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Tweeting disaster: an analysis of online discourse about nuclear power in the wake of the Fukushima Daiichi nuclear accident

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Abstract

Of all the online information tools that the public relies on to collect information and share opinions about scientific and environmental issues, Twitter presents a unique venue to assess the spontaneous and genuine opinions of networked publics, including those about a focusing event like the Fukushima Daiichi nuclear accident following the 2011 Tohoku earthquake and tsunami. Using computational linguistic algorithms, this study analyzes a census of English-language tweets about nuclear power before, during, and after the Fukushima nuclear accident. Results show that although discourse about the event may have faded rapidly from the news cycle on traditional media, it evoked concerns about reactor safety and the environmental implications of nuclear power, particularly among users in U.S. states that are geographically closer to the accident site. Also, while the sentiment of the tweets was primarily pessimistic about nuclear power weeks after the accident, overall sentiment became increasingly neutral and uncertain over time. This study reveals there is a group of concerned citizens and stakeholders who are using online tools like Twitter to communicate about global and local environmental and health risks related to nuclear power. The implications for risk communication and public engagement strategies are discussed.

Keywords

Environmental communication; Public perception of science and technology; Representations of science and technology

Introduction

The landscape in which the public obtains and interacts with science information has significantly changed over the past decade. In 2010, the Internet surpassed television for the first time to become Americans' primary source of information about science and technology [National Science Board, 2016]. Among the popular online tools that people use to follow science news, the microblogging service Twitter presents a unique platform that allows users to follow content 'tweeted' by traditional media and to receive user-generated information directly from scientists or key stakeholders. In part driven by a cultural change within the scientific community, more and more scientists are using Twitter to create additional opportunities for public education and to increase the visibility of their own work

[e.g., Bik and Goldstein, 2013; Osterrieder, 2013]. For example, Liang et al. [2014] show that the quality and influence of a nanotechnology researcher's work is closely related to his media activity and particularly the frequency of being mentioned on Twitter. In addition, key stakeholders, such as policymakers and elite organizations, have leveraged Twitter to amplify the outreach of traditional forms of communication [e.g., Golbeck, Grimes and Rogers, 2010]. Journalists, activists, and interest groups also use Twitter to reach out to target audiences and initiate conversations under different hashtags [Cha et al., 2012; Papacharissi and Fatima Oliveira, 2012].

Although Twitter and other online services have created great opportunities for audiences to connect with science, researchers are only beginning to understand the nature of these connections and to identify specific cultural and contextual concerns underlying Twitter discussions [Brossard and Schefeule, 2013]. Twitter usually reflects conversations that are taking place in existing offline networks. For example, Twitter users are likely to connect to those within geographically adjacent communities [Takhteyev, Gruzd and Wellman, 2012]. With respect to scientific topics, Runge et al. [2013] find a positive correlation between the volume of nanotechnology-related tweets sent from each U.S. state and the presence of a National Nanotechnology Initiative center in that state, suggesting the existence of a geographic community of like-minded innovators who use Twitter to communicate with each other.

Twitter has also served a role in coordinating local and regional discussions during high-profile events, such as the Arab Spring [Christensen, 2011]. Notably, Twitter discussions about high-profile events often feature varied sentiment over time [Thelwall, Buckley and Paltoglou, 2011]. Therefore, a systematic analysis of Twitter content at various time points can offer important insights into the deeply held concerns of the influenced communities [Eichstaedt et al., 2015; Thelwall, Buckley and Paltoglou, 2011]. Although the content produced by networked publics in times of political crisis has been examined [e.g., Papacharissi and Fatima Oliveira, 2012], few studies have investigated how geographically bounded communities discuss scientific topics in the aftermath of a focusing event. In this study, we attempt to fill this gap by depicting the sentiment and thematic content of Twitter discussions related to contested science (e.g., nuclear power) in the wake of a high-profile event: the Fukushima Daiichi nuclear accident following the 2011 Tohoku earthquake and tsunami in Japan. In addition, following Runge et al. [2013]'s approach, we examine the relationship between the volume of Tweets sent from each U.S. state and state-level industrial and environmental experiences, with a goal of understanding the structural factors that may drive online discussions.

The Fukushima Daiichi accident offered a unique occasion to observe the dynamics of science discussions online, given its disastrous consequences and the public discussion about nuclear safety that followed. In this study, we used computational linguistic algorithm [Su et al., 2016] to examine the sentiment and themes present in a census of English-language tweets related to nuclear power. While an analysis of Japanese-language tweets might provide critical information about public discussion in greater proximity to the accident cite, we focus on English-language ones primarily due to our interest in the U.S. Twitter users' reactions to the accident. The implications of this decision on the interpretation of our results, however, are discussed later in this manuscript. Our analysis of tweets over an

18-month period not only shows the immediate impact of the Fukushima accident on public discourse, but also the long-term impact of this event even after it fades from prominence in print and broadcast media outlets in the U.S. The results reveal the changing nature of science discussions on Twitter over the long run and have important implications for risk and science communication practices.

Nuclear power public opinion and information environment

Before the Fukushima Daiichi nuclear accident, nuclear power was experiencing a sort of renaissance as a prospective means of expanding available energy sources [Goodfellow, Williams and Azapagic, 2011]. Nuclear energy appeals to some environmentally minded citizens because the carbon emitted from energy production is estimated to be near zero [Kleiner, 2008]. Nuclear power is also believed to offer a stable source of energy that could provide energy independence and enhance national security [Nuclear Energy Agency, 2010]. The Energy Act of 2005 has proposed incentives to the U.S. nuclear industry, including tax credits and loan guarantees, to expand nuclear energy facilities and promote the use and development of nuclear power [Department of Energy, 2005].

Immediately following the Fukushima accident, the U.S. Nuclear Regulatory Commission conducted a series of safety inspections of American nuclear energy facilities and declared the facilities safe. The event also prompted the U.S. electric industry to implement additional safety enhancements for existing reactors and other facilities. However, public concern about the safety of nuclear power was roused by this accident, as it was by the nuclear disasters at Three Mile Island and Chernobyl [Friedman, 2011]. One major concern held by those opposing nuclear energy is that a foolproof way to safely dispose of nuclear waste has not yet been discovered. Other concerns can be attributed to the potential for accidents or meltdowns and the threat of having such materials falling into the wrong hands and applied to weaponry. Some people also believe that nuclear power is an outdated technology that is no longer economically effective [Kessides, 2012].

In general, public opinion about nuclear energy was prone to be favorable prior to 2011. According to the 2010 General Social Survey, 61% of Americans favored or strongly favored an increased use of nuclear power to generate electricity in the U.S., whereas 28% opposed or strongly opposed increased dependence on nuclear power [National Science Board, 2012]. However, a survey conducted shortly after the Fukushima accident in 2011 suggested that 39% of Americans favored whereas 53% opposed an increased use of nuclear power [Pew Research Center, 2011]. Interestingly, as the media coverage of Fukushima accident dramatically decreased over time, with a Google Trends search of "Fukushima Daiichi" returning only seven news headlines by November 2011, public support for nuclear energy slightly recovered. As of March 2012, 44% of the U.S. public supported nuclear energy whereas 49% opposed it [Pew Research Center, 2012a]. In addition, it was found that Americans' attitudes toward nuclear energy closely hinge on the nature of media content they constantly receive about this issue [Yeo et al., 2014].

The Fukushima Daiichi accident operated as a focusing event that prompted a worldwide response and concern for those in the vicinity of the contaminated area, as well as more localized discussions of the likelihood of a similar event in other

nuclear-dependent regions. Twitter became one of the most popular media platforms in which people shared opinions about the incidents at the Fukushima Daiichi nuclear power plant and deliberated on the perceived risks and implications for nuclear power more generally [Kittle Autry and Kelly, 2012; Binder, 2012; Friedman, 2011; Kinsella, 2012]. However, an analysis of a selected sample of tweets with the keyword "Fukushima Daiichi" or its variants showed that only a small proportion of these tweets contained some mentions of the risks or hazards caused by the accident [Binder, 2012]. Most of the early tweets posted at the onset of the accident merely expressed straightforward information rather than interpretations of the causes or implications of the disaster, whereas the later tweets became more interpretive [Binder, 2012]. Indeed, results of an analysis of the Twitter discourse surrounding a proposed merger of two energy companies in the wake of Fukushima accident suggest that the post-Fukushima discussions focused mostly on the safety and environmental concerns about building new nuclear power plants in the area, North Carolina [Kittle Autry and Kelly, 2012].

Tweeting nuclear: sentiments, themes, and community-based discussions

This study aims to examine how the opinions expressed in nuclear-related tweets evolved between December 2010 and May 2012, a short period before the Fukushima Daiichi accident and one year after it. An exploratory content analysis of the *New York Times* archived articles using the search terms "Fukushima" shows that many articles expressed negative sentiments with focused on widespread concerns for children and workers' exposure to radiation [Friedman, 2011]. Television coverage of the Fukushima accident was also observed to highlight the potential catastrophic consequences of leaking radiation [Friedman, 2011]. Although we could have foreseen negative sentiment dominating the early conversations of this disaster online, it was premature to anticipate how the tone of Twitter discussions would vary over one year after the disaster. We hence pose a research question (RQ) to investigate the tone of tweets related to nuclear power:

RQ1: How does the sentiment expressed in nuclear-related tweets change one year after the Fukushima Daiichi nuclear accident?

We are also interested in tracking the varied thematic dimensions that arise in tweets about nuclear power. Many of the content analyses of traditional media outlets can inform our attempts to identify the thematic emphasis of Twitter discourse. For example, in an analysis of two local newspapers' coverage of proposed reactors in the state of Georgia, the authors found that the pro- and anti-nuclear arguments most often reflect economic and environmental themes [Culley et al., 2010]. In particular, the anti-nuclear arguments often focus on the themes of 'need for alternative energy' other than nuclear and the 'health and safety risks' associated with the proposed reactors [Culley et al., 2010]. Many of these topical themes do not only reflect the salient concerns of local communities with respect to specific nuclear facilities, but also persist in discussions of nuclear power in general. In an interdisciplinary study on the future of nuclear power, researchers identified four major issues associated with the development of nuclear power, namely costs, safety, proliferation, and waste [Ansolabehere et al., 2003]. With these established areas related to different dimensions of nuclear power in mind, we developed four thematic categories, labeled as 'environment, health, and safety (EHS),' 'business,'

'energy,' and 'national security,' to capture the thematic shifts in tweets within the time framework of our study. We then pose the following question:

RQ2: How do the thematic contents of nuclear-related tweets change one year after the Fukushima Daiichi nuclear accident?

Lastly, this study aims to explore the geographic origins of online conversations driven by concerned citizens, energy stakeholders and nuclear activists. As mentioned earlier, the formation of Twitter networks is often based on the homogeneity of users' ideological, behavioral, and intrapersonal characteristics [Barbera, 2015; McPherson, Smith-Lovin and Cook, 2001]. People are likely to link to those with common interests and similar ideas on Twitter, and often with those who reside in proximate areas, such as within the same metropolitan region [Takhteyev, Gruzd and Wellman, 2012]. In our case, the post-Fukushima discussions on nuclear energy may presumably relate to concerns about one's proximity to Japan and the potential for radiation to be transported to regions like the West Coast of the U.S. In particular, previous studies suggest that proximity to a disaster area is positively related to preparedness behavior [Farley et al., 1993; Kunreuther, 1978]. After the Fukushima Daiichi accident began, it was reported that potassium iodide supplements, which can minimize the body's absorption of radiation, were quickly sold out of Los Angeles pharmacies [Wald, 2011]. Therefore, we hypothesize that people living closer to Japan are more likely to disseminate information about disaster preparation and other related issues on Twitter. With these assumptions in mind, we pose a hypothesis (H1) regarding the relationship between intensity of Twitter discussions and geographic proximity to Japan:

H1: The volume of nuclear-related tweets will be positively related to Twitter users' geographic proximity to the site of the Fukushima nuclear accident.

However, even for people who live in regions that are geographically distant from Japan, the Fukushima accident can still function as a focusing event that amplifies their perceived risk associated with nuclear power. For instance, the accident may draw citizens' attention to the safety of the nuclear power plants built in their residential area. With increasing access to global information, citizens can apply information about physically remote events to local situations, such as how safe nuclear reactors in one's own local area might be. We therefore posit a research question with respect to the local concerns of nuclear power:

RQ3: Does the volume of nuclear-related tweets relate to the number of nuclear power plants in the states where the tweets originate?

Methods

Data

This study gauges the volume, sentiment and thematic content of nuclear-related posts on Twitter, and when available, the geographic origins of collected tweets. We use the ForSight platform developed by Crimson Hexagon to collect and analyze a census of tweets posted between December 1, 2010 and May 31, 2012.

The ForSight platform uses algorithms to automatically track linguistic patterns — representing various underlying concepts and sentiments first identified by human coders — across a large amount of textual data [Hopkins and King, 2010]. Researchers in computer science have used such analysis, often known as sentiment analysis or opinion mining, to assess opinions in a range of contexts, such as discussion threads in online news websites, U.S. congressional floor debates, blogs, and public comments made online [Bansal, Cardie and Lee, 2008; Chmiel et al., 2011; Conrad and Schilder, 2007; Kwon, Shulman and Hovy, 2006; Pang and Lee, 2008]. With respect to the analysis of tweets collected by ForSight, human coders first read and code a subsample of tweets randomly selected by the algorithm, and then an automated analysis program applies the rules identified by human coders to analyze the rest of the tweets and retweets.[1]

To collect a census of nuclear-related tweets, Boolean searches[2] were generated to match relevant posts and to avoid irrelevant tweets as much as possible. We constructed these searches to reflect a wide variety of topics related to nuclear power. Therefore, comparisons could be made between relevant tweets before and after the event.

Based on this carefully constructed keyword search, ForSight collected a total of 11,064,381 English-language tweets during the time period, which can be posted within or outside the U.S. In addition, ForSight applies a nonparametric method to statistically analyze these texts [Hopkins and King, 2010]. The ForSight platform also collects the geographic origins of tweets from Twitter users' profiles, i.e. when Twitter users specify where they live. A total of 3,350,007 of the collected tweets were geotagged with the location the user specifies, enabling us to explore the factors that influence the volume of tweets posted by users who indicate they reside in the U.S.

Coding

Sentiments

Ten coders worked in three rotating teams to train the software to classify the tweets discussing nuclear power into four categories of sentiment, including 'optimistic,' 'neutral,' 'pessimistic,' and 'off-topic.' The optimistic category included tweets mentioning the benefits of nuclear power or positive outlook about the successful outcome of expanding nuclear technology. The pessimistic category included tweets expressing concerns about nuclear safety or conveying any other negative aspects of nuclear power. The neutral category included tweets expressing purely neutral opinion, that is no pessimistic or optimistic sentiment; and tweets containing no opinion (e.g., facts only). Tweets not explicitly mentioning any

[1] ForSight does not distinguish between original tweets and retweets if not manually specified, e.g., filtering out retweets by including Boolean search terms such as "RT." As a result, if a tweet were retweeted ten times, they will be counted as ten tweets in the data set.

[2] (nuclear OR "atomic energy" OR plutonium OR thermonuclear OR "fissile atom(s)" OR "atomic power" OR nucleonics OR "cold fusion" OR plutonium OR "containment vessel(s)" OR "control rod(s)" OR "fuel rod(s)" OR fission(s) OR atomic(s) OR atomistics OR "enriched uranium" OR "depleted uranium" OR "uranium 235" OR "u235" OR radioactive OR radiation OR fukushima OR "three mile island" OR chernobyl OR "heavy water" OR nuke OR "fast breeder reactor(s)" OR IAEA OR "fusion power" OR "yucca mountain") AND –"nuclear family" AND -microwave.

positives or negatives of nuclear power were also coded as neutral. In addition, each of the three sentiment categories had two subcategories: 'certain' and 'uncertain' (e.g., tweets could be coded as pessimistic-uncertain, optimistic-certain, neutral-uncertain, etc.) Specifically, tweets that either expressed ambiguity about using nuclear power or posed questions regarding any aspect of the issue, such as the financial feasibility of a new nuclear power plant, were coded as 'uncertain.' In contrast, all other tweets that did not contain any ambiguous language were coded as 'certain.'

An 'off-topic' category was established to ensure that the category list is exhaustive. We used this category to capture the tweets that were either irrelevant to the topic (e.g., mentions of nuclear power in the context of video games) or in a language other than English.[3]

While human coders were initially training the algorithm that analyzed the tweets, those tweets featuring both positive and negative language (e.g., pros and cons, risks and benefits, or advantages and disadvantages related to nuclear power) were skipped in order to ensure the reliability of human coding and to maximize the accuracy of subsequent automatic coding [Hopkins and King, 2010].

Themes

The coders also analyzed the selected Twitter posts in terms of their thematic contents and translated the tweets into corresponding topical categories. The process continued until the software had a statistically reliable number of coded tweets in each category. Computational software then recognized the identified linguistic patterns and relied on the patterns to analyze all collected tweets and reported the proportion of tweets in each category on a daily basis. The specific coding rules for our four topical categories, including 'business,' 'national security,' 'environment, health, and safety (EHS),' and 'energy' are shown below.

1. *Business*: tweets mentioning the commercial aspects of nuclear power, such as the financial investment of a nuclear power plant or cost analysis of the fuel cycle. Example: "CEO of biggest US nuclear-power producer touts 'cheap' natural gas."
2. *National security*: tweets mentioning military applications of nuclear power, such as nuclear missiles or bombs. Example: "most powerful US nuclear bombs are dismantled."
3. *EHS*: tweets mentioning the implications of nuclear power on environment and health, or the fallout and remedies occurred at nuclear accidents. Example: "radioactive water leaks from Tepco plant."
4. *Energy*: tweets mentioning electricity production with nuclear power. Example: "nuclear summit urges higher use of atomic power."

Analysis of community-based discussion on twitter

In order to explore the factors driving the local discussion about nuclear power, we used hierarchical ordinary least-square (OLS) regression to test two separate

[3]The detailed coding rules for each category are available upon request.

models predicting the volume of nuclear-related tweets within one month and six months after the Fukushima accident.[4] The short-term and relatively long-term trends were both examined in order to control for potential confounding effects of time. In particular, we examined whether the localized Twitter discussions about nuclear power were mainly driven by the concerns about the safety of nearby nuclear facilities or about the potential transported radiation from Japan.

Given the significant correlation between the volume of tweets originating from each state and the size of the population in each state, we controlled for the covariance between the two constructs before using the tweet volume as the dependent variable. We hence used the residuals that resulted from regressing the volume of tweets on states' populations as the dependent variables in our models [United States Census Bureau, 2012a].

Independent variables were entered in blocks, which were: (1) educational attainment rate [United States Census Bureau, 2012b]; (2) income per capita [United States Department of Commerce, 2012a]; (3) ideological leaning per state [United States Census Bureau, 2012c]; (4) household Internet access rate [United States Department of Commerce, 2012b]; (5) the number of nuclear power plants in each U.S. state [Energy Information Administration, 2012]; and (6) the geodesic distance between state capital city and the Fukushima Daiichi nuclear power plant [MapCrow, 2012].

The block-by-block approach allowed us to evaluate the variance explained by each set of variables as they were entered as predictors [Cohen and Cohen, 1983]. We reported the before-entry standardized betas to evaluate the main effects of each variable. The final betas that showed the unique relationship between dependent and independent variables while controlling for those variables already entered into the equation were also reported.

Results

Volume trend and triggering events

Prior to reporting the results of the hypothesis and research questions, we provide an overview of the spikes in tweets triggered by critical events occurring during the time period (Figure 1). As Figure 1 shows, the total number of nuclear-related tweets posted per week dramatically increased right after the Fukushima Daiichi accident. While there were only 7,034 tweets discussing nuclear on March 10, a total of 128,418 tweets expressing opinions about nuclear power were identified on March 11, the date when the tsunami hit the Fukushima Daiichi nuclear power plant. The volume of tweets reached its peak on March 15, with a total of 323,735 nuclear-focused tweets being posted on that single day. Although the volume of tweets rapidly declined thereafter, it remained at a rather high level compared to that before Japan's earthquake.

In addition, we rendered the trend of the volume of tweets from Crimson Hexagon's "Firehose" dataset to see if tweets conveyed discernable peaks that were

[4] Only 30% of all English-language tweets during our time frame were geotagged, which is information voluntarily provided by users. This resulted in unintentional sampling of the tweets, so we used inferential statistics to determine the factors related to the volume of tweets from users in each U.S. state.

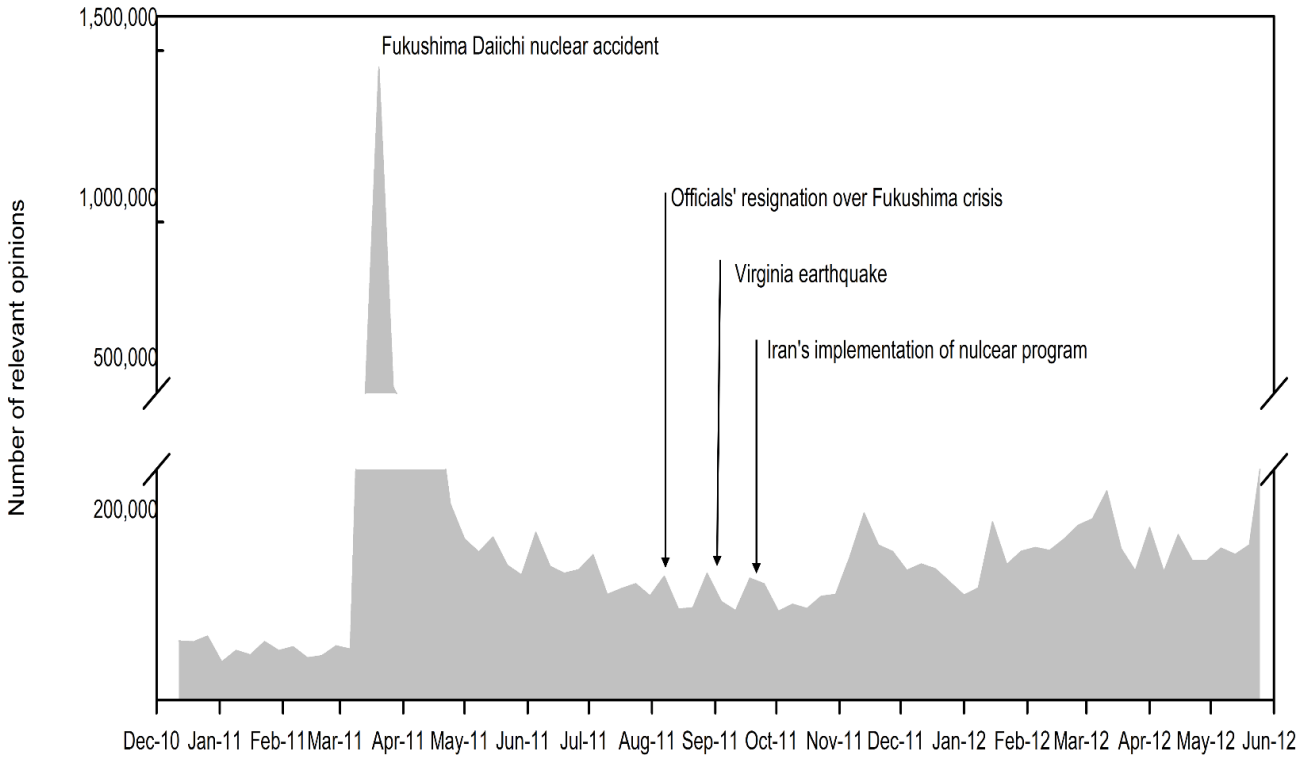

Figure 1. Volume of nuclear-related posts expressing opinions on Twitter from December 2010 to May 2012.
Note: only peaks that can be attributed to a single identifiable news event are annotated.

associated with certain news events. Not surprisingly, the volume of nuclear-related tweets corresponded to subsequent major events as Japan coped with the aftermath of the earthquake and devastation at the nuclear plant. The volume of tweets increased on August 4, 2011 when three top officials were discharged over the Fukushima crisis [Fackler, 2011]. A CNN news story on Japan's timetable for removing nuclear fuel from the damaged plant received hundreds of comments and retweets within a few hours [CNN, 2011]. The disaster also raised people's concerns about the safety of domestic nuclear facilities during felt earthquakes. On August 23, a large amount of tweets discussed the earthquake that occurred in the Piedmont region of Virginia and the automatic shutdown of nuclear reactors ten miles northeast of the earthquake's epicenter [CBS News, 2011].

There was also a sharp spike in the volume of tweets on September 12, 2011 in response to Iran's implementation of its first atomic power plant. The rigorous discussion about Iran's nuclear program continued on Twitter, as this event received vast attention from traditional media. In fact, the intermittent increases in tweet volume between November 2011 and May 2012 were almost exclusively triggered by news events related to international nuclear events, such as Iran's nuclear program and announcements about North Korea's nuclear disarmament.

In addition to exploring the content of tweets that comprised the discernible spikes in volume, we attempted to examine if key policy events play a role in boosting the level of Twitter attention to nuclear power. Drawing upon a number of selected policy reports on the topic, we focused on two major policy events specific to the actions taken by the U.S. government in response to the Fukushima accident.

However, it turned out that there was no discernible change in the volume of tweets on July 12, 2011 when the Nuclear Regulatory Commission (NRC) released the report that called for a wide range of improvements for the U.S. fleet of 104 nuclear reactors [Miller et al., 2011]. Also, very limited attention was paid on Twitter to the investigative report about the Fukushima accident given by the American Nuclear Society (ANS) when it was released in March 2012 [American Nuclear Society, 2012].

Sentiments

Figure 2 shows the proportional change of tweets expressing varied sentiments between December 2010 and May 2012. The proportion of optimistic tweets decreased from 32% in December 2010 to 20% in May 2012 (Figure 2A). The proportion of neutral tweets increased from 33% to 41% during this time period (Figure 2B). At the same time, the proportion of pessimistic tweets increased from 33% to 41% (Figure 2C). In terms of certainty expressed in the opinioned tweets, 12% were coded as optimistic and certain, while 8% were coded as optimistic and uncertain by the end of May 2012 (Figure 2A). As shown in Figure 2B, tweets coded as neutral became increasingly uncertain between July 2011 and May 2012. In May 2012, 26% of the total tweets were coded as neutral and uncertain whereas 15% of them were coded as neutral and uncertain. In contrast, the pessimistic tweets were consistently dominated by uncertainty across the time period. By the end of May 2012, 26% of the collected tweets were coded as pessimistic and certain while 12% of them were coded as pessimistic and uncertain.

It is noteworthy that the proportion of pessimistic tweets dramatically increased in March 2011 when the tsunami struck the Fukushima nuclear power plant and slightly decreased thereafter. The proportion of pessimistic and neutral tweets remained at almost the same level between August 2011 and May 2012. The overall sentiment of nuclear-related tweets was consistent with the tone of traditional news coverage on Fukushima accident at the time, which was dominated by the negative coverage of nuclear power [Friedman, 2011]. However, although triggering tremendous discussion in itself, the Fukushima accident did not make Twitter users become more pessimistic about nuclear power over the long term.

Themes

In terms of the thematic content of the collected tweets during the time period, about 37% of the total tweets discussed EHS-related issues related to nuclear power, whereas only 13% discussed the economic and business-related aspects (Figure 3). Moreover, about 25% of the collected tweets focused on the uses of nuclear power as a source of energy (Figure 3). Another 25% of tweets mentioned the role of nuclear power in influencing national security (Figure 3). Noticeably, the proportion of tweets in the EHS category dramatically increased when the Fukushima accident occurred and continuously grew thereafter. In contrast, the proportion of tweets in the business category steadily declined between March 2011 and May 2012. The proportion of tweets in both the energy and national security categories did not change much during the time period.

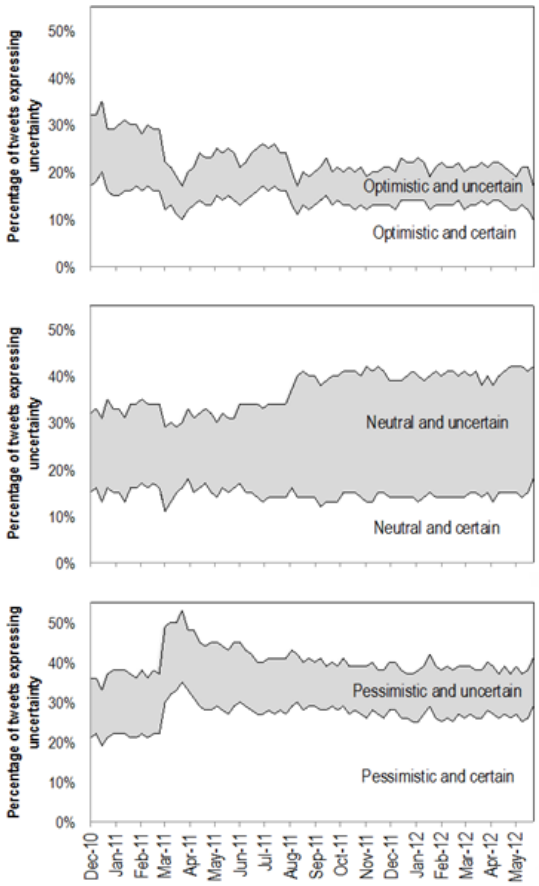

Figure 2. Sentiments of nuclear-related posts expressing opinions on Twitter from December 2010 to May 2012.

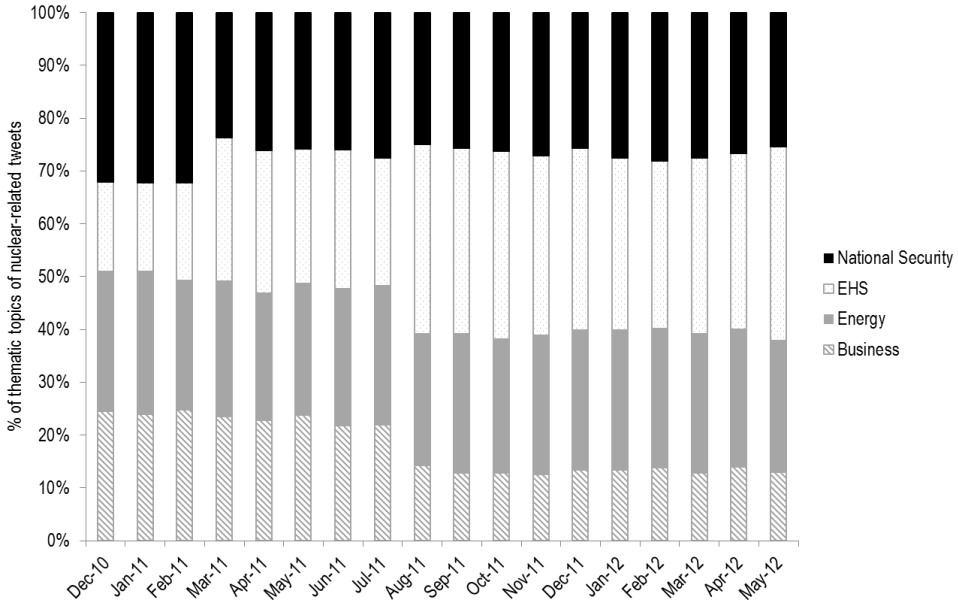

Figure 3. Themes of nuclear-related posts expressing opinions on Twitter from December 2010 to May 2012.

Predicting the volume of tweets originating from different states

According to the results shown in the final model (Table 1), the geodesic distance between the state capital of the tweets' origins and the Fukushima Daiichi nuclear power plant was negatively related to the volume of tweets collected between March 11 and April 12, 2011 ($\beta = -.41$, $p < .05$) and April 13 and October 14, 2011 ($\beta = -.43$, $p < .05$). The results indicate that the closer people lived to Japan, the more likely they were to discuss nuclear power on Twitter during and after the Fukushima accident. H1 was therefore supported. However, the number of nuclear power plants in each state had no significant relationship with the volume of tweets per state, as indicated by the non-significant final beta values.

Table 1. Predicting volume of nuclear-related tweets expressing opinions by state (number of tweets per capita by state) from March 2011 to October 2011.

	March 11 – April 12		April 13 – October 14	
	Before-entry	Final β	Before-entry	Final β
Block 1: Educational Attainment (Highest Degree Earned)				
% residents with high school degree	-.12	.04	-.20	-.18
% residents with baccalaureate degree	.18	-.05	.26	.03
% residents with post-graduate degree	.19	.29	.23	.12
Incremental R^2 (%)		4.2		7.4
Block 2: Income				
Per capita annual income in 2010	.14	.25	.08	.18
Incremental R^2 (%)		.7		.2
Block 3: Ideological Leaning				
% votes cast Democratic in the most recent state governor election$^+$	.13	.01	.14	.03
Incremental R^2 (%)		1.4		1.7
Block 4: Internet Access				
% households with Internet access	-.14	-.27	-.06	-.20
Incremental R^2 (%)		.4		.1
Block 5: Nuclear Power Plants				
No. of nuclear power plants in state	-.34*	-.21	-.37*	-.22
Incremental R^2 (%)		9.0*		11.5*
Block 6: Distance from Japan				
Geodesic distance between state capital and Fukushima Daiichi nuclear power plant	-.41*	-.41*	-.43*	-.43*
Incremental R^2 (%)		9.8*		11.0*
Total R^2		26.3%*		32%*

Note: N = 50. *p < .05. All coefficients are standardized betas. $^+$ Most states elected governors in 2010. Thirteen states had their most recent gubernatorial elections between 2007 and 2009 (see United States Census Bureau [2012a] for detailed info).

Discussion

As various stakeholders and concerned citizens increasingly turn to the Internet to seek information and deliberate about the merits and drawbacks of different energy options, it is important to understand the nature of aggregate opinions expressed online. Among the existing online tools that have been widely adopted

by energy policymakers and activists, Twitter is one of the most popular social media platforms that enables its users to subscribe to the most current information from both nontraditional online sources and online versions of traditional news outlets. Evaluating the aggregate of opinions expressed on Twitter is particularly useful in the context of a focusing event such as the Fukushima Daiichi nuclear accident. Inspired by previous studies on the structure of naturally formed networks on Twitter, we propose that this medium could offer unique insights into the opinions held by subsets of the public with knowledge or particular interests in nuclear energy and other aspects of the nuclear power issue [Anderson, Brossard and Scheufele, 2010; Pew Research Center, 2012b].

Given the popularity and utility of Twitter for many users, this study provided a systematic analysis of a census of English-language tweets related to nuclear energy and other uses of nuclear power in the wake of the Fukushima accident. Using computational software (ForSight) developed by Crimson Hexagon, we examined the sentiment, thematic content and uncertainty of nuclear-related tweets collected between December 1, 2010 and May 31, 2012, a short period before and about one year after the Fukushima Daiichi accident. To the best of our knowledge, this time frame allows us to examine how the public responds (on Twitter) to the Fukushima accident over a much longer period of time than previous studies have evaluated. As Fishman [Fishman, 1978] suggested, the issue attention cycle triggered by a news event is likely to be prolonged by pseudo-events that follow the same theme occurring afterwards. Our choice of time frame (four months before to 14 months after) enables us to capture the implications of later events dealing with the aftermath of this accident (e.g., the resignation of Japan's officials, the release of an ANS report, the anniversary of the accident, etc.).

Additionally, by assessing the volume of nuclear-related tweets originating from different states as a real-time indicator of the intensity of local discussion, we mapped how localized information exchange and deliberation over nuclear power manifested on Twitter after the Fukushima Daiichi accident.

Before discussing the results in detail, we would like to identify three limitations that need to be kept in mind when interpreting the findings. The first limitation of our method dealt with the coding rules we employed to categorize tweet themes. The four topical categories (i.e., EHS, business, national security, and energy) are not exhaustive but cover a number of the most important aspects of the nuclear power issue that presumably dominate the concurrent offline conversations. Future research may extend the coding categories to other aspects that are relevant to policy decisions, such as climate change mitigation.

Also, without systematically identifying the individuals who frequently tweet about nuclear power, we know little about the extent to which sentiments expressed on Twitter may represent overall public opinion. In fact, Twitter users are by no means representative of the U.S. public demographically [Pew Research Center, 2012c]. Some empirical evidence suggests that the reaction to major policy decisions on Twitter often differs a great deal from public opinion as measured by representative surveys [Pew Research Center, 2013b]. Further studies need to investigate the relationship between Twitter discourse and public perceptions of scientific issues.

In addition, this study only collected and examined English-language tweets and focused the analysis on U.S. Twitter users' reactions to the Fukushima accident. Given the origin of the disaster, analysis of Japanese-language tweets would provide critical information about public discussion in greater proximity to the accident site. Researchers may want to consider how cultural and linguistic factors may elicit different patterns of discussion on Twitter. For instance, research has shown that Japanese-language tweets are more likely to reference high-credibility sources than tweets in other languages [Thomson et al., 2012]. Therefore, it is reasonable to infer that the nature of tweets in Japanese might differ from English-language ones, in terms of nuclear energy and other issues. This suggests a need for empirical comparisons of Twitter content across cultural contexts.

Results of this study suggested that the volume of nuclear-related tweets varied during the time framework of this study. Although the volume dramatically increased and reached its peak within the week immediately following the accident, it rapidly declined thereafter. Nonetheless, the volume of nuclear-related tweets still remained at a relatively high level compared to that before Japan's earthquake, which indicated an escalation of public concerns over nuclear safety caused by this event. In this context, Twitter can function as a useful tool to assess genuine and spontaneous opinion generated by the Fukushima accident.

Indeed, the major discernible increases in tweet volume were associated with many news events that already received attention from traditional mass media, such as the resignation of officials in Japan or Iran's implementation of a nuclear program. As previously found, a majority of nuclear-related tweets during the Fukushima accident contained a link to the online content of traditional mass media [Binder, 2012]. These findings, on the one hand, reflect the fact that traditional media tended to leverage Twitter among other popular services to disperse news headlines and to route traffic to their websites. On the other hand, it illustrated the tendencies of Twitter users to replicate their customary uses of traditional mass media when using emerging online tools.

From an energy stakeholder's perspective, Twitter is likely to present an effective channel to amplify one's voices in terms of negativity rather than of positivity. Our results showed that 50% of total tweets express pessimistic views about nuclear power during the Fukushima Daiichi accident. The salience of pessimism resonated with the findings of previous studies. An analysis of 30 popular topics on Twitter from 29 selected days in 2010 suggested that a majority of these spiking events was associated with strong negative sentiment, such as a tsunami in Hawaii or earthquake in Chile [Thelwall, Buckley and Paltoglou, 2011]. Even some presumably positive events, such as the Oscars, were found to be capable of generating increased negative sentiment [Thelwall, Buckley and Paltoglou, 2011]. Given these findings, it was not surprising that the two neutrally toned nuclear policy events (i.e., the releases of NRC and ANS reports) did not trigger much discussion on Twitter in that no discernible increases in tweet volume followed the reports' releases. Despite the advantages of Twitter for dispersing information, it may play a limited role in elevating public awareness of relatively neutral and purely informative reports.

As the Fukushima faded from prominence in the news cycle, Twitter users increasingly expressed neutral opinions about nuclear power. One possible mechanism would be the fact that the 140 characters might encourage people to

prioritize a neutral description over an opinioned one [Binder, 2012]. More importantly, our study finds that the neutral opinions expressed on Twitter were primarily related to environment, health, and safety concerns. Overall, the environmental and health risk of nuclear technology is of Twitter users' primary concern, which became particularly salient after the Fukushima Daiichi accident. Although mass media coverage of Fukushima faded rapidly as other topics took precedence [Friedman, 2011], the accident itself altered the thematic focus of the nuclear discussions on Twitter over the long run. While economic and business-related concerns dominated the discussion about nuclear power on Twitter between December 2010 and July 2011, a greater proportion of tweets discussed EHS-related issues thereafter. The thematic shift of online discourse offers unique insights into the frames applied by concerned publics when discussing nuclear power. Any public outreach efforts aiming to enhance public understanding of nuclear power should address the nuance in concerns about nuclear technology's environmental and health effects.

Community-based Discussions of nuclear on twitter

Geographic proximity to the Fukushima accident was closely related to the amount of tweets users posted about nuclear power. The closer people lived to Japan, the more frequently they would discuss nuclear power on Twitter. However, we did not find a significant relationship between the volume of local Twitter discussions and the number of nuclear power plants within the U.S. state where the tweets originated. These findings prevented us from making explicit conclusions about whether citizens' concerns about the safety of local nuclear facilities were roused by the Fukushima accident.

Inspired by earlier studies on the structure of Twitter networks, we assumed that citizens living close to Japan would turn to Twitter, among other online platforms, to deliberate and exchange views about the potential radiation transported from the accident site. For instance, as Reuters reported in July 2011, members of local communities had suspected that radiation from Fukushima nuclear power plant had caused massive deaths and illness of seals in Alaska [Reuters, 2011]. Although scientists quickly ruled out the possibility, misinformation about sickened seals and transported radiation has been continuously tweeted and blogged until late 2012.

To be sure, Twitter presents a public forum for individuals to connect with members of their geographic community. However, the informality of tweeting may constrain the quality and accuracy of information circulated on the platform. Caution should be used when utilizing Twitter and other informal online services to retrieve and disperse information about local issues, considering that offline discussions may also be occurring that supplements or qualifies online sharing. Further studies need to scrutinize the quality of Twitter content and examine how it might influence the climate of opinion at the local level.

Operating as a real-time information network, Twitter has been widely adopted by policymakers and legislators for dispersing information and reaching out the general citizens [Golbeck, Grimes and Rogers, 2010]. Beyond its function as a tool for self-promotion, Twitter can also serve as a constantly updated resource for public expression in response to high profile events. Our study can be seen as an example for how analysis of the content of social media may inform policymakers

and other stakeholders about public opinion and citizens' underlying concerns related to policy issues.

In addition to reflecting spontaneous and trending opinions, Twitter, along with many other social media tools, allows policymakers and crisis managers to understand the concerns of a group of informed citizens who are well engaged in a given issue (known as "issue publics") [Converse, 1964; Price et al., 2006]. Issue publics play an important role in policy reform, in part due to their strong motivations to voice their opinions and mobilize their peers for social change [Price et al., 2006]. However, identifying issue publics can be difficult, as can tapping into their issue-related concerns. In the context of this study, it turns out that Twitter is a useful source for a convenience sample of issue publics concerned about science post a high-profile event. As shown in our results, Twitter is used by a group of concerned citizens living in close geographic proximity at the time of the Fukushima accident. Immediately and months after the accident, they were likely to express their concerns about the environmental and health implications of nuclear power, and particularly those linked to the possible transmission of pollution from Japan. Previous studies have examined how Twitter is used by networked publics to spread information in times of social and political crisis, our study is one of few studies that investigate how geographically bounded communities might express their concerns related to such events.

Twitter allows people who share common interests to connect and communicate efficiently. For institutional users (e.g., governmental agencies and regulatory organizations) who intend to leverage this tool to gain visibility and promote their own agendas, Twitter is a venue that can be used to gauge the candid opinions of concerned citizens and involved social groups. Therefore, an understanding of Twitter discourse allows policymakers to discursively frame their messages to address the primary concerns of issue publics, either in the wake of a focusing event or in general outreach efforts. More importantly, if broad engagement with all sections of the public in governance of energy issues is among policymakers' goals, understanding of public communication processes is a priority. Future studies should integrate these findings and further examine how emerging communication tools are being used for mobilizing groups and pursuing policy changes.

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