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Geoscience Communication Discussions

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 are widely viewed by the media who can then pass on information to the wider public. Here, we take the example of two 2018 earthquake-related events which were widely commented on Twitter by geoscientists: the Palu M_w7.5 earthquake and tsunami in Indonesia and the long-duration Mayotte island seismo-volcanic crisis. 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, following 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. It can also disseminate the information to people directly affected by the disaster and eventually 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 and time-consuming field surveys. This process often took months to reach a good apprehension of the event's characteristics. Thanks to worldwide geophysical instrumental 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 consequences within days

https://doi.org/10.5194/gc-2019-23
Preprint. Discussion started: 28 October 2019

Geoscience Communication
Discussions
Open Access
EGU

(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 discussion about the meaning and implications of geological events (Choo et al., 2015; Landwehr et al., 2016; Lee, 2019; Takahashi et al., 2015). Indeed, while Twitter is perhaps 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 2018 M_w7.5 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 (Feuillet et al., 2019; Lemoine et al., 2019). 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 – one to a few days – co-building of knowledge. This process has the advantage of being transparent to the public - notably to the media, overpassing laboratory walls (Britton et al., 2019), making science accessible to any non-academics or citizen scientists who can follow and participate in the discussion. It follows 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, earthquake scientists have begun to use information extracted from social media, websites, or app earthquake reporting, to automatically detect and locate earthquakes within tens of seconds of their occurrence (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. 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

https://doi.org/10.5194/gc-2019-23
Preprint. Discussion started: 28 October 2019

Geoscience Communication
Discussions
Open Access
EGU

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). We chose to analyse two 2018 events that illustrate complementary aspects of knowledge-building via social media.

On September 28, 2018 an earthquake of magnitude M_w7.5 occurred in north-west Sulawesi island, Indonesia. The earthquake ruptured the Palu-Koro fault system, a north-south left-lateral fault zone with a rapid average tectonic rate of about 4 cm/yr (Socquet et al., 2006), and previously identified to have a high seismic hazard (Pusat Studi Gempa Nasional - National Center for Earthquake Studies, 2017; Watkinson and Hall, 2017). It 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, we compiled the most informative tweets that were posted about the event's characteristics and processes. We used this compilation to build a timeline of the rapid progressive understanding of the earthquake rupture and of its effects. The timeline, which covers the five days following the event, is graphically shown on Figure 1 (see also Table S1 which also 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 on request to the corresponding author). Table S2 provides complementary web links to the Twitter feeds of several geo-scientists who actively participated in the online data dissemination and discussion in the few days following the event, giving access to secondary, more detailed discussions.

The case of Mayotte, in the Comoros archipelago between East Africa and Madagascar, is quite different: the island has been experiencing a long-standing seismic swarm of volcano-tectonic origin since May 2018 (Feuillet et al., 2019; Lemoine et al., 2019; Patton, 2018) but was not purported to have any significant seismic or volcanic hazard prior to this crisis. The seismic swarm is still active more than one year after its start, and has been recently linked to a migration of magma within the lithosphere and the eruption of an undersea volcano (Feuillet et al., 2019). We do not aim to analyse the full, >1 year long, Twitter activity related to the Mayotte seismic swarm, but we will focus on a peculiar long-period seismic event that happened on November 11, 2018 and triggered a surge in scholarly Twitter discussions in the following days. This surge resulted in a complex and long (>200 Tweets) Twitter thread with many branches opening secondary discussions, more like a wild bush than a well-structured tree. To simplify it, we have regrouped the

https://doi.org/10.5194/gc-2019-23
Preprint. Discussion started: 28 October 2019

Geoscience Communication
Discussions
Open Access

most relevant tweets linked to these discussions into three successive Twitter moments accessible online (Lacassin, 2018a, 2018b, 2018c), and invite the reader to consult and refer to this long thread (as for Palu, a PDF print is available on request). We will not do the same timeline analysis than for the Palu earthquake, but we will use the "Mayotte November 11, 2018 rumble event" example to outline the implications for citizen scientists, the efficient knowledge-building dialogue between scientists, some pitfalls inherent to Twitter informal use, and the opportunity to spread information toward more traditional print, broadcast and online media.

The aims of the two threads were quite different. With Palu, the scenario was quite well-defined - an earthquake and tsunami, with the focus of scientists being to unravel the details. With Mayotte, there was literally nothing known at first other than that a long period signal had occurred. There was no location and no idea about what the signal was. This resulted in the Twitter exchanges and thread on Mayotte being more chaotic and open than the more linear Palu thread. There was also very different societal impact. Mayotte earthquakes caused unrest and stress but no victims, while devastation and death was immediately seen in Palu.

Most authors of this paper contributed to the mentioned Twitter exchanges. Such an “embedded” view has the merit to provide an in-depth understanding of the geophysical observations and of the full context of related online exchanges at the time of the event. To provide an external, and more critical view, the paper also includes 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

The compilation of the Twitter exchanges following the Palu earthquake and tsunami reveals how first-order understanding of event characteristics is rapidly gained, within a few hours to one day, and a more complete one in less than a week.

The timeline built from the Twitter feeds (Figure 1, Table S1) shows that, already about 1 day after the earthquake, the geoscience community knew that:

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 the Palu Bay (from earthquake location and moment tensor solutions provided by monitoring agencies, published papers on the seismotectonic context and regional

https://doi.org/10.5194/gc-2019-23
Preprint. Discussion started: 28 October 2019

fault mapping; this information was shared via Twitter in the 2 hours following the event);

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 ante-post image correlation);

iii) the aftershock zone extended ~150 km in the north-south direction, and the mainshock hypocenter was located near its northern tip (from operational earthquake locations provided by monitoring agencies);

iv) a tsunami with run-ups of several meters hit the shores of the Palu Bay only (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);

v) there was dramatic surface spreading and liquefaction in and south-east of Palu City (from photos and videos shared by locals).

The exchanges and discussions continued via Twitter and by 5 days after the earthquake the community had assembled a fairly accurate description of the event and its effects. The acquired common knowledge was that:

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

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 ante-post image correlation, later confirmed by field observations posted on Twitter by Indonesian researchers ~15 days after the event).

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);

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);

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).

https://doi.org/10.5194/gc-2019-23
Preprint. Discussion started: 28 October 2019

vi) tsunami waves hit the Palu Bay coast only few minutes after the earthquake (from tide gauge records and videos shared on social media).

Ensuing 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 about the tsunami source (was it 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 analysis, tide-gauge records, and field observations. Data sharing and social interaction via Twitter appeared as a good way to put together complementary skills and expertise and to get feedback from fellow researchers on early scientific ideas. The satellite image correlation results, available on Twitter 1-2 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, enhanced the 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 potentially creates the opportunity for developing new international collaborations. Further highlighting the interest of social media, the analysis of the tsunami source by Carvajal et al. (2019) was enabled by videos posted on social media platforms and often shared via Twitter.

The spread of information via Twitter was not restricted to a small group of geoscience scholars; reporters used and quoted these Twitter discussions in their articles (e.g., Andrews, 2018b; Wei-Haas, 2018b). Also, journalists used the Twitter feed to identify academic experts to interview. However, some journalists did not appear to be interested by the full range of geophysical observations, but focussed on the possible tsunami source and on the issue of a "*failed tsunami alert*" (Fountain, 2018; Wright, 2018), which disagrees with scientific evidence, as has been explained by geoscientists on Twitter (Figure 2), then in the media (e.g., Morin, 2018). Indeed, there were inaccurate reports in international media outlets about a "failed" tsunami warning. The media were rather quick to blame the Indonesians, but geoscientists realised that there was not

https://doi.org/10.5194/gc-2019-23
Preprint. Discussion started: 28 October 2019

enough time to issue a warning given the very short distance between the earthquake source and the areas exposed to tsunami in Palu Bay (Figure 2). This process of fact-checking took only a few hours, on 2018 October 1st, between publication of the Associated Press dispatch (Wright, 2018) and critical explanation given by scholars on Twitter.

3.2 - The Mayotte Nov 11, 2018 rumble event

On November 11, 2018, more than 6 months after the start of an earthquake swarm, a peculiar seismic signal radiated from the region of Mayotte and 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. Its interpretation still remains somewhat mysterious, but it is certainly related with the ongoing volcano-tectonic crisis.

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, 2018a). Then it was retweeted by a citizen earthquake researcher, Jamie Gurney, who initiated an active discussion between academic researchers, 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, 2018b).

The exchanges involved both seismologists and other geoscientists to eventually co-build a rapid appraisal of the November 11 signal and of its broader geophysical and geological context. The dynamic and acute nature of the researchers' interactions are exemplified by the three successive Twitter moments (Lacassin, 2018a, 2018b, 2018c) that regroup the more significant tweets. A simple contextual analysis of the selected tweet thread, illustrated by the two successive word clouds in Figure 3, shows how the exchanges started with questions about the odd seismic signal itself – words: *signal, event(s), wave(s), seismic, frequency* – and its geographic origin – words: *Mayotte, location* (Figure 3a), then moved to a discussion more focussed on the event's geophysical source – words: *source, signal, CMT, CLVD, deformation* – and data processing – words: *data, model, InSAR, inversion* (Figure 3b). While many things remain to be understood about the geophysical processes at work offshore Mayotte, the preliminary waveform modelling shared via Twitter (Hicks, 2018a) and the related discussion resulted in the consensus hypothesis that the Nov. 11 seismic event was due to a deflation event in a large and deep magmatic chamber combined with

https://doi.org/10.5194/gc-2019-23
Preprint. Discussion started: 28 October 2019

Geoscience Communication
Discussions
Open Access
EGU

resonance and amplification of the seismic waves. This early hypothesis discussed on Twitter was subsequently supported by later in-depth analyses (Cesca et al., 2019; Feuillet et al., 2019; Lemoine et al., 2019).

Before the November 11 event, the long-standing earthquake swarm in Mayotte was largely ignored by the worldwide geoscience community; the swarm was studied by only a few researchers, mainly French, because Mayotte is a French territory. As noted by Lemoine et al. (Lemoine et al., 2019), the November 11 event "awakened the interest of the seismological community and the media". We understand that the rapid "explosion" of the informal Twitter discussions we report played a pivotal role in this awakening and helped hastening needed research in the region (Hicks, 2019). A few days after the November 11 event, at a meeting between the French geoscience community and stakeholders (funding agencies, ministry representatives) the Twitter exchanges 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 qualified by SH of "*new age science*" (hashtag #newagescience) and "*excellent citizen-scientist engagement*", and many other users outlined the quality of the discussion (Figure 4). It was the subject of two long articles in National Geographic (Wei-Haas, 2018a) and Gizmodo (Andrews, 2018a), themselves used 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 Nov. 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. The "bushy" nature of the thread, with many secondary discussions, makes it difficult to follow and apprehend 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 - in particular, those living in Mayotte where the scientific culture is low and animism belief is strong among a fringe of the population (Fallou and Bossu, 2019). In this case, the mention of a "sea monster" as being the culprit for the seismic hum is easily seen by some as harmless humour amongst experts, but such jokes may be easily misread by others.

https://doi.org/10.5194/gc-2019-23
Preprint. Discussion started: 28 October 2019

Geoscience Communication Discussions Open Access EGU

4 - Discussion: advantages and pitfalls of Twitter for knowledge 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 a rapid building of knowledge (e.g., Choo et al., 2015; Hicks, 2019). In the case of the 2018 M_w7.5 Palu earthquake, it took only 5 days to obtain a detailed description of the events and only a few days for the Nov 11, 2018 seismo-volcanic event in Mayotte. It takes several months to several 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 may provide direct and early scientific information for researchers, without any geographical and institutional barriers, acting as a "science newsfeed", which can be used to plan further in-depth research.

However, the knowledge built via Twitter is not exactly comparable to the knowledge built in a more long-term academic approach. Even if a long practice allows scientists to estimate the quality of a dataset or of a reasoning almost immediately, 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 of the knowledge built rapidly and without peer-review via Twitter. Questions over the legitimacy of that knowledge also arise. Who are qualified to speak? Do they have experience in a certain region and tectonic setting? Are they from a reputable academic institution? The contributions of recognised scientists from acknowledged institutions might be taken as gospel by a non-expert public. The issue of "what makes a credible scientist?" is however more complex. As shown in the Mayotte example, non-practising researchers and "hobby scientists" can also develop a good scientific understanding and be fully legitimate to discuss these topics. Nevertheless, Twitter discussions amongst a large group of diverse geoscientists can help with refinement of ideas/hypotheses, and to show outward-facing credibility for these.

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 and trending 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

https://doi.org/10.5194/gc-2019-23
Preprint. Discussion started: 28 October 2019

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 were an important information source for an early publication that 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 caution should be exerted when posting to Twitter or other social media.

4.2 - Argument 2 – Outside the laboratory walls

Twitter enables getting outside the laboratory walls in many ways. First, it opens the door to professional networking and new academic collaborations between scientists coming from different disciplines, institutions or even countries. In the case of the Palu earthquake, Indonesian geoscientists joined the discussion to provide data that could only be acquired locally. This led them to engage in a discussion with members of the international scientific community and 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 communication policies, and must sometimes use validated language elements (this was partly the case for French geoscientists after the discovery of the new volcano offshore Mayotte in May 2019).

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 clarifying or reframing the scientific questions and the way to explain them to the public. Non-academics can be the ones launching important discussions. In the case of Mayotte, it was a citizen scientist who warned of a strange seismic signal and it was the "explosion" of informal Twitter discussions that woke up the scientists 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 understandable 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 give in-depth comment. 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 social media or use other platforms. Also, how much checking does a journalist do to assess a tweeter’s scientific credibility?

https://doi.org/10.5194/gc-2019-23
Preprint. Discussion started: 28 October 2019

Geoscience Communication
Discussions

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

The process of knowledge-building on Twitter is open and public, which can help to improve the general public's and the media's understanding of how scientific research works. The above examples make clear 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 using 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. Scientists themselves are familiar with these aspects of their work but non-scientists are not because 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. Early information on Twitter can also provide excellent teachable material for educators. 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 just won't see it even though it's public.

4.4 - Argument 4 : A new type of scientific approach within "global virtual teams" (Zakaria et al. 2004) ?

Can instruments such as Twitter contribute to the emergence of a new type of scientific collaboration within "global virtual teams" (Zakaria et al. 2004)? This raises a number of questions among which is what do we acknowledge as being scientific. So far, academic scientific knowledge is validated through a rigorous process of peer review. This process does not need to be perfect - it is not - but it has the advantage of being shared collectively and can thus play its role of filter between "good" or "bad" science. Peer review is deeply rooted in scientific culture. Scientific institutions derive their credibility and legitimacy from the estimated quality of the work published by their researchers and researchers gain visibility and financial support by belonging to well-established institutions. Platforms such as Twitter allow a more spontaneous building of knowledge which, to be credible, must involve some form of peer review but in a much less formal way. 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. Early

https://doi.org/10.5194/gc-2019-23
Preprint. Discussion started: 28 October 2019

Geoscience Communication
Discussions

sharing of scientific results, preprints or manuscripts submitted to open peer-reviewed journals can provide a good way of getting feedback and help with the peer-review process. 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).

4.5 - Argument 5 : Helping people to understand hazards and risk mitigation

In "real" life, openness and spontaneity following a newsworthy event are always of great value, especially when the development of scientific theories and hypotheses turns into an interesting story. Improving people's understanding of natural phenomena can help to improve risk mitigation, at least indirectly. Take the case of the Palu earthquake, for example. International media insisted on a "failed" tsunami warning 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 few minutes after the event and released it ~30 minutes later (Fig. 1, Table 1); in the meantime the tsunami hit the Palu Bay coasts (Krippner, 2018). Later on the same day, BMKG issued a press release to explain their alert management process. This contradictory information is likely to open a debate that will improve the general public's understanding of what to expect (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 get better prepared. Twitter discussions are opportunities to prevent confusion and misunderstanding by reinforcing and disseminating information and advice given by local government agencies (Bartel and 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 aspects of modern science. These include: development of ideas for future project funding, early dissemination and discussion of preliminary results forming the basis of peer-reviewed publications, networking for developing 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.

https://doi.org/10.5194/gc-2019-23
Preprint. Discussion started: 28 October 2019

Much of the Twitter discussions we have shown 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 and workshops that are a usual way to exchange information and new ideas. Twitter democratises such scholarly interactions and expands their interdisciplinarity and geographic coverage, leading to more diverse scientific inputs. Much of these differences result from an increase in open data, willingness to openly share ideas, and the globalism of science. Moreover, in the examples described in this paper, the group of scientists involved in the discussions had not worked together before. They formed a group with a diverse range of backgrounds and with different expertise, questioning previous tweets, 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, PIs and 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 work, so how can scientists be rewarded for such public dissemination and preliminary ground-work? 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?

Since science on Twitter is carried out 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

https://doi.org/10.5194/gc-2019-23
Preprint. Discussion started: 28 October 2019

Geoscience Communication
Discussions

dissemination of more controversial subjects, such as human-induced seismicity, petroleum science, or climate change. Does exposing the "messy part of science" (see above) to the public help to increase trust in scientific evidence, or to reduce trust? 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. 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 the response from other scientists can be hostile and damaging. We need to specifically acknowledge 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 of 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 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, 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.

Author Contribution

This paper follows exchanges on Twitter to which most authors participated after Palu and/or Mayotte event. JG, 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, SH wrote the paper with inputs from all other authors, listed in alphabetical order.

Competing Interest

The authors declare that they have no conflict of interest.

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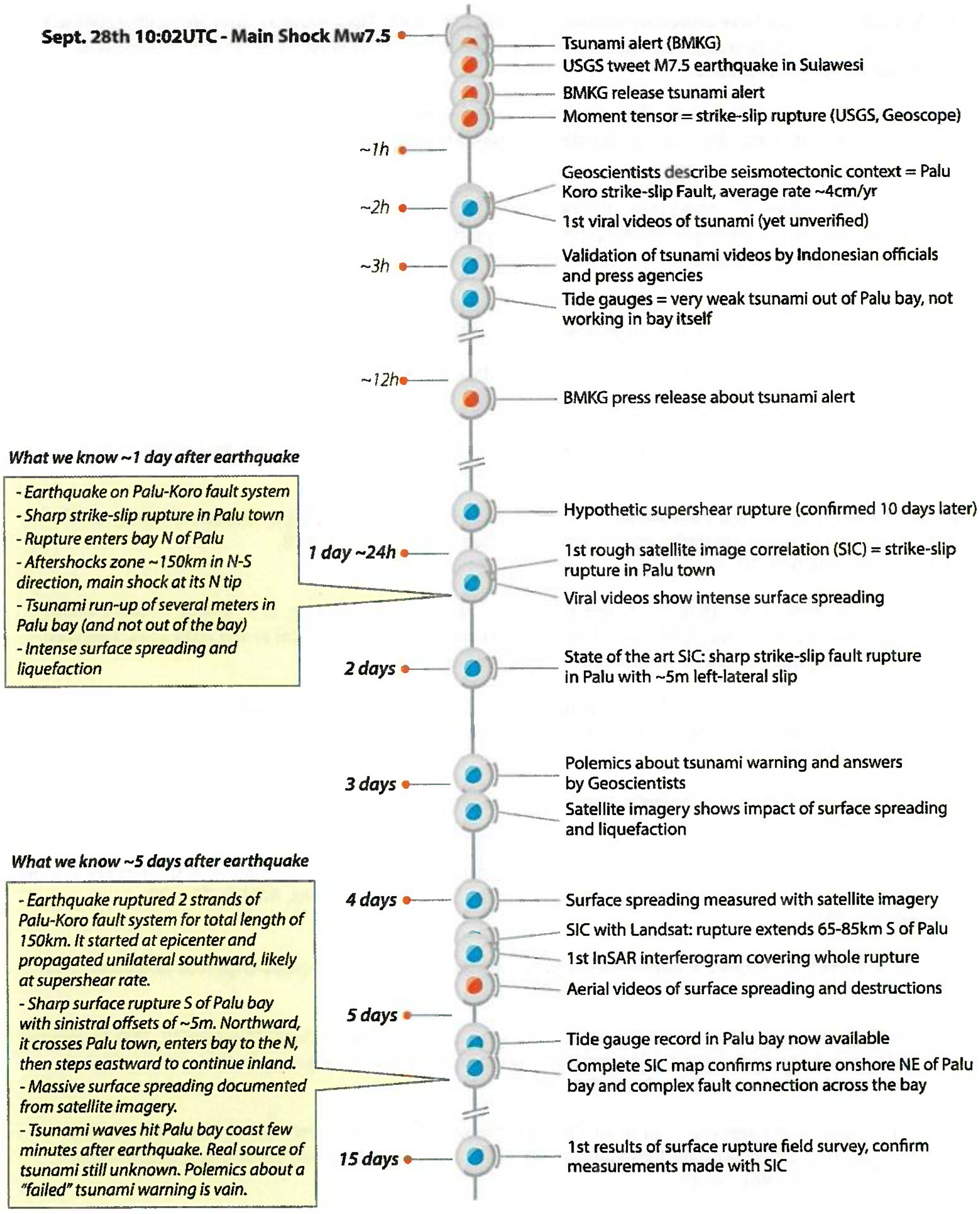

610 **Figure 1:** Timeline of geophysical events, acquisition and dissemination of observations, and knowledge building via Twitter in the hours and days following the Palu earthquake and tsunami of September 28, 2018. See Table S1 for links to relevant tweets.

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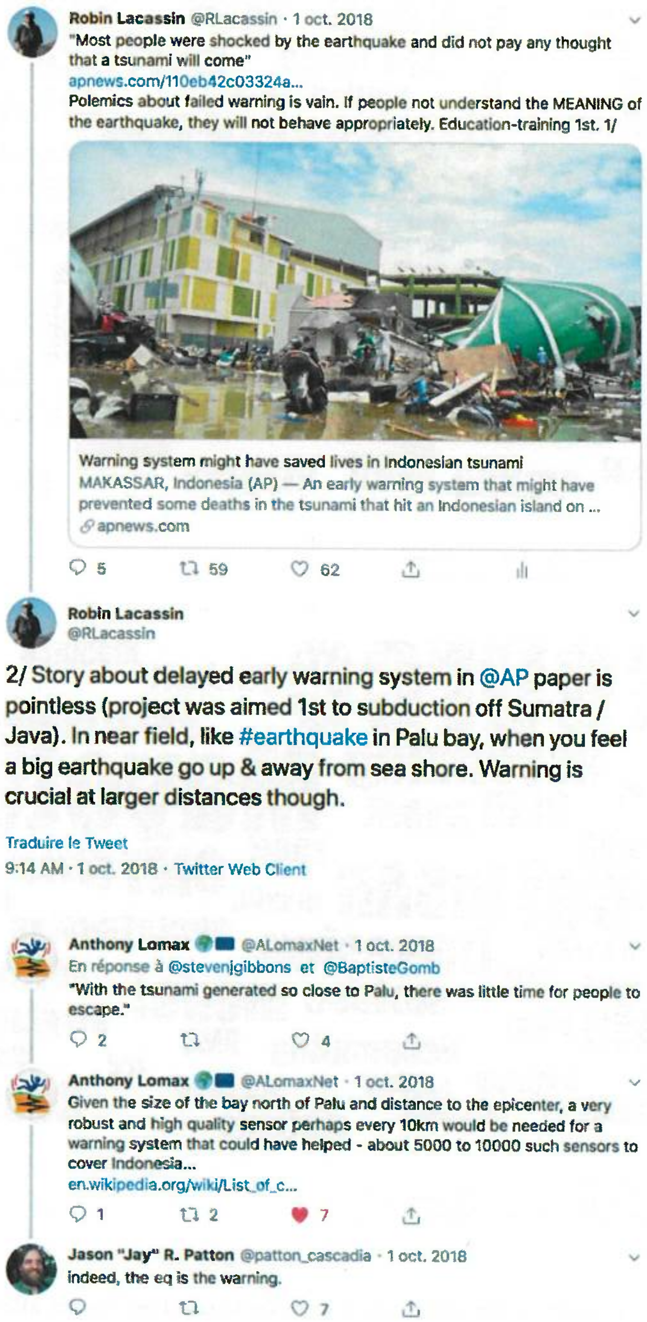

Figure 2: Example of tweets about the "failed tsunami warning" polemics.

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Preprint. Discussion started: 28 October 2019

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Discussions
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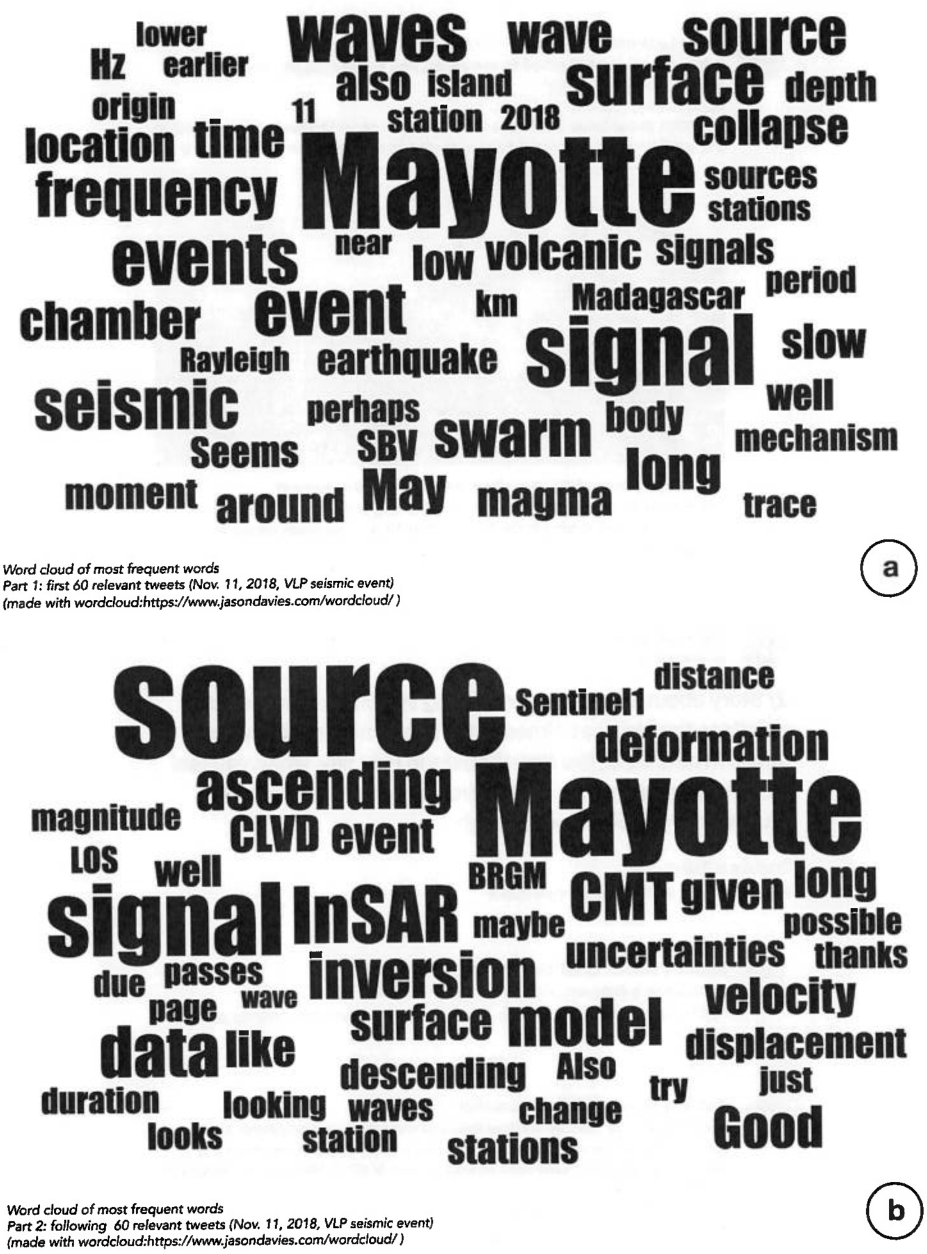

Figure 3: Word clouds outlining the evolution of topics discussed on Twitter after the Mayotte Nov 11, 2018 long period seismic event. Top word cloud illustrates first 60 tweets of the selected Twitter moment (see text), bottom one corresponds to the following 60 tweets.

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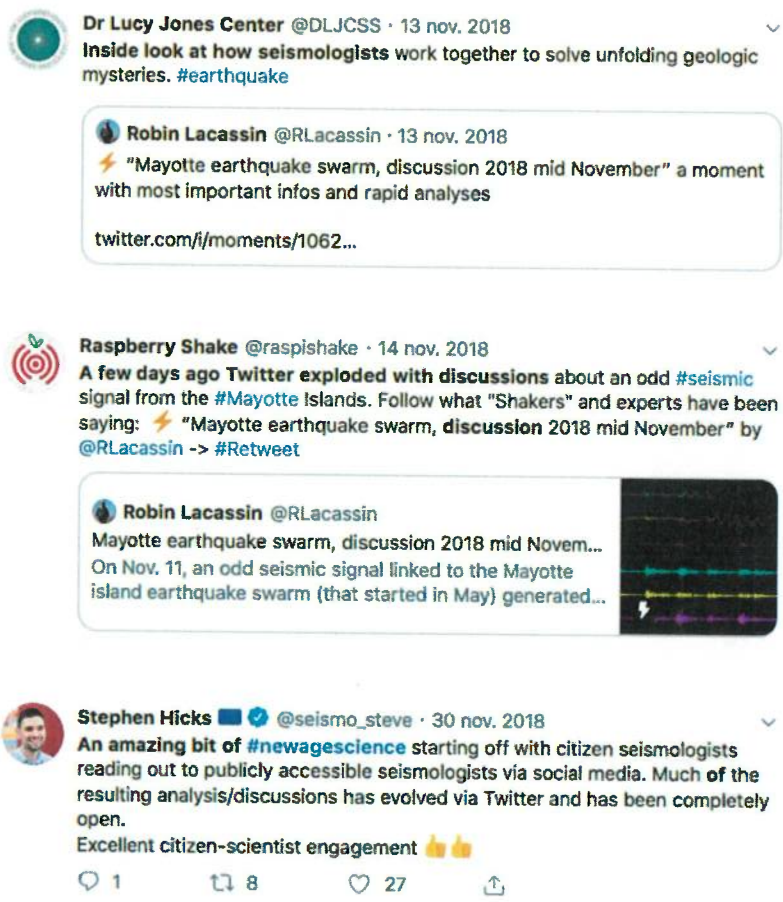

615 **Figure 4:** Example of tweets outlining the active online scientific discussion about the Mayotte Nov 11, 2018 event.