

GUIDANCE BOOKLET

WMO Stewardship Maturity Matrix for Climate Data (SMM-CD)

The SMM-CD Working Group *

International Expert Group on Climate Data Modernisation (IEG-CDM) **
(formally the Ad hoc Expert Team on Climate Data Modernisation)

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v02r00 20180912	The SMM-CD Working Group	Second baseline of the Matrix and the Guidance Booklet. Added “Uncertainty Analysis” aspect in Quality Management Category. Implemented additional edits. Sections affected: all.
v03r00 20190131	The SSM-CD Working Group	Third baseline of the Guidance Booklet. Modified ‘Definition’ section to reflect definitions of categories and aspects only. Clarified and updated the level definitions for the Data Integrity aspect.
v04r01 20200529	The SSM-CD Working Group	Fourth baseline of the Guidance Booklet corresponding to the 4 th baseline of the SMM-CD which is modified in response to feedback from the team members of IEG-CDM and WMO Expert Team on Data Development and Stewardship (ET-DDS) from the pilot of 18 global climate dataset assessments. Major modifications are made to the Usability & Usage and Quality Management categories. Additional examples based on the pilot assessments are added to Examples/Notes sections.
V04r02 20210409	The WMO SERCOM Expert Team on Data Requirements for Climate Data Services (ET-DRC)	Disclaimer statement was replaced with ‘NOTE: This document aims to facilitate the use of the Stewardship Maturity Matrix for Climate Data (SMM-CD) and will be subject to formal editing and publication as WMO guidelines.’
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NOTE: This document aims to facilitate the use of the Stewardship Maturity Matrix for Climate Data (SMM-CD) and will be subject to formal editing and publication as WMO guidelines.

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Feedback:

Please direct your suggestions to: Ge Peng; gpeng93@gmail.com. The latest unofficial version of this document will be maintained at and can be downloaded from [figshare.com](https://www.figshare.com) with the following persistent digital object identifier (doi): <https://doi.org/10.6084/m9.figshare.7002482>

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1. EXECUTIVE SUMMARY

The World Meteorological Organization (WMO) is a United Nations specialized agency in the field of weather, water and climate. As part of its activities, WMO fosters international collaboration to develop technical guidance and standards for the collection, processing, and management of data and forecast products. Under the technical advice of its Commission for Climatology, WMO has established a High-Quality Global Data Management Framework for Climate (HQ-GDMFC) initiative as an international collaborative initiative for developing standards and recommended practices for sourcing, securing and managing climate data, and for sharing infrastructure and responsibilities for, e.g., data exchange, analysis and data service provision. The goal of the initiative is to ensure mature data management and governance for climate datasets, which follows and builds upon the Global Climate Observing System (GCOS) climate data source reviewing process.

The HQ-GDMFC consists of three building blocks. (1) The Manual on the HQ-GDMFC, which is part of the WMO Regulatory material, and provides regulations and recommended best practice on climate data management, was recently adopted by the Eighteenth World Meteorological Congress (Cg-18), and has been published under WMO-No.1238 (WMO, 2019). (2) The WMO Stewardship Maturity Matrix for Climate Data (SMM-CD) was developed as a tool to enable dataset owners to assess and rate their datasets quantifiably, based on internationally-validated data stewardship best practices. It constitutes a formal annex to the WMO-No.1238, and focuses on datasets that are of global use, such as for global climate monitoring and assessment. The process will help WMO in evaluating the stewardship maturity of the datasets which are to be submitted for inclusion in the third building block. (3) the WMO Catalogue for Climate Data. This catalogue references easily discoverable and accessible high-quality climate datasets that are characterized by well documented methodologies and practices for their creation, management, stewardship and governance. Such a catalogue provides an authoritative and trustworthy source of climate datasets useful for producing information on key climate indicators. Most prominent target users for the catalogue include, but are not limited to, the climate policy community in the context of the Paris Agreement Global Stocktake which is expected to start in 2023. The initial climate datasets cover temperature, precipitation, ice sheets, sea ice, sea level, glaciers, and crowd-sourced data. The data included in the catalogue should be discoverable and accessible in a prominent position through the WMO Information System (WIS) and internet search engines.

The SMM-CD is intended to provide authoritative guidance in relation to the stewardship maturity of those datasets that are to be submitted for inclusion in the WMO Catalogue for Climate Data. Ultimately, the SMM-CD and the catalogue aim at improving the maturity in the management and governance of, and therefore the reliability of, climate datasets worldwide.

The stewardship maturity assessment has started on a global scale. and will be eventually extended to evaluate datasets at a regional and national level. This cascading approach (National, Regional, Global) should emerge in a horizon of few years after the operationalization of the process at the global level.

2. BACKGROUND

The World Meteorological Organization (WMO) is a specialized agency of the United Nations, consisting of members from 192 countries and territories. WMO provides the framework for international cooperation for the development of meteorology, climatology, and operational hydrology so that Member countries can reap the benefits of the mutual collaboration. WMO is the United Nations' authoritative voice on the state and behaviour of the Earth's atmosphere, its interaction with the land and oceans, the weather and climate it produces, and the resulting distribution of water resources, snow and ice.

WMO is committed to facilitating free and unrestricted exchange of meteorological and related data and information, products, and services (e.g., WMO Resolution 40 (Cg-XII), 1995; WMO Resolution 25 (Cg-XIII), 1999; WMO Resolution 60 (Cg-17), 2016). WMO is dedicated to ensuring and providing the highest possible quality of meteorological, climatological, hydrological, and marine information and related environmental data, products and services (WMO, 2017).

There are several challenges regarding climate data that hamper full implementation of high-quality climate services. Among these, much of the existing guidance on climate data management is out of date due to rapid recent advances in technologies. The National Meteorological and Hydrological Services (NMHS) of many Member countries report lack of knowledge and capacity in climate data management and there are significant gaps in stewardship, including a lack of standardization of terminology, processes and practices due to an inadequate regulatory framework. On the positive side, there is an opportunity to make better use of the proliferation of new data sources and advances in technology that can support climate services.

The WMO initiative on the High-Quality Global Data Management Framework for Climate (HQ-GDMFC) was developed to address these changes. It aims at making use of an extended range of environmental data types needed to support the Climate Services Information System (CSIS) of the Global Framework for Climate Services (GFCS). It also aims to harmonize the definitions and processes that deal with climate data, and provide a more rigorous, standards-based regulatory framework around climate data practices. The WMO Executive Council (Abridged final report EC-65) requested to move from a concept to a definition of the HQ-GDMFC (WMO CCI-17, 2018). The Commission for Climatology (CCI)¹ in collaboration with other Technical Commissions submitted in June 2019 a Manual on the High-quality Global Data Management Framework for Climate to the eighteenth session of the WMO Congress, which was formally adopted and officially published as part of the WMO technical regulations (WMO, 2019).

In parallel work, the WMO Workshop on Information Management (WWIM), jointly convened by CCI and the WMO Commission for Basic System (CBS), 4–6 October 2017, included a recommendation for a project plan for identifying high quality climate datasets and providing access to them (WWIM, 2017). A key conclusion was that a process needed to be defined on how datasets can be endorsed by WMO. Essentially, in addition to being high-quality climate data products, it was important that the management of datasets must also meet standards,

¹ The 18th WMO Congress (June 2019) established the restructuring of WMO, including the Commission for Climatology, into the Infrastructure and Application Commissions and a Research Board.

including in particular strong stewardship and governance of the data. It was decided to adopt a Maturity Model approach to quantify the extent to which these standards were met by individual datasets. Subsequently, the WWIM and following CBS Task Team on Information Management (TT-IM) developed a framework for a generic maturity model for information management, intended to be applied to all WMO domains.

An International Expert Group on Climate Data Modernisation (IEG-CDM) was then set up and developed the climate data-specific version of a WMO-wide stewardship maturity assessment model, to be used to consistently assess and score how the individual climate datasets are managed and stewarded.

The key points addressed during the meeting were summarized in a meeting report (WMO IEG-CDM, 2018) and recapitulated below:

- a. Identification of an initial and provisional limited number of climate related datasets which, after proper evaluation, could eventually become part of the WMO Catalogue of Climate Data;
- b. Development of a WMO-wide Stewardship Maturity Matrix for Climate Data (SMM-CD) based on existing maturity assessment models. The SMM-CD assesses and scores various aspects of the management and stewardship of datasets. This model has been subjected to a broad review process, and was road-tested by using it to assess the initial and provisional list of climate datasets identified in (a) above;
- c. Development of a data discovery and access process for the catalogue through the WIS and major internet search engines, by recommending key metadata requirements and methods of optimising internet searches. The aim is that non-technical users can easily discover these high-quality datasets.

3. SCOPE, RATIONALE AND INTENDED AUDIENCE

WMO endorsed datasets need to be of high scientific quality, commencing with well-established and utilized global datasets identified by various scientific domain Subject Matter Experts (SMEs). The process for a dataset to be included into the WMO Catalogue of Climate Data starts with an assessment of the stewardship maturity of the dataset by the data provider.

The assessment is then submitted to WMO and undergoes review by the respective domain SMEs. For example, the Global Climate Observing System (GCOS) has established data sources for key Essential Climate Variables (ECV) based on the expert knowledge and judgement of atmospheric, oceanic, and terrestrial communities. They are curated by the ECV Stewards, who are members of the three GCOS scientific panels (i.e., AOPC, OOPC, and TOPC) and focal points for the respective communities. The selection of the datasets by GCOS is based on five criteria, which have been derived and summarized from the GCOS Monitoring Principles (GCOS-143, 2010), adopted by WMO Resolution 9 (Cg-XIV) (2003) and revised according to the United Nations Framework Convention on Climate Change (UNFCCC, 2007)) and in line with the GCOS Observation Requirements (GCOS-200, 2016). The five criteria are:

- i. Worldwide in coverage
- ii. Free and open access

- iii. Quality controlled with documentation
- iv. Include metadata
- v. Considered and recommended by the appropriate GCOS Science Panel Experts

The GCOS ECV data source review process primarily addresses these five criteria in a non-quantitative way. It considers the maturity levels of observation networks by relying on community expertise. This review process aims to identify the best available data sources for climate variables and to help ensure the science quality of derived climate data products.

The aim of evaluating the stewardship maturity of a climate dataset is in recognition of the fact that the over-all quality of the data received by end users will also be influenced by the quality of data management, stewardship, and services. (See Peng et al. (2018) for a list of quality attributes associated with the science, product, stewardship, and services dimension of data and information quality). Quantitative assessments of how datasets are managed and stewarded are critical in ensuring and improving overall quality and ongoing reliability of individual climate datasets and should be also included in the process for identifying high-quality climate datasets. For example, if data files are corrupted during the data ingest process or during staging for data access without this being noticed because suitable data integrity practices or procedures are lacking, then the quality of the data product obtained by users is compromised.

In contrast to the GCOS ECV data source review process, a maturity matrix approach allows for comparable ratings across all climate variables. While a maturity matrix approach has been used by several organizations, the focus may vary. For example, the NCEI/CICS-NC Data Stewardship Maturity Matrix (DSMM) focuses more on data management aspects (metadata, preservation, accessibility, etc.) (Peng et al., 2015), namely assessing stewardship maturity. The European Core-Climax gives more weight to the product itself (uncertainty, peer-review, availability, etc.) (CORE-CLIMAX, 2015), namely assessing science and product maturity. See Peng (2018) for an overview of maturity models that can be utilized for Earth Science data and products.

The WMO approach concentrates on the data management and stewardship practices employed for the dataset. The SMM-CD was developed to quantify the 11 most important attributes of dataset stewardship, both to ensure the stewardship quality of these climate datasets, and to provide guidance on how to improve dataset stewardship practices. Utilizing the SMM-CD will enable WMO, its Member NMHS and other entities with climate data management responsibilities within the country. Regional Climate Centers and global data and analysis centres, to use a common approach for assessing the stewardship maturity of their datasets independent of the maturity of observation networks.

The following are some of the benefits of utilizing the SMM-CD:

- Divides data management activities into a manageable set of categories and aspects that will help data users identify the most relevant aspects for applications such as climate indicators defined in GCOS-206 (2017);
- Allows members and other relevant entities to assess their data management practices to identify those aspects that would benefit most from process improvement;

- Provides a roadmap and a way of measuring progress towards improving information management capability in support of WMO Programmes;
- Allows Members to identify an appropriate level of process maturity that should be used for the data they are managing;
- Provides a reference model for helping prioritize cost planning, resource allocation and funding for data management
- Allows for a quantitatively measured and consistent way to convey how the WMO endorsed high-quality climate datasets are managed.

4. CATEGORIES, ASPECTS AND MATURITY SCALE STRUCTURE

Eight categories for measuring the stewardship maturity of environmental datasets were initially identified by the WMO TT-IM (WMO EM-CDM, 2018). The SMM-CD Working Group recommended to minimize the number of categories and identified that, for climate data management purposes, four major elements should be highlighted on the SMM-CD, these being designated as the Categories. For each category the Working Group identified two or three sub-categories, these being referred to as “Aspects”. There are 11 rating aspects in total. The IEG-CDM members reviewed and considered this recommendation as foundation for this approach and the scope of the SMM-CD.

In terms of assessing maturity against each Aspect, IEG-CDM adopted the maturity scale levels from the NCEI/CICS-NC scientific data stewardship maturity matrix (DSMM, Peng et al. 2015). These are illustrated in Figure 1.

Figure 1. The maturity scale structure for the WMO-wide Stewardship Maturity Matrix for Climate Data (SMM-CD)

Maturity Scale Levels for Each Aspect				
Level 1	Level 2	Level 3	Level 4	Level 5
AD HOC	MINIMAL	INTERMEDIATE	ADVANCED	OPTIMAL
Not Managed	Limit-Managed	Managed	Well-Managed	Level 4 +
	Not Defined	Defined	Well-Defined	
		Partially Implemented	Fully Implemented	
				Measured, Controlled, Audited

- At Level 1, there are few or no procedures or processes defined or in place, or at least they

are not reported or poorly documented. Behaviours are *ad hoc*. Often, information about what has been done to the dataset is not publicly available. For example, an individual researcher created a data file and stored it on their own hard disk.

- At Level 2, some efforts have been made to move the dataset to a managed state. However, the procedure or process is typically defined by an individual entity (person, team, or project). The procedure or process is not documented and is not compliant with established national standards, e.g., by national Records Management authorities, or international standard. For example, a project may define a preservation process to address its own archival requirements but is not compliant with any international standard such as the ISO Open Archival Information System (OAIS) Reference Model (ISO 14721, 2012; CCSDS, 2012a).
- At Level 3 and higher, requirements or standards, procedures, and processes associated with that particular aspect are defined and compliant with national or international standards. For example, a data center may adopt the OAIS RM in defining its preservation process. Levels 3 and 4 measure the degree of compliance to the defined requirements or standards and the degree of implementation: Level 3 indicates lack of complete compliance with a partial implementation of standards, while at Level 4, well-defined procedures or processes are fully compliant with national or international standards and fully implemented. For example, at Level 4, the OAIS RM standard is fully applied to an archiving process, while at Level 3 only a part of the OAIS RM is implemented.
- At Level 5, a procedure needs to be in place and documented to quantitatively monitor the defined process. In some cases, Level 5 may measure whether an internal or external audit is regularly performed.

Sometimes, an organization may have a defined process in place but not yet applied to all its data holdings. The same is true of its data management capability. In this case, datasets from the same organization may have different maturity ratings. For example, one data center may have a Thematic Real-time Environmental Distributed Data Services (THREDDS) Data Server in place but not all datasets are being served through this particular THREDDS Data Server (TDS). Therefore, the accessibility ratings could be different.

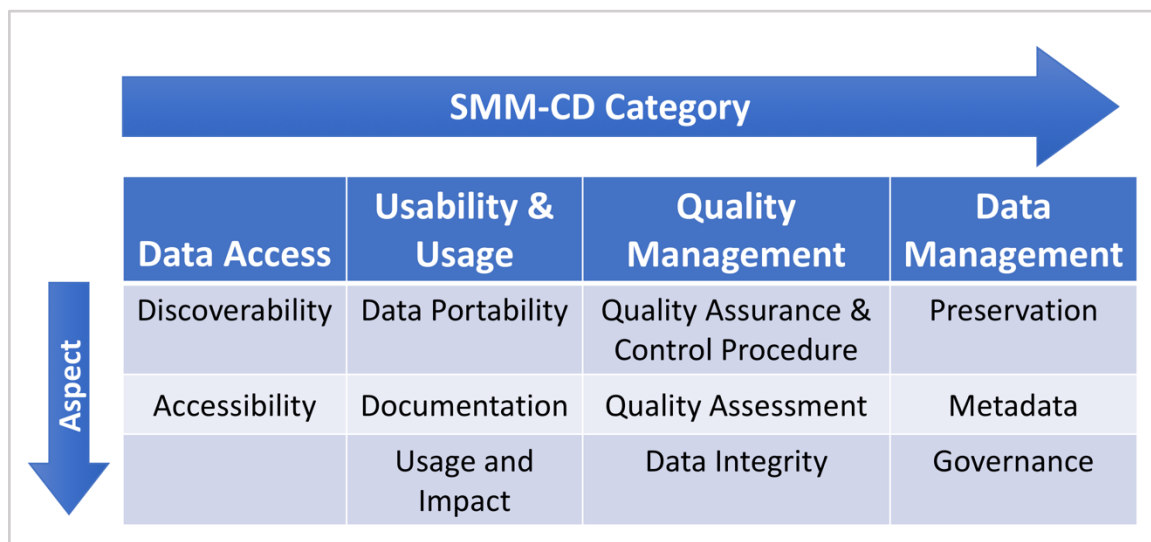
The requirements or standard against which the maturity of a dataset has been evaluated should be described in an assessment report prepared by the dataset point-of-contact or an evaluator. WMO defined requirements and standards are recommended where they are applicable. Generally speaking, the ratings should be assessed at the level that all the criteria in the current and lower levels are satisfied. A fraction may be used to indicate additional criteria may be satisfied at the level higher than the current. One could also use the justification or note section of the SMM-CD self-evaluation template (Lief and Peng, 2019) to denote additional capability or practices applied to the dataset beyond the overall rating for that particular aspect of the dataset.

It should be noted that dataset maturity ratings are a snapshot of the current state which may evolve overtime. Ideally the maturity ratings should be utilized to demonstrate the trustworthiness of individual datasets and to identify priorities for improving stewardship quality.

5. DEFINING CATEGORIES, ASSOCIATED ASPECTS AND MATURITY LEVELS

The four categories defined for SMM-CD are: Data Access, Usability & Usage, Quality Management, and Data Management. These, along with their selected Aspects, are shown in Figure 2 below. The current version of the matrix produced by the SMM-CD Working Group, along with illustrative examples and other “in progress” notes, is shown in Tables 1–4.

Figure 2. The diagram of SMM-CD categories and aspects.



5.1 DATA ACCESS CATEGORY

Data Access refers to the ability to locate (Discoverability) and get (Accessibility) the dataset in question, with higher levels of maturity corresponding to the ease for a potential user of being able to find and gain access to the dataset and associated information. The highest levels will contain broadly-available online information for search and discovery and capacity for sub-setting, aggregation and visualization.

Table 1. Expected behaviours for the Data Access category, along with illustrative examples and preliminary notes

<i>Aspect</i>	<i>Level 1</i>	<i>Level 2</i>	<i>Level 3</i>	<i>Level 4</i>	<i>Level 5</i>
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Discoverability	By personal contact only; Dataset information not discoverable.	Limited dataset information, such as scientific description of the methodology, available online.	Level 2 + minimal catalogue-level metadata; Dataset searchable online.	Level 3 + comprehensive set of collection-level discovery metadata + minimal granule metadata.	Level 4 + available on an international catalogue, prominently displayed online and routinely updated.
Examples and Notes	<i>Data users have to contact a person to find the data.</i>	<i>Journal article, technical report, or user guide is available online.</i>	<i>Example: Following WMO CORE Metadata Profile - collection-level.</i>	ESIP Attribute Convention for Data Discovery	<i>Example: for CoCoRaHS, data are discoverable through resources including NCEI Portal and CoCoRaHS</i>
Accessibility	Data not available publicly; Person-to-person contact needed.	Basic online services available for data access (e.g. FTP/HTTP direct download).	Non-standard data services.	Standard-based interoperability data services.	Level 4 + full capability of sub-setting, aggregation and visualization.

<p>Examples and Notes</p>	<p><i>Data is producer-owned and on a personal disk. Data is available internally or on a magnetic tape.</i></p>	<p><i>Direct file download through a known protocol such as ftp, sftp, http, or https.</i></p>	<p><i>Data is under web interface, but with old software (such as PHP, HTML, MS), which has problems on long-term existence. Check GEOSS Standards and Interoperability Registry</i></p>	<p><i>Data services such as THREDDS, Web Map Services, etc.</i></p>	<p><i>One can use a fraction to denote the state that only partial capability is available such as visualization without subsetting.</i></p>
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5.2 USABILITY AND USAGE CATEGORY

This Category describes how easily the data product may be understood and used by users and incorporated into the user’s own working environment. It incorporates aspects of compatibility of the publication medium with community standards and supporting documentation. Low levels of maturity correspond to formats that are difficult to work with and require pre-processing to incorporate the data, with minimal supporting documentation, while high levels of maturity reflect good interoperability, accessible and complete documentation.

Data Usage and Impact is also included in this category. It measures how much and at what impact level the dataset has been utilized based on relevant scientific literature. Note that citations refer not just to citations in peer-reviewed journals, but also in widely accepted, authoritative institutional reports. A general guidance on weak, intermediate, and strong citations is provided. It should be recognized, however that what is considered as an intermediate number of citations may vary largely with different disciplines, for example, hydrology versus cryosphere. In that case, one could document the domain citation baseline adopted, if available, in the assessment report. Data Impact includes the utility of the individual datasets in decision- or policy-making process. If a climate assessment report is published by an individual organization but on behalf of a national or international effort with official mandates, it should be considered as a national or international report.

Table 2: Expected behaviours for the Usability & Usage category, along with illustrative examples and preliminary notes

<i>Aspect</i>	<i>Level 1</i>	<i>Level 2</i>	<i>Level 3</i>	<i>Level 4</i>	<i>Level 5</i>
Data Portability	Non-machine readable.	Basic machine readable.	Standards-based machine readable.	Machine independent, self-describing, interoperable format.	Level 4 + capability of providing selected community formats.

<p>Examples and Notes</p>	<p><i>Such as non-digital data; paper forms or obsolete media.</i></p>	<p><i>Such as formatted binary data.</i></p>	<p><i>Such as JSON, CVS; The ASCII format may be considered as standard-based but not interoperable. GRIB can be machine independent but not as self-describing and interoperable as netCDF and may be assessed at 3.5.</i></p>	<p><i>Such as netCDF; OGC WaterML.</i></p>	<p><i>Example: for the World Ocean Database (WOD13) 'data are available in several formats, including ragged array netCDF which follows Climate-Forecast (CF) conventions and programs are available for further customization of data.'</i></p>
<p>Documentation</p>	<p>Product information not publicly available online.</p>	<p>Limited online documentation (e.g., User Guide).</p>	<p>Document on how the data product was created and how to use it, is available online.</p>	<p>Comprehensive documentation based on a standard template and available online.</p>	<p>Level 4 + online tutorial on using and analyzing the dataset; Complete production system information.</p>

Examples/Notes	<i>Documents, such as Readme or user guide could be available, but one has to know the right person to obtain them.</i>	<i>Just basic information for users to know what the variables in the file are and how to read data.</i>	<i>Including additional product information such as input data sources and processing steps.</i>	<i>Compliant with WMO documentation requirements on transparency and traceability; At this level, documents should be under document management (e.g., assigned a unique ID and version controlled).</i>	<i>Enough information including provenance for users to reproduce the data product from the initial data.</i>
Usage and Impact	No or weak citations in scientific publication in peer-review journal or as institutional reports.	Intermediate citations + referenced in institutional climate assessment reports (e.g., by NOAA).	Strong citations + referenced in national climate assessment reports (e.g., by USGCRP).	Level 3 + referenced in international climate assessment reports (e.g., by IPCC).	Level 4 + referenced in international decision & policy making published reports (e.g., by UNFCCC, UNISDR, World Bank, etc.)

Examples/Notes	<i>Less than 5 without any for national/international climate assessment reports or decision/policy making reports, or as data utilized in studies published in peer-reviewed journals.</i>	<i>Greater than 6 but less than 10. <u>Example:</u> NOAA 2016 State of the Climate.. <i>(The NOAA report is done with a collaboration of national and international scientists but without national and international mandates such as those for GCRP and IPCC reports. Therefore, the potential impact it may have on policy-making may be less than that by GCRP and IPCC, even if the part of report may be written by the same scientists.)</i></i>	<i>Greater than 10. <u>Example:</u> USGCRP (U.S. Global Change Research Program) 2014 Third National Climate Assessment.</i>	<i>Greater than 10. <u>Example:</u> IPCC (Intergovernmental Panel on Climate Change) Global Change 2014 Synthesis Report.</i>	<i>UNFCCC (United Nations Framework Convention on Climate Change).</i>
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5.3 QUALITY MANAGEMENT CATEGORY

Quality management encompasses quality assurance (QA) procedures including quality monitoring, quality control (QC) and quality assessment and communication of reliability. At the lower levels, quality monitoring and correction procedures are poorly defined, applied, and policed, whereas the higher levels move towards a well-managed full end-to-end quality assurance process traceability. High level QC might also include a retrospective QC, whereby the full historical climate record, not just incoming data, is assessed using best practice methodologies. This Category also includes data uncertainty analysis and assessment of Data

Integrity, which measures the checks put in place to ensure that data received, archived, and disseminated conforms to the initial data files (it may be viewed as the opposite to data corruption).

Table 3: Expected behaviours for the Quality Management category, along with illustrative examples and preliminary notes

<i>Aspect</i>	<i>Level 1</i>	<i>Level 2</i>	<i>Level 3</i>	<i>Level 4</i>	<i>Level 5</i>
Quality Assurance & Control Procedure	Ad hoc or no data quality assurance (QA) & quality control (QC) procedure or information unknown.	QA/QC procedure are defined, documented, and partially implemented.	QA/QC procedure are well-defined according to community best practices, documented and fully applied.	Level 3 + provision of error statistics published or tracked with results made available online and communicated to data providers; Procedure for user feedback, improvement prioritization in place	Level.4 + detailed analysis of errors and gaps at space-time unit level: (Station, grid- points, daily, monthly and or annual time-scale, etc.) QA/QC procedure monitored; Retrospective QC.
Examples and Notes			<i>Compliant with WMO QA/QC guidelines.</i>	<i>Example: Real-time quality status report tools: NOAA in situ SST quality monitor.</i>	<i>QA/QC is applied to the full historical record, which is what we would expect of a fully reliable dataset.</i>
Quality Assessment	Product quality assessment not done or done internally and information not available.	Product quality assessed; Assessment documented and published online.	Level 2 + uncertainty analysis included in the assessment and published.	Level 3 + product produced by authoritative entity.	Level 4 + product quality assessment method and results published in peer-reviewed journal.

Examples and Notes		<i>Published: the document is made publicly available, for example, on the product web site. Not necessarily peer-reviewed.</i>	<i>Example: Quality assessed by data producers for HADEX2</i>	<i>An authoritative entity can be a well-established trusted data repository or provider or an entity that is authorized by a legal entity to produce or manage data for a particular intended use. Example may include products produced by national weather and climate data centers.</i>	<i>Example: Uncertainty assessment of the ERA-20C reanalysis;</i>
Data Integrity	Unknown or no data integrity check.	Random data integrity check.	Data integrity verified systematically but methodology not commonly known.	Data integrity systematically verified and following well known practices but not necessarily consistent across platforms.	All steps in data integrity check systematically verified and adhering to well-known practice.

<p><i>Example and Notes</i></p>		<p><i>Data integrity check only being performed occasionally, and/or on some of the granules of the dataset, including manual checks.</i></p>	<p><i>Example: Establish a check to ensure that corrupted data triggers an alert with the goal of that data managers are prompted to intervene to ensure data sent is the same as received.</i></p>	<p><i>Data integrity verifiable with well-known technologies such as checksums or others. Archive might have different schemes in different databases.</i></p>	<p><i>Ensures that: data sent is same as received; data ingested is same as archived; data put online has not changed during staging process. Well known integrity practices such as checksum.</i></p>
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5.4 DATA MANAGEMENT CATEGORY

Data Management is the set of operations, procedures, protocols and policies required to organize, archive, quality control, secure and enable access to an organization’s data holdings. This characteristic refers to the processes undertaken to ensure the data and contextual metadata are securely archived. It covers not just the preservation of the data and metadata with appropriate safeguards, but well defined and enforced governance processes to ensure that the right procedures are followed at the right times by the right people. Lower levels refer to unsystematic approaches with risk of the dataset being lost, corrupted, or even inadvertently deleted. At higher levels, there are well-regulated and regularly audited processes to ensure that the security and integrity of the data set are guaranteed. The Metadata category includes the aspect of provenance metadata, with high levels corresponding to an ability to trace back to the original version of the data, and to link products to the version of the data from which they were derived.

A data collection is a grouping of environmental data that share common characteristics, for example, a product of homogeneous surface temperature data based on temperature measurements from global weather stations. A data collection often time refers to a dataset. A dataset may have one or many data files which may contain one or many variables. Collection-level metadata refers to metadata that describes a data collection as a whole such as title, overall spatial and temporal coverage. Granule-level metadata, on the other hand, refers to metadata that describes the smallest aggregation of data that can be independently managed (described, inventoried, and retrieved), for example, for individual weather station. In this case, granule-level metadata may contain a history of station location(s) and types of sensor(s) and method(s) used for measurements.

Rich metadata refers to how detailed and complete contextual metadata has been captured. Contextual metadata may be used to capture information about data provenance and quality. Contextual metadata can be captured in both collection-level and granule-level metadata records.

Table 4: Expected behaviours for Data Management category, along with illustrative examples and preliminary notes

<i>Aspect</i>	<i>Level 1</i>	<i>Level 2</i>	<i>Level 3</i>	<i>Level 4</i>	<i>Level 5</i>
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Preservation	Any storage location; Data only; Lock of systematic data backup.	Non-designated repository; Data backed up systematically.	Designated archive; Basic retention policy defined.	Level 3 + conforming to community archiving standards. Comprehensive retention policy defined and implemented.	Level 4 + archiving process performance controlled, measure and audited. Future archiving standard changes planned.
Examples and Notes	<i>Data backup is not done or done at the discretion of the data manager so users can't expect when or if it will be done (high risk of losing data).</i>	<i>The repository types are defined in Peng et al. (2015). Non-designated repositories such as institutional research centers are not held to all of the NARA-accepted archive standards but still adhere to basic good stewardship practices, such as off-site data backup and maintenance of adequate environmental control and security for their holdings.</i>	<i>Designated archives such as national centers are subject to all of the NARA-accepted archive standards.</i>	<i>Example: WMO CDMS specifications (WMO-No. 1131) – required and recommended components</i>	<i>State the type of audit, such as NARA record management, ISO 16363 (2012) (also, CCSDS, 2012b), or WDS-DSA-RDA core trustworthy data repositories (Edmunds et al. 2016)</i>

Metadata	Collection-level metadata not publicly available and/or not usable.	Limited collection-level metadata publicly available; Conforming to community-standard; Basic characteristics of dataset.	Level 2 + conforming to international standards in most aspects; limited quality and provenance metadata.	Fully compliant with international standards; Rich metadata content; Basic granule-level metadata; Support dataset provenance.	Level 4 + comprehensive granule-level metadata; Metadata quality controlled and regularly updated
Examples and Notes		<i>Limited number of metadata like lat/long only.</i>	<i>WMO Core Profile Metadata compliant; “Most aspects” may include archiving and usability metadata. ISO 19115-* are international metadata standards for geospatial data.</i>	<i>Sufficient information captured in the metadata for data to be used for homogeneity analysis; support product-level provenance.</i>	<i>Complete information available so that data product can be linked to the version of the data from which it was derived.</i>

Governance	Responsibility is not defined; No person is assigned.	Responsible entity is identified; Accountability and competency are not well-defined	Responsibility, accountability and compliance mechanisms are defined; adhere well to data management competency standards; Processes established conforming to community standards	Level 3 + competency defined; Conforming to international standards; Auditable	Level 4 + accountability and responsibility well-defined and fully compliant with international standards; Transparent; Monitored and audited
Examples and Note (organizational and process capability and competency)		<i>Reasonable competency: check WMO definition of competencies for data management.</i>	<i>Clear Point-of-Contact (POC), security protocols; Compliant with competency and standards in data management.</i>	<i>Auditable: information that could be used for audit as evidences has been collected or documented but not yet initiated the audit process.</i>	<i>Met Service data practices are audited: achieved high performance against relevant metrics.</i>

6. SMM-CD TEMPLATE

A SMM-CD self-evaluation template (MS Word format) has been developed to facilitate the assessment process (Lief and Peng, 2019). We encourage the use of this template to capture evidence when evaluating the stewardship maturity of a dataset.

The latest version of the template will be maintained at, and can be downloaded from figshare.com: [doi:10.6084/m9.figshare.7003709](https://doi.org/10.6084/m9.figshare.7003709).

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9. DEFINITIONS

- **Data Access** refers to the ability to locate (Discoverability) and get (Accessibility) the dataset in question.
- **Data Documentation** To ensure that data will be correctly understood and interpreted by users they should be appropriately documented; documentation should explain how the data were created, and their context, structure and content.
- **Data Governance** includes standard procedure, policies, approval process, along with accountabilities and compliance mechanism for ensuring the data is secure, accessible and useable.
- **Data Integrity** refers to the extent to which data are recorded, preserved and used exactly as intended, and that data are free from corruption or loss when transferred between systems or in storage throughout the data life-cycle. It is a critical aspect to the design, implementation and usage of any system which stores, processes, or retrieves data. Data integrity is the opposite of data corruption.
- **Data Management** is the set of operations, procedures, protocols and policies required to organize, archive, quality control, secure and enable access to an organization's data

holdings.

- **Data Portability** is a concept to protect users from having their data stored in closed platforms that are incompatible with one another. Data portability requires common technical standards to facilitate the transfer from one data controller to another, thus promoting interoperability.
- **Data Preservation** means ensuring data remains accessible and usable for as long as it is required for operational, research, business evidentiary or historical purposes. It includes securing the data and making provision for obsolescence of storage media used to store the data; the hardware used to access the data; and the software and hardware required to access the data.
- **Dataset Quality Assessment** The process of scientifically and statistically evaluating datasets and their level of stewardship to determine, based on appropriate documentation, whether they are of adequate quality.
- **Data Quality Assurance** refers to the processes for maintaining a desired level of quality in a dataset or collection. Data verification, quality control and validation are important steps in supporting defensible products and decisions. Data quality assurance is required across the whole data life cycle and should also include ensuring effective transmission and secure management of the data.
- **Data Quality Control** is the process of ensuring that errors in the data are detected, flagged and corrected. It involves checking the data to assess representativeness in time, space and internal consistency, and flagging any potential inconsistencies. The purpose of Quality Control (and broader Quality Management) is to ensure that meteorological and climate data available to potential users is sufficiently reliable to be used with confidence. Quality control is therefore part of the overall data quality assessment.
- **Data Quality Management** is the process of overseeing the activities, tasks and policies required to ensure that data maintain a required standard of excellence. Quality Management involves quality planning, the establishment and continued operation of a quality assurance system, including adequate quality control, and quality assessment and improvement processes.
- **Data Uncertainty** A measure of “noise” in the observational data that deviates from the correct, intended or original values. All measurements of an observed phenomenon have a degree of uncertainty regardless of precision and accuracy. Observational uncertainty is caused by two factors, the limitation of the measuring instrument (systematic error) and the skill of the observer making the measurements (random error). Further uncertainty can arise when, for instance, values are rounded, interpolated or extrapolated, such as when gridded analyses produce interpolated values that differ from the actual point value.
- **Data Usability and Usage** is how easily the data product may be understood and used by users and incorporated into the user’s own working environment.
- **Metadata** is information about data and sometimes referred to as “data about data”. It is important to distinguish between a number of different types of metadata, as described below. To ensure that data are fit for purpose for climate services and

research, entities that produce data for climate purposes are required to create and maintain all of the types of metadata described in the following entries.

- **Metadata, Contextual** is information about how the data were collected or generated, featuring the who, how, when and where a measurement was made. This information is required to establish fitness for purpose, as well as providing indispensable information for operations such as homogenisation. In the case of meteorological data, it includes such details as where and when the measurement was made, with what instrumentation, by whom, under what siting conditions, what changes to the above have occurred, quality control status, intellectual property information. If the data/information were created by processing or analysis methods, details of the algorithms and methodology used are also required. The Observing Systems Capability Analysis and Review Tool for Surface-based Observations (OSCAR/Surface) is the WMO official repository of contextual metadata for all surface-based observing stations and platforms.
- **Metadata, Collection-level** is metadata describing a data collection as a whole. A collection is a grouping of environmental data that share common characteristics, which often time refers to a dataset. A dataset may have one or many data files or contain one or many variables.
- **Metadata, Discovery** is metadata which enables a user to query or search a catalogue to determine what information is held, where it's held and by whom, along with some details about the data/information set. There is a considerable body of knowledge about the requirements for such metadata, including ISO 19115 (ISO 19115 Geographic Information – Metadata).
- **Metadata, granule-level** is metadata describing the smallest aggregation of data that can be independently managed (described, inventoried, and retrieved), for example, for individual variable or station.
- **Metadata, Network.** Changes to the way climate variables are measured apply not only at the individual station level, but to whole networks of stations. An example might be when manual observations are replaced by Automatic Weather Stations (AWS), or when a network of AWSs are progressively replaced by a model with a different central processing unit, or when new sensors are introduced. It is important again to document the time, location and details of any such changes. Moreover, to support the effective homogenisation simultaneous changes across an entire network should be avoided.
- **Metadata, Provenance** Apart from the need to know what changes to observation siting, practices, etc. have been made over time (an essential step in homogenisation procedures), it is important to know about changes to the versions of a dataset. This is because of the need for traceability – being able to identify the version of a dataset from which a particular analysis or product was derived. Provenance should therefore include details of any quality control or homogenisation processes, details of disaggregation or infilling, or any other changes made to the dataset. Climate products and services need to contain a link to the particular version of the data on which they are based.

10. ACRONYMS

AOPC	Atmospheric Observation Panel for Climate
BOM	The Bureau of Meteorology
CCI	Commission for Climatology
CDR	Climate Data Record
CEOS	Committee on Earth Observation Satellites
CF	Climate and Forecast
CICS-NC	NOAA's Cooperative Institute for Climate and Satellites - North Carolina
CISESS	NOAA's Cooperative Institute for Satellite Earth System Studies
CORE-CLIMAX	European Union Framework 7 Project in the context of Climate Services (www.coreclimax.eu)
CSIS	Climate Services Information System
DSMM	Data Stewardship Maturity Matrix
DWD	The Deutscher Wetterdienst
ECMWF	European Centre for Medium-range Weather Forecasts
ECV	Essential Climate Variable
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GFCS	Global Framework for Climate Services
GCOS	Global Climate Observing System
GPCC	Global Precipitation Climatology Centre
HQ-GDMFC	High-Quality Global Data Management Framework for Climate
IEG-CDM	International Expert Group for Climate Data Modernization
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JAXA	Japan Aerospace Exploration Agency
JMA	Japanese Meteorological Agency
KNMI	Royal Netherlands Meteorological Institute
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
Met Office	United Kingdom's national weather service
NARA	National Archives and Records Administration
NASA	National Aeronautics and Space Administration
NCEI	National Centers for Environmental Information
NCSU	North Carolina State University
NHMS	National Meteorological Service
NOAA	National Oceanic and Atmospheric Administration
NSIDC	National Snow and Ice Data Center
OAIS	Open Archival Information System

OAIS RM	Open Archival Information System Reference Model
OOPC	Ocean Observing Panel for Climate
RCC	Regional Climate Center
SMM-CD	Stewardship Maturity Matrix for Climate Data
TDS	THREDDS Data Server
THREDDS	Thematic Real-time Environmental Distributed Data Services
TOPC	Terrestrial Observation Panel for Climate
UNFCCC	United Nations Framework Convention on Climate Change
USGCRP	U.S. Global Change Research Program
WCRP	World Climate Research Programme
WGISS	CEOS Working Group on Information Systems and Services
WIGOS	World Meteorological Organization (WMO) Integrated Global Observing System
WMO	World Meteorological Organization
WIS	WMO Information System