

Artificial intelligence in support of weather warnings and climate adaptation

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ABSTRACT

In October 2021, the Swedish Meteorological and Hydrological Institute (SMHI) launched a novel national system for impact-based weather warnings, moving from the traditional format for meteorological, hydrological, and oceanographic warnings towards an assessment process that includes collaboration and consultation with regional stakeholders. For certain types of warnings, joint assessments of the potential impacts of weather events for a specific geographic area and time frame are made in collaboration with local and regional actors. As part of this new system, local and regional administrative efforts are made to create assessment-support documentation which are collated by practitioners at the municipal or organizational level, drawing on local knowledge, and subsequently compiled by the County Administrative Board. This process aims to support the collaborative decision-making processes ahead of the publication and in the evaluation of issued weather warnings.

This paper explores the potential of integrating long- and short-term perspectives in societal response to climate change impacts with focus on extreme weather events. We present a case of AI-based technology to support processes linked to the national system for impact-based weather warnings and its integration with local and regional climate adaptation processes. We explore opportunities to integrate an AI-based pipeline, employing AI-based image and text analysis of crowdsourced data, in the processes of the warning system, and analyse barriers and enablers identified by local, regional, and national stakeholders. We further discuss to what extent data and knowledge of historical extreme weather events can be integrated with local and regional climate adaptation efforts, and whether these efforts could bridge the divide between long-term adaptation strategies and short-term response measures related to extreme weather events. Thus, this study unfolds the existing and perceived barriers to this integration and discusses possible synergies and ways forward in risk management and climate adaptation practice.

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1. Introduction

The unprecedented occurrence of extreme weather events poses increasing challenges for societies to cope with both the imminent threat of e.g. floods, wildfires, and storms, but also to invest efforts in long-term climate adaptation strategies and measures (IPCC 2022; Romanello et al 2023). To ensure that society is transforming in a climate-proof direction, actions are needed both to decrease risks in the near time as well as in longer time perspectives. However, climate adaptation efforts focusing on these different time perspectives frequently fall under different framings, logics, motivations, and societal responsibilities.

Climate adaptation in the Swedish context is organised at the local, regional, and national level. The municipalities are responsible for, amongst other things, water and sewage, health and social care, spatial planning, emergency services, and prevention of natural disasters. Nonetheless, responsibility related to climate change and extreme weather events are handled by separate units, with none or limited coordination. The County Administrative Boards are responsible for support and monitoring of the municipalities work with climate adaptation, including coordination across administrative borders (Regeringskansliet 2018). Legislation and regulations are determined at the national level where also government agencies are designated to support regional authorities. The Swedish Expert Council on Climate Adaptation has the mandate to evaluate climate adaptation efforts and to provide strategic advice to the Swedish government.

The Technology Executive Committee of the United Nations Framework Convention on Climate Change (UNFCCC) has, in collaboration with the children and youth constituency of the UNFCCC, concluded that early warning systems can be cost-effective game-changers for climate adaptation and stressed the importance of innovative technologies in increasing their effectiveness. The potential of AI for detecting, monitoring, and forecasting events, and effectively communicating impending or ongoing disasters tailored to the needs of the target groups was highlighted (UNFCCC, 2023). Impact-based forecasting, predicting not only weather, but also its impacts, is an integrated concept of the WMO Guidelines for Multihazard Impact-based Forecast and Warning Services (WMO, 2015). As impact-based forecasting is increasingly being implemented as part of weather warning services (Taylor et al 2018), experiences and opportunities to integrate these with climate adaptation efforts are emerging. In the first report from the Swedish Expert Council on Climate Adaptation to the Swedish Government (2022), it was concluded that impact-based warning systems significantly improve the ability to act proactively and thereby reducing climate-related disaster risks, making them an important tool for climate adaptation. The report highlights that continued development of impact-based weather warning-systems is required, focusing on communication and response functions, based on who and what is in the risk zone. The recommendation of a nationwide system for impact-based warnings was, however, already highlighted in the Swedish Meteorological and Hydrological Institute's reporting to the government in 2015 on the progress of climate adaptation in Sweden since 2007, including assessments of the remaining need for national climate adaptation measures (Andersson et al., 2015). The Sendai Framework for Disaster Risk Reduction (UNDRR, 2015) was adopted by the UN member states in 2015 and includes the global target to "substantially increase the availability of, and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030" (UNDRR, 2015). To bridge the gap between disaster risk reduction and climate adaptation with a longer time perspective, the Swedish National Expert Council for Climate Adaptation (2022) recommended to supplement the Swedish National Climate Adaptation Strategy, listing the Sendai Framework for Disaster Risk Reduction (2015) in the target formulation.

In line with these recommendations and following WMO's recommendation to increase the relevance of weather warnings by explicitly linking them to the potential impacts, the Swedish Meteorological and Hydrological Institute implemented the Swedish national system for impact-based weather warnings in October 2021. The system implies a transition towards a more inclusive process, involving consultation with regional stakeholders for selected meteorological, hydrological, and oceanographic warnings.

Together with the County Administrative Boards, SMHI has determined regional threshold values for warnings. Prior to a warning, dialogues are held with the respective County Administrative Board to make a joint assessment of the potential consequences of the weather event. There are, however, exceptions where SMHI determines that collaboration is not initiated, such as in cases of high levels of uncertainty. When a decision on collaboration is made, the relevant County Administrative Boards make an assessment on local and regional impacts based on SMHI's proposal of a warning. They subsequently provide feedback to SMHI on the choice of alert level, the area concerned, and the warning text. Based on the feedback, SMHI publishes the warnings. Through this collaboration, preparations can be initiated already before the warnings are published, and warnings are regionally and locally adapted based on the specific consequences that may arise. There is also an opportunity for collaboration on the revision of a warning decision if the need arises during an event, although there might not be time for this in case of rapidly changing weather. Finally, after de-publishing of warnings, evaluations of the warnings are carried out by SMHI in collaboration with the County Administrative Boards.

While the warning system is not focused on long-term processes of climate adaptation, the assessment of threshold values, as well as the local and regional assessments of impacts, and the evaluations of the warnings with respect to what precisely happened, can be of value also for adaptation planning.

While Sweden only recently implemented this system, other countries, like the UK are already looking back at more than a decade of impact-based weather warnings (Taylor et al 2019). In 2018–2019 Kaltenberger et al (2020) carried out a survey study with response from 32 out of the 37 European National Hydrological and Meteorological Services (NHMS) that participated in the EUMETNET EMMA/Meteoalarm project; an integrated, regional warning system. Results of this survey indicated that fifty percent of the responding NHMSs expected to produce public impact-based weather warnings by 2024/2025, using subjective impact-based criteria, such as those generated from discussions on the "impacts of a forecasted event with stakeholders or expert partners" (Kaltenberger et al 2020:29). In addition, 47 % were planning to use criteria based on impact-models run with vulnerability and exposure datasets combined with meteorological information. At the time of the study, only 31 % reported some use of impact-based criteria, although often not made publicly available. To validate and monitor impacts on geographic areas in which warnings have

been issued, forecasters use various types of media. Survey results presented by [Kaltenberger et al \(2020\)](#) show that thirty-four percent of the respondents reported that they used media monitoring, as one of their methods to assess impact-based criteria. Notably, close to all NMHS (97 %) considered crowdsourced observations of both weather and impacts as important, either as ‘ground truthing’ or validation, and 47 % used social media reports to verify issued warnings. Furthermore, 78 % reported that they use “images or videos posted in social media or other channels to see ‘what’s happening out there’” ([Kaltenberger et al 2020:33](#)). While these results exemplify how crowd sourced data, drawn from social media or other communication channels, is regarded as relevant input to inform and evaluate impact-based weather warnings, these are to date commonly done manually by the individual practitioner, possibly supported by media search engines. Several recent studies have explored the use of social media data for the detection or validation of impacts of extreme weather events employing automated methodologies (e.g. [Rossi et al 2018](#); [Spruce et al 2021](#); [Dassanayake et al 2022](#)) which motivates the exploration of AI-based analytical methods to support these processes.

The potential of AI for supporting early warning systems is increasingly being highlighted ([Kuglitsch et al., 2024](#)). As machine learning (ML) algorithms provide the power to leverage vast amounts of data from complementary sources, such as satellite imagery, radar systems, and weather stations, systems are being proposed for improving monitoring and early warnings of weather events. For urban flooding events in particular, [Yu et al. \(2024\)](#) propose an approach combining satellite images with AI-powered tools to identify waterlogged scenes and estimate associated flood risk levels. Similarly, [Lo et al. \(2021\)](#) propose a system that integrates visual sensing input such as satellite imagery, drone feeds, and camera feeds from traffic cameras, with ML algorithms to detect waterlogging scenes. Moreover, AI-powered systems can process social media feeds and volunteered sensor data, enabling authorities to quickly assess the severity of a situation and adjust warning levels accordingly. In the context of disasters, such approaches have been employed to communicate evacuation strategies, disseminate warnings, and aid in the evaluation of damages ([Zhang et al., 2019](#)). However, the process of designing, implementing, validating, deploying, and maintaining AI solutions for real-world applications, especially in high-stakes scenarios, is not a trivial one. During the past decades, the major focus of both researchers and practitioners in this area has been on model-centric AI, i.e., trying to improve the performance by choosing the most appropriate architecture, learning algorithm, and hyperparameters, while typically relying on standard training data sets, benchmark validation and test data sets. In contrast, during the past several years, the AI community has started to openly acknowledge the challenges and opportunities associated with data-centric ([Gröger, 2021](#); [Sambasivan et al., 2021](#)), but also human-centric AI ([Jarrahi et al., 2023](#)). Some of the respective challenges and principles here include the systematic improvement of data fit and data consistency for the domain application at hand (while acknowledging the human-centeredness of such data-related activities), mutual improvement of model and data through iteration, and interaction between domain experts and AI as a sociotechnical system ([Jarrahi et al., 2023](#)). The translation of these principles into actual design and implementation steps is an open challenge, and as part of the AI4CA project, we aimed to contribute towards addressing it from a combination of AI and human-centered visual analytic methodologies.

This paper explores the potential of integrating long-and short-term perspectives in societal response to climate change impacts, examining how AI-based image processing and text mining could support impact-based weather warning systems. This study identifies enablers, synergies and barriers related to AI for weather warning systems, based on dialogues with local, regional and national stakeholders. Specifically, this paper aims to contribute to understanding how the provision of data to analyse the impact of forecasted events in the past could support climate adaptation efforts, and to what extent this system could facilitate a boundary-crossing function to bridge across the knowledge communities of climate adaptation and disaster risk management.

2. Materials and methods

To elicit insights and observations from stakeholders with expertise and involvement in the weather warning system and climate adaptation, this study engaged in three data collection stages (see [Table 1](#) and [Supplementary Material](#)) throughout the project. These comprised a series of interviews after the system had been implemented, and two workshops with practitioners. During the autumn and winter of 2021–2022, 10 semi-structured online interviews were held with representatives of both local, regional, and national authorities and organizations that were involved in the implementation and related processes of the then newly launched impact-based weather warning system. Participants were selected based on their expertise and role, representing municipalities, the regional and national climate adaptation administration, key organizations in the regional collaboration on weather warnings, and experts from SMHI. With the exception of one group interview due to the recent transfer of organizational responsibilities, interviews were held individually and lasted approximately one hour. All interviews were held online and were audio-recorded. The topics elaborated during the interviews were (i) the participants’ experiences of the newly introduced impact-based weather warning systems, (ii) opportunities and challenges of AI-based text and image analysis for impact-based weather warnings and/or climate adaptation, and

Table 1
Overview of interviews and workshops.

Timing	Method	Number of participants	Participant profile
Autumn/Winter 2021–22	Individual online interviews	12	Practitioners based at organizations, and municipal, regional and national authorities
October 2022	Workshop	22	National network for climate adaptation coordinators/ officers, based at the County Administrative Boards
March 2023	Workshop	15	Training for regional stakeholders involved in the impact-based weather warning system

(iii) demands of an AI-based system in support of the weather warning services (e.g. interface, content) to provide added value.

A common element during the interviews and the workshops was the three potential areas of use for the AI4CA Pipeline: (i) Validation of Earlier Warnings, (ii) Assessment Support Documentation and (iii) Support during ongoing weather warnings (Fig. 1).

These three areas were identified through initial iterations within the project team which comprised of experts from the weather warning unit at SMHI, and experts in climate adaptation and risk- and preparedness with responsibility for coordinating impact-based weather warning dialogues at the County Administrative Board. While the interviews only referred to a first paper prototype of the AI4CA visual interface, the two workshops included demonstrations of the prototype version of the interface.

In the autumn of 2022, we held a workshop with 22 participants as part of the national network meeting for regional climate adaptation coordinators, which are based at the Swedish County Administrative Boards. This group of participants was selected due to their expertise in climate adaptation with representation across Sweden, and as such particularly well-suited to explore the role of the system for climate adaptation. The workshop lasted for 1.5 h and discussions were audio-recorded. In the spring of 2023 a second workshop was held as part of the regional training program on the impact-based weather warning systems, with 15 stakeholders from 9 different regional authorities and organizations. This group of participants was selected as they represented the specific case of the regional collaboration which would be called upon in during an impact-based weather warning. The focus of the training event was to discuss and outline the decision-support documentation for the county, which directly linked to the use of the AI4CA pipeline. The training was coordinated by the County Administrative Board, and the workshop built on group discussions and a final joint discussion, which were audio-recorded. At the onset of both workshops, the project was presented in plenary. The discussions during these workshops were guided by the following topics: (i) challenges and opportunities for integrating climate adaptation perspectives within the warning system for extreme weather events (ii) the potential for supporting climate adaptation work at regional and local level, and following a short demonstration of the prototype version of the visual interface (Navarra et al. forthcoming), the respondents were asked about (iii) the potential usefulness with regards to their work, as well as for any requirement to increase the potential usefulness in a regional/local context. Prior to all interviews and workshops, participants were informed about the purpose of the study and provided their informed consent.

Through a content analysis (Clark et al 2021; Brinkmann, 2022) we systematically explored the perspectives of practitioners on an AI-based pipeline, with regards to the risks and possibilities for supporting the impact-based weather warning system as well as climate adaptation strategies and actions. We started by identifying aspects related to each of the three areas of application: (i) Validation of Earlier Warnings, (ii) Assessment Support Documentation and (iii) Support during ongoing weather warnings (Fig. 1), across the collected material. Within each of these three areas, we then identified key aspects and topics related to usability and application, which are presented and exemplified by individual responses in the results section. This coding provided us with a structured dataset for each of the three areas of application, while ensuring that both cross-cutting topics and individually raised content highlighted by the respondents would be captured to contribute to the analysis. While the profile and total number of participants, the timing of the data collection and the qualitative nature of the data collection limits the replicability of the study, it provided us with deeper insight and a broad representation of relevant perspectives from practitioners actively contributing to or involved in the new national system for impact-based weather warnings.

To further explore the potential of bridging the divide between short-term emergency response measures to extreme weather events and long-term climate adaptation strategies, this paper employs a theoretical perspective based on the concept of boundary objects (Star and Griesemer, 1989; White et al 2010; Star 2010), a concept that allows the analysis of entities, also referred to as artifacts, that have the ability to bridge across the boundaries between “social worlds, and facilitate communication across groups” (White et al., 2010). Thus, boundary objects can be both concrete and abstract, have many different shapes and are ascribed the capacity to function as mediators between different epistemological perspectives, facilitating the translation and co-production of knowledge across communities of science and practice (White et al 2010; Fox 2011, Hegger et al 2012; Cash et al 2003; Turnhout 2009). Star and

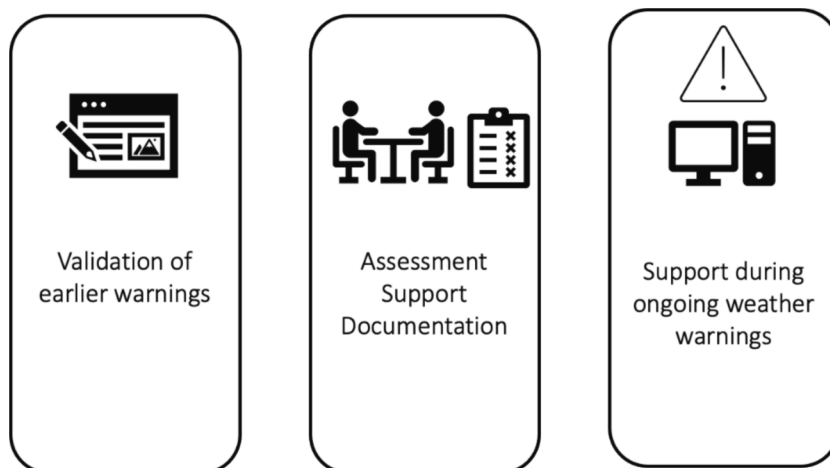


Fig. 1. Areas of application of AI-based text and image analysis in the impact-based weather warning system.

Griesemer (1989) describe boundary objects as “analytical concept of those scientific objects which both inhabit several intersecting social worlds [...] and satisfy the informational requirements of each of them” (Star and Griesemer 1989: 393), which then can emerge between different knowledge communities. Caccamo et al (2023) identify in their review a broad use of the concept within studies of innovation management, that draw on the understanding of boundary objects common in Organization and Management studies, i.e. as management tools, designed for the specific purpose to “enable knowledge-based collaboration” (Caccamo et al 2023:4). The authors employ three perspectives on knowledge boundary spanning with regards to boundary objects in their analysis, namely information processing, cognitive and learning perspectives. Information processing refers to the transfer of knowledge between communities of practice. Common examples refer to technological artifacts and knowledge representations. Cognition on the other hand refers to the dimension of a boundary object as “transcending the boundary of individual cognition” (Caccamo et al 2023) by means of sharing knowledge, referring to the concept of knowledge translation. Meanwhile, the third perspective, learning, focuses on the transformations of knowledge across epistemic communities, and how this knowledge can be transformed into action.

In this study, we explore the potential of the AI4CA pipeline and visual interface (Navarra et al. forthcoming), which emerged as a potential shared artifact, featuring aspects of information processing to facilitate knowledge integration across two communities of practice. We discuss to what extent the system could serve as a boundary object to facilitate the sharing of knowledge and perspectives across the climate adaptation and risk management processes and communities of practices, and whether this could bridge the gap between long-term adaptation and short-term risk management.

3. AI-based methods to support impact-based weather warnings

In this section we briefly introduce the key aspects and processes of impact-based weather warnings and the AI-based text and image analysis that were explored in this project.

3.1. Impact-Based weather warnings

In October 2021 SMHI introduced an impact-based warning system for meteorological, hydrological and oceanographic weather warnings. The system implies that warnings are created based on the societal impacts and implications of weather events rather than threshold based on weather event frequencies. Since communities and societal functions have different levels of disaster susceptibility, risk, and vulnerability, the same weather event can have both massive and insignificant impacts.

When setting warning thresholds in impact-based warning systems, a challenge is to understand the risk and impact at a sufficiently detailed level. A key factor to understanding risk, according to the WMO, is maintaining and obtaining relevant impact-data and historical datasets on disaster events and disaster risk management (Golding, 2022). Impact-data is often in the form of geographical data containing detailed information about anthropogenic structures such as roads, housing, or compounds used for vital societal functions, but also including socio-economic or social data. As part of the process of collecting information on impacts of weather events, domain experts increasingly also engage in searching news and social media outlets as a complementary data source. These datasets can contribute to the evaluation of severity, uncertainty, content and extend of on-going and past warnings. However, for

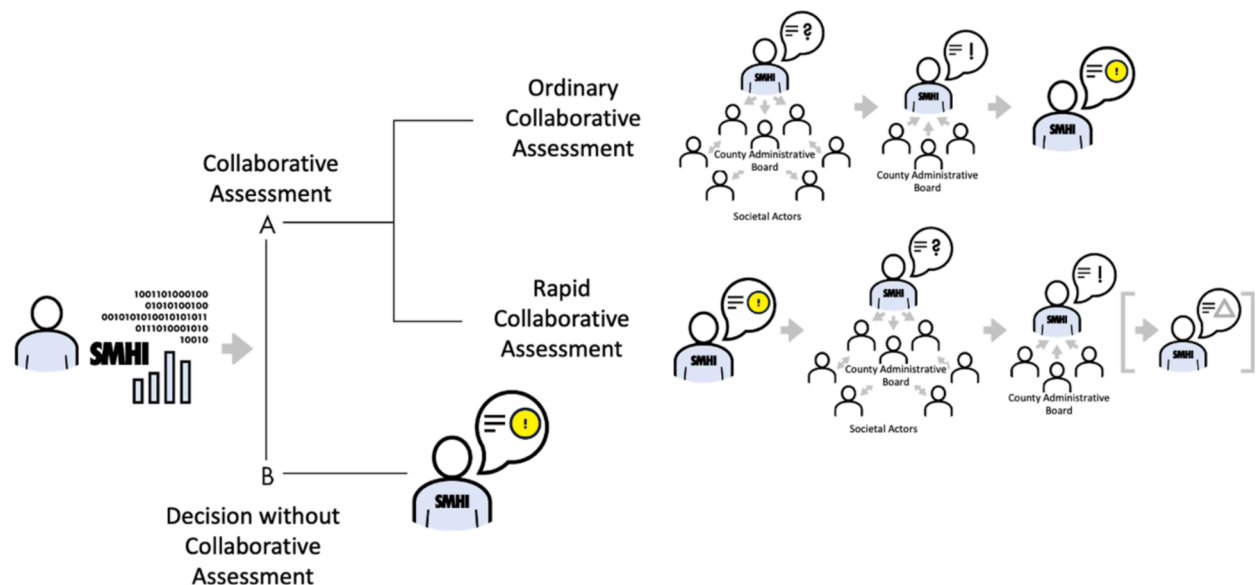


Fig. 2. The national system for impact-based weather warning.

Source: SMHI, 2024, <https://www.smhi.se/kunskapsbanken/meteorologi/varningar-och-meddelanden/for-samhallsaktorer/om-vadervarningar-for-samhallsaktorer-1.169487> . English translation by the authors

many geographical areas, obtaining high quality, relevant, and extensive impact-data is difficult. Especially in the case of media searches, the identification of relevant content is performed manually, making data collection time consuming and practically cumbersome. These datasets are often lacking important details that are necessary to assess disaster vulnerability. Furthermore, datasets are often static and do thus not reflect changes in disaster risks on different temporal scales. An example of this is how some areas have higher population densities in different seasons due to tourism or at different times of the day due to rush hours. Lastly, the geographical datasets do not capture the intangible effects of disaster or weather-related events, which cannot be expressed in terms of pure statistics since they are difficult to measure in monetary terms, e.g. health or psychological impacts such as personal trauma or injuries.

SMHI issues many different types of weather warnings. As described above, some warning types are collaboratively assessed with the respective County Administrative Board and regional stakeholders before a warning is published and disseminated. This is to ensure that regionally appropriate warning levels, i.e. Yellow, Orange, Red (<https://www.smhi.se/en/weather/warnings-and-advisories/2.4336/information>), content (text), geographical extent and timing are provided (see Fig. 2 below). The collaborative decision is made between the forecaster on duty at SMHI and the relevant societal stakeholders administered by the County Administrative Boards, who cooperate with other regional and local actors. The decisions are based on available forecast data, geographical information and impact-data combined with expert knowledge from the local or regional stakeholders. Examples of warnings that need ordinary collaborative assessment include warnings for flooding (riverine) and rain. If the disaster event has a short lead-time, the forecaster on duty for SMHI might choose to publish a warning first and then have the rapid collaborative assessment process afterwards. In cases without collaborative assessment, SMHI's forecasters on duty have to make this assessment on their own and publish and disseminate warnings without the input from stakeholders.

As part of the collaborative assessment, all actors affected by weather warnings need to understand what the warning system means, and how it affects their own operations. Therefore, there is a national guidance for weather warnings to support this work (SMHI, 2022).

The assessment support documentation is intended to be used by the responsible officer (e.g. on municipal or county level) during the consultation that follows a proposed or issued warning.

This documentation is developed as part of a long-term training process, organized by the regional County Administrative Boards, and envisioned to be elaborated and complemented by stakeholders from relevant organizations. The assessment support documentation is structured according to the different categories of weather warnings, as outlined above. It contains the following elements for each type of weather warning: (1) General impact/measures in the county, outlining experience-based descriptions of various impacts for each of the warning levels. These can further identify the various groups of actors that are related to each of these potential impacts/measures. (2) Examples of impact on specific societal sectors; (3) Risk factors and their impact, specified for the county, municipal, or organizational level; (4) Particularly sensitive objects and areas; (5) Critical values, i.e. levels or thresholds for certain indicators related to impacts; (6) Overall impact and measures, referring to any parts of the organization for which the impacts of a weather event might have further implications for the overall organization.

3.2. AI-based text-and image analysis

To address the challenges of supporting impact-based weather warnings and provide access and insight to relevant data, an AI driven analytical pipeline, the AI4CA visual analytics pipeline, was explored (Vrotsou et al., 2023; Navarra et al. forthcoming). The AI4CA visual analytics pipeline comprises a multi-step approach that integrates techniques from Machine Learning (ML), Natural Language Processing (NLP) and interactive visualization aiming to identify and explore (extreme) flooding events from social media posts for providing support to the SMHI impact-based weather warning system. The AI4CA pipeline is outlined as follows. First, social media posts matching a queried weather event are located and extracted from the social media platform. Second, image and text classification using transfer learning is applied to identify and label flood-related social media posts. Transfer learning is a ML technique where a model developed for one task is reused as the starting point for a model on a new related task, allowing the model to capitalize on its pre-existing knowledge and improve efficiency and performance. Third, subsequent text analysis based on Named Entity Recognition (NER) is performed. NER is an NLP technique used to identify and categorize key information within a text, such as names, locations, dates, and organizations. We apply NER to retrieve geographic information from the classified posts. Finally, an interactive visual interface allows for the multi-faceted visual exploration of the posts classified as flood related. Multiple linked views are available in the interface for exploring the different complementary facets (i.e. aspects) of the data; their spatial, temporal and contextual characteristics.

The AI4CA visual interface includes a map view for exploration of the spatial distribution of the data, a timeline view for navigating the temporal dimension and exploring the temporal distribution of the posts, as well as appropriate views to explore image and text content and their classification for a given weather event or warning. The interface allows filtering by time and space, making it possible to select and focus on certain periods and/or geographical areas for specific issued weather warnings. Another available functionality of interest is the ability to confirm whether the algorithmically assigned classification is correct or not directly in the system, thereby creating opportunities for the continuous improvement of these classifications. The design considerations and implementation of the AI4CA visual analytics pipeline is described in more depth in Vrotsou et al (2023) and Navarra et al. forthcoming respectively.

The AI4CA pipeline aims to assist experts in their search for relevant information from social media outlets to complement and further inform issuing of impact-based weather warnings. The pipeline could be launched in relation to a current warning for accessing citizen reports regarding ongoing events or it could be used for validating historically issued warnings. The main advantage of this

automated analysis approach is that it enables comprehensive relevant datasets to be retrieved and automatically annotated as flood relevant/irrelevant and could thereby replace the currently employed manual approach allowing for more time to be spent on expert analysis tasks. Moreover, it provides a visual interface in which the collected and annotated information can be visualized and flexibly explored from multiple perspectives, providing insights on the spatiotemporal characteristics of weather events and their impact.

4. Results

The national impact-based weather warning system involves a collaborative process, including stakeholders at different public administrative and organizational levels. Firstly, stakeholders are by design engaged in the collaborative assessment process following 7 of the 17 weather warning categories. Secondly, stakeholders from organizations and government authorities take part in developing assessment support documentation which facilitates a collaborative process to explore and discuss the potential impact of weather events in the local context. While climate adaptation is not an explicit part of this assessment, we explore the window of opportunity that this new system might present, integrating long-term climate adaptation considerations in the context of emergency services. This section is structured in accordance with the three processes that the AI4CA pipeline could support: Validation of Earlier Warnings, Assessment Support Documentation and Support during ongoing weather warnings (Fig. 1). In each of the interviews and workshops, we discussed these three processes with specific focus on the participants' professional roles, experiences, and perspectives. Based on the analysis of the qualitative data, we explore framings of climate adaptation and risk management in the context of the impact-based weather warning system, and the proposed AI4CA pipeline.

4.1. Validation of earlier warnings

The validation of earlier warnings, as well as missed warnings, is a routine task for weather warning practitioners. As such, respondents involved with the issuing and validation of weather warnings reported that this task is commonly done manually, e.g. by collecting, and comparing weather warnings with media reports, and is part of the routines connected to warnings. Similarly, practitioners involved in the local and regional processes of impact-based weather warnings argued that an automated analysis, such as the one proposed through the AI4CA pipeline, would facilitate an important work task. This is particularly central given that the County Administrative Boards are responsible for contributing with feedback that captures the regional and local perspective regarding accuracy of the forecast and observed impact. The support in validation of earlier warnings has been assessed as highly relevant by the participants in two ways. Firstly, in terms of validating the local impact in areas where warnings have been issued, to compare the severity of impact and correctness of the geographic extent and intensity. And secondly, to detect local impact in places that have not been included in the issued warning or events that have not been part of the forecast.

A second theme related to the validation process was elaborated in reference to the role of historical data in planning and decision making. As such, the AI4CA visual interface was expected to visualize historical impact, and as such provide a 'validation' function, featuring historical assessments that can support the identification of vulnerable areas. One participant specifically raised the possibility of regional comparisons between similar locations or similar features within the built environment. Given this functionality, the AI4CA visual interface would not only allow for an analysis of the impacts of historical events, but also provide for the development of typologies of vulnerable areas. This would enable the collaboration between climate adaptation and emergency preparedness practitioners to compare the impact of severe weather events in similar places, building support for comparative analysis.

From a planning perspective, regional climate adaptation coordinators identified the usefulness of validations in their dialogues with municipalities. Similarly, one group of respondents discussed the importance of also monitoring images after a flood event to identify the cause of the imminent flooding. Therefore, they suggested an extension of the analytical pipeline to include the detection of images of the same place before and after (without flooding) to analyse what happened and what impact and damages could be identified.

4.2. Assessment support documentation

The process of creating the assessment support documentation, produced by all organizations at different levels and geographical scales and subsequently compiled by the County Administrative Board, is a novel process that started in 2021. This process is guided by the County Administrative Boards and is expected to remain ongoing to ensure that the assessments cover the most recent local and regional developments. Assessment support documentation follows a structured survey that municipalities and organizations at the local and regional level compile. This allows them to identify thresholds for each of the weather warning types and to assess the potential impact to different areas and infrastructures in their area of responsibility. The results of our study indicate that there is a significant difference in how assessment support documents are created, stored, and distributed as some organizations need to restrict access to these documentations due to confidential information. Despite this, the overarching structure for the documentation allows for a comprehensive assessment of potential impact of the different weather warning categories.

With regards to the AI4CA pipeline and visual interface, respondents argued that the outcomes of the image- and text analysis could provide municipalities, counties, and organizations with examples from prior events that could support the development of the documentation. Respondents also noted that information from other areas, e.g. similar locations or infrastructure, could provide information to identify potential vulnerabilities in their own region.

Representatives of two counties argued that the use of images also has great potential in their own communication with the municipalities and organizations to increase the understanding for measures to decrease vulnerability. This includes specific climate

adaptation decisions, such as when a County Administrative Board decides whether the municipality's decision to adopt a development plan needs to be reviewed or repealed due to climate related risks.

An additional potential benefit of the AI4CA pipeline that respondents outlined, was the value of historical data to generate 'typologies' for the built environment, providing for a generic database on the impacts of historical extreme weather events to support local vulnerability assessment. However, in many places, the lack of documentation for historical events, and the lack of social media data for earlier events were raised as a hinder. Respondents emphasized that more recent data would be required to build up such a decision support system to ensure that a sufficient level of image and text documentation would be available online to avoid bias and provide a critical level of data for this analysis.

4.3. Support during ongoing warnings

The integration of real-time information to the weather warning system was the third potential functionality of the AI4CA pipeline and interface discussed with the participants. Although this functionality is not yet intended to be part of the pipeline, its design would allow for adaptation towards this purpose in the future. With respect to introducing real-time data to the workflow of an ongoing warning, several issues were discussed that would provide potential obstacles or even risks. One of the main aspects was related to the different time horizons on which e.g. emergency services and citizens might be responding to an extreme weather event. This would mean that images or texts published on social media would not necessarily be uploaded immediately, but might have a time lag. As such, respondents argued that the information provided by citizens might even be misleading. An example was a snapshot of a situation in one place, that might lead the efforts of emergency services towards a situation that has already been resolved, averting from other, more imminent tasks.

A second risk that was raised by the respondents was the prevalence of pictures taken of dramatic events which could influence the overarching assessment of the situation, and even lead to 'emotional decisions', rather than rational and contextual decisions, influencing first responders. An additional risk identified by the respondents, was the geographic bias given social media users might prevail in certain demographic groups. This could influence the geographic and temporal distribution of the available crowdsourced information. Further, events taking place further away from densely populated areas, would be underrepresented, introducing a further bias in the available information. A final concern that was expressed during the consultations, was related to trusting the algorithm that selects/classifies the texts and images as relevant. In response to each of these concerns, the role of humans in validating was emphasized. One specific suggested measure to mitigate these risks was integrating a function for immediate validation to the AI4CA pipeline. As such, real-time information could be confirmed and updated by first responders, combined with additional information, e.g. if roads are confirmed to be blocked, and the provision of alternative routes.

While the general functionality as part of the pipeline was considered as relevant, it would be required to be well-integrated to complement the flow of information from the weather warning services to the regional and local entities. One specific challenge raised by the respondents was the need for information to be provided quickly, while it is uncertain who can make the assessment of the relevance of the provided information, and how quickly that can be facilitated.

5. Bridging the gap between impact-based weather warning processes & climate adaptation

Climate adaptation efforts aim to decrease current vulnerabilities, but also to improve future resilience, develop strategies and increase the adaptive capacity of e.g. municipalities or organizations (Adger et al 2005; Adger et al 2018; Glaas et al 2024; Juhola and Kruse, 2015; Hung et al 2024). Impact-based weather warning systems could play a vital role with regards to climate adaptation measures, both by decreasing risks within a narrow time frame, but also given their outlined potential to assist climate adaptation efforts in a longer time perspective. This section presents barriers and enablers for bridging the gap between impact-based weather warnings and adaptation strategies and measures. We specifically examine to what extent a system as the one proposed in this study, comprising the AI4CA pipeline and corresponding visual interface (Vrotsou et al., 2023; Navarra et al. forthcoming), can function as a boundary object (Star 2010; White et al 2010), providing a shared structure for the communities of practice. This would enable them to interlink and translate across the processes, territories, and domains of emergency risk management and climate adaptation.

The general challenges outlined from both interviews and workshops regarding the alignment of climate adaptation and the design and use of the impact-based weather warning system were related to two aspects; Firstly, the difference in time horizons, and secondly, the validity and representativeness of the developed AI-based text and image analysis to support the warning system.

The most evident gap outlined by the respondents from a climate adaptation perspective, was the difference in time horizons and objectives in climate adaptation compared to the impact-based weather warning system. Respondents argued that impact-based weather warnings mainly related to short-term emergency responses, and that there was no alignment with the main objectives of climate adaptation which are based on long-term planning. Therefore, the system would need to integrate the long-and short-term perspectives and facilitate the analysis of impact and adaptation measures for the regions. The distinction between administrative boundaries of risk management and climate adaptation, as outlined, challenges in particular the AI4CA interface to facilitate spanning these boundaries while maintaining support for the analytical questions posed by each of these communities of practice.

A second overarching concern was the validity and representativeness of the data provided. One aspect referred to a general scepticism towards the reliability of the AI component and whether the categorization of images would need to be validated by humans at some point in the process. Participants further questioned the comparability of social media data across the country both in terms of who is reporting and their location. The demographics of those contributing to social media might as such introduce a bias in addition to the fact that submissions in more densely populated areas would be more frequent than in rural areas. Therefore, relevant events,

such as flooding of upstream less populated areas, which could influence the downstream environment, might not be captured. An additional trade-off that was discussed with regards to the visual interface, was what type of data and resolution that should be visible to whom. While some respondents preferred the text component over the image component, some argued for the representation of aggregated values rather than representation of 'real images' to only highlight hotspots of events. Others argued that for climate adaptation particularly, it would be valuable to have access to visual representations of impact to support the argument for the implementation of adaptation measures which are often object to budget prioritisations on local and regional level. These diverse perspectives on the relevance and usability of the data, accessibility, and the form of representation, present some challenges with regards to the use of the AI4CA pipeline and visual interface. As a boundary-spanning artifact (White et al 2010; Star 2010; Caccamo et al 2023), flexibility is required to serve the demands of the different communities of practice to ensure that the system supports a variety of processes, such as the development of decision support documentation.

Besides these identified challenges, two types of benefits were outlined by the respondents related to the AI4CA system, comprising of the AI-based pipeline and the visual interface, and its potential to create synergies between long-term climate adaptation efforts and the impact-based weather warning system, namely (i) vulnerability mapping, and (ii) the development and implementation of climate adaptation strategies.

In terms of vulnerability mapping, participants specifically raised the value of the integration of information about the impacts of extreme weather events for the purpose of identifying vulnerable areas. This could support local climate adaptation efforts and provide data for the local and regional climate-and vulnerability assessments (Regeringskansliet 2018; Englund and Barquet 2023). An additional benefit was the value of long-term monitoring of changes. This could be provided by the compilation of historical data that the AI4CA system could support, display, and make accessible for analysis, merging the mapping of impacts with the validation of issued weather warnings (Navarra et al. forthcoming). Thus, the system could enable the translation of data by integrating the analytical perspectives of different knowledge communities (Caccamo et al 2023). For the proposed system to support the integration of long and short-term actions, participants further argued that the integration with relevant meteorological and hydrological data would be relevant.

The second aspect, development and implementation of climate adaptation strategies, was mainly discussed in terms of providing tools to, e.g. assist municipality officers in "convincing" local decision makers of the need for adaptation, or be used in dialogues with regional climate adaptation coordinators and municipalities to obtain a common acceptance of where and why adaptation is needed. Here, in particular the value of 'real images' was raised to motivate climate adaptation, and the allocation of budget specifically to avoid future impacts. An additional aspect discussed, was the potential to use the monitoring functions to evaluate implemented adaptation measures, providing tools for strategic climate adaptation in the long term. As such, despite reservations on the reliability and representativeness of the data in general, participants highlighted the value of historical data to benefit the monitoring of experienced impacts.

An aspect raised by some of the respondents was to what extent longer-term focused climate adaptation should be directly aligned and integrated in the ongoing work on assessment support documentation. As such, the proposed system could support a continuous dialogue between different organizations concerned with emergency response and climate adaptation, to update and align documentation and provide a space for knowledge transfer and alignment across communities of practice.

While the proposed system could provide a platform that makes information available to support climate adaptation, both in the short and long term, it would also bridge the administrative silos, particularly in larger organizations where the related functions are separated organizationally. While some of the participants from smaller municipalities were both responsible for climate adaptation whilst also acting as points of contact for the impact-based weather warning system, this is generally uncommon, as these functions are usually distributed across different parts of the organization. As such, the proposed system could function as a boundary object, facilitating the exchange and integration of perspectives and knowledge (Star 2010; White et al 2010) across the short-term weather warnings, the long-term evaluations of weather warnings and strategic climate adaptation efforts. In particular, an integration of the decision support documentation, which could then be more closely informed by the system, in terms of linking the documentation of impacts of past events with the observed intensity of specific weather events, could support the local, regional and national efforts to decrease societal vulnerability and increase adaptive capacity and responsiveness.

6. Conclusions

This study set out to explore the potential of employing an AI-based analytic pipeline, comprising image and text analysis, and visualization to support the processes related to impact-based weather warnings, and how this system could provide synergies with long-term strategic climate adaptation. Drawing on interviews and workshops with Swedish practitioners engaged in the impact-based weather warning system and/or local and regional climate adaptation, this study makes two specific contributions: (i) it provides insights into the expectations and reservations with respect to how an AI-based analysis pipeline can contribute to both weather warnings and long-term climate adaptation, and (ii) by assessing the workflows and collaborative processes that are part of the impact-based weather warning system, we identify how an AI-based pipeline could support the integration of knowledge and perspectives, functioning as a boundary object.

Firstly, results of our study provide insights to the potential that practitioners recognized in the integration of AI-based text and image analysis to the impact-based weather warning system. While concerns regarding data bias and potential misinterpretation of input need to be addressed, we conclude that the practitioners see several benefits from supporting the validation of issued weather warnings, but also for data access to support the development of decision support documentation. In particular, employing an automated AI-based approach for the retrieval and annotation of relevant content, can provide access to larger and more focused

datasets and increase efficiency of data collection in terms of time to perform the task and content. Furthermore, while the analytical approach currently was focused on a social media platform, the steps of the pipeline itself can be generalized to any text and image input, and could hence be extended to consider additional data sources, such as news articles published online.

Secondly, based on the analysis of the interviews and workshop dialogues, we identified opportunities to align long-term climate adaptation perspectives and workflows with (short-term) emergency response in the analytic pipeline. To this end, the exploration of the local impact of historical events, and alignment of processes for validation of issued warnings with vulnerability mappings in support of climate adaptation efforts, are the main functionalities. Furthermore, the AI4CA pipeline and interface can support local risk assessments and communication of strategic climate adaptation measures. As such, the system could provide a collaborative space for integrating risk management and the development of adaptation strategies on local and regional levels. This could transcend the organizational silos between those working with current and emerging challenges, and those working with developing societal responses to cope with expected future changes.

Finally, although the involvement of crowd sourced data through social media raises concerns regarding representativity, the potential of an integrated system to raise awareness across organizational structures might further increase the understanding of the need for local action and investment in climate adaptation.

While the AI4CA analytic pipeline requires adaptation and integration into the existing workflows, our analysis indicates that its features provide distinct opportunities to strengthen the alignment of impact-based weather warnings with climate adaptation efforts. This would subsequently enhance societal capacity to adapt to and prevent future climate impacts.

CRedit authorship contribution statement

Tina-Simone Neset: Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Katerina Vrotsou:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Lotta Andersson:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Carlo Navarra:** Writing – review & editing, Visualization, Software, Conceptualization. **Fredrik Schück:** Methodology, Investigation, Conceptualization. **Magnus Mateo Edström:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Caroline Rydholm:** Writing – review & editing, Methodology, Conceptualization. **Clara Greve Villaro:** Writing – original draft, Methodology, Conceptualization. **Kostiantyn Kucher:** Writing – review & editing, Visualization, Software, Conceptualization. **Björn-Ola Linnér:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

The authors do not have permission to share data.

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