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CHAPTER 1. QUALITY MANAGEMENT

1.1 GENERAL

This chapter is general and covers operational meteorological observing systems of any size or nature. Although the guidance it gives on quality management is expressed in terms that apply to large networks of observing stations, it should be read to apply even to a single station.

Quality management

Quality management provides the principles and the methodological frame for operations, and coordinates activities to manage and control an organization with regard to quality. Quality assurance and quality control are the parts of any successful quality management system. Quality assurance focuses on providing confidence that quality requirements will be fulfilled and includes all the planned and systematic activities implemented in a quality management system so that quality requirements for a product or service will be fulfilled. Quality control is associated with those components used to ensure that the quality requirements are fulfilled and includes all the operational techniques and activities used to fulfill quality requirements. This chapter concerns quality management associated with quality control and quality assurance and the formal accreditation of the laboratory activities, especially from the point of view of meteorological observations of weather and atmospheric variables.

The ISO 9000 family of standards is discussed to assist understanding in the course of action during the introduction of a quality management system in a National Meteorological and Hydrological Service (NMHS); this set of standards contains the minimum processes that must be introduced in a quality management system for fulfilling the requirements of the ISO 9001 standard. The total quality management concept according to the ISO 9004 guidelines is then discussed, highlighting the views of users and interested parties. The ISO/IEC 17025 standard is introduced. The benefits to NMHSs and the Regional Instrument Centres (RICs) from accreditation through ISO/IEC 17025 are outlined along with a requirement for an accreditation process.

The ISO/IEC 20000 standard for information technology (IT) service management is introduced into the discussion, given that every observing system incorporates IT components.

Quality assurance and quality control

Data are of good quality when they satisfy stated and implied needs. Elsewhere in this Guide explicit or implied statements are given of required accuracy, uncertainty, resolution and representativeness, mainly for the synoptic applications of meteorological data, but similar requirements can be stated for other applications. It must be supposed that minimum total cost is also an implied or explicit requirement for any application. The purpose of quality management is to ensure that data meet requirements (for uncertainty, resolution, continuity, homogeneity, representativeness, timeliness, format, and so on) for the intended application, at a minimum practicable cost. All measured data are imperfect, but, if their quality is known and demonstrable, they can be used appropriately.

The provision of good quality meteorological data is not a simple matter and is impossible without a quality management system. The best quality management systems operate continuously at all points in the whole observing system, from network planning and training, through installation and station operations to data transmission and archiving, and they include feedback and follow-up provisions on timescales from near-real-time to annual reviews and end-to-end process. The amount of resources required for an effective quality management system is a proportion of the cost of operating an observing system or network and is typically a few per cent of the overall cost. Without this expenditure, the data must be regarded as being of unknown quality, and their usefulness is diminished.
An effective quality management system is one that manages the linkages between preparation for data collection, data collection, data assurance and distribution to users to ensure that the user receives the required quantity. For many meteorological quantities, there are a number of these preparation-collection-assurance cycles between the field and the ultimate distribution to the user. It is essential that all these cycles are identified and the potential for divergence from the required quantity minimized. Many of these cycles will be so closely linked that they may be perceived as one cycle. Most problems occur when there are a number of cycles and they are treated as independent of one another.

Once a datum from a measurement process is obtained, it remains the datum of the measurement process. Other subsequent processes may verify its worth as the quantity required, use the datum in an adjustment process to create the quality required, or reject the datum. However, none of these subsequent processes changes the datum from the measurement process. Quality control is the process by which an effort is made to ensure that the processes leading up to the datum being distributed are correct, and to minimize the potential for rejection or adjustment of the resultant datum.

Quality assurance includes explicit control of the factors that directly affect the data collected and processed before distribution to users. For observations or measurements, this includes equipment, exposure, measurement procedures, maintenance, inspection, calibration, algorithm development, redundancy of measurements, applied research and training. In a data transmission sense, quality control is the process established to ensure that for data that is subsequently transmitted or forwarded to a user database, protocols are set up to ensure that only acceptable data are collected by the user.

Quality control is the best-known component of quality management systems, and it is the irreducible minimum of any system. It consists of all the processes that are put in place to generate confidence and ensure that the data produced will have the required quality and also include the examination of data at stations and at data centres to verify that the data are consistent with the quality management system goals, and to detect errors so that the data may be either flagged as unreliable, corrected or, in the case of gross errors, deleted. A quality management system should include procedures for feeding back into the measurement and quality control process to prevent the errors from recurring. Quality assurance can be applied in real-time post measurement, and can feed into the quality control process for the next process of a quality system, but in general it tends to operate in non-real time.

Real-time quality control is usually performed at the station and at meteorological analysis centres. Delayed quality assurance may be performed at analysis centres for the compilation of a refined database, and at climate centres or databanks for archiving. In all cases, the results should be returned to the observation managers for follow-up.

A common component of quality control is quality monitoring or performance monitoring, a non-real-time activity in which the performance of the network or observing system is examined for trends and systematic deficiencies. It is typically performed by the office that manages and takes responsibility for the network or system, and which can prescribe changes to equipment or procedures. These are usually the responsibility of the network manager, in collaboration with other specialists, where appropriate.

Modern approaches to data quality emphasize the advantages of a comprehensive system for quality assurance, in which procedures are laid down for continuous interaction between all parties involved in the observing system, including top management and others such as designers and trainers who may otherwise have been regarded as peripheral to operational quality concerns after data collection. The formal procedures prescribed by the International Organization for Standardization (ISO) for quality management and quality assurance, and other detailed procedures used in manufacturing and commerce, are also appropriate for meteorological data.

The chapter gives an explanation of the related ISO standards and how they interconnect.

Proficiency in ISO quality systems is available through certification or accreditation, and usually requires external auditing of the implemented quality management system. Certification implies that the framework and procedures used in the organization are in place and used as stated. Accreditation implies that the framework and procedures used in the organization are in place, used as stated and technically able to achieve the required result. The assessment of technical competence is a mandatory requirement of accreditation, but not of certification. The ISO 9001 is a standard by which certification can be achieved by an organization, while accreditation against the ISO/IEC 17025 is commonly required for laboratories and routine observations.

The ISO 9000 standard has been developed to assist organizations of all types and sizes to implement and operate quality management systems. The ISO 9000 standard describes the fundamentals of quality management systems and gives definitions of the related terms (for example, requirement, customer satisfaction). The main concept is illustrated in Figure 1.1. The ISO 9001 standard specifies the requirements for a quality management system that can be certified in accordance with this standard. The ISO 9004 standard gives guidelines for continual improvement of the quality management system to achieve a total quality management system. The ISO 19011 standard provides the guidance on auditing the quality management system. All these standards are described in more detail in the related documents of the WMO Quality Management Framework.

1.2.1 ISO 9000: Quality management systems – Fundamentals and vocabulary

The following eight quality management principles are the implicit basis for the successful leadership of NMHSs of all sizes and for continual performance improvement:

(a) Customer focus;
(b) Leadership;
(c) Involvement of people;

Figure 1.1. The main concept of the ISO 9000 standards and the dependencies
(d) Process approach;
(e) System approach to management;
(f) Continual improvement;
(g) Factual approach to decision-making;
(h) Mutually beneficial supplier relationships.

All these principles must be documented and put to practice to meet the requirements of the ISO 9000 and 9001 standards to achieve certification. The main topic of these standards is the process approach, which can simply be described as activities that use resources to transform inputs into outputs.

The process-based quality management system is simply modelled in Figure 1.2. The basic idea is that of the mechanism likely to obtain continual improvement of the system and customer satisfaction through measuring the process indices (for example, computing time of a GME model, customer satisfaction, reaction time, and so forth), assessing the results, making management decisions for better resource management and obtaining inevitably better products.

1.2.2 ISO 9001: Quality management systems – Requirements

The basic requirements for a quality management system are given by this standard, including processes for improvement and complaint management and carrying out management reviews. These processes are normally incorporated in the quality manual. The ISO 9001 standard focuses on management responsibility rather than technical activities.

To achieve certification in ISO 9001, six processes must be defined and documented by the organization (NMHS), as follows:

(a) Control of documents;
(b) Control of records;
(c) Control of non-conforming products;
(d) Corrective action;

Figure 1.2. The PDCA control circuit (also named the Deming-circuit)
(e) Preventive action;
(f) Internal audit.

Furthermore, there must be a quality manual which states the policy (for example, the goal is to achieve regional leadership in weather forecasting) and the objectives of the organization (for example, improved weather forecasting: reduce false warning probability) and describes the process frameworks and their interaction. There must be statements for the following:

(a) Management;
(b) Internal communication;
(c) Continual improvement;
(d) System control (for example, through management reviews).

Exclusions can be made, for example, for development (if there are no development activities in the organization).

The documentation pyramid of the quality management system is shown in Figure 1.3. The process descriptions indicate the real activities in the organization, such as the data-acquisition process in the weather and climate observational networks. They provide information on the different process steps and the organizational units carrying out the steps, for cooperation and information sharing purposes. The documentation must differentiate between periodic and non-periodic processes. Examples of periodic processes are data acquisition or forecast dissemination. Examples of non-periodic processes include the installation of measurement equipment which starts with a user or component requirement (for example, the order to install a measurement network).

Lastly, the instructions in ISO 9001 give detailed information on the process steps to be referenced in the process description (for example, starting instruction of an AWS). Forms and checklists are helpful tools to reduce the possibility that required tasks will be forgotten.

1.2.3 ISO 9004: Managing for the sustained success of an organization – A quality management approach

The guidelines for developing the introduced quality management system to achieve business excellence are formulated in ISO 9004. The main aspect is the change from the customer position to the position of interested parties. Different excellence models can be developed by the

![Figure 1.3. The documentation pyramid of a quality management system](image-url)
ISO 9004 guidelines, for example, the Excellence Model of the European Foundation for Quality Management (EFQM)\(^1\) or the Malcolm Baldrige National Quality Award.\(^2\) Both excellence models are appropriately established and well respected in all countries of the world.

The EFQM Excellence Model contains the following nine criteria which are assessed by an expert team of assessors:

(a) Leadership;

(b) People;

(c) Policy and strategy;

(d) Partnerships and resources;

(e) Processes;

(f) People results;

(g) Customer results;

(h) Society results;

(i) Key performance results.

The Malcolm Baldrige model contains seven criteria similar to the EFQM Excellence Model, as follows:

(a) Leadership;

(b) Strategic planning;

(c) Customer and market focus;

(d) Measurement, analysis, and knowledge management;

(e) Human resources focus;

(f) Process management;

(g) Results.

There is no certification process for this standard, but external assessment provides the opportunity to draw comparisons with other organizations according to the excellence model (see also Figure 1.1).

1.2.4 **ISO 19011: Guidelines for auditing management systems**

This standard is a guide for auditing management systems and does not have any regulatory character. The following detailed activities are described for auditing the organization:

(a) Principles of auditing (ethical conduct, fair presentation, due professional care, independence, evidence-based approach);

(b) Audit planning (establishing and implementing the audit programme);

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(c) Audit activities (initiating the audit, preparing and conducting on-site audit activities, preparing the audit report);

(d) Training and education of the auditors (competence, knowledge, soft skills).

The manner in which audits are conducted depends on the objectives and scope of the audit which are set by the management or the audit client. The primary task of the first audit is to check the conformity of the quality management system with the ISO 9001 requirements. Further audits give priority to the interaction and interfaces of the processes.

The audit criteria are the documentation of the quality management system, the process descriptions, the quality manual and the unique individual regulations.

The audit planning published by the organization should specify the relevant departments of the organization, the audit criteria and the audit objectives, place, date and time to ensure a clear assignment of the audits.

1.2.5 **ISO/IEC 17025: General requirements for the competence of testing and calibration laboratories**

This set of requirements is applicable to facilities, including laboratories and testing sites, that wish to have external accreditation of their competence in terms of their measurement and testing processes.

The ISO/IEC 17025 standard aligns its management requirements with those of ISO 9001. This standard is divided into two main parts: management requirements and technical requirements. Hence, the quality management system must follow the requirements of the ISO 9001 standard, which include described processes, a management handbook that provides a connection between processes and goals and policy statements, and that these aspects be audited regularly. All laboratory processes must be approved, verified and validated in a suitable manner to meet the requirements. Furthermore, the roles of the quality management representative (quality manager) and the head of the laboratory must be determined.

An essential component of the technical requirements is the development of uncertainty analyses for each of the measurement processes, including documented and verified traceability to international metrology standards.

1.2.6 **ISO/IEC 20000: Information technology – Service management**

NMHSs make use of IT equipment to obtain data from the measuring networks to use in GME/LM models and to provide forecasters with the outputs of models. The recommendations of this standard are helpful for the implementation of reliable IT services. The new ISO/IEC 20000 standard summarizes the old British standard BS-15000 and the IT Infrastructure Library (ITIL) recommendations. The division of requirements follows the ITIL structure.

The ITIL elements are divided into service delivery and service support with the following processes:

*Service delivery:*

(a) Service-level management;

(b) Financial management;

(c) IT service continuity management;

(d) Availability management;
(e) Capacity management.

Service support:
(a) Change management;
(b) Incident management;
(c) Problem management;
(d) Release management;
(e) Configuration management.

Security management is common to both areas.

All these require that:
(a) The processes be adapted to the NMHS's organization;
(b) Particular attention be paid to user support.

Special attention has been placed on the change-management process, which can contain release and configuration management. Incident and problem management is normally covered by the implementation of a user help desk.

1.2.7 WMO Quality Management Framework

The WMO Quality Management Framework gives the basic recommendations that were based on the experiences of NMHSs. The necessary conditions for successful certification against ISO 9001 are explained in WMO (2005a, 2005b).

The Quality Management Framework is the guide for NMHSs, especially for NMHSs with little experience in a formal quality management system. The introduction of a quality management system is described only briefly in the following section, noting that WMO cannot carry out any certification against ISO 9001.

1.3 INTRODUCTION OF QUALITY MANAGEMENT

The introduction of successful quality management depends heavily on the cooperation of senior management. The senior management of the NMHS must be committed to the quality management system and support the project team. The necessary conditions for successful certification are summarized and the terms of ISO 9001 standards are explained in ISO 20000.

Senior-level management defines a quality policy and the quality objectives (including a quality management commitment), and staff have to be trained in sufficient quality management topics to understand the basis for the quality management process (see section 1.2.2). Most importantly, a project team should be established to manage the transition to a formal quality management system including definition and analysis of the processes used by the organization.

To assist the project team, brief instructions can be given to the staff involved in the process definition, and these would normally include the following:

(a) To document (write down) what each group does;
(b) To indicate the existing documentation;
(c) To indicate the proof or indicators of what is done;

(d) To identify what can be done to continually improve the processes.

Given that the documentation specifies what the organization does, it is essential that the main processes reflect the functions of the organization of the NMHS. These can be a part of the named processes (see Figure 1.4), for example:

(a) Weather forecasting (including hydrometeorological, agrometeorological, human biometeorological aspects) and weather warnings;

(b) Consulting services (including climate and environment);

(c) Data generation (from measurement and observational networks);

(d) International affairs;

(e) Research and development (global modelling, limited area models, instrumentation);

(f) Technical infrastructure (computing and communications, engineering support, data management and IT support);

(g) Administration processes (purchasing, financial and personnel management, organization, administration offices and immovables, knowledge management, central planning and control and legal affairs).

Even though these processes will meet the individual needs of NMHSs and provide them with subprocesses, normally there should be regulations for remedying incidents (for example, system failures, staff accidents).

The processes must be introduced into the organization with clear quality objectives, and all staff must be trained in understanding the processes, including the use of procedures and checklists and the measurement of process indicators.

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**Figure 1.4. Process landscape of an NMHS (example: DWD, WMO 2005a)**
Before applying for certification, the quality management system must be reviewed by carrying out internal audits in the departments and divisions of the organization, to check conformity of the quality management system as stated and as enacted. These documented reviews can be performed on products by specialized and trained auditors. The requirements and recommendations for these reviews are given in ISO 19011 (see section 1.2.4).

The management review of the quality management system will include the following:

(a) Audit results;
(b) Customer feedback;
(c) Process performance based on performance indicators;
(d) Status of preventive and corrective actions;
(e) Follow-up actions from previous management reviews;
(f) Changes in the quality management system (policy of the organization);
(g) Recommendations for improvement.

1.4 ACCREDITATION OF LABORATORIES

Accreditation requires additional processes and documentation and, most importantly, evidence that laboratory staff have been trained and have mastered the processes and methods to be accredited.

The documentation must contain the following aspects:

(a) A management manual for the laboratory;
(b) The process descriptions mentioned in section 1.2;
(c) The documentation of all processes and methods;
(d) Work instructions for all partial steps in the processes and methods;
(e) Equipment manuals (manual including calibrating certificates);
(f) Maintenance manuals.

Since procedures and methods are likely to change more frequently than the management aspects of the accreditation, the methods are usually not included in the management manual. However, there is specific reference to the procedures and methods used in the management manual.

As it is unlikely that all aspects of the accreditation will be covered once the quality management system is introduced, it is recommended that a pre-audit be conducted and coordinated with the certifying agency. In these pre-audits it would be normal for the certifying agency:

(a) To assess staff and spatial prerequisites;
(b) To assess the suitability of the management system;
(c) To check the documentation;
(d) To validate the scope of the accreditation.
The accreditation procedure consists of assessments by an expert panel (external to the organization), which includes a representative from the certifying agency. The assessment panel will focus on two main areas as follows:

(a) Documentation;

(b) An examination of the facilities included in the scope of the accreditation (for example, laboratories, special field sites).

The assessment of documentation covers verification of the following documents:

(a) A management manual (or laboratory guide);

(b) Procedure instructions;

(c) Work instructions;

(d) Test instructions;

(e) Equipment manuals;

(f) Maintenance manuals;

(g) Uncertainty analyses of specific quantities, test results and calibrations;

(h) Proof documents (for example, that staff training has occurred and that quantities are traceable);

(i) Records (for example, correspondence with the customer, generated calibration certificates).

The external expert team could request additional documents, as all aspects of the ISO/IEC 17025 standard are checked and in more detail than a certification under ISO 9001.

Besides the inspection of the measurement methods and associated equipment, the assessment of the facilities in the scope of the accreditation will include the following:

(a) Assessment of the staff (including training and responsibility levels);

(b) Assessment of the infrastructure that supports the methods (for example, buildings, access).

The following are also checked during the assessment to ensure that they meet the objectives required by management for accreditation:

(a) Organizational structure;

(b) Staff qualifications;

(c) Adequacy of the technological facilities;

(d) Customer focus.

In addition, the assessment should verify that the laboratory has established proof of the following:

(a) Technical competence (choice and use of the measuring system);

(b) Calibration of measurement equipment;
(c) Maintenance of measurement equipment;

(d) Verification and validation of methods.

Benefits and disadvantages of accreditation

Through initial accreditation by an independent certifying agency NMHSs prove their competence in the area of meteorological measuring and testing methods according to a recognized standard. Once accreditation is established, there is an ongoing periodic external audit, which provides additional proof that standards have been maintained, but more importantly it helps the organization to ensure that its own internal quality requirements are met.

An accreditation with suitable scope also provides commercial opportunities for the calibration, verification and assessment of measurement devices.

For organizations that do not have a quality management system in place, the benefits of accreditation are significant. First, it documents the organization’s system, and, through that, a process of analysis can be used to make the organization more efficient and effective. For example, one component of accreditation under ISO/IEC 17025 requires uncertainty analyses for every calibration and verification test; such quantitative analyses provide information on where the most benefit can be achieved for the least resources.

Accreditation or certification under any recognized quality framework requires registration and periodic audits by external experts and the certifying agency. These represent additional costs for the organization and are dependent on the scope of the accreditation and certification.

Seeking accreditation before an effective quality management system is in place will lead to an increased use of resources and result in existing resources being diverted to establish a quality management system; there will also be additional periodic audit costs.

1.5 QUALITY MANAGEMENT TOOLS

Several well-known tools exist to assist in the processes of a quality management system and its continuous improvement. Three examples of these tools are described below as an introduction: the Balanced Scorecard, Failure Mode and Effects Analysis, and Six Sigma.

The Balanced Scorecard (Kaplan and Norton, 1996) has at a minimum four points of focus: finances, the customer, processes and employees. Often the general public is added given that public interests must always be taken into account.

Each organization and organization element provides key performance indicators for each of the focus areas, which in turn link to the organization’s mission (or purpose, vision or goals) and the strategy (or working mission and vision).

Failure Mode and Effects Analysis is a method for the examination of possible missing causes and faults and the probability of their appearance. The method can be used for analysing production processes and product specification. The aim of the optimization process is to reduce the risk priority number.

The Six Sigma method was developed in the communications industry and uses statistical process controls to improve production. The objective of this method is to reduce process failure below a specific value.
1.6 **FACTORS AFFECTING DATA QUALITY**

The life history of instruments in field service involves different phases, such as planning according to user requirements, selection and installation of equipment, operation, calibration, maintenance and training activities. To obtain data of adequate or prescribed quality, appropriate actions must be taken at each of these phases. Factors affecting data quality are summarized in this section, and reference is made to more comprehensive information available in other chapters of this Guide and in other WMO Manuals and Guides.

**User requirements**: The quality of a measuring system can be assessed by comparing user requirements with the ability of the systems to fulfil them. The compatibility of user data-quality requirements with instrumental performance must be considered not only at the design and planning phase of a project, but also continually during operation, and implementation must be planned to optimize cost/benefit and cost/performance ratios. This involves a shared responsibility between users, instrument experts and logistic experts to match technical and financial factors. In particular, instrument experts must study the data quality requirements of the users to be able to propose specifications within the technical state of the art. This important phase of design is called value analysis. If it is neglected, as is often the case, it is likely that the cost or quality requirements, or both, will not be satisfied, possibly to such an extent that the project will fail and efforts will have been wasted.

**Functional and technical specifications**: The translation of expressed requirements into functional specifications and then into technical specifications is a very important and complex task, which requires a sound knowledge of user requirements, meteorological measuring technology, methods of observation, WMO regulations, and relevant operational conditions and technical/administrative infrastructures. Because the specifications will determine the general functioning of a planned measuring system, their impact on data quality is considerable.

**Selection of instruments**: Instruments should be carefully selected considering the required uncertainty, range and resolution (for definitions see Part I, Chapter 1), the climatological and environmental conditions implied by the users’ applications, the working conditions, and the available technical infrastructure for training, installation and maintenance. An inappropriate selection of instruments may yield poor quality data that may not be anticipated, causing many difficulties when they are subsequently discovered. An example of this is an underspecification resulting in excessive wear or drift. In general, only high quality instruments should be employed for meteorological purposes. Reference should be made to the relevant information given in the various chapters in this Guide. Further information on the performance of several instruments can be found in the reports of WMO international instrument intercomparisons and in the proceedings of WMO/CIMO and other international conferences on instruments and methods of observation.

**Acceptance tests**: Before installation and acceptance, it is necessary to ensure that the instruments fulfil the original specifications. The performance of instruments, and their sensitivity to influence factors, should be published by manufacturers and are sometimes certified by calibration authorities. However, WMO instrument intercomparisons show that instruments may still be degraded by factors affecting their quality which may appear during the production and transportation phases. Calibration errors are difficult or impossible to detect when adequate standards and appropriate test and calibration facilities are not readily available. It is an essential component of good management to carry out appropriate tests under operational conditions before instruments are used for operational purposes. These tests can be applied both to determine the characteristics of a given model and to control the effective quality of each instrument.

When purchasing equipment, consideration should be given to requiring the supplier to set up certified quality assurance procedures within its organization according to the requirements of the NMHS, thus reducing the need for acceptance testing by the recipient. The extra cost when purchasing equipment may be justified by consequent lower costs for internal testing or operational maintenance, or by the assured quality of subsequent field operations.
Compatibility: Data compatibility problems can arise when instruments with different technical characteristics are used for taking the same types of measurements. This can happen, for example, when changing from manual to automated measurements, when adding new instruments of different time-constants, when using different sensor shielding, when applying different data reduction algorithms, and so on. The effects on data compatibility and homogeneity should be carefully investigated by long-term intercomparisons. Reference should be made to the various WMO reports on international instrument intercomparisons.

Siting and exposure: The density of meteorological stations depends on the timescale and space scale of the meteorological phenomena to be observed and is generally specified by the users, or set by WMO regulations. Experimental evidence exists showing that improper local siting and exposure can cause a serious deterioration in the accuracy and representativeness of measurements. General siting and exposure criteria are given in Part I, Chapter 1, and detailed information appropriate to specific instruments is given in the various chapters of Part I. Further reference should be made to the regulations in WMO (2010c). Attention should also be paid to external factors that can introduce errors, such as dust, pollution, frost, salt, large ambient temperature extremes or vandalism.

Instrumental errors: A proper selection of instruments is a necessary, but not sufficient, condition for obtaining good-quality data. No measuring technique is perfect, and all instruments produce various systematic and random errors. Their impact on data quality should be reduced to an acceptable level by appropriate preventive and corrective actions. These errors depend on the type of observation; they are discussed in the relevant chapters of this Guide (see Part I).

Data acquisition: Data quality is not only a function of the quality of the instruments and their correct siting and exposure, but also depends on the techniques and methods used to obtain data and to convert them into representative data. A distinction should be made between automated measurements and human observations. Depending on the technical characteristics of a sensor, in particular its time constant, proper sampling and averaging procedures must be applied. Unwanted sources of external electrical interference and noise can degrade the quality of the sensor output and should be eliminated by proper sensor-signal conditioning before entering the data-acquisition system. Reference should be made to sampling and filtering in Part II, Chapter 1 and in Part II, Chapter 2. In the case of manual instrument readings, errors may arise from the design, settings or resolution of the instrument, or from the inadequate training of the observer. For visual or subjective observations, errors can occur through an inexperienced observer misinterpreting the meteorological phenomena.

Data processing: Errors may also be introduced by the conversion techniques or computational procedures applied to convert the sensor data into Level II or Level III data. Examples of this are the calculation of humidity values from measured relative humidity or dewpoint and the reduction of pressure to mean sea level. Errors also occur during the coding or transcription of meteorological messages, in particular if performed by an observer.

Real-time quality control: Data quality depends on the real-time quality-control procedures applied during data acquisition and processing and during the preparation of messages, in order to eliminate the main sources of errors. These procedures are specific to each type of measurement but generally include gross checks for plausible values, rates of change and comparisons with other measurements (for example, dewpoint cannot exceed temperature). Special checks concern manually entered observations and meteorological messages. In AWSs, special built-in test equipment and software can detect specific hardware errors. The application of these procedures is most important since some errors introduced during the measuring process cannot be eliminated later. For an overview of manual and automatic methods in use, refer to other paragraphs of this chapter as well as to Part II, Chapter 1 and WMO (1993a, 2010a, 2010b, 2010c).

Performance monitoring: As real-time quality-control procedures have their limitations and some errors can remain undetected, such as long-term drifts in sensors and errors in data transmission, performance monitoring at the network level is required at meteorological analysis centres and by network managers. This monitoring is described in section 1.8 of this chapter. Information
can also be found in Part II, Chapter 1 and in WMO (2010a). It is important to establish effective liaison procedures between those responsible for monitoring and for maintenance and calibration, to facilitate rapid response to fault or failure reports from the monitoring system.

Testing and calibration: During their operation, the performance and instrumental characteristics of meteorological instruments change for reasons such as the ageing of hardware components, degraded maintenance, exposure, and so forth. These may cause long-term drifts or sudden changes in calibration. Consequently, instruments need regular inspection and calibration to provide reliable data. This requires the availability of standards and of appropriate calibration and test facilities. It also requires an efficient calibration plan and calibration housekeeping. See Part IV, Chapter 4 for general information about test and calibration aspects and to the relevant chapters of Part I for individual instruments.

Maintenance: Maintenance can be corrective (when parts fail), preventive (such as cleaning or lubrication) or adaptive (in response to changed requirements or obsolescence). The quality of the data provided by an instrument is considerably affected by the quality of its maintenance, which in turn depends mainly on the ability of maintenance personnel and the maintenance concept. The capabilities, personnel and equipment of the organization or unit responsible for maintenance must be adequate for the instruments and networks. Several factors have to be considered, such as a maintenance plan, which includes corrective, preventive and adaptive maintenance, logistic management, and the repair, test and support facilities. It must be noted that the maintenance costs of equipment can greatly exceed its purchase costs (see Part II, Chapter 1).

Training and education: Data quality also depends on the skills of the technical staff in charge of testing, calibration and maintenance activities, and of the observers making the observations. Training and education programmes should be organized according to a rational plan geared towards meeting the needs of users, and especially the maintenance and calibration requirements outlined above, and should be adapted to the system; this is particularly important for AWSs. As part of the system procurement, the manufacturer should be obliged to provide very comprehensive operational and technical documentation and to organize operational and technical training courses (see Part IV, Chapter 5) in the NMHS.

Metadata: A sound quality assurance entails the availability of detailed information on the observing system itself and in particular on all changes that occur during the time of its operation. Such information on data, known as metadata, enables the operator of an observing system to take the most appropriate preventive, corrective and adaptive actions to maintain or enhance data quality. Metadata requirements are further considered in section 1.9. For further information on metadata, see Part I, Chapter 1 (and Annex 1.C).

1.7 QUALITY ASSURANCE (QUALITY CONTROL)

WMO (2010c) prescribes that certain quality-control procedures must be applied to all meteorological data to be exchanged internationally. Level I and Level II data, and the conversion from one to the other, must be subjected to quality control. WMO (2010b) prescribes that quality-control procedures must be applied by meteorological data processing centres to most kinds of weather reports exchanged internationally, to check for coding errors, internal consistency, time and space consistency, and physical and climatological limits, and it specifies the minimum frequency and times for quality control.

WMO (2010a) gives general guidance on procedures. It emphasizes the importance of quality control at the station, because some errors occurring there cannot be subsequently corrected, and also points out the great advantages of automation. WMO (1993a) gives rather detailed descriptions of the procedures that may be used by numerical analysis centres, with advice on climatological limits, types of internal consistency checks, comparisons with neighbouring stations and with analyses and prognoses, and provides brief comments on the probabilities of rejecting good data and accepting false data with known statistical distributions of errors.
Quality control, as specifically defined in section 1.1, is implemented in real time or near real time to data acquisition and processing. In practice, responsibility for quality control is assigned to various points along the data chain. These may be at the station, if there is direct manual involvement in data acquisition, or at the various centres where the data are processed.

Quality assurance procedures must be introduced and reassessed during the development phases of new sensors or observing systems (see Figure 1.5).

Figure 1.5. Process for observation generation
1.7.1 **Surface data**

1.7.1.1 **Manual observations and staffed stations**

The observer or the officer in charge at a station is expected to ensure that the data leaving the station have been quality controlled, and should be provided with established procedures for attending to this responsibility. This is a specific function, in addition to other maintenance and record-keeping functions, and includes the following:

(a) Internal consistency checks of a complete synoptic or other compound observation: In practice, they are performed as a matter of course by an experienced observer, but they should nevertheless be an explicit requirement. Examples of this are the relations between the temperature, the dewpoint and the daily extremes, and between rain, cloud and weather;

(b) Climatological checks: These for consistency: The observer knows, or is provided with charts or tables of, the normal seasonal ranges of variables at the station, and should not allow unusual values to go unchecked;

(c) Temporal checks: These should be made to ensure that changes since the last observation are realistic, especially when the observations have been made by different observers;

(d) Checks of all arithmetical and table look-up operations;

(e) Checks of all messages and other records against the original data.

1.7.1.2 **Automatic weather stations**

At AWSs, some of the above checks should be performed by the software, as well as engineering checks on the performance of the system. These are discussed in Part II, Chapter 1.

1.7.2 **Upper-air data**

The procedures for controlling the quality of upper-air data are essentially the same as those for surface data. Checks should be made for internal consistency (such as lapse rates and shears), for climatological and temporal consistency, and for consistency with normal surface observations. For radiosonde operations, it is of the utmost importance that the baseline initial calibration be explicitly and deliberately checked. The message must also be checked against the observed data.

The automation of on-station quality control is particularly useful for upper-air data.

1.7.3 **Data centres**

Data should be checked in real time or as close to real time as possible, at the first and subsequent points where they are received or used. It is highly advisable to apply the same urgent checks to all data, even to those that are not used in real time, because later quality control tends to be less effective. If available, automation should of course be used, but certain quality-control procedures are possible without computers, or with only partial assistance by computing facilities. The principle is that every message should be checked, preferably at each stage of the complete data chain.

The checks that have already been performed at stations are usually repeated at data centres, perhaps in more elaborate form by making use of automation. Data centres, however, usually have access to other network data, thus making a spatial check possible against observations from surrounding stations or against analysed or predicted fields. This is a very powerful method and is the distinctive contribution of a data centre.
If errors are found, the data should be either rejected or corrected by reference back to the source, or should be corrected at the data centre by inference. The last of these alternatives may evidently introduce further errors, but it is nevertheless valid in many circumstances; data so corrected should be flagged in the database and should be used only carefully.

The quality-control process produces data of established quality, which may then be used for real-time operations and for a databank. However, a by-product of this process should be the compilation of information about the errors that were found. It is good practice to establish at the first or subsequent data-processing point a system for immediate feedback to the origin of the data if errors are found, and to compile a record for use by the network manager in performance monitoring, as discussed below. This function is best performed at the regional level, where there is ready access to the field stations.

The detailed procedures described in WMO (1993a) are a guide to controlling the quality control of data for international exchange, under the recommendations of WMO (2010b).

1.7.4 Interaction with field stations

If quality is to be maintained, it is absolutely essential that errors be tracked back to their source, with some kind of corrective action. For data from staffed stations this is very effectively done in near real time, not only because the data may be corrected, but also to identify the reason for the error and prevent it from recurring.

It is good practice to assign a person at a data centre or other operational centre with the responsibility for maintaining near-real-time communication and effective working relations with the field stations, to be used whenever errors in the data are identified.

1.8 PERFORMANCE MONITORING

The management of a network, or of a station, is greatly strengthened by keeping continuous records of performance, typically on a daily and monthly schedule. The objective of performance monitoring is to review continually the quality of field stations and of each observing system, such as for pressure measurement, or the radiosonde network.

There are several aspects to performance monitoring, as follows:

(a) Advice from data centres should be used to record the numbers and types of errors detected by quality-control procedures;

(b) Data from each station should be compiled into synoptic and time-section sets. Such sets should be used to identify systematic differences from neighbouring stations, both in spatial fields and in comparative time series. It is useful to derive statistics of the mean and the scatter of the differences. Graphical methods are effective for these purposes;

(c) Reports should be obtained from field stations about equipment faults, or other aspects of performance.

These types of records are very effective in identifying systematic faults in performance and in indicating corrective action. They are powerful indicators of many factors that affect the data, such as exposure or calibration changes, deteriorating equipment, changes in the quality of consumables or the need for retraining. They are particularly important for maintaining confidence in automatic equipment.

The results of performance monitoring should be used for feedback to the field stations, which is important to maintain motivation. The results also indicate when action is necessary to repair or upgrade the field equipment.
Performance monitoring is a time-consuming task, to which the network manager must allocate adequate resources. WMO (1988) describes a system to monitor data from an AWS network, using a small, dedicated office with staff monitoring real-time output and advising the network managers and data users. Miller and Morone (1993) describe a system with similar functions, in near real time, making use of a mesoscale numerical model for the spatial and temporal tests on the data.

1.9 DATA HOMOGENEITY AND METADATA

In the past, observational networks were primarily built to support weather forecasting activities. Operational quality control was focused mainly on identifying outliers, but rarely incorporated checks for data homogeneity and continuity of time series. The surge of interest in climate change, primarily as a result of concerns over increases in greenhouse gases, changed this situation. Data homogeneity tests have revealed that many of the apparent climate changes can be attributed to inhomogeneities in time series caused only by operational changes in observing systems. This section attempts to summarize these causes and presents some guidelines concerning the necessary information on data, namely, metadata, which should be made available to support data homogeneity and climate change investigations.

1.9.1 Causes of data inhomogeneities

Inhomogeneities caused by changes in the observing system appear as abrupt discontinuities, gradual changes, or changes in variability. Abrupt discontinuities mostly occur due to changes in instrumentation, siting and exposure changes, station relocation, changes in the calculation of averages, data reduction procedures and the application of new calibration corrections. Inhomogeneities that occur as a gradually increasing effect may arise from a change in the surroundings of the station, urbanization and gradual changes in instrumental characteristics. Changes in variability are caused by instrument malfunctions. Inhomogeneities are further due to changes in the time of observations, insufficient routine inspection, maintenance and calibration, and unsatisfactory observing procedures. On a network level, inhomogeneities can be caused by data incompatibilities. It is obvious that all factors affecting data quality also cause data inhomogeneities.

The historical survey of changes in radiosondes (WMO, 1993b) illustrates the seriousness of the problem and is a good example of the careful work that is necessary to eliminate it.

Changes in the surface-temperature record when manual stations are replaced by AWSs, and changes in the upper-air records when radiosondes are changed, are particularly significant cases of data inhomogeneities. These two cases are now well recognized and can, in principle, be anticipated and corrected, but performance monitoring can be used to confirm the effectiveness of corrections, or even to derive them.

1.9.2 Metadata

Data inhomogeneities should, as far as possible, be prevented by appropriate quality-assurance procedures with respect to quality control. However, this cannot always be accomplished as some causes of inhomogeneities, such as the replacement of a sensor, can represent real improvements in measuring techniques. It is important to have information on the occurrence, type and, especially, the time of all inhomogeneities that occur. After obtaining such information, climatologists can run appropriate statistical programs to link the previous data with the new data in homogeneous databases with a high degree of confidence. Information of this kind is commonly available in what is known as metadata — information on data — also called station histories. Without such information, many of the above-mentioned inhomogeneities may not be identified or corrected. Metadata can be considered as an extended version of the station administrative record, containing all possible information on the initial set-up, and type and times of changes that occurred during the life history of an observing system. As computer
data management systems are an important aspect of quality data delivery, it is desirable that metadata should be available as a computer database enabling computerized composition, updating and use.

1.9.3 **Elements of a metadata database**

A metadata database contains initial set-up information together with updates whenever changes occur. Major elements include the following:

(a) Network information:
   (i) The operating authority, and the type and purpose of the network;

(b) Station information:
   (i) Administrative information;
   (ii) Location: geographical coordinates, elevation(s);
   (iii) Descriptions of remote and immediate surroundings and obstacles;
   (iv) Instrument layout;
   (v) Facilities: data transmission, power supply, cabling;
   (vi) Climatological description;

(c) Individual instrument information:
   (i) Type: manufacturer, model, serial number, operating principles;
   (ii) Performance characteristics;
   (iii) Calibration data and time;
   (iv) Siting and exposure: location, shielding, height above ground;
   (v) Measuring or observing programme;
   (vi) Times of observations;
   (vii) Observer;
   (viii) Data acquisition: sampling, averaging;
   (ix) Data-processing methods and algorithms;
   (x) Preventive and corrective maintenance;
   (xi) Data quality (in the form of a flag or uncertainty).

1.9.4 **Recommendations for a metadata system**

The development of a metadata system requires considerable interdisciplinary organization, and its operation, particularly the scrupulous and accurately dated record of changes in the metadata base, requires constant attention.

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1 It is necessary to include maps and plans on appropriate scales.
A useful survey of requirements is given in WMO (1994), with examples of the effects of changes in observing operations and an explanation of the advantages of good metadata for obtaining a reliable climate record from discontinuous data. The basic functional elements of a system for maintaining a metadata database may be summarized as follows:

(a) Standard procedures must be established for collecting overlapping measurements for all significant changes made in instrumentation, observing practices and sensor siting;

(b) Routine assessments must be made of ongoing calibration, maintenance, and homogeneity problems for the purpose of taking corrective action, when necessary;

(c) There must be open communication between the data collector and the researcher to provide feedback mechanisms for recognizing data problems, the correction or at least the potential for problems, and the improvement of, or addition to, documentation to meet initially unforeseen user requirements (for example, work groups);

(d) There must be detailed and readily available documentation on the procedures, rationale, testing, assumptions and known problems involved in the construction of the dataset from the measurements.

These four recommendations would have the effect of providing a data user with enough metadata to enable manipulation, amalgamation and summarization of the data with minimal assumptions regarding data quality and homogeneity.

1.10 NETWORK MANAGEMENT

All the factors affecting data quality described in section 1.6 are the subject of network management. In particular, network management must include corrective action in response to the network performance revealed by quality-control procedures and performance monitoring.

Networks are defined in WMO (2010c), and guidance on network management in general terms is given in WMO (2010a), including the structure and functions of a network management unit. Network management practices vary widely according to locally established administrative arrangements.

It is highly desirable to identify a particular person or office as the network manager to whom operational responsibility is assigned for the impact of the various factors on data quality. Other specialists who may be responsible for the management and implementation of some of these factors must collaborate with the network manager and accept responsibility for their effect on data quality.

The manager should keep under review the procedures and outcomes associated with all of the factors affecting quality, as discussed in section 1.6, including the following considerations:

(a) The quality-control systems described in section 1.1 are operationally essential in any meteorological network and should receive priority attention by the data users and by the network management;

(b) Performance monitoring is commonly accepted as a network management function. It may be expected to indicate the need for action on the effects of exposure, calibration and maintenance. It also provides information on the effects of some of the other factors;

(c) Field station inspection described below, is a network management function;

(d) Equipment maintenance may be a direct function of the network management unit. If not, there should be particularly effective collaboration between the network manager and the office responsible for the equipment;
The administrative arrangements should enable the network manager to take, or arrange for, corrective action arising from quality-control procedures, performance monitoring, the inspection programme, or any other factor affecting quality. One of the most important other factors is observer training, as described in Part IV, Chapter 5, and the network manager should be able to influence the content and conduct of courses and how they are conducted or the prescribed training requirements.

1.10.1 Inspections

Field stations should be inspected regularly, preferably by specially appointed, experienced inspectors. The objectives are to examine and maintain the work of the observers, the equipment and instrument exposure, and also to enhance the value of the data by recording the station history. At the same time, various administrative functions, which are particularly important for staffed stations, can be performed. The same principles apply to staffed stations, stations operated by part-time, voluntary or contract observers and, to a certain degree, to AWSs. Requirements for inspections are laid down in WMO (2010c), and advice is given in WMO (2010a).

Inspections reports are part of the performance monitoring record.

It is highly advisable to have a systematic and exhaustive procedure fully documented in the form of inspections and maintenance handbooks, to be used by the visiting inspectors. Procedures should include the details of subsequent reporting and follow-up.

The inspector should attend, in particular, to the following aspects of station operations:

(a) **Instrument performance**: Instruments requiring calibration must be checked against a suitable standard. Atmospheric pressure is the prime case, as all field barometers can drift to some degree. Mechanical and electrical recording systems must be checked according to established procedures. More complex equipment such as AWSs and radars need various physical and electrical checks. Anemometers and thermometer shelters are particularly prone to deterioration of various kinds, which may vitiate the data. The physical condition of all equipment should be examined for dirt, corrosion and so on;

(b) **Observing methods**: Bad practice can easily occur in observing procedures, and the work of all observers should be continually reviewed. Uniformity in methods recording and coding is essential for synoptic and climatological use of the data;

(c) **Exposure**: Any changes in the surroundings of the station must be documented and corrected in due course, if practicable. Relocation may be necessary.

Inspections of manual stations also serve the purpose of maintaining the interest and enthusiasm of the observers. The inspector must be tactful, informative, enthusiastic and able to obtain willing cooperation.

A prepared form for recording the inspection should be completed for every inspection. It should include a checklist on the condition and installation of the equipment and on the ability and competence of the observers. The inspection form may also be used for other administrative purposes, such as an inventory.

It is most important that all changes identified during the inspection should be permanently recorded and dated so that a station history can be compiled for subsequent use for climate studies and other purposes.

An optimum frequency of inspection visits cannot be generally specified, even for one particular type of station. It depends on the quality of the observers and equipment, the rate at which the equipment and exposure deteriorates, and changes in the station staff and facilities.
An inspection interval of two years may be acceptable for a well-established station, and six months may be appropriate for automatic stations. Some kinds of stations will have special inspection requirements.

Some equipment maintenance may be performed by the inspector or by the inspection team, depending on the skills available. In general, there should be an equipment maintenance programme, as is the case for inspections. This is not discussed here because the requirements and possible organizations are very diverse.
REFERENCES AND FURTHER READING