



OPEN ACCESS

EDITED BY
Anna Scolobig,
Université de Genève, Switzerland

REVIEWED BY
Fatemeh Jalayer,
University of Naples Federico II, Italy
Ahmet Cevdet Yalciner,
Middle East Technical University, Turkey
Remy Bossu,
European-Mediterranean Seismological
Centre, France

*CORRESPONDENCE
Simone Rödder,
simone.roedder@uni-hamburg.de

SPECIALTY SECTION
This article was submitted to
Geohazards and Georisks,
a section of the journal
Frontiers in Earth Science

RECEIVED 21 May 2022
ACCEPTED 12 August 2022
PUBLISHED 08 September 2022

CITATION
Rödder S and Schaumann F (2022), "It's
something that I do every day."
Exploring interdisciplinarity and
stakeholder engagement in
tsunami science.
Front. Earth Sci. 10:949803.
doi: 10.3389/feart.2022.949803

COPYRIGHT
© 2022 Rödder and Schaumann. This is
an open-access article distributed
under the terms of the [Creative
Commons Attribution License \(CC BY\)](#).
The use, distribution or reproduction in
other forums is permitted, provided the
original author(s) and the copyright
owner(s) are credited and that the
original publication in this journal is
cited, in accordance with accepted
academic practice. No use, distribution
or reproduction is permitted which does
not comply with these terms.

"It's something that I do every day." Exploring interdisciplinarity and stakeholder engagement in tsunami science

Simone Rödder ^{1*} and Felix Schaumann ²

¹Faculty of Business, Economics and Social Sciences, Department of Social Sciences, Universität Hamburg, Hamburg, Germany, ²Faculty of Business, Economics and Social Sciences, Department of Economics, Universität Hamburg, Hamburg, Germany

Tsunamis are natural hazards that can have devastating societal impacts. While tsunamis cannot be prevented, their risk to coastal communities can be mitigated through targeted measures such as early warning, evacuation training or tsunami-aware spatial planning. The particularities of tsunamis—being rare events with high impact and a short yet operable time span for warning—structure the associated research approaches and sociotechnical innovations. In this paper, we explore interdisciplinary knowledge integration and stakeholder engagement in tsunami science based on interviews with researchers from various tsunami-related fields. We find that the interviewees' academic identities are typically grounded in a disciplinary core, out of which they subsequently cross boundaries. For all respondents, however, it is a matter of course that becoming and being a member of the tsunami community includes the need to communicate across boundaries. Our results show that the idea of early warning unites the tsunami field. Notably, however, it is not the material technology but the political goal of effective early warning that holds an integrative function across disciplines. Furthermore, we find modelling to be seen as the "backbone of everything" tsunami-related, which in combination with visualisation techniques such as a global map of tsunami risks also serves to integrate stakeholders beyond the tsunami research community. Interviewees mention the interaction between scientists and engineers as the exemplary interdisciplinary collaboration in tsunami science. There were fewer examples of collaborations with social scientists, rendering this a demand rather than a lived reality in current tsunami science. Despite the widely shared view that stakeholder engagement is an important element of tsunami science, respondents emphasise the associated challenges and indicate that this practice is not yet sufficiently institutionalised.

KEYWORDS

tsunami, interdisciplinarity, stakeholder engagement, geohazard, early warning

Introduction¹

Tsunamis are natural hazards and pose societal risks, as evidenced by the 2004 Boxing Day and the 2011 Tohoku events. While tsunamis cannot be prevented from happening, their risk to coastal communities can be mitigated through targeted measures such as early warning, evacuation training or tsunami-aware spatial planning. These applications require both basic and applied research efforts to understand tsunami sources, wave propagation and local inundation dynamics, as well as efforts to understand the social dynamics around tsunami warning, local governance, public education and trust. Several sciences, including geology, geophysics, oceanography, physics and mathematics study the creation and evolution of tsunamis. Social sciences such as political science, human geography, economics and sociology, but also civil engineering and urban planning, are involved in tsunami risk assessment and mitigation on shore. The peculiarities of tsunamis lie in that they are rare events with often catastrophic impacts and a short yet operable time span for warnings. It is thereby the goal of scientists of different backgrounds involved in tsunami research to bridge disciplinary divides and work together to mitigate tsunami risks.

The paper at hand aims to explore interdisciplinary and stakeholder integration by reflecting on current practices and challenges in tsunami research. We are interested in understandings of interdisciplinarity, risk and uncertainty among tsunami scientists, and base our analysis on problem-centred interviews with participants of the EU COST Action “Accelerating Global science In Tsunami HAZard and Risk analysis” (AGITHAR) complemented by observing participation in AGITHAR’s initial meeting. In the following, we firstly revisit the challenge of interdisciplinarity from a sociology of science perspective (2). We then review the literature on interdisciplinarity in tsunami science and derive a set of research questions for the interview study (3). Subsequently, we introduce the study’s methodology and sample (4). The main part of the paper presents the results (5), discussion and conclusions (6).

Scientific disciplines and the origins of interdisciplinarity

The emergence of modern scientific disciplines dates back to the 18th century and there is no doubt as to their ongoing structural significance for both research and education. The complexity of disciplines as a phenomenon requires a

multidimensional definition. In social terms, disciplines are communities of specialists whose infrastructure includes university chairs and departments with associated training programmes in the form of degree courses, and journals with disciplinary members as authors and editors (Stichweh, 1984: 449). In epistemic terms, a discipline can be described as a self-reproducing context of concepts, theories and methods, which are confirmed, modified or discarded in time through research. In communicative terms, one observes publications that link to one another by means of citations and continually redefine the boundaries of the discipline by means of principally contingent acts of referencing (Stichweh, 2013: 2).

Yet, the advent of disciplines and their role in the production of scientific knowledge have always been accompanied by *interdisciplinarity* (Abbott, 2001: 121). Due to its historical character, the disciplinary scheme “cannot be conceived as a perfect order of knowledge” (Luhmann, 1992: 456), and the condensation of attention within disciplinary boundaries has disadvantages: “As soon as the disciplines burst apart like ice floes and, albeit in the water, bob along their own paths: what then becomes of the “in between”? What becomes of “overarching questions” that can only be dealt with when the expertise of several disciplines comes together?” (Luhmann, 1992: 456). Interdisciplinarity can then be seen as the attempt to address these “impediments to vision” and to reintroduce them into the research (Luhmann, 1992: 459). Another motive for interdisciplinarity links to societal interests. In addition to blue-sky research, scholars seek to develop solutions to real-world problems. For this, collaboration between disciplines (interdisciplinarity) is seen as a prerequisite, as is crossing the boundary between science and society by including non-scientists, an approach often associated with the labels *transdisciplinarity* or *stakeholder engagement*.

The science policy discourse around inter- and transdisciplinarity often frames disciplines as obstacles in the way of real-world problem-solving and useful knowledge production (Weingart and Stehr, 2000). Inter- and transdisciplinarity then are repair phenomena to remove knowledge-limiting disciplinarity, and research policy promotes the production of integrated knowledge. The pre-disciplinary 17th and 18th centuries and the disciplinary 19th and 20th centuries are now said to be superseded by post-disciplinary times (Weingart and Stehr, 2000: xi; Klein, 1999), characterised by a plurality and diversity of places, methods and actors in knowledge production. Criteria such as social relevance and robustness (Nowotny, 2003) complement quality assurance by peers, and extended peer communities come into play (Funtowicz and Ravetz, 1993). While the disciplines have so far enabled the accumulation of knowledge within paradigmatic “normal science” in Kuhn’s sense, the new “post-normal science” is characterised by uncertainties, value conflicts and an urgency of political decisions (Funtowicz and Ravetz, 1993). Climate sciences (Bray and von Storch, 1999) and tsunami science are cases in point. The question then is not *whether* but *how*

¹ We use UK spelling throughout the manuscript.

*interdisciplinary knowledge integration and stakeholder engagement are to be pursued by scientists in the tsunami field.*²

Why is interdisciplinary integration such a challenge? The fact that knowledge integration is a challenge is rooted in the principles of disciplinary differentiation. The neo-Kantian philosopher Wilhelm Windelband (1904) for example, distinguished the natural sciences from the humanities by attributing the search for general laws to the former and the description of unique individualities to the latter as their epistemic goals. Another answer to the question of how disciplines differ is by their methods. Mathematics, for example, can be characterised by the methodology of proof (Heintz, 2000). Physics, however, also sometimes uses proof, which shows that specific methods are not discipline-exclusive. Furthermore, methodological pluralism prevails within most disciplines. In a tradition of thought that began with Fleck's (1979) reflections on scientific styles of thought in the 1920s, Kuhn proposed the term paradigm to describe how communities of specialists group around a theory and make it the basis of their research activity (Kuhn, 1962). According to psychologist Heinz Heckhausen (1987) it is this conceptual level of integration that constitutes disciplinarity and goes hand in hand with specific types of abstractions. This results in incommensurability—a level of difference that even makes comparisons impossible—both between historically successive paradigms of a discipline and between disciplines. These challenges are exacerbated in transdisciplinary settings. By definition, transdisciplinary projects should meet and adequately address scientific and other demands, such as political, economic or public interests. This leads to a default expectation of challenges, as Maasen and Lieven (2006) have put it, based on an in-depth study of transdisciplinary practice: “Notably, negotiating, coordinating and integrating heterogeneous types of knowledge, values and interests are bound to cause complexities that border on the irresolvable task of rendering incommensurabilities commensurate” (2006: 402).

The different lenses that the disciplines apply to natural and social phenomena go hand in hand with socialisation processes into disciplinary communities: over the course of their training, junior researchers acquire specific sets of values and beliefs, such as in quantification and modelling. This is in line with organisational theory (Whitley, 2000), which finds that scientific reputation—gained by publications in prestigious, mostly disciplinary journals—is the key mechanism that controls the institutionalisation of a field as an epistemic

community (Gläser, 2006). Anthropologists of science have thus come to describe disciplines as “academic tribes” (Becher and Trowler, 2001: 39) that defend knowledge monopolies on certain territories. The sense of belonging to an academic tribe, typically evidenced by a formal academic degree, creates academic identities at the disciplinary level, which include interaction preferences as well as a certain sense of humour, dress and lifestyle. Science & Technology Studies scholar Sheila Jasanoff puts the resulting challenges as follows:

“[W]e academics, whatever our disciplines, tend to be rather a lazy lot when it comes to tending our relations with those outside our own disciplinary enclaves. Conversations with close colleagues are ever so much easier, more efficient, and often just plain more fun, because even quite fundamental disagreements are grounded in a common matrix of shared concepts and commitments. Why bother with the far more difficult task of engaging outsiders in one's most passionate pursuit when the results are bound to be time-consuming and by no means guaranteed to win understanding, let alone friends?” (Jasanoff, 1996: 264).

The field of tsunami science and its integration challenges

Knowledge production in tsunami science

Throughout the last decades, the field of marine geo-hazards—which include tsunamis—has been experiencing a continuous rise in publication activity (Camargo et al., 2019). Tsunami science in particular has seen a strong increase since 2005. The spike in this specific year can be traced back to research taking place in the aftermath of the Sumatra Tsunami on Boxing Day 2004 (Chiu and Ho, 2007; Sagar et al., 2010; Jain et al., 2021). The 2011 East Japan Tsunami triggered another rise in tsunami-related research activities, especially in Japan (Imamura et al., 2019). Yet, the surge in research activity after a tsunami event is often not sustained for more than a few years (Sagar et al., 2010).

Since the early 1990s, the development of tsunami early warning systems (TEWS) is pursued as one of tsunami science's key objectives (Synolakis and Bernard, 2006; Kanoğlu et al., 2015), on the basis of hazard and risk assessments and alongside other precautionary measures such as evacuation maps and tsunami signage installed at the inundation zone. The short, yet operable time span between the causing event and the incidence of the wave at the coast distinguishes tsunamis from other natural hazards. While hurricanes and other meteorological events can often be predicted days in advance, earthquakes are barely predictable at all. The resulting challenge for tsunami science is twofold. First, coastal communities must be equipped with hazard and risk assessments to initiate precautionary measures (Løvholt et al., 2019). Second, in the case of an event, the warning must reach local communities in

² Throughout this paper, we refer to any research that involves two or more disciplinary perspectives as interdisciplinary research. We furthermore differentiate narrow interdisciplinarity, which refers to the interaction of neighbouring scientific fields, such as geology and geophysics or sociology and communication science, from broad interdisciplinarity, which describes the interaction of fields with very different disciplinary cultures such as physics and sociology.

time and lead to an immediate evacuation. Both challenges contain natural and social elements that cannot easily be disentangled (Bradley et al., 2019; Raffiana et al., 2022). For the necessary precautionary measures to be in place, the science must be sound and the political and administrative processes must work. In the case of an event, successful evacuation not only depends on whether the warning has been issued and transmitted to local communities on time, but also on whether the local infrastructure is working properly and whether local communities have enough trust in the warnings to indeed evacuate (Pescaroli and Magni, 2015; UNDRR and UNESCO-IOC, 2019; Raffiana et al., 2022). With regard to evacuation it is furthermore important to distinguish between self-evacuation without an alarm being issued (can happen in the case of near-source or non-seismic tsunamis) and evacuation after an alarm is being issued by the authorities. Also the question arises how the implementation of early warning systems impact the capacity to self-evacuate. A dilemma, especially in densely populated areas and areas with infrastructures such as power plants, ports or refineries, is *not to evacuate* in the case of no wave, because the damage caused by an incorrect evacuation (which can be the more frequent case) is greater than that caused by a non-evacuation. This dilemma complicates matters for TEWS developers and decision-makers because of the high uncertainty and the short warning time.

Models play an important role in integrating different sources of knowledge that are important to tsunami science. Given the lack of empirical tsunami observations—since large tsunamis are rare events—numerical modelling is a key “tool to establish links between source parameters and hazard metrics” (Grezio et al., 2017: 1170). Tsunami modelling increasingly takes the form of a Probabilistic Tsunami Hazard Analysis (PTHA; Grezio et al., 2017; Løvholt et al., 2019; Behrens et al., 2021), which aims to estimate the probability of exceeding a certain tsunami metric at a given location within a given time period. According to Løvholt et al. (2019), PTHA usually comprises information on tsunami sources in a probabilistic manner, including uncertainties from both natural variability and lack of knowledge, as well as a description of how the tsunami and its associated uncertainties propagate to the impact site. However, the authors state that PTHA—due to its origin in seismic hazard analysis—is more developed in its description of earthquake-induced tsunamis and less developed for non-seismic tsunami sources. While PTHA integrates sources, wave propagation and inundation dynamics in a single framework, Probabilistic Tsunami Risk Analysis (PTRA) goes even further by estimating losses by accounting for exposed values and the vulnerability of coastal societies. As such, PTRA must include geophysical modelling of the source dynamics and hydrodynamic modelling of tsunami creation and propagation as well as geographic, economic and sociological accounts of exposed buildings, damage to critical infrastructure and local preparedness. Especially when considering the risk of mortality,

aspects related to the vulnerability of different societies and local tsunami protection measures have a large influence on PTRA results (Løvholt et al., 2019). PTHA can thus be considered a modelling framework that comprises the natural science aspects of tsunamis, whereas PTRA also includes human and societal aspects, and consequently requires input from social sciences as well as stakeholders such as coastal protection agencies and local governments.

Knowledge integration in tsunami science

The applied nature of the tsunami field makes interdisciplinary work indispensable, yet challenges to interdisciplinary research clearly show in the sparse literature on knowledge integration in tsunami science. Yonezawa et al. (2019) studied the International Research Institute of Disaster Science (IRIDeS) of Tohoku University in Japan. IRIDeS was established in the aftermath of the 2011 East Japan Earthquake and Tsunami with a strong focus on multidisciplinary (Imamura et al., 2019). To assess opportunities and limitations of IRIDeS's approach, Yonezawa et al. (2019) conducted semi-structured interviews with 15 researchers. They conclude that the integrated research focus alone was not sufficient to enable truly interdisciplinary work. Interviewees stated that they feel an obligation to “master the current established discipline as their own expertise first” (2019: 7) because they were not being equipped with a comparable interdisciplinary approach on which to build their careers. Further barriers mentioned include the negative effect of interdisciplinary research on internal evaluation and reputation mechanisms because of difficulties to publish and attract external funding. These barriers were mainly traced back to the organisational structure of the institute, which had four disciplinary-based subdivisions. An administrative restructuring in 2018, however, has redefined research areas based on real-world problems. This restructuring, according to the interviewees, led to more constructive exchanges between researchers with different disciplinary backgrounds. Still, the authors conclude that there are significant barriers to effective interdisciplinary research even in an environment that pursues interdisciplinarity as an organisational goal. Kelly et al. (2019) take a more general approach to enabling mechanisms and barriers in interdisciplinary research. The authors formulate their findings in 10 tips for interdisciplinary researchers related to common barriers. These include language barriers between disciplines, limited guidance for interdisciplinary students and young researchers and a lack of reputation opportunities for interdisciplinary research within established disciplines. Further, they state that interdisciplinary collaboration takes more time initially, is harder to publish and often lacks funding opportunities.

Researchers working in interdisciplinary projects also contribute to the literature. In disaster science, which includes tsunami science, several papers have been published about the relevance of interdisciplinarity, viable approaches towards it and associated challenges. [Takara \(2018\)](#) wrote a discussion paper based on conversations with fellow researchers on disaster risk reduction, in which he emphasises the importance of new knowledge systems, which should be “integrating scientific as well as local and indigenous knowledge” (2018: 1195). Takara views a consistent terminology as the backbone of any such knowledge system and proceeds to define and elaborate basic distinctions in interdisciplinary disaster risk reduction. Disaster risk, for instance, is defined as the product of hazard, exposure and vulnerability ([Takara 2018](#); [Løvholt et al., 2019](#)). The paper calls for a harmonisation and shared understanding of the terminology and concludes with five recommendations. These include a call for further interdisciplinarity in disaster science, stakeholder involvement and a stronger consideration of different social vulnerabilities and complex, compounding risks.

In a perspective essay, [Ge et al. \(2019\)](#) had a closer look at interdisciplinary teams in the context of research on disaster response. The three showcased teaming mechanisms are called grant-driven, institute-based and expertise-oriented. Grant-driven teams are multidisciplinary teams, which means that they involve researchers from different disciplines but without developing shared connections, approaches and concepts ([Hardy, 2018](#)). Institute-based and expertise-oriented teaming mechanisms in contrast are considered truly interdisciplinary. The difference is that institute-based teams have a rigid and localised organisational structure, whereas expertise-oriented teams are often a loosely structured network aiming for “long-term research proliferation” ([Ge et al., 2019](#)). Having established an interdisciplinary disaster research team, the challenge is to find common ground, as [Gilligan \(2019\)](#) puts it. The goal is to “build trust, facilitate communication, and develop interactional expertise.” In contrast to contributory expertise (the ability to fruitfully contribute to research within one discipline), interactional expertise describes the ability to interact by processing languages and concepts from different disciplines. Researchers with interactional expertise are useful in interdisciplinary teams because they mediate in communication and translation. [Gilligan \(2019\)](#) further emphasises the role of tacit knowledge, which is a form of knowledge about a field that develops through professional interaction and cannot be spelled out explicitly. In terms of strategies to foster interdisciplinarity in disaster science, the author proposes “intensive focused interactions” (e.g., interdisciplinary teaching, interdisciplinary research, workshops or sabbaticals) and collaborative fieldwork. He suggests a gradual approach, which continuously builds up interdisciplinary skills through meetings, projects and institutions and, through this mutual learning forms common ground in an emerging interdisciplinary research field. In

another perspective essay, Hardy expands on strategies of establishing common ground in hazard research. The author proposes a “sharing meanings approach” ([Hardy, 2018](#)), an iterative process of sharing, listening and questioning to productively make use of the tensions between disciplines. The article comes up with strategies on how to cope with different worldviews, disciplinary languages and perspectives on the research design and project goals. By employing these strategies, Hardy hopes that implicit assumptions can be made explicit, which in turn helps an interdisciplinary research team to progress towards a “hybrid methodology research design” (2018: 8).

In an empirical paper, [Martinez et al. \(2018\)](#) emphasise the beneficial role of qualitative research for understanding local phenomena and dispositions, both for social and natural scientists. Interviews with researchers participating in an EU project indicated that a shared methodology was considered very helpful across disciplinary backgrounds and helped to establish an encouraging atmosphere for interdisciplinarity. Yet, the authors also note that knowledge integration requires a lot of engagement and is not supported from the start in EU research projects. Specifically, they criticise that individual work packages and deliverables are often centred on established disciplines and that projects lack a pilot phase in which to develop common ground and a shared interdisciplinary research agenda. They conclude that, in practice, this often leads to mere grant-driven teams—multidisciplinary collaborations, where “one discipline works on one aspect of a project and a different discipline on another” (2018: 71). [Martinez et al. \(2018\)](#) had science and social science & humanities researchers work together on qualitative interviews, and natural science researchers stated that this increased their understanding and recognition for social sciences. [Kirby et al. \(2019\)](#), however, found that earth scientists perceive social scientists as significantly less competent than themselves or natural scientists in general, supporting often-held notions of hierarchies between “hard” and “soft” sciences.

Having reviewed experiences with and approaches to interdisciplinarity in disaster science, what are the lessons for tsunami science? As showcased by [Takara \(2018\)](#), disaster risk is composed of a natural hazard component and a social vulnerability component. Tsunami risk is different from other natural disasters in that it is largely influenced by the capabilities of local communities to self-evacuate quickly. This feature has consequences for interdisciplinary tsunami research, e.g., for possible new knowledge systems. Knowledge production across disciplines typically relies on integrating mechanisms, which provide a unifying framework (such as a model or a static or dynamic map) and allow researchers to more easily collaborate ([Sarewitz and Pielke, 2001](#)). For disaster response, [Ge et al. \(2019\)](#) propose data collection as an integrating mechanism. [Gilligan \(2019\)](#) suggests that collaborative fieldwork could serve as an integrating mechanism in disaster research. More research

is needed, however, to understand the mechanisms that integrate tsunami researchers and provide them with a shared understanding of their field. While insights into teaming mechanisms and the development of common ground through unified terminologies and shared meanings can be adapted from disaster science in general, the focus on numerical modelling and warning systems raises special questions about knowledge integration in tsunami research. An exploratory study of interdisciplinarity in tsunami research is so far lacking yet needed to tackle the challenges that this field poses.

Materials and methods

Methodologically, we employ the problem-centred interview approach (Witzel and Reiter, 2013). This perspective from interpretative social sciences puts the interviewees' understandings, meanings and practices front and centre. From this follows that we developed a semi-structured interview guide, i.e., a set of questions which broadly structure the interview while allowing us to adapt them to the respondents' expertise, interests and reflections. The interview guide was informed by our conceptual considerations on (inter-) disciplinarity and a literature review³. From the AGITHAR participants, we selected nine interviewees according to several pre-defined criteria. First, the interviewees have diverse academic backgrounds including seismology, mathematics, engineering, sociology, and statistics. This allowed us to include a broad range of perspectives on the field of tsunami science. Second, we covered different methodological approaches, including fieldwork, modelling, and development of early warning systems. Third, we aimed for diversity in geographical background and gender.

Our final sample includes four female and five male researchers. Three out of nine researchers came to the field prior to 2004, four between 2004 and 2011, and two joined the field after 2011. While our sample includes some early career researchers, the focus was on senior researchers because we expected them to have more years of experiences in collaborations and more insight into long-term developments of the field and the associated research community. All interviews were conducted in June 2020, remotely via Zoom or Skype. Depending on the respondents' preferences, it was an audio or a video call of about 45–60 min length. The audio track of the interviews was recorded and transcribed word-by-word. Throughout the interview process and transcription, we took notes, paying attention to emerging commonalities or conflicts.

³ We used Web of Science to perform a keyword search based on: "TS = (((interdisciplinar* OR transdisciplin*) AND (tsunami* OR "disaster science" OR "disaster research")))."

For the small number of interviews, we decided not to use any software for qualitative data analysis. Instead, we produced case descriptions of three to five pages for each interview, which were structured along predefined categories. In a second step, this allowed us to compare statements from different interviews. We identified several recurring themes, around which we organised further analyses. In our presentation, we cite from the interviews by referring to the respective number of the interview and the line of the respective quote (e.g., 2: 34).

Results

The tsunami community and boundaries in tsunami science

Tsunami science appears as composed of strong disciplines with firm boundaries and specific disciplinary abstractions of phenomena, such as waves, and concepts, such as risk.

It contains the whole geoscientific community, starting from oceanography, seismology, geology, geophysics. Already there you see many clashes, between oceanography and seismology, for example. Their understanding of what a wave is, is so completely different that you have to communicate a lot. And then, when it comes to the impact, you have the disaster managers who are often either military people or social scientists and there again, you have misunderstandings and different approaches to things. (1: 35)

The way respondents talk about their academic identities implies that they typically are grounded in a disciplinary core, out of which they subsequently cross boundaries.

My whole life I have been crossing disciplinary boundaries. (1: 27)

I am a geophysicist by training, a seismologist, and this is what I do well. I don't do, for example, social science research myself, I don't do landslide modelling, but I think I'm good at facilitating interdisciplinary work. And I think that's very characteristic for my view on interdisciplinarity. Being an interdisciplinary scientist doesn't mean that you have to address all these different disciplines, but you have to find the right people and bring them together. (2: 21)

Some claim to have developed interdisciplinary identities, yet still speak of "other disciplines" as their counterparts:

I call myself interdisciplinary researcher because from the beginning of my tsunami research I always collaborated with all scientists, and I shared my data and tools with the experts

from other disciplines and I also expect sharing from other disciplines. (9: 32)

I really jumped across fields, and I had to incorporate different methods. (4: 13)

In the latter case, the interviewee, who is a junior researcher, invokes that it might cause issues if a researcher does not “*fit in a traditional scientific environment*” (4: 263) because he works in different disciplines with no clear primacy of a disciplinary core. For all respondents, however, it is a matter of course that becoming and being a member of the tsunami community includes the need to communicate across boundaries.

It's something that I do every day. (7: 246)

Researchers' understandings of interdisciplinarity, and the need for it

There is no doubt as to the relevance of interdisciplinarity for the field. Unanimously, the interviewees characterise tsunami science as an interdisciplinary field.

Interdisciplinarity is one main, essential component of tsunami research. (9: 4)

I think it is humbling to know that we cannot address this problem with one discipline. (6: 27)

There is no way to work in tsunami risk assessment with one discipline only. (6: 33)

To explore the nature of interdisciplinarity in tsunami science, the researchers' own understandings of the concept are relevant. Throughout the interviews, we find experience-informed and rather sophisticated accounts of the phenomenon, indicating that tsunami researchers indeed work in contexts that they themselves perceive as interdisciplinary. As one interviewee puts it: Interdisciplinarity,

It's about different scientific approaches that are discipline-specific and to bridge by language the different approaches and to communicate over boundaries of disciplines in order to gain new knowledge that is not gainable within one discipline. (1: 4)

A framing of interdisciplinary research that pervades many interviews is to distinguish between basic and applied science, where basic “blue sky” research is done for its own sake and applied research strives to produce benefits for society.

Science is not only for the scientists, science is for the benefit of the society in general. (5: 37)

The judgement that “*most of the new knowledge gain comes from crossing disciplines*” (1: 22) is perfectly in line with the EU's and other funding organisations' dominant science policy discourse. While several respondents indicate an internal motivation—research works better when conducted interdisciplinarily—, the dominating motivation seems to be external: interdisciplinarity is necessary to tackle real-world issues and benefit society.

Interdisciplinary approaches to problems involve all the different elements of the problem - the societal as well as the scientific. (8: 9)

The major understanding of interdisciplinarity entails bringing multiple researchers with different backgrounds and competencies together to jointly solve a problem. According to all interviewees, the topic of tsunamis unavoidably requires knowledge from a range of different disciplines to achieve the field's overarching goal to mitigate tsunami impacts for coastal communities. Because of this, the field's interdisciplinarity is seamlessly expanded to include stakeholders beyond the disciplinary system of science.

Interdisciplinarity starts to connect not just scientists of different fields but also people who work more closely to society, connecting different types of scientists to engineers, policymakers and stakeholders, trying to tackle a problem from a more well-rounded and readily applicable approach. (8: 3)

You need to work interdisciplinarily in order to implement new scientific results in society. (2: 18)

The stated reasons for why tsunami science is interdisciplinary also shed light on organising dimensions within the field. Examples include the difference between the geoscientific nature of the natural disaster and the socioeconomic aspect of its impacts, as well as the associated difference between hazard and risk assessment.

To fully understand the hazard in combination with the risk, we must draw from different fields and different disciplines. (4: 37)

Hazard and risk are often invoked as categories to describe two big camps in tsunami science: the basic science part on the one hand and approaches that include vulnerabilities, impacts and damages on the other. A further differentiation was introduced by a scientist who distinguishes.

Source people, [...] tsunami modellers, [...] engineers and [...] social scientists. (2: 150)

Several respondents distinguish degrees of interdisciplinary collaboration, ranging from the interaction of neighbouring fields

to that of science with local communities, i.e., stakeholder engagement.

It can be between similar sciences, such as modellers and risk analysts and then it can be between geologists and mathematicians, for instance, which are different sciences. It can be across, but still within the natural sciences; it can be across even these borders, such as between social sciences and natural sciences and this is in tsunami science on all these scales. [...] It can also be among practitioners and basic science; it can be between early warning, which is operational, and risk analysts, which is also kind of operational, [...] and simply people trying to figure out how things occur in nature. And they all overlap. (7: 5)

As this example indicates, tsunami researchers typically hold a broad understanding of interdisciplinarity that even includes transdisciplinarity. This broad interdisciplinarity, however, is “where the big issues lie (...) because the mind-set and the culture how to work is so different” (7: 279/283). Interviewees mention the interaction between scientists and engineers as the exemplary interdisciplinary collaboration in tsunami science. There were fewer examples of collaborations with social scientists, rendering this a demand rather than a lived reality in current tsunami science.

We need to cooperate with [...] the social sciences in order to implement many results. (2: 31)

We have to communicate the results to the general public. [...] In this, the physical scientists, the natural scientists, should communicate very closely with sociologists, with decision-makers. (5: 257)

Often, the social sciences seemed to be limited to risk communication, tasked with taking the results of the natural sciences and disseminating them to society. This is also reflected by views on the interaction of social scientists with models, where interviewees stated that “they use the results” (1: 214, also 4: 167) and that models are “a tool to communicate” (6: 147).

Integrating mechanisms in tsunami science

The way interdisciplinarity in tsunami science is described is sometimes merely additive:

I think this gives the opportunity of working together for the same topic but looking at different facets of this topic and to have final results that have many aspects. (4: 38)

Others, however, have a more integrated understanding:

We kind of already blur the boundaries between different disciplines and we try to learn what others are looking at and try to comprehend that and incorporate that into our views, our meanings. [...] It's really by topic and we don't argue anymore about what disciplines we are bringing in, because whatever background is important and is appreciated. (6: 38)

It should be possible to create a common language, but I don't think it's very well established. (7: 121)

We were interested in whether, and if so, which integrating mechanisms exist in tsunami science, mechanisms that may provide a unifying framework (such as a model or a map) and allow researchers to develop joint projects and goals and to successfully collaborate across disciplinary boundaries. Not surprisingly, modelling is widely acknowledged to have a central role in tsunami science. Respondents describe it as the “backbone of everything” (2: 114) and as “instrumental” (6: 147, 7: 78). Some integrative functions are reported:

Modelling offers a way of assessing multiple aspects of a hazard, for example, earthquakes of different magnitudes that could happen in a particular region. (4: 162)

At the same time, respondents emphasise that models have clear limitations, can be misleading if applied blindly, and must be employed and communicated properly. Some respondents voice the concern that modelling outcomes might uncritically be mistaken for some absolute truth if the interaction with coastal stakeholders is not mediated by eye-levelled science communication. A social scientist gives an example:

What you choose is to do things pragmatically, like “this and this is the modelling, now you develop your evacuation maps” with this guideline. But the thing is, with the lack of science communication, people see that modelling not as a suggestion, but rather as a truth, like “that is exactly what's going to happen and if we don't do something then we're gonna die. (6: 202)

This researcher displays an empowerment approach to stakeholder engagement, arguing that tsunami risk communication must start with the stakeholders' needs.

They want to have things certain, “Should I move or not?” “Should I go or not?” And scientists cannot answer in that way. But then it needs time to explain that these are probabilities and I think it needs a certain level of humbleness to also tell them “We don't know.” But bringing in modelling without explaining that I think will create a problem. (6: 221)

A key aspect of tsunami science that requires interdisciplinary collaboration is early warning. Several respondents indicate that the idea of early warning unites the

tsunami field. Tsunami risk mitigation through risk analysis, risk assessment and early warning is considered a vital part of tsunami science by most interviewees:

Early warning science in the case of tsunamis would not be possible without interdisciplinary research or interdisciplinary interaction. (3: 108)

Several respondents, however, emphasise that early warning is “one branch of it and it’s important, but it’s not the only thing” (7: 74), that “the early warning system itself is the technical approach” (3: 282) and that it is an “important component of the science, but it’s more standalone” (2: 127). Asked about whether early warning could serve as an integrating mechanism for tsunami science, respondents were rather sceptical. Because early warning is not a core part of tsunami science, i.e. a genuinely scientific task, but more “an implementation of the science” (2: 130), it can serve as “an important motivation for improving modelling and source descriptions” (2: 124), but not as something that everyone works towards. In the words of another respondent, “the dream of effective early warning, that might be the bracket between different communities” (3: 285), but not the early warning system itself. Notably, it is thus not the material technology but the political goal of effective early warning that holds an integration function across the field.

Another candidate for an integrating mechanism is a global risk map, as obtained by a PTR. Determining tsunami risk and mapping its distribution is an important aim:

The term risk, in tsunami science, is very important; you should determine risk properly and you should map the distribution of risk. (9: 123)

Besides forming a shared goal, the development of comprehensive risk maps can also serve integration, especially when it comes to extending interdisciplinary collaboration beyond the aspects of hazard, into the domain of the social sciences:

When it comes to risk maps, for example, they [social scientists] are also involved, because developing a model for risk contains several parts: that is the hazard part obviously that comes from the natural sciences, but then it also contains the vulnerability part which comes much more from the social sciences. (1: 215)

The tsunami community’s history and relationship with society

Many respondents confirm the tsunami on Boxing Day 2004 to be a central turning point for tsunami science. Some entered the field because of the 2004 event and the subsequent rise in research funding.

Until 2004, that was a very very closed, small community, and then many new people came in. (1: 507)

After the Sumatra earthquake 2004, [...] tsunami science completely changed. This is when many of us started working on tsunamis. (3: 98)

After 2004 we saw that there are many more components that we need other experts and we saw that the interdisciplinary research makes the tsunami science much more developed. (9: 41)

Often, this point is linked to reflections about public research funding.

Each big disaster in a way fosters research, then you have many people doing something and then only few survive because then funding is decreased again. (1: 510)

According to several respondents, the current level of funding for tsunami research in Europe is seen as insufficient. Also drawing on the example of the 2011 tsunami event, interviewees complain that “the interest is after the events, not beforehand” (5: 103), such that the funding of tsunami-related research peaks after catastrophic events and subsequently declines again. This is linked to the characterisation of tsunamis as low-frequency, yet heavy-impact phenomena, a problem for data collection as well. As an effect of their low frequency, tsunamis “do not cause a constant coping with tsunami hazards” (5: 107), which is taken to explain the varying amounts of funding. To highlight the importance of this research and to secure funding, the applied field of tsunami science—paradoxically—depends on the actual reoccurrence of catastrophic tsunami events. This situation is sometimes contrasted with earthquakes, where constant coping with seismic hazard could be observed for several world regions.

In terms of hazard modelling, the field of earthquakes is more developed. [...] tsunami modelling is not as developed of a field and so there are still a lot of questions [...] It’s just a younger field. (8: 105)

Several respondents compare tsunami science to earthquake science. They note that tsunami science is structured differently to earthquake science due to the differences in predictability. While earthquake prediction and early warning is possible, the time between warning and event is much shorter than for tsunamis.

The difference between an earthquake and a tsunami is that the tsunami is triggered by the earthquake and then the waves are travelling. Just by the travel time, forecast is possible. Early warning is possible. (3: 85)

As a result, disaster prevention focuses on construction that can withstand seismic shocks, which explains the high degree of collaboration with engineers.

In the case of earthquakes, it's more important to build strong structures that will protect lives inside. So the built environment becomes very important, whereas in the case of tsunamis, there are some solutions like building sea walls [but] it may be more important to train the public to react rather than the engineers to build suitable structures [...]. So it may be that the community has to be involved more in the solution. (8: 159)

For tsunamis, the built environment is also important, but the travel time of tsunami waves additionally allows for evacuating coastlines and getting people to safety. This requires that the warning system is fast enough, populations trust the warning, and evacuation procedures are organised and clear. In case the official warning does not arrive or does not arrive in time, communities should be familiar with natural warning signs as well as with self-evacuation procedures. To understand the dynamics of trainings, power, trust and operational procedures in local communities, tsunami science thus needs—on top of interaction with engineers—collaboration with social sciences. In the interviews, however, examples of collaborations with engineers prevail.

If you go to the seismic hazard community, which is probably a bit more mature, [...] then you see that to an increasing degree now the engineers are being included in projects, so there is more focus from hazard towards risk, and that you're going more in this direction of urban planning and societal implementation of the results. (2: 100)

When asked about the extent to which tsunami science is conducted for preventing disasters, as opposed to understanding natural phenomena, interviewees univocally answered that both motivations are relevant. To mitigate disaster risk, tsunami scientists need to collaborate with stakeholders in a transdisciplinary way, where transdisciplinarity means that non-academic perspectives are included in the research process. Of the interviewees, only few were familiar with this terminology. Nonetheless, the value of stakeholder engagement was widely shared. A minority emphasised that stakeholder engagement is not a value in itself, and that it should be important in some areas of tsunami science (preparedness and early warning), but not in all.

Despite the shared view that stakeholder engagement is an important element of tsunami science, respondents emphasise the associated challenges and indicate that this practice is not yet sufficiently institutionalised:

No, [there is] not really [a trend towards the involvement of stakeholders]. That's still a big problem. (1: 434)

Uncertainty as an issue in stakeholder engagement and risk communication

Asked about the concept of uncertainty, respondents gave a technical definition based on the distinction of epistemic and aleatory uncertainties and a more qualitative interpretation of uncertainty as “everything we don't know or everything where we know we may potentially be wrong” (2: 198). Most respondents see uncertainty as something inevitable. The goal is to assess and quantify it:

They [tsunami scientists] try to reduce it, but more than reducing it - because you cannot really reduce it - it's their job currently to quantify that. (1: 324)

From my perspective, one must find ways of quantifying this uncertainty where it is feasible. (4: 107)

Regarding the interaction between scientists and stakeholders, most respondents state that stakeholders want definitive answers, and are not interested in uncertainties:

The biggest problem is that usually the disaster managers don't want to deal with uncertainty. (1: 316)

Especially people in charge of planning disaster management issues, they are aware of the uncertainties, but they try to neglect or try to hide the uncertainty. (1: 369)

Most stakeholders are not gonna ask for uncertainties. You have to give them actively. Otherwise, they're gonna either believe or not believe in what you tell them, in a very black and white manner. (2: 223)

Communities do not want to have uncertainties as an answer. (6: 221)

We find different positions concerning the consequences that should be drawn from this assessment. Most interviewees emphasise the importance of insisting on uncertainties when communicating scientific results:

One of the duties of the scientists is to make an assessment of the uncertainties involved in their results and to pass to the decision-makers a package with the results along with the uncertainties, if possible, to quantify the uncertainties. (5: 267)

A minority, however, disagrees with this view and argues that, while

quantifying uncertainty is really important, [...] it doesn't necessarily need to be the focus of what's communicated to stakeholders (8: 246)

Furthermore, another minority position calls for a “humble” way of communicating both what is known and what is not yet known.

Many respondents link the unwillingness of stakeholders to engage in a discussion of uncertainties to the difficulty of communicating probabilistic information. In this view, many people struggle to interpret statistics and prefer avoiding probabilities altogether:

Something that's really hard for the general public to interpret are probabilities and in general statistics. (8: 208)

People don't know mathematics, they don't know statistics that well, so they have their own interpretation of numbers, I think they tend to forget about uncertainty unless they are told to. (7: 139)

Communicating this to stakeholders, making them understand the uncertainties around this phenomenon, it might be a bit complex because they're the people who have to make decisions and they need something that they can rely on. (4: 141)

They are not interested in that [uncertainties and probabilities] because they think the message needs to be very clear like a traffic light. (3: 137)

Consequently, the importance of standard operational procedures (SOPs) is emphasised several times, whereby uncertainties are translated into discrete thresholds and all responsibilities and actions are clearly determined in advance.

They want to have clear thresholds when to act and how to act. [...] So I think that the scientists need to translate these uncertainties into thresholds. (1: 317/378).

SOPs follow a certain prescribed scenario. An earthquake occurs, then you look first at the magnitude, second you look at the location and third you look at the depth. [...] If the magnitude of the earthquake is below a certain threshold, nothing happens - green light. If the earthquake is higher than, let's say, 6.5, first information. If the earthquake is at the border line between the island arch and the seaside, second information. But if the earthquake is at a depth of 100 or 200 m, we have knowledge that this will not trigger a tsunami. So, two information, one positive, one

negative, doesn't meet - it's out. That's a SOP. And that works quite well. (3: 162)

Challenges of interdisciplinary integration and stakeholder engagement

Communication and language barriers are generally regarded the main challenges in interdisciplinary research and stakeholder engagement. We investigate this aspect by taking a closer look at understandings of the term risk. Most respondents define risk as a combination of hazard, vulnerability and exposure. Some do not include the element of exposure and define risk simply as a combination of hazard and vulnerability. The distinction between risk and hazard, however, is common and regarded by all interviewees as the standard definition in the field of natural hazards. Yet, some mention that this distinction still sometimes leads to confusion among researchers. Almost all respondents mention that the difference between risk and hazard is hard to understand for people outside the natural hazards' community.

The description as we discussed it [risk composed of hazard and vulnerability] is sort of an academic and scientific point of view. I sometimes made the experience that for stakeholders, in particular for decision-makers or -takers, it's hard for them to understand. (3: 214)

There is not necessarily a distinction between hazard and risk for people outside the community. (4: 86)

The general public still does not understand risk really well. (9: 135)

For normal persons, hazard and risk is the same thing, right? And therefore, you have to be careful, really explaining what you mean when you talk about risk. [...] I think, there's a danger there and you have to be very aware of how you communicate and that you make clear that when you talk about the risk, you really talk about the potential losses, whereas when you talk about the hazards, you don't really care so much about the consequences of an event, but you look more at the event itself. (2: 176)

Besides the technical definition of risk, several respondents also gave more accessible interpretations of the term. Specifically, the definition of risk as potential losses is shared by several respondents, similar to the interpretation of risk as expected negative consequences brought up by an interviewee. Due to this tangible definition, “risk may be easier to grapple with by society because then they understand what's at stake” (8: 182). Several respondents report that stakeholders are more interested in risk as compared to hazard. Therefore, one researcher calls for

accessible risk definitions when communicating with stakeholders:

Let's be a little bit brave to break the traditions and go beyond our comfort zones in defining risks and bringing in modelling and communicating that to certain people. (6: 310)

When asked about the challenges of interdisciplinary research in general, several respondents point to issues of language and communication. Some researchers also acknowledge missing recognition for interdisciplinary work and difficulties in publishing. Additionally, respondents diagnose the large amount of time and efforts that are required for successful interdisciplinary research:

We don't argue anymore about what disciplines we are bringing in because whatever background is important and is appreciated. But that requires a huge effort, energy as well, including facilitating skills, listening, being eye-levelled with different entities and that's not really the current tradition. So that is very challenging. (6: 38)

At the same time, interviewees point to several factors that are important and work well in an interdisciplinary research context. Most respondents emphasise the need for few clear goals at the outset of an interdisciplinary project. The importance of finding the right people for a given project and bringing the appropriate kinds of experience together is also mentioned several times, as is the need for interdisciplinary researchers to take time, be open, look beyond their own field and question themselves.

As options for future interdisciplinary projects, interviewees mention compiling a glossary for dealing with different disciplinary vocabulary, allocating time in the beginning to learn about others' work, assigning clear work items and responsibilities to individuals, supporting interdisciplinary publishing, being aware of stakeholders' needs and expectations, looking at the big picture before starting the technicalities of a project and being honest when things do not work as planned.

Discussion and conclusion

Throughout the interviews, we find experience-informed and rather sophisticated accounts of the phenomenon of interdisciplinarity, indicating that tsunami researchers indeed work in contexts that they themselves perceive as interdisciplinary. The way respondents' talk about their academic identities implies that they are typically grounded in a disciplinary core, out of which they subsequently cross boundaries. For all respondents, however, it is a matter of course that becoming and being a member of the tsunami community includes the need to communicate across boundaries. Interviewees mention the interaction between

scientists and engineers as the exemplary interdisciplinary collaboration in tsunami science. There were fewer examples of collaborations with social scientists, rendering this a demand rather than a lived reality in current tsunami science. Often, the envisioned role for social sciences seemed to be limited to risk communication, tasked with taking the natural science results and disseminating them to society.

Interdisciplinarity on the team or project level can be clearly distinguished from the interdisciplinarity of individual scientists. The latter seems to be rare yet there seems to be a need for "translators" (8: 301) with diverse backgrounds who speak different languages and understand the respective lenses and paradigms. This is in line with Gilligan's (2019) ideal of interactional expertise in interdisciplinary settings. Several respondents indicate that the idea of early warning unites the tsunami field. Notably, however, it is not the material technology but the political goal of effective early warning that holds an integrative function across the field. This is in line with Sarewitz and Pielke's research framework for disasters in context, which for applied research puts a primacy on good decisions, not on good science (2001). Furthermore, we find modelling to be seen as the "backbone of everything" tsunami related, which in combination with visualisation techniques such as a global map of tsunami risks also serves to integrate stakeholders beyond the tsunami research community. To assess and communicate model results appropriately, however, remains a major challenge (cf. Oreskes et al., 1994). Hazard and risk are often invoked as categories to describe two camps in tsunami science: the science part that does not involve vulnerability and exposure, on the one hand, and the approaches that include impacts and damages, on the other. Because the field's major goal is to mitigate tsunami risk for coastal communities, its interdisciplinarity is seamlessly expanded to include stakeholders beyond the disciplinary system of science. While one position is that the stakeholders need to carefully listen and understand the science, we also find the position that tsunami risk communication must start with the stakeholders' needs and prerequisites. Despite the widely shared view that stakeholder engagement is an important element of tsunami science, respondents emphasise the associated challenges and indicate that this practice is not yet sufficiently institutionalised. The integration of perspectives in tsunami research does not seem to proceed with the desired speed in practice, due to challenges concerning different operational logics and expectations, problems in communication and structural barriers such as missing incentives and reputation mechanisms. Urbanska et al. (2019) studied the effect of previous contacts between the two camps and found that those with interdisciplinary experiences are more likely to recognise the intellectual contributions of other disciplines. They conclude that interdisciplinary encounters must be further incentivised by funding organisations. This is in line with the results of this study.

We find two strategies that are proposed for enhancing interdisciplinary and stakeholder engagement, coming with

different roles for the individual tsunami researcher. First, there is a view that scientists should be directly involved in inter- and transdisciplinary collaborations and tsunami governance. Thereby, it is the scientists themselves that take on the role of communicating and organising applications from tsunami science. To some extent, this strategy is already implemented, as many interviewees engage in tsunami governance and assume roles in UN or local governance bodies. Second, there is a view that tsunami science and governance need more institutions and individuals that are capable of translating between scientists and stakeholders. These translators would be familiar with both perspectives and thereby able to switch between different jargons and operational logics. Importantly, having professionals and institutions with an explicit mandate to operate at the interface between science, policy, administration and coastal protection offers a way out of the dilemma that the academic reward system often impedes knowledge transfer engagements by researchers themselves. While these two strategies are not mutually exclusive and are probably both required to some extent, they are qualitatively different and imply different strategic decisions. A discussion about the merits and downsides of both approaches can help to formulate clear goals for future developments in tsunami science and its relation to society.

Problems regarding communication between disciplines and to stakeholders, as well as the nuances of interdisciplinary collaboration and project management, appear to be issues that the community has already reflected upon. However, we find nuances in the conclusions that researchers draw from this reflection. One view emphasises the need to explain the science better. This is related to the diagnosis of a lack of understanding of how the science works among stakeholders, often associated to complaints about widespread ignorance of and disinterest in probabilities and statistics. A slightly different view places more emphasis on the necessity to listen to the stakeholders, such that the burden of changing current practices lies more on the scientists than on the stakeholders. Ideas for improving the current research structure include increased publishing support for early career researchers, e.g., by helping with publication fees and setting up special issues on cross-cutting themes, aspects of project management, such as the assignment of responsibilities and clear communication of goals, assumptions and conflicts, and efforts of individuals, for example, being open and respectful when confronted with other perspectives. While some of these issues can be tackled by individual researchers, much of it relates to research structures. Successful interdisciplinary research and stakeholder engagement thus require funding flows and specific support for the time- and resource-intensive processes that are currently not fully factored into financial and reputation structures.

Using the terminology of Ge et al. (2019), projects and collaborations funded by the European Union (EU) are instances of either grant-driven teams or expertise-based

teams. This includes the EU's COST actions. As the funding format of a COST action restricts funding to networking, visiting and other more organisational activities but does not fund research itself, we assume that COST action teams tend to be expertise-based rather than grant-driven. In the case of AGITHAR, researchers explicitly address the need for facilitating tsunami hazard and risk analysis by bridging both social and cognitive gaps in the tsunami field. It has been noted, however, that by how the acquisition of funding works, knowledge integration is not supported from the start in EU research projects. Individual work packages and deliverables are often rather disciplinary, and the projects lack a pilot phase in which to develop common ground and a shared interdisciplinary research agenda (Martinez et al., 2018). The authors conclude that, in practice, this often leads to mere grant-driven teams—multidisciplinary collaborations, where “one discipline works on one aspect of a project and a different discipline on another” (2018: 71). We argue, however, that the normative idea of inter- and transdisciplinarity does not need to be that everybody collaborates with everybody throughout the entire project and for any topic. The task is rather to jointly develop a framework which differentiates disciplinary, interdisciplinary and transdisciplinary knowledge systems and objectives, as well as respective phases in the project, and working groups in line with their corresponding goals. A starting point could be Sarewitz and Pielke's research and policy framework for disasters in context (2001). To this end, training and acquisition of both interactional and contributory expertise in more than one discipline of tsunami science are needed.

This study is limited by its explorative scope and a small number of in-depths interviews. Future research can build on these results and conclusions in various ways. Firstly, a survey of the tsunami research community could shed light on the quantitative composition of the field and associated understandings of risk, uncertainty, interdisciplinarity and stakeholder engagement. Secondly, bibliometric studies of authorship patterns and co-citations could furthermore elucidate the communicative structure of the tsunami field. Thirdly, local action research projects could engage all relevant stakeholders to work towards tsunami risk mitigation in specific geographic contexts.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethics review and approval/written informed consent was not required as per local legislation and institutional requirements.

Author contributions

SR conceptualised the research project and FS collected and transcribed the data. SR and FS were both equally involved in analysing the data, as well as drafting and writing the paper.

Funding

This article is based upon work from COST Action CA18109 AGITHAR, supported by COST (European Cooperation in Science and Technology).

Acknowledgments

The authors gratefully acknowledge the time and effort of all tsunami scientists who made themselves available for interviews. We are indebted to Jörn Behrens and Finn Løvholt as well as two

reviewers for helpful and constructive comments on a previous version of this manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

- Abbott, A. (2001). *Chaos of disciplines*. Chicago, London: University of Chicago Press.
- Becher, T., and Trowler, P. (2001). *Academic tribes and territories. Intellectual enquiry and the culture of disciplines*. Buckingham: Open University Press.
- Behrens, J., Løvholt, F., Jalayer, F., Lorito, S., Salgado-Gálvez, M. A., Sørensen, M., et al. (2021). Probabilistic tsunami hazard and risk analysis: A review of research gaps. *Front. Earth Sci. (Lausanne)*, 9, 628772. doi:10.3389/feart.2021.628772
- Bradley, R., Guillas, S., Jain, G., Johnson, C., Malladi, T., and Wesely, J. (2019). *Integrating tsunami risk assessments in development planning: Lessons from western India*. doi:10.14324/111.444/000026.v1
- Bray, D., and von Storch, H. V. (1999). Climate science: An empirical example of postnormal science. *Bull. Am. Meteorol. Soc.* 80, 439–455. doi:10.1175/1520-0477(1999)080<0439:csaeo>2.0.co;2
- Camargo, J. M., Silva, M. V., Ferreira Júnior, A. V., and Araújo, T. (2019). Marine geohazards: A bibliometric-based review. *Geosciences* 9 (2), 100. doi:10.3390/geosciences9020100
- Chiu, W., and Ho, Y. (2007). Bibliometric analysis of tsunami research. *Scientometrics* 73, 3–17. doi:10.1007/s11192-005-1523-1
- Fleck, L. (1979). *Genesis and development of a scientific fact*. Chicago: University of Chicago Press.
- Funtowicz, S. O., and Ravetz, J. R. (1993). "The emergence of post-normal science," in *Science, politics and morality: Scientific uncertainty and decision making*. Editor R. von Schomberg (Dordrecht: Kluwer Academic Publishers), 85–123.
- Ge, Y., Zobel, C. W., Murray-Tuite, P., Nateghi, R., and Wang, H. (2019). Building an interdisciplinary team for disaster response research: A data-driven approach. *Risk Anal.* 41 (7), 1145–1151. doi:10.1111/risa.13280
- Gilligan, J. M. (2019). *Expertise across disciplines: Establishing common ground in interdisciplinary disaster research teams*. Risk Analysis.
- Gläser, J. (2006). *Wissenschaftliche produktionsgemeinschaften. Die soziale Ordnung der Forschung*. Frankfurt am Main: Campus.
- Grezio, A., Babeyko, A., Baptista, M. A., Behrens, J., Costa, A., Davies, G., et al. (2017). Probabilistic tsunami hazard analysis: Multiple sources and global applications. *Rev. Geophys.* 55, 1158–1198. doi:10.1002/2017RG000579
- Hardy, R. D. (2018). A sharing meanings approach for interdisciplinary hazards research. *Risk Anal.* 41 (7), 1162–1170. doi:10.1111/risa.13216
- Heckhausen, H. (1987). "Interdisziplinäre Forschung" zwischen Intra-, Multi- und Chimären-Disziplinarität," in *Interdisziplinarität. Theorie, praxis, probleme, hrsg. Jürgen kocka* (Frankfurt am Main: Suhrkamp), 129–145.
- Heintz, B. (2000). *Die Innenwelt der Mathematik. Zur Kultur und Praxis einer beweisenden Disziplin*. Wien, New York: Springer.
- Imamura, F., Takakura, H., Matsuzawa, T., and Ito, K. (2019). A platform for multidisciplinary research in disaster science through experiences from the 2011 Tohoku earthquake and tsunami. *J. Disaster Res.* 14 (9), 1318–1322. doi:10.20965/jdr.2019.p1318
- Jain, N., Virmani, D., and Abraham, A. (2021). Tsunami in the last 15 years: A bibliometric analysis with a detailed overview and future directions. *Nat. Hazards (Dordr)*. 106 (1), 139–172. doi:10.1007/s11069-020-04454-2
- Jasanoff, S. (1996). Is science socially constructed-And can it still inform public policy? *Sci. Eng. Ethics* 2, 263–276. doi:10.1007/BF02583913
- Kánoğlu, U., Titov, V., Bernard, E., and Synolakis, C. (2015). Tsunamis: Bridging science, engineering and society. *Phil. Trans. R. Soc. A* 373 (2053), 20140369. doi:10.1098/rsta.2014.0369
- Kelly, R., Mackay, M., Nash, K., Cvitanovic, C., Allison, E., Armitage, D., et al. (2019). Ten tips for developing interdisciplinary socio-ecological researchers. *Socioecol. Pract. Res.* 1, 149–161. doi:10.1007/s42532-019-00018-2
- Kirby, C. K., Jaimes, P., Lorenz-Reaves, A. R., and Libarkin, J. C. (2019). Development of a measure to evaluate competence perceptions of natural and social science. *PLoS ONE* 14 (1), e0209311. doi:10.1371/journal.pone.0209311
- Klein, J. T. (1999). *Mapping interdisciplinary studies: The academy in transition*. Washington, DC: Association of American Colleges & Universities.
- Kuhn, T. S. (1962). *The structure of scientific revolutions*. University of Chicago Press.
- Løvholt, F., Fraser, S., Salgado-Gálvez, M., Lorito, S., Selva, J., Romano, F., et al. (2019). *Global trends in advancing tsunami science for improved hazard and risk understanding*. Contributing Paper to GAR.
- Luhmann, N. (1992). *Die Wissenschaft der Gesellschaft*. Frankfurt am Main: Suhrkamp.
- Maesen, S., and Lieven, O. (2006). Transdisciplinarity: A new mode of governing science? *Sci. public policy* 33 (6), 399–410. doi:10.3152/147154306781778803

- Martinez, G., Armaroli, C., Costas, S., Harley, M. D., and Paolisso, M. (2018). Experiences and results from interdisciplinary collaboration: Utilizing qualitative information to formulate disaster risk reduction measures for coastal regions. *Coast. Eng.* 134, 62–72. doi:10.1016/j.coastaleng.2017.09.010
- Nowotny, H. (2003). Democratising expertise and socially robust knowledge. *Sci. Pub. Pol.* 30 (3), 151–156. doi:10.3152/147154303781780461
- Oreskes, N., Shrader-Frechette, K., and Belitz, K. (1994). Verification, validation, and confirmation of numerical models in the earth sciences. *Science* 263 (5147), 641–646. doi:10.1126/science.263.5147.641
- Pescaroli, G., and Magni, M. (2015). Flood warnings in coastal areas: How do experience and information influence responses to alert services? *Nat. Hazards Earth Syst. Sci.* 15 (4), 703–714. doi:10.5194/nhess-15-703-2015
- Rafliana, I., Jalayer, F., Cerase, A., Cugliari, L., Baiguera, M., Salmanidou, D., et al. (2022). Tsunami risk communication and management: Contemporary gaps and challenges. *Int. J. Disaster Risk Reduct.* 70, 102771. in press. doi:10.1016/j.ijdr.2021.102771
- Sagar, A., Kademani, B. S., Garg, R. G., and Kumar, V. (2010). Scientometric mapping of tsunami publications: A citation based study. *Malays. J. Libr. Inf. Sci.* 15.
- Sarewitz, D., and Pielke, R. (2001). Extreme events: A research and policy framework for disasters in context. *Int. Geol. Rev.* 43, 406–418. doi:10.1080/00206810109465022
- Stichweh, R. (2013). *Die Unhintergebarkeit von Interdisziplinarität: Strukturen des Wissenschaftssystems der Moderne*. Available at: https://www.fiw.uni-bonn.de/demokratieforschung/personen/stichweh/pdfs/101_stw_die-unhintergebarkeit-von-interdisziplinaritaet.pdf.
- Stichweh, R. (1984). *Zur Entstehung des modernen Systems wissenschaftlicher Disziplinen*. Frankfurt am Main: Suhrkamp.
- Synolakis, C. E., and Bernard, E. N. (2006). Tsunami science before and beyond boxing day 2004. *Phil. Trans. R. Soc. A* 364 (1845), 2231–2265. doi:10.1098/rsta.2006.1824
- Takara, K. (2018). Promotion of interdisciplinary and transdisciplinary collaboration in disaster risk reduction. *J. Disaster Res.* 13 (7), 1193–1198. doi:10.20965/jdr.2018.p1193
- UNDRR, and UNESCO-IOC (2019). *Limitations and challenges of early warning systems: A case study of the 2018 Palu-Donggala tsunami*.
- Urbanska, K., Huet, S., and Guimond, S. (2019). Does increased interdisciplinary contact among hard and social scientists help or hinder interdisciplinary research? *PLoS ONE* 14 (9), e0221907. doi:10.1371/journal.pone.0221907
- Weingart, P., and Stehr, N. (2000). *Practising interdisciplinarity*. Toronto: University of Toronto Press.
- Whitley, R. (2000). *The intellectual and social organization of science*. New York: Oxford University Press.
- Windelband, W. (1904). *Geschichte und Naturwissenschaft. Rede Zum Antritt Des Direktorats Der Kaiser-Wilhelms-Universität Strassburg Gehalten Am 1. Mai 1894*. Straßburg.
- Witzel, A., and Reiter, H. (2013). *The problem-centred interview*. London: SAGE.
- Yonezawa, A., Hammond, C. D., Brotherhood, T., Kitamura, M., and Kitagawa, F. (2019). Evolutions in knowledge production policy and practice in Japan: A case study of an interdisciplinary research institute for disaster science. *J. High. Educ. Policy Manag.* 42 (2), 230–244. doi:10.1080/1360080X.2019.1701850