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How citizens engage with the social media presence of climate authorities: the case of five Brazilian cities

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Citizen-government communication is essential in preparedness and adaptation to climate events. Local-level government authorities have sought to communicate via social media, but little is known about their communication strategies and citizens' participation in replying to their publications. This study draws on conceptual frameworks for Social Media Presence and Human Engagement to establish behavioural modelling and topic modelling approaches for assessing citizen-authority communication from a long-term perspective. Empirical analyses focus on official government authorities for the Brazilian cities of São Paulo, Rio de Janeiro, Belo Horizonte, Porto Alegre and Belém, which cover over 25 million people and 500 thousand followers on the X platform (former Twitter). Analyses are based on 10.2 thousand authorities' publications and their 5.5 thousand received replies from 2.6 thousand people over one year. Findings show that authorities use periodic passive posting, providing meteorological, hydrological, and geological alerts, forecasts, and momentary weather updates. Citizen engagement is short-term, providing corrections, additions, and updates but not connecting weather events with climate change. Practice-oriented implications concern the adequacy of social media for providing citizens awareness, keeping them updated, and building their trust in authorities over climate event developments.

INTRODUCTION

Local-level climate authorities are essential actors in climate governance[1]. They are established in cities, such as city hall departments or sectors, and form the lowest tier of employees that are closest to the population, as compared to the climate authorities established at the state or country level. Local-level climate authorities seek to reduce vulnerability and build climate resilience by implementing preparedness and adaptation actions[2–7]. Preparedness actions are efforts taken in advance to ensure an effective response to the impact of climate risks, such as warning the population about upcoming climate events and how to stay safe[3,8]. Adaptation actions are measures to adjust to actual or expected climate change and its effects[4,9,10], such as monitoring and removing houses from areas expected to become susceptible to flood. Citizen-government communication is essential in climate adaptation and preparedness for climate events.

Internet services allow local climate authorities to provide citizens with weather and climate information at low cost, bypassing traditional media outlets[3]. For instance, authorities have sought to communicate via social platforms like X (which was called Twitter before July 2023[11]), Facebook, Mastodon and Telegram. Social media platforms are increasingly essential for information sharing[12–14]. They interconnect large crowds of people, allowing for communication and information dissemination. Weather and climate researchers have relied on social media data to analyse people's perceptions and concerns about climate change[15–21]. Worldwide climate organisations, such as the World Meteorological Organisation, the United Nations Framework Convention on Climate Change, and the Intergovernmental Panel on Climate Change, have relied on social media for public communications. Local-level climate authorities can also use social media to communicate with citizens[22–24].

Despite the use and potential of social media platforms in preparedness activities and in spreading information about adaptation action, studies are needed to investigate what type of communications climate authorities have used in social media and how citizens behave when interacting with climate authorities on social media. Knowledge of these factors based on practical experience is relevant to understanding the characteristics of this type of citizen-authority communication. Because climate change is an unfolding phenomenon that is studied while actions are taken, studies have highlighted the need to analyse evidence from practical experiences[4] and consider behavioural data that allow for identifying perceptions that can support the process of policy design, communication, and information management[25]. Evidence about how citizen-authority communication is taking place can help to improve preparedness activities, citizen awareness about climate event risks, and inform adaptation actions.

This study draws on conceptual frameworks for Social Media Presence[22,26,27] and Human Engagement[28,29] to understand the characteristics of social media publications from local-level climate authorities and citizen behaviour in replying to their publications. These frameworks are established in the literature on social media and human behaviour when participating through technology. The Social Media Presence framework stands for the process of publishing content tailored to the interests and needs of the target audience, gaining attention and building connections[22,26,27]. This study seeks authorities' publication patterns that can reveal their intent in designing the social media presence. A publication has a structure characterised by the set of words present in it, and a publication pattern can be found when clustering together many publications with similar structures. The Human Engagement framework, in turn, focuses on assessing human behaviour when self-investing personal resources in an activity, including skills, time, and social abilities[28,29]. This

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framework is used to characterise citizen behaviour in interacting with a climate authority. It covers the frequency and recurrence of participation (quantitative analysis) and the content communicated during the participation (qualitative analysis)[29,30]. The content may contain hints of the motives and objectives driving participation.

Considering the Social Media Presence and Human Engagement lens, this study establishes a behavioural modelling, machine learning and topic modelling approach to derive climate authorities' social media presence and citizen engagement modes from social media platform data. In doing so, this study seeks to answer two research questions: *(1) What publication patterns emerge when local-government authorities communicate to the citizens through social media publications?* and *(2) How do citizens respond to authorities' publications?* By answering these questions, besides reducing the lack of studies on the nature of citizen-authority communication, this study provides evidence for practice-oriented social media communication activities. Authorities seeking to use social media as a communication channel need evidence of previous experiences with social media usage, challenges and new opportunities arising from them.

Empirical studies are conducted in the context of local-level climate authorities for five Brazilian cities: São Paulo, Belo Horizonte, Rio de Janeiro, Porto Alegre, and Belém. Three characteristics make these cities suitable and relevant for this study. *First*, they are important Brazilian cities located in different regions of the country and cover a large population (over 25 million inhabitants together). The large population of these cities make it challenging for climate authorities to communicate climate information in real-time and use a language understandable to all citizens regardless of their neighbourhood. *Second*, these cities have different climates and have been subject to extreme weather events, including heat waves, cold waves, heavy rain, and storms, which cause devastating impacts on infrastructure and loss of human lives. *Third*, authorities of the cities are active on social media. On average, they have been using the X social media platform for seven years, with Rio de Janeiro joining first (2009) and Belém joining most recently (2021). They bring together more than 500 thousand followers. These characteristics make these cities suitable for this study of assessing authority's social media presence and citizens' engagement. For this study, the climate authority of each of the five cities is analysed for one year, from 17 July 2021 until 16 July 2022. In this period, they made 10.2 thousand publications and received 5.5 thousand replies from 2.6 thousand citizens.

This study contributes to filling three types of gaps in climate studies using social media data: methodological gap, practical-knowledge gap, and population gap. The *methodological gap* arises because the method employed by previous climate studies on social media limits their analysis to messages posted during climate events lasting a few days or weeks[23,31–33] or containing specific hashtags[16–21], falling short in assessing the diversity of messages on citizen-authority routine communication in the long term. To fill this gap, all messages posted by the authorities and citizens' replies over a year are analysed in this study. The *population gap* refers to the Brazilian cities not sufficiently represented in the previous studies, which focus mainly on cities in Europe and the United States[23,31,33–35]. Social media data associated with the five cities addressed in this study have been little studied. Finally, the *practical-knowledge gap* concerns the need to catalyse learning from practical experiences[4]. This study addresses this gap by catalysing learning from one year of authority-citizen communication practice. While there are efforts regarding the communication strategy employed by communicators[35–38], citizen interaction in response to such communication is little known. By filling these gaps, this study provides practitioners and academics with new insights into the suitability of using social media to raise awareness, keep citizens updated, and build trust in climate authorities during climate events.

In the remainder of this paper, before presenting the results and discussions, a brief background on the conceptual frameworks is provided, and the methods derived from these frameworks are detailed.

BACKGROUND
First, this section provides a background on conceptual frameworks covering the subjects of climate change, social media presence and citizens' engagement. Then, it discusses weather and climate studies using social media data.

Climate preparedness, adaptation, and resilience
Local-level climate authorities have focused on preparedness, adaptation, and resilience efforts to reduce loss of human life, public safety threats, and public service disruptions[5,6,39]. Climate change adaptation, mitigation, and resilience are three concepts for addressing climate change[5,7,9,40]. Mitigation actions focus on reducing the emissions of greenhouse gasses to limit the extent of climate change[40]. Adaptation actions focus on adjusting natural or human systems to cope with the impacts of climate change[4,9,10]. They are part and parcel of comprehensive risk management[41]. Resilience is the goal, meaning a system or community that can withstand and recover from climate change impacts[8]. Resilience and adaptation are essential to cope with the expected effects of climate change that are already underway, those not stopped by mitigation. Studies have shown political initiatives to implement adaptation actions[2,10,39]. These actions can be proactive, occurring before the impacts of climate change are seen, or reactive, occurring in response to an existing impact or stimulus. Adaptation actions happen in the face of multiple stimuli, going beyond climate change. Extreme events faced by local authorities have worked as important adaptation stimuli[39].

When looking to improve climate resilience, local authorities put into place measures to reduce the degree of exposure to dangerous hazards and to increase populations' ability to cope with or recover from the consequences of disasters. Many interventions can take place to build climate resilience[2,40], including (1) climate risk and vulnerability assessments, disclosure, and monitoring and (2) preparedness by early warning systems and emergency response. The dynamic of information sharing is crucial in preparing for climate events. People increasingly use the Internet to search for information about weather events and ways to prepare for them[3]. People's behaviour can be active or passive depending on how they access the information. Newspaper, radio, or television are passive sources, while using the Internet to obtain hazard information is a more active behaviour. Passive behaviour is not a significant predictor of preventive action, and active information-seeking, like the one on Internet services, is an initial phase of hazard adjustment[3].

Both the actions of disclosure of information by authorities and seeking information by citizens can have relevance in preparedness, adaptability, and resilience in the long term[40]. Because climate change is an unfolding phenomenon, the citizen-authority relationship is practice-oriented, developing as extreme events occur. Due to this practical dimension, researchers have highlighted an openness for research to accompany the implementation of adaptation plans, catalyse learning from the results of practice, and scale up adaptation efforts based on case study experiences[4]. From this perspective, the present study offers a characterisation of the social media activities of climate authorities in five Brazilian cities. The study focuses on citizen-authority communication, considering both the proactivity of the authority in publishing information through social media and the proactivity of citizens in replying to their publications.

What is social media presence?

Social media platforms allow climate authorities to communicate directly with citizens in real-time as climate events unfold, but such communication requires clear goals and formats[26,27,36,38]. Communications carried out on social media can be analysed in light of the concept of social media presence. The concept of *social media presence* stands for having a profile (or account) on a social media platform, creating content tailored to the interests and needs of the target audience, gaining attention and building trust with such an audience[26,27]. Using online social media platforms requires the design of the communication to reach its goals following social media language[12,13,42], which includes short and focused text, mentions, and hashtags. Local-level climate authorities can construct their social media presence to achieve their target audience and be perceived as a credible information source[43,44]. In addition to the type of information communicated, various communication and posting behaviours can be employed in creating a social media presence.

Communication strategies can be broadly classified into single-loop or double-loop[24]. *Single-loop communication* means one can post information, but there is no way for someone to reply. *Double-loop communication*, in turn, takes place in two directions: one can post information, and others can publish a reply to it. Social media platforms like X, Mastodon and Telegram Channel implement double-loop communication by default. Still, they can be turned to single-loop communication when the user turns off the reply feature. The single-loop strategy prompts one-way communications from the authority to the public. The double-loop strategy offers more 'consultative' and 'participatory' forms of two-way communication.

Publication strategies can be broadly classified into passive or active[22] depending on whether they ask for a reply from people. *Passive publications* merely pass on information, announcements, and greetings but do not encourage responses. *Active publications*, in turn, prompted the public to initiate communication by asking for a task execution of feedback[45] via the comment box or asking them to use the 'links' in the publications.

What is citizen engagement?

Technology-mediated participation, such as via social media platforms, can be framed in the conceptual framework of human engagement[28]. Engaging means self-investing personal resources in an activity. Resources include skills, physical strength, time, and social abilities. When interacting with authorities, citizen engagement can also mean providing feedback and practical solutions for socially relevant issues[46] and co-producing public services[47]. The engagement process comprises four stages: point of engagement, period of sustained engagement, disengagement, and re-engagement. The *point of engagement* is when the human performs the first participation action, e.g., posting the first reply to a publication. It is followed by a *period of sustained engagement*, which is continuous and uninterrupted participation. *Disengagement* occurs when the period of sustained engagement ends. *Re-engagement* is a new engagement cycle composed of the three stages mentioned above. Several factors influence each stage's (re)occurrence and duration.

Theoretical lenses posit that psychological factors determine nonengagement and drive engagement stages[28]. Studies have investigated factors that affect individuals' likelihood to engage in a wide range of climate actions[48,49]. Such factors are associated with people's climate change beliefs, values, and emotions; for example, biospheric values provide a strong motivational base for consistent climate actions[50]. Assessing psychological factors behind people's participation in replying to the authority includes asking why a person decided to post a reply to an authority publication. The content or message produced during the

participation usually has hints about the motives and aims driving participation[22,24,45].

The stages of engagement can be quantitatively observed by the degree and duration[29] of participation. The *degree of engagement* is the intensity or number of actions citizens perform during the engagement period, e.g., the number of times the citizen replies to a publication. The *duration of the engagement* period can be short-term or long-term. Short-term engagement is characterised by only one engagement cycle, defined as "*transient*," while long-term engagement includes re-engagement cycles over time, indicating a "*regular*" behaviour[29,30].

Transient and regular behaviours are framed in the context of modes of engagement. In online systems, there is a gradation or inequality in the degree and duration of people's engagement[30,51,52]. Many people just watch without acting, such as posting a reply. They are often referred to as "lurkers"[53]. A long-tail distribution of engagement is observed among those who perform some action[30,53], indicating that few people perform many actions, and many people perform few actions. In this context, the concepts of transient and regular engagements originate from the volunteering literature[29,54,55], given the nature of participating in Internet services without willing a financial benefit. These concepts are important to distinguish between sporadic and ongoing (lasting) engagement. *Transient engagement* is occasional "helping" behaviour with no intention of repeating. In contrast, *regular engagement* is associated with ongoing engagement based on an implicit or explicit commitment to repeat when needed[54].

In the climate event context, using the Internet to obtain hazard information is already a more active behaviour than using passive sources such as radio or television[3]. Among those who use internet services, such as social media platforms, and perform some action, it is essential to distinguish between transient and regular ones. Given the gradual nature of engagement, regulars can be expected to have an elevated level of involvement with climate information.

Climate studies using social media data

Studies on weather and climate have analysed short-term interactions on social media by concentrating on single weather events. They found evidence that the X (called Twitter at the time of the studies) platform can support authorities in communicating risk[23] and group interaction[31,32] during specific events, such as heavy snow, riots, and floods. Interactions between news media, private organisations, emergency agencies, and the public were also observed on the X platform during hurricanes[32].

Studies on people's behaviour and perception on social media are based on hashtags or "terms," which are words used for searching for messages on the X platform. Analysis of messages containing "climate change," "#climatechange," "global warming," and "#globalwarming" shows that people are influenced by information spread by competent authorities[16]. Analysis of messages containing the terms "climate change" and "global warming" shows that citizens recognise weather anomalies and connect anomalies with climate change[17]. Messages with the "climate" word are posted predominantly by activists and show increased sentiment due to a book release, the winner of a green ideas contest, or a plea to a political figure[18]. Compared to the "climate change" term, the "global warming" term has been perceived as more negative[19]. Studies in Brazil show political activity during climate conferences[20] and call for national political actions[21].

These studies on climate using social media data elucidate general perceptions and opinions emerging on social media platforms. However, they still lack information on daily citizen-authority communication beyond single climate events and term-based data collection. To this end, emphasis needs to be placed
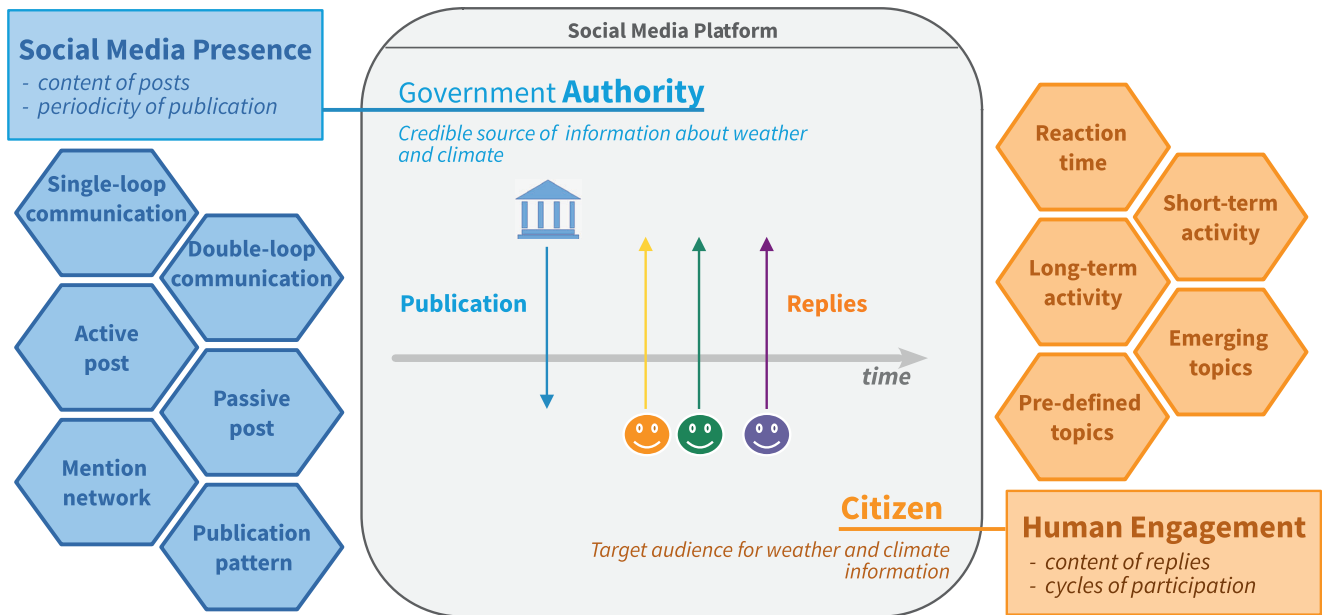
Fig. 1 Elements of social media presence and citizen engagement. Authority publications and citizen replies allow for characterising social media presence and engagement over time. Social media presence characterisation encompasses the periodicity of publication and content of posts, including single-loop communication, double-loop communication, active posts, passive posts, mention network and publication pattern. Human engagement characterisation encompasses cycles of participation and content of replies, including reaction time, short-term activity, long-term activity, pre-defined topic analysis and emerging topics analysis.

on people. In this study, all messages posted by the authority and citizens' replies over a year are analysed instead of messages containing specific terms and posted widely on the platform. Long-term interaction is considered by going beyond single events and seasonal periods, covering the entire year. Thus, this study follows the evolution of authority posting behaviour and citizen replying behaviour when developing awareness of climate risk.

METHODS
The methods employed in this study are based on Human Engagement[28,29] and Social Media Presence frameworks[24,26,27]. The elements of social media presence and citizen engagement are summarised in Fig. 1 and described in this section. Overall, the methods consider the typical dynamic of real-world social media platforms. This kind of platform allows authorities to publish textual content and citizens to reply to such publications. A *publication* usually contains information, including text data, mentions that link to other social media users, and audio-visual data. A *reply* includes all attributes of a publication, but it is linked to a previous publication. Each publication and reply contain a unique identifier of the user who published it and the date and time it was published. Considering this social media dynamic, the following subsection details (1) the method employed for characterising authorities' social media presence, (2) the method employed for characterising citizen engagement, and (3) the method used for selecting the Brazilian cities and collecting their social media data for the empirical case study.

Method for characterising social media presence
The social media presence analysis focuses on the content and periodicity of authority posts (Fig. 1). Emphasis is placed on when the authority publishes content and what it communicates by seeking recurring behaviours in terms of single-loop communication, double-loop communication, active post, passive post, mention network, and publication pattern. References in authority publications indicate what is being expressed. A reference is a

specific type of information within the authority publication. Reference to users (shown using the @ sign) is "mention," which comprises a *mention network*. It can reveal if the authority is calling the attention of citizens or other authorities like transit services.

Groups of publications with similar sets of words (textual structures) inform what the authority is expressing (publication patterns). A clustering approach is used to find groups of publications. Given a set of publications from the authority, the clustering seeks to put similar publications together. It is done in three steps: (1) pre-processing and cleaning the text message[56] ; (2) checking clustering structure and best number of clusters[29,57,58]; and (3) finding and interpreting the obtained clusters as publication patterns[59,60]. These three steps are detailed in the following.

Step 1: Pre-processing and cleaning the text message. Preprocessing consists of employing natural language processing to keep only one occurrence of repeated words in the message and to filter out numbers and stop-words, which are too frequent and semantically neutral words[56]. The filtering avoids artificial similarity among publications caused by the stop-words and superficial structure dissimilarity caused by numbers.

Step 2: Checking clustering structure and best number of clusters. To check the clustering structure and find the best number of clusters (k), k is varied from 1 to 20, and the Average Silhouette Width[29,58] and Within-Cluster Sum of Squares are measured. They also allow for identifying the suitable number of cluster parameters for the K-means algorithm. The Average Silhouette width (s) can be interpreted considering the following empirical rule[57]: strong clustering structure ($0.71 \leq s \leq 1.00$), reasonable structure ($0.51 \leq s \leq 0.70$); the structure is weak and could be artificial and additional methods of analysis are tried out ($0.26 \leq s \leq 0.50$); and, no substantial structure ($s \leq 0.25$). The within-cluster sum of squares (w) is used as an additional assessment; it measures the variability of publications within each cluster. The best k is the one in which the gain in reducing w is no longer worth the cost of increasing k. It is the "knee of a curve" or "elbow" method.

Step 3: Finding and interpreting centres as publication patterns. If a clustering structure exists, the K-means++ algorithm[59] generates the initial centroids for K-means. The K-means clustering, set to use the Jaccard Similarity Measure[60], clusters similar publications. The resulting centres are then analysed. The centres are authority publications with the lowest sum of the distance of the other publications in the same cluster. The centre represents the whole cluster, so it is a "publication pattern." This clustering approach allows for checking the existence and unveiling templates of recurrent publication patterns used by each authority to construct its social media presence.

Method for characterising citizen engagement

The analysis of citizen engagement quantitatively assesses how often a citizen publishes a reply and qualitatively assesses what is expressed in replies. *Quantitative* analysis of engagement is the analysis of short- and long-term engagement. In contrast, *qualitative* analysis of engagement is the analysis of the content of replies produced by citizens during participation, which is operationalised as analysing topics in the text of citizens' replies.

To assess short- and long-term engagement, citizen replying behaviour is observed over time. The degree and duration of engagement are analysed by considering the reaction time, activity ratio, relative activity duration and probability of activity duration metrics. The *reaction time* metric is the time elapsed between the authority's publication and the citizen's reply. It measures how long it takes to start the point of engagement or re-engagement. The 24 h activity is measured to distinguish transient and regular behaviour[30]. Citizens who reply to posts only within 24 h and never reply again are classified as transient. Citizens whose reply activity goes beyond 24 h are classified as regulars. For regular citizens, the *relative activity duration* metric[29] measures the proportion a/b, where a is the amount of time elapsed between citizens' first and last reply to the authority, and b is the amount of time elapsed between the citizen's first reply to the authority and the posting time of last authority publication. Activity ratio, in turn, is the ratio of the number of days the citizens replied to the number of days the authority posted. Finally, the probability of activity duration is a survival analysis. It measures the likelihood of citizens keeping engaged at any specific time after their first engaged day, shown as a Kaplan–Meier curve[61].

The qualitative analysis of what is expressed in citizen replies is based on a pre-defined and emerging topics approach. It shows whether citizens discuss climate change (pre-defined) and what they are discussing (emerging). *Pre-defined topics analysis* is based on studies that have searched for the occurrence of specific climate-related topics in social media posts for a diversity of purposes[16,17,19]. Relevant to the present study, searching for terms can be employed to seek evidence on whether citizens associate specific climate events with climate change phenomena[17]. Thus, based on Kirilenko et al.[17] approach, the pre-defined topic analysis consists of searching, in citizen's replies, for the occurrence of "climate change" and "global warming" terms and their variants forms of regular text and hashtags, written in English and Portuguese. When occurrences are found, one can conclude that the citizen replying to the authority explicitly refers to something related to climate change.

Emerging topic analysis in citizens' replies seeks to identify typical topics using unsupervised Latent Dirichlet Allocation (LDA)[62]. It is probabilistic topic modelling in which a list of words is represented as a "topic," and documents are represented as containing collections of these topics. The analysis is carried out in four steps: (1) pre-processing and cleaning the text message[56,63]; (2) forming documents with the replies[62]; (3) assessing the quality of a set of topics and the best number of topics[64]; and (4) interpreting the topics as themes. These steps are detailed in the following paragraphs[65,66].

Step 1. Pre-processing and cleaning the text message. Processing citizens' replies is a different step than processing authorities' publications, as the objective is not to find structures in citizens' replies but topics. A word normalisation (stemming and lemmatisation methods[63]) phase is added to reduce words from inflectional and derivational forms to a common base form. Citizens' replies are also processed to keep only one occurrence of repeated words, filtering out numbers and stop-words and removing hashtags, links and emojis. At the end of the pre-processing step, each reply is a list of words.

Step 2: Forming documents with the replies. The LDA method seeks for topics in documents[62]. The document formation step consists of putting together replies to the same publication. Modelling the set of replies to a publication as a document allows for two essential requirements that would be compromised if each reply were modelled as a document: preserving the context of replies that refer to the same publication from the authority and having documents with a relevant number of words (>2) to carry out the topic analysis. Thus, each set of replies to each authority publication is a document; topics are sought in these documents.

Step 3: Assessing the quality of a set of topics and the best number of topics. To find the best number of topics, LDA is run over the set of documents in several scenarios, changing the number of topics to be identified from 2 to 10. In each scenario, the quality of a set of topics is evaluated considering the Coherence Score metric[64] that measures how interpretable the topics are to humans. On a scale of 0 to 1, the closer to 1, the higher the probability that the topics form coherent human-perceived themes supported by the set of documents where they are found. The midpoint of 0.5 is used as an indicative threshold if the found topics have sufficient coherence for a qualitative analysis and interpretations to be carried out on them. Thus, topics lack interpretability if the Coherence Score is below the threshold. Otherwise, if the Coherence Score exceeds the threshold, topics are subject to further qualitative analysis for validity and interpretation (Step 4). When varying the number of topics, many scenarios for each city can exhibit a coherence score higher than the threshold. The elbow approach is used to get the number of topics in which the gain in increasing the coherence score is no longer worth the cost of increasing the number of topics. The topics obtained are subjected to qualitative analysis in step 4. This process uses the coherence score as a preliminary step to get the best scenario to interpret LDA topics as themes.

Step 4: Interpreting the topics as themes. LDA analysis outputs a set of words representing each topic. A word can be present in multiple topics, but all topics differ in at least one word. When interpreting the topics as themes, emphasis is placed on words that differentiate one topic from another and on stable topics[65]. Suppose a word that differentiates two topics is semantically equivalent (e.g., the word "wrong" and the word "incorrect"). In that case, the two topics are grouped into one, and the two words are indicated (e.g., "wrong/incorrect") along with the other words. Otherwise, each one is interpreted separately. A Reflexive Thematic Analysis[66] is employed to interpret topics as themes. By following such an approach, the analysis consists of (1) interpreting the topic words as named themes, (2) reviewing theme names by checking in the replies' dataset whether the theme name captures citizens' intent in replies to authority publications, and (3) reviewing themes names by checking whether they preserve differences between different topics.

Method for selecting the Brazilian cities and collecting their climate and social media data

Brazilian law on disaster information and monitoring systems[67] enforces the responsibilities of national, state, and municipal authorities regarding climate change information, monitoring, and action in severe events. At the national level, the Instituto Nacional

de Meteorologia (Brazilian National Institute of Meteorology, INMET) is the Brazilian government agency responsible for monitoring, analysing, and forecasting weather and climate. It provides weather alerts to be used by the local-level municipal authorities. The competencies of the local-level authorities are established by law[67] and include "*to keep the population informed about risk areas and the occurrence of extreme events, as well as about prevention, alert protocols, and emergency actions in disaster circumstances*". Municipalities are autonomous in defining their weather and climate authorities. This study examines how they are fulfilling the keep-the-population-informed responsibility by using social media support. Although using social media for citizen-authority communication is not mandatory, it is strongly recommended by the United Nations and the Brazilian Government[68].

To select the cities for the study, in the first step, all cities that are capitals of the 26 states and the Federal District of Brazil were analysed regarding social media usage. They differ between having a specific social media account for the weather and climate authority or having a general account for the city, where all information is published, including health, leisure, entertainment, and climate conditions. The latter option is typical in cities with few climate events or small cities with smaller administrative structures. Given the objective of this study of focusing the analysis on weather and climate information, in the second step, only cities that maintain an account exclusive for climate and weather information are analysed. It led to eight cities. The account's first and last publication was observed in the third step. It showed that three of these cities did not publish information over the 6 months before the date the data collection was set to start (July 2021); they were considered not active. These steps end up with five cities that have an active and exclusive social media account for climate information, which are: Belo Horizonte, the capital of the state of Minas Gerais; Belém, the capital of the state of Pará; Rio de Janeiro, the capital of the state of Rio de Janeiro; Porto Alegre, the capital of the state of Rio Grande do Sul; and São Paulo, the capital of the state of São Paulo.

These cities are state capitals with large populations, located in different regions of Brazil, and active on the X platform. They cover climate conditions according to Köppen climate classification[69]: Porto Alegre with a humid subtropical climate (Cfa), Belém with a tropical rainforest climate (Af), and Belo Horizonte with a subtropical highland climate (Cwb), Rio de Janeiro with a tropical savanna (Aw) close to tropical monsoon climate (Am) and São Paulo with an oceanic/marine climate (Cfb). Part of the context of preparedness for climate events in these cities can be understood from the meteorological warnings issued to their regions. When a climate event is about to occur, INMET issues warning alerts to cities as part of its legal attribution. It follows the Common Alerting Protocol[70]. Meteorological warning data is collected from INMET between July 2021 and July 2022 to understand climate events occurring in the studied cities.

Authority publications and citizen replies are collected daily using the X platform's Application Programming Interface (API).

The collection of new publications by the authority consists of a list of recent tweets, each with a unique identifier, time, and text. Considering the unique tweet identifier, their replies are collected. Replies comprise time, text, and the replier's unique identifier. By focusing on authority-citizen communication, only authority publications, citizen replies to authority, and authority replies to citizens are collected; therefore, interactions between citizens are out of the scope of this work.

All authorities are observed during a time window that starts on day 0 and ends on day n. This work's observation window is one year long, beginning on 17 July 2021 (day 0) and ending on 16 July 2022 (day 364). Tweets posted by the authorities during the observation window were open to reply. The default Web interface of the X platform prioritises showing users the most recent tweets published by accounts they follow. Information sharing is considered a natural behaviour on social media platforms. The observation window starts in Brazil's first winter weeks of 2021 and ends in the same period in 2022, covering the year's four seasons. This period allows for collecting behavioural data during different weather conditions.

When processing data and reporting results in this observational study, the best guidelines for working with social media data are employed[71]. No sensitive information such as name, location or birthday data is collected. Only publications and replies of users that defined their publications as *public visibility* are collected via the API of the X platform. Thus, publications and replies are not from protected accounts and are not published only to be seen by the user's followers. By the terms of service of the X platform, when tweets and replies are posted publicly, they can be made available to third parties and used for research purposes[72]. This data collection approach meets users' privacy and fits the study goal of observing *public conversations* between citizens and local government climate authorities.

RESULTS

This section assesses authorities' social media presence and citizen engagement in five Brazilian cities: Belém, Belo Horizonte, Porto Alegre, São Paulo, and Rio de Janeiro. It first details the context of the Brazilian climate authorities. Then, it presents the empirical results.

Climate and social media context of the five cities

Climate authorities for the cities of São Paulo, Belo Horizonte, Rio de Janeiro, Porto Alegre, and Belém are active on social media. Table 1 summarises the major characteristics of the cities regarding social media usage and population. They bring together 500 thousand followers. All authorities' communications on the platform were observed daily for a year, beginning on 17 July 2021, and ending on 16 July 2022. A total of 10,229 tweets posted by the authority, and 5471 replies posted by citizens were collected. Authorities rarely retweet publications; they made only 78 retweets within one year.

Table 1. General information on the population of the cities of the monitored local-level government authorities and their usage of the X platform.

City name	Population	Brazilian region	Handle of the government authority on X	Date joined X	Nr. followers on X
Belo Horizonte	2,521,564	Southeast	@defesacivilbh	Sep. 2012	137,558
São Paulo	12,325,232	Southeast	@cge_sp	Mar. 2011	71,367
Rio de Janeiro	6,747,815	Southeast	@alertario	Nov. 2009	286,261
Porto Alegre	1,488,252	South	@defesacivilpoa	Sep. 2018	7164
Belém	1,499,641	North	@defesacivilbel	Jan. 2021	3338

Population for the year 2021 as estimated by the Brazilian Institute of Geography and Statistics (IBGE): https://cidades.ibge.gov.br/brasil/panorama
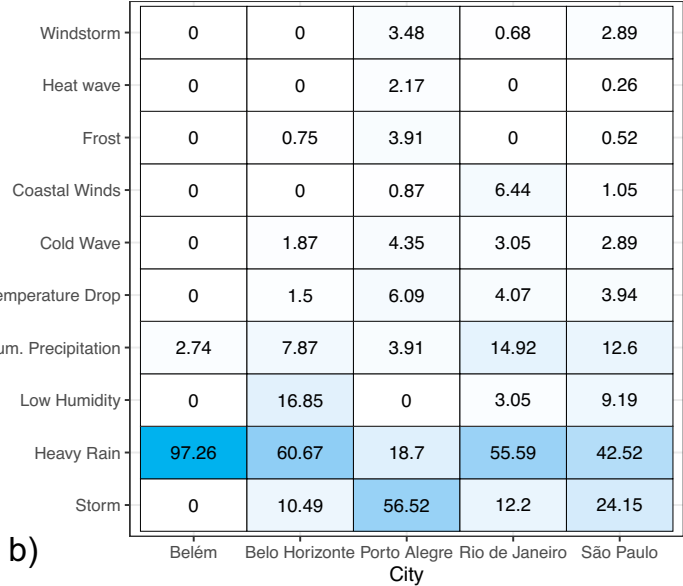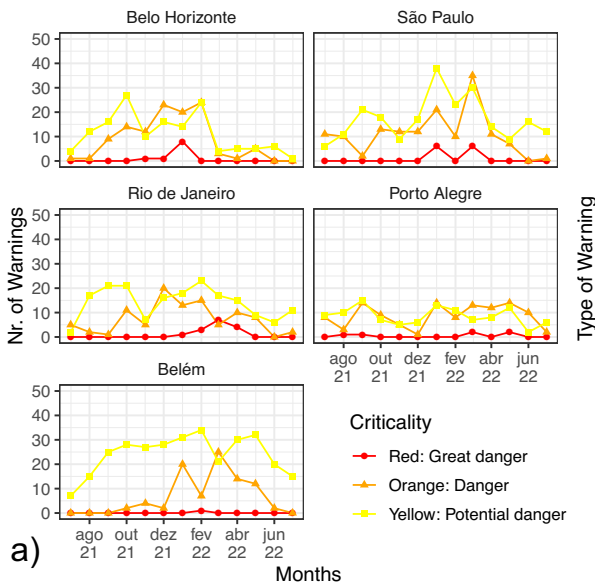Number of followers as of 17 July 2021.

Fig. 2   Meteorological warnings issued by the Brazilian National Institute of Meteorology (INMET). Data are from July 2021 to July 2022 for São Paulo, Belo Horizonte, Rio de Janeiro, Porto Alegre and Belém. **a** shows the monthly frequency of meteorological warnings categorised according to the severity defined by INMET. **b** shows the heat map showing the percentage of meteorological warnings categorised according to the type of climate event defined by INMET.

The cities have different climates and have been subject to severe weather events, including heat waves, cold waves, heavy rain, and storms. Figure 2 shows the frequency of meteorological warnings categorised according to the severity defined by INMET and the percentage of events by each type in the cities. Extreme event alerts are rare compared to moderate and severe events. Still, they occur notably in the rainy season (from December to April) in Belo Horizonte, São Paulo, and Rio de Janeiro. The type of meteorological event differs in the city set. For example, in Belém, the alerts fall into only two categories, most into the heavy rain category (97.26%). In contrast, in São Paulo, the alerts fall into 10 categories, with 42.52% falling in the heavy rain category. Storm alerts are the most common in Porto Alegre (56.52%), unlike the other cities.

Temporal dynamics of citizen-authority communication

The total number of publications, the number of unique people replying to publications and the number of replies daily per local government authority vary over time (Fig. 3). Unlike the other authorities, São Paulo exhibits a similar daily publication pattern over time, usually three publications per day and no publication on weekends. Days with bursts of activity occur regardless of the authority. Bursts are sharper in the metrics associated with citizen activity: the number of citizens and replies.

Days with bursts reveal citizen behaviour. For example, on 16 May 2022 (day 302), Porto Alegre's authority published an INMET Windstorm alert with the severity of the Great Danger with validity for the following two days. The alert states, "a great risk of damage to buildings, power cuts, falling trees and major disturbances in road transport." A conversation thread formed in reply to this publication. Citizens were concerned about children's classes, e.g., *"Why weren't classes cancelled? What about those who must walk a long way to school?"* Also, on 4 August 2021 (day 18), Belém's authority published *"INMET published yellow weather alert."* A conversation thread was formed by citizens asking for clarification, such as *"What does it mean?"* and authority explanations, such as *"Potential risk for heavy rain."*

Authority social media presence

The first question to be addressed regarding Social Media Presence is *what communication strategy do authorities employ?* Although social media is a two-way communication channel, it has been used by authorities mainly to spread information in a single-loop approach. The number of textual replies received by the authorities is 2656 in Belo Horizonte, 62 in São Paulo, 2602 in Rio de Janeiro, 89 in Porto Alegre, and 62 in Belém. Authorities rarely answered citizen replies. No answers are found from the São Paulo authority, while 10 are found from Belo Horizonte, 305 from Rio de Janeiro, 6 from Porto Alegre, and 6 from Belém.

Another evidence of one-way communication is the authority mention's network. São Paulo authority never uses mentions in their publications. All other authorities mention authorities but rarely mention citizens. The percentage of publications with mentions is as follows: 25.75% in Belo Horizonte, 5.61% in Rio de Janeiro, 8% in Porto Alegre, and 6.14% in Belém. The distribution of authorities' mentions (Fig. 4) shows that authorities mention other authorities (municipal and national) and rarely mention citizens.

Among the most mentioned accounts are other municipal authorities, including City Hall (*prefeiturabh, prefeiturabell, prefeitura_poa, prefeitura_rio*) and City Transit Service (*OfficialBhtrans, EPTC_POA, Operacoesrio, belemtransito*). A multi-level articulation can be seen when the city's authority mentions authorities at the state level (e.g., *defesacivilrs, Bombeiros_MG*) and the country level (e.g., *Inmet_, Marmilbr, fab_oficial, and decea_oficial*) of governance.

Linking the publication to trending topics is unusual. Rio de Janeiro is the authority that most uses hashtags, occurring in 5.61% of publications; hashtags appear in less than 1% of publications of other authorities.

The second question relevant in characterising Social Media Presence is: *do authorities employ standardised textual publication patterns?* The search for textual information patterns in the publication from local government authorities shows that content published by some authorities follows a standard structure. A Silhouette Width larger than 0.52 and a reduced Within-Cluster Sum of Squares are found in Belo Horizonte, Rio de Janeiro and Belém authorities (detailed information on Silhouette Width and
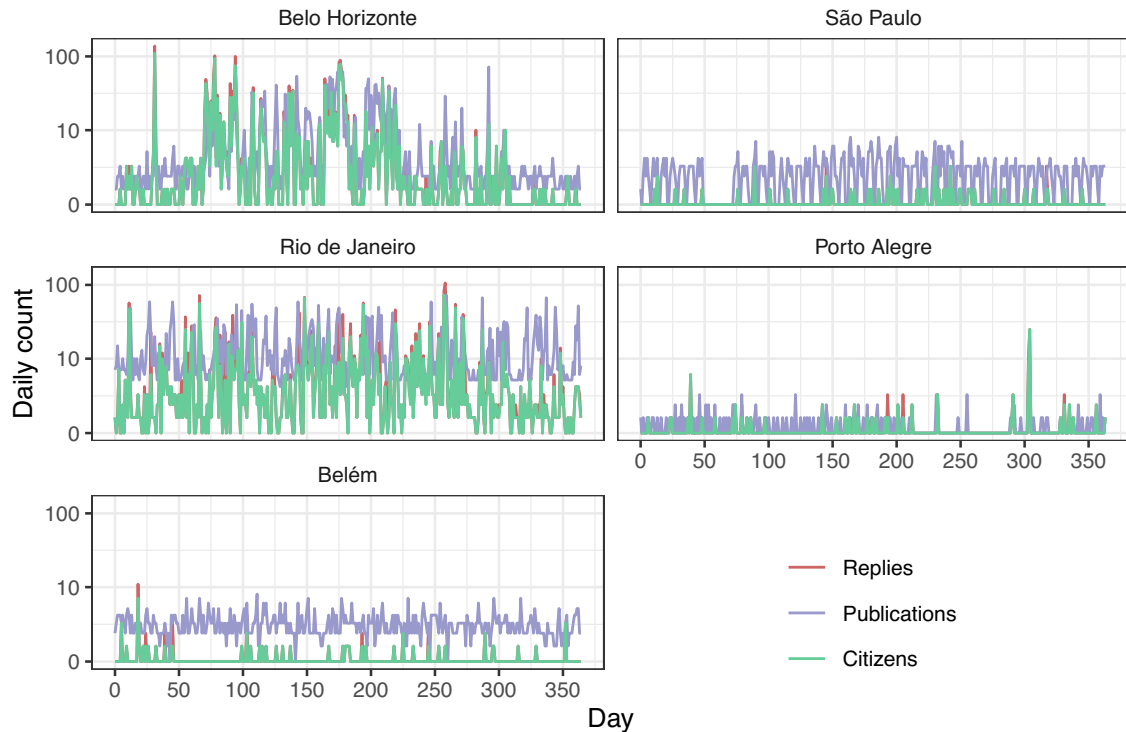
Fig. 3 Social media activity of climate authorities and replies from citizens over a year. On a daily basis, it shows the number of publications by the climate authority, the number of replies by citizens and the number of citizens replying to the climate authorities of the cities of São Paulo, Belo Horizonte, Rio de Janeiro, Porto Alegre and Belém. The horizontal axis is the day count, all beginning on 17 July 2021 (day 0) and ending on 16 July 2022 (day 364). The vertical axis is the value observed for the metric in the day (in logarithmic scale for better visualisation).

Within-Cluster Sum of Squares are available in Supplementary Note 1). This result indicates a reasonable or strong clustering structure in the publication data; hence, a clustering algorithm can find groups of similar publications. Each cluster can reveal a pattern of information the local government authority shares.

Finally, this analysis seeks to answer the following question: *what types of information do local government authorities publish to citizens, and are they active or passive publications?* For the 3 authorities in which Silhouette analysis indicates clustering tendency (Belo Horizonte, Rio de Janeiro and Belém), a deep analysis of the publications groups reveals the authority's communication pattern (Table 2). Each pattern is associated with a specific situation. Rain records alert is the most frequent theme in the publications from Belo Horizonte and Rio de Janeiro authorities. In Belém, the publications' most frequent and peculiar theme is the Tide Table. All authorities report weather forecasts. The identified publication patterns are *passive publications*, informative, and do not call for citizen interaction.

Citizen engagement

The first question to be answered regarding citizen engagement is: *how fast is citizen engagement with authorities' publication?* Citizens reply readily to authority's publications (Fig. 5). When a reply occurs, it is usually only a few minutes or hours after the authority's publication. It is a typical pattern in social networks where publications flow in users' timelines, and old information is rarely accessed. The publication of brief details on weather conditions at a specific time explains both the quick reply to new and rare replies to old publications. However, the authorities also publish information valid for a more extended period (e.g., long-lived alerts), such as a heavy rain alert for the next two days or the geologic risk during the coming days. The interaction period with

such publications is not associated with the validity period of its information.

Regarding the duration of activity, *do citizens exhibit short-term or long-term engagement?* Most citizens interacting with the authority exhibit a transient behaviour of reacting to a specific situation rather than exhibiting an ongoing (regular) interaction behaviour (Fig. 6). The distribution of participation rate for regular citizens is heavy tail, with most citizens showing a low participation rate. It indicates that even the regular citizens, who are more engaged than the transients, also show highly concentrated activity in a small group of citizens.

It is also relevant to ask: *how long does a long-term engagement last?* The duration of long-term engagement patterns is diverse (Fig. 7). Only a few citizens exhibit a relative activity duration closer to 1, the reference value for daily re-engagement after the first interaction with the authority. Regardless of the authority being analysed, the probability of engagement duration larger than 200 days is lower than 0.25. The likelihood of a citizen re-engaging in the interaction with the authority reduces as the time elapsed after the first interaction increases.

Finally, the citizen engagement analysis focuses on the content citizens produce during their participation by seeking to answer: *what do citizens express in their replies to authority's publications?* Topics can be found in citizens' replies to the authorities. After pre-processing and cleaning steps, the corpus of the resulting 4531 replies is analysed to find topics and interpret them as themes. The Coherence Score threshold of 0.5 is achieved in 4 out of 5 cities. As described in the Methods section, the threshold is the minimum required coherence to indicate that the topics may make sense to human beings and are qualified for further qualitative assessment and analysis. Besides the threshold, following the Elbow method, the analysed number of topics is the one up to which the gain in increasing the coherence score is worth the cost of increasing the number of topics. The results are
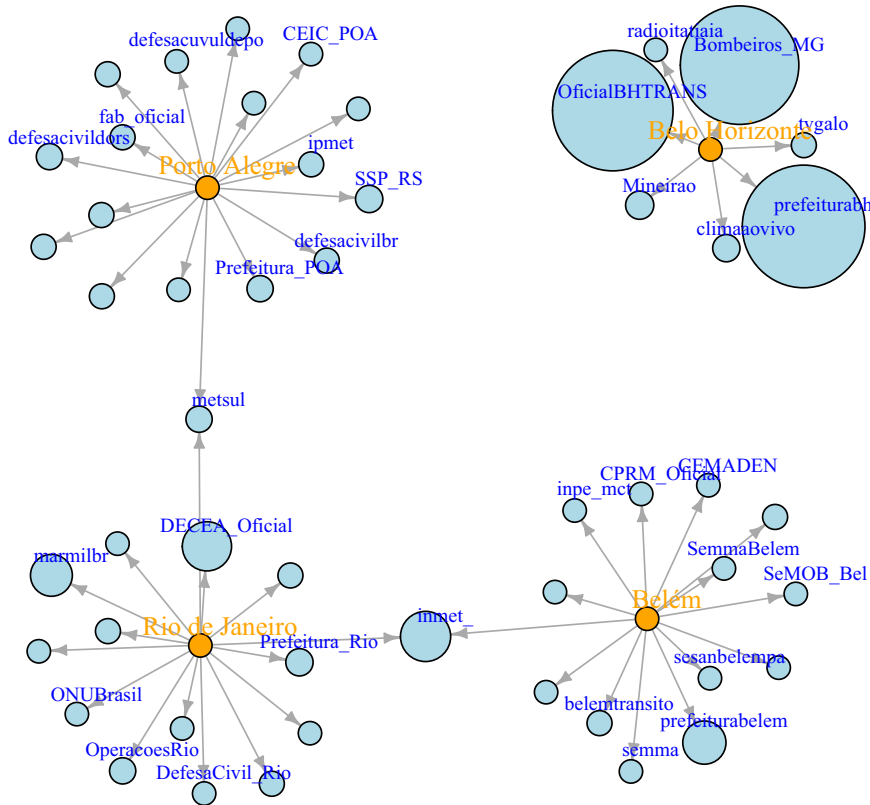
Fig. 4 Graph of mentions in publications from local government authorities. The Graph network shows the distribution of the number of times other social media accounts are mentioned in a publication from the climate authorities of the cities of Belo Horizonte, Rio de Janeiro, Porto Alegre and Belém. No mentions are found in São Paulo's authority publications. The larger the circumference, the larger the number of mentions. Labels are added to the mentioned government authorities.

Table 2. Weather and climate authority publication groups.

Cluster	Belo Horizonte	Rio de Janeiro	Belém
Geological risk alert	1.05%	-	-
Weather forecast	12.70%	39.13%	32.01%
Upcoming weather event alert (hours)	0.91%	-	-
Rain record update	64.29%	46.81%	-
Current weather information	15.92%	-	-
Long-lived Weather event alert (days)	5.13%	-	3.68%
Wind record update	-	14.06%	-
Technical inspection information	-	-	12.65%
Tide table information	-	-	40.14%
Phone and Newsletter information	-	-	11.52%
Sum	100%	100%	100%

K-means distribution of authority publications into clusters.

the following number of topics and respective coherence scores: 3 topics in Belo Horizonte (0.65), 3 topics in São Paulo (0.57), 3 topics in Rio de Janeiro (0.54), 6 topics in Belém (0.51).

Found topics are interpreted using a Reflexive Thematic Analysis considering the context in which they appear in citizens' replies to climate authorities. It allows for understanding what citizens are expressing and in which context. Table 3 shows the

final topics represented by top-4 words, named themes, and checkmarks mapping if the theme (line) is found in replies to the authority (column). Detailed analyses of the number of topics and coherence are available in Supplementary Note 2. The interpretation of topics as themes are as follows:

1. *Disagreeing with information about their locations*. The topic in this theme contains words of disagreement such as "no," "incorrect," or "wrong." Replies in this theme are mostly citizen efforts to call the authorities' attention to imprecision in the published information. For example: "The information is wrong; there is no rain here."
2. *Complementing the information with their locations*. The topic differs from others by the word "here" or the name of a location, typically a neighbourhood, but without words indicating disagreement. For example: "Here in Pampulha, it is raining heavily too." In this theme, citizens inform authorities about their locations not covered in the authority's post.
3. *Updating with current information*. The topics differ by the word "now" or "moment." It is an effort to update the information published by the authority. For example: "It was raining heavily, but now it has stopped."
4. *Informing about donation actions*. Citizens are taking advantage of the fact that people are reading the replies to publicise donation drive initiatives for needy people. The word "donation" is present in topics of this theme.
5. *Expressing thanks*. This theme represents replies with gratitude messages. Words like "thanks" and "gratitude" are indicators of this topic.

In the four authorities, citizens disagree and complement the authority's publication with information about their location.
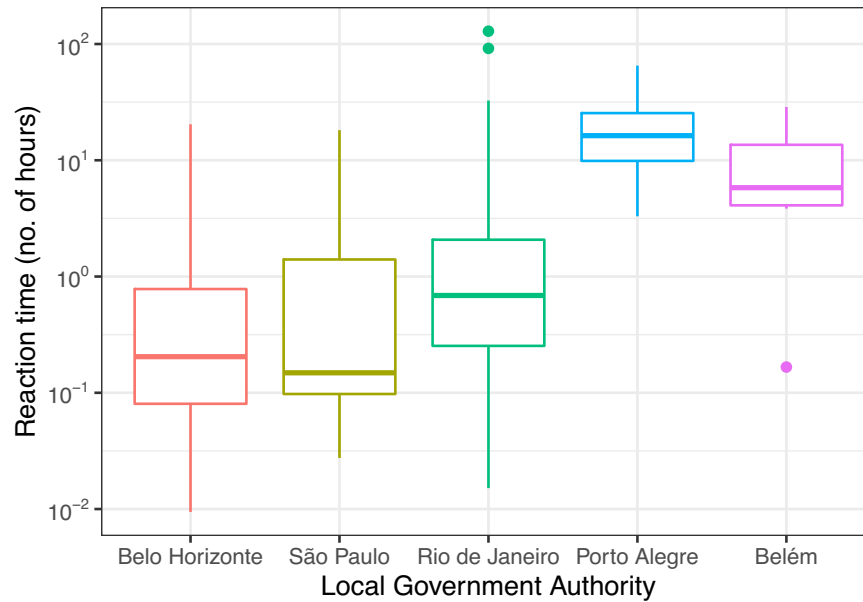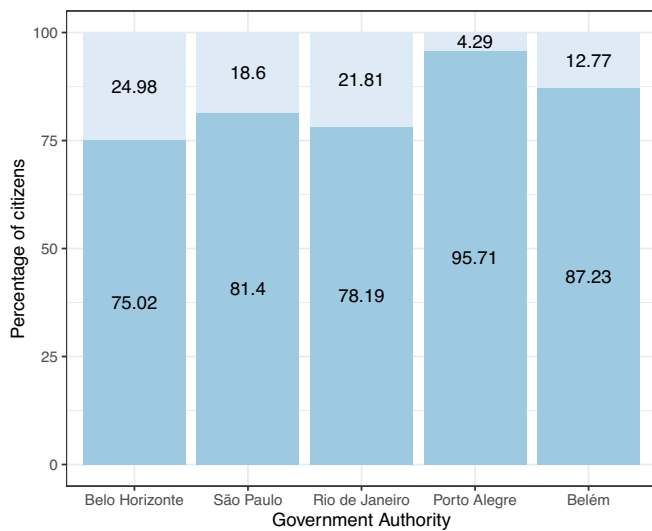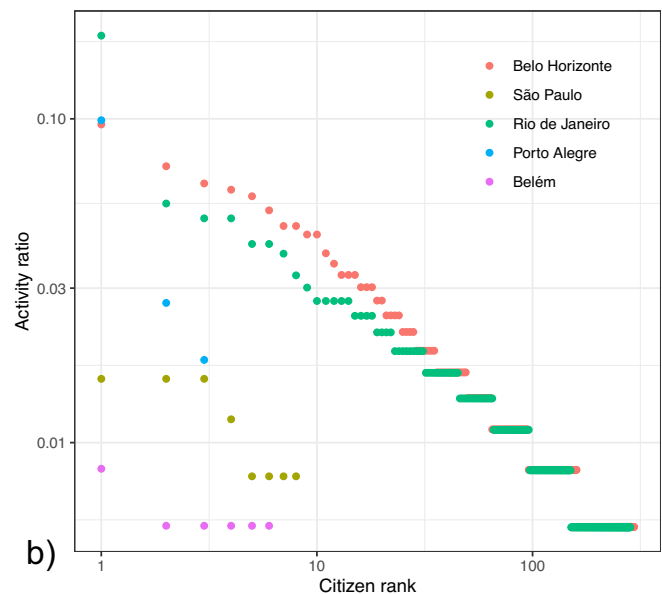
Fig. 5 Citizens' reaction time. The average citizen's reaction time distribution in replying to the climate authorities of São Paulo, Belo Horizonte, Rio de Janeiro, Porto Alegre and Belém. The reaction time is the amount of time (measured in hours) elapsed between a publication being made by the authority and citizens posting a reply to it. The vertical axis is in logarithmic scale for better visualisation.

Fig. 6 Regular and transient citizen engagement in replying to the climate authority. a shows the percentage of citizens exhibiting regular and transient engagement patterns. **b** shows the log-log analysis of the rank of citizens per activity ratio; each dot is a citizen, and only citizens exhibiting regular engagement are listed. Data are shown for the climate authorities of São Paulo, Belo Horizonte, Rio de Janeiro, Porto Alegre and Belém.

Providing an update with current information is also common in Belo Horizonte, Rio de Janeiro and Belém. Other themes are more specific in replies to some authorities. For example, the theme of citizens informing users about donation actions is only found in replies to Belem's authority.

DISCUSSIONS
This section deepens the analysis of the results and conclusions of this work. First, the results are analysed considering the context of the case studies and the existing literature. After that, the contribution and implications of the results are examined.

This study addresses what publication patterns emerge when local-government authorities communicate to the citizens through social media publications and how citizens respond to authorities' publications. Empirical analysis covers about 10 thousand authorities' publications and their 5 thousand received replies from 2 thousand people for one year. Publication patterns analysis uncovers how climate authorities build their social media presence for preparedness and climate adaptation activities. Overall, findings show that authorities use periodic passive posting, providing meteorological, hydrological, and geological alerts, forecasts, and momentary weather updates. Citizen replies analysis, in turn, uncovers how citizens engage with the
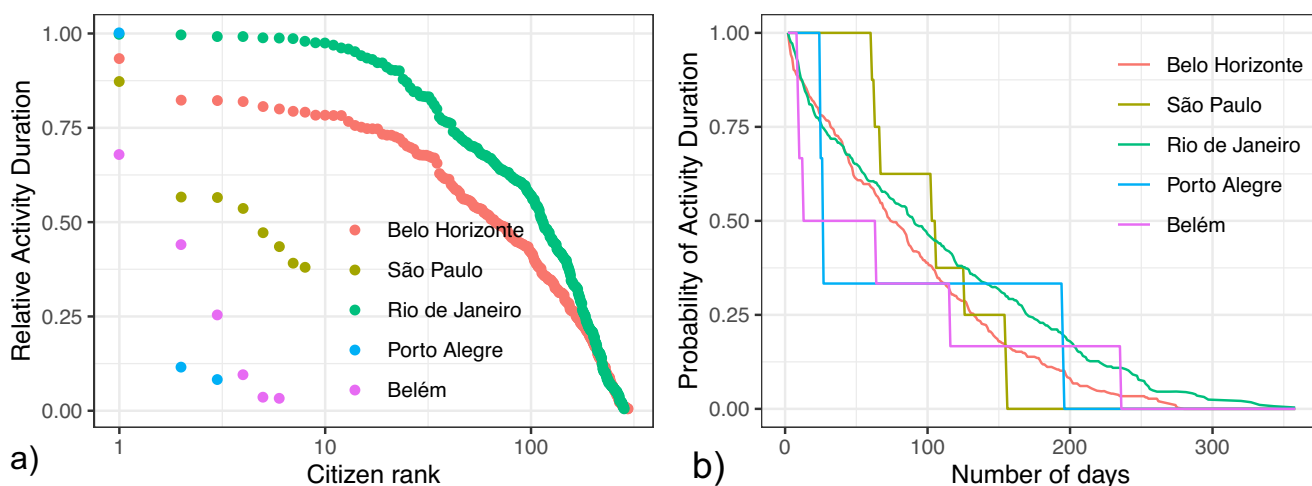
Fig. 7 Citizens' relative activity duration and probability of activity duration. a shows the relative activity duration per citizen rank; each citizen is represented as a dot. **b** shows the probability of activity duration per the number of days, depicted as a Kaplan–Meier curve. Data are shown for the climate authorities of São Paulo, Belo Horizonte, Rio de Janeiro, Porto Alegre and Belém.

Table 3. Topics identified by Latent Dirichlet Allocation (LDA) and their interpretation as themes found in citizen replies to climate authorities.

Themes (Topics with LDA top-4 words)	Belo Horizonte	São Paulo	Rio de Janeiro	Belém
Disagreeing with information about their locations (no/wrong, here, rain, wind)	X	X	X	X
Complementing the information with their locations (here/neighbourhood, rain, heavy, heat)	X	X	X	X
Updating with current information (now/moment, raining, heavy, heat)	X		X	X
Informing about donation actions (donate, go, look, spread)				X
Expressing thanks (gratitude, thanks, all, prevent)		X		X

information shared by the authority. Results show that citizen engagement is short-term, providing corrections, additions, and updates but not connecting weather events with climate change.

Since Web systems have been used to search[3] for weather information and climate authorities have been advised to use social media[67], authorities are expected to converge for structured communication and information on that channel over time. Findings from this study show that authorities build social media presence characterised by structured content type, mentions networks, and publication patterns. They use a periodic and passive posting in a one-way communications pattern, rarely replying to citizens, regardless of the double-loop communication nature of social media platforms. Their structured content covers events on weather alerts, weather forecasts, and geological risk updates. The option for one-way and standardised communications is sometimes associated with budgetary constraints[24] or lack of resources and time[38], given the operational effort for creating specific content "on the fly" and responding to each reply of a crowd of citizens through social media.

Citizens' engagement in replying to authorities is short-term, with a low probability of the engagement lasting more than a few days. The observation that most citizens are short-term engaged is not exclusive to the context of weather and climate local government authorities. A similar pattern of engagement is observed in other web-based socio-technical systems, such as Wikipedia[51], citizen science projects[30], and open-source software communities[52]. It fits well-known patterns on the internet, well documented as "participation inequality," 1% rule, or power-law distribution of participation. Since authorities' shared information has a strong connection with people's daily lives in their physical geographic space, this engagement is more likely to be higher than the engagement observed in activities not strongly

associated with the geographic area (such as the degree and duration of engagement observed in open-source projects).

Variations observed in social media presence among cities may be associated with the characteristics of risks they are coping with, considering the results of the national authority's data set of meteorological warnings. The social media presence created by the city of São Paulo diverges when one considers the non-formation of a network of mentions to other municipal authorities and the number of publications that vary little over time despite the variation in the number of meteorological alerts issued by the national authority over the year. Citizen engagement remains quite similar across cities regarding topics covered in replies, the probability of duration of the activity, and the occurrence of the most transient behaviour. The similarity suggests that citizen engagement characteristics are not tied to the specific publication pattern employed by the authorities. They are more likely to be associated with the type of information and human behaviour in Web systems[30,51,52].

Findings from this study show that citizens' replies do not directly connect local weather events with the global climate change phenomena. Previous studies highlight that people may refrain from entering a topic that can be controversial[73]. Citizens may need to gain knowledge of the general context of climate change or a view beyond the specific situation of their city[74,75]. Citizens' efforts focus on correcting or complementing authorities' information considering their "in-loco" view of the weather conditions. This behaviour of mentioning their location is connected to the concept of spatial psychological distance derived from the Construal level theory[76] and already considered in the context of climate change[77,78]. People tend to be more concerned with close spatial, temporal, social and hypothetical issues. The fact that citizen engagement is mostly short-term also

indicates that citizens reply to specific risk events reported by the authority rather than ongoing participation.

Although social media data are increasingly used to understand people's perceptions[16,17,21–24,31,32], studies on such data may not represent cities' populations. Only a small proportion of people actively use social media, and those who use it tend to be tech-savvy and young[13,14]. Using social media platforms frequently, as shown in this study, the local government authorities recognise their importance for sharing information with the citizens. Therefore, this study addresses the use of the platform by citizens and authorities without seeking generality beyond this domain. This study focuses on the context of cities, but there are also state/province, national and international organisations in multi-level governance of climate events. Local issues are removed at these higher levels of governance, but other factors, such as increased cultural and linguistic diversity, are added.

This study contributes to filling three types of gaps in the existing literature: methodological gap, practical-knowledge gap, and population gap. The methodological gap is filled by assessing climate-authority communication beyond periods of specific events or messages containing specific hashtags. The population gap is addressed by referring to social media activities of Brazilian cities that are not sufficiently represented in the previous studies. Finally, the practical-knowledge gap is filled by assessing the information produced in the professional behaviour of climate authorities seeking preparedness and community resilience. Findings from this practical-knowledge perspective answer the call for practice-based insights[4,25] and have implications for the suitability of social media platforms for (1) sharing weather preparedness information about specific areas of the city, (2) keeping citizens updated about the current situation during climate events, and (3) building trust between citizens and climate authorities seeking climate adaptation and community resilience. Reflections on these implications are detailed below.

Reflections on the suitability of social media for *sharing weather information about specific areas of the cities* are of great relevance. Current social media platforms need to consider the city areas or neighbourhoods when showing posts to users, which can lead citizens to receive an excess of irrelevant information during an extreme event. For example, Short Message Service[37] technology provided by some climate authorities, as currently implemented in Belo Horizonte, allows citizens to register the ZIP code so that only warnings involving that specific location are received. Because such a geographic delimitation does not occur on social media platforms, citizens experience the problem of receiving a considerable amount of information from geographic regions that they are not interested in. The bigger the city and the more weather events it experiences, the greater the problem. This problem can also impact citizen engagement. For example, topic analysis on citizen replies shows that citizens' comments are associated with what they see in their geographic region within the city. Thus, it is unlikely that citizens will have something to contribute to a publication about a climate event in locations they are not interested in. Therefore, in building the social media presence, it will be up to the authorities to identify which types of information apply to all city regions and that the social media platform would be the effective channel to disseminate.

Another necessary reflection of the obtained results is how authorities can *keep citizens updated about unfolding weather conditions and risks* using social media. The results of the authorities' social media presence and citizen engagement show an effort to update information during weather events. Authorities often publish bulletins updating rainfall, wind, and geological risk records. Citizens usually respond to these posts by correcting and complementing the information with what they observe in their region. However, it is unclear how often the authority should publish an update. Such a decision can generate several side effects. On the one hand, if the update takes too long, citizens are left with out-of-date information, which may compromise their preparedness to react to the weather event, or they may imagine that the authority is unaware of the current state. On the other hand, if the authority publishes updates more frequently, an overflow of posts (which currently approaches a hundred posts in a single day) can occur. Excessive publications from the authorities can compromise citizens' tracking and understanding of the evolving weather event. It is unclear if the social media platform can be used effectively in this context. Providing a website or app that stores the current state of the event and that citizens can access on demand could be more effective than relying on many publications on social media platforms. Perhaps authorities post it on social media because citizens are already on such platforms. This disassociation between the system being used and the system that would be the best to use reinforces that citizens' preferred systems do not necessarily align with those that best serve weather communication purposes, as previously reported by survey studies[36].

Findings from this study also trigger a reflection of the *dynamics of trust between citizens and climate authorities on social media*. The characterisation of citizen engagement sheds light on how citizens perceive the information shared by the authority, sometimes reporting inaccuracies. Authorities should pay attention to citizen engagement if they seek to improve the quality of their climate event forecast and publication patterns considering co-production. The duration of engagement and the degree of engagement suggest a citizen's desire to participate. For example, there is an opportunity to identify inaccuracies in authorities' estimates of weather situations by processing citizens' local reports as presented in their replies. Inaccuracies and complements reported by citizens in authority publications may also reveal the early stage of developing a mistrust that may compromise awareness of climate events. If the information is not understood or is imprecise (as the topic analysis results suggest), citizens cannot successfully prepare and adapt to upcoming weather events[79]. Over time, it may compromise citizens' trust in government authority. A deeper investigation of these dynamics is a promising avenue for future work focused on information credibility and its effects on climate preparedness and community resilience.

As a final remark, findings from this study can inform the *growing debate on how social media platforms are evolving and how it impacts their usefulness for citizens and climate authorities*. For example, the X platform has changed its design and management strategies[11] and has been highly criticised by climate change activists, leading some to abandon the platform[80]. A new restriction in the number of publications and visualisations has led the National Weather Service Centre at Wakefield, Virginia, United States, to announce on July 1st, 2023, that it may be unable to continue to publish severe weather reports on the X platform[81]. This case drew the attention of other authorities and the public, making the X platform reconsider the limits on the number of publications and visualisations of this public interest service[82]. New platforms like Mastodon, Bluesky, and Meta's Threads are also rising. Practice-oriented results and discussions offered by this study can support climate authorities in defining policies on whether and how social media platforms can serve their communication activities, seeking climate adaptation, preparedness, and resilience goals.

DATA AVAILABILITY
The data that support the findings of this study are available in Zenodo with the identifier https://doi.org/10.5281/zenodo.7831680 for social media data and https://doi.org/10.5281/zenodo.8018164 for meteorological warnings data.

CODE AVAILABILITY

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ETHICS

The author of this study has fulfilled the criteria for authorship required by Nature Portfolio journals. This study does not result in stigmatisation, incrimination, discrimination, or personal risk to individuals. Local and regional research relevant to our study was considered in citations.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44168-023-00080-3.

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