GCOS
KEEPING WATCH OVER OUR CLIMATE

WORLD METEOROLOGICAL
ORGANIZATION

INTERGOVERNMENTAL
OCEANOGRAPHIC
COMMISSION

WEATHER RADAR DATA REQUIREMENTS FOR CLIMATE MONITORING

GCOS-223

UNITED NATIONS
ENVIRONMENT PROGRAMME

INTERNATIONAL COUNCIL
FOR SCIENCE

Chair, Publications Board

World Meteorological Organization (WMO)

7 bis, avenue de la Paix

P.O. Box 2300

CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 84 03

Fax: +41 (0) 22 730 80 40

E-mail: Publications@wmo.int

Background Information for the mandate of the GCOS Task Team on the use of weather radar for climatological studies.

Action A24 of the GCOS Implementation Plan (GCOS-200), calls for the implementation of an archive for radar reflectivities. The Commission for Basic Systems (CBS) at its Sixteenth session (WMO-1183) endorsed the GCOS Implementation Plan and “Decides to support Members, as appropriate, in the implementation of the actions identified in the GCOS Implementation Plan”. EC-69 (WMO, 2017 - WMO, 1196) invited members “To work towards the full implementation of the Global Climate Observing System (GCOS) implementation plan.”

At the 22nd Session of the GCOS/WCRP Atmospheric Observation Panel for Climate (AOPC-22, Exeter, UK, March 2017), AOPC agreed on the creation of a dedicated task-team to work on a proposal on how best to proceed on the use of radar data for climate studies. The Task Team was established jointly with the Commission of Climatology (CCl).

The Task Team was charged with:

- Define climate monitoring requirements for precipitation radar data, define relevant metadata, and define best practices. Propose key parameters to be used for climate monitoring. Identify procedures for quality control of radar data specifically for climate applications.
- Propose recommendation on how to harmonize retrieval and calibration methods, taking into account existing working groups.
- Archives: Assess the status of existing international and national archives, including their extent and quality. Study whether existing data centres should be expanded or new structures should be created. Identify how to facilitate proper and standardized storage of local radar data for eventual reprocessing at a later stage to support climate monitoring.
- Suggest procedures for handling historical data, e.g. how to document the existing data, requirements for reprocessing with new algorithms, processing for extracting data from archives for quality control of the data.

The Task Team consists of Andreas Becker (Deutscher Wetterdienst (DWD)-Germany), Katja Friedrich (University of Colorado, USA), Rainer Hollmann,(Deutscher Wetterdienst (DWD)-Germany), Elena Saltikoff (Finnish Meteorological Institute (FMI), Finland), Joshua Soderholm (Bureau of Meteorology, Australia), Bernard Urban (MeteoFrance, France).

The Executive Council in 2018 was informed that AOPC had taken the lead to explore how to use radar to compliment precipitation climatology and requested that the work be undertaken in collaboration with CCl. The report of the first meeting of the task team was made available.

The Task Team has worked closely with the Commission for Instruments and Methods of Observation (CIMO) Inter-Programme Expert Team on Operational Weather Radars (IPET-OWR).

This report summarizes the recommendations of the task team. Further work should be carried on in collaboration with the WMO Integrated Global Observing System (WIGOS), CIMO IPET-OWR and CCl.

Table of Contents

1. EXECUTIVE SUMMARY 5

2. INTRODUCTION 5

3. WEATHER RADAR DATA REQUIREMENTS FOR CLIMATE MONITORING 6

3.1 Definition of key parameters 6

3.2 Metadata relevant for climate 7

3.3 Quality control and its documentation 8

3.4 Application of GCOS climate monitoring principles to radar data 8

4. Assessment of the status of existing archives 8

5. GUIDANCE ON HOW TO ORGANIZE PROPER AND STANDARDIZED STORAGE AND USER INTERFACE OF LOCAL RADAR DATA AND METADATA 11

5.1 General principles 11

5.2 Storage organization 11

5.3 User interface to the data and metadata 12

6. GUIDANCE TO HANDLE HISTORICAL DATA 12

6.1 Background.... 12

6.2 Inventory 13

6.3 Data rescue / conversion 13

6.4 Analysis.... 14

6.5 Useful links 14

7. Summary and recommendations....14

ANNEX 1: Draft for Mandatory Weather Radar Metadata for International Exchange by IPET-OWR....16

ANNEX 2: Survey and results 18

ANNEX 3: Use of Weather Radar Data for Climate Data Records in WMO Regions IV and VI-URSDCM report 25

1. Introduction and scope of this paper....26

2. Motivation for the Use of Weather Radar Data for Climatological Purposes....26

3. Encountered Challenges....27

4. Activities and Experiences of Deutscher Wetterdienst (DWD)....28

5. Use of Weather Radar for Climate Data Records in WMO Region VI 29

6. Conclusion 33

References....36

1. EXECUTIVE SUMMARY

An international task team, consisting of both radar experts and climate specialists, has defined requirements for radar data to be used for climate monitoring. The most essential parameter is radar reflectivity, dBZ, to be saved as 3-dimensional volumes (known as Level 2 data – note, the definitions for ground based radars are different from those used for satellites). For essential metadata, requirements for climate do not differ from other applications, but it is essential to save the history of metadata related to different measurement configurations over the years.

Processing historical data is an effort of considerable manpower that requires careful planning. It is suggested to follow the general recommendation for data rescue and harmonization and to provide special documentation. It is recommended that the rescue projects produce and save Level 2 data, which allows future reanalysis with newest algorithms

In a survey executed during 2017, several WMO members reported decade-long archives allowing access for researchers. It is recommended, as a next goal, to establish an international portal to allow harmonized access to radar data, metadata and documentation.

2. INTRODUCTION

Since the 1950s, weather radars have been widely used to detect and quantify precipitation and severe weather. The phenomena monitored with weather radar include in addition to precipitation also severe mesoscale phenomena such as hailstorms and tornadoes and issuing warning of severe hail, tornadoes, blizzards, and flooding has become impossible without the four-dimensional, high resolution data from operational state-of-the-art weather radar networks. Target applications are extreme precipitation statistics, long-term aggregations, severe convection statistics and reanalysis. The statistics are also useful for ground validation of satellite precipitation products, and development of hydrological models.

Radar networks are now covering large parts of the densely-populated areas of the world (See Figure 1). Some of the networks have collected data for over 30 years, and in spite of some of the older radar information having been lost due to the rapid growth of information technology, scientists have started to use the information for climate studies.

The long time series needed for climate studies require a considerable effort in homogenization, and current reanalysis project have challenges in spatial harmonization. Recovery of past data can be successful in some areas, but the global challenge is to manage the data archived today so more homogenous time series will be available for the future generation.

In 2016, the Global Climate Observing System (GCOS) Atmospheric Observations Panel for Climate (AOPC) established a task team to assess the weather radar data requirements for climate monitoring. This report documents the results of that task team. Its objective is to widely establish weather radar information for the climate science community by providing an overview of what is currently available, defining standards for storing historic and future radar data, and giving recommendations for managing historic and future radar data.

Task Team Members

- Andreas Becker, Deutscher Wetterdienst (DWD), Germany
- Katja Friedrich, University of Colorado, USA
- Rainer Hollmann, Deutscher Wetterdienst (DWD), Germany
- Elena Saltikoff, Finnish Meteorological Institut (FMI), Finland
- Joshua Soderholm, Bureau of Meteorology, Australia
- Caterina Tassone, GCOS, Switzerland

- Bernard Urban, Meteo France, France

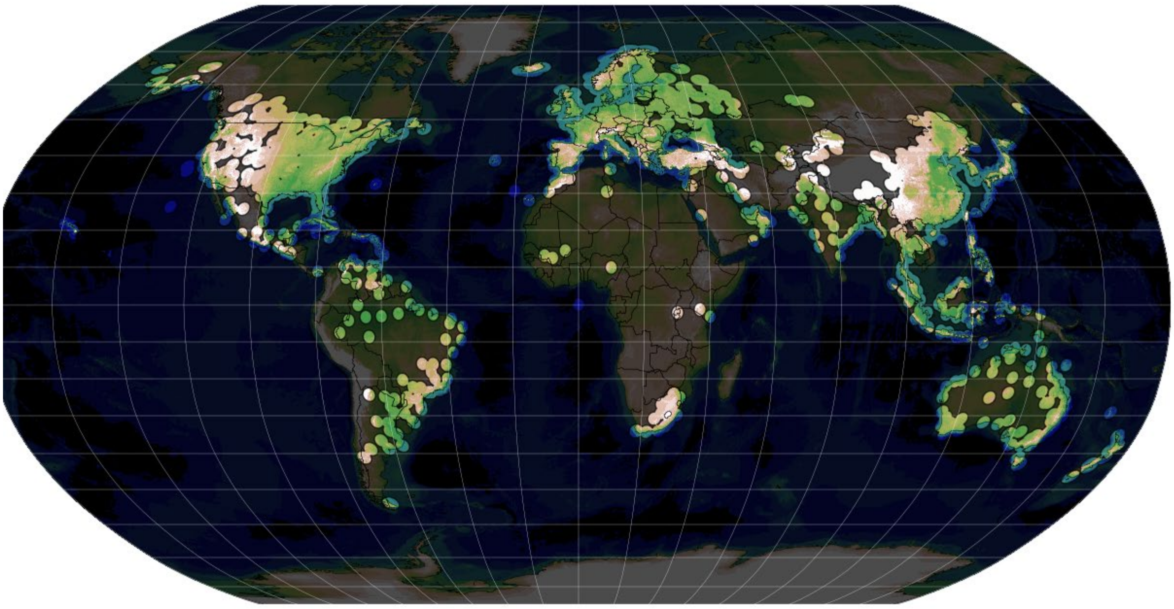


Figure 1. A map of radar coverage in the world by Maik Heistermann, from an articlesubmitted to *Bull.Am.Met.Soc.* (Saltikoff et al., 2019)

3. WEATHER RADAR DATA REQUIREMENTS FOR CLIMATE MONITORING

In a nutshell

- The following information should be saved:
    - Radar parameters (e.g., reflectivity in dBZ NOT accumulated rainfall rate in mm) as 3-dimensional volume scans in the highest resolution possible (NOT 2-dim images or composites).
    - Log of changes of important metadata (e.g., upgrades to Doppler).
- Minimum recommendations for metadata needed for radar data should be defined as in Annex 1 of this document.
- A terminology for radar matters, including metadata elements and quality control terms, should be defined jointly with the Commission for Instruments and Methods of Observation (CIMO) Inter-Programme Expert Team on Operational Weather Radars (IPET-OWR).

3.1 Definition of key parameters

Data for the following key radar parameters* should be saved as Level 2 files:

- Horizontal Reflectivity (ZH)
- Radial Velocity (VRAD)
- Spectrum Width (WRAD)
- Differential Reflectivity (ZDR)
- Correlation Coefficient (RhoHV)
- Differential phase (PhiDP)

*It is acknowledged, that single polarization radars cannot provide ZDR, RhoHV or PhiDP and that VRAD and WRAD are available only for Doppler radars.

For quality control purposes, when feasible, it is recommended saving uncorrected reflectivity (TH), signal quality index (SQI), and clutter-to-signal ratio (CSR).

For the level definitions we refer to the definitions in the WMO Integrated Global Observing System (WIGOS) guidance by IPET-OWR (see Table 1). It is noted that both international satellite and operational weather radar community in USA have also defined "Level 2". The definitions of levels in satellite terminology are fundamentally different due to different measurement and processing approaches.

To ensure that radar data can be easily used by the research community and other relevant parties, it is necessary to produce and store Level 3 products, such as rainfall rate or hydrometeor classification, and level 4 products, such as gauge adjusted rainfall. However, as processing algorithms develop over years, maintaining homogeneity in the time series is challenging, and for reprocessing purposes it is mandatory to save also Level 2 data. The difference in amounts of stored data is not significant and the problem is not the disk space, but rather the management of data.

Table 1 Full set of definitions of Data Levels

The table below is proposed by WMO IPET-OWR as the standard wording to describe 'levels' of weather radar data.

	Definition
Level 0	Data at full resolution as received at the sampling rate of the receiver. Generally only available internal to the system. Special equipment may be required to measure and record such data.
Level 1	Data in sensor units also known as "time series" or "I/Q" (in-phase and quadrature) data. Produced and processed by the instrument's signal processor. Generally not recorded except for limited durations on operational radars. Commonly recorded on research radars.
Level 2	Derived radar variables or moments (reflectivity, radial velocity, differential reflectivity, etc.) at full resolution after aggregation and filtering. Organized in polar coordinates by rays, range bins and quantities. Also, known as "sweep" and "volume scan" data.
Level 3	Radar products which are derived primarily from level 2 data. May be in the level 2 polar coordinates (particle ID, quality metrics, etc.), or in other coordinates systems such as vertical profiles or Cartesian grids (CAPPI, rain rate estimates, etc.).
Level 4	Higher order products which may include data from multiple measurements. This includes products which composite multiple radars (mosaics) as well as those that blend data from other sources (satellites, rain gauges, NWP etc.).

3.2 Metadata relevant for climate

The metadata needed for climate monitoring are not different from those for other applications, with the additional requirement for climate monitoring to keep track of the history of hardware and algorithm changes and make sure that data can still be processed in the future.

It is important to define a common data format and we endorse the efforts of IPET-OWR.

Conversion of old stored data to new formats defined after the data was originally stored can be supported and made easier by collecting and sharing the links to conversion software among the radar community

The modern data models and formats include some metadata in connection with actual data, which is not the case for historical data. In the future, not all metadata should be included in the data files and some of the more static metadata should be available separately (for example the model type of the radar at a given time can help define the properties of a dataset used in a certain study).

IPET-OWR has defined a set of metadata (Annex 1) which are considered mandatory for the international exchange of weather radar data. These values define the used instrument, and they are essential in describing its abilities to measure precipitation, especially the extreme values and small-scale variability.

3.3 Quality control and its documentation

The methods which should be used for quality control for climate monitoring are no different than those for other applications, with the additional requirement mostly related to the need to keep track of the history of changes in the quality control. This has to be recorded in the documentation of the applied quality control methods.

A special challenge when preparing or using the documentation, is the definition of terminology. For example, the term "Doppler filter 3 applied" has not been defined universally and it may have a different meaning for different radar manufacturers or software versions. Another example is the use of the term "clutter removed" which is completely ambiguous: different types of clutter have been removed during the decades of development of clutter cancellation methods, with some methods also removing valid weather signals. This can lead to a wrong interpretation of trends in precipitation climatology. And in this specific example, and valid also for other cases, it is also preferred to rather than remove data to flag data. Therefore, in order to have accurate documentation, it is mandatory to agree on a terminology which also includes metadata elements and quality control terms.

3.4 Application of GCOS climate monitoring principles to radar data

Most of the GCOS climate monitoring principles[1] are applicable to radar data.

The GCOS climate monitoring principle No. 2 states that "A suitable period of overlap for new and old observing systems is required". However, radars are advanced electronic devices with a limited lifetime which cannot be prolonged, and technology is advancing at such a speed that typically any outdated instrument is replaced with a next generation system, not an identical one. Therefore, due to high cost of radars and their infrastructures, overlapping time series are seldom available. According to GCOS climate monitoring principle No. 7 "High priority for additional observations should be focused on data-poor regions, poorly observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution." This is often not possible for radar observations, as regions with poor coverage cannot afford the high cost related to the purchase and maintenance of radars.

4. ASSESSMENT OF THE STATUS OF EXISTING ARCHIVES

Current interest of using radar data for climate monitoring and reanalysis is increasing. Knowledge of what is available at the present in existing archives is fundamental, as it contributes in providing guidance for the future use of radar for climate applications.

In 2014, the WMO Commission for Climatology (CCl) Task team on the Use of Remote Sensing Data for Climate Monitoring (TT-URSDCM), decided to prepare an *overview of the activities* within WMO Regions on radar climatologies. The information was compiled through personal communication, by examining the

---

[1] The ten basic principles (in paraphrased form) were adopted by the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) through decision 5/CP.5 at COP-5 in November 1999. This complete set of principles was adopted by the Congress of the World Meteorological Organization (WMO) through Resolution 9 (Cg-XIV) in May2003; agreed by the Committee on Earth Observation Satellites (CEOS) at its 17th Plenary in November 2003; and adopted by COP through decision 11/CP.9 at COP-9 in December 2003

webpages of the Region VI Members' NMHS and by reviewing the existing literature on the use of weather radar for climate data records. Most of the countries used radar only for weather observations and forecasting, however 10 countries (Belgium, Denmark, France, Germany, Ireland, Italy, The Netherland, Sweden, Switzerland, the United Kingdom and Northern Ireland) used weather radar data for climate applications. Literature included studies about severe storm occurrence, hail events, convection studies and thunderstorms activities. The TT-URSDCM report included a detailed account of the activities and experiences of DWD, that has started to reprocess and analyze the radar-based reflectivity measurements of the German network starting in 2001. Germany, together with Switzerland, were the only countries performing projects regarding generating, provision and archiving of long time series of adjusted radar precipitation. The report can be found in Annex 3.

As part of the process of *assessing the existing archives*, the GCOS radar task team prepared a survey on radar data archives. The survey consisted of 7 questions aimed at learning the existence of the archive, its completeness, the record length, the existence of metadata and the availability and access of the data. It was designed such that it would be possible to complete the whole survey in less than 10 minutes. The survey questions and the answers, are provided in Annex 2.

The survey was sent out on October 2017 to radar experts, to national focal points of the weather radar metadata group, as well as to the members of the Inter-Programme Expert Team on Operation Weather Radars (IPET- OWR). Figure 2 shows the map of the 47 countries who responded to the survey.

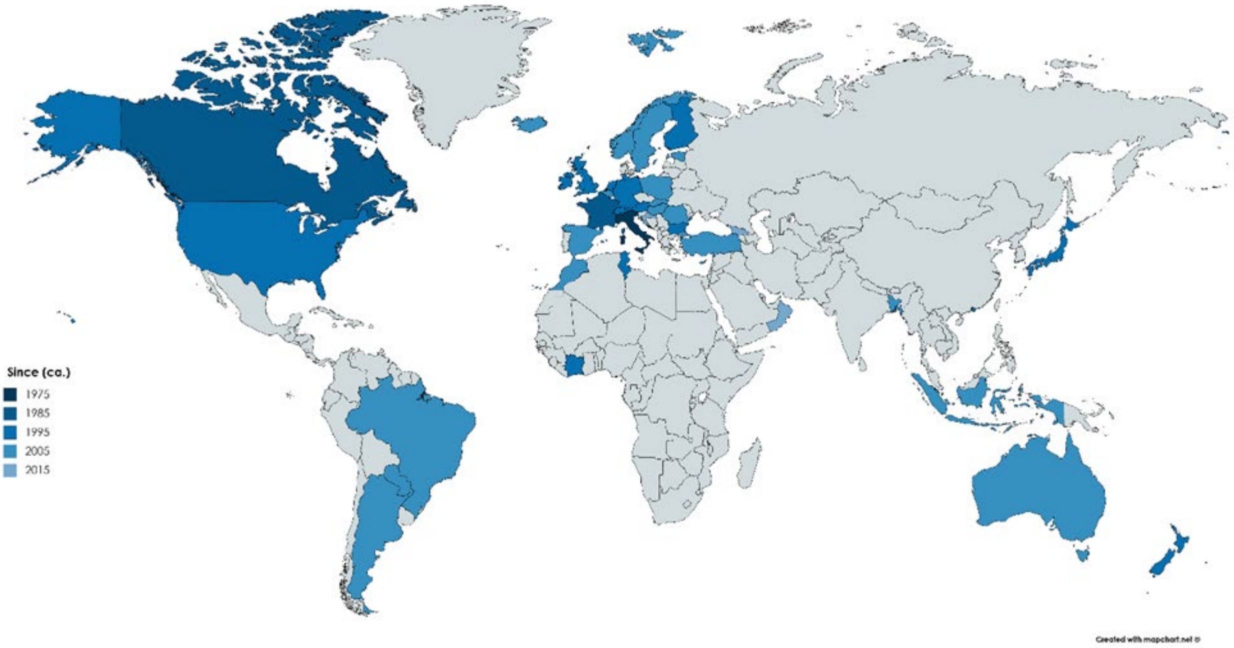


Figure 2. The oldest radar data by WMO member.

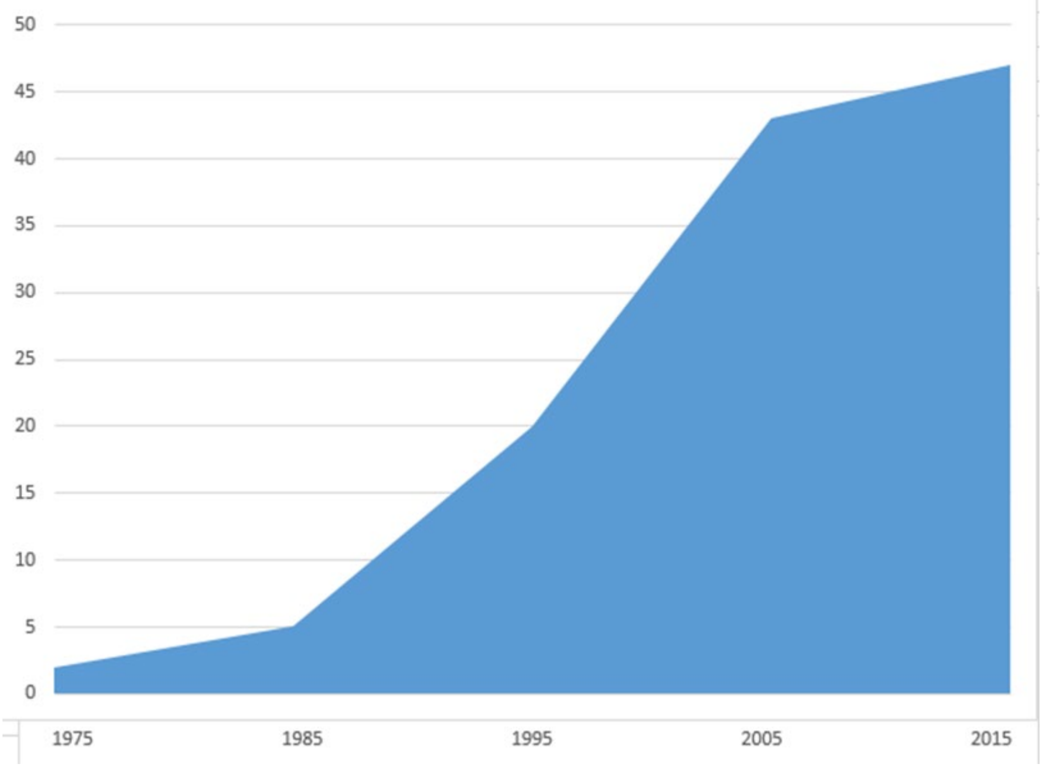


Figure 3. Cumulative sum of members archiving radar data since a particular year.

Question 1 asked to specify the earliest data in the archive. Results are summarized in figure 3. Note that even if the archives cover only one radar, or do not continue until present date, the entire country is shaded according to the oldest data. Twenty countries out of 47 have archives older than 1995. Each of the responsible person who had answered indicating that the archive went back to 1995 or more, was contacted via email requesting additional information on whether the archive had continuous digital records, since when and for how many radars.

From the individual comments of those members who have over 20 years of data we can summarize the following:

- Data from 1970s to 1990s is often patchy. Some of the oldest data is stored as images, and usually the resolution in vertical, horizontal and temporal directions is worse than in the later archives;
- Climate studies with the data from the first decades would in most cases not be cost-effective due to patchiness of the data;
- The continuous time series of reasonable quality start typically around 1998, so 20 years of data could be used already. However, during this period radar locations have changed, the coverage has increased and processing methods have improve, so the time series are by no means homogenous.

Results from the survey show also that 90% of the archives have saved dBz in original coordinates, 16 archives have recorded metadata inside the archive, 21 only partly and 10 do not have any. Almost every archive has metadata specifying the position of the radar, half of them have also metadata on the scanning strategy, while only 4 have electronic calibration results. The format of the archive content is documented in 25 archives, while 14 have only partial information and 7 do not document the format of. The data in 17 archives are available and regularly used, other 19 archives make the data available but recognize that it might be complicated to get access to the data. Only for data in 10 of the archives, retrieving one year of data requires the effort of having to ask IT people to mount disks or tapes. However, for more than 80% of the reviewed archives data are accessible to be used for researchers out of the institute. As data stretching in the past is very important for climate studies, this is a very encouraging result.

5. GUIDANCE ON HOW TO ORGANIZE PROPER AND STANDARDIZED STORAGE AND USER INTERFACE OF LOCAL RADAR DATA AND METADATA

5.1 General principles

NMHS spend in general a lot of resources to keep old climatological records safe (using backup storage locations for example) and usable in the future. This is not necessarily the case for radar data archives in other organizations. Many radar installations were originally made for real time applications only, and the storage strategy was not defined taking into account the climatological application. However, if an organization is serious about radar data archives, storage strategy should include the additional needs for climate studies.

5.2 Storage organization

The storage organization of an archive can have a big impact on access performance and load on the archiving system.

Meteorological measurements are obtained by transmission channels which are often specific of the type of the data (e.g. GTS for AWS stations and direct link to satellite). Meteorological measurements are also sorted simply by the type of the message carrying them. Climatological archiving is most naturally done by reproducing a division of the input data stream into a corresponding section of archived data.

Radar data is collected at once over a large spatial domain, and therefore the archive could be organized to ensure that the use of the radar data in the archive over this large domain is easier. This nominal high geo-temporal resolution of radar data, which is more difficult to find for traditional climate archive, is a particular strength and allows quality control based on stability over both time and space to be implemented.

The chunks of data of the archive have at least two “dimensions”: one dimension for the type of data and the other dimension for the time interval. For costly observation systems gathering huge amount of data, like satellite or radars, there can be other dimensions such as the name of the system and the kind of subtype of data archived. For a long time, due to the existing technologies, it was not possible to use a real database system, and the archive was file system based: one file contains one of the above chunk of data (in original or radar-specific data format), and the elements of the pathname of the file identifies the dimensions cited above.

The radar archive organization at Meteo France is used as an example below:

Files are in the archiving computer with pathnames like:

/RADAR/LOCAL/MOMU/2015/0208_1 which means it is a tar file of all reflectivity radar data for the 8 February 2015 for the radar of Momuy.

/RADAR/LAME_EAU/LOCAL/NIME/2016/0423_000005 which means it is a tar file of all 5 minutes QPE radar data for 23 April 2016 for the radar of Nîmes.

If a study focuses on a limited area (say 100 km^2) covered by a few radars, all the data available for these radars will need to be downloaded, which is 3 order of magnitude more (the area covered by a radar is typically around 200 km x 200 km = 40 000 km^2) than what is really needed.

The situation at the Deutscher Wetterdienst is similar and not likely to change soon. There the storage demanding data files are kept on a flat-file system and the database is limited to the pointers to these files. This puts a high demand on the format used for the data files, namely to stay de- and encodable for a long time if not forever, weighing sustainability of a format higher than the compression rate associated. Their reason for using a zipped clear-text format is that a zipped clear-text format might lose a bit on compression but will still be usable in 30 years, which is much more important.

With the new technologies, it is theoretically now possible to organize radar archives differently: database records having columns for name of radar, pixel location, date of pixel value, reflectivity value of pixel and metadata can now be used and this would eliminate the need to document and maintain decoders for the data formats used in the file system based archiving method. However, for the foreseeable future, the implementation of this more efficient archive in the NMHS will be prevented by the amount of work required to convert the existing file system archive to the new structure, and the need to plan for a migration path to a new database system if the old one becomes obsolete. The implementation of this more efficient archive in the NMHS would require extensive work.

5.3 User interface to the data and metadata

The way data are extracted from an archive by NMHS can vary wildly, as shown by the survey results about existing archives. The following recommendation would help improve this process:

- Automate access to the data, avoiding the involvement of a human operator. Widely used data access protocols (DAP) are encouraged. DAP services have significant interoperability and can provide both programmatic and web-based access.
- Homogenize the user interface to the catalogue of data and their related metadata. The obvious candidate would be a Global Information System Center (GISC), encompassed in WMO Information System (WIS). NMHS will have to add radar archives to the existing GISC catalogue, with at least the metadata in Annex 1.
- For increased efficiency, access to radar data of larger regions could be organized using WMO's Data Collection and Production Centres (DCPC).
- Improve data transfer capacity. The bandwidth requirements (capacity of computer system for data transfer) between a NMHS and an external user to download even small areas of interest for the studies can be problematic and various bandwidth throttle tricks are used to limit the risk of overloading the NMHS transmission lines, resulting in a poor end user experience. Copying the radar archives to a cloud service and downloading data requests from there could improve the situation.
- Establish a global portal to allow harmonized access to radar data, metadata and documentation. This will require a lot of transcoding work, as the underlying formats and aggregation granularity for the data are very diverse depending on the source but could be a more easily achievable goal once the suggestion made above to structure the archives as real databases will be implemented.

6. GUIDANCE TO HANDLE HISTORICAL DATA

6.1 Background

During the first decades of digital weather radar networks, radar measurements were sometimes saved as 2-dimensional image files. Even though these images are often problematic for reconstruction of precipitation records, they may have value as sources of qualitative interpretation, such as monitoring frequency of severe weather phenomena. In the same category are dataset without the minimum metadata described in annex 1. These cannot be used for quantitative studies, and should be at best be considered qualitative data similar to image files (or photographs).

The technology needed for reading very old media (such as magnetic tapes) may not be available in the future decades. Reprocessing of historical data should therefore be a repeated activity and it is advisable to save intermittent products comparable to Level 2 data, including at least minimal metadata with a posteriori analysis

Digital Archiving is a subject of existing standards, recommendations as well as national and international legislation. Some links of material are provided in end of this document.

Handling of historical weather radar consists of three major tasks:

- Inventory
- Data rescue
- Analysis

It is recommended that a NMHS planning to start a project to handle historical data, nominates an internal interdisciplinary team for planning the entire project, and especially for the inventory.

Homogenization and potential reanalysis of archives containing several years and several radars, similar to those reported in chapter 2, is an effort of several man months. For example, the operational Australian radar archive consists of approximately 800 years of data across more than 50 sites. Consolidation, quality control and post-processing of multiple archive sources has required several months of full-time work and remains an ongoing effort.

6.2 Inventory

The inventory should be documented carefully and in an unambiguous and uniform way. It may be fruitful to plan how inventory should be designed and executed through international projects to ensure uniformity across borders and agencies, especially if data from several countries or institutes will be archived in the same inventory. An example of a simple inventory table is in table 2.

In our example case in Australia the radar data was stored across a number of digital archives (maintained by different forecasting offices). Most of the data is overlapping, however some archives fill gaps in other archives. Careful analysis was required to source and merge the multiple sources.

As part of the inventory, it is also important to label the physical media (magnetic tapes, CD disks) in an uniform, unambiguous, clear and sustainable way.

Even though very few people will digitalize analogue radar data, it is often worth to document even the archives of analogue data. It might also be worth noting when reconstructing historical metadata, this information is generally found in engineering logs and reports (which is generally a separate database).

6.3 Data rescue / conversion

Urgency of rescue and conversion of different data sets depends among other things on vulnerability of the physical media (magnetic tapes become unreadable and the devices for reading them are rare), compatibility of software and hardware, and the availability of people who know and understand the contents. Due to a variety of issues (communications, software changes, user error) corruption is common in historical data. The data corruption can vary from a single sample, to essential metadata for an entire volume. Careful diagnostics is required to identify the types of frequency of corruption. Either the corrupted data can be rectified (e.g., headers) or removed depending on feasibility.

For several decades, there has been a big uncertainty of which media will stay readable after decades. Radar meteorologists are by no means the only people thinking about it, hence following national and international efforts and lessons learned thereof is recommended. After physical rescue (say, from magnetic tapes to disks), there is usually the need for converting data to widely known formats, Level 2 data if feasible, to allow later reprocessing. This is also the time to carefully document metadata. The goal is to preserve and document historic data for the next decades and make sure is usable to the current and next generation of researchers.

6.4 Analysis

As discussed in section 3, it is strongly recommended to archive level 2 data. In addition to that, many users want to convert the entire time series to climate variables such as precipitation amounts, which can require using external data sources such as gauge data for adjustment. This is a step that most likely will be repeated in the future, so it is crucial that it is well documented, including details such as the type of corrections that have been applied, and that the Level 2 data be saved for possible for future re-analysis.

6.5 Useful links

- Digital Preservation Handbook https://dpconline.org/handbook
- http://ec.europa.eu/research/participants/docs/h2020-funding-guide/cross-cutting-issues/open-access-dissemination_en.htm
- https://en.wikipedia.org/wiki/Digital_preservation
- Something about which media will stay readable after decades:
- https://www.pcworld.com/article/2984597/storage/hard-core-data-preservation-the-best-media-and-methods-for-archiving-your-data.html
- https://www.digitaltrends.com/computing/keeping-data-safe-eternity/

Table 2: Example of inventory table.

Radar name	Years	Parameters	Availability	Notes	Media
John Doe Hill	1985-1990	Mm/h	60%	Gif images	CD disks
	1990-2007	dBZ, VRAD, WRAD	80%	Lowest sweep	Tape
	2007-2017	dBZ, VRAD, WRAD	90%	Full volumes	Disk
Enannanstad	1992-1998	dBZ	40%	Cartesian CAPPI	Disk
	1998-2002	dBZ	20%		Disk
	2003-2010	dBZ, VRAD	80%	The new Radar	Disk
	2010-2017	dBZ, VRAD, ZDR	80%	Dualpol upgrade	Disk

7. SUMMARY AND RECOMMENDATIONS

The key points discussed and the recommendations from the task team are as follows:

1. Key radar parameter: the most important key radar parameter is horizontal reflectivity, ZH, which is the basis of precipitation estimates. The other key radar parameters are radial velocity (VRAD), spectrum width (WRAD), differential Reflectivity (ZDR), correlation Coefficient (RhoHV) and differential phase (PhiDP) and are important to improve the quality of precipitation estimates as well as independent variables related to mesoscale phenomena. It is recommended to save these key parameters as three-dimensional Level 2 data. This allows homogenization of the time series when more advanced methodologies are developed and supports studies related to three-dimensional structure of the atmosphere.
2. Metadata: mandatory metadata parameters for radar data for use in climate are as defined by IPET-OWR (Annex 1). We recommend that metadata includes the history of hardware and algorithm changes so that data can be processed in the future;

3. Quality control: quality control of radar data is mandatory for climate application and should be recorded in the documentation. We recommend that the radar community agrees on a terminology which also includes metadata elements and quality control terms.
4. Radar data archives: for radar data archives, storage strategy has to take into account the additional needs for climate studies. We suggest a real database system rather than the file system based used for radar archives so far. We also suggest a series of steps that will make extracting data from an archive more efficient.
5. Historical data: when handling historical data, the goal is to preserve and document historic data for the next decades and make sure is usable to the current and next generation of researchers. Three tasks are important when handling historical weather radar: inventory, data rescue and analysis. We recommend an interdisciplinary team composed by a scientist, an IT specialist and a professional in digital archiving, for planning the entire project.
6. Results from the survey showed that two decades time series are available at several NMHSs and coverage is soon ready to address climate requirements. Many NMHS have conducted promising prototype studies and are ready to invest into the development and generation of multi-decadal radar databases to support climate requirements. On the global scale the effort to address climate requirement is huge and several approaches are feasible. We recommend to establish an international portal to allow harmonized access to radar data, metadata and documentation, that should start with a proof of concept structure. We recommend adopting a standard open data format (e.g. ODIM H5 or CfRadial) and a widely used data access protocol.
7. Reprocessing and data rescue activities should build on experiences and lessons learned from other similar projects, e.g. in the context of satellite data archives.

This report is focusing on Level 2 data, acknowledging that Level 1 is generally not recorded on operational radars. In the case development of data transfer and storage will make this technically feasible, there may be a need to reconsider these recommendations.

ANNEX 1: DRAFT FOR MANDATORY WEATHER RADAR METADATA FOR INTERNATIONAL EXCHANGE BY IPET-OWR

This table lists weather radar related metadata which are considered mandatory for the international exchange of weather radar data. The metadata are listed according to their definition in the WMO Information Model for Radial Radar and Lidar Data. An additional column 'CfRadial' identifies the corresponding dimension, variable or attribute name which implements the metadata within the CfRadial 2.0 file format. Note that this is still work in progress.

IMID	Description	CfRadial
	Volume metadata	
1.0	Instrument type, distinguishing between “radar” and “lidar”	instrument_type
1.1	Site identifier, WIGOS identifier (see below)	instrument_name
1.2	Volume start time	time_coverage_start
1.3	Volume end time	time_coverage_end
2.0	Site longitude	longitude
2.1	Site latitude	latitude
2.2	Site altitude above geodetic datum. For a scanning instrument this is the center of rotation of the antenna.	altitude
2.3	Geodetic datum name	
3.2	Antenna beam width H	radar_beam_width_h
3.3	Antenna beam width V	radar_beam_width_v
3.5	Frequency	frequency
	Sweep metadata	
5.1	Target fixed angle	fixed_angle
5.4	PRT mode	prt_mode
5.5	Distance to centre of first range bin	meters_to_center_of_first_gate
	Ray metadata	
8.0	Elevation angle	elevation
8.1	Azimuth angle	azimuth
8.2	Time of acquisition (relative to volume start time)	time
8.8	Pulse repetition time(s)	prt
8.9	Nyquist velocity	nyquist_velocity
	Range bin metadata	
11.0	Length of range bin	meters_between_gates
	Dataset metadata	
12.0	Dataset identifier (user specified)	variable name
12.1	Quantity name	standard_name
12.2	Quantity units	units
12.3	Quantity value used to indicate missing data	_FillValue
12.4	Quantity value used to indicate no signal	_Undetect
13.0	Identifiers of datasets which are qualified by this dataset	qualified_variables

The site shall be identified (IMID 1.1) by its WIGOS identifier, the structure of which consists of four parts[2]. The part of the structure called “Local identifier” is the only part consisting of characters. Following the

---

[2] http://wis.wmo.int/page=WIGOS-Identifiers

ODIM NOD identifier convention (Michelson et al., 2014) [3], it is suggested as a best practice that the local identifier be harmonized to a five-character string, where the first two characters are the member country's ISO 3166-1 alpha 2 ccTLD[4] code (lower case), and the latter three characters are freely-selectable (also lower case).

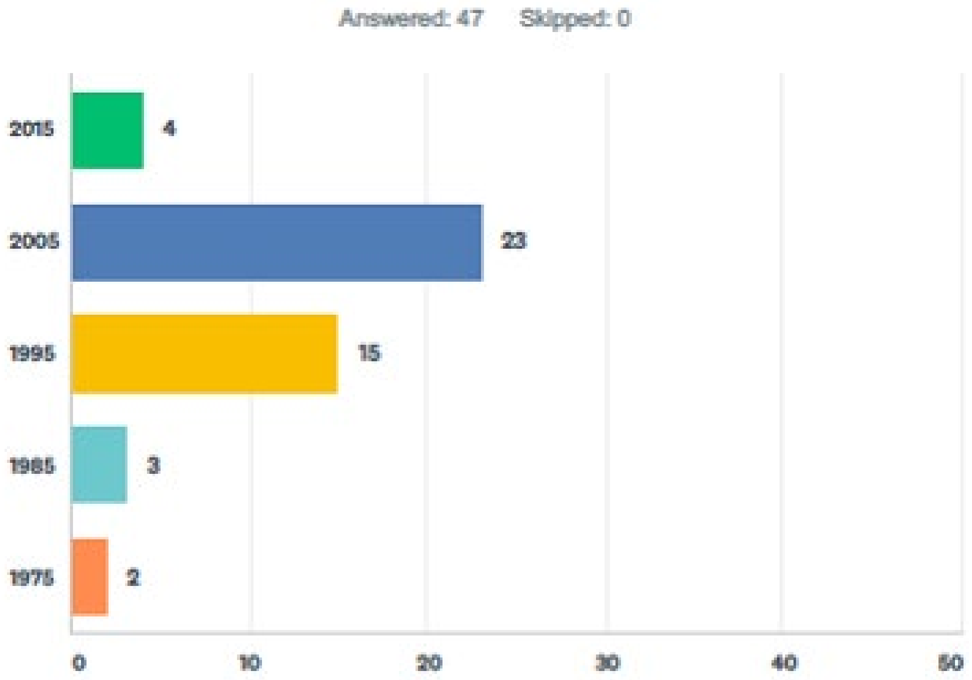
---

[3] Michelson D.B., Lewandowski R., Szewczykowski M., Beekhuis H., and Haase G., 2014: EUMETNET OPERA weather radar information model for implementation with the HDF5 file format. Version 2.2. EUMETNET OPERA Output O4. 38 pp.

[4] http://www.iso.org/iso/country_codes

ANNEX 2: SURVEY AND RESULTS

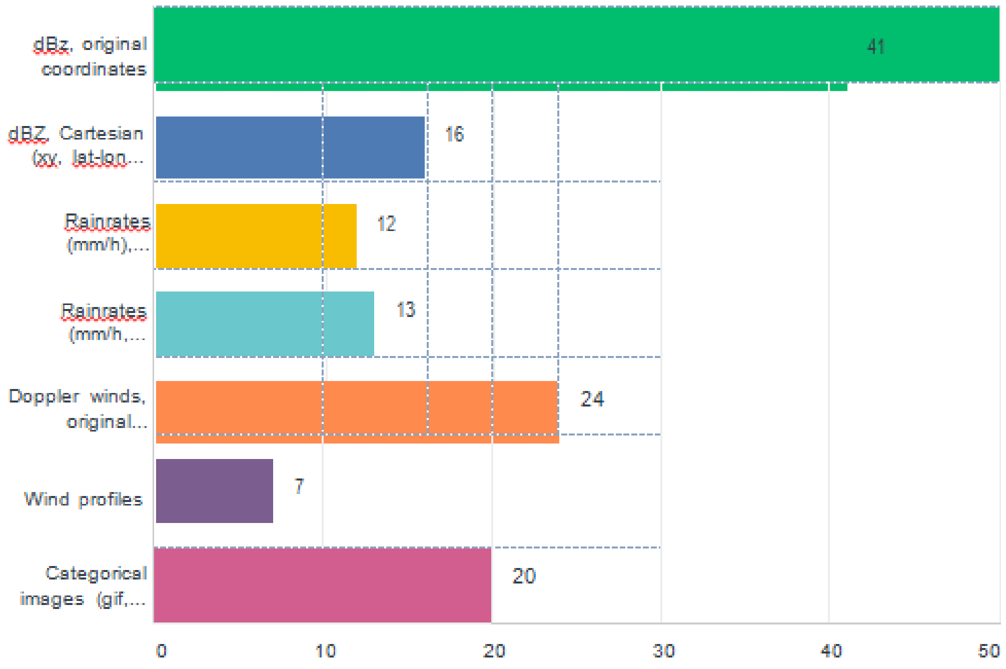
Q1: From when is the earliest radar data in your archives (approximately)



ANSWER CHOICES	RESPONSES	
2015	8.51%	4
2005	48.94%	23
1995	31.91%	15
1985	6.38%	3
1975	4.26%	2
Total Respondents: 47		

Q2: Which parameters have you saved

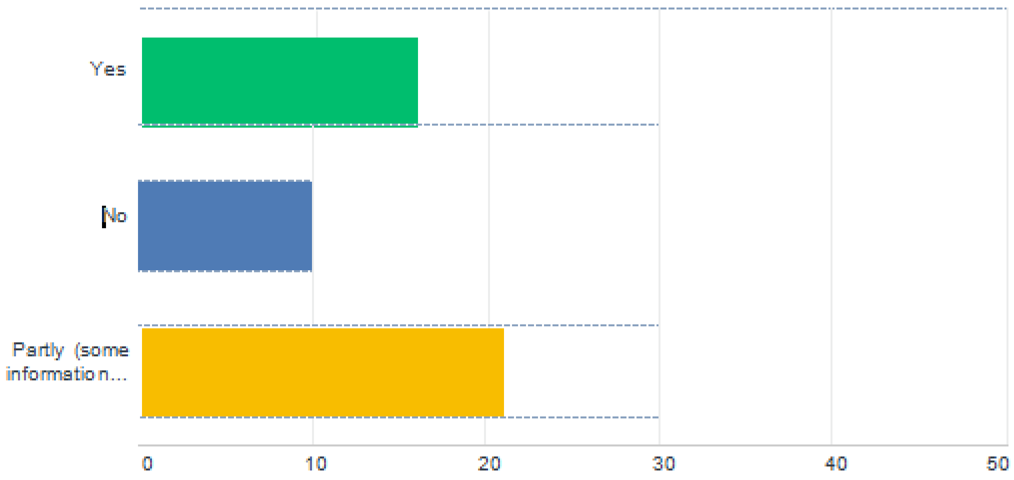
Answered: 46Skipped: 1



ANSWER CHOICES	RESPONSES	
dBz, original coordinates	89.13%	41
dBZ, Cartesian (xy, lat-long) coordinates	34.78%	16
Rainrates (mm/h), original coordinates	26.09%	12
Rainrates (mm/h, Cartesian coordinates	28.26%	13
Doppler winds, original coordinates	52.17%	24
Wind profiles	15.22%	7
Categorical images (gif, jpg, png, geoTIFF, …)	43.48%	20
Total Respondents: 46		

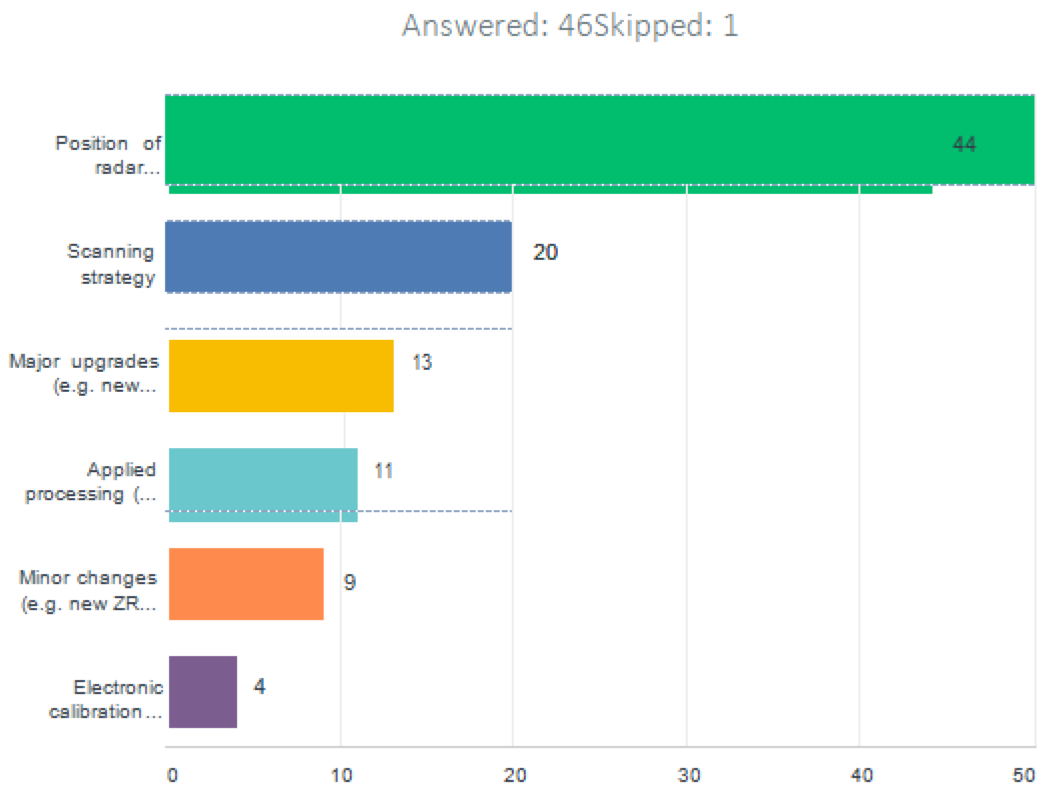
Q3: Which parameters have you saved

Answered: 47 Skipped: 0



ANSWER CHOICES	RESPONSES	
Yes	34.04%	16
No	21.28%	10
Partly (some information available elsewhere)	44.68%	21
Total Respondents: 47		

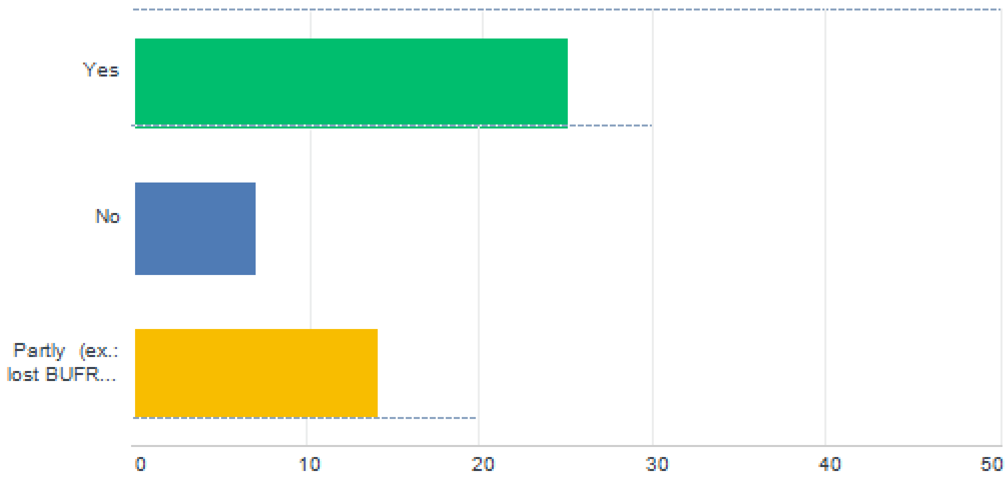
Q4: What kind of metadata is available



ANSWER CHOICES	RESPONSES	
Position of radar (geographic and height)	95.65%	44
Scanning strategy	43.48%	20
Major upgrades (e.g. new hardware or new software processing releases)	28.26%	13
Applied processing (ZR, VPR)	23.91%	11
Minor changes (e.g. new ZR relation)	19.57%	9
Electronic calibration results	8.70%	4
Total Respondents: 46		

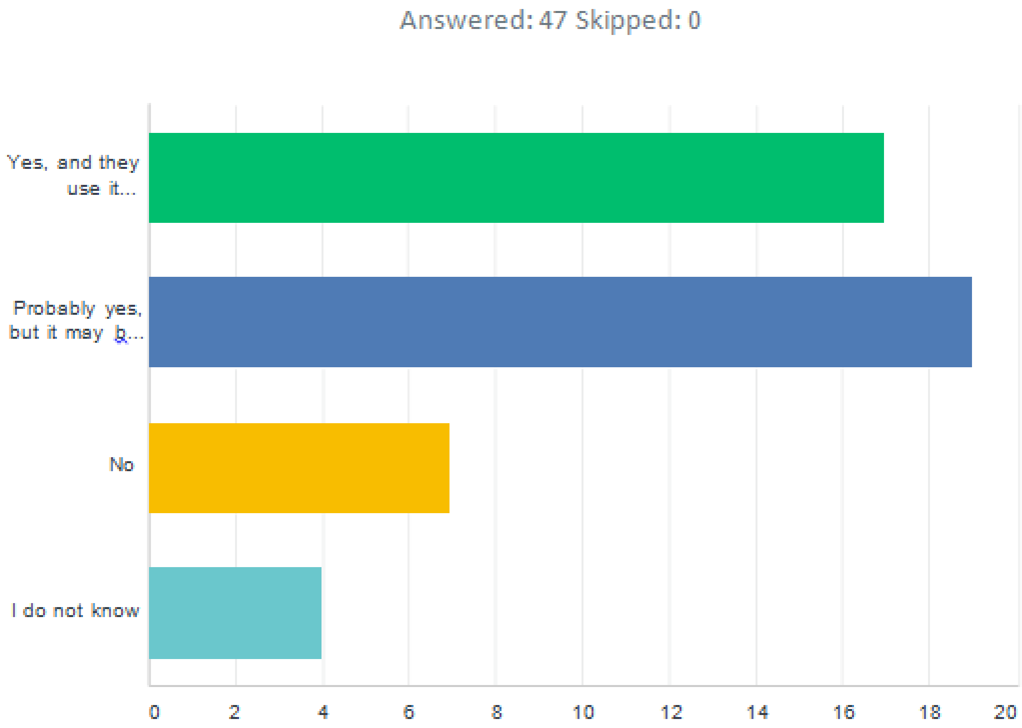
Q5: Is the format of the archive content document

Answered: 46 Skipped: 1



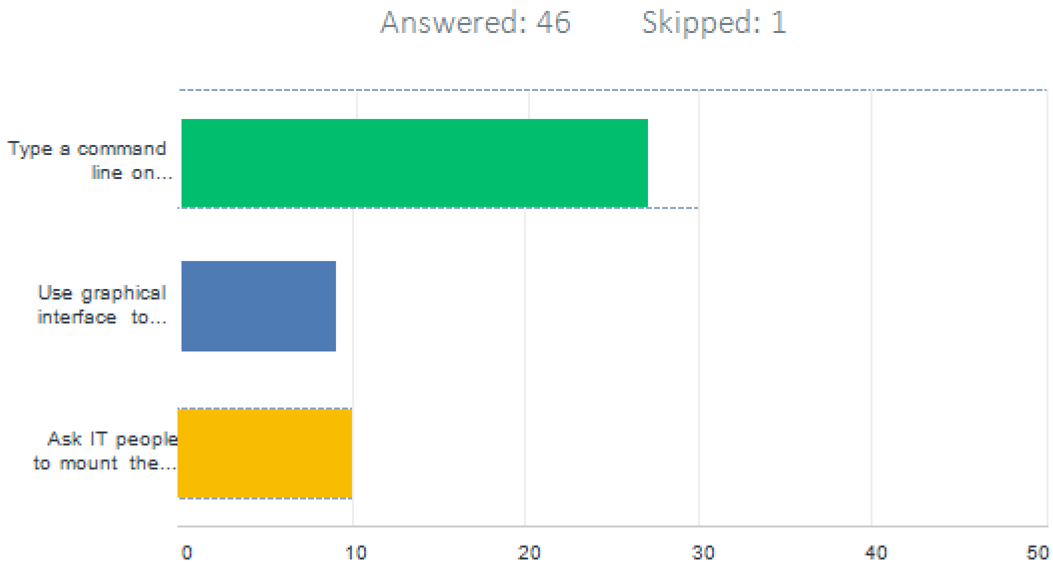
ANSWER CHOICES	RESPONSES	
Yes	54.35%	25
No	15.22%	7
Partly (ex.: lost BUFR tables, only binary software available to read the data)	30.43%	14
Total Respondents: 46		

Q6: Is the data available for researchers outside of your institute



ANSWER CHOICES	RESPONSES	
Yes, and they use it regularly	36.17%	17
Probably yes, but it may be complicated	40.43%	19
No	14.89%	7
I do not know	8.51%	4
Total Respondents: 47		

Q7: How would you describe the effort of retrieving one year of old data from your archives? (Select the option which is closest to the real procedure for a person who has the needed permissions.)



ANSWER CHOICES	RESPONSES	
Type a command line on terminal, ftp	58.70%	27
The Zipped file. Use graphical interface.	19.57%	9
To define what data.	21.74%	10
Ask IT people to mount the media (disks, tapes)		
Total Respondents: 46		

ANNEX 3: USE OF WEATHER RADAR DATA FOR CLIMATE DATA RECORDS IN WMO REGIONS IV AND VI-URSDCM REPORT

Use of Weather Radar Data for Climate Data Records in WMO Regions IV and VI

Luzia Keupp, Tanja Winterrath, and Rainer Hollmann For WMO CCl TT-URSDCM

3. February 2017 Version 1.2

1. INTRODUCTION AND SCOPE OF THIS PAPER

During the first meeting of the WMO CCl Task team on the Use of Remote Sensing Data for Climate Monitoring (TT-URSDCM) in 2014, the team recognized the increasing availability of radar data and emerging interest of Members to establish radar climatologies. Consequently, as part of the work plan of TT-URSDCM a task to create an overview of activities within Members on radar climatologies has been agreed.

This document provides the information which is available for WMO Region VI (Europe). The information has been compiled through personal communication and a literature survey, however it cannot guarantee completeness. The given examples provide a starting point in summarizing best practices of Member states to establish own climatologies. The authors are looking forward to further entrances and updates of list entries.
The document is structured as follows: After recalling the motivation in section 2, the challenges are shortly summarized in section 3, section 4 provides an example for Germany providing a few more details about the procedure followed and plans. Then section 5 gives an overview for several Members from Region VI. Finally, section 6 concludes this document.

2. MOTIVATION FOR THE USE OF WEATHER RADAR DATA FOR CLIMATOLOGICAL PURPOSES

While weather radar data is widely employed for Numerical Weather Prediction, climatological use is still not common. And yet, radar data holds many advantages when compared to other sources of precipitation data. The high temporal and spatial resolution as well as coverage of radar-based data, for example, enables the study of small-scale atmospheric structures and dynamics (e.g. of convective systems) (e.g. Berg et al. 2015, Goudenoofdt & Delobbe 2013, Marra & Morin 2015, Tabary 2007). This implies that also in regions without observational network, area-wide coverage is attained and extreme events – which occur regional and temporary – are captured. Furthermore, the data is often provided in near real-time (Ruber & Brugger 2009).

In contrast to this, the oftentimes small density (and irregularity) of gauge networks results in point data with debatable reliability and representativeness for the surrounding area. The variability of precipitation is therefore not reflected in the spatially interpolated data, especially regarding regions with heterogeneous topography (e.g. Berndt et al. 2014, Goudenhoofdt & Delobbe 2013, Ruber & Brugger 2009, Rudolph et al. 2011, Tabary 2007, Tapiador et al. 2012). Until now, satellite-derived precipitation data is no suitable alternative for regional studies of precipitation climatology, as temporal and/or spatial resolutions are still too low (e.g. Goudenoofdt & Delobbe 2013, Tapiador et al. 2012).

Altogether, radar data holds large potential for climatological applications which is far from being fully exploited until now. Thus, this paper aims to provide an insight in the possibilities of climatological use of weather radar data.

3. ENCOUNTERED CHALLENGES

By now, many classic problems regarding weather radar measurements like e.g. ground clutters, shielding or non-uniform vertical profiles of reflectivity (see Figure 1, e.g. Fairman et al. 2015, Overeem et al. 2009, Yuter 2015), can be solved – particularly by using long time series as well as Doppler and polarimetric radars (cp. Tabary 2007, Tabary et al. 2007, Winterrath et al. 2015).

Concerning the climatological analysis of radar data, some other issues arise which, however, can also be overcome by proper processing of the data:

As with all other data sources, in the context of data harmonization, difficulties emerge from the removal or replacement of sensors as well as the change of sensor calibrations (Overeem et al. 2009). Furthermore, originally hidden systematic errors can be amplified when applying long-term means (Wagner et al. 2014). Hence pre-processing needs to be conducted before using the data (cp. Kronenberg & Bernhofer 2015).

To derive robust data, validation and calibration is essential. Unfortunately, many regions feature a lack of gauge data and especially during times of intense wind or rainfall errors occur in the gauge measurements (e.g. Fairman et al. 2015, Hollman et al. 2006). Additionally, calibrations as well as retrieval algorithms have to be harmonized and orographic corrections need to be performed to ensure data comparability (Berg et al. 2015, Fairman et al. 2015). Missing data must not be treated as zero precipitation as this would falsify climatological assertions but be amended in an adequate way (Fairman et al. 2015).

The considered studies (see section 5) show the existence of a large number of techniques for the correction of systematic biases (e.g. Berndt et al. 2013, Fairman et al. 2015, Overeem et al. 2009, Wagner et al. 2014) as well as for radar-gauge merging respectively adjustment (e.g. Berndt et al. 2013, Goudenhoofdt & Delobbe 2009, Paulat et al. 2008, Winterrath et al. 2012). Regarding this, it is important to bear in mind that for using climatological radar data from different sources, comparable processing methods need to be applied to gain matchable results.

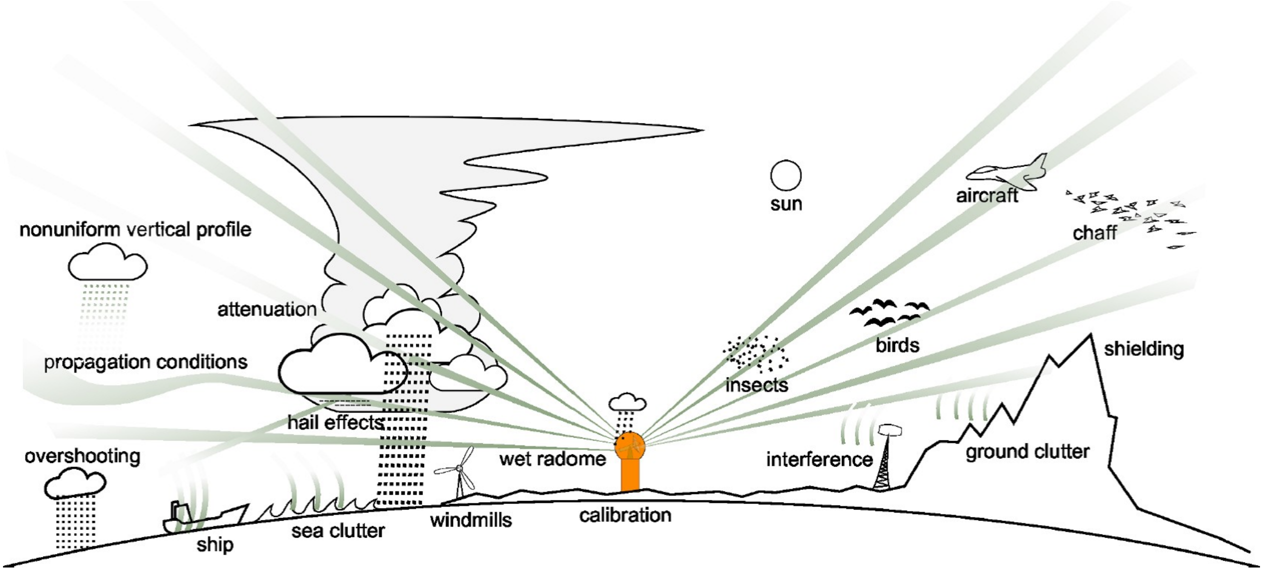


Figure 1: Phenomena Affecting Radar Data Quality (Holleman et al. 2006).

4. ACTIVITIES AND EXPERIENCES OF DEUTSCHER WETTERDIENST (DWD)

The DWD radar network currently consists of 17 C-band Doppler radar systems. All but one of the former 16 single-polarization ones have been replaced by dual-pol ones between 2011 and 2015. In the RADOLAN (Radar-Online-Adjustment) project, methods for the production of hourly gauge- adjusted quality-controlled radar data based on five-minute terrain-following precipitation scans have been developed. For the real-time adjustment, approx. 1300 automatic gauges are available (Effective 2016). The project being finalized, processed data is now made available to DWD users every hour.

To analyze the radar-based precipitation data, a new project on the “Generation of a decadal radar- based high-resolution precipitation climatology for Germany for the retrieval of recent changes in precipitation extremes” has started in June 2014 and is ongoing until August 2016. In the course of this undertaking three project modules are elaborated. First, a complete reprocessing of the radar- based precipitation data is performed, second, a statistical analysis of the 15-year precipitation data is executed, and third, client-specific products are generated. The reprocessing of the data comprises the application of one software version to all the data to improve homogeneity, the usage of all available gauge data in the adjustment procedure, as well as the design and application of (automatic) procedures for different kinds of data corrections to remove or at least reduce errors arising from different kinds of sources (Winterrath et al. 2015, Winterrath & Schmitt 2015).

While well-known radar-specific false enhanced signals, e. g. clutter, are clearly visible in single real-time products, signal reductions become visible only in the long-term totals. Therefore, besides applying the state-of-the-art real-time correction methods, DWD develops specific climatological correction algorithms. For artefacts originating from beam blockage by (permanent) obstacles and also distant-dependent signal enhancement, which is a permanent feature, long term means can be used for corrections. More complex climate-data corrections which are to be developed and applied in the future concern non-permanent periodic spokes as well as season- or intensity-dependent distance effects, the latter one being associated with deep convection (Winterrath et al. 2015). Furthermore, it is planned to perform a statistical analysis of the 15-year radar climatology for Germany and to examine extreme events by the use of objective indices. Additionally, the results are combined with non-meteorological data for impact and vulnerability studies.

The radar-based precipitation climatology is planned to be extended on an annual basis. Based on the dual-pol technology, new data products will be included in the future.

5. USE OF WEATHER RADAR FOR CLIMATE DATA RECORDS IN WMO REGION VI

The following statements on the recent state of weather radar use for climatological data records in the WMO Region VI is based on an examination of the webpages of the Region VI Members' national meteorological and hydro-meteorological services (NMHSs) (as listed online at WMO 2016), the WMO World Radar Database (WRD 2016) as well as a review of literature. Until now, little activity can be observed in terms of the use of radar for the establishment of precipitation time series sufficiently long for the use in climate research. Most of the Region VI countries employ radar data merely for weather observation and forecasting. Climate applications by means of weather radar data are pursued by ten countries (Belgium, Denmark, France, Germany, Ireland, Italy, Netherlands, Sweden, Switzerland, and United Kingdom of Great Britain and Northern Ireland).

Use of radar data for the compilation of climatologies of high precipitation events, convective events or hail is mainly listed for countries with no available information on radar precipitation climatologies, showing that multi-annual time series of radar data are existent. No claim to completeness is raised.

A summary is given in Table 1 and in Figure 2, while the following paragraphs present the situation for the different countries in more detail:

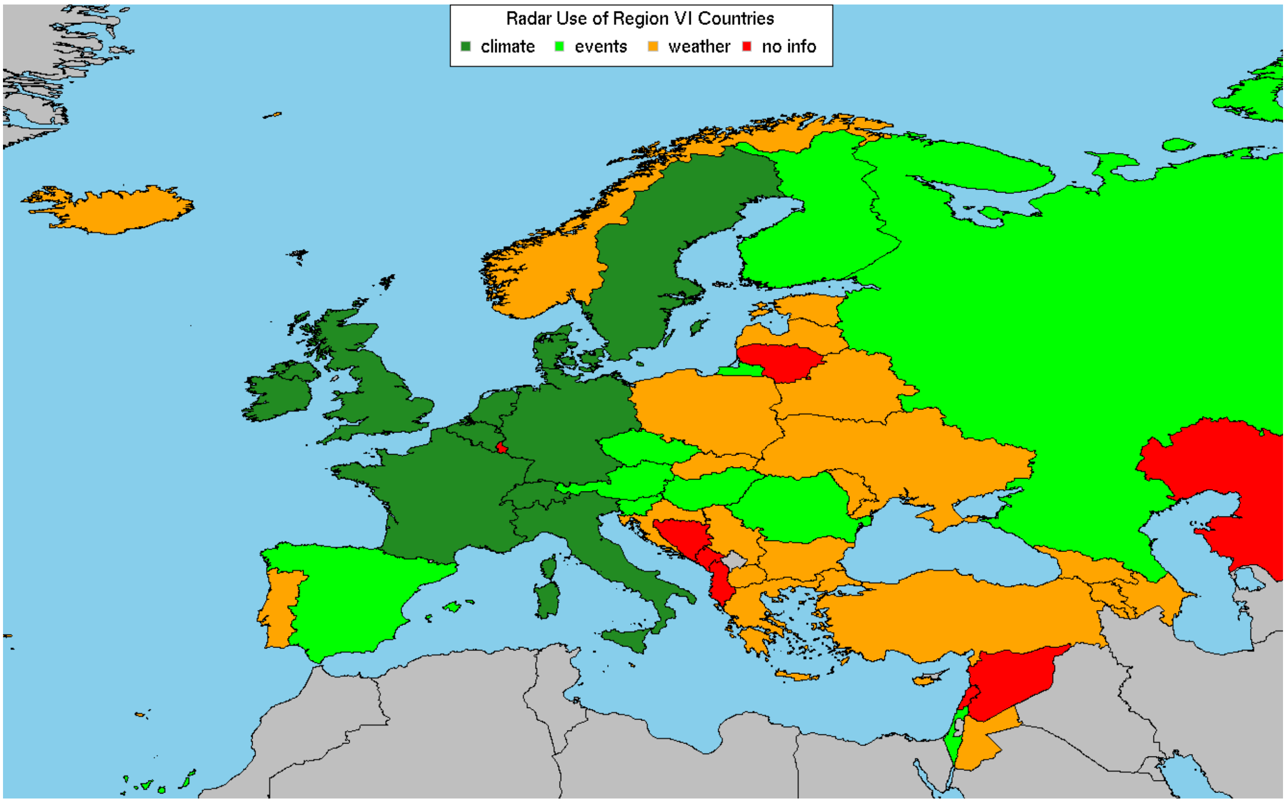


Figure 2: Use of Weather Radar Data in WMO Region VI Countries. Climate: multi-annual time series produced – events: climatologies of hail, convective or high precipitation events compiled but no information on radar-based precipitation climatologies – weather: only information on radar use for weather purposes – no info: no information on weather radar use at all.

Austria. Kaltenboeck & Steinheimer (2015) examine intensive convective events of the warm seasons 2008–2012 using C-band weather radar in combination with ERA-Interim Reanalysis data over Austria. Separating Austria in three different regions, they analyze severe storm occurrence regarding the different combinations of deep layer wind shear and CAPE strength.

Belgium. In their study, Goudenhoofdt & Delobbe (2009) examine and perform various radar- gauge merging methods and contrast the results with independent gauge data. The work is based on radar data from the Wideumont Radar in south-western Belgium, covering the years 2005 to 2008. Records of the same radar station but for 2002–2011 are also used by Goudenhoofdt & Delobbe (2013) for the analysis of convective storms. Furthermore, a reprocessing of the QPE (quantitative precipitation estimation) for the 2005–2015 period including different correction techniques and gauge-merging is conducted by Goudenhoofdt & Delobbe (2016a) (using DWD RADOLAN Z-R relationships), leading to a marked enhancement of the data when compared to (independent) rain gauge measurements. Extreme values are also analyzed (cp. Goudenhoofdt & Delobbe 2016b).

Czech Republic. Bližňák et al. (2016) examine the gauge-merged data of two radar stations for the warm seasons 2002–2011. Besides the derivation of a MJJAS total precipitation climatology, sub-daily extreme events as well as small-scale differences in precipitation amounts are investigated. Seven algorithms for hail detection from single-polarisation radar data are examined by Skripniková & Řezáčová (2014) regarding hail events in the Czech Republic and SW Germany evidenced by data from insurance companies and other sources. From this, criteria are defined to delineate hail occurrence and thus construct a 2007–2011 hail climatology for the Czech Republic.

Denmark. A ten year radar-based precipitation climatology (2002–2012) for Denmark is derived by Thorndahl et al. (2014). Using data from the Stevns C-band radar, various bias adjustment methods are examined revealing better results for hourly compared to daily adjustment. Additionally, it is shown that at least 10 to 20 randomly distributed rain gauges are necessary for valid mean field bias adjustment.

France. For France, Tabary et al. (2012) report about the production and validation of a decadal time series of radar-gauge merged precipitation spanning 1997–2006, intended to be used as a reference database. Weckwerth et al. (2011) study convection in parts of France and Germany (Vosges Mountains, Rhine Valley, Black Forest Mountains, Swabian Mountains) in the May to August periods 2000–2006 as well as 2008 based on radar data. This work is conducted in relation to the COPS (Convective and Orographically-induced Precipitation Study) field campaign in summer 2007.

Germany. As the current approach at DWD has been described in detail above (see section 4), here only additional work is cited. Hourly RADOLAN-QPEs of the German Free State Saxony covering the 4.2004–12.2009 period are processed by Kronenberg & Bernhofer (2015) to be suitable for analyses of annual or bigger timescales of precipitation. Error accumulation is prevented by a detection and elimination of outliers, adaption by means of elevation data and bias- adjustment using independent gauge data. The resulting dataset is then compared with two datasets covering the same domain. The utilization of the applied method for other study areas is limited as it is only valid for regions with high correlations between precipitation and elevation. Wagner et al. (2014) examine the 2005–2009 period of the German radar composite RX. Long-term means are used to detect systematic biases, and the susceptibility of the data regarding climatologically amplified formerly minor systematic errors is highlighted. Three different geostatistical interpolation techniques are employed by Berndt et al. (2014) for the merging of radar and rain gauge data at different spatial and temporal resolutions. The study is based on radar data of the Hanover station from 2008 until 2010. Using a so-called disaggregation technique, Paulat et al. (2008) construct a combined gauge-radar dataset of precipitation in Germany (2001–2004). Additionally, COSMO-7 model forecasts are studied regarding their representation of the findings.

A hail climatology for the summer half-years 2002–2011 (continuation intended) is compiled by Junghänel et al. (2016) employing pre-processed single-polarized C-band Doppler radar data, lightning data, observations from weather stations and volunteers as well as insurance data. The resulting frequency map shows the annual average number of hail days per square kilometer.

Finland. Based on five years of corrected summer rainfall intensity data of seven C-band Doppler radars (MJJAS 2000–2005), return periods of rainfall intensities are derived from probability respectively (complementary) cumulative density functions by Koistinen et al. (2008). Two-minute point values – which show higher intensities than gauge-based results – as well as different combinations of area-time accumulations are studied, revealing the necessity for “post detection quality filtering”. Saltikoff et al. (2010) use adjusted radar data of the summer seasons 2001–2005 in combination with ECMWF MARS temperatures as well as 70 years of hail reports to derive a hail climatology for Finland yielding partially differing results.

Hungary. Based on the TITAN method and data from three C-band radars, thunderstorm activity in Hungary between 2004 and 2012 is studied by Seres & Horváth (2015). Three different intensity types of “thunderstorm ellipses” are defined and occurrence frequencies as well as spatial and temporal differences are examined.

Ireland. *See United Kingdom of Great Britain and Northern Ireland*

Israel. Weather radar QPE data from October 1990 to September 2013 are employed by Marra & Morrin (2015) to deduce Intensity-Duration-Frequency curves covering the different climates of Israel. Several adjustments are applied before examining the data and the results are compared to rain gauge-based ones, showing overestimations of the radar with respect to the gauge data.

Italy. The convective activity during the warm seasons 2005–2007 in the Veneto region in northern Italy is documented in a radar-based time series by Calza et al. (2008). Stanzani et al (2000) match raw as well as gauge-calibrated radar precipitation estimates from a radar station in Bologna against (independent) gauge network data for 1997–1998 (except from 11/97 to 03/98 with no data available). The results show underestimations in terms of the raw data and good results regarding the calibrated data.

Netherlands. Based on the data of the two Dutch Radar stations, a 10-year (1998–2007) precipitation climatology is constructed by Overeem et al. (2009) comprising several – separately deployed and compared – adjustment techniques, partially involving gauge data. When compared to gauge-based data, a newly developed adjustment method combining mean-field bias and spatial adjustment yields the best results, also regarding variance differences. On the KNMI web page, daily precipitation maps based on radar data are available from 2009 on (KNMI 2016).

Norway. There are activities to compile radar climatologies which were reported on in a presentation, but there are no hints in the literature.

Romania. Data of two Doppler radars are used by Maier & Haidu (2011) to produce a climatology of hail for the summer seasons of 2004 to 2009 over the Apuseni Mountains in Romania. The derived maps show a high spatial variability of hail frequency and severity related to the prevailing topography.

Russian Federation. Hail activity in two Russian regions is investigated by Zharashuev (2012) studying convective cells in the periods 2002–2008 (Stavropol radar) respectively 2004–2009 (Kirovskoe radar Crimean Paramilitary Service).

Slovenia. Stržinar & Skok (2016) construct a hail climatology for Slovenia for the period 2002– 2010. In doing so, they apply and compare different algorithms.

Spain. García-Ortega et al. (2011) use data from a C-band radar near Zaragoza to identify hail days in the Middle Ebro Valley between 2001–2008, which are confirmed by observers. Afterwards, the atmospheric conditions during those days is examined using reanalysis data.

Sweden. Based on radar and gauge data, Berg et al. (2015) generate a time series of precipitation over Sweden spanning 2009–2014. They point out the need for inter-radar calibration as well as gauge-independent radar composite adjustments.

Switzerland. While Rudolph et al. (2009) focus on high precipitation events in the Alps of Switzerland and the adjacent countries during the 2000–2007 period using radar data, the ongoing MeteoSwiss project “CombiPrecip” goes beyond this. It aims at the construction of hourly gauge- radar merged precipitation fields from 2005 on by means of geostatistical combination methods. Data from all Swiss radar stations, covering and exceeding the Swiss territory, is employed (MeteoSwiss 2013, 2014).

United Kingdom of Great Britain and Northern Ireland. Including several corrections and adjustments, Fairman et al. (2015) compile an eight-year time series of precipitation over Great Britain and Ireland. Comparisons against annual totals reveal high overestimations in some and underestimations in other parts of the study area. Besides poor radar data quality regarding Ireland, errors concerning the gauge-based data are assumed.

United States. Nelson et al. (2003) produced a high-resolution precipitation data set climatology based on NEXRAD radar estimates for a five-year period (1996-2000) over the Mississippi River basin – nearly 2/3 of the continental United States (CONUS). Nelson et al. (2010) also produced a reanalysis of radar-based precipitation estimates for a five-year period over the southeastern United States. Recently Ortega et al. (2015) have produced a 10-year climatology of severe weather based products based on the NEXRAD operational level-II products. The Multi-Year Reanalysis of Severe Storms (MYRORSS) data set consists of some 18 severe weather based products at high resolution. In addition Nelson et al (2016) have produce the companion QPE climatology for the same time period over CONUS.

Central and Northern Europe. Data from the border-crossing CERAD (Central European Radar) and BALTRAD (Baltic Radar) networks adjusted by in-situ observations provides the basis for the 10/1999–12/2000 precipitation time series over Central and Northern Europe compiled by Rubel & Brugger (2009).

6. CONCLUSION

When compared to other data sources, the large potential of weather radar data for climatological application arises from its high spatial as well as temporal resolution and coverage, implying that also small scale differences in precipitation and extreme events can be captured.

During the last decade solutions for a lot of general problems in terms of radar measurements (see Figure 1) were found. Some specific issues arise when analyzing radar data for climatological purposes. These include e.g. sensor modifications over time, amplification of originally minor systematic errors, lacking validation data (lacks and errors in gauge data). Nevertheless, even most of them can be handled by adequate processing. To use radar observation for climate monitoring, there is in addition a need for harmonized calibrations and retrievals, for comparable methods regarding bias correction and radar-gauge adjustments, as well as for an adequate treatment of missing data. As an example, Deutscher Wetterdienst has started to reprocess and analyze the radar- based reflectivity measurements of the German radar network starting in 2001. Currently, the compilation of decadal gauge-adjusted radar precipitation climatology is ongoing until August 2016. It comprises the design and application of various correction schemes spanning different levels of complexity. A statistical analysis of the 15-year radar climatology as well as a studyof extreme events will be performed.

The examination of the WMO World Radar Data Base, RA VI NHMSs' web pages and a search for literature reveals some activity in terms of climatological use of radar-based precipitation data which is listed in Table 1 and displayed in Figure 2. It is evident that only a few Members of RA VI (Germany, Switzerland) are currently performing projects regarding generating, provision and archiving of long time series of adjusted radar precipitation.

Even though the number of countries deriving radar-based precipitation climatologies is still small, the examples listed in this paper are encouraging.

Table 1: Countries with Information Regarding Multiannual Radar Data Use.

Country	**Details**	**Time**	**Reference**
Austria	Intensive convective cores	2008–2012	Kaltenboeck & Steinheimer 2015
Belgium	Convective events (SW Belgium)	2002–2011	Goudenhoofdt & Delobbe 2013
	Radar-gauge merging methods (SW Belgium)	2005–2008	Goudenhoofdt & Delobbe 2009
Czech Republic	Total precipitation MJJAS, sub-daily extreme events, small scale differences	2002–2011	Bližňák et al. 2016
	Hail climatology	MJJA 2007–2011	Skripniková & Řezáčová 2014
Denmark	Bias adjustment methods	2002–2012	Thorndahl et al. 2014
Finland	Rainfall intensity return periods	MJJAS 2000–2005	Koistinen et al. 2008
	Hail climatology	MJJAS 2001–2005	Saltikoff et al. 2010
France	Radar-gauge precipitation time series as reference database	1997–2006	Tabary et al. 2011
	Convective events (NE France and SW Germany)	MJJA 2000–2006, 2008	Weckwerth et al. 2011
Germany	Radar-gauge precipitation time series	2001+ (ongoing)	Winterrath et al. 2015 Winterrath & Schmitt 2015
	Processed climatology for at least annual means (Saxony, E Germany)	4/2004–12/2009	Kronenberg & Bernhofer 2015
	Bias detection	2005–2009	Wagner et al. 2014
	Radar-gauge merging, Hanover station	2008–2010	Berndt et al. 2014
	Radar-gauge combination	2001–2004	Paulat et al. 2008
	Hail climatology	2002–2011	Junghänel et al. 2016
Hungary	Hail climatology	2004–2012	Seres & Horváth 2015

Country	**Details**	**Time**	**Reference**
Ireland	Radar-gauge precipitation time series	2006–2013	Fairman et al. 2015
Israel	Intensity-Duration-Frequency curves	10/1990–09/2013	Marra & Morrin 2015
Italy	Convective events (N Italy)	MJJAS 2005–2007	Calza et al. 2008
	Radar-gauge comparison (N Italy)	01–10/1997, 04–12/1998	Stanzani et al. 2000
Netherlands	Radar-gauge precipitation time series	1998–2007	Overeem et al. 2009
	Daily radar precipitation maps	2009+ (ongoing)	KNMI 2016
Romania	Hail climatology (NW Romania)	JJA 2004–2009	Maier & Haidu 2011
Russian Federation	Hail climatology (two Russian regions)	2002–2008 / 2004–2004	Zharashuev 2012
Slovenia	Hail climatology	2002–2010	Stržinar & Skok 2016
Spain	Hail climatology and atmospheric conditions in the (NE Spain)	2001–2008	García-Ortega et al. 2011
Sweden	Radar-gauge precipitation time series	2009–2014	Berg et al. 2015
Switzerland	Radar-gauge precipitation time series (CombiPrep)	2005+ (ongoing)	MeteoSwiss 2013, MeteoSwiss 2014
	High precipitation events (Alps)	2000–2007	Rudolph et al. 2009
United Kingdom	Radar-gauge precipitation time series	2006–2013	Fairman et al. 2015
United States	Radar-gauge Climatology Radar-Gauge Reanalysis Radar-Gauge QPE Climatology Multi-Year Reanalysis of Severe Storms	1996-2000 2002-2007 2002-2011 2002-2011	Nelson et al. 2003 Nelson et al. 2010 Nelson et al. 2016 Ortega et al. 2015
C & N Europe	Radar-gauge precipitation estimation	10/1999–12/2000	Rubel & Brugger 2009

REFERENCES

Berg, P., Norn, L. & Olsson, J. (2015): Creation of a high resolution precipitation data set by merging gridded gauge data and radar observations for Sweden. – Journal of Hydrology, in press, DOI: 10.1016/j.jhydrol.2015.11.031.

Berndt, C., Rabiei, E. & Haberlandt, W. (2014): Geostatistical merging of rain gauge and radar data for high temporal resolutions and various station density scenarios. – Journal of Hydrology 508, 88–101, DOI: 10.1016/j.jhydrol.2013.10.028.

Bližňák, V., Kašpar, M. & Müller, M. (2016): Radar-based precipitation climatology of the Czech Republic in the warm part of the year. – EMS Annual Meeting Abstracts 13, EMS2016-262.

Calza, M., Dalla Fontana, A., Domenichini, F., Monai, M. & Rossa, A.M. (2008): A Radar- based Climatology of Convective Activity in the Veneto Region. FORALPS Technical Report, 4. Trento: Università degli Studi di Trento, Dipartimento di Ingegneria Civile e Ambientale, ISBN: 978-88-8443-233-9.

Fairman, J.G., Shultz, D.M., Kirshbaum, D.J., Hray, S.L. & Barrett, A.I. (2015): A radar-based rainfall climatology of Great Britain and Ireland. – Weather, 70, 5, 153–158, DOI: 10.1002/wea.2486.

García-Ortega, E., López, L & Sánchez, J.L. (2011): Atmospheric patterns associated with hailstorm days in the Ebro Valley, Spain. – Atmospheric Research 100, 401–427, DOI: 10.1016/j.atmosres.2010.08.023.

Goudenhoofdt, E. & Delobbe, L. (2009): Evaluation of radar-gauge merging methods for quantitative precipitation estimates. – Hydrology and Earth System Sciences 13, 195–203, DOI: 10.5194/hess-13-195-2009.

Goudenhoofdt, E. & Delobbe, L. (2013): Statistical Characteristics of Convective Storms in Belgium Derived from Volumetric Weather Radar Observations. – Journal of Applied Meteorology and Climatology 52, 918–934, DOI: 10.1175/JAMC-D-12-079.1.

Goudenhoofdt,L & Delobbe, L. (2016a): Generation and Verification of Rainfall Estimates from 10-Yr volumetric Weather Radar Measurements. – Journal of Hydrometeorology 17, 1223– 1242, DOI: 10.1175/JHM-D-15-0166.1.

Goudenhoofdt, L. & Delobbe, L. (2016b): Extreme value analysis based on a 10-year radar- based precipitation reanalysis. – EMS Annual Meeting Abstracts 13, EMS2016-677.

Holleman, I., Michelson, D., Galli, G., Germann, U. & Peura, M. (2006): Quality information for radars and radar data. OPERA_2005_19. OPERA workpackage 1.2.

Huuskonen, A., Saltikoff, E. & Holleman, I. (2014): The Operational Weather Radar Network in Europe. – Bulletin of the American Meteorological Society 95, 897–904, DOI: 10.1175/BAMS- D-12-00216.1.

Junghänel, T., Brendel, C., Winterrath, T. & Walter, A. (2016): Towards a radar- and observation-based hail climatology for Germany. – Meteorologische Zeitschrift, PrePub, DOI: 10.1127/metz/2016/0734.

Kaltenboeck, R. & Steinheimer, M. (2015): Radar-based severe storm climatology for Austrian complex orography related to vertical wind shear and atmospheric instability. – Atmospheric Research 158/159, 216–230, DOI: 10.1016/j.atmosres.2014.08.006.

Koistinen, J., Kuitunen, T., Pulkkinen, S,, Hohti, H. & Kotro, J. (2008): Derivation of extreme event mesoscale area-intensity return periods of rainfall based on a large sample of radar data. Contribution to ERAD 2008 - The Fifth European Conference on Radar in Meteorology and Hydrology.

KNMI (2016): Neerslag radararchief. Gecorrigeerde dagelijkse radarbeelden (in Dutch). Adjusted Precipitation Radar Maps from 01/01/2009 on https://www.knmi.nl/nederland-nu/klimatologie/geografische-overzichten/radar (State: 2016) (Last Access: 2016-03-16).

Kronenberg, R. & Bernhofer, C. (2015): A method to adapt radar-derived precipitation fields for climatological applications. – Meteorological Applications 22, 636–649, DOI: 10.1002/met.1498.

Maier, N. & Haidu, I. (2011): Radar Climatology of Hail in the Apuseni Mountains. Contribution to the Air and Water conference dedicated to the World Meteorological Day and World Water Day, March, 18–19, 2011, Cluj Napoca, Romania. Cluj-Napoca: Physical and Technical Geography Department of the Babeş-Bolyai University, ISSN: 2067-743X.

Marra, F. & Morrin, E. (2015): Use of radar QPE for the derivation of Intensity–Duration– Frequency curves in a range of climatic regimes. – Journal of Hydrology 531, 427–440, DOI: 10.1016/j.jhydrol.2015.08.064.

MeteoSwiss (2013): Hourly Precipitation Estimation through Raingauge-Radar: CombiPrecip. Documentation of MeteoSwiss Grid-Data Products. Zurich: Federal Office of Meteorology and Climatology MeteoSwiss.

MeteoSwiss (2014): Räumliche Daten CombiPrecip (in German). http://www.meteoschweiz.admin.ch/home/suche.subpage.html/de/data/products/2014/raeumliche-daten-combiprecip.html?query=Radar&topic=/content/meteoswiss/tags/topics/klima (State: 2014-

12-01) (Last access: 2016-03-15).

Nelson, B.R., O.P. Prat, S. Stevens, J. Zhang, K. Howard, and Y. Qi, 2016: “Assessment of NOAA’s NEXRAD Reanalysis, 2016 AGU Fall Meeting, December 12-16, 2016, San Francisco, CA, USA

Nelson, B.R., D.-J. Seo, and D. Kim, 2010: Multisensor Precipitation Reanalysis, *J. Hydromet*., 11, 666-682.

Nelson, B.R., W. F. Krajewski, A. Kruger, J. A. Smith, and M. L. Baeck, 2003: Archival precipitation data set for the Mississippi River Basin: Algorithm Development, J. Geog. Res., 108, NO. D22, 18-1-14.

Ortega, K., 2015: “A Radar-based Storm Climatology for the Contiguous United States for Improved Severe Weather Climatologies and Warnings” 2015 AMS Meeting, Phoenix, AZ, USA.

Overeem, A., Holleman, I. & Buishand, A. (2009): Derivation of a 10-Year Radar-Based Climatology of Rainfall. – Journal of Applied Meteorology and Climatology 48, 1448–1463, DOI: 10.1175/2009JAMC1954.1.

Paulat, M., Frei, C., Hagen, M. & Wernli, H. (2008): A gridded dataset of hourly precipitation

in Germany: Its construction, climatology and application. – Meteorologische Zeitschrift 17, 6, 719–732, DOI: 10.1127/0941-2948/2008/0332.

Rubel, F. & Brugger, K. (2009): 3-hourly quantitative precipitation estimation over Central and Northern Europe from rain gauge and radar data. – Atmospheric Research 94, 544–554, DOI: 10.1016/j.atmosres.2009.05.005.

Rudolph, J.V., Friedrich, K. & Germann, U. (2009): A Radar-based Climatology of High Precipitation Events in the European Alps: 2000–2007. Contribution to the Conference on Mesoscale Meteorology, American Meteorological Society, August 2009, Salt Lake City, USA.

Saltikoff, E., Tuovinen, J.-P., Kotro, J., Kuitunen, T. & Hohti, H. (2010): A Climatological Comparison of Radar and Ground Observations of Hail in Finland. – Journal of Applied Meteorology and. Climatology, 49, 101–114, DOI: 10.1175/2009JAMC2116.1

Seres, A.T. & Horváth, Á. (2015): Thunderstorm climatology in Hungary using doppler radar data. – Időjárás – Quarterly Journal of the Hungarian Meteorological Service 119, 2, 185–196.

Skripniková, K. & Řezáčová, D. (2014): Radar-based hail detection. – Atmospheric Research 144, 175–185, DOI: 10.1016/j.atmosres.2013.06.002.

Stanzani, R., Alberoni, P.P., Nanni, S., Mulazzani, C. & Pasquali, A. (2000): Raingauge and C- Band Radar Monthly Rainfall Comparison in the Po Plain Area. – Physics and Chemistry of the Earth B 25, 981–984, DOI: 10.1016/S1464-1909(00)00137-4.

Stržinar, G. & Skok, G. (2016): Comparison of different radar-based hail detection algorithms in Slovenia. – EMS Annual Meeting Abstracts 13, EMS2016-265.

Tabary, P. (2007): The New French Operational Radar Rainfall Product. Part I: Methodology. – Weather and Forecasting 22, 393–408, DOI: 10.1175/WAF1004.1.

Tabary, P, Desplats, J., Do Khac, K., Eideliman, F., Gueguen, C. & Heinrich, J.-C. (2007): The New French Operational Radar Rainfall Product. Part II: Validation. – Weather and Forecasting 22, 409–427, DOI: 10.1175/WAF1005.1.

Tabary, P., Dupuy, P., L'Henaff, G., Gueguen, C., Moulin, L., Laurantin, O., Merlier, C. & Soubeyroux, J.-M. (2012): A 10-year (1997–2006) reanalysis of Quantitative Precipitation Estimation over France: methodology and first results. – Weather Radar and Hydrology (Proceedings of a symposium held in Exeter, UK, April 2011). IAHS Publication 351, 255–260 (Abstract).

Tapiador, F.J., Turk, F.J., Petersen, W., Hou, A.Y., García-Ortega, E., Machado, L.A.T., Angelis, C.F., Salio, P., Kidd, C., Huffman, G.J. & de Castro, M. (2012): Global precipitation measurement: methods, datasets and applications. – Atmospheric Research 104/105, 70–97, DOI: 10.1016/j.atmosres.2011.10.021.

Thorndahl, S., Nielsen, J.E., Rasmussen, M.R. (20149: Bias adjustment and advection interpolation of long-term high resolution radar rainfall series. – Journal of Hydrology 508, 214– 226, DOI: 10.1016/j.jhydrol.2013.10.056.

Wagner, A., Seltmann, J. & H. Kunstmann (2014): The German radar composite RX: Qualitative performance analysis for a precipitation climatology. Contribution to ERAD 2014 - The Eighth European Conference on Radar in Meteorology and Hydrology.

Weckwerth, T.M., Wilson, J.W., Hagen, M, Emerson, T.J., Pinto, J.O., Rife, D.L. and Grebe, L. (2011): Radar climatology of the COPS region. – Quarterly Journal of the Royal Meteorological Society 137, 31–41, DOI: 10.1002/qj.747.

Winterrath, T., Brendel, C. & Schmitt, A. (2015): Erstellung einer radargestützten Niederschlagsklimatologie. Dritter Zwischenbericht (in German), available at: ftp://ftp-anon.dwd.de/pub/data/gpcc/radarklimatologie/Dokumente/Zweiter_Zwischenbericht_Radarklimatologie_oeffentlich.pdf. Offenbach (Main): DWD.

Winterrath, T., Rosenow, W. & Weigl, E. (2012): On the DWD quantitative precipitation analysis and nowcasting system for real-time application in German flood risk management. – Weather Radar and Hydrology (Proceedings of a symposium held in Exeter, UK, April 2011). IAHS Publication 351.

Winterrath, T. & Schmitt, A. (2015): Erstellung einer dekadischen radargestützten hochauflösenden Niederschlagsklimatologie für Deutschland zur Auswertung der rezenten Änderung des Extremverhaltens von Niederschlag. Projektinformation (in German), available at: ftp://ftp-anon.dwd.de/pub/data/gpcc/radarklimatologie/Dokumente/projektinformation.pdf.

Offenbach (Main): DWD.

WMO (2016): Members of Regional Association VI (Europe) - National Meteorological or Hydrometeorological Services. http://www.wmo.int/pages/members/region6_en.html (State: 2016) (Last Access: 2016-03-16).

WRD (2016): WMO Radar Data Base. wrd.mgm.gov.tr (State: 2016) (Last Access: 2016-03-16).

Yuter, S.E. (2015): Precipitation Radar. In: North, G.R., Pyle, J. & Zhan, F. (eds.): Encyclopedia of Atmospheric Sciences (Second Edition). Oxford: Academic Press, 455–469, DOI: 10.1016/B978-0-12-382225-3.00328-5.

Zharashuev, M.V. (2012): Statistical Analysis of Hail Activity in Stavroppol Krai and Crimea.

– Russian Meteorology and Hydrology 37, 455–460, DOI: 10.3103/S1068373912070047.

GCOS Secretariat
Global Climate Observing System
c/o World Meteorological Organization
7 *bis,* Avenue de la Paix
P.O. Box No. 2300
CH-1211 Geneva 2, Switzerland
Tel: +41 22 730 8275/8067
Fax: +41 22 730 8181
Email: gcos@wmo.int