

# Climateurope2

## **Overview of procedures for data verification, including FAIRness and quality management of climate service data sources and processing methodologies**

### ***Deliverable 2.4***

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## Acronyms

AR	Assessment Report
C3S	Copernicus Climate Change Service
C3S-CDS	Copernicus Climate Change Service - Climate Data Store
CF	Climate and Forecast
CI	Continuous Integration
CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
ECV	Essential Climate Variable
ES-DOC	Earth System Documentation
ESGF	Earth System Grid Federation
ESM	Earth System Model
FAIR	Findable, Accessible, Interoperable, and Reusable
FIP	FAIR Implementation Profiles
GCM	General Circulation Model
IEC	International Electrotechnical Commission
INSPIRE	Infrastructure for Spatial Information in the European Community
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
NetCDF	Network Common Data Form
PID	Persistent Identifiers
PROV-DM	Provenance Data Model
QA	Quality Assurance
QC	Quality Control
RCM	Regional Climate Model
TIB	Technische Informationsbibliothek

W3C	World Wide Web Consortium
WCRP	World Climate Research Programme
WDCC	World Data Center for Climate
WG	Working Group

## About Climateurope2

Timely delivery and effective use of climate information is fundamental for a green recovery and a resilient, climate neutral Europe, in response to climate change and variability. Climate services address this through the provision of climate information for use in decision-making to manage risks and realise opportunities.

The market and needs for climate information has seen impressive progress in recent years and is expected to grow in the foreseeable future. However, the communities involved in the development and provision of climate services are often unaware of each other and lack interdisciplinary and transdisciplinary knowledge. In addition, quality assurance, relevant standards, and other forms of assurance (such as guidelines, and good practices) for climate services are lagging behind. These are needed to ensure the saliency, credibility, legitimacy, and authoritativeness of climate services, and build two-way trust between supply and demand.

Climateurope2 aims to develop future equitable and quality-assured climate services to all sectors of society by:

- Developing standardisation procedures for climate services
- Supporting an equitable European climate services community
- Enhancing the uptake of quality-assured climate services to support adaptation and mitigation to climate change and variability

The project will identify the support and standardisation needs of climate services, including criteria for certification and labelling, as well as the user-driven criteria needed to support climate action. This information will be used to propose a taxonomy of climate services, suggest community-based good practices and guidelines, and propose standards where possible and appropriate. A large variety of activities to support the communities involved in European climate services will also be organised.

## Executive Summary

This deliverable presents the preliminary results of Task 2.3, which aims to evaluate the practices used for data and process quality management in climate services.

The document is organized into three main parts. First, Section 3 provides an analysis of the methodologies used in the climate services community. This includes tools for verifying compliance with the FAIR principles, a navigation system to help climate services participants find the most relevant WMO documentation for their needs, and an analysis of the services provided by Copernicus. The second main part (Section 4) focuses on the communication aspect of quality verification, while the third part (Section 5) presents two ideas for the future development of quality control within the community and the challenges they face. The landscape of standards and guidelines is included in the Appendix.

The main lesson learned from the analysis is that extensive documentation already exists, including ISO standards, WMO guidelines, and community conventions. Given the volume of documentation and the complexity of climate services, it is highly recommended to seek support from officially trained experts on ISO and WMO compliance for internal auditing.

In the next version of this deliverable, the team will focus on two key areas: monitoring the development of AI-generated information through chatbots to democratise the access to climate services and gathering input from the private sector regarding the current landscape of governance tools.

## Keywords

Climate services, Quality Control, Quality Assurance, Communication, Quality Management, Verification, FAIR principles

# 1 Introduction

The objective of this report is to analyse the current landscape of quality verification practices in the climate services community. To achieve this, we have structured the report as follows. It begins with an introduction to quality verification, covering topics such as quality requirements, quality control and assurance workflows, communication, and the diversity of services. Next, a list of definitions is provided to enhance the understanding of the subsequent analyses. The core section of the report then presents verification tools for compliance with the FAIR principles, a guideline for using WMO documentation, and an analysis of Copernicus services as well as other quality verification workflows developed within the climate services community. This is followed by an overview of standards in quality communication, leading into an analysis of challenges and opportunities. Finally, the report concludes with a summary of key findings.

## Quality requirements

The standard ISO/IEC 25010:2023 (Systems and software engineering – Systems and software Quality Requirements and Evaluation (SQuaRE) – Product quality model) defines quality as:

“The quality of a system is the degree to which the system satisfies the stated and implied needs of its various stakeholders, and thus provides value.”

As this definition suggests, the quality of a service is directly linked to what stakeholders consider valuable and necessary to take decisions. Therefore, it is essential that the requirements of a service are properly defined. However, properly defining these requirements is not straightforward, as there are many processing levels between the initial stage where Essential Climate Variables (ECV) are acquired, and the final stage where decisions are taken by climate service users. Hence, it is crucial that communication between different climate service levels is fluid and open, and an effective environment of co-production between providers and users at multiple levels is established. Unless final users can take decisions with the provided information, climate information cannot evolve into a successful climate service. Additionally, it is important to note that the quality of a climate service involves many aspects that might not be directly related to the scientific quality of data, such as the timeliness of product delivery and user-friendliness.

The standardisation of quality requirements in climate services would contribute to the improvement of many aspects, such as consistency, efficiency, compliance, scalability, cost reduction, and interoperability. However, this process faces certain difficulties:

- The time- evolution of the socioeconomic situation
- The time-evolution of technical and scientific capabilities
- The necessity of tailoring data

Regarding the first two, the time-evolution of aspects influencing a service is a delicate topic that can sometimes change very quickly, for example, due to an innovative scientific discovery or the outbreak of war. A successful climate service should incorporate a Quality Management System (QMS) that is flexible enough to handle the revision of quality requirements efficiently.

Regarding the necessity of tailoring data, this challenge clearly opposes the establishment of a general set of requirements. However, it cannot be easily avoided, especially as the processing level of climate information increases, since users working in different industries might have different needs. Additionally, policies and regulations for decision-making vary between countries.

Once quality requirements and quality degrees have been defined, the next step is the definition of how these qualities can be assessed, a concept known as quality metrics. These can either have a quantitative or qualitative output. On the one hand, quantitative metrics that can be read and interpreted by both humans and machines should ideally be chosen, since they allow automation, and thus increase efficiency and interoperability. However, complex quality assessments, such as the impact assessment of a service, lead to a qualitative output, which might not be easily analysed by machines and might not fully rely on objective evidence.

## Quality control and assurance

Quality Management Systems (QMS) are formalised systems designed to coordinate activities to meet customer and regulatory requirements on a continuous basis. The part of quality management focused on fulfilling quality requirements is called Quality Control (QC), and the part focused on providing confidence that quality requirements will be fulfilled is called Quality Assurance (QA) [ISO 9000:2015, *Quality management systems – Fundamentals and vocabulary*]. In simple terms, the difference between QC and QA is that QC is about detecting and fixing non-conformities to requirements, while QA is centred on preventing these non-conformities.

The tools used in QC/QA can be either scientific/technical or knowledge-based. Technical tools provide quantitative assessments and can usually be automated, while knowledge-based tools guide the user through a manual conformity check between the developed product and a hypothetical convention of the respective domain.

Providing trust is one of the key objectives of QC/QA. To achieve that goal, one major aspect to consider is the transparency of QC results and QA implementations. Continuous and fully-automated internal QC can lead to a robust system, but adding external independent assessments from experts can significantly enhance transparency. Additionally, user contributions are a noteworthy external input.

In other words, climate services are not systems represented by a linear path. Instead, they are better described as a set of interconnected loops, where participants at different levels continuously exchange information and work towards improvement.

## Communication within a stage and between stages

Efficient communication and reporting are essential for eliciting productive responses from the target audience. However, this is challenging since a process might involve participants from a wide variety of disciplines with different backgrounds. Ideally, each participant should receive quality information in the form of metadata and a report that corresponds to their experience, interest and use of QC/QA information, but this is usually not cost-effective or scalable. Therefore, QMS administrators often find themselves searching for a balance between providing tailored information and ensuring scalability.

Regarding transparency, QMS should ensure that assessments are findable, accessible, and citable. The linkage between data and assessment reports is a crucial topic, similar to the debate about the location of metadata in relation to the corresponding data. The provision of a findable and accessible linkage between data and assessment report, like a Permanent Identifier (PID) inside the metadata, can contribute to and increase in data uptake and reuse, which is a FAIR principle. Additionally, machine-readable assessments can significantly increase efficiency by enabling the automation of corrective processes. For this reason, quality assessments are usually given in the form of metadata and accompanied by a report for completeness.

Finally, it is usually recommended to preserve metadata even when the data needs to be erased. Similarly, maintaining a historical track of assessments and their respective reactions can contribute to transparency in decision-making and increase trust between the user and the service provider.

## **Types of climate services: perspective and demands**

QMS can be highly complex, especially as the number of stakeholders and requirements increases. Therefore, standardising QMS to include both large-scale services such as the Copernicus Climate Change Service (C3S) and small-scale climate services, such as those presented in academia via use cases, is challenging. Both are climate services, but their resources and demands may not be comparable. Additionally, private and public climate services might have different views on openness and transparency.

## 2 Terms and definitions

To enhance the understanding of the analysis of multiple quality verification workflows, we have compiled a list of definitions that are applicable throughout this document unless otherwise specified. The sources of these definitions are as follows:

1. ISO 19157:2013 Geographic information - Data quality
2. ISO 9000:2015 Quality Management Systems - Fundamentals and vocabulary
3. Vocabulary agreed upon by the Climateurope2 consortium

In the following list of definitions, the source of each term is specified in square brackets at the end of the description. If two sources are listed, it indicates that both sources agree on the same definition:

- **Accuracy:** closeness of agreement between a test result or measurement result and the true value [1]
- **Conformance:** fulfilment of specified requirements [1]
- **Metadata:** information about a resource [1]
- **Metaquality:** information describing the quality of data quality [1]
- **Data quality unit:** a combination of a scope and data quality elements [1]
- **Scope of the data quality unit:** specifies the extent, spatial and/or temporal, and/or common characteristic(s) that identify the data on which data quality is to be evaluated. [1]
- **Data quality element:** a component describing a certain aspect of the quality of geographic data. [1]
- **Quality assurance:** part of quality management focused on providing confidence that quality requirements will be fulfilled. [2, 3]
- **Quality control:** part of quality management focused on fulfilling quality requirements. [2]
- **Process:** set of interrelated or interacting activities that use inputs to deliver an intended result. [2]
- **Quality:** degree to which a set of inherent characteristics of an object fulfils requirements. [1, 3]
- **Grade:** category or rank given to different requirements for an object having the same functional use. [2]
- **Requirement:** need or expectation that is stated, generally implied or obligatory. [2]
- **Verification:** confirmation, through the provision of objective evidence, that specified requirements have been fulfilled. [2, 3]
- **Validation:** confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled. [2, 3]

# 3 Collection of practices and processes used for quality control and assurance in climate services

In climate research, the topics of quality control (QC) and quality assurance (QA) of data, along with approaches to standardise them, have been discussed for many years. The specific approaches used depend on the objectives of the QC/QA process. These approaches may focus on content validation, checking metadata compliance with standards and project conventions, ensuring metadata completeness, or assessing fitness-for-purpose. Over decades, these methodologies have evolved, often as bottom-up initiatives, targeting the FAIR Data principles even before explicitly referencing them. While Persistent Identifiers (PIDs) have played a less central role in the past, their importance is growing. Maturity models have also been introduced to standardise quality results and enhance the transparency of applied QC/QA processes.

This section is divided into four parts. First, the FAIR principles are briefly introduced, along with tools for verifying dataset compliance with these principles. Next, a guidance document is presented that connects World Meteorological Organization (WMO) documentation with key aspects of climate services. Third, the quality workflows of certain Copernicus services are discussed. Finally, various climate services within the community are analysed.

## 3.1 FAIR principles and standards

### 3.1.1 Recap on FAIRness of data and software

The impact of climate services depends on the trustworthiness of its output datasets including, for example, being able to trace back the full input data flow, its quality, as well as processing software and its settings, by the end-user. In section 2.1.2 we will dive further into this provenance aspect of climate services, which is related to the “Reproducibility” FAIR principle that is especially important in this sector. The 14 FAIRness principles to determine the level of FAIRness of data have been developed by GO-FAIR and are listed here <https://www.go-fair.org/fair-principles/>.

In order to provide optimised access to, and (re)use of data, it is important that the data are as FAIR as possible. FAIR data means that data is Findable, Accessible, Interoperable and Reusable for humans and machines, which can only be achieved if the data is readily available through machine accessible services, supported by complete machine interpretable metadata, and follows international metadata and data standards. FAIRness of data is important for re-use of data: Not only in general for the availability of the data, but also for machines and human users to access information related to the quality of the data. Many metadata elements are required for this, but especially some of the specific attributes checked under the I and R. Each of the FAIRness principles contains a reference to recommendations of how they could be met in practice. Section 2.1.3 will describe the state-of-the-art of FAIRness validation tools that aim to assess the FAIRness of (meta)data, software and support FAIR (meta)data management.

### 3.1.2 Importance of provenance

Detailed provenance can reveal inconsistencies or anomalies in the data, enabling early detection and correction of errors. It aids the identification of inefficiencies or problematic areas in data collection and processing. The latter can reveal, as part of an audit trail, the transformation and processing steps

the data underwent, assisting the investigation of potential errors or biases introduced during the processing stages, thereby facilitating comparison among different methodologies, especially when standards procedures are not yet defined across institutions and climate data providers. Thus, it contributes to the Reusability principle of FAIR. It ensures that the steps and data used to create a particular climate product can be reconstructed and verified. However concrete replication and reproducibility requires linking the provenance knowledge base to the data and software repositories, and being used to feed those technical components that enable reproducibility [Iturbide, 2022][Spinuso, 2022]. We recognize that implementing provenance and reproducibility mechanisms in large-scale data systems is complex, requiring advanced tools to capture details like intermediate states, logs, and dependencies, which may not integrate seamlessly with existing systems across organizations. Furthermore, the obsolescence of software and hardware over time can impede long-term reproducibility. Determining when full reproducibility of research data (including model and derived products) is critical for influencing decision-making should guide the level of investment. We believe organizations should establish and communicate a clear reproducibility policy, defining applicable rules and expectations for their datasets. This can also foster discussions on standardized transparency goals, particularly for stakeholders in climate data services.

As a preliminary work in this direction, in D2.2 [Spinuso et al., 2024] we have discussed highly relevant concerns and use cases that will benefit from a structured standardised approach to provenance management. These have been gathered via the direct experience of the partners in Data Management operations and from current and emerging use cases identified by WMO and IPCC. Both organisations consider provenance information a fundamental enabler to achieve FAIRness of climate data and climate change assessment products, respectively. WMO includes provenance as a *required* component in the updated specification of a Climate Data Management Systems, which is soon to be finalised and published.

Concerning standardisation, in D2.2 we have discussed the state of the art of applications and infrastructures that adopt interoperable provenance models for climate data analysis, involving models and observation. We show how tools and technologies designed for provenance management, such as W3C PROV-DM<sup>1</sup> (Provenance Data Model), can help systematically capture and manage provenance data. However, this is not yet defined and recognised as a standard within the climate service community because of the expertise needed in adapting the data model, which is often lacking in the different institutions. Efforts of WMO will try to overcome this gap, for instance by thoroughly investigating adoption of standards and methods for the implementation of the traceability concepts in the WIGOS/WIS2.0 metadata model<sup>2</sup>, thereby facilitating its support globally.

Finally, provenance standards can greatly impact how facilities implement change-management protocols in sensor networks. By setting standards to track updates to sensor technologies and data acquisition pipeline configurations, changes become traceable and are consistently communicated across national and international observational networks, as well as to downstream users.

### 3.1.3 FAIRness validation tools

The path to FAIR data can be seen as a route that parties involved in a certain domain agree on how to achieve it. Especially for aspects such as Interoperability and Reusability, the path depends a lot on agreed solutions (e.g. vocabularies) in the domain. But it is important to have a common target and means to validate how far a data provider is in the process. The implementation of the FAIR principles in practice requires evaluation of the FAIR level of data. This need for evaluation led to the generation

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<sup>1</sup> <https://www.w3.org/TR/prov-dm/>

<sup>2</sup> <https://github.com/wmo-im/wmds/tree/master>

of multiple assessment tools that support the convergence process in different domains<sup>3</sup>. A few important tools (both manual and automated) are listed and described in more detail below. It must be noted that these tools are still under development, while others are still emerging.

## F-UJI - Automated FAIR Data Assessment Tool

F-UJI is a web service and open-source tool to programmatically assess FAIRness of research data objects at the dataset level using its persistent identifier (Devaraju and Huber, 2023). It is based on the FAIRsFAIR Data Object Assessment Metrics<sup>4</sup>. The tool outputs a score for each metric, as well as grouped scores and visualisations that present an overall picture of the FAIRness of the dataset, which can be downloaded for further implementation. It can be used to evaluate large numbers of datasets at the same time through its open-source GitHub code<sup>5</sup>, or simple inspection for one dataset at a time in the webclient<sup>6,7</sup>.

## FAIR Aware - supporting FAIR (meta)data management

FAIR-Aware helps you assess your knowledge of the FAIR Principles, and better understand how making your data(set) FAIR can increase the potential value and impact of your data (Versa et al., 2021). It does not assess a specific object type, but rather the knowledge of the people handling the objects by allowing you to evaluate the current state of your knowledge of FAIR practices, and provides rich guidance texts that help to identify areas of improvement. The tool is discipline-agnostic, making it relevant to any scientific field. This entry-level awareness raising tool is an excellent first step in a journey towards becoming more FAIR-enabling. FAIR-Aware also has a [trainer functionality](#) available that allows you to evaluate the results of your group, to facilitate a broader approach to awareness spreading<sup>8</sup>. We refer the reader to the [website](#) and the [source code](#) for more information.

## FOOPS! - supporting ontology FAIRness

FOOPS! (Ontology Pitfall Scanner for FAIR) is a tool for assessing FAIRness level for ontologies and serves as a validator to provide the means for researchers to assess whether a vocabulary (OWL or SKOS) conforms to the best practices for publishing ontologies on the Web (Garijo et al., 2021). The validation is based on several important publications that proposed metrics for the assessment of semantic artefacts<sup>9</sup>:

- [Coming to terms with FAIR ontologies: A position paper](#)
- [Best Practices for Implementing FAIR Vocabularies and Ontologies on the Web](#)
- [D2.5 FAIR Semantics Recommendations Second Iteration](#)

The [tool](#) can be accessed online, and the [source code](#) is published in GitHub.

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<sup>3</sup> <https://www.thehyve.nl/articles/evaluation-fair-data-assessment-tools>

<sup>4</sup> <https://zenodo.org/records/6461229>

<sup>5</sup> <https://github.com/pangaea-data-publisher/fuji>

<sup>6</sup> <https://zenodo.org/records/11084909>

<sup>7</sup> The online user interface of F-UJI is available at: <https://www.f-uji.net/>

<sup>8</sup> <https://doi.org/10.5281/zenodo.5084861>

<sup>9</sup> [https://foops.linkeddata.es/assets/iswc\\_2021\\_demo.pdf](https://foops.linkeddata.es/assets/iswc_2021_demo.pdf)

## Manual/process guidance (FIP, FIP wizard)

Achieving machine to machine FAIR data, software and services is a process. The FAIRness validation tools listed above aim to provide a quantitative view on the level of FAIRness of a certain dataset or object, by using a machine accessible URL as starting point. This has the advantage of a fairly objective first check of FAIRness level, but misses out on the process steps and solution decisions a data provider needs to take to improve the FAIRness.

Therefore, in contrast to the automated tools, in an effort to support the data provider in formulating the decision steps in the FAIRness process and to accelerate broad community convergence on FAIR implementation options (so choosing the same solutions for the same issues in the community), the GO FAIR community has launched the development of machine-actionable FAIR Implementation Profiles (FIP). The FIP is a collection of FAIR implementation choices made by a community of practice for each of the FAIR Principles. Community specific FAIR Implementation Profiles are themselves captured as FAIR datasets and are made openly available to other communities for reuse (ref: [Go-FAIR website](#)).

The FAIR Implementation Profiles representing the implementation strategies of various communities can be used as the basis to optimise the reuse of existing FAIR-enabling resources (is e.g. a certain technology or standard) and interoperation within and between domains. Ready-made and well-tested FAIR Implementation Profiles created by trusted communities can find widespread reuse among other communities, and vastly accelerate convergence onto well-informed FAIR implementations.

The creation of the FIP is done via the [FIP Wizard 4.0](#). This version is by now a stable and robust tool. However, as the FIP Wizard generates and relies on information that is open to the community at large, it requires some expert guidance in its use in order to ensure the quality of the output. This means that anyone who wishes to create a FIP is recommended to first participate in a FIP Introduction workshop conducted by a GFF qualified 3PFF facilitator. (Ref: GO-FAIR Github)

As an impression, making a FIP will typically involve three activities summarised below:

1. Completing the FIP Questionnaire: Answer the questions of the FIP Wizard questionnaire by selecting for each FAIR Principle, the FAIR Enabling Resources from the drop-down lists, setting the implementation status, and stating your considerations behind that choice.
2. Minting New Nanopublications: the FIP-Wizard offers implementation choices (solutions, standards, technology) to fulfil a certain FAIR metric. These are stored as a so-called nano publication. When a new community starts to work in the FIP-Wizard there can/will be a need to add community agreed solutions not present in the wizard yet.
3. Publish the FIP.

After this, the participants will work on the steps to improve FAIRness based on the selected planned solutions, and after some time a new FIP version will be created to track the process. In this way the FIP wizard offers very valuable guidance in the work. It has been used by many of the ENVRI RI's involved in the ENVRI-FAIR project.

### 3.1.4 Recommendations for FAIRness validation

In order to support climate services to process their input data in an optimal way, it is important for data providers to maximise the FAIRness of their datasets and software. It is equally important that the output datasets of climate services are published in a FAIR way. One can not be realised without the other: FAIR output needs FAIR input, only then can the output metadata and data contain machine

accessible information on data quality, provenance information (regarding the origin of data, processing info, accuracy, ...).

Attention for FAIRness in the publication process is key. It is recommended to data providers/publishers to make use of the existing tools and training. A combined use of automated checks, plus following the FIP process will provide best insights, guidance and community convergence.

### 3.2 WMO - Quality management guidelines in climate services

The World Meteorological Organization (WMO), through its programmes and activities, is dedicated to ensuring the highest possible quality of all meteorological, climatological, hydrological, marine, and related environmental data, products, and services supporting 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 the adoption and implementation of an organisation-wide quality management approach, associated with meeting the WMO's main objectives and strategic priorities. A Quality Management System (QMS) is an end-to-end system covering all activities from raw measurements and observations to services delivered to end-users.

A QMS ensures that all the activities necessary to design, develop and deliver a product or service are conducted effectively and efficiently. It focuses on product and service quality, and on the means to achieve it. It is possible to achieve consistent quality by utilising quality assurance and quality control of functions and products. Meeting customer and applicable statutory and regulatory requirements and facilitating opportunities to enhance service delivery drive the system.

The development of a QMS in the delivery of climate services includes application of guidelines with respect to various components of the service, including: data source selection, acquisition and validation; data processing; quality control; data storage and distribution; user feedback; and continuous improvement.

A QMS based on WMO guidelines can help ensure several critical criteria are identified and attained, such as data accuracy, reliability, consistency, and timeliness. For a comprehensive overview of WMO guidelines on establishing a QMS, key relevant publications are explained in Table 1:

**Table 1.** Key WMO guidelines on establishing a Quality Management System (QMS). An explanation for each publication is provided below the corresponding title.

WMO No. 1221: Guidelines on Quality Management in Climate Services	
<b>1</b>	This document focuses on implementation of a Quality Management System (QMS) in relation to the provision of climate services. Using a process approach, it is possible for an organization to work on continual improvement by focusing on its processes. It is much easier to identify areas for improvement, assess the risk of implementing changes and validate that the changes have resulted in improvements to the process by breaking the overall QMS down into smaller processes. This is an important aspect of implementing the process approach because improvement is also one of the quality management principles, and one of the main reasons for implementing a QMS. The provision of climate services is suitable for adopting the process approach, thus making the process approach an effective tool for improving these services. The QMS maps the inputs and outputs with respect to

	the different processes, as well as the resources needed. Processes can also be monitored to see if they are providing the intended outputs needed to meet customer requirements.
2	<b>WMO No. 1238: Manual on the High-quality Global Data Management Framework for Climate (HQ-GDMFC)</b>
	The Framework establishes standards and recommended practices for sourcing, securing, managing, assessing, and cataloguing climate data, and for sharing infrastructure and responsibilities for, for example, data exchange, analysis and data service provision. The HQ-GDMFC provides a robust data foundation for the generation of climate products and the delivery of climate services. This manual provides guidance and requirements on the development, provision, exchange and maintenance of high-quality climate datasets. The standards and recommended practices it describes are intended to ensure that the data made available for climate assessment, monitoring, applications and related services meet sustainably a minimum set of requirements with regard to quality, governance, accessibility and usability.
3	<b>WMO No. 8: Guide to Instruments and Methods of Observation</b>
	This guide provides comprehensive standards and best practices for the measurement, observation, and reporting of meteorological and other environmental data. The Commission for Instruments and Methods of Observation (CIMO) Guide provides detailed instructions on: <ul style="list-style-type: none"> <li>• the design, installation, calibration, and operation of instruments and sensors used in data acquisition, ensuring consistency and reliability in the data collected worldwide.</li> <li>• procedures for the validation of data obtained from various instruments and methods of observation, emphasising importance of calibration, regular maintenance, and quality control to ensure data validity.</li> <li>• data processing methodologies related to instrument-generated data, including guidelines on how to handle, adjust, and process data to maintain its accuracy and reliability.</li> <li>• quality control procedures for ensuring the accuracy and reliability of data collected by different instruments and observation methods.</li> <li>• data management related to the secure storage of observational data, ensuring that the data is safely stored and remains accessible for future use.</li> </ul>
4	<b>WMO No. 49: Technical Regulations</b>
	This publication outlines the fundamental principles, requirements, and standards governing all meteorological and related activities within the WMO framework. It includes regulations on: <ul style="list-style-type: none"> <li>• standards and practices for the recognition and use of data sources in meteorology and climatology.</li> <li>• the standardisation of data acquisition processes, ensuring that observations meet specific quality and performance criteria to help maintain consistency across global data acquisition networks.</li> <li>• recommendations for the validation of data, ensuring that observations meet specified quality standards before they are disseminated or used in analyses.</li> </ul>

	<ul style="list-style-type: none"> <li>• general guidelines on the processing of data, ensuring that methodologies are consistent with WMO standards to facilitate global data exchange and analysis.</li> <li>• principles and guidelines for implementing quality control measures across various meteorological and hydrological services.</li> <li>• guidelines on data management, including secure storage practices, to ensure that data is preserved and protected according to WMO standards.</li> <li>• guidelines for the ongoing evaluation and enhancement of services, in order to remain aligned with evolving scientific and technological standards.</li> </ul>
5	<b>WMO No. 100: Guide to Climatological Practices</b>
	<p>This publication covers the principles and practices of climatology, including the collection, processing, and dissemination of climatological data. It addresses:</p> <ul style="list-style-type: none"> <li>• the recognition and certification of data sources to ensure the quality and consistency of climate data.</li> <li>• standardised procedures for data acquisition in climatology, ensuring that climate data is consistent, accurate, and comparable across different regions and time periods.</li> <li>• procedures for the validation of climatological data, including methods for detecting and correcting errors, ensuring the integrity of long-term climate records.</li> <li>• methodologies for the processing of climate data, ensuring that long-term climate records are accurate, consistent, and comparable.</li> <li>• quality control protocols to ensure the validity and consistency of climatological data, which are essential for long-term climate records and analyses.</li> <li>• recommendations for the distribution of climatological data, ensuring that data sharing practices are secure and reliable.</li> <li>• guidelines for incorporating user feedback into the development and dissemination of climatological products, ensuring that they meet user needs and expectations.</li> </ul>

Creating a decision tree for more specific aspects of quality management of climate service data sources and processing methodologies based on WMO guidelines will ensure several critical criteria are identified and attained, such as data accuracy, reliability, consistency, and timeliness.

Table 2 outlines the relationship between key aspects of climate services and relevant WMO documents. By clicking on the row labels, readers are directed to the Appendix, where a brief explanation of each WMO document is provided. Similarly, clicking on the column labels redirects readers to a section of the Appendix containing a decision tree, which helps users assess their compliance with WMO guidelines and determine appropriate actions. Additionally, this section includes key indicators of compliance. This structured information ensures that climate service data sources and processing methodologies meet WMO's high standards, thereby promoting data integrity and reliability in climate services. It also serves as a guideline for adhering to a Quality Management System (QMS) when making decisions.

Please note that WMO documents 8, 49, 100, and 1238 form the foundation of the Quality Management System (QMS) and should be considered alongside the specific documentation for each climate service aspect.

The standardisation and adoption of provenance data in Climate Data Management Systems, will be investigated by a dedicated Expert Team on Climate Data Development and Stewardship (ET-DDS),

with active contributions from Climateurope2 partners. This effort will influence the further development of WIS2 and WIGOS systems and metadata, enhancing global climate data sharing.

**Table 2.** Relationship between specific WMO documentation (rows) and aspects of climate services (columns): data source selection (DSS), data acquisition (DA), data validation (DV), data processing (DP), quality control (QC), data storage (DS), data distribution (DD), user feedback and review (UF&R), and continuous improvements (CI). By clicking on each column title, readers are directed to the Appendix, where decision trees and key indicators have been added for each aspect. By clicking on each row label, readers are directed to a description of the selected WMO document.

	<a href="#">DSS</a>	<a href="#">DA</a>	<a href="#">DV</a>	<a href="#">DP</a>	<a href="#">QC</a>	<a href="#">DS</a>	<a href="#">DD</a>	<a href="#">UF&amp;R</a>	<a href="#">CI</a>
<a href="#">305</a>									
<a href="#">306</a>									
<a href="#">488</a>									
<a href="#">1025</a>									
<a href="#">1083</a>									
<a href="#">1100</a>									
<a href="#">1112</a>									
<a href="#">1143</a>									
<a href="#">1157</a>									
<a href="#">1165</a>									
<a href="#">1181</a>									
<a href="#">1185</a>									
<a href="#">1194</a>									

	<a href="#">DSS</a>	<a href="#">DA</a>	<a href="#">DV</a>	<a href="#">DP</a>	<a href="#">QC</a>	<a href="#">DS</a>	<a href="#">DD</a>	<a href="#">UF&amp;R</a>	<a href="#">CI</a>
<a href="#">1203</a>									
<a href="#">1209</a>									
<a href="#">1269</a>									

### 3.2.1 WMO-Compliant NHMS and Case Studies

The WMO has been the principal supporting organisation for National Meteorological and Hydrological Services (NMHSs) since its inception. Through its extensive range of guidelines, manuals, and other documents, which are regularly updated, revised, and improved in line with scientific and technological developments, the WMO provides standardisation and a framework for international cooperation to advance meteorological, climatological, hydrological, and related environmental services, thereby improving the well-being of all.

It is important to emphasise the significance of standardisation and quality control in the observation and measurement of climatological data, which is primarily conducted by national and international hydro-meteorological services and space agencies. This data forms the foundation, and its quality significantly influences the quality of the climate services produced.

The WMO has developed several self-evaluation tests and questionnaires to assess the state of NMHS climate services, with four categories of fulfilment: basic, recommended, full, and advanced. One of the most important is the Checklist for Climate Services Implementation, with its results presented on the WMO's Climate Services Dashboard<sup>10</sup>.

The WMO has issued the Guide to the Implementation of Quality Management Systems for National Meteorological and Hydrological Services and Other Relevant Service Providers (WMO-No. 1100, 2017) and Guidelines on Quality Management in Climate Services (WMO-No. 1221, 2018), providing clear and detailed step-by-step instructions to NMHSs. The main recommendation from the WMO is to implement the QMS across the entire NMHS, as all their activities are more or less interconnected within the Earth system environment. However, QMS can be applied solely to climate services, if necessary. Following the application of *the ISO 9001:2015 - Quality Management Systems* standard in conjunction with the aforementioned guides, a process approach is advised, covering climate data, climate monitoring, climate prediction, and service delivery. This is illustrated by the case studies presented in Table 3.

**Table 3:** Case studies of WMO-Compliant National Meteorological and Hydrological Services (NHMSs).

1	Republic Hydrometeorological Service of Serbia (RHMZ)
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<sup>10</sup><https://app.powerbi.com/view?r=eyJrIjojY2JmYzZmNDYtNmU3ZS00ZTAwLWlyYjAtOTcyMzY0ZDc5NDJiliwidCl6ImVhYTZiZTU0LTQ0ODctNDBjNC05ODI3LWwNDRiZDhIOGQzYyIsImMiOjI9>

	<p>The ISO 9001 standard was introduced as the basis for the QMS at the Republic Hydrometeorological Service of Serbia (RHMZ) in 2012, under the WMO’s recommendation, since RHMZ was involved in providing aeronautical meteorological services. The QMS was implemented across the entire NMHS using the as-is method, following the organisational structure of the RHMZ and encompassing climate services, alongside all other services. Today, RHMZ is assessed and certified by a third party as meeting the requirements of ISO 9001:2015 for various activities, including: ensuring the functioning of the Hydrometeorological Early Warning System; providing services in the field of aeronautical meteorology; conducting meteorological and hydrological observations, analyses, and forecasts; calibrating and standardising meteorological instruments; performing climate analyses; monitoring climate variability; producing climate forecasts; and assessing the impact of climate change. Additionally, RHMZ holds the ISO 17025:2017 certificate, demonstrating its competence in performing calibration in its Meteorological Laboratory. This certification covers the entire chain of service creation, starting from the measurement of meteorological data (including instruments, measurement locations, and methods used), through to data quality control, management, storage, and international exchange, and extending to the analysis, forecasts, and creation of products (such as climate monitoring and early warning systems) for sectors including agriculture, water, energy, health, and civil engineering.</p>
2	<p style="text-align: center;"><b>Croatian Meteorological and Hydrological Services (DHMZ)</b></p> <p>Another case study that illustrates certified compliance with WMO quality management system guidelines is the ISO certification of Climate Services by the Croatian Meteorological and Hydrological Service (DHMZ). The WMO Climate Services Branch facilitated a twinning project between the Bureau of Meteorology of Australia (BoM) and the DHMZ on quality management systems in climate services, as an extension of the Lead Auditors course. The auditing process, conducted by external auditors and an ISO-affiliated company, took approximately nine months. The certificate was awarded to DHMZ during a high-level governmental ceremony on World Meteorological Day. The scope of this QMS ISO certificate in climate services is “processing, control, archiving and distribution of data, and development of climate databases and applications, climate modelling, climate change monitoring, and biometeorology”. On March 2024 DHMZ was the first NMHS in the world to obtain a certificate following ISO 9001:2015 in conjunction with WMO guidelines, as part of the WMO pilot project.</p>
3	<p style="text-align: center;"><b>CARPATCLIM and DANUBECLIM</b></p> <p>A notable example of good practice is the CARPATCLIM - Climate of the Carpathian Region project, financed by the European Commission through the Joint Research Centre. This project involved the collaboration of National Meteorological and Hydrological Services (NHMS), institutes, and universities from ten countries in the production of the Climate Atlas of the Carpathian Region, followed by the DANUBECLIM project, which included two additional NHMS from two more countries. The highest quality product was achieved by utilising the maximum available volume of daily data over a 50-year period, gathered from more climatological stations than those usually included in international exchanges. This data underwent rigorous quality checks using unified software and methods for homogenisation and interpolation (MASH and MISH), alongside cross-border data harmonisation. Another significant outcome of the project was the creation of a Metadata Catalogue, developed in line with the INSPIRE directive and in accordance with FAIR principles.</p>

The lessons learned from the case studies presented in Table 3 are as follows:

- **Continuity and sustainability of observations:** With technological advances, new methods of observation and measurement are emerging, increasing the volume of data available for creating climate services. However, standardisation of observations and measurements must be maintained over time to achieve consistent long-term tracking of essential climate variables (WMO-No. 1269, 2021). Therefore, the implementation of new observational methods should ensure the continuity of existing data, either by translating new data to match the old (e.g., resolution) or by dual implementation of new and old technologies. This is exemplified by the line of SENTINEL satellites developed by the EU's Copernicus Programme<sup>11</sup>.
- **Expertise in WMO and ISO Compliance:** To ensure full compliance with WMO guidelines and the proper implementation of relevant ISO standards, WMO recommends seeking input from trained experts or auditors who can serve as an internal control, particularly before undergoing an external audit. These internal auditors will have the requisite technical expertise that allows them to address potential gaps in the QMS and therefore expedite the certification process by external auditors. As part of capacity building, WMO offers workshops once or twice a year to train new experts, who receive official accreditation upon successful completion of the course.

## 3.3 Copernicus

Copernicus is the European Union's leading Earth observation program, delivering precise and timely environmental data to support climate change monitoring, disaster management, and sustainable resource use. Through its network of Sentinel satellites and ground-based sensors, Copernicus offers comprehensive insights into the planet's land, atmosphere, and oceans. Managed by the European Commission in collaboration with the European Space Agency, the program ensures free and open access to its data, fostering innovation and informed decision-making. Copernicus stands at the forefront of global efforts to understand and protect our environment.

### 3.3.1 Copernicus Climate Change Services (C3S)

C3S has established a comprehensive Evaluation and Quality Control (EQC) framework for all its products and services. The goal is to ensure that users are served well and that this will continue to be the case as their needs evolve. Previous work by C3S on EQC for datasets in the Climate Data Store (CDS) has focused on creating comprehensive quality assurance reports, which contain detailed technical information about data, metadata and documentation, assessments of data maturity, results of routine checks on data integrity and completeness, output from various diagnostic tools, and descriptions of relevant use cases (refer to Nightingale et al. 2019; Lacagnina et al. 2022; Yang et al. 2022). This approach was recently revised for CDS datasets to further enhance the direct relevance and the usability of quality information by the users the service targets (Dee et al. 2024).

This approach is guided by the key objective for C3S to simplify data discovery and access, and to ensure that all information provided is fit for purpose. The role of EQC is to generate useful statements about the technical and scientific quality of the datasets available on the CDS, presented in a form that can be mapped directly to user requirements associated with specific application contexts. Those statements, in combination with other documented information about the datasets, constitute a knowledge base that can help users to assess fitness for purpose, given their needs and requirements.

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<sup>11</sup> <https://sentwiki.copernicus.eu/web/copernicus-programme>

The ambition is to enable users to select, locate, access, and process climate data that are fit for purpose, simply by expressing their requirements in their own words.

This will make it easier for non-specialists to use climate data effectively for purposes that extend beyond scientific analysis, such as policy development, environmental impact studies, business plans, public awareness, etc. In addition to simplifying access to the wealth of climate data available today, more information about data quality will be provided that users can understand and use to determine fitness for purpose.

The revised C3S EQC framework makes a distinction between quality assurance and quality assessment.

Quality assurance serves to inform users that data, metadata and documentation comply with a well-defined set of verifiable technical requirements. It provides evidence that this compliance has been checked independently from the producers. Quality assurance for each CDS dataset is implemented by verifying a set of well-defined technical requirements associated with the dataset. Specific assessment criteria for the respective data streams (e.g. reanalysis, projections) are developed to account for the different nature of these and the different types of checks that may have to be applied to verify the requirement. The role of EQC evaluators is to check these criteria and document the outcome to users. Each requirement is formulated as a verifiable statement about data records, metadata, documentation, or all three combined. The outcomes of the quality assurance process for each dataset are displayed on the CDS web pages in the form of summary checklists. The user can click on the checklist to see the actual statements of technical requirements for the dataset, how they are verified, and additional information about non-compliance if needed.

The purpose of quality assessments, on the other hand, is to provide science-based information about accuracy, uncertainties, sources of uncertainty, temporal consistency, strengths, and weaknesses of a dataset in the context of a realistic use cases. In many instances, especially for datasets that are widely used, relevant information is available in the published literature. In either case, it requires a dedicated effort to generate or extract this type of information and present it in a form that is helpful to CDS users. The applications published on the CDS provide examples of real use cases for CDS datasets. A user of an application might ask for information about the accuracy of the parameters in the reference period or the main sources of uncertainty in the data used in the tool, and how those uncertainties affect the results. A thorough assessment of those user questions, based on published literature and additional data analysis if needed, could provide useful information for users of this application as well as related applications based on similar methods.

EQC evaluators are tasked with developing quality assessments that are designed to generate useful statements about fitness for the purpose of CDS datasets. The assessments address concrete questions about data quality associated with real use cases. Many of the assessments are implemented in Jupyter notebooks that can be shared, re-used, and modified by users. Assessments can involve multiple CDS datasets and use other sources of reference data. Assessments build on relevant scientific literature, including published documents developed by producers and users of the datasets.

The EQC framework for datasets will also be applied to applications and training resources.

### 3.3.2 C3S Atlas

The C3S Atlas provides two forms of climate information: the “Copernicus Interactive Climate Atlas: gridded monthly dataset”, which includes various sources of climate data from global and regional

climate models, emission scenarios, variables, and warming levels; and the products available in the C3S viewer<sup>12</sup>, which are straightforward temporal or spatial aggregations of the gridded dataset.

Quality Assurance (QA) and Quality Control (QC) protocols implemented in the C3S Atlas<sup>13</sup> aim to ensure that the datasets and products provided under this initiative are consistent, reliable, and accurate across different datasets and workflows for climate index calculation. The protocols focus on creating a harmonised and CF-conformal<sup>14</sup> climate index gridded dataset<sup>15</sup> (and derived products from this dataset through simple temporal or spatial aggregations) from multiple climate sources, identifying and correcting issues in the original data, and ensuring the reproducibility and reusability of the workflows following the FAIR principles (Iturbide et al., 2022).

QA/QC protocols are implemented in all phases of the C3S Atlas workflow for index calculation. The workflow utilises as input the Evaluation and Quality Control framework of the C3S Climate Data Store<sup>16</sup> (C3S-CDS) and is aligned with widely validated and publicly available Python software for index calculation (xclim), regridding (xESMF), and bias adjustment (ibicus), which prevent errors and ensure traceability. The software implements several QA protocols such as unit and integration tests, static code analysis and Continuous Integration (CI) practices. The workflow also includes a protocol to manage potential errors that arise after publication. If an error originates from the input data, it is published through the "Earth System Documentation" site<sup>17</sup>. If the affected input data are part of the C3S-CDS catalogues, the simulations are either removed or modified accordingly, and a message is sent to the users. Similarly, if an issue is detected in the C3S Atlas workflow and it affects the products, it is fixed in the next version of the data, which is documented in the metadata of the files.

The C3S Atlas significantly contributes to creating a harmonised climate dataset from various sources (GCMs, RCMs, reanalysis, observations, etc.), which includes standardising time calendars, spatial coordinates, map projections, variable units, and CF-conformal metadata for data description. This greatly enhances the dataset's usability for users. Fit-for-purpose QC protocols are also designed to identify potential issues in the original data (units, coordinates, etc.) as well as during the workflow. This includes spatial maps presented as mosaics to identify spatial displacements with respect to a reference, such as the coastline; climatologies for different ensemble members to characterise ensemble dispersion and identify issues with individual climate projections and climate stripe-plots to pinpoint various types of issues, such as simulations deviating significantly from the ensemble range or periods with missing values.

### 3.3.3 Copernicus Land Monitoring Service (CLMS)

The Copernicus Land Monitoring Service (CLMS)<sup>18</sup> is one of six thematic Copernicus services. CLMS is jointly implemented by the European Environment Agency (EEA) and the European Commission DG Joint Research Centre (JRC). It provides geographical information on land cover and its changes, land use, ground motions, vegetation state, water cycle and Earth's surface energy.

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<sup>12</sup> <https://atlas.climate.copernicus.eu>

<sup>13</sup> <https://atlas.climate.copernicus.eu>

<sup>14</sup> <https://cfconventions.org/>

<sup>15</sup> <https://confluence.ecmwf.int/display/CKB/Gridded+data+underpinning+the+Copernicus+Interactive+Climat+e+Atlas%3A+Description+of+the+datasets+and+variables>

<sup>16</sup> <https://climate.copernicus.eu/quality-assurance-climate-data-store>

<sup>17</sup> <https://errata.ipsl.fr/static/index.html>

<sup>18</sup> <https://land.copernicus.eu/en>

## CORINE Land Cover

CORINE Land Cover (CLC)<sup>19</sup> is the oldest and most sought-after database of CLMS. CLC was specified to standardise data collection related to land in Europe to support environmental policy development. The project is implemented by national teams under the management, guidance and close quality control of EEA.

Quality control (QC) and quality assurance (QA) are key elements of the European CLC projects<sup>20</sup>. QA includes the standardised production of input satellite imagery, the provision of implementation guidelines and helpdesk, as well as technical acceptance procedures, while QC is ensured via the verification activity. Besides European QA/QC activities, national teams apply their own internal QA/QC steps. Two different QA/QC activities can be distinguished: verification (two phases) and validation.

- **Verification (phase 1):** has a corrective purpose and is implemented as part of the production process. Verification results are created to inform the data producer about quality issues. The first verification is done when 10-20% of the country area is interpreted. The main purpose is to reveal problems and give feedback in the early phase of implementation in order to influence further production.
- **Verification (phase 2):** is due when around 75% of the country area is interpreted with the aim to check the database close to completion and suggest overall improvements if still needed.
- **Validation:** aims to assess the accuracy of the final database and is implemented after completion of the production. Its main goal is to inform users of the databases about quality in quantitative terms. It should be fully independent from production and rely on independent very-high-resolution in-situ data as reference (i.e. must not have been used in compilation of the CLC databases) as well as on independent experts working on validation (not having participated in the mapping exercise).

A custom-made software tool, **InterCheck** serves as a software platform to carry out the verification. Automated technical conformity checks layers to reveal technical mistakes (e.g. polygons smaller than minimum mapping units, invalid codes) and topological mistakes (e.g. a hole in the revised CLC database, overlapping and multipart polygons). Beside application of the software, verification is carried out by visual checking of CLC layers: checking CLC code statistics (to reveal invalid and non-relevant codes), visual evaluation of “critical” classes (sampled according to CLC code, polygon size range, etc.) and checking CLC-Change statistics (to reveal invalid and non-relevant changes).

A verification report is written as well, describing and explaining the main issues and suggestions for improvements. The result of the verification is expressed in qualitative terms (i.e. no accuracy figures are provided).

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<sup>19</sup> <https://land.copernicus.eu/en/products/corine-land-cover>

<sup>20</sup> <https://land.copernicus.eu/en/technical-library/clc-product-user-manual/@@download/file>

## Pan-European High Resolution Layers

Complementary to land cover/land use mapping in the CLC datasets, Pan-European High Resolution Layers (HRL)<sup>21</sup> provide information on specific land cover characteristics as well, but on higher resolution and with more frequent updates<sup>22</sup>.

QA of HRL<sup>23</sup> follows the ISO 9001 standard for Quality Management and the Infrastructure for Spatial Information in the European Community (INSPIRE) data quality elements<sup>24</sup>, which are based on the ISO 19157 standard. Technical QC/QA activities include:

- Continuous monitoring and maintenance of the processing infrastructure,
- QA within the production process, applying planned and systematic checks at various stages between data collection and the final product, as well as
- Final QC after the main production of the HRLs (but still before making final data aggregation and re-projection), where the accuracy and precision of the products is being assessed.

Quality requirements include: thematic and geometric accuracy and consistency, logical/topological consistency, thematic coding/attributes as well as metadata completeness and compliance to INSPIRE.

## Copernicus Global Land Operations (GLOPS)

CLMS also develops and provides different products like the Dry Matter Productivity (DMP) and Net Primary Production (NPP) based on EO input data and with global coverage. Validation of these products conform to at least the CEOS LPV procedures (Committee on Earth Observation Land Product Validation)<sup>25</sup>. The QC approach consists of two major components:

- **Direct validation** – comparison of satellite products to ground measurements. This is usually limited by a small number of reference sites.
- **Indirect validation** - inter-comparison between products as well as evaluation of their temporal and spatial consistency with similar datasets or other suitable reference datasets. It allows extending the evaluation over large areas or time periods but only relative discrepancies between existing datasets can be assessed.

The criteria under evaluation include: product completeness, spatial, statistical and temporal consistency, requirements assessment and error evaluation (accuracy, precision and uncertainty assessment).

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<sup>21</sup> <https://www.wekeo.eu/data?view=dataset&dataset=EO%3ACLMS%3ADAT%3AHRL>

<sup>22</sup> <https://www.copernicus.eu/en/news/news/observer-vegetated-land-cover-characteristics-vlcc-new-era-land-monitoring>

<sup>23</sup> <https://land.copernicus.eu/en/technical-library/hrl-grassland-2018-product-user-manual/@@download/file>

<sup>24</sup> [https://knowledge-base.inspire.ec.europa.eu/document/download/f646f233-9d96-41d9-96dd-aed930bbe447\\_en?filename=jrc83209\\_online\\_data\\_quality\\_in\\_inspire.pdf](https://knowledge-base.inspire.ec.europa.eu/document/download/f646f233-9d96-41d9-96dd-aed930bbe447_en?filename=jrc83209_online_data_quality_in_inspire.pdf)

<sup>25</sup> <https://land.copernicus.eu/en/technical-library/quality-assessment-report-annex-dmp-gdmp-npp-gpp-version-1.1/@@download/file>

## 3.4 Validation and quality control within the climate research community

### 3.4.1 CMIP quality control frameworks

The Coupled Model Intercomparison Project<sup>26</sup> (CMIP) of the World Climate Research Programme (WCRP) provides climate projections to understand past, present and future climate changes. CMIP and its associated data infrastructure have become essential to the Intergovernmental Panel on Climate Change (IPCC) and other international and national climate assessments.

CMIP conventions have always been influential for the climate modelling community. The quality control for CMIP data aims to operationalise automatic technical quality checks of data. The scientific QC/QA is developed by the modelling centres/data creators, whereas the data managers and infrastructure providers are responsible for the technical QC/QA.. Within CMIP5 a three level federated quality control approach<sup>27</sup> was set up (Stockhouse et al, 2012):

- QC level 1 (on all datasets): metadata compliance to project conventions like controlled vocabularies,
- QC level 2 (on all datasets): compliance of data and metadata to community standards like NetCDF/CF and further project conventions plus basic data checks like data ranges, and
- QC level 3 (on IPCC WGI AR5 snapshot): double- and cross-checks of data and metadata consistency including documentations, DataCite metadata completeness and data accessibility.

Data issues found during QC1 and QC2 are reported to the data creators for correction and publication of a new dataset version. QC3 is a quality control approach to ensure that the collected and long-term archived data and documentation from various sources are consistent and DataCite metadata is complete.

The basic checks of QC1 have become part of the ESGF data publisher (PrePARE checker<sup>28</sup>) and are applied to all data disseminated by ESGF. QC2 has been adopted by the Coordinated Regional Climate Downscaling Experiment<sup>29</sup> (CORDEX) and the Copernicus Climate Change Service -Climate Data Store (C3S-CDS) CMIP6<sup>30</sup>. Different QC checker tools have been developed using similar checks. For example, all these tools include a NetCDF/CF compliance check. C3S-CDS CMIP6 has added consistency checks of the model documentations of ES-DOC<sup>31</sup> and of the CMIP6 controlled vocabulary for models<sup>32</sup>.

Ongoing developments in CMIP7, carried out in dedicated CMIP7 Task Teams (TT), aim to improve the quality of the datasets published in the ESGF that are related to the AR7 Fast Track. The concept of essential information provided as model documentation (ES-DOC, Model Documentation TT<sup>33</sup>) or

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<sup>26</sup> <https://wcrp-cmip.org/>

<sup>27</sup> <https://cmip5qc.wdc-climate.de>

<sup>28</sup> [https://cmor.llnl.gov/mydoc\\_cmip6\\_validator/](https://cmor.llnl.gov/mydoc_cmip6_validator/)

<sup>29</sup> <https://cordex.org/>

<sup>30</sup> <https://confluence.ecmwf.int/display/CKB/CMIP6%3A+Global+climate+projections#heading-QualitycontroloftheCDS-CMIP6subset>

<sup>31</sup> <https://es-doc.org/>

<sup>32</sup> [https://wcrp-cmip.github.io/CMIP6\\_CVs/docs/CMIP6\\_source\\_id.html](https://wcrp-cmip.github.io/CMIP6_CVs/docs/CMIP6_source_id.html)

<sup>33</sup> <https://wcrp-cmip.org/cmip7-task-teams/model-documentation/>

for the data citation (Data Citation TT<sup>34</sup>) aims to ensure that all datasets have mandatory minimal documentation and are citable with their DOIs while minimising the overhead on modelling centres. The development of a Rapid Evaluation Framework (REF; Model Benchmarking TT<sup>35</sup>) includes a minimum set of diagnostics that will ensure a minimum scientific quality of datasets within the AR7 Fast Track. The REF will utilise validation methods from different community evaluation frameworks such as ESMValtool (see section 2.3.4), PCMDI Metrics Package<sup>36</sup> (Lee et al., 2024) and International Land Model Benchmarking<sup>37</sup> (ILAMB, Collier et al., 2018).

Efforts to develop a modular community QC2 checker tool are ongoing. QC2 application has moved towards the modelling centres or, in case of CMIP6, has been restricted to the most relevant data subsets in C3S-CDS CMIP6. QC3 remains largely repository/project and purpose specific. The QC3 applied to the subset of the CMIP6 input data used within the IPCC WGI AR6, which is long-term preserved in the IPCC Data Distribution Centre (DDC), has been extended by a quality control of the CMIP6 data use information provided by the WGI AR6 authors. For transparency, the applied scripts for metadata corrections have been made available in the official GitHub repository for IPCC WGI<sup>38</sup> (Stockhause et al., 2023). FAIR checker tools are applied to sample data in the archives to guide implementations for improved data FAIRness but they have not (yet) become part of the technical quality control of individual datasets.

The C3S-CDS CMIP6 data subset are subject to the C3S-CDS Evaluation and Quality Control framework<sup>39</sup> (see section 2.2.3), which includes an independent assessment. This scientific evaluation of selected datasets and regions extends the technical CMIP QC framework and was applied to CMIP6 and CORDEX climate projections in the CDS<sup>40</sup>.

### 3.4.2 ESMValtool

A community-developed, open-source software package for Earth System Model (ESM) data evaluation is ESMValTool<sup>41</sup> (Eyring et al., 2020) developed by the ESMValGroup consortium<sup>42</sup>, which was used for contributions to several chapters of the IPCC WGI AR6 for some of the analyses and figure creations. The software aims at raising the standard for model evaluation by providing well-documented source code, scientific background documentation of the diagnostics and metrics included, as well as a detailed description of the technical infrastructure. One of the goals of the ESMValTool development is to provide a mature and fast benchmarking and evaluation framework that produces well-established analyses as soon as model output from CMIP simulations becomes available.

The ESMValTool framework consists of two components: ESMValCore and ESMValTool. ESMValCore provides core functionalities commonly used in climate science that are available to all diagnostics such as horizontal and vertical regridding, masking of missing values across different datasets, or computation of multi-model statistics. These pre-processing functionalities can be applied to CMIP-style data from Earth system models, but also to observation and reanalysis datasets. ESMValTool is a

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<sup>34</sup> <https://wcrp-cmip.org/cmip7-task-teams/data-citation/>

<sup>35</sup> <https://wcrp-cmip.org/cmip7-task-teams/model-benchmarking/>

<sup>36</sup> [https://github.com/PCMDI/pcmdi\\_metrics](https://github.com/PCMDI/pcmdi_metrics)

<sup>37</sup> <https://ilamb.org/>

<sup>38</sup> <https://github.com/IPCC-WG1/DDC-AR6-CMIP6-Data-Archival>

<sup>39</sup> <https://climate.copernicus.eu/quality-assurance-climate-data-store>

<sup>40</sup> <https://confluence.ecmwf.int/display/CKB/Evaluation+of+CDS+climate+projections>

<sup>41</sup> <https://docs.esmvaltool.org>

<sup>42</sup> <https://github.com/ESMValGroup>

collection of diagnostic and metric packages that has initially been designed to process and analyse the output from CMIP models, but has been extended to also provide the capability to compare different observation and reanalysis datasets, and work with observational uncertainties. All processing steps from ESMValCore and ESMValTool are saved in a provenance record. With the split into two different components, the pre-processing operations and software design, written and maintained by software developers, are clearly separated from the actual content evaluation methods developed by the research community.

The ESMValGroup is overseen by a Steering Group supported by a science, a technical, and a user engagement team. The implementation of new features is reviewed by the scientific team focussing on the relevance for the larger scientific community and by the technical team checking the conformance with the technical guidelines and ensuring the software design is not unnecessarily changed<sup>43</sup>. This code review process ensures all code and documentation contributions are of good quality. The user engagement team creates and maintains the content and structure of the tutorial episodes<sup>44</sup> that are available online for new users to get familiar with ESMValTool.

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<sup>43</sup> <https://docs.esmvaltool.org/en/latest/community/review.html#>

<sup>44</sup> <https://tutorial.esmvaltool.org/>

## 4 Communication of quality assessment, control and assurance

Regarding the reporting of quality and verification results, ISO 19157 *Geographic information - Data quality* provides a comprehensive workflow. Here, we include some relevant points and for further information we refer the reader to the original document. For consistency, in this section we follow the verbal forms used in ISO standards for “shall”, “should”, “may” and “can”<sup>45</sup>.

### Data quality reporting ...

#### Why?

- To facilitate the discovery and utilisation of the dataset, it is crucial to showcase its adherence to data product specifications and user requirements. Additionally, demonstrating compliance allows for informed assessments of the quality of information derived from the dataset, enabling rational and optimal decision-making despite inherent data imperfections.

#### When?

- Changes in data, such as deletions, modifications, or additions, must be tracked. It's also important to note when a dataset's product specification is altered or new user-defined quality requirements emerge. Additionally, adjustments shall be made to reflect changes in the real world.

#### How?

- Data quality shall be reported as metadata with the optional addition of a standalone human readable quality report for providing details. Metadata provides synthetic and structured information which increases interoperability and can lead to automatisisation. When both methods are used, the metadata should include a reference to the quality report. As suggested in Climateurope2 deliverables D2.1 (Stockhause et al., 2024) and D2.2 (Spinuso et al., 2024), it is recommended to use Persistent IDentifiers (PIDs) to reference the quality report inside the metadata.
- Following the principle of the hierarchical level, data quality specified at upper level is applicable to lower levels.
- A data quality unit includes data quality elements and the corresponding scope. In turn, a data quality element shall include a measure, evaluation methods, and the corresponding results. In order to increase comparability between quality reports, the utilisation of standardised quality measures is encouraged.
- Metaquality elements can be added to provide an assessment of a quality evaluation and its result. Metaquality elements also contain a measure, evaluate and result.
- The dates when the evaluations were carried should be specified.

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<sup>45</sup> <https://www.iso.org/ISO-house-style.html>

## 5 Gaps, challenges and opportunities

This section provides an overview of a pilot implementation of quality branding within the AtMoDat project and a feasibility study of quality mapping within the DestinationEarth project.

### 5.1 EASYDAB/AtMoDat standards

Within the project "AtMoDat"<sup>46</sup>, a pilot implementation for quality branding of Earth System data was developed. It consists of the Earth System Data Branding<sup>47</sup> (EASYDAB; Ganske et al., 2022) hosted by the Technische Informationsbibliothek (Technical Information Library, TIB) and a quality guideline for atmospheric model data, which was developed by the World Data Center for Climate (WDCC). Use of the EASYDAB label is coupled to an agreement with TIB, which among other things involves meeting a set of generic requirements. How these generic requirements are to be implemented for any specific dataset have to be detailed in quality guidelines drawn up by the dataset repository. However, EASYDAB does not perform formal assessment of the content of these guidelines as part of its approval process. The repositories commit to labelling only those datasets of their data holdings with the EASYDAB label, for which the approved quality guideline has been applied. EASYDAB aims to allow repositories to demonstrate their engagement for data curation including high quality metadata.

The aim of EASYDAB is to provide a trusted label for high-quality Earth System data. Becoming such a trusted label requires a community engagement process and transparent procedures for approving repository policies and for applying these policies to the labelled data. The foundation of an international organisation similar to the DataCite experience might be required to enable the uptake by other nations.

The approved quality guideline AtMoDat (Ganske et al., 2021) as part of the pilot implementation utilises the quality control level 3 developed for CMIP5 (see section 2.x above). The AtMoDat guideline additionally includes the quality control of the repository's DataCite DOI implementation (landing page contents comply with DataCite recommendations) and data FAIRness, which is controlled via the application of the automated FAIR quality control tool F-UJI<sup>48</sup> (Devaraju et al., 2022) on the DOI landing page. It describes the high-quality control procedure applied by the WDCC on parts of its data holdings. Separating the dataset quality checks from the repository infrastructure (landing page) checks would enable a wider application of an EASYDAB-approved quality guideline for datasets from the atmospheric or even Earth System modelling community and open the chance for it to become a community-recognised standard for high-quality data. For the EASYDAB label to be meaningful, "high-quality" data needs to be clearly defined, commonly understood and acknowledged by the Earth System community. In particular, the limitation of high quality to technical quality control without scientific quality control or evaluation needs to be clearly expressed. As an alternative to labelling as high quality or not, labelling as a set of quality levels could be considered to solve the absoluteness problem of the high (technical) data quality of the EASYDAB-labeled data.

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<sup>46</sup> <https://www.atmodat.de/>

<sup>47</sup> <https://www.easydab.de/>

<sup>48</sup> <https://fairsfair.eu/f-ujj-automated-fair-data-assessment-tool>

## 5.2 Quality Mapping for Destination Earth

Destination Earth is a European Union initiative aimed at creating a digital twin of the Earth to model and simulate natural and human activities, with the objective of improving environmental predictions, supporting sustainable development, and informing policy decisions on climate change. In 2022, Dr. Philip Heinisch published a report on the feasibility of Quality Mapping in the context of the Destination Earth initiative.

The objective of Quality Mapping is to bridge the gap between expert-based uncertainty and the need for policymakers and decision-makers to clearly and definitively assess the actionability of scientific findings. The initially proposed method includes providing an actionability index in addition to regular quality reports, which would be derived automatically and transparently using reproducible mapping processes that translate quality information into a set of quality/actionability indices.

The study identified the following challenges in implementing an automatic and general Quality Mapping:

- Actionability and the definition of “what is good enough” for decision support is not static and requires constant revision and co-production between providers and users.
- The choice of quality indicators and reporting language is context-dependent. Uncertainty and quality indicators can be hard to interpret by non-experts, and thus block decision-making. In fact, these can sometimes be interpreted differently, which highlights the importance of being user-aware when communicating these results.
- There is no clear benefit to current adaptation and mitigation models; in fact, it could be detrimental if quality metrics are condensed too early.
- Both climate and socio-economic data should be considered.

## 5.3 Use of Artificial Intelligence in climate services provision

One of the challenges faced by climate services is the communication between service providers and stakeholders, largely due to the varied experience and knowledge of the latter. To address this, some groups are advocating for the use of Artificial Intelligence, particularly the development of chatbots based on Large Language Models (LLMs), to offer a more tailored experience (Dee et al., 2024). While the development of these chatbots is expected to progress over the next two years, and we plan to present a new perspective in the next iteration of this deliverable, Deliverable D2.9, several key questions remain unanswered. These questions were identified during a conversation with Dr. Fai Fung from the MetOffice and include:

- How can the quality of generated answers be measured?
- How should human cognitive aspects, particularly in interpreting responses, be factored into answer generation?
- Who is responsible for encoding such decisions?
- How should the final answer be represented?
- To what extent can the user influence the generated response?
- What are the limitations of these chatbots in terms of extrapolation?
- Do we have sufficient data to build a trustworthy chatbot?
- How will issues such as hallucinations be addressed?
- Is the cost of developing and maintaining these chatbots sustainable?

## 6 Conclusions

The main findings of this report are as follows:

- **FAIR Principles:** Tools with both quantitative and qualitative assessment outputs are already available to achieve compliance with FAIR principles.
- **WMO Extensive Documentation:** WMO offers comprehensive documentation to support the development of robust Quality Management Systems. In the present report we have introduced a navigation system that links important aspects of climate services with the relevant documentation provided by WMO. The identified aspects are: data source selection, acquisition and validation; data processing; quality control; data storage and distribution; user feedback; and continuous improvement. In addition, as part of capacity building, WMO offers periodic workshops to train officially recognised experts on WMO and ISO compliance.
- **ISO standards:** As shown in the Appendix, the landscape of ISO standards is also very broad and covers many aspects related to climate services. Specially important are the following families: 9000 - Quality Management, 25000 Software Product Quality Requirements and Evaluation, 19100 Geographic Information and 14000 Environmental Management.
- **Community-Developed Vocabulary, Tools, Formats, and Metrics:** These resources help ensure the use of verified workflows, enhance comparability, improve transparency, and enable task automation. Important conventions already exist in the community, like the *Climate and Forecast Convention*, which helps homogenise vocabulary and format.
- **Quality Communication:** As summarised in Section 4, *ISO 19157 Geographic Information - Data Quality* appears to be the current primary standard, and is also considered by WMO.

Challenges:

- **Context-Dependent QC/QA Workflows:** As demonstrated by the variety of services discussed in this report, QC/QA workflows are dependent on the specific service. This is expected, as each service has different quality requirements, users, and infrastructure, leading to the adoption of different workflows. Unfortunately, the diversity of services and workflows challenges the comparability of services and hinders the establishment of absolute quality scales.
- **Granularity of Quality Reporting:** The content and format of quality reports is influenced by the users of the service, making it difficult to find a one-size-fits-all approach. Periodic user feedback is crucial to adapt reporting to meet user needs.
- **Navigating the Documentation:** The extensive list of standards and guidelines provided in the [Appendix](#) highlights the challenge of navigating these documents, especially for new community members. This challenge is compounded by the fact that the documentation is maintained by different entities, is not centralised, contains redundancies, and is often interlinked, making full compliance more difficult.
- **Time evolution:** With time many of the previously mentioned aspects evolve, like vocabulary, formats, documentation, service needs, etc.
- **Customised, fit-for-purpose information generated by AI-trained chatbots:** These chatbots are gaining attention for their potential to democratise information. However, as discussed in Section 5.3, many questions remain unanswered regarding their training and reliability.

Regarding the first two challenges, they highlight the importance of ensuring that standards are flexible while still promoting agreement, reproducibility, efficiency, comparability, and trust. This is not a trivial task, but it is crucial to ensure that a set of directives can be adopted by as many organizations as possible. The current combination of general standards provided by ISO,

meteorological guidelines from the WMO and community conventions is an example of such a compromise.

As for the time evolution challenge, the key to managing extensive documentation and the evolving aspects of climate services may lie in continuous and frequent capacity building. Only through proper education and training can an organization keep pace with the advancements made by the climate services community.

For the follow-up version of this deliverable, specifically deliverable D2.9, efforts will focus on two key areas: first, monitoring the development of AI-generated information through chatbots, and second, enhancing information exchange with the community, particularly with the aim of gathering insights from the private sector. In the current deliverable, a survey<sup>49</sup> was designed to collect information about quality verification and related standards, but only a few responses were received. Consequently, WP2 partners have decided that in the next phase, more emphasis should be placed on alternative approaches, such as interviews. Although interviews may be slower in reaching a large number of people compared to surveys, they can lead to richer interactions and, therefore, a more fruitful exchange of ideas.

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<sup>49</sup> <https://ec.europa.eu/eusurvey/runner/CE2WP2VerificationOfDataAndProcessQuality>

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# Appendix

## Landscape of existing standards and guidelines about quality and verification

List of ISO standards:

- ISO 9000 family - Quality Management
  - ISO 9000:2015 Quality management systems - Fundamentals and vocabulary
  - ISO 9001:2015 Quality management systems - Requirements
  - ISO 9004:2018 Quality management - Quality of an organization - Guidance to achieve sustained success
- ISO/IEC 25000 family Software engineering - Software product Quality Requirements and Evaluation (SQuaRE)
- ISO 19100 family - Geographic information
  - ISO 19115:2014 Geographic information – Metadata
  - ISO 19157:2013 Geographic information – Data quality
  - ISO 19158:2012 Geographic information – Quality assurance of data supply
  - ISO 19131:2022 Geographic information - Data product specifications
- ISO 14000 family - Environmental management
  - ISO 14001:2015 Environmental management systems – Requirements with guidance for use
  - ISO 14090:2019 Adaptation to climate change – Principles, requirements, and guidelines
  - ISO 14091:2021 Adaptation to climate change – Guidelines on vulnerability, impacts and risk assessment
- ISO 10000 standards
  - ISO 10005:2018 - Quality management – Guidelines for quality plans
  - ISO 10012:2003 - Measurement management systems – Requirements for measurement processes and measuring equipment
  - ISO 10013:2021 - Guidelines for Quality management systems – Guidance for documented information
- ISO/IEC 17025:2017 - General requirements for the competence of testing and calibration laboratories
- ISO/IEC/IEEE 29119 series Software and systems engineering – Software testing
- ISO/IEC 12207:2017 Systems and software engineering – Software life cycle processes
- ISO/IEC 33000 family - Process assessment

Other standards:

- Open Geospatial Consortium<sup>50</sup> standards.

WMO Guidelines:

- WMO No. 8: Guide to Instruments and Methods of Observation
- WMO No. 49: Technical Regulations

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<sup>50</sup> <https://www.ogc.org/standards/>

- **WMO No. 100:** Guide to Climatological Practices
- **WMO No. 305:** Manual on the Global Data-Processing and Forecasting System (GDPFS)
- **WMO No. 306:** Manual on Codes
- **WMO No. 488:** Guide to the Global Observing System
- **WMO No. 1025:** Manual on Codes – International Codes
- **WMO No. 1083:** Manual on the Global Data-Processing and Forecasting System (GDPFS)
- **WMO No. 1100:** Guide to the Implementation of Quality Management Systems for National Meteorological and Hydrological Services and Other Relevant Service Providers
- **WMO-No. 1112:** WMO Strategy for Service Delivery
- **WMO No. 1131:** Climate Data Management Specifications (CDMS)
- **WMO No. 1143:** Quality Management Framework (QMF) for WMO
- **WMO No. 1157:** WMO Information System (WIS) Manual
- **WMO No. 1165:** Manual on the WMO Integrated Global Observing System (WIGOS)
- **WMO-No. 1181:** WMO Guidelines on Validation of Satellite-Derived Climate Data Records
- **WMO-No. 1185:** Guide to the Direct Broadcast Network for Near-real-time Relay of Low Earth Orbit Satellite Data
- **WMO No. 1194:** Guidelines on the Role, Operation, and Management of National Meteorological or Hydrometeorological Services
- **WMO-No. 1203:** Guide to the WMO Information System (WIS)
- **WMO No. 1209:** Competency Framework for the Provision of Climate Services
- **WMO No. 1221:** Guidelines on Quality Management in Climate Services
- **WMO No. 1238:** Manual on the High-quality Global Data Management Framework for Climate (HQ-GDMFC)
- **WMO No. 1269:** Guidelines on Surface Station Data Quality Control and Quality Assurance for Climate Applications
- **WMO No. 1285:** Guidelines for the Assessment of Competencies for Provision of Climate Services
- **WMO-TD No. 1376:** Guidelines on Climate Data Management

Other guidelines:

- **QA4EO:** GEOSS Quality Assurance Framework for Earth Observation
- **FAIR principles:** A guideline to improve the Findability, Accessibility, Interoperability, and Reuse of digital assets.

## WMO document description

### WMO No. 8: Guide to Instruments and Methods of Observation

This guide provides comprehensive standards and best practices for the measurement, observation, and reporting of meteorological and other environmental data. It includes information on the calibration, validation, and recognition of data sources and instruments, ensuring they meet WMO standards.

### WMO No. 49: Technical Regulations

This publication outlines the regulatory framework for global meteorological activities, including the standards and practices for the recognition and use of data sources in meteorology and climatology.

### WMO No. 100: Guide to Climatological Practices

This publication covers the principles and practices of climatology, including the collection, processing, and dissemination of climatological data. It addresses the recognition and certification of data sources to ensure the quality and consistency of climate data.

#### **WMO No. 305: Manual on the Global Data-Processing and Forecasting System (GDPFS)**

This manual provides guidelines for the operation of the Global Data-Processing and Forecasting System, which processes data for weather forecasting and other applications. It includes protocols for the validation of data used in forecasting, ensuring that only accurate and reliable data is utilized in operational models.

#### **WMO No. 306: Manual on Codes**

This manual provides standardized codes for the representation and exchange of meteorological, hydrological, and other environmental data. Accurate data source recognition is essential for ensuring that the coded data is correctly interpreted and used.

#### **WMO No. 488: Guide to the Global Observing System**

This guide provides information on the design, operation, and maintenance of observing systems that contribute data to the Global Observing System (GOS). It emphasizes the importance of standardized data sources for global data exchange.

#### **WMO No. 1025: Manual on Codes – International Codes**

This manual provides standardized codes for the representation and exchange of meteorological and related data. It includes guidelines for the validation of data as it is encoded, ensuring that the data is correctly formatted and free of errors before it is transmitted or used.

#### **WMO No. 1083: Manual on the Global Data-Processing and Forecasting System (GDPFS)**

This manual provides guidelines for the operation of the GDPFS, which processes and uses data for forecasting and other applications. It includes provisions for user feedback on the accuracy and reliability of forecasting products, ensuring that the GDPFS adapts to meet the needs of its users.

#### **WMO No. 1100: Guide to the Implementation of a Quality Management System for National Meteorological and Hydrological Services**

This guide provides detailed instructions on establishing and maintaining a Quality Management System (QMS) within NMHSs. It outlines the processes for collecting and analyzing user feedback as part of the QMS, ensuring that services are continuously improved based on user reviews and satisfaction.

#### **WMO-No. 1112: WMO Strategy for Service Delivery**

This strategy document outlines the WMO's approach to delivering high-quality services that meet the needs of its users. It places strong emphasis on user engagement, feedback mechanisms, and the continuous review of services to ensure that they are user-focused and responsive to evolving needs.

#### **WMO No. 1143: Quality Management Framework (QMF) for WMO**

This publication focuses on the quality management principles and guidelines applicable to all WMO activities and services. It provides a comprehensive framework for implementing quality control and

quality assurance processes within WMO-related activities, ensuring that all services adhere to high-quality standards.

#### **WMO No. 1157: WMO Information System (WIS) Manual**

This manual provides operational details and standards for the implementation and management of the WMO Information System (WIS). It focuses on the practical aspects of data distribution within the WIS, including secure data exchange protocols, metadata standards, and the reliability of data dissemination services.

#### **WMO No. 1165: Manual on the WMO Integrated Global Observing System (WIGOS)**

This manual provides the regulatory framework for WIGOS, which integrates all WMO observing systems. It includes standards and procedures for data validation across different observing systems, ensuring that data is accurate, consistent, and comparable.

#### **WMO-No. 1181: WMO Guidelines on Validation of Satellite-Derived Climate Data Records**

This publication provides guidelines specific to the validation and processing of climate data records derived from satellite observations. It focuses on the methodologies for processing satellite data to ensure that it meets WMO standards for accuracy and reliability, particularly in climate monitoring.

#### **WMO-No. 1185: Guide to the Direct Broadcast Network for Near-real-time Relay of Low Earth Orbit Satellite Data**

This publication provides guidelines on observation networks and systems for ensuring that the data collected are adequate for the needs of climate services, applications and research, based on the 10 Global Climate Observing System (GCOS) principles for climate monitoring.

#### **WMO No. 1194: Guidelines on the Role, Operation, and Management of National Meteorological or Hydrometeorological Services**

This publication provides guidelines on the effective management and operation of NMHSs. It emphasizes the importance of user engagement, including the collection and review of feedback to continuously improve the services provided by NMHSs.

#### **WMO-No. 1203: Guide to the WMO Information System (WIS)**

This guide explains how data is exchanged globally within the WMO community, including standards for data source recognition and metadata, ensuring data traceability and reliability.

#### **WMO No. 1209: Competency Framework for the Provision of Climate Services**

This framework provides guidance on the skills and competencies required for delivering high-quality climate services. It supports continuous improvement by encouraging ongoing professional development, regular skills assessments, and the adaptation of services to incorporate the latest scientific advancements and user needs.

#### **WMO No. 1238: Manual on the High-quality Global Data Management Framework for Climate (HQ-GDMFC)**

The Framework establishes standards and recommended practices for sourcing, securing, managing, assessing, and cataloguing climate data, and for sharing infrastructure and responsibilities for, for

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example, data exchange, analysis and data service provision. In this way HQ-GDMFC provides a robust data foundation for the generation of climate products and the delivery of climate services. This manual provides guidance and requirements on the development, provision, exchange and maintenance of high-quality climate datasets. The standards and recommended practices it describes are intended to ensure that the data made available for climate assessment, monitoring, applications and related services meet sustainably a minimum set of requirements with regard to quality, governance, accessibility and usability.

## WMO No. 1269: Guidelines on Surface Station Data Quality Control and Quality Assurance for Climate Applications

This document focuses on the processes for maintaining a satisfactory level of quality in a data set or data collection so that the data available to potential users are sufficiently reliable and complete and can be used with confidence. It provides a relatively high-level overview of the principles underpinning the effective quality assurance (QA) of climate data as well as considerations for the operational QA and quality control (QC) of meteorological data from surface observing stations at various stages of the data life cycle.

## WMO decision trees and key indicators

### Data source

Decision tree:

- **Is the data source recognized by WMO?**
  - **Yes**: Proceed to data acquisition.
  - **No**: Evaluate the credibility and reliability of the source.
- **Is the source peer-reviewed or widely accepted in the scientific community?**
  - **Yes**: Proceed with caution, implement additional validation.
  - **No**: Do not use the source.

Key indicators of WMO-recognized data sources:

- **Official WMO Platforms**: Check if the data is published or referenced on official WMO websites, bulletins, or reports. WMO regularly publishes climate data, weather reports, and other relevant information.
- **WMO-endorsed Databases**: Data from sources that are endorsed by or partnered with the WMO, such as the Global Climate Observing System (GCOS), the World Weather Watch (WWW), or the WMO Information System (WIS), are recognized by the WMO.
- **National Meteorological and Hydrological Services (NMHSs)**: Data provided by NMHSs of member states is usually recognized by the WMO since these services operate under WMO standards and guidelines.
- **International Collaborative Projects**: Data from international projects or programs under the WMO's purview, such as the Global Atmospheric Watch (GAW) or the Global Framework for Climate Services (GFCS), are WMO-recognized.

- **WMO Programs:** Participation in WMO programs or initiatives often means the data produced is recognized by the WMO. Examples include the WMO Integrated Global Observing System (WIGOS) and the WMO Regional Climate Centres (RCCs).
- **WMO Data Portals:** Data available through WMO's official data portals like the WMO Data Repository or linked through the WMO Information System (WIS) is recognized.
- **Partner Organisations:** Data shared by WMO partner organisations such as the United Nations (UN), World Health Organization (WHO), or the Intergovernmental Panel on Climate Change (IPCC) also typically carries WMO recognition.
- **Peer-reviewed Publications:** If the data is used in peer-reviewed studies or reports endorsed by the WMO, it is likely recognized.

One can also directly contact the WMO or relevant NMHSs to confirm if specific data is recognized or endorsed by the organisation.

## Data acquisition

Decision tree:

- **Is the data acquisition process standardised according to WMO guidelines?**
  - **Yes**: Proceed to data validation.
  - **No**: Standardise the data acquisition process.
  - **Can the process be standardised?**
    - **Yes**: Standardise and proceed to data validation.
- **No**: Consider alternative data sources.

Key Indicators of data acquisition in compliance with WMO:

- **Standardised Instruments**: Data obtained from instruments calibrated according to WMO specifications.
- **Data Formats**: Usage of WMO-approved formats (e.g., Binary Universal Form for the Representation of meteorological data [BUFR], General Regularly-distributed Information in Binary form [GRIB]).
- **Observation Practices**: Observation intervals and methods following WMO recommendations.
- **Participation in Global Networks**: Alignment with global initiatives such as the Global Climate Observing System (GCOS) or World Weather Watch (WWW).

## Data validation

**Purpose:** Data quality control goes beyond validation and involves ongoing monitoring, reviewing, and correcting data to ensure its accuracy, consistency, and reliability over time. Quality control encompasses both the validation of incoming data and the subsequent handling of data anomalies, errors, or inconsistencies.

**Scope:** Quality control includes procedures such as detecting outliers, checking consistency between different datasets (e.g., comparing temperature and humidity readings), identifying trends that suggest systematic errors, and applying corrections if necessary.

**Process:** It can involve both automated checks and manual inspections by experts. This step often includes historical comparison (e.g., comparing current observations with long-term climatological records) and the use of statistical techniques to identify and correct data anomalies. QC ensures that the data remains high-quality throughout its lifecycle.

Decision tree:

- **Is there a protocol for data validation?**
  - **Yes:** Apply the protocol.
  - **No:** Develop a validation protocol.
  - **Is the validation protocol in line with WMO standards?**
    - **Yes:** Proceed to data processing.
    - **No:** Revise the protocol to align with WMO standards.

Key Indicators of WMO-Compliant Data Validation Protocol:

- **Automated and Manual Quality Control:** Ensuring that both types of quality control measures are in place, including:
  - **Range Checks:** Verifying that data fall within expected minimum and maximum values.
  - **Consistency Checks:** Checking consistency between related variables (e.g., temperature and humidity).
  - **Spike Detection:** Identifying sudden and unrealistic changes in data values.
  - **Duplicate Data:** Ensuring no duplication of data points.
- **Compliance with Metadata Standards:** Ensuring complete and accurate metadata (e.g., instrument type, calibration data, observational methods) for all datasets.
- **Standardised Validation Procedures:** Following WMO guidelines for specific checks like range, consistency, and homogeneity tests.
- **Use of WMO Flagging Systems:** Implementing WMO-approved codes and flags for data validation status.
- **Audit and Certification:** Validation by a recognized authority or alignment with internationally recognized WMO-compliant systems (e.g. GCOS [Global Climate Observing System], Global Atmosphere Watch [GAW] quality assurance protocols).

## Data processing

Decision tree:

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- **Are the processing methodologies consistent with WMO guidelines?**
  - **Yes**: Proceed with processing.
  - **No**: Adjust methodologies to align with WMO guidelines.
  - **Can the methodologies be adjusted?**
    - **Yes**: Adjust and proceed with processing.
    - **No**: Review the need for the data source or methodology.

#### Key Indicators of WMO-Compliant Processing Methodologies:

- **Accurate and Precise Processing**: Ensures no loss of data integrity, accuracy meets WMO standards.
- **Consistency Over Time**: Processing methodologies ensure long-term comparability of datasets.
- **Homogenization Procedures**: Adjustments for non-climatic factors are in line with WMO practices.
- **Quality Control Integration**: Quality checks are incorporated into each stage of data processing.
- **Transparency and Documentation**: Every processing step is documented, with clear metadata following WMO standards.
- **Error Handling and Flagging**: Procedures for identifying and flagging errors are WMO-compliant.

## Quality control

**Purpose:** Data quality control goes beyond validation and involves ongoing monitoring, reviewing, and correcting data to ensure its accuracy, consistency, and reliability over time. Quality control encompasses both the validation of incoming data and the subsequent handling of data anomalies, errors, or inconsistencies.

**Scope:** Quality control includes procedures such as detecting outliers, checking consistency between different datasets (e.g., comparing temperature and humidity readings), identifying trends that suggest systematic errors, and applying corrections if necessary.

**Process:** It can involve both automated checks and manual inspections by experts. This step often includes historical comparison (e.g., comparing current observations with long-term climatological records) and the use of statistical techniques to identify and correct data anomalies. QC ensures that the data remains high-quality throughout its lifecycle.

Decision tree:

- **Is there an established quality control (QC) framework?**
  - **Yes:** Implement QC checks.
  - **No:** Develop a QC framework.
- **Is the QC framework comprehensive and WMO-compliant?**
  - **Yes:** Proceed with QC checks.
  - **No:** Revise QC framework.

Key Indicators of a WMO-Compliant QC Framework:

- **Automated and Manual QC Processes:** Integration of both real-time and post-processing checks, with standardized data flagging, including:
  - **Range Checks:** Data values are checked against predefined minimum and maximum thresholds to ensure they fall within physically reasonable limits.
  - **Internal Consistency Checks:** Relationships between different variables are verified for consistency (e.g., temperature and dew point, wind speed and direction).
  - **Temporal Consistency:** Ensuring that changes in data over time (e.g., sudden jumps or spikes) are realistic.
  - **Spatial Consistency:** Data from nearby stations are compared to detect inconsistencies or anomalies.
- **Multi-Level QC:** Applying basic to advanced checks, with cross-referencing against historical data. For example:
  - **Level 0:** Raw data is checked for basic completeness and format compliance.
  - **Level 1:** Automated and manual checks ensure data falls within acceptable ranges and is consistent across variables.
  - **Level 2 and above:** More complex checks, such as advanced statistical analysis, homogenization, and adjustments for known biases, are applied.
- **Comprehensive Metadata Management:** Full documentation of all QC processes, data sources, and adjustments.

- **Calibration and Maintenance Protocols:** Regular instrument calibration and meticulous maintenance records.
- **Homogenization and Adjustment:** Procedures to ensure data homogeneity and correction of non-climatic biases.
- **Continuous Feedback and Improvement:** Regular audits, peer reviews, and improvements based on QC outcomes.

## Data storage

Decision tree:

- **Is data storage secure and compliant with WMO standards?**
  - **Yes**: Store data.
  - **No**: Update storage protocols.
  - **Can storage protocols be updated?**
    - **Yes**: Update and store data.
    - **No**: Consider alternative storage solutions.

Key Indicators of Secure and WMO-Compliant Data Storage:

- **Data Integrity**: Systems to prevent corruption and unauthorised alterations, with version control and validation against WMO standards.
- **Access Control and Security**: Strong encryption, role-based access control, and robust authentication mechanisms.
- **Redundancy and Backups**: Regular backups, redundancy across multiple locations, and a tested disaster recovery plan.
- **Metadata Compliance**: Comprehensive metadata management in line with WMO standards.
- **Retention and Archiving**: Long-term storage and data retention policies that comply with WMO guidelines.
- **Compliance with International Standards**: Adherence to ISO standards and WMO regulations.
- **Scalability and Performance**: Systems designed for large data volumes with regular performance monitoring.
- **Accessibility and Interoperability**: Standardised access protocols and compatibility with WMO and global data-sharing networks.
- **Data Protection and Legal Compliance**: Compliance with relevant data protection laws and ethical guidelines.
- **Governance and Regular Audits**: A strong governance framework, with regular security audits and staff training.

## Data distribution

Decision tree:

- Are data distribution methods secure and reliable?
  - **Yes**: Distribute data.
  - **No**: Improve distribution methods.
  - **Can distribution methods be improved?**
    - **Yes**: Improve and distribute.
    - **No**: Review alternative distribution strategies.

Key Features of WMO-Compliant Data Distribution Systems:

- **Security Protocols**: Systems must use secure communication protocols (e.g., HTTPS, FTPS, VPNs) and encryption (e.g., SSL/TLS) to protect data in transit and at rest.
- **Standardised Data Formats**: Data must be distributed in WMO-approved formats such as Binary Universal Form for the Representation of meteorological data (BUFR), General Regularly-distributed Information in Binary form (GRIB), or NetCDF to ensure interoperability.
- **High Availability and Redundancy**: Systems must include redundancy and failover mechanisms to ensure uninterrupted data distribution, even in case of infrastructure failures.
- **Real-Time and Non-Real-Time Capabilities**: Systems should support both real-time data distribution (for operational forecasting) and non-real-time data (for research and historical analysis).
- **Compliance with WMO Guidelines**: Systems must adhere to WMO Technical Regulations, including WMO-No. 49, which governs data sharing and transmission protocols.
- **Metadata and Documentation**: Data must be accompanied by comprehensive metadata in line with WMO standards, ensuring transparency and traceability of data products.
- **User Access Control**: Role-based access control (RBAC) and authentication mechanisms should be in place to ensure that only authorised users can access sensitive data.

## User feedback and review

Decision tree:

- **Is there a mechanism for user feedback and review?**
- **Yes**: Collect feedback and conduct reviews regularly.
- **No**: Establish a feedback and review mechanism.
- **Is the feedback mechanism effective?**
  - **Yes**: Use feedback to improve data services.
  - **No**: Revise the feedback mechanism.

Key indicators of WMO-compliant user feedback and review mechanisms:

- **Accessibility of Feedback Channels**
  - **Multiple Communication Channels**: Provide users with various accessible channels for feedback, such as online forms, emails, hotlines, and in-person consultations during workshops or conferences. Channels should be available for both general users and specialised stakeholders like researchers and governmental agencies.
- **Structured and Standardised Feedback Collection**
  - **Standardised Feedback Forms**: Use structured forms or surveys that ask specific questions about the quality, timeliness, and usability of data and services. Standardised forms help in comparing feedback over time and across different user groups.
  - **Categorised Feedback**: Categorise feedback based on aspects such as data accuracy, accessibility, documentation quality, user support, and suggestions for improvements. This enables more efficient analysis and response.
- **Clear Communication of Review and Response Process**
  - **Transparent Process**: Clearly communicate to users how their feedback will be reviewed and addressed. Include timelines for acknowledgment and response, so users know when they can expect to hear back from the data provider.
  - **Feedback Acknowledgment**: Ensure that users receive acknowledgment after submitting feedback, indicating that their input has been received and is being reviewed.
- **Actionable Feedback Implementation**
  - **Feedback Loop Closure**: Ensure that feedback leads to tangible actions and improvements. After implementing changes based on user feedback, communicate those improvements back to the users to close the feedback loop.
- **User Involvement in Decision-Making**
  - **User Committees and Advisory Panels/User-centric development**: Involve users in decision-making processes through advisory panels, user committees, or focus groups. These groups can provide ongoing input and help shape the future direction of data services.
- **Comprehensive User Satisfaction Surveys**
  - **Annual or Biennial Surveys**: Conduct comprehensive user satisfaction surveys regularly (e.g., annually or biennially) to gauge overall satisfaction levels with services, data

quality, and support. These surveys should be designed in collaboration with WMO guidelines.

- **Benchmarking and KPIs:** Use key performance indicators (KPIs) from user satisfaction surveys to benchmark performance and track improvements over time.
- Feedback from a Diverse User Base
  - **Inclusive Engagement:** Ensure that feedback mechanisms reach a diverse user base, including national meteorological and hydrological services (NMHSs), international agencies, researchers, private sector users, and the general public. Inclusive engagement ensures that the feedback collected represents the full spectrum of users.
  - **Multi-Language Support:** Provide feedback channels in multiple languages to accommodate users from different regions and linguistic backgrounds.
- Tracking and Reporting on Feedback
  - **Feedback Tracking System:** Implement a tracking system for all feedback received, ensuring that each piece of feedback is logged, categorised, and followed up on. This system should also track the status of responses and any actions taken.
  - **Regular Reporting:** Publish regular reports on feedback received, actions taken, and improvements made. These reports can be shared with users through newsletters, websites, or annual reports.
- Data and Service Performance Metrics
  - **Performance Metrics Review:** Establish and monitor key performance metrics (e.g., data availability, timeliness, and accuracy) based on user feedback. Performance metrics should align with WMO standards and be used to assess and improve service quality.
  - **User-Centred Performance Goals:** Set performance goals that reflect user needs and expectations, ensuring that improvement.
- Stakeholder Workshops and Training Sessions
  - **Workshops and Training:** Regularly organise workshops, training sessions, or webinars where users can provide direct feedback, ask questions, and discuss their needs with data providers. These sessions should encourage interaction and provide opportunities for in-depth discussions.
  - **Feedback on Training:** Gather feedback from users on training and support services to ensure they meet user needs and align with WMO standards.
- Long-Term Relationship Building
  - **Ongoing Engagement:** Establish long-term relationships with users through regular communication and engagement. This helps build trust and ensures that feedback is consistently collected and acted upon over time.
  - **User Conferences and Forums:** Host or participate in user conferences and forums where stakeholders can provide feedback and discuss service improvements with WMO representatives and data providers.

## Continuous improvement

Decision tree:

- **Is there a process for continuous improvement?**
  - **Yes**: Implement ongoing improvements.
  - **No**: Develop a continuous improvement process.
- **Is the process aligned with WMO guidelines?**
- **Yes**: Proceed with continuous improvement.
- **No**: Align the process with WMO guidelines.

Key indicators of WMO-compliant continuous improvement process:

- Regular Performance Assessments
  - **Key Performance Indicators (KPIs)**: Establish and regularly review KPIs to assess performance in areas such as data quality, timeliness, service delivery, and user satisfaction. These KPIs should be in line with WMO standards.
  - **Internal Audits and Self-Assessments**: Conduct periodic internal audits and self-assessments to identify areas for improvement. These assessments should be structured according to WMO recommendations and use standardised criteria.
  - **External Reviews**: Engage in external reviews by independent bodies or WMO audits to verify compliance and identify further opportunities for improvement.
- User Feedback Integration
  - **Structured Feedback Mechanisms**: Collect and analyze user feedback through surveys, forums, and other channels. The feedback should be systematically integrated into the improvement process to address user needs and enhance service quality.
  - **Action on Feedback**: Implement changes based on feedback, and track the effectiveness of these changes. Report back to users on how their feedback has been addressed, closing the feedback loop.
- Ongoing Capacity Development
  - **Training and Professional Development**: Provide ongoing training and capacity development for staff to stay updated with WMO guidelines, emerging technologies, and scientific advancements. This should include both technical and operational training in areas such as data analysis, meteorological modeling, and IT systems.
  - **Collaboration with WMO and International Partners**: Engage in continuous collaboration with WMO, regional meteorological centers, and international partners to share best practices, participate in capacity-building initiatives, and adopt new methodologies.
- Implementation of Best Practices and Lessons Learned
  - **Adoption of Best Practices**: Regularly update processes to reflect best practices identified through WMO guidelines, international standards (such as ISO), and the experiences of other meteorological organizations.
  - **Lessons Learned Integration**: Systematically capture and apply lessons learned from past events, projects, and operational experiences to improve future performance.
- Innovation and Technological Upgrades

- **Adoption of New Technologies:** Continuously evaluate and implement new technologies, such as advancements in remote sensing, data analytics, cloud computing, and artificial intelligence, to improve data collection, processing, and distribution.
- **R&D Investment:** Invest in research and development (R&D) to explore innovative methods for data acquisition, modeling, and forecasting, aligned with WMO initiatives such as the WMO Global Innovation Hub.
- **Proactive Risk Management**
  - **Risk Identification and Mitigation:** Integrate risk management into the continuous improvement process by identifying potential risks (e.g., data breaches, system failures, climate hazards) and developing mitigation strategies. Regularly update risk assessments to reflect changes in technology, user needs, and environmental conditions.
  - **Disaster Recovery and Resilience Planning:** Ensure that disaster recovery and business continuity plans are regularly reviewed and updated, focusing on resilience to ensure service continuity during emergencies.
- **Transparent Reporting and Documentation**
  - **Regular Reporting:** Provide regular reports on performance metrics, user satisfaction, and improvement initiatives to stakeholders, including users, WMO, and national authorities. Transparency in reporting fosters trust and accountability.
  - **Comprehensive Documentation:** Maintain comprehensive and up-to-date documentation of processes, methodologies, and improvements. This ensures that changes are well-documented and can be audited against WMO guidelines.
- **Benchmarking and Peer Comparison**
  - **International Benchmarking:** Regularly compare performance against international benchmarks set by WMO and other leading meteorological organizations. Use peer comparison to identify areas where improvements can be made and adopt best practices from other organizations.
  - **Participation in WMO Benchmarking Initiatives:** Engage in WMO-led benchmarking activities, such as the Global Data-Processing and Forecasting System (GDPPFS), to assess and improve data processing and forecasting capabilities.
- **Stakeholder Engagement and Collaboration**
  - **Engagement with Users and Stakeholders:** Regularly engage with stakeholders, including national meteorological and hydrological services (NMHSs), government agencies, researchers, and the private sector, to gather insights and collaborate on continuous improvement initiatives.
  - **Regional and International Collaboration:** Participate in regional and international collaboration efforts led by WMO, such as regional associations and specialized centers, to stay updated on global best practices and emerging challenges.
- **Strategic Planning and Long-Term Vision**
  - **Long-Term Strategic Planning:** Develop and regularly update a long-term strategic plan that outlines goals for continuous improvement in alignment with WMO's strategic priorities. This plan should be flexible enough to adapt to emerging trends and challenges in meteorology and climate science.
  - **Proactive Anticipation of Future Needs:** Anticipate future user needs, climate challenges, and technological advancements, and incorporate these considerations into the strategic plan. This forward-looking approach ensures that improvements are not just reactive but also proactive.