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The 'last mile' for climate data supporting local adaptation

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Non-technical summary. The 'last mile' is a transportation planning term that describes the movement of people and goods from a transportation hub to a final destination; a local place such as a home or a shop. This is the final step of the logistics process that unites the product with its new owner. We present and explain challenges of science-guided adaptation at the local level, and how this is an equivalent 'last mile' challenge for climate adaptation.

Technical summary. The 'last mile' issue, a term used in transportation planning, describes the movement of people and goods from a transportation hub to a final destination, a local place such as a home or a shop. This is the critical final step of the logistics process that unites the product with its new owner, and the point of the value chain. This analogy aptly describes the last steps between presenting scientific evidence of climate change to decision-makers for use in local adaptation and planning. Climate change data (observational and model simulation data e.g. climate change projections and predictions) remain under-utilised, especially by local institutions and actors for which adaptation is a priority. The assumptions and assertions of the classical data–information–knowledge–wisdom are challenged, and a derivative form of the information hierarchy is proposed. Elements of the classical information hierarchy are offset by four balancing elements of access (to data); usability (of information); governance (of knowledge) and politics (of wisdom). These balancing elements and their relatedness coincide with newer models of innovation relating to the interaction between different stakeholders across the different levels of governance, the inclusion of stakeholder expectations, transparency and accountability.

Social media summary. Climate data to wise decision-making in the 'last mile': a novel perspective on science-guided local adaptation.

1. Introduction

The chain of events that result in the practical use of climate science at the local level is referred to the 'last mile' challenge for climate change evidence to become actions in support of climate change adaptation. The 'last mile', is a term used in transportation planning that describes the movement of people and goods from a transportation hub to a final destination, a local place such as a home or a store. This is the critical step that unites a product with its new owner. This analogy aptly describes the last step of presenting scientific evidence of climate change to decision-makers for use of that information in local adaptation and planning. Examples of local adaptation that relies on climate science includes urban greening to reduce temperatures, facilitate managed retreat from sea-level rise, installing desalination plants in drought-prone areas (Stults & Woodruff, 2017). Successful adaptation to climate change depends on, among other factors, knowing how and how much the climate is changing by when (e.g. downscaled predictions and projections of temperature, or precipitation in the future). However, climate science is often under-utilised because of its low 'usability', especially by institutions and actors for which the urgency of adaptation is a priority, such as at the local or community level (Kirchhoff et al., 2013; Lemos et al., 2012; Moser & Ekstrom, 2010).

Responding to climate change science at the local or community level requires complex *local governance* (Nordgren et al., 2016; Revi et al., 2014). Local governance is the act of planning and achieving objectives not only stipulated in legislation or regulations, but also those of society itself. Actions of governance radiate outwards from local government and civil society but spans multiple levels (local, regional, national, inter-municipal and global) and sectors (governmental, civil-society and private) (Aylett, 2015; Bulkeley & Betsill, 2005). Even though local adaptation is often facilitated cooperatively with higher administrative levels such as national and sub-national government (Cole, 2015; De Freitas et al., 2013; Nalau et al., 2015), there is a wide-held belief that 'things can get done' at the local level (hence the term local 'authorities') where the impacts of climate change are observed, experienced and reported (Dessai et al., 2005;

van Aalst & Agrawala, 2005). Given these local contexts, there is general agreement on the importance of local and place-based actions to support a shift to sustainability (Lorenz et al., 2017; Pasquini et al., 2015). There is also an increasingly pressing need to adapt to the impacts of climate change (IPCC, 2014).

The provision of locally relevant (see Tribbia & Moser, 2008 for examples) climate change data and information (observational and model simulation data e.g. forecasts, climate change predictions and projections) is only part of the solution to adaptation (Lemos et al., 2012). There are many other barriers and limitations to climate change adaptation at the local level (Carlsson-Kanyama et al., 2013; Nordgren et al., 2016; Sanchez-Rodriguez, 2009). They may include individual-level barriers such as a lack in understanding of climate change and adaptation options. Barriers could also involve the regulatory or institutional level through deferred or delayed action due to electoral politics or due to a mismatch of time scales between climate change and election cycles (Rölfer et al., 2020; Vincent et al., 2017). Often, such barriers separate the useful outputs from climate science from becoming evidence, used to inform decision-making and achieve societal and individual objectives and desires.

In this paper, we apply the assumptions and assertions of the classical information hierarchy (Ackoff, 1989; Rowley, 2006; see Section 2) to the transformation of climate change data (multi-scale observations, projections and predictions) to wisdom for local adaptation. We also challenge these assumptions based on the observation that improvements in the provision of climate change data (e.g. more and further downscaled climate change projections) alone have not led to an automatic or spontaneous increase in uptake into science- and decision-making processes (Dilling & Lemos, 2011) in urban areas, or by local governance (Lorenz et al., 2017; Schreurs, 2008). Simply put, the return on investment in producing climate change data is not borne out in terms of wiser decisions and adaptation to change (Revi et al., 2014). In this paper, we present an inverse and accompanying governance hierarchy, and elaborate its relationship with the information hierarchy. We offer a more accurate representation of the interface between climate change data and their application by actors responsible for local climate change adaptation. By proposing a connected governance hierarchy, we create a framework for hierarchical parity that is more realistic of the 'last mile' challenge of producing usable and used climate change science.

2. The (climate change) information hierarchy

The relationship between climate science and data and its wise use at the local level can be simplified by the data–information–knowledge–wisdom (DIKW), or *information hierarchy* (Figure 1; Ackoff, 1989; Rowley, 2007; Zins, 2007). The information hierarchy explains an idealised and logical flow of how scientific data becomes societal wisdom (Cortner, 2000; Weiss, 1979). The information hierarchy precludes contemporary arguments for the importance of post-normal science ('facts [are] uncertain, values in dispute, stakes high and decisions urgent'; Funtowicz & Ravetz, 1993), social learning and co-production (Kirchhoff et al., 2013). The hierarchy assumes the direct evolution of data to wisdom, a post-normal concept of embedding and internalising science into society (Rowley, 2006).

Data which are described as discrete, without meaning and context, or elementary and recorded description of materiality (Rowley, 2007) are at the base of triangle. The base has the largest area, concomitant with its perceived value in the scientific process. *Information*, despite remaining an elusive concept, is understood as formatted and interpreted data with context and potential for application (Rowley, 1998). The third section of the triangle represents *knowledge* which is information that has been organised and processed to convey understanding, experience, accumulated learning and expertise to act in a particular way, that is, useful information and usable science (Dilling & Lemos, 2011; Kirchhoff et al., 2013). Finally, *wisdom*, at the apex of the triangle, is the ability and capacity for appropriate behaviour, based on knowledge, and 'what is good' (Rowley, 2006). The four elements of the hierarchy are related, with an upward distillation of data towards a conclusion of achieved wisdom at the apex of the triangle. The hierarchy has been criticised for its simplicity, structure and validity of the relationships between elements (Fricke, 2008). Yet, the hierarchy persists in the information literature and has been applied in a variety of settings, other than in information technology (Aven, 2013; Spiekermann et al., 2015; Weichselgartner & Kasperson, 2010).

Now, applied to evidence-based adaptation, climate change *data* include both observational and model simulation data. Downscaled climate projections or decadal scale predictions are of increasingly adequate resolution to produce indices of important climate variables to inform (as *information*) climate adaptation planning processes at, increasingly, local levels (Cabos et al., 2018; Daron et al., 2018; Giorgi & Gutowski, 2015). There is an obvious connection between climate change simulation data (different climate models, projection of climate variables under various greenhouse gas scenarios) and information derived from these data, such as future temperature and precipitation indices. *Knowledge* is a derivative of information and through co-production becomes actionable (Arnott et al., 2020; Mach et al., 2020). Knowledge is recognised as an important determinant and indicator of adaptive capacity (Williams et al., 2015), whereas *wisdom* refers to actions taken to enhance sustainability of human activities (Rowley, 2006). Is such a hierarchy useful for improving the usability of information for local climate adaptation science? (Dilling & Lemos, 2011; Kalafatis et al., 2015).

The implied flow of the classical hierarchy, upwards from data to wisdom, depicts decreasing uncertainty and reduced energy towards the apex of the triangle, that is, decreasing social entropy. Social entropy and social entropy theory (Bailey, 2006, 2009; Swanson et al., 1997) is a useful concept to explain the failing of the information hierarchy in relation to the conversion of climate change data to wisdom. The interpretation of the social entropy in this instance results in the perception that the least energy is expended on effecting change through wise decision-making. This is at the apex of the information hierarchy. However, the literature provides convincing arguments that, in fact, the opposite is true (see Supplementary Table 1). Energy is required in excess for social action (at the apex; Bailey, 2009, 2006) and equally so, actively adapting societies, require an abundance of energy (Mavrofides et al., 2011). The energy required to effect change is contained in economic, cultural, social, human, environmental and symbolic capital (Carmona et al., 2017; Mavrofides et al., 2011). These are forms that the various capitals assume when they are perceived and recognised as legitimate (Mavrofides et al., 2011).

The argument for the increasingly higher resolution and costly production of downscaled climate change data (as model simulations and projections) cannot be rationalised in the absence of the elements of the information hierarchy that also acknowledge the importance of the energy and predictability required to reduce

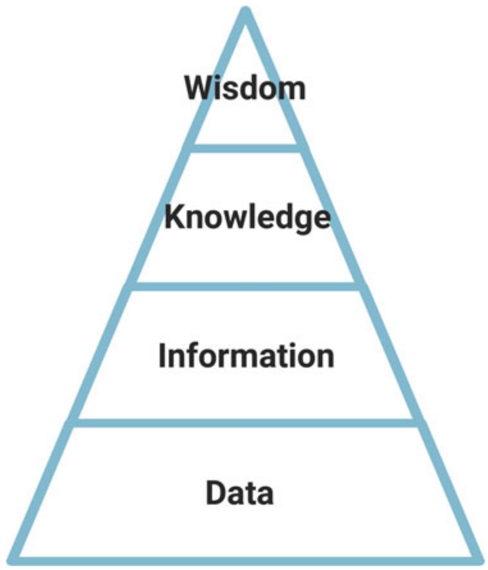

Fig. 1. DIKW or information hierarchy (Ackoff, 1989).

social entropy. The climate information hierarchy is fundamentally inadequate in describing the relationship between climate data and information, and the elements of knowledge and wisdom, as social action. Another conception of the transformation from climate change data to wisdom is thus required. We are proposing that the climate information hierarchy is a useful construct with an additional, equivalent but inverse hierarchy of local governance actions. Such an inverse governance hierarchy is required to complete the 'last mile' challenge for usable climate science to be used for adaptation. This conception, depicting a hierarchical parity or co-equality is described in the next section.

3. Hierarchical parity

Achieving parity and reducing entropy where it matters most for societal processes of adaptation can support the implementation of decision-making structure that (should) make use of scientific data. Therefore, we propose a parallel and inverse elaboration of the information hierarchy that offers a clarification of the interface between scientific outputs as climate data and societal goals for local climate adaptation (Figure 2).

The elements of the classical information hierarchy (B) are offset by a parallel 'upside-down' governance hierarchy (depicted as an upside-down triangle). In relation to each other there are four balancing elements (C) of: access (to data); usability (of information); governance (of knowledge) and politics (of wisdom). The objective of these balanced information-governance hierarchies is to elaborate on the pathway (starting at A in Figure 2) from climate change data to planning and achieving local climate adaptation using. It initiates at the scientific *production of climate change data* and concludes as the *local governance* of climate change adaptation. Each element of the two inverse hierarchies is balanced by actions (E) and by different sets of actors (D).

3.1. Access to data

It remains an increasing challenge to ensure that the growing volumes of data are easily and freely available to enable new scientific research, and that these data and information are useful to, understandable and accessible by a broad interdisciplinary audience (Benestad et al., 2017; Overpeck et al., 2011). Notwithstanding the volume of global and regional climate data available, the demand for locally relevant climate change data is only sometimes satisfied since specific adaptation measures require information on specific parameters not yet evaluated in climate model simulations (Hackenbruch et al., 2017). Barriers and limitations include the lack of access to technical data (Jones et al., 2015; Measham et al., 2011; Prieur-Richard et al., 2018) and the scale and type of data (Bai et al., 2018; Cheng et al., 2017). There is often simply no local access to data, and no basis or mechanism for questioning practices in the scientific process. Local actors require awareness of, and often access to climate data for subsequent use. Access to climate data may be of direct value to local institutions which have the capability to store and analyse such data. Many local governance agencies also may have no interest in climate change data for a lack of capacity. Local observations and knowledge are often not recognised by the scientific establishment as climate change data, and not included in the production of information. The absence of local knowledge in the production of climate information is a source of distrust later.

3.2. Usability of information

Access and possession of 'raw' climate change data (model simulation data and projections) are, for the most part, of no particular value for local decision-makers. Without the data interpreted for the local context (indices of change), they are likely to remain unused. The demand for locally relevant climate change information is often not satisfied because of the insufficient availability of appropriate climate information. The need for climate change information at the regional-to-local level is one of the central issues within the global change debate and there are many examples of how such information is becoming available (Abba Omar & Abiodun, 2017; Giorgi et al., 2009). The efforts of the IPCC in this regard are noticeable (IPCC, 2013). However, scientific and technical factors account for only a fraction of the barriers to information uptake (Jones et al., 2015). Barriers and limitations include the nature and type of climate information (Jones et al., 2015; Porter et al., 2015), and resource and capacity limitations (Lemos et al., 2012; Pasquini et al., 2013).

At the local governance level, especially for larger administrative units such as municipalities and cities, there are in-house expertise and infrastructure (i.e. computers, specialised software, etc.) capable of accepting climate data, converting and interpreting to inform specific local issues. Climate services (Brasseur & Gallardo, 2016; Street, 2016) are a major contributor to the production of useful climate information. There are numerous applications of how climate change data are converted to information relevant to specific sectors and users (Buontempo et al., 2018, 2020; Golding et al., 2017). However, the production of information remains a predominantly scientific function, even though there is a much higher likelihood of decision-makers showing an interest and opinion in how the data are interpreted. At this stage, the concepts of science and local actor co-development, with climate data transformed to deliver useful information, becomes a possibility (Norström et al., 2020; Shepherd, 2019).

3.3. Governance of knowledge

Although information is more *useful* to local decision-makers (as indices of change, e.g. mean, max, min surface temperatures and

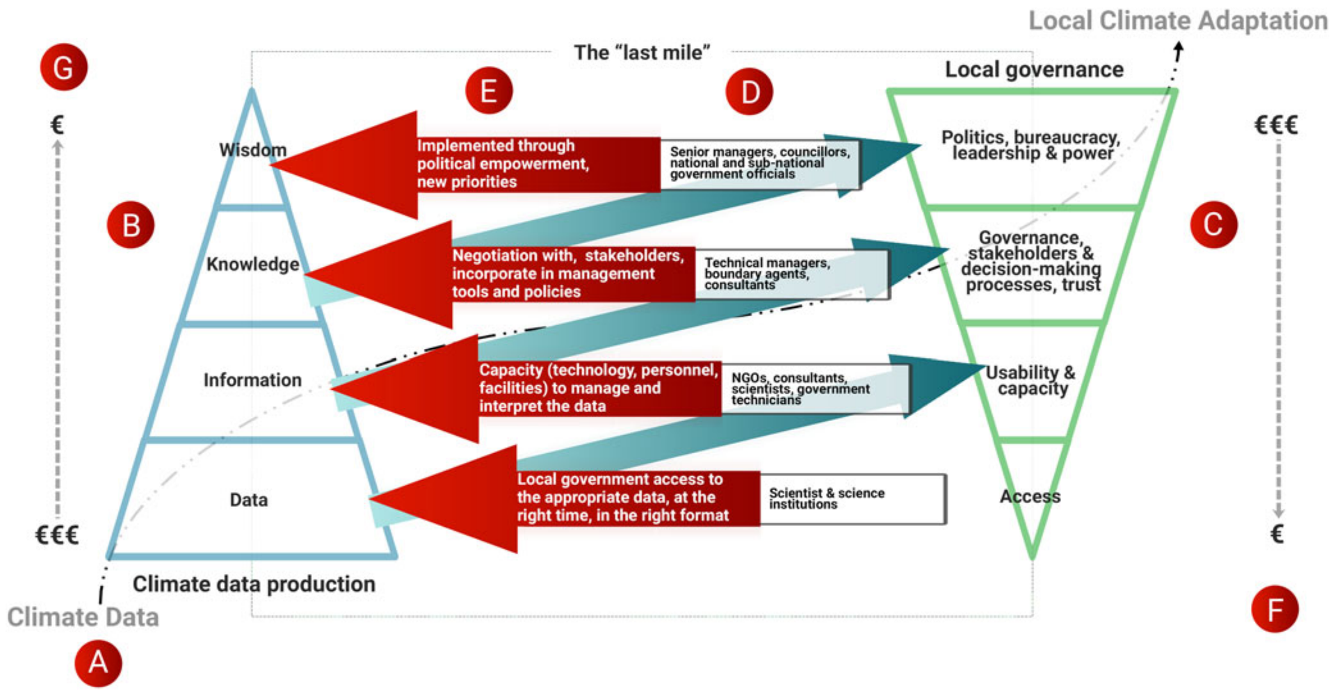

Fig. 2. Interface between climate data or the 'last mile' for the conversion of climate data and information to wise evidence-based local climate adaptation. The different elements of the diagram are indicated by capital letters and explained in the text.

precipitation), it often still falls short of becoming knowledge *used* for decision-making. The demand for locally relevant climate change knowledge for integrating into decision-making processes is very rarely satisfied because of a range of less ethereal but equally debilitating for adaptation planning. Barriers and limitations include institutional settings (Aylett, 2015; Colenbrander & Bavinck, 2017; Pasquini et al., 2013), alignment of local policy (Araos et al., 2017; Carter et al., 2015; Measham et al., 2011), engagement of society (Baker et al., 2012; Prieur-Richard et al., 2018; Weichselgartner & Kasperson, 2010) and resource limitations and budget cuts (Baker et al., 2012; Nordgren et al., 2016; Porter et al., 2015).

Local government and local processes are complex, and heavily affected by local economic, environmental and social contexts. The framing of adaptation as a decision problem, whereby the responses to impacts of change are addressed within existing decision processes, is constrained by societal values and principles, regulations and norms and the state of knowledge (Gorddard et al., 2016). Furthermore, decision-making for climate change adaptation requires an integrated and cross-sectoral approach to adequately capture the complexity of interconnected systems (Olazabal et al., 2018).

Even well-established and formal legislative processes such as development planning, environmental impact assessments, land-use planning, building regulations, local economic planning, disaster management, etc., are context-sensitive to communities within their environment. The issue of trust in scientific information is critical at this stage (Kulin & Johansson Sevä, 2021; Lacey et al., 2018). This is trust in both the quality of the information itself (results of a scientific process), as well as the stakeholder processes (local governance process) that forms part of local decision-making. Notions of acceptance and incorporation of climate information are seldom within the domain of only one individual or functional unit within local government. Much wider consultation is required before climate data can be considered useful for informing local sector plans or other integrated management mechanisms. It is in this context that co-production of climate services have grown in prominence during the last decade (Bremer & Meisch, 2017; Mach et al., 2020; Vincent et al., 2018).

3.4. Politics of wisdom

The generation of knowledge, as a composite of local knowledge and management processes, integrated with new information derived from climate data, is a state from which actions can be taken. The demand for locally relevant climate change wisdom is very rarely satisfied because of intangible, unpredictable socially complex and non-linear parameters that contribute to high social entropy. The final and most substantive barriers and limits to adaptation actions are of socio-political nature, where rationality in decision-making is not assured. Barriers and limitations include the complexity and influence of local politics (Bulkeley & Betsill, 2005; Jones et al., 2015; Ordner, 2017); leaders and leadership (Bateman & Mann, 2016; Pasquini & Shearing, 2014), societal desires and objectives (Pasquini et al., 2013; van der Voorn et al., 2017), fairness and climate justice (Paavola & Adger, 2006; Shi et al., 2016) and the role of networks (Bidwell et al., 2013; Pasquini & Shearing, 2014).

For example, climate leaders, especially in complex living systems, require a range of leadership activities including administrating (classic top-down leadership), enabling (clearing the path for others to drive productive change) and adapting to changing environments (Bateman & Mann, 2016). The more complex characteristics of political will, and bureaucracy are also recognised as drivers of decision-making (Colenbrander & Bavinck, 2017), as is decision-making politics (Tschakert et al., 2016). Even in the presence of actionable climate knowledge that incorporates local scientific data and information, and is integrated into local processes, decisions are often made based on external factors, such as market prices, or personal (normative) values. These can often be unknown to local technocrats, and even less so by climate scientists.

3.5. The 'last mile' for data provision and local adaptation?

The classical information hierarchy cannot progress towards its apex without concomitant input to both the scientific and governance processes depicted in the two connected hierarchies. The combined (both hierarchies) input towards achieving wisdom can be defined as the 'last mile challenge' for climate adaptation at the local level. In logistics, in the 'last mile' there are different users with different expectations ordering different types of goods (perishable, fragile, etc.) that requires different vehicles for delivery. Nearly half the cost of delivery is associated with the 'last mile'. Other challenges in the last mile includes poor road infrastructure from the warehouse to the home which delays deliveries. With increasingly dense neighbourhoods, planning for deliveries must consider the most efficient route to reach the customers on time. Although we did not specifically align logistics 'last mile' challenges with those identified by the two hierarchies of climate adaptation at the local level, there are common principles relating to cost, efficiency of delivery, variety of needs, etc. that are clear.

The dual input to both the science and governance process can often frustrate scientists because of the energy demand (G in Figure 2; in the form of time, resources and local processes) leading to their reduced interest and involvement. The conversion of climate data and information to knowledge is an energy-intensive process, and the continued engagement of science and scientists in local governance rapidly diminishes due to the high costs and increasing level of disorganisation and complexity. Discordantly, the cost of wisdom for local governance is highest at the level of the socio-political element of the hierarchy, and notoriously unpredictable (F in Figure 2). The likelihood for misunderstanding and disinterest between climate change scientists and local governance actors are high.

The value of appropriately scaled and relevant climate change data and information of higher degrees of certainty is not disputed and should continue (IPCC, 2013). The information hierarchy applied to climate change data demonstrates the failures of assumptions relating to the transformation of data to wisdom. Adaptation actions to achieve measures of sustainability, and to realise adaptation policies requires an understanding of the pyramidal inverse to the classical hierarchy. This provides relief to the tension created when delineating the conversion of climate data for local adaptation.

During the scientific process, and with the use of climate data and information in mind, it would be valuable to imagine the modified information hierarchy as a map with waypoints in each of the main elements of the information hierarchy balanced by its inverse local governance counterpart. As such, the modified framework provides an outline against which to plan the conversion of climate data through to climate wisdom. In other words, such conversion requires substantial energy through planning and intent. The modified information hierarchy identifies commitment and investment from institutions within every element of the two interlinked hierarchies. It also points to necessity of non-overlapping mutual dependency and complementary skill sets to achieve adaptation goals.

The complexity of climate data transformation at the boundary between science and society requires a new set of tools that are relevant for adaptation science. The use of trans-disciplinary and participatory processes, system dynamics and agent-based modelling are likely to provide analytical capabilities of complex socio-ecological systems (Bai et al., 2018; Berbés-Blázquez et al., 2017). Essentially, the complexities of local communities can only be understood as a system, and so analysed (Bailey, 2009). This implies a necessary and complete breakdown of discipline barriers and governance silos. System dynamics and agent-based modelling are useful to test the impact of climate wisdom and decision-making and offer a tool for negotiation between scientists, local communities and the networks that span these groups. The complexity of developing adaptation planning actions, and satisfying multiple development objectives at local levels, will not be overcome without a systems-perspective.

Even with the introduction of a governance element to offset (achieve parity) the simplicity of the information hierarchy, the use of climate change data and information remains a challenge. The hierarchical parity presented here is not an approach *per se*, and the terms used in the paper are subject to much interpretative scope. The purpose of the parity, and the use of social entropy places the emphasis on the energy and intentionality required to make climate change data useful, and used for adaptation at the local level. It offers an organised rationale for the management of knowledge in the climate change science-to-policy space. The complex processes for scientific decision-making resulting in the creation of data, as well as the role of private sector in this framework remains to be explored.

4. Conclusions

Social entropy dictates that the mere existence of useful information does not imply that an act of change is imminent or even likely (Mavrofides et al., 2011). The co-existence and mutual influence of both information and energy (to act and cause change) is required to solve the 'last mile' issue in adaptation. There are many convincing arguments to improve the uptake of climate science results into decision-making processes. Nevertheless, the uptake remains in its infancy. With this paper, we provide a way of highlighting challenges in uptake from the point of view of the energy, information and organisation needed to transform data into wise decision-making at the local level. This facilitates the identification of possible bottlenecks that might hinder the uptake condemning climate change data to the valley of death (Butler, 2012).

The steps of access (to data); usability (of information); governance (of knowledge) and politics (of wisdom) provide a foundation for building a bridge between scientific results and their societal use, especially at the local level. These balancing elements and their relatedness coincide with newer models of innovation policy at European and international levels which stress interaction between different stakeholders across the different levels of governance, the inclusion of stakeholder expectation levels, transparency and accountability (IPCC, 2018, 2019).

The creation of the modified information hierarchy is key to understanding evidenced-based climate adaptation, and the challenge of the 'last mile' in this context. In many cases it relates to the need for increased knowledge co-creation of adaptation policies, demanding a strong political will and alignment of needs (Conway & Mustelin, 2014). In most cases, it will require an essential type of leadership: transcendent, bridging lateral boundaries rather than working downwards or upwards along hierarchical authority lines (Bateman & Mann, 2016). Additionally, it

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requires trust, the human dimension of engagement (Colglazier, 2016) built upon ethical considerations for adaptation researchers and decision-makers. The 'optimal trust gap' and its importance for engagement between science community and local authorities (Lacey et al., 2015) shows the importance of considering to which extent the managed trust has a substantial role in crossing the 'last mile' (Lacey et al., 2018). Science and transdisciplinarity together could build a strong basis for a pragmatic 'last mile' approach to adaptation policy at the local level, both an art and a science (Moser, 2014; Swart et al., 2014).

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