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Towards benchmarking citizen observatories: Features and functioning of online amateur weather networks

Mohammad Gharesifard[a, b, *], Uta Wehn[a], Pieter van der Zaag[a, b]

[a] *UNESCO-IHE, Institute for Water Education, P.O. Box 3015, 2601, DA Delft, The Netherlands*
[b] *Delft University of Technology, Department of Water Resources, P.O. Box 5048, 2600 GA Delft, The Netherlands*

A B S T R A C T

Crowd-sourced environmental observations are increasingly being considered as having the potential to enhance the spa-tial and temporal resolution of current data streams from terrestrial and areal sensors. The rapid diffusion of ICTs during the past decades has facilitated the process of data collection and sharing by the general public and has resulted in the for-mation of various online environmental citizen observatory networks. Online amateur weather networks are a particular example of such ICT-mediated observatories that are rooted in one of the oldest and most widely practiced citizen science activities, namely amateur weather observation. The objective of this paper is to introduce a conceptual framework that enables a systematic review of the features and functioning of these expanding networks. This is done by considering dis-tinct dimensions, namely the geographic scope and types of participants, the network's establishment mechanism, revenue stream(s), existing communication paradigm, efforts required by data sharers, support offered by platform providers, and issues such as data accessibility, availability and quality. An in-depth understanding of these dimensions helps to analyze various dynamics such as interactions between different stakeholders, motivations to run the networks, and their sustain-ability. This framework is then utilized to perform a critical review of six existing online amateur weather networks based on publicly available data. The main findings of this analysis suggest that: (1) there are several key stakeholders such as emergency services and local authorities that are not (yet) engaged in these networks; (2) the revenue stream(s) of online amateur weather networks is one of the least discussed but arguably most important dimensions that is crucial for the sustainability of these networks; and (3) all of the networks included in this study have one or more explicit modes of bi-directional communication, however, this is limited to feedback mechanisms that are mainly designed to educate the data sharers.

Keywords:
Citizen science
Citizen observatories
ICT-enabled citizen participation
Online amateur weather networks

1. Introduction

The term 'citizen science' was first used in January 1989 when 225 volunteer citizens from all states of the United States of America took part in a program to collect rain samples, test their acidity and report the results (Haklay, 2014). It took 25 years for this term to be added to the Oxford English Dictionary which defined it as: “the collection and analysis of data relating to the natural world by members of the general public, typically as part of a collaborative project with profes-sional scientists” (Oxford English Dictionary, 2014). However, citizen science activities in practice are much older than the creation of their name tag and actually many of the current science branches have been created thanks to curiosity and enthusiasm of amateurs (Haklay, 2015; Lankford, 1981; Mims, 1999).

During the past two decades, a shift has taken place in the gen-eral perception of the competence of citizens to participate in earth observation and environmental conservation and furthermore their po-tential influence on decision making processes (Wehn et al., 2015a). This shift coincided with advancements in Information Communica-tion Technologies (ICTs) such as user-friendly and affordable sen-sor devices, web-platforms and mobile applications (Wehn et al., 2015b) and resulted in the formation of diverse citizen science projects in many science domains, including atmospheric and space weather studies. As an example, *Zooniverse* is a hub for several climate and space-related initiatives including *Solar Stormwatch* (a project for mapping eruptions from the surface of the Sun) and *Old Weather* (that tries to model the Earth's climate using historic ship logs); other notable examples are the *National Eclipse Weather Experiment* (NEWEx) that focuses on atmospheric data collection from the partial solar eclipse (Barnard et al., 2016; Harrison and Hanna, 2016; Portas et al., 2016), and *Aurorasaurus* that takes advantage of the interest and curiosity of people about aurora borealis (northern light) to improve early warning systems of geomagnetic storms (Tapia et al., 2014).

The focus of this paper is online amateur weather networks: vir-tual platforms that host, aggregate and visualize amateur weather data. Amateur weather observation is not a new activity and meteorology science is one of the domains that was initiated as a result of ef-forts, enthusiasm and interest of amateur weather observers (Bell et al., 2013; Eden, 2009). The 1970s were known as “the renaissance of

* Corresponding author. UNESCO-IHE, Institute for Water Education, P.O. Box 3015, 2601 DA Delft, The Netherlands.

Email address: m.gharesifard@unesco-ihe.org (M. Gharesifard)

organized weather observing by weather amateurs" (Eden, 2009), when the first networks of amateurs such as the Climatological Observers Link (COL) were formed and weather observers started to exchange ideas and publish bulletins and magazines. Nowadays, there are a range of online amateur weather networks that aggregate and visualize citizen-contributed weather data.

Wiggins and Crowston (2011) identified five mutually exclusive types of citizen science initiatives and labeled them as Action, Conservation, Investigation, Virtual, and Education. Based on this classification, online amateur weather networks match the description for 'Investigation' initiatives as they focus on a scientific goal (i.e. improving local weather information and forecasts), depend on the contribution of citizens to observe the physical environment (i.e. weather attributes), range from regional to international in geographic scope, and highly depend on the spatial distribution of the participants. Although all online amateur weather networks fall within the same typology, each of these platforms has its own set of characteristics such as geographic scope, goals, origin and underlying processes of operation. We refer to these comparable features as 'dimensions' since each of them provides a common basis for comparison between different platforms, and, as a whole, they represent each network as a distinct entity. Building on the previous efforts in conceptualizing the dimensions of e-participation and citizen science initiatives, this paper introduces a framework that can be utilized to systematically review these expanding networks. A systematic review of different online amateur weather networks is valuable for benchmarking purposes by researchers, platform operators and also weather enthusiasts. Such evaluations can generate valuable insights about the features and functioning of different networks that may consequently help enhance citizen participation in these networks. Moreover, the framework of this research can be utilized by researchers and platform operators as a tool to monitor the changes of the weather networks over time. In this paper, we review six of the most popular weather networks using publicly available data, namely; (1) Citizen Weather Observer Program (CWOP),[1] (2) the UK Met Office Weather Observation Website (WOW),[2] (3) Weather Underground (WU),[3] (4) Davis WeatherLink (DWL),[4] (5) European Weather Network (EWN)[5] and (6) Het Weer Actueel (HWA).[6]

This paper is structured as follows. Section 2 presents a review of relevant theoretical contexts regarding e-participation and citizen science initiatives and introduces the conceptual framework developed in this study. In Section 3, we present the details of the methods used for conducting this research. The results of the research are presented in Section 4. Section 5 is dedicated to the discussion and conclusions; this section presents a number of recommendations on how to improve the current state of online amateur weather networks and, consequently, enhance citizen participation in meteorological observations.

[1] http://wxqa.com/.

[2] http://wow.metoffice.gov.uk/.

[3] http://www.wunderground.com/.

[4] http://www.weatherlink.com/.

[5] http://euweather.eu/.

[6] http://www.hetweeractueel.nl/.

2. Theoretical context

2.1. Dimensions of e-participation and citizen science initiatives

Conceptualizing ICT-enabled citizen participation is a relatively new practice since such activities have existed only for the past two decades. A number of previous studies have identified and defined 'dimensions' for e-participation (Macintosh, 2004), citizen science (Haklay, 2015; Roy et al., 2012), and citizen observatories (Ciravegna et al., 2013; Wehn et al., 2015b).

In 2004, Macintosh characterized e-participation using ten dimensions (row 1 in Table 1) and recognized such activities as a novel way of citizen engagement in democratic debates (Macintosh, 2004). This categorization was based on earlier research, including a study that was conducted on behalf of the Organisation for Economic Co-operation and Development (OECD) e-government group (Macintosh and Coleman, 2003). The discussion was centered around the concept of 'e-democracy' and included examples of top-down participatory activities, defined by authorities for citizens like e-petitioning and e-voting. Although the conclusions of this research were based on several case studies and e-participation activities in Europe, it did not capture important aspects such as the overarching goals, the communication paradigm, nor the revenue streams of such initiatives. Moreover, this study seems to have a pro-technology bias; this is evident from multiple arguments in the text; for example "such a framework has the potential to demonstrate how ICTs have contributed to specific democratic processes and to describe the conditions under which best practice can emerge" (Macintosh, 2004, p. 10).

With the advancements in ICTs and the emergence of new citizen observatory projects, similar attempts to depict different dimensions of such projects have been made. In 2012, a team of biologists and ecologists analyzed 234 citizen science projects using publicly available data and published their findings in a collaborative report (Roy et al., 2012). The results included two distinct dimensions; (1) 'degree of mass participation' and (2) 'degree of investment'. They further broke down these dimensions into detailed 'attributes' (row 2 in Table 1) to provide a basis for comparison between these projects. Based on information from publicly available data, the study has a neutral view about the strengths and weaknesses of each project but at the same time is limited to the dimensions that the research could discuss and score. In this regard, they state that "we could not reliably assess the source of funding, amount of funding received, the motivation of the project leaders, or the 'success' of the project" (Roy et al., 2012, p. 15). Investigating financial aspects of managing such platforms is highly important as it helps explaining critical issues such as the motivations behind running these networks, sustainability of the platforms, data ownership and level of access for the general public. The data collection method in this research may have limited the number of dimensions that the researchers could 'reliably' analyze, but, at the same time, allowed them to study a larger collection of projects that would be very difficult to assess otherwise.

Another instance of such a categorization can be found in Haklay (2015) which is based on lessons learned from European citizen science projects. This research stems from the Geographic Information Science domain perspective and distinguishes three main policy dimensions for citizen science projects; 'geography', 'policy application area' and 'level of engagement and type of citizen science activity' (Haklay, 2015). Further classifications are introduced for each policy dimension and these classifications are then used to discuss and compare different examples of citizen science projects. The summary of these dimensions and classifications is shown in row 3 of Table 1.

Table 1
Dimensions of e-participation/citizen science/citizen observatories (based on previous research). Domain column: shows the focus area of each research; dimension column: summarizes different aspects of the citizen science initiatives identified/studied in each research; ↔ symbol shows the range of attributes.

Domain	Dimension	Description/range/attribute	Source
E-participation	Level of participation	What level of detail or how far to engage citizens	(Macintosh, 2004)
	Stage in decision making	When to engage	
	Actors	Who should be engaged and by whom	
	Technologies used	How and with what to engage citizens	
	Rules of engagement	What personal information will be needed/collected	
	Duration & sustainability	For what period of time	
	Accessibility	How many citizens participated and from where	
	Resources and promotion	How much did it cost and how wide was it advertised	
	Evaluation & outcomes	Methodological approach and results	
	Critical factors for success	Political, legal, cultural, economic, technological factors	
Citizen Science	Degree of mass participation	Geographic scope (Narrow↔Wide) Selection of sites (Pre-selected↔Self-selected) Snapshots (Sufficient↔Not sufficient) Repeat visits (Required↔Not required) Personal training (Provided↔Not provided) Supporting material on website (provided↔Not Provided) Special equipment (Required↔Not required) Quality of data viewable (Poor↔Good) Viewable data (Static↔Dynamic) Involvement through smartphone (No↔Yes) Involvement through personal contact (No↔Yes) Photo requested (No↔Yes)	(Roy et al., 2012)
	Degree of investment	Aims stated (Poor↔Good) Background provided (Poor↔Good) Registration required (No↔Yes) Supporting material on website (Not provided↔Provided) Targeted at school children (No↔Yes) Types of data question (Few↔Many) Involvement via a website (No↔Yes) Best quality of data requested (Lower↔Higher)	
Citizen science (in EU)	Geography (levels)	Local community City level Regional level State/Country Continental	(Haklay, 2015)
	Policy application area	Environmental monitoring Environmental decision making Agriculture and food Urban planning and smart cities Health and medical research Humanitarian support Science awareness Support of scientific efforts	
	Level of engagement & type of citizen science activity	Passive sensing Volunteer computing Volunteer thinking Environmental and ecological observations participatory sensing Civic/community science	
Citizen observatories	Sensors & transmission	Physical sensor↔Social sensor	(Ciravegna et al., 2013) (Wehn et al., 2015b)
	Stakeholders	Authorities↔Citizens	
	Area of application	Physical environment↔Human behaviour	
	Purpose of citizen observatory	Protect environment↔Strengthen governance	
	System integration	Stand-alone↔Integrated	
	Measurement	Objective↔Subjective	
	Implementation	Bottom-up↔Top-down	
	Communications paradigm	Uni-directional↔Interactive	
	Communication and decision mode	Implicit data provision↔Technical expertise	
	Authority and power	Individual education↔Direct authority	

One of the strengths of this study is the inclusion of new forms of participation, such as passive sensing or implicit data provision by citizens. However, this conceptualization is mostly focused on the potential of citizen science to inform policy and decision making and does not capture several other important dimensions of citizen science projects (e.g. stakeholder groups, communication paradigms, revenue stream, and establishment mechanisms).

Wehn et al. (2015b) presented a framework for analyzing citizen participation in decision making via engagement in ICT-enabled observatories. This framework includes dimensions drawn from Fung's democracy cube (i.e. a framework for analyzing public participation in complex governance processes) and its dimensions, which are 'participants', 'communication and decision modes', and 'authority and power' (Fung, 2006). Two major changes were applied to the original 'democracy cube' to form the adjusted version; firstly, the generic scale of the 'scope of participation' is replaced with a spectrum of specific stakeholders who participate in flood risk management. Secondly, two elements were added to the 'communication and decision scale'; namely 'explicit data collection' and 'implicit data collection'. 'Implicit data collection' refers to the situation in which citizen observations are mined and collected from social media but citizens do not necessarily realize that this information is utilized and/or included in the decision making process. 'Explicit data collection', on the other hand, is added to include citizen's volunteered and intended observations that are usually collected using mobile phones or innovative sensor devices. Furthermore, Wehn et al. (2015b) present a whole range of different dimensions for citizen observatory projects (row 4 in Table 1) that builds on their earlier work in the WeSenseIt project[7] (Ciravegna et al., 2013). The dimensions presented in Wehn et al. (2015b) and Ciravegna et al. (2013) cover several critical aspects of ICT-enabled citizen observatories; however, they do not capture the ease or difficulty of participation (e.g. effort required data sharers and support offered by the initiators), characteristics of the produced data, nor the revenue stream to sustain the initiative.

Although the dimensions introduced and discussed in the aforementioned studies show a degree of overlap, similarity and plurality, there are several instances of inconsistency and disagreement in the way they try to define and depict these initiatives. One of the main underlying reasons for the inconsistencies is the fact that these research efforts differ in terms of scale and scope. Some discuss broad topics such as policy making, while others are focused on environmental monitoring or water management. Furthermore, some incorporate projects and initiatives at global scale, while others keep their center of interest at continental, national or local levels. Another contributing factor may be the type of the 'research lens' that researchers used for their studies. Building on these efforts by integrating their identified dimensions, eliminating their inconsistencies, and complementing their findings with other relevant features, the next section introduces the conceptual framework for this research that allows us to compare and contrast features and functioning of existing online amateur weather networks based on publicly available data.

2.2. Conceptual framework

The structure of our conceptual framework covers eight key dimensions of online amateur weather networks that are described in detail hereafter, along with the rationale for their inclusion. Each dimension consists of a range of relevant classifications that are either directly comparable for different platforms or need qualitative scores to make the comparison possible (Table 2).

2.2.1. Geographic scope and number of stations

The first dimension of our framework is *'geographic scope and number of stations'*. This is a combined dimension that shows the geographic coverage of online amateur weather networks as well as the number of stations that share their data via these platforms. Thus it is a good indicator to demonstrate how widespread each network is. Geographic scope and/or number of engaged participants have been recognized as separate dimensions by previous studies (Haklay, 2015; Macintosh, 2004; Roy et al., 2012). However, as we are studying a specific type of citizen science activity, combining these two dimensions enables us to define a more concrete indicator that depicts the extent of these networks. The classification introduced in this dimension distinguishes local, national, regional (supra-national) to global which includes the actual number of stations that share their data via these online platforms.

2.2.2. Type of participants

Citizen science and e-participation studies typically include a dimension for actors, stakeholders or 'type of participants' (Ciravegna et al., 2013; Macintosh, 2004; Wehn et al., 2015b). In this research, participants refer to individuals, groups or organizations that are involved in data collection/sharing, aggregation and visualization in online amateur weather networks. The classification of the type of participants follows the suggested categorization by Wehn et al. (2015b) that captures a broad range of possible actors of ICT-enabled citizen observatories. However, four changes were made to the classification

Table 2
The range, scores and sources of the dimensions of online amateur weather networks, as proposed in this study. Abbreviation: (L = Low (or none); M = Moderate; H=High; Y=Yes; N=No).

Dimension	Range	Score	Source
(1) Geographic scope & no. of stations	Local (No. of participants) National (No. of participants) Regional (No. of participants) Global (No. of participants)	Directly comparable	- Geography (Haklay, 2015) - Geographic scope/Level of engagement (Roy et al., 2012) - Accessibility (Macintosh, 2004)
(2) Type of participants	Netizens Citizen scientists Volunteers (Scientific) experts Private sector Non-Governmental Organizations (NGOs) Emergency services Local authorities National organizations Regional organizations International organizations	Directly comparable	- Participants (Wehn et al., 2015b) - Actors (Macintosh, 2004)
(3) Network establishment mechanism	Bottom-up Commerce driven Top-down	Directly comparable	- Implementation mechanism (Ciravegna et al., 2013; Wehn et al., 2015b)
(4) Revenue stream to sustain the network	Government sponsorship Data/information usage fee Subscription fee Asset sale Advertising Licensing Donation	Directly comparable	- Resources and promotion (Macintosh, 2004) - Revenue streams (Osterwalder and Pigneur, 2010)
(5) Communication paradigm	Uni-directional Bi-directional Interactive	Directly comparable	- Communication paradigms (Ciravegna et al., 2013)
(6) Effort required by data sharers	Registration efforts Monetary Investments Knowledge requirements	L/M/H L/M/H L/M/H	- Perceived behavioral control factors (Gharesifard, 2015) - Degree of mass participation attributes (Roy et al., 2012)
(7) Support offered by platform providers	Diversity of supported sensor types Supporting material Usability of the web-platforms Usability of the apps Stated descriptions about the aims	L/M/H Y/N L/M/H L/M/H Y/N	- Perceived behavioral control factors (Gharesifard, 2015) - Support provided by platform managers (Roy et al., 2012)

[7] http://wesenseit.eu/.

Table 2 (*Continued*)

Dimension	Range	Score	Source
(8) Data accessibility, availability and quality	Level of access to data for general public Diversity of accessible weather parameters Metadata quality and accessibility Data quality control	L/M/H L/M/H L/M/H L/M/H	- Data accessibility, availability and quality (Roy et al., 2012)

by Wehn et al. (2015b) in order to create the present spectrum; (1) two categories of volunteers and trained volunteers are merged to decrease the complexity of the classification; (2) Non-Governmental Organizations (NGOs) and international organizations are added to complement this classification; (3) in this research 'regional organizations' refer to supra-national organizations (unlike in Wehn et al. (2015b) where it refers to sub-national organizations); and (4) the category of 'citizens' is replaced by 'netizens' to capture the implicit form of data sharing (e.g. via social media).

Moreover, it is important to distinguish between the definitions of 'netizens', 'citizen scientists', and 'volunteers' in this dimension. 'Netizens' represents the situation in which observations made by the general public are mined and collected (e.g. via social media) but the data sharer is not necessarily aware of the fact that this information is collected by the networks. 'Citizen Scientists' on the other hand refer to those personal weather station (hereafter PWS) owners who explicitly and intentionally are engaged in sharing their PWS data via these networks. The 'Volunteers' category is included to capture individuals, groups and organizations that are systematically targeted and recruited to freely undertake a task in these networks that normally helps the network reach its pre-defined goals. Thus, both 'Citizens Scientists' and 'Volunteers' carry out voluntary activities; however, the difference lies in the way they got engaged in the activity.

Lastly, '(Scientific) experts' refer to academic individuals or organizations (e.g. universities and schools) that are engaged in data collection/sharing, aggregation or visualization.

2.2.3. *Network establishment mechanism*

This dimension is incorporated to depict the origin of each platform. *'Network establishment mechanism'* is described as the establishment system of citizen observatories and has three distinct classes; 'top-down', 'bottom-up' and 'commerce driven'. The first two classification where previously identified by Ciravegna et al. (2013); in a top-down setup, authorities and stakeholders at upper-levels of policy making initiate the citizen observatory while in a bottom-up setup stakeholders such as citizen scientists or volunteers start the citizen observatory. The third category (i.e. commerce driven) is added to capture the establishment mechanism of networks that neither have risen from official administrative bodies nor from grassroots levels, but rather have been set up by for-profit organizations (e.g. private companies).

2.2.4. *Revenue stream to sustain the network*

This dimension of our framework depicts how each network generates its revenue or receives its required funding. Despite its importance, previous research has not captured and studied this dimension for citizen science initiatives. Macintosh (2004) touches on funding issues when she discusses 'resources and promotion' and briefly mentions that due to the novelty of e-participation initiatives, they are mostly funded by national governments and from their research and development (R&D) budget. In this study, we classify the existing revenue streams for online amateur networks into seven distinct categories. This classification is adopted from Osterwalder and Pigneur's seminal work on business models (2010) (in which revenue streams are one element) and was adjusted to best describe the revenue streams of online amateur weather networks. (1) The first revenue stream is 'government sponsorship' that usually exists in a top-down set up. In this case, governments have (or envision) strategic use of the data and thus allocate resources (e.g. from their R&D budget) to establish and maintain an online amateur weather network. (2) Rather than the rare case of commercializing raw citizen-contributed data, platform managers may combine citizen contributed weather data with other data sources such as satellite and radar data and sell these data products to individuals or organizations. They may also process the data (e.g. using models) to generate information such as forecasts, warnings, maps, etc and make profit from selling these products. This category of revenue streams is here referred to as 'data/information usage fee'. (3) 'Subscription fee' refers to the membership fees that platform users may have to pay in order to gain continuous access to services provided by the platform (e.g sharing weather data via an online platform or using the ad-free version of a website or mobile application). (4) 'Asset sale' refers to selling physical products such as amateur weather station hardware devices or their accessories such as data-loggers or modems. (5) 'Advertising': some networks offer advertisement opportunities on their platform while others may share users' log-data with advertisers, advertising networks/servers or analytics companies (e.g. Google 'AdSense') for targeted advertisement in return for a share of the advertising income. (6) 'Licensing' is generated as result of providing intellectual property rights to data sharers or the general public. An example of this classification may be licenses to use a specific weather software or application that is developed by the network. (7) 'Donation' indicates the network's full or partial dependence on the contributions of others (their members or the general public) to sustain the initiative.

2.2.5. *Communication paradigm*

There are three distinct patterns of communication between different stakeholders within a citizen science initiative; 'unidirectional', 'bi-directional' and 'interactive' (Ciravegna et al., 2013; Wehn et al., 2015b). The *'communication paradigm'* dimension is introduced to distinguish between online amateur weather networks that only act as recipient of amateur weather data and those that provide regular/occasional feedback through different communication channels or even form an interactive exchange of information among the weather observers, data aggregators and end users of the data.

2.2.6. *Effort required by* ***data sharers***

Although not the focus of this research, several studies have identified motivations and barriers for participation in different citizen science initiatives, for example taking part in an online crowdsourcing game (Müller et al., 2010), water quality monitoring (Minkman, 2015), ecological citizen science projects (Rotman et al., 2012) and most relevant to this research, sharing PWS data (Gharesifard and Wehn, 2016a,b). Some of these drivers and barriers are general across all projects, but others may be highly case specific. The classification *'Effort required by data sharers'* is mainly informed by (Gharesifard and Wehn, 2016a,b). Roy et al. (2012) also pointed out general attributes and indicators for this dimension such as efforts and time spent on answering questions during the registration process (Roy et al., 2012). This dimension allows us to compare and contrast online amateur weather networks exclusively based on the level of effort that is required from the data sharers' side. These efforts are grouped into three different categories; (1) registration efforts, (2) monetary investments, and (3) knowledge requirements.

2.2.7. Support offered by platform providers

This dimension considers the investments made by the founder, owner or manager of the online amateur weather network to communicate about the platform and facilitate citizens' participation. This dimension is also based on the results of previous research by Gharesifard and Wehn (2016a,b). Other research was also consulted to complement the classification of this dimension (Ciravegna et al., 2013; Roy et al., 2012; Wehn et al., 2015b). The classification introduced for this dimension is (1) 'diversity of supported sensor types' which refers to the flexibility of the network to incorporate data from a variety of (physical and social) sensors, (2) 'supporting material' provided for the participants such as set-up instructions and data collection guidelines, (3) 'usability of web-platforms', (4) 'usability of mobile applications' and (5) 'stated descriptions about the aims' of these platforms.

2.2.8. Data accessibility, availability and quality

The last dimension of our framework is *'data accessibility, availability and quality'*. This dimension was previously identified by Roy et al. (2012) and is tailored here to best fit the specific case of online amateur weather networks. Including this dimension enables us to compare and contrast four important aspects of online amateur weather networks; (1) 'level of access to data for the general public' reflects the opportunity for the general public to retrieve and/or store data from the network, distinguishing between real-time weather data and historical weather data, (2) 'diversity of accessible weather parameters' is about the variety of weather attributes that is collected or calculated on each platform, (3) 'metadata quality and accessibility' indicates the quality of the information available about the shared weather data and to what extent this information is accessible to the general public, and (4) 'data quality control' depicts the integrity of the network's quality control procedures and whether self regulatory tools (e.g. the possibility of comparing the data shared by neighboring stations) are available that allow the general public to assess the quality of shared data.

2.2.9. Summary

Fig. 1 depicts our conceptual framework for analyzing the features and functioning of online amateur weather networks. The inner ring of the framework portrays the eight aforementioned dimensions and the outer layer shows the suggested classification for each dimension. Dimensions 1–5 of the framework are directly comparable for all online amateur weather networks, however, dimensions 6, 7 and 8 require qualitative scores to make the comparison possible and this scoring mechanism is introduced in Table 2. As an example, 'Registration efforts' range from Low (or none) to High and (existence of) supporting material can be scored Yes or No.

3. Methodology

Similar to the previously introduced research by Roy et al. (2012), this study also primarily relies on publicly available information. This information is mainly collected from the websites of the six aforementioned online amateur weather networks, and where possible, other relevant/linked online resources. Secondary literature that either reviewed these platforms and their functionalities (e.g. Burt, 2012; Chadwick, 2002; Gharesifard, 2015; Tweddle et al., 2012) or studied the trends of their evolution and future potentials (e.g. Bell et al., 2013; Eden, 2009; Muller et al., 2015) as well as available manuals and instructions were also consulted to enrich the review of the websites. Moreover, we incorporated the feedback of 43 PWS owners who are engaged in sharing data via one or more of these platforms to complement the first two data sources. These station owners participated in an online survey that was conducted in 2014, aiming to identify the drivers and barriers for sharing data via online amateur weather networks in the Netherlands, UK and Italy (for more information see Gharesifard, 2015; Gharesifard and Wehn, 2016a,b).

The introduced dimensions and classifications of the conceptual framework are designed in a way that enables systematic evaluation of online amateur weather networks based on publicly available data and thus can be employed to compare similar amateur weather networks. We chose, as much as possible, to keep the classifications directly comparable and, if not possible, use simple relative scoring mechanisms ('low (or none)-moderate-high' or 'yes/no' responses) to increase the reliability of the findings (see Table 2).

Due to the fact that the conceptual framework of this research is designed to enable comparison of different online amateur weather networks based on publicly available data, it does not include all possible dimensions that may be perceived for such platforms. For example, it was not possible to reliably incorporate and discuss dimensions such as 'communication and decision modes' and 'authority and power' as suggested by Ciravegna et al. (2013) and Wehn et al. (2015b) solely based on public domain data. However, as Roy et al. (2012) also pointed out, our approach may complement studies in which platform representatives are invited to evaluate their own platforms. This is due to the fact that we were able to study the platforms from a more neutral point of view.

4. Results

This section presents the review of the six aforementioned online amateur weather networks and contains a comparative analysis of these networks based on the previously introduced elements of our conceptual framework.

4.1. Dimension 1: Geographic scope and number of member stations

The geographic scope of the online amateur weather networks can be easily established by the spatial coverage of their member stations; however, there are a number of complexities involved in retrieving the number of member stations from publicly available information. Firstly, these networks are ever expanding and the number of member stations change on a daily basis; thus it is important to indicate a reference date (or time frame) when discussing such figures. Secondly, and surprisingly, the majority of online amateur weather networks do not seem to have a consistent and unequivocal way for reporting the number of their member stations; this gets even more complicated when they incorporate data shared from other sources such as synoptic stations, met-offices and road stations. Accordingly, we choose to record and report the approximate number of stations (of any type) that were engaged in sharing data on each of these networks in January 2016. In most cases, this figure was retrieved from the platform but where not possible, the references are mentioned.

WU (with ~180,000 members), DWL (with ~20,000 members), CWOP (with ~17,000 members) and WOW (with ~10,000 members[8]) are global scale networks since stations located in any country can register and share data on these networks. EWN is a regional network for Europe with approximately 5000 members. Lastly, HWA is

[8] Source: https://ams.confex.com/ams/96Annual/webprogram/Paper285181.html.

Fig. 1. Conceptualization of the features and functioning of online amateur weather networks in this study.

a relatively small Dutch weather network (with ~375 members) that only hosts stations from the Netherlands and Belgium. HWA is also categorized as a supranational (regional) network since it incorporates stations from more than one country.

4.2. Dimension 2: Type of participants

'Netizens' (implicit form of data provision) and 'volunteers' (with the definition provided in Section 2.2.2) are not among the participant groups in any of the networks in this study; however, 'Citizen scientists' are obviously a common type of participants among all six networks.

Due to the large number of member stations of the networks, most networks have at least one school or university that shares its data on their platform; however, a systematic patterns of inclusion of '(Scientific) experts' was found in three of the networks: (1) WOW explicitly encourages and incorporates weather data from schools and universities, (2) DWL has a special focus on weather education and even provides educational resources such as training materials for teachers, (3) The University of Utah is directly involved in the process of data aggregation for the CWOP network.

The 'private sector' has a strong presence in the majority of the online amateur weather networks. HWA, EWN and WU were initiated by individuals and later on either became independent private entities or formed partnership with private companies. DWL was formed by Davis Instruments, a private company. CWOP is a public private partnership and has two privately owned servers (APRS and FindU) that form the main channel of data flow in this network.

'National organizations' are also very much engaged with the online amateur weather networks in this study. They are either among the founders or partners of the networks or contribute data to these networks. More specifically, (1) the National Oceanic and Atmospheric Agency (NOAA) and the National Weather Service (NWS) of the United States are partners of CWOP; (2) WOW is developed by the UK National Meteorological Service and has been supported by the Department for Education and the Royal Meteorological Society. National meteorological services in UK, the Netherlands, Australia and New Zealand share their data on this platform; (3) WU incorporates national weather service data from different airports worldwide and NOAA in the US; (4) EWN includes synoptic and climatological stations of several countries and also a network of road stations in Finland and Sweden; (5) The Royal Netherlands Meteorological Institute (KNMI) collaborates with HWA.

Lastly, there is no evident sign of systematic involvement of 'NGOs', 'emergency services', 'local authorities', 'regional organizations', and 'international organizations' on data collection/sharing, aggregation and visualization activities of the networks in this study.

4.3. Dimension 3: Network establishment mechanism

HWA and EWN were both initiated by individual citizens and thus classified as bottom-up networks.

DWL was initiated by a private company and matches the characteristics of a commerce-driven initiative that is market-based and for-profit. Although the original idea for WU is the result of a PhD research in 1991 at the University of Michigan, in 1995 it became an independent commercial entity and launched the web-platform that exists today; thus WU is also categorized as a commerce-driven system.

CWOP was originally designed by NOAA in 2002 to collect the contributed weather data by amateur radio (a.k.a. ham radio) stations and feed them into its Forecast Systems Laboratory (FSL) for research purposes and therefore is a top-down set up. Finally, WOW was launched in June 2011 by the United Kingdom's national weather service (Met Office) with support from the Royal Meteorological Society and the Department for Education, and thus is a top-down set up.

4.4. Dimension 4: Revenue model to sustain the network

In a top-down initiated network, the revenue stream usually consists of government sponsorship. CWOP and WOW were both initiated by national governments and sponsored and partially funded by the US and UK governmental agencies, respectively.

None of the networks directly profit from selling citizen-contributed data and all of them provide a certain degree of access to current and/or historical weather data for the general public free of charge (see discussion on level of access to data in the eight dimension); however, networks may complement these data with other data streams (i.e. official in-situ observations and satellite/radar data) and provide paid services such as on request historical data or information like local/national weather reports, forecasts, warnings, maps, etc. NOAA ingests CWOP data into its partner data centers (NODC,[9] NCDC[10] and NGDC[11]) through the Meteorological Assimilation Data Ingest System (MADIS)[12] (CIRA, 2015; Davis Instruments, 2009); MADIS data is then used to develop a range of commercial data products. According to the Met Office, citizen contributed data is 'extremely useful' for their weather monitoring and forecast purposes (Met Office, 2015). The Met Office in the UK has a long history of providing commercial weather forecasts for a wide range of clients. For example, it held a contract with the BBC to provide its weather forecasting for almost a century (The Guardian, 2015). Similarly, the WU includes PWS data in its forecast system that is referred to as BestForecast™ and offers commercial weather services such as forecasts and weather summaries (e.g. for the Associated Press); moreover, they also provide on-demand paid weather data and information through an API system.[13]

In commerce driven networks, 'subscription fee' is a common revenue stream. WU provides both 'freemium' and premium subscription services. Its premium membership scheme offers faster and ad-free access to their website content, with improved radar animations, but requires a yearly subscription fee. DWL also asks an annual subscription fee from member stations that have not purchased a WeatherLinkIP data logger or Vantage Connect wireless modem to publish their data on this network.

DWL and WU are the only two networks that have the 'asset sale' revenue stream that is defined as "selling ownership rights to a physical product" (Osterwalder and Pigneur, 2010, p. 31). Davis Instruments is one of the main producers of weather-related products such as weather stations, physical sensors and communication devices. In a similar way (although in a totally different context), WU offers few commercial products such as logo-imprinted T-shirts and hoodies via its online store.

The majority of the networks analysed in this study use advertising as a source of revenue. EWN, HWA, WU and CWOP (on its findu.com server) in their privacy policy, explicitly or implicitly clarify that users' browser information collected via cookies and web beacons may be used by advertisers, advertising networks/servers or analytics companies (e.g. 'AdSense' service offered by Google) for targeted advertisement. WU also has its own targeted advertisement system that identifies potential customers for a product or service based on their geographic location, weather condition, visit time/day and various visitor segments (e.g. lifestyle segments based on ESRI sourcebook). Moreover, HWA has its own traditional advertisement scheme that allows interested companies to display ads on its main page or sub-pages for a period of time at a specific cost.

'Licensing' and 'donations' are the least common revenue streams among the networks under this study. DWL is the only network that has 'licensing' revenue from a range of licensed software products that its provider Davis Instruments offers to weather enthusiasts, farmers, emergency services and the general public. CWOP's findu.com is also the only example that occasionally has asked for donations (Dimse, 2013); however, this is not a fixed revenue stream for the CWOP weather network.

4.5. Dimension 5: Communication paradigm

The most explicit form of data flow that exists in all examined networks concerns the weather data that is regularly uploaded by weather observers. Apart from this common, uni-directional pattern, all of the networks in this study have one or more explicit communication channel(s) that enables data sharers to exchange information with each other, and/or, with network operators. These channels are mainly used to communicate about issues such as device set-up, maintenance, troubleshooting and data quality control. The communication channels that are used by the networks in this study are summarized in Table 3. Communication channels can potentially facilitate interactive information exchange between amateur weather observers, data aggregators (the platform operators) and end users of the data; however, it seems that (so far), the communication paradigm in all of these networks is limited to the bi-directional form, mainly aimed at educating the data sharers. As an example, according to the CWOP website, one of its main goals is to "provide feedback to the data contributors so they have the tools to check and improve their data quality" (Chadwick, 2015).

*4.6. Dimension 6: Effort required by **data sharers***

'Registration efforts' are assessed based on the efforts and time needed to follow a number of pre-defined steps that are required to complete the registration process on each platform. WOW, WU, DWL and EWN have fairly simple initial registration processes and only require filling out an online form that includes a limited number

Table 3
Communication channels of the different networks.

Communication channel	CWOP	WOW	WU	DWL	EWN	HWA
Contact form	–	✓	✓	✓	✓	✓
Email	✓	✓	✓	✓	–	✓
Telephone	–	✓	–	✓	–	✓
Text message system	–	–	–	–	–	✓
Online forum(s)	✓	✓	✓	–	–	✓
Internal messaging system	–	–	✓	✓	–	✓
Social media	✓	✓	✓	✓	✓	✓

[9] National Oceanographic Data Center.

[10] National Climatic Data Center.

[11] National Geophysical Data Center.

[12] MADIS is a meteorological observational database and data delivery system operated by the National Weather Service of the United States.

[13] http://www.wunderground.com/weather/api.

of personal information and station coordinates (normally latitude, longitude and ground elevation). WOW is the only platform in this study that allows data sharers to post 'quick observations' without the need for registration or logging in. CWOP, on the other hand, requires more efforts from the participants and includes two extra steps in its registration process; (1) manual check of the shared weather data on FindU.com server by the station owner and (2) a response by the station owner to an email from CWOP and confirming that the station is up and running (Hardiman, 2012). After approximately one week, the registered station will appear on different web sites that visualize CWOP data (e.g. MesoWest[14]). Lastly, HWA demands the largest registration efforts as it requires the data sharers to test their station for a minimum period of two months before they can post their data on this platform.

Sharing PWS data on online amateur weather networks requires initial and long-term 'monetary investments' by the individual amateurs. Initial monetary investment is done to purchase hardware devices and a software application (which may have license fees) that are supported by the network. Other costs include ongoing operation and maintenance expenses such as electricity bills, costs of changing a broken sensor and also periodic subscription fees. Sharing data on WOW requires the least monetary investments as it is the only 'device independent' (it is possible to share data on this network using all levels of equipment even without having a PWS) and 'software independent' (it supports any software including self-developed APIs) network in this study. Although the range of supported hardware and software differ for CWOP, WU, EWN and HWA, they all require having a PWS and at least a free (open source) software application that uploads the weather data to these networks; furthermore, none of these networks require one-off or periodic subscription fee(s), thus they are all categorized as networks with moderate monetary investments. Sharing data on DWL is the most expensive option as it only incorporates the data produced by Davis PWSs and requires members to have annual subscription or to purchase an additional piece of hardware (a WeatherLinkIP data logger or Vantage Connect cellular modem).

According to our earlier study on the motivations and barriers of sharing PWS data (Gharesifard and Wehn, 2016a,b), two types of knowledge are required for sharing data via an online network; (1) basic understanding of meteorology (e.g. weather parameters and how they are measured, and (2) knowledge about methods and techniques involved in setting up a PWS, data collection, sharing data via online weather networks and also maintaining a PWS. The first type is a common requirement for sharing data on any online amateur weather network; however the second one highly depends on the type of software and hardware devices that are supported by the network. WOW, the only device/software independent network in this study, requires the lowest level of hardware/software knowledge. CWOP, WU and DWL require a moderate level of knowledge as CWOP incorporates several software and hardware devices and also hosts ham radio stations that are not included in any other network in this study; WU also supports a wide range of software and hardware devices, for example Netatmo weather stations (compact and wireless devices for smart phones and tablets) that are very easy to set-up and run; DWL supports limited software and hardware devices, however, it provides alternative (but more expensive) methods such as purchasing a Vantage Connect modem that eliminates the need for using onsite computer interface. Sharing data on EWN and HWA requires a relatively high level of hardware/software knowledge as these networks support quite a limited list of software applications and do not provide alternative hardware solutions to facilitate the data sharing process.

[14] http://mesowest.utah.edu/.

4.7. Dimension 7: Support offered by platform providers

With regards to 'diversity of supported sensor types', WOW receives the highest scores among the networks in this study, as it is the only device independent and thus most flexible network in terms of incorporating data from various (physical and social) sensors. DWL, in contrast, receives the lowest score, as it only incorporates PWSs and software applications developed by Davis Instruments. Sharing data on CWOP, WU, EWN and HWA requires having a physical sensor device (i.e. PWS) and at least one open source application that convert PWS data in to an acceptable format for these platforms, thus all four networks are ranked moderate for this classification.

All networks in this study except EWN provide 'supporting material' in some form or other on their web-platform. These resources cover a wide range of topics such as choosing a PWS, set-up and installation guides, data collection guidelines, hardware/software manuals, data quality control and weather observation handbooks. CWOP, WOW and WU provide a large number of supporting materials for their audience. DWL's material is mostly limited to product manuals and instructions about set-up, use and troubleshooting hardware and software but it also provides some information and educational resources for teachers. HWA has limited software manuals that are only available to its members.

With regards to 'usability of web-platforms', factors such as having concise content, ease of browsing/finding relevant information and availability of interactive features such as maps, tables and charts were taken into account. Based on these criteria, WU receives the highest rating among the networks in this study. In addition to the simplicity of browsing and retrieving information from the WU platform, it has an interactive weather map (WunderMap) that is one of the most comprehensive products of its kind and enables the user to view weather attributes from a huge network of official and PWSs and also combines this data with radar data, satellite data, model data, extreme conditions and many more layers. WOW is also very easy to use with concise information and has an interactive map with less comprehensive information (compared to the WU) that allows visitors to easily switch and view data shared from official stations and WOW stations with the option to filter out the sites with no data. The other four web-platforms are rated as low in terms of usability of their web-platform for different reasons; CWOP has an old-fashioned and unpolished web-platform with lots of information that makes finding relevant information cumbersome; HWA and EWN have semi-interactive maps with little or no flexibility for displaying various information, tables and charts and DWL's has a platform with very little information available and a static map, lacking an interactive feature.

'Usability of the apps' was assessed based on similar criteria as for the usability of web-platforms. Moreover, the overall ratings and reviews of users on the Google Play Store and Apple App Store were considered while rating different networks for this dimension. WU has a comprehensive app with several interactive features (e.g visualization of PWS/radar/satellite data, current weather conditions, 10-day forecast, and many more options) which is the most downloaded, among the networks in this study. CWOP, DWL, EWN, and HWA have simple apps with very limited interactive features (mostly limited to visualization of PWS data, current weather conditions, and forecasts), and thus are rated low for this classification. Finally, WOW does not have an app (yet) and thus is not rated.

All of the networks in this study except HWA describe their aims either on their first page or sub-pages. The majority of networks implicitly or explicitly declare their aims to be the collection and visualization of citizen-contributed weather data. CWOP provides a more detailed description of its aims which are as follows: “1) to collect weather data contributed by citizens; 2) to make these data available for weather services and homeland security; and 3) to provide feedback to the data contributors so they have the tools to check and improve their data quality” (Chadwick, 2015).

4.8. Dimension 8: Data accessibility, availability and quality

The 'level of access to data for the general public' is assessed based on the possibility for the general public to view and download weather data from a network and whether extra efforts such as registration and logging in are required to view/download the data. All of the networks in this study provide access to real-time weather data without the need to register on their web-platform, thus networks were compared based on their level of access to historical weather data; Table 4 summarizes the resulting comparison. Based on this information, WU and HWA provide the highest and DWL provides the lowest level of access to data.

All of the networks in this study provide access to the principal weather parameters such as precipitation, pressure, temperature, dew point, wind (at least speed and direction), humidity and solar/UV radiation; however, WU and WOW have more diverse accessible weather parameters. For example, it is possible to share and view parameters such as soil temperature (at 10, 30 & 100 cm depths), weather codes (present weather, ground state, visibility, total cloud cover), 'weather impacts', 'river level' and state of ground (e.g. flooded, ground frozen, etc) on WOW. WU also provides data about visibility, leaf wetness, pollen, air quality and even flu activity based on the weather patterns.

WOW and HWA both use a rating system that provides an overview of the overall quality of observations at each station. In these networks, individual weather stations are rated based on their exposure, rainfall data and measurement of air temperature. Moreover, each station has a separate page where metadata related to that station is displayed. It is possible to share many details on these pages; however, the completeness of the metadata is to some extent dependent on the data sharer. In case of CWOP, each station page contains information such as its location, station type/software used, the units of the data shared, error messages (if any) and contact information of the station owner; however, there is little data about the instrument exposure (unless the data sharer wants to share such data). WU and DWL provide a page with very little information that is limited to hardware/software used and coordinates/altitude of the station (only in case of WU) and even if the data sharer is willing to do so, the standard format does not allow sharing additional information about the station. In the case of EWN, the network does not provide any metadata about its member stations and although most of these stations may have detailed metadata on their personal webpage, it is not managed by the network.

The level of 'data quality control' of the networks is compared based on two distinct aspects; (1) the network's quality control procedures and (2) self regulatory tools that enable data quality assessment by the general public. With regards to the first category, CWOP, WOW and WU compare citizen contributed data against pre-defined thresholds to filter out obvious extremes. CWOP and WU check the spatial consistency (through comparing the weather data to nearby stations) and temporal consistency (through monitoring data fluctuation over specified time intervals) of the data. Moreover, CWOP and

Table 4
Data accessibility, availability and quality of different networks.

Network	Descriptions	Is historical data available to view?	Is historical data available to download?	Is any type of authorization involved?
CWOP	– Recent observations of the station, based on the defined sharing intervals and for up to 56 days. – Graphs showing means and standard deviations of the data for these periods: (3d, 7d, 14d, 4w, 8w, 13w, 26w, 39, 52w). – Historical data in form of graphs at Findu.com server for these intervals: (12hrs, 1d, 2d, 3d, 5d, 10d)	Yes	Yes	No
WOW	– Recent observations of stations (reports) can be viewed for the past month. – It is possible to view historical data in form of graphs for longer periods of time depending on the availability of the data.	Yes	No	Yes, logging in required to download all weather reports from one station
WU	– It is possible to view full available historical data for each station, city, state, zip code or area code without the need to be logged in. – WU also has an API that is able to provide historical weather data records through HTTP requests for those who need weather history over a long period of time and/or for a specific location.	Yes	Yes	No
DWL	– Access to historical data is only available for the station owner and is accessible via the 'Web Download' option in the WeatherLink software. – WeatherLink.com only stores up to 800 days of historical data (depending on the achieve interval may be over 2 years) and suggest to download the data in case the station owner is willing to access a longer period of historical data.	No	No	Yes, logging in required with station owner's credentials to download historical data

Table 4 (*Continued*)

Network	Descriptions	Is historical data available to view?	Is historical data available to download?	Is any type of authorization involved?
EWN	– It is possible to view historical data for the last 1d, 3d, 1w, 1m, 3m, 6m and up to one year in graphic format. – No tabular data is available to view or download.	Yes	No	No
HWA	– Full available daily and monthly historical weather data are viewable and downloadable in tabular format for each station.	Yes	Yes	No

WU also use feedback mechanisms such as sending notification of errors or quality reports via email or a built in messaging system to inform the station owners about the quality of their station data. Providing quality control reports or notifications for the general public is another method that is used by CWOP; this network provides an aggregated quality report covering the past 14 days for stations that are registered for weather quality emails. The report lists stations that might have calibration problems (over a period of 28 days) and those with temporal/spatial inconsistencies. Moreover, WU filters out the data from stations with extreme data or data with spatial/temporal inconsistency and DWL and HWA display a notification on station pages with no (current) data. With regards to self regulatory quality control tools, all of the networks in this study except DWL make it possible to compare the data shared by any station with nearby stations by providing a direct link to neighboring stations and/or comparison graphs. Moreover, metadata (as discussed in the previous section), especially information about equipment used and site exposure are also useful self-regulatory tools that are provided in a more comprehensive way by the WOW and HWA networks.

Fig. 2 summarizes the results of the assessment of six of the most popular weather networks using our conceptual framework.

5. Discussion and conclusions

While it is not possible to portray a picture of all conceivable dimensions that might be relevant for citizen science initiatives, it is worth highlighting the dimensions that have particular resonance for better understanding the features and functioning of these innovative efforts. The analysis of six of the most popular weather networks (which included around 200,000 PWSs) in this research, based on publicly available information, suggests the following.

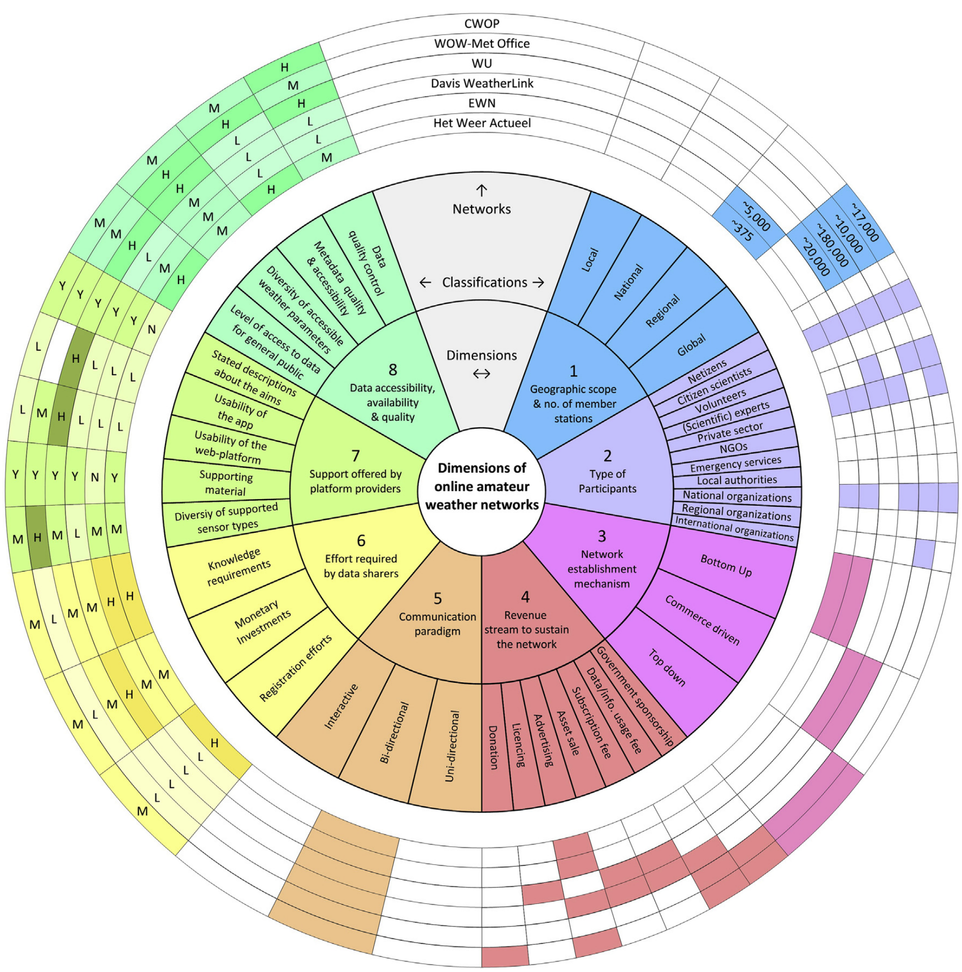

Fig. 2. Summary of the assessment of six online amateur weather networks. Colored cells in dimension 1 to 5 indicate the applicable range for each network. Dimensions 6–8 use a qualitative scoring system where L = Low (or none), M = Moderate, H=High, Y=Yes, and N=No.

Surprisingly, NGOs, emergency services, local authorities, and regional/international organizations are not (yet) well-engaged with the weather networks of this study. These actors, if engaged as data contributors, will help enhance the spatial and temporal resolution of the data and, if actively involved in data aggregation activities, are likely to boost the operational capacity of the network. Moreover, as the end users of the data, these stakeholders may help strengthening the belief of the data contributors that their efforts are valued and used in the decision making processes at local and regional levels.

The revenue stream of online amateur weather networks is one of the least discussed but arguably most important dimensions that is crucial for the sustainability of these networks. Comparing the network establishment mechanism and revenue streams suggests that there is a connection between these two dimensions. Both bottom-up networks in this study have limited revenue streams and are entirely dependent on advertising which might not be sufficient to support their future growth. Top-down systems are very dependent on government sponsorship and may need to consider alternative revenue streams to be able to cope with the growth of the network. In contrast, the commerce driven initiatives have more diverse revenue streams that help strengthen their financial sustainability.

Although all of the networks included in this study have one or more explicit pattern of bi-directional communication, they are mostly focused on educating the data sharers. An interactive exchange of information among the weather observers, data aggregators and end users of the data (e.g. policy makers) have the potential to help improve the functionality of the platforms, build bilateral trust between data sharers and end users of the data, enhance/maintain the enthusiasm of the amateur weather observers over time and foster more inclusive environmental decision making.

Creating an enabling environment for the citizen scientists by reducing the efforts required by participants and/or increasing the support offered by the networks will certainly diminish the barriers for greater public participation. Moving towards flexible and device/software-independent networks with simplified registration processes, providing easily accessible supporting materials and user-friendly web-platforms and mobile applications are concrete measures that networks may consider. These measures will help to trigger the participation of those who consider amateur weather observations a salient activity but have the impression that they lack knowledge, skills or financial resources to participate.

To conclude, the framework introduced in this study enabled a systematic review of the features and functioning of online amateur weather networks as hubs for one of the oldest and most widely practiced citizen science activities. This was facilitated by breaking down the complexities of these initiatives into distinct elements that are comparable across different cases. This systematic review of different online amateur weather networks may be valuable for benchmarking purposes by researchers, platform operators and also weather enthusiasts to compare and contrast different online amateur weather networks. Such evaluations can also generate valuable insights about the features and functioning of different networks that may help enhance citizen participation in these networks. Furthermore, the framework of this research can also be utilized by researchers and platform operators as a tool to monitor the changes of the weather networks over time. Although the dimensions and classification introduced in this framework are common among many other citizen science initiatives (beyond amateur weather networks), further research is needed to explore the applicability of this framework to evaluate and compare other citizen science initiatives.

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