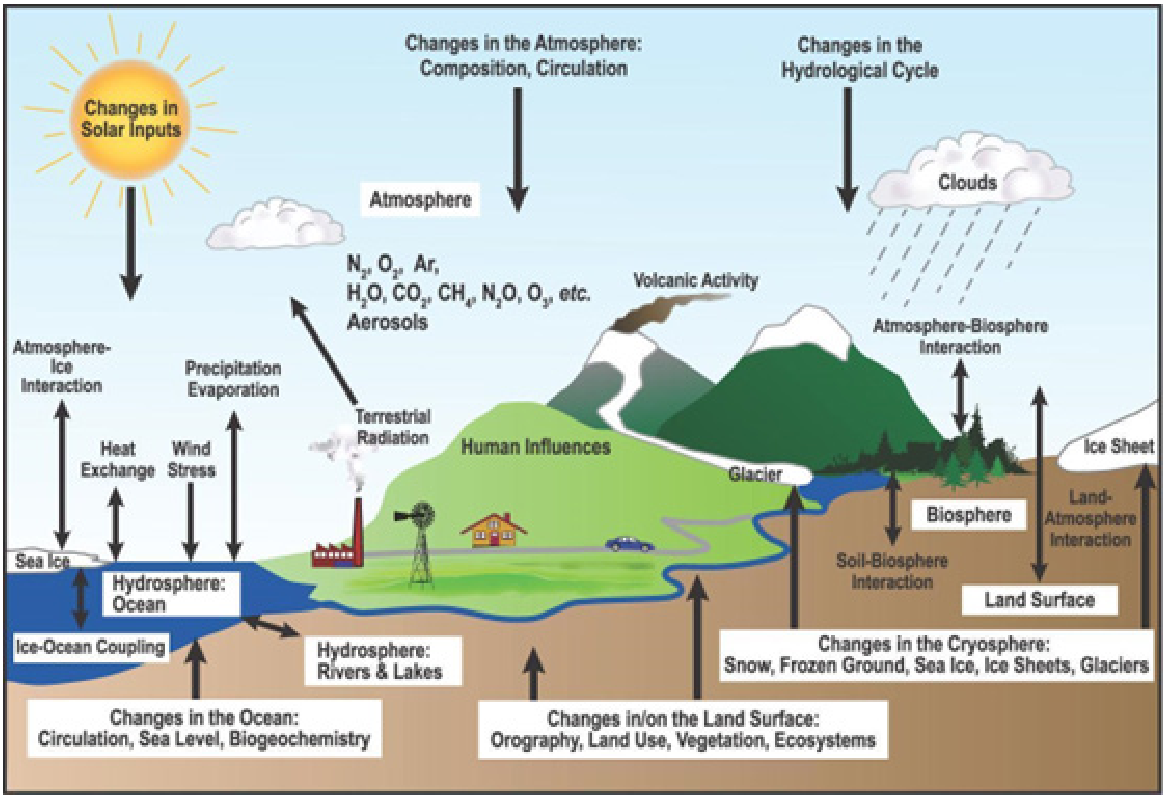


**Figure 1.1 Schematic view of the components of the global climate system, their processes and interactions, and some aspects that may change**

*Source:* IPCC, AR4, Chapter 1, FAQ 1.2, Figure 1 (2007)

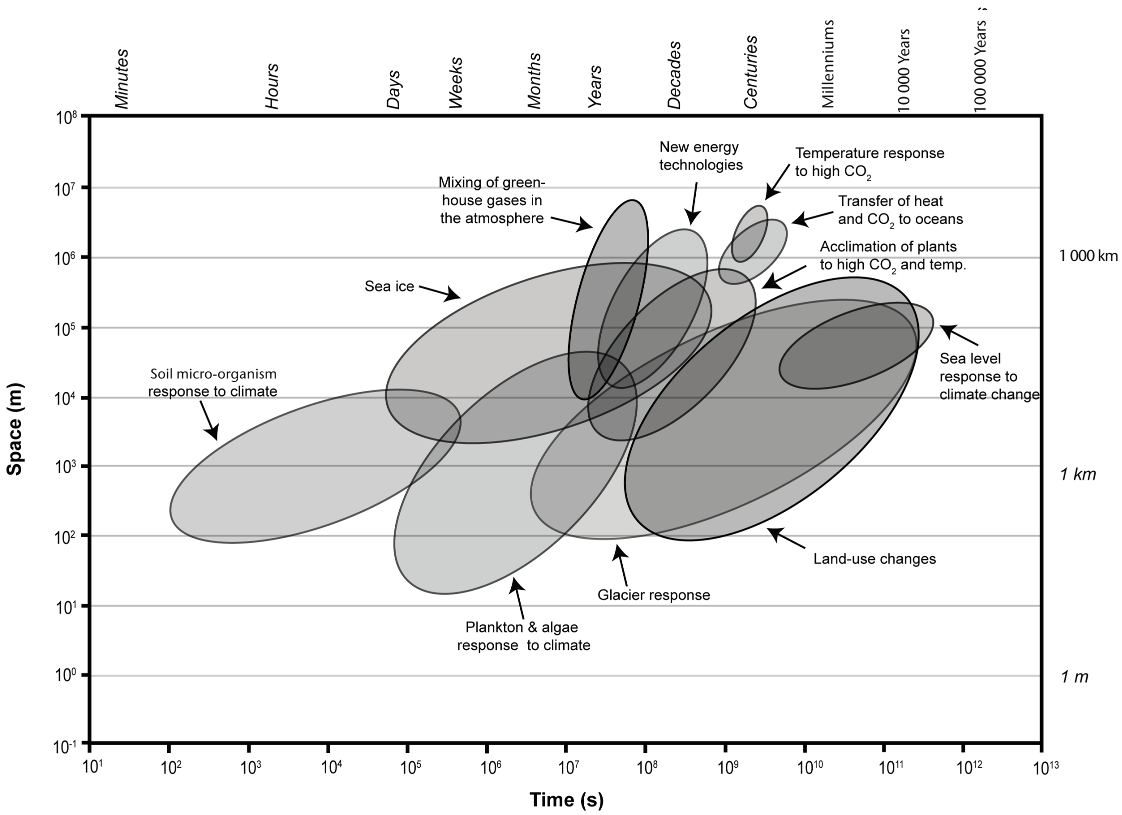


**Figure 1.2. Temporal and spatial scales**

*Source:* Todd Albert, United States of America availability of drinking water and food. Longer timescales of decades and centuries are important for studies of climate variation caused by natural phenomena such as atmospheric and oceanic circulation changes and by human activities.

Changing climate systems have become a major issue for humans. Human activities, especially the burning of fossil fuels, have led to changes in the composition of the global atmosphere. Marked increases in emissions of powerful greenhouse gases such as tropospheric carbon dioxide and methane during the industrial era, along with increased aerosols and particulate emissions, are significantly affecting the global climate. Over one fifth of the world's tropical forests were cleared between 1960 and 2000, likely altering the complex mesoscale and global hydrological cycles. Artificial canyons formed in cities by buildings, together with asphalt road surfaces, increase the amount of radiation absorbed from the sun, thus forming urban heat islands. Accelerated run-off of rainwater and the removal of trees and other vegetation reduces the amount of transpired water vapour that would otherwise help to moderate temperatures, but reduced water vapour due to reduced transpiration limits the absorption of terrestrial radiation. Pollution from vehicles and buildings accumulates, especially in calm conditions, and causes many human health problems and damage to structures. The climate community is currently focusing on several areas: monitoring to identify and describe changes in the climate system, improving models to be able to give credible guidance about what future conditions are likely to be, identifying the actions needed to mitigate the negative effects of climate change, and formulating policies that will enable the world to adapt to a changing climate.

### 1.2.3 ***Uses of climatic information and research***

Climatology has become a dynamic branch of science with a broad range of functions and applications. New techniques are being developed and investigations are being carried out to study the application of climatology in many fields, including agriculture, forestry, ecosystems, energy, industry, the production and distribution of goods, engineering, design and construction, human well-being, transportation, tourism, insurance, water resources, disaster management, fisheries and coastal development. Viable research programmes on the climate system and its broad influence and on the applications of climate knowledge for societal benefits are needed to enable climatologists to inform and advise users and answer a myriad of

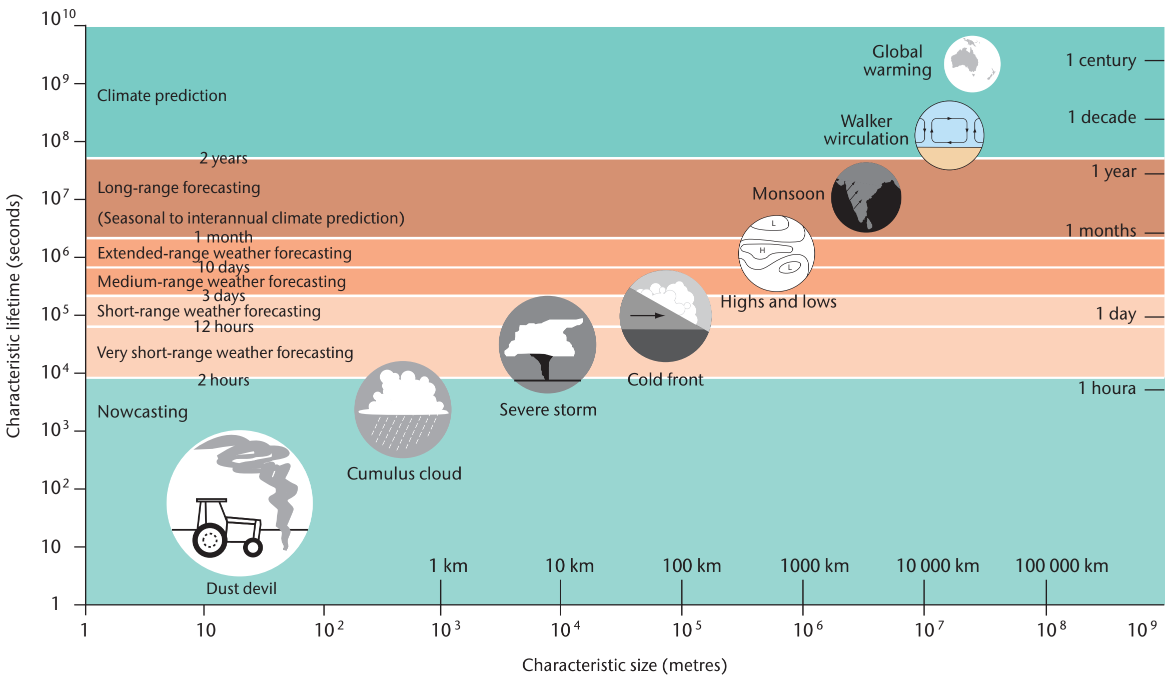


**Figure 1.3. Lifetime of atmospheric phenomena**

*Source:* Zillman (1997)

questions about the climate. Previously, the study of climate provided basic data, information and techniques to delineate local, mesoscale and global climates. While these are primary deliverables, they are also the raw material for deeper analysis and for services when coupled with other social, economic and physical data.

Climate data encompass long-term observational data, variables derived from observations such as sea level pressure, and data products such as gridded databases, reanalyses, predictions and projections (*Manual on the High-quality Global Data Management Framework for Climate* (WMO-No. 1238)). The crucial role of climate data to support planning for disaster mitigation and sustainable development and to guide measures to address the consequences of climate change are now firmly established in various conventions, including the United Nations Framework Convention on Climate Change. A major activity in most countries is the development of strategies and tactics to either mitigate or adapt to the societal effects of climate change. Climatology has become interdisciplinary in the sense that physical and biological sciences that describe the environment are merged with social sciences that describe human activities so that complex societal problems can be addressed. The term "climatology" has evolved into what is now often termed "climate science".

Since many users of climatological information are not climate scientists, the provider of the information should exploit technology and novel ways to portray and explain the information in a manner that is understandable to the user. It has become necessary to synthesize complex information into a simple metric such as an index, indicator or visualization. Determining how to present information effectively has become an area of study applicable to many disciplines, including climate science.

Applied climatology makes maximum use of meteorological and climatological knowledge and information to solve practical social, economic and environmental problems. Climatological services are designed for a variety of public, commercial and industrial users. Assessments of the effects of climate variability and climate change on human activities, as well as the effects of human activities on climate, are major factors in local, national and global economic development efforts, social programmes and resource management.

Given the impact of economic development and other human activities on climate and the way in which climate variability and climate change influence human societies, further research is needed into the physical and dynamical processes involved in the climate system, and such processes need to be described statistically. It is essential for stakeholders to understand human-induced and natural climate variability, climate sensitivity to human activities, and the predictability of weather and climate for periods ranging from days to decades so that they can adopt more effective responses to economic and societal problems.

Improving the prediction of climate is now a substantial global activity. Initially, predictions were based on empirical and statistical techniques, but now they derive more and more from expanded numerical weather prediction techniques. Increasingly complex models are being developed that represent the features of and the interactions among the atmosphere, oceans, land interface, sea ice, and atmospheric aerosols and gases. The models can be used to simulate climate change over several decades and to predict seasonal and inter-annual variations in climate. Such seasonal outlooks generally take the form of the probability that the value of an element, such as the mean temperature or aggregated rainfall over a period, will be above, close to or below normal. At present, seasonal outlooks are accurate for climate predictions in regions where there is a strong relationship between the sea-surface temperature and the weather, such as in many tropical areas. Because of their probabilistic nature, however, much care is needed in their dissemination and application.

All climate products and services used in research, operations, commerce and government, whether developed using past weather and climate data or to estimate the future climate, are underpinned by data obtained through the extensive and systematic observation and recording of a number of key variables that enable the climate to be described for a wide range of timescales. The suitability of a climate service depends greatly on the spatial density and accuracy of the observations and on the data management processes. Without systematic observations of the climate system, there can be no climate services.

The need for more accurate and timely information continues to increase rapidly as users' requirements become more diverse. It is in the interest of every country to apply consistent practices when performing climate observations and handling climate records and to maintain the necessary quality and usefulness of the services provided.

## 1.3 WMO climate-related programmes and initiatives

WMO facilitates studies on climate, its variations and extremes, and its influences on a variety of activities, including human health, safety and welfare, to support evidence-based decision-making on how best to adapt to a changing climate. WMO supports climate policymaking by providing authoritative advice and information on climate-change mitigation and adaptation. WMO draws on the best available scientific expertise from the NMHSs of its Members and international data centres and agencies. Moreover, it promotes a better understanding of the societal impacts of climate change within the United Nations system by supporting the United Nations Framework Convention on Climate Change, the chief global forum for international collaboration and action on climate change, and through a wide range of scientific and technical inputs. At the annual sessions of the Conference of the Parties to the Framework Convention, WMO plays a crucial role by providing the latest scientific advice and information to Governments, including the *Statement on the State of the Global Climate* and the *Greenhouse Gas Bulletin*. By promoting and coordinating many of the observing systems and research networks that underpin climate science, WMO has played a leading role in convincing Governments to address climate change.

The World Climate Programme (WCP) facilitates the analysis and prediction of Earth system variability and change for use in an increasing range of practical applications that are of direct relevance, benefit and value to society. These useful applications of climate information focus on user interaction and stimulate socioeconomic benefits that underpin GFCS. The scope of the World Climate Programme is to determine the physical basis of the climate system that allows increasingly skilful climate predictions and projections, develops operational structures to provide climate services, and develops and maintains an essential global observing system that is fully capable of meeting the climate information needs.

The Capacity Development Programme, with assistance from development partners, promotes collaboration between Members and WMO Programmes to support NMHSs in providing essential weather-, climate- and water-related services and in contributing to global efforts to protect life and property from natural hazards. The range of support includes education and training, demonstration projects, regional activities, research, development partnerships, institutional arrangements and guidance, technical advice, and advocacy to strengthen weather-, climate- and water-related services through compliance with WMO regulations.

The World Climate Research Programme (WCRP) coordinates climate research initiatives at an international level. The science activities it supports address cutting-edge topics that cannot be tackled by a single country, agency or discipline acting alone. WCRP fosters innovation and collaboration through the organization of global meetings, workshops and conferences. The actual research projects are carried out by scientists worldwide as part of projects at their home institutions. To ensure that policymakers and end users can benefit from the latest scientific advances, WCRP represents the state-of-the-art knowledge of its community towards high-level policy forums and towards the producers of operational climate predictions.

WCRP is guided by its two main objectives: to determine the predictability of climate and to determine the effect of human activities on climate. The better variability and change in the climate system are understood, the better society's knowledge of climate predictability and its predictive capacity will be. If global communities are equipped with tools for seamless climate predictions, they can better respond to the impacts of climate variability and change on major social and economic sectors, including food security, energy, transport, the environment, health and water resources. WCRP contributes to such services to society by advancing and communicating the global state of the art in climate science. WCRP collaborates closely with related programmes at the international and national levels, including observations, modelling, interactions between society and the climate system, and similar relevant topics.

The Global Climate Observing System (GCOS) is a co-sponsored programme that regularly assesses the status of global climate observations and produces guidance for its improvement. It is co-sponsored by WMO, the Intergovernmental Oceanographic Commission of UNESCO, the United Nations Environment Programme and the International Science Council. GCOS expert panels maintain definitions of essential climate variables (ECVs). They identify gaps by comparing the existing climate observation system with these ECVs. ECVs are the observations required to systematically observe Earth's changing climate. The expert panels regularly develop plans on how to sustain, coordinate and improve physical, chemical and biological observations. The observations supported by GCOS help to solve challenges in climate research and also underpin climate services and adaptation measures.

The Regional Programme supports the six regional associations that coordinate regional activities. It supports them by identifying the needs of Members, establishing requirements for regional networks, planning and monitoring progress, organizing regional subsidiary structures and promoting regional partnerships. The Programme ensures that the particular needs of regions are considered, taking into account the best interests of WMO as a whole. The Programme also assists weather services at the national and regional levels, enabling them to play a key role in the protection of life and property and in socioeconomic development.

The cross-cutting Regional Programme provides two-way communication between Members and the Secretariat, facilitating expert assistance, in particular for developing and least developed countries and small island developing States and island territories. Through the Programme, WMO builds partnerships with relevant regional and subregional organizations and intergovernmental and economic groupings.

The Agricultural Meteorology Programme supports food and agricultural production and activities by assisting NMHSs in meeting the needs of farmers, herders and fishers in order to develop sustainable agricultural systems, improve production and quality, reduce losses and risks, decrease costs, increase efficiency in the use of water, conserve natural resources, and decrease pollution from chemicals that contribute to the degradation of the environment. Climate information is used mainly for agricultural planning purposes, while recent weather data and weather forecasts are used mostly in current agricultural operations.

The Hydrology and Water Resources Programme promotes the effective use of hydrology in sustainable development to reduce the risk and impacts of water-related disasters and to support effective environmental management at the international, regional, national and basin levels. It strengthens the capabilities of Members, in particular those in developing countries or countries in transition, through technology transfer and capacity development. The Hydrology and Water Resources Programme supports Members by helping them to developing their capacities to perform various tasks: measuring basic hydrological elements from networks of hydrological and meteorological stations; collecting, processing, storing, retrieving and publishing hydrological data, including surface water and groundwater; providing data and information to planners and water managers; managing extremes, in particular through integrated flood and drought management; installing and operating hydrological forecasting systems; and integrating meteorological and climatological information and forecasts into water resources management.

All the above programmes host websites that provide reports and information on activities and projects relating to the programme. The websites are routinely updated with the latest information.

### 1.3.1 *WMO Technical Commissions*

Following approval of the WMO reform package at the Eighteenth World Meteorological Congress, in June 2019, the previous eight technical commissions, including the Commission for Climatology, were merged into two new technical commissions:

(a) The Commission for Observation, Infrastructure and Information Systems (Infrastructure Commission, or INFCOM) contributes to: the development and implementation of globally coordinated systems for acquiring, processing, transmitting and disseminating Earth system observations and related standards; the coordination of the production and use of standardized analysis and model forecast fields; and the development and implementation of sound data and information management practices for all WMO Programmes and their associated application and services areas;

(b) The Commission for Weather, Climate, Hydrological, Marine and Related Environmental Services and Applications (Services Commission, or SERCOM) contributes to the development and implementation of globally harmonized weather, climate, water, ocean and environment-related services and applications to enable informed decision-making and socioeconomic benefits for all user communities and society as a whole.

## 1.4 Global and regional climate activities

All countries should understand and provide for the climate-related information needs of the public. This requires climate observations; data management and transmission; various data services; climate-system monitoring, practical applications and services for different user groups; forecasts on subseasonal and inter-annual timescales; climate projections; policy-relevant assessments of climate variability and change; and research priorities that increase the potential benefits of all these activities. Many countries, especially developing and least developed countries, may not have the sufficient individual capacity to perform all these services. The Third World Climate Conference, held in Geneva in 2009, proposed the creation of GFCS to strengthen the production, availability, delivery and application of science-based climate prediction and services. The Framework is intended to provide a mechanism for developers, providers of climate information and climate-sensitive sectors around the world to work together to help the global community to better adapt to the challenges of climate variability and change.

GFCS accelerates and coordinates the technically and scientifically sound implementation of measures to improve climate-related outcomes at the national, regional and global levels. As a framework with broad participation and reach, GFCS enables the development and application of climate services to assist decision-making at all levels in support of addressing climate-related risks.

The implementation of GFCS is comprised of five components: observations and monitoring; the Climate Services Information System (CSIS); research, modelling and prediction; the user interface platform and capacity development. The focus is on developing and delivering services in five priority areas, which address issues basic to the human condition and present the most immediate opportunities for bringing benefits to human safety and well-being:

(a) Agriculture and food security;

(b) Disaster risk reduction;

(c) Energy;

(d) Health;

(e) Water.

WMO has developed the network of Global Producing Centres for Long-range Forecasts (GPCLRFs) and the RCCs to help Members to cope effectively with their climate information needs. The definitions and mandatory functions of the GPCLRFs and RCCs are contained in the *Manual on the Global Data-processing and Forecasting System* (WMO-No. 485), Part I, and are part of the WMO Technical Regulations. Part II of the Manual also provides the criteria for the designation of GPCLRFs, RCCs and other operational centres by WMO.

The designated GPCLRFs produce global long-range forecasts according to the criteria defined in the *Manual on the Global Data-processing and Forecasting System* (WMO-No. 485) and are recognized by WMO on the basis of the recommendation of the Commission for Basic Systems. In addition, WMO has established a Lead Centre for Long-Range Forecast Multi-Model Ensembles and a Lead Centre for the Standard Verification System for Long-range Forecast, which provide added value to the operational services of the GPCLRFs.

The RCCs are designed to help WMO Members in a given region to deliver better and more consistent climate services and products, such as regional long-range forecasts, and to strengthen the capability of Members to meet national climate information needs. The primary clients of an RCC are NMHSs, and products are provided to NMHSs for further definition and dissemination and are not distributed to users without the permission of the NMHSs in the region. The responsibilities of an RCC do not duplicate or replace those of NMHSs. It is important to note that NMHSs retain the mandate and authority to provide the liaison with national user groups and to issue advisories and warnings. Further, all RCCs are required to adhere to the principles of WMO Resolution 40 (Cg-XII) concerning the exchange of data and products.

The complete suite of products and services of RCCs varies from one region to another, according to the priorities established by the relevant regional association. Some essential functions, however, must be performed by all WMO-designated RCCs according to established criteria, thus ensuring a certain uniformity among RCC services around the globe. These functions include:

(a) Operational activities for long-range forecasting, including: the interpretation and assessment of relevant outputs from GPCLRFs, the generation of regional and subregional tailored products, and the preparation of consensus statements concerning regional and subregional forecasts;

(b) Climate monitoring, including regional and subregional climate diagnostics, the analysis of climate variability and extremes, and the implementation of regional climate watches for extreme climate events;

(c) Data services to support long-range forecasting and climate monitoring, including the development of regional climate data sets;

(d) Training in the use of operational RCC products and services.

In addition to these mandatory RCC functions, a number of activities are highly recommended. These include:

(a) Downscaling of climate-change scenarios;

(b) Non-operational data services such as data rescue and data homogenization;

(c) Coordination functions;

(d) Training and capacity-building;

(e) Research and development.

Recognizing that climate information can substantially aid adaptation to and mitigation of the impacts of climate variability and change, WMO has helped to establish the Regional Climate Outlook Forums. The main purpose of the Forums is to produce and disseminate a regional assessment of the state of the regional climate for the upcoming season. The Forums bring together national, regional and international climate experts on an operational basis to produce regional climate outlooks using a consensus-based approach and based on input from NMHSs, regional institutions, RCCs and GPCLRFs. The Forums facilitate enhanced feedback from users to climate scientists and catalyse the development of user-specific products. Impediments to the use of climate information are reviewed. Participants share successful lessons from applications of past products and enhance sector-specific applications. The regional forums often lead to national forums, at which detailed national climate outlooks and risk information, including warnings, are developed for decision makers and the public.

The format of the Regional Climate Outlook Forums varies from region to region. At most Forums, regional and international climate experts meet to develop a consensus for regional climate outlooks, usually in a probabilistic form. Other activities sometimes include the following:

(a) A broader forum comprising both climate scientists and representatives from user sectors for the presentation of consensus climate outlooks, discussion and identification of expected sectoral impacts and implications, and the formulation of response strategies;

(b) Training workshops on seasonal climate prediction to strengthen the capacity of national and regional climate scientists;

(c) Special outreach sessions involving media experts to develop effective communication strategies.

These global and regional programmes each host websites that contain reports, activities and other programme information. The websites are routinely updated with the latest information.

## 1.5 National climate activities

In most countries, the NMHS has held key responsibilities for national climate activities for many years. Such responsibilities have included:

(a) Quality control, archiving and management of recent and historical climate observations;

(b) The provision of climatological information;

(c) Research on climate;

(d) Climate prediction;

(e) The application of climate knowledge.

Academia and private enterprise have been increasing their contributions to these activities.

In some countries, the NMHS has a single division responsible for all climatological activities. In other countries, the NMHS assigns responsibilities for different climatological activities (such as observation, data management and research) to different units. Sometimes they assign responsibilities based on common skills, such as across synoptic analysis and climate observation, or across research in weather and climate prediction. In some countries, subnational activities are handled by area or branch offices, while in others, the necessary pooling and retention of skills for certain activities are achieved through a regional cooperative entity serving the needs of a group of countries.

Where there is a division of responsibility within an NMHS, or where responsibilities are assigned to another institution altogether, it is essential that those applying the climatological data in research or services liaise closely with those responsible for obtaining and managing the observations. This close communication is paramount to determine the adequacy of the networks and the content and quality control of the observations. It is also essential that personnel receive training that is appropriate to their duties so that the climatological aspects are handled as effectively as they would in an integrated climate centre or division. If data are handled in several places, it is important to establish a single coordinating authority to ensure that there is no divergence among data sets. Climatologists within an NMHS should be directly accountable for or provide advice about the following:

(a) Planning of station networks;

(b) Location or relocation of climatological stations;

(c) Care and security of observing sites;

(d) Regular inspection of stations;

(e) Selection and training of observers;

(f) Installation of instruments or observing systems in a way that ensures that representative and homogeneous records are obtained (see Chapter 2).

Once observational data are acquired, they must be managed. The functions involved in the management of information from observing sites include data and metadata acquisition, quality control, storage, archiving and access (see Chapter 2). Dissemination of the collected climatic information is another requirement. NMHSs need to anticipate, investigate and understand the climatological information needed by government departments, research institutions, academia, commerce, industry and the general public. They must also be able to promote and market the use of the information and provide advice on how to use it, and they must make their expertise available for the interpretation of the data (see Chapters 4 and 5).

An NMHS should maintain a continuing research and development programme or establish a working relationship with an institution that has research and development capabilities directly related to the climatological functions and operations of the NMHS. The research programme should consider new climate applications and products that increase users' understanding and application of climate information.

Studies should explore new and more efficient methods for managing an ever-increasing volume of data, improving user access to archived data, and digitizing paper-based records. Quality-assurance programmes for observations and summaries should be routinely evaluated to develop better techniques in a more timely manner. The use of information dissemination platforms should also be developed (see Chapter 5).

For national and international responsibilities to be achieved and for NMHS climate activity capacities to be built, suitably trained personnel must be available. Competency frameworks (the *Guide to Competency* (WMO-No. 1205) and the *Compendium of WMO Competency Frameworks* (WMO-No. 1209)) define standards and recommended practices for services, for taking observations and for generating, sharing and accessing meteorological, climatological and hydrological data. An NMHS should maintain and develop links with training and research establishments dealing with climatology and its applications. Institutions supplying education and training opportunities to NMHS staff should be encouraged to adjust their training courses and programmes to better support the competency frameworks. In particular, the NMHS should ensure that relevant staff attend training programmes that supplement general meteorological training with climatology-specific education and skills.

The essential components of a national climate service programme are:

(a) Mechanisms to ensure that all users' climate information and prediction needs are recognized;

(b) Collection and quality control of meteorological and related observations, management of databases and provision of data;

(c) Coordination of meteorological, oceanographic, hydrological and related scientific research to improve climate services;

(d) Multidisciplinary studies so that the climate service can determine national risk and sectoral and community vulnerability related to climate variability and change, formulate appropriate response strategies and recommend national policies;

(e) Development and provision of climate information and prediction services to meet user needs;

(f) Linkages to other programmes with similar or related objectives to avoid unnecessary duplication of efforts.

To be successful, a national climate service programme must have a structure that works effectively in the country in which it is based. The National Frameworks for Climate Services (NFCSs), which are part of GFCS, are coordinating mechanisms that enable the development and delivery of climate services at the national level. Established NFCSs improve risk management. Through NFCSs, science-based climate information and predictions are developed and incorporated into decision-making and policymaking.

NFCSs contribute to the implementation of the Paris Agreement, which calls for science-based research and systematic observations (Article 7, section 7c). In supporting the implementation of the Paris Agreement, NFCSs complement national adaptation plans in medium- and long-term adaptation to climate impacts. National adaptation plan elements that require effective and timely climate services include the assessment of climate vulnerabilities, the identification of adaptation options, the development of products that help to improve how climate and its impacts are understood, and the enhancement of capacity for the planning and implementation of adaptation for climate-sensitive sectors. The Paris Agreement (Article 4, section 2) requires each party to prepare, communicate and maintain successive nationally determined contributions that it intends to achieve. The NFCS mechanism supports countries in meeting this requirement by ensuring the delivery of multisectoral climate information and services to policymakers. This information is based on: national and international data on temperature, rainfall, wind, soil moisture and ocean conditions; risk and vulnerability analyses; assessments; long-term projections and scenarios; and non-meteorological data such as agricultural production, health trends, the population distribution in high-risk areas, road and infrastructure maps, and other socioeconomic variables.

The main functions of an NFCS are to serve as:

(a) A platform for institutional coordination, collaboration and co-production among relevant technical departments across line ministries at the national and subnational levels (NMHSs and technical experts across line ministries of water, agriculture, health, energy, etc.) to develop and deliver user-oriented climate services. Often, sectoral subcommittees or working groups are established as part of the NFCS to facilitate in-depth and regular interaction among NMHSs and their sectoral counterparts (climate and health working groups, interdisciplinary working groups on climate and agriculture, climate and energy subcommittees, disaster risk reduction platforms, etc.);

(b) A legal framework for collaboration at the national level to generate and share user-oriented climate services for relevant social and economic sectors;

(c) An opportunity to bridge the gap between available climate services and user needs at the national, subnational and local levels, continuously identifying user needs for climate services, communicating available climate products and services to users in the relevant sectors, and obtaining feedback from users on climate products and services;

(d) A vehicle for scientific coordination to synthesize the state of the climate at the national level and distil climate knowledge outputs for evidence-based policymaker actions;

(e) An operational bridge between climate research, NMHSs and other relevant national institutions to increase collaboration on climate knowledge and to share data and expertise and thus improve services;

(f) A functional chain linking climate knowledge with action on the ground to maximize the application of climate information and products by identifying bottlenecks that are holding back improvements in the delivery of climate services;

(g) A vehicle to enhance the contribution of climate science to the development of national adaptation plans, disaster risk reduction, sustainable development goals and national development policies by enhancing the integration of climate information and products into decision-making and national policies.

It is important to understand that a national climate service programme is an ongoing process and that its structure may change over time. As an integral part of the process, user feedback and needs should be continuously reviewed and incorporated into the programme and useful products and services should be developed. Gathering requirements and specifications is a vital part of programme development. Users can contribute by evaluating products, and their feedback is used to refine products and develop new, improved products. Measuring the benefits of the application of products can be a difficult task, but interaction with users through workshops, training and other outreach activities will aid the process. Well-documented user requirements and positive feedback can greatly strengthen the case for a national climate service programme and support requests for international financial support for aspects of the programme. Documented endorsement of the programme by one or more representative sections of the user community is essential to guide future operations and to promote the service as a successful entity.

## 1.6 Quality management

WMO, through its Programmes and activities, is dedicated to ensuring that all meteorological, climatological, hydrological, marine and related environmental data, products and services are of the highest possible quality, especially those that support the protection of life and property, safety on land, at sea and in the air, sustainable economic development and protection of the environment.

To achieve this goal, WMO is committed to adopting and implementing an organization-wide approach to quality-management to meet its main objectives and strategic priorities. The quality-management approach provides the NMHSs of WMO Members and other relevant stakeholders with a framework to help them to:

(a) Understand their purpose and the context in which they operate nationally and internationally;

(b) Plan and instigate their strategic direction;

(c) Identify and provide the appropriate resources to achieve their planned objectives;

(d) Deliver high-quality products and services consistently;

(e) Evaluate and review their organizational practices, procedures and processes to drive continual improvement.

One of the ways to ensure an effective national climate service programme is to implement a quality-management system (QMS). Many NMHSs strive to make observations on quality and, ultimately, to provide high-quality products and services. They are therefore familiar with the concept of quality, but they are not necessarily familiar with how to implement a system. By definition, a QMS is a set of policies, processes and procedures required for the planning and execution of various core business processes to improve the performance of an NMHS. A QMS enables organizations to identify, measure, control and improve the various core business processes that will ultimately lead to improved business performance and enhanced customer satisfaction.

The components of QMS are determined by each NMHS and its objectives and goals. A QMS based on an international standard, such as that established by the International Organization for Standardization (ISO), is helpful because it provides a set of requirements that can be adopted to drive quality in an NMHS. The adoption of ISO 9001 will ensure a focused quality-management approach for the delivery of climate products and services. ISO 9001 is the only standard in the ISO family against which organizations can be certified for compliance (or registered) through an independent third-party (external) audit process. This process provides validation of the system; compliance with ISO 9001 is recognized through certification.

A quality-management principle is a fundamental rule for leading, operating and developing an organization with the objective of continually improving performance over the long term through an approach focused on all stakeholders, particularly customers. According to the *Manual on the WMO Integrated Global Observing System* (WMO-No. 1160), the following quality-management principles should be taken into account:

(a) Customer focus;

(b) Leadership;

(c) Engagement of people;

(d) Process approach;

(e) System approach to management;

(f) Improvement;

(g) Evidence-based decision-making;

(h) Relationship management.

A key approach underpinning the adoption of ISO 9001 is the management standard, which is based on the management of processes and their interaction using what is known as the plan-do-check-act cycle. This involves the establishment of objectives and processes in such a way that the resources on hand to meet requirements are taken into consideration. The plan is then implemented and the resulting outputs, such as products and services, are verified to ensure they are in line with the plan. If any potential improvements are identified, appropriate measures are taken and the entire cycle is repeated. During the cycle, any risks and opportunities identified need to be addressed to increase the efficiency of the system.

The key benefits of implementing a QMS are:

(a) Consistency in the issuing of quality products and services;

(b) Assistance in meeting customer needs;

(c) More efficient ways of working that will save time, money and resources;

(d) Improved operational performance thanks to the reduction in errors;

(e) Better motivated and more engaged staff, with more efficient internal processes;

(f) Facilitation and identification of training opportunities;

(g) Better identification of risks and opportunities.

A QMS also provides the framework within which to coordinate and direct an organization's activities to meet customer and regulatory requirements and improve the organization's effectiveness and efficiency on a continuous basis. It should thus be an end-to-end system that encapsulates all activities, from raw measurements and observations to services delivered to end users. The focus of a QMS is on improving quality and performance to meet or exceed stakeholder expectations and, in particular, customer expectations. A viable QMS also takes into account the context of the NMHS and the environment in which it operates and delivers its products and services. A QMS is an important part of the climatological practices of NMHSs and plays a key role in driving quality through the whole value chain, from the setting up of instrumentation and the storage and quality control of data to the production of climatological products and services. This value chain is made stronger by the people involved. Although no person is involved in every aspect of the chain, the competencies of the people involved are necessary for the objectives to be achieved (*Technical Regulations* (WMO-No. 49), Volume I).

WMO endorses the delivery of climate products and services within an ISO 9001 quality-management framework. To support this approach, it has provided a comprehensive set of WMO technical regulations and guidance documents, including the *Technical Regulations* (WMO-No. 49), Volume I, the *Guide to the Implementation of Quality Management Systems for National Meteorological and Hydrological Services and Other Relevant Service Providers* (WMO-No. 1100), the *Guide to Competency* (WMO-No. 1205), the *Compendium of WMO Competency Frameworks* (WMO-No. 1209) and the *Guidelines on Quality Management in Climate Services* (WMO-No. 1221), all of which provide a sound foundation for the operation of NMHSs and compliance with national and international regulatory requirements.

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# 2. OBSERVATIONAL CLIMATE DATA AND MANAGEMENT

## 2.1 Introduction

Historians have recorded information about the weather for thousands of years. In the past, they recorded the information based on other people's accounts, rather than their personal observations. Such accounts may have been vague, truncated or affected by memory lapses. This type of weather information was embedded in an immense array of other kinds of information, and much of it is contained in national libraries and archives. National archives of meteorological information are a relatively recent phenomenon, with the earliest typically having been established during the first half of the twentieth century. Since the 1940s, and especially following the establishment of WMO, standardized forms and procedures have gradually become prevalent, and national meteorology-specific archives have been designated.

The quantification of climatological data developed thanks to improvements to instrumentation, which facilitated observations of continuous and discrete variables and the recording of appropriate values in journals and logbooks. Until the 1970s, these original forms constituted the bulk of all the holdings of climatological information at most collection centres. These centres were either a section of the local or national government or the central office of an industry such as mining, agriculture or aviation. Gradually, climatological data-gathering activities were assembled within a concerted programme of observation and collection to serve national and international interests. Since the late twentieth century, most weather information has been transmitted digitally to centralized national collection centres, primarily to support weather forecasting, but more recently for a broader range of purposes. It has been common practice, however, for climate centres around the world to rely on the original observing documents to obtain older historical data for the creation of the climate record.

Rapid advances in computer technology are dramatically improving the collection, transmission, processing and storage of operational geophysical data, and archives are increasingly being populated with data that have never been recorded on paper. The power and ease of use of computers, the ability to record and transfer information electronically, and the development of international exchange mechanisms have given climatologists tools to rapidly improve how climate is understood. Every effort should be made to obtain a complete, digital collection of all primary observed data. Collecting data electronically at the source allows rapid and automatic control measures to be applied, including error-checking, prior to the data's transmission from the observation site.

Management of the vast variety of data requires a systematic approach that encompasses paper records, microform records (where relevant) and digital records. The *Manual on the High-quality Global Data Management Framework for Climate* (WMO-No. 1238) provides definitions, standards and recommended practices for managing data for climate purposes. It also provides the basis for data set stewardship assessment (see section 2.5). The framework and specifications for a systematic approach are given in the *Manual on the WMO Information System* (WMO-No. 1060). This publication and the manuals and guides it references are designed to ensure that WMO Members use sufficiently standardized data, information and communications practices, procedures and specifications.

This chapter discusses general concepts and considerations for observing and managing climate data. Detailed information and guidance relating to specific topics can be found in the reference material listed in the final section of the chapter.

## 2.2 Observations

The WMO Integrated Global Observing System (WIGOS) provides a framework for the integration and sharing of observational data from NMHSs and other sources. Although the main purpose of WIGOS is to improve WMO observing systems, it also interfaces with co-sponsored and non-WMO observing systems. The current goal is to facilitate the production of weather and climate services and products for the five initial priority areas of GFCS: agriculture and food security, disaster risk reduction, energy, health, and water. WIGOS achieves interoperability and compatibility through the application of internationally accepted standards and best practices. Data compatibility is supported by the use of standardized data representation and formats. WIGOS aims to improve the quality and availability of data and metadata in order to develop capacity and improve accessibility.

A key component of WIGOS is the WMO Global Observing System. This coordinated system of land- and space-based observing subsystems provides high-quality, standardized meteorological and related environmental and geophysical observations in a cost-effective way. The WMO Global Ocean Observing System is a similar coordinated system of marine and ocean observing networks. The transmission of data from these networks and from other land, marine, air and satellite networks to central processing locations allows the timely preparation of weather and climate analyses, forecasts, warnings, services and research for all WMO Programmes and for relevant environmental programmes of other international organizations.

This guidance on observations specifies the elements needed to describe the climate and the locations at which the elements are measured, the instrumentation required, the siting of stations, network design and network operations. The guidance is based on the *Guide to Instruments and Methods of Observation* (WMO-No. 8), the *Guide to the Global Observing System* (WMO-No. 488), the *Guidelines on Climate Observation Networks and Systems* (WMO/TD-No. 1185), the *Manual on the WMO Integrated Global Observing System* (WMO-No. 1160) and the *Manual on Marine Meteorological Services* (WMO-No. 558), Volume I. Each edition of the *Guide to Instruments and Methods of Observation* (WMO-No. 8) has a slightly different emphasis, so it is advisable to retain older editions for reference purposes. Cross references to other WMO publications containing more detailed guidance are provided in the sections below. Guidance is also based on 10 climate monitoring principles set forth in the *Report of the GCOS/GOOS/GTOS Joint Data and Information Management Panel: Third Session* (WMO/TD-No. 847) and in the *Manual on the WMO Integrated Global Observing System* (WMO-No. 1160):

(a) The impact of new systems and changes to existing systems should be assessed prior to their implementation;

(b) A suitable overlap period between new and old observing systems is required;

(c) The details and history of local conditions, instruments, operating procedures, data-processing algorithms and other factors pertinent to interpreting data (metadata) should be documented and treated with the same care as the data themselves;

(d) The quality and homogeneity of data should be regularly assessed as a part of routine operations;

(e) Consideration of the needs for environmental and climate monitoring products and assessments should be integrated into national, regional and global observing priorities;

(f) The operation of historically uninterrupted stations and observing systems should be maintained;

(g) For additional observations, high priority should be given to data-poor areas, poorly observed parameters, areas sensitive to change, and key measurements with inadequate temporal resolution;

(h) Long-term requirements should be specified to network designers, operators and instrument engineers at the outset of system design and implementation;

(i) Measures should be taken to promote enabling research observing systems to perform long-term operations with careful planning;

(j) Data management systems that facilitate the access, use and interpretation of data and products should be included as essential elements of climate monitoring systems.

The above principles were established primarily for surface-based observations, but they also apply to data for all data platforms. The following additional principles are specific to satellite observations:

(a) Constant sampling within the diurnal cycle (to minimize the effects of orbital decay and orbit drift) should be maintained;

(b) Overlapping observations should be ensured for a period sufficient to determine inter-satellite biases;

(c) Continuity of satellite measurements (elimination of gaps in the long-term record) through appropriate launch and orbital strategies should be ensured;

(d) Rigorous pre-launch instrument characterization and calibration, including radiance confirmation against an international radiance scale provided by a national metrology institute, should be ensured;

(e) On-board calibration suitable for climate-system observations should be ensured and associated instrument characteristics should be monitored;

(f) Operational generation of priority climate products should be sustained, and peer-reviewed new products should be introduced as appropriate;

(g) Data systems needed to facilitate users' access to climate products, metadata and raw data, including key data for delayed-mode analysis, should be established and maintained;

(h) Use of functioning baseline instruments that meet the calibration and stability requirements stated above should be maintained for as long as possible, even when they exist on decommissioned satellites;

(i) Complementary in situ baseline observations for satellite measurements should be maintained through appropriate activities and cooperation;

(j) Random errors and time-dependent biases in satellite observations and derived products should be identified.

### 2.2.1 ***Elements***

A climatic element is any one of the properties of the climate system described in section 1.2.2. Measurements or observations of these elements are made as part of a variety of kinds of stations and networks. Details about these networks can be found in the *Manual on the WMO Integrated Global Observing System* (WMO-No. 1160), the three volumes of the *Technical Regulations* (WMO-No. 49), in particular Volume III, and the *Guide to Agricultural Meteorological Practices* (WMO-No. 134). These documents should be kept readily available and should be consulted as needed.

ECVs are defined as the physical, chemical and biogeochemical variables that critically contribute to the characterization of the Earth's climate (GCOS-200). They fall into the following categories:

(a) Atmosphere surface: precipitation, pressure, surface radiation budget, surface wind speed and direction, temperature and water vapour;

(b) Upper atmosphere: earth radiation budget, lightning, temperature, water vapour, wind speed and wind direction;

(c) Atmospheric composition: aerosols, carbon dioxide, methane, other greenhouse gases, clouds, ozone, and precursors for aerosols and ozone;

(d) Hydrosphere: groundwater, lakes and river discharge;

(e) Cryosphere: glaciers, ice sheets, ice shelves, permafrost and snow;

(f) Biosphere: above-ground biomass, albedo, evaporation from land, fire, fraction of absorbed photosynthetically active radiation, land cover, land surface temperature, leaf area index, soil carbon and soil moisture;

(g) Anthroposphere: anthropogenic greenhouse gas fluxes, anthropogenic water use;

(h) Ocean physical: surface heat flux, sea ice, sea level, sea state, sea-surface currents, sea-surface salinity, sea-surface stress, sea-surface temperature, subsurface currents, subsurface salinity and subsurface temperature;

(i) Ocean biogeochemical: inorganic carbon, nitrous oxide, nutrients, colour, oxygen and transient tracers;

(j) Biological/ecosystems: marine habitats and plankton.

Data sets of observations of these variables provide the empirical evidence needed to understand and predict the evolution of climate, guide mitigation and adaptation measures, assess risks, enable the attribution of climate events to underlying causes, and underpin climate services.

It is important to recognize that the data sets of some, or perhaps all, of the elements are subject to many sources of error or discontinuities. Upper-air radiosonde data sets, for example, usually have many discontinuities and biases resulting from instrument and operational procedural changes and incomplete metadata. Satellite observations have been available since the 1970s, and some have been assembled and reprocessed to generate continuous records. Just as the radiosonde record has deficiencies, so do satellite data. The deficiencies include limited vertical resolution, orbit drift, satellite platform changes, instrument drift, complications with calibration procedures, and the introduction of biases through modifications made to processing algorithms.

Greater spatial and temporal coverage can be achieved with remote sensing than with in situ observations. Remotely sensed data also supplement observations from other platforms and are especially useful when such observations are missing or corrupted. Although there are advantages to using remotely sensed data, there are also problems associated with using such data directly for climate applications. Most importantly, the short period of record means that remotely sensed data are often less useful than conventional instrumental data in inferring long-term climate variability and change. Also, remotely sensed data may not be directly comparable to in situ measurements. For example, satellite estimates of the Earth's skin temperature are not the same as temperature measurements taken in a standard screen, and the relationship between radar measurements of reflectivity and precipitation amounts collected in rain gauges may be quite complex. With care, however, it is possible to construct homogeneous series that combine remotely sensed and in situ measurements.

### 2.2.2 Instrumentation concerns

This section provides guidance on some basic surface instrumentation and on the selection of instruments. Several other WMO publications that are necessary companions to this Guide should be readily available and consulted as needed. A thorough survey of instruments suitable for measuring climate and other elements at land and marine stations is provided in the *Guide to Instruments and Methods of Observation* (WMO-No. 8). Details of the instrumentation needed to measure agrometeorological elements are given in the *Guide to Agricultural Meteorological Practices* (WMO-No. 134) and, for hydrological purposes, in the *Guide to Hydrological Practices* (WMO-No. 168), volumes I and II.

When instruments are selected, including any associated data-processing and transmission systems, the 10 climate monitoring principles set out in section 2.2 should be followed and several other concerns should be taken into account, namely:

(a) Reliability (the instrument should function within its design specifications at all times);

(b) Suitability: (the instrument should be suitable for the operational environment at the station and for other equipment with which it must be operated);

(c) Accuracy;

(d) Simplicity of design;

(e) Reasons for taking observations.

Ideally, all instruments should be chosen to provide the high level of accuracy and precision required for climatological purposes. They should also continue to provide the required level of accuracy for a long period of time, as instrument "drift" can lead to serious inhomogeneities in a climate record; accuracy is of limited use without reliability. The Measurement Quality Classifications for Surface Observing Stations on Land (proposed for inclusion in the *Guide to Instruments and Methods of Observation* (WMO-No. 8)) is intended to be used by network designers, managers and data users to assess and monitor measurement quality at an existing station. The Measurement Quality Classifications scheme will help climatologists to better understand and quantify contributions to overall measurement uncertainty. The scheme is also applicable to support the design and optimization of a new system so that it delivers fit-for-purpose measurements and to support decisions on the purchase and evaluation of measurement systems.

The simpler the instrumentation, the easier it is to operate and maintain and the easier it is to monitor its performance. It is sometimes necessary to install redundant sensors to properly track performance and reliability over time. Complex systems can easily lead to data inhomogeneities, data loss, high maintenance costs and changing accuracy. There may be a variety of options for obtaining climate observations. When these options are considered, it is important to compare personnel, maintenance and replacement costs. Prices can often be negotiated with manufacturers on the basis of factors such as quantities purchased.

Autographic and data-logger equipment exists for the recording of many climatic elements. Observers should ensure that the equipment is operated properly and that information recorded on charts, for example, is clear and distinct. Observers should be responsible for regularly verifying and evaluating the recorded data by checking them against direct-reading equipment and for making time marks at frequent, specified intervals. The recorded data can be used effectively to fill gaps and to complete the record when direct observations are missed because the person responsible for recording the data is absent from the observing station, for instance because of illness. The *Guide to Instruments and Methods of Observation* (WMO-No. 8) gives specific guidance on the maintenance and operation of recording instruments, drums and clocks.

Automatic weather stations (AWSs) have been used to generate additional data to supplement the data from manned stations and to increase network densities, reporting frequencies and the quantities of elements observed, especially in remote and largely unpopulated areas where human access is difficult. Some of the sensitivity and accuracy requirements of these automated stations are given in the *Guide to Instruments and Methods of Observation* (WMO-No. 8); others are being developed, especially for studies of climate variability. Although AWSs have considerable potential to provide high-frequency data, and although they provide additional data from remote locations, there are several significant costs associated with operating them. The stations need to be maintained, resulting in labour costs. There are also costs associated with ensuring that the stations are reliable, accessible for installation and maintenance (including restoring service after outages) and compliant with WMO standards. Furthermore, there must be sufficient labour available, suitable power sources, a secure site and suitable communications infrastructure. The additional costs of these factors must be carefully weighed against the significant benefits, such as a denser or more extensive network. AWSs can be powerful alternatives to manned observational programmes and are sometimes the preferred option or the only option, but a strong organizational commitment is needed to ensure that the stations are managed and maintained for the long-term.

Historically, most climatological data for the upper air have been derived from measurements recorded using balloon-borne radiosondes for synoptic forecasting. It is important for each

NMHS to issue suitable instruction manuals to each upper-air station for the proper use of equipment and interpretation of data. It is also important to note that there are several issues concerning the quality of radiosonde measurements for climate monitoring and climate-change detection purposes. The issues include radiation errors, non-uniform spatial coverage and lack of comparisons among types of radiosondes; metadata concerning instrumentation and data-reduction and data-processing procedures are crucial for the use of radiosonde data in climate applications.

The climate monitoring principles should guide the development and operation of an upper-air observing system. Such a system may change over time as technology improves. A key requirement of the network is therefore that there should be sufficient overlap among systems for continuity to be maintained and for the accuracy and precision of old and new systems to be compared fully. Measurement systems should be calibrated regularly at the site. It is imperative that instrument replacement strategies take into account changes in other networks, such as the use of satellites. The Global Positioning System (GPS) provides a good opportunity for sounding the upper atmosphere, especially to detect the amount of humidity, which is related to the zenith tropospheric delay of a GPS signal. The global network of terrestrial GPS station receivers is well maintained and the measurements and data obtained by the receivers can be used to monitor the climate system.

The most common surface-based active remote-sensing technique is the use of weather radars. Atmospheric and environmental conditions can adversely affect radar data, and caution should be exercised when interpreting the information. Some of these effects include returns from mountains, buildings and other non-meteorological targets; attenuation of the radar signal when weather echoes are viewed through intervening areas of intense precipitation; temperature inversions in the lower layers of the atmosphere, which bend the radar beam in such a way that ground clutter is observed where it is not normally expected; and the bright band, which is a layer of enhanced reflectivity caused by the melting of ice particles as they fall through the freezing level in the atmosphere, which can result in overestimation of rainfall. Use of radar data in climate studies has been limited by access and processing capabilities, uncertainties in calibration and calibration changes, and the complex relationship between reflectivity and precipitation.

Wind profilers use radar to construct vertical profiles of horizontal wind speed and direction from near the surface to the tropopause. Although they work best in clear air, they can also be used in the presence of clouds and in moderate precipitation. When equipped with a radio-acoustic sounding system, profilers can also measure and construct vertical temperature profiles. The climatic characteristics and geographical constraints of the area should dictate the types and the nature of the instruments that are installed.

The accuracy and efficiency of a lightning-detector network gradually decrease on its outer boundaries. The detection wave propagates without too much attenuation over distance, depending on the frequency band used, but if a lightning flash is too far away from the network, the stroke is no longer be detected. (The minimum distance beyond which strokes are no longer detected depends on the stroke amplitude and the network configuration.) Also, measurements of the same element should be taken simultaneously by more than one instrument for a period long enough to calibrate the instruments and increase the quality of the data.

Many long-distance aircraft are fitted with automatic recording systems that report temperature and wind, and in some cases humidity, at regular intervals while the aircraft is in the air. Some aircraft record and report frequent observations during take-off and descent to significantly augment the standard radiosonde data, at least throughout the troposphere. Such data are assimilated into operational meteorological analysis systems and, through reanalysis programmes, they ultimately contribute substantially to the broader climate record. Uncertainty regarding the calculation of aircraft measurements should be evaluated along with the effects of the sampling interval and the averaging time. The examination of typical time series of vertical acceleration data often indicates a high variability of statistical properties over short distances. Variation in the air speed of a single aircraft or among different aircraft types alters the sampling distances and changes the wavelengths filtered. Although aircraft data are not as precise and accurate as most ground observing systems, they can provide useful supplemental information to meteorological databases.

The WMO Space Programme coordinates satellite data processing and dissemination activities based on common standards. A focus of the programme is the integration of space weather observations through the review of space- and surface-based observation requirements, the harmonization of sensor specifications, and the monitoring of plans for space weather observation. The objectives of the programme include enhancing the accessibility of current and next-generation satellite data and products, responding to user needs, promoting data exchange through common standards and the WMO Information System, and stimulating coordinated data processing with traceable quality. To achieve these objectives, WMO has analysed how the typical cycle of satellite system development relates to user-readiness projects. The recommended best practices are discussed in *Guidelines on Best Practices for Achieving User Readiness for New Meteorological Satellites* (WMO-No. 1187). With remote-sensing evolving rapidly, the latest documents should be referred to when remote-sensing data are processed, archived and used under the Space Programme.

## 2.3 **Climatological networks**

A network of stations is a collection of stations of the same type (such as a set of precipitation stations, radiation-measuring stations or climatological stations) administered as a group. Each network should be optimized to provide the data and perform as required at an acceptable cost. Most optimizing methods rely on data from a pre-existing network available over a long enough period to correctly document the properties of the meteorological fields. The methods are based on temporal and spatial statistical analyses of time series. It is difficult to assess a priori how long the data series must be, because the number of years necessary to capture variability and change characteristics may vary with the climatic element. It has been common practice to assume that at least 10 years of daily observations are necessary to produce the relevant base statistical parameters for most elements, and at least 30 years for precipitation. Observed global and regional climatic trends and variability in many areas of the globe over the past century suggest, however, that such short periods of records may not be representative of similar periods to follow.

The identification of redundant stations allows network managers to explore options for network optimization. For example, for the network's objectives to be attained more effectively, resources could be used to establish stations at locations where observations are needed. Network managers should take advantage of the relatively high spatial coherence that exists for some meteorological fields, such as temperature. The techniques used to evaluate the level of redundancy of information include the use of the spatial variance–covariance matrix of the available stations, multiple linear regression, canonical analysis and observation-system simulation experiments. Care should be taken, however, when stations are considered for removal, since redundancy and spatial coherence are important tools for assessing data quality and homogeneity.

The density and distribution of climatological stations to be established in a land network within a given area depend on the meteorological elements to be observed, the topography and land use in the area, and the requirements for information about the specific climatic elements concerned. The network should give a satisfactory representation of the climate characteristics of all types of terrain in the territory of the Member concerned (for example, plains, mountainous regions, plateaux, coasts and islands). For data used in sectoral applications within an area, a greater density of stations may be needed where human activities or health are sensitive to climate, and a lesser density in locations with fewer people. Regional basic synoptic networks of surface and upper-air stations and regional basic climatological networks of climatological stations will be established to meet the requirements laid down by the regional associations.

WMO is in the process of implementing a radical overhaul of the international exchange of observational data, which underpins all weather, climate and water services and products. In some parts of the world, observations are either not made or not exchanged internationally; in other parts of the world, they are made or exchanged, but not frequently enough. The Global Basic Observing Network initiative will be a fundamental element of WIGOS. The initiative will address how the basic surface-based observing network is designed, defined and monitored at the global level. Once implemented, the availability of the most essential surface-based data will be improved.

Each Member should establish and maintain at least one reference climatological station for determining climate trends. Such stations need to provide more than 30 years of homogeneous records and should be situated where few anthropogenic environmental changes have occurred and few are expected to occur. Information on agrometeorological and hydrometeorological networks and sites is found in the *Guide to Agricultural Meteorological Practices* (WMO-No. 134) and the *Guide to Hydrological Practices* (WMO-No. 168), volumes I and II, respectively; additional guidance is provided in the *Manual on the WMO Integrated Global Observing System* (WMO-No. 1160).

A country’s environmental information activities are often conducted by many parties. The contributions made by the parties are complementary, but at times they also overlap. A country benefits from environmental information collected and disseminated by government agencies and non-government entities (including private companies, utilities and universities). Formal partnerships between the NMHS and the other parties are highly desirable to optimize resources. Because data and information obtained from non-NMHS sources are not usually under the control of the NMHS, metadata are critical to ensure that the information is used as effectively as possible. At stations maintained by the NMHS, metadata on instrumentation, siting, processing procedures, methodologies and anything else that would enhance the use of the information should be obtained and documented. The metadata should also be maintained and accessible. To promote the open and unrestricted exchange of environmental information, including weather observations, it is highly desirable that the NMHS be granted full use of all climate data and information obtained from partnerships, without restriction. An appropriate contract or memorandum of understanding between the NMHS and other organizations may need to be drafted and signed by senior management.

In addition to data from the standard and private networks of climatological stations, there are sometimes observational data from networks of temporary stations established in connection with research and study programmes, as well as measurements made in mobile transects and profiles. An NMHS should endeavour to obtain such data and associated metadata. Although the data may not be ideal for typical archiving, they will often prove to be quite valuable as supplementary information, for example, for investigations of specific extreme events. When these observations are collected from data-poor areas, they are highly valuable. It is also worth noting the initiatives of WMO and GCOS to maintain and protect national long-term meteorological observations through WMO recognition of centennial observing stations.

### 2.3.1 *Siting considerations*

The precise exposure requirements for specific instruments used at climatological stations, which are intended to optimize the accuracy of the instrumental measurements, are discussed in the *Guide to Instruments and Methods of Observation* (WMO-No. 8). The representativeness and homogeneity of climatological records are closely related to the location of the observing site. A station sited on or near a steep slope, ridge, cliff, hollow, building, wall or other obstruction is likely to provide data that are representative of the site itself, but not of the wider area. These stations, such as lighthouses, may be of value if they have been in a stable environment for a long period of time. If a station is or will be affected by the growth of vegetation (including the growth of trees near the sensor and tall crops or woodland nearby), the erection of buildings on adjacent land, or increases (or decreases) in road or air traffic (because, for example, of changes in the use of runways or taxiways), the data provided will be neither broadly representative nor homogeneous.

A climatological observing station should be sited at a location that permits the correct exposure of the instrumentation and allows for the widest possible view of the sky and surrounding country if visual data are required. Stations should be sited on a level piece of ground with only short grass or other bare ground conditions that are natural to the site. The site should be situated well away from trees, buildings, walls and steep slopes and should not be in a hollow. A plot size of about 9 × 6 m is sufficient for outdoor temperature-sensing and humidity-sensing instruments, and an area of 2 × 2 m of bare ground within the plot is ideal for observations of the state of the ground and measurements of soil temperature. A slightly larger plot (10 × 7 m) is preferable if the site will enclose a rain gauge in addition to the other sensors.

A rule used by many NMHSs is that the distance of any obstruction, including fencing, from the rain gauge must be more than twice the height, and preferably four times the height, of the object above the gauge. In general terms, anemometers should be placed at a distance from any obstruction of at least 10 times, and preferably 20 times, the height of the obstruction. The different exposure requirements of various instruments may give rise to a split site, with some elements observed from one point and others observed nearby. All data from a split site are combined under a single site identifier.

It is critical to include notes, drawings or photos, or a combination thereof, that describe the station exposure. Such notes, drawings and photos should be updated regularly, even if only to indicate that the station exposure is unchanged. If the site's environment changes seasonally (for example, through changes in nearby vegetation) this information should also be recorded. This information is an important part of a station's metadata, and it forms a critical component of historic investigations and homogeneity assessments.

Prevention of unauthorized entry is a very important consideration and may require enclosure by a fence. It is important that such security measures do not compromise site exposure. Automatic stations will normally need a high level of security to protect against entry by animals and unauthorized entry by humans. They will also require the availability of suitable and robust power supplies and may need additional protection against floods, leaf debris and blowing sand.

Stations should be located at sites that are subject to administrative conditions that will allow the continued operation of the station, with the exposure remaining unchanged for a decade or more. For stations used or established to determine long-term climate change, such as reference climatological stations and other baseline stations in the GCOS network, constancy of exposure and operation is required over many decades.

Observing sites and instruments should be properly maintained so that the quality of observations does not deteriorate significantly between station inspections. Routine, preventive maintenance schedules include carrying out regular "housekeeping" tasks at observing sites (such as cutting grass and cleaning exposed instrument surfaces, including thermometer screens) and conducting the instrument tests recommended by manufacturers. Routine checks carried out at the station or at a central point should be designed to detect equipment faults at the earliest possible stage. Depending on the nature of the fault and the type of station, the equipment should be replaced or repaired according to agreed priorities and time intervals. It is especially important that a log be kept of instrument faults and remedial action be taken where data are used for climatological purposes. The log will be the principal basis for the site's metadata and will therefore become an integral part of the climate record. Detailed information on site maintenance can be found in the *Guide to Instruments and Methods of Observation* (WMO-No. 8).

The nature of urban environments makes it impossible to conform to the standard guidelines on site selection and the exposure of instrumentation required to establish a homogeneous record that can be used to describe the larger-scale climate. Nonetheless, urban sites do have value in their own right for monitoring real changes in local climate that might be significant for a wide range of applications. Guidelines for the selection of urban sites, the installation of equipment and the interpretation of observations are provided in *Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites* (WMO/TD-No. 1250). A fundamental premise of the guidance is that the purpose of the observations needs to be clearly understood and that measurements need to be obtained that are representative of the urban environment. It will often be possible to conform to standard practices, but sometimes, it may be necessary to adopt a flexible approach to the siting of urban stations and the installation of equipment, which makes maintaining metadata that accurately describe the setting of the station and instrumentation all the more important.

### 2.3.2 *Scheduling considerations at manned stations*

Observations at climatological and precipitation stations should be made at least once (and preferably twice) a day at fixed hours throughout the year. For practical reasons, observation times should fit in with the observer's working day. Usually there will be one observation in the morning and one in the afternoon or evening. If daylight saving time is used for part of the year, the observations should continue to be made according to the fixed local time; the dates on which daylight saving time commences and ends must be recorded. The times of observation should be either the main or the intermediate standard times for synoptic observations (0000, 0300, 0600 UTC, and so on), though if observations already take place at other times, they should not be altered to bring them in line with standard times. If conditions dictate that only one observation a day is possible, the observation should be taken between 0700 and 0900 hours local standard time.

Times at or near the normal occurrence of daily minimum and maximum temperatures should be avoided. Precipitation amounts and maximum temperatures noted in an early morning observation should be credited to the previous calendar day; maximum temperatures recorded at an afternoon or evening observation should be credited to the day on which they are observed.

Times of observation often vary among networks. Summary observations, such as temperature extremes and total precipitation, made for one 24-hour period (such as from 0800 one day to 0800 the next day) are not equivalent to those made for a different 24-hour period (such as from 0000 to 2400).

If changes are made to the times of observations across a network, simultaneous observations should be carried out at both the old and new times at a basic network of representative stations for a period covering the major climatic seasons. These simultaneous observations should be evaluated to determine whether any biases result from the change in observation times. The station identifiers for the old and new observation times must be unique for reporting and archiving. If possible, such network-wide changes should be avoided.

The observer should note in the station logbook and on the report forms the nature and times of occurrence of any damage to or failure of instruments, any maintenance activities, and any change in the station's equipment or exposure. Such events must be logged because they might significantly affect the observed data and thus the climatological record. Where appropriate, instructions should be provided for transmitting observations electronically. If mail is the method of transmission, the station should be provided with mailing instructions and stamped addressed envelopes for sending the report forms to the central climate office.

### 2.3.3 *Observer competency*

The *Guide to Competency* (WMO-No. 1205) provides the general framework for competencies, and the *Compendium of WMO Competency Frameworks* (WMO-No. 1209) describes the framework specifically for personnel performing meteorological observations. The latter describes the knowledge and skills required to perform many observing functions. Observers should be trained and certified by an appropriate meteorological service to establish their competence to make observations, maintain equipment and perform their duties to the required standards. They should have the ability to interpret instructions for the use of instrumental and manual techniques that apply to their own particular observing systems. Guidance on the instrumental training requirements for observers is given in the *Guide to Instruments and Methods of Observation* (WMO-No. 8).

Often, observers are volunteers or part-time employees, or they take observations as part of their other duties. They may have little or no training in climatology or in taking scientific observations, so they depend on having a good set of instructions. Instructional booklets for ordinary climatological and precipitation station observers should be carefully prepared and made available to observers at all stations. The instructions should be unambiguous and should simply outline the tasks involved. They should provide only the information that the observer actually needs to perform the tasks satisfactorily. Illustrations, graphs and examples could be used to stimulate the interest of the observer and facilitate the understanding of the tasks to be undertaken every day. Sample copies of correctly completed pages of a logbook or journal and of a report form should be included in the instruction material available to the observer. Ideally, a climate-centre representative should visit the site, install the station and instruct the observer.

An observer must gain familiarity with the instruments and should be aware in particular of the sources of possible error in reading them. The instructions should include descriptive text with simple illustrations showing the functioning of each instrument. Detailed instructions on day-to-day care, simple instrument maintenance and calibration checks should be given. If correction or calibration tables are necessary for particular observing and recording tasks, the observer should be made thoroughly familiar with their use. Instructions should also cover the operation of computer terminals used for data entry and transmission.

Instructions must cover both visual and instrumental observations. Visual observations are particularly prone to subjective error, and their accuracy depends on the skill and experience of the observer. Since it is very difficult to check the accuracy or validity of an individual visual observation, as much guidance as possible should be given so that correct observations can be made.

To complement the instruction material, personnel responsible for station management in the climatological service should contact observing stations regarding any recurring observing errors or misinterpretation of instructions. Regular inspection visits provide the opportunity to address siting and instrument problems and to further the training of the observer.

Some climate centres arrange special training courses for groups of volunteer observers. Such courses are especially useful in creating a uniformly high standard of observations, since they address a wider range of problems than may be raised by a single observer at an on-site visit.

### 2.3.4 ***Quality management of climatological station operations***

Guidance for on-site quality control of observations is provided in the *Guide to the Global Observing System* (WMO-No. 488). Checks should be made for gross errors, existing extremes, internal consistency in a sequence of observations, consistency in the sequence of dates and times of observation, consistency with other elements and calculations, and the accuracy of copies and encoded reports. If there are any errors, remedial action, such as correcting the original data and the report, should be taken before transmission. Errors detected after transmission should also be corrected and the corrected report should be sent again. Checks should also be made if a query about data quality is received from an outside source, and any necessary amendments should be recorded and corrections should be transmitted. Records of an original observation containing an error should include a notation or flag indicating that the original value is erroneous or suspect. On-site quality control must also include ensuring that the standard exposure of the sensors is maintained, carrying out site maintenance, and ensuring that the proper procedures for reading the instrumentation and checking autographic charts are carried out. Any patterns of measurement error should be analysed, for example, to check whether they relate to instrument drift or malfunction, and summaries of data or report deficiencies should be prepared monthly or annually.

Climatological stations should be inspected to ensure the maintenance and correct functioning of the instruments and thus a high standard of observations. Automated stations should be inspected at least once every six months. Special arrangements for the inspection of ship-based instruments are described in the *Guide to Instruments and Methods of Observation* (WMO-No. 8).

Before each inspection, the inspector should determine, to the fullest extent possible, the quality of the information and data received from each station on the itinerary. At each inspection, it should be confirmed that:

(a) The observer's training is up to date;

(b) The observer remains competent;

(c) The siting and exposure of each instrument are known, recorded and still the best obtainable;

(d) The instruments are of an approved pattern, in good order and verified against relevant standards;

(e) There is uniformity in the methods of observation and procedures for calculating derived quantities from the observations;

(f) The station logbook is well maintained;

(g) The required report forms are sent punctually and regularly to the climate centre.

Inspection reports should include sketches, photographs or diagrams of the actual observing site and should indicate any physical objects that might influence the observed values of the climatic elements. The reports must also list any changes in instruments or calibration, changes in exposure and site characteristics since the previous visit, and the dates of appropriate comparisons and changes. Inspectors must also be prepared to advise observers on any problems arising with the transmission of data, including automated data entry and transmission systems.

To determine the spatial and temporal variations of climate, it is of paramount importance to check the relative accuracy of individual sensors in use in a network at a particular time and to check them periodically. Similarly, the performance of replacement sensors and systems needs to be measured against the performance of the instruments that were replaced. Details on calibration techniques can be found in the *Guide to Instruments and Methods of Observation* (WMO-No. 8). For climatology, it is not generally sufficient to rely upon manufacturers' calibrations and it is wrong to assume that calibration will not drift or otherwise change with time. Records of instrument changes and calibration drifts must be kept and made available as metadata, as they are essential to the assessment of true climate variations.

During inspections of remotely sited AWSs, observations should be taken using travelling standards for later comparison with the recorded AWS output received at the data reception point. Some NMHSs have automated procedures in place for detecting faults and instrumental drift. The automated procedures compare individual measurements with those from a network and with values analysed from numerically fitted fields. These automated procedures are useful for detecting not only drift, but also anomalous step changes.

## 2.4 **Climate data processing**

The basic goal of climate data processing is to capture, preserve and provide access to climate data and products for use by planners, decision makers and researchers. Permanent archiving is an important objective. The data management system of a climate archive must provide the information to describe the climate of the domain of interest for which the archive has been established, be it national, regional or global. Many of the eventual uses of climate data cannot be foreseen when data acquisition programmes are being planned, and new applications frequently emerge long after the information has been obtained. The initial use of meteorological and related data is often only the first of many applications. Subsequent analysis of the data for diverse purposes leads to a significant and ongoing enhancement of the return on the original investment in the data acquisition programmes. The global climate-change issue, for example, is stretching the requirements for climate data and data-management systems far beyond those conceived when the original networks were established. To meet these expanding needs, it is critically important that climate information – both current and historical – be managed in a systematic and comprehensive manner. Conventional meteorological data are now augmented by data from a wide array of new instruments and systems, including satellites, radar systems and other remote-sensing devices, and by model data. This creates effective and comprehensive climate data management systems (CDMSs), which are essential for modern climate centres.

The *Manual on the High-quality Global Data Management Framework for Climate* (WMO-No. 1238) provides guidance and requirements on the development, provision, exchange and maintenance of high-quality climate data sets. The standards and recommended practices it describes are intended to ensure that the data made available for climate assessment, monitoring, applications and related services sustainably meet a minimum set of requirements on quality, governance, accessibility and usability. The Manual enables the effective development and exchange of high-quality climate data based on a reliable, integrated, underpinning data infrastructure at the global, regional and national levels. The High-quality Global Data Management Framework for Climate provides a robust data foundation for the generation of climate products and the delivery of climate services through the Climate Services Information System of GFCS.

Collaboration within GFCS applies to several disciplines in which many of the data-related activities are considered as falling under the definition of climate data. One such discipline is marine and hydrological sciences. The scope of the data in the High-quality Global Data Management Framework for Climate encompasses all the ECVs (see 2.2.1) under the auspices of WMO, including observational data and data derived from climate analysis, reanalysis, prediction and projection. The procedures provided are also applicable to externally sourced data and data on socioeconomic impacts outside the auspices of WMO.

### 2.4.1 *Climate database management*

The primary goals of database management are to maintain the integrity of the database at all times and to ensure that the database contains all the data and metadata needed to meet the requirements for which it was established, both now and into the future. CDMSs allow efficient storage, access, conversion and updating of many types of data, including digital and non-digital data, by enhancing data security.

It is essential that both the development of climate databases and the implementation of data management practices take into account the needs and capabilities of existing and future data users. While this requirement may seem intuitive, information that is important for a useful application is sometimes omitted, and data centres sometimes commit insufficient resources to verify the quality of data for which users explicitly or implicitly demand high quality. In all new developments, data managers should attempt to have at least one key data user on the project team or to engage in some kind of regular consultation with users to stay abreast of changing needs and issues experienced by user communities. Examples of stakeholder communities are those involved in climate prediction, the study of climate-change impacts, climate-change mitigation, agriculture, public health, disaster and emergency management, energy, natural resources management, urban planning, finance and insurance.

A CDMS should be monitored routinely to determine how well the processes that use and support the database are performing. Examples of the processes that support the data are metadata maintenance, database ingestion, quality-control actions that modify the database, and information retrieval. Each process should be monitored, evaluated and, if necessary, improved. It is strongly recommended that data managers think in terms of end-to-end data management. Information on systemic data-quality issues, loss of data, and other practices that harm the climate record should be referred back to observation managers for rectification.

A security policy to prevent loss of or damage to the CDMS should ensure that:

(a) All personnel are aware of their professional responsibilities;

(b) The archives and database environment is secure and protected against physical hazards, such as fire and excess humidity;

(c) User-level security is enforced for digital data and database components, with only a small, registered group of people permitted to insert, update, delete or otherwise manipulate the data;

(d) Personnel with write access to a database agree not to perform any transactions besides the operations and practices approved by the data manager;

(e) All changes to data tables have an audit trail, with controls in place to restrict who has access to the audit trail;

(f) Password security principles are applied: strong passwords should be used, consisting of seemingly unrelated letters, numbers and characters, and they should be changed regularly, never shared and never written down on paper;

(g) All unnecessary services are disabled on the database computer;

(h) The database is protected against attacks from viruses and hackers;

(i) Regular backups are made: typically a full weekly backup, with incremental daily backups, given that work carried out since the most recent backup is likely to be lost and needs to be repeated should a computer failure occur;

(j) At regular intervals, typically monthly, a complete backup of the data tables is placed in a safe, secure, fireproof location that is remote from the physical location of the climate database (it is common to have three copies of the same archive in different secure places and, if possible, in different towns or cities);

(k) Backups of the CDMS are performed before any changes are made to the system software, design or applications.

An important function of a database manager is to estimate data storage requirements, including the estimation of future growth. With the increasing use of automatic stations, there is also the question of whether or not to save data at time steps smaller than the hourly time step, such as minute data. The ability to manage minute data or even grid-point data will significantly affect the resources needed to process the data. Account must be taken of the additional information to be included in data records (for example, data-quality flags, original messages, and the date and time of record updates), metadata needs and any redundancy necessary to ensure that databases can be restored. Some data types, such as those from remote sensing, marine sensors and AWS with a high temporal resolution, require large amounts of storage. Unconventional data (such as soil moisture, phenological observations and vegetation indices) may have storage needs that are different from those of more traditional observations. AWS often generates data that are relevant to the quality of observations but are not strictly climate data (for example, information on the battery-level voltage for an AWS). The quality-control process often generates values and information that may be different from the original data, so there is a storage requirement for keeping both the original data and any different data generated by quality-control processes. Non-digital records should be stored in a controlled environment that minimizes their deterioration from temperature and humidity extremes, insects, pests, fire, flood, accidents or deliberate destruction.

With an ever-increasing amount of information being generated and retained, the problem arises as to whether or not to continue to store all the records in their original manuscript form. All too often, climatological records are stored in basements, sheds and other undesirable facilities. They are frequently not catalogued, and they may be inaccessible and subject to deterioration. As a means of reducing paper costs, making better use of space, and providing security for original documents, it is recommended that the manuscript data be scanned into a digital file and carefully preserved. It is important to remember that no storage medium is permanent, so archival arrangements need to be reviewed regularly.

### 2.4.2 *Design of climate database management systems*

All CDMSs are based on some underlying model of the data. This model design is very important for the quality of the resulting system. An inappropriate model will tend to make the system harder to develop and maintain. In general, a database designed for current meteorological data will allow the rapid retrieval of recent data from a large number of stations. By contrast, many climate data applications involve the retrieval of data for one or a few stations over a long period. It is essential to document the overall design and underlying data model of the CDMS to facilitate subsequent extensions or changes as needs and technologies evolve. Similar considerations apply to a metadata model.

In general, a CDMS has five components. The governance component refers to a consistent set of policies and governance processes needed to build a solid foundation for the establishment and management of authoritative sources of climate data and related services. The data management component addresses the functionality required to effectively manage climate data and includes data ingestion and extraction, data rescue, quality control of observations, quality assessment, and climate metadata management. The data delivery component refers to the functionality required to deliver climate data and includes data discovery (both climate data and climate metadata) and data delivery. The data analysis component involves a wide variety of analytical techniques that are applied to climate data and may result in the generation of a range of derived data products. Some examples are spatial and image analysis, homogenization and numerical modelling processes. The data presentation component represents a diverse set of techniques used to communicate climate-related information such as written reports, graphical static and interactive presentations and multimedia presentations. All these components require the computer infrastructure functionalities to support a CDMS. Not all components are required. Details about CDMSs are provided in the publication *Climate Data Management System Specifications* (WMO-No. 1131), which also discusses whether the functionality is considered to be required, recommended or optional.

### 2.4.3 *Data acquisition considerations*

Manually observed data should be transferred to a CDMS as soon as possible and by whatever means is most practical. It is advantageous to collect data at least daily, since doing so is likely to improve the quality of the data, decrease the manual effort needed for quality control, accelerate the detection of technical errors, and increase opportunities for improved access to more data. Nevertheless, the submission of monthly data is an acceptable alternative when daily data transmission is not practical, such as when observations are recorded on paper and sent to the NMHS by mail.

Non-digital records are generally digitized during an entry process. A fundamental goal of a data-entry process is to duplicate the raw data so that they reflect, as closely as possible, the data recorded during the capture process. A key-based entry system should be efficient and easy for a data-entry operator to use. The system could also be designed to validate the data as they are entered and to detect likely errors. It is also possible to set default values for some elements, thus eliminating unnecessary keystrokes.

Many weather observations are recorded by institutions or organizations other than NMHSs, and acquisition of the data in their original form may be difficult. In such cases, efforts should be made to collect copies of the original report forms. If it is impossible to secure either the original or a copy of the record, a note to this effect should be made in the inventory of the centre's holdings and should include information pertaining to the existence and location of the data, the volume of data available, the period covered by the data, the stations in the network, as applicable, and the elements observed.

The CDMS should also contain information about media reports, pictures and other similar information beyond traditional data and metadata. It is possible to record such information by using a digital camera or scanner to capture an image of the report, by noting the date, area and type of event (flood, drought, heavy precipitation, etc.), by identifying the media and by writing additional comments about the event.

It is important to retain both the data value that was originally received and the latest quality-controlled value. The original value will likely pass through an initial automated quality-control process at ingestion and, as necessary, a more extensive quality-control process. Even if the value is rejected during either of these processes, it must still be retained. Some CDMSs retain not only the original and latest values, but also all changes to the data and information on when the data was recorded, why, how and by whom.

Another aspect of data acquisition is the recording of occurrences when data were expected but not received. Loss of data can occur as a result of situations such as inoperable instrumentation, data transmission errors and acquisition processing errors. Lost data can be reconstructed with varying levels of certainty. For example, a missing precipitation measurement can be considered to be zero when it is known from other data that local and synoptic conditions precluded the occurrence of precipitation. In other cases, lost data can be estimated with reasonable certainty (see section 3.5.8). In all cases, data set documentation should flag the reconstructed or estimated data appropriately.

The schema in Figure 2.1 shows a data flow as used frequently by NMHSs that have sufficient information technology capacities.

### 2.4.4 *Metadata*

An adequate set of metadata must be available to inform future users about the nature of the data in the system, how the various data sets were collected, and any inherent problems. A user should be able to use the metadata to identify the conditions under which the observation (or measurement) was made and any aspects that may affect its use or understanding. It is recommended that database management include all information that can affect the homogeneity of a data set or series. Descriptions of and requirements for metadata are provided in *WIGOS Metadata Standard* (WMO-No. 1192). Other helpful metadata information can be found in the *Guidelines on Climate Metadata and Homogenization* (WMO/TD-No. 1186). These standards are part of the contributions of the *Manual on the WMO Integrated Global Observing System* (WMO-No. 1160) to co-sponsored observing systems in support of all WMO Programmes and activities. Most modern metadata are available in digital form, but older metadata may exist only on paper.

Metadata are needed not only for climate data but also for the CDMS itself. Each process within the system (for example, key entry or quality control) should be described in full. A history of

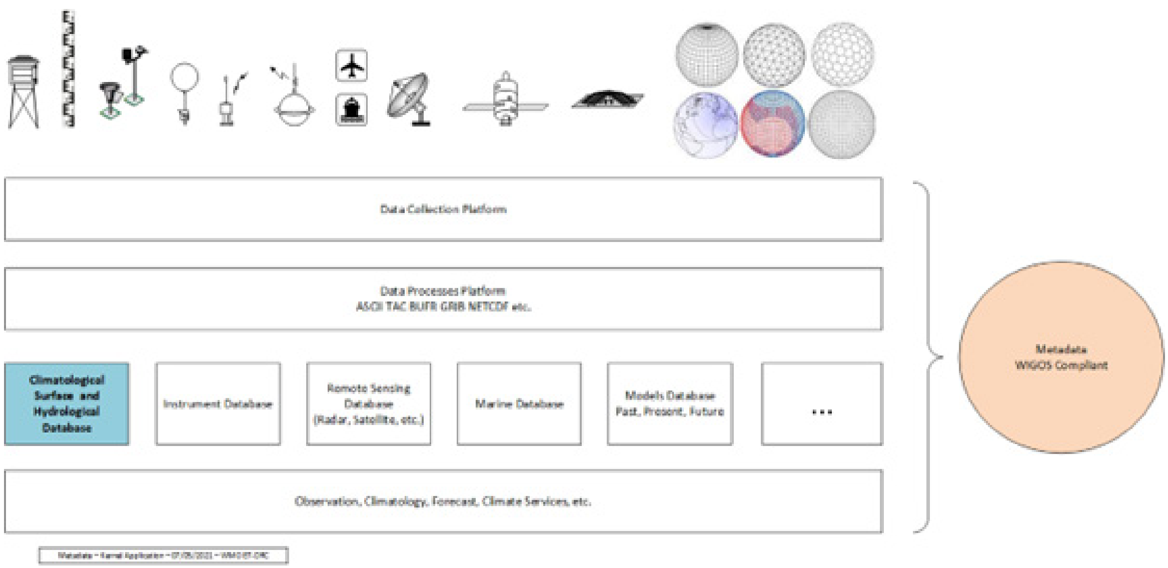


**Figure 2.1. Schema of a typical data flow**

*Source:* WMO Expert Team on Data Representation and Codes any changes made to any part of the system (such as software, hardware or manual procedures) should be documented and maintained. Since observing practices, quality-control techniques and data-handling procedures change over time, these metadata are critical in the climatological analysis of historical data. The analyst uses the metadata to identify and understand how a data value was observed and processed to separate meteorological influences from possible non-meteorological influences in the data record.

Inventories of the data contained in the CDMS should be prepared routinely. Stratification could be performed, for example, by data element, station location or time. Lists of contents should be produced and maintained to describe and define the data content of the individual files and to provide information on the codes and observational practices used. Knowing what is contained in the CDMS is important for the efficient retrieval of information from the system.

### 2.4.5 *Quality control*

The purpose of quality control is to verify whether a reported data value is representative of what was intended to be measured and has not been contaminated by unrelated factors. It is important, therefore, to be clear from the outset what the readings of a particular data series are supposed to represent. Data should be considered satisfactory for permanent archiving only after they have been subjected to adequate quality control.

Procedures for quality control help assure defined data-quality levels throughout the life cycle of the data and should be an integral part of an entity's QMS. It should be noted that the procedures serve in particular to ensure data-quality levels that support climate applications and services. It should also be noted that quality-control procedures need to be adapted to the specific climate conditions of a country and fine-tuned to fit existing and planned observational and information technology infrastructure as well as available human resources. The quality-control procedures applied should be well documented and made available to data users.

If manuscript records constitute the source document, trained personnel should scrutinize them as soon as the records reach the archiving centre. This should happen before any manuscript records are digitized. The forms should be reviewed to ensure that elements such as the station name, identifying number and location are properly identified and that the data are legible and are recorded properly (for example, to the correct level of precision and in the proper columns). If any problems are discovered, the observation sites should be contacted to clarify the issues or correct the problems. If resources do not permit the quality control of all data, priority should be given to the most important climate elements.

When observed data are available in digital form, the archiving centre should subject them to full, elaborate quality-control procedures on a regular, systematic basis. Computer software can examine all the available data and list those that fail pre-defined tests but are not so useful for identifying the underlying problem. Skilled human analysts can often make judgments about the cause of errors and determine any corrections that should be applied, but they are normally overwhelmed by the vast quantity of observations. The best technique is a combination of the two, with computer-generated lists of potential errors presented to the human analyst for further action. For data sets with very large data volumes (such as AWS data with 1-minute resolution), human intervention is likely to be impractical and quality control will be entirely or almost entirely automated.

Statistical techniques (see Chapter 3) are invaluable for detecting errors and, in some cases, for suggesting what the "correct" value should be. Objective, automated screening of data is essential for validating large quantities of data. A manual review of the automated output is needed, however, to ensure that the automated procedures are performing as expected. Graphical and map displays of data and data summaries are excellent tools for visual examinations. These techniques integrate and assimilate large quantities of data and enable a trained analyst to recognize patterns and thus assess physical reasonableness, identify outliers, spot suspect data and evaluate the performance of automated procedures. Additional advice is found in *Guidelines on Surface Station Data Quality Control and Quality Assurance for Climate Applications* (WMO-No. 1269).

In a database, a given value is generally available at different stages of quality control. The original data, as received in the database, must be kept, but data are often changed during the validation processes. These different stages of the value are reflected in quality flags. A multitude of flags could be constructed, but the number of flags should be kept to the minimum needed to describe the quality assessment and reliability of the raw data or estimated values. A two-digit quality flag code – one digit for the type of data, one for the stage of validation – meets most requirements. When data are acquired from numerous sources, a third flag for the source, or provenance, of the data is often useful. Examples of codes for "type of data", "validation stage" and "acquisition method" are given in Tables 2.1, 2.2 and 2.3.

**Table 2.1. Example of types of data codes**

| *Type of data code* | *Meaning* |
|---|---|
| 0 | Original data |
| 1 | Corrected data |
| 2 | Reconstructed (such as by interpolation, estimation or disaggregation) |
| 3 | Calculated value |

**Table 2.2. Example of a "validation stage" flag code**

| *Validation stage code* | *Meaning* |
|---|---|
| 1 | Missing data (data not received or observation not made) |
| 2 | Data eliminated once controls completed |
| 3 | Not controlled (newly inserted data or historical data not subject to any control) |
| 4 | Declared doubtful as identified as an outlier by preliminary checks, awaiting controls (data possibly wrong) |
| 5 | Declared doubtful after automatic controls or human supervision (data probably wrong) |
| 6 | Declared validated after automatic controls or human supervision (but further modification allowed, for example, if a subsequent study reveals that the data can still be improved) |
| 7 | Declared validated after automatic controls and human supervision and no further modification allowed |

**Table 2.3. Example of a data acquisition method flag code**

| *Acquisition method code* | *Meaning* |
|---|---|
| 1 | Global Telecommunication System |
| 2 | Key entry |
| 3 | Automated weather station telecommunication network |
| 4 | Automated weather station digital file |
| 5 | Manuscript record |

Tables 2.1–2.3 are examples of the many different ways to construct the quality information associated with data. An international data-quality coding system is required to standardize information on quality. WMO and its Services Commission is tackling this challenge.

### 2.4.6 ***Data errors***

Data errors arise primarily as a result of instrumental, observer, data-transmission, key-entry and data-validation process errors, as well as changing data formats and data summarization problems. When a set of quality-control procedures are drawn up, all potential causes of errors should be considered, and efforts should be made to reduce them. System designers are advised to work closely with operational quality-control personnel when developing automated and semi-automated error-flagging procedures.

Metadata errors often manifest themselves as data errors. For example, an incorrect station identifier may mean that data from one location came from another; an incorrect date stamp may mean the data were observed at a different time. Data that are missing from the correct place and time should be detected using completeness tests; data that have been ascribed to an incorrect place or time should be detected using consistency and tolerance tests.

Format errors include repeated observations and impossible format codes, such as alpha characters in a numeric field, embedded or blank fields within an observation, impossible identification codes and impossible dates. The actual causes of a format error include miskeying, the garbling of a message in transmission, and operator mistakes. Procedures should be introduced to eliminate, or at least reduce, format errors.

Completeness errors concern missing data. Incomplete data are much more critical for some elements than for others. For monthly extremes and event data such as the number of days with precipitation above a certain threshold, missing daily data may render the recorded value highly questionable. Total monthly rainfall amounts may also be strongly compromised by a few days of missing data, in particular when a rain event occurred during the missing period. The monthly averaged temperature, by contrast, may be less susceptible to missing data. For some applications, data completeness is a necessity, but since very few station data sets are 100% complete over an extended period of time, estimating the missing data will normally require provisions for spatial or temporal interpolation.

Internal consistency relies on the physical relationships among climatological elements. All elements should be verified thoroughly against any associated elements within each observation. For example, psychrometric data should be checked to ensure that the reported dry bulb temperature equals or exceeds the reported wet bulb temperature. Similarly, the relationship between visibility and present weather should be checked for adherence to standard observation practices.

Data should be checked for consistency with the definitions. For example, a maximum value must be greater than or equal to a minimum value. Physical bounds provide rules for further internal consistency checks. For example, sunshine duration is limited by the duration of the day, global radiation cannot be greater than the irradiance at the top of the atmosphere, wind direction must be between 0° and 360°, and precipitation cannot be negative.

Temporal consistency tests the variation of an element over time. Many climatological data sets show significant serial correlation. A check should be made by comparing one observation with previous and subsequent ones. Using experience or analytical or statistical methodologies, data reviewers can establish the amount of change that might be expected in a particular element during any time interval. For some elements, a lack of change over an extended period could indicate an error.

Spatial consistency compares each observation with observations taken at the same time at other stations in the area. Each observation can be compared with what would be expected at the site based on observations at neighbouring stations. Where there is a significant difference between the expected and actual observations, the data should be flagged for review, correction or deletion, as necessary. Only like quantities should be compared directly, such as wind speeds measured at the same height; values measured at similar elevations, such as flat, open topography; and values measured within a climatologically similar area. Unlike quantities may sometimes be transformed or standardized to enable valid comparisons.

Summarization consistency errors can be detected by comparing different summaries of data. For example, the sums and means of daily values can be calculated for various periods, such as a number of weeks, months or years. Checking that the total of the 12 monthly reported sums is equal to the sum of the individual daily values for a year provides a quick and simple cross-check for an accumulation element such as rainfall. Systematic errors in upper-air station data can sometimes be revealed by comparing monthly averages with the averages derived for the same location and height from a numerical analysis system. Modelled data such as forecasts and reanalyses can also be used to detect consistency errors. The cause of any inconsistencies should be reviewed and corrected.

Tolerance errors are values that are either impossible for a particular element, such as negative precipitation, or unlikely. The thresholds for determining that values are unlikely are usually time- and location-dependent and should be established using historical values or using spatial interpolation methods. It may be possible to perform some tolerance tests using completely different data streams, such as satellite or radar data. For example, a very simple test for the occurrence or non-occurrence of precipitation using satellite data would be to check for the presence of clouds in a satellite image.

### 2.4.7 ***Data rescue***

Data rescue involves organizing and preserving climate data that is at risk of being lost through deterioration, destruction, neglect, technical obsolescence or simply through dispersion of climate data assets over time. Data rescue measures include organizing and imaging paper, microfilm and microfiche records; keying numerical and textual data and digitizing strip-chart data into a usable format; and archiving data, metadata and quality-control outcomes and procedures.

The *Guidelines on Best Practices for Climate Data Rescue* (WMO-No. 1182) provide detailed guidance on all facets of climate data rescue. The International Data Rescue (I-DARE) portal is a Web-based resource for people interested in data preservation, rescue and digitization. It provides a single point of entry for information on the status of past and present data rescue projects worldwide, on data that need to be rescued and on the methods and technologies involved. It is a gateway for the exchange of information on all aspects of data rescue, including established and emerging rescue technologies. Because its goals are to enhance the visibility of existing data rescue activities, to stimulate new ones and to better coordinate international data rescue efforts, the I-DARE portal is a useful communication tool. It will also help to identify gaps and opportunities, prioritize data rescue in regions where it is most needed and attract funding for projects.

### 2.4.8 ***Exchange of climatic data***

The exchange of data is essential for climatology. For WMO Members, the obligation to share data and metadata with other Members and the conditions under which data and metadata may be passed to third parties have been covered in the recent past under several resolutions: Resolution 60 (Cg-17) (for the GFCS); Resolution 25 (Cg-XIII) (for hydrological data), Resolution 40 (Cg-XII) (for meteorological data), and Resolution XXII-6 of the Intergovernmental Oceanographic Commission (for oceanographic data). Resolution 1 of the 2021 extraordinary session of the World Meteorological Congress (Cg-Ext 2021) is one of three initiatives launched to meet the explosive growth in demand for weather and climate data products and services from all sectors of society. The demand is for weather, climate and water monitoring and prediction data to support essential services needed by all sectors of society.

The initiative under Resolution 1 is a Unified Data Policy that commits WMO to broadening and enhancing the free and unrestricted international exchange of data from all parts of the world and data products from all WMO Members. Under the two-tiered approach to the international provision and exchange of Earth system data, Members shall provide, on a free and unrestricted basis, the core data that are necessary for the provision of services in support of the protection of life and property and for the well-being of all nations, and they should also provide the recommended data required to support Earth system monitoring and prediction activities at the global, regional and national levels and to further assist other Members with the provision of weather, climate, water and related environmental services in their States and Territories. Members should provide public research and education communities with free access to all recommended data exchanged under the auspices of WMO for their non-commercial activities. The Resolution provides additional details describing data, elements and further recommendations.

The Unified Data Policy provides a comprehensive update of the policies guiding the international exchange of weather, climate and related Earth system data among the 193 WMO Member States and Territories. The new policy reaffirms the commitment to the free and unrestricted exchange of data, which has been the bedrock of WMO since it was established more than 70 years ago. Through this Policy and two other initiatives (the Global Basic Observing Network and the Systematic Observations Financing Facility), WMO is dramatically strengthening the world's weather and climate services through a systematic increase in much-needed observational data and data products from across the globe.

The World Data System is an Interdisciplinary Body of the International Science Council. Its mission is to promote the long-term stewardship of, and universal and equitable access to, quality-assured scientific data and data services, products and information across all disciplines in the natural and social sciences and the humanities. The World Data System aims to facilitate scientific research by coordinating and supporting the provision, use and preservation of relevant data sets while strengthening their links with the research community. The World Data System collaborates with WMO on meteorology and climatology, oceanography, palaeoclimatology, solar radiation and radiation balance, glaciology, greenhouse gases, ozone and ultraviolet radiation, aerosols, and remote sensing (physics and chemistry). There is also collaboration in a publishing network for geoscientific and environmental data.

## 2.5 **Stewardship maturity assessment**

The *Manual on the High-quality Global Data Management Framework for Climate* (WMO-No. 1238) defines data stewardship as the formal accountability for ensuring effective controls … around the management and use of … the climate record". It also notes that stewardship assigns "rights and responsibilities for acquiring and managing climate data and information". The rights include determining how the information will be managed and what access constraints will apply; the responsibilities are related to the maintenance, quality and security of the information and enabling appropriate access. The *Manual* describes the stewardship maturity matrix as "a unified framework for measuring the level of stewardship practices applied to data". The matrix "generally defines measurable, level-progressive practices of key components of stewardship such as preservation, accessibility, and transparency/traceability, rating each component on a level scale from 'not managed' to 'optimally managed'".

A stewardship maturity assessment in the form of a matrix measures how well a data set has been created and curated to ensure the accessibility, usability and integrity of the data and to ensure that data users have sufficient documentation. It is necessarily limited to facets that can be (independently) assessed. The assessment provides information on the extent to which a data set is accompanied by clear documentation, has support channels with clear coding practices, applies quality-control and quality-assurance procedures, provides uncertainties and adheres to data format and archiving standards. It does not explicitly assess aspects related to the scientific rigour involved in creating the data set, such as the reliability of the underpinning observations, the processing details, homogenization, scientifically based adjustments and so forth.

Once the stewardship maturity of a data set has been assessed and scores are available, there are a number of different ways that data managers and users of the data sets can use the information. For data managers, having an independent set of assessments across a number of aspects could be useful to help them to identify where to focus limited resources to improve the quality of stewardship. There may be some aspects that require little effort to obtain higher ratings. Furthermore, if the ratings are compared with other similarly well-managed products, the scores may even help with prioritizing cost planning, resource allocation and funding for future data management with the aim of improving stewardship maturity for those data sets. Data set creators can use the scores similarly when outlining major updates or ensuring the stewardship maturity of new data sets.

There are a number of ways that data users can or should use the scores from this matrix. For users with minimal requirements, the scores can be used to choose the data set with the highest level of maturity for a specific application. Mature data sets and systems make it easy for users to assess which data set they need, but users are strongly encouraged to take a more in-depth approach, thinking about their application of the data and the scores for each category and aspect. Data sets that have different aims and processing levels will have different maturity scores, but the appropriate data set for a particular user's application may be one with a lower overall score. For example, when studying sea-surface temperatures, a user could access a highly processed gridded data set that has not been assessed, but the user might instead use a data set of raw ship track and buoy information that has been assessed. Just because the latter data set has been assessed, it does not necessarily make it the right choice for a particular application, even if the score of the assessed data set is high.

Dunn et al. (2021) provide more detailed information about the rationale, development and uses of stewardship maturity matrices and assessments.

## 2.6 References

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# 3. STATISTICAL CLIMATE DATA ANALYSIS

## 3.1 Introduction

One of the roles of a climatologist is to identify users, understand the climate and environmental information that the users need to make decisions and provide the users with information in a manner that is understandable to the user. This role requires the analyst to summarize collections of data, understand and infer what physical processes the data represent, and describe uncertainties in the inferences.

Inferences are often based directly on probability theory, and the use of statistical methods to make inferences is therefore based on formal mathematical reasoning. Statistics is a tool used to bridge the gap between raw data and useful information, and it is used for analysing data and climate models and for climate prediction. Statistical methods allow a statement of the confidence of any decision based on the application of the procedures.

The confidence that can be placed in a decision is important because of the potential risks associated with making a wrong decision. Observed data represent only a single sample of the physical system of climate and weather, and they are generally observed with some level of error. Conclusions can be correct or incorrect. Quantitative factors that describe the confidence of the decisions are therefore necessary to properly use the information contained in a data set.

New and improved statistical and analytical methodologies are rapidly emerging. The increase in computing capacity has led to the rapid explosion of data analysis methodologies such as machine learning, artificial intelligence and neural networks. Data science is an analytic process designed to explore large amounts of data (big data) in search of consistent patterns or systematic relationships among elements, and then to validate the findings by applying the detected patterns to new subsets of data. It is often considered a blend of statistics, artificial intelligence and database research. It is rapidly developing into a major field, and important theoretical and practical advances are being made. Data science is fully applicable to climatological problems when the volume of data available is large, and ways to search the significant relationships among climate elements may not be evident, especially at the early stages of analysis. The discipline is not concerned with identifying the specific relations among the elements involved. Instead, the focus is on producing a solution that can generate useful predictions.

This chapter concentrates on qualitative and quantitative analysis. It is intended to provide approaches, explanations and caveats that data analysts should consider to fully understand the characteristics of a data set and the assumptions of the methodology being used. It does not provide detailed specifics of complex subjects. The references at the end of the chapter and textbooks on theory and methods provide more detailed information.

For many of the calculations and techniques described in this chapter, it is better to use computers to process and display the data. It is necessary, however, to draw attention to the dangers of applying automated analysis and presentation methods in an overly mechanical way, since automated procedures can be misused and the results misinterpreted. While there are unquestionable advantages to using a computer, assumptions implicit in most analysis software might be ignored or might not be clearly articulated, which can lead to erroneous results and decisions. Methodologies must be thoroughly understood and presented by the analyst so that valid conclusions can be drawn by both the analyst and the user.

Meteorological and hydrological data are complex. They are heterogeneous, dynamic, multidimensional, inherently geospatial and multitemporal. The data are used for critical safety purposes and are essential to major socioeconomic activities. They are required to be operationally accessible at all times, in real time, through a diversity of formats, protocols and standards, and to also form the basis of a secure, long-term climate record on which key economic and policy decisions depend. All these considerations, from the complexity of the data and the volume of data to the demands placed upon them and their critical availability for decision-making, will lead to several analytical challenges in the coming years (see section 3.5.11).

## 3.2 Qualitative data descriptors

Prior to the description or use of a data set, the data should be checked for accuracy and validity. Accuracy refers to the correctness of the data, while validity refers to the applicability of the data to the purpose for which the values will be used. The user of a data set should never assume, without confirmation, that a data set is accurate and valid, especially if the user does not have relevant information from the quality-control processes applied during the assembling of the data set. The influence of external factors such as inhomogeneities, dependence on time, and variations in space complicates the interpretation of what the data set may represent. It is also important to know how the data were collected, processed and compiled, and sometimes even to know why the data were initially collected, since many data sets contain observations taken for a primary purpose other than climatology, such as weather forecasting. A stewardship maturity assessment (see section 2.5) helps the user of the data set in having a good understanding of the data quality.

The initial step in using a data set is usually to look for some basic features and patterns. Some that are often sought are the middle or typical value, the spread or range of the observations, the existence of unexpected observations, the way in which the observations trail off from either side of the middle value, and the clustering of observations and extremes. Without systematic organization, it is not easy to interpret large quantities of data to find these and similar features. The first step is to gain a general understanding of the data through visual displays of the distribution of the observed values.

There are many ways of portraying data to obtain a qualitative appreciation of what the data are telling the climatologist. One way to organize a data set is to sort the observations by increasing or decreasing magnitude. The ordered observations can then be displayed graphically or as a table, which makes certain characteristics apparent, such as the extreme values and the range.

A second way to organize a data set is to group the data into intervals. A graphical display of the number of cases or the percentage of the total number of observations in each interval immediately gives an indication of the shape of the distribution (i.e., histogram or frequency distribution) of the data values. Some information contained in the original data set is lost when the observations are grouped and, in general, the fewer the number of intervals, the greater the loss. The number of intervals should ensure the necessary balance among accuracy, ease of communication, the way in which the information will be used and the statistical tests to which the data will be subjected.

Frequency distributions can be classified by their shape:

(a) Unimodal symmetrical curves: these curves are common for element averages, such as annual and longer-term average temperature, with longer averaging periods generally resulting in more symmetrical distributions;

(b) Unimodal moderately asymmetrical curves: many curves of averaged data are mostly (but not quite) symmetrical;

(c) Unimodal strongly asymmetrical curves: these shapes are far from symmetrical and exhibit a high degree of skew; they are common for precipitation amounts and wind speeds, which are bounded below by zero;

(d) U-shaped curves: these curves are common for elements that have two-sided boundaries, such as the fraction of cloud cover (there are greater tendencies for skies to be mostly clear or mostly overcast);

(e) Multimodal or complex curves: these curves are common for elements observed daily in areas with strong seasonal contrasts. In such a case the frequency distribution curve built using the whole data set may show a highly characteristic bimodal shape.

Data sets with very complex frequency distributions are likely to be better understood if the data are stratified a priori to reflect the different underlying processes, for example if the data are sorted by season.

A third approach to organization is to form a cumulative frequency distribution, also called an ogive. A graph is constructed by plotting the cumulative number or percentage of observations against the ordered values of the element. The ogive representation of the data is useful for determining what proportion of the data is above or below a certain value. The proportion of values below a certain value, expressed as a percentage, is called a percentile. A proportion based on tenths is called a decile, based on quarters is called a quartile, and based on fifths is called a quintile. Quintiles have a particular use in calculations of precipitation normals (see the *WMO Guidelines on the Calculation of Climate Normals* (WMO-No. 1203)).

Other visualizations include box plots, stem and leaf diagrams and data arrays. For data with two elements, such as wind speed and direction, scatter diagrams can be constructed by plotting the value of the first element against the value of the second. Wind roses also provide excellent depictions of wind information. Double-mass curves, which are frequently used by hydrologists and for data homogeneity detection, are constructed by plotting the cumulative value of one element against the cumulative value of the second element. Visualization techniques are limited only by the imagination of the analyst, but all techniques involve the sorting and classification of the data. No matter which technique is used, the resulting graphic should be informative and should not inadvertently lead users to unsupported conclusions.

A graph of data values plotted against time is an important qualitative tool for identifying time-related variations such as linear trends, a curve, or even an abrupt upward or downward shift. What might appear as a sustained trend in the most recent period of a climate record could be part of a slow oscillation related to multidecadal variations that cannot be clearly seen, either because the time interval of the apparent sustained trend is only a part of the whole oscillation, or because the nature of the series projected into the future is unknown.

## 3.3 Quantitative summary descriptors

Rather than presenting the entire data set to illustrate a particular feature, it is often useful to extract several quantitative summary measures. The summary measures help to describe patterns of variation in observations. Understanding these patterns furthers the knowledge of the physical processes that underlie the observations and improves inferences that can be made about past and current climate conditions.

Care must be taken to ensure that the contents of a data set that are summarized by quantitative measures are actually comparable. For example, a series of temperature observations may be comparable if all the observations are taken using the same instrumentation, at the same time each day, at the same location, and following the same procedures. If the procedures change, then artificial variations can be introduced into the data set. Sometimes the summary descriptors of a data set identify unexpected variations; any unexpected patterns should be examined to determine whether they are artificially induced or real effects of the climate system.

More than one series of observations can be simplified by examining the distribution of observations of one variable when specified values of the other variables are observed (conditional frequencies). The conditions are often based on prior knowledge of what can be expected or on information about the likelihood of certain events occurring. Conditional frequency analysis is especially useful in developing climate scenarios and in determining the local impacts of events such as the El Niño-Southern Oscillation phenomenon and other teleconnection patterns (strong statistical relationships among weather patterns in different parts of the Earth).

Any series of observations can be modelled using mathematical functions that reproduce the observations. Care must be taken when applying such techniques for a number of reasons. For example, the application of a mathematical function generally assumes that the observational data set fairly represents the physical process that is being observed, and that the data contain no errors. The main purpose of fitting a function is to approximate the distribution of the observations. If the fit is acceptable, then with just a few parameters, the summary function of the observations should provide a realistic description of the data that is compatible with the underlying physics in a smoothed form that ignores data errors. A secondary purpose is to describe the data within a theoretical framework that is sufficiently simple so that an unrealistic description of the data with too much weight placed on data errors or random factors that are extraneous to the processes being studied. The degree of smoothing is usually determined by how the data will be used and what questions the climatologist is trying to answer.

One approach to summarizing the distribution of a set of observations is to fit a probability distribution to the observations. These distributions are functions with known mathematical properties and only a small number of parameters (typically no more than three). The functions are always constructed so that the relative magnitudes of different values reflect differences in the relative likelihoods of those values being observed. If an observed frequency or conditional frequency distribution can be adequately described by a known probability density function, then it is possible to exploit the properties and relationships to analyse the data and make probabilistic and statistical inferences with a desired level of confidence. There are specific techniques for fitting distributions to observations, such as the methods of moments, probability-weighted moments (L-moments) and maximum likelihood. An understanding of the statistical theory underlying a distribution function is necessary to make proper inferences about the data to which the function is being applied.

How well a summary function describes the observations can be determined by examining the differences between the observations and the values produced by the function. Objective goodness-of-fit tests should be applied. Data sets can usually be modelled by more than one function, and the test measures can be compared to find the best or most useful fit. The chi-square and Kolmogorov-Smirnov tests are commonly used. The chi-square goodness-of-fit test assumes that data values are discrete and independent (no observation is affected by any other observation). The chi-square test is sensitive to the number of intervals, and the Kolmogorov-Smirnov test is effective if the data set has a large number of observations.

Observations often tend to cluster around a particular value. Any measure of central tendency should be accompanied by a measure of the degree of variation in the values of the observations from which the central tendency is derived. The arithmetic mean, commonly known as the average, is one of the most frequently used statistics in climatology. For observations that tend to cluster around a central value, the mean represents a number towards which the average in a very long time series of observations or other large data set would converge as the number of data values increases. The mean is not representative of the central tendency of strongly asymmetrical distributions.

A weighted mean is calculated by assigning different levels of importance to the individual observations so that, for example, more trustworthy or more representative observations have a greater influence on the mean than less reliable or less representative observations. Weights are generally mathematical relations that may have no inherent relation to the physical processes that are measured, but physical considerations should be taken into account whenever possible when the weighting methods are chosen. Generally speaking, weighting methods give good results when both physical and statistical properties vary continuously and quite slowly over the studied space and time. A common application of weighted means is spatial, whereby an observation is weighted by the area it represents.

There are several advantages to using mean values: the mean is a very convenient standard of reference for fluctuations in observations (since the sum of the departures from a mean is zero); the mean is easy to calculate; means for different non-overlapping subsets of the whole observational record can be combined; and the errors in estimates of mean values from samples are smaller than the errors for other measures of central tendency. Means, however, also have limitations. Data sets or distributions that are totally different in their internal structure may have the same mean value. For example, the mean of a bimodal distribution of cloud cover may be the same as the mean of a unimodal distribution, but the interpretation of the two means would be very different. In addition, the mean is greatly affected by exceptional and unusual values, with just a few extreme observations destroying the representative character of the mean. Observations that do not cluster towards a central value (such as cloud cover, which tends to cluster at either 0 or 8 oktas) are not well represented by a mean. For a mean to be useful, it must convey a valid meaning with respect to the actual conditions described by the data set, rather than merely being the result of a mathematical calculation.

The median is the middle of a cumulative frequency distribution: half of the data are above the median, the other half are below. Extreme variations have less of an influence on the median than on the mean because the median is a measure of the ascending (or descending) order of the observations. Since the median is based on the number of observations, the magnitude of extreme observations does not influence the median. The median is especially useful when observations tend to cluster around the centre, but some observations are also very high or very low (for example, monthly rainfall in arid climates, where most months have very low rainfall but there are a small number of large totals). As with the mean, data that do not cluster towards a central value are not well represented by the median.

Means make use of every observation and medians are resistant to outliers. These properties may be balanced by different kinds of trimmed means. Trimmed means are calculated by removing a small percentage of the highest and lowest values and then averaging the remaining values.

The mode is the value in the data set that occurs most often. Unlike the mean, it is not affected by the values of other observations, and unlike the median, it is not affected by the ranked position of other observations. Modes from small samples or from samples that have more than one cluster of observations are unreliable estimates of central tendency. If the observations fall into clusters (i.e. there is a multimodal distribution), the data set might be comprised of dissimilar factors, each of which has a different central value around which the observations tend to cluster.

For elements with a circular nature, such as wind direction, the concept of the mean can be ambiguous. The modal value, such as the prevailing wind direction, is often a more useful measure of central tendency for elements that are measured by direction.

A vector quantity that associates a direction with its magnitude, such as wind velocity, can be mathematically transformed into independent components, and these components can then be averaged and combined into a resultant mean vector. A mathematical resultant vector calculated from data with opposing directions and equal speeds will have a magnitude of zero; this calculation may not be meaningful for describing a climate. An alternative approach that may be more meaningful for climate descriptions is to calculate both an average scalar direction, in which the speed is ignore but circularity is taken into account (for example, wind directions of 355 degrees and 5 degrees are separated by 10 degrees, not 350 degrees), and an average scalar magnitude, in which the direction is ignored. An alternative is to combine the resultant vector direction with the scalar average magnitude.

In a perfectly symmetrical frequency distribution with one mode, such as the Gaussian distribution, the values of the mean, median and mode will be exactly the same. If the frequency distribution is skewed to high values (skewed to the right), the mean will have the highest value, followed by the median and then the mode. This sequence is reversed if the frequency distribution is skewed to low values (skewed to the left). These relationships (see Figure 3.1) and the features of the measures (see Table 3.1) should be considered whenever a measure of central tendency is selected to represent a data set.

**Table 3.1. Comparison of features of measures of central tendencies**

| *Feature* | *Mean* | *Median* | *Mode* |
|---|---|---|---|
| Affected by outliers | Yes | No | No |
| Representative of central tendency when frequency distributions are narrowly spread | Yes | Yes | Yes |
| Representative of central tendency when frequency distributions are widely spread | No | Maybe | No |
| Representative of central tendency when observations are clustered into more than one group | No | Maybe | No |
| Representative of central tendency when frequency distributions with one cluster are skewed | No | Yes | Yes |
| Ease of calculation | Easiest | Easy from ordered data | Easy from histogram |
| Departures sum to zero | Yes | Not always | Not always |
| Possibility for more than 1 | No | No | Yes |
| Indicator of variability | No | No | Only if more than one mode |

Once a suitable estimate of the central tendency is chosen, it is possible to measure the variability of individual observations around that value. The measurement of variation and its explanation is of fundamental importance. However, a record of only a few observations generally gives a poor basis for judging the variability. Variability can be measured absolutely or relatively. The deviation of each observation from the central tendency can be reduced to a value that represents and describes the entire data set. This single number is the absolute variability.

The simplest measure of absolute variability is the range of the observations. Although easy to calculate, the range has many limitations. If the extreme values are very rare or they fall well beyond the bulk of observations, then the range will be misleading. The range provides no information about the nature of the frequency distribution within the extreme limits. The range

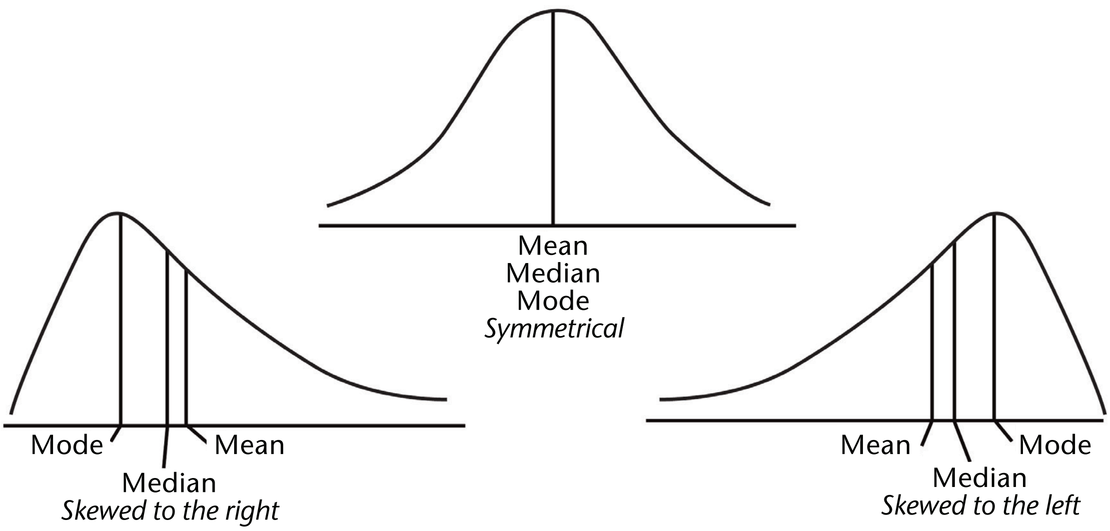


**Figure 3.1. Relationships among the mean, median and mode**

*Source:* WMO-No. 100, 3rd ed., Figure 4.15

also ignores the degree of concentration of the values almost entirely and fails to characterize in a useful manner the data set as a whole. Also, the range offers no basis for judging the reliability of the central tendency.

The interquartile range is another common measure of absolute variability. It is the range of the central 50% of the ordered observations. When coupled with the median, it describes some of the characteristics of the frequency distribution.

The average deviation is the mean of the absolute value of all the deviations of individual observations from the chosen measure of central tendency. While deviations may be calculated from the mean, median or mode, they should theoretically be calculated from the median because the sum of the absolute deviations from the median is less than or equal to the sum from either the mean or mode.

The standard deviation is the square root of the mean of the square of all the individual deviations from the mean. Deviations are taken from the mean instead of the median or mode because the sum of squares from the mean is a minimum. Squaring the deviations gives greater weight to extreme variations. The standard deviation is used in the derivation of many statistical measures. It is also used extensively as a normative quantity to standardize different distributions for comparative purposes.

Absolute measures of variability may have serious limitations when they are used for comparative purposes. Comparisons should be made only if averages from which the deviations have been measured are approximately equal in value, and when the units of measurement are the same. For example, comparing standard deviations calculated from a temperature data set and from a heating degree-day data set is meaningless.

Often, comparisons are required when the means are not approximately equal or when the units of measurement are not the same. Some kind of measure is therefore required that takes into account the mean from which deviations are measured and that reduces different units of measurement to a common basis for the purposes of comparison. The relation of the absolute variability to the magnitude of the central tendency is the relative variability. One such measure is the coefficient of variation, which is the ratio of the standard deviation to the mean of a data set.

Skewness is a measure of the departure from symmetry. It is a relative and dimensionless measure, allowing comparisons among data sets. Skewness is positive when the mean is greater than the mode, and negative when the mode is greater than the mean. Positive skewness is a characteristic of precipitation data sets that have a lower limit of zero but an unbounded upper limit. Daily maximum temperature data sets sometimes tend towards positive skewness, while daily minimum temperature data sets sometimes tend towards negative skewness.

Symmetrical frequency distributions may have different degrees of flatness in the central part of the distribution. Kurtosis is a dimensionless ratio that provides a relative measure, for comparative purposes, of flatness or peakedness. Positive kurtosis indicates a narrow maximum in the centre of the frequency distribution, with frequencies falling sharply to low values away from the mean. Negative values indicate a large, flat central region, and are typical of many meteorological distributions, such as upper-air humidity. A large number of data values are required for a kurtosis calculation to be meaningful.

One often needs to detect or describe the relationship between or among elements. A relationship may be evident from visual displays of data, such as a scatter diagram, but quantitative measures are often calculated. A correlation coefficient is a measure that quantifies a relationship. One of the problems with using a simple correlation coefficient is that the implied relationship is linear. Often, meteorological elements are related in a non-linear manner, and the data set may need to be transformed (see section 3.5.3) prior to the calculation of a correlation coefficient. Another measure, the Spearman rank correlation, is also sometimes used. The Spearman rank correlation measures agreement between the ordered ranks of two data sets. It is less sensitive to extremes than the correlation coefficient; it measures linear association and sometimes indicates non-linear association.

It is important to note that correlation does not imply a cause-and-effect relationship, but only that elements behave in a similar way. Often, factors other than those being investigated could be responsible for the observed association. Many apparent relationships in meteorology and climatology are too complex to be explained by a single cause. Just as a positive or negative correlation does not imply causation, a zero correlation does not necessarily imply the absence of a causative relationship.

Contingency tables are a simple yet effective way of discovering important relationships among factors, especially for large data sets. They are most often formed from qualitative descriptors (such as "mild", "moderate" or "severe"), or from dichotomous variables (indicating whether an event did or did not occur). They can also be formed from the joint frequency of two elements, such as wind speed and direction, or the diurnal distribution of visibility. The independence of the elements of a contingency table is often assessed by using a chi-square test. When this test is used, the serial dependence often found in climatological time series, according to which an observation is more likely to be similar to its preceding observation than dissimilar, violates the assumptions of the test, in which case the conclusions drawn from the test may be suspect.

Measures that summarize trends in a time series depend on the kind of trend that is being isolated. Linear trends are represented by the slope of a straight line. Non-linear trends are represented by the coefficients of the mathematical variables defining the equation for a curve fit, such as the coefficients of a polynomial function. Similarly, periodic features are also represented by the coefficients of the mathematical variables defining the oscillations, such as the frequency, phase and amplitude of trigonometric functions. In meteorology and climatology, successive observations tend to be more similar to each other than dissimilar. A calculated measure used to summarize the relationship between each observation and its predecessor is autocorrelation.

An index reduces complex conditions to a single number that retains some physical meaning and can be used to monitor a particular process. It expresses the relationship between observed and baseline conditions as a single value. The baseline is usually, but not always, the average climatic state. An example is the Palmer Drought Severity Index, which is a summary comparison of a complex water-balance system consisting of precipitation, evaporation, run-off, recharge and soil properties to climatically average conditions. The development of an index has four components: the selection of the elements that are to be included in the index, the selection and calculation of the baseline, the method of construction of the index, and the weights or importance of each of the included elements.

Examination and selection of the data to be included in the index often constitute a more complex task than the actual calculation of the index. One of the concerns when a baseline is chosen is that the characteristics of the observations used to define the baseline may change over time; it is essential that the observations used be homogeneous (see section 3.5.1). Another concern is that the baseline should represent normal, standard or expected conditions, since most users of an index assume that the baseline represents such conditions. When a baseline is selected, care should be taken to explicitly define what is to be compared and for what purpose.

Selection of weights is a critical consideration. The importance of each element that contributes to the index should be weighted in relation to the purpose of calculating the index. If the index is to be calculated in the future, care must also be taken to periodically review the contribution of each element to identify changes in factors such as importance, data accuracy, measurement and processing.

An alternative definition of "index" has been used in the development of climate indices. Climate indices are diagnostic tools used to describe the state of the climate system and monitor climate. They have been developed specifically to assess the changing frequency, intensity and duration of climate extremes, including measures of extrema, that is, the number of occurrences above or below a specified threshold. Under the auspices of the Expert Team on Climate Change Detection and Indices, 27 indices were developed as core climate-change indices (see the *Guidelines on Analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation* (WMO/TD-No. 1500)). These have subsequently been expanded under the auspices of WMO to include more sector-specific indices calculated using the software package Climpact, with associated observational data sets available via the Climdex project. The software and data sets are continuing to be maintained and upgraded; it is advisable to keep abreast of new developments.

Climate normals summarize climatic conditions over a defined time period. They are used for two principal purposes. They serve as a benchmark against which recent or current observations can be compared, including by providing a basis for many anomaly-based climate data sets (for example, global mean temperatures). They are also widely used, implicitly or explicitly, to predict the conditions most likely to be experienced in a given location. Detailed calculation methodologies and time periods defined for standard normals, normals, reference normals and period averages are given in the *WMO Guidelines on the Calculation of Climate Normals* (WMO-No. 1203).

## 3.4 Interpretation of summary characteristics of climate

Although it is possible to calculate numerous summary measures, it may not be appropriate to use them to describe the data set. The fact that a calculation can be made does not mean that it should be. All measures that reduce observations in order to detect and describe a climate signal or relationship are based on assumptions, and if the assumptions are not valid, the summary measures may be misleading. There are four issues that must be considered in detail before summary measures are used: data set errors, inhomogeneity, independence of observations and neglect of important factors.

Faulty inferences are often made when quantitative measures are used to compare data that are not actually comparable, such as in a comparison of inhomogeneous observations. If possible, any data set being analysed should be made homogeneous (see section 3.5.1).

Many meteorological data sets violate the assumption of independence. Before a data set is summarized, care should be taken to remove, if possible, dependence between observations. For example, the effect of known annual cycles can be largely removed by summarizing departures from the known cycle. If persistence (autocorrelation) is known to affect a series of observations, as sometimes occurs with daily temperatures observed during a synoptic surface high-pressure event, this should be taken into account in the analytical model. If dependence is not accounted for by the models, subsampling by selecting only one of the several available observations during the persistent event would remove the persistence affecting all the observations taken during the event. Care must also be taken in this process, however, so as not to mask any underlying oscillation, which can lead to an incorrect analysis. Some smoothing techniques, such as filtering or moving averages, may increase dependence, and this increase should be taken into account.

An incomplete or erroneous explanation can occur when quantitative evidence is presented concerning only one factor, with other important factors ignored. For example, if temperatures are compared over a cold season at a coastal location and a continental location, the averages may be similar enough to suggest that the climates are the same, but such a conclusion would not be drawn if the greater variability at the continental location were taken into account.

Specific assumptions concerning, for example, the consistency and homogeneity of the data or the nature of the dependence between observations are implicit in all analysis techniques. These assumptions should be clearly identified and assessed by the analyst, and the interpretation of a summary measure should be tempered by the extent to which the assumptions are satisfied. If any of the assumptions are violated, the interpretation of a summary measure should be changed to account for the violations. The usual interpretation of the measure may still suffice, but the real or suspected violations should be disclosed with the measure. For example, if annual average temperatures are calculated from a data set that is known from the metadata to be inhomogeneous, the assumption that all data are comparable is violated. This violation should be disclosed, as should its effect on the calculation of the mean. When analysing large data sets with techniques such as neural networks, artificial intelligence or data science, it is critical to know the assumptions, rules and workings of the process so that judgments can be made about the validity of the techniques for the purposes of the analysis.

## 3.5 Data analysis considerations

The topics in this section are some of the considerations that an analyst should be aware of when examining data and drawing conclusions. Technological advances in hardware and software have made it easier and quicker to process a large volume of data and output a variety of statistics, graphics and conclusions. The guidance in this section is intended to remind data analysts of some of the characteristics of geophysical data, the most prevalent problems with such data, and how those characteristics and problems could affect the results and conclusions of statistical packages and any data analysis. The topics discussed are important for proper analysis or are not usually considered.

### 3.5.1 *Data errors*

A homogeneous climate data set is one in which all the fluctuations contained in its time series reflect the actual variability and change of the represented climate element. Most statistical methods assume that the data under examination are as free from instrumentation, coding, processing and other non-meteorological or non-climatological errors as possible. Meteorological and climatological data, however, are generally neither homogeneous nor free from error. The types of errors range from systematic errors (ones that affect a whole set of observations in the same way, such as constant instrument calibration errors and improper conversion of units) to random errors (any one observation is subject to an error that is as likely to be positive as it is negative, such as parallax differences among observers reading a mercury barometer). Errors themselves may be independent or correlated. Random, independent errors are those that have no dependence from one observation to the next. Dependent errors are correlated from one observation to the next. It is therefore advisable to assess the data for suitability to the statistical methods being used and, if possible, adjust the data to meet the assumptions of the methods. Conversely, if possible, the methods could be adjusted to fit the data. The analyst should be aware of violations of assumptions inherent to the statistical method and of the effect of these violations on the results of the analysis.

The best way to keep the climate record homogeneous is to avoid changes and errors in the collection, handling, transmission and processing of the data. It is highly advisable to maintain observing practices and instruments as unchanged as possible. It is also highly advisable to maintain a quality-management system. Unfortunately, most long-term climatological data sets have been affected by a number of factors not related to the broader-scale climate. These include changes in geographical location; local land use and land cover; instrument types, exposure, mounting and sheltering; observing practices; calculations, codes and units; data processing and archiving procedures; and historical and political events. Some changes may cause sharp discontinuities, such as steps (for example, following a change in instrument or site), while others may cause gradual biases (resulting, for example, from increasing urbanization in the vicinity of a site). In both cases, the related time series become inhomogeneous, and these inhomogeneities may affect the proper assessment of climatic trends. Techniques for examining these time series changes include both parametric and non-parametric statistical methods. Note that site changes do not always affect observations of all elements, nor do changes affect observations of all elements equally. The desirability of a homogeneous record stems primarily from the need to distil and identify changes in the broader-scale climate. There are some studies, however, that may require certain “inhomogeneities” to be reflected in the data, such as an investigation of the effects of urbanization on local climate or of the effects of vegetation growth on the microclimate of an ecosystem.

Although many objective techniques exist for detecting and adjusting the data for inhomogeneities, the actual application of these techniques remains subjective. At the very least, the decision about whether to apply a given technique is subjective. This means that independent attempts at homogenization may easily result in quite different data. It is important to keep detailed and complete documentation of each of the steps and decisions made during the process. The adjusted data should not be considered absolutely “correct”, nor should the original data always be considered “wrong”; the original data should always be preserved.

Caution is needed when data are in submonthly resolution (such as daily or hourly observations) because one of the uses of homogeneous daily data is for assessing changes in extremes. Extremes, no matter how they are defined, are rare events that are often created by a unique set of weather conditions. If few extreme data points are available for the assessment, determining the proper homogeneity adjustment for these unique conditions can be difficult. Extremes should be considered as part of the whole data set, and they should therefore be homogenized not separately from, but together with all the data. Homogenization techniques for monthly, seasonal and yearly temperature data are generally satisfactory, but homogenization of daily data and extremes remains a challenge.

Guidance on methods to identify inhomogeneities, techniques to homogenize a data set and evaluation of a resulting homogenized data set is given in *Guidelines on Homogenization* (WMO-No. 1245). Homogeneity assessment and data adjustment techniques are areas of active development, and both the theory and practical tools are continuing to evolve. Efforts should be made to keep abreast of the latest techniques.

### 3.5.2 ***Model-fitting to assess data distributions***

The examination of residuals (the difference between observations and a model) is a powerful tool for understanding data and suggesting how they or the model need to be changed. A graphical presentation of residuals is useful for identifying patterns. If residual patterns such as oscillations, clusters and trends are noticed, then the model used is usually not a good fit for the data. Outliers (a few residual values that are very different from the majority of the values) are indicators of potentially suspicious or erroneous data values. If no patterns exist and the values of the residuals appear to be randomly scattered, the model may be accepted as a good fit for the data.

If the data have been fitted by an acceptable statistical frequency distribution, meeting any necessary independence, randomness or other sampling criteria, and the fit has been validated, the model can be used as a representation of the data. The model also provides estimates of central tendency, variability and higher-order properties of the distribution (such as skewness or kurtosis). The confidence that these sample estimates represent real physical conditions can also be determined. Other characteristics, such as the probability of an observation exceeding a given value, can also be estimated by applying probability and statistical theory to the modelled frequency distribution.

### 3.5.3 ***Data transformation***

The normal or Gaussian frequency distribution is widely used, as it has been studied extensively in statistics. If the data do not fit the normal distribution well, the analyst should attempt to fit the data with another well-studied statistical distribution, such as fitting extreme values with the generalized extreme value or Weibull distribution or fitting precipitation data with a zero-bounded gamma distribution. Other distributions involve counting, random draws and threshold exceedances.

There are several ways to tell whether a distribution of an element is substantially non-normal. Visual inspection of histograms, scatter plots, probability–probability and quantile-quantile plots are relatively easy to perform. A more objective assessment can range from a simple examination of skewness and kurtosis to inferential tests of normality. The analyst must ensure that the non-normality is caused by a valid reason. Invalid reasons for non-normality include data entry mistakes and missing data values that have not been declared missing. Another invalid reason for non-normality may be the presence of outliers, as the outliers may well be a realistic part of a normal distribution.

Another approach is to apply a transformation to the data that may result in a frequency distribution that is nearly normal, allowing the theory underlying the normal distribution to form the basis for many inferential uses. If a transformation is applied, care should be taken to ensure that the transformed data still represent the same physical processes as the original data.

The most common data transformations are the square root, cube root, logarithmic and inverse transformations. The square root makes values less than 1 greater and values greater than 1 smaller. If the values can be positive or negative, a constant offset must be added before the square root is taken so that all values are greater than or equal to 0. The cube root has a similar effect to the square root but does not require the use of an offset to handle negative values. Logarithmic transformations compress the range of values by making small values relatively larger and large values relatively smaller. A constant offset must first be added if zero or negative values are present. An inverse makes very small numbers very large and very large numbers very small; values of 0 must be avoided.

The transformations all compress the right side of a distribution more than the left side and are therefore effective on positively skewed distributions such as precipitation and wind speed. If a distribution is skewed negatively, the data must be reflected (the values are multiplied by –1, then a constant is added to ensure all values are greater than 0) before they are transformed, to reverse the distribution, then reflected again after the transformation, to restore the original order of the data.

The above transformations are ordered according to their relative power, from weakest to strongest. A good guideline is to use the minimum amount of transformation necessary to achieve the desired shape of the frequency distribution. If a meteorological or climatological element has an inherent, highly non-normal frequency distribution, such as the U-shape distribution of cloudiness and sunshine, there are no simple transformations for the normalization of the data.

Data transformations offer many benefits, but they should be used in an informed manner. The very act of altering the relative distances between data points, which is how these transformations aim to improve normality, raises issues regarding the interpretation of the data. All data points remain in the same relative order as they were prior to transformation, which allows interpretation of results in terms of the increasing value of the element. However, the transformed distributions will likely be more complex to interpret physically, given the curvilinear nature of the transformations. The analyst must therefore be careful when interpreting results based on transformed data.

### 3.5.4 *Time series analysis*

Time series in climatology have been analysed using a variety of techniques that decompose a series into time-domain or frequency-domain components. A critical assumption of these models is that of stationarity (when characteristics of the series such as mean and variance do not change over the length of the series). This condition is generally not met by climatological data, even if the data are homogeneous.

Most statistical forecasting methods are based on the assumption that time series can be rendered approximately stationary when a transformation is applied. For example, a time series exhibiting a linear trend can be detrended by subtracting the equation for a straight line from the data. When the mathematical transformations used to achieve stationarity are reversed, predictions can be made for the original series.

Another reason to transform a time series is to obtain meaningful sample statistics such as means, variances and correlations with other variables. Such statistics are useful as descriptors of future behaviour if the series is stationary. For example, if the series is consistently increasing over time, the sample mean and variance will grow with the size of the sample, and they will always underestimate the mean and variance in future periods. If the mean and variance of a series are poorly defined, its correlations with other variables will also be poorly defined.

A second approach is to model sub-intervals of a time series with wavelet analyses. Allowing sub-intervals of a time series to be modelled with different scales or resolutions relaxes the condition of stationarity. These analyses are particularly good at representing time series with sub-intervals that have differing characteristics, such as when the time series has spikes or sharp discontinuities. Compared with the classical techniques, it is particularly efficient for signals in which both the amplitude and frequency vary with time. One of the main advantages of these "local" analyses is the ability to present time series of climate processes in the coordinates of frequency and time, studying and visualizing the evolution of various modes of variability over a long period. Such analyses are used not only as a tool for identifying non-stationary scales of variations, but also as a data analysis tool to gain an initial understanding of a data set. There have been many applications of these methods in climatology, such as in studies of the El Niño-Southern Oscillation phenomenon, the North Atlantic Oscillation, atmospheric turbulence, space–time precipitation relationships and ocean wave characteristics.

Wavelet analyses do have some limitations, however. The most important limitation is that an infinite number of wavelet functions are available as a basis for analysis, and results often differ depending on which wavelet is used. This makes it somewhat difficult to interpret results, because different conclusions can be drawn from the same data set if different mathematical functions are used. It is therefore important to relate the wavelet function to the physical world before selecting a specific wavelet. Wavelet analysis techniques are emerging fields and, although the mathematics has been defined, future refinements in techniques and application methodology may mitigate the limitations.

Other common techniques for analysing time series are autoregressive and moving-average analyses. Autoregression is a linear regression of a value in a time series against one or more prior values in the series (autocorrelation). A moving-average process expresses an observed series as a function of a random series. A combination of these two methods is called a mixed autoregressive and moving-average (ARMA) model. An ARMA model that allows for non-stationarity is called a mixed autoregressive integrated moving-average (ARIMA) model. These regression-based models can be made more complex than necessary, resulting in overfitting. Overfitting can lead to the modelling of a series of values with minimal differences between the model and the data values, but since the data values are only a sample representation of a physical process, a slight lack of fit may be desirable to represent the true process. The non-stationarity of the parameters used to define a model, non-random residual (indicating an inappropriate model) is another problem, as is periodicity that is inherent in the data but not modelled. Split validation is effective in detecting model overfitting. Split validation refers to the practice of developing a model based on a portion of the available data and then validating the model on the remaining data that were not used in the model's development.

Once the time series data have been modelled by an acceptable curve and the fit has been validated, the mathematical properties of the model curve can be used to make assessments that would not be possible using the original data. These include measuring trends, cyclical behaviour, and autocorrelation and persistence, together with estimates of the confidence of these measures.

### 3.5.5 ***Multivariate analysis***

Multivariate data sets are a compilation of observations of more than one element over time and/or space. These data sets are often studied for many different purposes. The most important purposes are to establish whether there are simpler ways of representing a complex data set, whether observations fall into groups that can be classified, and whether interdependence exists among elements. Such data sets are also used to test hypotheses about the data. The sequence of the observations is generally not a consideration in multivariate analyses. Time series of more than one element are usually considered as a separate analysis topic with techniques such as cross-spectral analysis.

Principal components analysis – sometimes referred to as empirical orthogonal functions analysis – is a technique for reducing the dimensions of multivariate data. The process simplifies a complex data set and has been used extensively in the analysis of climatological data. Since most of the variance is usually explained by just a few components, the methods are effective in reducing "noise" from an observed field. Individual components can often be related to a single meteorological or climatological element, but it should be noted that the principal components are a statistical construct and are not, by definition, based on physics. The method has been used to analyse a diversity of fields, including sea-surface temperatures, regional land temperature and precipitation patterns, tree-ring chronologies, sea level pressure, air pollutants, radiative properties of the atmosphere, and climate scenarios. Principal components have also been used as a climate reconstruction tool, such as for estimating a spatial grid of a climatic element from proxy data when actual observations of the element are not available.

Factor analysis reduces a data set from a larger set of observations to a smaller set of factors. It is similar to principal components analysis, except that the factors are could be correlated. Since a factor may represent observations of more than one element, meteorological or climatological interpretation of a factor is often difficult. The method has been used mainly in synoptic climatology studies.

Cluster analysis attempts to separate observations into groups with similar characteristics. There are many clustering methods, and different methods are used to detect different patterns of points. Most techniques iteratively separate the data into more and more clusters, thereby presenting the problem for the analyst of determining when the number of clusters is sufficient. Unfortunately, there are no objective rules for making this decision. The analyst should therefore use prior knowledge and experience in deciding when a meteorologically or climatologically appropriate number of clusters has been obtained. Cluster analysis has been used for diverse purposes, such as constructing homogeneous regions of precipitation, analysing synoptic climatologies, and predicting air quality in an urban environment.

Canonical correlation analysis seeks to determine the interdependence between two groups of elements. This analysis is used, for example, in making predictions from teleconnections, in statistical downscaling, in determining homogeneous regions for flood forecasting in an ungauged basin, and in reconstructing spatial wind patterns from pressure fields. A similar analysis that may be explored is singular value decomposition. This method, as with canonical correlation analysis, finds linear combinations of the two groups of elements such that the linear combinations attempt to capture the maximum possible covariance.

These methods all have limitations and are all based on certain assumptions. The interpretation of the results depends greatly on the assumptions being met and on the experience of the analyst. Other methods, such as multiple regression and covariance analysis, are even more restrictive for most meteorological or climatological data. Multivariate analysis is complex, with numerous possible outcomes, and care is required in its application.

### 3.5.6 *Comparative analysis*

By fitting a model function to the data, be it a frequency distribution or a time series, it is possible to use the characteristics of that model for further analysis. The properties of the model characteristics are generally well studied, allowing a range of conclusions to be drawn. If the characteristics are not well studied, bootstrapping may be useful. Bootstrapping is the estimation of model characteristics from numerous random samples drawn from the original observational series. It is an alternative to making inferences from parameter-based assumptions when the assumptions are in doubt, when parametric inference is impossible, or when parametric inference requires very complicated formulae. Bootstrapping is simple to apply, but it may conceal its own set of assumptions that would be more formally stated in other approaches. More advanced data science methodologies that are similar to bootstrapping are rapidly emerging, and analysts should keep abreast of developing techniques.

There are many tests available for comparing the characteristics of two models to determine how much confidence can be placed in claims that the two sets of modelled data share underlying characteristics. In principle, any computable characteristic of the fitted models can be compared, although there should be some meaningful reason (based on physical arguments) to do so. Some of these tests are parametric, depending on assumptions about the distribution, such as normality, and others are non-parametric, so they do not make assumptions about the distribution. Parametric tests are generally better (in terms of confidence in the conclusions), but only if the required assumptions about the distribution are valid.

The seriousness of rejecting a true hypothesis (or accepting a false one) is expressed as a level of confidence or probability. The selected test will show whether the null hypothesis can be accepted at the level of confidence required. If the null hypothesis is rejected, the alternative hypothesis must be accepted. Regardless of which hypothesis is accepted (null or alternative), the conclusion may be erroneous. When the null hypothesis is rejected but it is actually true, a type I error has been made. When the null hypothesis is accepted and it is actually false, a type II error has been made. Unfortunately, reducing the risk of a type I error increases the risk of a type II error, so a balance must be struck between the two types. This balance should be based on the seriousness of making either type of error. In any case, the confidence of the conclusion can be calculated in terms of probability and should be reported with the conclusion.

### 3.5.7 *Smoothing*

Smoothing methods provide a bridge between making no assumptions based on a formal structure of observed data (the non-parametric approach) and making very strong assumptions (the parametric approach). Making a weak assumption that the true distribution of the data can be represented by a smooth curve allows underlying patterns in the data to be revealed to the analyst. Smoothing increases signals of climatic patterns while reducing noise induced by random fluctuations. The applications of smoothing include exploratory data analysis, model building, goodness-of-fit of a representative (smooth) curve to the data, parametric estimation, and modification of the standard methodology.

It is important to remember that smoothing alters the properties of the data and can increase temporal or spatial autocorrelation or impose particular structures on the data (for example, empirical orthogonal function analysis). Care should be taken when smoothed fields are used as the input to any further statistical processing. Before applying smoothing techniques, the analyst should know and understand what processing has already been applied to the data.

A range of more sophisticated, often non-parametric, smoothers is also available. These include local maximum likelihood estimation, which is particularly useful when prior knowledge of the behaviour of the data set can lead to a good "first guess" of the type of curve that should be fitted. These estimators are sometimes difficult to interpret theoretically.

With multivariate data, smoothing is more complex because of the number of possibilities of smoothing and the number of smoothing parameters that need to be set. As the number of data elements increases, smoothing gradually becomes more difficult. Most graphs are limited to only two dimensions, so a visual inspection of the smoother is limited. Kernel density can be used to smooth multivariate data, but the problems of boundary estimation and fixed bandwidths can be even more challenging than with univariate data.

Large empty regions in a multivariate space usually exist unless the number of data values is very large. Collapsing the data to a smaller number of dimensions with, for example, principal components analysis, is a smoothing technique. The goal of the dimension reduction should be to preserve any interesting structure or signal in the lower-dimension data while removing uninteresting attributes or noise.

One of the most widely used smoothing tools is regression. Linear and nonlinear regression models are powerful for modelling a target element as a function of a set of predictors, allowing for a description of relationships and the construction of tests of the strength of the relationships. These models are susceptible, however, to the same problems as any other parametric model, since the assumptions made affect the validity of inferences and predictions.

Regression models also suffer from boundary problems and unrealistic smoothing in sub-intervals of the data range. These problems can be solved by weighting sub-intervals of the data domain with varying bandwidths and by applying polynomial estimation near the boundaries. Regression estimates can be affected by observations with unusual response values (outliers). When using adjusted non-parametric smoothing, it is often difficult to unambiguously identify a value as an outlier, because the intent is to smooth all the observations. Outliers could be a valid meteorological or climatological response, or they could be aberrant; additional investigation of each outlier is necessary to ensure the validity of the value. Regression estimates are also affected by correlation. Estimates are based on the assumption that all errors are statistically independent of each other; a correlation can affect the asymptotic properties of the estimators and the behaviour of the bandwidths determined from the data.

### 3.5.8 *Data estimation*

One of the main applications of statistics to climatology is the estimation of values of elements when few or no observed data are available or when expected data are missing. In many cases, the planning and execution of user projects cannot be delayed until there are enough meteorological or climatological observations; estimation is used to extend a data set. Estimation also has a role in quality control, since it allows an observed value to be compared with neighbouring values in both time and space. Techniques for estimating data are essentially applications of statistics, but they should also rely on the physical properties of the system being considered. In all cases, it is essential that statistically estimated values should be realistic and consistent with physical considerations.

Interpolation uses data that are available both before and after a missing value (time interpolation), or data surrounding the missing value (space interpolation), to estimate the missing value. Extrapolation extends the range of available data values. There are more possibilities for error in extrapolated values because relations are used outside the domain of the values from which the relationships were derived. Even if empirical relations found for a given place or period of time seem reasonable, care must be taken when applying them to another place or time, because the underlying physics at one place and time may not be the same at another.

Mathematical methods involve the use of only geometric or polynomial characteristics of a set of point values to form a continuous surface. Inverse distance weighting assumes that the closer an observation location is to the location where the data are being estimated, the better the estimation. This assumption should be carefully validated since there may be no inherent meteorological or climatological reason to justify the assumption. Curve fitting methods, such as spline functions, assume that the physical processes can be represented by a mathematical spline. There is rarely any inherent justification for this assumption. Both methods work best on smooth surfaces, so they may not result in adequate representations on surfaces that have marked fluctuations.

The physical consistency that exists among different elements can be used for estimation. For instance, if some global radiation measurements are missing and need to be estimated, elements such as sunshine duration and cloudiness could be used to estimate a missing value. Proxy data may also be used as supporting information for estimation. When simultaneous values at two stations close to each other are compared, sometimes either the difference or the quotient of the values is approximately constant. This is more often true for summarized data (for months or years) than for data representing shorter time intervals (such as daily data). The constant difference or ratio can be used to estimate data. When these methods are used, the series being compared should be sufficiently correlated for the comparison to be meaningful. If these conditions are not met, in particular if the variances of the series at the two stations are not similar, these techniques should not be used. More complex physically consistent tools include regression, discriminant analysis (for the occurrence of phenomena) and principal components analysis.

Deterministic methods are based upon a known relation between an in situ data value (the predictand) and the values of other elements (the predictors). This relation is often based on empirical knowledge about the predictand and the predictors. The empirical relation can be found using either physical or statistical analysis, and it is frequently found using a combination of the two, with a statistical relation being derived from values based on the knowledge of a physical process. Statistical methods such as regression are often used to establish such relations. The deterministic approach is stationary in time and space and must therefore be regarded as a global method reflecting the properties of the entire sample. The predictors may be other observed elements or other geographical parameters, such as elevation, slope or distance from the sea.

Spatial interpolation is a procedure for estimating the value of properties at unsampled sites located within an area that is covered by existing observations. The rationale behind interpolation is that observation sites that are close together in space are more likely to have similar values than sites that are far apart (spatial coherence). All spatial interpolation methods are based on theoretical considerations, assumptions and conditions that must be fulfilled for a method to be used properly. Therefore, when a spatial interpolation algorithm is selected, the purpose of the interpolation, the characteristics of the phenomenon to be interpolated, and the constraints of the method have to be considered.

Stochastic methods for spatial interpolation are often referred to as geostatistical methods. A feature shared by these methods is that they use a spatial relationship function to describe the correlation among values at different sites as a function of distance. The interpolation itself is closely related to regression. These methods require certain statistical assumptions to be fulfilled. For example, the process might be required to follow a normal distribution, or it might be required to be stationary in space, or constant in all directions.

Although there are many tools for spatial interpolation, kriging is a spatial interpolation approach that has been used often to interpolate elements such as air and soil temperature, precipitation, air pollutants, solar radiation and winds. The technique considers the rate at which the variance between points changes over space; this is expressed in a variogram. When developing a variogram, it is necessary to make some assumptions about the nature of the observed variation on the surface, such as the constancy of means over the entire surface, the existence of underlying trends, and the randomness and independence of variations.

A problem with kriging is the critical assumptions that must be made about the statistical nature of the spatial variation. Although many variants of kriging allow flexibility, the method was developed initially for applications in which distances between observation sites were small. With climatological data, the distances between sites are usually large and the assumption of smoothly varying fields between sites is often not realistic. In these cases, alternative approaches such as climatologically aided interpolation can also be explored.

Advances in computer capacity for intensive computations have led to the development and use of new techniques. These new techniques include the machine learning techniques of neural networks and random forests. Such methods have been used to generate realistic fields of wind, satellite rainfall retrievals and monthly air temperature, among other fields. A machine learning methodology is likely to emerge as a mainstream spatial interpolation tool.

Since meteorological and climatological fields such as precipitation are strongly influenced by topography, some methods, such as Analysis Using Relief for Hydrometeorology (AURELHY) and Parameter-elevation Regressions on Independent Slopes Model (PRISM), incorporate the topography into an interpolation of climatic data by combining principal components analysis, linear multiple regression and kriging. Depending on the method used, the topography is described by the elevation and by the slope direction generally averaged over an area. The topographic characteristics are generally at a finer spatial resolution than the climate data. Figure 3.2 is an example of AUREHLY.

The most advanced physically based methods are those that incorporate a description of the dynamics of the climate system. Similar models are routinely used in weather forecasting and climate modelling (see section 4.4.1). As the computer power and storage capacity that these methods require are becoming more readily available, these models are being used more widely in climate monitoring, especially to estimate the value of climate elements in areas remote from actual observations (see section 4.6).

Time series often have missing data and values that need to be estimated at timescales that are finer than those provided by the observations. As a general rule, the longer the period to be estimated, the less confidence one can place in the estimates. It is assumed that the conditions

**Figure 3.2. February normals over France for the period 1981–2010, as measured using the AURELHY method**

*Source:* Météo-France

within the period to be estimated are similar to those occurring just before and just after the period to be estimated. Care must be taken to ensure that this assumption is valid. As with spatial interpolation, temporal interpolation should be validated to ensure that the estimated values are reasonable. Metadata and other corollary information about the time series are useful for determining the reasonableness.

At the regional to local scale, a range of tools have been developed to infill and estimate meteorological variables in data-sparse regions. Such tools include stochastic weather generators, which use the statistical characteristics of observed meteorological time series to simulate weather time series.

Any estimation is based on some underlying structure or physical reasoning. It is therefore very important to verify that the assumptions made in applying the estimation model are fulfilled. If they are not fulfilled, the estimated values may contain errors that could be serious and lead to incorrect conclusions. In climatological analysis, model assumptions are often not met. For example, in spatial analysis, for interpolation between widely spaced stations to be performed, the climatological patterns between stations should be known and it should be possible to model them. In reality, however, many factors influence the climate of a region, such as the topography, local peculiarities and the presence of water bodies. Unless these factors are adequately incorporated into a spatial model, the interpolated values will likely be wrong. In temporal analysis, interpolating over a large data gap assumes that the values representing conditions before and after the gap can be used to estimate the values within the gap. Consequently, the more variable the weather patterns are at a location, the less likely it is that this assumption will hold and the more likely it is that interpolated values will be wrong.

Validation of the results of the interpolation methodology is essential whenever estimation is performed. Split validation is a simple and effective technique. A large part of a data set is used to develop the estimation procedures and a single, smaller subset of the data set is reserved for testing the methodology. The data in the smaller subset are estimated using the procedures developed from the larger portion, and the estimated values are compared against the observed values. Cross-validation is another simple and effective tool that allows various assumptions about the models (such as the type of variogram and its parameters or the size of a kriging neighbourhood) or about the data to be compared using only the information available in the sample data set. Cross-validation is carried out by removing one observation from the data sample and then estimating the removed value based on the remaining observations. This is repeated over and over again, with a different observation removed each time until all observations have been checked. The residuals between the observed and estimated values can then be further analysed statistically or they can be plotted for visual inspection. Cross-validation offers quantitative insights into how any estimation method performs. An analysis of the spatial and temporal arrangement of the residuals often suggests further improvements to the estimation model.

The seriousness of any interpolation error depends on how the data will be used. Conclusions and judgments based on requirements for the microscale will be affected by errors to a greater extent than those based on requirements for the macroscale. When estimating data, it is important to carefully consider how sensitive the results are to the way the data will be used.

### 3.5.9 ***Extreme values***

Many practical problems in climatology require knowledge of the behaviour of extreme values of climatological elements. This is particularly true for the engineering design of structures that are sensitive to high or low values of meteorological or climatological phenomena. Structures can last for years or even centuries, and accurate estimation of return periods can be a critical factor in their design. Design criteria may also be described by the expected number of occurrences of events that exceed a fixed threshold.

Classical approaches to extreme-value analysis involve fitting an extreme-value probability distribution to the observed extremes. The data are the maxima (or minima) of values observed in a specified time interval, such as the minimum temperature in a year. The distributions imply assumptions such as stationarity and independence of data values. Constructing and adequately representing a set of maxima or minima from sub-intervals of the whole data set requires a large data set, which may be a strong limitation if the data sample covers a limited period. An alternative is to select values beyond a given threshold to create what is known as a partial duration series.

Once a distribution has been fitted to an extreme-value data set, return periods are computed. A return period is the mean frequency with which a value is expected to be equalled or exceeded (such as once every 20 years). Although lengthy return periods for the occurrence of a value can be calculated mathematically, the confidence that can be placed in the results may be minimal. As a general rule, confidence in a return period decreases rapidly when the period is more than about twice the length of the original data set. Confidence also decreases when the data are non-stationary (as many climate data are) and, in particular, when the climate is changing faster than the timescale for the return period.

Since extreme climate events can have significant impacts on natural and human-made systems, it is important to know whether and how climate extremes are changing. Some types of infrastructure currently have little margin to buffer the impacts of climate change. Adaptation strategies for non-stationary climate extremes should take into account the decadal-scale changes in climate observed in the recent past, as well as future changes projected by climate models. Newer statistical models, such as the non-stationary generalized extreme value, have been developed to try to overcome some of the limitations of the more conventional distributions. As models continue to evolve and as their properties become better understood, they will likely replace the more common approaches to analysing extremes. The *Guidelines on Analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation* (WMO/TD-No. 1500) provide more insight into how a changing climate should be taken into account when extremes are assessed and estimated.

### 3.5.10 *Robustness*

Statistical inferences are based on observations and on the assumptions of the underlying models (such as randomness, independence and model fit). Climatological data often violate many of these assumptions because of the temporal and spatial dependence of observations, data inhomogeneities, data errors and other factors.

The effect of assumptions on the results of analyses should be determined quantitatively if possible, and at the very least qualitatively, in an assessment of the validity of the conclusions. The purpose of an analysis is also important. General conclusions based on large temporal or spatial scale processes with a lot of averaging and on a large data set are often less sensitive to deviations from assumptions than more specific conclusions.

If results are sensitive to violations of assumptions, the analyst should flag this fact when disseminating the results to users. It may also be possible to analyse the data using other methods that are less sensitive to deviations from assumptions, or that do not make any assumptions about the factors causing the sensitivity problems. Since parametric methods assume more conditions than non-parametric methods, it may be possible to reanalyse the data using non-parametric techniques. For example, using the median and interquartile range instead of the mean and standard deviation decreases sensitivity to outliers or gross errors in the observational data.

### 3.5.11 *Emerging data challenges*

Technologies such as cloud computing, Web services and data analytics present new operating concepts that will improve operational efficiency, information-sharing and service delivery and enable users to exploit data more easily. Volume, velocity, variety and veracity are referred to as the “four v’s of big data”. This phrase describes the fact that massive amounts of data (volume) are being generated or moved frequently (velocity), that the nature of the data can be very different (variety), and that the trustworthiness of the data depends greatly on the source (veracity). The four v’s are especially related to data analytics, the aim of which is to extract insights from multifaceted data where the underlying relationships are often complex or poorly understood. An important fifth “v” is value, that is, how any data, big data or just lots of data will benefit organizations and services to users.

The growth in data volume and complexity – both observed inputs (especially from satellites) and processed/post-processed outputs – will continue to increase, as will the use of automated systems to extract value from data. The explosion of data and the associated boom in analytics will lead to the deployment of machine-learning technologies. Cloud computing technologies are already mature, and the associated services are becoming financially competitive against in-house hardware solutions. Such technologies include platforms for the aggregation and combination of a wide variety of data sources. It is anticipated that there will be a gradual shift to a true hybrid cloud environment, allowing workloads to be switched seamlessly among cloud environments, whether public or private.

Application programming interfaces (APIs) and Web services are now common solutions for machine-to-machine interaction. Since they offer standard interfaces and allow the exchange of data, solutions should be implemented to facilitate machine-to-machine communication. Lightweight interfaces allowing users to interact with data should be developed. Since such interactions often require users to be authenticated, it will be necessary to accept validated third-party authentication services.

Although the meteorological community understands and shares an inherent imperative to cooperate globally, there is a complementary imperative to act and to deliver services locally. Accordingly, it is necessary to build a bridge between global data and local information. The growing ability to quantify and qualify personal data through the plethora of social networks, applications and other devices enables meteorological and hydrological service providers to reach an increasingly diverse range of actors and users than ever before and thus to bridge the gap between the global and local levels. Furthermore, these two-way networks enable service providers to better understand and respond to the needs of the communities they serve.

Sources of data are becoming more diverse and include voluntary networks, third-party conventional data, new sensors and crowdsourced data. The variety of sources presents many challenges to data management and analysis. Competition from commercial data and service providers is increasing. The trend in the dissemination of data and products is towards open-source platforms. These and other emerging issues are discussed in more detail in the *WMO Guidelines on Emerging Data Issues* (WMO-No. 1239).

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# 4. CLIMATE PRODUCTS

## 4.1 Introduction

Climate products are defined in the *Implementation Plan of the Global Framework for Climate Services* as derived syntheses of climate data. They combine climate data with climate knowledge to add value. Climate products are information packages that include data, summaries, tables, graphs, maps, reports and analyses. Spatial distributions may be illustrated on maps. More complex products, such as climate atlases or analyses, may combine several kinds of visualization with descriptive text. There may also be databases with software tools that allow online customers to produce statistics and visualizations according to their own needs. For products such as climatic atlases or technical regulations, data should be for a standard reference period (see the *WMO Guidelines on the Calculation of Climate Normals* (WMO-No. 1203) for further details). Climate products may contain information that is retrospective, current (climate monitoring), predicted from initial conditions or projected using scenarios.

Another class of products is climate watches. These advisories are a mechanism to heighten awareness in the user community that a significant climate anomaly exists or might develop and that preparedness measures should be initiated. As described in *Guidelines on Climate Watches* (WMO/TD-No. 1269), the advisories are:

(a) Issued to heighten awareness in the user community concerning a particular state of the climate system;

(b) Disseminated to serve as a mechanism for initiating preparedness activities by users and/or a series of events that affect user decision-making;

(c) Based on real-time monitoring (current status) of conditions and climate outlooks;

(d) Issued by individual NMHSs, perhaps in coordination with other NMHSs or RCCs in the region or beyond;

(e) Developed as a result of continuous and iterative collaboration with users.

Products and the data on which they are based should be of the highest quality possible given the time constraints for providing the information. There is a strong and ongoing requirement for climate-related products to be provided as soon as possible after the aggregating period. Historically, products were issued as a hard copy; now, many are only issued online. As such, maintaining the quality standards for such products is a concern. Users must be alerted to possible problems concerning the data, and since these products are often delivered automatically, such alerts should be included with the products.

It is usually possible to enhance the value of historical and statistical climatological data tables by including a supporting text that helps the user to interpret the data and emphasizes the most important climatological elements. In all publications, sufficient information and data should be included regarding the location and elevation of the observing stations, the homogeneity of the data from all stations, the periods of record used, and the statistical or analytical procedures employed. Instead of the information and data being specified in the publications, users should be notified where or how it can be obtained.

In accordance with *The WMO Strategy for Service Delivery and Its Implementation Plan* (WMO-No. 1129), the presentation of products should be checked carefully before the products are made accessible to potential users. For example, climatic maps should be well designed, with carefully chosen colours and scales; they should have clear titles and notations on the map of what is being analysed; the data period should be clearly identified; and the responsible organizations should be listed. The maps should also be reasonably consistent in terms of the colours, layout and data, to facilitate comparisons. Consultation with everyone who is affected by environmental information products is encouraged. Input from parties concerned should be considered when climate products are created, modified or discontinued.

### 4.1.1 *Climate product categories*

Climate products may be broadly categorized as periodic or occasional, standard or specialized, and public or private. A periodical climatological publication is one that is scheduled for preparation and publication on a routine basis over set time intervals. Most climatological data periodicals are issued on a monthly or annual basis. Some services, however, also publish periodicals at different intervals, such as weekly or seasonally. Weekly and monthly publications are issued immediately after the close of the period in question and usually contain recent data that have not necessarily been subject to comprehensive quality control. These periodicals contain up-to-date data that can be of great importance to various economic, social and environmental sectors, so their publication is valuable, even though the data may contain a few errors or omissions. Quarterly and seasonal data periodicals are often issued to disseminate summarized seasonal data such as winter snowfall, growing-season precipitation, summer cooling degree-days and winter heating degree-days.

Unlike climate-data periodicals, which are produced to a schedule, occasional publications are produced as the need arises. They are in a form that will satisfy many users for a considerable time, so they will not need frequent updating. Occasional publications are designed for users who need information when planning for capital investments or designing equipment and buildings to last for decades and centuries; for members of the general public whose interests are academic or casual; and for researchers in the atmospheric and oceanic sciences. They are also designed to summarize or explain unusual events, such as extreme weather, and to describe or update an important predicted event such as a strong El Niño. The content and format of a specific occasional publication must reflect the interests and needs of the users for whom it is published.

Standard products can be used by a wide range of users. For example, energy management entities and fruit growers can make use of a degree-day product. Such standard products fill the gap between the climate data periodicals and those tailored to individual users. Standard products should be locally developed to meet the needs of groups of users.

Specialized products are those that are developed specifically for an individual user or sector. Such applied climatological products are tailored to the needs of a particular user or user group. The products provide a bridge between the observed data and the specific requirements of a user, and they transform the observations into a value added product for end users. Developing these products involves analysing the data and presenting the information with a focus on the specifications that will enable the user to gain optimum benefit from the application of the information. The use of the product usually dictates the types of analysis and data transformation that need to be performed and the methods used to deliver the product.

Public climate products are those that are readily and freely available to anyone who wishes to obtain them, whereas private climate products are typically developed for, and purchased by, an individual user or sector. Public climate products are typically periodical and standard, while private climate products are often occasional and specialized.

## 4.2 **National products**

Most NMHSs issue monthly bulletins containing data from a selection of stations in particular areas of a country or in the country as a whole. When they are issued within a week or two after the end of each month, they usually contain recent data that might not have been subject to full quality control, but if they are issued a month or more later, they should meet the normal quality-control standards for historical climatological data (see sections 1.6, 2.3. and 2.4.5). Maximum and minimum temperatures and total precipitation for each day should be listed, as perhaps should temperatures at fixed hours and the associated humidity values. Daily mean

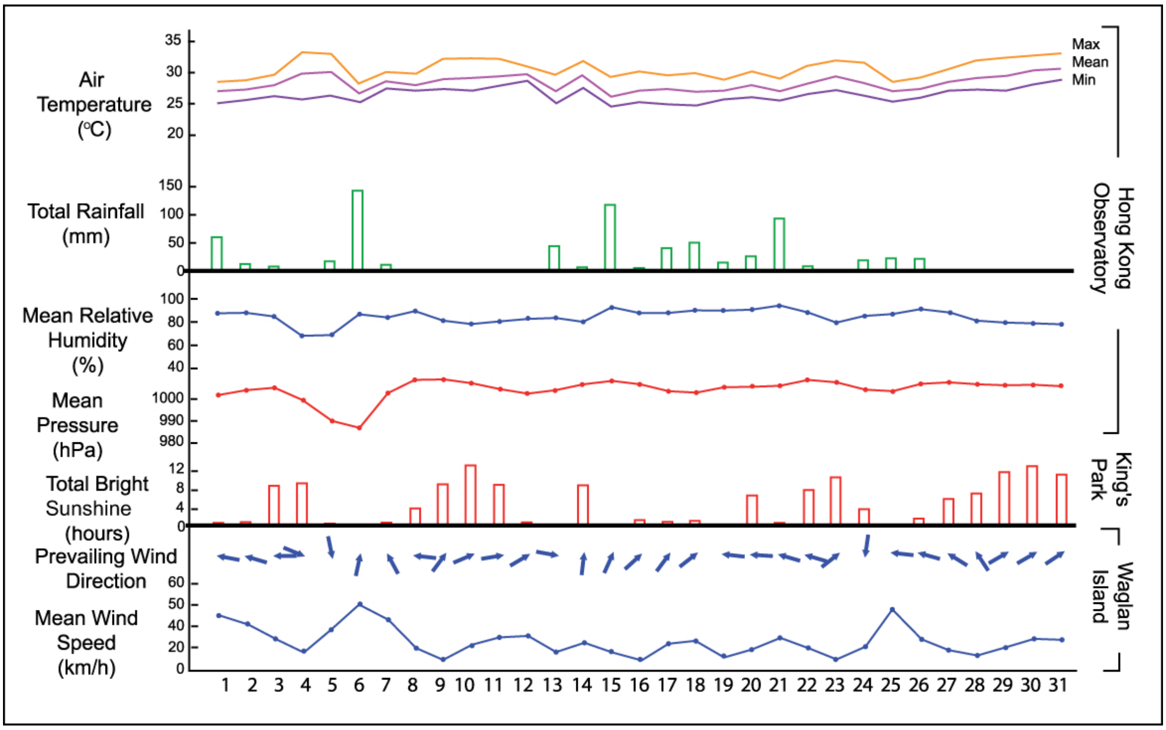


**Figure 4.1. Example of a graphical display of daily values of several elements**

*Source: Guide to Climatological Practices* (WMO-No. 100), 3rd ed., Figure 6.6.

wind speed and prevailing direction, duration of bright sunshine and other locally important data such as heating, cooling and growing degree-days could also be included (see Figure 4.1). Monthly averages, extremes and other statistical data from all stations should also be included when available.

While most monthly bulletins contain only surface climatological data, some NMHSs include a selection of basic data from upper-air stations or issue separate monthly bulletins containing upper-air data. In such monthly bulletins, daily and monthly mean data are usually published for the standard pressure surfaces. The data usually include altitude (in geopotential metres), temperature, humidity, wind speed and wind direction for one or two scheduled ascents each day.

Some of the most useful national products are those containing simple tables of monthly and annual values of mean daily temperature and total precipitation. Such tables are prepared by NMHSs and are made available either in a manuscript or, as is now common, electronically. Some NMHSs include historical climatological data series in yearbooks or other annual bulletins. These publications often provide historic context for contemporary observations by including climate rankings. Monographs on the climate of a country or area are valuable to a wide range of users and should be published and updated periodically and made available electronically for ease of access and exchange.

According to the *Technical Regulations* (WMO-No. 49), Volume II, each Member should prepare aerodrome climatological tables for each regular and alternate international aerodrome within its territory. Figure 4.2 is an example of an aeronautical table.

Long-term, continuous and homogeneous series of data are of great value for comparative climatological studies and research on climatic fluctuations, trends and changes. Several NMHSs have published such series for a selection of stations where observational practices and the environmental surroundings have remained essentially unchanged over long periods of time. The collection of maps, in atlas format, is another valuable national product. Legends and captions on climatic maps should include precise information regarding the element mapped, some indication of the number of stations from which data have been obtained, and the period of record used to generate each map or diagram (see, for example, Figure 4.3).

**Aerodrome Climatological Summary - Model D**

**MELBOURNE AIRPORT • YMML**

Latitude: -37.6655° • Longitude: 144.8321° • Elevation 113.4m

Month: January

Period of Record: 30 Jun 1970 to 25 Jan 2013

Note: A dash indicates no observations. An asterisk indicates the event has occurred but with a frequency less than 0.05%.

**61644 Total Observations**

| Frequencies (per cent) of the Occurrence of Concurrent Wind Direction (10°Sections) and Speed within specified ranges | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Wind direction** | **Wind speed (in knots)** | | | | | | | | | | | | |
| | **calm** | **1-5** | **6-10** | **11-15** | **16-20** | **21-25** | **26-30** | **31-35** | **36-40** | **41-45** | **46-50** | **>50** | **Total(%)** |
| **calm** | 7.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7.0 |
| **360** | 0 | 1.1 | 1.8 | 1.5 | 1.5 | 1.0 | 0.4 | 0.1 | * | 0 | 0 | 0 | 7.6 |
| **010** | 0 | 0.4 | 0.7 | 0.7 | 0.8 | 0.4 | 0.1 | * | 0 | 0 | 0 | 0 | 3.1 |
| **020** | 0 | 0.3 | 0.4 | 0.3 | 0.3 | 0.1 | * | * | * | 0 | 0 | 0 | 1.5 |
| **030** | 0 | 0.3 | 0.3 | 0.2 | 0.1 | * | * | * | 0 | 0 | 0 | 0 | 0.8 |
| **040** | 0 | 0.2 | 0.2 | 0.1 | * | * | * | 0 | 0 | 0 | 0 | 0 | 0.5 |
| **050** | 0 | 0.2 | 0.1 | * | * | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.4 |
| **060** | 0 | 0.2 | 0.1 | * | * | * | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 |
| **070** | 0 | 0.2 | 0.1 | * | * | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 |
| **080** | 0 | 0.2 | 0.1 | * | * | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 |
| **090** | 0 | 0.2 | 0.1 | * | * | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 |
| **100** | 0 | 0.1 | 0.1 | * | * | * | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 |
| **110** | 0 | 0.2 | 0.1 | * | * | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 |
| **120** | 0 | 0.3 | 0.3 | 0.1 | * | * | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 |
| **130** | 0 | 0.3 | 0.6 | 0.2 | 0.1 | * | 0 | 0 | 0 | 0 | 0 | 0 | 1.2 |
| **140** | 0 | 0.4 | 0.8 | 0.4 | 0.2 | * | 0 | 0 | 0 | 0 | 0 | 0 | 1.7 |
| **150** | 0 | 0.5 | 1.3 | 0.9 | 0.2 | * | 0 | 0 | 0 | 0 | 0 | 0 | 3.0 |
| **160** | 0 | 0.5 | 1.8 | 1.5 | 0.4 | * | 0 | 0 | 0 | 0 | 0 | 0 | 4.2 |
| **170** | 0 | 0.6 | 2.7 | 2.9 | 1.0 | * | 0 | 0 | 0 | 0 | 0 | 0 | 7.2 |
| **180** | 0 | 1.0 | 3.8 | 4.3 | 1.4 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 10.6 |
| **190** | 0 | 0.9 | 3.1 | 2.9 | 0.8 | 0.1 | * | 0 | 0 | 0 | 0 | 0 | 7.8 |
| **200** | 0 | 0.9 | 2.1 | 1.4 | 0.4 | 0.1 | * | 0 | 0 | 0 | 0 | 0 | 4.8 |
| **210** | 0 | 0.9 | 1.8 | 1.0 | 0.3 | * | * | 0 | 0 | 0 | 0 | 0 | 4.1 |
| **220** | 0 | 0.9 | 1.5 | 0.8 | 0.3 | 0.1 | * | 0 | 0 | 0 | 0 | 0 | 3.6 |
| **230** | 0 | 0.9 | 1.6 | 1.0 | 0.4 | 0.1 | * | 0 | 0 | 0 | 0 | 0 | 4.0 |
| **240** | 0 | 0.9 | 1.4 | 0.8 | 0.3 | 0.1 | * | 0 | 0 | 0 | 0 | 0 | 3.6 |
| **250** | 0 | 0.9 | 1.4 | 0.7 | 0.3 | 0.1 | * | 0 | 0 | 0 | 0 | 0 | 3.2 |
| **260** | 0 | 0.8 | 1.0 | 0.4 | 0.2 | 0.1 | * | 0 | 0 | 0 | 0 | 0 | 2.6 |
| **270** | 0 | 0.9 | 0.9 | 0.3 | 0.2 | 0.1 | * | 0 | 0 | 0 | 0 | 0 | 2.4 |
| **280** | 0 | 0.7 | 0.7 | 0.2 | 0.1 | * | * | * | 0 | 0 | 0 | 0 | 1.7 |
| **290** | 0 | 0.7 | 0.6 | 0.2 | 0.1 | * | * | * | 0 | 0 | 0 | 0 | 1.6 |
| **300** | 0 | 0.6 | 0.4 | 0.2 | 0.1 | * | * | * | 0 | 0 | 0 | 0 | 1.3 |
| **310** | 0 | 0.4 | 0.3 | 0.2 | 0.1 | * | * | * | 0 | 0 | 0 | 0 | 1.0 |
| **320** | 0 | 0.3 | 0.2 | 0.2 | 0.1 | * | * | 0 | 0 | 0 | 0 | 0 | 0.9 |
| **330** | 0 | 0.4 | 0.3 | 0.3 | 0.2 | * | * | * | 0 | 0 | 0 | 0 | 1.1 |
| **340** | 0 | 0.5 | 0.4 | 0.4 | 0.2 | 0.1 | * | * | 0 | 0 | 0 | 0 | 1.7 |
| **350** | 0 | 0.8 | 1.0 | 0.8 | 0.5 | 0.2 | 0.1 | * | * | 0 | 0 | 0 | 3.5 |
| **Total(%)** | **7.0** | **19.5** | **34.2** | **25.0** | **10.5** | **2.8** | **0.8** | **0.2** | ***** | **0** | **0** | **0** | |

Australian Government
Bureau of Meteorology



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**Figure 4.2. Aeronautical climatology, model D**

*Source:* Aerodrome Climatologies, Bureau of Meteorology, Australian Government.

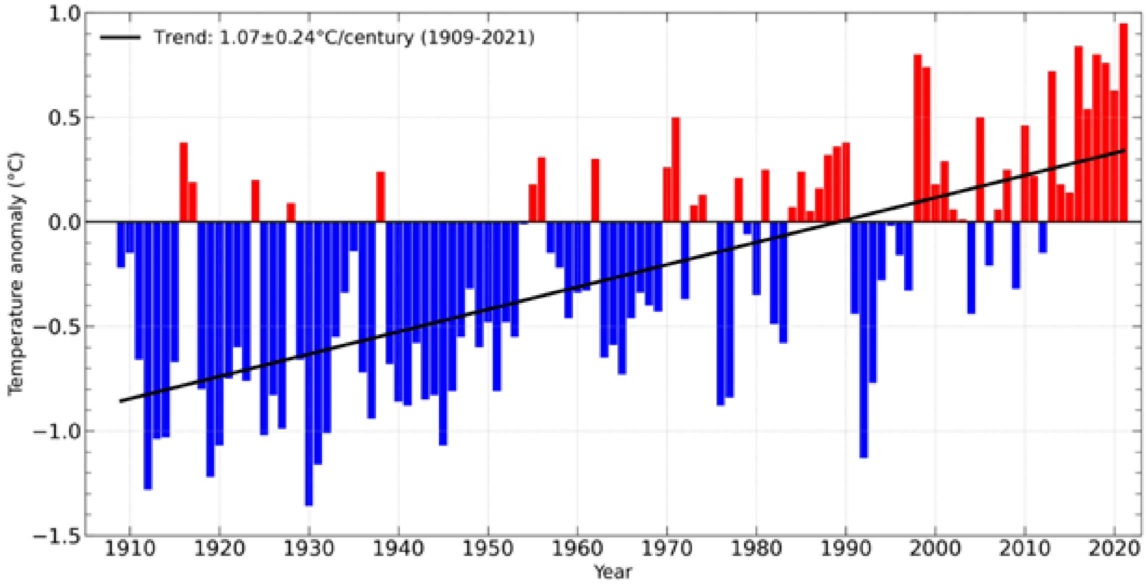


**Figure 4.3. The evolution of average annual temperatures in New Zealand, derived from homogenized long-term data series at seven urban locations. Over the period 1909–2021, the observed trend is about + 0.1°C per decade. The y-axis shows the deviation from the average annual temperature over the normal period 1981–2010.**

*Source:* https://niwa.co.nz/seven-stations

National products often include climate indices, which are widely used to characterize features of the climate for climate monitoring and prediction and also to detect climate change. The features may apply to individual climatological stations or describe some aspect of the climate of an area. Indices usually combine several elements into the characteristics of, for example, droughts, continentality, heating degree-days, large-scale circulation patterns and teleconnections. Figure 4.4 is an example of a product that simply depicts the state of a complex phenomenon.

Climate outlooks are forecasts of the values of climate elements averaged or accumulated over timescales of about one month to several years. Seasonal forecasts are more commonly used and can be generally issued once a month. Alternatively, some forecasts are issued only for specific seasons or at other pre-defined intervals. The climate elements typically forecast are average surface air temperature and total precipitation. Increasingly, other parameters, such as the number of days with precipitation, the amount of snowfall, the frequency of tropical cyclones and the onset and end of monsoon seasons are also forecast at some centres.

Owing to the impact of varying and changing climatic conditions on society and ecosystems, countries around the world have created a variety of climate monitoring products at different spatial and temporal scales. National climate monitoring products (NCMPs) are products that specifically summarize climatic conditions at a national scale and show how current conditions compare with those in the past. The WMO *Guidelines on Generating a Defined Set of National Climate Monitoring Products* (WMO-No. 1204) provide a specification for a shortlist of NCMPs that can be produced consistently and easily by most countries.

If the necessary data are not available within a given country, the relevant NMHS should obtain regional or global data and analyses from foreign or international agencies and process the information into a form suitable for local to national use. The NMHS should, however, add its own views to these global analyses about the connection between the local climate conditions and large-scale climatic fields. For monitoring activities, the climate service needs to develop expertise in analysing the state of past and current climates and global to regional teleconnections and it needs to provide summarized information to public and private sector users. Good monitoring products are essential for climate predictions and updates.

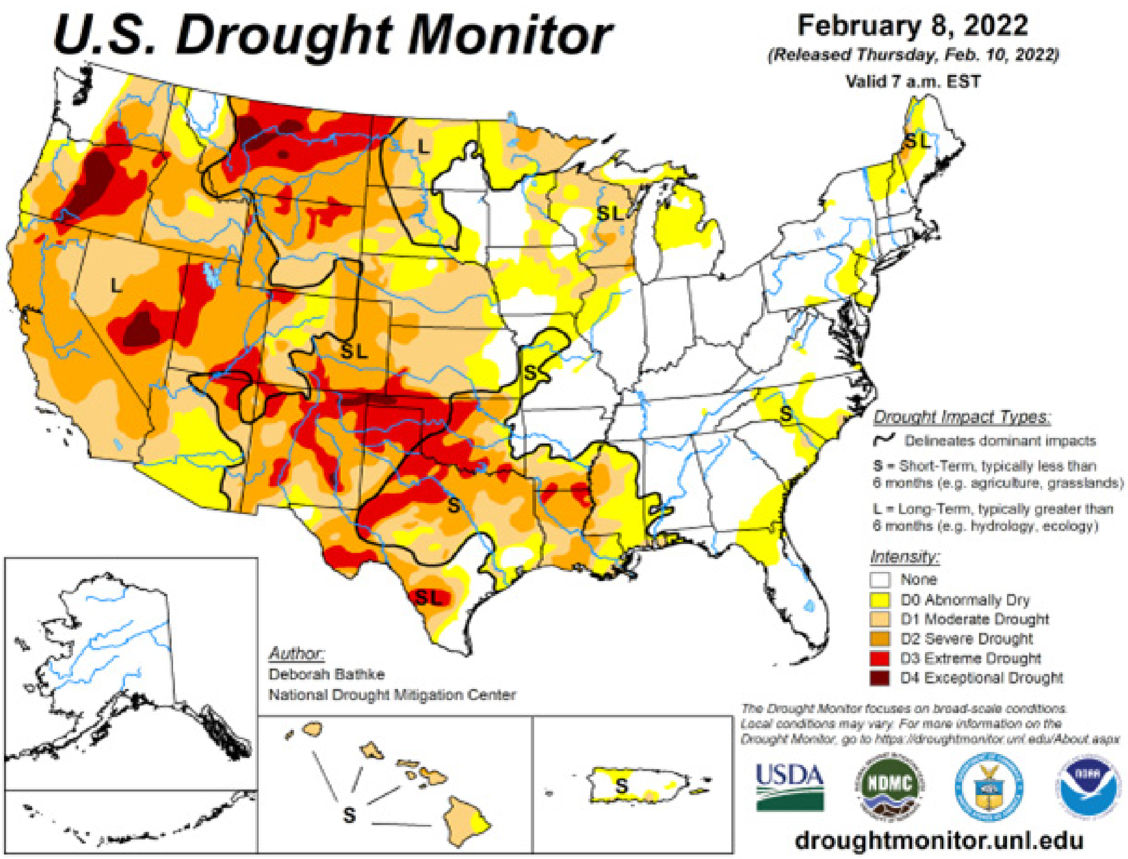


**Figure 4.4. Contour map of drought categories and impacts**

*Source:* https://droughtmonitor.unl.edu

## 4.3 Regional products

Regional products include climate information spanning more than one country or geopolitical area. These typically require contributions from several NMHSs or individuals with expertise spanning the region. Regional products are an effective means of presenting a coherent set of information generated from adjacent but distinct NMHSs and countries. WMO issues annual regional updates on the state of the climate and on climate-change indicators to political leaders and decision makers. RCCs are centres of excellence that create regional products that support regional and national climate activities, thereby strengthening the capacity of WMO Members in a given region to deliver better climate services to national users. For example, Figure 4.5 is part of a seasonal forecast summary for March to May 2022 that was prepared by the RCC for East African decision makers of the Intergovernmental Authority on Development (IGAD).

Regional Climate Outlook Forums cooperatively produce consensus-based climate outlooks using input (climate predictions) from national, regional and international climate experts. By bringing together countries with similar climatological characteristics, the Forums ensure consistency in access to, and the interpretation of, climate information. In addition, through the interactions that take place at the Forums among users in the key economic sectors of each region and among extension agencies and policymakers, the likely implications of the outlooks for the most pertinent socioeconomic sectors in a given region are assessed and the ways the sectors could use the outlooks are explored. News media and the Internet are other common means of disseminating forecasts to the public.

Forecasts of tropical sea-surface temperatures can also be regarded as regional products, and are useful given the importance of sea-surface temperature forcing in tropical regions. In particular, forecasts for the El Niño-Southern Oscillation forecasts are in great demand and are

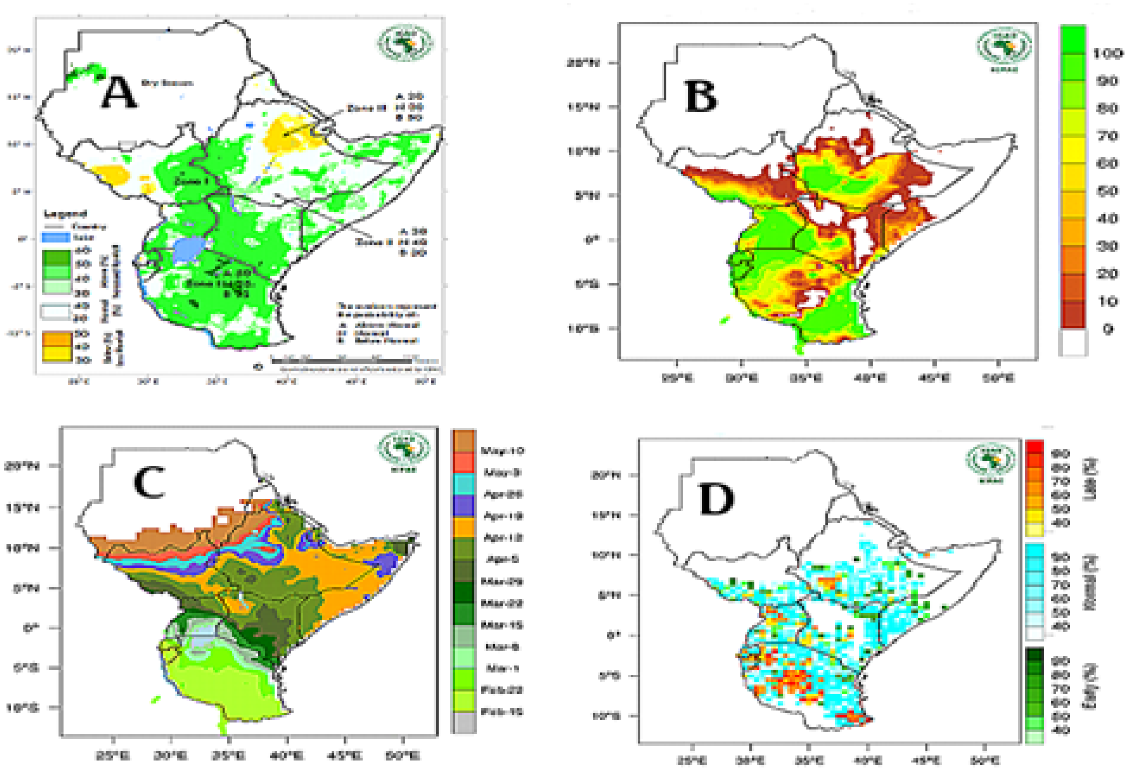


**Figure 4.5. East African seasonal precipitation forecasts, for decision makers, of (A) precipitation, (B) probability of precipitation exceeding 300 mm, (C) onset dates of precipitation and (D) onset probability of precipitation**

*Source:* March–May 2022 seasonal forecast summary of the RCC of IGAD.

largely disseminated by most of the GPCLRFs and other international institutions. Ultimately, the forecasting element, frequency and lead time can vary depending on the characteristics of the climate of a particular country or region and, importantly, should be related to users' needs.

## 4.4 Global climate models

Global climate models (GCMs) are designed mainly for representing climate processes on a global scale. They provide the essential means to study climate variability and climate change for the past, present and future. The models are based upon the physical laws governing the processes and interactions of all the components of the climate system and are expressed in the form of three-dimensional mathematical equations. The highly nonlinear governing equations are solved numerically on a four-dimensional grid of the atmosphere (three space dimensions plus time). Many physical processes, such as individual clouds, convection and turbulence, take place on much smaller spatial and temporal scales than can be properly resolved by the grid. These processes have to be included through a simplified representation called parameterization, a method used to replace the small-scale, complex processes in the model with a simplified process. Figure 4.6 shows a model output relating cumulative carbon dioxide emissions to global warming.

These models first became practicable in the 1960s, and since then they have undergone rapid development and improvement. They have developed in parallel with numerical weather prediction models. Initially, GCMs were directed at coupling the atmosphere and ocean; today, most state-of-the-art GCMs include representations of the cryosphere, biosphere, land surface, and atmospheric chemistry and aerosols in increasingly complex integrated models that are sometimes called Earth system models.

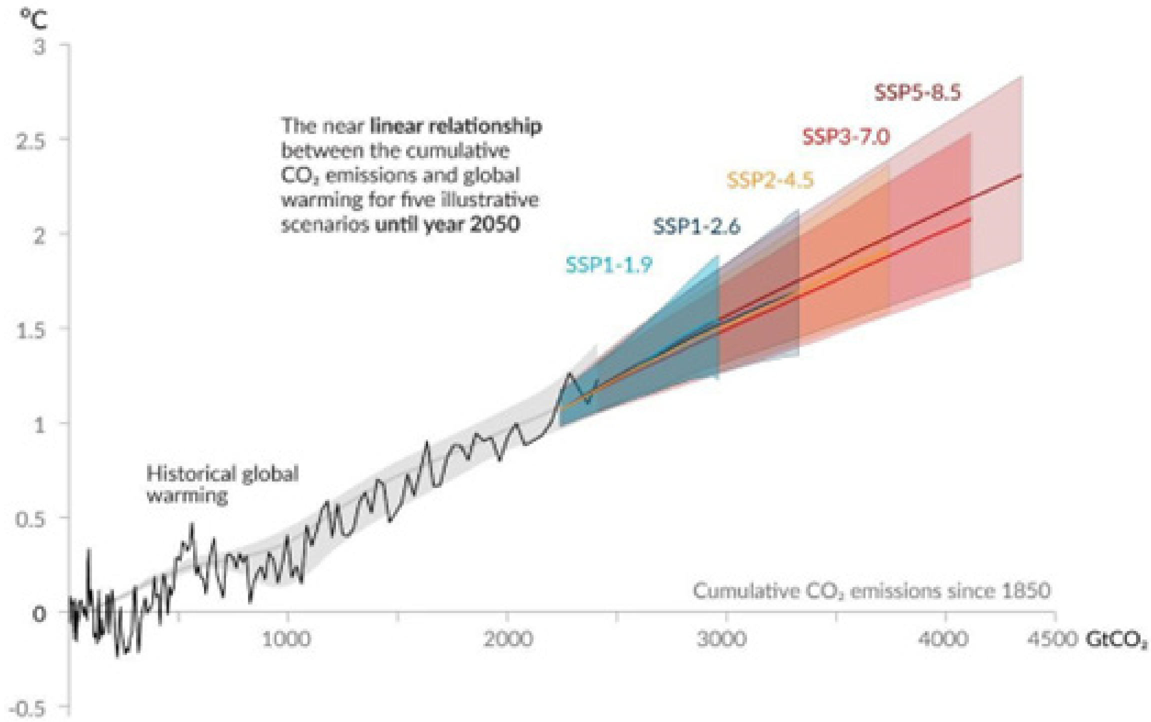


**Figure 4.6. Cumulative carbon emissions since 1850 and projections until 2050**

*Source:* Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Confidence in GCMs has increased substantially as a result of three factors: systematic model comparisons (for example, the Coupled Model Intercomparison Project), the ability shown by some models to reproduce major trends in the climate of the twentieth century and in some palaeoclimates, and the improved simulation of major general circulation features related to phenomena such as the El Niño-Southern Oscillation. In many parts of the world, GCMs generally provide credible climate simulations at subcontinental scales and for seasonal to decadal timescales. GCMs are therefore considered suitable tools to provide useful climate predictions and projections. They have formed the basis for the climate projections in IPCC assessments and contribute substantially to operational seasonal forecasting, especially through the GPCLRFs community and climate outlook forums.

There is considerable interest in refining the spatial resolution of GCMs to simulate climate on smaller scales, where most impacts are felt and adaptive capacity exists. Smaller-scale climates are determined by an interaction of forcings and circulations on global, regional and local spatial scales and on subdaily to multidecadal temporal scales. The regional and local forcings are caused by complex topography and land-use characteristics, features at land–ocean interfaces, regional and local atmospheric circulations such as sea breezes and tropical storms, the distribution of aerosol particles and atmospheric gases, and the effects of lakes, snow and sea ice. The climate of an area may also be strongly influenced through teleconnection processes by forcing anomalies in distant locations. The processes are often highly non-linear, making projection and prediction difficult at global scales. As a response to these modelling challenges, regional climate models (RCMs) and statistical downscaling models have been developed to obtain climate information at a finer spatial resolution. RCMs are nested, limited-area, high-resolution models within a coarser global model. Statistical downscaling involves the application of statistical relationships between the larger and smaller scales that have been identified in the observed climate. Both approaches can be used to provide more relevant information at regional and local scales for applications through climate predictions and climate projections.

### 4.4.1 *Global products*

Global products include climate information spanning the majority of the globe or the entire globe. These typically require contributions from numerous NMHSs and many individuals with expertise spanning the national and regional boundaries. Global products are an effective means of presenting a comprehensive set of information generated from many NHMSs and countries.

WMO issues annual global updates on the state of the climate and on climate-change indicators to political leaders and decision makers. WMO also collaborates with its Members to produce global seasonal outlooks such as the El Niño/La Niña Update and the Global Seasonal Climate Update. The El Niño/La Niña Update is a consensus-based product that uses inputs from a worldwide network of forecasting centres and provides an indication of the phase and strength of the El Niño-Southern Oscillation. The Global Seasonal Climate Update summarizes the current status and the expected future behaviour of seasonal climate in terms of major general circulation features and large-scale oceanic anomalies around the globe and their likely impacts on continental-scale temperature and precipitation patterns. The editions of Global Seasonal Climate Update are the collaborative effort of the WMO Lead Centre for Long-range Forecast Multi-Model Ensemble Prediction (LC-LRFMME), GPCLRFs and the National Oceanic and Atmospheric Administration of the United States, among other entities. Both updates should be considered as complementary to more detailed regional and national seasonal climate outlooks such as those produced by the Regional Climate Outlook Forums and the NMHSs.

The WMO Lead Centre for Annual-to-Decadal Climate Prediction collects and provides hindcasts, forecasts and verification data from a number of contributing centres worldwide. Predictions from each institute are portrayed as anomalies from 1981 to 2010 (1971–2000 for pre-2019 forecasts) alongside the average of all the models. Verifying observations for the forecast periods are also available. Skill scores are available for participating models and the multi-model ensemble mean. The Centre also provides time series for global mean near-surface air temperature, Atlantic multidecadal variability, Pacific decadal variability for participating models and the multi-model ensemble mean.

Periodicals sponsored by WMO include data from Members. Examples are Monthly Climatic Data for the World (which has data from all CLIMAT stations), World Weather Records (single-station, historical, monthly and annual values for station pressure, sea level pressure, temperature and precipitation), and Marine Climatological Summaries (monthly, annual and decadal climatological statistics and charts for the oceans).

Since 1993, WMO, in cooperation with its Members, has also issued annual statements on the status of the global climate to provide credible scientific information on climate and its variability.

A useful monthly publication, especially in relation to El Niño-Southern Oscillation diagnostics and other climate teleconnections, is the Climate Diagnostics Bulletin published by the Climate Prediction Center of the National Oceanic and Atmospheric Administration of the United States.

## 4.5 **Sector products**

Climate information by sectors should be included in a manual or other publication that describes details about the information and its uses so that users can simply apply the information to the design and implement their projects.

An example of an application-driven product can be found in the requirement by a fruit grower for daily degree-hour data for pesticide management of fire blight disease. When only daily maximum and minimum temperatures are available for the locations of interest, degree-days can be calculated from the average of the maximum and minimum values. Since degree-hours are required but not available, an analysis is necessary to develop relationships between degree-days calculated from daily temperature extreme data and degree-hours. The conditions for which the relationships are valid and the degree of error in the relationships must also be assessed. Once the relationships have been established, the user can be given a product that contains degree-hours, even though degree-hours are not measured directly.

Flood analysis is another example. Flooding is a natural feature and varies in scale from water running off a saturated hillside to large rivers bursting their banks. The impacts of floods range from waterlogged fields and blocked roads to widespread inundation of houses and commercial property and, occasionally, loss of life. Flood frequency estimates are required for the planning and assessment of flood defences; the design of structures such as bridges, culverts and reservoir spillways; and the preparation of flood risk maps for the planning of new developments and insurance interests. A product that provides the probability of observed precipitation amounts is a necessary component in the development of flood frequency estimates. Developing the precipitation risk information involves the value added statistical analysis of the observed precipitation data that are usually presented in standard summaries. If the resulting risk analyses will be of use to a number of different users, a general publication may be warranted.

## 4.6 Reanalysis products

In operational numerical weather analysis and prediction, analysis refers to the process of creating an internally consistent representation of the environment on a four-dimensional grid. The time-critical nature of weather prediction means that the initializing analysis must usually begin before all observations are available. Reanalysis uses the same process (and often the same systems), but as it is done weeks or even years later, it uses a more complete set of observations. These reanalysis systems generally incorporate a prediction model that provides information on how the environment is changing with time while maintaining internal consistency. Unlike the analysis in operational weather predictions, in which the models are constantly updated to incorporate the latest advances in research, reanalysis is performed with a fixed modelling system throughout the period of reanalysis to avoid the inhomogeneities that generally exist in the operational analyses because of model differences over time.

The output of a reanalysis is on a uniform grid and no data are missing. It is important to note that the reanalysis values are estimates, rather than real data. The estimates are based on unevenly distributed observational data. The result is an integrated historical record of the state of the atmospheric environment for which all the data have been processed in the same manner. Reanalysis outputs are often used in place of observational data, but this must be done with care. Although the analysis algorithms will make good use of observations when they are available, in regions where observations are scarce the reanalysis grid will be strongly influenced by the prediction model. For reanalysis projects that span decades, the type and coverage of data throughout the period, such as between the pre- and post-satellite periods, are, for the most part, highly heterogeneous. Further, the influence of the observations compared with the influence of model varies from one climatic variable to another, with some variables strongly influenced by the observational data used and others purely model-derived. These aspects should be carefully considered when the reanalysis data products are interpreted. For example, reanalyses of dynamical variables are far better than reanalyses of precipitation, partly because processes leading to precipitation are not well represented in the models. Figure 4.7 is an example of a reanalysis product.

The limitations of reanalysis outputs are most obvious in areas with a complex topography (in particular, in mountain regions), as well as in other areas when the assimilation and processing schemes are unable, because of smoothing, to reproduce real atmospheric processes with high spatial and temporal gradients. Also, there remains the issue of localizing to spatial and temporal scales finer than the reanalysis grid. Efforts are ongoing to perform regional reanalysis using more local observational data with higher-resolution limited-area models. As with any other analysis technique, validation of models, quality assurance and indicators of error are necessary to properly interpret the results.

The information not only from atmospheric sciences, but also from oceanography, hydrology and remote sensing, is used to create environmental databases from which systematic changes can be better assessed. Reanalyses.org is a collaboration of the Atmospheric Circulation Reconstructions over the Earth initiative, the GCOS Working Group on Surface Pressure, the WCRP, and their respective partners. It provides overviews and the current status of global and regional atmospheric, oceanographic and observation reanalyses. All these reanalysis efforts have been widely used in climate monitoring, climate variability studies and climate-

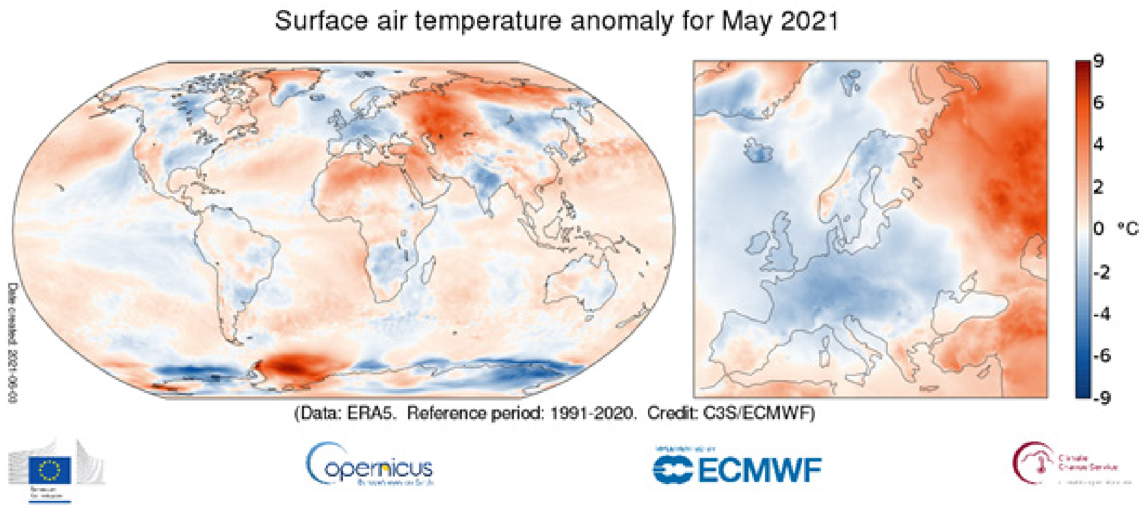


**Figure 4.7. Surface air temperature anomaly for May 2021 relative to the May average for the period 1991–2020.**

*Source:* Reanalysis Data ERA5. Copernicus Climate Change Service (C3S), https://climate.copernicus.eu/copernicus-coldest-spring-europe-2013-May-global-temperature-above-average

change prediction. It is important to assess how accurately a reanalysis technique represents the observed features in a given region before using the data produced by that technique for further climatological studies. A greater understanding of the physical, chemical and biological processes that control the environment combined with data from a range of sources that go well beyond the atmospheric sciences should promote improvements in reanalysis databases. As the numerical models become more complete and as computer technology allows for higher resolutions, more accurate and comprehensive reanalysis products will emerge.

## 4.7 Gridded data products

Gridded climate data facilitate the spatial analysis of climate variables and the static or dynamic visualization of climate patterns and trends. The products are values of surface or upper-air climate variables (for example, air temperature, atmospheric moisture or sea-surface temperature) or indices (for example, number of frost days) arranged on a regular grid with coverage ranging from local and national to regional and global. In addition to the scale of coverage, the resolution of gridded data can vary from as little as a few square metres in the case of suburban data sets to 200–300 km in the case of global-scale data sets. Similarly, temporal resolution may vary from the subhourly to the annual timescale. A range of organizations are involved in the production of gridded climate data sets, such as national and regional climate centres and university research groups. Some data sets are updated regularly or periodically, while some are static or contain a time series of climate variables.

While some of the observed gridded climate data sets are based purely on surface observations, others are constructed from reanalysis systems (see section 4.6) and blended data sets, including observations from both surface and satellite-based platforms. Some observation-based gridded climate data sets use values interpolated from stations for which data have been adjusted and homogenized.

Because gridded climate data are in essence an alternative to site-specific instrumental measurements, irrespective of whether the gridded data have been derived from original observations using interpolation techniques (see section 3.5.8) or from the output of numerical or statistical climate models, the data should be subject to validation. This is achieved through a comparison with observations from the surface or upper-air climate stations that are located at or close to a particular grid point.

## 4.8 References

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# 5. SERVICE DELIVERY

## 5.1 Introduction

Climate services involve the production, translation, transfer and use of climate knowledge and information for informed decision-making and climate-smart policy and planning (WMO (2014)). Service is defined as the delivered product and the activities associated with the people, process and information technology required to deliver it, or as an activity – such as advice and interpretation of climate information – carried out to meet the needs of the user or an activity that can be carried out by a user (see *The WMO Strategy for Service Delivery and Its Implementation Plan* (WMO-No. 1129)). The service should be based on an understanding of the user's requirements or broad user requirements. It should provide information, products and advice that are tailored, as far as possible, to the user in terms of their timing, format and content, and it should maintain a dialogue with the user or seek feedback for ongoing delivery and improvements.

To be effective, services should be:

(a) Credible: for the user to confidently use them in decision-making;

(b) Available and timely: ready when and where required by the user;

(c) Dependable and reliable: consistently delivered on time and according to the required user specification;

(d) Usable: presented in user-relevant formats so that the client can make full use of them;

(e) Useful: capable of responding adequately to user needs;

(f) Expandable: applicable to different kinds of service;

(g) Sustainable: affordable and consistent over time;

(h) Responsive and flexible: adaptable to evolving user needs;

(i) Authentic: acceptable to stakeholders in a given decision context.

Such services include the provision of observational and reanalysis data from national and international databases, as well as products such as maps, risk and vulnerability analyses, assessments, predictions and projections, and information and knowledge derived from them. Depending on the user's needs, these data and information products may be combined with non-meteorological data, such as agricultural production, health trends, population distributions in high-risk areas, road and infrastructure maps for the delivery of goods, and other socioeconomic variables (see *The WMO Strategy for Service Delivery and Its Implementation Plan* (WMO-No. 1129)). Service delivery is a continuous, cyclic process for developing and delivering user-focused services (Figure 5.1). It comprises four stages:

(a) Stage 1: Identifying and engaging with users, understanding their needs, and understanding the role of climate information in decision-making;

(b) Stage 2: Involving users, providers, suppliers and partners in developing services and striving to ensure that user needs are met;

(c) Stage 3: Producing and disseminating data, products and information (i.e. services) that are fit for purpose and relevant to user needs;

(d) Stage 4: Collecting and acting on user feedback and performance metrics to continuously evaluate and improve products and services.

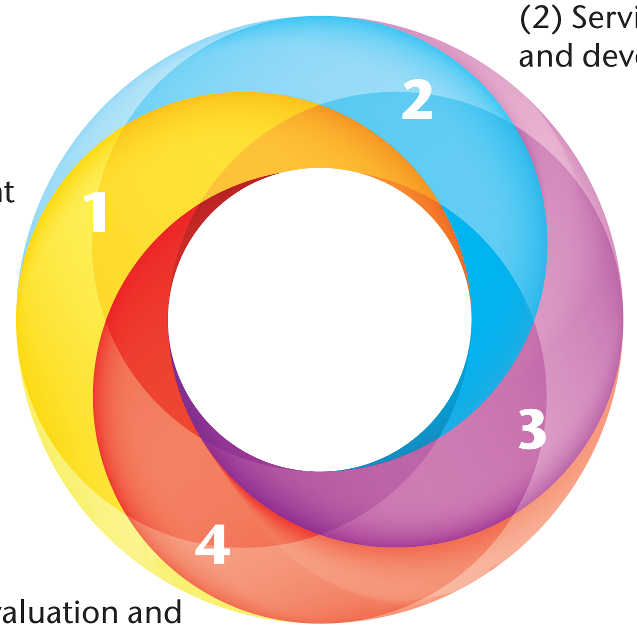


**Figure 5.1. Four stages of a continuous, cyclic process for developing and delivering services**

*Source: Guide to Climatological Practices* (WMO-No. 100), 3rd ed., Figure 7.1.

The GFCS was established to provide a credible and integrative platform for guiding and supporting activities implemented within climate-sensitive areas (*The WMO Strategy for Service Delivery and Its Implementation Plan* (WMO-No. 1129)). It aims to enable society to better manage the risks and opportunities arising from climate variability and change (Hewitt et al., 2012, 2020). The GFCS puts a strong emphasis on user involvement and capacity development, and the engagement of all partners in this concerted effort is designed to maximize benefits for all users.

## 5.2 Users and uses of climatological information

The users of climate services are many and varied, ranging from schoolchildren to global policymakers. They include diverse groups, such as the media and public information personnel, farmers, the armed forces, government departments, business and industry personnel, water and energy managers, consumers, tourists, legal professionals, health officials, humanitarian and relief organizations, and meteorological services. Climate services are used for a wide range of needs, including school projects, building designs, agricultural operations, water management, operations on air-conditioning systems and large dams, energy production and distribution planning, and famine and drought preparations and responses.

The current interest in climate change and its consequences has brought about an additional need for climate information. In the past, climate services were limited mostly to information about the physical environment of the atmosphere near the Earth's surface. Today, users may require information about many aspects of the broader climate and Earth system (solid earth, air, sea, biosphere and land surface, and ice). Data related to climate are now used to describe, represent and predict both the behaviour of the whole climate system (including the impact of human activity on climate) and the relationship between climate and other aspects of the natural world and human society. There is therefore an increasing need for the monitoring and detailed description of the climate on both the spatial and temporal scales, with current events placed in a range of historical perspectives. High-quality baseline climate data sets are being compiled for which complex statistical quality-assurance techniques have been devised. During the compilation of such data sets, procedures are put in place to detect and, if possible, correct data for outliers, and to account for inhomogeneities such as changes in the instrumentation or location of observing stations. Researchers and other expert users of climate products are also keenly interested in metadata to help interpret and analyse data homogeneity and quality.

During the past few decades, national and international investment in climate observations, research and modelling have driven significant progress in experimental and practical climate prediction and in scientific understanding of climate variability and change. These efforts provide a robust scientific foundation for producing climate prediction products based on forecasts for the coming months and years. Timely, actionable and reliable climate predictions play a crucial role in decision-making for individual users, various sectors and national development planners. The predictions help with managing development opportunities and risks and with adopting adaptation and mitigation measures. Climate projections, which differ from climate predictions by assuming radiative forcing scenarios, are similarly useful for decision makers.

As described in *Use of Climate Predictions to Manage Risks* (WMO-No. 1174), the effective application of climate prediction also relies on climate information becoming appropriately integrated into different users' policies and practices. Through effective climate services, climate information can be disseminated to enable this integration into robust decision-making. This process involves strong partnerships among providers, such as NMHSs and their stakeholders (government agencies, private interests and academia) for the purpose of interpreting and applying climate prediction information for decision-making and sustainable development, and for improving climate prediction products. Climate services also rely heavily on strong relationships between providers and users of information, requiring a two-way flow of information on science capability, information requirements and feedback on the use of information.

The uses of climatological information can be classified into two broad categories: strategic and tactical. Strategic uses refer to products that aid in the general long-term planning and design of projects and policies. Adapting to climate change is becoming a routine and necessary component of planning at all levels. NMHSs are critical players in national development planning for climate-change adaptation in almost all sectors (*Climate Services for Supporting Climate Change Adaptation* (WMO-No. 1170)). The following types of information are usually required for strategic uses: probability analyses and risk assessments of meteorological events for design specifications and regulations; summaries of historical conditions as background information about past climate conditions; and climate predictions, projections and scenarios as indicators of future expectations. An example of strategic use is an analysis of climate data for designing a dam. Tactical uses refer to products and data that aid in solving short-term, specific, immediate problems. Typical information provided for tactical uses includes copies of official observations of the occurrence of a meteorological event, summaries of historical data, and the placement of an event into its historical context. An example of tactical use is the analysis of recent observational data to support water usage management during a drought. Sometimes uses can be strategic and tactical at the same time. For example, the use of historical storm data to calculate the probabilities of tropical storms occurring and moving at certain speeds and in certain directions is a strategic use of data, but if the same data are used to forecast the movement of a current storm, it is a tactical use.

The uses of climate information include the following:

(a) Monitoring specific activities driven by meteorological conditions (for example, fuel consumption for heating and cooling, air pollution levels (to determine whether thresholds have been crossed), variability of sales of goods, and drought-related inflation in commodity markets);

(b) Predicting the behaviour of sectoral systems that react to meteorological events with a known response time, and in which the knowledge of recent weather and climate allows some forecasting of sectoral impacts (for example, energy production and consumption, the need to restock goods, crop production, plant diseases, Heat-Health Warning Systems, food security, and water supply and demand);

(c) Monitoring to identify the character of a given event or period, especially deviations from the norm (for example, intensity of extreme rainfall or dryness over climatological periods);

(d) Designing equipment for which the knowledge of local climatology is critical to effectiveness and efficiency (for example, civil engineering works, air-conditioning systems, and irrigation and drainage networks);

(e) Conducting impact studies (for example, knowledge of historical conditions in order to assess the consequences of installing a power plant or other industrial enterprise that could affect air quality);

(f) Studying the influence of meteorological conditions on economic sectors (for example, public transport and tourism);

(g) Planning and carrying out risk management for the provision of community services (for example, water and energy services and emergency preparedness and responses).

(h) Supporting climate-change adaptation and mitigation.

To promote the use of climate services, effective user engagement is important throughout the service development and delivery process (*The WMO Strategy for Service Delivery and Its Implementation Plan* (WMO-No. 1129) and *Guidance on Good Practices for Climate Services User Engagement* (WMO-No. 1214)). Such engagement will help to increase knowledge of user needs and the impact of climate services on the protection of life and property, the preservation of the environment and the promotion of economic development and prosperity. This shared knowledge leads to more effective products and services that are better aligned with external demands and are fit for purpose.

The following principles embody an effective delivery of climate-related services:

(a) User engagement and feedback are essential for designing and delivering effective services;

(b) Sharing best practices leads to effective and efficient service design and implementation;

(c) Partnerships with other international and regional organizations also engaged in delivering services are essential for maximizing the use of weather-, climate-, water- and environment-related information in the decision-making process;

(d) The concepts and best practices of service delivery are applied to all WMO activities and accepted by the entire WMO.

Figure 5.2 shows the tasks that need to be completed to move towards a service-oriented culture.

## 5.3 Interaction with users

There can be a strong educational and communication aspect to the provision of climate services. Many people who need climate information have a limited understanding of meteorological science and related concepts, so they might not know what information is available (including the limitations and applicability of the information), what information might benefit them and how best to use the information. Many users of climate information might not know how best to incorporate climate information into their decision-making processes. Often, they request products that they know are available. NMHSs need to develop more detailed methods and tools in partnership with users. This will improve users' involvement in developing and delivering services (see *The WMO Strategy for Service Delivery and Its Implementation Plan* (WMO-No. 1129)).

Even the best information issued on time will have little impact if it does not generate the necessary response from users. Most of the utility of climate-related information stems from the communication of the information to users and their response to the information. Ultimately, the utility of climate-related information depends on its social and economic impact. When


**Figure 5.2. The six tasks required to move towards a more service-oriented culture**

*Source: Guide to Climatological Practices* (WMO-No. 100), 3rd ed., Figure 7.2

available information is underutilized, communication between providers and users needs to be improved. Effective service delivery is therefore about providing products and services that are useful to users. NMHSs should not evaluate user needs in isolation, but rather in collaboration with users, providers and partners. The service provider and service user need to be mutually aware of the timeline of service production and the decision-making process. Having a service that is fit for purpose implies that an agreement has been reached, either implicitly or explicitly, among all involved, and that it takes into account some or all of the following (see *The WMO Strategy for Service Delivery and Its Implementation Plan* (WMO-No. 1129)):

(a) Current and evolving user needs;

(b) Provider capabilities, including strengths and limitations;

(c) Types of services to be provided and how they will be provided;

(d) How services will be used;

(e) Expectations of acceptable outcomes and provider performance;

(f) Acceptable costs or levels of effort;

(g) Risks inherent in applying the information to decision-making.

The climate service should ensure that expertise in the communication, interpretation and use of climate information is available. The service personnel are the link between the technical climatological aspects of the data, analyses, projections and scenarios, and users of the information who may not be technically proficient. Depending on the nature of the service, climate service staff should be prepared to respond to requests for data with additional information, in particular about sites, elements and instrumentation, mathematical definitions of various parameters, the ways in which observations are performed, and the science of meteorology and climatology. Mechanisms to support users should be formalized and well known to users. Climate service personnel should cultivate a broad range of skills and expertise or have access to people with the necessary expertise.

Users sometimes organize meetings and activities to which climate service personnel are invited. A positive response to these invitations builds stronger relationships and gives the service personnel the opportunity to learn about users and their needs. It is important and very rewarding to be involved in users' activities as much as possible. User feedback usually leads to better products, new applications, and more efficient and inclusive dissemination of climate information. Continuous or frequent communication with users is essential for ensuring that existing products still meet user requirements and for determining what changes need to be made to products and services to satisfy users.

Customer service personnel need to be courteous and tactful and recognize the importance of professional services; user needs may be urgent for many reasons. Ideally, the climate service should have good basic communications with technological and training facilities supporting customer service personnel. Customer service staff are the people with whom the public directly interacts and the people on whom the service provider's reputation depends.

Clearly advertised contact points should be available for a variety of communication methods, together with information about service standards such as hours of operation and turnaround times. For data and products, the service providers may have an up-to-date and powerful system backing their service. Modern communications and technology can now transfer and deliver information over the Internet. It is recommended that an Internet platform be established that can be considered as a "single gateway" from which users can fulfil their needs. Alternative methods of delivery may be required, for example, for users without Internet access, where cell phone coverage is lacking or when high cell phone charges prohibit access to products and services. Climate services that are based on providing expert advice usually require a dialogue between the service provider and the user. A variety of methods of personal contact should be established, including face-to-face discussions, online meetings, e-mail, postal mail and telephone calls.

Methods for distributing products and services are subject to change, especially in the current era of rapidly evolving information technology, and it is important that Members remain agile and responsive to such changes (see *The WMO Strategy for Service Delivery and Its Implementation Plan* (WMO-No. 1129)). At an NMHS with numerous offices, the standards, formats and even products of some offices may be inconsistent with those of others. Frequent liaison among offices is vital; face-to-face or online meetings should be held at regular intervals. Centralized and commonly applicable operational procedures and single reference databases help to ensure consistency, as do well-written documents, quality standards, instructions and manuals.

Service fees can be a sensitive area for users and a cause of criticism and dissatisfaction if they are not applied consistently or are considered unreasonably high. It is therefore important to establish a clear and transparent pricing policy and instructions for implementing the policy. This may involve a formal policy underpinned by a set of principles and a series of practical charges for direct use by those providing the services operationally. The policy should be made available to everyone involved in providing services and to users.

Service delivery does not stop once the product or service has been delivered. User outreach and engagement must continue to ensure that services are received and acted upon and that full benefit is achieved by the user. NMHSs should evaluate the end-to-end service delivery process and its outputs, including checking on any third parties that disseminate products and services on behalf of an NMHS. The purpose of this evaluation is to identify the strengths of the service and areas for improvement in terms of effectiveness, efficiency, impact, satisfaction and value to stakeholders, customers, users, partners and employees. More specifically, these evaluations should be as follows (see *The WMO Strategy for Service Delivery and Its Implementation Plan* (WMO-No. 1129)):

(a) Specific: precisely targeted to the area being measured;

(b) Measurable: able to collect data that are accurate and complete;

(c) Actionable: easy to understand, interpret and act upon;

(d) Relevant: measuring only things that are important and relevant to an organization's goals and objectives and avoiding the common mistake of measuring too many things, which is time-consuming and produces meaningless results;

(e) Timely: carried out without delays;

(f) Agreed upon: acceptable levels of performance are agreed upon as part of the evaluation of user needs or the fit-for-purpose assessment;

(g) Owned: owners should be clearly identified and, ideally, they should have the ability, influence and resources to take action to ensure that targets are met;

(h) Consistent: evaluation methods should not promote conflicting behaviour.

One of the ways of gauging customers' satisfaction is to use surveys. Surveys may have several levels of formality, scope and standardization, ranging from frequent customer liaison visits or user workshops to bulk information-gathering exercises using standardized surveys submitted by email or completed online or by telephone. Formal and informal methods are both appropriate and useful for gathering user feedback. Surveys may be conducted at regular intervals or following the delivery of a service. Customer satisfaction results can prove important when viewed alongside interviews highlighting differences between customer perception and technical performance.

The interaction with users, as analysed by the Expert Team on User Interface for Climate Services in the *Guidance on Good Practices for Climate Services User Engagement* (WMO-No. 1214), should be part of a quality-management framework set up by the management of a climate service on the basis of customers' needs (*Guidelines on Quality Management in Climate Services* (WMO-No. 1221)).

## 5.4 Information and dissemination of products and services

In the provision of climate services, it is essential to put users first. As the needs of users evolve, the capabilities of service providers should also adapt over time. Methods of distributing products and services are subject to change, especially in the modern era of information technology, and it is important that Members remain agile and capable of responding to these changes (*The WMO Strategy for Service Delivery and Its Implementation Plan* (WMO-No. 1129)).

Engagement between users and providers occurs at numerous levels, ranging from relatively passive engagement through websites and Web tools to much more active engagement and focused relationships. Based on user needs, this engagement may be limited only to the provision of information, or it may be a dialogue-based focused delivery, or it may be far more extensive, with a highly tailored and targeted service. These categories transition from a more passive to an active delivery mechanism and potentially increase the amount of time and expense involved in the provision and uptake of the service (*Guidance on Good Practices for Climate Services User Engagement* (WMO-No. 1214); Hewitt et al., 2017.

How well a user interprets a provided service depends very much on how the information is presented and provided. Where it is practical to do so, the important facts should be shown visually with accompanying text used to qualify, emphasize and explain. The presentation should be logical, clear, concise and tailored to the user and the aims of the presentation. For example, the style used to impart climate information to a researcher will be different from the style of an article for a newspaper or popular magazine. It can be useful for service providers to train users in how to use and interpret the service.

The approach used to summarize data in a periodical climatological bulletin, which would be intended for a wide range of technical and non-technical users, should be different from that used to prepare an interpretative report on a specific problem in applied climatology. Technical information for users who have limited knowledge of atmospheric sciences should be simple and easy to understand while remaining scientifically correct. It is advisable to avoid specific scientific terminology and acronyms unless they are defined in detail.

More knowledgeable users will be better able to understand complex information and presentations, but some distillation of technical or scientific information is usually desirable. The climate service must therefore be able to anticipate, investigate and understand the requirements of government decision makers, industrial and commercial interests and the general public. It must also be able to understand the issues and respond to questions and user needs with current knowledge and professional skill.

The GFCS was established to provide a credible, integrative and unique platform for guiding and supporting activities implemented within climate-sensitive investment areas – notably agriculture, energy, disaster risk reduction, human health and water – to support risks and opportunities relating to climate variability, adaptation and mitigation. The structure of the GFCS is built upon five components, two of which are relevant to service dissemination:

(a) The User Interface Platform: a structured means for users, climate researchers and climate information providers to interact at all levels;

(b) The Climate Services Information System: a mechanism through which climate information (past, present and future) will be routinely collected, stored and processed to generate products and services that inform often complex decision-making across a wide range of climate-sensitive activities and enterprises.

User Interface Platforms (UIPs) facilitate interactions to enable users, researchers and providers of climate services across the entire climate services value chain to come together to develop, deliver and use climate information in support of robust climate-sensitive decision-making. UIPs use a wide range of methods designed to promote mutual understanding, including formally established committees, working groups, internship programmes, one-to-one discussions, workshops, conferences and inter-agency task teams. Communication, outreach and training approaches are equally wide-ranging. They include radio broadcasts, social media, public service announcements and the use of technologies such as map interfaces, portals and information servers. In many areas of this work, there are opportunities to build upon dialogues that are already well-established or are growing in effectiveness, such as the Regional Climate Outlook Forums, community liaison working groups in the disaster management community, and national health working groups. The proposed enhanced interaction between users and providers aims to reconcile the availability of credible climate information with the needs of users for information to support their decision-making. This mutual understanding can then frame an end-to-end climate service that may involve developing useful products. WMO Members that have already implemented a formal QMS are more likely to be focused on meeting user needs and to consider quality management as a key aspect of service delivery.

The Climate Services Information System is the means by which research outputs and technological developments are transformed into improved operational climate information. The System is formed by institutions (the physical infrastructure), computer capabilities and tools, and operational practices. Together with professional human resources, it develops, generates and distributes a wide range of climate information products and services that can be used at the global, regional and national scales.

## 5.5 Marketing of services and products

Communication is vital to create a positive message about the value of climate services. It increases awareness of the need for such services and why they are beneficial. Communication also helps individuals and organizations to make better-informed decisions. Creating an overall communication strategy for a climate service provider should therefore involving establishing a list of objectives and identifying ways to achieve them using a wide variety of communication methods and media.

Communication is an important aspect of marketing, which is not only about advertising and selling climate services. Communication allows potential users to learn what services and products are available, understand the utility of the services and products, and gain an understanding of the value of the information, as discussed in *The WMO Strategy for Service Delivery and Its Implementation Plan* (WMO-No. 1129). Marketing, public relations, advertising, and promoting and disseminating climate information are essential to the success of most climate services. Climate information is unlikely to be sufficient in its own right. Instead, it often needs to be complemented with non-climate information to be of social and economic benefit. The benefits of using a product must be marketed. This is because the relevance of climate information is often not apparent to those who are in a position to benefit from the products or to those who approve funding for climate programmes. The benefits and worth of using the products must be clearly demonstrated in social and economic terms. Studies are needed to assess the value of climatological services. Such studies should not be the responsibility of the climatologist alone, but rather a shared responsibility of all stakeholders. One way to show the effectiveness of services is by demonstrating the value to the users.

To ensure that a marketing and communication programme is effective, it is important to:

(a) Focus on user needs by gaining a clear understanding of the user's requirements and how the climate information is used;

(b) Provide capacity-building for the climate-service provider and users;

(c) Identify the target market;

(d) Promote the benefits of climate services and products to users;

(e) Develop a product or service for a specific user need and promote its application to solve a user's problems;

(f) Promote the professional skills of climate services personnel;

(g) Make decisions on product accessibility and delivery methods and offer various alternatives to users;

(h) Evaluate the economics of the products and services;

(i) Inform users through promotion and public relations;

(j) Monitor user satisfaction and assess service performance and marketing efforts;

(k) Ensure the credibility and sustainability of climate services by being transparent about the reliability and limitations of the products and services offered.

## 5.6 Capacity development

Capacity development is a cross-cutting GFCS component focused on investing in people, practices and institutions to develop capacities to provide and use climate information for decision-making. *Capacity Development for Climate Services: Guidelines for National Meteorological and Hydrological Services* (WMO-No. 1247) provides NMHSs and other climate service providers with information on resources, strategies, procedures and best practices to help to develop their capacities in the provision and use of climate services at the global, regional and national levels.

The WMO Capacity Development Strategy recognizes four types of capacity:

(a) Institutional;

(b) Infrastructural;

(c) Procedural;

(d) Human resources.

These capacities must be considered collectively to achieve sustainable capacity development. The NMHS guidelines recommend that institutional capacity should include NMHSs having the mandate and visibility to be the primary provider of climate services. As such, NMHSs should target climate service providers and users, mobilize regional and global institutional support and have standard assessment, monitoring and evaluation mechanisms. Infrastructure capacity includes enhancing observation networks and facilities and data retrieval and integration. It also includes integrating observations from diverse sources. Procedural capacity includes socioeconomic benefit analysis, quality-management systems and the utilization of available WMO regulations, frameworks and guidance. Human resources capacity includes management and leadership development, training for meteorologists and climatologists, impact modelling and scenario-based training, analytical capacity development, user engagement and gender equality.

Capacity development in all aspects of service delivery should be incorporated into relevant training events. Such activities should also include information on the users of the climate information, their decision-making processes and how they apply climatological information to such decisions. Users often have a limited understanding of the services they receive or the quality or appropriateness of the services and information. It is therefore also highly recommended to train users and customers on how to derive the maximum benefit from the products and services and how to ensure that they fully understand the capabilities of NMHSs.

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