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Earth's Future

RESEARCH ARTICLE
10.1029/2024EF005618

The Importance of Accounting for Stakeholder Values, Power Relationships and Language in Constructing Relevant and Trustworthy Climate Information

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Key Points:

- Accounting for stakeholder values, power relationships and language is important to construct user-relevant climate information
- These aspects cannot be treated separately as they influence each other in the information construction
- Risk level, scientific complexity, user values, power and language guide the choice and design of user engagement in a given situation

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Citation:
Maraun, D., Bojovic, D., Parker, W., Shepherd, T. G., Sobolowski, S., Caminade, C., et al. (2026). The importance of accounting for stakeholder values, power relationships and language in constructing relevant and trustworthy climate information. *Earth's Future*, *14*, e2024EF005618. https://doi.org/10.1029/2024EF005618

Received 29 NOV 2024
Accepted 15 DEC 2025

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Abstract Facing increasing risks from climate change, governments at all levels have started to mainstream the use of climate information. It has been widely acknowledged that the inclusion of stakeholder knowledge and needs, for example, in a co-design and co-production process, is important for producing user-relevant information. Here we start from a hypothetical example and two real-world case studies from South America and West Africa to discuss the role of user values, power relationships and language in the construction of climate information. While these aspects have been discussed individually in several papers, we focus on the mutual influences of these aspects in the information construction and argue that, therefore, they cannot be considered separately. We identify five dimensions—the level of risk, the complexity of the scientific problem, user values, power relationships and language—to characterize the complexity of a given user context. Analyzing these dimensions can guide the choice and design of user engagement in a given situation. In particular, even basic research may benefit from such an engagement. Regularly accounting for these aspects in research projects may require substantial changes in the way research funding is organized and how the work of researchers is rewarded.

Plain Language Summary Facing increasing risks from climate change, local, national and transnational governments have started to support and require the use of climate information in private and public investments. It is widely known that including the knowledge and needs of information users is important for producing user-relevant information. Here we discuss, for this process, the role of what is important for users, how influential some users are, and which background information and technical terms users are familiar with. We illustrate our arguments with a made-up example and two real-world case studies from South America and West Africa. While these aspects have been discussed separately before, we focus on how they influence each other. We argue that they cannot be considered separately. We explain how understanding these aspects in the specific situation of users, for example, engineers, risk analysts or decision makers, can help setting up a useful collaboration with the users. To account for these aspects in

regular research, funding agencies would have to provide the necessary funding for a close collaboration with users.

1. Introduction

Human societies and ecosystems face growing risks from climate change (IPCC, 2023). Increasingly, governments at all levels have started mainstreaming the inclusion of "climate proofing" in public and private investments (e.g., the African Adaptation Initiative (AAI, 2015) or the new European Union Strategy on Adaptation to Climate Change (European Commission, 2021) for supra-national examples).

It has become widely acknowledged that including stakeholder knowledge and needs is important to produce user-relevant and fit-for-purpose climate information. Thus it is now common practice in climate research addressing stakeholder needs to request desired indicators, time horizons and perhaps also the choice of relevant scenarios. But beyond this checklist-style interaction, collaboration with stakeholders during the climate information production process is often quite limited, ad-hoc, and sometimes scientists even just assume a set of user needs (Nightingale et al., 2020; Skelton et al., 2017).

Social scientists investigating the creation, usability and uptake of climate information emphasize that many types of applied climate research require stakeholder inclusion from the very beginning of the project design and throughout to produce user-relevant results (Findlater et al., 2021; Lemos et al., 2012, 2018). The process through which this is done is often termed co-production or co-design to signify that providers and users of climate information work collaboratively to define adequate indicators, and design and produce desired outputs (Bremer et al., 2019; Hernandez et al., 2022; Meadow et al., 2015; Norstrom et al., 2020; Vincent et al., 2020, 2021).

Previous efforts to analyze the role of science, scientists or co-production processes—in general or in climate science in particular—deep dived into the classification of: (a) scientific uncertainty, based on decision stakes and systems uncertainties (Funtowicz & Ravetz, 1993; Nowotny et al., 2001) or the level of interaction between scientific disciplines and non-scientific knowledge (Max-Neef, 2005; Olazabal et al., 2025); (b) the role scientists take on in communicating policy alternatives (Pielke Jr, 2007); (c) different aspects of co-production processes (Berkhout et al., 2014; Bixler et al., 2015; Bremer & Meisch, 2017; Chambers et al., 2021; Turnhout et al., 2020); or (d) efforts to shift climate services from delivering better data toward the aspiration of achieving better decisions (Findlater et al., 2021).

In recent years, several strands of research have emerged considering the construction of climate information and its translation into a specific user context (Bremer & Meisch, 2017; Jagannathan et al., 2020; Norström et al., 2020). The 6th Assessment Report of the IPCC refers to this process as climate information distillation (Doblas-Reyes et al., 2021) and highlights the importance of considering multiple lines of evidence and accounting for user context and user values, as well as the relevance of communication in this process. Further, recent research highlights the role of transdisciplinary research in addressing multiple lines of evidence to integrate the social dimensions of complex problems (Fossa Riglos et al., 2024), as well as to overcome barriers in this process caused by power imbalances (Bojovic et al., 2021; Steynor et al., 2020).

At present, however, this emerging body of literature about applying social science concepts to the construction of user-relevant climate information is often overlooked by climate scientists. Moreover, some scientists push back against the inclusion of users into a co-design process, because they prioritize the advancement of science over user-relevance, or feel confident relying on their own assumptions about user needs, or wish to retain control over the scientific process, or simply lack sufficient resources (Skelton et al., 2017). In any case, professionalizing or even operationalizing the use of co-design and co-production processes in climate science and expanding them into domains previously considered "pure science" may require a major restructuring of climate research in terms of how resources and capacities are allocated and spent (Knutti, 2019; Turnhout & Lahsen, 2022). It is therefore crucial to understand when, to what extent, and in which research contexts a co-production process is required to ensure that the resulting information is salient, relevant, and informative.

The aim of this paper is therefore twofold: first, demonstrating the relevance of values, power relationships and language, and their interactions, to the process of climate information construction; and second, providing climate scientists with guidance on how to assess and account for these elements in their research and stakeholder collaboration. We recognize that much of what we describe below is already established in the social sciences realm. We seek to bring these insights to the climate information context, using terminology that is accessible for climate scientists, and in a way for climate scientists to connect to. To illustrate the relevance of these insights, we use a hypothetical example and two real-world case studies from a climate information context. Building on this discussion we propose criteria along five dimensions for guiding the choice and design of user engagement in a given situation. While our target audience is mainly climate scientists, we believe that our discussions are also relevant for stakeholders, funding agencies, and science educators.

2. Illustrating the Problem

To begin, we present the hypothetical example and two-real world case studies. The former is designed to illustrate the conceptual discussions and to clarify the major points we would like to make. We decided to use a hypothetical rather than a real-world example to avoid singling out or naming specific individuals, groups or projects, and to condense many different issues into one hypothetical example. It is important to note that not all of the challenges and problems illustrated will arise in every situation. Our example is invented but draws upon real-world experience with a number of different projects. The context represents a plausible situation of climate information construction. We complement the hypothetical example with two real-world case studies to illustrate the difficulties of accounting for all aspects we discuss in reality, but also to highlight that an in-depth stakeholder process is possible even with limited resources.

2.1. A Hypothetical Example

2.1.1. Setting and Research Question

Imagine a river catchment of medium size (<10,000 km^2) in a mid-latitude region characterized by complex topography. Several towns and villages are situated along the river, and a dam for hydropower generation has been built in the vicinity. The flood risk along the river depends on processes operating across a range of scales, from the large-scale circulation driving multi-day rainfall events to local orographic forcing of extreme rainfall and soil moisture preconditioning, from the actual runoff to the effects, and possible failure, of local dams and weirs.

Within the project, a consortium of researchers with diverse expertise (climate modelers, hydrologists, water resources and hydraulic engineers) invited stakeholders to identify metrics to assess whether the infrastructure along the river is climate proof, and to develop cost-efficient climate change adaptation plans. The invited stakeholders, suggested by the state government, represented the regional planning agency and the involved hydropower company. The overarching question discussed in this workshop for both the scientists and stakeholders was: what climate information is needed and in what format(s) to facilitate implementation in the regional planning?

2.1.2. The Chosen Approach

In an initial workshop, user needs were discussed. The regional planners were particularly interested in knowing whether existing flood defenses (based on a 100-year design value) would be sufficient to protect a planned residential area. Furthermore, the hydropower company had to ensure that the dam can withstand a 1000-year flood, or a plausible worst-case flood event.

Modeling the flood risk for specific infrastructure such as the dam requires computationally expensive hydraulic modeling. The hydraulic engineers therefore requested information about selected meteorological events under future climate conditions, representing both specific return levels (100- and 1000-year events) as well as a plausible worst-case event.

The hydrological modelers and hydraulic engineers proposed to use a weather generator to produce long meteorological time series in order to sample very rare events. The weather generator was calibrated against 10 rain gauges and 5 temperature stations, with 60 years of overlapping observational data. The parameters of the weather generator were then modified by change factors to simulate a plausible range of future climate change outcomes. Together with the climate scientists, the hydrological modelers decided to derive these change factors from an ensemble of available regional climate model (RCM) projections. A high emissions scenario (RCP8.5,

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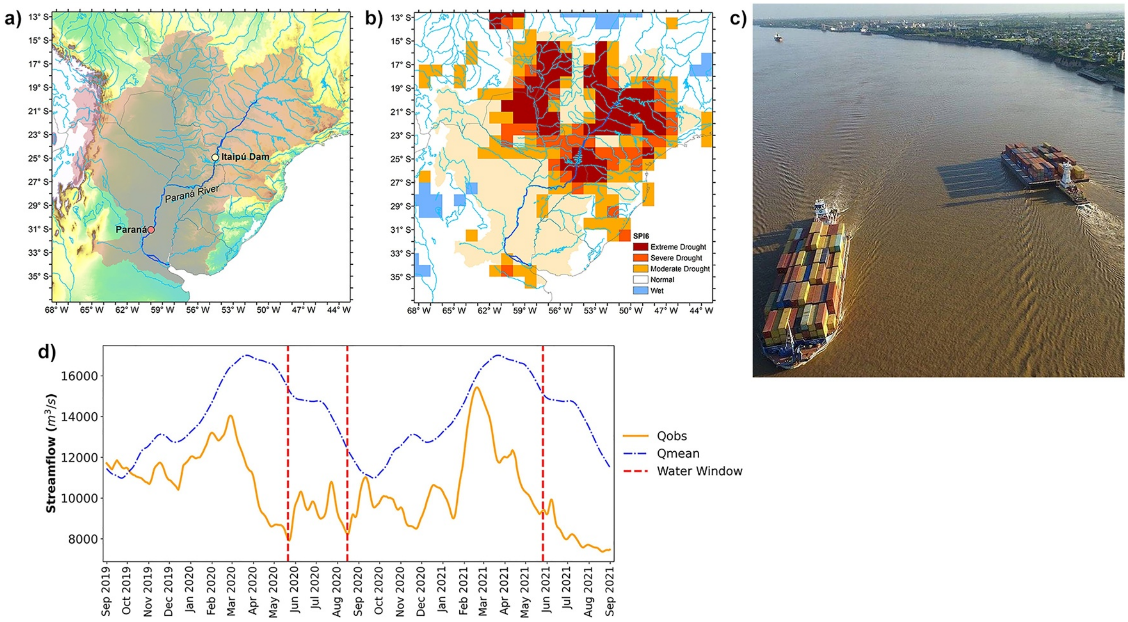

Figure 1. (a) The La Plata Basin with the Paraná River highlighted in blue and the location of the Itaipú Dam in yellow and the Paraná hydrometric station (red), (b) Meteorological drought in the La Plata Basin based on the 6-month Standardized Precipitation Index (SPI6) from the Global Drought Observatory, (c) barges on the Paraná River, (d) temporal evolution of Paraná streamflow observations (orange full line) and long-term daily mean (dashed blue line) at the Paraná (Túnel Subfluvial) hydrometric station, using data from the National System of Hydrological Information. The periods of opening of the Itaipú dam (Water Windows) in May and August 2020 and May 2021 are marked in red dashed lines.

representative concentration pathway) was chosen because of the large number of available climate model simulations and because it was considered to represent a "business-as-usual" emission scenario at the time.

Change factors for the end of the 21st century were derived from each RCM simulation, but not all simulations could be used as input to the hydrological model because of limited computational resources. Thus, the hydrological modelers decided to represent the range of plausible climatic changes by selecting only three values, namely the median and the 10th and 90th percentiles of change factors across all models, separately for each weather generator parameter. These three sets of change factors were applied to the weather generator, to produce three 10,000-year long future weather time series for the 10 rain gauges and 5 temperature stations.

These time series were then used to drive the hydrological model in order to simulate three 10,000-year time series of plausible future runoff. From each of these time series, three events were selected, representing a 100-year event, a 1000-year event and the worst-case event. In total 9 events were used as input for hydraulic modeling of the infrastructure at risk. It was found that the planned residential area would be flooded every 70–120 years, depending on the considered RCM simulation. A new flood defense system would thus be required, along with significant interventions to modify natural river banks.

In the final project workshop, these results were presented to the stakeholders. To simplify the presentation, the focus was set on the events representing the median change factors.

2.2. Case Study: Operation Water Window in Southeastern South America

The operation "Water Window" ensured limited navigability of the Paraná River during the hydrological drought of 2020–2021. The operation was possible due to improved knowledge of the drivers of precipitation at sub-seasonal to multi-decadal time scales, as well as multilateral collaboration.

Southeastern South America (SESA) is a densely populated region where agriculture, livestock, and hydropower generation significantly contribute to the gross national products of Argentina, Brazil, Paraguay and Uruguay. The region is part of the second largest river basin in South America, the La Plata Basin (Figure 1a).

Southeastern South America has experienced a long-term summer wetting trend since the beginning of the 20th century (Vera & Díaz, 2015) which is attributable to human influence (Doblas-Reyes et al., 2021). This trend has favored increases in agricultural production (Greene et al., 2015) and an expansion of the agricultural frontier (Zak et al., 2008). However, the region is also subject to large variability on interannual to multi-decadal time scales related to different modes of internal variability (Barreiro et al., 2014; Díaz & Vera, 2017; Grimm & Saboia, 2015; Robledo et al., 2020; Ropelewski & Halpert, 1987). The large interannual variability makes the region prone also to severe drought events (Cavalcanti et al., 2015), with negative impact on both agricultural productivity and waterborne transport of grains. Improvements in the understanding of the role of these climate modes on interannual and intraseasonal time scales (Alvarez et al., 2016; Osman et al., 2021; Vera & Osman, 2018) has led to a more comprehensive picture of precipitation variations over SESA, which has translated to more accurate seasonal forecasts.

In the past 10 years, three extreme droughts have affected the agricultural areas in Argentina, causing significant losses in soybean and maize production. A total loss of US$ 24,170 million, representing 57.45% of the international reserves of the Argentinean Central Bank, occurred in 2021 (Thomasz et al., 2023). This example shows the magnitude of the climate impact on the Argentinian economy, indicating that severe droughts have macroeconomic impacts, with the external sector as the main transmission channel in an economy with historical restrictions on the balance of payments, international reserve accumulation and sovereign credit risk (Thomasz et al., 2023). The impacts caused by extreme drought events motivated the creation of the Regional Climate Center Network for Southern South America (RCC-SSA). As part of RCC-SSA, the Drought Information System for Southern South America (SISSA for the acronym in Spanish) uses the CHIRPS-GEFS precipitation forecasts to provide accumulated precipitation 15 days in advance. This information is used to calculate the Standardized Precipitation Index (Guttman, 1999) to forecast changes in drought severity. Moreover, the six countries integrating the RCC-SSA generate a unified seasonal outlook of precipitation and temperature for Southern South America once a month.

In 2020 a severe drought event started (Figure 1b), with significant rainfall shortages in the headwaters of the Paraná River, which is the main waterway for the grain exports of Argentina and Paraguay. The precipitation shortages during much of 2020 and 2021 propagated through the hydrological cycle and generated hydrological drought conditions in the Paraná River, with extremely low river levels unprecedented in the last 50 years (Barbosa et al., 2021). To maintain the export capacity, an international effort to ensure the river's navigability over a limited period was initiated by the government of Paraguay and coordinated between Argentina, Brazil and Paraguay. For this, the national authorities involved in the water management sector of the basin from the three countries evaluated the status of the river between the headwaters and the mouth of the river, together with the precipitation forecasts on intraseasonal to seasonal time scales over SESA. Once a period of approximately 10 days of good conditions was determined based on the river status and precipitation forecasts, the Binational Entity ITAIPU (operator of the Itaipú hydropower plant) was allowed to increase river levels (Gwynn, 2023) to allow the navigation of grain export barges carrying over 150,000 tons of grains. This process, called "Water Window" ("ventana de agua"), was performed during May 2020 August 2020 and May 2021 (Figure 1d), in conjunction with dredging in key sections of the Paraná River, each time enabling the passage of barges carrying grains worth around 45 million dollars (Figure 1c).

This case study shows how the creation of scientific and decision-making multi-national networks to share information, evaluate scenarios and develop joint strategies, considering the necessities of each country, can be powerful in resolving climate-related emergencies.

2.3. Case Study: Climate and Health in Senegal

The impact of climate change on health is a forefront issue in Senegal. Severe heat waves, with temperatures sometimes exceeding 46–48°C, already resulted in heat-related illnesses and exacerbated chronic conditions. Change in precipitation patterns have caused prolonged droughts, water scarcity, and the emergence of waterborne diseases. Extreme rainfall damaged healthcare infrastructure and contaminated fresh water supply. Changes in temperature and precipitation affected vector-borne diseases such as dengue and malaria (Diouf, Sy, Diouf, et al., 2023).

Given such important stakes for public health, participative workshops including climate scientists, health and environmental stakeholders were organized in various cities of Senegal (Dakar, Kaffrine, Kedougou, Matam,

Figure 2. Photos of participants during climate and health participatory workshops held in several cities of Senegal from July 2021 to October 2022.

Saint-Louis, and Ziguinchor) between July 2021 and October 2022 (Figure 2). Training activities led by two facilitators were carefully designed prior to these activities, to ensure a diversity of attendees and that all materials and outputs were translated to the main spoken languages in Senegal (Pular, Wolof and French). Disease scenario results for Senegal were already published prior to the workshops. Disease prioritization per region was then co-constructed with health experts during the project's launch workshop. Finally, disease model outputs, based on an ensemble of 31 GCMs and two emission scenarios (ssp245 and ssp585) were tailored following feedback from stakeholders and later included in the National Climate Adaptation Plan of Senegal (Diouf, Sy, & Mbungu, 2023). These activities were led by the Ministry of Health and the Centre for Ecological Monitoring, with financial support from the Green Climate Fund and Save the Children.

At these workshops, again conducted in the main spoken languages, scientific presentations highlighted future scenarios for malaria, meningitis and Rift Valley Fever at country scale. Other climate-sensitive and non-communicable diseases such as respiratory and cardiovascular diseases were also under focus. Regions most at risk of heatwaves and flooding were identified and adaptation measures were subsequently tailored at regional level. Collegial discussions highlighted the need to share climate data and climate information with the health sector on a regular basis. Such climate information would need to be in an intelligible format and tailored to the needs of the health sector and stakeholders that use different jargons. The lack of funding and capacity building for climate-health related activities was also underlined. Focus groups at the workshops also highlighted the need to develop new training activities involving climate, health and environmental scientists as well as stakeholders in the region.

Insights from the workshops indicated a number of key actions to be taken: strengthen healthcare sector institutions to integrate climate adaptation into national health policy; enhance epidemiological surveillance of climate-sensitive diseases; increase investment in climate and health research; promote intersectoral collaboration for integrated resilience policies; invest in infrastructure resilience; implement effective education and communication strategies regarding climate-related health risks; and mobilize stakeholders to support climate resilience projects at local and district health levels. To foster the information uptake, the development of new interdisciplinary teaching programmes focusing on environmental health has been set up in Senegal and elsewhere (Obame-Nkoghe et al., 2024).

One key outcome of the workshops was the strengthening of collaborations among various national stakeholders, ranging from the Ministry of Health and Social Action (MSAS), to various national agencies, to NGOs as well as to Senegalese universities and research institutions. The initiative enhanced multi-sectoral coordination on climate and health issues at national scale, and workshop outputs were used in the national Health Adaptation Plan. The initiative also led to the development and funding of new interdisciplinary research projects, leveraging partnerships with European and US institutions, thereby expanding the scope and impact of research. The project benefited significantly from the involvement of an academic health minister, who seized the opportunity to mobilize significant funding through climate and environmental funds for health projects in collaboration with organizations such as CDC Africa, WHO, FAO, UNICEF, and Swiss TPH. These efforts aim to collectively reinforce Senegal's capacity to adapt to climate change, especially in mitigating impacts on public health.

3. Relevance and Interplay of Information Construction, User-Values, Power Relationships and Language

In the following, we will illustrate—referring to the hypothetical example and the case studies—how user values, power and language, and their interplay, affect the construction of climate change information. Our discussion is by no means exhaustive. In particular, with respect to modeling, we limit ourselves to the discussion of aspects related to climate modeling; similar considerations arise for the hydrological and hydraulic modeling. While we discuss the hypothetical example in the main text, we complement these discussions with the real-world case studies in Table 1.

3.1. Information Construction

In the 6th assessment report of the IPCC, Doblas-Reyes et al. (2021) highlighted the process of climate information construction, emphasizing that the generation of trustworthy regional climate projections relies on the integration of multiple lines of evidence, a process-based fitness-for-purpose model evaluation, and a comprehensive uncertainty assessment including the reconciliation of different information sources. To properly address climate risks, Weaver et al. (2017) argued for a more thorough exploration of the tails of the distribution of physical variables, where our scientific knowledge-base is less complete, and where sophisticated climate models are less helpful. They demand greater attention to the strength of uncertain processes and feedbacks in the physical climate system and call for synthesizing multiple lines of scientific evidence, including simple and complex models, physical arguments, and paleoclimate data, as well as new modeling experiments to better explore the possibility of extreme scenarios and out-of-sample events.

In the hypothetical example, the scientists have adopted a widely used approach at the interface between climate change and hydrological modeling. But given the aim of constructing trustworthy and relevant information, the project falls short in several respects:

Regional river flooding is caused by multi-day heavy rainfall events, which themselves are organized in a range of phenomena such as slowly moving mid-latitude storms. To realistically represent such rainfall events, the chosen modeling chain thus has to represent physical processes across a broad range of spatial and temporal scales, from local convection to its mesoscale organization, to synoptic low pressure systems, to their steering by the planetary-scale Rossby waves of the jet streams. A plausible representation of the response of key processes and their interplay is a prerequisite for the generation of any trustworthy climate change information of regional river flooding. Yet the researchers in the hypothetical example did not assess the fitness of the chosen climate models at generating trustworthy simulations of future rainfall. As a result, the researchers did not exclude inadequate models nor did they assess how the model performance—and a possible sub-selection—affects the range of projection uncertainties.

These shortcomings severely limit the interpretation of the results: first, it is not clear whether (all of) the model simulations can be considered plausible. Second, it is not clear whether many models share common errors and therefore potentially systematically underestimate the range of projection uncertainty, or whether badly performing models unnecessarily inflate projection uncertainties. The use of change factors rather than directly using climate model data does not circumvent this problem as the plausibility of the change factors themselves depends on the plausible representation of the rainfall. The equivalent argument holds for bias adjustment (Maraun et al., 2017; Maraun & Widmann, 2018).

In addition, the fitness of the chosen weather generator has not really been assessed. The evaluation considered standard diagnostics, which are not directly relevant for the representation of extreme multi-day amounts across a catchment. Here, diagnostics such as 5-day rainfall totals (and high return levels thereof) as well as diagnostics representing spatial structure (Widmann et al., 2019) would have been essential. The weather generator uses a first-order Markov chain to represent temporal dependence, so changes at longer time-scales are not explicitly represented. Furthermore, representativeness issues have not been addressed (Maraun & Widmann, 2015, 2018):

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Table 1
Information Construction and Consideration of Values, Power Relationships and Language in the Different Case Studies

	Hypothetical example	SESA case study	Sahel case study
Information construction	Highly technical model-based approach. No fitness-for-purpose assessment, very limited stakeholder involvement	Combination of precipitation forecasts and river condition information, interpreted with expert judgment	Synthesis of modeling results, observations, and local knowledge to identify preliminary adaptation priorities
Values	Protecting power plant and residential area. Other values (e.g. cultural, ecological) associated with the river, as well as matters of equity and justice, not considered. Risk averseness of stakeholders only superficially considered in information construction.	Protecting private-sector grain economy; impacts on river ecosystems not considered.	Protecting health of citizens across a range of regions
Power	Only the most powerful stakeholders involved, yet with very little role in information construction.	Stakeholders from multiple countries included, but only government officials; stakeholders concerned with river usage for other purposes not consulted	Wide range of stakeholders from health-related sectors participated in non-hierarchical workshops, though activities and discussions were driven largely by academics; stakeholders had limited opportunity to influence workshop design
Language and communication	Only median modeling results presented, with little uncertainty information. Choices and their consequences not made transparent, limitations hidden behind technical language.	Results shared publicly, but in very technical language	Workshop activities undertaken in local dialects; workshop findings emphasize that health adaptation measures should use language intelligible to stakeholders

do the change factors represent the local changes, which might be affected by local factors such as orographic forcing, soil moisture, or just a broader area-mean change signal at the effective RCM-resolution? Finally, the change factors are not derived from individual models, but by lumping the model ensemble together, independently for each change factor. Thus, the derived change factors are by construction physically inconsistent with each other, often leading to implausible future weather simulations.

More fundamental questions arise in the representation of a plausible worst-case event. First, does the chosen 90th percentile of RCM-simulated change factors represent a plausible worst-case response of regional climate for the selected scenario? Second, is a weather generator, which has been trained on observed data, structurally capable of extrapolating to a worst-case event that could occur far outside the observed range? This concern holds in particular as not only a single variable is extrapolated, but a spatial field of rainfall and temperature. And third, is internal (natural) climate variability well sampled, when the weather generator is calibrated to rather short observational records, and when internal variability may not have been sufficiently sampled in the RCM ensemble used to derive the change factors?

3.2. User Values

Social and political values are often seen as a source of bias in science. However, an emerging consensus among philosophers is that such values can influence science appropriately in various ways (Douglas, 2009; Elliott, 2017). In the climate context, it has been recognized that incorporating user values into information construction can increase the relevance and usefulness of the constructed information for those users (Doblas-Reyes et al., 2021; Parker & Lusk, 2019). The hypothetical example illustrates a failure to do so: in the given context, the level of risk averseness is a key consideration linked to user-values, yet this has not been made explicit or factored into the research. The issue is complicated by the fact that multiple users are involved and affected; different users often have different values. Each has their own agenda, which is not necessarily aligned with the others. There could be differences in levels of risk averseness, relevant time horizons, liability exposure, etc.

Risk averseness of stakeholders can affect various methodological choices (Parker & Lusk, 2019). Is it more important to avoid overestimation or underestimation of high return levels? How should the plausible worst-case event of interest be defined: should it be the 1000-year return level, or the worst event simulated for the whole ensemble, or the worst conceivable event? Risk averseness similarly affects the choice of concentration pathway: should it be the worst-case event within a likely scenario, or within the worst-case scenario of the chosen RCP8.5? (and should the RCP8.5 be considered plausible?) The researchers have decided to choose the 90th percentile of simulated change factors across the model ensemble—this is definitely not the worst simulated case, let alone the worst conceivable event; it may not be responsive to the actual risk-averseness of the users.

Here, a subtle but important point arises: it is not obvious what should be considered plausible. Even bracketing the deep question of what it means for something to be "plausible" or a "real possibility" in the first place (Dhami et al., 2022; Katzav, 2023; Wiek et al., 2014), in practice what is considered plausible is often strongly influenced, if not defined, by climate modeling results. This was illustrated in the hypothetical example. Yet an ensemble of models, especially if it is an ensemble of opportunity (Tebaldi & Knutti, 2007), may not capture the full range of outcomes consistent with current knowledge and uncertainties and, moreover, may be collectively biased in the direction of underestimation or overestimation. Assessments of what is plausible may require scientific expert judgment, factoring in the limitations of current models and ensembles, in conjunction with broader background knowledge of climate system processes and past climatic changes.

3.3. Power Relations

Power dynamics affect the construction of climate information in various ways. One way is the nature of the stakeholder involvement. An adequate stakeholder selection process can address inequalities, avoiding further marginalizing certain groups (Akerlof et al., 2023; van Breda & Swilling, 2019). This is precisely why a careful stakeholder mapping and selection process is needed for a genuine, power-balanced knowledge co-production process (Baulenas et al., 2023). This mapping makes it possible to make explicit the interests in dispute and thus to inscribe the knowledge co-production device in a realistic scenario of interdisciplinary and intersectoral work.

Still, even if a proper stakeholder mapping and engagement is conducted, the participatory process needs to account for and address existing and new power dynamics (Taylor et al., 2025). There is a role here for intermediaries or facilitators to maintain a balanced discussion during the consultation and co-production process, something that natural scientists are not generally trained to do. Hence the importance of having an interdisciplinary scientific team, where natural and social scientists genuinely collaborate, before immersing themselves into transdisciplinary ambitions.

Engaging with power dynamics means that a stakeholder group or a "community" should not be treated as a homogeneous entity, but rather as a highly complex and heterogeneous one with its own power dynamics (Agrawal & Gibson, 1999; Bixler et al., 2015). Further on, power imbalance can happen when representatives of different groups are invited to the stakeholder consultation, but their voices are not heard or considered or are discounted, for example, because they feel intimidated by the scientists' authority or by a hierarchical relationship between stakeholders, or are less experienced in developing ideas in a public arena (Vincent et al., 2020). Gender (dis)balance is yet another example of power dynamics to take into consideration (Shenk et al., 2025). Besides understanding the stakeholder arena and properly engaging with all the parties, understanding the nature of the participatory process is also important (Bixler et al., 2015). In climate services co-production processes, not rarely, participation has a functional nature, where participants serve to help achieve goals pre-defined by scientists (Findlater et al., 2021; Hobley, 1996).

Brisbois and de Loë (2016), following Lukes's and Gaventa's three-dimensional framework of power (Gaventa, 1980; Lukes, 2005), distinguished between Instrumental, Structural and Discursive power. These three dimensions of power can differently affect collaboration and participation in climate knowledge co-production processes. These power dimensions are particularly obvious in relationships between scientists and other participants. Instrumental dimension of power is frequent in co-production processes, where different participants, for example, scientists and local communities' representatives have different resources in terms of available time —stakeholders often volunteer their time (Turnhout et al., 2020) -, expert knowledge, and command of technical language. Another example is the Global South and North power dynamic. Researchers from richer countries have key advantages in buying proprietary data, downloading and storing data, producing data and analyzing data. Likewise, researchers may not have the financial resources to access publications (Díaz et al., 2025; Testani et al., 2025).

Structural power reflects in the final say over the information production and use (Brisbois & de Loë, 2016). Clearly, if the participatory process has a predetermined agenda, the received inputs will only to a certain extent shape and affect the final decision on which climate information will be produced. Discursive power is frequently observed in the language that is set for the collaboration. Namely, if the scientific approach is highly technical, as it was in the example with the complex modeling chain, then the involved users cannot judge the adequacy and limitations of the chosen approach, in particular when the assumptions made and their implications for the analysis are not made transparent. This leaves the stakeholders with little option other than being forced to trust the researchers. In such a situation, in our experience, scientists often downplay the limitations of their approaches. Note that these power dynamics based on the wielding of expertise occur not only between scientists and stakeholders, but also between the stakeholders themselves and between different scientific disciplines (and between the scientists themselves, Hernández & Fossa Riglos, 2021). This power relation can significantly shape the information construction yet is not often considered explicitly.

In the (hypothetical) example, there was no consideration of the locally-based expert knowledge. Such knowledge could include that windfall of trees into the river may lead to log jams causing the worst floods in a particular town, implying that the compound event of extreme rain and wind needs to be considered to assess high return levels. Or it could include that soil moisture is important for runoff and preconditioning (e.g., many extreme floods occur not because of extreme rainfall but rather heavy rainfall over already saturated catchments), although for the event selection only rainfall was considered. In both cases, the knowledge is physically based but highly contextual, including local knowledge, so would not be part of a standardized risk analysis such as was performed in the hypothetical example. This shows the importance of multiple knowledge systems and transdisciplinary approaches and leads to another way that power affects the construction of climate information: through the power asymmetry between scientific and "other" knowledge (Hernández et al., 2022; Taylor et al., 2025). Finally, and as proposed in the literature, the co-production process needs to start from an early stage, to address power dynamics and expand the negotiation and solution possibilities (Olazabal et al., 2025). A well guided transdisciplinary co-production process will empower both stakeholders and scientists through creation of new, more robust, knowledge and experience (Lawrence, 2006; Polk, 2015).

3.4. Language and Communication

Language (spoken and written) is often the medium in which "information construction", "user values" and "power relations" play out. Here we focus on language as a tool for communication. In its broadest sense it is a system of words (vocabulary) and conventions (grammar) that are employed in a structured manner. Communication then is the process by which messages, constructed using the building blocks described in the previous sentence, are transferred between actors. These definitions may appear trivial but are critical for understanding the issues that currently plague the development of relevant and actionable climate information and, ultimately, taking action. In particular, we note that language is not a neutral medium. As Table 1 illustrates, communicating findings in overly technical or specialized language can at best be confusing and unhelpful to stakeholders, at worst it is an exercise in power for example, "controlling the message" (see the discussion on Brisbois and de Loë (2016) discursive power in the previous section). Explicitly considering language and communication in the construction or co-production of climate information then holds the key to developing strategies for improvement. Let us look first at our hypothetical example in an effort to define "Language and Communication" in context.

Our hypothetical example plays host to diverse actors who represent different communities or disciplines. Each has their own unique language and conventions of communication (sometimes colloquially referred to as jargon). However, there are often significant overlaps in terminology across neighboring disciplines, even though the precise vocabulary, definitions and concepts employed by the scientific community often do not match well with those of other communities (see Stiller-Reeve et al., 2015 for an example). Here, the use of specific terms without making definitions and the underlying concepts explicit may cause serious misunderstandings. The communication in our hypothetical example is done in a traditional top-down manner. That is, messages were transferred via "discussion of user needs" in the planning workshop and "presentation" of results in the final workshop. The choice of which messages to send (e.g., median change factors) also had implications for the relevance and utility of the information provided.

Specifically, the use of technical language by scientists and engineers in our hypothetical example can mask shortcomings in the approaches chosen. This then affects the construction of reliable or trustworthy climate information. The potential shortcomings of the weather generator can be glossed over by oversimplifying what it does, and does not, do.

Also, a focus on the "median" paints a picture that is perhaps overly optimistic. In an attempt to simplify the results, the scientists and engineers communicated a standard indicator rather than selecting more user-specific indicators. Also, the use of non-technical terms for specific concepts may even cause confusion within a discipline, let alone in an interdisciplinary context. For instance, as discussed above, the term "plausible worst case" may have different meanings to different actors, partly owing to their having different values. Similar arguments hold for the use of the term "robust": often this means "most models show the same trend", but to others it may furthermore imply trustworthiness or fitness for purpose, as well as indicating a result with social relevance as suggested by Gibbons et al. (1994). Sometimes, certain concepts are also labeled wrongly by scientists. For instance, in the hypothetical examples, the RCP8.5 scenario has been referred to as "business-as-usual", ignoring that it will manifest only if greenhouse gas concentrations increase much more strongly than currently anticipated (Hausfather & Peters, 2020).

If they are not communicated clearly then "user values" are either implicit or assumed by the scientists. This also goes for expectations. Often these can be assessed by asking actors' roles and responsibilities. In our hypothetical example this wasn't done and as such terms like "worst case" and "risk aversion" remain poorly defined. Undertaking a dialog between the developers, hydropower company representatives and scientists alike could help clarify important values and better constrain the outcomes. Otherwise, in the absence of such communication, the parties are left to make assumptions about each other's values and word choice/definition, both overall and with respect to the task at hand.

As mentioned above, language and communication play a key role in the context of power relations. Scientists and engineers can use technical jargon, often unintentionally, to assert authority and thus to cement power imbalances. Also, the mode of transferring messages in our example largely encourages parties to fall into familiar roles of "provider" and "user" where communication is largely top-down and unbalanced with respect to power relations (presentations, reports, recommendations, etc.) Such one-way communication reinforces power imbalances. For instance, in our hypothetical example the lack of continuous engagement serves to maintain power imbalances as there is only an initial and a final workshop. The intervening work is largely a "black box" to the stakeholders and trust is enforced rather than earned.

Often shortcomings that arise from choices related to what information gets communicated, or which approaches are employed, use "simplification" as justification. Instead we could enter into dialog about, for example, uncertainty calculations around return values, plausible worst-case events, and observational uncertainty.

4. Complexity Dimensions and the Level of Co-Production

A multitude of practices exist to collaborate with users, ranging from top-down to bottom-up approaches involving co-exploration and co-production (Berkhout et al., 2014; Bojovic et al., 2015; Bremer & Meisch, 2017; Doblas-Reyes et al., 2021; Reed et al., 2018). Sometimes, the stakeholders are only informed about the outcome of a project. Often, user-interaction is limited to sending out questionnaires, surveys, or checklists of data requirements without further involvement apart from, maybe, a final stakeholder workshop to present the research results. In these approaches, stakeholder values, power relationships and language are typically ignored. No mutual understanding of the problem is developed, and the project results are likely not relevant for all, or potentially even misleading for some involved user groups. In some cases, these approaches may be suitable for the given context, but sometimes their choice may be a result of a lack of awareness of the scientists about the issues discussed in this manuscript. In almost all cases, however, the choice will at least implicitly also be determined by a lack of expertise, and financial and time resources to conduct a fully-fleshed knowledge co-production. Understanding the minimum requirements regarding stakeholder involvement is thus crucial to ensure a successful - in terms of generating user-relevant results - research project.

To guide the choice of a suitable approach to user interaction we argue it is important to understand and make explicit the specific context in the light of our previous discussion. Therefore, we suggest to analyze the context along five dimensions:

- RISK: The actual level of risk, as determined by the hazard, vulnerability and exposure, in relation to the values (in particular risk aversion) of the involved stakeholders.
- COMPLEXITY: The complexity of the scientific problem, including the level of aggregation, time horizon, uncertainties and our level of ignorance, and the overall tractability of the problem.
- VALUES: The diversity of values among stakeholders, including cultural diversity, and values of affected groups that are not involved in the knowledge production and decision process.
- POWER: The diversity of power relationships among stakeholders, between stakeholders and scientists, and among scientists.
- LANGUAGE: The diversity of the involved backgrounds (e.g., scientific), and the used "vocabularies" by the different actors, including the potential for misuse.

Each problem will be specific in each of these dimensions and may require a nuanced approach to stakeholder involvement.

If the actual level of risk (perception) is high, much is at stake for the involved users and a thorough information construction as well as accounting for user values, power relationships and language is important to ensure that the research results are trustworthy and relevant for all affected stakeholders. Yet in such a situation, the typical initial phase of a co-production process, engagement through awareness raising (Bojovic et al., 2021), is possibly dispensable, as it is more probable for stakeholders to be familiar with the problem and open for collaboration. If we are facing a scientific problem of a high complexity, substantial resources may have to be allocated to the information construction. The more diverse the values within the stakeholder community the more attention the engagement process requires. One needs to make sure that all the values are considered and that agreements are reached on how to balance competing values. Similarly, recognizing and convening power relationships requires a careful facilitation process during the new knowledge co-production. For example, if there is a strong power-imbalance within the stakeholder communities, or between communities, for example, in societies with strong hierarchy, a careful user selection process and expert facilitation of the participatory process is indispensable. Then again, if there is power asymmetry between different scientific disciplines, an effort should first be made to achieve a genuine interdisciplinary collaboration, before reaching out to the stakeholder community. The power asymmetry between scientific and "other" knowledge holders should also be acknowledged and managed in order to have all voices heard.

In any case, the project leaders should do the background research needed to understand the context: the urgency of the problem under consideration and perceived risks; the culture and values of the groups at stake; the power dynamics among stakeholders, between stakeholders and researchers, and among researchers; and different languages, approaches and working cultures used by different knowledge holders. Understanding the context will help understand the complexity of the issue in terms of the dimensions discussed above and acknowledge the myriad of challenges and, sometimes competing, decision paths stakeholders face. This will also help to avoid engagement fatigue of the users, and therefore avoid a loss of trust with partners and ultimately help ensure productive outcomes.

5. Discussion

We have illustrated and discussed, using one hypothetical and two real-world case studies, how user values, power dynamics, and language affect the construction of climate information. But crucially, we have also highlighted that these aspects influence each other and thus cannot be considered in isolation. If unacknowledged, these issues will linger in the background, affect the knowledge production and may ultimately compromise the success of any research project that aims to inform decisions. Thus, reflection and awareness of the five dimensions introduced above is a crucial first step before a project starts. As much as possible, a structured iterative process and continuous reflection should be used.

Yet accounting for these dimensions may cause tension.

First, tension may arise in terms of resources: a co-production process with several user groups is expensive, both in terms of funding and time. Often it may therefore be impossible to consider all dimensions at the necessary level of depth. These limitations should be openly acknowledged, and the research may be divided into manageable sub-projects. For instance, if the level of scientific complexity is high, one may consider first constructing generic climate information, which may be translated to specific user-contexts in follow-up projects. In any case, awareness and transparency help to focus resources on the most relevant aspects.

Limited resources may not only be an issue for the researchers, but also for the involved users: they may not have the resources for a continuous contribution throughout the course of a project, and they may not have the resources to implement the project results, for example, adaptation plans. Often, also legal requirements and cultural issues may hinder the implementation.

Tension may also arise from conflicts among stakeholders. Here, researchers need to be aware that often not all user groups at risk are included in the process. In some cases, this may be an extreme case of a power imbalance: some stakeholders simply have no voice, are overlooked, or deliberately ignored. Here, researchers may face a significant ethical dilemma: a specific user, for example, a private company or local government, may insist on excluding specific user groups. If the funding is provided by this user, the only solution to this dilemma might be to withdraw from the project. The acceptance of stakeholder engagement also depends on the social and political culture in a country regarding how science is publicly acknowledged, circulated and legitimized (Jasanoff, 2004).

Above all, researchers need to be modest in approaching stakeholder communities, avoiding a power imposition by the scientists and recognizing the authority of the community partners. Modesty also helps to keep an open mind and being alert to the issues discussed above. Long-term relationships with user groups (if not exclusive) help to understand the user context in terms of the five complexity dimensions. Thereby, such relationships also help to minimize costs and build trust. As discussed, implementing transdisciplinary co-production processes may be crucial to ensure the success of research projects of societal relevance. Although rewarding, this process is expensive and time consuming. It is therefore necessary to build an environment that fosters rather than impedes the regular use of such approaches.

Many funding agencies focus on basic research and either do not support or (potentially) even allow for transdisciplinary research. But as we have shown, even basic research may in some situations benefit from a genuine inclusion of stakeholders. Some agencies, such as the Wellcome Trust in the UK or the Austrian Climate Research Programme (ACRP) explicitly request stakeholder involvement, but the funding of some of these programmes may be limited to rather small projects of national relevance, often without sufficient funding for basic research. But as discussed above, providing user-relevant information may often require a thorough information construction and thus basic research. This separation of funding into basic and applied research strengthens a dangerous disconnect that ultimately impedes the success of societally relevant research. Funding agencies should therefore consider revising their policies. But importantly, applying our criteria may also suggest that a specific research endeavor may not require a deep transdisciplinary interaction. In such cases, a co-design and co-production process would not add value.

Also employers need to acknowledge both the importance and resource intensity of transdisciplinary research, and include this when measuring the output of their researchers. Several initiatives exist to revisit criteria for research assessments, such as the Declaration on Research Assessment, the Leiden Manifesto, or the Coalition for Advancing Research Assessment (CoARA). Some research councils have included non-academic impact as a key evaluation criterion (e.g., the Austrian Climate Research Programme and the Norwegian Research Council). In the UK, the Research Excellence Framework, which is a major component of research funding, includes a significant evaluation component based on what are called "impact case studies", where "impact" means a change in practice in a non-academic body.

This paper provided a framework to help unpack complex decisions and understand whether and to what extent stakeholder engagement is crucial to provide usable and relevant climate information. In particular, we looked into the level of risk, scientific complexity, stakeholders' values, power relationships and language used within and across communities. Understanding these five, interconnected, dimensions of a climate-dependent problem, could help scientists decide how much effort is necessary to focus on the knowledge co-production process, and integration of other types of knowledge. With a reflective approach and analyzing in depth the configuration (social, political, economic, etc.) in which the process of co-production of climate services will take place, it is possible to generate a work space between interested parties (including scientists), where everyone is empowered through knowledge sharing that leads to usable and socially appropriate climate information.

Acknowledgments

DM acknowledges the ACRP SPIRIT (KR18AC0K14748) and MoCCA (FO999913124) projects. SPS, DB and SS acknowledge the Impetus4Change project (HorizonEurope Grant 101081555). FJDR acknowledges the Climateurope2 project (Horizon Europe Grant 101056933). LD acknowledges funding from Agencia Nacional de Promoción de la Investigación, el Desarrollo Tecnológico y la Innovación (Agencia I+D+i), Argentina (PICT-2020-SERIEA-I-INVI-00540) and CONICET (PIBAA28720210100758CO). DB acknowledges the AI4S fellowship within the "Generación D" initiative by Red. es, Ministerio para la Transformación Digital. The authors want to thank Sokhna Thiam (African Population and Health Research Center, Senegal), Jacques-André Ndione (Regional Agency for Agriculture and Food, Togo), Amadou Thierno Gaye (University Cheikh Anta Diop, Senegal), Codou Badiane Mané and Ibrahima Sy (Ministry of Health and Social Action, Senegal) for their involvement in the health case study. For the SESA case, we thank the CLIMAX (http://www.climax-sa.org/) and CLIM. AR projects and Strategic Project on the Parana River of the Ministry of Science and Technology of Argentina and UBA, CONICET and PICT funds from Argentina. W.G. acknowledges partial support from U.S. Department of Energy Office of Science Award DE-SC0016438 and U.S. NOAA Grant NA23OAR4310629. SS acknowledges the funding from Agence Nationale de la Recherche - France 2030 as part of the PEPR TRACCS programme under Grant ANR-22-EXTR-0011 (LOCALISING). This manuscript contributes to the WCRP Lighthouse Activity My Climate Risk and to the WCRP Core project Regional Information for Society (RIfS): Robust Information Working Group. The information and views expressed are those of the author(s) and do not necessarily reflect the official opinion of the European Commission. Open Access funding provided by Universitat Graz/KEMÖ.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Daily streamflow records from the Paraná river can be accessed online through the National System of Hydrological Information (https://snih.hidricosargentina.gob.ar/). SPI6 data can be obtained through the Global Drought Observatory (https://drought.emergency.copernicus.eu/tumbo/gdo/download/). The code and data used to create the panels are available as supplementary information.

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