

We thank the reviewer for the thorough evaluation of our manuscript and the helpful comments. We respond to these comments as follows:

This paper gives a broad consideration of how to improve interoperability of data, models, communication and governance for disaster risk management and climate adaptation. The paper starts with a comprehensive and thoughtful review of well-established ideas. I found it instructive to think about interoperability with regard to communication and governance, which I hadn't considered before.

[1] My main reflections are that more explanation of key terms or projects is needed because without this the narrative is quite difficult to follow. Real examples would also be extremely helpful throughout. A more detailed description of the DIRECTED project is warranted because at the moment it appears to be a fairly high level overview of what is planned rather than an active project tackling the issues that have been identified earlier in the paper. Detailed comments follow below:

We agree that our presentation would benefit from additional explanation of key terms and examples to illustrate the issues addressed and the underlying ideas of the proposed concepts. This point is also mentioned in other comments below and has also been raised by reviewer #1. Therefore, we refer to our answers to these points where we make suggestions for possible examples [R1-6, R1-7, R2-10, R2-16]

The paper does not intend to describe the DIRECTED project in depth but we will add further details as described in our answer to comment [R2, 17]. We will also elaborate on the description of the innovations for interoperability, Data-Fabric and Risk-Tandem in section 3.2

[2] Title: In the title or early on in the paper it would be helpful to indicate that the focus of the paper (if I understand correctly) is Europe. This would help to set what follows in context.

We do not have a particular focus on Europe per se. However, due to the location of the real-world labs in Europe, the conditions there are at the centre of our considerations, particularly at the governance level. The transferability of results for the real-world labs will be bounded to western cultural settings. The methods should be applicable in other contexts as well, given the policy context of e.g. the SENDAI Framework. The core premise of the co-production approach is that it is tailored to context and thus applicable in a range of geographies and decision domains requiring trans-disciplinary participation between a wide range actors across the science-society interface. As such, e.g. the Tandem approach has been applied in both European contexts and beyond, in Africa, Asia and Latin America. Also with regard to models, data and knowledge transfer, the approaches we discuss are quite universal and can also be transferred to other regions.

[3] Line 3: Consider whether 'emerging' is the appropriate word here. I would argue that many of the complications that are described in the paper are widely known about.

We suggest to replace the word 'emerging' with 'manifest'.

[4] Line 4: I would argue there are other factors like a lack of investment and capacity in local scientific organisations, which may have implications for interoperability (in some countries). This connects to the need to be clear about the examples that have informed the development of the ideas on which the paper is based.

Yes, a lack of investment and capacity in local organisations may result in interoperability issues, but we think based on the framing of the three overarching challenges these issues are also covered. Through the work with stakeholders in our real-world labs and in exchange with other research initiatives in the Horizon Europe program as well as The Mission on Adaptation to Climate Change we have learned that organisations often lack long term investment in dedicated DRM and CCA capacity building. Even institutions that are actively involved in research and innovation may not have organisation spanning DRM and CCA capacities. We observe that special project related roles within these organisations are created, but are often not permanent. Access to knowledge is kept in “Silos” and does not permeate the organisations. The DIRECTED co-production approach acknowledges this reality and builds bridges and lasting relationships between actors from different disciplines within organisations and across borders. Resources such as the Data Fabric with integrated models and the Risk-Tandem Framework with guiding documents and training modules will be made available long term.

[5] Line 19: comma missing between ‘drought’ and ‘heavy rainfall’

We will add the comma.

[6] Line 37-38: A little more information regarding what ‘limited imagination’ pertains to would be helpful here. I would argue that decision makers not understanding the information or information not being action-focused can also be barriers.

Good point. We will prick-up this suggestions and propose to remove reference to ‘limited imagination’ and instead refer to the fact that ‘whilst learning from other regions facing similar risks is possible, a lack of ‘lived experience’ and the uncertainty of the true impact of the many interacting complex factors at play in different locales, could still prove challenging to act upon.

[7] Line 59: Would be helpful to give examples of the kinds of hazard variables that might be affected here, especially when taking a multi-hazard view (e.g. the impact of extreme precipitation on slope stability).

We agree and suggest to add examples as follows

“Therefore, information on local climate change impacts on hazard variables **such as rainfall intensity and volume, prolonged dry spells or higher extreme temperatures** needs to be produced, but importantly also needs to be accessible and embedded in practical planning processes in a structured and transparent way.

[8] Line 60: I wonder if there’s another word that could be used instead of ‘adversely’ here just because it’s not often used at the start of a sentence. ‘Responsibilities... exchange of information and communication, *which has an adverse effect*’ might work better if that’s what your intended meaning is.

We agree and suggest to delete the word ‘Adversely’.

[9] Line 62: ‘homogeneous’ – explain what the homogeneity relates to

In this context ‘homogeneous’ relates to how risk communication approaches by authorities typically use one message to communicate to multiple audiences e.g. early warning alerts, rather

than a tailored or targeted approach to meet the needs of different audiences. See also examples in [R2-10]

[10] Line 64: General point – some examples throughout this section would help to reinforce and/or illustrate the points you are making. It would also help to root the discussion in the geographic context of the paper (or highlight contrasting situations in other contexts if appropriate).

We propose to add some examples for better illustration:

“Adversely, Responsibilities for planning, implementation and management are distributed across administrative offices which complicates and impedes the exchange of information and communication. In addition, the communication of climate and disaster risks to the public is typically one-way and homogeneous but can be enhanced through two-way dialogues that identify, engage and consult with specific stakeholders to develop tailored communications (requiring detailed analysis of the composition of different actors within an audience) and three-way participation where communication becomes a collective and continuous process of knowledge production between citizens, science and decision-makers (Stewart, 2024) e.g. using methods such as art- and citizen science, interactive games, role plays etc. Key differences and examples of the continuum between one-way, two-way, and three-way communications are provided by Stewart (2024). Moving from product to process, Tandem (Daniels et al., 2020) was applied in a southern African urban context addressing adaptation and disaster risk challenges in peri-urban areas using a trans-disciplinary ‘Learning Lab’ approach and ‘embedded researchers’ to bring stakeholders together to identify and prioritize challenges and co-create solutions and creating long lasting relationships, which support ongoing networks such as the public-private multi-stakeholder partnership, the Lusaka Water Security Initiative (LuWSi). Recent applications (Bharwani et al., 2024) diversified Tandem’s use in different socioeconomic settings and decision domains. A rural Indonesian community of smallholder coffee and cacao farmers co-created weather forecasts with the national meteorological office to tailor farmer field school curricula with local ecological knowledge, concepts and terminology. In Sweden urban planners, meteorological scenario modellers, hydro-climatologists and city officials co-explored compound events related to flooding (cloudburst events and spring floods) as well as heatwave scenarios to inform the city’s 2024 Stockholm’s Environmental Programme (2020-2023) and the Climate Adaptation Action Plan (2022-2025). In Colombia, a participatory group, the river basin council, including representatives from local and regional communities and institutions addressing water scarcity and inequitable access (farmers, municipalities, NGOs, indigenous populations and the private sector), co-designed a graphical web tool interface that translated hydro-meteorological data into accessible, relevant and usable information and language for basin planning, that continues to be used today. All of these processes enhanced information interoperability, as well as the capacity and confidence of stakeholders to work with and recognize the limits of climate information (Bharwani *et al.*, 2024).”

[11] Line 75: Here, it would be worth considering what the implications of these consistencies would be on decision makers (e.g. confusion and decision making that isn’t joined up across borders?)

We agree and suggest to follow the suggestion by amending the text:

“One example is the production of flood hazard and risk maps during the implementation of the European Floods Directive (2007/60/EC, 2007) with diverging definitions regarding the extreme flood scenario, which leads to inconsistencies in hazard and risk information across federal state or national borders and eventually causes confusion in decision making for trans-boundary flood risk management.”

[12] Line 84: Give full name for INSPIRE

We will spell out INSPIRE as: Infrastructure for Spatial Information in the European Community (INSPIRE)

[13] Line134-135: Is there an example that could be given here (if it's possible to do that)?

We think it is rather the norm than an exception that licences restrict the sharing of data. If need we propose to add the following examples:

“Licensing terms can restrict the use and sharing of data, since for instance scientific users might not have a legal team to handle subtleties of non-open licenses (e.g., [CC BY-NC-SA](#)), non-commercial users might not have the financial means to pay for expensive data licenses, or commercial users might not want their derived products to have open licenses (e.g., [CC BY-SA](#)). Furthermore, privacy regulations, such as those mandated by the General Data Protection Regulation (Regulation (EU) 2016/679), while necessary to protect basic human rights, impose additional layers of complexity, often requiring the anonymisation of data. For instance, simply revealing the total number of minors in a vulnerable region, while potentially valuable for risk assessment models, could also be exploited by Human traffickers, and thus requires extra care and consideration before sharing.”

[14] Section 2.2: Some illustrative examples would help to root this section in the European context.

We have added some examples in response to comment [R2-10]

[15] Line 247: Explain what ESPREssO is to help readers who may not be familiar with the project.

We suggest to add the following short explanation for the ESPREssO project:

Enhancing synergies for disaster prevention in the European Union (ESPREssO) project addressed the integration of DRR and CCA.

[16] Section 3.1: Again, some real examples would bring this section to life. At the moment it feels quite ‘hypothetical’. It would be great to include some vignettes of where these sorts of things have been attempted and it has worked/not worked.

In response to the other reviewer ‘s comments we propose to add several examples and explanation, wee [R1-5, 6, 7]. Regarding Data and Models we included a standardized resilience measurement tool that tries to overcome these interoperability gaps. We suggest to included the following text (ll 308):

“For example, the Flood Resilience Measurement for Communities (FRMC) tool not only quantitatively assesses different sources of resilience against flood risks on the community level but also highlight strengths and weaknesses in community resilience using different perspectives that

can be visualized, arranged and displayed flexibly according to the user needs (Zurich Flood Resilience Alliance 2019; <https://zcralliance.org/resources/item/the-flood-resilience-measurement-for-communities-frmc/>).”

[17] Line 363: Some introductory information about DIRECTED would be very helpful here (e.g. when it started, objectives, geographic focus) because it is only mentioned briefly at the start of the paper and there’s a lot of content before it is presented here. Is it being used in practice? Who is involved?

Our proposition is to add the following explanation of the DIRECTED Project

“The DIRECTED project with its trans-disciplinary consortium of researchers, practitioners and industry partners has begun its work in late 2022 and is scheduled to conclude in September 2026. The project’s main objective is strengthen the disaster resilience of societies by overcoming existing silos in DRM and CCA. DIRECTED aims to strengthen interoperability between modelling tools used in DRM and CCA to improve communication and governance processes. These innovations for interoperability are co-developed and implemented in an iterative approach with local project partners and stakeholder groups in four European Real Word Labs in Denmark, Germany, Italy and along the Danube River. For more detailed information on the regions and project partners, we refer to the website here (<https://directedproject.eu/#about>).”

[18] Line 365: explain what is meant by ‘new and improved’

Here ‘new and improved ways’ refers to the processes, methods and tools being applied and tested to co-design technical and governance DRM and CCA solutions (in the Real World Labs) within the Risk-Tandem framework. However, for clarity we propose to edit the sentence to the following and have added a reference to a paper (in publication) that can provide more details on the methods and tools.

“The Risk-Tandem framework is a novel approach combining risk management approaches and tools with iterative co-production methods and processes, in efforts to promote the co-design of fit-for-purpose solutions contributing toward strengthened risk governance alongside DRM and CCA stakeholders (see Parviainen et al. 2024, in review).”

[19] Line 369: a short explainer of the TANDEM framework would be helpful here. Also the IIASA risk layering approach and the SHIELD model should be explained.

We suggest to add the following explanations for these frameworks and approaches:

“The Tandem framework (Daniels et al., 2020) is a practical, non-prescriptive guide to co-design climate services by integrating diverse stakeholder goals and values, enhancing trust, and addressing multiple preferences, goals, capacities, and power dynamics. The framework has been applied in diverse settings with a range of users from municipalities in southern Africa, farmers in Indonesia, city planners in Sweden, and communities and institutions in a Colombian river basin. Each case demonstrated the framework’s effectiveness in moving from ‘useful’ to ‘usable’ information, increasing institutional embedding, improving climate information uptake, and building capacity and confidence among users and providers of climate information (Bharwani et al., 2024).

Within a risk-layer approach, frequencies and corresponding losses of disaster events are grouped into risk-layers (e.g., low, middle, high) and further related to generic risk instruments (e.g. risk reduction, risk financing and assistance). Losses in this context can be tangible or intangible, they can be measured in monetary terms based on market methods or not (Hochrainer-Stigler et al. 2023). Either way, the approach relies on the principle that different types of decision makers—e.g., in households, businesses, or the public sector—are experiencing different contexts, and each of them should therefore adopt the most appropriate strategy given their probabilistic hazard exposure, the cost efficiency of the risk-mitigating solutions they can use, and their access to financing instruments. Hence, through risk layering, gaps in individual risk measures as well as most appropriate instruments to increase resilience can be identified, both from a quantitative as well as a governance perspective (Hochrainer-Stigler et al. 2024).“

[20] Line 373: More explanation of what an ‘open-source federated data infrastructure’ is would be useful here. What does ‘federated’ mean in this context? In my experience, making information open-source can sometimes be problematic for individuals and/or organisations. It might be worth considering the challenges this might present to what you are proposing.

We suggest to add the following additional explanation to the text:

“The software underlying the federated data infrastructure will be implemented based on open source solutions and extensions to it will be made available under an open source license. This allows an easy uptake to reuse or further develop the solutions in DIRECTED beyond the project for anyone interested. The platform will be federated in a way, such that not all data sources and models have to be hosted and run in the same infrastructure, but can be connected across different institutions and deployments via Application Programming Interfaces (APIs). This way, we address the limitations arising from restrictions on data sharing which is not always freely and openly possible in the context of DRM. The open source federated data infrastructure will feature some open data and information products, but not necessarily all data will be openly available.”

[21] Line 380: expand APIs

We will expand APIs: Application Programming Interfaces (APIs)

[22] Line 385: more information on the individual real world laboratories is necessary here, e.g. the main challenges the approaches would help to overcome in each setting, who’s involved, progress so far, etc. This would help to connect this section to the earlier sections.

We suggest to add the following information about the real world laboratories, but are open to shorten, if this is too extensive.

“All Real-World Laboratories (RWLs) have identified stakeholder needs and developed use cases for the Data Fabric, selecting back-end components for model integration. Currently, they are co-designing the front-end aspects of their Data Fabric implementations, while also developing user role-specific training modules. In the Capital Region of Denmark the primary challenge lies in future planning efforts, particularly involving flood simulations, impact assessments, and uncertainty analysis for adaptation measures around Roskilde Fjord. Key stakeholders include multiple municipalities in the region. For Emilia-Romagna Region, focus areas include real-time modelling and forecasting of pluvial and coastal flooding, as well as wildfire propagation. The main

stakeholders driving this work are the regional civil protection authorities, firefighting services, and volunteer organizations. These groups prioritize inter- and intra-organizational communication and coordination, with a specific focus on engaging tourists in the region. The Danube Region has two focus areas in Vienna (Austria) and the Hungarian Zala region. This RWL addresses urban pluvial flooding and the impacts of climate-related floods and droughts on agriculture and tourism. Stakeholders range from local first responders to international insurance companies. A key objective is the development of consistent, cross-national data sets and models for disaster risk management (DRM) and climate change adaptation (CCA). The Rhine-Erft Region focuses on improving communication and coordination among stakeholders, including the Waterboard Erftverband, municipalities, and emergency management services. Current efforts involve integrating social vulnerability into cost-benefit analyses for climate change adaptation, with a focus on strengthening governance at all levels.”

## References

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