

**Authors' answer to editor's request for additional minor revision regarding the paper “Rapid collaborative knowledge building via Twitter after significant geohazard events”  
by Lacassin R. et al., Geoscience Communication Discussion, 2019.**

In our second revision we have accepted and implemented all changes suggested by the Editor. The modifications are shown in red on the marked-up text that follows (as there are no changes to the figures / figure captions, we do not append the figures to this marked-up Ms - refer to the complete Manuscript revision 2 file).

# Rapid collaborative knowledge building via Twitter after significant geohazard events

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## Abstract

Twitter is an established social media platform valued by scholars as an open way to disseminate scientific information and to publicly discuss research results. Scientific discussions on Twitter are viewed by the media who can then pass on information to the wider public. Social media is used widely by geoscientists, but there is little documentation currently available regarding the benefits of this to the scientist and the public, or the limitations. Here, we take the example of two 2018 earthquake-related events which were widely commented on Twitter by geoscientists: the Palu  $M_w$ 7.5 earthquake and tsunami in Indonesia and the long-duration Mayotte island seismo-volcanic crisis in the Indian Ocean. We build our study on a content and contextual analysis of selected Twitter threads about the geophysical characteristics of these events. From the analysis of these two examples, we show that Twitter promotes very rapid building of knowledge in the minutes to hours and days following an event via an efficient exchange of information and active discussion between the scientists themselves and with the public. We discuss the advantages and potential pitfalls of this relatively novel way to make scientific information accessible to scholarly peers and to lay people. We argue that scientific discussion on Twitter breaks down the traditional "ivory towers" of academia, participates to the growing trends towards open science, and may help people to understand how science is developed, and, in the case of natural/environmental hazards, to better understand their risks.

# 1 - Introduction

In the aftermath of a potentially destructive natural event, such as a powerful earthquake, tsunami, volcanic eruption, or major landslide, it is crucial to rapidly determine its key geophysical and geological characteristics. With such evidence-based understanding, the geoscientific community can credibly explain the phenomenon to the media and stakeholders. Geoscientists can also disseminate the information to people directly affected by the disaster and engage discussion with them (e.g., Stewart et al., 2018). A rapid understanding is also crucial to evaluate the risk of cascading events (e.g., triggered earthquakes), such as the 2016 central Italy earthquakes (Chiaraluce et al., 2017; Patton, 2016), and to direct further scientific actions. Decades ago, this understanding was achieved at a much slower pace and within closed research teams by a progressive acquisition of geophysical data via time-consuming field surveys. This process often took months to reach a good understanding of the event's characteristics. Thanks to worldwide geophysical instrument networks (e.g., global and regional seismic networks) and satellites (e.g., optical or radar imagery), together with open data, researchers now generally have enough information to get a satisfactory first-order description of the geophysical event, and an estimation of its potential consequences, within days (e.g., Hayes et al., 2011). Scholarly interactions via social media, sometimes involving citizen expertise and observations, may transform both the timeliness and the way our geophysical understanding is built and shared (Hicks, 2019; Williams and Krippner, 2019).

Twitter stands as a very efficient and simple tool to publicly disseminate scientific information and rapidly engage in discussion about the cause and implications of geological events (Choo et al., 2015; Landwehr et al., 2016; Lee, 2019; Takahashi et al., 2015). While Twitter is not the most popular social media platform, compared to, e.g. Facebook, (Fallou and Bossu, 2019; Williams and Krippner, 2019), it is valued by scholars as an interactive and open way to discuss research-related issues and to comment on research results in a concise way (Shiffman, 2017; Van Noorden, 2014). Twitter is also widely used by journalists, who can pass on information to a wider public (Engesser and Humprecht, 2015).

Here we take the examples of the 28 September 2018  $M_w$ 7.5 Palu earthquake and tsunami in north-west Sulawesi, Indonesia (Bao et al., 2019; Socquet et al., 2019) and of the protracted 2018-2019 Mayotte island seismo-volcanic crisis in the Indian Ocean (Cesca et al., 2020; Lemoine et al., 2019; Feuillet et al., 2020). We analyse the timelines of Twitter threads from these events to show that a virtual team of scholars sharing complementary data, observations and analyses, and engaging in subsequent discussions, may lead to a very rapid co-building of knowledge in just one to a few days. This process overpassing laboratory walls (Britton et al., 2019) has the advantage of being transparent to the public and to the media. It makes science accessible to any non-academics or citizen scientists who can follow and participate in the discussion. Our findings follow growing trends towards open science, and also potentially bears the opportunity for a new type of collaborative scientific approach within dynamic and remotely-working "global virtual teams" (Zakaria et al., 2004).

## 2 - Studied events and methodology

For around a decade now, scientists studying natural hazards have begun to use information extracted from social media, websites, or app earthquake reporting, to automatically detect and locate hazardous events, such as flooding (e.g., Jongman et al., 2015). Social media posts can also be used to locate earthquakes within tens of seconds of their occurrence time (Bossu et al., 2008, 2018; Earle et al., 2010; Steed et al., 2019). Here, rather than relying on such a quantitative survey based on large-scale keywords or hashtags statistics, or website traffic analysis combined with geolocalisation, we build our study on the contextual analysis of qualitative content of selected Twitter conversational threads. **We do this to shed light on actual interactions people have on Twitter during these events, emphasizing on the type of information shared via this social media rather than solely overarching issues.** Examples of recent geological events that have received extensive Twitter commentary are: the April 2015 Gorkha earthquake in Nepal (See analysis of Twitter response by Lomax et al., 2015); the Mexico earthquakes of September 2017, the Agung eruption of 2017 (Indonesia); the tsunami induced by volcanic collapse at Anak Krakatau (Indonesia) in December 2018; the July-August 2019 Stromboli eruptions and pyroclastic flows (Italy); the July 2019 Ridgecrest earthquake sequence (California, USA); and the protracted Lusi mud volcano eruption (Indonesia) that started in 2006. We chose to analyse two 2018 events that illustrate complementary aspects of knowledge building via social media.

On the 28 September 2018 an earthquake of magnitude  $M_w 7.5$  occurred in north-west Sulawesi island, Indonesia. The earthquake ruptured the Palu-Koro fault system, a north-south left-lateral fault zone with a relatively rapid average slip rate of about 4 cm/yr (Socquet et al., 2006) previously identified to have a high seismic hazard (Pusat Studi Gempa Nasional - National Center for Earthquake Studies, 2017; Watkinson and Hall, 2017). This earthquake triggered a tsunami with run-ups reaching 6-8 m high on the Palu Bay coast (Carvajal et al., 2019; Ulrich et al., 2019), as well as widespread liquefaction and surface spreading inland (Valkaniotis et al., 2018; Watkinson and Hall, 2019). To show how key geophysical information was rapidly disseminated and discussed via Twitter, we compiled informative tweets that were posted about the event's characteristics and processes. This list of tweets should not be considered exhaustive as it is strongly dependent on who we follow on Twitter and what is retweeted. We use it to illustrate how this way to spread information enhances the dissemination and discussion of scientific results. From this compilation we build a timeline of the rapid progress of understanding of the earthquake rupture and of its effects. The timeline (Table 1), which covers the five days following the event, is graphically shown on Figure 1 (see also Table S1 which contains web links to selected relevant individual tweets). A Twitter "moment" (Lacassin, 2019) gives online access to the full content of the tweets including images, maps and videos (a PDF print of the full thread is also available from Figshare repository: <https://doi.org/10.6084/m9.figshare.11830809.v1>). Table S2 provides complementary web links to the Twitter feeds of several geoscientists who actively participated in the online data dissemination and discussion in the few days following the event, giving access to secondary, more detailed discussions.

In contrast to the Palu case, the case of Mayotte, in the Comoros archipelago between East Africa and Madagascar, represented emergent scholarly interaction over a much more protracted time period, without direct

125 damage caused by the unrest, and which lacked initial responses from official government agencies. The is-  
land had been experiencing a long-standing seismic swarm of volcano-tectonic origin since May 2018  
(Patton, 2018; Lemoine et al., 2019; Feuillet et al., 2020), but was not purported to have any significant seis-  
mic or volcanic hazard prior to this crisis. The seismic swarm is still active more than one year and a half af-  
ter its start, and has been recently linked to a migration of magma within the lithosphere and the eruption of  
130 an undersea volcano (Cesca et al., 2020; Feuillet et al., 2020). We do not analyse the full, >1 year long, Twit-  
ter activity related to the Mayotte seismic swarm, but we focus on a **particular** long-period seismic event that  
happened on 11 November 2018. This event triggered a surge in scholarly Twitter discussions in the follow-  
ing days. The surge resulted in a complex and long (>200 Tweets) Twitter thread with many branches open-  
ing secondary discussions, more like a **wild bush** than a well-structured tree. To simplify this thread, our first  
aim was to select and regroup the most relevant and informative tweets linked to these discussions. We orga-  
135 nize these selected tweets into three successive Twitter moments accessible online (Lacassin, 2018a, 2018b,  
2018c), and we invite the reader to consult and refer to this long thread (as for Palu, a PDF print of the full  
thread is also available from Figshare repository: <https://doi.org/10.6084/m9.figshare.11830824.v1>). Our  
purpose is not to do the same timeline analysis than for the Palu earthquake, but to use the "Mayotte 11 No-  
vember 2018 rumble event" example to outline the efficient knowledge-building dialogue between scientists  
140 trying to interpret a mysterious event and dealing with uncertainties about it. To illustrate the time evolution  
of ideas during this active dialogue, we generated two word clouds from the selected tweets. We also use the  
Mayotte case to outline the role of citizen scientists at the start of the discussion, to discuss some pitfalls in-  
herent to using an informal platform like Twitter, as well as the opportunity to spread information toward  
more traditional print, broadcast and online media.

145 The evolution of the two threads were quite different. With Palu, the scenario was quite well-defined and oc-  
curred at a rapid pace over a short amount of time: an earthquake followed by a tsunami, with the focus of  
scientists being on the key observations to explain what happened. With Mayotte, we knew very little at first  
apart from an initially innocuous seismic swarm followed by the detection of a long-period seismic signal.  
There was no accurate location for and no idea about what the signal was. This resulted in the Twitter ex-  
150 changes and the overall thread on Mayotte being more chaotic and open than the more linear Palu thread.  
There were also very different societal impacts. The Mayotte earthquakes caused uncertainty, unrest, and  
stress but there was no important damage, injury or fatalities. In contrast, devastation and death was im-  
mediately seen in Palu.

Most authors of this paper contributed to the mentioned Twitter exchanges. Such an "embedded" view has  
155 the merit to provide an in-depth understanding of the geophysical observations and of the full context of on-  
line exchanges at the time of the event. To provide an external, and more critical view, the paper also in-  
cludes some authors (MD, LF) who were not involved in these specific Twitter discussions.

## 3 - Results: knowledge building and sharing via Twitter

### 3.1 - The case of the 2018 Palu earthquake

160 Our compilation of the Twitter exchanges following the Palu earthquake and tsunami reveals how we can rapidly gain a first-order understanding of event characteristics, within a few hours to one day, and a more complete one in less than a week. After the initial tweets issued by responding agencies (e.g. USGS in the USA, BMKG in Indonesia), most of the exchanges we quote involved academic researchers from different countries and institutions (see Tables 1 and S1), and with specialities encompassing seismology, earthquake geology, tectonic geodesy, remote sensing, natural hazards and science communication. We will not investigate in more detail the sociology of the people involved in the Twitter discussions, because out of the scope of the present study, but future work should address this critical subject.

The timeline built from the Twitter feeds (Figure 1 and 2, Table 1) shows that, already about one day after the earthquake, the geoscience community knew that:

- 170 i) the earthquake happened on the Palu-Koro fault system, with a sharply localised strike-slip rupture directly beneath Palu City, and an epicenter located in the Minahasa peninsula on the north-east shore of Palu Bay (from earthquake location and moment tensor solutions provided by monitoring agencies, published papers on the seismotectonic context, and regional fault mapping; this information was shared via Twitter in the 2 hours following the event - see Figure 2a);
- 175 ii) the rupture entered Palu Bay, but the geometry of its prolongation offshore toward the Minahasa peninsula was uncertain (from early post-earthquake satellite imagery and preliminary image correlation using pre- and post-event data);
- iii) the aftershock zone extended ~150 km in the north-south direction, and the mainshock hypocenter was located near the northern tip of this zone (from operational earthquake locations provided by monitoring agencies);
- 180 iv) a tsunami with run-ups of several meters hit the shores of the Palu Bay and was not recorded out of the bay (from reports and videos shared via social media by local people, and the tide gauge records that were available in the hours following the event - see Figure 2b);
- v) there was dramatic surface spreading and liquefaction in and south-east of Palu City (from photos and
- 185 videos shared by locals).

The exchanges and discussions continued via Twitter and by five days after the earthquake, the geoscientific community had assembled a fairly accurate description of the event and its effects. The acquired common and credible knowledge was that:

- 190 i) the earthquake ruptured two strands of the Palu-Koro fault system for a total length of ~150 km (from the aftershock distribution provided by monitoring agencies, radar and optical image analysis results, and early earthquake source models);

- 195 ii) the strand south of Palu Bay had a sharp and extremely localized surface rupture with sinistral offsets of ~5 m (from satellite imagery and state-of-the-art pre-and post-event image correlation, later confirmed by field observations posted on Twitter by Indonesian researchers ~15 days after the event - see Figure 2d);
- iii) the rupture started on an inland fault east of Palu Bay, then crossed Palu City from north to south (from satellite and InSAR imagery, and early earthquake source models);
- 200 iv) the earthquake rupture propagated unilaterally southward, likely at a supershear speed (faster than S-waves), a fairly unique observation for earthquakes (from early earthquake source duration and rupture length estimates, the latter based first on the distribution of early aftershocks, then on satellite images - see Figure 2c);
- v) massive liquefaction and lateral spreading occurred in several sectors of Palu City (from aerial video footage shared by local government agencies, satellite imagery, photos and videos shared by locals on social media);
- 205 vi) tsunami waves hit the Palu Bay coast only a few minutes after the earthquake (from tide gauge records and videos shared on social media).

Ensnung Twitter exchanges during the next weeks focussed on the surface rupture description in the field by Indonesian scientists, the bathymetry of Palu Bay, the possible fault geometry across it, and hypotheses 210 about the tsunami source. These hypotheses explored whether the tsunami was due to the seismic rupture itself or to underwater landslides and coastal collapse, or a combination of the two.

In this process of common knowledge-building, geoscientists used a diverse range of data types that were openly shared and discussed on Twitter: published papers and maps about the seismotectonic context, teleseismic data, local seismic waveforms, high-resolution optical satellite images, Synthetic Aperture Radar (SAR) satellite data analysis, tide gauge records, and field observations from both science groups and local 215 residents. Data sharing and social interaction via Twitter appeared as an effective way of getting prompt and diverse feedback from fellow researchers on early scientific ideas. The satellite image correlation results, available on Twitter one to two days after the earthquake, were then rapidly shared as a more formal report via the open repository zenodo.org (Valkaniotis et al., 2018). Some ideas and initial hypotheses about a supershear rupture and about the offshore fault geometry in Palu Bay, both discussed on Twitter, provided impetus for accelerated development of in-depth scientific papers (Bao et al., 2019; Ulrich et al., 2019). Indonesian geoscientists, absent from the earlier scholarly exchanges on Twitter (only official agencies were providing advice), progressively joined the discussion, providing, for example, tide gauge records and field observations of fault surface rupture and offsets. This created the opportunity for developing new international 220 collaborations. Further highlighting the use of social media, an analysis of the tsunami source by Carvajal et al. (2019) used videos posted on social media platforms such as Twitter and YouTube.

The spread of information via Twitter was not restricted to a small group of geoscience scholars. Journalists used and quoted these Twitter discussions in their articles (e.g., Andrews, 2018a; Wei-Haas, 2018a), using 230 the thread to identify academic experts to interview for their articles. However, some journalists were not interested by the full range of geophysical observations, but focussed instead on a “*failed tsunami alert*”

(Fountain, 2018; Wright, 2018). Based on an Associated Press (AP) dispatch, on 1 October 2018, quoting some scientists (Wright, 2018), there were inaccurate reports in international media outlets about a “failed” tsunami warning. According to these reports a network of tide gauges and buoys would have been able to issue an early tsunami warning after the earthquake, thus saving lives. The media were quick to blame the Indonesian authorities, saying that such a warning would have been impossible because the Indonesian buoy network was not well maintained. But geoscientists realised that there was not enough time to issue any warning given the very short distance between the earthquake source and the areas exposed to tsunami in the very narrow Palu Bay (Figure 3). As stated by Carjaval et al. (2019) “*the most remarkable features of the tsunamis that devastated Palu were the very short, nearly instantaneous arrival times*”. The first tsunami waves indeed hit the coast between 1 and 2 minutes after the earthquake. After evidence-based explanation given by scholars on Twitter (Figure 3), the process of fact-checking by some journalists took only a few hours after publication of the AP dispatch (e.g., Morin, 2018).

As described above, the case of the Palu earthquake and tsunami provides an excellent example of how scholarly discussions on Twitter can provide initial and rapid scientific results, whilst also reinforcing local official authorities on-the-ground, and helping to guide journalistic outputs.

### 3.2 - The Mayotte Nov 11, 2018 rumble event

On 11 November 2018, more than six months after the start of an earthquake swarm between Madagascar and the Comoros archipelago in the Indian Ocean, a peculiar seismic signal radiated from the region of Mayotte. The signal was recorded worldwide by seismic networks, but not detected by their automatic event identification algorithms because of its odd spectral characteristics. It was an unusually long, low frequency, highly monochromatic signal, like a low-pitched hum that travelled as seismic waves across the Earth.

As noted by journalist Maya Wei Haas in her National Geographic article “*only one person noticed the odd signal on the U.S. Geological Survey's real-time seismogram displays. An earthquake enthusiast [...] saw the curious zigzags and posted images of them to Twitter*” (Wei-Haas, 2018b). This image (Figure 4a) was then retweeted by a citizen earthquake researcher, Jamie Gurney, who initiated an active discussion between academic researchers (Figure 4), with some interactions from the media and the public. Analysis of openly-accessible seismic waveform data from around the world by seismologists then confirmed the signal originated in the Mayotte region (e.g., Hicks, 2018a).

The Twitter discussion involved a group of seismologists but also specialists of earthquake geology, volcanology, tectonics, geodesy, geo-mechanics, hazards and science communication. Their exchanges eventually co-built a rapid appraisal of the 11 November signal and of its broader geophysical and geological context. The nature of the researchers' interactions are exemplified by the three successive Twitter moments (Lacassin, 2018a, 2018b, 2018c) that regroup our compilation of tweets (see Figure 4 for a choice of tweets illustrating the early discussion between researchers). A simple content analysis of the selected tweet threads, illustrated by the two successive word clouds in Figure 5, shows how the exchanges started with questions about the odd seismic signal itself using words such as: *signal, event(s), wave(s), seismic, frequency*, and its geographic origin: *Mayotte, location* (Figure 5a), then moved to a discussion more focused on the event's



270 geophysical source using words of: *source, signal, CMT, CLVD, deformation*, and data processing (words:  
*data, model, InSAR, inversion*) (Figure 5b). While many things remain to be understood about the geophysi-  
cal processes at work offshore of Mayotte, the preliminary waveform modelling shared via Twitter (Hicks,  
2018b) and the related discussion resulted in the consensus hypothesis that the 11 November seismic signal  
275 was due to a deflation event in a large and deep magmatic chamber combined with resonance and amplifica-  
tion of the seismic waves. This early hypothesis discussed on Twitter was subsequently supported by later in-  
depth analyses (Lemoine et al., 2019; Cesca et al., 2020; Feuillet et al., 2020).

The Twitter interactions on Mayotte brought the global geoscience community's attention to the event. Be-  
fore the 11 November event, the long-standing earthquake swarm near Mayotte was largely ignored by the  
worldwide geoscience community; the swarm was studied by only a few researchers, mainly French, because  
280 Mayotte is a French territory. As noted by Lemoine et al. (2019), the 11 November event "*awakened the in-  
terest of the seismological community and the media*". We understand that the rapid "*explosion*" of the infor-  
mal Twitter discussions we report played a pivotal role in this awakening and helped hasten needed research  
in the region (Hicks, 2019). A few days after the 11 November event, at a meeting between the French geo-  
science community and stakeholders (funding agencies and ministry representatives), the Twitter exchanges  
285 were used to demonstrate the urgency in funding research and surveys on the Mayotte earthquake swarm (N.  
Feuillet, personal communication to RL).

The full interactive process on Twitter was the subject of two long articles in National Geographic (Wei-  
Haas, 2018b) and Gizmodo (Andrews, 2018b), with journalists gathering information and contacting re-  
searchers via Twitter before interviewing them via email or phone (Figure 6). These articles were then used  
290 as primary sources by other media, and stimulated stand-alone reports in more traditional news organisations  
(e.g., Sample, 2018).

The long thread about the Mayotte November 11 seismic event reveals the efficiency of knowledge-building  
via scholarly online interactions, but it also outlines some pitfalls that are inherent to the informal aspect of  
exchanges via Twitter. While after the Palu earthquake and tsunami geoscientists were posting solid observa-  
295 tions (i.e. 'knowns'), for Mayotte they were trying to understand a peculiar event with large uncertainties  
thus opening many secondary discussions about 'unknowns'. The resulting "bushy" nature of the thread  
makes it difficult to follow and comprehend in real time and summarising it *a posteriori* is challenging. Also,  
some of these secondary discussions were casual or humorous and were at risk of being seen as insensitive  
and taken out of context by the general public. We infer that scientific Twitter exchanges dealing with uncer-  
300 tainties and unknowns, as for Mayotte, are more prone to such pitfalls than those sharing knowns.

## 4 - Discussion: advantages and pitfalls of Twitter for knowl- edge exchange and co-building

### 4.1 - Argument 1 – Very rapid co-building of knowledge

The two case studies described above support previous work showing that Twitter allows rapid building of  
305 knowledge (e.g., Choo et al., 2015; Hicks, 2019). In the case of the 2018  $M_w$ 7.5 Palu earthquake, it took only

five days to obtain a detailed description of the events and only a few days for the 11 November 2018 seismo-volcanic event in Mayotte. It takes several months to years for scientific teams to gather relevant information, analyse it, and publish it in an academic journal after a long review-revision process. Using Twitter thus makes information and basic explanations accessible to the scientific community and to the public more quickly. Communicating such ideas to the public may have high impact in places where operational infrastructure and associated communication are limited. Moreover, Twitter provides direct and early scientific information for researchers, without any geographical and institutional barriers, acting as a "science news-feed" that can be used to plan further in-depth research.

However, the knowledge built via Twitter is not exactly comparable to the knowledge built by a longer-term, classical academic approach. Even if a long practice of research allows scientists to estimate the quality of a dataset or of a methodology almost immediately (if not intuitively), it does not substitute peer review as a process to check the validity of a result and 'establish' knowledge. A question therefore arises over the credibility and legitimacy of the knowledge built rapidly and without peer-review via Twitter: **can it be believed and on what ground?** The fact that the author of a tweet comes from a recognized expert institution increases his/her credibility. But this is not enough to ensure the scientific quality of his/her tweet. And the reverse is also true. As shown in the Mayotte example, non-practising researchers and "hobby scientists" can develop a good scientific understanding and be fully legitimate to discuss these topics (Figure 4). The question that arises is thus the following: how can we ensure that the most qualified comments receive the most attention?

Rapid dissemination of early scientific analysis products (for example using up-to-date remote sensing data) to scientists working in the field is another aspect of using social media platforms. This use of social media is similarly to modern trends in using preprint servers for early sharing of scientific results. Twitter interaction now is also forming the basis of collaborations, leading to the development of ideas and subsequent co-writing of papers within diverse, multi-disciplinary teams (e.g., Hicks et al., 2019; Ulrich et al., 2019 included coauthorships that were instigated from Twitter discussions). By widening stakeholder interactions, such open discussions may also help to enhance the scholarly value of open datasets.

A risk to sharing "breaking science" information on Twitter and social media is that this same information can enable publications by the global community before the local scientists who provided the initial information. There are vulnerabilities for those field teams who are committing resources as part of a response initiative, and are required to, or feel a duty to provide timely public information about an event. Elements of such a scenario unfolded following the 2016 Kaikōura earthquake in New Zealand, when tweets, blog posts and media releases by the responding agencies were an important information source for an early publication by researchers without collaboration with the responding agency scientists. This publication (Shi et al., 2017) predated, by several months, publications of field observations and analysis by teams on the ground. This example raises questions about the ownership of scientific knowledge that is shared in the public domain, and suggests that some scientists may choose to completely restrict, or be more selective about, publicly posting their scientific analysis into the public domain.

## 4.2 - Argument 2 – Science beyond the laboratory

345 Twitter allows us to step outside **the laboratory in many ways**. First, it opens the door to professional net-  
working and new academic collaborations between scientists coming from different disciplines, institutions,  
or even countries. In the case of the Palu earthquake, most of the early exchanges involved non-Indonesian  
academic researchers; then Indonesian geoscientists joined the discussion and provided data that could only  
be acquired locally (e.g. field observations about the earthquake rupture or liquefaction induced landslides).  
This led them to engage in a discussion with other members of the international scientific community and  
350 paved the way for new collaborations, such as sharing of tsunami source models for operational hazard  
analyses. In the short term, however, it might be difficult for local scientists to get involved in social media if  
they are busy with the management of the crisis and/or collecting the first information from the field. Also,  
scientists from local monitoring organisations or universities may have strict social media usage and commu-  
nication policies.

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Twitter also opens the door to exchanges with the global public. The scientific value of contributions from  
non-academics varies between examples, but there are always some external inputs that help to clarify or re-  
frame the scientific questions and the way to explain them to the public. Non-academics can launch impor-  
tant discussions. In the case of Mayotte, it was a citizen scientist who drew attention to a strange seismic si-  
360 gnal (Figure 4a), and it was the subsequent "explosion" of informal Twitter discussions that woke up the sci-  
entists and the authorities (Lemoine et al., 2019; Hicks, 2019). Among Twitter users, journalists "listening  
in" are particularly important as they can pass on some of the scientific content of the discussions in an un-  
derstandable way. The challenge for them is to have access to information that is as fresh as it is credible.  
From this point of view, Twitter is an important resource because it can serve as a pool of potential experts to  
365 give in-depth comment (Figure 6). On the other hand, perhaps this trend reduces the diversity in these pools,  
with public comment favouring scientists on Twitter rather than those who avoid Twitter and/or use other so-  
cial media platforms. Also, how much checking does a journalist do to assess a Tweeter's scientific credibil-  
ity?

## 4.3 - Argument 3 – Opening the scientific process to the public

370 The process of knowledge-building on Twitter is open and public, which may help to improve the general  
public's and the media's understanding of how scientific research works. The examples described above  
show that the process of knowledge co-construction is not linear. Some discussion threads might look like  
well-structured "trees" (e.g. the Palu earthquake) but others resemble "wild bushes" with many secondary  
branches of discussions opening up over time (e.g. the Mayotte seismo-volcanic crisis). Scientists are seen  
375 by the public to use a wide variety of data and following indirect, non-chronological and unstructured  
thought paths before reaching a conclusion. As a window on the scientific process, Twitter also helps to  
make clear that the scientific work is organised in disciplines and subdisciplines, whose knowledge and  
know-how may be difficult to articulate but which are all necessary to build a global view of a subject. Sci-  
entists themselves are familiar with these aspects of their work but non-scientists may not be, largely because  
380 scientific knowledge is often presented retrospectively as having been constructed in a cumulative and  
chronological manner. Epistemologists have long denounced this misconception (e.g., Kuhn, 1996). Twitter

can contribute to make the “messy part of science” more tangible and visible. Early information on Twitter can also provide excellent teachable material for educators.

385 One limitation is that the thread has to be "visible" on Twitter, using a proper #hashtag for instance. Also, if  
the public is not aware of the sphere and the discussion is not "visible" to them, they will not see it even  
though it is public. Moreover, some schools of thought, especially those from a public safety standpoint, may  
argue that scientists should concentrate on disseminating the certainty of known, well-established facts and  
interpretation about a hazardous event, rather than on communicating uncertainties and cutting-edge research  
390 (e.g., Jones, 2020). It is our view that scientists must reach a careful balance between knowledge-building  
and being sensitive to a damaging geohazard event very soon after it has happened.

#### 4.4 - Argument 4 : Helping people to understand hazards and risk mitigation

Improving people’s understanding of natural phenomena can help to improve risk mitigation, at least indi-  
rectly. Take the case of the Palu earthquake, for example. International media insisted that a "failed" tsunami  
395 warning was responsible for the associated fatalities, but scientists quickly realized and explained that there  
was not enough time to issue an efficient alert because of the proximity of the earthquake (see above). In  
fact, the Indonesian agency in charge (BMKG) issued an alert a few minutes after the event and cancelled it  
~30 minutes later (Figure 3d, Table 1); in the meantime the tsunami hit the Palu Bay coasts (Krippner, 2018).  
Later the same day, BMKG issued a press release to explain their alert management process. This contradic-  
400 tory information is likely to open a debate that will improve the general public's understanding of what to ex-  
pect (or not) from early-warning systems. More generally, by bringing facts and evidence-based arguments  
into the public debate, the scientific community can contribute to the quality of people’s information and, in  
the long-term, help to prepare. Twitter discussions are opportunities to prevent confusion and misunderstand-  
ing by reinforcing and disseminating information and advice given by local government agencies (Bartel and  
405 Bohon, 2019).

## 5 - Concluding remarks

Using examples of Twitter discussions following two very different geophysical events, we have shown that  
open scientific discussion and hypothesis-building on social media can promote and enhance many key as-  
pects of modern science. These include: development of ideas for future project funding, early dissemination  
410 and discussion of preliminary results forming the basis of peer-reviewed publications, networking for devel-  
oping international collaborations, demonstrating impact of research, and public dissemination of research  
and results. Twitter can be seen as a modern method of crowdsourcing scientific ideas; however, this can  
raise moral issues over the proper acknowledgement of how these ideas were progressively developed. In  
these concluding remarks, we combine the results from the present study with our own experience on social  
415 media to identify some interesting questions and implications for modern scientific methods and communica-  
tion.

Our analysis has shown that Twitter discussions do not represent a significant change over the common methods adopted in traditional scientific research. For example, scientific discussions on Twitter may be compared to traditional in-lab scholar discussions at coffee time and encounters at scientific conferences that are a usual way to exchange information and new ideas. Twitter democratizes such scholarly interactions by expanding their interdisciplinarity and geographic coverage, leading to more diverse scientific inputs. Many of these differences result from an increase in open data, willingness to openly share ideas, and the globalization of science. Moreover, in the examples described in this paper, the group of scientists involved in the discussions had not previously worked together. They formed a group with a diverse range of backgrounds and with different expertise, questioning previous tweets, thereby providing an effective and rapid analogue to traditional peer review.

Nevertheless, there are key differences compared to the traditional scientific method that we should be wary of. Whilst we have demonstrated that the use of Twitter for scientific knowledge-building and dissemination can be a fulfilling experience, the immediate tangible benefits for scientists that may be needed for, e.g. career progression, may not be obvious. For example, **research managers** less accustomed to science on social media may find such efforts to be a distraction from traditional research work. The current academic system rewards scientists mostly based on peer-reviewed publications, so how can scientists be rewarded for such public dissemination and preliminary ground-work? Also, what happens if research papers are published which use the scientific ideas developed on Twitter without appropriate credit? How can credit be given to the incremental development of scientific ideas from Twitter?

Based on our experience, since science on Twitter conducted fully in the public domain, we should be wary of comments being taken out of context, and the potential for posts “going viral”. As a Twitter user gains followers, their responsibility and the risk of such issues dramatically increases, and as the number of comments/replies from followers grow, so does the time required to reply responsibly. In such cases, should this public-facing approach be left to social media and public relations experts? Alternatively, should media and communication training become a standard for scientists working in fields with public-facing aspects?

Aside from occasional conspiracy theorists and charlatan earthquake / volcanic eruption predictors, we have found from our experience of Twitter that communicating about natural geohazards can be less affected than other topics by the well-recognized disadvantages of the platform - such as trolling, personal abuse, etc. However, challenges still remain for the scientific discussion and dissemination of more controversial subjects, such as human-induced seismicity, petroleum science, or climate change. Does exposing the “messy part of science” (see above) help to increase public **trust in scientific evidence**? For example, it might be possible for some people to clearly see the uncertainty in some scientific arguments and to “prey” on them for political gains. Overall, opening up the scientific processes and involving the general public as stakeholders should help to improve trust in experts. Future development of “best” practices for scientists involved in such subjects will be needed. But offering communication training is only one step toward supporting scientists in effective conveyance of their work. Current issues like climate change show us that scientists need to be openly communicating and building trusting relationships with global communities, but at the same time, the response from a minor part of other scientists can be hostile and damaging. We need to specifically acknowl-

455 edge and reward scientists for these crucial efforts, and keep working to change the culture to support science communicators.

Together with the growing popularity of open science and preprint archives, discussing science on Twitter can importantly fill in the traditional “radio silence” from science between a newsworthy/impactful event and the publication of related scientific papers that follow months to years later. Our study has specifically  
460 focussed on potentially hazardous geological events, but our experiences reported here can assist the usage of social media for many other fields of research.

## Supplementary Information

Table S1 lists main geophysical events, and informations shared via Twitter after the Palu event, 455 with links toward relevant tweets. Table S2 provides web links to Twitter feeds of geo-scientists who participated in the online data dissemination and discussion after the Palu event.

PDF prints of the full threads of selected tweets are available from Figshare repository: <https://doi.org/10.6084/m9.figshare.11830809.v1> for the Palu earthquake and tsunami, <https://doi.org/10.6084/m9.figshare.11830824.v1> for the Mayotte VLP seismic event.

## 470 Author Contribution

This paper follows exchanges on Twitter in which most authors participated after the Palu and/or Mayotte events. JG and DW, as citizen scientists, alerted the scientific community about the Mayotte Nov. 11 event (JG), or translated Indonesian geohazard information in english (DW). RL conceived the study, compiled and analysed the data. All authors commented on the results. RL, MD and SH wrote the paper with input 475 from all other authors, listed in alphabetical order.

## Competing Interest

The authors declare that they have no conflicts of interest.

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## Figure Captions

**Figure 1:** Timeline of informations posted on Twitter in the hours and days following the Palu earthquake and tsunami of 28 September 2018. The timeline illustrates the acquisition and dissemination of observations 490 regarding geophysical events, and the progress of knowledge building via Twitter. See Table 1 for detailed informations on the timing, and Table S1 for links to relevant tweets and twitter accounts. See examples of tweets posted by geoscientists on Figures 2 and 3. Red dots correspond to information posted by responding agencies, blue dots to observations and discussions posted by researchers from different countries and institutions.

**Figure 2:** Screenshots of tweets chosen to illustrate how researchers shared and explained observations regarding the Palu earthquake and tsunami of 28 September 2018. Simplified timeline (from Figure 1) is shown on the left for reference. (a) within 2 hours geoscientists described the seismotectonic context of the earthquake. (b) geoscientist shared and translate official validation of viral videos about the tsunami in Palu. (c) researchers hypothesized supershear rupture. (d) geoscientist shared satellite image correlation results showing sharp rupture with 5m left-lateral offset across Palu town, and other researchers started to discuss these results. Refer to Figure 3 for tweets about the tsunami warning.

**Figure 3:** Screenshots of selected tweets about tsunami warning in the case of Palu. (a-b) geoscientists quote media articles regarding a possibly “failed” tsunami warning, and explain that such warning was extremely difficult in the case of the Palu earthquake (see text for more explanation). (c) example of geoscientists engaging discussion with local people. (d) geoscientist reports that Indonesian agencies issued an alert in due time and cancelled it only after the tsunami hit Palu.

**Figure 4:** Screenshots illustrating early Twitter exchanges about the very long period seismic signal near Mayotte on the 11 November 2018. The selected screenshots shows that Twitter discussion was initiated by citizen scientists (a-c), then progressively involved academic researchers (d-f). Those researchers then started an active discussion about the seismic signal and its possible origin (e-j).

**Figure 5:** Word clouds illustrating the evolution of topics discussed on Twitter after the Mayotte 11 November 2018 very long period (VLP) seismic event. Top word cloud (a) illustrates first 60 tweets of the selected Twitter moment with most frequent words about the VLP signal (*signal, event(s), wave(s), seismic, frequency*) and its geographic origin (*Mayotte, location*). The bottom one (b), which corresponds to the following 60 tweets, shows a discussion more focused on the geophysical source of the VLP event (*source, signal, CMT, CLVD, deformation*) and data processing (*data, model, InSAR, inversion*).

**Figure 6:** Screenshots of tweets by journalists Maya Wei-Haas and Robin George Andrews. After promoting their media article on the Mayotte 11 November 2018 event (a, d), journalists acknowledged academic researchers who were first identified and contacted via Twitter, then interviewed via email or phone (b, c, e).

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