Quaderno di METEOROLOGIA APERTA N°1

CHARACTERISTICS AND REPRESENTATIVENESS OF PRECISION METEOROLOGY IN ITALIAN NATIONAL CONTEXT

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1. SUMMARY

Meteorology and climatology have assumed an increasingly significant role in the economy and society at large. Whether they have an impact on management, decision-making or contractual agreements – particularly when used as evidence - they must be based on clear, precise and science-based information. An appropriate choice of sensors, stations, networks, type of dataset and analysis techniques can effectively address this need and achieve advanced levels of representativeness, which - in all cases – must refer to specific use cases and conventional definitions.

2. THE NATIONAL CONTEXT

2.1. STATE OF THE ART

The state of meteorological monitoring systems in Italy is currently a fragmented landscape. This is due to the absence of a National Meteorological Service, to the reliance on different actors, skills and institutions, and to the significant participation of private organisations. The main networks of weather stations and meteorological radar belong to the Air Force Meteorological Service, the National Civil Protection Department, regional bodies (e.g., environmental agencies, civil protection agencies, soil conservation agencies, agrometeorological services, etc.), research institutes (e.g., universities, CNR), NGOs, and public and private bodies operating in the area (e.g., land reclamation authorities, utilities, airports). These networks are characterised by a good density of weather stations, a significant historical data series and, in some cases, by the use of advanced sensors. Overall, this provides an adequate national coverage and a solid base of data that can be used for applications that require both a uniform and coordinated view and a rather high level of detail.

With regard to how data from public sources can be used in this field, reference should be made to the Guidelines of the Agenda for Digital Italy Agency [2] of the Presidency of the Council of Ministers and to the guidelines, policies and strategies adopted by WMO[3], the European Union[4] and ISTAT[5].

2.2. THE UNIFIED NATIONAL DATABASE

A national and coordinate system of meteorological monitoring sensors spread across the country was therefore established. The creation of this unified database enabled full use and significant enhancement of a common strategic infrastructure, as it was created and managed with public funds, both for mandatory purposes, such as monitoring climate change, and for several other applications, thanks to the aggregation of knowledge from public bodies, companies and citizen associations. This process began with a qualitative selection that led to, having defined the types of stations, sensors and data deemed suitable for use, a census being undertaken and integrated into the national system. This included:

- about 5,000 *in situ* stations belonging to over 30 networks that collect hourly and daily meteorological data;
- about 30 weather radars, almost all in C-band, belonging to the National Department of Civil Protection, regions and other bodies;
- some lightning monitoring networks using new technologies able to monitor and distinguish *Cloud-to-Groud* (CG), *In-Cloud* (IC) and *Cloud-to-Cloud* (CC) lightning strikes.

Almost none of the required characteristics for these sensors can be directly verified. As a result, the analysis is transferred to the organisations that install, manage and use the networks, aiming to assess whether an adequate guarantee of compliance with set standards could be provided, formal certifications could be achieved or, lastly, these networks were aligned to the guidelines developed by the WMO, the standardisation reference body.

3. NETWORK CHARACTERISTICS

Meteorological data is collected by measuring instruments called sensors, which identify the quantitative values that are being attributed to a given variable. A meteorological station normally contains several sensors, and – in turn – it forms part of a larger network of observations made up of several stations. Therefore, sensors represent the endpoint of an articulated system whose effectiveness is mainly determined by the following factors:

- location of stations;
- measurement technologies;
- transmission modes;
- maintenance and updates;
- validation and different data processing.

The sensors belong to two main categories:

- *in situ* sensors (ground weather stations);
- remote sensors (radar and weather satellites).

3.1. *IN SITU* SENSORS

3.1.1. Weather station networks

Available data originate from the following types of networks:

- **certified networks:** these networks are subject to formal certification procedures with regard to the type of instrumentation installed, the positioning of the survey sites, maintenance procedures and data validation;
- **networks compliant with WMO standards:** these are networks belonging to associations, research institutes, NGOs, land management companies that comply with installation, management, maintenance and validation procedures as per WMO Guidelines;

- **official networks:** these are networks belonging to governmental bodies and organisations that are legally responsible for meteorological-environmental monitoring. The fact that a network is official does not strictly guarantee that such network is fully WMO-compliant.

3.1.2. Stand-alone sensors

Isolated sensors and stations are generally not used. They may be used if they have been in operation for several years, if they are certified or if they comply with WMO standards.

3.2. REMOTE SENSORS

3.2.1. Weather radars, and their regional, national and transnational networks

Data acquired from meteorological radars and their networks is used to define precipitation (particularly if intense) at high temporal and spatial resolution, with infrastructure generally being installed and managed by regional authorities, the Air Force, the National Civil Protection Department, research organisations and meteorological services (or similar) from neighbouring countries.

3.2.2. Other sensors and remote networks

Other types of sensors with advanced and consolidated technology can contribute to a better and more detailed definition of the meteorological event:

- **Lightning detection networks:** for this type of monitoring, which also allows for detailed analysis of intense convective rainfall, the data is collected by new generation monitoring networks capable of discerning *Cloud to Ground* (CG), *In Cloud* (IC) and *Cloud to Cloud* (CC) lightning strikes,
- **Geostationary and polar meteorological satellites:** they are used to further define and verify the quality of meteorological phenomena.

4. DATA AND DATASETS CHARACTERISTICS

The quality of meteorological data collected in this way is generally considered reliable for its intended uses, which include in particular:

- updating the database;
- dataset aggregation with grids at different resolutions;
- operational use of historical and near real-time data.

However, quality is a necessary - but not the only - condition to be satisfied before data is definitively acquired. When evaluating data quality, consideration should also be given to other characteristics that need to be verified in order to identify a selection of data and datasets that are clearly defined, usable and robust. The same evidence is also required for the procedures used.

Data characteristics:

- **availability:** made available according to *open data* criteria;
- **accessibility:** standard formats;
- **free of charge:** free distribution in usable formats;
- **continuity:** included in a consistent historical series;
- **usability:** can be acquired timely;
- **third parties:** not attributable to other parties;
- **transparency:** accompanied by metadata;
- **unambiguousness:** they lend themselves to one single interpretation.

Dataset features:

- **continuity:** in time and space;
- **coverage:** adequate and consistent;
- **invariance:** over time of the same native dataset;
- **homogeneity:** representativeness remains constant in space and time;
- **representativeness:** defined.

Procedures used:

- **integration:** even between different sensors;
- **reanalysis:** retrospective analysis;
- **spatialisation:** implementation of regular grids at various resolutions.

5. REPRESENTATIVENESS OF METEOROLOGICAL DATA

"The representativeness of an observation is the degree to which it accurately describes the value of the variable needed for a specific purpose. Therefore, it is not a fixed quality of any observation, but results from joint appraisal of instrumentation, measurement interval and exposure against the requirements of some particular application".
WMO "*Guide to Instruments and Methods of Observation - Volume I - Measurement of Meteorological Variables*" (WMO-No. 8, 2018, Cap. 1.1.2).

This concept is used to define the spatial extent of the region around the observation point for which the value of a given observed quantity can be considered valid. In other words, the representativeness of an observed value can be conceptualised as follows: the result of an observation made at a given specific point can be compatible with the result of observations of the same value made at other specific points.
Both the WMO Guidelines and the extensive literature on the topic point out that representativeness is closely linked to the intended use of the data. As a result, its definition includes components of heuristic nature and contributions from experience.

5.1. REPRESENTATIVENESS OF SENSORS, STATIONS AND NETWORKS

5.1.1. Representativeness of sensors and stations

Meteorological sensors, like all measuring instruments, are subject to error factors that can be attributed to the instrument itself, or may be stochastic, systematic, linked to accuracy or uncertainty or have another origin. Thus, weather stations themselves may suffer from inadequacies due to location, maintenance regime, data transmission or processing. Furthermore, meteorological parameters are variable in time and space; in most cases these variations are captured by standard sensors, in other cases they are difficult or even impossible to detect, also due to structural reasons. For example, a significant thermal inversion in the air layers close to the ground cannot be measured by a thermometer which, in order to be compliant, must be located at a height of between 1.25 and 2 m above ground level. A strong wind gust can be significantly underestimated if the anemometer is not set at a height of 10 m. An intense storm can hardly be properly detected where the network of rain gauges is too thin.

On the other hand, meteorological radars are allegedly affected by attenuation processes, subject to over-estimation, and do not provide a precise value because the reflectivity values given in dBZ need to be converted into precipitation intensity (mm/h) using different equations depending on the type of precipitation.

In general terms, in the analysis of mesoscale phenomena the punctual value measured by single weather stations or single sensors is considered to be on average representative for a radius of 10-30 km with respect to their location, while C-band weather radars are representative for radii of 125 km, within which they return a sampling for every 1 sq. km of the area.

5.1.2. Representativeness of networks

The concept of representativeness can be referring to the single sensor, to the single weather station, to the single network or, finally, to all the networks, even if they consist of different sensors (weather stations, radar, lightning sensors). However, in absolute terms, an isolated station or sensor has a much lower representativeness than what can be achieved using multiple sensors, even if they use different technology, and auxiliary co-variables.

Representativeness depends on many factors. Some general standards can be found in the literature and are related to the purpose of the measurement. Agrometeorological or environmental applications require a higher level of detail than required by mesoscale or global applications.
The standards also change according to the topographical layout of the territory (e.g., the variability in mountainous areas is higher than in lowland areas), climatic homogeneity, measurement technique, location, land use, data transmission, data validation and others.
The spatial representativeness of the single meteorological sensors and stations, indicated within a radius of about 10-30 km from their location, does not consider a network structure, which often causes redundant coverage of the territory. Therefore, a single point is drawn from several measurements of different origin (e.g., rain gauge and radar) resulting in a greater guarantee of data acquisition, verification by comparison as well as a more effective spatialisation.

Since the national context of reference is structured in networks, representativeness is defined for this specific set-up rather than for single sensor or station and identifies the minimum conventional unit area to which it is possible to attribute the same value. The size of this area is a function of the density of the network, the type of sensors that contribute to the measurement and the intended use of the data. On the basis of the current national consistency of the measurement structures, the value of 1 sq. km is appropriate and able to reconcile the need for detailed representation of meteorological phenomena and their adaptation to the required spatial resolution. This value can also be derived from information acquired from auxiliary co-variables (e.g., DTM, land use maps, radar data).

5.2. REPRESENTATIVENESS OF DATASETS

5.2.1. Spatialisation and data integration

In precision applications, the meteorological data is attributed to defined space-time windows. Therefore, the absence of a meteorological station on a specific point requires the definition of some criteria of territorial representativeness that are adequate and proportionate to the specific need.
This is achieved through the spatialisation of the data, a process by which the value attributed to a point is not represented by a single data measured by a specific sensor, but instead it is expressed by the value obtained from the set of sensors that tap into that point and extended to the area it represents.

The spatialisation process does not consist of a mere geostatistical interpolation, but rather of the modelling of the statistical-climatological parameters that determine the particular spatial distribution of the values of the meteorological variable of interest. This is carried out as part of the reanalysis method.

5.2.2. Reanalysis and grids

The reanalysis (or retrospective analysis) of meteorological data is one of the main developments of recent meteorology and climatology. It represents a fundamental tool for studying climate variability and understanding climate mechanisms. This type of elaboration defines the scientific method used to create a global archive of how meteorological parameters change over time. It combines simulation models with real observations to generate a synthetic assessment of the state of the atmosphere. The reanalysis allows the development of datasets of past weather and climatic trends, both near real-time and historical.

The time series of the past states of the atmosphere are reproduced in all its facets on three-dimensional grids, i.e. matrices, which cover the earth's surface and also reconstruct the vertical profile of weather and climatic variables. The product of the reanalysis is therefore the distribution of the data on regular grids of different sizes, according to the accuracy required for a given use and to the temporal depth deemed suitable to provide a useful view of the variability of climatic dynamics.

Reconciliating of a series of measures irregularly distributed over the territory to a grid is very important for the following specific purposes:

- reduction of lack of spatial homogeneity resulting from the use of station data only;
- total coverage with reliable data of areas without stations,
- climate and meteorological analysis,
- processing of indices at different scales,
- input to statistical/mathematical models.

Reanalysis datasets are valued products in the statistical and analytical field because, as opposed to traditional measurements, they provide data that are continuous and homogeneous in space and time, making them easy to use for a range of applications. The potential of reanalysis is maximised in contexts, like the Italian one, where it is possible to calibrate the process over consistent historical records and a sufficiently dense and homogeneous network coverage.

In order to achieve high quality results and avoid the introduction of spurious and artificial trends, it is very important that the specific analytical setup is used without modification over the entire validity period.

In fact, a dataset consisting of grids at different temporal resolutions would compromise its temporal homogeneity. This would generate a spatialisation of the data on cells of different areal coverage and introduce a variability in the representativeness of the data, due to detrimental interference with coarse-mesh grids.
On the other hand, with a constant setup, the grid that supports the dataset is always composed by the same cells, thus enabling an easy and homogeneous reprocessing of the data.
The results of the process are plotted on grids with variable grid step. Wide scales can be used for the representation of global phenomena and scales of increasing granularity can be used for more detailed needs, according to the data availability and the models employed. The computational and economic resources necessary for advanced reanalysis should not be underestimated. In the case of Italy, the consistency between historical meteorological data and the technologies adopted make it possible to reach a grid resolution of 1 km. Hence this maximum level of definition can be achieved for the products of meteorological reanalysis, which in turn must ensure the necessary homogeneity in the setup of the datasets.

The 1 sq. km pixel also marks the limit below which representativeness would lose not only numerical consistency but also reliability.

5.3. APPLICATIONS OF PRECISION METEOROLOGICAL DATA

Technological evolution requires that operating and decision-making processes are based on a growing number of variables; among these, the one connected to atmospheric phenomena, whose dynamics have a significant impact both in the short and medium-long term, appears with increasing frequency. Meteorology and climatology have achieved such a level of innovation that they can meet this need and provide precise representations of individual atmospheric events. In addition, recent scientific advances have also made it possible to update and re-aggregate added value to all the historical meteorological data collected over the last decades. The ability to work with this temporal *continuum* of datasets (historical, near real-time and forecasting) has considerably increased the representativeness of such data. This has widened its use within decision-making, management and contracts; these applications require that a past phenomenon - or its temporal case history - is backtracked to values (or ranges of values) and a specifically defined space-time framework.

This data is today widely used for risk management, where they support all severe weather assessment activities as well as the adoption of policies aimed at mitigation of potential damages caused by adverse events. However, this availability of historical series also allows medium-long term analyses that support testing of new insurance instruments (e.g., parametric insurance solutions), for which it is necessary to develop robust weather-climate indices based on datasets of adequate historical background.

Another application includes contracts in the broadest sense, not only insurance contracts. Contractual agreements may include clauses that apply upon the occurrence of certain weather conditions or when certain threshold values are breached, limiting the contractual liability or conditionality of the obligations agreed upon between the parties. In these situations, the supplier of meteorological data, especially if accepted by both parties, must guarantee professionalism, objectivity and impartiality, and also be able to provide scientific evidence of the reliability of the data provided.

Similarly, in the forensic field, both in the role of court-appointed expert witness and *ex parte* expert witness, the consultant must be able to offer a representative picture that accurately captures the severity and intensity of the phenomenon and its space-time characteristics, supported by an objective approach based on official data and science-based elaborations.

For companies and organisations that operate in close contact with the territory, such as agriculture, water management or environmental management in general, meteorology has always been an important component both in operational activities as well as in planning and design. The ability to access more refined products now enables the application of highly sustainable digital and smart solutions. It should also be pointed out that, for these latter applications, the WMO accepts that an instrument may not adhere to its own guidelines because the operational, localised and targeted need for meteorological data can be at odds with a high level of representativeness and territorial spatialisation of the data itself.

5.4. SUMMARY AND CONCLUSIONS: THE CONVENTIONAL METEOROLOGICAL PIXEL

"*In the simplest terms, if the data can answer the question, it is representative*" (Ramsey and Hewitt, 2005).

Representativeness of meteorological data is of interest to a wide range of international actors, from the WMO - the reference organisation - to a widespread scientific community, to technical, operational and regulatory bodies and institutions, to the world of economics and the environment, to community-based organisations. For these organisations, the definition of representativeness is tailored according to various considerations of technical-scientific or legal-administrative nature, albeit always in relation to the purpose and methods of use of the data.

The conventional surface area value that acts as a minimum pixel of representativeness is therefore not immediately identified but it is the result of a complex process that, on the one hand, synthetises supporting technologies, and on the other hand pragmatically considers the specific needs of the function, on the basis of a substantial wealth of experience deriving from widespread use.

5.4.1. A single pixel

The first conclusion is that, for precision applications, it is appropriate to identify a single pixel of reference for all meteorological parameters, both for data collected in real-time and data subjected to reanalysis, for the following reasons:

- meteorological data collected in real-time is feeding into the historical dataset,
- datasets must be constant in time and space; in the reanalysis processes, in fact, a different spatialisation of the data compromises their homogeneity by introducing detrimental interferences.

5.4.2. The choice of 1 sq. km

The second conclusion is the identification of 1 square kilometre as the minimum surface area - or pixel - of representativeness due to the following reasons:

- it provides a detailed representation of meteorological phenomena,
- it is sustainable by the technologies used,
- it is adapted to the scale of operational needs,
- it is credible and reasonable,
- it is a consistent basis for dataset standardisation for all applications.

From a purely operational point of view, a blanket application of this surface area unit can be mitigated, for example, by extending the value of one pixel to a limited amount of neighbouring pixels.

5.4.3. Convention as a tool

The third conclusion is around the assumption that conventionality, which forms the basis of the definition of representativeness (although with the provisos expressed so far), may lead to a different value to cater for new needs or technological advances.

6. NOTES

1) Massimo Crespi, former Inspector of the State Forestry Corps, Director of the Experimental Centre for Avalanches and Hydrogeological Defense of Arabba (Veneto Region), Director of the Meteorological Centre of Teolo (ARPA Veneto), Director of Research and Communication of ARPA Veneto, Director General of Planning and Programming of the Veneto Region, National Delegate at the UN WMO (World Meteorological Organization), Director of the Environmental and Hydrological Monitoring Centre of the European Union in Asunciòn (Paraguay). Currently CEO of Radarmeteo Srl and President of Hypermeteo Srl.
2) Digital Italy Agency of the Presidency of the Council of Ministers. (2018). "Public data - Guidelines for public information assets".
3) WMO: World Meteorological Organization, UN Technical Agency tasked with global coordination of meteorology, climatology and operational hydrology.
4) European Commission, (2018). *Data portal: Open data maturity in Europe. Report*.
5) ISTAT. The charter of services, dissemination and communication to users.

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