Walter, Stefanie; Lörcher, Ines; Brüggemann, Michael (2019): Scientific networks on Twitter: Analyzing scientists' interactions in the climate change debate. In *Public Understanding of Science*, 696-712. Available online at https://doi.org/10.1177/0963662519844131.

Scientific Networks on Twitter: Analyzing Scientists' Interactions in the Climate Change Debate

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Abstract
Scientific issues requiring urgent societal actions – such as climate change – have increased the need for communication and interaction between scientists and other societal actors. Social media platforms facilitate such exchanges. This study investigates who scientists interact with on Twitter, and whether their communication differs when engaging with actors beyond the scientific community. We focus on the climate change debate on Twitter and combine network analysis with automated content analysis. The results show that scientists interact most intensively with their peers, but also communication beyond the scientific community is important. The findings suggest that scientists adjust their communication style to their audience: They use more neutral language when communicating with other scientists, and more words expressing negative emotions when communicating with journalists, civil society, and politicians. Likewise, they stress certainty more when communicating with politicians, indicating that scientists use language strategically when communicating beyond the scientific community.

Key words: science communication, Twitter, climate change, social media, automated content analysis, network analysis

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Introduction

Social media are increasingly considered important communication platforms for scientists. *Nature* even recently published an article headlined "Top Chinese university to consider social-media posts in researcher evaluations" (Cyranoski, 2017). Scientists use social media to interact with their peers, discuss their research findings, and distribute them to a large and heterogeneous audience. Most importantly, these tools enable interactions with the wider public and diverse actors from outside academia, such as journalists, politicians, and civil society organizations. Especially the networking site Twitter easily facilitates such interactions. Twitter can be regarded as a "multi-referential discourse system" (Dang-Ahn et al., 2013) that offers manifold ways of linking to other content and users. It is not only an important online network in which current issues are discussed; entirely new issues and positions might emerge that transgress to the offline sphere (recent examples are the #metoo or #blacklivesmatter debates). The number of scientists who actively use Twitter is rising, but it is currently still low (Priem et al., 2012; van Noorden, 2014). Analyzing the social media use of scientists is nevertheless important, because those who turn to social media and reach out to other societal actors might have a disproportional impact on public debates. Conversations can also reach an audience beyond Twitter, for example, when tweets are used as sources or are embedded in journalistic articles (Broersma and Graham, 2013).

Yet few studies have investigated how scientists and scientific institutions use social media. To date they have primarily examined what kind of scientific information is being shared (Mohammadi et al. 2018) and whether scientists use social media for one-way or two-way communication, i.e., to distribute information or engage in dialogue (Walter et al., 2017; Su et al., 2017). This research has found that the former is more common (Lee and VanDyke, 2015; Lee et al., 2017; Su et al., 2017). Yet, analyzing *with whom* scientists interact on social media is important, because these communication practices reveal whether scientists still primarily communicate within their peer community, or whether they aim to engage in debate with the wider public.

Studying scientists' communicative behaviors also sheds light on their role perceptions and their relationship with "the public." Their online interactions may reveal more traditional or more innovative patterns of science communication, reflected by communication taking place primarily within or also beyond the scientific community, e.g., through direct interactions with journalists, politicians, and civil society organizations. Furthermore, *the way* that scientists communicate on social media might vary depending on who they are talking to. Therefore, this study asks *how and* *with whom do scientists interact on Twitter?* Specifically, we look at whether scientists use social media actively or passively, and analyze whether the content of their tweets expressing negative emotions and uncertainty differs depending on who they are interacting with. We conduct a Twitter network analysis and automated content analysis of scientists' tweets using the discourse on climate change as a case study. The next section discusses different role perceptions of scientists and their expected communication practices in more detail.

Scientific roles and science communication

When thinking about how scientists communicate, the classic image of the scientist in the ivory tower comes to mind. This image is related to the ideal-typical role of the "pure scientist" who primarily focuses on his or her research (Pielke, 2007), which evolved from the scientific norms of autonomy and objectivity. Scientists have traditionally been expected to generate factual knowledge by following scientific methods that seek to assure intersubjectivity, reliability and validity (Popper 2008), and also to be impartial (Weber, [1922] 1980; Merton, 1973). Peer-reviewed publications play an important role in communicating scientific findings (Weigold, 2001). From this point of view, scientists' communicative practices focus primarily on communication *within* – and seek minimal engagement outside – the scientific arena (cf. Turnhout et al., 2013). Direct interactions with stakeholders – such as politicians, journalists, and civil society organizations – are not essential to the work of pure scientists (cf. Pielke, 2007).

Yet, there are reasons why scientists might want to seek communication beyond the scientific arena. Effective communication "can create favorable attitudes toward science and science funding among policy makers and the broader public by making clear the benefits that scientific activity offers to society" (Treise and Weigold, 2002: 311). For the vast majority of scientists, fostering positive public attitudes towards science is one of the core reasons for interacting with the news media (Peters et al., 2008). Their increased orientation towards the public and the media, and the growing influence of media logics on their communication, have been referred to as the "mediatization of science" (Peters, 2013).[1] Scientists "increasingly take advantage of traditional and online media to increase the impact of their research" (Scheufele, 2014: 13586). Recent surveys of scientists from different countries and disciplines have shown that most (60–70%) have had some form of professional contact with journalists in recent years, but only a small

[1] The mediatization of science also involves increased media attention to scientific issues.

group engages in frequent interactions with the news media (Bray and von Storch, 2010; Ivanova et. al., 2013; Peters et al., 2008).

Broader societal changes have also increased the need for communication beyond the scientific community. Today, we are increasingly facing global risks (Beck, 2001) and knowledge is becoming more and more relevant to economic and political developments (Stehr, 1994). Modern science, e.g. in the field of genetics, often touches upon ethical and political questions (Scheufele, 2014). These changes have enhanced the importance of science for society, and scientists are drawn into political conflicts as experts who serve political purposes (Bauer and Bucchi, 2007; Rödder et al., 2012; Weingart, 2002).

But scientists might also choose to get more involved in political decision-making processes. For instance, they have long served as experts in advisory committees and consulted with policy makers (Jasanoff, 1990). Following the norm of impartiality (Jasanoff, 1990), they can take up the role of the "honest broker" and present different policy alternatives to decision-makers, while taking stakeholders' concerns into account (Pielke, 2007). Others might decide to get even more politically involved by becoming "issue advocates" who side with a societal or political group and promote a certain political agenda (Pielke, 2007), or their suggested policy options may be in line with their own political preferences (Scheufele, 2014). This type of scientist focuses more on communication *beyond* the scientific community and has a greater interest in using their research for policy-making purposes (cf. Pielke, 2007). Hence, they have an incentive to seek interactions with politicians, civil society, and journalists.

The news media are an important channel through which to inform the citizens, as well as politicians and other stakeholders, about the latest scientific results. Scientists recognize that traditional journalistic content has an important influence on public opinion, as well as political decision-making processes (Allgaier et al., 2013; Post and Ramirez, 2018). Public relations or science information professionals traditionally established the links between scientists and journalists, or served as spokespersons for the former (Weigold, 2001). However, the rise of digitally enabled communication allows scientists to more easily engage in direct communication outside their field. This is especially important since scientists are often dissatisfied with how the media reports scientific findings (Pew Research Center, 2009; Post, 2008).

Based on the different roles that scientists follow, we can differentiate between four types of actors that they might seek to interact with: (1) other *scientists* – to discuss their research, (2) *journalists* – to communicate their research indirectly to a broader audience, (3) *politicians* and (4) *civil society* – to directly engage with stakeholders, present policy alternatives, or promote a political agenda. Social media give scientists the opportunity to directly engage with these different types of actors.

Social media, and the networking site Twitter in particular, easily enable scientists to connect with other actors. Few studies have aimed to determine the exact number of scientists using Twitter (Bart, 2009; van Noorden, 2014; Priem et al., 2012). Numbers vary due to different sampling strategies, but based on a large-scale survey by *Nature* from 2014, we can assume that approximately 13% of scientists visit Twitter regularly, with shares of over 20% among the "soft" sciences (van Noorden, 2014). Thus, while scientists acknowledge the importance of social media (Allgaier et al., 2013), it is currently still only used by a minority. But those scientists might have a disproportional impact on public debates, because they have the opportunity to connect and communicate with stakeholders from different professional and institutional backgrounds. This connection is particularly relevant for post-normal issues like climate change (von Storch, 2018) where political action is urgent. However, we know little about who scientists interact with on Twitter and how these interactions look like. The next section outlines our expectations regarding their communicative practices.

Hypotheses

Empirical findings indicate that the "pure scientist" is still the most widespread role among scientists, and contacts with journalists or other societal actors are rare (Wilke and Morton, 2015; Schäfer et al., 2011). Yet communicating with the public, especially with the news media, has increasingly become "normal" in recent decades as science has become more mediatized (Rödder and Schäfer, 2010). However, the mediatization of science has been moderate compared to other social domains (Rödder and Schäfer, 2010), as only a few "visible scientists" (Goodell, 1977) or even "celebrity scientists" (Giberson and Artigas, 2007) have developed a more intimate relationship with the news media. Most scientists are still convinced that they should refrain from public communication, because it could harm their integrity and authority or even damage their careers (Liang et al., 2014; Dunwoody and Ryan, 1985; Mellor, 2010). This might be related to concerns about a lack of control when interacting with the news media, including the fear of incorrect quotations and sanctions by peers as a result of media visibility (Peters et al., 2009).

Scientists nevertheless have an incentive to use social media, particularly to interact with their peers – for example to develop research ideas with new collaborators, receive pre-review feedback, and disseminate and discuss their results (Darling et al., 2013). Furthermore, live tweeting from conferences has become a habit among scientists (Darling et al., 2013; Shiffman, 2012; Walter and Brüggemann, forthcoming). Scientists use Twitter during conferences to "make notes, share resources, hold discussions and ask questions as well as establishing a clear individual online presence" (Ross et al., 2011: 214). Ultimately, social media are also a source of information to help scientists stay up to date on the latest scientific developments and publications (Bonetta, 2009; McGowan et al., 2012). Extant research has shown that scientists use Twitter primarily to discuss their work *within* the scientific community, and secondarily to reach out to and engage with the public (Collins et al., 2016; Priem et al., 2012; Bik and Goldstein, 2013; Young, 2009). A study by Collins et al. (2016) revealed that most scientists consider other scientists to be their preferred Twitter audience. Therefore, we expect that scientists use social media primarily for "internal" communication within the scientific community. Our first hypothesis is:

H1: On Twitter, scientists primarily address other scientists rather than journalists, political actors, or civil society.

When communicating *beyond* the scientific community on social media, interactions with journalists represent a more conventional approach to science communication: They reinforce journalists' traditional gatekeeping role and draw attention to scientists' findings (Weingart, 2001). Although it is mainly more experienced scientists with frequent publications who interact with journalists (Ivanova et al., 2013), social media might also allow more junior scholars to get in touch with journalists. Some scientists believe that media engagement has beneficial effects on their careers (Tsfati et al., 2011) and interactions with journalists on social media can help reach an audience beyond the social media sphere.

Due to scientists' still-restrained interactions with the public and the news media, we do not expect them to *actively* address journalists more than their peers. Furthermore, scientists prefer to be approached by journalists and only communicate with them when required, rather than proactively seeking contact (Rödder, 2012), while journalists are particularly active users (Just and Holtz-Bacha, 2017; Kamps, 2015). Hence, we hypothesize that:

H2: On Twitter, scientists are mainly addressed by journalists rather than political actors or civil society.

Surveys of scientists have furthermore shown that they adopt media logics when communicating in public (Peters, 2013). This means that they take news factors such as negativity into account (Esser and Strömbäck, 2014; Mazzoleni and Schulz, 1999). This can be expected to hold especially true for highly mediatized scientific issues, such as climate change (Schäfer, 2008; Rödder and Schäfer, 2010), and communications with journalists on Twitter. When scientists communicate among each other, they use factual and accurate language, which avoids exaggerations and emotions (Hofmann, 2014). Consequently, we assume that:

H3: The tone of scientists' tweets directed at journalists expresses more negative emotions compared to tweets directed at scientists.

An important incentive for scientists to communicate with the news media is to convey their research findings to the broader public and to affirm established knowledge (Tsfati et al., 2011; Scheufele, 2014). Unlike their internal peer communications, climate scientists do not actively communicate uncertainties about their research findings to the media, due to fears that interest groups could misinterpret or exploit their findings (Post, 2016). Research suggests that scientists are more likely to interact with journalists the more certain they are of scientific knowledge (Post, 2016), and are sometimes even in favor of overstating scientific findings in public (Post and Ramirez, 2018). This is likely because scientists often face skepticism, especially on polarized and politicized scientific issues such as climate change (Capstick and Pidgeon, 2014; Whitmarsh, 2011; Hoffman, 2011). Hence, we expect that:

H4: Scientists stress certainty more when interacting with journalists, politicians and civil society than within the scientific community.

A more innovative approach to science communication that is easily facilitated by social media is to *directly* engage with stakeholders without having to rely on intermediaries, i.e., journalists. The way that discussions of scientific issues take place on social media differs from debates in the academic literature, which makes them more accessible to non-specialists (Bonetta, 2007; 2009). Direct interactions with political and civil society actors might be especially appealing to "advocacy scientists" who aim to get involved in the decision-making process to promote a certain political agenda (Pielke, 2007). By connecting scientists with stakeholders, social media also have the potential to organize "connective action" (Bennett & Segerberg, 2012). Social media networks may reveal "discourse coalitions" (Hayer, 1993) or "interpretive communities" (Zelizer, 1993) that influence public debates beyond the social media sphere. Scientists who consider themselves "honest brokers" might use also the opportunity to interact directly with politicians or civil society organizations (Pielke, 2007).

Since we know little about such interactions, it is difficult to hypothesize whether scientists are active or passive in their dealings with politicians and civil society. Nor is it possible to make profound assumptions about the language they use in tweets addressed to these groups, although we would expect similarities with their approach to communicating with journalists, because scientists might consider all public actors outside academia to be "non-scientific experts." When communicating with these public actors, they might adopt media logics – i.e. use comprehensible and simple language and emphasize core messages (Peters, 2013). We pose the following research question to explore these issues: *How do scientists interact with politicians and civil society on Twitter?*

Data and measures

We chose Twitter to analyze the communicative behavior of scientists on social media, as it is relatively widely used and considered the most useful social media platform by academics (e.g., Lupton, 2014). We focus on the issue of climate change in our empirical analysis, as it is a scientific topic for which we are likely to find deviations from the traditional role of the "pure scientist." This rationale is justified on two levels. First, given the traditionally more passive role of "pure scientists," in order to understand how scientists communicate with other groups in the social media era, we should study an elite group of experts whose communication strategies on social media are not well understood, but who are willing to ignite an open public debate – and potentially suffer the consequences of doing so. Second, previous research on climate change communication has not examined communication between scientists and other elites in the social media sphere. To this end, we aim not only to uncover *what these interactions look like* by actively searching for them where they are more likely to take place, but also to understand *why* they take place. Climate change is a post-normal issue (Krauss et al., 2012), "where facts are uncertain, values in dispute, stakes high and decisions urgent" (Funtowicz and Ravetz, 1993: 744). Thus scientists are expected to engage more actively in public discussions by managing the uncertainties associated with their findings, being transparent about the value questions involved, and formulating policy advice. The climate change issue challenges the traditional perception that scientists should refrain from interactions with the public (Funtowicz and Ravetz, 1993). It may instead strengthen the scientific roles of advocates or honest brokers, and foster interactions with journalists as well as politicians and civil society organizations. This study is carried out under favorable conditions, since more than in other scientific disciplines, we will be able to detect newly emerging patterns in science communication.

Twitter provides scholars access to large amounts of information from diverse actors and groups, and most importantly, the interactions between them. The data for this study was collected by [anonymized for peer review] collecting tweets from Twitter's API using Python. The [anonymized for peer review] saves climate-related tweets on a daily basis using the following search terms: #climatechange OR "climate change" OR "global warming." The study covers tweets from a 6-month period from October 1, 2017 to March 31, 2018 (N=2,876,417). The data collected via Twitter's API does not provide access to the universe of *all* relevant tweets, and therefore it may not capture some exchanges of interest. Furthermore, while Twitter has become an important tool for science communication, it is currently only actively used by a relatively small number of scientists (van Noorden, 2014). Thus we cannot rule out the possibility that the intensity and style in which scientists communicate on Twitter is distinct. Scientists who use Twitter may be self-selecting into this type of communication behavior, and not be representative for scientists as a whole.

Despite these drawbacks, Twitter is a rich source of data. Using the R programming language and the information provided in the tweets' meta-data, we limited the data set to English-language tweets (2,662,632). We then selected tweets sent by Twitter users from the US, as the debate on climate change is more polarized there than in other countries (Pew Research Center, 2015). Hence scientists there might be more likely to engage in discussions beyond the scientific community. Using the *quanteda* package (Benoit et al., 2017), we created a dictionary of US states, their capitals (and abbreviations), as well as the 300 most populated US cities to classify users based on the "location" information they provide in their Twitter profiles. In addition, we draw on a study by Baberá (2014) to classify important Twitter accounts from the US. This leads to a total of 922,438 tweets. As this study is only interested in *interactions* among users in the climate debate, we excluded Twitter users who did not mention any other users in their tweets (by using @-mentions).

We use the self-identifying information on Twitter accounts' user descriptions to classify users as scientists, journalists, civil society, or politicians. While we cannot make any claims about users who did not openly declare their profession or did not provide any information in their user description, we are nevertheless able to capture the opinions of a small group of experts that would otherwise have been very difficult and resource intensive to reach. Most importantly, our data collection strategy allows us to capture the various ways in which these individuals interact in the climate change debate. We used automated content analysis, more specifically a dictionary approach, to classify the Twitter users.[2] We included words and phrases in the dictionary that allowed us to capture the accounts of individuals as well as collectives and organizations. The vast advantage of this approach compared to past research (Lotan et al., 2011) is that we do not need to limit our sample for human coding purposes.

We used the user descriptions provided in the meta-data of users' Twitter accounts to classify them, since these provide the same information available to other Twitter users to understand who they are talking to (unless they personally know the user). Such meta-data is only available for users who send tweets, but not for those who do not tweet (about climate change) themselves. For users with missing meta-data, we first used the *twitteR* package (Gentry, 2015) to download user information from Twitter based on their usernames. The user descriptions were then content analyzed in R using the *quanteda* package (Benoit et al., 2017). Since important and well-known users often do not specify their profession in their profiles, as they assume it is well known – for example, CNN does not specify that it is a television channel – we manually validated the automated coding for the most important actors in the network (i.e., the 500 Twitter users in the data set who tweet the most and/or are mentioned the most by other users). We furthermore carried out a reliability test on the automated classification of 500 randomly selected users and compared it to the classification of a human coder. The human coder did not only classify users based on the user descriptions provided in the Twitter profiles; when in doubt, additional information could be used for the coding, e.g., by looking up an organization to see whether it qualifies as a civil society organization. The results showed that the automated coding can be considered reliable (Krippendorff's Alpha = 0.74).

To analyze the relationships between scientists and other users, we use network analysis measures at the node and network levels. A network can be defined as "a structure composed of a set of actors, some of whose members are connected by a set of one or more relationships" (Knoke

[2] We did not include Twitter accounts in our analysis that were classified to more than one of the actor group, as it is not clear in which role they are communicating.

and Yang, 2010: 8). We look at the composition of the network by taking the number of *nodes* (Twitter users) and *edges* (links between Twitter users based on retweets and @-mentions) into account. We furthermore look at the share of scientists among the users in the network. *Connected components* are subsets of nodes in which every node has a path to every other node of the subset, but none of them is connected to any other nodes in the network. The *size of the largest component* reflects the number of nodes that belong to the largest component of the network. Both combined reflect how fragmented a network is. *Reciprocity* measures the extent to which a tie between user A and user B is matched by an edge from user B to user A by calculating the number of reciprocated ties divided by the total number of ties (Borgatti et al., 2018: 179).

At the level of an individual node in the network, *degree centrality* measures the extent to which a node in the network is connected to all other nodes by calculating how many ties a node has within a network. Network centrality is further divided into in-degree and out-degree centrality. *In-degree centrality* measures the number of incoming ties (i.e. messages received) and *out-degree centrality* the number of outgoing ties (i.e. messages sent). These measures are used to analyze whether scientists actively engage in discussions on Twitter, or whether they are instead passive receivers of messages from other users. We used the *igraph* package for R (Gabor Csardi and Tamas Nepusz, 2006) for the network analysis and the software Gephi for the network visualization.

To analyze *how* scientists communicate on Twitter, we created a subset of tweets sent by scientists addressed to one of the groups mentioned above. In a first step, all @-mentions, punctuations, and URLs were removed from the text. We then removed empty strings and duplicated the texts of tweets if several users were mentioned in a single tweet (N=8,048). We analyzed the content of tweets using the well-established Linguistic Inquiry and Word Count (LIWC) program for computerized text analysis. Dictionaries can be particularly useful for coding emotion, as they are difficult for humans to reliably code (cf. Soroka et al., 2015: 113). The LIWC dictionary has been developed over several years; its internal and external validity have been assessed (Pennebaker et al., 2015), and it has been applied in analyses published in a number of widely cited studies (Jang and Oh, 2016; Shim et al., 2011; Young and Soroka, 2012). The LIWC dictionary consists of approximately 6,400 words, divided into categories that measure the percentage of words reflecting words within the respective category based on the total number of words in the tweet. We use the category "negative emotion" (e.g., ugly, nasty) to analyze how negatively valenced the language of tweets is, and the category "certainty" (e.g., always, never) to measure the extent to which scientists use words expressing certainty in their tweets.

Results

To better understand how (and with whom) scientists communicate on Twitter, we first look at the role they play in the overall climate change debate on Twitter. Among the actors that are of interest to this study, scientists make up the largest group (3.34%), followed by journalists (3.10%), civil society (2.76%), and politicians (1.23%) (Table 1). We were unable to classify the majority of Twitter users (76.91%) as belonging to any of these groups ("other"). These users might either belong to other professional groups that are not of interest here (e.g., artists), or they do not provide any useful information for classifying their profession. Another group of users (12.67%) did not provide any information in their user description ("missing value"), and we cannot exclude the possibility that some of the actors that are of interest to our study fall into this category. The results should furthermore be interpreted with caution, as we cannot make any statements about actors who did not clearly reveal their professions in their Twitter profile (with the exception of the 500 most important accounts in the network, which we manually validated, see above), and it is possible that their communicative behavior differs from those who did. While the number of classified Twitter accounts amounts to approx. 10%, this number is still as high as 13,000 Twitter users, who are included in the analyses below.

[Table 1 about here]

[Figure 1 about here]

The network in Figure 1 shows the interactions among scientists, journalists, politicians, and civil society actors. For simplicity, the remaining users were excluded and only the largest component of the network is shown. We used an algorithm (OpenOrd) designed to better distinguish clusters within the network. To highlight the most important clusters, we calculated modularity and assigned labels to the most important user (in terms of in-degree) in the ten largest clusters of the network. The Twitter account of Donald Trump (@realDonaldTrump) has the highest in-degree, meaning that other users in the network mention him most frequently. The most active Twitter account, based on the out-degree, is Andrew Revkin's (@Revkin), a well-known American science and environmental journalist. The edges in the network take the color of the actor that is being addressed, which indicates the level of attention each actor group receives in the debate. Scientists (blue) are at the margin of the network, and the low in-degree shows that they receive little attention from others. Politicians (red) are on the opposite side of the network and have, on average, the highest in-degree. Journalists (yellow) are located somewhere between the two groups. Civil society actors (green) receive little attention, though they are – along with scientists – addressing other users the most.

Next, we look at the interactions of scientists and each of the actor groups separately (Figure 2). For this purpose, we only selected cases for the analysis in which scientists either address or are being addressed by the respective actor group. Our results show that out of the 8,516 scientists in our overall sample, a little less than 30% (N= 2,457) engage in interactions with other scientists (Figure 2 a), see also Appendix I). The network of scientists and journalists (Figure 2 b)) is slightly larger (N=2,615), while the networks showing interactions among scientists and civil society actors (Figure 2 c), N=1,689), and scientists and politicians (Figure 2 d), N=1,422), are smaller. In these networks, scientists make up 50–70% of the users.

[Figure 2 about here]

Looking in more detail at the composition of the networks (Appendix I), we see that the network including scientists only is the most fragmented: It has 536 components, and the largest component comprises approximately 47% of the users. Nevertheless, the percentage of reciprocal ties is the highest in this network: Approximately 3% of the ties in the network are mutual, meaning that 3% of the scientists who mention another scientist in their tweets are also being mentioned by that user. In the network of scientists and politicians, the largest component fills more than 70% of the network, while the rest of the network is divided into smaller components, which are far fewer than in the other networks. This means that the scientist–politician network is less fragmented than the other networks. At the same time, the likelihood of reciprocal ties is the lowest (0.2%), meaning that communication in this network is rather one-sided.

Centrality measures indicate a user's structural importance within the network. We only calculated centrality measures for scientists to analyze how their position in the network varies depending on who they interact with. Degree centrality measures the number of ties a user has with other users in the network. The results show that the degree is relatively similar across the networks and ranges between 1.61 and 1.96, which means that scientists are, on average, connected with two other users (Table 2). The in- and out-degree – which differentiate between incoming and outgoing ties – vary more substantially. We expected that scientists on Twitter mainly address other scientists rather than the other actor groups (H1). Yet, when looking at the out-degree, we see that scientists address journalists and politicians significantly more in their tweets than they mention other scientists. Our first hypothesis therefore has to be rejected. What is more, the in-degree in all networks is either equal to or lower than the out-degree, which means that scientists address users more often than they are addressed themselves. We expected to find a high in-degree of scientists in the network with journalists – as a result of journalists addressing scientists frequently in their tweets (H2). However, our results show that journalists show little interest in engaging in discussions with scientists, as scientists' in-degree in this network is only 0.29. H2 is therefore also rejected. Politicians address scientists even less frequently (in-degree=0.09), and only the network with civil society communication is balanced, which is reflected in an equally high in- and out-degree of scientists (0.84 and 0.85, respectively). Overall, our results suggest that scientists who engage in conversations about climate change on Twitter take a proactive role, which contradicts the traditional image of the "pure scientist."

[Table 2 about here]

To analyze the content of scientists' tweets, we created a subsample of tweets *sent* by scientists that address journalists, political, civil society actors, or other scientists. When scientists communicate with each other, on average 1.64% of the words in their tweets express negative emotions (Table 3). This suggests that the language in scientists' tweets is rather neutral, but what is important is that the percentage of negative emotions varies significantly depending on *who* they address in their tweets. When scientists mention journalists, the tone of their tweets is significantly more negative, which is in line with H3. The same pattern can be observed when scientists address civil society actors and politicians. This might indicate that scientists stress the negative consequences of climate change in public discussions when communicating beyond the scientific community.

[Table 3 about here]

We assumed that the extent to which scientists use words related to certainty in their tweets would vary depending on who they are addressed to: We expected scientists to stress certainty more when they interact with journalists, politicians and civil society than with other scientists (H4). When scientists interact with each other, 1.03% of the total number of words in their tweets expresses certainty. This percentage is significantly higher when they address politicians, but it does not differ significantly for journalists and civil society. Thus, our last hypothesis can only be partially confirmed.

Conclusion

This study analyzed how (and with whom) scientists interact on Twitter by conducting a network and automated content analysis of Tweets about climate change. We investigated whether scientists follow traditional communicative practices and primarily interact within the scientific community, or if they engage directly with journalists, politicians and civil society organizations. Our findings suggest that on Twitter the communicative behavior of the scientists included in our sample strongly deviates from the ideal-typical role of the "pure scientist" who mainly interacts with other scientists. Instead, we find that communicating beyond the scientific community is equally important. Interactions with journalists are particularly common, while communication with civil society and politicians is less frequent. It is striking that the out-degree of scientists in all networks is higher than their in-degree, which means that they are active senders of messages addressed to others rather than passive receivers. In line with our findings, past research has shown that scientists actively use social media to influence policy-making (Kapp et al., 2015).

Moreover, the analysis of the tone and content of the tweets indicates that different scientific norms and roles apply when communicating outside the scientific community. Scientists whose communication we captured in our data use more words expressing negative emotions when addressing journalists, civil society and politicians than when communicating with other scientists. This might imply that scientists adapt to journalistic news factors such as negativity, or that they dramatize their findings in order to promote them or to act as issue advocates. The different communicative practices, which depend on the addressee of scientists' tweets, are also reflected in the finding that scientists in our sample emphasize certainty more when communicating with politicians than in discussions within the scientific community. This is in line with previous research suggesting that scientists do not mention the uncertainties associated with climate science when communicating in public (Post, 2016). These findings suggest that scientists adjust to media logics and should be seen in the context of the broader trend of the increased mediatization of science (Peters, 2013).

The results have to be interpreted against the backdrop that some scientists are power users and very important actors in the Twitter network. NASA, for example, is one of the most important scientific institutions in the Twitter discourse on climate change captured by our study. It is an independent agency of the executive branch of the US federal government, and is therefore a hybrid between science and politics. Future research should more closely examine hybrid actors that can be placed between science, politics, and advocacy and have proven to be influential in our analysis. Furthermore, the findings have to be seen in light of the focus on the US, where the climate change debate is more polarized. Thus we are more likely to find deviations from the role of the "pure scientist" compared to other countries and fields of research. While studies of equally pressing topics, such as genetics or vaccination, are likely to yield similar results, they might differ and follow more conventional practices for "normal" scientific issues. As scientists' climate change related communication on Twitter is likely to differs from other domains with less uncertain, urgent and value-laden scientific issues, which are less mediatized and politicized, the results of this study cannot necessarily be generalized. Twitter is not used equally across different academic disciplines and the extent to which scientists use social media and engage with actors beyond the scientific sphere might likewise vary and depend on their field of expertise. Future studies should determine whether this is the case by exploring scientists' communicative behavior in different academic fields and countries, including those that are less influenced by "post-normality."

It would also be valuable to investigate the content of the tweets in more depth to better understand if the topics and frames also vary depending on who scientists address in their tweets. Such an analysis would also further validate our findings regarding certainty and negativity, which must be interpreted carefully, as there are other possible explanations of why scientists stress specific words when addressing journalists, civil society, and politicians. In addition to the explanation that scientists dramatize their findings in order to promote them or to act as issue advocates, scientists might discuss details of their research with their peers, which might contain uncertainties (e.g., research on aerosols). When talking to other public actors, scientists are likely to focus on more basic, consensual, and certain findings, e.g., related to the causes of climate change.

References

Allgaier J, Dunwoody S, Brossard D, et al. (2013) Journalism and Social Media as Means of Observing the Contexts of Science. *BioScience* 63(4): 284–287.

Barberá P (2014) *Replication data for: Birds of the Same Feather Tweet Together. Bayesian Ideal Point Estimation Using Twitter Data*: Political Analysis.

Bart, M (2009, August 28). Twitter in Higher Education: More than 30 Percent of Faculty Say They Tweet. *Faculty Focus*. Retrieved from https://www.facultyfocus.com/articles/edtech-news-and-trends/twitter-in-higher-education-more-than-30-percent-of-faculty-say-they-tweet/

Bauer M and Bucchi M (2007) *Journalism, Science and Society: Science Communication Between News and Public Relations*. New York / London: Taylor & Francis.

Beck U (2001) *World risk society*. Cambridge: Polity.

Benoit K, Watanabe K, Nulty P, et al. (2017) *quanteda: Quantitative Analysis of Textual Data*. Available at: http://quanteda.io.

Bik HM and Goldstein MC (2013) An introduction to social media for scientists. *PLoS biology* 11(4): e1001535.

Bonetta, L (2007). Scientists Enter the Blogosphere. *Cell*, *129*(3), 443–445.

Bonetta, L (2009). Should You Be Tweeting? *Cell*, *139*(3), 452–453. https://doi.org/10.1016/J.CELL.2009.10.017

Bray, D., & von Storch, H. (2010). *CliSci2008: A survey of the perspectives of climate scientists concerning climate science and climate change*. Geesthacht: GKSS-Forschungszentrum Geesthacht.

Borgatti SP, Everett MG and Johnson JC (2018) *Analyzing social networks*. London: Sage.

Broersma M and Graham T (2013) Twitter as a News Source: How Dutch and British newspapers used tweets in their news coverage, 2007–2011. *Journalism Practice* 7(4): 446–464.

Brossard D (2013) New media landscapes and the science information consumer. *Proceedings of the National Academy of Sciences*.

Capstick SB and Pidgeon NF (2014) What is climate change scepticism?: Examination of the concept using a mixed methods study of the UK public. *Global Environmental Change* 24: 389–401.

Collins K, Shiffman D and Rock J (2016) How Are Scientists Using Social Media in the Workplace? *PloS one* 11(10): e0162680.

Cyranoski D (2017) Top Chinese university to consider social-media posts in researcher evaluations. *Nature*.

Dang-Ahn M, Einspänner J and Thimm C (2013) Mediatisierung und Medialität in Social Media: Das Diskurssystem "Twitter". In: *Sprache und Kommunikation im technischen Zeitalter wieviel Technik (v)erträgt unsere Gesellschaft?* Berlin: de Gruyter, 1 Abb.

Darling E, Shiffman D, Côté I, et al. (2013) The role of Twitter in the life cycle of a scientific publication. *Ideas in Ecology and Evolution* 6.

Dunwoody S and Ryan M (1985) Scientific Barriers to the Popularization of Science in the Mass Media. *Journal of Communication* 35(1): 26–42.

Esser F and Strömbäck J (2014) *Mediatization of politics: Understanding the transformation of western democracies*. Basingstoke: Palgrave Macmillan.

Funtowicz SO and Ravetz JR (1993) Science for the Post-Normal Age Futures. *Futures* 25(7): 739–755.

Gabor Csardi and Tamas Nepusz (2006) The igraph software package for complex network research. *InterJournal* Complex Systems: 1695 http://igraph.org.
Gentry J (2015) *twitteR: R Based Twitter Client*. Available at: https://CRAN.R-project.org/package=twitteR.
Giberson K and Artigas M (2007) *Oracles of science: Celebrity scientists versus God and religion*. Oxford, New York: Oxford University Press.
Goodell R (1977) *The visible scientists*. Boston: Little Brown.
Hoffman AJ (2011) The culture and discourse of climate skepticism. *Strategic Organization* 9(1): 77–84.
Hofmann AH (2014) *Scientific writing and communication: Papers, proposals, and presentations*. New York, NY: Oxford Univ. Press.
Ivanova, A, Schäfer, MS, Schlichting, I., & Schmidt, A. (2013). Is there a Medialization of Climate Science? Results from a Survey of German Climate Scientists. *Science Communication*, *35*(5), 626–653.
Jang SM and Oh YW (2016) Getting attention online in election coverage: Audience selectivity in the 2012 US presidential election. *New Media & Society* 18(10): 2271–2286.
Jasanoff, S (1990). The Fifth Branch: Science Advisers as Policymakers. Cambridge: Harvard University Press.
Just MR and Holtz-Bacha C (2017) Introduction. In: Holtz-Bacha C, Just MR and Davis R (eds) *Twitter and elections around the world: Campaigning in 140 characters or less*. London, New York: Routledge Taylor & Francis Group.
Kamps HJ (2015) *Who Are Twitter's Verified Users?* Available at: https://medium.com/three-pipe-vc/who-are-twitter-s-verified-users-af976fc1b032.
Kapp JM, Hensel B and Schnoring KT (2015) Is Twitter a forum for disseminating research to health policy makers? *Annals of epidemiology* 25(12): 883–887.
Knoke D and Yang S (2010) *Social network analysis*. Los Angeles: Sage.
Krauss W, Schäfer MS and Storch H von (2012) Post-normal climate science. *Nature + culture* 7(2): 121–132.
Lee NM and VanDyke MS (2015) Set It and Forget It. *Science Communication* 37(4): 533–541.
Lee NM, VanDyke MS and Cummins RG (2017) A Missed Opportunity?: NOAA's Use of Social Media to Communicate Climate Science. *Environmental Communication: A Journal of Nature and Culture*: 1–10.
Liang X, Su LY-F, Yeo SK, et al. (2014) Building Buzz. *Journalism & Mass Communication Quarterly* 91(4): 772–791.
Lotan G, Graeff E, Ananny M, et al. (2011) The revolutions were tweeted: Information flows during the 2011 Tunisian and Egyptian revolutions. *International Journal of Communication* 5: 31.
Lupton D (2014) *'Feeling Better Connected': Academics' Use of Social Media*.
Mazzoleni G and Schulz W (1999) "Mediatization" of Politics: A Challenge for Democracy?: Political Communication. *Political Communication* 16(3): 247–261.
McGowan BS, Wasko M, Vartabedian BS, et al. (2012) Understanding the factors that influence the adoption and meaningful use of social media by physicians to share medical information. *Journal of medical Internet research* 14(5): e117.
Mellor F (2010) Negotiating uncertainty: Asteroids, risk and the media. *Public Understanding of Science* 19(1): 16–33.
Merton RK (1973) *The sociology of science: Theoretical and empirical incvestigations*. Chicago: Univ. of Chicago Pr.

Mohammadi, E, Thelwall, M, Kwasny, M, & Holmes, KL (2018). Academic information on Twitter: A user survey. *PLOS ONE*, *13*(5).

Pennebaker JW, Boyd RL, Jordan K, et al. (2015) *The development and psychometric properties of LIWC2015*. Austin, TX: University of Texas at Austin.

Peters HP (2013) Gap between science and media revisited: Scientists as public communicators. *Proceedings of the National Academy of Sciences* 110(Supplement 3): 14102–14109.

Peters, H. P., Brossard, D., de Cheveigne, S., Dunwoody, S., Kallfass, M., Miller, S., & Tsuchida, S. (2008). Interactions with the Mass Media. *Science*, *321*(5886), 204–205. Retrieved from http://www.sciencemag.org

Pew Research Center (2015) *Global Concern about Climate Change, Broad Support for Limiting Emissions*.

Pew Research Center (2009) *Public Praises Science; Scientists Fault Public: Media Scientific Achievements Less Prominent Than a Decade Ago*.

Pielke RA (2007) *The honest broker: Making sense of science in policy and politics*. Cambridge u.a.: Cambridge Univ. Press.

Post S (2008) *Klimakatastrophe oder Katastrophenklima?: Die Berichterstattung über den Klimawandel aus Sicht der Klimaforscher*. München: Verlag Reinhard Fischer.

Post S (2016) Communicating science in public controversies: Strategic considerations of the German climate scientists. *Public Understanding of Science* 25(1): 61–70.

Priem J, Costello K and Dzuba T (2012) *Prevalence and use of Twitter among scholars*: Figshare.

Rödder S (2012) The Ambivalence of Visible Scientists. In: Rödder S, Franzen M and Weingart P (eds) *The Sciences' Media Connection –Public Communication and its Repercussions*. Dordrecht: Springer, 155–177.

Rödder S, Franzen M and Weingart P (2012) *The Sciences' Media Connection –Public Communication and its Repercussions*. Dordrecht: Springer.

Rödder S and Schäfer MS (2010) Repercussion and resistance. An empirical study on the interrelation between science and mass media. *Communications* 35(3).

Ross C, Terras M, Warwick C, et al. (2011) Enabled backchannel: Conference Twitter use by digital humanists. *Journal of Documentation* 67(2): 214–237.

Schäfer MS (2008) Medialisierung der Wissenschaft?: Empirische Untersuchung eines wissenschaftssoziologischen Konzepts. *Zeitschrift für Soziologie* 37(3): 206–225.

Schäfer MS, Ivanova A, Schlichting I, et al. (2011) Deutsche Klimaforscher auf der Medienwelle? *Mitteilungen DMG / Deutsche Meteorologischen Gesellschaft*(3): 20–22.

Scheufele, DA (2014). Science communication as political communication. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(Supplement 4), 13585–13592.

Shiffman DS (2012) Twitter as a tool for conservation education and outreach: What scientific conferences can do to promote live-tweeting. *Journal of Environmental Studies and Sciences* 2(3): 257–262.

Shim M, Cappella JN and Han JY (2011) How Does Insightful and Emotional Disclosure Bring Potential Health Benefits? Study Based on Online Support Groups for Women With Breast Cancer. *Journal of Communication* 61(3): 432–454.

Soroka S, Young L and Balmas M (2015) Bad News or Mad News? Sentiment Scoring of Negativity, Fear, and Anger in News Content. *The ANNALS of the American Academy of Political and Social Science* 659(1): 108–121.

Stehr N (1994) *Knowledge societies*. London, Thousand Oaks: Sage.

Su LY-F, Scheufele DA, Bell L, et al. (2017) Information-Sharing and Community-Building: Exploring the Use of Twitter in Science Public Relations. *Science Communication* 39(5): 569–597.

Treise D and Weigold MF (2002) Advancing Science Communication. *Science Communication* 23(3): 310–322.

Tsfati, Y, Cohen, J, & Gunther, AC (2011). The Influence of Presumed Media Influence on News About Science and Scientists. *Science Communication*, *33*(2), 143–166.

Turnhout, E., Stuiver, M., Klostermann, J., Harms, B., & Leeuwis, C. (2013). New roles of science in society: Different repertoires of knowledge brokering. *Science and Public Policy*, *40*(3), 354–365.

van Noorden R (2014) Online collaboration: Scientists and the Social Network. *Nature* 512(7513): 126–129.

von Storch, H (2018) Kommunikative Herausforderungen für Klimaforscher [Communicative challenges for climate researchers]. In: Lüthje, C (ed) Wissenschaftskommunikation [Science Communication]. Nomos 2018, 23–28.

Walter, S and Brüggemann, M (forthcoming). Opportunity makes opinion leaders: analyzing the role of first-hand information in opinion leadership in social media networks. *Information, Communication & Society*, 1-21.

Walter S, De Silva-Schmidt F and Brüggemann M (2017) From "Knowledge Brokers" to Opinion Makers: How Physical Presence Affected Scientists' Twitter Use During the COP21 Climate Change Conference. *International Journal of Communication* 12: 22.

Weber M ([1922] 1980) *Wirtschaft und Gesellschaft*. Tübingen: Mohr.

Weigold MF (2001) Communicating Science. *Science Communication* 23(2): 164–193.

Weingart P (2001) *Die Stunde der Wahrheit?: Zum Verhältnis der Wissenschaft zu Politik, Wirtschaft und Medien in der Wissensgesellschaft*. Weilerswist: Velbrück Wiss.

Weingart P (2002) The moment of truth for science: The consequences of the 'knowledge society' for society and science. *EMBO Reports* 3(8): 703–706.

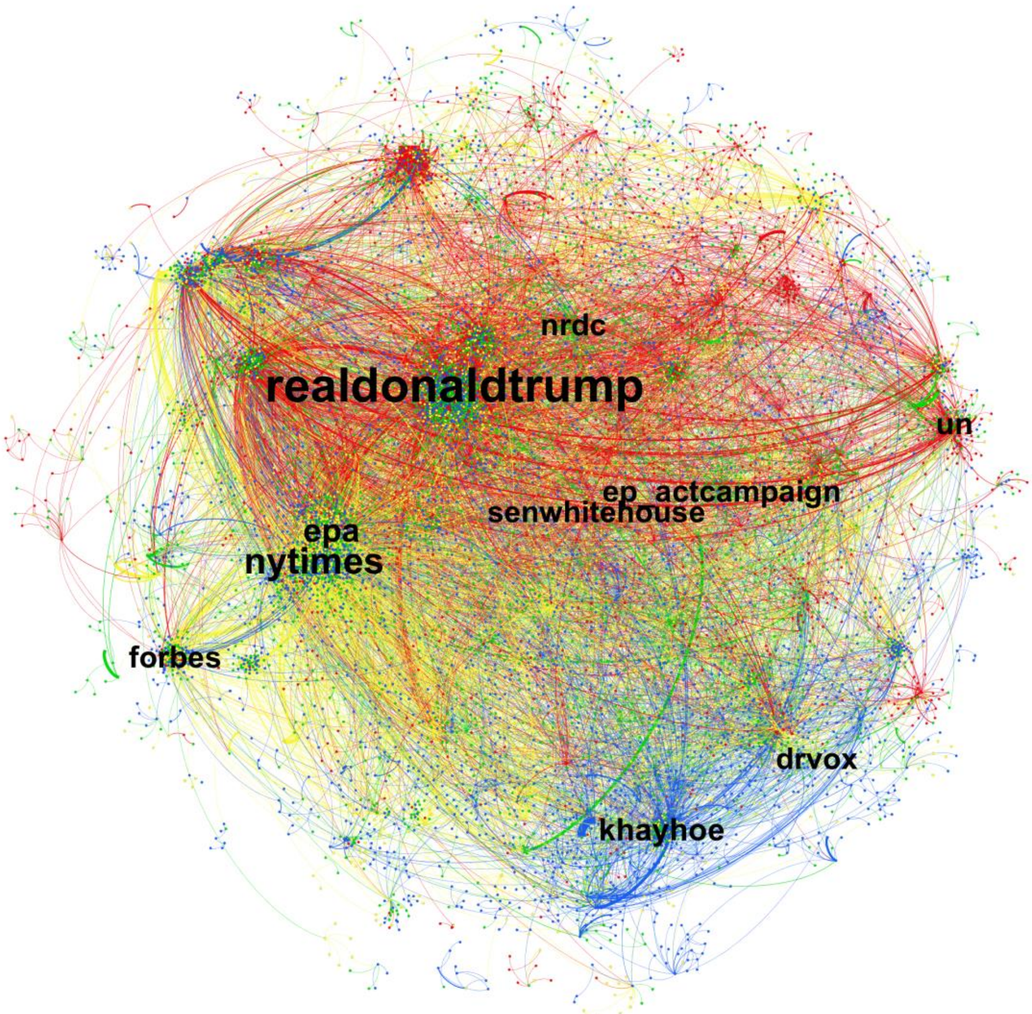
Whitmarsh L (2011) Scepticism and uncertainty about climate change: Dimensions, determinants and change over time. *Global Environmental Change* 21(2): 690–700.

Wilke AK and Morton LW (2015) Climatologists' patterns of conveying climate science to the agricultural community. *Agriculture and Human Values* 32(1): 99–110.

Young JR (2009) 10 High Fliers on Twitter. *Chronicle of Higher Education* 55(31): A10.

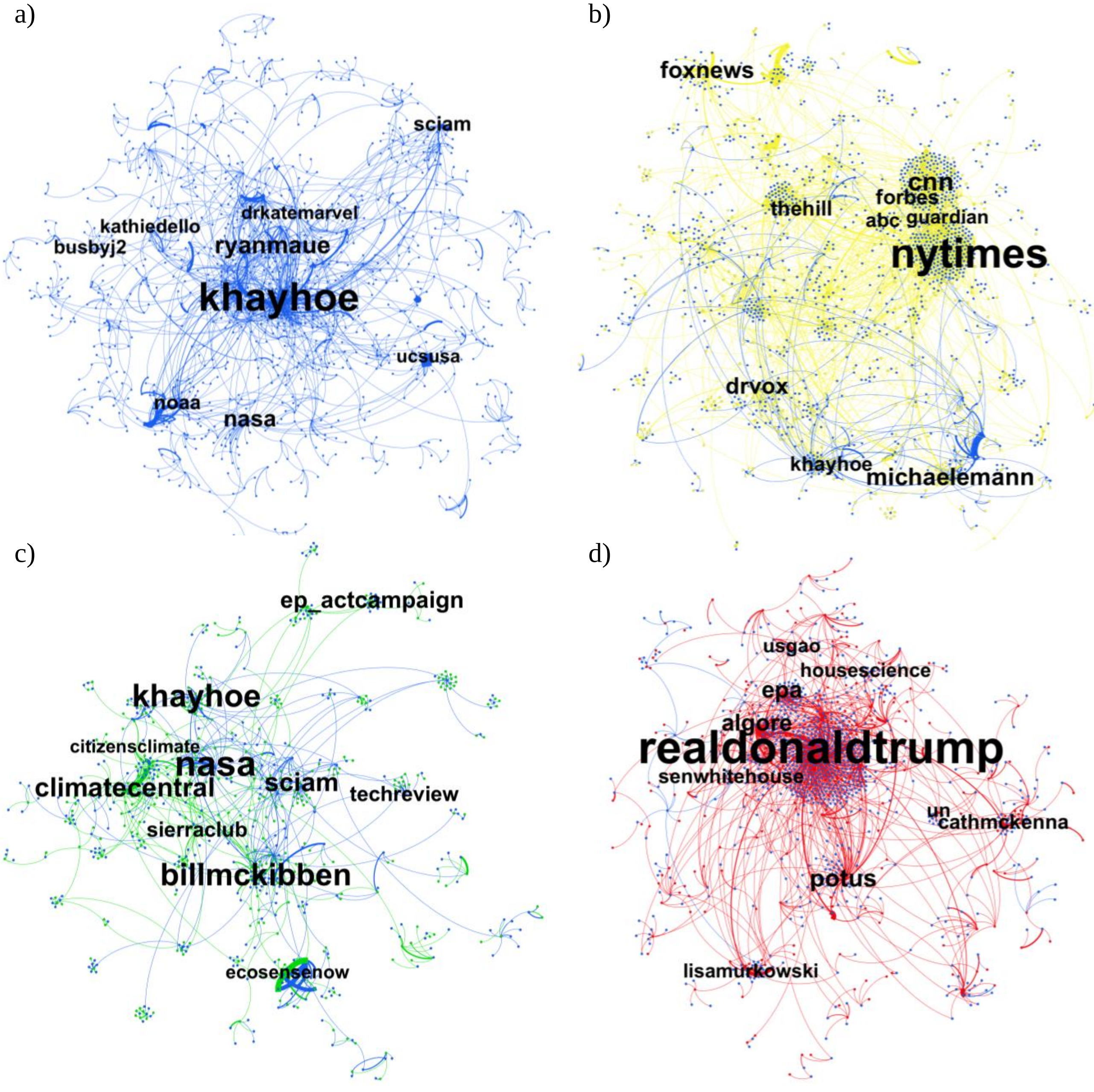
Young L and Soroka S (2012) Affective News: The Automated Coding of Sentiment in Political Texts. *Political Communication* 29(2): 205–231.

Figure 1: Overall network of the climate debate on Twitter



Note: For better visualization, Figure 1 only shows the largest component of the network, and users that could not be classified as scientists, journalists, civil society, or politicians are omitted. See Table 1 for network measures.

Figure 2: Scientists' interactions with a) scientists, b) journalists, c) civil society, d) political actors



Note: For better visualization, the networks only show the largest component.

Walter, Stefanie; Lörcher, Ines; Brüggemann, Michael (2019): Scientific networks on Twitter: Analyzing scientists' interactions in the climate change debate. In *Public Understanding of Science*, 696-712. Available online at https://doi.org/10.1177/0963662519844131.

Table 1: Actor distribution, centrality measures, and node color of the network shown in Figure 1

	N (percent)	In-degree	Out-degree	Degree	Node color
Scientists	8516 (3.34%)	1.92	2.04	3.96	blue
Journalists	7893 (3.10%)	7.99	1.08	9.07	orange
Civil society	7025 (2.76%)	2.24	2.33	4.57	green
Politicians	3132 (1.23%)	18.47	1.11	19.58	red
Other	196086 (76.91%)	1.15	1.65	2.80	(n.a.)
Missing value	32301 (12.67%)	0.89	1.18	2.07	(n.a.)
Total/Average	254953 (100%)	1.60	1.60	3.20	

Note: While Figure 1 only depicts the largest component, the measures provided in Table 1 are based on the full network.

Table 2: Comparison of scientists' centrality measures in the networks shown in Figure 2

Network	a) Scientists ⇔ Scientists	b) Scientists ⇔ Journalists	c) Scientists ⇔ Civil society	d) Scientists ⇔ Politicians
Av. in-degree scientists (min-max)	0.98 (0-78)	0.29*** (0-20)	0.84 (0-39)	0.09*** (0-9)
Av. out-degree scientists (min-max)	0.98 (0-30)	1.48*** (0-49)	0.85* (0-12)	1.51*** (0-17)
Av. degree scientists (min-max)	1.96 (1-101)	1.77 (1-58)	1.69* (1-39)	1.61*** (1-17)

Note: Stars indicate statistically significant difference compared to scientists' interactions with each other (column 1) based on t-tests: * p < 0.05, ** p < 0.01, *** p < 0.00. The t-test results can be found in Appendix II.

Table 3: Differences in the content of scientist's tweets in the networks shown in Figure 2

Tone	a) Scientists ⇒ Scientists (N=2932)	b) Scientists ⇒ Journalists (N=3087)	c) Scientists ⇒ Civil society (N=831)	Scientists ⇒ Politicians (N=1198)
Negative emotions	1.64	2.33***	2.68**	2.19***
Certainty	1.03	1.16	1.09	1.26*

Note: This analysis is only based on tweets that were sent by scientists and were addressed to one of the other user groups (N=8,048). Stars indicate statistically significant difference compared to scientists' interactions with each other (column 1) based on t-tests: * p < 0.05, ** p < 0.01, *** p < 0.00. The t-test results can be found in Appendix III.

Appendix I:

Comparison of network-level measures for the networks in Figure 2 a)-d)

Network	a) Scientists ⇔ Scientists	b) Scientists ⇔ Journalists	c) Scientists ⇔ Civil society	d) Scientists ⇔ Politicians
Nodes	2457	2615	1689	1422
Edges	2405	2839	1423	1617
Number of scientists	2457	1604	840	1005
(Proportion of nodes)	(100%)	(61.34%)	(49.73%)	(70.68%)
Weakly connected comp.	536	350	393	131
Size largest component	1146	1818	726	1127
(Proportion of network)	(46.64%)	(69.52)	(42.98)	(79.25)
Reciprocity	3.19%	1.00%	1.42%	0.19%

Note: While Figure 2 a)-d) only depict the largest components, the measures provided here are based on the full network.

Appendix II:

T-values and level of significance for results presented in Table 2:

Network	Scientists⇔Scientists vs. Scientist⇔Journalists	Scientists⇔Scientists vs. Scientists⇔Civ. society	Scientists⇔Scientists vs. Scientists⇔Politicians
Av. in-degree scientists	-11.92***	-1.42	-16.85***
Av. out-degree scientists	7.14***	-2.30*	9.01***
Av. degree scientists	-1.88	-2.24*	-4.06***

* p < 0.05, ** p < 0.01, *** p < 0.00

Appendix III:

T-values and level of significance for results presented in Table 3:

Network	Scientists⇔Scientists vs. Scientist⇔Journalists	Scientists⇔Scientists vs. Scientists⇔Civ. society	Scientists⇔Scientists vs. Scientists⇔Politicians
Negative emotions	5.59***	2.93**	4.09***
Certainty	1.58	0.46	2.52*

* p < 0.05, ** p < 0.01, *** p < 0.00