Comprehensive authors' answer to the reviews by C. Jackson and B. Bartel regarding the paper "Rapid collaborative knowledge building via Twitter after significant geohazard events" by Lacassin R. et al., Geoscience Communication Discussion, 2019.

Our paper has now received two detailed reviews outlining that: "it will be an important contribution to the science communication literature" (Reviewer 2, Beth Bartel). We thank both reviewers for their thorough work that will help us to strengthen our presentation of results and our discussion.

Hereafter, in this comprehensive Author Comment, we answer to their detailed comments, explaining how we implement the related changes in our revised manuscript. Below, R1 and R2 respectively refer to comments by Reviewer 1, Christopher Jackson, and Reviewer 2, Beth Bartel (line numbers are those quoted by reviewers and correspond to the initially submitted manuscript). We also answer to the two editor's comments made on initial version of this comprehensive authors' answer (noted "Editor's additional comment")

R2 - Abstract - *A statement about the purpose of the analysis would be helpful.*

Answer: Agreed. We have added the following sentence to the abstract: "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."

R1 - L88 - *Could you perhaps provide an example or two of where this approach has been successfully used in another field? This type of analysis will be new to most (it certainly was to me). Note that your example need not be a STEM discipline.*

Answer: Agreed. There are many cases where social media posts are used to detect and locate hazardous events, such as flooding. We include a reference for this.

First two sentences changed to: "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)."

R1 - L105 - *How were the "most informative tweets" chosen? This sounds rather arbitrary, and my concern would be that such a subjective approach may, as the authors later go on to discuss, could exclude certain voices. Indeed, if voices are excluded, what impact might that have on the quality and robustness of the derived science? I think this needs discussing more; i.e. who is "in" and who is "out" when compiling your underlying data...*

Answer: Agreed.

We have changed "we compiled the most informative tweets" to "we compiled informative tweets". We recall that our objective is not to do a complete analysis of all tweets posted on the subject, but to use chosen tweets and tweet threads to illustrate how this way to spread and discuss scientific information is useful. We have also added the following sentences: "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."

R1 - L111 and L128 - *I strongly suggest you post all data underpinning your analysis on something like FigShare (https://figshare.com/). The data do not appear confidential, plus something like FigShare is a longer-lasting archive than someone's hard-drive. Plus people do not live forever...*

Answer: As suggested we put the pdf prints of the full threads on Figshare :

https://doi.org/10.6084/m9.figshare.11830809.v1 for the thread related to the Palu earthquake
https://doi.org/10.6084/m9.figshare.11830824.v1 for Mayotte
These links are now given in the text and in the section supplementary infos at the end.

R2 - Section 2, Studied Events and Methodology - *I would like more specific information on the Mayotte analysis. What did the analysis consist of? What were you looking for? Was the primary analysis the development of the word clouds? Or the exercise of organizing the discussion into three Twitter moments? Was it mainly looking through the tweets for themes? Was anything about it systematic? How would you describe it should you want someone to repeat it? (The same goes for Palu, but to a lesser extent.)*

R2 - Lines 128-130 - *seem to set the Mayotte analysis up as a contrast to the Palu analysis, but it appears from the list starting on line 130 that you are looking at the same things, possibly with the exception of the role of citizen scientists, which is not addressed in the Palu discussion.*

R2 - Line 133 - *The word "aims" is likely not the best choice here, as it implies that each thread had a different goal. Presumably commenters didn't start the threads with different goals in mind. Instead, I assume that you mean either that the aims of the analyses of each thread were different of that the nature or characteristics or circumstances of each thread were different. (I'm not italicizing to be a jerk, just to emphasize the words I think could be substituted.)*

Answer: We group these three comments by Beth Bartel as they are about the same issues: what are the differences between the Mayotte and Palu cases and related analyses? To address these issues, while keeping the text concise, we have implemented the following changes:

First, we have added the following sentence to the start of the first paragraph to show the contrasting nature of Mayotte compared to Palu: "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 damage caused by the unrest, and which lacked initial responses from official government agencies".

Then we have modified the second part of this paragraph (from former L120 to L132). It now reads: "We do not analyse the full, >1 year long, Twitter activity related to the Mayotte seismic swarm, but we focus on a peculiar long-period seismic event […] The 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, our first aim was to select and regroup the most relevant and informative tweets linked to these discussions. We organize these selected tweets into three successive Twitter moments accessible online […] Our purpose is not to do the same timeline analysis than for the Palu earthquake, but to use the "Mayotte 11 November 2018 rumble event" example to outline the efficient knowledge-building dialogue between scientists 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 implications of citizen scientists at the start of the discussion, to discuss some pitfalls inherent to the informal use of Twitter as well as the opportunity to spread information toward more traditional print, broadcast and online media."

Last, we have also significantly modified the following paragraph (from former L133) which now writes: "The evolution of the two threads were quite different. With Palu, the scenario was quite well defined and occurred at a rapid pace over a short amount of time: an earthquake and 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 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 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 immediately seen in Palu."

R1 - L148 - *There seems to be some switching between passive and active voice. I would stick to one...preferably the latter...*

Answer: Agreed. Changed the sentence to be in the active voice.

R2 - Section 3.1: Lines 152-188 - *It would be helpful to call out who posted info on Twitter other than the monitoring agencies (since you do refer to them), to show who was contributing to the knowledge-building process. You don't need specific names, but it would be helpful to know: academic scientists? Researchers from other institutions? Other?*

R2 - Line 198 - *It would be helpful to know more about the scientists, e.g., example institutions or at least institution types (as in comment above); all academics? From other agencies? You write later about the democratization of science, and about the diversity and subdisciplines of geoscience; this would be a good place to lay the groundwork for those statements by pointing out the diversity of voices in the conversation. (All seismologists, or various disciplines? Different data types being shared and considered together? Different career stages, nationalities, etc.?)*

Editor's additional comment - *I would like to follow-up on Reviewer 2's comment on line 198, which you have responded to. I agree that a full analysis of the "voices" in the conversation is out of the scope of this paper. However, I agree with the general idea behind Reviewer 2's point and would like to see slightly more information here. I realise that it would be a quantitative and mostly subjective overview, but I also think it is useful to understand if researchers outside seismology were involved in the discussion. This is particularly pertinent since you later state that the "twitter interactions on Mayotte brought the global geoscience community's attention to the event". The geoscience community is much more than seismology. Therefore, please include some description of who this "geoscience community" was composed of.*

Answer: We group these comments. This is an important and worth-studying subject. But our purpose here is not to do a detailed sociological study of people involved in the Twitter discussions. Such a sociological analysis would devote another study, and paper. This would be very interesting, but would complicate our purpose and lengthen a lot the paper. We acknowledge reviewer's suggestion but we prefer not implementing such an analysis in the present paper.

To clarify this point and to take into account Editor's recommandation while remaining short, we modified the first paragraph of section 3.1 (about the Palu case), which now reads as: " […] 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."

We also modified the first sentences of the third paragraph of section 3.2 (about Mayotte) as follows: "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."

R1 - L197 - *"...as good a way..." compared to what?*

Answer: our purpose is not to compare data sharing and social interaction via Twitter with other ways to discuss scientific information.

To clarify, we modified the sentence as: "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."

R2 - Line 206 - *Regarding "creates": Be careful with the use of present vs. past. Present implies a general truth, in this case that Twitter creates the opportunity for developing new international collaborations. I think what you meant and what I think is appropriate in this section is that the Twitter interactions during the Palu event created the opportunity for developing new international collaborations. (In which case, use past tense, created.) This is an example of why defining your pronouns is also important (see General comments under Technical Corrections, below). If you want to make a general statement here, I suggest something like "Exchanges like this create the opportunity. . .."*

Answer: Agreed. We have changed "creates" to "created"

R1 - L208 - *As written, this makes it sound like Twitter is not a social media platform. I would perhaps rephrase this sentence.*

Answer: Agreed. We have changed this part of the sentence to "… was enabled by videos posted on social media platforms such as Twitter and YouTube."

R2 - Lines 210-222 - *I recommend reworking this paragraph for clarification. It is worth expanding on this - don't be afraid to take up more space explaining the situation.*

R2 - Line 220 - *Wasn't the geometry of Palu Bay, not only the timing, part of the scientific discussion? If I'm remembering wrong, ignore. If this was indeed part of the discussion, consider bringing it in.*

R1 - L222 - *I would rephrase this sentence, as I am not sure "critical explanation" makes sense here in this context.*

Answer: We group these comments, and we agree with the suggestion to give more explanations about the "failed" tsunami alert.

The text now reads as follows: "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."

R2 - Line 222+ - *This section would benefit from a short concluding paragraph.*

Answer: Agreed

We have inserted the following sentence at the end of this discussion: "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."

R2 - Lines 230-236 - *As I wrote in the margin, I think a shot of these early tweets would be a helpful figure.*

Answer: Agreed. We added screenshots of these early tweets by citizen scientists as a new figure.

R1 - L240 - *See comment related to L105.*

Agreed. We have changed this part of the sentence to "…that regroup our compilation of tweets".

R2 - Line 241 - *I'm not convinced that this work is a contextual analysis. My impression is that it is another form of content analysis. I'm not an expert in this, however.*

Agreed. We have now stated that this is "a simple content analysis of the selected tweet…".

R2 - Line 253 - *An intro sentence would be helpful here.*

We've added the following sentence to the start of this paragraph: "The Twitter interactions on Mayotte brought the global geoscience community's attention to the event".

R2 - Lines 263-268 - *An intro and/or conclusion sentence with main point(s) would be helpful. Also, I don't find the SH tweet quote helpful, especially as he is an author (meaning you can just state that idea in your text as authors, rather than quoting the tweet). Here quoting these casual tweets is a little like saying "after this event, someone told me over coffee that ___." As in, it is not evidence of anything. You can make the arguments based on your analysis instead. I also don't find the corresponding figure helpful (Figure 4), especially in the absence of other tweet examples that would be more pertinent in this paper, such as the tweets that started the Mayotte conversation. I recommend either removing the figure or reworking this paragraph and the figure caption to justify including it.*

We agree that the screenshots displayed on Figure 4 were casual. We delete them, and we recall that we now provide screenshots of the tweets by citizen scientists that were at the start of the discussion.

R2 - Lines 274-278 - *Valid points, but they need back-up. They seem speculative. The comments on the people living in Mayotte are also potentially demeaning, and I recommend more careful wording here. What was the mention of the "sea monster"? Please clarify context.*

Can you comment on how the pitfalls with Mayotte compare to the Palu example? Were they absent from the Palu case? (Aside from the bushy nature of the thread, which you have made a clear case for already.)

Answer: The argument about animism belief and 'sea monster' is not central to the paper and would open avenues for another debate. We now focus the paragraph more on the specific nature of the bushy discussion in the case of Mayotte and the difference with Palu. And we deleted the final sentences about animism belief and 'sea monster'.

The paragraph now reads : "The long thread about the Mayotte 11 November 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 observations (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 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. We infer that scientific Twitter exchanges dealing with uncertainties and unknowns, as for Mayotte, are more prone to such pitfalls than those sharing knowns."

R1 - L298 - See comment related to L105.

Answer: Agreed. We have changed this question to "How do we judge who is qualified to speak?". We also added a further question: "How do we ensure that the most qualified comments receive the most attention?"

R1 - L299 - *How do you define a "reputable academic institution" or "credible scientist" (L301)? My concern here is that such definitions are rather poorly defined, and could potential lead to the exclusion of particular voices not known by the 'in-crowd' who are driving the scientific discussion. Now, I am not accusing you of this, but I think this manuscript would be a good place to explore this problematic issue.*

Answer: Agreed. But our paper is not about reputability and credibility in Science, and we cannot explore this subject in more detail. To clarify we have added the following sentence: "Whilst scientific credibility is important, it is not straightforward to make such a classification, particularly for members of the public not part of the scientific community."

R2 - Section 4.1 Lines 302-305 - *I don't see two of the ideas stated here clearly stated in and supported by the analysis (noted in the margins). Specific quotes or figures in the analysis to support these ideas would be helpful.*

Answer: Agreed, our text needed clarification and simplification.

To clarify our point we changed the paragraph as follows: " 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? 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? " In this revised paragraph we refer to the new version of Figure 4 that now shows screenshots of the tweets by citizen scientists at the start of the discussion about the 11 Nov event.

R2 - Lines 310-315 - *This is an important discussion. You may want to clarify a bit: Are you referring to use of open access data, or people using info posted by agencies on Twitter, or. . .? If I understand right, you are referring to researchers (not at the responding agency) using tweets, blog posts, and media releases posted by the responding agency to further their own science without collaboration with the responding agency scientists, and faster than the responding agency scientists can publish.*

R1 - L312 - *Please cite the "early publication" mentioned here, otherwise this comments sounds too anectodal (when it need not).*

R1 - L314 - *What precisely do you mean by "some caution"? More specifically, what guidance would you provide people regarding their engagement with scientific discussions on Twitter? I know such guidelines might be hard to define, but some comments here would be useful.*

Answer: we regroup these comments as they are about the same paragraph and discussion. We agree that this discussion needed some clarifications.

We clarified the sentences about NZ case which now read as follows: "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." We now cite the related paper (Shi et al. 2017).

We have elaborated and changed the last sentence to "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."

R2 - Section 4.2 - Line 320 - *Who was already in the discussion, and was it already international? It would be helpful to know more about the discussion the Indonesian scientists "joined." (Noting that they, too, are part of the international scientific community – you may want to reword to make this clear.)*

Answer: agreed. We added some details.

The corresponding sentence now reads as follows: "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). "

We also changed "discussion with members of the international scientific community" to "discussion with other members of the international scientific community"

R1 - L326 - *What are "validated language elements"?*

R2 - Lines 325-328: *What are the implications? Problem? Limitations? And what specifically happened with Mayotte in May 2019? And does it relate to / show up in your analysis?*

Answer: We regroup these comments by both reviewers. Discussing this point, and communication issues following the discovery of the undersea volcano in May 2019, would be another subject. We deleted this sentence and keep the discussion more general.

The paragraph now ends: "Also, scientists from local monitoring organisations or universities may have strict social media usage and communication policies"

R1 - L365 - *I remove "rigourous" from here, given this is not always the case. In fact, this is something you yourselves go on to say...*

Agreed. Removed.

R2 - Section 4.4 - *You may be able to combine or reorganize some of the sections, for example 4.1 with 4.4.*
R2 - Lines 367-371 - *This mixes peer review (process) and publications (output). These should be considered separately. This may also fit into section 4.1, as noted above.*
R2 - Lines 374-375 - *How does this relate to social media? This seems an argument for open-access journals.*
R1 - L375 - *Twitter-based discussions and data generation may potential offer a route for the scientific community to better value the data itself. Too often we are concerned with the paper narrative, and not the fundamental quality and quantity of the data underpinning it.*

Answer: Agreed. We regroup these four comments about the same discussion (former section 4.4). We have removed former section 4.4. We simplified this discussion, and combined aspects of it into Section 4.1

Corresponding paragraph, now in section 4.1, reads as follows: "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."

R2 - ***Section 4.5 Lines 380-381:*** *Justification or citation? Lines 382-383: Justification or citation?*

Answer: we have deleted these sentences.

R1 - L386 - *What is the difference between "issued" and "released"?*

Answer: Our wording was misleading, as "released" should have been "cancelled". Changed.

R2 - Section 5: *Concluding remarks. I suggest focusing this section first on the benefits of using social media to rapidly characterize geophysical events, which is your main point (and what your analysis is focused on) throughout the rest of the paper.*
You bring up other important discussion points, not all of which are addressed directly by your analysis. Since you are using this space to remark on the nature of science and science communication beyond your analysis, make this clear somewhere, such as at the end of the first paragraph. Use examples, describe the experiences of authors or at least state whether the statements are based on the experiences of authors, or use citations where possible. At the very least, set the expectations of readers by letting readers know that you are diverting from your analysis-based conclusions.

Editor's additional comment - *In your response to R2 and section 5, you might want to use a different verb than "to throw up".*

Answer: As suggested by the title "Concluding remarks" our aim here is to broaden the discussion using the result of this study but also our own experience. Giving examples and more details about these experiences would lengthen a lot this conclusion. To clarify our objectives we added the following explanations:

Added the following sentence to the end of the first paragraph in Section 5: "In these concluding remarks, we combine the results from the present study with our own experience on social media to identify some interesting questions and implications for modern scientific methods and communication." (initial wording has been changed as recommended by editor).
Added "Our analysis has shown that Twitter discussions …" to the start of Paragraph 2.
Added "Based on our experiences" to the start of Paragraph 4.

R1 - L438 - *Although 'science in the open' could be risky for the reason you state, I see absolutely nothing good coming from the opposite; i.e. 'closed science', in which the process and critique of science is done behind closed-doors, potentially by people with vested interests and/or conflicts-of-interest.*

Answer: Agreed. To further enhance this conclusion we added the following sentence: "Overall, opening up the scientific processes and involving the general public as stakeholders should help to improve trust in experts"

R2 comments about FIGURES and TABLES:

Figure 1: *Needs a legend. What does red mean, what does blue mean? Also, curved line to the right of the circles is a nice idea but could be removed - it tricked me into thinking there were a lot of points stacked on one another. Reword the text for consistency in format. You may try changing all statements to read as though they end in "posted," since this is a timeline of information as it appears on Twitter, not as it is produced. Modify the caption to reflect this. "Polemics about a "failed" tsunami warning is vain." – I recommend a reword. Polemics is not common enough, vain is not quite right here. Edit this also in other appearances in the manuscript.*

Figure 2: *I would like to see an example of knowledge-building as the first figure of tweets, since that's what the paper most focuses on. Then, I would like to see figures showing examples of the other points you would like to make - e.g., interactions with journalists, correcting misinformation, transfer of knowledge/information to non-geoscientists, peer review process online, and/or contributions of non-geoscientists to the scientific discussion.*
Please include a more descriptive figure caption for Figure 2..

Former Figure 3: *More descriptive figure caption. Include a sentence on the implications of the word clouds (you can repeat from the main text). Do this for all figure captions. A reader should be able to read the figure caption to get the point of the figure without having to go back to the text. (This will increase the reach of your ideas - think of the people who are only going to read the abstract, intro, figures, and conclusions!)*

Answers: Following reviewer's recommendations we have significantly changed and improved the different figures and their captions as follows:

- **Figure 1** (Palu timeline) and its legend has been improved as recommended.
- **New Figure 2** now shows screenshots of tweets chosen to illustrate how geoscientists spread and explained context and observations regarding the Palu earthquake and tsunami.

- **New Figure 3** shows screenshots illustrating discussions about the “failed” tsunami warning and related explanations by geoscientists. It also shows an example of geoscientists engaging discussion with local people.
- **New Figure 4** regroups screenshots of selected early tweets at the start of the Mayotte 11 November event discussion. It now outlines initial citizen scientist implication and ensuing exchanges between researchers.
- **Figure 5** (former Figure 3) caption has been improved as recommended.
- **New Figure 6** now outlines interaction with journalists.

Refer to marked-up manuscript that follows for new versions of the Figures and captions.

Table 1: *I think these tables are key to understanding your analysis. I recommend at least Table 1 in the text rather than having them as a supplement.*

Answer: Agreed. Former Table S1 was too wide to fit in main text page format. We simplified it, removing the column with the links to relevant tweets, and put it in the paper as Table 1. We keep the complete table in supplements (Table S1)

Table 2: *Table 2: The link to Ken’s doesn’t work*

Fixed.

Both reviewers made handwritten annotations directly on hardcopies of the paper, recalling the different points already discussed above plus suggesting minor typo or formal changes. We implement the majority of these minor changes in our revised manuscript.

In the following marked-up manuscript, changes related to R1-R2 comments are in red, those related to Editor's comments in purple.

New versions of the Figures, of their captions, and of the new Table 1 (simplified version of Table S1 given in supplement) are appended.

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_w7.5 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_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 (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. 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_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 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 damage caused by the unrest, and which lacked initial responses from official government agencies. The island 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 seismic or volcanic hazard prior to this crisis. The seismic swarm is still active more than one year and a half after its start, and has been recently linked to a migration of magma within the lithosphere and the eruption of an undersea volcano (Cesca et al., 2020; Feuillet et al., 2020). We do not analyse the full, >1 year long, Twitter activity related to the Mayotte seismic swarm, but we focus on a peculiar long-period seismic event that happened on 11 November 2018. This event triggered a surge in scholarly Twitter discussions in the following days. The 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 this thread, our first aim was to select and regroup the most relevant and informative tweets linked to these discussions. We organize 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 November 2018 rumble event" example to outline the efficient knowledge-building dialogue between scientists 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 inherent to using an informal platform like Twitter, as well as the opportunity to spread information toward more traditional print, broadcast and online media.

The evolution of the two threads were quite different. With Palu, the scenario was quite well-defined and occurred 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 exchanges 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 no there was no important damage, injury or fatalities. In contrast, 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 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

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:

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);

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);

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 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:

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);

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);

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);

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).

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. 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 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 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 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 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 geophysical 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 was due to a deflation event in a large and deep magmatic chamber combined with resonance and amplification 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. Before 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 Mayotte is a French territory. As noted by Lemoine et al. (2019) , the 11 November 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 hasten needed research in the region (Hicks, 2019). A few days after the 11 November event, at a meeting between the French geoscience community and stakeholders (funding agencies and 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 the subject of two long articles in National Geographic (Wei-Haas, 2018b) and Gizmodo (Andrews, 2018b), with journalists gathering information and contacting researchers via Twitter before interviewing them via email or phone (Figure 6). These articles were then 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 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 observations (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 uncertainties and unknowns, as for Mayotte, are more prone to such pitfalls than those sharing knowns.

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 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 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? 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 across the laboratory walls

Twitter allows us to step 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, 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 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.

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 reframe the scientific questions and the way to explain them to the public. Non-academics can launch important discussions. In the case of Mayotte, it was a citizen scientist who drew attention to a strange seismic signal (Figure 4a), and it was the subsequent "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 (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 social media platforms. Also, how much checking does a journalist do to assess a Tweeter’s scientific credibility?

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

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 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. Scientists themselves are familiar with these aspects of their work but non-scientists may not be, largely 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 and visible. 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 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 (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 indirectly. Take the case of the Palu earthquake, for example. International media insisted that a "failed" tsunami 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 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 prepare. 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. In these concluding remarks, we combine the results from the present study with our own experience on social media to identify some interesting questions and implications for modern scientific methods and communication.

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 democratises 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, 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 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, 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. 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 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 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, 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.

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 from all other authors, listed in alphabetical order.

Competing Interest

The authors declare that they have no conflicts of interest.

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This paper is a collaborative study following Twitter discussions between co-authors. It is dedicated to the late Sutopo Purwo Nugroho, former chief spokesman of the Indonesia disaster mitigation agency (BNPB) for his open communication toward the public, in particular via Twitter. RL has his position funded by CNRS (Centre National de la Recherche Scientifique, France). Part of this research was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration. We thank Christopher Jackson and Beth Bartel for their detailed and helpful reviews. This study contributes to the IdEx Université de Paris ANR-18-IDEX-0001. This is IPGP contribution n° xxxx.

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 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).

References

Andrews, R. G.: Indonesian Tsunami: What Happened, How To Survive One, And How To Help, Forbes, 1st October [online] Available from: https://www.forbes.com/sites/robinandrews/2018/10/01/indonesian-tsunami-what-happened-how-to-survive-one-and-how-to-help/ (Accessed 5 July 2019b), 2018a.

Andrews, R. G.: Geologists Joke About "Sea Monster" After Mysterious 30-Minute Rumble Emanates from Waters Near Madagascar, Gizmodo [online] Available from: https://gizmodo.com/geologists-joke-about-sea-monster-after-mysterious-30-m-1830738921 (Accessed 5 July 2019a), 2018b.

Bao, H., Ampuero, J.-P., Meng, L., Fielding, E. J., Liang, C., Milliner, C. W. D., Feng, T. and Huang, H.: Early and persistent supershear rupture of the 2018 magnitude 7.5 Palu earthquake, Nature Geoscience, 12(3), 200–205, doi:10.1038/s41561-018-0297-z, 2019.

Bartel, B. and Bohon, W.: The Hazards of Hazard Communication: Importance, Rewards, and Challenges of Science in the Public Sphere: A white paper summary of presentations from session PA23B at the 2018 Fall Meeting of the 485 American Geophysical Union. [online] Available from: https://www.iris.edu/hq/files/Science_Highlights/Hazards_of_Hazard_Communication_White_Paper_2019.pdf , 2019.

Bossu, R., Mazet-Roux, G., Douet, V., Rives, S., Marin, S. and Aupetit, M.: Internet Users as Seismic Sensors for Improved Earthquake Response, Eos, Transactions American Geophysical Union, 89(25), 225–226, doi:10.1029/2008eo250001, 2008.

Bossu, R., Roussel, F., Fallou, L., Landès, M., Steed, R., Mazet-Roux, G., Dupont, A., Frobert, L. and Petersen, L.: LastQuake: From rapid information to global seismic risk reduction, International Journal of Disaster Risk Reduction, 28, 32–42, doi:10.1016/j.ijdrr.2018.02.024, 2018.

Britton, B., Jackson, C. and Wade, J.: The reward and risk of social media for academics, Nat Rev Chem, 3(8), 459–461, doi:10.1038/s41570-019-0121-3, 2019.

Carvajal, M., Araya-Cornejo, C., Sepúlveda, I., Melnick, D. and Haase, J. S.: Nearly Instantaneous Tsunamis Following the Mw 7.5 2018 Palu Earthquake, Geophys. Res. Lett., 12, 200, doi:10.1029/2019GL082578, 2019.

Cesca, S., Letort, J., Razafindrakoto, H. N. T., Heimann, S., Rivalta, E., Isken, M. P., Nikkhoo, M., Passarelli, L., Petersen, G. M., Cotton, F. and Dahm, T.: Drainage of a deep magma reservoir near Mayotte inferred from seismicity and deformation, Nature Geoscience, 13(1), 87–93, doi:10.1038/s41561-019-0505-5, 2020.

Chiaraluce, L., Di Stefano, R., Tinti, E., Scognamiglio, L., Michele, M., Casarotti, E., Cattaneo, M., De Gori, P., Chiarabba, C., Monachesi, G., Lombardi, A., Valoroso, L., Latorre, D. and Marzorati, S.: The 2016 Central Italy Seismic Sequence: A First Look at the Mainshocks, Aftershocks, and Source Models, Seismol. Res. Lett., 88(3), 757–771, doi:10.1785/0220160221, 2017.

Choo, E. K., Ranney, M. L., Chan, T. M., Trueger, N. S., Walsh, A. E., Tegtmeyer, K., McNamara, S. O., Choi, R. Y. and Carroll, C. L.: Twitter as a tool for communication and knowledge exchange in academic medicine: A guide for skeptics and novices, Med. Teach., 37(5), 411–416, doi:10.3109/0142159X.2014.993371, 2015.

Earle, P., Guy, M., Buckmaster, R., Ostrum, C., Horvath, S. and Vaughan, A.: OMG Earthquake! Can Twitter Improve Earthquake Response?, Seismol. Res. Lett., 81(2), 246–251, doi:10.1785/gssrl.81.2.246, 2010.

Engesser, S. and Humprecht, E.: Frequency or Skillfulness: How professional news media use Twitter in five Western countries, Journalism Studies, 16(4), 513–529, doi:10.1080/1461670X.2014.939849, 2015.

Fallou, L. and Bossu, R.: Taking into account the cultural context to improve scientific communication – Lessons learned from earthquakes in Mayotte, EGU Seismology [online] Available from: https://blogs.egu.eu/divisions/sm/2019/03/08/taking-into-account-the-cultural-context-to-improve-scientific-communication-lessons-learned-from-earthquakes-in-mayotte/ (Accessed 30 August 2019), 2019.

Feuillet, N., Jorry, S. J., Crawford, W., Deplus, C., Thinon, I., Jacques, E., Saurel, J. M., Lemoine, A., Paquet, F., Daniel, R., Gaillot, A., Satriano, C., Peltier, A., Aiken, C., Foix, O., Kowalski, P., Laurent, A., Beauducel, F., Grandin, R., Ballu, V., Bernard, P., Donval, J. P., Geli, L., Gomez, J., Guyader, V., Pelleau, P., Rinnert, E., Besançon, S., Bertil, D., Lemarchand, A. and Van der Woerd, J.: Birth of a large volcano offshore Mayotte through lithosphere-scale rifting, Nature, in revision, 2020.

Fountain, H.: Indonesia Tsunami's Power After Earthquake Surprises Scientists, New York Times, 30th September [online] Available from: https://www.nytimes.com/2018/09/30/world/asia/indonesia-tsunami-science.html (Accessed 5 September 2019), 2018.

Hayes, G. P., Earle, P. S., Benz, H. M., Wald, D. J., Briggs, R. W. and the USGS/NEIC Earthquake Response Team: 88 Hours: The U.S. Geological Survey National Earthquake Information Center Response to the 11 March 2011 Mw 9.0 Tohoku Earthquake, Seismol. Res. Lett., 82(4), 481–493, doi:10.1785/gssrl.82.4.481, 2011.

Hicks, S.: Tweet - Low-frequency seismic rumblings originated close to the island of Mayotte, Twitter [online] Available from: https://twitter.com/seismo_steve/status/1062042619264581633 (Accessed 1 October 2019b), 2018a.

Hicks, S.: Tweet about preliminary CMT inversion, Twitter [online] Available from: https://twitter.com/seismo_steve/status/1065976362253647874 (Accessed 15 July 2019a), 2018b.

Hicks, S.: Geoscience analysis on Twitter, Nat. Geosci., 3, 682, doi:10.1038/s41561-019-0425-4, 2019.

Hicks, S. P., Verdon, J., Baptie, B., Luckett, R., Mildon, Z. K. and Gernon, T.: A Shallow Earthquake Swarm Close to Hydrocarbon Activities: Discriminating between Natural and Induced Causes for the 2018–2019 Surrey, United Kingdom, Earthquake Sequence, Seismol. Res. Lett., doi:10.1785/0220190125, 2019.

Jones, L. M.: Empowering the public with earthquake science, Nat Rev Earth Environ, 1(1), 2–3, doi:10.1038/s43017-019-0007-4, 2020.

Jongman, B., Wagemaker, J., Romero, B. R. and De Perez, E. C.: Early Flood Detection for Rapid Humanitarian Response: Harnessing Near Real-Time Satellite and Twitter Signals, ISPRS International Journal of Geo-Information, 4(4), 2246–2266, doi:10.3390/ijgi4042246, 2015.

Krippner, J.: Timeline of BMKG tsunami warning, Twitter [online] Available from: https://twitter.com/janinekrippner/status/1046728583627108354 (Accessed 9 October 2019), 2018.

Kuhn, T. S.: The Structure of Scientific Revolutions, University of Chicago Press. [online] Available from: https://books.google.com/books/about/The_Structure_of_Scientific_Revolutions.html?hl=&id=xnjS401VuFMC, 1996.

Lacassin, R.: Mayotte earthquake swarm, discussion 2018 mid November, Twitter [online] Available from: https://twitter.com/i/moments/1062037784909832192 (Accessed 4 July 2019c), 2018a.

Lacassin, R.: 2/n Mayotte earthquake swarm, 2nd part of discussion - 2018 mid Nov, Twitter [online] Available from: https://twitter.com/i/moments/1064977870529925121 (Accessed 4 July 2019a), 2018b.

Lacassin, R.: 3/n Mayotte earthquake swarm, 3rd part of discussion…, Twitter [online] Available from: https://twitter.com/i/moments/1067410879233368065 (Accessed 4 July 2019b), 2018c.

Lacassin, R.: Palu earthquake – Co-building knowledge timeline, Twitter [online] Available from: https://twitter.com/i/moments/1073575303979692032 (Accessed 3 July 2019), 2019.

Landwehr, P. M., Wei, W., Kowalchuck, M. and Carley, K. M.: Using tweets to support disaster planning, warning and response, Saf. Sci., 90, 33–47, doi:10.1016/j.ssci.2016.04.012, 2016.

Lee, J.-S. M.: How to use Twitter to further your research career, Nature, doi:10.1038/d41586-019-00535-w, 2019.

Lemoine, A., Bertil, D., Roullé, A. and Briole, P.: The volcano-tectonic crisis of 2018 east of Mayotte, Comoros islands, EarthArXiv, doi:10.31223/osf.io/d46xj, 2019.

Lomax, A., Bossu, R. and Mazet-Roux, G.: Real-Time Science on Social Media: The Example of Twitter in the Minutes, Hours, Days after the 2015 M7.8 Nepal Earthquake, in 2015 AGU Fall Meeting, AGU. [online] Available from: https://agu.confex.com/agu/fm15/meetingapp.cgi/Paper/77222 (Accessed 7 October 2019), 2015.

Morin, H.: Indonésie : polémique « vaine » sur le système d'alerte tsunami, Le Monde, 1st October [online] Available from: https://www.lemonde.fr/sciences/article/2018/10/01/indonesie-polemique-vaine-sur-le-systeme-d-alerte-tsunami_5362931_1650684.html (Accessed 5 September 2019), 2018.

Patton, J. R.: EarthquakeReport Italy, Twitter [online] Available from: https://twitter.com/patton_cascadia/status/792868409734291457 (Accessed 8 October 2019), 2016.

Patton, J. R.: EarthquakeReport offshore of Madagascar, the Comoros Archipelago, Mayotte, Twitter [online] Available from: https://twitter.com/patton_cascadia/status/996465298680115200 (Accessed 8 October 2019), 2018.

Pusat Studi Gempa Nasional - National Center for Earthquake Studies: Peta Sumber dan Bahaya Gempa Indonesia Tahun 2017, Pusat Litbang Perumahan dan Pemukiman, Bandung, Indonesia. [online] Available from: http://geotek.lipi.go.id/wp-content/uploads/2018/02/BUKU-PETA-GEMPA-2017.pdf, 2017.

Sample, I.: "Magma shift" may have caused mysterious seismic wave event, The Guardian, 30th November [online] Available from: http://www.theguardian.com/science/2018/nov/30/magma-shift-mysterious-seismic-wave-event-mayotte (Accessed 15 July 2019), 2018.

Shiffman, S. D.: The Benefits of Twitter for Scientists, American Scientist [online] Available from: https://www.americanscientist.org/blog/macroscope/the-benefits-of-twitter-for-scientists (Accessed 29 August 2019), 2017.

Shi, X., Wang, Y., Liu-Zeng, J., Weldon, R., Wei, S., Wang, T. and Sieh, K.: How complex is the 2016 M w 7.8 Kaikoura earthquake, South Island, New Zealand?, Sci Bull. Fac. Agric. Kyushu Univ., 62(5), 309–311, doi:10.1016/j.scib.2017.01.033, 2017.

Socquet, A., Simons, W., Vigny, C., McCaffrey, R., Subarya, C., Sarsito, D., Ambrosius, B. and Spakman, W.: Microblock rotations and fault coupling in SE Asia triple junction (Sulawesi, Indonesia) from GPS and earthquake slip vector data, Journal of Geophysical Research, 111(B8), doi:10.1029/2005jb003963, 2006.

Socquet, A., Hollingsworth, J., Pathier, E. and Bouchon, M.: Evidence of supershear during the 2018 magnitude 7.5 Palu earthquake from space geodesy, Nature Geoscience, 12(3), 192–199, doi:10.1038/s41561-018-0296-0, 2019.

Steed, R. J., Fuenzalida, A., Bossu, R., Bondár, I., Heinloo, A., Dupont, A., Saul, J. and Strollo, A.: Crowdsourcing triggers rapid, reliable earthquake locations, Sci Adv, 5(4), eaau9824, doi:10.1126/sciadv.aau9824, 2019.

Stewart, I. S., Ickert, J. and Lacassin, R.: Communicating Seismic Risk: the Geoethical Challenges of a People-Centred, Participatory Approach, Annals of Geophysics, 60, doi:10.4401/ag-7593, 2018.

Takahashi, B., Tandoc, E. C., Jr. and Carmichael, C.: Communicating on Twitter during a disaster: An analysis of tweets during Typhoon Haiyan in the Philippines, Comput. Human Behav., 50, 392–398, doi:10.1016/j.chb.2015.04.020, 2015.

Ulrich, T., Vater, S., Madden, E. H., Behrens, J., van Dinther, Y., van Zelst, I., Fielding, E. J., Liang, C. and Gabriel, A.-A.: Coupled, Physics-Based Modeling Reveals Earthquake Displacements are Critical to the 2018 Palu, Sulawesi Tsunami, Pure Appl. Geophys., 81, 5679, doi:10.1007/s00024-019-02290-5, 2019.

Valkaniotis, S., Ganas, A., Tsironi, V. and Barberopoulou, A.: A preliminary report on the M7.5 Palu 2018 earthquake co-seismic ruptures and landslides using image correlation techniques on optical satellite data, , doi:10.5281/zenodo.1467128, 2018.

Van Noorden, R.: Online collaboration: Scientists and the social network, Nature, 512(7513), 126–129, doi:10.1038/512126a, 2014.

Watkinson, I. M. and Hall, R.: Fault systems of the eastern Indonesian triple junction: evaluation of Quaternary activity and implications for seismic hazards, Geological Society, London, Special Publications, 441(1), 71–120, doi:10.1144/sp441.8, 2017.

Watkinson, I. M. and Hall, R.: Impact of communal irrigation on the 2018 Palu earthquake-triggered landslides, Nat. Geosci., 463, 878, doi:10.1038/s41561-019-0448-x, 2019.

Wei-Haas, M.: The Science of Indonesia's Surprise Tsunami, National Geographic, 1st October [online] Available from: https://www.nationalgeographic.com/environment/2018/09/indonesia-tsunami-sulawesi-explained-science-geology/ (Accessed 5 July 2019b), 2018a.

Wei-Haas, M.: Strange waves rippled around the world, and nobody knows why, National Geographic, 28th November [online] Available from: https://www.nationalgeographic.com/science/2018/11/strange-earthquake-waves-rippled-around-world-earth-geology/ (Accessed 5 July 2019a), 2018b.

Williams, R. and Krippner, J.: The use of social media in volcano science communication: challenges and opportunities, Volcanica, 1(2), i–viii, doi:10.30909/vol.01.02.i-viii, 2019.

Wright, S.: Warning system might have saved lives in Indonesian tsunami, Associated Press, 1st October [online] Available from: https://apnews.com/110eb42c03324a08bff5b3e6b58c309e (Accessed 5 September 2019), 2018.

Zakaria, N., Amelinckx, A. and Wilemon, D.: Working Together Apart? Building a Knowledge-Sharing Culture for Global Virtual Teams, Creativity and Innovation Management, 13(1), 15–29, doi:10.1111/j.1467-8691.2004.00290.x, 2004.

New table (simplified version of Table S1)

Table 1: Time table of main events and preliminary geophysical information posted on Twitter about the Palu earthquake and tsunami of 28 September 2018 (supplementary table S1 provides links to relevant tweets)

Important event, information or result	**Tweeted by (@nnn refers to twitter account)**	**Time posted (hh:mm UTC)**	**Day posted (UTC)**
Foreshock M6.1 (USGS loc and time)		07:00	28.09.2018
Main shock M7.5 (USGS loc and time)		10:02	28.09.2018
BMKG first tsunami alert	@infoBMKG	10:07	28.09.2018
BMKG tweet main shock	@infoBMKG	10:09	28.09.2018
Preliminary first motion mechanism: Strike-slip	@ALomaxNet	10:16	28.09.2018
USGS tweet main shock	@USGSBigQuakes	10:20	28.09.2018
BMKG cancel tsunami alert	@infoBMKG	10:36	28.09.2018
Strike-slip Moment tensor	e.g. @geoscope_IPGP	10:47	28.09.2018
Seismotectonic context: strike-slip rupture on Palu-Koro Fault, a major fault system with ~4cm/yr long term rate (comparable to San Andreas Fault)	several	12:00	28.09.2018
First viral videos of tsunami in Palu (unverified and unvalidated at this time)	several	12:00	28.09.2018
Confirmation of tsunami, and official validation of viral videos	e.g. @AP quoting Indonesian agency, @janinekrippner, @Sutopo_PN	13:00	28.09.2018
Seimotectonic map showing past seismicity	@CPPGeophysics	15:20	28.09.2018
Tide gauges: very weak signal out of Palu bay - and not working at Pantaloan in the bay itself	e.g. @RLacassin	15:37	28.09.2018
BMKG press release about tsunami alert and why they ended it	@infoBMKG	00:40	29.09.2018
Synthetic poster of seismotectonic context and seismicity	@patton_cascadia	01:07	29.09.2018
Supershear rupture hypothesized (will be confirmed later)	@ALomaxNet, @DocTerremoto		
Planet Labs imagery suggests rupture right in Palu town	@SotisValkan	13:40	29.09.2018
1st rough Planet Labs satellite image correlation (SIC) reveals fault rupture in Palu (results will become viral)	@SotisValkan	14:04	29.09.2018
Videos of dramatic surface spreading / liquefaction (will become viral) - and ensuing discussion	e.g. @janinekrippner, @patton_cascadia	15:33	29.09.2018
About 1 day after earthquake, we already know:	Earthquake on Palu-Koro fault system, with sharply localised strike-slip rupture in Palu town itself - Rupture enters the bay N of Palu (but it's uncertain how it prolongates offshore and northward) - Aftershock zone extend for ~150km in N-S direction, main shock near its N tip - Tsunami with run-up of several meters in Palu bay (and not out of the bay), dramatic surface spreading and liquefaction in and SE of Palu town		
State of the art SIC: localized strike-slip rupture in Palu with ~5m of coseismic slip (will become viral)	@SotisValkan	09:52	30.09.2018
Updated SIC map of rupture in Palu and displacement profile	@SotisValkan	16:10	30.09.2018
Discussion in international medias and social networks about a "failed" tsunami warning	Several	06:00	01.10.2018

Important event, information or result	Tweeted by (@nnn refers to twitter account)	Time posted (hh:mm UTC)	Day posted (UTC)
Geoscientists explain tsunami warning was very difficult in the case of the Palu earthquake	Several	09:00	01.10.2018
Satellite imagery: surface spreading / liquefaction (confirmed by video footage), and tsunami impact	e.g. @davepetley @StefLhermite	12:24	01.10.2018
Map of coseismic displacement now for 20km south of Palu (from Planet Labs SIC)	@SotisValkan	17:44	01.10.2018
Surface spreading measured with SIC	@SotisValkan	10:09	02.10.2018
Wider SIC map from Sentinel2 imagery: rupture extends >50km south of Palu	@SotisValkan	16:45	02.10.2018
SIC with Landsat images: confirms sharp rupture extending 65-85km S of Palu	@TTremblingEarth	18:11	02.10.2018
First InSAR interferogram (from ALOS2 satellite) covering whole rupture	@planet_mech	19:21	02.10.2018
Aerial video footage of massive surface spreading and destructions SE of Palu	@Sutopo_PN	21:16	02.10.2018
Tide gauge record in Pantaloan now available. Tsunami 1st arrival only few minutes after earthquake, ~2m height	@marufins @ALomaxNet @RLacassin	12:45	03.10.2018
Complete SIC map (Sentinel2 imagery): rupture stepping onshore E of Palu bay; imply complex connection across the bay. Epicenter at N tip of rupture.	@SotisValkan	15:57	03.10.2018
Validated INSAR interferogram, and along-track displacement map, covering whole rupture (from ALOS2 satellite)	@GSI_chiriin	09:53	05.10.2018
Known and unknown 8 days after earthquake:	Earthquake ruptured 2 strands of Palu-Koro fault system for a total length of ~150km. One strand S of Palu bay shows sharp localized surface rupture and sinistral offsets of ~5m. It crosses Palu town and enters the bay to the N. Rupture does not continue straight northward, but steps eastward to continue inland. Earthquake rupture started to the N at hypocenter and propagated southward, likely at supershear rate. Massive surface spreading documented from satellite imagery. Tsunami waves hit Palu bay coast few minutes after earthquake. Tsunami warning was very difficult in the case of the Palu earthquake.		
First results of surface rupture field survey by Indonesian geologists	@pamumpuni	20:42	13.10.2018

New table (simplified version of Table S1)

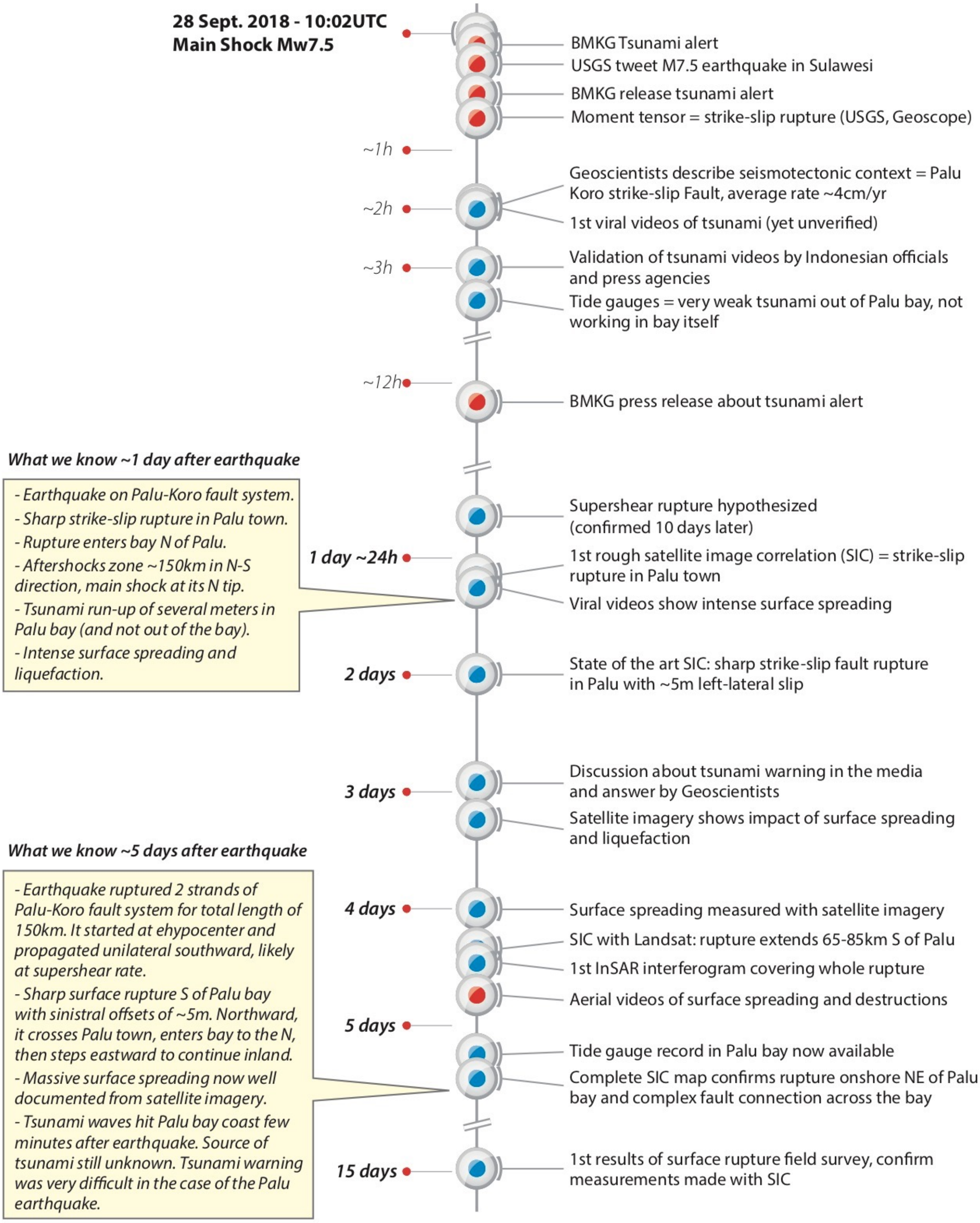

Figure 1: Timeline of informations posted on Twitter in the hours and days following the Palu earthquake and tsunami of 28 September 2018. The timeline illustrates the acquisition and dissemination of observations regarding geophysical events, and the progress of knowledge building via Twitter. See Table 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.

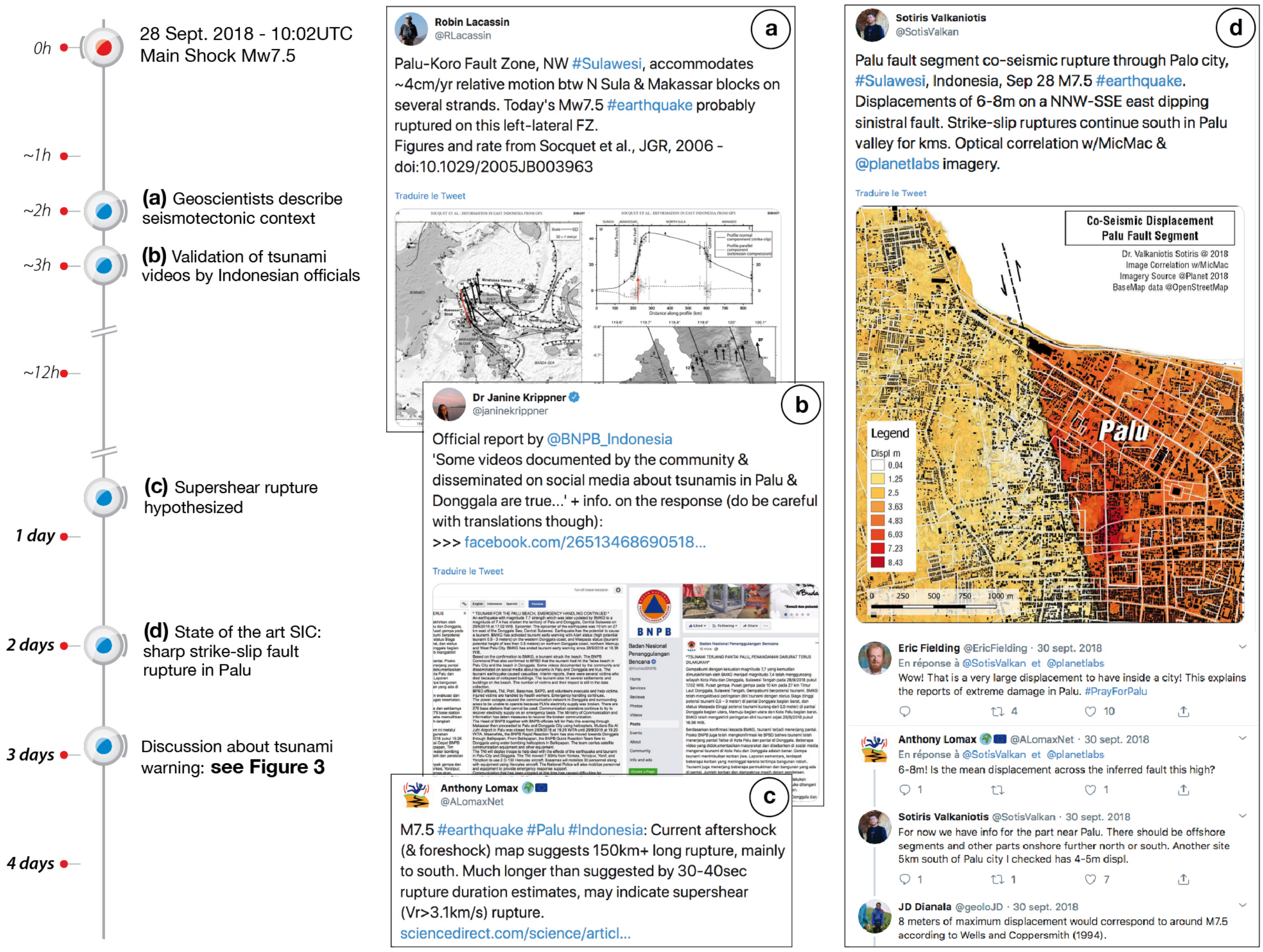

Figure 2: Screenshots of tweets chosen to illustrate how researchers shared and explained observations regarding the Palu earthquake and tsunami of 28 September 2018. Simplified timeline (from Figure 1) is shown on the left for reference. (a) within 2 hours geoscientists described the seismotectonic 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.

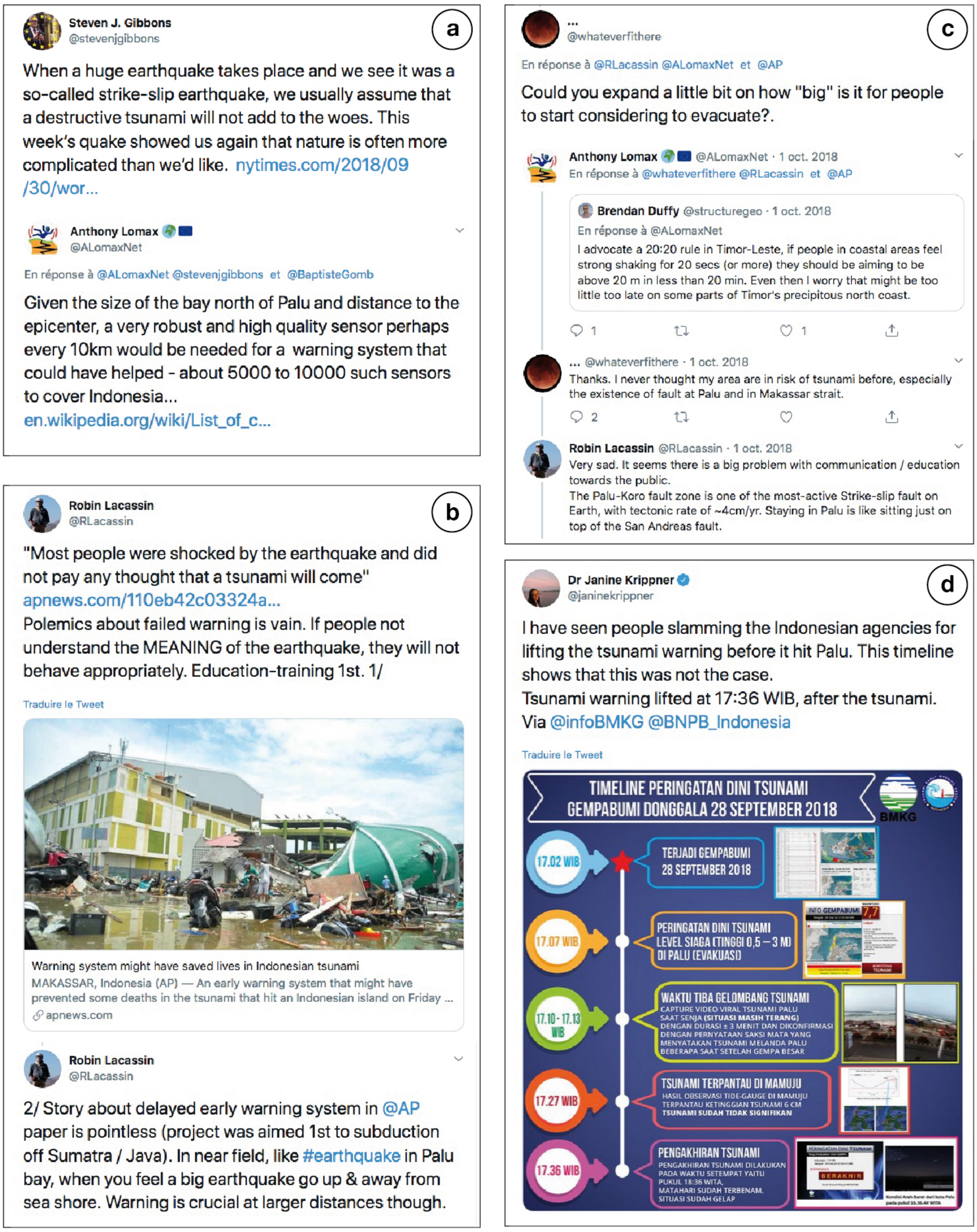

Figure 3: Screenshots of selected tweets about tsunami warning in the case of Palu. (a-b) geoscientists quote media articles regarding a possibly "failed" tsunami warning, and explain that such warning was extremely difficult in the case of the Palu earthquake (see text for more explanation). (c) example 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.

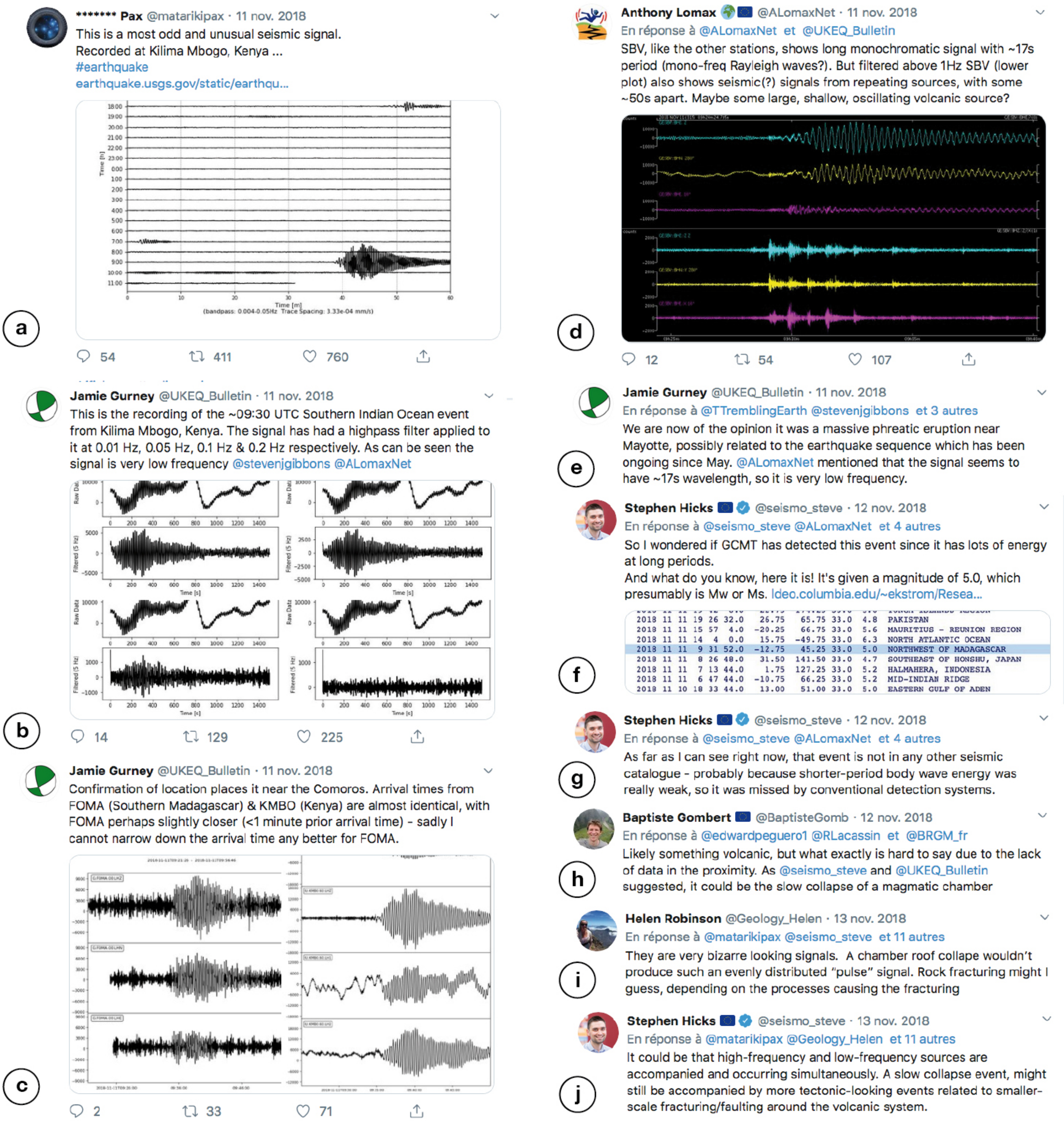

Figure 4: Screenshots illustrating early Twitter exchanges about the very long period seismic signal near Mayotte on the 11 November 2018. The selected screenshots shows that Twitter discussion was initiated by citizen scientists (a-c), then progressively involved academic researchers (d-f). Those researchers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

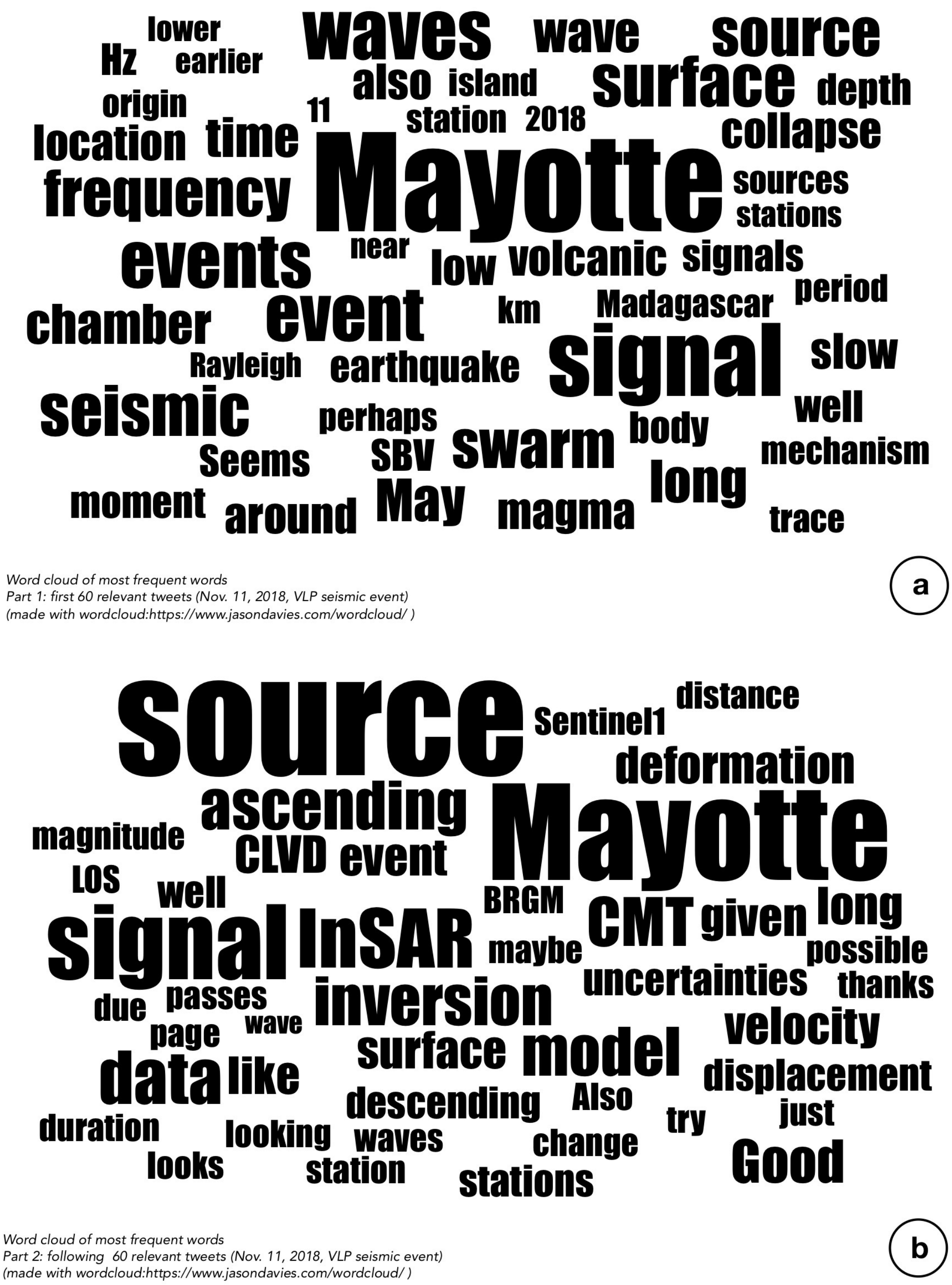

Figure 5: Word clouds illustrating the evolution of topics discussed on Twitter after the Mayotte 11 November 2018 very long period (VLP) seismic event. Top word cloud (a) illustrates first 60 tweets of the selected Twitter moment with most frequent words about the VLP signal (*signal, event(s), wave(s), 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*).

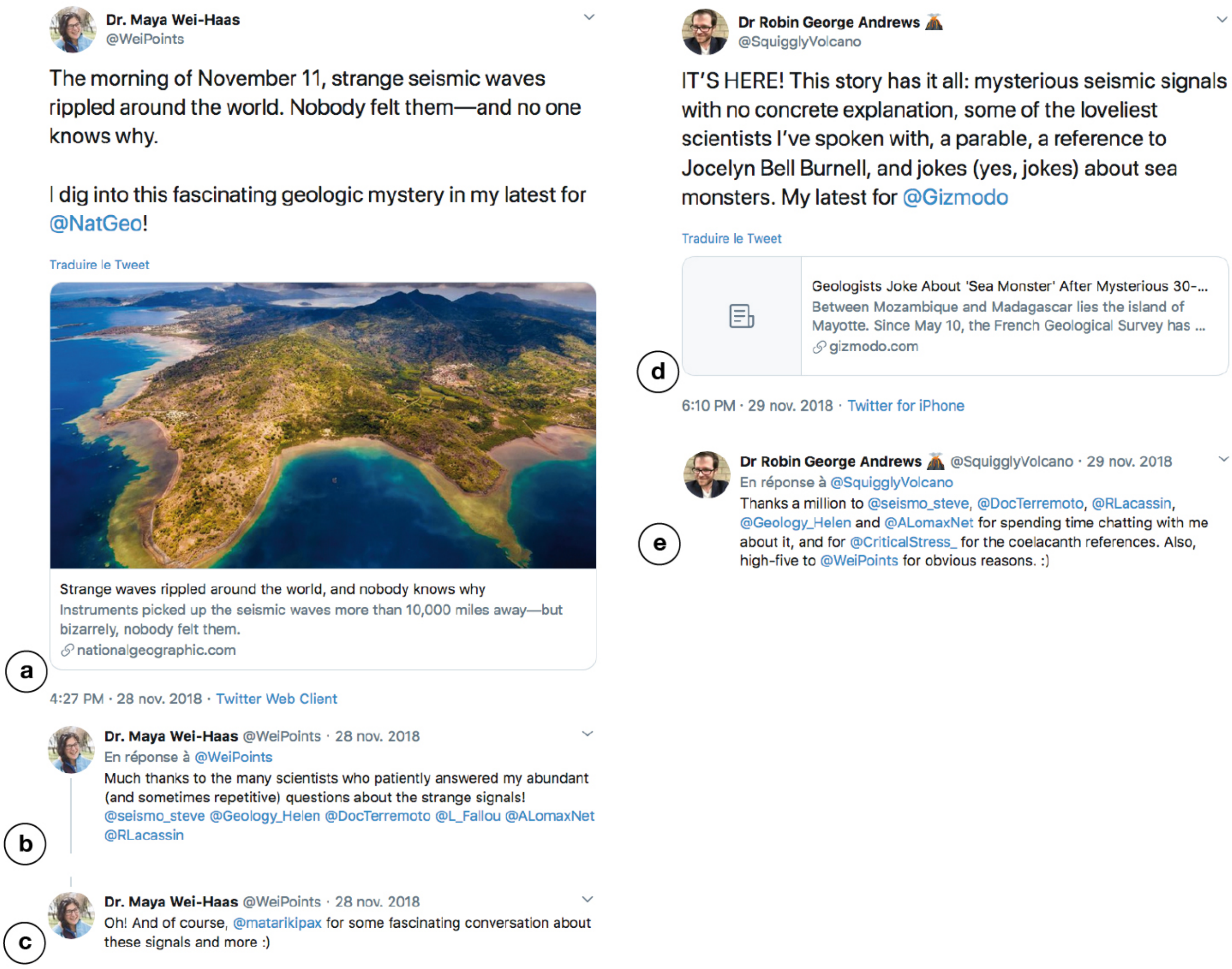

Figure 6: Screenshots of tweets by journalists Maya Wei-Haas and Robin George Andrews. After promoting their media article on the Mayotte 11 November 2018 event (a, d), journalists acknowledged academic researchers who were first identified and contacted via Twitter, then interviewed via email or phone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