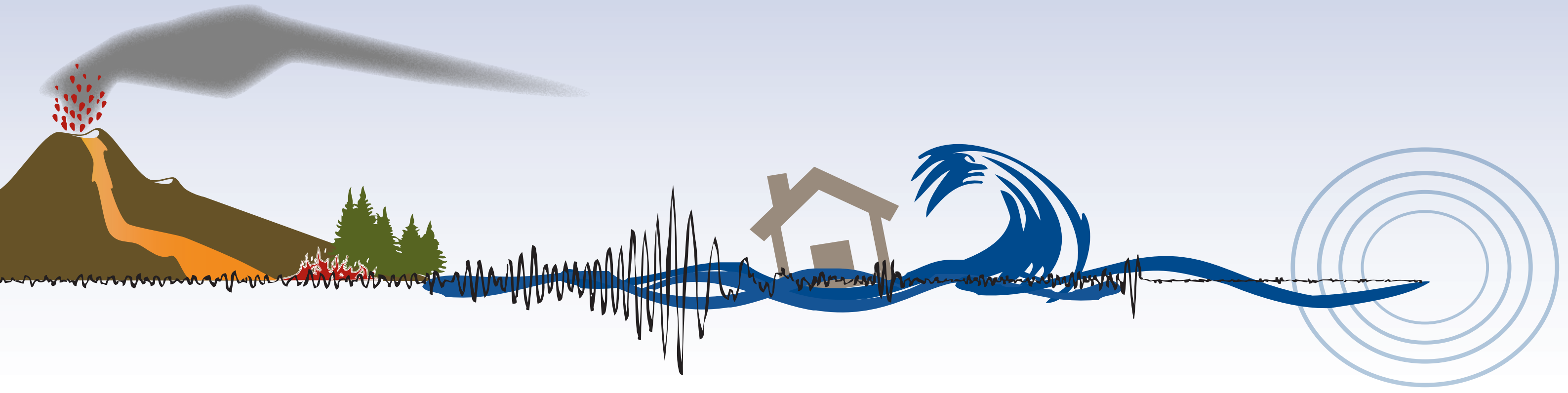
December 2021

The Australasian Journal of Disaster and Trauma Studies

VOLUME: 25, NUMBER 3

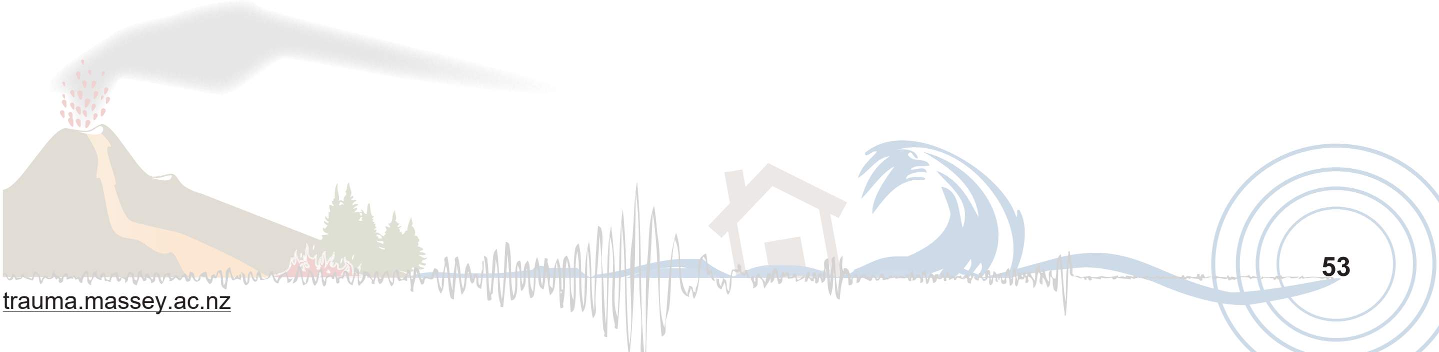


Contents:
Volume 25, Number 3

Editorial

Research Updates

Practice Update



ISSN: 1174-4707

Published by:
School of Psychology
Massey University
New Zealand

Australasian Journal of Disaster and Trauma Studies Volume 25, Number 3

Citizen science initiatives in high-impact weather and disaster risk reduction

Lauren J. Vinnell[1],
Julia S. Becker[1],
Anna Scolobig[2],
David M. Johnston[1],
Marion L. Tan[1],
Lisa McLaren[1]

[1] Joint Centre for Disaster Research, Massey University, New Zealand.

[2] Environmental Governance and Territorial Development Institute, University of Geneva, Switzerland.

Author correspondence:
Lauren Vinnell,
Joint Centre for Disaster Research,
Private Box 756,
Wellington 6140
New Zealand.
Email: l.vinnell@massey.ac.nz

URL: http://trauma.massey.ac.nz/issues/2021-3/AJDTS_25_3_Vinnell.pdf

Abstract

High-impact weather events cause considerable social and economic harm, with these effects likely to increase as climate change drives extremes and population growth leads to commensurate growth in exposure. As part of the World Meteorological Organization's World Weather Research Programme, the 10-year High-Impact Weather (HIWeather) Project facilitates global cooperation and collaboration to improve weather prediction, forecasting, and warning. As part of this, the HIWeather Citizen Science Project identifies and promotes activities which involve citizens in the warning value chain, from "sensors" where they passively provide data, through to "collaborators" where they are involved in designing, running, interpreting, and applying the research. As well as benefitting global efforts to reduce societal impacts of weather and other natural hazards, citizen science also encourages hazard awareness and scientific literacy and interest. This editorial introduces the HIWeather Citizen Science Project special issue, summarizing the three papers in this issue in the broader context of high-impact weather and citizen science.

Keywords: *Citizen science, high-impact weather, earthquakes, disaster risk reduction*

This editorial introduces a special issue exploring the role of citizen science in understanding impacts and improving warnings for natural hazards, namely high-impact weather and earthquakes. Citizen science offers ways to collect large amounts data to inform research and communication around natural hazards as well as to engage and educate the public. Given the potential of citizen science and the increasing impacts of natural hazard events, particularly those which are weather-related, it is important to highlight the work happening in this space. First, we briefly introduce the challenge of high-impact weather and the global High-Impact Weather (HIWeather) project. Following this, we define citizen science and the typologies used to develop projects. We then summarize the papers in this special issue which include: 1) the use of weather sensors in schools (Kox et al., 2021), 2) an app to crowdsource weather impacts (Kempf, 2021), and 3) an overview of the development and use of citizen reports of earthquake shaking (Goded et al., 2021).

High-Impact Weather

High-impact weather covers a vast range of meteorological events including flooding, drought, severe wind, thunderstorms, hailstorms, heatwaves, blizzards, tornadoes, and cyclones. In 2020 alone, there was at least 389 extreme weather events which in total claimed over 15,000 lives, affected 100 million people, and led to at least US$171 billion of economic loss (UNDRR, 2020). Last year saw 201 flood-related disasters, up from a yearly average across the previous two decades of 163 events, and 127 storm-related disasters, up from 102 on average per year between 2000 and 2019 (UNDRR, 2020). Although extreme weather-related fatalities were lower in 2020 than previously, potentially due to COVID-19 restrictions limiting the number of people outside, there is a clear pattern of extreme weather events increasing in intensity and frequency due to both anthropogenic climate change (Tippet, 2018) and global population growth exposing more communities to risk (Paton & Buergelt, 2019).

High-impact weather events. While the weather-related research in this special issue focuses on Europe, the work is relevant to the primary audience of this journal in Australasia. Aotearoa New Zealand has experienced numerous high-impact weather events in recorded history, typically involving flooding, severe winds, snow, ex-tropical cyclones, and occasionally tornadoes. Severe events causing limited fatalities and moderate levels of damage occur nearly yearly in New Zealand. More extreme impacts are fortunately relatively rare, such as the storm in April 1968 which led to the capsizing of a ferry in Wellington and 53 fatalities (Ministry for Culture and Heritage, 2014). Extreme weather events in Australia are typically drought, which contributes to extensive wildfires, and flooding, but the country also experiences many other types of weather including cyclones, heatwaves, cold snaps, dust storms, and thunder storms. Extreme weather in Australia has led to at least 5,000 deaths in the last 130 years (Coleman, 2016) with recent events also causing billions of dollars of damage, such as the 2019-20 bushfire season which led to losses of up to AU$100 billion (Bushfire & Natural Hazards Cooperative Research Centre, 2020). Island nations in the Pacific and Southeast Asia are particularly prone to tropical storms and related impacts including flooding and heavy wind. In 2017 alone, 198 weather events in Indonesia were classed as health crises with 198 fatalities and over 200,000 people made homeless (Haryanto et al., 2019).

The HIWeather Project

In response to identified gaps in the application of scientific understanding of weather to societal problems, in 2015 the World Meteorological Organization's (WMO) World Weather Research Programme launched the 10-year High-Impact Weather Project (HIWeather; WMO, n.d.). This project enables international collaboration to improve global resilience to extreme weather events through maximizing the timeliness and usefulness of predictions, forecasts, and warnings (Golding et al. 2019; Ruti et al. 2020; WMO, 2017; Zhang et al. 2019). There are five thematic areas: user-oriented evaluation; human impacts, vulnerability, and risk; communication; multi-scale forecasting; and predictability and processes. Across these themes is the flagship Citizen Science Project. The main aim of this project is to identify and promote existing citizen science projects, predominantly but not exclusively within the weather space, to provide tools for others interested in undertaking similar work (WMO, 2021).

Citizen Science

Citizen science involves "the participation of individuals or groups in generating new scientific knowledge" (WMO, 2021, p. 2). Members of the public participate in research projects, typically with varying involvement of professional scientists. The role of citizens can range from passive data collectors, through interpreters contributing to data analysis, to engagers and collaborators involved in all aspects of the project including design and implementation (Haklay, 2013). Similarly, the role of scientists can range from largely leading the project, to collaborating with citizens, to co-creating the project (Bonney et al., 2009; Doyle et al., 2020; Shirk et al., 2012). Given the wide range of definitions of citizen science and accompanying terms, it is important for terminology to be considered and explained in the specific context of the project, including what to call people involved in citizen science (Eitzel et al., 2017). For example, public familiarity with the concept of citizen science tends to be higher than their familiarity with the specific term "citizen science" (Lewandowski et al., 2017).

Citizen science as it is currently commonly understood can be traced back to the start of the 20th Century (Bonney et al., 2016). Recently, there has been a growth in the popularity of citizen science due in large part to technology development including the Internet, personal computers, and smartphones (Aristeidou & Herodotou, 2020; Silvertown, 2009). Such tools are particularly useful (from a professional scientist perspective) for projects which need a large amount of data over a large area (Silvertown, 2009). There is also good evidence for improvements in science knowledge and awareness among the citizens who participate (Bonney et al., 2016) and well-developed projects can help to reduce inequities in science (Soleri et al., 2016). Projects which aim to have a greater impact, particularly broader social and societal benefits, are more effortful and resource intensive (Bonney et al., 2016). Despite a recent proliferation of interest in and use of citizen science, there is still both considerable unexplored potential (Aristeidou & Herodotou, 2020) and scientific challenges including ensuring appropriate data quality and ethical considerations around using public data (Riesch & Potter, 2014).

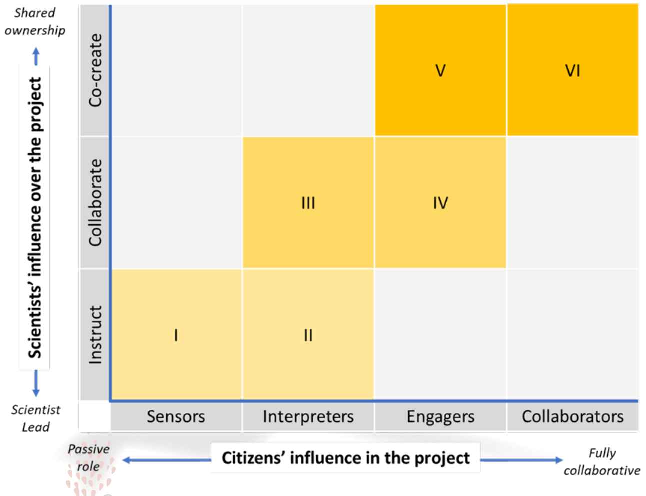
While modern citizen science likely originated at the start of the 20th Century in the field of ecology (see Silvertown, 2009 for an overview), citizen science has also been considered in the domain of natural hazards with efforts to produce frameworks for citizen science projects in disaster risk management including motivations, technicalities, and ethics (Hicks et al., 2019; Orchiston et al., 2016). This special issue presents examples of citizen science projects relating to high-impact weather (Kempf, 2021; Kox et al., 2021) as well as relevant considerations from an earthquake-related project (Goded et al., 2021). These projects also present different *typologies* of citizen science (explained in the next section), with one project more intensively engaging its participants (Kox et al., 2021) and the others presenting examples of crowdsourcing large amounts of data (Goded et al., 2021; Kempf, 2021).

Typologies of Citizen Science

Citizen science projects vary widely and have different levels of engagement from both scientists and the citizen volunteers. Some projects are led by scientists who instruct volunteers in data collection, while others are co-designed with communities. Projects along this spectrum are useful for creating new scientific discoveries, for raising awareness about weather-related issues, and for improving the science-society dialogue. Project typologies (classifications based on categories) have been created which aim to define citizens' roles within a project. Two commonly used typologies are from Haklay (2013) and Shirk et al. (2012). McLaren et al. (in prep) constructed a matrix (see Figure 1) which combined and adapted categories from these two typologies to explore the distribution of influence scientists and citizen volunteers have within a project. These typologies can be used when developing citizen science projects to help these projects clarify and achieve their aims and when considering existing work to identify particular strengths and limitations (for more information on these typologies and their use, please see the HIWeather Citizen Science Guidance Note; WMO, 2021).

The papers included in this special issue present different types of citizen science on the two main continuums describing how much influence the scientists have over the project (from instructing to co-creating) and the citizens' role in the project as sensors, interpreters, engagers, or collaborators. The projects presented by Kempf (2021) and Goded et al. (2021), which crowdsource data online, exemplify citizen science projects where scientists lead and citizens have a relatively passive role. These projects are effective ways for scientists to collect large amounts of data but are less effective at increasing interest, awareness, and understanding of science among citizens. The project presented by Kox et al. (2021), where high school students built and operated weather monitoring stations, is more collaborative; as such, quantity of data is lower but the citizens who participated likely gained more benefit.

Figure 1
Typologies of Citizen Science



Note. From McLaren et al. (in prep).

Citizen science in schools. In this special issue, a range of citizen science methods are presented as tools to understand weather impacts. Kox et al. (2021) provide an update on the Klimawandelanpassung auf regionaler Ebene citizen science project (KARE-CS) which works with two schools in the Bavarian Prealps region of Germany. These schools were supported to build micro weather stations which were low-cost, independent, comparable to professional stations, appealed to youth, and were simple to set up and use. The school students were able to use these stations to produce valid weather data and carry out detailed analyses; this data approach was combined with observations of weather phenomena and impacts. It is useful when undertaking a citizen science project to understand what was liked and disliked about the project as well as why people were motivated to take part (Raddick et al., 2013). In their work, Kox et al. carried out a survey with the school children to assess their views and motivations. Overall, the pupils had positive views of the project and particularly the self-building aspect of the monitoring station. Most reported that they took part due to a general interest in science and to contribute to research efforts.

Working with specific groups, especially within schools, is an effective way to increase understanding of weather and hazard phenomena and impacts as well as interest in science. While effective, these projects also tend to be relatively intensive and therefore have limited reach.

Crowdsourcing Online

Another common citizen science method to engage populations more broadly is through crowdsourcing with tools such as smartphone apps. Further work in Germany utilised an existing weather smartphone app to crowdsource weather data. Kempf (2021) reports on the rollout and early observations of this initiative, which saw the public provide more than 600,000 observations over 5 months from approximately 125,000 active users. Key considerations in this project included ensuring the system was understandable by lay audiences, privacy concerns such as geolocating observations, copyright of images shared by users to supplement their observations, and false observations. These considerations demonstrate the complexity of such projects but measures were able to limit the impacts of challenges to citizen-provided data, such as automatic plausibility checks to identify false reports and adapting response scales to meet user expectations. Overall, citizens rarely misused the system. This citizen science project offers insights and support for similar other projects using smartphone apps to crowdsource data.

Beyond the domain of high-impact weather, crowdsourced data has a long history in earthquake research. One key way to involve citizens in earthquake science is to provide the opportunity for them to report their experiences of earthquake shaking. The United States Geological Survey offers an online platform for citizens who feel earthquake shaking to report their location, intensity of shaking, and damage in “Did You Feel It?” reports (Wald & Dewey, 2005).

In this special issue, Goded et al. (2021) present an overview of “Rapid” and “Detailed” Felt Reports collected from people across Aotearoa New Zealand since 2004, totalling nearly one million long-form reports from over 30,000 earthquakes. These reports can be submitted online or via an app to GeoNet, New Zealand’s geological hazards monitoring service run by GNS Science. In “Felt Rapid” reports, citizens report the intensity of shaking they experienced from one of six cartoons demonstrating effects on people, buildings, and contents. For “Felt Detailed” reports, people complete a survey on a range of factors including what they did in response to the shaking, building damage, impacts on their neighbourhood, tsunami-related behaviour, and demographic factors. This information is used by scientists for a number of purposes, including assigning Modified Mercalli Index intensities to specific earthquake events and feeding data into strong motion maps to help understand ground shaking. In this paper, Goded et al. summarize these reports as well as current and planned research to use this citizen science-collected data and discuss the broader role of citizen science in improving earthquake understanding and resilience.

Citizen seismology projects can backfire if information is incomplete or missing, with reduced trust in the science organizations, as was seen during an earthquake sequence in Mayotte in 2018 (Fallou et al., 2020). In response to some earthquakes not being presented in the local earthquake information app, which uses crowdsourced information similar to USGS’s “Did You Feel It” reports, over 10,000 people spontaneously formed their own information-sharing group on social media; due to a lack of seismologists in this group, however, misinformation and conspiracy theories arose. This example demonstrates the importance of ensuring alignment between scientific communication and audience needs, as well as the important role that scientists play in citizen projects to ensure accurate, useful information is being produced and shared. For example, members of the public tend to have more confidence in findings of citizen science projects which include professional scientists in some capacity (Lewandowski et al., 2017). The roles which both citizens and scientists play in particular projects is therefore important to consider reflexively at the beginning, throughout, and after the project.

Conclusion

High-impact weather events cause considerable social and economic harm globally, with these effects likely to increase as climate change drives extremes and population growth leads to commensurate growth in exposure. Citizen science is increasingly used internationally as a way of both gathering large amounts of data and to engage and educate the public about natural hazards such as high-impact weather events as well as scientific processes generally. The papers in this special issue demonstrate different ways in which citizens can contribute to developing our understanding of hazard impacts and improving warnings. Kox et al. (2021) describe a project involving schools, encouraging youth to learn more about hazard monitoring and to engage in science and research. Kempf (2021) and Goded et al. (2021) demonstrate how advances in technology over the last decades, such as the rise of smartphones, can be used to obtain large amounts of data about impacts of hazard events including severe weather and earthquakes. This data can help researchers understand these hazards better, such as how earthquake shaking is experienced and how people respond (Goded et al., 2021), and improve forecasts and warnings as citizens report on-the-ground impacts of severe weather. Across these projects, it is clear that citizen science is diverse, demonstrated by the typologies described in this editorial, and that it can be beneficial for both research and society.

This editorial introduced the HIWeather Citizen Science Project, summarizing the papers in this issue and presenting the research in the broader context of high-impact weather and citizen science. The editorial team would like to thank those involved in the production of this special issue, including the wider HIWeather team, the contributing authors, and the peer reviewers.

References

Aristeidou, M., & Herodotou, C. (2020). Online citizen science: A systematic review of effects on learning and scientific literacy. *Citizen Science: Theory and Practice, 5*(1), 1-12. https://doi.org/10.5334/cstp.224

Bonney, R., Cooper, C. B., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K. V., & Shirk, J. (2009). Citizen science: A developing tool for expanding science knowledge and scientific literacy. *BioScience*, *59*(11), 977–984. https://doi.org/10.1525/bio.2009.59.11.9

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

Bushfire & Natural Hazards Cooperative Research Centre. (2020). *Calculating the losses this fire season.* www.bnhcrc.com.au/news/2020/calculating-losses-fire-season

Coleman, S. (2016). *Built environment: Increased extreme weather events.* Australian Government Department of the Environment and Energy. https://doi.org/10.4226/94/58b65a5037ed8

Doyle, E. E. H., Lambie, E., Orchiston, C., Becker, J. S., McLaren, L., Johnston, D., & Leonard, G. (2020). Citizen science as a catalyst for community resilience building: A two-phase tsunami case study. *Australasian Journal of Disaster and Trauma Studies, 24*(1), 23-49.

Eitzel, M. V., Cappadonna, J. L., Santos-Lang, C., Duerr, R. E., Virapongse, A., West, S. E., Kyba, C. C. M., Bowser, A., Cooper, C. B., Sforzi, A., Metcalfe, A. N., Harris, E. S., Thiel, M., Haklay, M., Ponciano, L., Roche, J., Ceccaroni, L., Shilling, F. M., Dörler, D., … Jiang, W. (2017). Citizen science terminology matters: Exploring key terms. *Citizen Science: Theory and Practice, 2*(1), 1-20. https://doi.org/10.5334/cstp.96

Fallou, L., Bossu, R., Landès, M., Roch, J., Roussel, F., Steed, R., & Julien-Laferrière, S. (2020). Citizen seismology without seismologists? Lessons learned from Mayotte leading to improved communication. *Frontiers in Communication, 5,* 1-17. https://doi.org/10.3389/fcomm.2020.00049

Goded, T., Tan, M. L., Becker, J. S., Horspool, N., Canessa, S., Huso, R., Hanson, J., & Johnston, D. M. (2021). Using citizen data to understand earthquake impacts: Aotearoa New Zealand's earthquake Felt Reports. *Australasian Journal of Disaster and Trauma Studies*, *25*(3), 61-78.

Golding, B., Mittermaier, M., Ross, C., Ebert, B., Panchuk, S., Scolobig, A., & Johnston, D. (2019). *A value chain approach to optimising early warning systems. Contributing paper to the 2019 edition of the Global Assessment Report on Disaster Risk Reduction (GAR 2019).* https://www.preventionweb.net/files/65828_f212goldingetalvaluechain.pdf

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: Volunteered Geographic Information (VGI) in theory and practice* (pp. 1–396). Springer. https://doi.org/10.1007/978-94-007-4587-2

Haryanto, B., Lestari, F., & Nurlambang, T. (2019). Extreme events, disasters, and health impacts in Indonesia. In R. Akhta (Ed.), *Extreme weather events and human health* (pp. 227-245). Springer. https://doi.org/10.1007/978-3-030-23778-8_16

Hicks, A., Barclay, J., Chilvers, J., Armijos, M. T., Oven, K., Simmons, P., & Haklay, M. (2019). Global mapping of citizen science projects for disaster risk reduction. *Frontiers in Earth Science*, *7*, 1–18. https://doi.org/10.3389/feart.2019.00226

Kempf, H. (2021). Experience from large-scale crowdsourcing via weather apps. *Australasian Journal of Disaster and Trauma Studies, 25*(3), 87-93.

Kox, T., Rust, H. W., Wentzel, B., Göber, M., Böttcher, C., Lehmke, J., Freundl, E., & Garschagen, M. (2021). Build and measure: Students report weather impacts and collect weather data using self-built weather stations. *Australasian Journal of Disaster and Trauma Studies*, *25*(3), 79-86.

Lewandowski, E., Caldwell, W., Elmquist, D., & Oberhauser, K. (2017). Public perceptions of citizen science. *Citizen Science: Theory and Practice, 2*(1), 1-9. https://doi.org/10.5334/cstp.77

Ministry for Culture and Heritage. (2014). *The Wahine disaster.* New Zealand History. https://nzhistory.govt.nz/culture/wahine-disaster

Orchiston, C., Hudson-Doyle, E., Johnston, D., Becker, J. S., Crowley, K., Beatson, A., Lambie, E., Neely, D. P., & Pepperell, B. (2016). Citizen science in disaster risk management workshop: Summary report. *GNS Science Miscellaneous Series, 90.* 35 p.

Paton, D., & Buergelt, P. (2019). Risk, transformation and adaptation: Ideas for reframing approaches to disaster risk reduction. *International Journal of Environmental Research and Public Health, 16,* 2594-2612. https://doi.org/10.3390/ijerph16142594

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), 1-41. https://doi.org/10.3847/AER2011021

Riesch, H., & Potter, C. (2014). Citizen science as seen by scientists: Methodological, epistemological, and ethical dimensions. *Public Understanding of Science, 23*(1), 107-120. https://doi.org/10.1177/0963662513497324

Ruti, P., Tarasova, O., Keller, J., Carmichael, G., Hov, Ø., Jones, S., Terblanche, D., Anderson-Lefale, C., Barros, A. P., Bauer, P., Bouchet, V., Brasseur, G., Brunet, G. DeCola, P., Dike, V., Kane, M. D., Gan, C., Gurney, K. R., Hamburg, S., ... Yamaji, M.. (2020). Advancing research for seamless earth system prediction. *Bulletin of the American Meteorological Society, 101*(1), 23-35. https://doi.org/10.1175/BAMS-D-17-0302.1

Shirk, J. L., Ballard, H. L., Wilderman, C. C., Phillips, T., Wiggins, A., Jordan, R., McCallie, E., Minarchek, M., Lewenstein, B. V., Krasny, M. E., & Bonney, R. (2012). Public participation in scientific research: A framework for deliberate design. *Ecology and Society*, *17*(2), 29. https://doi.org/10.5751/ES-04705-170229

Silvertown, J. (2009). A new dawn for citizen science. *Trends in Ecology & Evolution*, *24*(9), 467–471. https://doi.org/10.1016/j.tree.2009.03.017

Soleri, D., Long, J. W., Ramirez-Andreotta, M. D., Eitemiller, R., & Pandya, R. (2016). Finding pathways to more equitable and meaningful public-scientist partnerships. *Citizen Science: Theory and Practice, 1*(1), 1-11. https://doi.org/10.5534/cstp.46

Tippett, M. K. (2018). Extreme weather and climate. *Climate and Atmospheric Science, 1,* 1- 2. https://doi.org/10/1038/s41612-018-0057-1

United Nations Office for Disaster Risk Reduction. (2020). *2020: The non-COVID year in disasters.* www.undrr.org/publication/2020-non-covid-year-disasters

Wald, D. J., & Dewey, J. D. (2005). *Did You Feel It? Citizens contribute to earthquake science.* United States Geological Survey. https://pubs.usgs.gov/fs/2005/3016/pdf/FS-2005-3016.pdf

World Meteorological Organization. (n.d.). *The High-Impact Weather Project (HIWeather)*. https://public.wmo.int/en/projects/high-impact-weather-project-hiweather

World Meteorological Organization. (2017). *Catalysing innovation in weather science: WWRP Implementation Plan 2016-2023.* https://public.wmo.int/en/resources/library/catalysing-innovation-weather-science-wwrp-implementation-plan-2016-2023

World Meteorological Organization. (2021). *High Impact Weather (HIWeather) citizen science guidance: Note for weather, climate and water projects.* https://library.wmo.int/index.php?lvl=notice_display&id=21966#.YZrvTtBByUm

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.

Using citizen data to understand earthquake impacts: Aotearoa New Zealand's earthquake Felt Reports

Tatiana Goded[1],
Marion L. Tan[2],
Julia S. Becker[2],
Nick Horspool[1],
Silvia Canessa[1],*
Rand Huso[1],
Jonathan Hanson[1],
David M. Johnston[2].

[1] GNS Science, Lower Hutt, New Zealand.

[2] Joint Centre for Disaster Research, Massey University, Wellington, New Zealand.

* Former GNS Science staff.

Author correspondence:
Tatiana Goded
GNS Science
1 Fairway Drive
Avalon
Lower Hutt 5011
New Zealand.
Email: t.goded@gns.cri.nz

URL: http://trauma.massey.ac.nz/issues/2021-3/AJDTS_25_3_Goded.pdf

Abstract

Aotearoa New Zealand's national seismic network, GeoNet, administers Felt Reports, including the Felt RAPID and Felt Detailed databases, which are being collected at present. NZ has a long tradition of using earthquake Felt Reports provided by the public to analyse the damage caused by moderate to large earthquakes. From traditional paper-based Felt Reports to current online reports (using the GeoNet website or a mobile app), researchers have been using such data to obtain a geographical distribution of the damage caused by an earthquake and to assess what actions people take during shaking. Felt Reports include questions on people's reactions, indoor and outdoor effects of earthquake shaking, building damage, and tsunami evacuation. The database of long online Felt Reports (Felt Classic between 2004 and 2016 and Felt Detailed from 2016 to the present) comprises over 930,000 reports from more than 30,000 earthquakes. Current research being carried out using this data includes: 1) updating of the NZ Ground Motion to Intensity Conversion Equation and Intensity Prediction Equation, 2) understanding human behaviour for earthquakes and related hazards such as tsunami, 3) developing a predictive model of human behaviour in earthquakes to estimate injuries and fatalities, and 4) improving public education. This paper summarises the history of NZ earthquake Felt Reports as well as the research currently being carried out using this data. Finally, we discuss how citizen science helps in the understanding of earthquake impacts and contributes to the aim of improving Aotearoa New Zealand's resilience to future events.

Keywords: *New Zealand, Felt Reports, citizen science, macroseismic intensity*

The term "citizen science" applies to the participation of the public in collection and analysis of data for scientific studies. It is sometimes referred to by other terms, including community science, participatory assessment, community-based monitoring, and volunteer monitoring (Shirk et al., 2012). Data contributed by the public is beneficial as it can fill gaps in data that arise from having limited technical networks (Fehri et al., 2020) and provide additional complementary information. Citizen science has often contributed to studies in biology and environmental science (Bonney et al., 2009), but has also been applied to other areas including natural hazard and climate change.

The public participate in earthquake science when they contribute to reporting, collecting, and analysing individual or community experiences of earthquakes (Allen, 2012). For example, an initiative involving citizen science in Aotearoa New Zealand (NZ) surveyed members of the public on how they responded and evacuated during the Kaikōura earthquake in 2016 (Blake et al., 2018). Using the results, the authors argued the need to enhance community capacity in responding appropriately to earthquake-related hazards. The public can also contribute through providing details of their experience of an earthquake through submitting *Felt Reports*. Felt Reports come in many forms, from historical paper-based Felt Reports to the more modern online questionnaires and thumbnail-based surveys. With modern technology, citizens can now rapidly contribute their near-real-time experience of earthquakes through web or app platforms. Examples of these rapid citizen-reporting platforms include the United States

Geological Survey's (USGS) *Did You Feel It?* (DYFI) system (Quitoriano & Wald, 2020), the European-Mediterranean Seismological Centre's LastQuake app (Steed et al., 2019), and GNS Science's GeoNet system (Lane et al., 2020). As platforms that collect Felt Reports from the public are crowdsourcing data, they can be considered a form of citizen science (Haklay, 2013).

In this paper, we focus on the Felt Reports submitted in NZ, in particular the long-form reports. First, to set the context, we discuss seismic intensity and Felt Reports, then Felt Reports as citizen science and their contributions to society. We then summarise past and present Felt Report initiatives in NZ. Finally, we discuss the current research trends in using Felt Reports and their benefits for understanding NZ earthquakes.

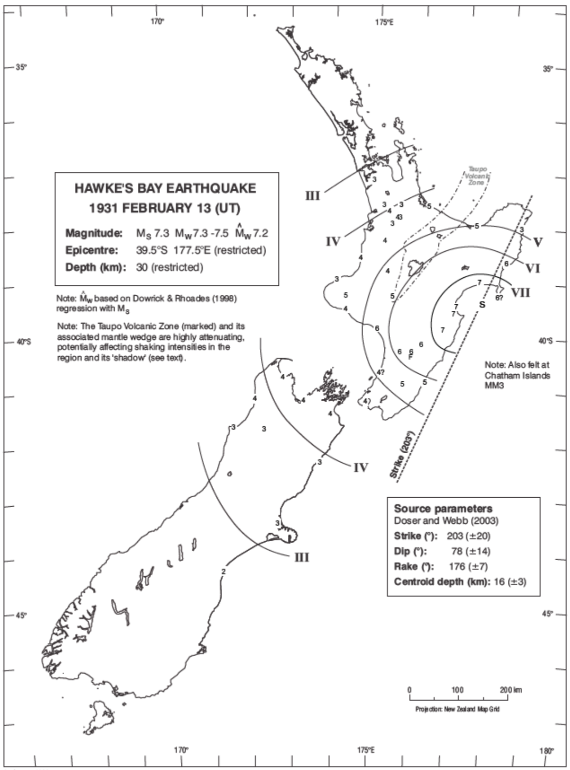
Seismic Intensity and Felt Reports

Seismic intensity has been traditionally used worldwide to quantify the extent of the damage caused by an earthquake. Intensities provide a simple representation of the complexity of the ground motion and the extent and nature of the damage (Wald et al., 1999a). When communicating about earthquakes, magnitude and macroseismic intensity can be commonly interchanged and misunderstood by the public (Celsi et al., 2005). Citizens' participation in Felt Reports helps educate the public on the difference between magnitude and macroseismic intensity (Celsi et al., 2005). An earthquake magnitude is a measure of the energy released by the earthquake, which is a unique value for each event. In comparison, earthquake intensity measures the level of shaking at any given location. A single earthquake event can therefore have a large range of intensities: higher intensities for locations closer to the epicentre and decreasing intensities as the epicentral distance increases. Intensities can also considerably vary depending on the soil conditions.

In the past, intensities were assigned after gathering data from fieldwork, an arduous task that could take weeks or months to be finalised. At present, Internet-based macroseismic surveys such as Felt Reports are the most popular means for the public to contribute, and substantial reports have become available from these worldwide. These Internet-based surveys have been implemented in the last 15 years by several international seismological institutions (see Goded et al., 2018). The most popular one is the USGS's DYFI project (Wald et al., 1999a) which is being used worldwide, with more than 5 million Felt Reports since 1999 (Quitoriano & Wald, 2020).

The measured intensity depends on people's perceptions of the severity of earthquake shaking, as well as the effects on objects and on the landscape, together with building damage. Intensity estimates have been provided with the use of macroseismic intensity scales. In NZ, the NZ version of the Modified Mercalli intensity scale (Dowrick, 1996; Dowrick et al., 2008) is currently used. This scale ranges from 1 to 11, in increasing order of shaking level (and thus damage; Dowrick et al., 2008). Macroseismic intensity has become an important metric for communicating hazard and risks (Becker et al., 2018, 2020), with the usefulness of intensity data widely acknowledged (e.g., Boatwright & Phillips, 2017; Hough, 2014; Quitoriano & Wald, 2020; Tosi et al., 2015; Wald et al., 2011; Worden et al., 2012). Intensity data are commonly communicated using maps (see Figure 1 for an example). An intensity map, based on accurate intensity estimations, could provide a good understanding of the geographical damage distribution following an earthquake. These maps help decision makers decide on intervention priorities. Intensity maps are also of great interest to the public, to understand which areas have been most affected and to guide their decision-making (Becker et al., 2019, 2020).

Figure 1
Example of an Intensity/Isoseismal Map for New Zealand, corresponding to the Ms7.3 13/2/1931 Hawke's Bay Earthquake



Note. Figure from Downes and Dowrick (2014).

Seismic strong-motion coverage may be insufficient to provide comprehensive maps of shaking levels. For example, in NZ, there are approximately 325 strong-motion stations (SMS) distributed around the country. To provide an intensity measure of the shaking level following an earthquake, accurate values are estimated near the SMS (using a ground motion to intensity conversion equation, GMICE); however, far away from the SMS, intensities will be based on attenuation equations, increasing the uncertainty. Felt Reports thus have an immense value as they can be used to fill gaps, with institutions often receiving thousands of reports from citizens after large events. As an example, after the Mw7.0 4 September 2010 Darfield earthquake, GeoNet (NZ's national geological hazards monitoring service at GNS Science, http://www.geonet.org.nz/) received 7,564 Felt Reports within the *Felt Classic* database (described below). Thumbnail-based reports, where the public chooses from a set of cartoons depicting different levels of shaking intensity, are even more numerous and faster to receive; for example, around 58,000 were received for a recent event, a magnitude M7.3 earthquake in Te Araroa, off the East Coast, which occurred on 5 March 2021.

Intensities are not only used to produce shaking intensity maps. Intensity datasets derived from Felt Reports are used to develop the relationship between magnitude and intensity (used for historical earthquakes), between magnitude, source distance, and intensity (called intensity attenuation relations or intensity prediction equations, IPE), and between ground-motion data (e.g., acceleration or velocity) and intensities (GMICEs). These relationships are commonly used in hazard and risk tools such as ShakeMap (e.g., Horspool et al., 2015; Wald et al., 1999b) or RiskScape (King et al., 2009).

Felt Reports and Citizen Science

As well as the benefits from gathering shaking data itself, the contribution of such data has additional social benefits. Citizen science projects vary widely, with some projects designed and coordinated by scientists with citizens contributing passively or actively through data collection or analysis (e.g., crowdsourced projects with "citizens as sensors"; Haklay, 2013). For example, there are projects around the world where citizens collect weather data (e.g., rainfall, snow, hail) to send to their relevant meteorological agency (Shuttleworth, 2021). At the "extreme" end of citizen science, the citizens themselves can drive projects, and they are involved in the project design, data collection, and analysis (Haklay, 2013). An example comes from a project in the Congo which aimed to tackle illegal logging and improve environmental management (Stevens et al., 2014). A data collection tool for monitoring appropriate to the local context was developed by locals including Pygmy hunter-gatherers, other indigenous communities, and a local non-governmental organization. In between these two extremes, there are varying degrees of participation and collaboration between scientists and citizens, leading to a range of different types of projects (Bonney et al., 2009; Haklay, 2013; Shirk et al., 2012). Wherever the project sits within the spectrum, citizen science can play a role in creating new scientific outputs and outcomes.

In terms of typologies of citizen science, Felt Reports fall more toward the contributory and crowdsourcing definitions, whereby citizens act as sensors and participation is through contributing data. Citizens' participation in science, through Felt Reports, not only improves understanding of earthquakes, but it also provides understanding of human behaviour and social impacts. Casey et al. (2018) explained how DYFI provides emotional support to people who have just had a traumatic experience from feeling a large earthquake. Data from citizens also helps us to understand people's behaviour during earthquakes. For example, Goltz et al. (2020a) studied data from eight earthquakes around the world, including the M_w6.2 22nd of February 2011 Christchurch, NZ, earthquake. They concluded that flight from buildings is still a prevalent action during a damaging earthquake, even in countries such as NZ where the "drop, cover, and hold" action is recommended. Even though the NZ MMI scale (Dowrick, 1996; Dowrick et al., 2008) does include some public reactions at all intensity levels, it could still be greatly improved by adding more information based on social science studies on human behaviour following large events. As an example, at MMI 6 the scale mentions "people and animals alarmed" and at MMI 8 that "alarm may approach panic", with no description of a typical human response at those intensity levels. There is much room to understand public reactions and to improve communication of desirable response actions to hazards at different intensity levels (Dowrick, 1996; Dowrick et al., 2008).

Felt Reports also perform a role related to the sharing of knowledge on earthquakes (Hicks et al., 2019). The online Felt Report platforms often also allow for the rapid release of information to the public, and the data can be used to enhance earthquake detection and warning systems (Finazzi, 2020). Other benefits of engaging citizens in felt reporting include relationship building (emerging from engagement between trained scientists and citizens), capacity building of the public to collect and interpret data, assisting with helping people make sense of what has happened following earthquake events, and developing community resilience (Becker et al., 2019; Wein et al., 2016). People's engagement in earthquake science will ultimately improve their understanding of the phenomenon, and likely lead to them taking more notice of actions that help with earthquake preparedness, response, and recovery.

New Zealand Historical Felt Reports

The first recorded earthquakes are based on the rich Māori oral tradition, grounded in their extended occupation of Aotearoa NZ and utilisation of its natural resources (King et al., 2007). In the late 1860s, a network of human observers was set up by Sir James Hector (Nathan, 2015). Whenever a "Reporter Network" member experienced an earthquake, they posted an A5-sized survey form to the New Zealand Institute, founded in 1867 (now named the Royal Society of New Zealand – Te Aparangi). These early records are stored in James Hector's personal correspondence at Te Papa Tongarewa Museum (Wellington). These felt observations were later addressed to the New Zealand Geological Survey and, following its founding in 1926, to the NZ Government's Department of Scientific and Industrial Research (DSIR). The collection also includes collated letters, newspaper cuttings, and other first-hand, primary observations of earthquake intensity.

GNS Science is a Crown Research Institute (in existence since 1992) operating on behalf of the NZ government to deliver geoscience research and societal benefits across a wide range of themes, including natural hazards and risk. GNS Science can trace its lineage back to the NZ Geological Survey (founded in 1865) and maintains a collection of Felt Reports that are a unique historical record of NZ's earliest recorded earthquakes and destructive geohazard events. The Felt Report database is the only known collection of these original records in existence in NZ and is therefore extremely valuable due to our relatively short history of human occupation and by allowing the extension of the known earthquake catalogue to a pre-instrumental time with approximate epicentres and magnitudes. Derived epicentres and magnitudes from 1901 to 1993 have survived (Viskovic et al., 2020).

GNS Science holds over 87,000 unique historical paper-based Felt Report records from the 1870s to 1993, of which those from 1901 to 1932 have been digitally scanned (14,000 records). Unfortunately, the Felt Reports for the period of 1993 until 2004, when the Reporter Network was disbanded, are completely lost, both paper and digital copies (Viskovic et al., 2020). An example of an historical Felt Report is provided in Figure 2.

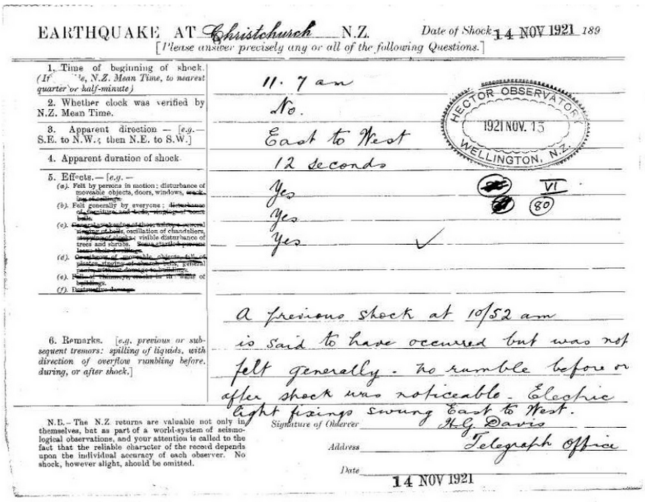
New Zealand Online Felt Reports (Felt RAPID, Felt Classic, and Felt Detailed)

From 2004, GeoNet has had three types of online questionnaires: *Felt Classic* (FC: GNS Science, 2004), *Felt Detailed* (FD: GNS Science, 2016), and *Felt RAPID* (FR: GNS Science, 2015). FC and FD are long questionnaires of around 40 questions each. FD succeeded FC, while FR is an independent survey. FC questionnaires were operative between October 2004 and August 2016. During this period, GeoNet received more than 856,000 Felt Reports from the catalogue of 267,478 different earthquakes during that period. The FC questionnaire was similar to the traditional version that had been used for the decades prior to 2004 (e.g., Downes & Dowrick, 2014). From August 2016, two different surveys have been conducted via the GeoNet website: FD and FR.

FD (provided in Appendix 1) is GeoNet's newest questionnaire, with similar questions and answers to FC plus some additional questions related to tsunami evacuation and social science. FD consists of 40 questions divided into 10 sections: 1) General questions on the earthquake, 2) Earthquake experience, 3) Earthquake effects, 4) Building information, 5) Building damage effects, 6) Neighbourhood effects, 7) Tsunami evacuation, 8) Tsunami information, 9) Information about earthquakes, and 10) Demographic information (see

Figure 2

Example of a Paper Felt Report Corresponding to a Christchurch Earthquake from 1921



EARTHQUAKE AT Christchurch N.Z. Date of Shock 14 NOV 1921 189

[*Please answer precisely any or all of the following Questions.*]

1. Time of beginning of shock. (*If [illegible]le, N.Z. Mean Time, to nearest quarter or half-minute*)	11. 7 am
2. Whether clock was verified by N.Z. Mean Time.	No.
3. Apparent direction — [*e.g.*—S.E. to N.W.; then N.E. to S.W.]	East to West
4. Apparent duration of shock	12 seconds
5. Effects.—[*e.g.* — (*a*). Felt by persons in motion; disturbance of moveable objects, doors, windows, ~~cracking of ceilings~~.	Yes
(*b*). Felt generally by everyone; ~~disturbance of furniture and beds, ringing of some bells~~.	Yes
(*c*). ~~General awakening of those asleep; general ringing of bells~~, oscillation of chandeliers, ~~stopping of clocks~~; visible disturbance of trees and shrubs. ~~Some startled persons leave their dwellings~~.	Yes ✓
(*d*). ~~Overthrow of moveable objects, fall of plaster, ringing of church bells, general panic, without damage to buildings~~.	
(*e*). ~~Fall of chimneys, cracks in the walls of buildings~~.	
(*f*). ~~Destructive damage~~.	
6. Remarks. [*e.g. previous or subsequent tremors: spilling of liquids, with direction of overflow rumbling before, during, or after shock.*]	a previous shock at 10/52 am is said to have occurred but was not felt generally. no rumble before or after shock was noticeable. Electric light fixings swung East to West.

HECTOR OBSERVATORY
1921 NOV. 15
WELLINGTON, N.Z.

VI

(80)

N.B.—The N.Z returns are valuable not only in themselves, but as part of a world-system of seismological observations, and your attention is called to the fact that the reliable character of the record depends upon the individual accuracy of each observer. No shock, however slight, should be omitted.

Signature of Observer H.G. Davis

Address Telegraph Office

Date 14 NOV 1921

Appendix 1 for the complete FD questionnaire). The FD questionnaire also has a considerable number of extra questions compared to the USGS DYFI survey, including: 1) more detailed options around people's behaviour (see further discussion in the human behaviour section below), 2) questions around the type of building, 3) questions around damage effects in the neighbourhood, and 4) questions around potential tsunami evacuation. FD currently has 12,160 Felt Reports from a total of 98,667 catalogued earthquakes (up to 14 September 2020).

Table 1

Correspondence Between Felt RAPID and MMI Assignments

Felt RAPID description	MMI level
Weak shaking	3
Light shaking	4
Moderate shaking	5
Strong shaking	6
Severe shaking	7
Extreme shaking	>=8

FR (Table 1 and Appendix 2) is a questionnaire available on Internet-capable and mobile devices where the person contributing their response chooses from a set of six cartoons (each corresponding to a different intensity level; Appendix 2) depicting their experience of the earthquake (GNS Science, 2015). The purpose of FR is to obtain quick and numerous responses from the public using a simplified questionnaire. Research on the use of FR data for science is currently in progress, with the aim to obtain quick intensity maps using the fast and numerous FR data available minutes after an earthquake. FR has gathered more than 1,158,000 reports since it started on 18th May 2016 (with earthquakes generating FR reports occurring every day). Data from FR reports is mainly used by the media and GeoNet as a public communication tool. Reports from FC and FD questionnaires have been used since their development to assign MMI intensities (Coppola et al., 2010; Goded et al., 2014, 2017a,b, 2018, 2019) using the NZ MMI scale (Dowrick, 1996; Dowrick et al., 2008).

Both FC and FD questionnaires are similar to the traditional version that had been used for the decades prior to 2004 (e.g., Downes & Dowrick, 2014). FR directly assigns one intensity level to each chosen cartoon. Levels go from MMI 3 to a maximum of 8. Both FD and FR are limited to no greater than intensity 8, as above that level, further detailed information of the building damage is required (see more details below).

The Mw7.8 2016 Kaikōura earthquake occurred when GeoNet was adapting the method to assign intensities from FC to the new FD surveys. FD was created as a faster and easier way to fill in questionnaires than FC. Between August and November 2016 there was only the FR questionnaire on GeoNet's website, during which the East Cape (2/9/2016, M7.2) and Kaikōura earthquakes occurred. Members of the public stated that they were disappointed about not having the "long reports" available on GeoNet's website (C. Little, GeoNet, personal communication), showing their willingness to fill in seismic surveys and collaborate in science research. FD reports were released on GeoNet's website shortly after the two events to collect data for those specific events; since a few days after the Kaikōura event, FD has been permanently available on GeoNet's website.

This meant that fewer long-form Felt Reports were received for the Kaikōura event (just above 3,500) than for the smaller Mw6.5 21/7/2013 Cook Strait and Mw6.6 16/8/2013 Lake Grassmere events in a nearby region, with around 5,500 reports each. A reason for this lower number of reports could be due to the switch from FC to FD questionnaires, the inexistence of the FD questionnaire on GeoNet website at the time of the earthquake (it appeared in GeoNet news some hours after the event), and the lack of awareness from the public of the new surveys when the earthquake occurred.

MMI Scale, Community Intensities, and ShakeMaps

This citizen science-derived data is used to estimate the macroseismic intensity at different locations. With this information, shaking intensity maps are produced of the geographical damage distribution from a damaging event, used by decision makers and end users. In this section, we will describe NZ's MMI scale and two types of intensity maps derived from Felt Report data: community maps and ShakeMapNZ maps. The next section will describe the use of these intensity data to update two equations commonly used in the engineering community to assess seismic hazard and risk: the GMICE and the IPE.

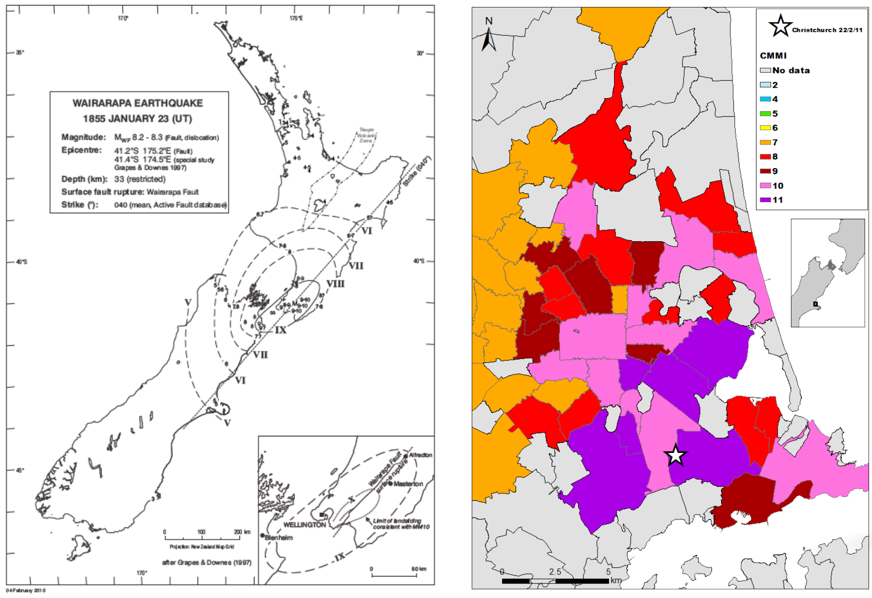
New Zealand's MMI scale. A macroseismic scale, used for high damage events, provides a set of descriptions of the effects of earthquakes on people, buildings, non-structural components, and the environment, together with a list of vulnerability classes and damage grade descriptors for different types of buildings. A macroseismic scale can therefore be used to assess the level of shaking intensity generated by an earthquake at different locations, providing a geographical distribution of the potential damage. Maps of this damage distribution (or intensity maps) are used by emergency responders following a damaging event to establish intervention priorities (e.g., Potter et al., 2020). There are different ways of producing these intensity maps: directly by assigning intensities from Felt Reports using a macroseismic scale (as for the community intensity maps described below) or using additional types of data (like peak ground acceleration (PGA) from ground motion stations) converted to intensities by using several equations (GMICE, IPE, and ground motion prediction equations (GMPE)). An example for this type of maps is ShakeMap (Wald et al., 1999b), now adapted to NZ (ShakeMapNZ; Horspool et al., 2015, in prep.)

Community intensities. Intensities are a measure of the earthquake's shaking intensity at a regional scale, and they should be provided within a specific region. In NZ, intensities have been estimated in three different ways:

- Generating contours of decreasing intensity at locations further from the epicentre. These are called isoseismal maps. These maps were traditionally generated for historical earthquakes. See Figure 3 (left) for an example.
- Per location, by using a group of Felt Reports in a specific town/city, providing intensity maps, traditionally from historical reports in combination with isoseismal maps.
- Community intensity maps, where intensities are provided for either a suburb in urban areas, or a town for rural areas. Alternatively, our team is also producing maps of intensity within grid cells (at 0.02 degrees spacing) and within circles at different distances from the SMSs. The latter database is used to update NZ's GMICE (Moratalla et al., 2020) and IPE equations. See Figure 3 (right) for an example.

Figure 3

Example of an Intensity/Isoseismal Map for New Zealand, Corresponding to the Mw8.2-8.3 23/2/1855 Wairarapa earthquake and a Community Intensity Map, Corresponding to the Mw6.2 22/2/2011 Christchurch Earthquake



Note. Left: Figure from Downes and Dowrick (2014). Right: Figure from Goded et al. (2019).

Currently, community MM intensities (or CMMI) are assigned using a method developed for NZ by Goded et al. (2018) and improved in Moratalla et al. (2020). Automatic intensity evaluations can be made through two different approaches: regression-based or expert-based (Musson & Cecic, 2012; Tosi et al., 2015). A regression-based approach obtains results through a regression between the automatic scores and the "postal traditional" intensities (assigned manually by a seismologist using paper or online surveys, to be distinguished from the "traditional intensities", which are assigned on site) to align with past datasets. However, these will refer to assignments from paper/online questionnaires, and not from field studies. An example is the USGS DYFI method (Atkinson & Wald, 2007; Mak & Schorlemmer, 2016; Wald et al., 1999a, 2011). The expert-based approach follows the specifications of a macroseismic scale and assigns a set of scores using the experience of an expert panel. This method has the advantage that it can be implemented in a short timeframe and several methods can be used to calibrate it, such as the use of GMICE (see Gerstenberger et al., 2007 for NZ data), systems like ShakeMap (Wald et al., 1999b) and the recently developed ShakeMapNZ (Horspool et al., 2015), and traditional macroseismic surveys where intensities are assigned to a community by a seismologist. "Traditional" (on site) and "postal traditional" (through questionnaires) assignments are very scarce nowadays due to being quite time-consuming and costly, hence the need for new methods to obtain intensity information.

The method to obtain CMMI values in NZ (Goded et al., 2018; Moratalla et al., 2020) uses an expert-based approach developed by the Italian Geophysics and Vulcanology Institute (Instituto Nazionale de Geofisica e Vulcanologia, INGV; Sbarra et al., 2010; Tosi et al., 2015), and adapted to GeoNet's online questionnaires and the NZ version of the MMI scale. The method used to assign CMMI is based on a score distribution for each answer to the questions in the survey. The score distribution has been chosen through an expert panel with experience using the NZ MMI scale. The intensities derived from this score distribution are first normalized then weighted by the corresponding MMI level. All the weighted scores per Felt Report are then added, and the CMMI corresponds to the mean of all the added weighted scores corresponding to all the reports in that community (suburb/town), to obtain a CMMI for each community with five or more Felt Reports (Moratalla et al., 2020). CMMI values assigned as explained above are limited to no greater than intensity 8. In NZ, at MMI 8 and above, buildings can suffer considerable damage and the assignment of intensity values involves an engineering study of the building's damage level and building type (Coppola et al., 2010). This limitation for high intensity levels is well known and has been noted in previous studies (e.g., Dewey et al., 2002; Wald et al., 1999a, 2011).

The method to obtain CMMI values can be summarised with the following steps (Goded et al., 2018; Moratalla et al., 2020):

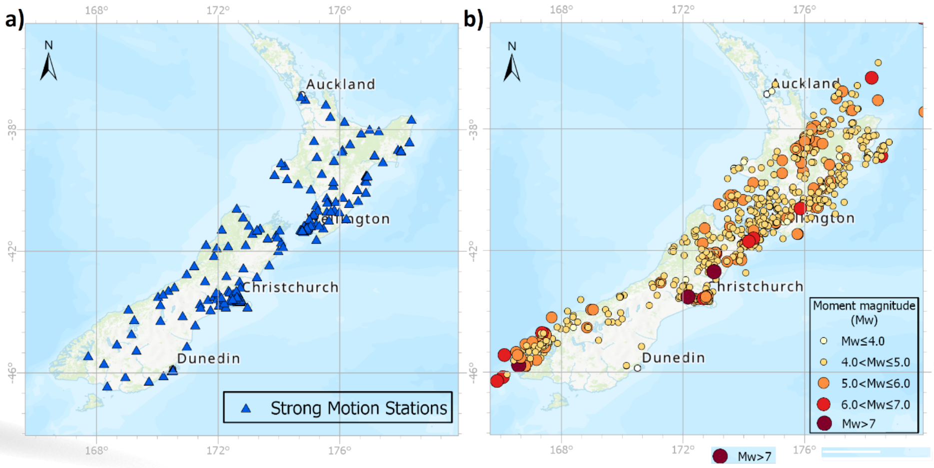
- A score system was developed to assign scores to each element of the matrix of answers and intensities. A score was assigned to each answer amongst all the intensity values, creating an intensity distribution for each answer to the questionnaire. Weights have also been used for the questions, similar to the DYFI data from USGS (Wald et al., 1999a).
- The score distribution of MMI per community is obtained by adding, for each intensity level, all the scores from all the reports belonging to that community. Scores are then normalized with respect to the sum of all the scores per report.
- Each normalized score per Felt Report is then weighted by the corresponding MMI level. All the weighted scores per Felt Report are then added.
- The CMMI corresponds to the mean of all the added weighted scores corresponding to all the reports in that community (suburb/town). A CMMI is only obtained in communities with five or more Felt Reports.

Data quality procedures include elimination of duplicated Felt Reports from the same address, elimination of reports with insufficient information, and correction of misspelt addresses (Goded et al., 2018). Community intensities using this method have been calculated for the complete set of GeoNet FC data (2004-August 2016) and FD data until the end of September 2020, comprising a total of 607,301 Felt Reports from 7,265 earthquakes. The New Zealand Strong-Motion Database (SMDB; Van Houtte et al., 2017), corresponding to 276 NZ earthquakes with magnitudes 3.5-7.8 and 4-185 kilometre depths, has been used to include strong-motion data (e.g., PGA and Peak Ground Velocity, PGV) from the SMS in the CMMI database. The resulting database of intensity and strong-motion data for the 2004 to September 2020 period is the first of its kind in NZ. The database contains 174,214 CMMI values for communities with five or more Felt Reports. The earthquakes in the database in this study are shown in Figure 4. This figure includes the SMSs with records from the database.

It should be noted that no uncertainty estimates have been obtained yet for the CMMI values. Working on uncertainties will be part of future improvements to this method. However, comparison with traditional intensity evaluations (analysed manually by a seismologist) was carried out for three moderate-to-large earthquakes in NZ: M_w 7.1 4/9/10 Darfield (7,564 reports, 317 communities), M_w 6.2 20/1/2014 Eketahuna (10,885 reports, 331 communities), and M_w 7.8 14/11/16 Kaikōura (3,509 reports, 164 communities) earthquakes. Results indicate matching CMMI values for 68% in the case of the Kaikōura and Eketahuna earthquakes, with around

Figure 4

Geographical Distribution of Earthquakes from the 2004-September 2020 CMMI Database



Note. Figure 4a shows strong motion stations marked as triangles. The CMMI database (4b) corresponds to the intensity data around the SMSs used to develop the most recent NZ GMICE (Moratalla et al., 2020).

20 to 25% of communities at one MMI level lower using FD than traditional assignment. The Darfield earthquake had 43% matching and 54% one MMI level lower when using FD CMMI assignments. Thus, an uncertainty of around 1 MMI level is expected for the CMMI method.

ShakeMaps. The CMMI intensities derived from FC and FD Felt Reports have also been used to produce intensity and strong motion maps using ShakeMap. ShakeMap was developed by the USGS following the devastating 1994 Northridge Earthquake to rapidly map areas of potentially damaging shaking following an earthquake (Wald, 1999b). In the past 16 years, many seismic network operators have adopted and calibrated the ShakeMap software for their region, including Italy (Michelini et al., 2008) and Canada (Kaka & Atkinson, 2005).

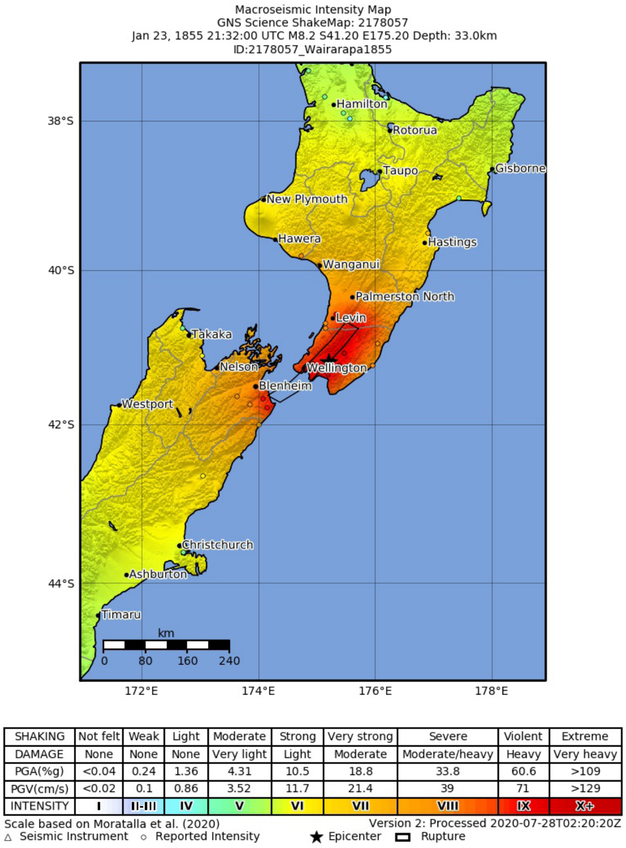
The strength of ShakeMap is not in the map itself, but how observed data in the form of strong or weak ground motions and macroseismic intensity data are combined with ground motion prediction equations to produce estimates of ground shaking in several ground motion intensity types (Worden et al., 2012). This allows decision makers to move from using magnitude and location as an indicator of an earthquake's severity to using the spatial distribution of shaking intensity (Wald et al., 1999b).

ShakeMap integrates data with ground motion prediction models to estimate ground motions and their uncertainties in areas without instrumentation. The data comprises observed instrumental ground motions from seismic recording stations and felt report data from the public. ShakeMap produces maps of gridded shaking intensity in the form of PGA, PGV, response spectral acceleration (0.3s, 1s, 3s), and macroseismic intensity. ShakeMapNZ is the ShakeMap system adapted to NZ. It was developed in 2015 (Horspool et al., 2015) and has been automatically generating shakemaps until recently. Since May 2019, a new version of ShakeMapNZ has been installed, using the latest version 4 developed at USGS, based on Python Programming Language (Worden et al., 2020); however, at present this version is only manually generated. It is intended to be run automatically and be open to the public again in the near future.

Recently, the first ShakeMapNZ atlas of past earthquakes in NZ has been created, with a total of 61 earthquakes, comprising four paleoearthquakes, 10 large historical events, and 47 earthquakes from the instrumental period (1968-2019), with magnitudes 6.0+ (Horspool et al., in prep). An example is provided in Figure 5, corresponding to the M8.2 Wairarapa earthquake on 23/1/1855.

Figure 5

ShakeMapNZ Intensity Map Corresponding to the M8.2 23/1/1855 Wairarapa Earthquake



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.04	0.24	1.36	4.31	10.5	18.8	33.8	60.6	>109
PGV(cm/s)	<0.02	0.1	0.86	3.52	11.7	21.4	39	71	>129
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Note. Figure from Horspool et al. (in prep).

Updating New Zealand's GMICE And IPE Equations

The existence of the large CMMI and SMDB has given us the opportunity to update two equations for NZ: The GMICE and the IPE.

A new GMICE for New Zealand. NZ's GMICE has recently been updated (Moratalla et al., 2020). Previously, this GMICE was from Gerstenberger et al. (2007), in which DYFI data (Wald et al., 1999a) from the Western US was combined with nearly 6,500 points recorded for NZ to develop PGV to intensity conversion equations. The NZ relationships were based only on PGV and lacked high intensity MMI data. They were developed prior to a large dataset resulting from the Canterbury 2010-2011 and Kaikōura 2016 earthquake sequences. Two main factors provided us with the opportunity to update NZ's GMICE: 1) recent publication of NZ's SMDB (Van Houtte et al., 2017), in which strong-motion data corresponding to 276 NZ earthquakes (including Darfield Mw 7.1, 4/9/2010, Christchurch Mw 6.2, 22/2/2011, and Kaikōura Mw 7.8, 14/11/2016) have been filtered and analysed individually according to the specific features of each record (instead of using GeoNet's automatic filtering system), thus considerably improving its quality; and 2) recent development of a method to obtain MMI at a community (suburb/town) level using GeoNet's online Felt Reports, together with the generation of the first database of community intensities for GeoNet's FC and FD online Felt Reports (Goded et al., 2018), as explained above.

In the new GMICE, Felt Reports were regrouped into circles at 500 metres, 1,000 metres, and 2,000 metres from the SMSs. The CMMIbySMS values mentioned in this paper refer to the community intensity data used to develop the GMICE, where communities are circles around the SMSs. The distance of 1000m was chosen as the optimal distance to have sufficient Felt Reports in the community and sufficiently similar soil characteristics between an SMS and the locations of associated Felt Reports. The intensity database contains 67,572 Felt Reports from 917 earthquakes, with magnitudes 3.5-8.1, and 1,797 recordings from 247 NZ SMSs, with hypocentral distances of 5-345 kilometres. Only SMSs with three or more responses were used to calculate CMMIbySMS.

As a first step towards obtaining a new GMICE for NZ, the CMMI data were converted to traditional intensities, similarly to what was done within the DYFI programme between their Community Weighted Sum and their Community Decimal intensity using data from the Northridge earthquake (Wald et al., 1999a). Traditional MMI (MMItrad) data were available in the database for three main earthquakes that occurred in the last 10 years: M_w7.8 Kaikōura 2016, M_w 7.1 Darfield 2010, and M_w 6.2 Eketahuna 2014. Moratalla et al. (2020) compared these MMItrad data with CMMI data, also available for these three earthquakes, and derived a relationship based on 767 data pairs. Once all the CMMI data were converted to traditional MMI values, the data were compared to data from other regions. It was observed that previous underestimations (below MMI 4) and overestimations (above MMI 6) of data were corrected when using traditional MMI values.

The new GMICE was created using Total Least Squares linear regression, also known as Deming regression (Deming, 1943) or orthogonal regression, to fit the logPGM-MMItrad (PGM: Peak Ground Motion) data pairs and develop the GMICE for NZ. More details on this GMICE can be found in Moratalla et al. (2020).

A new IPE for New Zealand. Using the recent CMMI database, a new IPE (or intensity attenuation model) is currently being developed for NZ. The previous intensity attenuation model for NZ, from 2005 (Dowrick & Rhoades, 2005), used intensities from 89 earthquakes between 1855 and 1998, based on isoseismal data. Development of the new IPE is currently underway, so no results are available yet.

Understanding Human Behaviour

In recent FD Felt Report surveys (from 2016 to present), additional questions have been included that relate to people's actions during earthquake shaking and following the earthquake regarding tsunami evacuation. These questions are similar to the behavioural response questions used in studies by Lindell et al. (2016), Goltz et al. (2020b), and Vinnell et al. (2020). Analysis of these behavioural questions is useful for tracking longitudinal changes in response during and after earthquakes. This can be used to understand the efficacy of educational campaigns such as the ShakeOut earthquake drill and tsunami hīkoi (McBride et al., 2019), for updating and improving the MMI scale over time, and to develop casualty and evacuation models that attempt to predict human behaviour as outlined in the following section.

Predictive Model of Human Behaviour in Earthquakes

Recent studies investigating human casualties during earthquakes and tsunami have revealed that human behaviour plays an important role in the determination of injuries and deaths (Horspool et al., 2020; Johnston et al., 2014). To improve existing earthquake and tsunami casualty models, human behaviour needs to be included. Data on human behaviour during earthquake shaking and tsunami evacuation collected by Felt Reports is valuable for better understanding human behaviour and developing predictive models. Felt Report data from the past 4 years covers a range of earthquake shaking intensities (MMI 3 to MMI 9), times of day, seasons, contextual settings (e.g., at home, at work, on the street), and geographic regions, allowing robust statistical analysis to determine key variables that drive human behaviour during and following earthquakes.

Table 2 shows the behavioural response question currently in the FD survey and the corresponding question in the DYFI survey (Goltz et al., 2020a; Quitoriano & Wald, 2020). FD has a larger variety of behavioural answers than the current DYFI. The answer "Moved to doorway" is currently not in FD but is planned to be included in a future version of the survey. FD has the same responses as Lindell et al. (2016) to retain consistency in survey responses and analysis in NZ. Research in progress is using regression models to

Table 2
Questions on Behavioural Response for the NZ Felt Detailed and the USGS Did You Feel It? Surveys

	Felt Detailed (GeoNet)	Did You Feel It? (USGS)
Question	"What was your first response while the earthquake was shaking?"	"How did you respond?
Response	Continued what I was doing before	Not specified
	Stopped what I was doing but stayed where I was	Took no action
	Dropped, covered under a sturdy piece of furniture (e.g., table or desk), and held on to it	Moved to doorway
	Tried to protect other people nearby	Dropped and covered
	Tried to protect property nearby (e.g., prevent things from falling)	Ran outside
	Immediately left the building I was in	Other (please specify)
	Continued driving	
	Stopped driving and pulled over to the side of the road	
	Not applicable	
	Other (please explain)	

assess statistical relationships between these variables and demographic factors.

Improving Public Education

The information gained from Felt Reports is also useful for targeting educational initiatives to improve resilience to earthquakes. For example, we know that most buildings in NZ are designed to remain standing during strong shaking, so public education focuses primarily on earthquake mitigation (e.g., retrofitting buildings, securing loose items) and preparedness activities (e.g., household, work, and community preparedness). In terms of responses to shaking, people are asked to drop, cover, and hold to avoid injury (McBride et al., 2019), and if located near the coast, evacuate inland or to higher ground after feeling a long duration or strong earthquake. Despite such best practice advice, Felt Reports for the 2016 Kaikōura earthquake indicate that only 18.2% of participants undertook the recommended drop, cover, and hold action upon feeling shaking, which shows a continuing need to focus on promoting these actions via public education initiatives such as the ShakeOut earthquake drill (Vinnell et al., 2020). Likewise, Horspool et al. (2020) highlight that 8% of injuries during the Kaikōura earthquake occurred when people were struck by unsecured contents, suggesting that education programmes need to continue to advocate earthquake mitigation and preparedness actions. Finally, the time an earthquake occurs might impact the responses received. For example, the Kaikōura earthquake occurred at midnight, when people were most likely asleep, even though many of them were awakened by the event.

In terms of future work, there is an opportunity to analyse the current FD questions in more detail, such as those related to tsunami evacuation, to inform public education. Additional questions could also be included to gain a better understanding of people's actions. As an example, asking why individuals might *not* drop, cover, and hold would further guide the development of targeted information encouraging people to take appropriate protective action. Additionally, the Felt Reports provide a comprehensive data set over a long period of time, from which the impact of education on people's behaviour can be evaluated longitudinally, and education programmes adjusted accordingly.

Conclusions and Future Work

Earthquake Felt Reports are a constructive way for the public to contribute to science. Thanks to such contributions, scientists can better understand the geographical distribution of damage following earthquake shaking, and consequently are better able to inform decision makers and first responders on priority interventions. Even if instrumental-based parameters such as magnitude and PGA are commonly used in the science and engineering community, the use of intensity data based on Felt Report information is still considered important for two main purposes: 1) to be able to compare damage caused by modern and historical earthquakes, and 2) to fill in gaps where modern instruments are scarce. Citizen science via Felt Reports plays a key role in providing detailed shaking maps that can be used by first responders and the public. Additionally, Felt Reports contribute to a better understanding of how the physical environment behaves during shaking and how humans respond, for which the data can be fed into updating both physical and social (e.g., injury) models. Self-reflection from the public when filling out a questionnaire also helps people to understand the impacts of earthquakes. Whether the mechanism be updated data and models or self-reflection by participants, improved understandings can help with developing preparedness for future earthquakes and can be used to target appropriate educational interventions.

NZ has a long tradition of using Felt Report information provided by the public to analyse earthquake damage. From historical paper-based Felt Reports to the more modern Internet-based questionnaires and thumbnail-based surveys, NZ has gathered a large amount of Felt Report information. Uses of Felt Reports include analysis of human post-event responses, shaking intensity maps, rapid shaking maps (e.g., ShakeMapNZ), or development and improvement of equations such as GMICE or IPE. NZ Felt Report-based research has burgeoned in recent years, with an increasing number of studies taking advantage of the large number of Felt Reports following moderate-to-large events, including the 2010-2011 Canterbury earthquake sentence and the Mw 7.8 2016 Kaikōura earthquake.

This paper summarises the most recent research carried out in NZ using Felt Report data, from citizen science to the update of equations and development of community intensity maps and ShakeMapNZ. There is still considerable work to be carried out, including:

- Analysis of intensity data derived from FR thumbnail-based surveys, comparing them with the more detailed FC and FD questionnaires. Preliminary analysis has been carried out for more than 4 months of data (mid-November 2020 to early April 2021), corresponding to 1,683 Felt Reports with both intensities assigned from FD and FR data (from a total of 103 earthquakes), using an updated FD questionnaire which also includes the FR question, thus comparing the MMI derived from FD and FR corresponding to the same respondent. Preliminary results show around 50% of reports with matching intensities, with a tendency of FR to underestimate the MMI compared to FD by one MMI level (28%) or more (6%).
- Testing the use of the quick and numerous FR responses for the release of quick ShakeMaps following a damaging event.
- Improvement of the current FD questionnaire (see Appendix 1), including reducing the number of questions, improving questions related to social science, and updating the code. A major improvement is for the public to be able to choose their address from a drop-down list, as currently the public fills it in manually, leading to a considerable number of unusable misspelt addresses. Another improvement is to automatically store the earthquake ID corresponding to the event felt by the responder, as currently the responder needs to fill it in manually.
- Updating the current GMICE to include other parameters such as spectral acceleration at different periods.
- Updating NZ's prediction equation.
- Inclusion of shaking intensity maps as a product delivered by GeoNet.
- Development of an automated system for providing shaking layers (such as ShakeMapNZ) minutes after a damaging event in NZ, using Felt Report information (FR and FD) automatically fed in as input parameters.

Data and Resources

The availability of the data used in this project is as follows:

- Original Felt Reports are stored at GNS Science in cardboard boxes and manila folders, grouped based on earthquake date. Due to privacy concerns all original Felt Reports are deemed confidential and unable to be shared with the public. Plans are currently underway to make records public where there is no risk of identifying individuals involved (Viskovic et al., 2020). Published research products derived from the historical Felt Report database exist and are available for researchers (e.g., Downes & Dowrick, 2014).
- Historical reports are currently stored by GNS Science and not available to the public.
- FR data is publicly available through GeoNet's website and the dataset metadata available from the GNS Dataset Catalogue (GNS Science, 2015). They can be downloaded from http://api.geonet.org.nz/intensity?type=reported&publicID=2016p858000, changing the last digits to the needed public ID. The link provided corresponds to the 2016 M_w 7.8 Kaikoura earthquake. More information on GeoNet felt report data can be found at https://www.geonet.org.nz/data/types/felt
- FC and FD data are not publicly available. They can only be used for research purposes if the research team has obtained ethical approval. The use of FC and FD data for research purposes in this project has been approved as a low-risk project by the Massey University Human Ethics Committee. However, the metadata for both datasets are available from the GNS Dataset Catalogue (GNS Science, 2004 for FC and GNS Science, 2016 for FD).
- The CMMI database for FC and FD is undergoing further testing and is not publicly available. Once the database has undergone further testing, work towards making it publicly available will be considered.
- The NZ SMDB has been used in this study to include strong-motion data in the CMMI database. This database is publicly available through the GeoNet website: https://www.geonet.org.nz/data/supplementary/nzsmdb

References

Allen, R.M. (2012). Transforming earthquake detection? *Science*, *335*(6066), 297–298. https://doi.org/10.1126/science.1214650

Atkinson, G.M., & Wald, D.J. (2007). “Did You feel It?” intensity data: A surprisingly good measure of earthquake ground motion. *Seismological Research Letters, 78*(3), 362-368. https://doi.org/10.1785/gssrl.78.3.362

Becker, J.S., McBride, S.K., Potter, S.H., Gerstenberger, M.C., & Christophersen, A. (2018). Effective communication of Operational Earthquake Forecasts (OEF): Findings from a New Zealand workshop. *GNS Science Report, 2016*(45), 49p. https://doi.org/10.21420/G2DH00.

Becker, J.S., Potter, S.H., McBride, S.H., Doyle, E.E.H., Gerstenberger, M.C., & Christophersen, A. (2020). Forecasting for a fractured land: A case study of the communication and use of aftershock forecasts from the 2016 M w 7.8 Kaikōura earthquake in Aotearoa New Zealand. *Bulletin of the Seismological Society of America, 91*(6), 3343-3357.

Becker, J.S., Potter, S.H., McBride, S.K., Wein, A., Doyle, E.E.H., & Paton, D. (2019). When the earth doesn't stop shaking: How experiences over time influenced information needs, communication, and interpretation of aftershock information during the Canterbury Earthquake Sequence, New Zealand. *International Journal of Disaster Risk Reduction, 34*, 397-411. https://doi.org/10.1016/j.ijdrr.2018.12.009

Blake, D., Johnston, D., Leonard, G., McLaren, L., & Becker, J. (2018). A citizen science initiative to understand community response to the Kaikōura earthquake and tsunami warning in Petone and Eastbourne, Wellington, Aotearoa/New Zealand, *Bulletin of the Seismological Society of America*, *108*(3B), 1807–1817. https://doi.org/10.1785/0120170292

Boatwright, J., & Phillips, E. (2017). Exploiting the demographics of "Did You Feel It?" responses to estimate the felt area of moderate earthquakes in California. *Seismological Research Letters, 88*(2A), 335-341. https://doi.org/10.1785/0220160041

Bonney, R., Cooper, C.B., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K.V., & Shirk, J. (2009). Citizen science: A developing tool for expanding science knowledge and scientific literacy. *BioScience*, *59*(11), 977–984. https://doi.org/10.1525/bio.2009.59.11.9

Casey, J.A., Goldman-Mellor, S., & Catalano, R. (2018). Association between Oklahoma earthquakes and anxiety-related Google search episodes. *Environmental Epidemiology, 2*(e016). https://doi.org/10.1097/EE9.0000000000000016

Celsi, R., Wolfinbarger, M., & Wald, D.J. (2005). The effects of magnitude anchoring, earthquake attenuation estimation, measure complexity, hubris and experience inflation on individuals' perceptions of felt earthquake experience and perceptions of earthquake risk. *Earthquake Spectra, 21*, 987-1008.

Coppola, J.M., Cowan, L.X., Downes, G.L., Fenaughty, K.F., Grimwood, P.D., Leach, P., & Robertson, E.J. (2010). Felt earthquake reporting via the Internet in New Zealand. *Seismological Research Letters, 81*, 984-991. https://doi.org/10.1785/gssrl.81.6.984

Deming, W. E. (1943). *Statistical adjustment of data.* Wiley.

Dewey, J.W., Hopper, M.G., Wald, D.J., Quitoriano, V., & Adams, E.R. (2002). Intensity distribution and isoseismal maps for the Nisqually, Washington, earthquake of 28 February 2001. *USGS Open-File Report, 02*(0346), 57 p.

Downes, G.L., & Dowrick, D.J. (2014). Atlas of isoseismal maps of New Zealand earthquakes: 1843-2003. 2nd edition (revised). *GNS Science Monograph, 25.* 1 DVD

Dowrick, D.J. (1996). The Modified Mercalli earthquake intensity scale: Revisions arising from recent studies of New Zealand earthquakes. *Bulletin of the New Zealand National Society for Earthquake Engineering, 29*, 92–106.

Dowrick, D.J., Hancox, G.T., Perrin, N.D., & Dellow, G.D. (2008). The Modified Mercalli intensity scale – revisions arising from New Zealand experience. *Bulletin of the New Zealand Society for Earthquake Engineering, 41*(3), 193-205.

Dowrick D.J., & Rhoades, D.A. (2005). Revised models for attenuation of Modified Mercalli intensity in New Zealand earthquakes. *Bulletin of the New Zealand Society for Earthquake Engineering, 38*(4), 185–214.

Fehri, R., Khlifi, S., & Vanclooster, M. (2020). Testing a citizen science water monitoring approach in Tunisia. *Environmental Science and Policy*, *104*, 67–72. https://doi.org/10.1016/j.envsci.2019.11.009

Finazzi, F. (2020). Fulfilling the information need after an earthquake: Statistical modelling of citizen science seismic reports for predicting earthquake parameters in near realtime. *Journal of the Royal Statistical Society*, *Series A: Statistics in Society, 183*(3), 857–882. https://doi.org/10.1111/rssa.12577

Gerstenberger, M.C., Worden, C.B., & Wald, D.J. (2007). A probabilistic relationship between ground shaking parameters and MMI based on felt report data. In *Proceedings of the New Zealand Society of Earthquake Engineering Technical Conference*, Palmerston North, New Zealand, Paper 34, 8 pp.

GNS Science. (2004). *"Felt Classic" felt report dataset* [Data set]. GNS Science. https://doi.org/10.21420/C8AY-5173

GNS Science. (2015). *"Felt Rapid" felt report dataset* [Data set]. *GNS Science*. https://doi.org/10.21420/RS7F-VE53.

GNS Science. (2016). *"Felt Detailed" felt report dataset* [Data set]. GNS Science. https://doi.org/10.21420/KYR8-J660

Goded, T., Cousins, W.J., & Fenaughty, K.F. (2014). Analysis of the severe damage online Felt Reports for the Canterbury (New Zealand) 2011 aftershocks on 22 February Mw6.2, 13 June Mw6.0 and 23 December Mw6.0. *Seismological Research Letters, 85*, 678-691.

Goded, T., Gerstenberger, M., Stirling, M., Cousins, J., & Canessa, S. (2019). High intensity assignments for the 22 February 2011 M_w 6.2 Christchurch (Canterbury, New Zealand) earthquake: A contribution towards understanding the severe damage caused in this event. *Seismological Research Letters, 90*(4), 1468-1482. https://doi.org/10.1785/0220180385

Goded, T., Horspool, N., Gerstenberger, M., Coomer, M.A., Becker, J.S., McBride, S., Canessa, S., & Lewis, A. (2017a). A comparison between GeoNet's 'Felt RAPID' and 'Felt Detailed' online questionnaires. In *Proceedings of the New Zealand Society of Earthquake Engineering Technical Conference,* Wellington, New Zealand, Paper 181, 8 pp.

Goded, T., Horspool, N., Canessa, S., & Gerstenberger, M. (2017b). Modified Mercalli intensities for the M7.8 Kaikoura (New Zealand) 14 November 2016 earthquake derived from 'Felt Detailed' and 'Felt RAPID' online questionnaires. *Bulletin of the New Zealand Society for Earthquake Engineering*, *50*(2), 352-362.

Goded, T., Horspool, N., Canessa, S., Lewis, A., Geraghty, K., Jeffrey, A., & Gerstenberger, M. (2018). New macroseismic intensity assessment method for New Zealand web questionnaires. *Seismological Research Letters, 89*(2A), 640-652. https://doi.org/10.1785/0220170163

Goltz, J.D., Park, H., Nakano, G., & Yamori, K. (2020a). Earthquake ground motion and human behaviour: Using

DYFI data to assess behavioural response to earthquakes. *Earthquake Spectra, 36*(3), 1231-1253. https://doi.org/10.1177%2F8755293019899958

Goltz, J. D., Park, H., Quitoriano, V., & Wald, D.J. (2020b). Human behavioral response in the 2019 Ridgecrest, California, earthquakes: Assessing immediate actions based on data from "Did You Feel It?". *Bulletin of the Seismological Society of America, 110*(4), 1589-1602.

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: Volunteered Geographic Information (VGI) in theory and practice* (pp. 1–396). Springer. https://doi.org/10.1007/978-94-007-4587-2

Hicks, A., Barclay, J., Chilvers, J., Armijos, M.T., Oven, K., Simmons, P. & Haklay, M. (2019). Global mapping of citizen science projects for disaster risk reduction. *Frontiers in Earth Science*, *7*, 1–18. https://doi.org/10.3389/feart.2019.00226

Horspool, N.A., Chadwick, M., Ristau, J., Salichon, J., & Gerstenberger, M.C. (2015). ShakeMapNZ: Informing post-event decision making. In *Proceedings of the New Zealand Society for Earthquake Engineering Technical Conference*, Rotorua, New Zealand, Paper 40, 369-376.

Horspool, N., Elwood, K., Johnston, D., Deely, J., & Ardagh, M. (2020). Factors influencing casualty risk in the 14th November 2016 MW7.8 Kaikōura, New Zealand earthquake. *International Journal of Disaster Risk Reduction, 51*, 101917, https://doi.org/10.1016/j.ijdrr.2020.101917

Horspool, N., Goded, T., Moratalla, J., Litchfield, N., Van Dissen, R., Lukovic, B., Heron, D., & Massey, C. (2021). *ShakeMapAtlas: A database of shaking intensity maps for past significant earthquakes in New Zealand* [Manuscript in preparation].

Hough, S.E. (2014). Earthquake intensity distributions: A new view. *Bulletin of Earthquake Engineering, 12*, 135-155.

Johnston, D., Standring, S., Ronan, K., Lindell, M., Wilson, T., Cousins, J., Aldridge, E., Ardagh, M. W., Deely, J. M., Jensen, S., Kirsch, T., & Bissell, R. (2014). The 2010/2011 Canterbury earthquakes: Context and cause of injury. *Natural Hazards, 73*(2), 627-637. https://doi.org/10.1007/s11069-014-1094-7

Kaka, S.I., & Atkinson, G.M. (2005). Empirical ground-motion relations for ShakeMap applications in southeastern Canada and the northeastern United States. *Seismological Research Letters, 76*(2), 274-282. https://doi.org/10.1785/gssrl.76.2.274

King, A.B., Bell, R., Heron, D. W., Matcham, I., Schmidt, J., Cousins, W. J., Reese, S., Wilson, T., Johnston, D. M., Henderson, R., Smart, G., Goff, J., Reid, S., Turner, R., Wright, K. C., & Smith, W. D. (2009). RiskScape Project: 2004 – 2008. *GNS Science. Consultancy Report*, *2009*(247), 162 p.

King, D., Goff, J., & Skipper, A. (2007). Māori environmental knowledge and natural hazards in Aotearoa/New Zealand. *Journal of the Royal Society of New Zealand, 37*(2), 59–73. https://doi.org/10.1080/03014220709510536.

Lane, E.M., Thomas, K.L., Schoenfeld, M.R., Wilson, T.M., & Hughes, M.W. (2020). The scientific response to the 14 November 2016 Kaikōura tsunami – Lessons learnt from a moderate event. *International Journal of Disaster Risk Reduction*, *47*, 101636. https://doi.org/10.1016/j.ijdrr.2020.101636

Lindell, M.K., Prater, C.S., Wu, H.C., Huang, S.K., Johnston, D.M., Becker, J.S., & Shiroshita, H. (2016). Immediate behavioural responses to earthquakes in Christchurch, New Zealand, and Hitachi, Japan. *Disasters*, *40*(1), 85-111. https://doi.org/10.1111/disa.12133

Mak, S., & Schorlemmer, D. (2016). What makes people respond to "Did You Feel It?"? *Seismological Research Letters, 87*(1), 119-131. https://doi.org/10.1785/0220150056

McBride, S. K., Becker, J.S., & Johnston, D.M. (2019). Exploring the barriers for people taking protective actions during the 2012 and 2015 New Zealand ShakeOut drills. *International Journal of Disaster Risk Reduction, 37*, 101150. https://doi.org/10.1016/j.ijdrr.2019.101150

Michelini, A., Faenza, L., Lauciani, V., & Malagnini, L. (2008). ShakeMap implementation in Italy. *Seismological Research Letters, 79*(5), 688-697. https://doi.org/10.1785/gssrl.79.5.688

Moratalla, J., Goded, T., Rhoades, D., Canessa, S., & Gerstenberger, M. (2020). New ground motion to intensity conversion equations (GMICEs) for New Zealand. *Seismological Research Letters*, *92*(1), 448-459. https://doi.org/10.1785/0220200156

Musson, R.M.W., & Cecic, I. (2012). Intensity and intensity scales. In P. Borman (ed.), *New manual of seismological observatory practice 2* (pp. 1-41). Deutsches GeoForschungsZentrum. https://doi.org/10.2312/GFZ.NMSOP-2_ch12

Nathan, S. (2015). *James Hector: Explorer, scientist and leader*. Potton & Burton.

Potter, S.H., Harrison, S., Thomas, K.-L., Leonard, G.S., Skilton, J., Apiti, M., Balfour, N.J., Harvey, S., Coomer, M.A., & Kilgour, G.N. (2020). Connecting real-time hazard and impact data with users: Proof of concept of a visualisation tool. *GNS Science Report 2020*(22), 73p. https://doi/org/10.21420/ZJJG-9C59.

Quitoriano, V., & Wald, D. (2020). USGS "Did You Feel It?" – Science and lessons from 20 years of citizen science-based microseismology. *Frontiers in Earth Science, 8*, 1-13.

Sbarra, P., Tosi, P., & De Rubeis, V. (2010). Web-based macroseismic survey in Italy: Method, validation and results. *Natural Hazards, 54*, 563-581. https://doi.org/10.1007/s11069-009-9488-7

Shirk, J. L., Ballard, H.L., Wilderman, C.C., Phillips, T., Wiggins, A., Jordan, R., McCallie, E., Minarchek, M., Lewenstein, B.V., Krasny, M.E., & Bonney, R. (2012). Public participation in scientific research: A framework for deliberate design. *Ecology and Society*, *17*(2), Article 29. https://doi.org/10.5751/ES-04705-170229

Shuttleworth, S. (2021). Old weather: Citizen scientists in the 19th and 21st centuries. *Science Museum Group Journal*, *3*(3), 150304. https://doi.org/10.15180/150304

Steed, R. J., Fuenzalida, A., Bossu, R., Bondár, I., Heinloo, A., Dupont, A., Saul, J., & Strollo, A. (2019). Crowdsourcing triggers rapid, reliable earthquake locations. *Science Advances*, *5*(4), eaau9824. https://doi.org/10.1126/sciadv.aau9824

Stevens, M., Vitos, M., Altenbuchner, J., Conquest, G., Lewis, J., & Haklay, M. (2014). Taking participatory citizen science to extremes. *IEEE Pervasive Computing*, *13*(2), 20–29. https://doi.org/10.1109/MPRV.2014.37

Tosi, P., Sbarra, P., De Rubeis, V., & Ferrari, C. (2015). Macroseismic intensity assessment method for web questionnaires. *Seismological Research Letters, 86*(4), 985-990. https://doi.org/10.1785/0220150127

Van Houtte, C., Bannister, S., Holden, C., Bourguignon, S., & McVerry, G. (2017). The New Zealand Strong Motion

Database. *Bulletin of the New Zealand Society for Earthquake Engineering*, *50*(1), 1-20.

Vinnell, L. J., Wallis, A., Becker, J.S., & Johnston, D.M. (2020). Evaluating the ShakeOut drill in Aotearoa/New Zealand: Effects on knowledge, attitudes, and behaviour. *International Journal of Disaster Risk Reduction, 48*, 101721. https://doi.org/10.1016/j.ijdrr.2020.101721

Viskovic, P., Christophersen, A., Holloway-Bryers, A., & Ferris, B. (2020). Recommendations for organisation, storage and digitisation of paper and film records of seismograms and Felt Reports. *GNS Science Internal Report, 2020*(02), 21p.

Wald, D.J., Dengler, L.A., & Dewey, J.W. (1999a). Utilization of the Internet for rapid community intensity maps. *Seismological Research Letters, 70*(6), 680-697. https://doi.org/10.1785/gssrl.70.6.680

Wald, D.J., Quitoriano, V., Heaton, T.H., Kanamori, H., Scrivner, C.W., & Worden, B.C. (1999b). TriNet "ShakeMaps": Rapid generation of peak ground-motion and intensity maps for earthquakes in Southern California. *Earthquake Spectra, 15*(3), 537-556. https://doi.org/10.1193%2F1.1586057

Wald, D.J., Quitoriano, V., Worden, B., Hopper, M., & Dewey, J.W. (2011). USGS "Did You Feel It?" Internet-based macroseismic intensity maps. *Annals of Geophysics, 54*, 688-707. https://doi.org/10.4401/ag-5354

Wein, A., Potter, S., Johal, S., Doyle, E., & Becker, J. (2016). Communicating with the public during an earthquake sequence: Improving communication of geoscience by coordinating roles. *Seismological Research Letters, 87*(1), 112-118. https://doi.org/10.1785/0220150113

Worden, C.B., Gerstenberger, M.C., Rhoades, D.A., & Wald, D.J. (2012). Probabilistic relationships between ground-motion parameters and Modified Mercalli intensity in California. *Bulletin of the Seismological Society of America, 102*(1), 204-221.

Worden, C.B., Thompson, E.M., Hearne, M., & Wald, D.J. (2020). *ShakeMap Manual Online: technical manual, user's guide, and software guide*, U. S. Geological Survey. http://usgs.github.io/shakemap/. https://doi.org/10.5066/F7D21VPQ.

Appendices

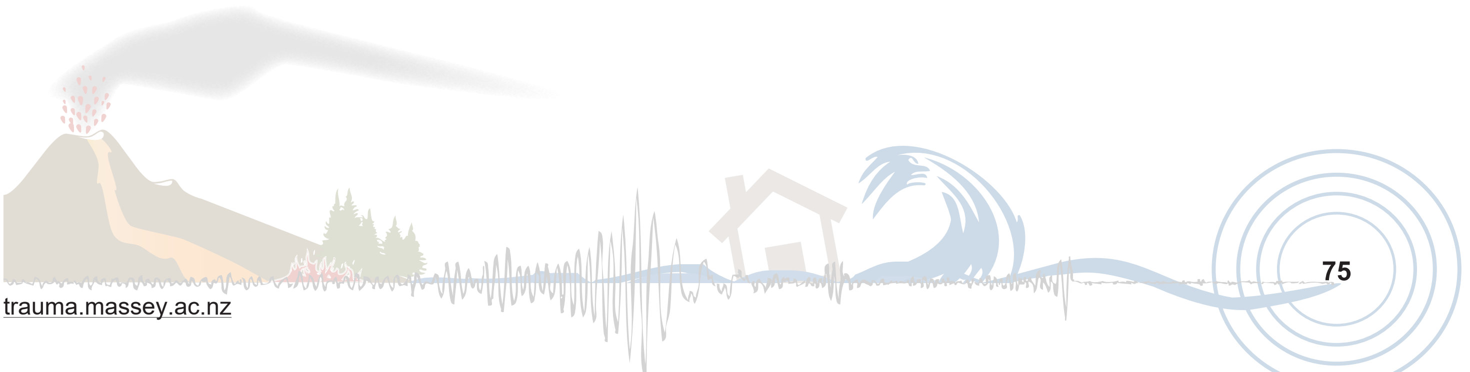
Appendix 1: GeoNet's "Felt Detailed" online questionnaire

Stars mark the questions used to assign a community Modified Mercalli intensity (CMMI)

Reference	Question	Answers
Section 1: General questions		
1*	Details of this earthquake	Public ID Earthquake date Earthquake time (NZST) Earthquake location Magnitude
2*	What was the address of the location where you were when the earthquake occurred?	Street number Street name Suburb Town/City/Locality
3*	At the time of the earthquake were you	Indoors Outdoors In a stopped vehicle In a moving vehicle Not applicable Other (please specify)
4*	What were you doing when the earthquake occurred?	Sitting / Lying Standing Walking/Running Sleeping and was woken up Travelling in a vehicle Not applicable Other (please specify)
5	Did you feel the earthquake?	Yes No
Section 2: Your experience of the earthquake		
6	How long did the earthquake feel (in seconds)?	Open answer
7*	How would you best describe the shaking?	Heard, but not felt Gentle, hardly recognised as an earthquake (like light trucks passing) A jolt or mild, but unmistakably an earthquake (like heavy traffic passing) Moderate Strong, powerful Violent, severe Other (please specify)
8	What was your first response while the earthquake was shaking?	Continued what I was doing before Stopped what I was doing but stayed where I was Dropped, covered under a sturdy piece of furniture (e.g., table or desk), and held on to it Tried to protect other people nearby Tried to protect property nearby (e.g., prevent things from falling) Immediately left the building I was in Continued driving Stopped driving and pulled over to the side of the road Not applicable Other (please explain)
9	What was your reaction?	No reaction Very little reaction Excited but not alarmed A bit frightened Very frightened Extremely frightened Don't know/Not applicable Other (please specify)

Section 3: Earthquake effects within your building		
10*	Did objects such as glasses, dishes, ornaments or other small shelf items rattle, topple over or fall off shelves?	No Rattled slightly Rattled loudly A few toppled or fell off Many toppled or fell off Nearly everything toppled or fell off No shelves with unrestrained objects Don't know/Not applicable
11	Were cupboard or appliance doors thrown open?	No Yes Yes, and contents were ejected Don't Know / Not applicable
12*	Did any items of furniture, appliances (TV, fridge, filing cabinet, computer, microwave) or machinery slide (not just sway) or topple over?	No Yes, slid a little Yes, slid a lot Yes, toppled over Don't know/Not applicable
13*	Did any items of furniture, appliances (TV, fridge, filing cabinet, computer, microwave) or machinery slide (not just sway) or topple over?	Response options: No Yes, slid a little (less than 5cm) Yes, slid a lot (more than 5cm) Yes, toppled over Don’t know/Not applicable Items: TV, Computer, Microwave, Fridge, Filing cabinet, Oven, Light machinery, Heavy machinery
14	Check which services failed, if any:	No services failed Water Electricity Gas Telephone Sewerage Elevators Sprinklers Internet connection Other (please specify)

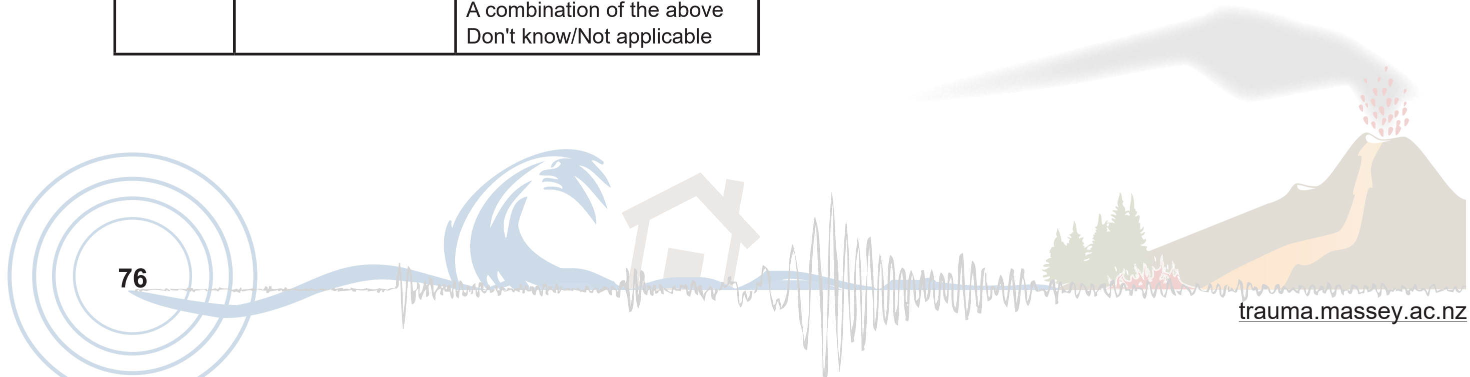
Section 4: Your building		
15	What was the built environment?	Residential Business/Industrial Rural Don't Know / Not applicable
16	Please select the type of building or structure	Family home or flat Low-rise building (e.g. offices, supermarket, church, theatre or warehouse) Multi-storey building I was outside Other (please specify)
17	If you were in a multi-storey building, what floor were you on?	
18	If you were in a multi-storey building, what is the total number of storeys?	
19	When was the building constructed?	Before 1940 Between 1940 and 1960 Between 1960 and 1980 Between 1980 and 1990 After 1990 Don't know/Not applicable
20*	Choose the main building material for the exterior walls that experienced the damage:	Wood Stucco (cement) Brick/stone veneer Concrete block Solid brick Sheet material (fibre cement board, plywood) Don't know/Not applicable Other (please specify)
21	The ground is mainly...	Level or nearly level Steeply sloping/hilly Don't know/Not applicable
22	What is the main type of ground under the building?	Peat/Soil Rock Clay Fill Sand River gravels Don't know/Not applicable
23	Choose the structural style of the building foundations	Unbraced piles Braced piles Perimeter only concrete Concrete slab on ground Raised concrete slab Pole house Don't know/Not applicable Other (please specify)



Section 5: Damage caused by the earthquake to your building		
24*	Was there any damage to…?	Hot water cylinder: *No damage* *Leaked* *Fell over* *Don't Know / Not applicable* Chimneys *No damage* *Horizontally cracked or loose bricks dislodged* *Twisted or broken at roofline* *Fallen from roofline* *Fallen from base* *Don't Know / Not applicable* Elevated water tanks *No damage* *Shifted/leaking* *Twisted and/or brought down* *Don't Know / Not applicable* Entire building *No damage* *Hairline cracks* *Wide cracks* *Segments of walls bulged* *Building lightly distorted* *Building severely distorted* *Segments of walls collapsed* *Some walls totally collapsed* *Don't know/Not applicable*
25*	What other damage occurred? Check all that apply, if any	Some domestic wood-framed windows cracked Some glass fallen out of domestic wood-framed windows Some domestic aluminium-framed windows cracked Some glass fallen out of domestic aluminium-framed windows Some large shop windows cracked Some glass fallen out of large shop windows Hairline cracks in interior walls Cracks around window/door openings in interior walls Major cracks in interior walls Suspended ceilings damaged Masonry or concrete roof tiles dislodged Masonry or concrete roof tiles fallen
26	What do you believe caused the building damage?	Earthquake shaking Landslide Ground cracking or other ground damage A combination of the above Don't know/Not applicable

Section 6: Earthquake effects in your neighbourhood		
27	Are you aware of any effects in your neighbourhood?	Yes No
28*	Did any of the following effects occur? (Tick all that apply)	No visible effects Cracks on dry and level ground Cracks on permanently wet ground Ground cracks on hillsides Ground cracks on ridge tops Landslides or rockfalls from natural slopes Landslides or rockfalls from cut slopes Boulders dislodged Ground slumping of road edges Ground slumping on river banks Ground slumping on hillsides Building damage from landslides or slumps Considerable water splashed over the sides of rivers, lakes or estuaries Considerable water splashed over the sides of swimming pools Water or sand thrown from holes or cracks in the ground, or a lake/river bed Unusual sea level changes within one hour of the earthquake Tsunami Trees and bushes were shaken strongly and some branches/trees broken

Section 7: Tsunami evacuation		
29	If you felt the earthquake, did you think it could trigger a tsunami?	Yes No Unsure Not applicable
30	Did you evacuate?	Yes, I went inland Yes, I went inland and uphill Yes, I climbed up a tree or similar Yes, I went to the upper floor of a building No, I did not evacuate Not applicable Other action (please specify)



Section 8: Earthquake -Tsunami information		
31	When you evacuated, did you…?	Evacuate immediately after the earthquake Look for information to help decide whether or not to evacuate Wait for an official tsunami warning Wait to be told to evacuate Evacuate because you saw others evacuating
32	How many minutes after the earthquake did you evacuate?	
33	What was the main reason you decided to return after you initially evacuated?	When I felt it was safe (after seeing evidence that there was no danger) After discussing with others When I saw others returning After a reasonable time When I received an official 'All Clear' message Other (please specify)
34	How long were you evacuated for?	<1 hour 1-2 hours 3-6 hours 7-12 hours >12 hours Other (please specify)

Section 9: Information about earthquakes		
35	What items of information about earthquakes are the most valuable for you? (Tick all that apply)	General details about what has happened in an earthquake (magnitude, depth, location, shaking intensity, cumulative felt reports about the specific earthquakes) Earthquake forecasts about what might happen in future (e.g., projected numbers of future earthquakes, probabilities of occurrence in the future) Magnitudes of earthquakes Shaking intensities of earthquakes (MM) Peak ground acceleration (PGA) of specific earthquakes Impacts of earthquakes (e.g., damage, loss) None of the above Other (please specify)
36	When you talk to family/friends/ neighbours about the earthquakes, what do you most talk about? (Please specify)	
37	The tone and information provided by GeoNet is: (Tick one answer on each line) a. Too scientific. Can't understand it. b. Too general. Not enough specifics. c. Just right. In the middle	Strongly agree Agree Neutral Disagree Strongly disagree

Section 10: Demographic Information		
38	Age: year of birth	
39	Gender	Male Female Gender diverse Prefer not to disclose
40	Final comments	

Appendix 2: GeoNet's "Felt RAPID" questionnaire

Choose the shaking that best describes your experience.

Weak Shaking

- Vibration similar to a light truck driving past
- Hanging objects may swing slightly

Light Shaking

- Vibration similar to heavy traffic passing, or a sharp jolt
- A light sleeper may be awakened
- Walls may creak
- Glassware, crockery, doors of windows rattle

Moderate Shaking

- Most sleepers are awakened
- Pictures knock against the wall
- Open doors may swing open and shut
- Some glassware and crockery may break

Strong Shaking

- Walking is difficult
- Furniture and appliances may move on smooth surfaces
- Objects fall from walls or shelves
- Appliances move on bench or table tops
- Glassware and crockery break

Severe Shaking

- Standing is difficult
- Furniture and appliances are shifted
- Cracks in walls or ceilings may occur
- Substantial damage to fragile or unsecured objects

Extreme shaking

- Buildings are damaged or destroyed.

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).

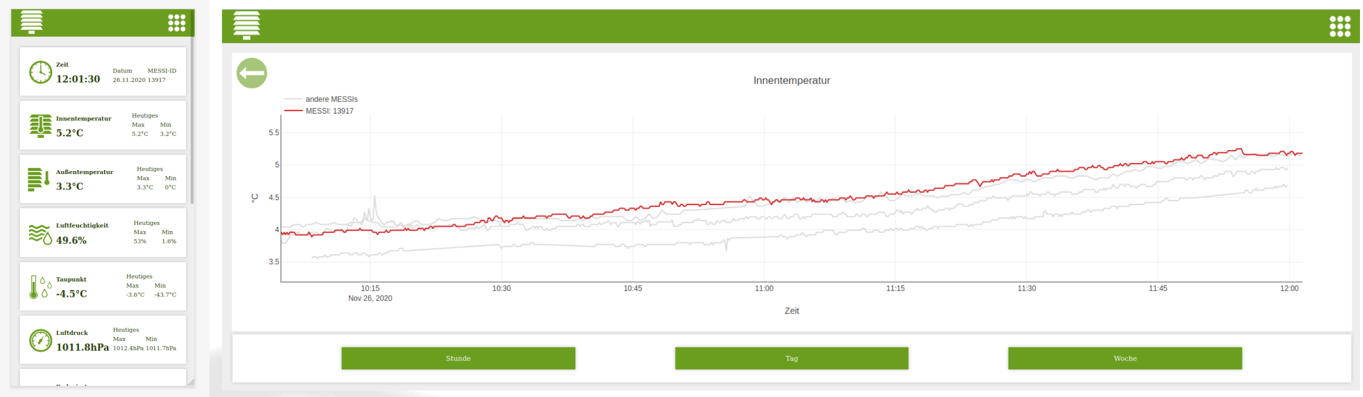
Figure 1
MESSI with Attached Tipping Bucket Rain Gauge to Collect Precipitation

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

The students 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, 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



Zeit 12:01:30 Datum 26.11.2020 MESSI-ID 13917

Innentemperatur 5.2°C Heutiges Max 5.2°C Min 3.2°C

Außentemperatur 3.3°C Heutiges Max 3.3°C Min 0°C

Luftfeuchtigkeit 49.6% Heutiges Max 53% Min 1.6%

Taupunkt -4.5°C Heutiges Max -3.6°C Min -43.7°C

Luftdruck 1011.8hPa Heutiges Max 1012.4hPa Min 1011.7hPa

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.

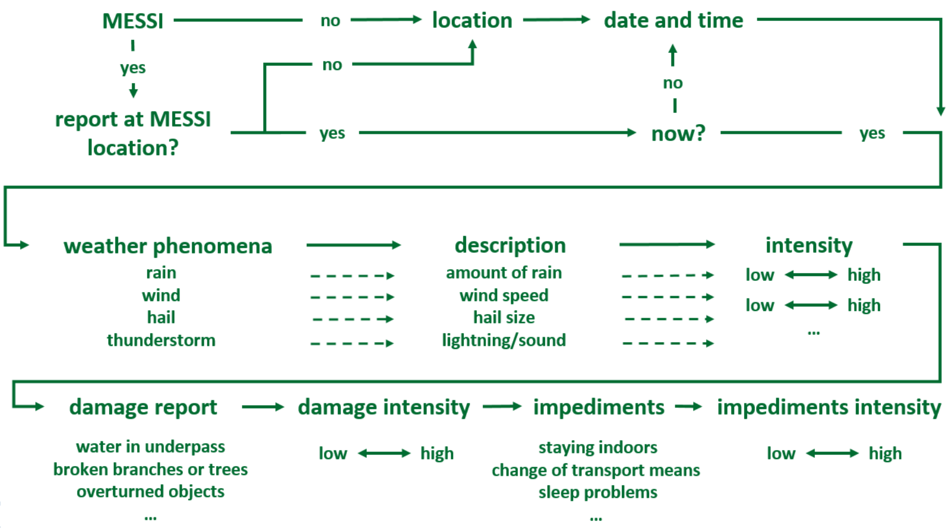
In order to be able to statistically adjust measurements inside the radiation shield later, there is a second thermometer outside the radiation shield not affected by the thermal inertia of the housing but exposed to radiation. The radiation sensor also offers a further possibility to correct the temperature 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.

Figure 3

Schematic Weather and Impact Reporting Procedure



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.

Preliminary Data and First Insights

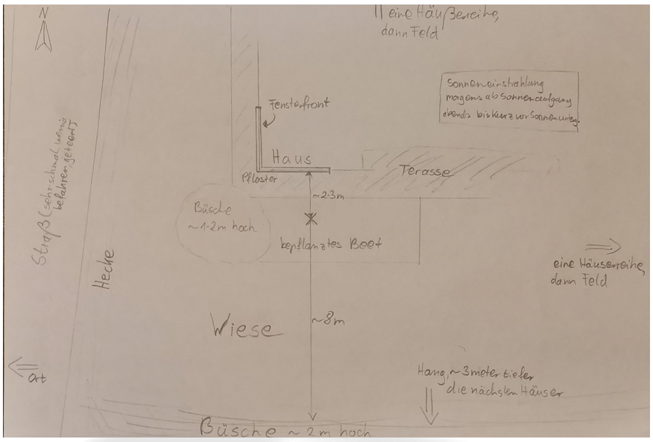
The data was first analysed together with the students in digital workshops in November 2020. Due to the limitations in collaborative work during the pandemic, we concentrated on three main aspects: 1) the measuring site, 2) data collection, and 3) project evaluation. The project also ran in the summer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



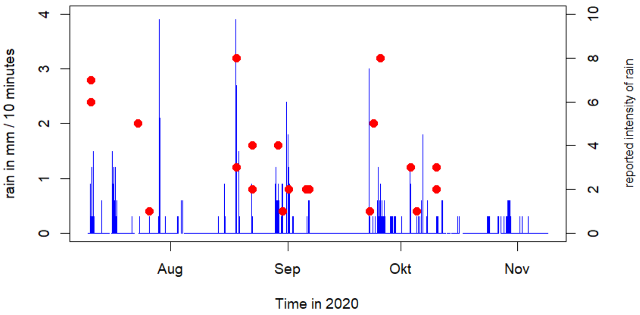
Note. The cross in the centre denotes the location of the MESSI. Objects are labelled (e.g., house, terrace, street, hedge), a height (bushes 1-2 metres) and a distance (2-3 m from MESSI to house), and the north arrow are given.

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

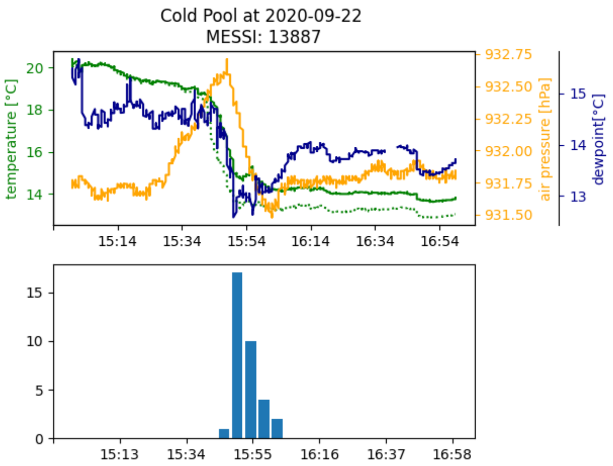
10-Minute Rainfall Accumulation and Reported Intensity



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.

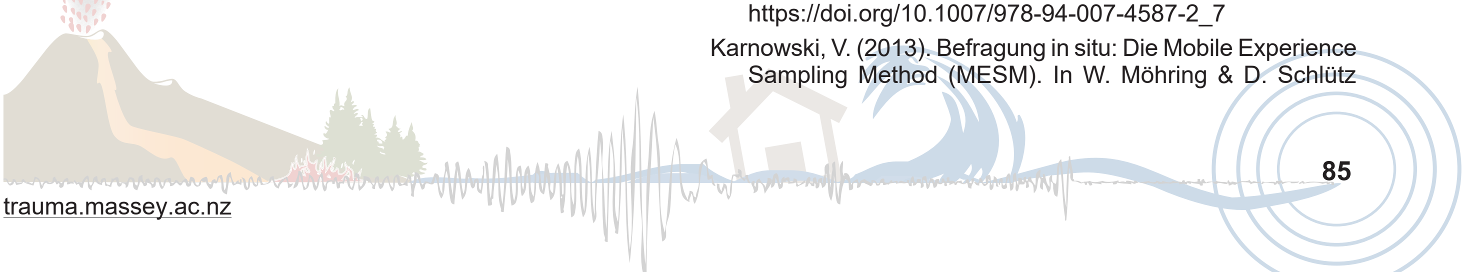
Elevant, K. (2010). Collaborative observations of weather: A weather information sharers' community of practice. In *Proceedings of the 6th International Conference on Web Information Systems and Technology* (pp. 392–399). SciTePress - Science and and Technology Publications. https://doi.org/10.5220/0002810203920399

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

Experience from large-scale crowdsourcing via weather apps

Harald Kempf[1]

[1] German National Meteorological Service, Offenbach, Germany.

Author correspondence:
Dr. Harald Kempf,
Deutscher Wetterdienst
- Zentrale -
Frankfurter Straße 135
63067 Offenbach am Main
Germany.
Email: harald.kempf@dwd.de

URL: http://trauma.massey.ac.nz/issues/2021-3/AJDTS_25_3_Kempf.pdf

Abstract

This practice update presents the experience of launching a large-scale crowdsourcing feature using categorized user reports through an established weather app in Germany. Starting from the motivation for using crowdsourcing, this paper covers all development stages of the campaign from design through to legal considerations to the final rollout of the feature and first data analysis. Of particular focus is parameter choice and the possibility for automatic plausibility checks. We found that the newly-designed crowdsourcing feature was widely embraced by app users, which led to a very high number of reports. Analysing a sample dataset of approximately 660,000 observations from July to November 2020, we provide insight on data composition and quality of the reports as well as examples of the data integration into operational procedures. We offer some recommendations for potential new crowdsourcing campaigns based on our preliminary experience. Finally, we discuss possible future extensions as well as options to introduce standards and achieve an international data exchange.

Keywords: *Crowdsourcing, app, weather, best practice*

Crowdsourcing offers the chance to gather previously unavailable data on meteorological phenomena and thus greatly add to existing observation capabilities of meteorological services. Crowdsourcing as a form of citizen science, where members of the public are encouraged and supported to provide data, has the potential to mitigate problems and insufficiencies such as a lack of observation capacities (e.g., hail, snow depth) or sparse measuring networks. Furthermore, it can capture the actual impact on people of meteorological phenomena as a new type of measurement. This data offers the potential to connect local meteorological forecasts to local impact and thus greatly increase the usability and value of severe weather warnings.

Data obtained via crowdsourcing has an extremely wide range of potential applications. It can be employed to benefit forecasting and warning services, be used in assimilation and *nowcasting* (forecasting on a very short time scale), and as potential on-the-ground data for verification of forecasts and warnings. Consequently, a rising number of meteorological services launch new crowdsourcing campaigns, strengthen connections to voluntary weather observers and storm spotters, or make use of existing crowdsourced datasets. An overview of European meteorological services activities in this field is presented in Krennert et al. (2018) while organizations such as the European Meteorological Services Network (EUMETNET) and the World Meteorological Organization (WMO) are also developing inventories of existing crowdsourcing approaches to increase their visibility. Within the scope of this paper, we will focus on the aspect of crowdsourcing via categorized reports by untrained users with a focus on high-impact weather.

Design and Implementation

The German National Meteorological Service (DWD) operates an established weather app called WarnWetter, with approximately 10 million downloads and an active userbase of about one million users per month. This app was extended to include a new feature for crowdsourced weather reports by anonymous app users. While the basic version of the app is freely available on multiple app stores (e.g., https://play.google.com/store/apps/details?id=de.dwd.warnapp), the new feature could only be provided to users of the paid version of WarnWetter due to legal restrictions.

Designing the new crowdsourcing functionality required the consolidation of a wide array of requirements. Initially, stakeholder mapping was performed to identify the useful parameters to be obtained. These parameters of interest were investigated in regard to existing experience of other crowdsourcing actors (mostly other meteorological services) and possible existing standards for reporting (e.g., typical categories and thresholds). Ultimately, a selection of categories and values was made in a compromise between the demands of different stakeholders (e.g., forecasters, model developers, special users) and a range of existing crowdsourcing approaches, in order to ensure the compatibility of potential future data exchanges.

Other important concerns were user friendliness and simplicity of the implementation. The overwhelming majority of users will most likely not be able to accurately report phenomena on a fine-grained meteorological scale. The final parameter set was partially composed of meteorological and impact-based parameters (see Table 1). User reports feature observations in standardized categories with corresponding values and special attributes. In addition, they can optionally report text comments and pictures of meteorological phenomena or impact.

Functionality and user interface design was implemented to allow for seamless integration into the existing app framework. The whole reporting process was required to be straightforward and fast in order to make it accessible for a wide range of potential users. Another major effort was the preparation of the legal framework around the crowdsourcing feature both in regard to collecting, storing, and processing potentially personal data and in regard to displaying raw user input, especially including user pictures, within a governmental app. Consequently, a strict opt-in is required to use the crowdsourcing feature. The according terms and conditions have to be accepted during registration or at a later point. Users can opt-out of the feature at any time.

Table 1
Overview of Parameter Categories as Presented in the App and Associated Plausibility Checks

Category	Value scale	Plausibility check
Lightning	4 levels, meteorological	Lightning or radar
Wind	5 levels, meteorological	Wind or radar data from numerical weather prediction (NWP)
Hail	6 levels, meteorological	Radar
Rain	5 levels, impact	Radar and cloud area fraction (CAF)
Slipperiness	3 levels, meteorological	NWP temperature
Snowfall	3 levels, meteorological	Radar or CAF and NWP temperature
Snowcover	5 levels, meteorological	NWP temperature
Cloudiness	4 levels, meteorological	CAF
Fog	3 levels, meteorological	-
Tornado	6 levels, impact	Radar

Note. In most cases numerical, meteorological values are used as a scale (e.g., time between strikes for lightning intensity). Wind initially had an impact-based scale, which was abandoned in favour of a meteorological scale (inspired by Beaufort) in order to better accommodate user reporting preferences.

To address potential privacy concerns, reporting was implemented quasi-anonymously. In order to prevent sabotage and harmful reports, a random device ID is associated with each report. Since this token is fully randomized and independent of personal data (such as other accounts or device hardware), it is not considered to be personalized information according to German law. It is also not possible to de-anonymize any users and observations are stored with only 250 metre spatial accuracy to avoid potential identification or tracking of users. Thus, overall the stored data does not qualify as "personal data", which drastically simplifies the handling and offers full General Data Protection Regulation compliance.

Users can optionally add pictures to their observations, submitted under a CC0-like licence which offers maximum flexibility to use and share the data. Due to peculiarities in German law, the CC0-licence could not be used directly and copyrights remain with the users. However, DWD gains all rights to use the data according to the terms and conditions.

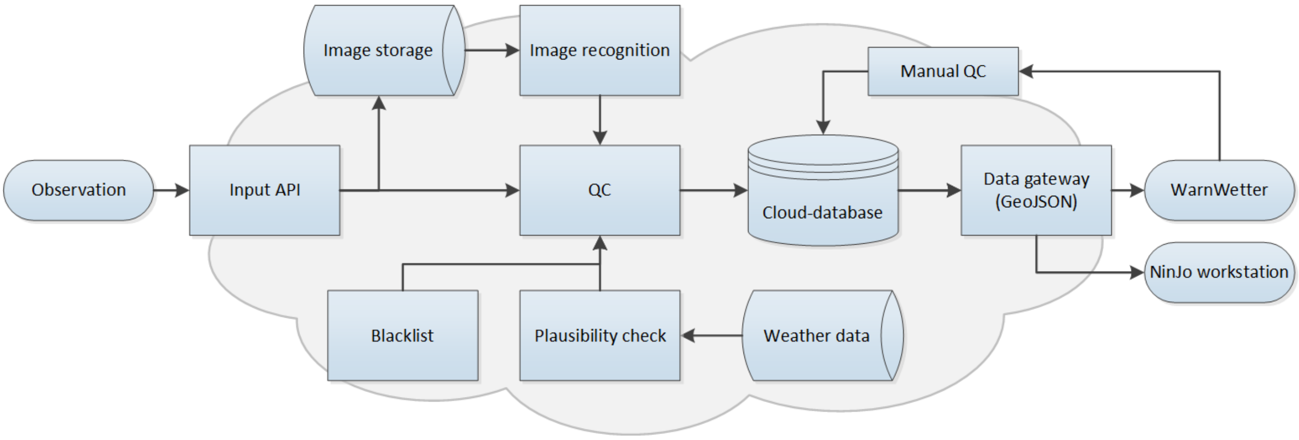
Especially considering the potential display of illegal or harmful images in the app, further measures were taken in order to minimize this risk. Automatic unsafe content detection is applied to any user images. Images with clearly visible persons or body parts are flagged and not displayed in the app. Furthermore, reporting options for users have been implemented to instantly prevent any harmful images from being displayed.

To avoid potentially misleading false observations, a plausibility check was implemented in the application's backend. The algorithm compares user observations to different datasets of existing meteorological observations and forecasts (predominantly radar measurements and NWP data) and automatically flags suspicious observations. Messages flagged as suspicious are not displayed to other users but are kept for further processing.

Data is stored in a cloud-hosted database and a web endpoint has been created which provides reports as GeoJSON (JavaScript Object Notation) files. Furthermore, an on-site data archive has been implemented at DWD. A schematic of the data processing is provided in Figure 1. At the end of the concept and development phase, extended testing of the new crowdsourcing feature was performed through pre-existing development channels.

Figure 1

Data Flow in the App Backend



Note. A plausibility check is applied to every observation in multiple steps. Most importantly, there is a comparison to existing weather data from radar, lightning measurements, satellite, and NWP. Observations are stored in a SQL-database and provisioned via a web interface in GeoJSON format.

Rollout and Early Observations

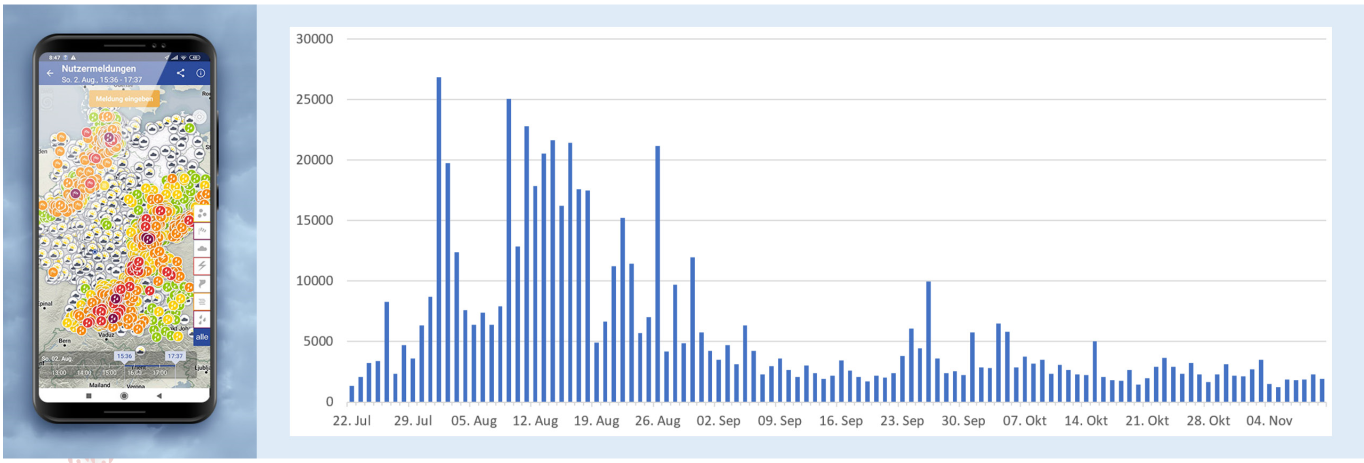
The crowdsourcing feature was released to users using a staged rollout over the course of 1 week without any major technical difficulties. As the functionality was designed for intuitive usability, only a short introduction was provided to users in addition to minimal explanatory help text within the app.

Shortly after the full rollout, an overwhelming number of more than 26,000 messages per 24 hours was observed in a heavy rain event (as seen in Figure 2). Due to the very high number of messages and the maximum display period of 24 hours in the app, older smartphones were under serious stress when rendering all observations. As a quick response, the timeframe of messages to be displayed by default was limited to 1 hour in a point release. Further performance tweaks and new functionality were quickly provided in another full release. After the initial surge, the number of reports steadily decreased down to a baseline level of about 2,500 reports per 24 hours with expected spikes in severe weather situations (see Figure 2).

For a more detailed first analysis of observations, a subset recorded between the release of the feature on the 7th of July and the 11th of November 2020 was selected. This subset comprises about 660,000 observations from about 125,000 unique active contributors. Analysis revealed that the majority of observations were provided by casual (rather than consistent) users, with about 41% of users reporting only once. If this is due to users only testing out the new functionality or due to reporting only in a severe weather event is still to be evaluated. Another

Figure 2

Crowdsourcing Screen in the App WarnWetter and Number of Reports During a Heavy Rain Event on 2nd August 2020.



Note. Left side of figure: Crowdsourcing screen in the app WarnWetter as seen by users during a heavy rain event on 2nd of August 2020. Right side of figure: Total number of reports per day for the sample period from the official launch on 7th of July until the 11th of November.

47% of users reported up to 10 observations and about 7% up to 20. Of the remainder, 5% reported more than 20 times and about 0.5% of users contributed more than 100 reports each. A few users even actively scripted reports to be provided by their personal weather stations and webcams even though no API was provided.

About 8.5% of messages in the sample set included an accompanying image. The majority of images were reported in association with observations of cloudiness (about 80% overall). Nevertheless, a wide range of high impact situations featured in the user pictures (see Figure 3). User pictures were overall useful, especially for high impact situations such as slippery conditions. Only a few cases of false reports were observed (e.g., using images copied from the Internet) and almost no harmful reports (all of which were filtered by the unsafe content detection) even though reporting was de facto performed anonymously. Only 0.01% of images were reported by users to be problematic, and most of these reports were actually false positives.

Meteorologically-false reports were flagged reasonably well by the automatic plausibility checks, due to the fact that many false reports were drastically wrong (e.g., reports of F3 tornadoes in calm weather). Only 0.4% of observations were reported at least once by other users to be not accurate, suggesting that the automatic control was sufficiently restrictive.

However, any plausibility checks need to be carefully crafted to allow for previously unknown data to be accepted when comparing to pre-existing conventionally measured or predicted data. As the sample period was mainly covering late summer and autumn, the observed high rejection rates for typical winter parameters such as snowfall, snow cover, and slipperiness are to be expected. For some categories such as lightning, hail, and wind however, the high number of flagged messages indicates that the initial choice of plausibility checks was too restrictive (see Figure 4). While this is not necessarily harmful (no false reports are displayed), the omission of potentially useful reports should be minimized.

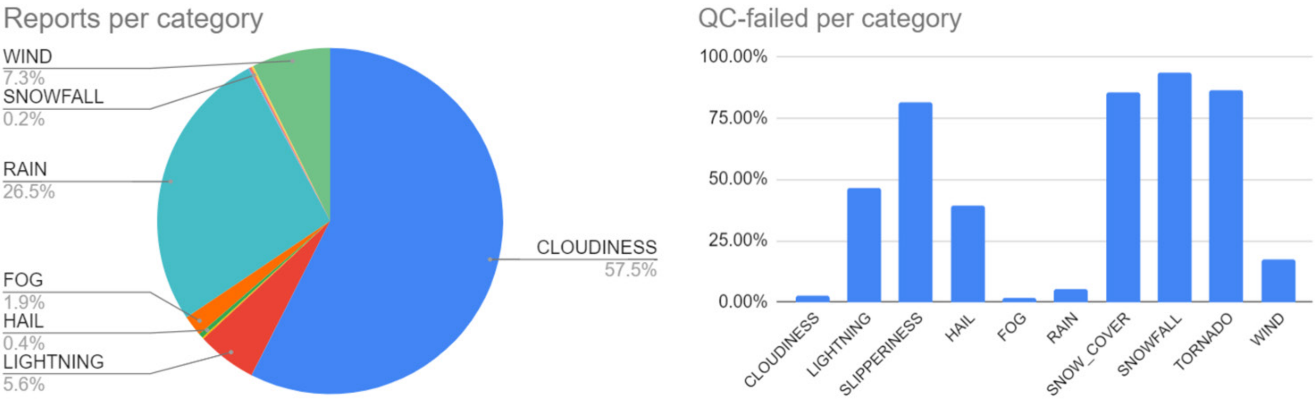
Figure 3

Sample of User Pictures Provided Through the App

Note. Overall about 9% of messages included pictures, with a strong focus on cloudiness. Visual confirmation of the impact can be beneficial, especially for forecasters and users in civil defence.

Figure 4

Reports and Plausibility Check Failures per Category



Note. Left side of figure: Distribution of reports throughout the different categories. Right side of figure: Percentage of messages that failed the plausibility checks per category. Sample subset with 660,000 observations from July to November 2020.

Conclusions and Recommendations

Overall, the algorithm for automatic plausibility checks performed reasonably well. Manual plausibility checks could in principle be performed (e.g., by forecasters on duty). It would be beneficial to implement a two-stage process which combines an automatic flagging with a manual plausibility check. Manual inspection could thus be limited to suspicious reports only, making it much more feasible. Further automated plausibility checks via clustering would also be an option; however, the data is usually only available with sufficient density in urban regions. Automatic plausibility checks need to be carefully tuned and balanced for optimal performance between too permissive and too restrictive. In countries with strong seasonal differences, parameters for the checks might need to be split into independent summer and winter sets.

We also observed an interaction between reporting options offered to the users and plausibility checks. If citizens' willingness to report a meteorological phenomenon is high but there is no suitable reporting category provided, citizens may tend to misuse categories or thresholds. This is likely one reason behind the elevated level of wind observations flagged as suspicious (see Figure 4). Users were initially offered the option to report damaging effects of wind only, but they also wanted to report strong wind without damage. This led to a mismatch between observations and reports that was flagged by the plausibility check, as predicted wind speeds were not likely to cause any damage.

In response, the wind scale was adapted to match the user expectations more closely, moving away from an impact scale with three levels to a meteorological scale with five levels. A continuous monitoring of data quality and trends (e.g., high percentages of observations flagged by the automatic plausibility check) is strongly advised, especially in the early phases of a crowdsourcing campaign.

Any necessary changes in the reporting values or plausibility check parameters need to be carefully deliberated and meticulously tracked. Overall, the creation of a versioning system for these profiles seems advisable in order to keep track of all changes and to provide information on the exact profile used for a specific observation at any time. Especially for the use of crowdsourced observations in the context of numerical weather prediction and the operational production chain, the data and metadata quality are of extreme importance (Nipen et al., 2019).

When planning a new crowdsourcing effort, it is also necessary to reserve ample time for legal preparations during development, as challenges of data and privacy handling can be quite demanding depending on the local laws. Aiming for the minimal required amount of personal information and a *privacy by design* approach is often the key to being compliant to data protection laws, as illustrated throughout the current paper. Data minimization also has a positive effect on data handling and long-term storage.

When launching a new crowdsourcing campaign, it is important to estimate the initial number of observations that will be sent in, especially since this amount will also strongly depend on the severity of the current weather. A scalable implementation of all required components is therefore paramount to provide sufficient capacity reserves and a satisfactory user experience.

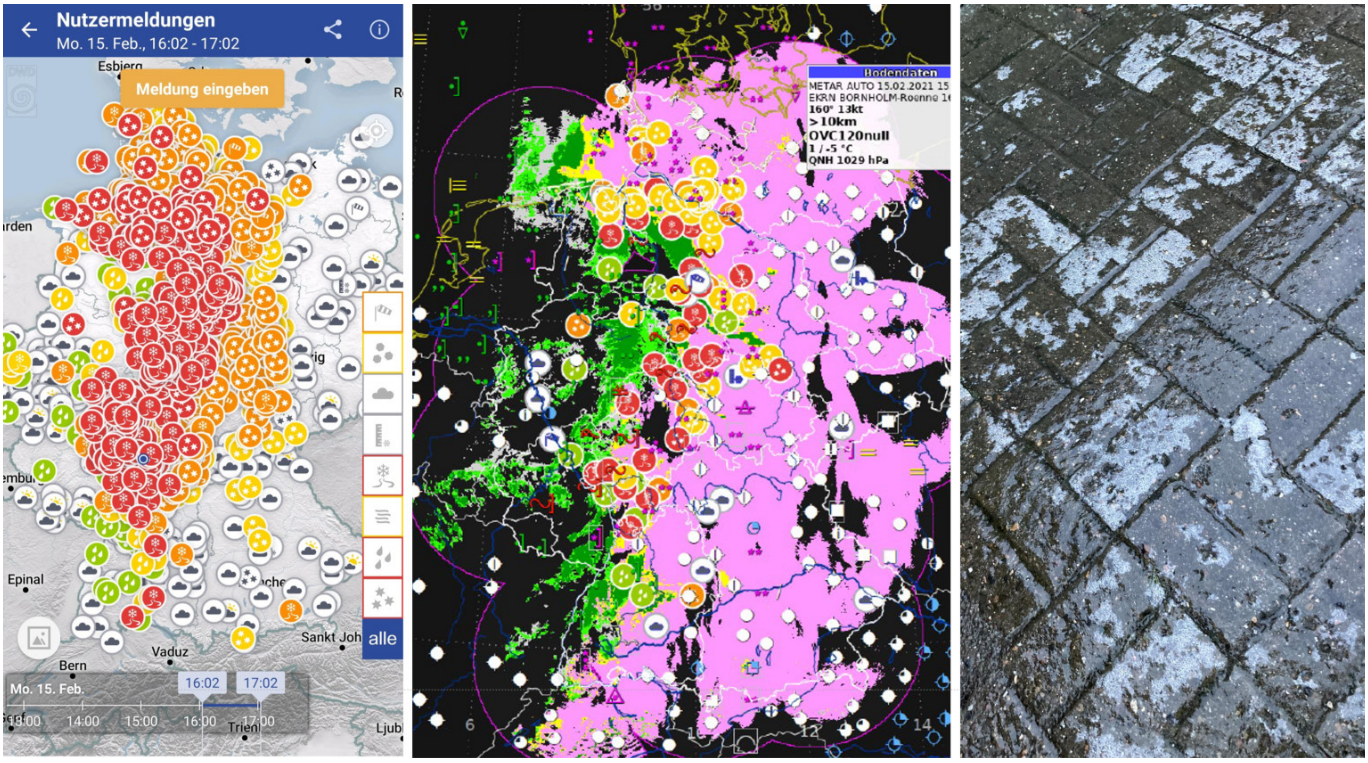
Further, any new feature that is to be released for the use of the general public should have early large-scale testing followed by a small-scale rollout in order to avoid potential problems. Early testing by a dedicated user group also offers the chance for an overall more participatory nature of user involvement, potentially even actively including users in development cycles in a citizen science approach (Sturm & Martin, 2019). This approach is especially useful in order to find a good match for the offered reporting options between user expectations and expert needs. Key stakeholders such as emergency managers can be involved at this stage in order to tailor the functionality and results to their needs.

Close involvement can also have an educational aspect by increasing the sensibility of users to high-impact weather situations. Citizens can act as weather/impact observers via active queries ("Is there fog at your location?") or to verify forecast and warning accuracy ("Was there a thunderstorm at your location?"; "Was this warning accurate for you?"). Such participatory approaches might also offer better verification options, as the direct use of impact data in verification remains largely challenging due to a number of factors such as missing correct negatives (Crocker, 2018).

Another option for strengthening the involvement of users is aligned education programmes or gamification efforts. This can help to further increase the understanding of meteorological phenomena and severe weather risks and motivate users to maintain their reporting. Approaching special user groups such as trusted spotters, storm chasers, or citizens in civil defence can

Figure 5

Use of Crowdsourcing Data in Forecasting



Note. Left panel: Situation during a freezing rain event in February 2021 as seen in the app. Middle panel: The NinJo forecaster workstation as a filtered dataset in conjunction with data on the precipitation phase. Right panel: Sample of user-provided impact images during the event.

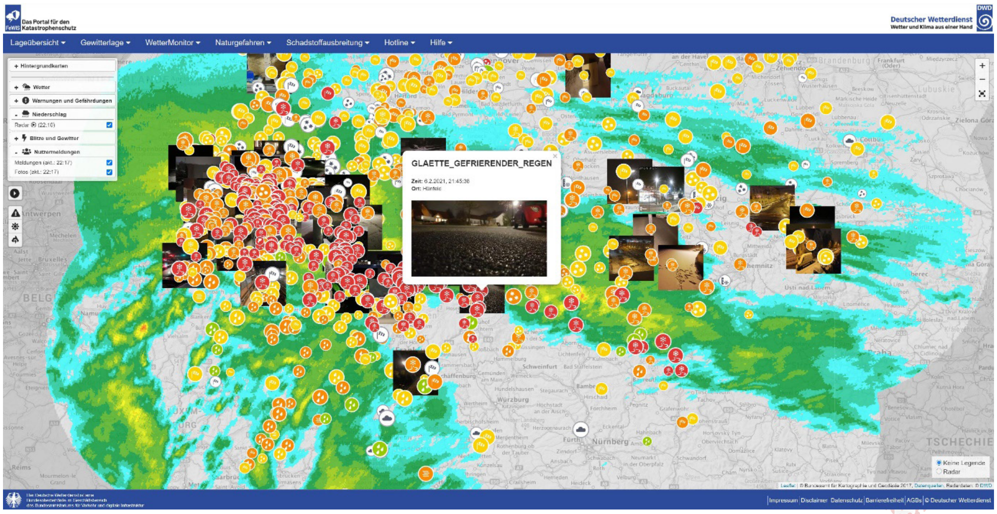
offer potentially better observations as well as create a group of dedicated, trustworthy observers.

Data integration into existing systems and availability as datasets in common formats should be a high priority in order to make the best use of the data. Integration into operational systems also has the potential to provide an easy mechanism for manual quality control insofar as the systems can be extended to include according editing tools. Of central importance is the early integration into forecaster workstations, so that the data can be actively used to improve forecasts and warnings in high-impact situations. An example of this integration can be seen in Figure 5 for a high-impact freezing rain event. Both the general public and the forecasters benefited from the highly localized impact information gathered through crowdsourcing.

Crowdsourcing data was also directly provided to situation rooms and special users in civil defence via the fire brigades weather information (FeWIS) system, thus raising situational awareness and enabling a swifter and more precise response to the high impact event (see Figure 6). Especially for users in civil defence and emergency management, real-time impact information

Figure 6

Integration of Crowdsourcing Data Directly Within the FeWIS System for Special Users in Civil Defence



Note. Localized impact information can provide valuable insight into the current situation and the expected development during a high impact event (in this example, freezing rain and snowdrift).

is a key requirement, which in many cases cannot be provided by conventional meteorological measurements.

When displaying impact data from crowdsourcing, the choice of the right colour scale for visualization is of great importance. In our campaign, report categories were mapped to DWD´s warning thresholds and thus made use of the official four-colour scheme used in warnings. Preliminary analysis suggests that untrained users will have a tendency to report systematically stronger impacts than expected. Wind reports were a prime example of this tendency with users reporting hurricane force winds even in normal storms, potentially due to a subjectively felt higher impact or due to the rarity of the event. Consequently, it might be advisable to update the mapping of parameter colours if this mismatch becomes too strong, or to choose an independent colour scheme.

Full documentation including versioning metadata and in an accessible format such as GeoJSON facilitates the use of crowdsourced data by other actors and especially in research and development. Potential first steps include comparisons to other conventional observation sources to create trust in the new data source. This also makes it possible to draw on existing experience, for example in the comparison of data to radar observations (Barras et al., 2019). Especially in urban regions, the density of crowd observations will be very high (Meier et al., 2017) and accordingly the data can be of great use in climatological modelling of urban heat islands and city planning (Venter et al., 2020). Extensive experience exists for automated crowdsourcing (e.g., through private weather stations) – associated cross references can in part also be helpful for quality control in non-automated crowdsourcing (Fenner et al., 2017). If user images are part of the crowdsourcing effort, sophisticated data analysis tools such as machine learning can be employed for automatic classification and to build up impact databases. Through aligned datasets, the impact classification can be improved even further, especially for stakeholders in emergency management.

Involvement in international efforts to create standards is advisable, as the same platforms can also offer information on common best practice in crowdsourcing. Aligned efforts include the WMO High-Impact Weather (HIWeather) Citizen Science program and the EUMET crowdsourcing working group. Cooperation will also foster the potential for standardization, joint quality control techniques, and international data exchange.

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://doir.org/10.1175/BAMS-D-18-0090.1

Crocker, R. (2018). Can ad-hoc citizen observations be used to verify weather warnings? *Meteorologische Zeitschrift, 27*(6), 455-465. https://doi.org/10.1127/metz/2018/0879

Fenner, D., Meier, F., Bechtel, B., Otto, M., & Scherer, D. (2017). Intra and inter 'local climate zone' variability of air temperature as observed by crowdsourced citizen weather stations in Berlin, Germany. *Meteorologische Zeitschrift, 26*(5), 525-547. https://doi.org/10.1127/metz/2017/0861

Krennert, T., Pistotnik, G., Kaltenberger, R., & 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

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. 10.1016/j.uclim.2017.01.006.

Nipen, T., Seierstad, I., Lussana, C., Kristiansen, J., & Hov, Ø. (2019). Adopting citizen observations in operational weather prediction. *Bulletin of the American Meteorological Society, 101*(1), 43-57. https://doi.org/10.1175/BAMS-D-18-0237.1

Sturm, U., & Tscholl, M. (2019). The role of digital user feedback in a user-centred development process in citizen science. *Journal of Science Communication, 18*(1), Article 3, 1-19. https://doi.org/10.22323/2.18010203

Venter, Z., 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,* 111791. https://doi.org/10.1016/j.rse.2020.111791

This page intentionally left blank.

Instructions for Authors

This journal has been established to provide a resource for the Australasian region (New Zealand, Australia and the Pacific), and as such we prioritise and seek contributions from Australasia. We will occasionally consider contributions from other parts of the globe but only if the articles cover issues directly relevant to an Australasian readership.

MANUSCRIPT FORMAT:
Well written English manuscripts of NOT MORE THAN 10,000 words will be considered for publication.

The format and style of the article, including referencing, must follow current American Psychological Association (APA style) conventions.

Authors are requested to supply an abstract of no more than 300 words when submitting an article. The abstract should be a condensed, accurate representation of the rationale, methodology, significant results, conclusions and recommendations contained within the article.

Authors should also provide 4 - 5 keywords that clearly describe the subject matter of the article. Other options for manuscript formats are provided at http://trauma.massey.ac.nz/info/submissions.html.

TABLES, FIGURES AND GRAPHICS:
Each table and figure should possess a brief title and a concise description of its content and should be included in full at the end of a manuscript.

Care should be taken to ensure that tables and figures will be viewable within the limitations of web browsers. Tables and figure numbers and titles should also be inserted into the manuscript text at an appropriate position.

Other pictures or other graphics required for the article should be attached as separate files.

Web compatible GIF, PNG or JPG image formats are preferred.

OTHER DETAILS:
Contributions should be original and not published or submitted for publication in any other journal, electronic or otherwise.

One corresponding author should be designated. Their email address should appear on the manuscript cover page.

As an electronic journal, article reprints will not be provided in the traditional sense. Authors wishing to distribute published copies of their article may do so with the proviso that they clearly acknowledge the source of the publication.

Papers should be submitted, in Microsoft Word format, to the editor via email: **ajdts@massey.ac.nz.**

Peer Review Process

On receipt of an article, the editor will assess its appropriateness for inclusion in the Journal. If the content of the article is appropriate and in an acceptable format, the editor will send the article for review. A final decision on acceptance will be made after the submission has been reviewed.

Acceptance or rejection of a contribution will be based on the "blind" peer review of a submission by at least two members of either the Editorial Board or by others invited to review the article due to their particular expertise. The editors will make a decision to accept, seek revision, or reject a contribution based on the reviewers' comments and recommendations. Contributors will receive a copy of the reviewers' comments at the same time as they receive a response from the editor. Copies of reviews and the editors' decision will also be sent to each reviewer. It is anticipated that the review process should take from 6 to 8 weeks.

The Editor will assume that the paper is an original contribution. Papers appearing in the journal should not be published elsewhere without the written consent of the Publisher of the journal. A copyright declaration will be required of all papers accepted for publication.

Contact Details

WORLD WIDE WEB SITE
Australasian Journal of Disaster and Trauma Studies
http://trauma.massey.ac.nz/

EDITOR
Professor David Johnston
Email: D.M.Johnston@massey.ac.nz
Telephone: +64 (04) 801 5799 ext. 63672

MANAGING EDITOR
Lauren Vinnell
Email: ajdts@massey.ac.nz

POSTAL ADDRESS
Joint Centre for Disaster Research
Massey University
P.O. Box 756
Wellington 6140
New Zealand

PUBLISHED BY: SCHOOL OF PSYCHOLOGY, MASSEY UNIVERSITY, NEW ZEALAND