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Boundary organizations to boundary chains: Prospects for advancing climate science application

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ABSTRACT

Adapting to climate change requires the production and use of climate information to inform adaptation decisions. By facilitating sustained interaction between science producers, boundary organizations narrow the gap between science and decision-making and foster the co-production of actionable knowledge. While traditional boundary organization approaches focused on intense one-on-one interactions between producers and users increases usability, this approach requires significant time and resources. Forming “boundary chains”, linking complimentary boundary organizations together, may reduce those costs. In this paper, we use longitudinal observations of a boundary chain, interviews and surveys to explore: (1) how producer-user interactions increase understanding and information usability and (2) if and how efficiencies in climate information production, dissemination and use arise as a result of the boundary chain. We find that forming and sustaining an effective boundary chain requires not only interest, commitment and investment from every link in the chain but also a level of non-overlapping mutual dependency and complementary skill sets. In this case, GLISA’s strength in producing scientific information and their credibility as climate scientists and HRWC’s strengths in facilitation, connection with potential information users, and their recognition and reputation in the watershed add value to the boundary chain enabling the boundary chain to accomplish more with greater efficiency than if each organization in the chain tried to work independently. Finally, data show how the boundary chain increased efficiencies in educating potential users about the strengths and limitations of climate science and improving the production, dissemination, and use of climate information.

Introduction

One of the most pressing environmental problems society faces today is climate change. Projected climate change induced impacts are wide ranging from increasing flooding and more frequent and intense storms to acidifying oceans and rising seas (Melillo et al., 2014). Adapting to these impacts requires the production and use of climate change science to inform adaptation decisions. Yet, while climate research continues to advance rapidly, the actual use of climate science

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to inform adaptation decisions has advanced more slowly (Lowrey et al., 2009; NRC, 2009, 2010; Rice et al., 2009; Kirchhoff, 2013). Recent research suggests that when use does happen it is typically in the context of a boundary organization (Kirchhoff et al., 2013a,b; Lemos et al., 2014; McNie, 2013). Boundary organizations facilitate the use of science by sustaining interactions between science producers and users and stabilizing the science-policy interface (Guston, 2001; Kirchhoff et al., 2013a). While we know in general terms that interaction in the context of boundary organizations improves climate information use, we do not yet know much about the specifics of how and why that occurs. For example, we do not yet fully understand how interactions shape producers' understanding of users' information needs or users' understanding of climate information or exactly how user input helps producers customize climate information to fit particular decision needs.

While boundary organizations improve climate information usability, reliance on traditional boundary organization approaches that employ intensive scientist-user interactions is challenged by constraints (e.g., time and staff for both scientists and users to sustain interactions) (Dilling and Lemos, 2011; Kirchhoff, 2013). Moreover, as the demand for climate information increases, sustaining or expanding one-on-one producer–user relationships critical to usability may overwhelm the availability of a limited group of climate information producers (or brokers) to meet the informational demands of an ever-expanding pool of potential users (Bidwell et al., 2013).

Recent scholarship suggests a strategy for overcoming these challenges is to create a *boundary chain*—joining a minimum of two complementary boundary organizations together to collaborate, share costs and pool resources (Lemos et al., 2014, p. 274). In theory, boundary chains reduce workloads and risks for each individual organization making the provision of usable information more efficient (Lemos et al., 2012, 2014). While boundary chains hold promise, scholars have not yet examined fully the nature of potential efficiencies (or other benefits) that may develop for climate information producers or their partner organizations as a consequence of forming the boundary chain. Moreover, while we know more about the climate production part of the chain (e.g., through study of the National Oceanic and Atmospheric Administration (NOAA)-funded Regional Integrated Sciences and Assessments (RISAs)), we know much less about other types of boundary organizations that may form complimentary links in the boundary chain (e.g., various non-governmental organizations that have closer ties to climate information users such as watershed groups). In particular, less is known about other organizations' motivation to form the boundary chain or how they or their stakeholders benefit as a result. In addition, we know very little about potential "carry-over" effects that may aid climate information dissemination and use (e.g., users working outside the boundary chain to explain climate information to others within their own organization or to share climate information widely).

In this article, we explore the interactions between climate information producers and potential users in the context of a boundary chain to illuminate how interaction shapes information, perspectives, and actions of participants (scientists, users, intermediaries) within and beyond the boundary chain and how and what efficiencies develop as a result of these strategic partnerships. We draw on longitudinal data collected over a period of two years (2011–2012) comprised of detailed meeting notes, interviews, and participant observation of interactions between two boundary organizations that form a boundary chain: (1) the Great Lakes Integrated Sciences + Assessment (GLISA), a consortia of climate science producers and brokers, and (2) the Huron River Watershed Council (HRWC), a non-governmental organization with ties to potential climate information users in the Huron River watershed in Southeast Michigan, USA. We also draw on a survey of HRWC stakeholders and the experience and insights of the two key boundary spanners in the boundary chain: the GLISA climate information producer/broker (Daniel Brown) and HRWC's boundary spanner/information broker/facilitator (Rebecca Esselman).

In the following sections, we review the literature on boundary organizations and climate information usability and discuss GLISA, HRWC, and the development of the boundary chain. Next, we review our research methods and discuss our results. Finally, we offer some concluding thoughts.

Boundary organizations: bridging science and application

The idea of a boundary between science and society and the subsequent development of the concept of a boundary organization stems from 1960s philosophers of science. In the 1960s and 1970s, philosophers of science struggled to articulate the boundaries of scientific activities from non-scientific ones (Popper, 1965) by primarily trying to institutionalize scientific norms (Merton, 1968). In the 1980s, Gieryn (1983) shifted thinking from focusing on the institutionalization of scientific norms to the idea of "boundary work". Gieryn (1983) defined boundary work as "the way scientists set their work apart from non-scientific activities" and distinguish science from "non-science" (pg. 181–182). For Gieryn (1983), boundary work enabled the establishment of a social boundary for science by dividing scientific activities from politics or policy.

In the 1990s, the increasing focus on developing knowledge for decision making along with the concomitant need to gird against potential negative effects such as the politicization of science or "scienticization" of politics, necessitated more active management of science-society interactions (Ehrlich and Ehrlich, 1996; Gieryn, 1995; Sarewitz, 2004). From this new emphasis emerged boundary organizations that help to manage science-society interactions by creating a neutral setting where science producers and users interact while maintaining both accountability (to science or to policy) and their own separate identities (Guston, 1999; Lynch et al., 2008). In general, boundary organizations possess three characteristics: (1) they involve information producers, users, and mediators; (2) they create and sustain a legitimate space for interaction and stimulate the creation of products and strategies that encourage dialogue and engagement between scientists and decision-makers; and, (3) they reside between the worlds of producers and users with "lines of responsibility and accountability to each" (Guston, 1999, p. 93).

A large body of empirical research on boundary organizations especially that related to the production of usable climate information shows that interactive research approaches improve knowledge usability (Bales et al., 2004; Feldman and Ingram, 2009; Hansen, 2002; Kirchhoff, 2013; McNie, 2013). First, interaction between producers and users helps to increase information use by bridging gaps created by cultural, behavioral and cognitive differences as well as differences in organizational structure and composition (Carbone and Dow, 2005; Carlile, 2002; Moser, 2009; Nelson et al., 2002; Roncoli et al., 2009). Second, interaction between scientists and users in a boundary organization context increases use and dissemination of climate information among user networks (Roncoli et al., 2009) and it fosters building of trust, legitimacy, and capacity for using the information in decision-making (Carbone and Dow, 2005; Kirchhoff, 2013; Lemos and Morehouse, 2005; McNie, 2013; Pagano et al., 2002). Third, sustained interaction shapes the information itself as scientists gain more knowledge of how information fits users' decision contexts (knowledge fit) (Lemos et al., 2012). For example, user's may perceive information as having poor fit if they believe the information is too uncertain to use or that it lacks the perceived level of accuracy and reliability needed for decision making (Hartmann et al., 2002). Facilitating in-depth discussions about the information itself, such as how stream flows are reconstructed from tree rings, positively influences users' perceptions of fit and their willingness to deploy the information (Rice et al., 2009). Users also benefit from producers' explanations of choices, trade-offs, and limitations of different kinds of knowledge/information. For example, in an Arizona decision simulation experiment disclosing both data sources and assumptions helped policy makers evaluate model fit, influencing their perceptions of model usability (White et al., 2010). Finally, interaction also aids in improving knowledge interplay, how new knowledge connects to other kinds of knowledge users already employ by helping users better integrate information in their decision making (Lemos et al., 2012). For example, in their study of coastal managers in California, Tribbia and Moser (2008) found that users needed help to successfully integrate scientific knowledge into practical management. Knowing more about knowledge fit and interplay helps scientists to tailor information to user needs and operational contexts (Cash et al., 2006).

While research on boundary organizations has progressed substantially over the last twenty years, much of what we know about boundary organizations, interaction, and information use relies on retrospective observational studies that are a once in time examination of whether information was used or not and why. There are no studies that we know of that employ a longitudinal approach to examine how interactions between producers and users actually affects participants' (scientists and users) perceptions and actions (within and outside the boundary organization context) over time or how interactions change the information being developed. For example, without these studies we do not yet understand how interactions improve producers' understanding of users' climate information needs and how to tailor information. Moreover, we do not yet fully understand how interaction shapes users' understanding of climate information.

Given the this emphasis on interaction to increase usability, one of the challenges boundary organizations face is the relatively high transaction costs involved in sustaining ongoing boundary work (Kirchhoff, 2013; Kirchhoff et al., 2013a). Organizational theorists argue that boundary organizations pursue "linking" strategies with outside actors to accomplish organizational goals (Keller, 2010); in particular, linking strategies are employed when there are shared dependencies or to secure resources (Pfeffer and Salancik, 1978). Recent scholarship on boundary organizations reflects a similar idea in theorizing that "boundary chains" or partnerships between two (or more) boundary organizations may make the goal of providing usable information more efficient (Lemos et al., 2014). While this idea holds promise, research to date has yet to examine the nature of potential efficiencies that develop as a consequence of bringing complementary organizations together in a boundary chain. Moreover, much of the existing research on boundary organizations has focused on the perspective of the climate information producers (see for example, Bolson et al., 2013; McNie, 2013) not on those organizations partnering with them. As a result, we know very little about what motivates partner boundary organizations (e.g., those with established ties with potential climate information users) to link with boundary organizations that produce climate information. That is we do not know how these partnerships benefit the partner organizations or their stakeholders and what efficiencies develop as a result. This paper aims to address these gaps in the literature by examining a boundary chain formed between GLISA and HRWC to understand how interaction shapes the information, perspectives, and actions of participants (scientists, users, intermediaries) within and beyond the boundary chain and how and what efficiencies in climate information dissemination and use develop as a result of this strategic partnership.

GLISA, HRWC, and the GLISA-HRWC boundary chain

Initially funded in 2010, GLISA serves potential climate information users in eight US states (Minnesota, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania and New York) and one Canadian province as part of the network of 11 NOAA RISA programs across the United States. The NOAA RISA Program focuses on integrating physical and social sciences to inform the development of usable climate information and decision support tools (Pulwarty et al., 2009). Specifically, the RISAs: "(1) advance the understanding of policy, planning, and management contexts; (2) develop regionally relevant knowledge on impacts, vulnerabilities, and response options through interdisciplinary research and participatory processes; (3) innovate products and tools to enhance the use of science in decision-making; and (4) test diverse governance structures for managing scientific research (for more information see, http://cpo.noaa.gov/ClimatePrograms/ClimateSocietalInteractionsCSI/RISAProgram.aspx) (Lemos et al., 2014, p. 275). As is common for RISAs, GLISA is both a broker of locally-scaled climate science and a producer of climate information collaborating with potential information users to tailor and customize climate information.

Unlike GLISA, HRWC enjoys a much longer history. The HRWC traces its origin to collaborative efforts to understand and respond to the 1956 drought that severely impacted water supplies in Detroit, Michigan and the surrounding area (HRWC, 2013). The drought prompted urgent calls for an "intermunicipal entity" to guide coordinated planning and ongoing monitoring of the health of the river (WRC, 1957, p. 143–144). This effort led to the creation of the Huron River Watershed Intergovernmental Committee in 1958, the precursor organization to the HRWC. Passage of the Local River Management Act in 1964 (MI Pl. 253) paved the way for the HRWC to become the first watershed council in Michigan in 1965 (HRWC, 2013). Today, HRWC brings municipalities from across the watershed together to tackle water management issues. Specifically, HRWC provides water resource information, research services, and leveraging support to member governments; advises and cooperates with state agencies to identify and resolve problems and needs in the watershed; and, engages in education and stewardship activities in the watershed.

The GLISA-HRWC boundary chain came together in 2011 when HRWC partnered with GLISA on the Climate Resilient Communities Project (CRCP). The CRCP aimed to both increase climate literacy and create actionable climate knowledge to facilitate adaptation to local climate change impacts in the Huron River watershed. To accomplish these aims, the CRCP brought climate scientists from GLISA together with three teams of approximately 8–12 people in a series of meetings (monthly for the first six months then quarterly thereafter) facilitated by HRWC staff. Meetings were designed to foster open discussion, deliberation and collaboration around local climate impacts, the production of locally relevant climate information, and the development of potential responses. The monthly discussions took place in three teams—water infrastructure, instream flows, and natural areas management. Each team was comprised of team members who were familiar with HRWC (e.g., through participation in other projects) and who had an interest in learning more about local climate changes, helping to produce climate information, and using that information to build climate resiliency. Membership in each team differed. The water infrastructure team was comprised of county drain commissioners and their staff, municipal floodplain managers, municipal and university stormwater managers and engineers, and town and city engineers. The instream flows team included representatives from academia, federal and state agencies concerned with inland waterways, and municipal and city water managers and dam operators as well as county drain commission staff. Lastly, the natural areas management team encompassed staff from land conservancies, municipal and county parks and recreation departments as well as urban forestry and land management and restoration professionals. While the original CRCP project concluded in 2012, the GLISA-HRWC boundary chain has continued collaborations on hazard mitigation planning and other activities driven by HRWC's larger watershed resiliency goals.

Materials and methods

Data was collected through a longitudinal observational study of interactions between stakeholders participating in the Climate Resilient Communities Project, climate scientists from GLISA, and facilitators from HRWC over an two year period between 2011–2012. In addition to observing interactions at a series of monthly meetings, four in-depth interviews were conducted with key participants at each boundary organization including climate information brokers at GLISA and meeting facilitators at HRWC. Climate brokers were asked about their interactions with HRWC and stakeholders, the origins of and motivation for the GLISA-HRWC partnership, and the production of climate information. HRWC staff were asked about the origins of and motivation for the GLISA-HRWC partnership, interactions with GLISA, interactions with stakeholders, and the production of climate information. Finally, we include results from a survey of participants drawn from the original 2011–2012 series of meetings as well as more recent meetings ($n = 17$). The survey, disseminated via the web in 2014, included questions about the length of participation, relevance and benefits of the CRCP for their jobs, learning about climate change impacts and solutions, and dissemination and use of climate information.

Results and discussion

Forming the GLISA-HRWC boundary chain

Interest from their stakeholders and recognition that climate change may negatively impact both residents in the watershed and the health of the Huron River motivated the HRWC to pursue the CRCP. "The impetus for and crafting of the project originated in conversations with people ... about climate-related risks and issues that are being observed in the Huron River basin" (ISF meeting notes January 2012). For example, each fall, HRWC hosts a river round up on the banks of the Huron River. According to HRWC staff, "...of the last seven round ups that we have had in the fall, the water's been so high for five of them that we can't go to our big river sites" (HRWC interview 2011). Separately, through HRWC's water quality monitoring program, staff also noticed higher, earlier flows in the fall. Historically, HRWC conducts monitoring from May to October but several years of "...earlier snow melt and bigger flow events early in the year" as well as "seeing some of our biggest storms in February and March" prompted HRWC to consider shifting their monitoring program to begin earlier in the season (HRWC interview 2011). Taken together, these and other experiences with altered climate and flow patterns spurred HRWC's interest in looking at climate trends to inform potential adjustments to existing programs and to help build resilience in the watershed (HRWC interview 2011).

While HRWC had interest in climate information and funding to work with stakeholders in the CRCP, HRWC did not actually have climate information at the ready; rather, HRWC needed a partner like GLISA to help them understand what climate information was relevant to bring to their stakeholders. HRWC staff had "notions of what the audiences would be" and what information they might need but their ideas about both the climate information needed and potential audiences for that information changed over time (HRWC interview 2011). For example, early on HRWC thought they needed "some downscaling efforts" for the Huron River watershed (HRWC interview 2011). Once HRWC and GLISA climate brokers discussed downscaling in more detail, staff at HRWC realized "...we don't really want downscaled climate models. We just want some narratives..." about how climate is changing in the watershed (HRWC interview 2011). HRWC staff felt that climate models with their coarse spatial resolution, complexity, and large uncertainties could potentially obfuscate the climate change conversation whereas, with narratives of potential climate change impacts, conversations could be more focused on impacts and potential actions. The evolution of the development of climate information for the CRCP follows a similar pattern as that observed among other GLISA partners (Briley et al., 2015). Iteration between HRWC, GLISA, and key HRWC stakeholders prior to the start of the CRCP helped refine the narratives to be salient for watershed communities.

In addition to tangible outputs (e.g., narratives about climate change impacts in the watershed, climatologies, and reports), the HRWC-GLISA partnership enabled HRWC staff to rely on the credibility of GLISA as climate information producers. According to HRWC staff, "dealing with GLISA and seeing...it's a consortium...there's a little bit more trust or credibility...then if it was just one scientist...there is a broader spectrum of scientists who are looking at the data" (HRWC interview 2011). Being a consortia and having "researchers coming to this project who already have established their credibility in this area" (HRWC interview 2011) provided a solid grounding for GLISA as a credible climate information producer and an important partner to HRWC in their effort to enhance climate literacy and build climate resilience in the watershed.

Improving user's understanding of climate information and the limits of climate science

Interactions between a GLISA climate broker (hereafter GLISA or producer) and HWRC stakeholders' (hereafter participants or users) in each of the three sector teams (Natural Areas (NA), Water Infrastructure (WI), and Instream Flows (ISF)) helped to improve both users' understanding of climate information and the limits of climate science. For example, during the January meeting of the ISF team, dam operators discussed the challenge they face: to manage dams to reduce flood risk while also maximizing power generation (ISF meeting notes January 2012). A local dam operator indicated that while NOAA river flow forecasts helped him manage flows from recent rain events, having predictions about future rain events and river flows in advance would improve dam operation allowing dam operators to optimize for both flood management and hydropower production (ISF meeting notes January 2012). In response, GLISA noted that predicting statistically meaningful changes in hourly-scale storm regimes, the associated changes in flow rates, and the resulting impacts on hydropower at a watershed scale lay beyond the capability of available climate science (ISF meeting notes January 2012). Also, separately during meetings of the WI team, participants expressed a desire for better future hourly rainfall predictions to aid in urban flood management, planning, and infrastructure design (WI meeting notes February 2012). A county engineer put it this way, "...daily precipitation totals may not help much since it doesn't really get at what is taxing the infrastructure which are these short, very intense rain events that overwhelm the system" (WI meeting notes May 2012). In response, the GLISA climate broker pointed out that projections of extreme events and changes in daily precipitation curves carry greater uncertainty and require significantly more robust baseline observations compared to monthly averages (WI meeting notes February–May 2012). In both examples, participants learned more about climate information and its limits through discussions of the climate information they wanted, the capabilities of existing climate science for the region, and the capacity of the workgroups to meet those needs.

While there was often a gap between what climate information users' wanted and what climate science could produce, the three teams often found adaptation actions that could be taken to improve resilience despite the lack of availability of better climate information. For example, rather than better climate information, over a few meetings of the ISF team, participants recognized that better communication between dam operators, more stream gauging, and schematics of how the dams are operated currently, would actually do more to reduce flood risks today than waiting for better climate predictions (ISF meeting notes, January–March 2012). This realization shifted the focus of the ISF group towards more practical actions (e.g., improving communications, funding additional stream gauges) to improve dam operations and to reduce flood risks (ISF meeting notes, March 2012). Similarly, the WI team opted to focus their energies on efforts to improve green infrastructure adoption and to work with the state of Michigan to update existing design storm criteria for stormwater infrastructure to incorporate more recent weather station data (WI meeting notes March–May 2012). In all three workgroups, viewing their respective elements of the watershed from a broad, long-term, systemic perspective helped identify adaptation efforts that would reduce vulnerabilities to weather regardless of climate projections.

Improving information usability

In addition to exploring the limits of climate science, during the first seven months of the CRCP meetings for each subgroup, the GLISA climate broker and participants discussed and critiqued area climatologies to improve information usability. Climatologies provide a summary of current, locally-relevant climate conditions, along with historical trends in seasonal and annual temperature and precipitation (for more information and example climatologies see http://glisa.umich.edu/resources/great-lakes-climate-stations). For example, participants in the three teams responded positively to the narrative and graphics of the Ann Arbor, MI climatology noting that the climatology showed an overall increase in precipitation confirming what participants experienced in the field (ISF and WI meeting notes May 2012). While the overall response was positive, users made several suggestions to improve usability. For example, participants indicated that early graphics depicting average daily temperatures and average monthly precipitation over the most recent thirty year time period were less useful for decision makers. One participant noted that the Average Daily Temperatures graphic (see Fig. 1, part a) "doesn't add much" and that it might actually confuse users looking for a particular extreme event that he or she experienced in the past (ISF meeting notes May 2012). Because each day is an average of thirty years of temperature data for that day (or 30 years of precipitation data for each day (Fig. 1, part b)), the extremes do not show up in the graphic. Based on this feedback, GLISA chose not to include the Average Daily Temperatures and Average Monthly Precipitation graphics in the final climatologies.

GLISA-participant interactions also resulted in key changes in the metrics or thresholds that GLISA reports making the data more relevant to decision making. For example, as standard practice, climate scientists (including GLISA) typically report intense precipitation events in 1-inch or half-inch intervals and cold weather temperatures at or near 32°F (Kunkel et al., 2013; Walsh et al., 2014). Yet, CRCP participants noted that these thresholds have limited value for decision makers. For rainfall, thresholds of 1.25 and 1.75 inches of precipitation per day are more relevant because, when precipitation exceeds 1.25 inches nuisance flooding tends to occur and, when rainfall exceeds 1.75 inches, green infrastructure gets overwhelmed. For temperature, thresholds of 28°F to 43°F are preferable since decision makers are more concerned with subsurface temperatures for many infrastructure applications (e.g., road maintenance, salting requirements) (Jaffe and Woloszyn, 2014). These relatively small changes in precipitation and temperature thresholds helped GLISA adjust the information to make it more relevant for decision making.

Beyond better metrics and thresholds, GLISA-CRCP participant interactions helped to inform the creation of visuals to convey abstract climate impacts and trends in more concrete and relatable formats. For example, GLISA presented the change in total annual precipitation in Ann Arbor, Michigan using the graphic shown in Fig. 2, part a. This graphic depicts a dramatic 25% increase in precipitation for the most recent 30 year period from 1981–2010 as compared to the previous 30 year period from 1951–1980. While the change in total precipitation amount is dramatic, CRCP participants noted that the change is difficult to grasp without a means to visualize the actual volumetric change. To make the change more tangible, GLISA created informational graphics using the iconic University of Michigan stadium to illustrate the change in the volume of stormwater over time (see Fig. 2, part b). This creative depiction of stormwater trends resonated with CRCP participants and local decision makers helping GLISA engage with a broader audience.

Finally, results from a survey of participants provide a measure of how improving usability leads to use of climate information. For example, an analysis of survey data shows that 25% of survey respondents report incorporating recommendations from the CRCP into local planning documents and funding decisions. Similarly, approximately 40% of respondents report incorporating recommendations and information from the CRCP into policies and programs. For example, one participant said they are now integrating climate change information into landscape planning and education (NA participant #1 from 2012) while another indicated their agency's new Forestry Plan incorporates climate change (ISF participant #1 from 2012).

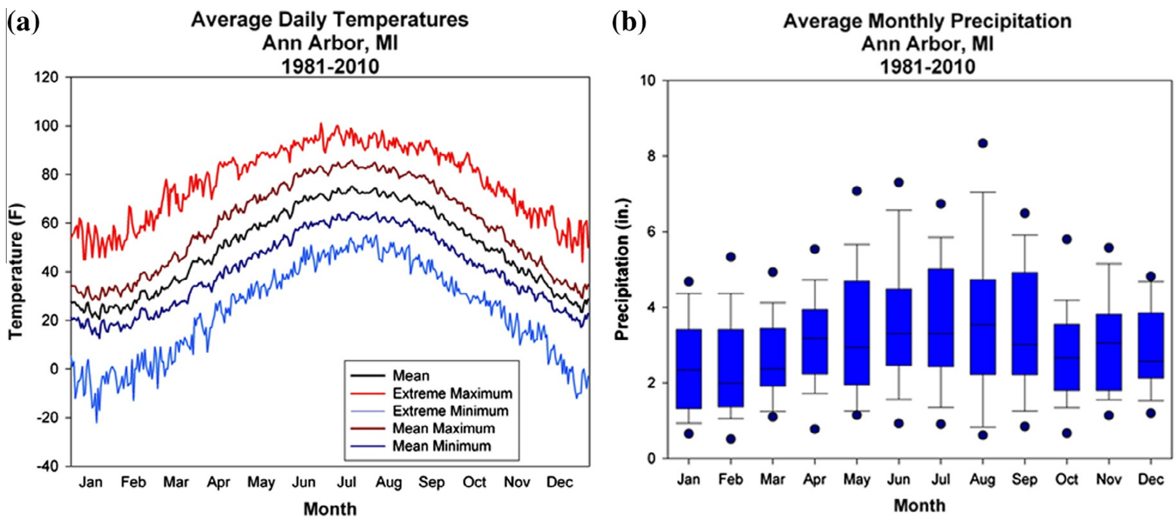

Fig. 1. (a) Graphic showing mean, maximum, and minimum temperatures for Ann Arbor for the period 1980 through 2010 (GLISA, 2012a). (b) Graphic showing average monthly precipitation for the period 1980 through 2010 (GLISA, 2012a). The central lines indicate median values. The boxes indicate 75th percentiles, and the whiskers indicate the 95th percentiles.

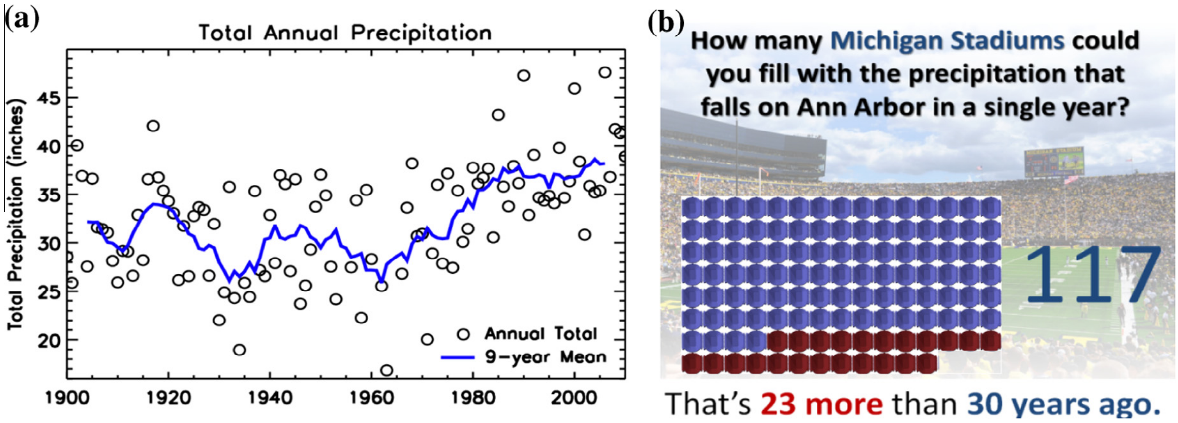

Fig. 2. (a) Graphic depicting a 9-year moving average total annual precipitation trend for Ann Arbor, Michigan from 1900 to 2010 (GLISA, 2012b). (b) An infographic prepared by GLISA showing how many University of Michigan Football Stadiums, a prominent local landmark, could be filled by the precipitation that Ann Arbor now receives in a single year.

The boundary chain: efficiencies in climate information production, brokering and use

The GLISA-HRWC boundary chain enabled HRWC staff's to learn more about the climate science and ultimately facilitated HRWC staff's assumption of a quasi-climate broker role. HRWC staff learned more about climate science from GLISA climate brokers helping them to become "more comfortable" with the climate information co-produced for the CRCP (HRWC interview 2011). At the start of the CRCP, climate science was just as unfamiliar for HRWC staff as it was for HRWC stakeholders. Through the course of the CRCP monthly meetings, HRWC staff and stakeholders alike learned more about climate science and modeling including its strengths and limitations. In particular, facilitating all three sector teams gave HRWC staff a much broader and deeper understanding of climate science and climate trends for the Huron River watershed. As learning deepened over time and as the project transitioned to a new phase post-2012, HRWC staff have assumed a quasi-climate broker role disseminating climate information to new stakeholders outside of the original boundary chain. In some cases, GLISA climate scientists attended the events in a supporting role, while in other cases HRWC staff have brokered climate information independently. While HRWC staff are not climate scientists, their knowledge of local climate change and trends gained through the GLISA-HRWC boundary chain together with their reputation and name recognition in the watershed have enabled them to assume a limited brokering role introducing relevant climate science to new audiences and expanding opportunities for building resilience in the watershed. While HRWC's depth of climate science knowledge is limited having GLISA as a credible climate science partner makes the arrangement workable.

GLISA also derives benefits from the GLISA-HRWC partnership such as more efficient recruiting. Typically, RISA's develop clients slowly through one-on-one interactions that build trust and upon which productive producer-user relationships build over time (Lemos et al., 2012). As RISA's become more well-known in a region, the burden on RISA scientists for bringing in new clients lessens as clients begin to seek out RISA scientists on their own. In the Great Lakes region, GLISA is still a relative newcomer (Bidwell et al., 2013; Lemos et al., 2014); as such, they are not well known as a source of climate information. Not being independently recognized as a climate information producer could limit GLISA's ability to broker climate information more widely in the region. However, in establishing the GLISA-HRWC boundary chain, GLISA benefited from HRWC's widespread recognition, established reputation, and connections with stakeholders. Through the CRCP, HRWC brought stakeholders to the table to not only learn about climate change and trends from GLISA but also to help GLISA tailor and customize climate information for them (CRCP meeting notes 2012). In this way, HRWC took on the burden of recruiting "clients" for GLISA and shortening the lead time to the establishment of productive iterative relationships with stakeholders (CRCP meeting notes 2012). As the GLISA-HRWC partnership moves beyond the CRCP project, HRWC continues to interface with and recruit new clients through their role as a quasi-climate broker aiding GLISA's development of new clients.

In addition to more efficient recruiting of new clients, the GLISA-HRWC partnership helps GLISA be more efficient in climate information production. Typically, RISA's tailor and customize climate information through one-on-one interactions (Lemos et al., 2012). But, these one-on-one interactions require significant investment by RISA climate brokers to iterate with each user to create usable information for specific decision needs (Kirchhoff, 2013). The GLISA-HRWC partnership enabled GLISA to explore a new approach that involved not one-on-one relationships but rather a "one-to-many" configuration that saves time and resources while still enhancing usability. The development of the Ann Arbor, Michigan climatology illustrates this approach. Over a three month period from May to June, 2012, GLISA and participants in all three teams iterated the climatology until it became more usable for decision making (ISF, WI, and NA meeting notes May–June 2012). Since participants hailed from different backgrounds and worked in different fields, they offered a variety of perspectives and feedback.

As a result of this diverse input and adjustments made by GLISA, the climatology serves the needs of a variety of potential users. Thus, with the "one-to-many" approach facilitated by the boundary chain, rather than tailoring climate information for individual users, the GLISA-HRWC partnership facilitated the production of climate information applicable to a wide variety of users.

For HRWC stakeholders participating in the GLISA-HRWC boundary chain, benefits, such as learning about climate change impacts and solutions accumulate, over time. For example, the longer stakeholders participate, the greater their knowledge of local climate change impacts and solutions. On the one hand, survey results show that most new participants (those who began participating in 2013 or in 2014) note their knowledge of local climate change impacts has slightly increased (3 out of 4 participants from 2013 to 2014) and their understanding of solutions to prepare for climate change impacts is only somewhat improved ($n = 4$). On the other hand, the majority of those who have participated since 2012 note their knowledge of local climate change impacts has greatly to moderately increased (11 out of 12 participants) and 33% say their knowledge of solutions is significantly better.

Besides learning more about climate change impacts and solutions themselves, participants (independent of the time they have been involved in the partnership) share that knowledge and the climate information products they helped to produce within their organization and networks. For example, 75% report discussing what they have learned through the CRCP with colleagues at least occasionally while 75% went beyond discussions to sharing of climate information products with four or more people. Discussions with colleagues encompass topics such as how climate information may have "application to drainage ordinances" (WI participant from 2014) to broader discussions "of the project and outcomes with national colleagues . . .and Michigan colleagues as part of the Michigan Green Communities Network" (ISF participant #1 from 2012) to sharing ideas "widely with other scientists within my agency" (ISF participant #2 from 2012). Similarly, sharing products ranges from sharing reports and websites (ISF participant #3 from 2012, NA participant #2 from 2012) to referring others to fact sheets and project recommendations (NA participant #2 from 2012). By sharing knowledge and information within their organization and networks, CRCP participants create carry-over effects extending the benefits of the boundary chain to non-participants. These carry-over effects further leverage the boundary chain aiding climate information dissemination, improving climate literacy and building resilience without requiring additional organizational effort from either GLISA or HRWC.

Conclusion

Insights from this work suggest that forming and sustaining an effective boundary chain requires not only interest, commitment and investment from every link in the chain but also a level of non-overlapping mutual dependency and complementary skill sets. For the former, forming and sustaining the boundary chain fundamentally requires interest from each organization in the chain to come to the table. In the case of the GLISA-HRWC boundary chain, this involves both GLISA's interest in fostering climate information usability among potential users of information, potential user's interests in learning about what climate information is available, and HRWC's interest in increasing climate literacy and building resilience in the Huron River watershed. If both boundary organizations and users derive value from participating in the boundary chain, then commitment and investment by every link in the chain helps sustain the ongoing partnership. Part of the value of the boundary chain arises out of a mutual dependency and complementary skill set. In this case, the GLISA-HRWC boundary chain builds on each organization's strengths—GLISA's strength in producing scientific information and their credibility as climate scientists and HRWC's strengths in facilitation, connection with potential information users, and their recognition and reputation in the watershed. The complementary strengths reveal a dependency which, together with the strengths each organization has, enables the boundary chain to accomplish more with greater efficiency than if each organization in the chain tried to work independently. That is, HRWC depends on the availability of credible and trusted climate information that they are not able to produce on their own, while GLISA depends on HRWC to bring potential users to the table ready to learn about local climate trends and to aid in the development of actionable knowledge.

The GLISA-HRWC boundary chain proved to be efficient in educating potential users about the strengths and limitations of climate science and improving the production, dissemination, and use of climate information. For example, survey results showed how participants gained knowledge about climate change impacts and solutions over time while interviews and observations of CRCP meetings revealed how HRWC staff's climate knowledge also deepened over time. For participants and HRWC staff, learning created opportunities for sharing information beyond the boundary chain. On the one hand, as participants learned more and as climate information products were developed over time, they shared that information with others in their organization and networks outside of the boundary chain. These actions further leveraged the boundary chain aiding climate information dissemination, improving climate literacy and building resilience without requiring additional organizational effort from either GLISA or HRWC. On the other hand, as HRWC's knowledge deepened, staff assumed a limited climate broker role sharing climate information with audiences outside the boundary chain. In assuming a quasi-climate broker role, HRWC took on the burden of recruiting "clients" for GLISA, shortening the lead time to the establishment of productive iterative relationships with a wide range of stakeholders outside of the original CRCP project. Finally, beyond improved dissemination, the GLISA-HRWC partnership enabled GLISA to be more efficient in climate information production. That is, interacting with a wide range of potential users simultaneously enabled GLISA to iterate climate information increasing usability for a variety of users over a shorter period of time.

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