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► To cite this version:

D. Vlachogiannis, O. Rössler, A. Fischer, H. Huebener, D. Maraun, et al.. Challenges to link climate change data provision and user needs: Perspective from the COST-action VALUE. *International Journal of Climatology*, 2019, 39 (9), pp.3704-3716. 10.1002/joc.5060 . hal-04729984

HAL Id: hal-04729984

<https://cnrs.hal.science/hal-04729984v1>

Submitted on 11 Oct 2024

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VALUE SPECIAL ISSUE ARTICLE

Challenges to link climate change data provision and user needs: Perspective from the COST-action VALUE

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Funding information

EU COST Action ES1102, Grant/Award Number: EU FP7, EU COST Action ES1102

The application of climate change impact assessment (CCIA) studies in general and especially the linkages between different actor groups typically involved is often not trivial and subject to many limitations and uncertainties. Disciplinary issues like competing downscaling approaches, imperfect climate and impact model data and uncertainty propagation as well as the selection of appropriate data sets are only one part of the story. Interdisciplinary and transdisciplinary challenges add to these, as climate data and impact model data provision and their usage require at least a minimum of common work and shared understanding among actors. Here, we provide the VALUE perspective on current disciplinary challenges and limitations at the downscaling interface and elaborate transdisciplinary issues that hamper a proper working downscaling interface. The perspective is partly based on a survey on user needs of downscaled data that was distributed among 62 participants across Europe involving 22 sectors. Partly, it is based on the exchanges and experiences gained during the lifetime of VALUE that brought together different actor groups of different disciplines: climate modellers, impact modellers, statisticians and stakeholders. We outline a sketch that summarizes the linkages between the main identified actor groups: climate model data providers, impact modellers and societal users. We summarize review and structure current actors groups, needs and issues. We argue that this structuring enables involved actors to tackle these issues in a more organized and hence effective way. A key solution to several difficulties at the downscaling interface is to our understanding the development of guidelines based on benchmark tests like the VALUE framework. In addition, fostering communication between actor groups—and financing this communication—is essential to obtain the best possible CCIA as a prerequisite for robust adaptation.

KEYWORDS

climate change, climate services, downscaling, user needs, VALUE

1 | INTRODUCTION

The growing anthropogenic changes of atmospheric greenhouse gas and aerosol concentrations and man-made land-use changes have modified the climate over the last decades and will likely continue to do so over the coming century

(Intergovernmental Panel on Climate Change, 2014). In fact, even in the presence of drastic mitigation measures, the inertia of the climate system inevitably leads to further warming over the next decades, and the Earth's temperature is expected to increase at least by one-and-a-half degrees, compared to pre-industrial conditions, provided that the

enfolding UNFCCC COP21 agreement is implemented (United Nations, 2015). Hence, robust Climate Change Impact Assessment studies (CCIA) are—among others—an important cornerstone to assess the vulnerability of a given system (i.e., impact on natural systems, society and economy) and to develop adaptation strategies in a reliable manner. Today's central importance of CCIA finds its expression not only by the vast number of research projects that have been accomplished in this field, but also in the demand of the society, authorities and institutions, as well as the private sector to receive answers to climate change related questions (Field *et al.*, 2014).

Despite its relevance and wide usage, the application of CCIA in general and especially the linkages between different actor groups typically involved is often not trivial and subject to many limitations and uncertainties. As most of the users are experts on their own topic, but not necessarily on climate or climate model data, they are often unsure about the data origin, data access, data appropriateness, data reliability and quality, correct usage of data and what kind of information can be drawn from them. We here refer to climate data users as the community of researchers, administrations, environmental consultants, experts from private companies like insurance, policy advisors or NGOs, in line with the definition of the IS-ENES initiative (Swart and Avelar, 2011). In contrast, climate data providers generate and provide climate data or derive information out of it.

CCIA typically rely on projections from global climate models, that is, coupled ocean—atmosphere general circulation models that are further downscaled by dynamical or statistical downscaling models (Maraun *et al.*, 2010; Rummukainen, 2010) to provide local-to-regional information for driving impact models or to derive local scale climate information. Hence, the quality of the climate data and its local-to-regional derivative becomes critical. Climate data users operate from a position of trust. They need to consider the consequences of their actions and provided information. If not, poor decision-making and maladaptation may occur with potentially large costs at a later stage. Hewitson *et al.* (2014) argue that any type of climate model output to be used in a decision-making context needs to be plausible, defensible and actionable. McNie (2007) defined a theoretical basis for “useful data”, and proposed following Cash and Clark (2002) that data should be salient, credible and legitimate.

Given these high expectations, it is still an open issue how one can guarantee the provision of the best climate model data quality available. The challenge lies in the multitude of aspects to consider: data availability and quality, the quality of the climate models, the kind of data users request and the downscaling method (if applied). With respect to downscaling, numerous techniques are known today and their skills have been evaluated in several case studies as well as intercomparison projects (Goodess, 2005;

Christensen and Christensen, 2007; Benestad *et al.*, 2008; van der Linden and Mitchell, 2009; Maraun *et al.*, 2010; Nikulin *et al.*, 2015). The EU COST-Action VALUE has developed a comprehensive framework to systematically intercompare different downscaling approaches for climate change applications (Maraun *et al.*, 2015). The first results of this most comprehensive benchmark test are published in this journal issue.

From the perspective of a climate data user similar challenges exist: one needs to select the most appropriate data from a variety of possibilities to best suit a given project. Over recent years, a variety of projects and portals have put effort in providing data set to users, for example, ENSEMBLES, CORDEX, CMIP5, ClipC, IS-ENES, climate4impact, to name a few. In addition, numerous smaller, national or institutional data set exist (see Table 1), not speaking about further individual data sets. This easy accessibility is generally very welcomed and commendable for all different kinds of disciplines. However, from a user perspective, it prompts some practical questions on data selection: which emission scenarios to choose, how many ensemble members to apply, which climate model represents my location of interest best, and which climate model variables can be judged trustworthy. In the view of Barsugli *et al.* (2013), the “practitioner's dilemma” is no longer the lack of downscaled projections; it is how to choose an appropriate data set, assess its credibility and use it wisely.

However, disciplinary issues as discussed above are only one part of the story. Interdisciplinary and transdisciplinary challenges add to these, as climate data provision and its usage require at least a minimum of collaborative work. With “interdisciplinary” we mean the exchange of knowledge and methods between different scientific disciplines for the goal of new emerging scientific knowledge. By “transdisciplinary”, we understand in line with Bergmann *et al.* (2012) the “research process” that involves “societal actors with practical knowledge” and “problem-appropriate scientific disciplines” to answer “real-world problems scientifically.” A crucial part in transdisciplinary approaches is the definition of a common framework, a common language and mutual learning.

The downscaling interface on the whole is thus subject to challenges of disciplinary, interdisciplinary and transdisciplinary matter. In Europe, some of these challenges have been recognized and tackled within the EU COST-Action VALUE by bringing together the providers and users of climate information and thereby bridging the gaps between scientists, stakeholders and statisticians. The main goal of VALUE is to provide a web-based validation portal to enable an objective selection of downscaling methods, and to guide users to those localized data that best fit their CCIA. To develop guidance, the needs of the users were first investigated. This included an European-wide user survey accompanied by a review of already existing studies.

TABLE 1 Overview over some of the existing internet portals to provide climate data, be it observations, climate model data, on-the-fly-downscaled data or climate derivatives like indices

On-the-fly-downscaled data or climate derivatives like indices		Internetseite	Observations	GCM	RCM	Incl. Downscaling	Climate indices	Comments
Supranational portals								
	ClipC	http://www.clipc.eu/home		x			x	
	Downscaling Portal	https://www.meteo.unican.es/downscaling/intro	x		x	x		
	ECAD	http://www.ecad.eu	x					
	CORDEX	http://www.cordex.org/			x			
	ENES	https://verc.enes.org/		x	x			
	ESGF	esgf.llnl.gov	x	x	x			
	Copernicus	http://climate.copernicus.eu/						
	CCAFS	http://www.ccafs-climate.org/	x	x		x		
	World Bank	http://sdwebx.worldbank.org/climateportal/		x		x		Climate information
	ENSEMBLES	http://ensemblesrt3.dmi.dk/			x			
	PRUDENCE	http://ensemblesrt3.dmi.dk/			x			
	Impact2c	www.atlas.impact2c.eu		x	x		x	
National portals								
Austria	CCCA	https://www.ccca.ac.at/en/datenportal/	x			x		Bias corrected RCM
Australia	CSIRO	www.climatechangeinaustralia.gov.au/en		x	x	x	x	
Canada	PCIC	www.pacificclimate.org	x	x		x		
Finland	Climate Guide	www.ilmasto-opas.fi/en						
France	DRIAS	www.drias-climate.fr			x	x	x	
Portugal	Portal do Clima	www.portaldoclimae.pt/en						
Switzerland	C2SM	www.ch2011.ch		x	x	x	x	
United Kingdom	UKCIP	www.ukclimateprojections.metoffice.gov.uk	x	x		x		
United States	DCHP	http://gdo-dcp.ucllnl.org/downscaled_cmip_projections	x	x		x		
United States	USGS	http://cida.usgs.gov/climate/derivative		x		x	x	
United States	MACA Statistical Downscaling	maca.northwestknowledge.net		x		x		
United States	CalAdapt	cal-adapt.org	x	x		x		

The current paper provides the perspective and displays the experiences of the VALUE network about user needs and challenges currently present at the downscaling interface. A basic assumption in this paper is that the downscaling interface is currently working improperly. Although several positive CCIA examples can be found in the literature (Snäll *et al.*, 2009; Eitzelmüller *et al.*, 2011; Addor *et al.*, 2014; Hansen *et al.*, 2014), they are not common practice. The consequences can be found in many projects that—at least in our opinion appraisal—either use falsely downscaled data, apply suboptimal methods, or draw wrong conclusion from the data. The aim here is therefore to elaborate why the downscaling interface works imperfectly and to suggest possible ways to improve it.

First, we define the actor groups involved at the climate data provision-usage interface and suggest a structure of this

interface. Thereafter, we concentrate on the user needs as found by our survey and by a literature review of user needs in Europe. These needs are confronted with current possibilities and limitations of climate data providers resulting in a conclusion of current scientific gaps. We then add to these scientific challenges and limitations several non-scientific issues that hinder a better linkage at the downscaling interface. Doing so, we summarize possible ways to tackle the current gaps and conclude.

2 | ACTOR GROUPS AT THE DOWNSCALING INTERFACE

A first essential step to overcome limitations at the downscaling interface is an inventory of actors, their functions

and their background. This structuring helps to organize and assign current challenges and to tackle these challenges in a structured way. Three different actor groups—being climate data providers, impact modellers and societal users are interacting at the climate data—user interface. To illustrate the disciplinary, interdisciplinary and transdisciplinary interactions, we provide a sketch of the constellation of these actors and their interactions (Figure 1). We refer to “climatologists” (purple colour) as scientist who develop and apply climate models (global or regional) or post-process and analyse their results from a meteorological or climatological perspective. These groups make up what we call the “data providers”. “Impact modellers” (green colour) are the vast group of researchers, consultants, and other modellers that use the climate data in their specific model to derive climate change impact scenarios in their field of experience. They are mainly interested in the usage of the climate data. “Societal users” (red colour) are users that articulate their specific needs and make decisions, which are derived from everyday experiences and local expert knowledge. The needs can be identified together with climate and related impact

information from both other actor groups. This general grouping needs to be specified twofold: First, all three actor groups can recruit from different sectors (stripes, Figure 1), be it research, administration, the private sector or consultancies, and hence each actor group has its own characteristics of involved people. The exception is the lack of the research sector by definition in the actor group of societal users. Second, each actor group is subdivided into first- and second-order actors, with the first-order actors being directly involved at the linkage and the second-order actors being the framing community of each actor group.

First-order actors refer to the group “intermediaries” in other projects like ClipC (Groot *et al.*, 2014). We refrain from defining a fourth group “intermediaries”—as in ClipC—in our conceptualization, as we value the “origin” of an actor higher than their function at the downscaling interface. Second-order actors are climate modellers, impact modellers or societal users that either generate the climate data to be downscaled, make use of other impact results, or receive information from societal users without any direct contact to actors from the other groups. These framing actors

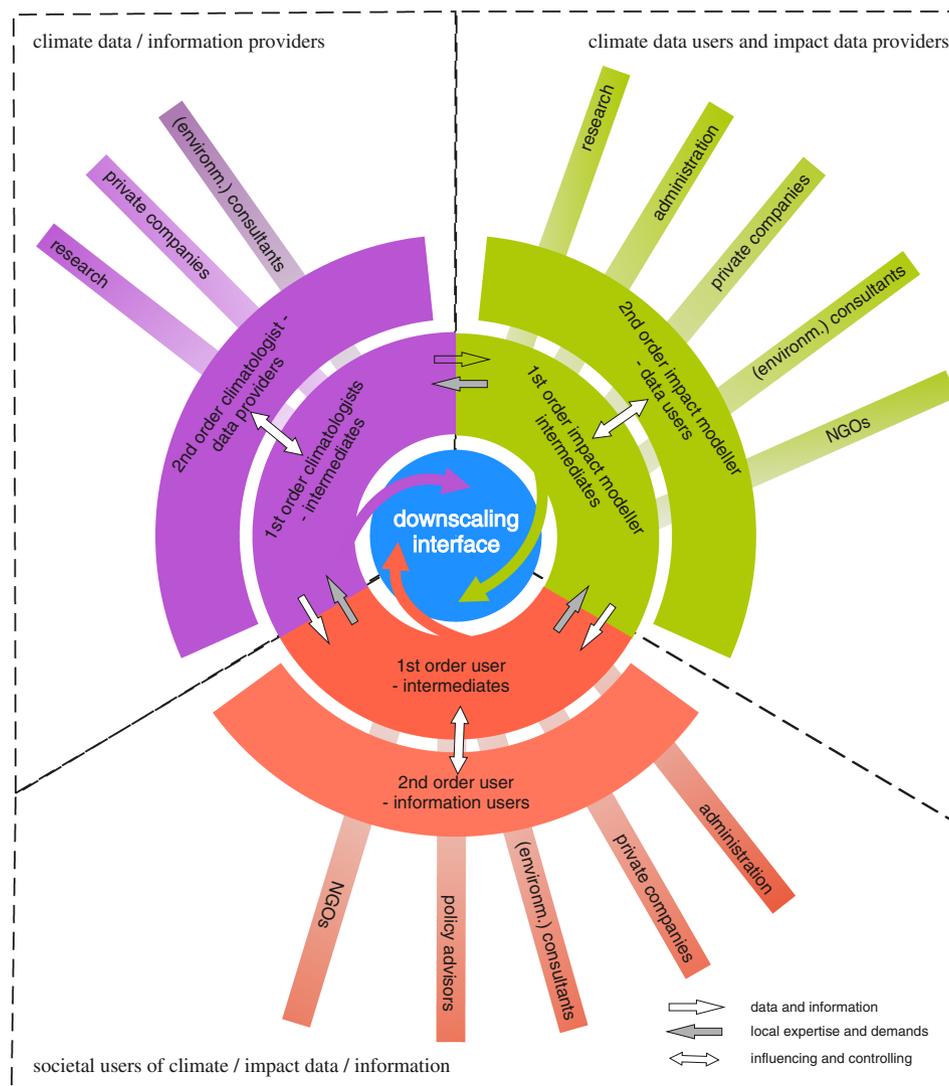


FIGURE 1 Constellation of actors at the downscaling interface, illustrating the transdisciplinary setting, the different sectors actors may recruit from, as well as the main perspective the actors have on the data/information [Colour figure can be viewed at wileyonlinelibrary.com]

are important as they also influence the demands and needs articulated from the first-order actors (societal users and impact modellers) or have a community based controlling function. Thus, we suggest the presence of an inner circle of actors with scientific and non-scientific backgrounds that is actively shaping the downscaling interface. For example, they decide which data, models, methods and thresholds to apply today and in which direction science do research. Direct interactions among the second-order actors are missing. They influence however the process via influencing the first-order actors in a transdisciplinary setting.

3 | WHAT DO USERS OF CLIMATE DATA NEED? RESULTS FROM SURVEYS

Based on the idealized conceptualization above, we question whether there are specific needs of each user group and if and how climate providers can meet these expectations. Our experiences are completely in line with statements by colleagues that there is not *the one user*, but every specific user has their own needs that drive the foresight itself (Cuhls, 2003). Still, we argue that some more general needs can be extracted from literature, experiences or surveys. Even more, an overview of general needs is essential to give data providers some guidance and to elucidate how user needs and climatological offers match.

3.1 | The survey of the VALUE initiative

Specific user needs have been gathered by several surveys in various countries, for example, Austria (Formayer *et al.*, 2011), Finland (Haanpää *et al.*, 2009), and recently Switzerland (MeteoSwiss, 2016). Furthermore, at least three European projects compiled an overview of user needs, extracted from other project reports: IS-ENES project (Swart and Avelar, 2011), the ClipC initiative (Groot *et al.*, 2014), and EUPORIAS project (Hewitt *et al.*, 2013). Within VALUE, we also conducted a survey on user expectations on downscaling data in general and their needs in specific. We distributed a questionnaire among the VALUE participants to approach experts from their country or network, both from science and the non-science sector. Sixty-two experts from all parts of Europe and different CCIA sectors responded. In total, 26 questions were asked about user's key variables, their temporal and spatial structure, accuracy needed, data structure (time series vs. probability density functions), the type of intended application as well as the background of the user. Here, we present the main findings of this survey and set them into context of the many different surveys conducted in Europe. Most participants (39) called themselves "impact modellers" (72% of all answers; please note that eight participants skipped the question), five decision makers (9.3%), five consultants (9.3%) and five found themselves to belong to another group (9.3%), with most

participants from the hydrology sector (60%). This clearly shows a bias in the participant structure in terms of sector (water), and in terms of working environment (most participants are from academia). All the responses shown below were hence controlled by this strong bias, by differentiating the results between the answers of all participants and the non-hydrologists and impact modellers, respectively. Table 2 summarizes some results of the VALUE questionnaire based on all 62 responses and those results obtained from the underrepresented group ($n = 12$, blue values). A further bias might origin from an uneven distribution of responders across Europe. Following the geographical structure of Jordan (2005), we received a quite balanced picture with participants originating from working in all parts of Europe [north ($n = 9$), west (10), south (20), southeast (7), central-Europe (23), Europe as a whole (11)], and also outside of Europe (13). Only East-Europe, being Russia, Belorussia and Ukraine were not represented.

The two key variables for all users were unsurprisingly precipitation and temperature, followed by wind, radiation and humidity. This ranking is irrespective of the kind of user

TABLE 2 User's key variables, required accuracy, and their spatial and temporal resolution; based on VALUE questionnaire with 62 participants. Blue numbers indicate responses of participants that are societal users from the non-water sectors. Multiple choices allowed

Parameter and accuracy needed							
	Key variable (%)		Accuracy (%)		I do not know (%)		
Temperature	96	84	"±5"	"±10–20"	20	28	
Precipitation	98	92	"±10"	"±10–50"	17	25	
Wind speed	67	67	"±20"	"±10–20"	41	45	
Rel humidity	55	25	"±10"	"±5–20"	48	67	
Global radiation	54	25	"±5"	"±10–20"	43	70	
Other	30	25	"±10"	"±10–20"	58	75	
Spatial resolution needed							
	Point scale (%)		<1 km (%)	Aggregated (%)		I do not know (%)	
Temperature	17	27	38	27	13	18	0
Precipitation	19	25	45	16	13	33	0
Wind speed	10	36	29	18	10	9	13
Rel humidity	9	33	30	22	9	0	18
Global radiation	11	33	25	11	11	0	18
Other	12	25	33	0	12	12	21
Temporal resolution needed							
	Hourly (%)	Daily (%)	>Daily (%)		I do not know (%)		
Temperature	33	9	58	73	10	18	0
Precipitation	38	17	55	75	8	8	0
Wind speed	38	28	47	55	4	18	11
Rel humidity	30	0	49	55	5	45	17
Global radiation	25	0	54	44	7	45	15
Other	25	13	54	50	0	38	21

Total number of participants ($n = 62$). Answers of participants that are not impact modellers or from the water sector ($n = 12$).

and probably might refer back to the usage of energy-balance equations, or their potential to cause catastrophic extremes like heat waves, floods and droughts and wind gusts. Most impact modellers are in favour of daily and hourly data at the point scale and require high spatial resolution. All other users agree in preferring daily data but are also interested in aggregated values over a region. The accuracy needed for all key variables fluctuates depended on the respective parameter, but $\pm 10\text{--}20\%$ are widely accepted. The high accuracy required constitutes a challenge to current climate model data and downscaling techniques. We also asked for the lowest accuracy the user can still work with and found only a very slight increase in tolerance. Interestingly, a significant part of users was sure of what kind of data they need, but were unsure about their temporal, spatial resolution or accuracy.

Generally speaking, the survey showed that impact modellers basically demand climate model data that has the same characteristics as observations. This makes sense as they use observed records to calibrate their models and the projected climate data are therefore requested to be as similar to observed climate data as possible: that is, time series as absolute values with “correct” representation of mean values, intensity, frequency, day-to-day variability and extremes. In terms of the data associated uncertainties and uncertainty bands, users (decision makers even more than impact modellers) believe that they conceptually understand what uncertainties are, but handling of uncertainties is diverse or partly unclear. Groot *et al.* (2014) put this self-appraisal into a different light by showing that the concept of uncertainty is different for the various actor groups and, partly, even more a phrase than a concept.

The results of the VALUE survey in principle confirm previous studies in terms of key variables and their resolution. However, our survey misses the importance of climate indices for many users, as for example, highlighted by the synthesis report of the ClipC project (Groot *et al.*, 2014). Swart and Avelar (2011) even find that the first product for every user is climate indices, based on which additional data can be chosen. This deviation of findings may originate in the fact that the cited surveys are based on merely societal user responses, whereas our main responses come from impact modellers that have a long history in working with meteorological input time series.

3.2 | Overview of other surveys conducted

As part of VALUE a review of national surveys or experiences has been compiled and personal experiences from several European countries were gathered (Benestad *et al.*, 2014). This comprehensive overview basically underpins the findings of our survey, but also adds some further aspects: besides climate data and climate indices, derivatives of climate data such as snow depth or snow water equivalent have been requested. In addition, numerous interviewees

demand information about flood zones of a community under climate change, land falling tropical storms, hailstorms or 10 min rainfall intensity extremes. These very specific demands nicely illustrate a problem in user surveys: An impression on the ICCS2 conference (Pingel, 2012) was that user surveys are considered more as a wish-list than a list of absolutely necessary information. It furthermore shows some unawareness of relevant or available data that in turn might lead climate data providers to the impression that users “don’t know what they want, but want everything” (quoting: D. Jacob). External surveys also highlight the importance of consistency in space, time, and inter-variable dependencies—a claim that refers back to the statement above that data should be as close to the observation data as possible.

Our review not only revealed which data or information is needed, but also how these should be presented or disseminated. Again, we found strong differences with respect to the user groups: to give a broad overview of the heterogeneity, societal users like decision makers and program initiators may need regional climate projection information on a single page (see ICCS2 impression, Pingel, 2012), aggregated in an understandable way, for example, graphics or maps. In Figure 1 we thus distinguish between data relevant for impact modellers and (data derived) information crucial for the societal users. Déandreis *et al.* (2014) furthermore highlight that climate information might not only be provided via data files, be it raw data or indices, but also via statistics, plots and maps. Natural science impact modellers in turn need the “raw climate data” (cp. Figure 1) in a way they are familiar with. By “raw climate data” they mostly understand climate model data as close to the raw data as possible, but bias corrected and downscaled to their region of interest. Users from the economic research or users from the private sector typically need information about changes in the impacts (heat waves, floods, wind damages etc.), and are often satisfied with (regional) changes in the occurrence probability of the impacts—either from the climatological community or from the impact modelling community.

4 | CHALLENGES AT THE DOWNSCALING INTERFACE

4.1 | Limitations in climate model data provision

The large list of requested variables can thus be summarized in the general need to obtain the correct future weather data in consistency with climate model projections. How far are we to meet this demand from the perspective of a climate data provider? A number of limitations and challenges have to be considered in this context:

First, one needs to be aware that climate models are, fundamentally, a simplification of nature and therefore, by definition, cannot perfectly reproduce all aspects of the climate

system (Räisänen, 2007; Randall *et al.*, 2007). Mostly because of limited technical resources, climate models are furthermore restricted in their system complexity and in their temporal and spatial resolution. Above that, even though numerous processes are simulated by the climate models, they might be prone to substantial biases (Flato *et al.*, 2013; Wang *et al.*, 2014). These biases relate back to a large degree to the coarse resolution of the climate models. Current generation GCMs from CMIP5 come at a horizontal resolution of 100–300 km, which is too coarse for many applications, in particular over complex terrain. These models generally provide a good representation of many large-scale climate phenomena and their response to climate change, but often fail to represent regional climate characteristics and changes thereof (Zubler *et al.*, 2016).

To better capture regional climate features, regional climate models (RCMs) at a higher spatial resolution are increasingly used as a downscaling tool (Giorgi and Bates, 1989; Christensen and Christensen, 2007; van der Linden and Mitchell, 2009; Rummukainen, 2010). RCMs, such as those from the CORDEX initiative (Giorgi *et al.*, 2009), currently provide a horizontal resolution of about 12.5 km (0.11°). This kind of simulations often but not always add value to lateral boundary conditions (LBCs) in various situations (Feser *et al.*, 2011; Di Luca *et al.*, 2015; Prein *et al.*, 2015). Yet, errors or limitations from the driving LBCs are inherited (Laprise *et al.*, 2008; Hall, 2014). Moreover, the resolution is still too coarse to explicitly resolve a number of important processes, such as convection and local thermal circulations. The misrepresentation of convection in RCMs has been suggested to be a major factor for the underestimation of high-intensity precipitation events (Frei *et al.*, 2006; Boberg *et al.*, 2009; Prein *et al.*, 2015) and the failure in correctly reproducing the diurnal cycle of precipitation and other variables (Brockhaus *et al.*, 2008). Even more important, there is evidence that models, which parameterise deep convection, may substantially misrepresent the response of summertime convective precipitation extremes to global warming (Kendon *et al.*, 2014; Ban *et al.*, 2015; Meredith *et al.*, 2015). Given these serious limitations on the sub-daily scale, hourly data (let alone shorter granularity) can most often not be delivered to users with scientific integrity. Higher resolution convection permitting simulations are required to correctly represent sub-daily convective precipitation extremes in models (Kendon *et al.*, 2014; Ban *et al.*, 2015). However, this is still a field of research that has only recently been initiated, due to large computational costs (Prein *et al.*, 2015). Another source of RCM bias, besides the spatio-temporal resolution, is related to the vegetation prescription. State-of-the-art RCMs are usually run with static vegetation, where land-use changes are not considered. Yet, Noblet-Ducoudré *et al.* (2012) demonstrated that regional impacts from land-use changes can be at least as important as greenhouse gas forcings although biophysical

feedbacks on regional climate are still uncertain in magnitude and sign. Multi-model simulations of land-use changes are still in their infancy although robust information is needed to aid land management decisions.

To circumvent biases and resolve the scale discrepancy between coarse resolved climate model output and the local scale, statistical downscaling methods come into play. These methods establish statistical links between large-scale and observed local-scale weather (Benestad *et al.*, 2008; Maraun *et al.*, 2010; Takayabu *et al.*, 2016). Over recent years a vast number of different statistical downscaling methods have been put forward, each with its own capabilities and limitations regarding different aspects of local daily data: for example, representation of the multi-variate structure, temporal structure, spatial consistency, variability and extremes.

A cornerstone for the future development of improved climate models and statistical downscaling methods—and hence downscaled data that better match the needs of the user community—is the availability of high-quality observations. Observations are essential to validate and calibrate dynamical models and indispensable to statistically downscale climate model data. Ideally, observations reach as far back in time as possible, but at least 30 years must be covered to build reliable statistics thereof. Although extensive meteorological observational datasets are available in Europe today (ECA&D, EOBS), some regions still lack appropriate observations that give rise to uncertainty. Often, the station network is too sparse to capture the high spatial variability and the data are not homogenized accounting for station re-locations over the time-span of the measurements. In some cases, high-quality data are available, but the access to the data is either strongly restricted or it involves very high costs. Especially for private companies or consultancies, the costs are high and, hence, they even preclude the use of the data. The emergence of high resolution free observational climate databases also contribute to confound the users since very little quality assessment has been performed and for some areas they are completely inaccurate (Bedia *et al.*, 2013). Still, an open data policy for observational climate data sets (e.g., MET Norway) is strongly appreciated.

One further challenge to bridge the gap between users and providers in terms of climate data provision are the different perspectives of the two groups. Climate data providers have the desire to provide only data that can be disseminated on a sound scientific fundament, while impact modellers have the desire to obtain as much data/information as possible to drive their models. Therefore, the two groups need to discuss, which kind of data can be provided, even if it is with less confidence, and it should be discussed what kind of data might be not perfect but still better than nothing for the impact modellers. There is a trade-off between providing data that is requested, even though it might not have the highest reliability, and not providing it and let the impact modellers fend for themselves (and perhaps produce a data

set themselves that is even less sophisticated than what could be provided). This line has to be negotiated carefully and continuously between the two actor groups, because as research develops the line might shift.

The limitations described in this section clearly indicate that the general users wish for a “future weather” is far from being realizable. This in turn strengthens the need for truly tailored regional climate data products that help to achieve at least some aspects of the user needs. At the same time, climate model data need not get overloaded by users expectations, as in practice only a limited amount of processes, variables and aspects will be relevant in a specific context (Maraun *et al.*, 2015) that can be distilled case wise.

4.2 | Non-scientific issues that cause improper downscaling

Besides scientific issues, a number of non-scientific aspects hamper the downscaling interface to work properly. These are not climate data or downscaling methodology specific, but are issues common in inter- and transdisciplinary projects, such as different concepts and perspectives on data, different background knowledge, and different use of languages (e.g., Eppler, 2007; Strasser *et al.*, 2014). In our view, the following three issues matter most at the downscaling interface: (a) knowledge-based issues, (b) communication-related issues, (c) structural issues. In the following, we elaborate each of the issues and suggest some possible ways how to tackle them.

4.2.1 | Knowledge-based issues

Issues based on divergent knowledge of actors are most obvious, most relevant and yet the hardest to solve. Trivially, if all actors would have the same common knowledge, many problems at the downscaling interface would not occur. Mutual learning is hence found to be an essential part in transdisciplinary studies in general (Pohl and Hirsch, 2008; Mobjörk, 2010), but also in joint efforts of CCIAAs and hence at the downscaling interface (e.g., Strasser *et al.*, 2014). Here, we do not refer to the knowledge of actors, but more specifically to the knowledge relevant to exchange data and information at the downscaling interface (see Figure 1). However, different aspects should be taken into account for any use of modelled regional climate change data. These aspects are to our experience not always as present to impact modellers and societal users as they should be:

1. Climate models are simplifications of real climate and suffer from substantial errors, either due to an inadequate model structure (physical processes might be missing or misrepresented) or due to unconstrained model parameters. These errors result in considerable model uncertainties from large (e.g., the representation of heat-waves in GCMs) to local scales (e.g., extreme precipitation in a downscaling method).

2. Internal climate variability affects the estimation of biases and the projection of climate change far into the 21st century, in particular at regional scales.
3. The difference between the real climate and the modelled climate (a model is not the real climate and can only produce the aspects/physics of the climate that are included into the model) and the uncertainties and limitations arising when applied on a local or regional scale model.
4. The scale discrepancy between point data and area-averaged gridded data.
5. The missing synchrony between observed data and present simulations with free running climate models.
6. The problem to handle an ensemble—of several equally probable times series—instead of a single time series.

An increased user knowledge of these aspects might help to overcome limitations at the downscaling interface, as it results in a more targeted exchange of information about what is needed from the user, and raise understanding of what kind of data and information can and cannot be provided by downscaling methods. In turn, the above list displays some obstacles a user faces today and highlights the need for guidance along with the data or information provided.

On the other hand, climate data providers often lack knowledge on how the climate data is incorporated into impact models, what the critical thresholds are and how climate information is applied in daily business. This knowledge might help climate modellers to better understand the data requests—including the need for a certain accuracy. It might also help solving some problems: if climate data providers knew more about the intended use of the data, they might be able to come up with some supportive statements about the data or with another kind of data that might improve the usability of the climate information in impact studies or societal use.

A part of these issues might be solved by expecting all actors involved to obtain some elementary knowledge about the system of interest. This fact again calls for mutual learning as an essential part of a joint downscaling and climate change assessment. However, since all individuals participating in this exchange are experts in their own field, we cannot expect everyone to become an expert on everything. But, being humble and aware of one’s own limited competence, and involving and accepting one other’s expertise—although it might be difficult at first—helps to gain a common understanding and can lead to new knowledge. Within VALUE, we also made this experience.

Apart from lacking knowledge on how to improve CCIAAs, a different side of the same medal is the unawareness of climate change effects at all. For instance, some research communities consider climate change as not relevant or of minor importance to their field. This lack of

consideration directly affects the research results, as specific solutions for their possible future demands will be underrepresented, if not completely missing.

To overcome obstacles based on divergent knowledge that are typical in transdisciplinary projects, fewer scientific solutions are present (Hinkel, 2008) than for societal or technical integration of actors. In the field of knowledge integration, Hinkel (2008) suggests to first define a common language, based on which a joint methodological concept can be developed resulting in coupled models rather than in coupled theories. The willingness of all actor groups to learn, and adapt common practices, the “societal integration” (Hinkel, 2008), is a prerequisite whose importance was also highlighted by the ClipC consortium (Groot *et al.*, 2014). To define a common language, glossaries clarifying the understanding of terms in a certain community are very helpful. Based on this a joint methodological concept can be developed. The VALUE project as well as the ClipC consortium generated such a glossary for the climate and downscaling community, respectively. For the purpose of mutual learning between the actor groups at the downscaling interface,

TABLE 3 Tentative proposal of a change in behaviour of actors at the downscaling interface

Climate model data provider	Climate model data/ information user
Be brave! Provide model output data at the (highest) native temporal and spatial model resolution to expert users. This might, for example, include providing values for specific landscapes (like upper Rhine valley). Such an open data policy requires detailed guidance and co-exploration of the further analyses with the data providers.	Be careful! Check for analogues in the research area that might be useful for inter or extrapolating climate model data for the requested temporal and spatial scale.
Be brave! Refuse provision of implausible data, just because the user asks for it. Be aware of your responsibility for subsequent adaptation decisions, which rely on the quality of the data provided.	Be careful! Not every user need can be distilled from climate model data. Be brave and think of alternative ways.
If absolutely necessary: provide bias-adjusted model output. Bias correction may induce considerable artefacts and expert knowledge on both the corrected climate model and the considered climate is required to avoid misleading interpretation. This holds in particular for quantile mapping and even more sophisticated approaches.	Train your impact model/research method/decision support tool on working with relative change values (compared to observations) instead of absolute values if feasible.
If the requested data simply cannot be delivered with good consciousness: try to find variables that might be useful for the planned impact research or decision support and that could be provided with higher confidence.	Develop assessment tools in your specific research area (e.g., assessment of critical levels that might or might not be exceeded by future climate), which are able to cope with the kind of data that can usually be provided with good consciousness from the climate model data providers (like, e.g., probabilities of exceeding certain thresholds in the future).

additional glossaries that have to be compiled by societal users and impact modellers for their specific field of interest are worthwhile.

In actual projects that work on the downscaling interface, for example, for the purpose of a CCIA study, the establishment of a “task force” that elaborates a common language, common understanding and mutual knowledge very early in a project was suggested by Strasser *et al.* (2014). This idea is also present in several projects at the FAO (personal communication H. Kanamaru). This task force should consist of delegates from each actor group that are also responsible for the outreach in their specific actor group. An advantage of this procedure lies in its smaller group size and that delegates are likely more committed to the transdisciplinary process. The relevance of this commitment was also one of the findings of the EUPORIAS review (Hewitt *et al.*, 2013), where the nomination of a person being responsible for the stakeholder needs was considered as crucial (Groot *et al.*, 2014). This person could be the delegate from the climate community in the “task force” setting. The commitment of the involved actor groups to work on the transdisciplinary interface goes even further, as it demands a change in the “behaviour” of data providers and users as well. Both sides need to agree on the work-sharing to tackle this issue. Table 3 shows a tentative proposal of such a responsibility sharing.

4.2.2 | Communication-related issues

Climate model data as an input in impact research or decision-making must not only be delivered, but also be communicated in a way the user understands and that enables the user to apply the climate data and information within their own decision context. To fulfil this demand, many producers of climate data and climate service providers (CSCs) use the internet as their main outreach tool. This is reasonable as it provides easy access for the users to the data they request (at least theoretically, as not all data are as easily available as necessary). However, a number of problems come along:

1. Some data are either not available for scientific exploitation for a long time after their initial production (e.g., PRUDENCE and ENSEMBLES project), or their use is restricted to non-commercial use.
2. A large amount of data are stored in formats and indexed in climatological terms. So, from a user perspective, required data are hard to find and process.
3. Not all data portals provide an ingenious guidance system on the strengths and weaknesses of certain data/output of certain models or methods that addresses not-climatologists and also non-scientific users.
4. The communication of uncertainties inherent to the climate model data is a complex challenge, even more in a one-direction communication setting like webpages.

Thus, many users find resort to the information that is most-readily accessible instead of the data that would suit their information needs best.

In contrast, climate data providers may not always be interested in providing the data as “easily” as required by the users. This might be due to doubts on—be justified or not—users’ awareness of the central differences between observational and model data (see section A of this sub-chapter). Hieroglyphic data portals enforce the users to contact the climate data providers and receive some guidance about the downloaded data—or shove potential users towards more convenient portals even if the data provided are less resilient. Another reason might be the self-conception of climate data providers as being climate scientists for which outreach is not an essential part of their duty. While it is basically true that climate change research is not necessarily connected to communication issues, at least the outreach portals should be developed by people who see their calling in both subjects: climatology and communication.

Moreover, outreach and communication aspects are highly underrated by science funding agencies, as well as by the research community itself, obstructing a higher interest of scientists to develop new and hopefully better forms of communication. Certainly, this lack of outreach has been realized by founding organizations that promote the development of new, much more user-oriented portals, like ClipC, that try to combine user guidance with data provision (Groot *et al.*, 2014). Other strategies tend to provide outreach reports along downscaled national climate change data sets, like the Swiss CH2011 project (CH2011), the French Jouzel report 2014 (Ouzeau *et al.*, 2014), the KNMI report from the Netherlands (KNMI, 2014), the SIAM report (Santos *et al.*, 2002).

Beyond data portals, several studies proved the added value of constant direct face-to-face communication between data providers and data users for a successful downscaling product and CCIA (Almeida *et al.*, 2015, H. Hübener, personal communication). However, an ideal communication between providers and users, if not a financed part of a project from the start, is often difficult or non-existent.

When an eventual impact of climate change on a user activity is perceived, the decision-making process has to be based on the best climate information that climatologists and impact modellers can provide (Meinke *et al.*, 2009)—it is here that several linkage problems arise. Often, climatologists do not describe in a proper manner the inherent uncertainty associated to climate projections (Burke *et al.*, 2015), whether stemming from uncertain future emission paths, model deficiencies or internal climate variability. It is important to explain what the numbers really represent, be it observation or model results. Furthermore, uncertainties vary by variable, region, future time period and season.

To provide all kinds of users from different regions, subjects, backgrounds and interests with the information, they

need much more information on the (physical, empirical) reliability of each part of the data or information. In the cases when climatologists provide a bandwidth of the model results, impact modellers sometimes do not know how to consider this interval for the information they provide to users. In some cases when the bandwidth or uncertainty is accounted for in all the linkages from climatologist to user the uncertainties have increased enormously (Jones, 2000). This chain of problems has as a consequence that information is often perceived as too uncertain to be of any practical use, or that there is a failure in quantifying uncertainty (Kiem *et al.*, 2014). At this point, improved communication is needed that clearly states the robust and certain part of the projection. Reasons for the found uncertainties should be given additionally, but should not obscure the main result. Current scientific focus on uncertainties is of high relevance, but it should not prevent a clear answer (if present) to the raised societal question.

4.2.3 | Structural issues

Callahan *et al.* (1999) state, among other more technical problems, an “institutional aversion to incorporating new tools into decision-making.” Lee and Whitely (2010) find barriers in the form of “limited staff capacity, lack of clear guidance on how to integrate climate change into planning, lack of management support, institutional inertia, limited data availability, limited funding, lack of mandate to plan for climate change and complexity of the problem.”

We add to this list some barriers at the climate data provider side of the “fence”: missing or too little funding/manpower for data provision, post-processing and communication in climate research projects, too little appreciation of outreach in the scientific community and inflexible actors also at the climate data provider side. One example to illustrate the issue of post-processing is the divergent number of simulations performed and provided in data portals as, for example, found in CORDEX simulations. With a more general focus on CCIA, a major obstacle is the insufficient funding of comprehensive impact studies and dissemination of impact model results, as those data sets are the basis for adaptation strategies.

Some of these barriers could be overcome by funding, some might need time and dedicated fighters for more appreciation for outreach activities in the scientific community. Callahan *et al.* (1999) propose a combination of technical improvements and reciprocal and iterative mutual education between climate data providers and managers to overcome these barriers.

Besides, working at the downscaling interface is not as ideal as Figure 1 might suggest. In reality it is often much more chaotic and scattered, because the overwhelming part of actors at the interface work rather independently than jointly, using data and downscaling methods they can get hold of or that they can understand and perform on their

own. This more chaotic cast adds further complexity to the downscaling interface. One reason might be the missing or underdeveloped number of climate change consultancies, or “intermediaries” as described by Groot *et al.* (2014) that can help link the different actor group and provide guidance along the downscaling and CCIA process.

The internet portal www.climate-knowledge-hub.org collects those intermediators for Europe and shows a yet unfinished collection of approximately 180 intermediators. Private intermediators, national and regional climate service centres are crucial and independent contact points, but they are not present in every country or region and, even if so, there is still a great mismatch in numbers between climate data providers and users. This is even more the case if not the climate model data itself but a tailored downscaling is needed to fulfil the user needs. And the number of users will likely drastically increase in the coming years, also due to the political willingness to foster adaptation also at the community level (COM, 2013).

Still, the “number problem”—lots of users and only relatively few providers—remains. This is where new ideas and developments to overcome structural issues come into play. The national meteorological services and—if separate institutions—CSCs as professional “border organizations” might play a crucial role here, given that they are suitably funded and aimed. For sure, they cannot themselves serve every request. CSC can be contact points that establish the first contacts between actor groups and/or accompany the downscaling process. The new Swiss National Climate Service Centre (NCCS) and the Climate Service Center in Germany (GERICS) strive this way.

Recently many different internet portals have emerged all claiming they incorporate climate data user’s demands in a much more specific way. Several of these portals allow for on-the-fly calculation of user-tailored climate change information at the regional scale (CCAFS, Santander Downscaling Portal). Although this seems a very promising way to cope with the number problem, all concerns raised above still hold, with a very sophisticated request tool still needed on how to ensure that proper tailored information is available to users on portals/platforms (without face-2-face meetings). This remains an open question and challenge.

Another way to overcome the number problem is to establish a new profession of climate change advisors: Well trained, private consultants who can advise local authorities or other environmental offices how to access, apply and interpret downscaled climate data or information for each specific case. An example of this kind of profession might be the energy advisors, a new professional branch that is quite successful in some European countries (Owen *et al.*, 2014). Today, some large consultancy companies offer already a climate change impact and adaptation program. But, they are hardly affordable for some communities. An

essential prerequisite for such a profession would be some kind of certificate that guarantees a solid education.

5 | CONCLUSION

The inter and transdisciplinary downscaling interface is composed of numerous actors with different backgrounds, different perspectives and diverse knowledge. This setting calls for solutions on an individual basis. However, while this might be the ideal case, it remains unrealistic given the vast number of CCIA. Hence, a structure of user groups and their needs, as well as a structure of issues hampering a proper downscaling, and finally a guidance of how to choose among all the present climate model data sets help to abstract from individual challenges. Furthermore, this structuring might help to foster research in a direction helpful for the different users.

We have presented here a suggestion of such a structuring of actors, needs and issues. In addition, the VALUE platform shall result in a guidance of how to select the most appropriate downscaling methodology or data for a given case study. Still, current climate models and current downscaling techniques cannot meet some user needs, and some likely cannot be met also in the near future. We think, it is also the duty of the climate data providers to be clear about these limitations. In turn, the impact modellers and the societal users are responsible to develop reliable solutions for these cases. Furthermore, what can and what cannot be provided remains a fine line that has to be negotiated continuously between the three actor groups, as scientific knowledge progresses.

Apart from the data limitations, we showed that common inter- and transdisciplinary issues might hamper a proper usage of downscaling data or even the development thereof. The incorporation of established techniques to solve transdisciplinary issues have to be applied in CCIA, but will most likely be dismissed due to financial obstacles.

Finally, internet portals like ClipC or downscaling platforms are of great help to provide climate data to as much CCIA conductors as possible. Nevertheless, we doubt that those portals and guidelines will solve the great communication challenges if not a minimum of mutual—common knowledge is built up. Thus, international, national or even regional climate service centres are crucial to lead the optimal way, to help network building and to foster knowledge and communication among the first-order users and providers (see Figure 1) at the downscaling interface. An increasing number of private companies—intermediaries—that advise communities or corporations in CCIA might accompany these centres. Those consultants should be regularly trained and certified to ensure a high standard for CCIA.

Based on both, an ever-increasing disciplinary knowledge and a shared—mutual knowledge on how to work

together transdisciplinarily, the partly huge challenges currently present at the downscaling interface might be tackled. This will help to provide the best possible basis for profound adaptation to climate change.

ACKNOWLEDGEMENTS

VALUE is funded via the EU FP7 programme as EU COST Action ES1102. We thank the VALUE community for their input to this perspective and review paper. We also like to thank all participants of the survey conducted.

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How to cite this article: Rössler O, Fischer AM, Huebener H, et al. Challenges to link climate change data provision and user needs: Perspective from the COST-action VALUE. *Int J Climatol*. 2019;39: 3704–3716. <https://doi.org/10.1002/joc.5060>