Build and measure: Students report weather impacts and collect weather data using self-built weather stations

Thomas Kox[1,2],
Henning W. Rust[2,3],
Bianca Wentzel[2,3],
Martin Göber[2,4],
Christopher Böttcher[2,3],
Jonas Lehmke[2,3],
Elisabeth Freundl[5],
Matthias Garschagen[1]

[1] Department of Geography, Ludwig Maximilian University of Munich, Munich, Germany.

[2] Hans Ertel Centre for Weather Research, Berlin, Germany.

[3] Freie Universität Berlin, Institute of Meteorology, Berlin, Germany.

[4] Deutscher Wetterdienst, Offenbach, Germany.

[5] Energiewende Oberland, Penzberg, Germany.

Author correspondence:
Thomas Kox
Department of Geography,
Ludwig Maximilian University of Munich,
Luisenstraße 37,
80333 München,
Germany.
Email: t.kox@lmu.de

URL: http://trauma.massey.ac.nz/issues/2021-3/AJDTS_25_3_Kox.pdf

Abstract

The citizen science component of a project on climate change adaptation at the European regional level (Klimawandelanpassung auf regionaler Ebene; KARE-CS) established a layperson weather network with two high schools in the Bavarian Prealps south of Munich, Germany, to measure small-scale weather phenomena and impacts of weather and to build decision-relevant knowledge about weather and climate change. Over the summer of 2020, local students collected weather data with self-build micro weather stations and reported observed weather phenomena and impacts. The preliminary results show that despite the ongoing COVID-19 situation, the students actively engaged in the project, created valid data, and enabled detailed data analysis of weather observations and reports. First insights show that visual observations of weather phenomena such as heavy rainfall aligned well with the measurements. Students' primary motivations to participate in the project were the desire to contribute to scientific research and their interest in science and weather. The project continued over the summer of 2021 with further analysis ongoing.

Keywords: *Citizen science, motivation, weather, impacts, observation*

The Bavarian Prealps is one of the regions in Germany with the highest frequency of heavy rainfall events due to orographic effects. These events eventually cause extreme snow loads with a high damage potential in winter and, in combination with localized, stationary thunderstorms, trigger flash floods in summer. At the same time, the region south of Munich is confronted with enormous urban growth pressure, accompanied by high competition for land and increased soil sealing, intensifying run-off and limiting the potential flood retention.

Although the existing network of automatic weather stations operated by the German Weather Service (Deutscher Wetterdienst; DWD) can measure several meteorological parameters with high accuracy at high temporal resolution and under standardized conditions, small-scale weather phenomena like thunderstorms and hail may slip through such a station network undetected (Krennert et al., 2018). Weather data collected outside the station network by weather spotters or layperson observations can be numerous and account for much larger areas and thus supplement and enrich the official observation network by providing weather data about the areas between weather stations. In addition, those observations and reports can be used to identify the impact of weather such as flooded roads due to extreme rain or broken trees from damaging wind gusts, which cannot directly be reflected from automatic weather station data (Elevant, 2010; Krennert et al., 2018).

Citizen science approaches in the field of weather forecasting and environmental monitoring have been taking place for some time (Bonney et al., 2014; Gharesifard & Wehn, 2017; Krennert et al., 2018; Muller et al., 2015). Layperson weather networks, volunteer weather observers, and weather spotters who detect local weather phenomena and extremes form a community of practice whose importance for national weather services should not be underestimated (Cifelli et al., 2005; Elevant, 2010). Prominent examples are

Skywarn (Waxberg, 2013), the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS; Cifelli et al., 2005), and the European Severe Storms Laboratory (ESSL; Dotzek et al., 2009).

The weather and impact data collected by members of such citizen science groups can be useful, for example, to determine the occurrence and approximate size of hail (Barras et al., 2019) or to verify the occurrence of thunderstorms. Hence, these groups and the information they collect can contribute to and act as a basis for verification and subsequent calibration of severe weather warnings (Krennert et al., 2018; Marsigli et al., 2021).

Members of these communities not only obtain key scientific insights but also increase their understanding of the topic and gain a growing interest in the research process (Bonney et al., 2016; Pettibone et al., 2016). With closer collaboration and the transition to co-production of information, the role of citizens is shifting away from a pure user of weather information to a collaborator and partner in producing this information (Kox et al., 2018). A better public understanding is desirable to build decision-relevant knowledge about weather risks as well as climate change awareness. These benefits of citizen science align with the goals of the World Meteorological Organization's (WMO) High Impact Weather (HIWeather) initiative to increase community resilience to high impact weather events through knowledge creation, participation, and trust in science (Zhang et al., 2019).

In the course of a project on climate change adaptation at the European regional level (*Klimawandelanpassung auf regionaler Ebene*; KARE[1]), a citizen science component (KARE-CS) was created to support local communities in the Bavarian Prealps in adapting to the impacts of extreme rain and subsequent flash floods. This component of the project aimed to increase understanding of the impacts of weather, weather risks, and climate change.

In this research update, we present the current status of the KARE-CS project, including the underlying technical aspects and process of the weather and weather impact observations (Procedures section). We provide insight into the first data collected during the measurement campaign in the summer of 2020 (Preliminary Data and First Insights section). In particular, we focus on the measuring sites, the weather data, and first evaluations of the participants' motivation to take part in the citizen science network. Finally, we draw first conclusions and provide an outlook on the measuring campaign for 2021 (Outlook section).

Procedures

The project consists of two components: a local network of self-build micro weather stations and reports of weather events and weather impacts.

In 2020, 23 students (aged 14 to 18) were recruited from environmental school clubs and voluntary groups at two local upper secondary schools in the Bavarian Prealps. Together with their teachers, project scientists, and a local community foundation they maintained 25 micro weather stations and individually reported weather events and impacts between June and November 2020. The students participated as volunteers aside from their usual school activities with the support of their teachers. Workshops, digital teaching materials, and manuals were used to familiarise the students with the weather station, the reporting, and the basics of weather forecasting. Due to the ongoing COVID-19 situation, several adjustments to the original work plan had to be made. In particular, school closures and travel and contact restrictions resulted in hurdles for co-operation and especially the instalment of the technical infrastructure. We reflect on these challenges in the following sections.

Technical infrastructure. In recent years, youth are increasingly involved in voluntary projects to measure and observe weather and other environmental phenomena (Pesch & Bartoschek, 2019). Several ready-to-use micro weather stations are commercially available, which are reasonably accurate and are used in crowd-sourcing projects (e.g., Meier et al., 2017; Venter et al., 2020). A prominent national example is senseBox, an open-source hardware toolkit for building environmental monitoring devices (Pesch & Bartoschek, 2019).

For the purpose of our project, a measuring approach had to meet the following technical and social requirements:

1) Participation: Students self-assemble devices during a workshop of a few hours using pre-manufactured parts.
2) Quantity: A sufficient number of devices can be built by using a low-cost design.
3) Self-sufficiency: Devices should be free in placement (e.g., no drilling necessary and sufficiently far from buildings), which can be achieved by independence of external power supply and Internet connection. For the use of the data, a data privacy-sensitive visualisation has to be provided.

1 www.klimaanpassung-oberland.de/

4) Comparability: The device should be technically close to professional stations (e.g., through the selection of sensors and a ventilated design).
5) Appeal: The device should appeal to young people (e.g., by using 3D-printed parts).
6) Simplicity: The device should be easy to set up and easy to use.

The micro weather station was named "MESSI", resembling the German word for measuring ("*messen*"). MESSI was designed in-house (Printed Circuit Board design, sensor choice, and 3D-printed housing). Production was partly in-house and partly external. For serial production, the 3D-printed parts were produced by injection moulding, with the exception of the top and bottom layer. The following parameters are measured (instrument errors as reported by the manufacturer in parentheses): the atmospheric parameters air temperature (inside (0.15 kelvin) and outside (0.3 kelvin) the radiation shield), relative humidity (2%), air pressure (0.5 hectopascals), radiation (in the visible and infrared range), and precipitation. For measuring precipitation, a simple commercial tipping bucket generating pulses was added, connected via an expansion port (Figure 1).

The students assembled the MESSIs with the help of a construction manual and could test its functionality with simple experiments. The project was introduced during group video calls, in which students could eventually seek help if they had problems with assembling the weather station. A web application (Figure 2) was used to provide the measurement data and a link to the impact reporting as well as information on the project and assembly, installation, and maintenance instructions. At the end of the first measurement campaign in November 2020,

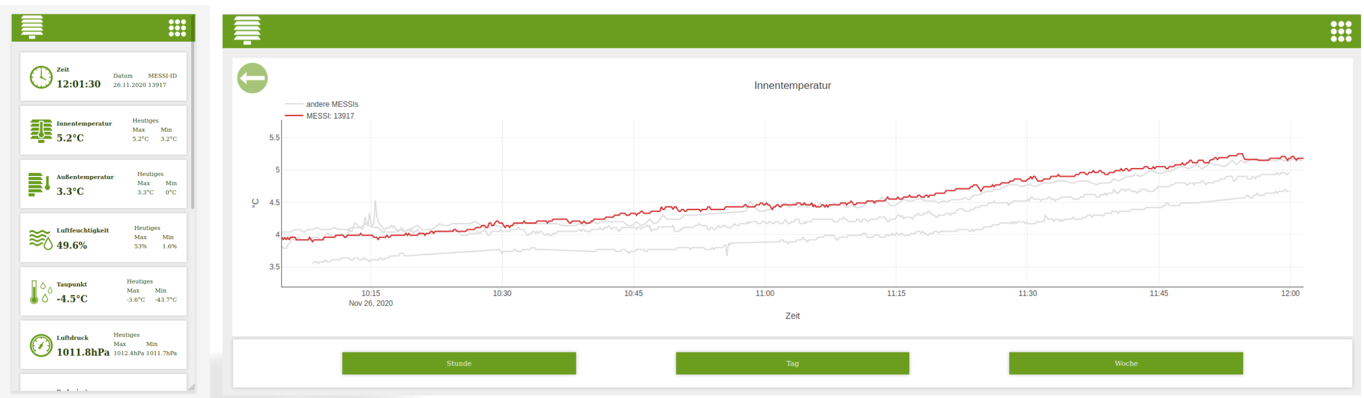
Figure 1
MESSI with Attached Tipping Bucket Rain Gauge to Collect Precipitation

Note. Photo: Andreas Trojand (licensed under CC BY-NC-ND 3.0 DE).

the students undertook a first analysis of their own data during a digital workshop (reported in the next section).

Measurements were taken at regular intervals (a few seconds) and stored after approximately 5 minutes in packets on flash memory. The Long Range Wide Area Network (LoRaWAN) radio standard was used for data transmission. We chose The Things Network (TTN), which provides an open-source LoRaWAN stack, to enable the login of devices and gateways and manage the encrypted data transfer. Packets are sent via LoRaWAN to gateways and forwarded to a server. The station can therefore be operated completely autonomously and Wi-Fi or a mobile phone network is not necessary. Additionally, energy consumption is low

Figure 2
Screenshot from Web Application Usable by Participants



Note. Left: Overview of the current measured values of the chosen measurement device (MESSI) and the minimum and maximum values of the current day. Right: Time series of a chosen parameter (temperature inside radiation shield) for a chosen time period. Shown are the values of the own measurement device (red) and the values of up to 10 nearest measurements devices (grey). The user is able to choose between different time periods (last 60 minutes, last 24 hours, and last week).

during transmission. Thus, the device has sufficiently low power consumption that it can be operated with a rechargeable battery fed by two small solar cells.

In order to be able to statistically adjust measurements inside the radiation shield later, there is a second thermometer outside the radiation shield not affected by the thermal inertia of the housing but exposed to radiation. The radiation sensor also offers a further possibility to correct the temperature measurement, which can be distorted by the lack of active ventilation during direct solar radiation. The microcontroller replaces the typically used but very expensive data loggers of commercial stations.

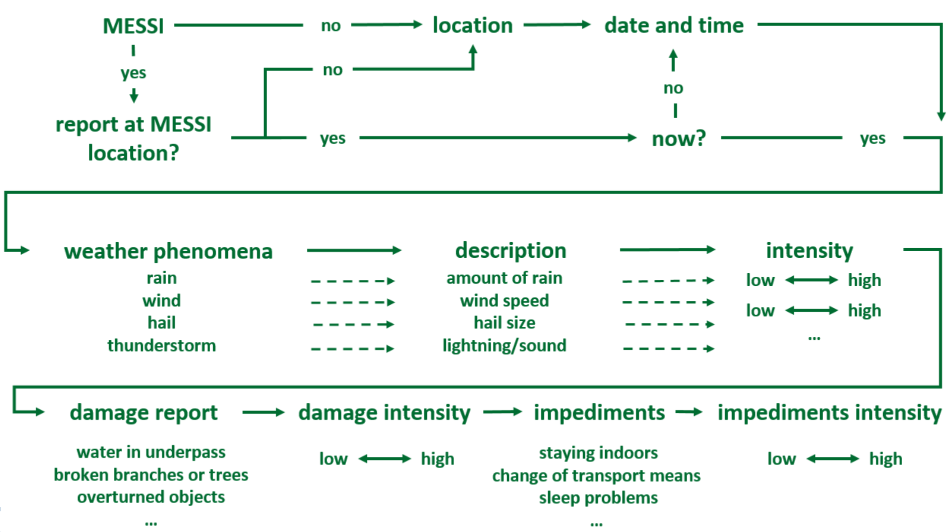
In order to create measuring conditions that are as uniform as possible and to minimise direct weather influences on the sensors, a separate housing was developed. The design of this housing is adapted to the sensors contained and is based on professional sensors and measuring procedures (WMO, 2008). The housings are printed with the help of a 3D printer and thus offer the possibility of spontaneous adaptations to new sensor technology and the expansion of the measuring station with additional sensors. In summary, as a prototype, a very small, low-cost device has been successfully developed.

Weather and impact reports. Parallel to the automatic collection of weather data via the micro weather stations, the students could submit online reports on observed weather events and local impacts of weather. They submitted the reports via a browser-based template on their computer or smartphone as a form of mobile experience sampling, an *in situ* approach asking the participants to report on their behaviour and feelings using mobile phones (Karnowski, 2013). The report procedure is outlined in Figure 3.

At the start, the students are asked if they are in charge of their own MESSI and if so, to provide the ID. Next, the students provide the place and time of their observation. Information on the location is not needed if they submit a report from the location of their MESSI as the location of the device is provided by the ID. If the report refers to a recent event (last 30 minutes), it is also not necessary to enter the time as a time stamp is created automatically. In the case that a report concerns a recent weather event at the location of the MESSI, these steps are therefore omitted and the time required for reporting is reduced. Once location, date, and time are specified the students provide observed conditions of (severe) weather phenomena including amount of rainfall, wind speed, hail size, and thunderstorms (yes/no eye witness report on lightning and estimate of distance from own location based on the sound of thunder). In addition, they provide information about the severity of the events and observed damage, both on a self-assessed numeric scale (1-10) and in written statements (e.g., overturned garden furniture, broken trees, flooded underpasses). They also provide details of adverse effects the weather and weather impacts had on their everyday life; again, on a self-assessed numeric scale (1-10) and in statements (e.g., staying indoors, changing means of transport, sleeping problems).

Students are requested to report especially severe weather. However, what is to be considered severe is not determined in advance. Instead, the answer to this question is part of the research. The aim is to capture the subjective impact of the event in a spatially-aggregated form for specific regions. Although citizens' weather reports provide subjective and less precise information than standardised weather stations (Barras et al., 2019), the subjectivity of the reports can conversely be used to provide information about what impacts of weather actually mean to people.

Figure 3
Schematic Weather and Impact Reporting Procedure



Preliminary Data and First Insights

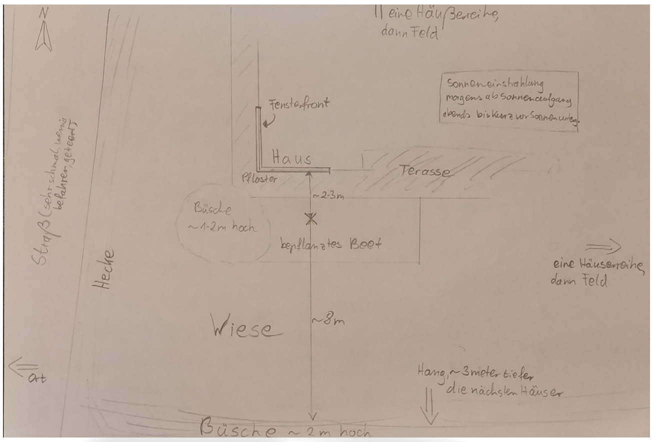
The data was first analysed together with the students in digital workshops in November 2020. Due to the limitations in collaborative work during the pandemic, we concentrated on three main aspects: 1) the measuring site, 2) data collection, and 3) project evaluation. The project also ran in the summer of 2021, but we are only reporting on the 2020 campaign here.

Documentation of the measuring site. Through the decisions made for the placement of the MESSI and through the monitoring of one's own measurements, students have the learning opportunity of dealing with the influence of the station's surrounding on their measurements, an issue which is also of paramount significance for professional, long-term measurement. Long, homogeneous series of measurements are essential for monitoring long-term climate change. If possible, only changes in the atmosphere should be measured, not changes in the station's environment (e.g., due to urbanisation). This mainly affects temperature, wind, and humidity due to, for example, high heat storage capacity of buildings, heat radiation from walls, or reduced evaporation.

During the final workshops students drew sketches of their measuring site highlighting potential influences on their measurements (see Figure 4 for an example). The aim was to make the students aware that the quality of the measurements is affected by the placing of the device and that potential environment changes (growing trees, new buildings, etc.) will have an impact on the long-term comparability of measurements. This is so that students may understand why documentation of the site is important. Documenting scientific metadata on the measurements is also a genuine scientific contribution by the citizens since this task would exceed the resources of professional scientists. For example, with the sketch the students also gave indications of the times of the day the MESSI could be in direct sunlight, which leads to a warming of the housing and consequently a higher temperature. This radiation bias can be reduced statistically using both temperature measurements and the radiation measurements.

Figure 4

Sketch of the Environment Surrounding the MESSI Location Drawn by one of the Participants During a Workshop



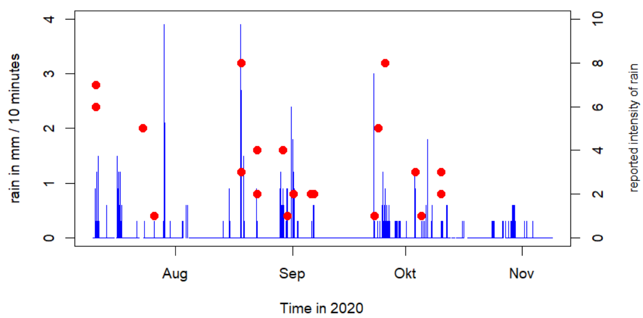
Note. The cross in the centre denotes the location of the MESSI. Objects are labelled (e.g., house, terrace, street, hedge), a height (bushes 1-2 metres) and a distance (2-3 m from MESSI to house), and the north arrow are given.

Weather data. Figure 5 provides an example of the high temporal variability of intense precipitation in summer in the Bavarian Prealps. The 20 eye observations by the students align well with the dates of the measured events. It should be noted that in the area and time investigated only one heavy rain observation could be found in the European Severe Weather Data Base, where trained, voluntary weather spotters can report on severe events (Dotzek et al., 2009). This shows the potential of layperson eye observations to augment this data base.

Interesting meteorological phenomena were detected in the data set such as a cold pool: an area of dense air that forms when rain evaporates and descends during intense rain underneath a thunderstorm. Figure 6 shows the sudden drop in temperature by about 6K in 20 minutes, accompanied by a fast rise and subsequent fall in air pressure by 1 hPa and a drying of the air by a maximum of 2K in dew point (relative humidity rises to 100%, not shown). Our network of spatially (few kilometres distance) and temporally (10 seconds) high resolution data offers the potential to investigate these small scale, severe weather phenomena in more

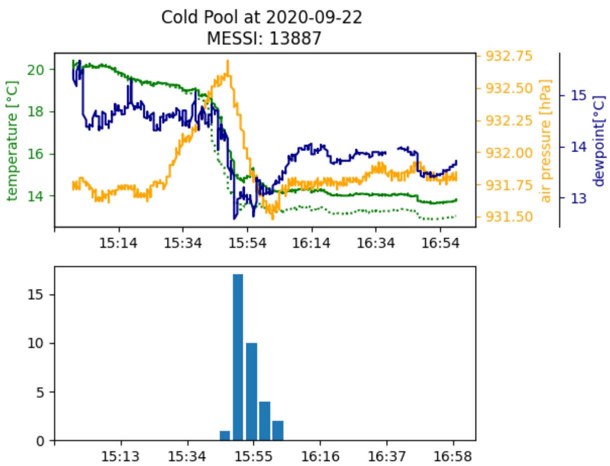
Figure 5

10-Minute Rainfall Accumulation and Reported Intensity



Note. Blue lines: 10-minute rainfall accumulation measured at one MESSI. Red dots: Reported intensity on a 10-point scale from "very slight" to "very heavy" in the same post code area.

Figure 6
Cold Pool Detected by MESSI on 22nd September 2020



Note. Upper panel: Temperature inside (green dotted line) and outside (solid) the housing, dew point (blue), and air pressure at station height (yellow, at about 600m). Lower panel: Precipitation in number of pulses per 5 minutes. Three pulses denote about 1mm of rain.

detail than with professional networks of about 25km resolution alone. Whether and how the potential of the data of such networks can indeed be realized for both scientific investigations and operational forecasting is an open question and the focus of current and future research (Meier et al. 2017; Muller et al. 2015).These examples illustrate that the students actively participated in the project and created valid data, thus enabling further scientific investigations. A focus of the project is small scale variability of intense precipitation on short (i.e., minutes) and longer (i.e., hours) time scales. Furthermore, we attempted to investigate cold pool events to possibly derive their properties in that area and time (see e.g., Kirsch et al., 2021).

Students' Motivation to Take Part in the Project

The project was evaluated via an online questionnaire completed by 15 participants at the end of the measurement campaign in November 2020. The evaluation focused on the activities (building the MESSI, weather reports, workshops) and the citizen science aspects (students' knowledge, attitudes, behaviour, ownership, motivation, and engagement; see Kieslinger et al., 2018). The main intention at this point was to evaluate the overall project process and to identify the students' motivation to take part in the project.[2]

Understanding participants' motivation is important to run a successful citizen science project (Pesch & Bartoschek, 2019; West & Pateman 2016). West and Pateman (2016) found in their review of environmental volunteering and citizen science literature that the evidence on volunteer motivation is highly variable due to considerable heterogeneity of both participants and motives. Amongst the most common stated motivations for participants in citizen science are an intrinsic interest in the particular topic of the project—such as an interest in nature—or motivations related to enjoyment, recreation, and social interaction, where participants look for enjoyable activities or a way to become part of a community of like-minded people (Land-Zandstra et al., 2021). Benefiting society by creating knowledge about weather has been found to be a key driver to influence the willingness of citizens to become (and remain) engaged in sharing their personally collected weather data (Gharesifard & Wehn, 2016; Pesch & Bartoschek, 2019). For citizen science projects in general, altruism and fun are strong drivers, and lack of time a major obstacle (Gharesifard & Wehn, 2017). "Citizen science is a 'serious leisure' activity and … the most likely participants will join with some existing interest in the subject, and will be keen to learn more" (Haklay, 2013, p. 113).

To capture participants' motivation, we used an adaptation of items from Raddick et al.'s (2013) work on an astronomy citizen science project. We asked about participants' motivations in two ways: First, we asked them to rate each motivation on a five-point Likert-type scale. Second, we asked them to state their primary motivation for participating. The items and results are shown in Table 1.

The primary motivations reported by students were the desire to contribute to scientific research and an interest in science in general (and weather and geoscience in particular). Participating for pleasure and community reasons was a less important motivation. It cannot be ruled out that a sense of duty to participate as a student of the school contributed. Although participation was voluntary, limiting the influence of sense of duty, it is possible that the sample of students was biased by interest in and contribution to science. We expect to see other motivations in a group of people taking part in a citizen science project as weather enthusiasts or hobby meteorologists.

Outlook

The ongoing COVID-19 situation had a major impact on the intended activities. The size of the network was

2 The evaluation also covered other aspects, including participants' overall satisfaction with the project and technical difficulties to allow for an iterative improvement of the project. An evaluation of the learning effects for the participants by a pre and post-test of students' weather literacy, awareness of climate change, and expectation and perception of the local weather was also part of the questionnaire. First insights are published in Kox et al. (2021).

Table 1
Participants' Motivations for Contributing to the Project

Motivation	Item	Mean	Primary motivation
Contribute	I look forward to contributing to scientific research.	4.40	4
Learning	I find the weather report helpful in learning about weather.	3.73	1
Discovery	By observing the weather, I can discover something new that not all students can do.	4.00	2
Community	I can work on a project together with others.	3.47	1
Teaching	I can acquire knowledge that I can use to teach other people.	3.13	0
Joy	I enjoy observing the weather.	3.33	0
Helping	I am happy to help you.	4.47	0
Weather/ Geoscience	I am interested in geography and weather.	4.07	3
Science	I am interested in science.	4.67	4

Note. Scores could range from 1 to 5. Numbers in the primary motivation column are counts; 0 indicates that no participants gave this motivation when asked which was the primary reason for participating. Items adapted from Raddick et al. (2013). *N* = 15.

greatly reduced, and the quantity of data was therefore insufficient for the comparison of impact data. The timespan between contact restrictions, re-opening of schools, and the establishment of interactive online workshops was short. The interaction between all participants was severely limited. However, the six requirements listed in the Procedures section were still met.

The 2020 measurement campaign focused in particular on the collection and processing of data and on the evaluation to allow for an iterative improvement of the project. In 2021, the project was further expanded to 50 devices for a new measurement campaign in summer 2021 with one additional school and a new group of students. We will further investigate small-scale variability of intense precipitation on short and longer time scales as well as cold pool events. A long-term aim is to examine to what extent weather and impact data from the layperson weather network represent a useful data source for damage analysis and the further development of impact-based weather forecasts.

Acknowledgements

This research was part of the project KARE-CS funded by the BMBF (German Federal Ministry of Education and Research) under the grand agreement 01LR2009B. Martin Göber's research was carried out in the framework of the Hans Ertel Centre for Weather Research funded by the BMVI (German Federal Ministry of Transport and Digital Infrastructures) under the grand agreement 4818DWDP3A. The authors would like to thank all participating students, teachers, local technical support in Bavaria, and Andreas Trojand for assistance with MESSI development.

References

Barras, H., Hering, A., Martynov, A., Noti, P.-A., Germann, U., & 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

Bonney, R., Phillips, T. B., Ballard, H. L., & Enck, J. W. (2016). Can citizen science enhance public understanding of science? *Public Understanding of Science, 25*(1), 2–16. https://doi.org/10.1177/0963662515607406

Bonney, R., Shirk, J. L., Phillips, T. B., Wiggins, A., Ballard, H. L., Miller-Rushing, A. J., & Parrish, J. K. (2014). Citizen science. Next steps for citizen science. *Science, 343*(6178), 1436–1437. https://doi.org/10.1126/science.1251554

Cifelli, R., Doesken, N., Kennedy, P., Carey, L. D., Rutledge, S. A., Gimmestad, C., & Depue, T. (2005). The community collaborative rain, hail, and snow network: Informal education for scientists and citizens. *Bulletin of the American Meteorological Society, 86*(8), 1069–1078. https://doi.org/10.1175/BAMS-86-8-1069

Dotzek, N., Groenemeijer, P., Feuerstein, B., & Holzer, A. M. (2009). Overview of ESSL's severe convective storms research using the European Severe Weather Database ESWD. *Atmospheric Research, 93*(1-3), 575–586.

Elevant, K. (2010). Collaborative observations of weather: A weather information sharers' community of practice. In *Proceedings of the 6th International Conference on Web Information Systems and Technology* (pp. 392–399). SciTePress - Science and and Technology Publications. https://doi.org/10.5220/0002810203920399

Gharesifard, M., & Wehn, U. (2016). To share or not to share: Drivers and barriers for sharing data via online amateur weather networks. *Journal of Hydrology, 535*, 181–190. https://doi.org/10.1016/j.jhydrol.2016.01.036

Gharesifard, M., & Wehn, U. (2017). What drives citizens to engage in ICT-enabled citizen science? In M. Jennex, L. Ceccaroni, & J. Piera (Eds.), *Advances in knowledge acquisition, transfer, and management: Analyzing the role of citizen science in modern research* (Vol. 96, pp. 62–88). IGI Global.

Haklay, M. (2013). Citizen science and volunteered geographic information: Overview and typology of participation. In D. Sui, S. Elwood, & M. Goodchild (Eds.), *Crowdsourcing geographic knowledge* (pp. 105–122). Springer Netherlands. https://doi.org/10.1007/978-94-007-4587-2_7

Karnowski, V. (2013). Befragung in situ: Die Mobile Experience Sampling Method (MESM). In W. Möhring & D. Schlütz

(Eds.), *Handbuch standardisierte Erhebungsverfahren in der Kommunikationswissenschaft* (pp. 235–247). Springer.

Kieslinger, B., Schäfer, T., Heigl, F., Dörler, D., Richter, A., & Bonn, A. (2018). Evaluating citizen science - Towards an open framework. In S. Hecker, M. Haklay, A. Bowser, Z. Makuch, J. Vogel, & A. Bonn (Eds.), *Citizen science: Innovation in open science, society and policy* (pp. 81–95). UCL Press.

Kirsch, B., Ament, F., & Hohenegger, C. (2021). Convective cold pools in long-term boundary layer mast observations. *Monthly Weather Review, 149*(3), 811-820. https://doi.org/10.1175/MWR-D-20-0197.1

Kox, T., Göber, M., Wentzel, B., Freundl, E., & Rust, H. (2021). Fostering weather and climate literacy among pupils by engagement in a weather citizen science project. In *Proceedings of Austrian Citizen Science Conference 2020* (2 p.). Proceedings of Science. https://doi.org/10.22323/1.393.0002

Kox, T., Kempf, H., Lüder, C., Hagedorn, R., & Gerhold, L. (2018). Towards user-orientated weather warnings. *International Journal of Disaster Risk Reduction, 30*(A), 74–80. https://doi.org/10.1016/j.ijdrr.2018.02.033

Krennert, T., Kaltenberger, R., Pistotnik, G., Holzer, A. M., Zeiler, F., & Stampfl, M. (2018). Trusted Spotter Network Austria – A new standard to utilize crowdsourced weather and impact observations. *Advances in Science and Research, 15*, 77–80. https://doi.org/10.5194/asr-15-77-2018

Land-Zandstra, A., Agnello, G., & Gültekin, Y. S. (2021). Participants in citizen science. In K. Vohland, A. Land-Zandstra, L. Ceccaroni, R. Lemmens, J. Perelló, M. Ponti, R. Samson, & K. Wagenknecht (Eds.), *The science of citizen science* (pp. 243–259). Springer International Publishing. https://doi.org/10.1007/978-3-030-58278-4_13

Marsigli, C., Ebert, E., Ashrit, R., Casati, B., Chen, J., Coelho, C. A. S., Dorninger, M., Gilleland, E., Haiden, T., Landman, S., & Mittermaier, M. (2021). Review article: Observations for high-impact weather and their use in verification. *Natural Hazards and Earth System Science, 21*(4), 1297–1312. https://doi.org/10.5194/nhess-21-1297-2021

Meier, F., Fenner, D., Grassmann, T., Otto, M., & Scherer, D. (2017). Crowdsourcing air temperature from citizen weather stations for urban climate research. *Urban Climate, 19*, 170-191.

Muller, C. L., Chapman, L., Johnston, S., Kidd, C., Illingworth, S., Foody, G., Overeem, A., & Leigh, R. R. (2015). Crowdsourcing for climate and atmospheric sciences: Current status and future potential. *International Journal of Climatology, 35*(11), 3185–3203.

Pesch, M., & Bartoschek, T. (2019). *Volunteer's demographics and motivations in senseBox and openSenseMap*. Forum Citizen Science 2019. https://osf.io/xn796/

Pettibone, L., Hahn, J., & Vohland, K. (2016). *GEWISS Dialogforum: Was ist Partizipation in citizen science?* GEWISS. www.deutsche-digitale-bibliothek.de/item/5XZP55WGZ6PIPBHX4DPYL32BXVVYOPH4

Raddick, M. J., Bracey, G., Gay, P. L., Lintott, C. J., Cardamone, C., Murray, P., Schawinski, K., Szalay, A. S., & Vandenberg, J. (2013). Galaxy Zoo: Motivations of citizen scientists. *Astronomy Education Review, 12*(1), 10106.

Venter, Z.S., Brousse, O., Esau, I., & Meier, F. (2020). Hyperlocal mapping of urban air temperature using remote sensing and crowdsourced weather data. *Remote Sensing of Environment, 242*, p.111791. https://doi.org/10.1016/j.rse.2020.111791

Waxberg, G. (2013). Under the radar: National Weather Service aided by SKYWARN® spotters. *Weatherwise, 66*(2), 32–37.

West, S., & Pateman, R. (2016). Recruiting and retaining participants in citizen science: What can be learned from the volunteering literature? *Citizen Science: Theory and Practice, 1*(2), 15. https://doi.org/10.5334/cstp.8

World Meteorological Organization. (2008). *Guide to meteorological instruments and methods of observation.* https://library.wmo.int/index.php?id=12407&lvl=notice_display#.Ya2VetBBxyw

Zhang, Q., Li, L., Ebert, B., Golding, B., Johnston, D., Mills, B., Panchuk, S., Potter, S., Riemer, M., Sun, J., Taylor, A., Jones, S., Ruti, P., & Keller, J. (2019). Increasing the value of weather-related warnings. *Science Bulletin, 64*(10), 647–649. https://doi.org/10.1016/j.scib.2019.04.003