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How to provide actionable information on weather and climate impacts?–A summary of strategic, methodological, and technical perspectives

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Climate change will result in more intense and more frequent weather and climate events that will continue to cause fatalities, economic damages and other adverse societal impacts worldwide. To mitigate these consequences and to support better informed decisions and improved actions and responses, many National Meteorological and Hydrological Services (NMHSs) are discussing how to provide services on weather and climate impacts as part of their operational routines. The authors outline how a risk framework can support the development of these services by NMHSs. In addition to the hazard information, a risk perspective considers the propensity for a given hazard to inflict adverse consequences on society and environment, and attempts to quantify the uncertainties involved. The relevant strategic, methodological and technical steps are summarized and recommendations for the development of impact-related services are provided. Specifically, we propose that NMHSs adopt an integrated risk framework that incorporates a hazard-exposure-vulnerability model into operational services. Such a framework integrates all existing forecast and impact services, including the underlying impact models, and allows for flexible future extensions driven by the evolving collaboration with partners, stakeholders and users. Thereby, this paper attempts to unify existing work streams on impact-related services from different spatial and temporal scales (weather, climate) and disciplines (hydrology, meteorology, economics, social sciences) and to propose a harmonized approach that can create synergies within and across NMHSs to further develop and enhance risk-based services.

KEYWORDS

climate service, weather and climate risk, extreme weather and climate, National Weather Service, impact assessment, co-design, user needs, hazard-exposure-vulnerability

1 Introduction

Weather and climate events pose a multitude of risks to societies (WMO, 2020). Providing effective decision support services concerning these risks is a challenge for research institutions, service providers and users alike. Here we address National Meteorological and Hydrological Services (NMHSs) in identifying common strategies and best practice guidelines for the integration and provision of impact information into weather and climate services. NMHSs' primary objective is the provision of actionable decision support service with respect to meteorological, climatological and hydrological information (Mosley, 2001; WMO, 2015; Göber et al., 2023). Ultimately, these services should increase preparedness, activate swift response and prevent/reduce negative impacts of the hazard.

In recent years, an increasing number of NMHSs have begun to provide not only information on the hazard itself, but also information on the potential impact (Uccellini and Ten Hoeve, 2019; Kaltenberger et al., 2020; WMO, 2020). This shift is motivated by the fact that the ideal basis for risk-reducing actions is knowledge of the potential societal impacts. It is challenging to evaluate potential adverse impacts based on weather and climate information alone (Anderson-Berry et al., 2018; Uccellini and Ten Hoeve, 2019; Kaltenberger et al., 2020; Potter et al., 2021). Moreover, besides information on the potential impacts, other measures (e.g., preparedness planning, mitigation works) can influence the decision-making process (Potter et al., 2018; Taylor et al., 2018). In accordance with the IPCC, we refer to impacts as the consequences of realized risks on natural and human systems (IPCC, 2023). Risks result from dynamic interactions between the hazard (a spatio-temporally constrained weather or climate event) with the exposure (the geographical distribution of points of interest, e.g. infrastructure, persons) and vulnerability (the susceptibility of these points of interest to the hazard) (Reisinger et al., 2020). Hazards, exposure and vulnerability may each be subject to uncertainty in terms of magnitude and likelihood of occurrence, thereby contributing to the probabilistic nature of risks (Kropf et al., 2022).

To provide actionable climate and weather services, we propose the implementation of a risk framework by NMHSs that includes the hazard-exposure-vulnerability (HEV) dimensions as building blocks in a model to calculate impacts and risks of extreme weather and climate events (Birkmann et al., 2013; IPCC, 2021). In comparison to traditional representations of risk modeling where hazard, exposure and vulnerability are discrete building blocks, e.g., using the famous IPCC risk propeller (O'Neill et al., 2022), we here propose a continuous representation of risk modeling in a smooth risk plane (Figure 1). The mechanics of this modeling approach allows for a gradual increasing interaction of these three building blocks, starting with hazard only information up to a full risk assessment (Röösli et al., 2021). We therefore refer to the full risk triangle as shown in Figure 1 as the "larger picture" into which the traditional hazard modeling activity of a NMHS is naturally embedded. By increasing the complexity of the provided exposure and vulnerability information (from uniform over categorical to more sophisticated levels), the model generates the impact-related output as required by the user (numbered items in Figure 1, Table 1 for detailed examples). In addition, existing HEV-models are also capable of integrating cost/benefit perspectives on specific risk reduction and adaptation measures, e.g., CLIMADA (Bresch and Aznar-Siguan, 2021) and the Oasis Loss Modelling Framework (n.d.).

An integrated HEV-model (operated at a NMHS or in collaboration with other organizations), that flexibly incorporates the existing NMHS service landscape and the various impact-related services requested, resembles the first of two pillars of a NMHS' impact strategy. The second pillar is transdisciplinary collaboration, as implementing an impact strategy does not only involve research and development but also an increased exchange with existing but also new public and private actors. The implementation of impact-related services in cooperation with so-called boundary organizations is therefore key. We refer to boundary organizations (BO) as all downstream users, service providers or consultancies that can independently access the hazard event and impact information to produce additional impact and risk assessments either for their own purposes or for other specific users and applications. The provision of a modular, open-source and -access HEV-model will support this co-design process. Potential services might comprise purely physical (e.g., hydrological impacts), social (e.g., lives threatened), economic (e.g., economic damages) but also environmental, cultural or institutional assessments. In another dimension, the model can provide either qualitative (e.g., impact-oriented warnings or forecasts) or quantitative assessments (e.g., potential economic damage, potentially affected people, data-driven impact-based decision support services for specialized users) (Table 1).

The implementation of such a process at a NMHS requires strategic, methodological and technical considerations, which are further detailed below and complemented by a discussion with recommendations and practice-oriented steps.

2 Strategic perspectives of impact-related services

Many NMHSs are currently revising their strategies triggered by changing user requirements, budgetary or legal constraints, novel technical developments and as a response to rapid climate change (WMO, 2020).

NMHSs respond to changing user preferences by refining both their products and services as well as the product's design procedure, e.g., following the value chain approach (Nurmi et al., 2013; Golding et al., 2019). From the outset, the design process ideally involves potential users through interdisciplinary expertise and co-design strategies. As a result, the usability of the NMHS' portfolio increases, which in turn may result in favorable behavioral changes, support individual and especially institutional decision making and render socioeconomic benefits for society.

Providing impact-related services represents one way of responding to changing user preferences toward individualized and decision-relevant services. Recent advances in method development and data availability have resulted in model improvements that allow NMHSs already today to generate and provide impact-related warnings and forecasts fully probabilistically and seamlessly from the nowcasting to the

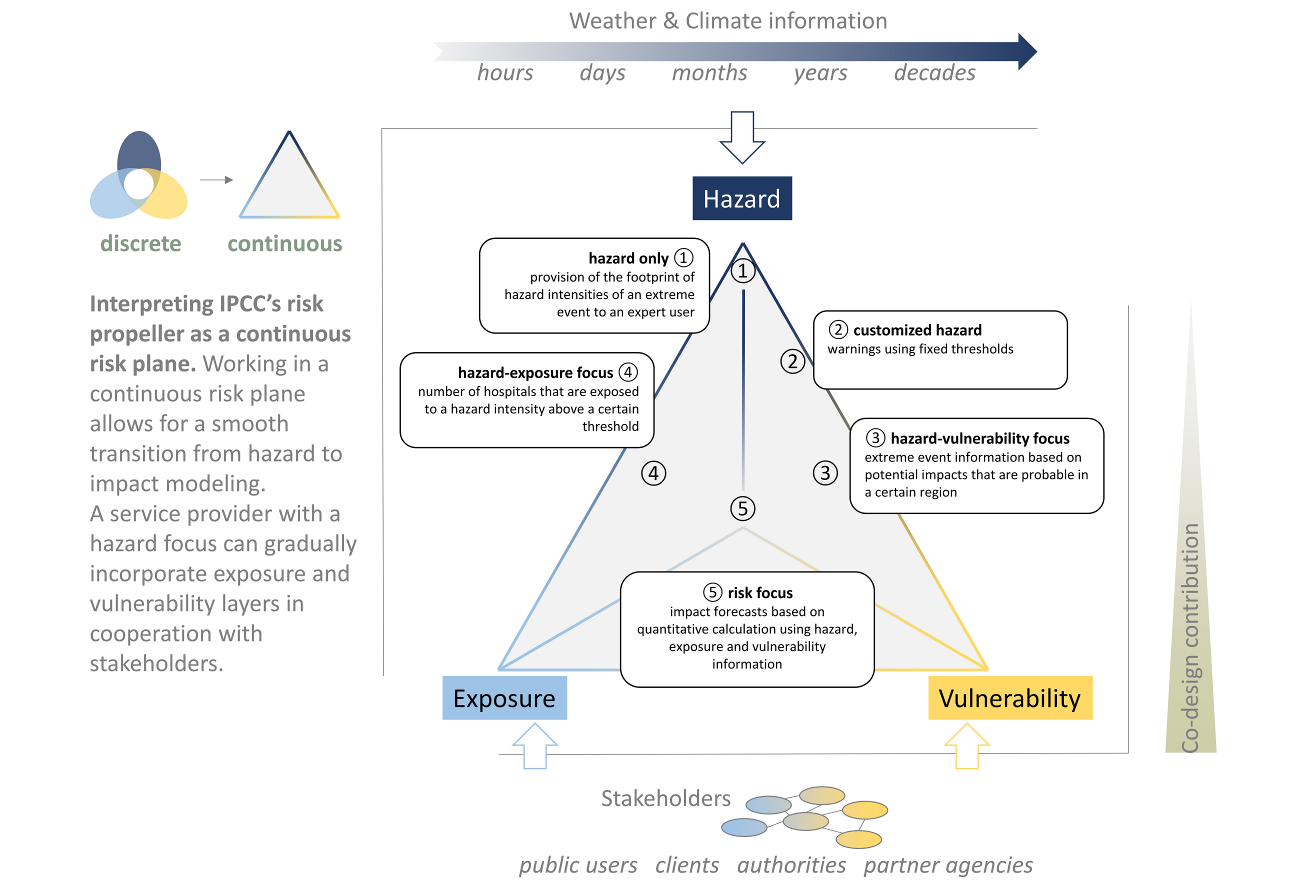

FIGURE 1
Modeling impacts for weather and climate services in a continuous risk plane. A hazard-exposure-vulnerability (HEV)-model uses the building blocks hazard (a spatio-temporally constrained weather or climate event), exposure (the geographical distribution of points, lines or polygones of interest) and vulnerability (the susceptibility of these points of interest to the hazard) to calculate impacts and risks of extreme weather and climate events. Traditionally, risk modeling is done using discrete HEV building blocks (IPCC risk propeller, left of figure). Here, we propose continuous risk modeling in a HEV-plane (risk triangle, center of figure). The risk triangle displays different weather and climate services (numbers ①-⑤) as potential realizations in the HEV-plane. As a common first step the desired weather or climate information (top of figure) is transformed into a spatio-temporal hazard event, e.g., containing the hazard's intensities ①. Moving down, exposure and/or vulnerability information is included to a varying degree into the risk assessment (②-⑤), with a full risk assessment reached at ⑤. Concrete examples for the five realizations in the HEV-plane are listed in Table 1. Co-design requirements and interaction with boundary organizations (BO), e.g., stakeholders, partners and users, increases from top to bottom (bottom and lower right of figure).

climate forecast scale (Röösli et al., 2021). Therefore, impact-related services are in line with other key strategic developments (probabilistic and seamless forecasts) and, if produced by an integrated HEV-model (Figure 1), can help to unite existing NMHS products within a single framework.

Individual NMHSs might argue that they lack the legal mandate to act in this field, because the responsibility (and related expertise) lies with other governmental bodies or private service providers (Kaltenberger et al., 2020). While this might be the case today, the situation might change in the future, e.g., due to adapted legal requirements and/or increasing risks driven by climate change. Adopting an integrated HEV-model now allows one to fulfill the current mandate, but also to move toward impact-related services in partnership with others in the future (Figure 1).

Another NMHS's concern might be liability. To avoid that false alarms could undermine the provider's reputation or even cause liability issues, it is again of utmost importance to co-develop the impact-related services with the users from the start and to reiterate that these services do not replace decision making. Moreover, starting out with more qualitative impact advisories instead of impact warnings (see Methodological Perspectives) will help to avoid false expectations and to circumvent potential liability issues.

3 Methodological perspectives of impact-related services

"Understanding disaster risk and forecasting hydrometeorological[1] impacts are generally beyond the remit of meteorologists and hydrologists. However, since the risks and impacts are often triggered by extreme hydrometeorological

1 While our present discussion refers mostly to meteorological hazards, we acknowledge that our reasoning also holds true for hydrometeorological hazards and related impact assessments not in the focus here, as highlighted in the WMO report (WMO, 2015).

TABLE 1 Examples of actionable impact information as obtained from a HEV-model.

Product type (cf. Figure 1)	Forecast range	Actionable information	Intended users	Representation in HEV-plane			Details
				Hazard-event	Exposure	Vulnerability	
Hazard only ①	Short / medium	Wind speed	All users	Storm footprint based on wind speed	-	-	Wind footprint, e.g., ensemble mean of daily max wind, as provided by numerical weather model. **Use case**: Tropical cyclone track forecasting
Customized hazard ②	Short / medium	Wind warning level	All users	Storm footprint based on wind speed	-	Fixed official warning thresholds	Categorization of wind footprint by warning level. **Use case**: Warning of tropical cyclone occurrence by Saffir-Simpson scale
Hazard-vulnerability focus ③	Short / medium	Probability of sewage system failure	Local infrastructure managers	Maps with hourly precipitation sums	-	Sensitivity of sewage system to extreme precipitation	Risk map with hot spots for sewage system failure. **Use case**: Coordination of rapid response teams
Hazard-exposure focus ④	Short / medium	Number of vacant hospital beds exposed to heatwave	Hospital managers, emergency services	Map with multi-day heatwave extent	Location of hospitals and their number of vacant beds	-	Risk map with potential hospital bed shortage. **Use case**: Cancelation of non-emergency hospital services to free staff and beds
Risk focus ⑤	Short / medium	Map with expected building damages	Emergency services, post-event assessment teams	Map with daily max wind forecast	Location and value of buildings	Sensitivity of building damage to max wind	Impact map for building damage hotspots. **Use case**: Planning of personnel for post-event insurance claim services
Hazard only ①	Extended / long	Sunshine duration	All users, energy sector, tourism	Map of monthly expected sunshine duration	-	-	Regional aggregation of sunshine duration as direct model output. **Use case**: Solar energy generation potential
Customized hazard ②	Extended / long	Map with wildfire danger	Planners in fire departments, tourism managers	Map with wildfire index	-	Fixed official warning thresholds	Categorization of forecasted wild fire index by warning levels, that are associated with certain behavioral restrictions. **Use case**: Outside leisure activity planning in tourist regions
Hazard-vulnerability focus ③	Extended / long	Map with expected crop yield losses by crop type	Farmers, local decision makers	Map with high probability of prolonged drought conditions	-	Sensitivity of specific crop variety to drought conditions	Translation of drought conditions into potential crop yields. **Use case**: Pre-sowing decision support for crop choice
Hazard-exposure focus ④	Extended / long	Map combining riverine traffic and forecasted river discharge	Hydrological experts, water traffic authorities	Map of forecasted weekly min/max river discharge at specific gauge stations	Daily number of shipping vessels at specific gauge stations	-	Interacting forecasted river extreme discharge with usual shipping activity to anticipate potential impacts of decision-making. **Use case**: Optimization of decision timing for efficient logistics
Risk focus ⑤	Long / projections	Guidance for future health care requirements by region	Political decision makers, public health experts	Maps of changes in severity of heatwaves in a warming climate	Maps of demographic changes of population	Sensitivity of heat-related mortality by age cohorts	Quantification of local heat-related deaths for future scenarios. **Use case**: Adaptation of building standards of health care facilities, e.g., retrofitting of air-conditioning systems

Illustration of concrete impact-related applications as represented by the individual numbers (cf. column 1) in Figure 1, their representation in the HEV modeling plane (cf. columns 5–7) and intended users (cf. column 4). An exemplary use case is provided in the last column. The applicability from the weather to the climate forecast range (cf. column 2) is illustrated by the following lead times: short range (≤2 days), medium range (≤15 days), extended range (≤6 weeks), long range (months to years), projections (decades).

events, it may be argued that NMHSs are best equipped to forecast their impact in partnership with others" (WMO, 2015).

This quote highlights two aspects: (i) NMHSs possess substantial expertise, both, with respect to the hazard and technically in the provision of operational services, (ii) impact-related services require interdisciplinary and transdisciplinary (user engagement and co-design) partnerships. Working with BO from the start will bring together the interdisciplinary expertise, will ensure the usefulness of the services to be developed and share the burden of developing, providing and communicating the service. As a matter of fact: the more the services focus on impacts, the more tailor-made the services become, and the more such partnerships are required (Figure 1). At the same time, the provision of tailor-made products for a range of users remains only feasible if the underlying service architecture is strictly modular and flexible and/or supported by stakeholders or BO.

Another important aspect concerns the metrics to be provided, which range from qualitative metrics (e.g., text-based, based on forecasters' judgment, simple impact indicators) to quantitative assessments (e.g., economic damages, affected people). Depending on the metric requirements, less complex impact advisories (potentially derived from non-public impact forecasts) can be a good starting point in place of actual impact warnings or forecasts. Impact advisories are also less strict on data availability and quality or on output evaluation, verification and uncertainty assessments. Quantitative assessments, on the other hand, will benefit from standardized and generalizable metric definitions that are clearly defined and communicated and comparable across impacts, e.g., people affected or monetized damage.

The successful development of any impact-related service will rise and fall with data availability across the full risk plane (Kaltenberger et al., 2020). Data on hazard, exposure and vulnerability are prerequisites for impact estimates (Table 1). In addition, impact observations are needed ex-ante to calibrate vulnerability functions and ex-post to validate impact-related services (Themessl et al., 2022). Alternatively, NMHSs should be prepared to provide their hazard event data to BO to allow for impact assessments with their bespoke exposure and vulnerability information, e.g., to meet user requirements best or to comply with confidentiality.

Accounting for uncertainty throughout the impact-modeling chain is a crucial part of developing impact-related services. This amounts to fully probabilistic risk assessments that combine present probabilistic weather and climate forecasts with suitable uncertainty considerations for the exposure and vulnerability component (Kropf et al., 2022). The associated quality or skill of the impact-related service will strongly depend on the hazard type and the time scale considered. E.g., impacts of an extreme wind event might only be forecasted with sufficient accuracy few days in advance, while temperature-related impacts can be skillful on seasonal time scales and beyond (Merz et al., 2020; Domeisen et al., 2022; Delgado-Torres et al., 2023). Therefore, hazard-specific decision protocols and communication guidelines that clearly name the target group, how to interpret and deal with associated uncertainties, probabilities and the forecast skill must accompany each impact-related service (see Technical Perspectives). This is needed to avoid false accuracy and false expectations.

4 Technical perspectives of impact-related services

Moving toward impact-related services requires specific technical steps. The focus lies on technical steps that are independent of the scope of the service, e.g., the weather or climate scale. This opens up the possibility for synergies in tackling these steps.

Implementing impact-related services at a NMHS for the first time usually requires introducing new concepts, methods and data sources into the operational setting (Röösli et al., 2021). Using a common approach like a HEV-model does not avoid this effort, it only provides a reusable framework for new concepts and its elements, especially if provided open-source and free to use. To facilitate the initial implementation of this framework, it needs to be attached to a strong use case and priority should be given to a generalizable structure. In this way the concepts become part of an operational setting and the efforts for subsequent developments building on the same concepts are reduced considerably. It is generally recommended to start small in terms of implementing the HEV-model at a NMHS and grow with collected experiences.

In the rapidly expanding field of impact-related services, transparent collaboration is a powerful catalyst to bring new concepts to widely used applications. Whilst some methodologies for calculating impact-related information are established, several extensions like compounding events and time-dependent exposure and vulnerability are currently being researched and developed. Different organizations using the same open-source software for their HEV-model allows sharing of new solutions quickly. This supports not only a quick transition from research to application, but also synergies among NMHSs in this common undertaking. At the same time, successfully launched impact-related services by NMHSs supported by a flexible, modular and open-access framework would allow BO, consultancies and other service providers to build upon the same framework and existing interfaces and to create additional services and products that are beyond the mandate of NMHSs. Examples of such services are listed in Table 1, where additional services could be iteratively improved using the same HEV model.

Integrating impacts requires an (extreme) event perspective. In both weather and climate services, the standard for meteorological information is continuous weather data in time and space. On the other hand, observed impacts are normally associated with a specific event, e.g., aggregated precipitation in 24 h within a specific region or spatio-temporal extension of a drought defined by soil moisture indices. Derived statistical evidence, like calibrated damage functions, will require the hydrological and meteorological data to share the same event definition. This requirement calls for an event-based strategy that transforms continuous weather and climate data according to definitions of extreme weather and climate events. While this sounds like a strong limitation at first sight, the event definition is very flexible and is usually defined by the context. On spatial scales, an event can cover anything from a single grid cell to a huge region, e.g., a continent. On temporal scales, an event can be as short as a lightning and as long as a multi-year drought. Sometimes the events can be derived from continuous data using thresholds (e.g., Beusch et al., 2023), sometimes meteorological features are identified and tracked in model data (e.g. Hodges, 1995). Using harmonized event definitions within and across NMHSs will not only make the extreme weather and climate services consistent but also ensures the reusability of impact-related methodologies between the different services and beyond. This automatically ensures a truly seamless handling of impact information.

Having implemented and operationalized an HEV-model is part of the solution, the other part being evaluated model configurations for specific hazard and impact types. These model configurations contain all specifications for the elements hazard, exposure and vulnerability to produce meaningful results in the form of quantitative impact estimates or qualitative impact advisories. These model configurations can be a result of data analysis of past events or of transdisciplinary efforts including stakeholder and expert knowledge. To speed up the generation of new and reliable model configurations, establishing structures for evaluating published model configurations from the scientific literature or the development of new model configurations is important. Here, the interaction of NMHSs with BO in identifying, defining and applying these model configurations is again key.

Another important aspect of HEV-model configurations is the metric on how to measure the quality of the implementation. This aspect should be thought of from the beginning and actively monitored. As such a new service requires resources, it will be important to evidence the success and skill of the new implementation. As observations of impacts are rare, available with a delay and sometimes uncertain, the methodologies normally applied to measure the quality of meteorological and climatological services will have to be adapted. First concepts on comparing impact data with meteorological services are being conceived (e.g., Wyatt and Robbins, 2023). In particular, one should consider that a successful implementation might affect the quality measure under consideration, e.g., behavioral responses affecting the forecasted impact (Scolobig et al., 2022).

Finally, a disclaimer for impact-related products and services needs to be provided with any operational impact service. The role and liability of each stakeholder must be established by actively communicating the disclaimer during the delivery of impact-related products and services. Such a document provides information on the intended use of the product and its uncertainties and shortcomings and can help to address liability concerns raised in the strategic perspectives part of this document. Collaborating with other NMHSs on the elaboration and establishment of such disclaimers could speed up this process.

5 Discussion

Based on the strategic, methodological and technical perspectives raised above we here provide four general recommendations on how to integrate impact information into weather and climate services. These recommendations specifically address applied scientists, senior forecasters and strategic decision makers within NMHSs but also practitioners within the community of stakeholders and BO:

i) First of all, be bold: although risk assessments and impact forecasts seem to be beyond the remit of meteorologists and hydrologists, there are very few others that hold expertise in hazard modeling and in running operational services. Collaborating in inter- and transdisciplinary teams with external partners and users will get the job done.
ii) Use a hazard-exposure-vulnerability mindset: when working with weather and climate data in any project, try to be aware of the potential risks, i.e., the exposure and vulnerability components, even if you are only interested in the hazard for now (Table 1). The weather and climate information should be considered as a potential hazard (in terms of structure) so it can be (re)used in an impact model outside your project or even outside your organization.
iii) Use an integrated HEV-model: a HEV-model is not an add-on of your current activities, it is a way of integrating your current activities into a larger picture. A suitable model integrates your current hazard forecast and warning system and allows you to switch seamlessly between hazard and impact/risk forecasts and warnings–if desired. A HEV-model also works seamlessly from the weather to the climate scale (Table 1).
iv) Think about (strategic) collaborations early on, as BO matter in providing products and services to public and private actors. Research institutions can help, but it will ultimately be BO who can deliver the required services.

How to start - first steps:

1) How to create a basic running HEV-system? Look around for existing HEV-models, see refs. (Bresch and Aznar-Siguan, 2021; Oasis Loss Modelling Framework, n.d.). Pay attention to their usability (open-source code/license of usage, comprehensive documentation, compatibility with your system, potential collaboration with other NMHSs), applicability (relevant use cases/demonstrators available incl. scientific publications, possibility for extension) and reliability (broad and active developer and user community, active code maintenance, helpdesk available). Check the requirements needed to integrate the code on your system? Has someone integrated this model under similar circumstances before? Install the model and try to reproduce existing use cases and adapt them to your needs.
2) First impact assessments: Impact assessments become useful if done in collaboration with accredited partners, relevant agencies, or users. Look around for relevant partners and engage in a co-design process from the very start. Only then will the product be useful and used.
3) Extending your impact portfolio: as many studies, use cases or data sources already exist in the global impact model community, you need a strategy of how to build on this knowledge without starting from scratch every time. E.g., the CLIMADA model (Bresch and Aznar-Siguan, 2021) provides running use cases solely based on open-source data that can be adapted to your needs. This guideline of if and how to use certain knowledge or expertise should revolve around following questions: how to evaluate published studies/use cases for usability? Do their output

metrics coincide with your user requirements? Have the studies/use cases been validated? Do you have access to relevant validation/verification data for your application? Do you have access to relevant exposure/vulnerability data? Has the use case been operationalized? What is the outcome?

4) Make robust, future-ready decisions: integrating impacts into a NMHS is a new and rapidly developing field. To make a robust decision now means to establish concepts and technological solutions that can be flexibly adjusted to the yet unspecified requirements of the future.
5) Spread the word: talk about your experiences, share your developments open-source, publish your work and thereby help others.
6) Carefully assess the potential of existing collaborations (e.g., with emergency services) to build on and new ones to establish (e.g., with engineering consultancies serving their clients managing risks).

6 Conclusion and outlook

Prospectively, operating a HEV-model and integrating it into operational warning and climate services of a NHMS requires adaptations in the well-established procedures. Operational forecasters have always been using a HEV-mindset implicitly, especially when issuing warnings. Having an objective HEV-system in operation still poses a great change for forecasting operations and also for the structures and mindsets of the recipients of the HEV products and forecasts. This is especially valid with respect to communication and further processing of HEV products instead of processing traditional hazard information.

By gathering hands-on recommendations and a set of first steps from the authors' experiences, we hope to provide an insightful contribution to a timely discussion on an international level.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TG: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing, Supervision. TR: Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. DB: Conceptualization, Writing – review & editing. BE: Methodology, Writing – review & editing. AF: Conceptualization, Writing – review & editing. DI: Methodology, Writing – review & editing. SK: Conceptualization, Methodology, Writing – review & editing. LM: Writing – review & editing. GM: Conceptualization, Writing – review & editing. RS: Methodology, Writing – review & editing.

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Conflict of interest

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