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RESEARCH ARTICLE

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From proof-of-concept to proof-of-value: Approaching third-party data to operational workflows of national meteorological services

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Abstract

National meteorological services (NMS) are limited by practical and financial boundaries in the number of official meteorological measurements that it can collect. This means that large regions are often unobserved. These gaps can be filled by novel data sources, including measurements from personal weather stations that are owned and operated by amateur citizen scientists, or opportunistic sensing from devices that are not designed to measure meteorological variables, like commercial microwave links (radio connections between mobile phone towers). These types of data are known as “third-party data” (3PD) as they are not owned or operated by NMS or research institutes (e.g., university, government department). Demonstration of the quality and value of these novel data sources is an active area of research. NMS, like the Royal Netherlands Meteorological Institute (KNMI), are faced with some unique challenges when it comes to transferring research to operations. KNMI is in the early stages of developing an operational pipeline for 3PD. We outline some use cases where we have demonstrated the quality of 3PD. We discuss our experiences with some of these challenges that can occur when transferring between proof-of-concepts on 3PD developed in research settings into real operational workflows providing valuable services. Hence, in this work we introduce our third-party data life cycle, in which we provide an integral overview of this transitioning process considering business and social aspects, technical feasibility assessments, the importance of quality control, and aspects related to data integration and alignment with the existing official data sources. We also reflect on how these potential new applications could fit into KNMIs long-term strategies and contribute to the high-resolution weather forecast and early warning issuing. We hope that sharing these experiences will provide some general guidelines to organizations in need of providing new services stemming from 3PD and transform them into “daily business.”

KEYWORDS

commercial microwave links, early warning issuing, high-resolution weather, personal weather stations, quality control, research-to-operations, third-party data

1 | INTRODUCTION

Meteorological observations are the cornerstone of many of the core tasks carried out at national meteorological services (NMS). The Royal Netherlands Meteorological Institute (KNMI) advises on, and warns society, about reducing risks with atmospheric or seismic origins. Climate monitoring and weather forecasting are two of KNMI's core tasks. Observations are crucial for both these tasks. Observations are important at several stages of the numerical weather prediction (NWP) chain, including in data assimilation, tuning physical parameterisations, statistical post-processing of NWP forecasts and verification.

In the past, NMS, including KNMI, almost exclusively used observations from official observing networks that are maintained in-house so that their quality and adherence to World Meteorological Organization (WMO) standards is ensured. This type of data is known as “first-party data” (check Table 1 for definitions) and these networks form the backbone of the worldwide Global Observing System as we know it today. Distances between official stations can be large and many regions are thus unobserved. To comply with WMO requirements, NMS measurement sites are typically exclusively located in rural areas. This leads to significant atmospheric observation data gaps at national and regional scales. An increasing fraction of the global population lives in cities (over 56% in 2020, chart from The World Bank: https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS?end=2020&start=1960). Also, the interaction between weather and urban features may exacerbate hazardous circumstances for citizens (e.g., heavy rainfall resulting in floods due to impervious surfaces and fast response times (Berne *et al*., 2004) or urban land-use leading to increased temperatures in the Urban Heat Island effect (Deilami *et al*., 2018)). Therefore, more in situ urban weather observations are desirable.

TABLE 1 Terminology used throughout this article

Term	Definition
NMS	National Meteorological Service
PWS	Personal Weather Stations, affordable devices that citizens can install
CML	Commercial Microwave Links, installed by mobile network operators
First-party data	Observations from official observing networks from NMS
Second-party data	Observations from other government agencies or trusted partners
Third-party data (3PD)	Observations from PWS, CML, smartphones, crowdsourcing, or any other novel data source
Opportunistic sensing	Obtaining information from devices that have not been acquired or designed to measure large scale rainfall operationally, but can be used as such
Crowdsourcing	Involves (internet) users to collect observations and is one form of opportunistic sensing
R2O	Research to Operations
WOW-NL	Weather Observations Website for the Netherlands, accessible via https://wow.knmi.nl/

Data from other sources can potentially play an important role in filling these gaps. Other sources of meteorological observations can include data from networks maintained by other professional users, such as other government departments or universities. Such data is called “second-party data” and considered relatively trustworthy for operational use. An example is a network of road sensors, maintained by the Dutch agency responsible for infrastructure (Rijkswaterstaat), that provides observations of temperature and other variable observations to KNMI, who uses them to issue warnings for slippery roads. All other sources of data are known as “third-party data” (3PD). One example of 3PD that has successfully been implemented at KNMI, in the sense that it feeds weather models, is Mode-S, where aircraft transponder data intended for air traffic control is used to derive wind and temperature observations in the atmosphere (see also section 2). Important to note is that the future observing system envisaged by the World Meteorological Organization, WIGOS, will consist of tiered observing networks providing integration of data with different performance levels. This brings the benefits of the reference quality provided by first party data, and the advantages of increased capabilities in time and space from second and third-party data (WMO, 2020), nicely together. By providing metadata in line with WIGOS standards, users can decide whether the observation data can be considered fit-for-purpose for their application.

Weather often displays large variability in space and time. This is especially true for rainfall and wind gusts. For rainfall, the current accuracy by ground-based weather radars, coverage by rain gauges, and accuracy and spatiotemporal resolution of satellites are often not sufficient for many applications such as short-term weather forecasting, flood prediction and water balance monitoring. Extreme wind gusts are typically very small-scale and so the measurements taken only at official weather stations leave vast distances unobserved. Additional weather observations, in the form of 3PD, can complement dedicated sensors to improve the quality, spatial temporal resolution and coverage of quantitative products. Examples of 3PD are "opportunistic sensors" for rainfall, often not designed for (large-scale) rainfall observation, such as satellite broadcast receivers (Mercier *et al.*, 2015), windshield wipers (Rabiei *et al.*, 2013), commercial microwave links (CML; Overeem *et al.*, 2013a; 2013b), or crowdsourced personal weather stations (PWS; de Vos *et al.*, 2017). This matches the rise in demand for environmental opportunistic sensing (Muller *et al.*, 2015; Zheng *et al.*, 2018). Of these 3PD, CML and PWS are in process to be evaluated for potential implementation.

PWS are a set of meteorological devices that typically measure temperature, rain, pressure and wind and that can be installed by amateur weather enthusiasts. PWS devices range in quality and price but are generally affordable and accessible to the general public. They are installed by the station owners with little guidance, often in densely populated (urban) environments, and they rarely adhere to WMO standards. Data from these devices can be uploaded to any of the available websites that host PWS data, such as the WOW network (https://wow.metoffice.gov.uk and https://wow.knmi.nl) run by the UK MetOffice, or a commercial network like those run by Netatmo (https://www.weathermap.netatmo.com), Weather Underground (https://www.wunderground.com/wundermap), or Weather Cloud (https://weathercloud.net/en/about-us). The networks differ in the ease to obtain data from the platform, and the number and types of devices in the network, for example, only Netatmo devices can contribute to the Netatmo weather map while the WOW network is heterogeneous. Crowdsourcing measurements from such platforms yield meteorological sensor observations far denser than most first- and second-party networks can provide.

CML are close to the ground radio connections, installed and maintained by mobile network operators for the purpose of cellular telecommunication. Radio signals propagate from a transmitting antenna at one telephone tower (base station) to a receiving antenna at another telephone tower. These signals are attenuated by raindrops along the link path. By comparing signal levels to those from dry periods, the rain-induced attenuation and, subsequently, the path-averaged rainfall intensity between telephone towers can be retrieved (Upton *et al.*, 2005; Messer *et al.*, 2006; Leijnse *et al.*, 2007). Exhaustive overviews on the history and physics of CML rainfall retrieval are provided by Messer and Sendik (2015), Uijlenhoet *et al.* (2018) and Chwala and Kunstmann (2019). A key advantage is the existing infrastructure of ~5 million links in global use (Ericsson, 2018). These could potentially provide rainfall estimates, although they have not been designed for this purpose. Since approximately 2005, a growing community of researchers has, in close collaboration with mobile network operators, developed retrieval algorithms to obtain rainfall estimates from CML data, which has resulted in tens of peer-reviewed scientific publications, with large-scale tests in Germany (e.g., Graf *et al.*, 2020) and the Netherlands (e.g., Overeem *et al.*, 2016b). Several hurdles have to be overcome before (merged) CML rainfall products can become operational, such as gaining access to CML data (Overeem *et al.*, 2021).

3PD provide a huge potential to increase the spatial density of official NMS networks (examples of this can be seen in Nipen *et al.*, 2020, and in section 2), that have gained a growing interest among the research community in recent years. For example, Météo-France is working at deriving road and pavement conditions from the real-time data provided by cars (http://tesla.dmi.dk/crowd/prs/EmilieMallet.pdf); the German MetOffice (i.e., DWD) provides reporting capabilities via the WarnWetter app (https://www.dwd.de/DE/leistungen/warnwetterapp/warnwetterapp.html), so users can inform the NMS about severe weather conditions that subsequently might be used to optimize the prediction systems; NOAA acquires rain, hail, and snow observations via the CoCoRaHS project which is helpful to better understand local patterns of precipitation (Reges *et al.*, 2016).

Most studies aim to assess the value of 3PD to feed official meteorological processes and services (Elmore *et al.*, 2014; Reges *et al.*, 2016; Overeem *et al.*, 2016b; de Vos *et al.*, 2019a; Mandement and Caumont, 2020; Graf *et al.*, 2021), but to date there are few operational implementations of 3PD at NMS. In this work, we use the experience we acquired with PWS and CML to discuss what more is needed aside from "offline" academic research into these techniques to integrate 3PD in operational use. We also provide our vision as recommendations to NMS on how the inclusion of 3PD might require rethinking some well-established processes and services. Section 2 presents a summary of the KNMI activities using 3PD and some discussion of the potential value of some select 3PD sources; section 3 presents the 3PD life cycle, which describes the process to take novel data sources from Research to Operations; section 4 describes the organizational challenges, considering business and social aspects; and section 5 provides a high-level overview of the possible steps to utilize 3PD in a NMS organization using examples from the KNMI, a mid-sized NMS, and also providing general recommendations to increase its usage and adoption.

2 | SUMMARY OF THE RELATED KNMI'S 3PD WORK

KNMI has a decade of experience working with various types of 3PD. Many pilot studies have been conducted, often with research partners from universities. Collaborations with partners from universities, such as Wageningen University & Research and Utrecht University, are key to the ability of an NMS to explore these novel data sets. One early standout application of 3PD at KNMI is the use of Mode-S, information from air traffic control radar that follow all aircraft in airspace near airports, used to derive temperature and wind observations in the upper atmosphere (de Haan, 2011). These are now being operationally assimilated into KNMI's high-resolution numerical weather prediction model, Harmonie-Arome. The operationalisation of this 3PD source was logical given that the potential added value is high, as there are few other upper air observations, and the amount of additional preprocessing is moderate (Figure 2). Other KNMI (pilot) studies demonstrating the value of 3PD include measuring air temperature from smartphone battery temperature (Overeem *et al.*, 2013a; 2013b; Droste *et al.*, 2017), and upper-air wind measurements from hot air balloon data (de Bruijn *et al.*, 2016). However, other investigations into 3PD sources were not able to demonstrate any potential added value. For example, a pilot study was initiated to investigate the ability of public transport data to improve the resolution of meteorological observations within a city. The data was initially assessed to have sufficient coverage and potential in filling a gap in urban monitoring. However, examination of the data showed that the quality was too low to contribute in any meaningful way to KNMI operations, and so the project was discontinued. Estimating road temperatures from car data is another example of pilot study that was eventually discontinued as the business case was not sufficiently strong (this example is discussed in section 3.1).

More recently the focus has shifted to data from PWS (internal report: Koole, 2016; MSc thesis: Merkus, 2016; de Vos *et al.*, 2017; Chen *et al.*, 2021a) and CML (Overeem *et al.*, 2011; de Vos *et al.*, 2019b). Research into these data sources have focused on the assessment of different statistical corrections (Cornes *et al.*, 2020), developing novel quality controls (QCs; Cornes *et al.*, 2020; de Vos *et al.*, 2019a; Chen *et al.*, 2021a), adding functionalities to existing QCs (MSc thesis: van Andel, 2021), or exploring potential applications for QC'd (Garcia-Marti *et al.*, 2019; Dirksen *et al.*, 2020; Garcia-Marti *et al.*, 2021) or raw/unadjusted 3PD. For example, the potential and limitations of hydrometeorological monitoring using unadjusted nontraditional and opportunistic sensors was demonstrated for two case studies in the Amsterdam metropolitan area (de Vos *et al.*, 2020a; 2020b). Several variables from 3PD were evaluated against traditional observations, including air temperature estimates from both smartphone batteries and PWS, rainfall estimates from CML and PWS, solar radiation from smartphones, wind speed from PWS, air pressure from smartphones and PWS, and humidity from PWS. This allowed for detection of the passage of a front and quantifying the urban heat island effect.

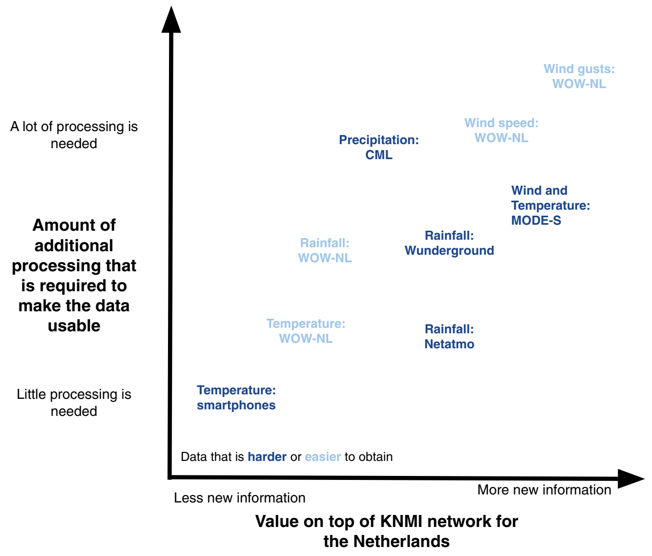

FIGURE 1 3PD can add valuable information on top of the official observing network, but it often requires preprocessing before it can be used in any meaningful way. Here we give an indication of where various 3PD sources lie on these two axes. It is noted that the judgements on both the axes are valid only for the Netherlands. Other regions, such as developing countries with different infrastructure availability, will have different estimates of the added value. We estimate the amount of additional preprocessing that is required relative to official KNMI stations. This may include factors such as the number of steps or the amount of computation time [Colour figure can be viewed at wileyonlinelibrary.com]

We focus for the remainder of the paper on examples from PWS and CML as we have substantial recent experience with these novel data sources that have shown potential for operational use. We make subjective estimates of the potential added value and amount of preprocessing required by some 3PD sources used at KNMI in Figure 1 and discuss some examples below. These data sources, like all 3PD, are sometimes easier or harder to obtain (as noted by colours in Figure 1). For example, the WOW-NL data is owned by KNMI and so there are no additional costs associated with accessing this data, which is in contrast to Netatmo data. Various 3PD sources require varying degrees of preprocessing before any meaningful information can be extracted (estimated on the vertical axis of Figure 1), and they have varying potential return for a NMS (horizontal axis of Figure 1). For example, PWS from the WOW or Wunderground networks contain devices from several manufacturers, which each have their own set of biases. This data set generally needs a more intensive quality control procedure than the Netatmo dataset, which contains a single type of device. Additionally, the investment in 3PD does not have the same potential return for all variables. Variables that vary a lot in space, like precipitation or wind, generally have more potential value for KNMI than slowly varying variables, assuming their quality can be assured. The value of 3PD is related to the capacity of a variable to extend the range of services provided by NMS.

These ideas are demonstrated nicely by the recent quality control (QC) of WOW wind speeds in the Netherlands (Chen *et al*., 2021a; 2021b). There is a large potential for added value for this variable, given the large distances between official KNMI stations, but the strong influence of the station placement requires a very strict QC process (Chen *et al*., 2021a; 2021b). This leads to the placement of wind speed from the WOW-NL network near the end of both the horizontal and vertical axes in Figure 1. The extreme wind event on the June 4, 2019 provides an example of the added value of the WOW-NL wind speed observations. KNMI issued a Code Orange for thunderstorms containing heavy wind gusts and hail. At 2110 UTC the thunderstorm was moving across the northeast of the Netherlands. There were no KNMI stations recording strong wind speeds at 2110 UTC (top left in Figure 2); however, there were several WOW-NL stations that observed strong wind speeds at the same time (bottom left Figure 2). At 2120 UTC there are again several WOW-NL stations that record strong wind speeds which complement the two KNMI stations that measure strong wind speeds. This clearly demonstrates the added value of increased spatial density of wind speed measurements.

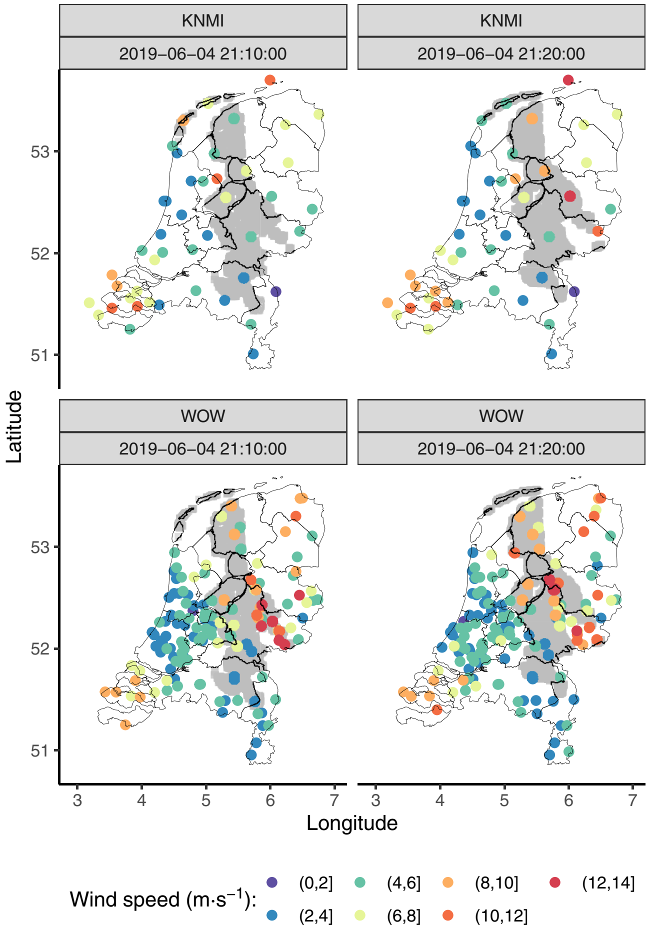

FIGURE 2 Wind speed observations on the June 4, 2019 from the KNMI network (top) and the WOW-NL (check Table 1) network after the quality control procedure (bottom). A Code Orange was issued for thunderstorms with heavy wind gusts and hail. Grey shading indicates where rainfall was observed by a climatological KNMI gauge-adjusted radar product (https://dataplatform.knmi.nl/dataset/rad-nl25-rac-mfbs-em-5min-2-0) [Colour figure can be viewed at wileyonlinelibrary.com]

Estimation of rainfall from CML and PWS are other examples of how considerations between effort and added value must be balanced. In general, estimates of rainfall from 3PD sources have moderate potential for added value in the Netherlands given the existence of the radar product, leading to their central placement on the horizontal axis of Figure 2. KNMI has ample experience with CML rainfall estimation in the Netherlands (e.g., Overeem *et al*., 2011; 2016a; 2016b; de Vos *et al*., 2019b). This type of data requires substantial preprocessing (high placement on the vertical axis of Figure 2) and the added value in the Netherlands is moderate. However, it should be noted that added value in the Netherlands is not the only priority for a global-oriented organization like KNMI, as research into rainfall estimation from CML is now focusing on low- to middle-income countries in (sub)tropical regions (Rios Gaona *et al*., 2018; Overeem *et al*., 2021) where the impact of complementary rainfall information is often highest. KNMI has been investigating the quality of Netatmo PWS data for several years (e.g., de Vos *et al*., 2019a; 2020a; 2020b). The limited additional preprocessing required for this case, the likely higher density compared to CML, and the fact that PWS observe rainfall directly (low placement on the *y*-axis in Figure 1) makes it a strong candidate for operational use.

These examples show that the past decade has been fruitful for KNMI when it comes to research exploring the possibilities and potential added value of 3PD. However, the transfer of research to operations remains a challenge. Decisions about priorities for operationalisation should be guided by both technical feasibility and potential added value. In the following sections we share our experiences at carrying out this transition of research-to-operations that hopefully will provide some guidance to other organizations.

3 | THE THIRD-PARTY DATA LIFE CYCLE: RESEARCH TO OPERATIONS

Research to operations (R2O) is the process of transferring research insights into online backbone services that might be reused by the public or private organizations across sectors (NRC, 2003). Large organizations such as ECMWF (Buizza *et al.*, 2017) or NOAA (Whitney and Leshner, 2004) have defined strategies to facilitate this process and to close the gap between research knowledge and actionable applications. In the past decades, several R2O processes in the climate and atmospheric sciences domains have been deployed to transfer research insights into the fields of weather forecasting, (earth observation) data assimilation or postprocessing (Brachet, 2004; Vannitsem *et al.*, 2021). Nevertheless, 3PD applications are "new" in these well-established domains and the road ahead for the R2O process is unclear, and yet to be explored in collaboration with partners (e.g., EUMETNET members) that are facing similar challenges with these novel 3PD observations.

Recent research has shown potential from 3PD to contribute to weather forecasting, concretely to numerical weather prediction (NWP; Hintz *et al.*, 2019a; Nipen *et al.*, 2020), or data assimilation (DA; Hintz *et al.*, 2019b; Sgoff *et al.*, 2022). Also, 3PD observations combined with additional data sources can have a role in nowcasting activities (Nuottokari *et al.*, 2022) and the verification of high-impact weather (Marsigli *et al.*, 2020). Finally, the high density of 3PD monitoring networks can be a powerful ally at devising high-resolution climate services for disaster risk reduction and issuing local early warnings for severe weather conditions (Bielski *et al.*, 2017; Meissen and Fuchs-Kittowski, 2014).

The maturity of 3PD applications at KNMI is still in an early stage. A 3PD life cycle has been defined that is derived from the CRISP-DM model (Shearer, 2000) and aligned with the R2O life cycle. Figure 3 shows the 3PD life cycle that consists of five phases. The cycle starts with the business context (definition of business case) and gradually progresses towards the deployment phase by assessing the value of 3PD and integrating the data with existing data flows for application in newly developed products or services that are subsequently evaluated for deployment. The remainder of this section describes each of these phases.

3.1 | Business context

A central element of the business context phase is motivating with solid arguments how the incorporation of 3PD might add value to the current state-of-the-art, either by creating new products or improving the existing ones. Therefore, the core activity in this first phase of the 3PD life cycle consists in assessing the viability of the initial business case in terms of data value, affordability and technical feasibility. If 3PD collections are sufficient in terms of quality and quantity, affordable to obtain and feasible to handle by the NMS' technical infrastructure (considering some adaptations might be required), then the application can be deemed as a viable business opportunity. The outcome of this evaluation also depends on the business objectives of an organization and their ability to invest in the application of 3PD. The evaluation result is used to decide on the continuation of the 3PD application (i.e., Go/No go; Figure 3).

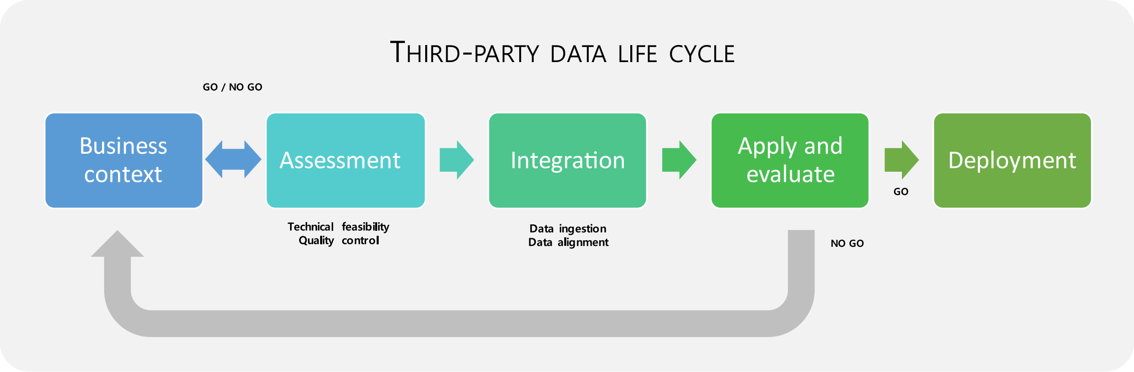

FIGURE 3 Schema depicting the 3PD life cycle that is based on the CRISP-DM model (Shearer, 2000). Cycles typically start with a business/research idea and gradually progresses towards its deployment through series of refinements and analyses [Colour figure can be viewed at wileyonlinelibrary.com]

The definition of the business context including 3PD is an iterative process. Thus, the evaluation of business value and decision making might take place few to several times. Each iteration provides more insight and details on the business value, which will be as well a relevant input before proceeding at developing the service to operations. An illustrative example at KNMI might be the evaluation of temperature measurements by cars. The KNMI assessed whether it was possible to derive an indicator for road surface temperature conditions as a proxy to the slipperiness of the road network (e.g., below zero degrees Celsius) (de Vries, 2017). During the initial evaluation of the collection, the dataset was found valuable, and the estimated costs and effort were found acceptable. However, the quantity of car data was too limited (e.g., insufficient spatiotemporal coverage) to be deemed as a viable business opportunity. Therefore, the development of this research line did not continue, and no further steps were taken until a sufficiently large dataset becomes available (de Vries, 2017). Similar results were found in later research on car temperature sensor data in Rennes, Paris, Barcelona and Dijon, where this data source showed promising for determination of UHI effects in cities, but observations were generally too sparse on their own (Marquès *et al*., 2022).

3.2 | Assessment of third-party data collections

If the business case is evaluated positively and the 3PD application is expected to provide valuable contribution for the business, the next step is to assess the suitability of the 3PD application for the intended task. This comprises two actions: first, evaluating the technical feasibility to collect and engineer the data (cost); second, assessing the value of the observations on its quality (value). Moreover, the available amount or quantity of (high quality) data is verified to be sufficient for the business case. The following subsections describe examples of data assessments that has experienced with the application of WOW-NL and Netatmo observations.

3.2.1 | Technical feasibility

Past experiences with different types of crowdsourced projects have shown that citizens installing PWS at their premises are highly engaged to share their weather observations. This often results in large 3PD collections (i.e., big data) that are of potential value to advance towards a higher-resolution weather forecast, but simultaneously poses challenges for the feasibility of engineering this "big data." For example, the WOW network for the region of the Netherlands and Belgium has progressed in 6 years' time from 200 K observations per month (January 2015) to nearly 6 M observations per month (December 2020).

Engineering large 3PD collections requires information about the technical capabilities to govern and manage the data, hence giving insights on the technical feasibility. This information is not straightforward when 3PD usage is new for an organization, which can lead to decision hurdles for the retrieval, storage and processing of 3PD. For example, after working with WOW-NL and Netatmo data, it seems sensible to align and aggregate the 3PD observations before reaching the data storage phase, since the spatial and temporal dimensions are highly inconsistent. However, if this decision is taken, it might affect the access to (very) fine resolution data. Therefore, using the schema of the original data might be the preferred option, but performance-wise, might be rather challenging due to existing technical limitations. Thus, a well-defined strategic plan for managing 3PD is essential for an organization when 3PD usage is expected to grow substantially.

Another important factor for the technical feasibility is the availability of 3PD metadata. This concerns information about the owner, spatial and temporal resolution and extent, the data lineage, as well as any data constraints and quality information, which can be provided as part of the 3PD delivery or obtained via data exploration. A well-defined metadata policy based on international standards (e.g., ISO-19115) is highly recommended for 3PD discovery, interpretation, and interoperability.

3.2.2 | Quality control: Filters and adjustments

Observations from PWS require strict quality controls, mainly due to the station placement and the quality of the device. Amateur citizen scientist place their PWS in the best locations available to them, but unfortunately, these locations rarely meet the criteria for spatial representativeness as stated in the WMO (2018) recommendations for siting of surface weather stations. Taking WOW-NL as an example, we compared the location of the stations with the land cover map of the Netherlands. In an evaluation of 1,000+ PWS, it was found that 57% PWS contributing observations during the period 2015–2020, are placed in residential areas, 13% in urban grasslands (e.g., close to recreational areas), and 9% are in agricultural areas. Weather stations that are poorly placed are susceptible to suffer from biases stemming from obstructions, or local radiative and cooling effects (Bell *et al.*, 2015; Meier *et al.*, 2017). Second, compared to the official instruments, PWS tend to have a lower quality, they are infrequently maintained or calibrated, and the metadata can be inconsistent or incomplete. As a result of the abovementioned potential sources of error, the measurements produced by a PWS can have quality issues, hence motivating the development of custom-made QCs for 3PD. There is a growing body of literature dedicating efforts to devise quality controls for 3PD. For a broader description of the efforts carried out by KNMI in the 3PD field we refer the reader to the section 2 of this paper and references cited therein. However, it is out of the scope of this section to describe in detail the all the quality control procedures that have been developed at KNMI, but to distil from our experiences the stages that, in our vision, a QC for 3PD could consider.

The goal of a QC procedure is to produce a set of high-quality observations. The procedure to do this is twofold. First, each observation must be quality checked and labelled with a quality flag. Second, if necessary, an adjustment factor must be applied to the measurement to remove any remaining biases. In general, we recommend dividing the QC in three stages: (a) intrastation (or within-station) filters, (b) interstation (or between-station) filters and (c) adjustments. The following list describes in more detail each of the phases:

- Intrastation filters: These filters can be applied using data of a single station. These filters do not necessarily require additional datasets although often some climatological information might be required. For example, these filters can check whether a particular PWS provides an acceptable temporal coverage (e.g., reporting observations at least 80% of the time); has complete and consistent metadata (e.g., no duplicated coordinates); requires uniformization of the temporal dimension (e.g., mapping observations to a rounded time slot, averaging multiple measurements within time slot); records values that are within a plausible climatological range compared to other PWS or official stations; or contains unrealistic temporal variability (Napoly *et al.*, 2018; Fenner *et al.*, 2021). Intrastation filters that compare with climatologies from official stations or check temporal variability have implications for the amount of working memory that must be used as more data must be loaded for comparisons.
- Interstation filters: These filters exploit spatial correlations and consider the observations provided by the surrounding observations at a similar moment in time to the target observation from a PWS. They can flag unrealistic values (Chen *et al.*, 2021a), detect faulty zeroes, outliers or to classify wet and dry periods (e.g., Overeem *et al.*, 2011; de Vos *et al.*, 2019a). Surrounding stations can be selected by proximity and/or statistical similarity. Once data of the surrounding stations are selected, it is possible to assess whether the observation under inspection is acceptably similar by computing statistical metrics (Lussana *et al.*, 2010; Båserud *et al.*, 2020) or by estimating confidence intervals from an assumed distribution (Chen *et al.*, 2021a).
- Adjustments: These filters are often applied later in the QC procedure after first ensuring the observations are of an acceptable quality. Adjustments can be station-specific or applied across a whole network. The use of systematic (Droste *et al.*, 2020; de Vos *et al.*, 2019a; van Andel, 2021) or station-specific methods (Chen *et al.*, 2021a) depends on the error characteristics of the stations in the network. Furthermore, the adjustments can include information from additional data sources, such as the air temperature correction using the atmospheric lapse rate from an elevation dataset (Napoly *et al.*, 2018) or solar radiation data (Cornes *et al.*, 2020).

A QC for a particular meteorological variable can implement one or more of these phases and within each of them, contain pieces of code with variable sophistication levels. This, in turn, might have an effect on the temporal cost of computing the quality metrics that needs to be considered during the process of R2O. It is important to note that the original QCs developed in "research mode" might be subjected to modifications when they enter a R2O workflow, so that they can be applied in a near-real time set up. Some possible impediments to the real-time operation of QC methods can include the time taken to gather various datasets on top of the crowd-sourced data, the time taken to select neighbouring stations for the interstation checks (although this need not be calculated at every time step), and the collection of an archive of data for the bias adjustment. As seen, computational costs are important and at each step in the chain we should have a rough estimate on how temporally expensive our QCs are, since this may imply potential code efficiency improvements are needed, or that certain types of (near) real-time apps can be successfully created or not.

3.3 | Integration of third-party data

Once quality metrics have been obtained, the 3PD life cycle progresses towards its integration with the official products. At this point, it is necessary to discuss the creation of the necessary data flows, feeding different services, and what are the key challenges to create datasets comparable to the existing ones. The KNMI is currently establishing workflows to provide quality-controlled 3PD observations. In parallel, researchers are discussing the requirements to aggregate the continuous flow of observations to provide, for instance, high-resolution gridded map products that enable the subsequent assessment of the added value. The following subsections delve into these considerations.

3.3.1 | Data ingestion cycles

Quality controls take 3PD collections to a data maturity stage that might be comparable to the existing products KNMI (and NMS) are already offering. Previously cited literature examples illustrated that 3PD collections are highly versatile, hence it is possible to use them into well-consolidated workflows within weather forecasting and numerical modelling. However, the high spatiotemporal resolution of the 3PD monitoring networks imply that potentially more innovative research and development lines lay ahead. It is at this point where R2O developments have a crucial role to approach 3PD into operational use.

Currently R2O for 3PD can be considered a "bare field" waiting for developments, thus it is important that NMS decide what services they wish to provide and promote the creation of data ingestion cycles, providing observations with variable quality levels and/or temporal granularities, as follows:

- Real-time operation: Observations with little processing (or QC) and aggregation that are released in a (near) real-time basis (e.g., 10 mins). These workflows are envisioned for targeted groups of users (e.g., decision makers, forecasters) to assess the severity of extreme weather and thus issuing events and warning in (near) real-time. Hence, these observations can be subjected to some science-based thresholds to decide whether hazardous weather (e.g., very local severe rainfall, advance of cold/warm fronts, sudden air pressure drops, existing conditions for slippery roads) conditions occurred and require an action of the target user.
- Fast ingestion cycle: Provision of standardized observations and/or its aggregated product in the range of 1–2 hr. The standardization process requires filtering the low-quality observations using QC methods that can work in a fast regime, but also averaging the observations of clusters of stations once a spatial unit is decided. These workflows could be used for applications at the urban scale (e.g., detecting strong local wind conditions, mapping or monitoring urban heat islands).
- Slow ingestion cycle: Provision of standardized observations undergoing more refined QCs, often including comparisons with reference data (e.g., radar, official stations, model simulations) and bias correction processes. These observations might be more suitable for data assimilation, post-processing, NWP, forecasting and verifications, or contributing to create climate time-series, because the statistical corrections ensure the highest quality possible of 3PD observations. These workflows might require longer processing times (e.g., 1–7 days).

3.3.2 | Data alignment

The data ingestion cycles defined in the previous sub section are not designed in isolation. Regardless of the ingestion speed, the integration of quality-controlled observations in a final product requires discussion (at least) on the following challenges:

- Temporal persistency and synchronicity: KNMI stations acquire measurements simultaneously, usually every minute, and these are subsequently aggregated into our products. 3PD monitoring networks often have a high acquisition frequency, but there is limited synchrony between various devices and networks. At the time of designing R2O pipelines and the envisioned applications, it is necessary to assess what is the most suitable temporal unit (or units) for each weather variable and aggregate the observations at a time interval. In our experience with QCs, we are currently using 5- and 10-min intervals for precipitation (van Andel, 2021) and wind speed (Chen *et al*., 2021a), respectively. In addition, given the volunteered nature of PWS, it is important to investigate the temporal persistency of the stations in the context of R2O. Temporal persistency refers to stations consistently reporting observations in most of the time slots during any given period. Hence, PWS with a high temporal persistency might be candidates to create 3PD climate time-series, whereas low-persistent PWS might be better suited for (near) real-time applications.
- Spatial representativity: KNMI stations are spaced in a way that balances financial considerations with the optimal coverage for large-scale phenomena at locations that meet prescribed measurement conditions (WMO regulations). However, the spatial distribution of 3PD stations tends to be biased towards urban and peri-urban areas, so PWS might form clusters of stations, which in turn might have an impact at the time of integrating 3PD with other sources. In addition, the measurement conditions of 3PD can deviate

substantially KNMI station conditions. Hence, when a NMS tackles the spatial densification of the official networks with PWS, it is important to identify the most suitable stations to include in the combined network layout (Sosko and Dalyot, 2017). For example, weather phenomena that tend to be more homogeneous in space and time (e.g., temperature, air pressure), might not require the inclusion of as many PWS stations to get a better large-scale picture, in contrast to more volatile and erratic phenomena (e.g., wind speed, precipitation). However, the previous may not be applicable to the urban environment, since human-made developments might substantially impact the measurements collected by the stations. These differences between the urban and national scale implies that it is important to tackle the process of spatial densification with care and keeping in mind the potential domains of the envisioned applications. The density of the combined networks will determine the possible range of applications to be deployed via the R2O pipelines.

- Concordance between 3PD networks: In the future, it seems plausible that several weather monitoring networks might be deployed in the same area. Hence, researchers might find out that some networks (or types of sensors) are more suitable to monitor a concrete phenomenon (e.g., urban heat islands) (de Vos *et al.*, 2020a; 2020b). If this is the case, researchers might need to investigate data fusion techniques that are able to combine observations coming from different networks (Lesiv *et al.*, 2016). This step requires proper quality control of 3PD as well as a profound knowledge of each of the monitoring networks, so that researchers are aware of the general errors or biases before attempting a merging effort in a R2O pipeline.

Data ingestion processes should not be detached from the NMS' data management practices and legal considerations. It is necessary to consider national requirements for data policy and identifying possible issues with data ownership or stewardship. For example, when acquiring weather observations from private partners (e.g., Netatmo, Wunderground, car manufacturers) it must be clear what can (e.g., research) and cannot (e.g., data redistribution) be done with data. This could be established via bilateral agreements with the private partners or under a European legal framework.

3.4 | Apply and evaluate third party data in applications

In this phase, a prototype of the final service is prepared, including the data analysis that will be used in the operational phase. Upon conclusion of this step, it is necessary to evaluate whether the inclusion of 3PD added actual value (e.g., improved accuracy and/or resolution, enabling new functionalities) (GSM Association, 2021) to the previous state-of-the-art (both from a business and technology perspective), to check if novel observations contribute to improved products for KNMI users. For example, there is evidence that rainfall Netatmo data is of interest for water boards; we know that the processing of road traffic cameras for fog detection is useful for Rijkswaterstaat (Dutch agency responsible for infrastructure), whereas temperature, rainfall and wind speeds from 3PD monitoring networks is of interest to KNMI's forecasters. At MetNo, the NMS in Norway, temperature observations from 3PD are already integrated in the operational production of weather forecasts, using the QC method TITAN (Båserud *et al.*, 2020). Crowdsourced data is essential for the verification of high-resolution NWP forecasts in urban areas. As seen, this type of verification supports decision makers and helps forecasters, but the evaluation of the existence of added value is not always straightforward and requires extensive feedback and collaboration with users. Note that this phase is less mature for KNMI because the organization has not yet reached a point in time in which a substantial number of uses cases with 3PD are used in daily operations. At best the quality of estimates based on 3PD has been evaluated on a few months or years of data. We perceive this as an essential step towards an operational product, but the actual development of a prototype and testing the 3PD-based estimates by end users is generally still lacking.

3.5 | Deployment of third-party data application

Reaching the deployment phase implies arriving to the end of the 3PD life cycle. In this point, there is already proof-of-value (either scientific and/or business-oriented) that 3PD is contributing to extend a final NMS operational service or product. Hence, the proof-of-value can proceed at being published for a wider audience. Ideally, the process of deploying this final stage of R2O should be carried out by multidisciplinary teams, in which scientists, operational staff, and software developers come together to ensure a smooth transition. For example, data architects and cloud engineers can design the workflows necessary to deploy the application in a cloud infrastructure, software developers can take care of the backend processes and design the front-end user interface, whereas scientists might need to adapt the analysis to work in a real-time operational environment and make sure the results are still consistent.

Creating these new operational workflows requires working in an organized manner, thus it could be helpful for the team members (especially for scientists) to acquire experience about development paradigms (e.g., AGILE) and methodologies (e.g., Kanban, Scrum), to advance breaking down the analysis into implementable pieces. Throughout this process, it is important to keep checking whether operational conditions are fulfilled, such as having sufficient human or financial resources. Failure to meet these conditions can delay the deployment of the final services. It is worth to note that the deployment of a new operational service with 3PD does not imply its immediate acceptance (nor usage) within the user community. Thus, a good documentation and promotional activities (e.g., adding service to a data discovery catalogue or spatial data infrastructure) might help at encouraging users at using these services. In this sense, it is important to verify that the operational conditions of the novel 3PD operational service (e.g., service levels, maintenance, contact points) is in line with the NMS policies.

4 | ORGANIZATIONAL CHALLENGES: SOCIAL AND BUSINESS ASPECTS

Up to this point we have focused on the technical aspects of the usage and incorporation of 3PD into operational workflows. However, the application of 3PD is often a strategic decision with business and social consequences. This section identifies some key business and social aspects for 3PD to be viable in operational weather monitoring.

4.1 | Business aspects

KNMI is the NMS for the Netherlands and their business concerns weather, climate, and seismology information services for society. Hence, data collected by KNMI's observational networks are used for these services for which policies have been defined (e.g., data governance). However, using 3PD in KNMI's (or NMS) business would require revisiting these data governance policies. In section 3.1 we discussed the business evaluation of 3PD applications in terms of value, affordability, and feasibility. This section addresses more strategic business questions regarding 3PD usage or application.

One important question for NMS business is the assurance of 3PD provision in case of operational deployment. This requires (contractual) arrangements with the 3PD provider. In van Poelgeest and de Vries (2021), the authors presented four types of arrangements for 3PD in public services: *Ruler* (data must be provided as a result of legislation); *Buyer* (data are purchased via tendering and contractual arrangements); *Facilitator* (data are collected by offering free services that ease the access, visualization, management and control of data); and *Dealer* (data are delivered as part of a collaboration agreement). Buying 3PD from professional data providers is the most common role for KNMI. However, since 2015, the KNMI is also facilitating the access to WOW-NL. The adoption of this new role required gaining experience about the user engagement and how to attract and keep users on board (see section 4.2). A question that remains from a business strategy perspective is, what investment in user engagement is required and acceptable? In our view, we think the answer to this question is very specific to each organization, but it is important to have this discussion. Finally, deals or partnerships where data is exchanged as part of a collaboration is the standard practice between NMS across the world (WMO) and between government agencies, but rather uncommon with commercial companies or NGOs. For 3PD we expect that partnerships will become the preferred arrangement to ensure data provision.

Besides updating the data governance policy for 3PD, new business models might need to be developed. For example, CML data could be of value for a wide array of applications, from improving and localizing weather forecasting services, early warnings (e.g., landslides), crop production monitoring, or agricultural weather micro-insurance products. CML data has the potential for NMS or private companies to accurately nowcast rainfall up to a few hours in advance for regions where this is currently not possible because of the absence of ground-based weather radars. Utilization of CML data creates a new range of applications with opportunities for multiple partners (e.g., insurers, mobile network operations) at valorising the link data (GSM Association, 2019; 2021; MEMO, 2020). This CML example demonstrates that 3PD applications can offer new business opportunities because they are of interest and value to external partners and stakeholders (e.g., government agencies, private companies, NGOs). As mentioned before, good contractual arrangements are of key importance here and the role of these new business models needs to be evaluated carefully.

Finally, setting up terms and conditions with 3PD suppliers might be a challenging task, especially when working with other (international) parties that might have similar agreements. This implies that the overlap, redundancy and legal issues between stakeholders and 3PD providers need to be thoroughly reviewed to avoid further problems.

4.2 | Social aspects

The inclusion of 3PD collections in consolidated operational meteorological workflows at NMS implies the necessity of considering social aspects, often detached from science, and establishes a dependency relationship between the data-providing users and data-receiving NMS. These social aspects can be grouped in three categories: (a) social engagement; (b) outreach; (c) striving-for or resisting innovation.

Social engagement is aimed at promoting the long-term commitment of the volunteers reporting observations. Researchers have come up with various methods to do so, such as, forecasters from NMS have personal interactions with amateur meteorologists (Longmore *et al.*, 2015), extract crowdsourced contributions from social media for local severe weather (Clark *et al.*, 2018), or establish a network of trusted collaborators that receive basic training in meteorology (Krennert *et al.*, 2018). In our experience at KNMI with 3PD projects, we have witnessed that third parties are motivated to share their data in return for QC insights and feedback on the state of their network quality (e.g., water authorities). We also had past positive experiences at inviting amateur weather enthusiasts to visit KNMI's premises and attend talks about weather provided by our experts.

The outreach is the pursue of an NMS to reach an increasing number of citizens, as a way of ensuring more contributors in the future. Here we provide a couple of approaches. First, NMS could provide software and tools to report severe local conditions (e.g., hail size (Barras *et al.*, 2019) and wind damage (Karjalainen and Jokinen, 2019)), which might be of interest for different strategic sectors (e.g., loss insurance estimates, safe communities). Second, NMS could organize educational campaigns (e.g., primary and secondary school) (Brossard *et al.*, 2012) or promote community building. In the context of WOW-NL, the KNMI has provide real-time accessibility to the observations acquired by the network, but a more direct contact with users is required to consolidate the data provision.

The early adoption of innovations might be challenging for NMS, since operational tasks must continue regardless of new developments. New ideas are typically explored in research projects having a scientific outcome (e.g., peer-reviewed publication, use case) providing advice for operational use. Organizations like municipalities, universities, or start-ups can have a more practical approach to collect data. The SensHagen project in Zwolle (https://senshagen-zwolle.opendata.arcgis.com/) and the Urban AirQ in Amsterdam (http://making-sense.eu/campaigns/urbanairq/) are examples of municipalities willing to explore the possibilities of citizen science monitoring. While the generated insights from scientific publications and 3PD gathering in pilot studies is highly useful, the actual operational implementation of 3PD requires an additional step to innovate existing NMS procedures and products. Different than at these organizations, an NMS always needs to keep the operational demands in mind. Hence, transitioning into 3PD innovations can be extra challenging due to (a) push-back from within NMS concerning what should be achieved with 3PD (e.g., climate scientists have different needs than risk assessment advisors); or (b) scepticism and resistance to change or expand well-consolidated workflows and infrastructure. To combat these points, we recommend that NMS invest in research showing the potential of 3PD (possibly in collaboration with the abovementioned organizations) and developing prototypes and minimum viable products showing the value of 3PD.

The actions described above are targeted to strengthening the bond with citizen data-providers. This might not seem a core competence of NMS, but it is important to note that NMS should not assume that 3PD observations are ensured in the long-term. Hence, once NMS start using 3PD observations, a dependency relationship is established. In this context, it seems important to convert this dependency into a healthy bond between parties. Devising plans ensuring the long-term engagement of users (subsequently ensuring data provision) might require the creation of a dedicated team of social scientists and communication experts, that help at "taking the pulse" of the data-reporting community. This team could help at creating and managing classical engagement or educational campaigns (Cappa *et al.*, 2018), assess how other novel engaging mechanisms such as gamification techniques (e.g., acquisition of virtual rewards) could be beneficial (Bowser *et al.*, 2013), or identify strategic sectors to create partnerships with user groups (e.g., local associations).

5 | CONTEXTUALIZING 3PD IN NMS AND RECOMMENDATIONS TO INCREASE USAGE OF 3PD

The transition between proof-of-concept to proof-of-value is not complete without assessing the impact of 3PD on the current NMS policies and digital infrastructure. In our view, this transition not only requires assessing how these novel data collections can be incorporated into the existing operational workflows in the organization, but also into the organizations' modus operandi when it comes to policies and data management practices. In the following subsections, we present the initial steps of this assessment exercise, in which we discuss how 3PD could fit into the long-term strategies of the organization and what are the key infrastructural aspects to consider for incorporating 3PD into "daily business." We conclude with a couple of concrete recommendations to enhance the use of 3PD by NMS.

5.1 | Incorporating 3PD within organization's goals

A remarkable trait of 3PD monitoring networks is their potential to feed most of the well-consolidated workflows in monitoring and forecasting, assuming proper quality controls are in place. NMS often have long-term strategies that are regularly updated or revisited to ensure they are still in line with governmental and societal demands. In this sense, research to underpin the value of 3PD observations for NMS products and services would allow managers to make informed decisions whether resources should be allocated to incorporate 3PD in operational products and in ongoing research to improve these. Such a decision will usually comply with the organization's strategy. To achieve inclusion of 3PD observations may require adaptation of the NMS strategy.

In case of KNMI, a highlight of their strategy is to operate a multihazard Early Warning Center (EWC; KNMI, 2020), straddling on two fundamental pillars: the Modernisation of the Observational Infrastructure, and a robust digital infrastructure (I-strategie; KNMI, 2019). In addition to the EWC developments, our Observations Strategy (2015–2024) (KNMI, 2015) establishes as a mission to convert observations into innovative and high-quality products and services.

In this context, 3PD observations are in a prominent position to make contributions to these long-term strategies at an administrative level. For instance, one of the ambitions within the MWI programme is to merge official data with other sources such as 3PD that can be used in the QC processes to identify missing data or outliers. In addition, there are ongoing efforts to investigate the added value of 3PD networks (i.e., Dutch Water Boards, Netatmo) for improving radar rain gauge products. Within the I-strategie programme, a project has been initiated to offer data spaces to include observations from various 3PD collections. This is intended to give structure to these observations (e.g., spatiotemporal heterogeneity), including the optimization of data access, and to provide a facility that can handle large volumes of 3PD observations. This is also relevant to explore and learn the "ways towards a new service," so that not every new idea with 3PD leads to a different architecture (i.e., a standard framework). Finally, within the EWC strategy there are some research lines intended to illustrate the value of 3PD to expand the current operational services. For example, there is an ongoing effort dedicated to combine multifidelity data, in which official KNMI observations are merged with WOW-NL observations and trusted observations from another government agency. The density of the combined network opens the door to create high-resolution temperature interpolations that might be useful to issue warnings for ice formation over roads during the winter season.

5.2 | Readiness of the organization's digital infrastructure for 3PD

The incorporation of quality-controlled 3PD observations into NMS operational workflows requires a digital infrastructure capable of handling sheer volumes of observations (i.e., big data) in a controlled, structured and scalable manner that enables processing and servicing observations. The storage of 3PD observations is often provided by dedicated data repositories, such as data lakes or data spaces. These repositories should be designed with flexibility in mind to allow handling the high heterogeneity of 3PD monitoring networks. For example, data stores can operate with a variable number of sensors reporting observations at different times, and software is able to aggregate data at different temporalities and spatial units and prepare instances of 3PD collections with different parametrizations.

The processing and analysis of 3PD requires a quality-controlled data distribution platform that allows merging these observations with other data streams. More specifically, this data merging (or fusion) of 3PD into fit-for-purpose operational workflows (e.g., high-resolution wind speed or rainfall) can implement two approaches: (a) merge 3PD with official data (Haese *et al.*, 2017); (b) merge distinct 3PD collections (Graf *et al.*, 2021). In both cases, the selected merging methods need to consider the different nature of the data acquisition by the monitoring instruments (e.g., sampling strategy, temporal resolution). For example, CML provide path-averages (often assumed to be point measurements), whereas PWS yield point measurements. In this context, these processing requirements are best served by Cloud Services, in which its access and analyses is enabled by virtual (research) environments (e.g., European Weather Cloud; Spinuso *et al.*, 2016). Hence, the establishment and management of these 3PD virtual environments and repositories, require incorporating knowledge and expertise on cloud technologies, which is often available by collaborating with data engineers, data architects and software developers in your organization.

The fact that official and 3PD sources will coexist in the same data space or data lake opens opportunities for researchers to experiment and combine these data collections for new analyses. Virtual research environments will provide the possibility of creating an experimental "sandbox" or workbench where users can try different analyses leading to new proof-of-concepts and ensuring reproducibility or results (de Vos *et al*., 2020a; 2020b). This recommendation is in line with the path taken by other supranational organizations, such as the Copernicus Climate Data Store (CDS), ECMWF, or Google Earth Engine, which offer APIs and/or lightweight browser-based interfaces for users to seamlessly interact with big climate data stores.

At KNMI, data architects and engineers are assessing how to create a digital infrastructure that is capable of handling 3PD collections that fulfils the strategic requirements of the EWC (e.g., near real-time capabilities, monitoring severe weather events). These developments are currently ongoing and gradually maturing following a fit-for-purpose strategy. The general premise is to pursue the development of services using 3PD that provide added value for the organization and that can be assigned appropriate digital infrastructure resources to allow engineering and processing in a controlled, structured and scalable manner.

5.3 | Recommendations to valorize 3PD

1. Unifying data formats: Format heterogeneity associated to 3PD networks might hamper data exchange between organizations in the future. Thus, larger organizations such as WMO or EUMETNET could issue commendations defining adequate data types promoting a certain homogenization and structure of the observations.
2. Sharing resources (e.g., via EUMETNET): Collaborate on open-source QC software to accelerate the process towards 3PD-based products; joint purchase of real-time 24/7 3PD data on a European level with the subsequent transfer to all NMS and, preferably, universities.
3. Sharing results: Test different 3PD QC and retrieval algorithms on large benchmark datasets in collaboration with different institutes (e.g., COST action OPENSENSE); knowledge exchange between NMS at using 3PD in operational products.
4. Joining efforts: Connect professional profiles within an NMS (e.g., from researchers to forecasters) to identify high-value and original ideas using 3PD for novel indicators of severe weather. Keep in mind that (local) climate zones serviced by NMS can differ in a way that affects the added value and/or required processing of 3PD (e.g., frequent occurrence of solid precipitation, orography, etc.). In addition, the business drivers might be different, depending on the services or applications that a NMS provides and the position of a weather service by law (e.g., inclusion of hydrology, aviation, commercial activities)
5. Focused efforts: Identify the most promising 3PD sources for a region given the gaps between requirements and the observing capability of official networks (such as the associated network density). For instance, PWS are generally promising for high-income countries. CML are often promising for low- to middle-income countries in (sub)tropical climates because real-time weather radar and (crowdsourced) rain gauge data are often lacking. CML can still add value in case of high network densities in a high-income country such as Germany (Graf *et al*., 2020). Subsequently, identify the level of suitability of 3PD collections for different applications (e.g., 3PD might not be appropriate to detect climate trends)
6. Combining datasets: Following the quality assurance of a 3PD dataset, investigate how to merge these collections with data from dedicated sensors (or satellites), keeping in mind that 3PD availability and usability may differ for regions around the globe.

6 | CONCLUSION

In this work we share our experiences resulting from a decade of work with 3PD collections. We think this contribution provides a panoramic view of the core elements (e.g., technicalities, business aspects, policies) that NMS might need to consider at incorporating 3PD collections into daily operational services. Substantial research has been carried out at KNMI on 3PD, but most of these efforts have faced hurdles to transition between being a "proof-of-concept" to becoming a "proof-of-value" that can be used in operational services. Hence, in this work we share our insights on how this transition could be within NMS.

In our view, 3PD collections are here to stay and expand well-consolidated workflows in meteorology and climate sciences. Thus, we think NMS should be well-prepared for these changes. Looking to the future, we think 3PD has the potential of becoming a game-changer when it comes to carrying out impact-based analysis and issuing high-resolution warnings and events, particularly in urban areas. Hence, we recommend that NMS increases their efforts in the evaluation of how 3PD can contribute to their operational services and, simultaneously, be ready for new big data engineering and data fusion challenges. We also recommend that NMS assess how to start a process of institutionalizing 3PD so that it becomes a standard component of our businesses.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

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REFERENCES

Barras, H., Hering, A., Martynov, A., Noti, P.A., Germann, U. and Martius, O. (2019) Experiences with >50,000 crowdsourced hail reports in Switzerland. *Bulletin of the American Meteorological Society*, 100(8), 1429–1440. https://doi.org/10.1175/BAMS-D-18-0090.1.

Båserud, L., Lussana, C., Nipen, T.N., Seierstad, I.A., Oram, L. and Aspelien, T. (2020) TITAN automatic spatial quality control of meteorological in-situ observations. *Advances in Science and Research*, 17, 153–163. https://doi.org/10.5194/asr-17-153-2020.

Bell, S., Cornford, D. and Bastin, L. (2015) How good are citizen weather stations? Addressing a biased opinion. *Weather*, 70(3), 75–84. https://doi.org/10.1002/wea.2316.

Berne, A., Delrieu, G., Creutin, J.D. and Obled, C. (2004) Temporal and spatial resolution of rainfall measurements required for urban hydrology. *Journal of Hydrology*, 299(3–4), 166–179. https://doi.org/10.1016/j.jhydrol.2004.08.002.

Bielski, C., O'Brien, V., Whitmore, C., Ylinen, K., Juga, I., Nurmi, P., Kilpinen, J., Porras, I., Sole, J.M., Gamez, P., Navarro, M., Alikadic, A., Gobbi, A., Furlanello, C., Zeug, G., Weirathe, M., Martinez, J., Yuste, R., Castro, S., Moreno, V., Velin, T. and Rossi, C. (2017) Coupling early warning services, crowdsourcing, and modelling for improved decision support and wildfire emergency management. In *Proceedings; 2017 IEEE International Conference on Big Data*. Boston, MA: IEEE, pp. 3705–3712. https://doi.org/10.1109/BigData.2017.8258367.

Bowser, A., Hansen, D., He, Y., Boston, C., Reid, M., Gunnell, L. and Preece, J. (2013) Using gamification to inspire new citizen science volunteers. In: *ACM International Conference Proceeding Series*. New York, NY: ACM, pp. 18–25. https://doi.org/10.1145/2583008.2583011.

Brachet, G. (2004) From initial ideas to a European plan: GMES as an exemplar of European space strategy. *Space Policy*, 20(1), 7–15. https://doi.org/10.1016/j.spacepol.2003.11.002.

Brossard, D., Lewenstein, B. and Bonney, R. (2012) Scientific knowledge and attitude change: the impact of a citizen science project. *International Journal of Science Education*, 27(9), 1099–1121. https://doi.org/10.1080/09500690500069483.

Buizza, R., Andersson, E., Forbes, R. and Sleigh, M. (2017) The ECMWF research to operations (R20) process. ECMWF Technical Memoranda. Available at: https://www.ecmwf.int/node/17549.

Cappa, F., Laut, J., Porfiri, M. and Giustiniano, L. (2018) Bring them aboard: rewarding participation in technology-mediated citizen science projects. *Computers in Human Behavior*, 89, 246–257. https://doi.org/10.1016/j.chb.2018.08.017.

Chen, J., Saunders, K. and Whan, K. (2021a) Quality control and bias adjustment of crowdsourced wind speed observations. *Quarterly Journal of the Royal Meteorological Society*, 147, 3647–3664. https://doi.org/10.1002/qj.4146.

Chen, J., Saunders, K. and Whan, K. (2021b) QCWind: quality control for citizen science wind observation. Github repository. Available at: https://github.com/jieyu97/QCwind.

Chwala, C. and Kunstmann, H. (2019) Commercial microwave link networks for rainfall observation: assessment of the current status and future challenges. *WIREs Water*, 6, e1337. https://doi.org/10.1002/wat2.1337.

Clark, M.R., Webb, J.D.C. and Kirk, P.J. (2018) Fine-scale analysis of a severe hailstorm using crowd-sourced and conventional observations. *Meteorological Applications*, 25(3), 472–492. https://doi.org/10.1002/met.1715.

Cornes, R.C., Dirksen, M. and Sluiter, R. (2020) Correcting citizen-science air temperature measurements across the Netherlands for short wave radiation bias. *Meteorological Applications*, 27(1), 1–16. https://doi.org/10.1002/met.1814.

de Bruijn, E.I.F., de Haan, S., Bosveld, F.C., Schreur, B.W. and Holtslag, A.A.M. (2016) Observing boundary-layer winds from hot-air balloon flights. *Weather and Forecasting*, 31(5), 1451–1463. https://doi.org/10.1175/WAF-D-16-0028.1.

de Haan, S. (2011) High-resolution wind and temperature observations from aircraft tracked by Mode-S air traffic control radar. *Journal of Geophysical Research: Atmospheres*, 116(10), 1–13. https://doi.org/10.1029/2010JD015264.

de Vos, L.W., Droste, A.M., Zander, M.J., Overeem, A., Leijnse, H., Heusinkveld, B.G. and Uijlenhoet, R. (2020a) Hydrometeorological monitoring using opportunistic sensing networks in the Amsterdam metropolitan area. *Bulletin of the American Meteorological Society*, 101(2), E167–E185. https://doi.org/10.1175/BAMS-D-19-0091.1.

de Vos, L.W., Leijnse, H., Overeem, A. and Uijlenhoet, R. (2017) The potential of urban rainfall monitoring with crowdsourced automatic weather stations in Amsterdam. *Hydrology and Earth System Sciences*, 21(2), 765–777. https://doi.org/10.5194/hess-21-765-2017.

de Vos, L.W., Leijnse, H., Overeem, A. and Uijlenhoet, R. (2019a) Quality control for crowdsourced personal weather stations to enable operational rainfall monitoring. *Geophysical Research Letters*, 46(15), 8820–8829. https://doi.org/10.1029/2019GL083731.

de Vos, L.W., Overeem, A., Leijnse, H. and Uijlenhoet, R. (2019b) Rainfall estimation accuracy of a nationwide instantaneously sampling commercial microwave link network: error dependency on known characteristics. *Journal of Atmospheric and Oceanic Technology*, 36, 1267–1283. https://doi.org/10.1175/JTECH-D-18-0197.1.

de Vos, M.G., Hazeleger, W., Bari, D., Behrens, J., Bendoukha, S., Garcia-Marti, I. and Walton, J. (2020b) Open weather and climate science in the digital era. *Geoscience Communication*, 3(2), 191–201. https://doi.org/10.5194/gc-3-191-2020.

de Vries, J. (2017) Voertuig-sensoren als mobiel meteorologisch netwerk. KNMI internal paper.

Deilami, K., Kamruzzaman, M. and Liu, Y. (2018) Urban heat Island effect: a systematic review of spatio-temporal factors, data, methods, and mitigation measures. *International Journal of Applied Earth Observation and Geoinformation*, 67, 30–42. https://doi.org/10.1016/j.jag.2017.12.009.

Dirksen, M., Knap, W.H., Steeneveld, G.J., Holtslag, A.A.M. and Tank, A.M.G.K. (2020) Downscaling daily air-temperature measurements in the Netherlands. *Theoretical and Applied Climatology*, 142(1–2), 751–767. https://doi.org/10.1007/s00704-020-03313-1.

Droste, A.M., Heusinkveld, B.G., Fenner, D., and Steeneveld, G.J. (2020) Assessing the potential and application of crowdsourced urban wind data. *Quarterly Journal of the Royal Meteorological Society*, 146(731), 2671–2688. https://doi.org/10.1002/qj.3811

Droste, A.M., Pape, J.J., Overeem, A., Leijnse, H., Steeneveld, G.J., Van Delden, A.J. and Uijlenhoet, R. (2017) Crowdsourcing urban air temperatures through smartphone battery temperatures in São Paulo, Brazil. *Journal of Atmospheric and Oceanic Technology*, 34(9), 1853–1866. https://doi.org/10.1175/JTECH-D-16-0150.1.

Elmore, K.L., Flamig, Z.L., Lakshmanan, V., Kaney, B.T., Farmer, V., Reeves, H.D. and Rothfusz, L.P. (2014) MPING: crowd-sourcing weather reports for research. *Bulletin of the American Meteorological Society*, 95(9), 1335–1342. https://doi.org/10.1175/BAMS-D-13-00014.1.

Ericsson. (2018) Ericsson microwave outlook. Internal report. Available at: https://www.ericsson.com/4a312c/assets/local/reports-papers/microwave-outlook/2018/ericsson-microwave-outlook-report-2018.pdf.

Fenner, D., Bechtel, B., Demuzere, M., Kittner, J. and Meier, F. (2021) CrowdQC+: a quality-control for crowdsourced air-temperature observations enabling world-wide urban climate applications. *Frontiers in Environmental Science*, 9, 720747. https://doi.org/10.3389/fenvs.2021.720747.

Garcia-Marti, I., De Haij, M., Leijnse, H., Noteboom, J.W. and Overeem, A. (2021) Enhanced capability to monitor drought using citizen weather stations. *EGU General Assembly*, 2021, EGU21-6329. https://doi.org/10.5194/egusphere-egu21-6329.

Garcia-Marti, I., de Haij, M., Noteboom, J.W., van der Schrier, G. and de Valk, C. (2019) Using volunteered weather observations to explore urban and regional weather patterns in the Netherlands. *American Geophysical Union, Fall Meeting*, 2019, IN22A-08.

Graf, M., Chwala, C., Polz, J. and Kunstmann, H. (2020) Rainfall estimation from a German-wide commercial microwave link network: optimized processing and validation for 1 year of data. *Hydrology and Earth System Sciences*, 24, 2931–2950. https://doi.org/10.5194/hess-24-2931-2020.

Graf, M., El Hachem, A., Eisele, M., Seidel, J., Chwala, C., Kunstmann, H. and Bárdossy, A. (2021) Rainfall estimates from opportunistic sensors in Germany across spatio-temporal scales. *Journal of Hydrology: Regional Studies*, 37, 100883. https://doi.org/10.1016/j.ejrh.2021.100883.

GSM Association. (2019) Mobile technology for rural climate resilience: the role of mobile operators in bridging the data gap. Internal report. Available at: https://www.gsma.com/mobilefordevelopment/wp-content/uploads/2019/10/GSMA_AgriTech_Climate_Report.pdf.

GSM Association. (2021) Digital innovation for climate-resilient agriculture: using rainfall data from mobile networks for localised and scalable services. Available at: www.gsma.com/mobilefordevelopment/wp-content/uploads/2021/03/Digital_Innovation_for_Climate_Resilient_Agriculture.pdf.

Haese, B., Hörning, S., Chwala, C., Bárdossy, A., Schalge, B. and Kunstmann, H. (2017) Stochastic reconstruction and interpolation of precipitation fields using combined information of commercial microwave links and rain gauges. *Water Resources Research*, 53, 10740–10756. https://doi.org/10.1002/2017WR021015.

Hintz, K.S., O'Boyle, K., Dance, S.L., Al-Ali, S., Ansper, I., Blaauboer, D., Clark, M., Cress, A., Dahoui, M., Darcy, R., Hyrkkanen, J., Isaksen, L., Kaas, E., Korsholm, U. S., Lavanant, M., Le Bloa, G., Mallet, E., McNicholas, C., Onvlee-Hooimeijer, J., Sass, B., Siirand, V., Vedel, H., Waller, J. A. and Yang, X. (2019a) Collecting and utilising crowdsourced data for numerical weather prediction: propositions from the meeting held in Copenhagen, 4–5 December 2018. *Atmospheric Science Letters*, 20(7), 1–8. https://doi.org/10.1002/asl.921.

Hintz, K.S., Vedel, H. and Kaas, E. (2019b) Collecting and processing of barometric data from smartphones for potential use in numerical weather prediction data assimilation. *Meteorological Applications*, 26(4), 733–746. https://doi.org/10.1002/met.1805.

Karjalainen, I. and Jokinen, P. (2019) *Crowdsourcing observations with FMI weather app*. Abstract presented in the 99th Annual Meeting of the American Meteorological Society (AMS), Phoenix, AZ.

KNMI. (2015) Observations strategy KNMI 2015-2024. KNMI publication 233. Available at: http://publicaties.minienm.nl/documenten/observations-strategy-knmi-2015-2014.

KNMI. (2019) The KNMI I Strategy, Edition 2019. Internal report.

KNMI. (2020) KNMI Meerjarig Strategisch Plan 2025 (In English: KNMI Multi-year Strategic Plan 2025). Available at: https://cdn.knmi.nl/system/readmore_links/files/000/000/198/original/KNMI_strategie_2025.pdf?1599125132.

Koole, M. (2016) Rapportage WOW-NL evaluatie. Internal KNMI report IR-2016-08. Available at: http://publicaties.minienm.nl/download-bijlage/84604/evaluatie-wow-apr2016-martijn-2-1b-ir-2016-08.pdf.

Krennert, T., Pistotnik, G., Kaltenberger, R. and Csekits, C. (2018) Crowdsourcing of weather observations at national meteorological and hydrological services in Europe. *Advances in Science and Research*, 15, 71–76. https://doi.org/10.5194/asr-15-71-2018.

Leijnse, H., Uijlenhoet, R. and Stricker, J.N.M. (2007) Rainfall measurement using radio links from cellular communication networks. *Water Resources Research*, 43, W03201. https://doi.org/10.1029/2006WR005631.

Lesiv, M., Moltchanova, E., Schepaschenko, D., See, L., Shvidenko, A., Comber, A. and Fritz, S. (2016) Comparison of data fusion methods using crowdsourced data in creating a hybrid forest cover map. *Remote Sensing*, 8(3), 261. https://doi.org/10.3390/rs8030261.

Longmore, S., Miller, S., Bikos, D., Lindsey, D., Szoke, E., Molenar, D., Hillger, D., Brummer, R. and Knaff, J. (2015) An automated mobile phone photo relay and display concept applicable to operational severe weather monitoring. *Journal of*

Atmospheric and Oceanic Technology, 32(7), 1356–1363. https://doi.org/10.1175/JTECH-D-14-00230.1.

Lussana, C., Uboldi, F., and Salvati, M.R. (2010) A spatial consistency test for surface observations from mesoscale meteorological networks. *Quarterly Journal of the Royal Meteorological Society*, 136(649), 1075–1088. https://doi.org/10.1002/qj.622

Mandement, M. and Caumont, O. (2020) Contribution of personal weather stations to the observation of deep-convection features near the ground. *Natural Hazards and Earth System Sciences*, 20(1), 299–322. https://doi.org/10.5194/nhess-20-299-2020.

Marquès, E., Masson, V., Naveau, P., Mestre, O., Dubreuil, V. and Richard, Y. (2022) Urban heat Island estimation from crowd-sensing thermometers embedded in personal cars. *Bulletin of the American Meteorological Society*, 103, E1098–E1113. https://doi.org/10.1175/bams-d-21-0174.1.

Marsigli, C., Ebert, E., Ashrit, R., Casati, B., Chen, J., Coelho, C., Dorninger, M., Gilleland, E., Haiden, T., Landman, S. and Mittermaier, M. (2020) Observations for high-impact weather and their use in verification. *Natural Hazards and Earth System Sciences*, 21, 1–24. https://doi.org/10.5194/nhess-2020-362.

Meier, F., Fenner, D., Grassmann, T., Otto, M. and Scherer, D. (2017) Urban climate crowdsourcing air temperature from citizen weather stations for urban climate research. *Urban Climate*, 19, 170–191. https://doi.org/10.1016/j.uclim.2017.01.006.

Meissen, U. and Fuchs-Kittowski, F. (2014) *Towards a reference architecture of crowdsourcing integration in early warning systems*. ISCRAM 2014 Conference Proceedings - 11th International Conference on Information Systems for Crisis Response and Management, (May), 334–338.

MEMO. (2020) MEMO|SMHI: microwave-based environmental monitoring. Available at: https://smhi.se/memo.

Mercier, F., Barthès, L. and Mallet, C. (2015) Estimation of finescale rainfall fields using broadcast TV satellite links and a 4DVAR assimilation method. *Journal of Atmospheric and Oceanic Technology*, 32, 1709–1728. https://doi.org/10.1175/JTECH-D-14-00125.1.

Merkus, T. (2016) *Integrating formal data and volunteered geographic information: a case with amateur weather data and formal KNMI data*. MSc thesis, Utrecht University, Utrecht, the Netherlands. Available at: https://studenttheses.uu.nl/bitstream/handle/20.500.12932/25090/Master_thesis_Thomas_Merkus_s6020461.pdf?sequence=2&isAllowed=y.

Messer, H. and Sendik, O. (2015) A new approach to precipitation monitoring: a critical survey of existing technologies and challenges. *IEEE Signal Processing Magazine*, 32, 110–122. https://doi.org/10.1109/MSP.2014.2309705.

Messer, H.A., Zinevich, A. and Alpert, P. (2006) Environmental monitoring by wireless communication networks. *Science*, 312, 713. https://doi.org/10.1126/science.1120034.

Muller, C.L., Chapman, L., Johnston, S., Kidd, C., Illingworth, S., Foody, G., Overeem, A. and Leigh, R.R. (2015) Crowdsourcing for climate and atmospheric sciences: current status and future potential. *International Journal of Climatology*, 35, 3185–3203. https://doi.org/10.1002/joc.4210.

Napoly, A., Grassmann, T., Meier, F. and Fenner, D. (2018) Development and application of a statistically-based quality control for crowdsourced air temperature data. *Frontiers in Earth Science*, 6, 1–16. https://doi.org/10.3389/feart.2018.00118.

Nipen, T.N., Seierstad, I.A., Lussana, C., Kristiansen, J. and Hov, Ø. (2020) Adopting citizen observations in operational weather prediction. *Bulletin of the American Meteorological Society*, 101(1), E43–E57. https://doi.org/10.1175/BAMS-D-18-0237.1.

NRC – National Research Council. (2003) *Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations*. Washington, DC: The National Academies Press. https://doi.org/10.17226/10658.

Nuottokari, J., Gregow, E., Hohti, H., Kotro, J., Karjalainen, I., Ylhäisi, J., Hieta, L., Partio, M. and Karjalainen, J. (2022). Seamless Nowcasting system development at the Finnish Meteorological Institute. Available at: https://weber.itn.liu.se/~chrsc91/DATS-workshop-norrkoping/docs/FMI-Nowcasting-ULJAS-Nuottokari-JH_modifications.pptx.

Overeem, A., Leijnse, H. and Uijlenhoet, R. (2011) Measuring urban rainfall using microwave links from commercial cellular communication networks. *Water Resources Research*, 47, W12505. https://doi.org/10.1029/2010WR010350.

Overeem, A., Leijnse, H. and Uijlenhoet, R. (2013a) Country-wide rainfall maps from cellular communication networks. *Proceedings of the National Academy of Sciences of the United States of America*, 110(8), 2741–2745. https://doi.org/10.1073/pnas.1217961110.

Overeem, A., Leijnse, H. and Uijlenhoet, R. (2016a) Retrieval algorithm for rainfall mapping from microwave links in a cellular communication network. *Atmospheric Measurement Techniques*, 9, 2425–2544. https://doi.org/10.5194/amt-9-2425-2016.

Overeem, A., Leijnse, H. and Uijlenhoet, R. (2016b) Two and a half years of country-wide rainfall maps using radio links from commercial cellular telecommunication networks. *Water Resources Research*, 52, 8039–8065. https://doi.org/10.1002/2016WR019412.

Overeem, A., Leijnse, H., van Leth, T.C., Bogerd, L., Priebe, J., Tricarico, D., Droste, A. and Uijlenhoet, R. (2021) Tropical rainfall monitoring with commercial microwave links in Sri Lanka. *Environmental Research Letters*, 16(7), 074058. https://doi.org/10.1088/1748-9326/ac0fa6.

Overeem, A., R. Robinson, J.C., Leijnse, H., Steeneveld, G.J., Horn, B.K. and Uijlenhoet, R. (2013b) Crowdsourcing urban air temperatures from smartphone battery temperatures. *Geophysical Research Letters*, 40(15), 4081–4085. https://doi.org/10.1002/grl.50786.

Rabiei, E., Haberlandt, U., Sester, M. and Fitzner, D. (2013) Rainfall estimation using moving cars as rain gauges—laboratory experiments. *Hydrology and Earth System Sciences*, 17, 4701–4712. https://doi.org/10.5194/hess-17-4701-2013.

Reges, H.W., Doesken, N., Turner, J., Newman, N., Bergantino, A. and Schwalbe, Z. (2016) CoCoRaHS: the evolution and accomplishments of a volunteer rain gauge network. *Bulletin of the American Meteorological Society*, 97(10), 1831–1846. https://doi.org/10.1175/BAMS-D-14-00213.1.

Rios Gaona, M.F., Overeem, A., Raupach, T.H., Leijnse, H. and Uijlenhoet, R. (2018) Rainfall retrieval with commercial microwave links in São Paulo, Brazil. *Atmospheric Measurement Techniques*, 11, 4465–4476. https://doi.org/10.5194/amt-11-4465-2018.

Sgoff, C., Acevedo, W., Paschalidi, Z., Ulbrich, S., Bauernschubert, E., Kratzsch, T. and Potthast, R. (2022) Assimilation of crowd-sourced surface observations over Germany in a regional weather prediction system. *Quarterly Journal of the*

Royal Meteorological Society, 148, 1752–1767. https://doi.org/10.1002/qj.4276.

Shearer, C. (2000) The CRISP-DM model: the new blueprint for data mining. *Journal of Data Warehousing*, 5, 13–22.

Sosko, S. and Dalyot, S. (2017) Crowdsourcing user-generated mobile sensor weather data for densifying static geosensor networks. *ISPRS International Journal of Geo-Information*, 6(3), 1–22. https://doi.org/10.3390/ijgi6030061.

Spinuso, A., Veldhuizen, M., Bailo, D., Vinciarelli, V. and Langeland, T. (2016) SWIRRL. Managing provenance-aware and reproducible workspaces. *Data Intelligence*, 4(2), 243–258.

Uijlenhoet, R., Overeem, A. and Leijnse, H. (2018) Opportunistic remote sensing of rainfall using microwave links from cellular communication networks. *WIREs Water*, 5, e1289. https://doi.org/10.1002/wat2.1289.

Upton, G.J.G., Holt, A.R., Cummings, R.J., Rahimi, A.R. and Goddard, J.W.F. (2005) Microwave links: the future for urban rainfall measurement? *Atmospheric Research*, 77, 300–312. https://doi.org/10.1016/j.atmosres.2004.10.009.

van Andel, JPC. (2021) *Quality control development for near real-time rain gauge networks for operational rainfall monitoring*. MSc thesis, Utrecht University, Utrecht, the Netherlands. Available at: http://dspace.library.uu.nl/handle/1874/404528.

van Poelgeest, S., and de Vries, M. (2021) Verkenning Publiek Gebruik Data van Derden. Retrieved from https://www.geonovum.nl/documents/rapportage-verkenning-publiek-gebruik-data-van-derden-eindversie0pdf

Vannitsem, S., Bremnes, J.B., Demaeyer, J., Evans, G.R., Flowerdew, J., Hemri, S., Lerch, S., Roberts, N., Theis, S., Atencia, A., Ben Bouallègue, Z., Bhend, J., Dabernig, M., De Cruz, L., Hieta, L., Mestre, O., Moret, L., Plenković, I. O., Schmeits, M., Taillardat, M., Van den Bergh, J., Van Schaeybroeck, J., Whan, K. and Ylhaisi, J. (2021) Statistical postprocessing for weather forecasts. *Bulletin of the American Meteorological Society*, 102, E681–E699. https://doi.org/10.1175/BAMS-D-19-0308.1.

Whitney, P.L. and Leshner, R.B. (2004) The transition from research to operations in Earth observation: the case of NASA and NOAA in the US. *Space Policy*, 20(3), 207–215. https://doi.org/10.1016/j.spacepol.2004.06.004.

WMO. (2018) *Guide to instruments and methods of observation. Volume III: observing systems (Vol. I)*. Geneva: WMO. Available at: https://library.wmo.int/doc_num.php?explnum_id=9872.

WMO. (2020) Vision for the WMO Integrated Global Observing System in 2040. Available at: https://library.wmo.int/doc_num.php?explnum_id=10278.

Zheng, F., Tao, R., Maier, H.R., See, L., Savic, D., Zhang, T., Chen, Q., Assumpção, T.H., Yang, P., Heidari, B., Rieckermann, J., Minsker, B., Bi, W., Cai, X., Solomatine, D. and Popescu, I. (2018) Crowdsourcing methods for data collection in geophysics: state of the art, issues and future directions. *Reviews of Geophysics*, 56, 698–740. https://doi.org/10.1029/2018RG000616.

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