Text for Meteorologica [Dutch version]

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Title: Vele handen maken licht werk: 10 jaar WOW (Many hands make light work: 10 years WOW)

Introductory paragraph:

2024 marks the tenth anniversary of the WOW (Weather Observations Website), a unique way the Dutch, Belgium, Australian and UK meteorological offices are crowdsourcing real time weather data. The availability of WOW data is drastically changing the landscape of meteorological data and the implications are large. In this letter we touch upon these changes and the new possibilities for weather and climate services in the Netherlands.

Introduction

Technology for measuring our living environment is rapidly changing. Motivated by a concern of citizens about their natural surroundings, joining measurement campaigns using crowd-sourced data is getting more-and-more popular. The developments in technology, which makes IoT (Internet of Things) sensors available to the non-specialists, fuel this development. In the field of meteorology, both the quality of hobbyists' weather stations has improved, as well as the automated reporting capabilities of these stations. A fully automatic weather station, measuring rainfall, wind vectors, humidity and temperature with Wi-Fi data reporting capabilities are available for less than two hundred euros, putting high quality instruments into the hands of increasing numbers of interested members of the public.

2024 marks the tenth anniversary of the Weather Observations Website network in the Netherlands (WOW-NL; http://wow.knmi.nl). Initially launched by the UK MetOffice and the Royal Meteorological Society, this unique partnership between the national meteorological services (NMS) of the Netherlands, Belgium, Sweden, Ireland, Australia, New Zealand and the United Kingdom, has provided a common and publicly funded space for weather enthusiasts at sharing the weather measurements provided by their personal weather stations (PWS). The ubiquity of wireless networks and decreasing hardware prices means that a fully automated PWS is within reasonable reach. These favorable conditions have prompted 1000+ citizens in the Netherlands to install a PWS in their personal spaces and start to contribute to monitoring the weather. The WOW-NL network has roughly collected 430 million observations in the period 2015-2023, and we expect to hit the 500 million marks by the end of 2024. Figure 1 illustrates the growth of WOW-NL in this period with a substantial jump between 2018 and 2019 when the number of observations collected by WOW-NL was larger than that of the KNMI network of 34 automatic weather stations (on land). Looking into the spatial dimension, Figure 2 illustrates the most up-to-date geographical representation of WOW-NL. Organic growth in the number of PWS in NL over the past decade has resulted in a network of observation locations that covers the majority of the country. The main clustering is around major cities, a substantial source of new information outside of the normal locations of KNMI's Automatic Weather station Network. It is interesting to notice the presence of WOW-NL stations in the BES islands but note that the KNMI equipment on these islands also provides information to WOW.

The density of the WOW-NL network has reached a point that major cities can be monitored in near real-time. Figure 3 depicts the geographical distribution of WOW stations around the Utrecht metropolitan region, roughly an area of 10x10km. Here the reader can see that 30+ PWS already contribute in monitoring suburban meteorological patterns and it holds the promise that with a further increase in the density of WOW stations in this area, the Utrecht area may grow into a testbed for urban climate monitoring.

Rubbish in, rubbish out?

Researchers at KNMI have acquired substantial experience working with quality controls for crowd-sourced temperature, precipitation and wind. Now we know that after applying different filters (e.g. intra-station, inter-station, bias adjustments), the remaining time-series are of sufficient quality to feed workflows further down the line. These quality controls were also tested in a EUMETNET project in which the participant NMS received two 3PD datasets at the European scale (i.e. WOW & Netatmo), which turned into a fundamental exercise to understand the differences in the quality reported by the two networks. Our active participation in EUMETNET's working groups has served as a benchmark to understand how European NMS are facing similar challenges and moving in the same direction.

The development of high-resolution services using 3PD is quite a unique research line among European NMS. At KNMI we apply multi-fidelity methods to skillfully combine official and 3PD observations (i.e. WOW-NL) to produce hourly gridded maps at 1km of spatial resolution. Multi-fidelity methods are particularly suited to handle data with variable quality levels (i.e. the high-fidelity KNMI network and the low-fidelity WOW network) and can provide an estimate of weather variables at each point of time, along with an uncertainty metric. The benefit of this approach is that a strict quality control is not required, only obvious outliers are removed, as the gridding method weights the input data on the basis of their trustworthiness. Figure 4 shows a map combining official and WOW-NL observations to obtain the probability of exceedance of wind speed over 5 Beaufort during the passing of Storm Darcy. As seen, the inclusion of 3PD data provides much more detail during severe weather events. The application of this novel methodology to 10 years of WOW-NL data resulted in what we call the "Community Climatology", which is currently being used by researchers in the RIVM to assist in their processes. One of these applications by RIVM is in the evaluation of relations between heat stress, mortality and heat waves. Specifically for this application, the realistic inclusion of urban climate has added value.

Digital infrastructure

Parallel to the above research lines has been the integration of 3PD in the organization's digital infrastructure. In 2022 the KNMI developed the "WOW Livestream", which is a near real-time database for WOW-NL. Every 15 minutes scheduled services connect with the repositories in the UK Met Office and retrieve the last batch of observations produced within a bounding box wrapping the Netherlands, Belgium, and parts of the UK and Germany. Currently, raw observations are available through the KNMI's intranet, but the future might bring aggregated data products for a larger pool of external users. As seen, 3PD collections are born in the times of cloud technologies, which motivates changing the way we do science with large data collections. At KNMI we are testing how virtual research environments (VRE) can help researchers with doing data analysis in the cloud. Enacting this simple concept of "bringing code to data" using VREs frees the user of data management activities (e.g. download, update) and sets a piece of research in the right course to comply with open science (e.g. data provenance, FAIR principles), which facilitates collaboration between peers.

Right. So what now?

The maturity of these research lines has reached a tipping point in which they can be bound together into a coherent and self-contained new process, hence ensuring that the KNMI has solid foundations to remain a leading NMS using 3PD observations at the European level in the future. However, in this data-intensive context, the seamless provision of high-quality 3PD observations is a new endeavor that needs to be proficiently handled by NMS. The KNMI is now beginning a process of institutionalization of 3PD collections, which turns these novel observations into part of our "daily business". Key to the success of this process is defining new policies for 3PD and aligning them with existing data management policies and (inter) national legislation.

The future looks promising for 3PD. Climate sciences are now experiencing a revolution with the incursion of AI/ML in the weather forecasting chain. These data-driven methods undoubtedly have the potential to produce weather forecasts at finer spatial and temporal scales, thus opening the door to high-resolution (e.g. suburban scales) products. However, the application of these techniques requires vast amounts of observations along the numerical weather processing chain, a gap that seems natural to fill with 3PD observations. In addition, the extra heap of observations at the suburban scale enables us to create high-resolution and near real-time services taking the pulse to cities during the onset of extreme weather events (e.g. heatwaves, rainfall events like Limburg 2021).

Community building

The acquisition of data from the public and its incorporation into the products and services of KNMI is a ground shaking little revolution on its own. Traditionally, NMS are authoritative sources of weather-related information. NMS collect their own observations and produce aggregated views, which are made available to society. It would seem that the interaction with citizens is uncharted territory for the KNMI, but the set-up of the WOW network actually mirrors the construction of the current network of manual rain gauges. That network has its roots in the latter part of the 19th century, when citizens were asked to participate. This approach is still alive today and could be considered citizen science *avant la lettre*.

Fast-forward to contemporary times, the KNMI is aware of the importance of building up a community of WOW users. However, the acceptance of 3PD observations requires revisiting the well-consolidated weather monitoring processes. NMS must accept a dependency relationship on external agents for their data provision. Simultaneously, NMS must strive to create a community of users where a dialogue with social agents is established. Only in this way can we turn the initial dependency into a healthy and long-lasting bond with society. This opens an exciting new avenue in which citizens become active participants, hence contributing to products that improve as a result of their involvement. Promoting this engagement is of the essence to build resilient societies for future generations.

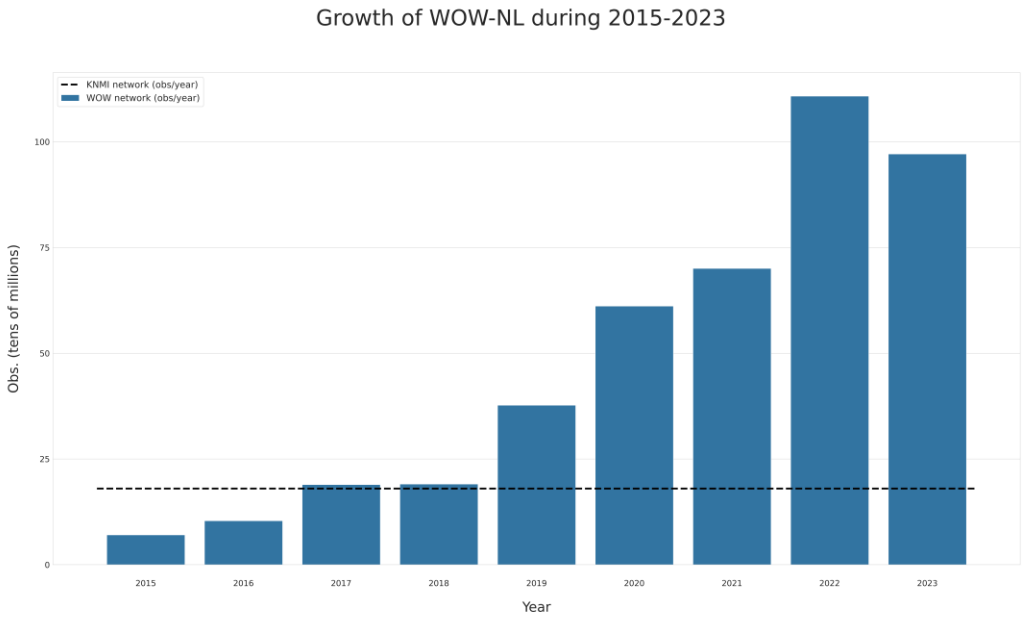

Figure 1. Number of observations (i.e. in tens of millions) collected by the WOW-NL network in the period 2015-2023. The dotted line represents the observations collected by KNMI's official network of 34 land stations. As seen, since 2019 WOW-NL is consistently collecting more observations than KNMI's network. Currently the total amount is roughly 430 million observations, and we expect to hit the 500 million marks by the end of 2024.

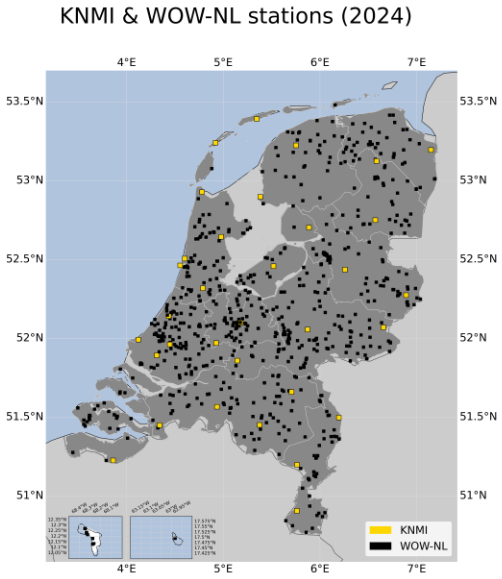

Figure 2. Geographic representation of KNMI's network (yellow) and WOW-NL (black). The KNMI network consists of a set of 34 lands stations, conceived to monitor large atmospheric weather patterns. In the past 10 years, more than 1000 PWS have contributed weather observations to this network. For instance, in 2023 more than

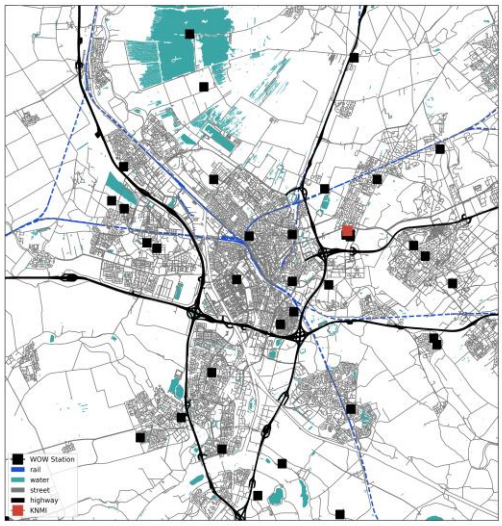

Figure 3. Zoom-in to Utrecht's metropolitan region. The map roughly represents an area of 10x10 km

around the city center and shows an overlay of streets and transportation modes, along with waterbodies. The red square represents KNMI's location in de Bilt, whereas the black squares depict the geographic distribution of WOW-NL stations. As seen, 3PD networks like WOW acquiring observations within cities, might represent the gate for new applications in urban meteorology.

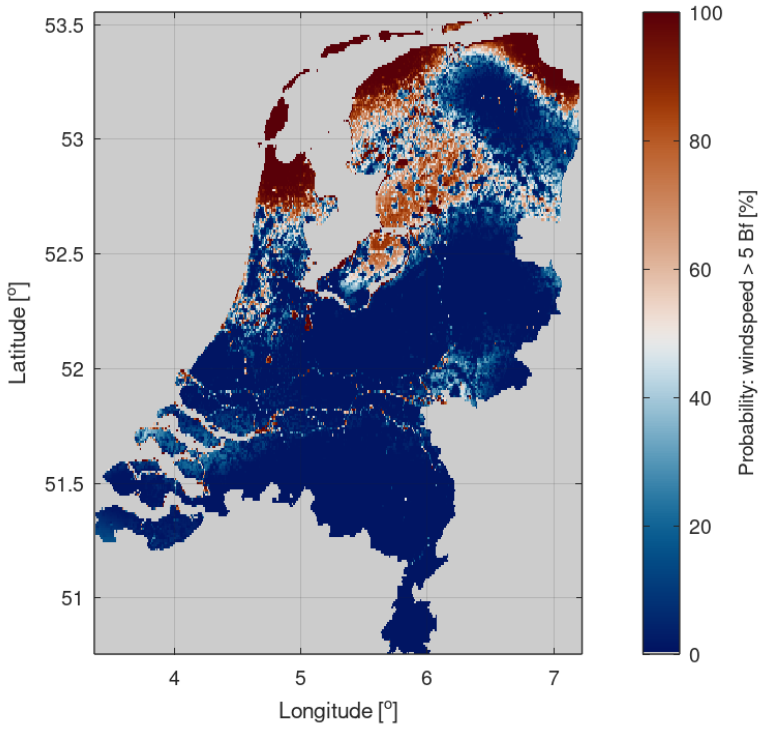

Figure 4. The map illustrates the probability that 5 Beaufort wind speed is exceeded on February 7th, 2021 (storm Darcy). Here we combine KNMI and WOW-NL wind speed observations, along with surface roughness, to devise these experimental high-resolution maps that might be the base for new applications.