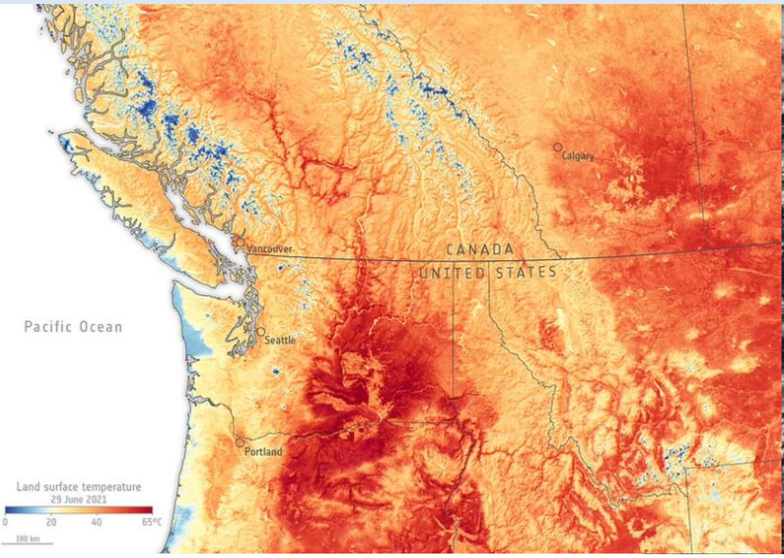
Weather-Water-Climate Value Chain(s): Giving *VOICE* to the Characterization of the Economic Benefits of Hydro-Met Services and Products



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Weather-Water-Climate Value Chain(s): Giving *VOICE* to the Characterization of the Economic Benefits of Hydro-Met Services and Products

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Foreword

This study presents the concept of the Earth system observations, science, and services (ESOSS) information value chain. The value chain concept can be used to characterize the process of the creation, communication, and use of weather, water (fresh and salt), and climate information and knowledge from observations, research (basic and applied), modeling, forecasting, dissemination, decision support, and associated services through market transactions and the provision of nonmarket goods and services. The value chain—perhaps better conceived of as a process—involves a broad range of stakeholders with varying resources, objectives, and constraints that shape the nature and translation of the information as it moves from observations to end-user decisions. Understanding these processes, stakeholders, and decisions and outcomes is fundamental to identifying, measuring, and demonstrating the socioeconomic value of ESOSS.

In this paper we present and discuss an initial approach to operationalize the value chain concept and how the broad set of social sciences—in addition to economics—can be used to study and improve the process. Focusing on information and socioeconomic value as one approach to discussing the information process, we propose a framework for elucidating value chains called the *Value of Information Characterization and Evaluation* or ***VOICE***. The intent of this framework is to provide an initial prototype that could be leveraged and further developed to encourage the use of the value chain concept in studies of ESOSS. We present several brief case studies to illustrate different ways the value chain concept can help us understand, communicate, and enhance societal benefits of ESOSS.

This study is part of an ongoing AMS Policy Program project on valuation that is supported, primarily, by a grant from the National Oceanic and Atmospheric Administration (NA19NWS4620018). The project consists of studies (including this one) and related capacity-building efforts to enable improved understanding, communication, and enhancement of societal benefits of information and services in weather, water (fresh and salt), and climate.

Dr. Paul Higgins' 2021 AMS Policy Program paper "Societal Benefits of Earth System Observations, Science, and Services: Understanding, communication, and enhancement for weather, water (fresh and salt) and climate" further explores the role of ESOSS in modern society, particularly as they relate to weather, water, and climate to 1) improve understanding of the societal benefits of ESOSS; and 2) enable the enhancement of the societal benefits of ESOSS.

A second related study, being led by Dr. William Hooke, will explore policy issues that could enhance or diminish the value of the weather, water, and climate enterprise. This policy emphasis is critical because policy choices help to determine whether, when, and how information matters; how benefits and costs are distributed (who pays, who benefits, and how much); and a wide range of additional factors that influence the advancement and use of information and services. As a result, the policy framework is hugely influential in determining the societal benefits that result from ESOSS.

Executive Summary

Every year, weather-related hazards such as hurricanes, floods, heat waves, droughts, and tornadoes cause billions of dollars of damage and affect millions worldwide in both developed and developing countries. “Day-to-day” routine events (not considered “disasters”) likely have an even larger aggregate impact on society and affect everyone everywhere.

In this paper we present and develop the concept of the “weather information value chain” as a means for understanding, discussing, and analyzing the socioeconomic value of Earth Observations, Science, and Services (ESOSS) (also referred to here as “hydro-met” as shorthand for hydrological, meteorological, and climatological). The value chain concept provides a useful approach to understanding and discussing the entire process of information creation, communication, and use.

From an economist’s perspective, a primary reason for adopting the concept in hydro-meteorological studies is to explicitly connect the information service or product (e.g., observation, data, forecasts, warnings) being evaluated with relevant societal decisions and outcomes to ensure the validity and reliability of economic analyses.

An important distinction lies between the economic impact of weather (not our focus here) and the value of current or improved weather information (this paper’s primary concern). There are weather-related impacts that are unavoidable and weather-related impacts that potentially could be avoided with better information or behavior changes. The value of weather information is related to avoiding impacts, facilitating more efficient response, or realizing new opportunities.

There are many different uses and approaches to characterizing a value chain or an information process. Any given information process is dynamic and complex. Over time, the characterization of the information process changes as knowledge, technology, institutions, and policies evolve. Relationships among components of the enterprise also shift. Notably, the private sector now plays a more significant and growing role not only in the provision of hydro-met information but also in observation systems, modeling, forecasting, and dissemination.

To begin to formalize a process for building and evaluating value chains we propose the “Value of Information Characterization and Evaluation,” or ***VOICE*** approach. The value of information (VOI) depends on changes in outcomes that result from decisions made (or potentially made) using the information. Ultimately, VOI is a function of the ability of decision-makers to receive, understand, and act on information about uncertain future events. The ***VOICE*** approach provides a framework to gather and organize the relevant data to rigorously tell the end-to-end story of any given weather information chain or explain explicitly how the information relates to decisions, outcomes, and values. This can facilitate both retrospective and prospective evaluations of existing and planned services, respectively.

The value chain framework encourages consideration of the relative merits of investing in different areas of the information process, not just those associated with improvements in prediction quality attributes. For example, investments in communication may yield higher payoffs than improving on the accuracy and precision of hydrological, meteorological, and climate information. Likewise, developing systems and enhancing resources so that vulnerable individuals or communities have the ability to respond to weather, water, or climate threats will not only improve socioeconomic outcomes but increase the value of the hydro-met information used to respond to those threats.

The value chain concept can be used for multiple purposes, as illustrated by the case studies included in this study. These purposes include, for example, facilitating decision-making; enhancing collaboration among experts from different disciplines; framing and synthesizing information and understanding; and communicating with external users and audiences. The seven case studies provided by contributing authors include U.S. and international studies as well as applied and theoretical work.

Case Study	Primary Contributor	Type of Study
Weather-Economics Literature Review	Lou Nadeau (Eastern Research Group)	Literature review
Kazakhstan Climate Resilient Wheat	Glen Anderson (Winrock International)	Applied development project
Impact-Based Decision Support Services and the Impacts of Winter Storms	Heather Hosterman (Abt Associates)	Applied benefits study for strategic efforts for National Hydro-Met Service (NWS)
NOAA Fleet Societal Benefit Study	Jeffery E. Adkins (NOAA Contractor)	Conceptual model used throughout applied benefits study
WMO High Impact Weather (HIWeather) Value Chain	Brian Golding (Met Office and WMO)	Framework to integrate across activities in international research program (WMO)
A Public-Private-Academic Partnership to Advance Solar Power Forecasting	Sue Ellen Haupt (NCAR)	Framework to integrate across activities in focused research program and indicate activities and contributions of research efforts
GOES-R Socio-Economic Benefits Study	Michael Jamilkowski (The Aerospace Corporation)	Applied benefits study of operational observing system

Based on our development of this white paper, discussions with researchers, practitioners, and decision-makers across the weather enterprise, and our professional experience, we offer the following recommendations related to the value chain concept, the ***VOICE*** framework, and economic analysis in general concerning weather, water, and climate information:

- All major investments or changes in hydro-met services should be subject to economic analysis. We believe that the value chain approach and ***VOICE*** template provide a useful framework to organize such an undertaking.
- A critical review should be undertaken of the use of economics in national hydro-met service policy making to identify where and why it has been helpful or unhelpful in policy making, and under what conditions it could have been more beneficial.

- More and better primary studies on the value of hydro-met information across a broad range of hydro-met phenomena, information products and services, stakeholders, and end users should be implemented to build the body of knowledge to support and improve the weather enterprise.
- Those funding new studies should require them to meet higher design, implementation, and documentation standards. We advocate adopting requirements based on established criteria, such as those recommended for the evaluation of studies for use in benefits transfer to ensure quality and transparency of the study and enhance the value of studies as resources in future benefits transfer applications. In this vein, studies of the value of hydro-met information should fully characterize the weather information value chain or study relevant components thereof as a fundamental part of such benefits studies.
- Researchers should begin to evaluate the potential contributions of behavioral economics (and closely related fields in anthropology, psychology, geography, and sociology) more thoroughly to understanding and improving weather information processes and decision-making across the value chain.
- A white paper should be developed to discuss and examine the value of incorporating approaches and concepts from philosophy and their relationship to the weather information value chain and the provision of hydro-met information in general to better address ethical and other issues outside the realm of the physical and social sciences.
- Efforts should be made to further develop and implement the concept of the weather information value chain and the ***VOICE*** template to fully map out the relationships between the creation and value of hydro-met information to enhance the validity and reliability of their economic analysis.

1 Introduction

Every year, weather-related hazards such as typhoons, floods, heat waves, droughts, and tornadoes cause billions of dollars of damage and affect millions worldwide in both developed and developing countries. Guha et al. (2015) report that between 2004 and 2013 an annual average of 127 meteorological, 32 climatological, and 192 hydrological disasters affected an average of 191 million people each year and caused an average annual $122 billion (U.S. dollars) of damage (Guha 2015; Table 4). CRED and UNDRR (2021) reported an average of 369 weather- or climate-related disasters and an associated $119 billion in losses each year over the 2000–19 period. As stated in Löw et al. (2020), "Overall losses from natural disasters in 2019 came to $150 billion, approximately the same level as in 2013 ($140 billion). At around $52 billion, insured losses made up one-third of overall losses, which is roughly in line with the loss burden in 2016. Worldwide, a total of 820 relevant loss events were recorded in the NatCatSERVICE database. Disasters claimed the lives of some 9,000 people during the year."

"Day-to-day" routine events (not considered "disasters") likely have an even larger aggregate impact on society [e.g., in motor vehicle collision injuries as shown in Mills et al. (2019) and Black et al. (2015)] and affect virtually everyone on the planet in some manner every year (Lazo et al. 2009). While not all (or perhaps even most) of the impacts can be avoided or mitigated, with appropriate information systems and processes there are undoubtedly significant societal benefits of geospatial information on weather, water, and climate.[1]

As stated in the 2018 National Academies of Sciences study on integrating social and behavioral sciences within the weather enterprise:

> There is growing recognition that a host of social and behavioral factors affect how we prepare for, observe, predict, respond to, and are impacted by weather hazards. For example, an individual's response to a severe weather event may depend on their understanding of the forecast, prior experience with severe weather, concerns about their other family members or property, their capacity to take the recommended protective actions, and numerous other factors. Indeed, it is these factors that can determine whether a potential hazard becomes an actual disaster. Thus, it is essential to bring to bear expertise in the social and behavioral sciences (SBS)—including disciplines such as anthropology, communication, demography, economics, geography, political science, psychology, and sociology—to understand how people's knowledge, experiences, perceptions, and attitudes shape their responses to weather risks and to understand how human cognitive and social dynamics affect the forecast process itself (National Academies of Sciences, Engineering, and Medicine 2018, p. 1).

With direct relevance to the integration of economics in the weather enterprise, as noted in the recently published WMO et al. (2015) guidebook on socioeconomic benefit assessment for national meteorological and hydrological services (NMHS), *Valuing Weather and Climate:*

[1] Throughout this paper we discuss weather, water, and climate. In general, this is consistent with the concept of Earth Observations, Science, and Services or ESOSS (https://www.ametsoc.org/index.cfm/ams/policy/policy-memos/earth-observations-science-and-services/) and as described in AMS (2012).

Economic Assessment of Meteorological and Hydrological Services, there are several reasons NMHS (and others) should be interested in or do undertake economic analysis including:

- program evaluation/program justification such as
    - validating the provision of basic hydro-met services,
    - validating past and current investments in specialized met/hydro services,
    - justifying new investments in hydro-met services,
- determining the value of NMHSs to user goals, and
- prioritization or reallocation of resources.

In this paper we introduce and develop the concept of the "weather information value chain" as a means for understanding, discussing, and analyzing the socioeconomic value of Earth Observations, Science, and Services (ESOSS) (also referred to here as "hydro-met" as shorthand for hydrological, meteorological, and climatological). In developing a framework to operationalize the concept, we draw upon prior work and resources in economics to better understand the creation of value from hydro-met information, explicate the difficulties of valuation, and identify opportunities for value enhancement. Several case studies that have applied value chain approaches to value hydro-met information are presented and reviewed to demonstrate the implementation of the concept. We then assess and integrate the various methods and techniques applied in past research and applications into a consolidated value chain framework called "Value of Information Characterization and Evaluation" or ***VOICE***. This serves at this time as an initial prototype to be developed, critiqued, or revised to further incorporate the value chain approach into the weather enterprise.

A primary reason for adopting the value chain concept in hydro-meteorological studies is to explicitly connect the information service or product (e.g., observation, data, forecasts, warnings) being evaluated with actual societal outcomes to ensure the validity and reliability of economic analyses. Far too many studies in the hydro-met literature assume or imply that there is economic value simply because there is a change in the quality (e.g., accuracy, precision, lead time; however measured) of the hydro-met information. Without robust evidence connecting ESOSS to end-user decisions and outcomes, the results of any economic study should be questioned.

Another reason for using a value chain concept is to let actors across the weather information process develop a more holistic understanding of the process. Having a more holistic understanding may identify and facilitate potential improvements and opportunities to enhance socioeconomic outcomes. Furthermore, an understanding of the full process and open discussion between actors may help further the implicit socioeconomic goals of the weather enterprise "for the protection of life and property and the enhancement of the national economy."

We present an overview of economic assessment of the benefits of hydrological, meteorological, and climatological (a.k.a., hydro-met) services and products. While the emphasis is on meteorological information, hydrological and climate information generally flows from the same or similar observation networks, modeling, and communication approaches—thus the applications and methods discussed are largely applicable for all three types of services.[2]

Economics is a social science that studies human behavior and decision-making. Although economics and valuation are emphasized in this paper, a broader integration of the social sciences in the weather enterprise can help NMHSs and others understand the weather-related decision-making process and thus enhance product development, communication approaches, and ultimately decision-making to increase societal value (National Academies of Sciences, Engineering, and Medicine 2018). Just like economics, each social science discipline or field listed below has its own focus; history; body of theory, knowledge, and application:

• Anthropology	• Education	• Political Science
• Archaeology	• Geography	• Psychology
• Communication	• History	• Risk analysis
• Decision sciences	• Law	• Risk Communication
• Economics	• Linguistics	• Sociology

Within each social science, and across social sciences, many different approaches, and theories are part of the body of knowledge in each field. An important evolving branch of economics is "behavioral economics." Newly developed concepts from behavioral economics and related studies (see Pesendorfer2006; Thaler and Sunstein 2008; Kahneman 2011) provide significant opportunities to improve our understanding of behavior and decision-making and further enhance societal value. Such knowledge also helps to make sense of weather-risk "conundrums" such as why some people do not protect themselves adequately from environmental hazards despite having access to high quality prediction information (e.g., weather warnings). Simplistically, behavioral economics is something of a cross between social-psychology and economics that challenges many of the foundational assumptions of neo-classical microeconomics. As with other social sciences, there are opportunities for integration across the various disciplines, associated paradigms, and attendant methods, to examine and address issues throughout the weather information value chain. This often requires collaborations and dialogue to overcome discipline-specific terminologies for modeling and understanding the information and decision-making processes.

[2] There are differences between weather, water, and climate that may make the value chain approach different, and it would be interesting/useful to explore these differences. Understanding these differences in the relationship between information and outcomes in different aspects of ESOSS may help to better integrate these information processes and increase societal values.

2 Weather Information Value Chain Concept

Figure 1 presents one possible conceptual model of the "weather information value chain."[3] Starting from the left, this is the process by which hydro-met systems are observed and modeled and forecasts and warnings created, generally by NMHS. This information is then disseminated through multiple channels and potentially altered by secondary information providers (e.g., private weather services, media channels such as television and radio, internet, and mobile platforms) and communicated to end users. End users may (or may not) then use this information to make decisions about an uncertain future. It is within the context of information improving, reinforcing, or changing the decisions of end users, that economists would argue there is actual or potential economic value to this information.[4]

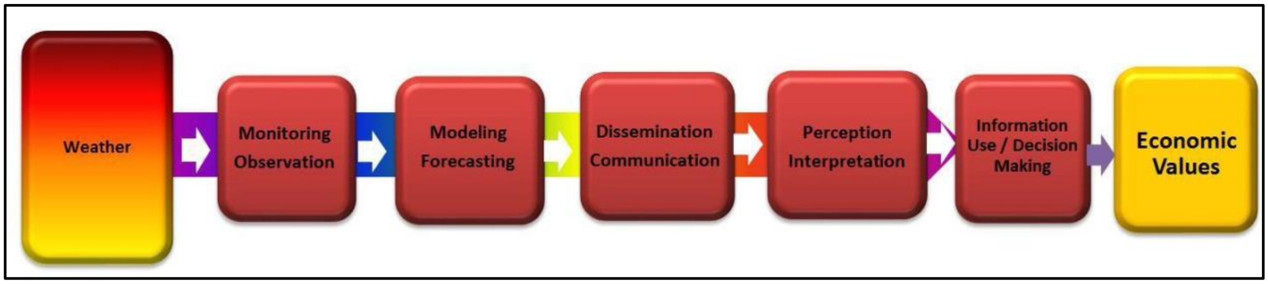

Figure 1: Weather Information Value Chain

There are several ways of presenting an information value chain, each unique to particular end uses such that every user should evaluate the adequacy of this figure for their specific analysis. For sake of clarity, the content and linkages between the component boxed identified in Figure 1 are simplified; in a real application, they are typically composed of many extremely detailed and complex activities, interactions, and processes. For instance, an observation system supporting a forecasting function might include upper air soundings, the Automated Surface Observing Systems (ASOS), aircraft, buoy data, satellites [both geostationary (GEO) and low-Earth orbit (LEO)], and radar (see, e.g., https://www.weather.gov/about/observation-equipment). Each system type contains a myriad of subcomponents, activities, protocols, internal linkages, and external connections to the broader network of weather enterprise elements.

Researchers and stakeholders generally understand something about the workings within each of the boxes. In general, a given NMHS can spell out the details in the first couple of boxes for their organization but the boxes farther right along a value chain are probably less well understood by the NMHS and more heterogeneous for any given set of end users. In fact, for many potential value chains, starting from products or services on the left side or a chain, it is quite likely an NMHS does not even know who some of the end users are!

We also note that the example provided in Figure 1 and described above may initially be considered something of a traditional model of information creation by a centralized national

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[3] See Appendix A for a preliminary discussion of the idea of "Conceptual Models."

[4] See also the discussion of the characterization and assessment of information quality in Stvilia et al. (2007).

hydro-meteorological service (NMHS) and dissemination by secondary providers (e.g., broadcast meteorologists or newspapers). The concept of a value chain can be used to discuss where there have been and continue to be institutional and structural changes in the information process. For instance, observation systems that have historically been entirely developed and run by the NMHS are being supplemented by observational inputs from the private sector as noted in the AMS statement on “The Public/Private Partnership in the Provision of Weather and Climate Services” over 20 years ago.

> The public sector infrastructure—observation system, communication, data processing, and computing systems, and a system for forecasts and warnings—while designed and maintained by the public sector to discharge its own responsibilities, is also essential to the private sector in the generation of its products and services. A vigorous and healthy partnership between the private sector and the public sector is therefore of great importance to the expanding use of weather and climate information in the United States.[5]

With this in mind, we recognize that any given information process is dynamic and complex. Over time the characterization of the information process changes as knowledge, technology, institutions, and policy change. The private sector plays a more significant and growing role not only in the provision of hydro-met information but in observation systems, modeling, forecasting, and dissemination.

There are many different uses and approaches to characterizing a value chain or an information process. For instance, Lazo et al. (2015) developed a model of the hurricane evacuation decision process using a variety of methods including mental modeling, interviews, focus groups, and surveys (Figure 2). The focus in their project was more on the “right hand” side of the information and decision-making process illustrated in Figure 1, recognizing that information from multiple sources plays a role in perception, interpretation, and decision-making. Much of the “left hand” side of the value chain presented in Figure 1 was lumped together in this project under “external information” in Figure 2. Researchers addressing other parts of the research project used similar methods to characterize “upstream” components of the information process (see Bostrom et al. 2016). The shaded box in Figure 2 represents a modification to that presented in Lazo et al. (2015, p. 1839) indicating where economic valuation would be placed.

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[5] https://www.ametsoc.org/index.cfm/ams/about-ams/ams-statements/archive-statements-of-the-ams/the-public-private-partnership-in-the-provision-of-weather-and-climate-services/.

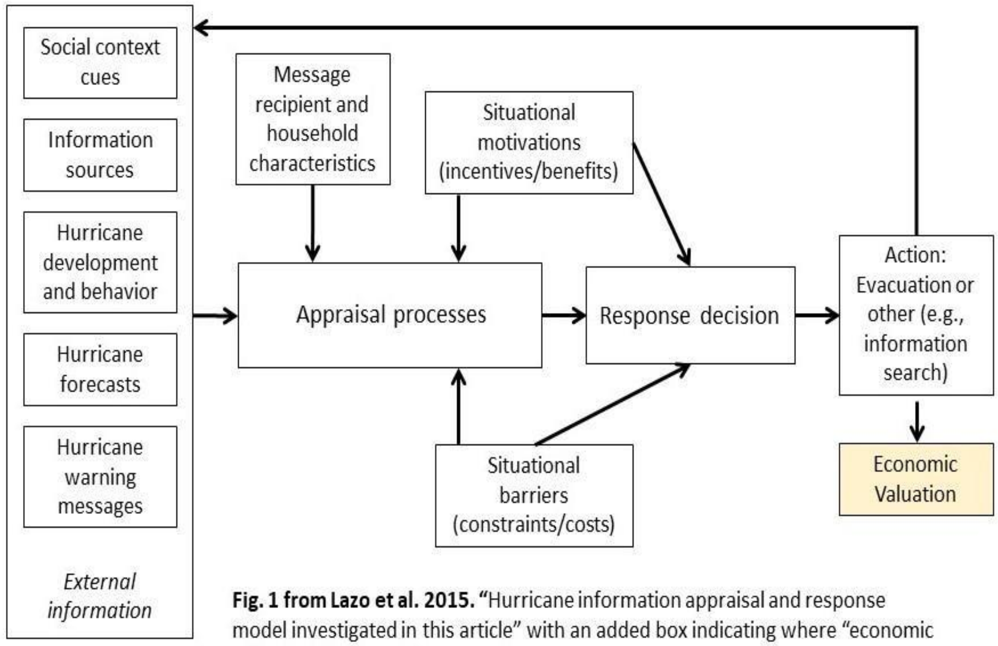

Fig. 1 from Lazo et al. 2015. "Hurricane information appraisal and response model investigated in this article" with an added box indicating where "economic valuation" fits into this approach.

Figure 2: Hurricane Information Value Chain based on Lazo et al. (2015)

There is an important difference between the economic impact of weather and the value of current or improved weather information, and the two are not *necessarily* directly related. The economic impact of weather is "outcomes" that occur with the actualization of weather events (which is not causally related to weather information) and the decisions made by end users. In this sense, weather information has *ex ante* value, and the economic impacts of weather are *ex post* measures of weather occurrences intersecting with decisions that were made possibly using previously available information. Another way to say this is that there are weather-related impacts that are unavoidable and weather-related impacts that potentially could be avoided with better information or behavior changes. The value of weather information is related to the avoidable impacts or improved outcomes.

To the extent that impacts are considered negative it should also be noted that there is value to weather information when it enhances positive impacts (e.g., increases utility, leads to improved efficiency, or improves profits). It also worth noting that to the extent that social systems and technologies are dynamic, so are exposure, vulnerability, and opportunity.[6] We can "design" out the sensitivity of a system or component through new technologies, sometimes intentionally (building codes, construction standards, land use restrictions) or unintentionally (relation between indoor plumbing/HVAC and reduced exposure to lightning—grounding of current). More importantly, the capacity of individuals, households, and enterprises to use weather information is arguably growing as technological advances permit manipulation of automated

[6] This is discussed further in a preliminary way in Appendix A: The Concept of Conceptual Models

elements to gain efficiencies. Even the proliferation of mobile phone use and attendant weather apps applies here.

While impacts (outcomes) and the value of information are not *necessarily* directly related, event outcomes reflect the hazard event and the various collective responses, which include those well or poorly or indifferently informed by various sources of weather information. Thus, we may use potential changes in impacts as a basis to ask “experts” what proportion of those impacts might be attributable to, or influenced with, better information[7]. Similarly, experts could be asked by what percent current impacts would increase without the currently available information. This is the basis of the benchmarking or expert elicitation that has been used in some economic studies of the value of improved hydro-met products and services (see GOES-R case study in Section 6.8 and Lubar et al. 2021).

From an economic analysis perspective, we advocate that it is useful, if not actually necessary, to both adequately characterize the relevant portions (if not the entire) of the hydro-met information process and apply appropriate information quality measurements along the chain being evaluated in an economic study. This is to ensure that any value estimates are valid and reliable.[8] Without a solid “chain of evidence,” valuation studies are black boxes wherein the quality of the study and any results can be questioned. The degree of rigor necessary in developing, characterizing, and quantifying the process depends ultimately on the purpose of the economic study and the use of the resulting value estimates. As we will suggest below, using criteria originally developed for the evaluation of primary sources in benefits transfer studies may be a useful tool for evaluating the quality of the “value chain” in studies of the value of hydro-met information.

We also propose that the value chain concept provides a useful approach to understanding and discussing the entire process of information creation, communication, and use—even if there is not a specific valuation component in the discussion. Using an “economic” approach to problem definition can involve identifying each stakeholder (or actor or agent depending on your desired terminology) and characterizing the role that they play. This economic approach may then involve determining what the objective (explicit or implicit; formal or informal) of each stakeholder is, what resources they must input into meeting that objective, and what constraints they face in meeting their objective. Economists will recognize this as the basic three components of an economic agent’s maximization (or minimization) problem. Characterizing the various objectives, resources, and constraints that different stakeholders hold can improve our understanding of the value creation process as well as lead to identifying gaps and opportunities to improve the process. Demuth et al. (2012) is an example of a research effort that begins to

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[7] See Tsirkunov et al (2007)and Rogers and Tsirkunov (2013).

[8] The concept of characterizing the value chain to obtain valid and reliable economic estimates applies both to the baseline or counterfactual condition and the change (or usually the improvement) in the information process. Economic values are measured as a change between states of the world and our argument here is that both the initial and final conditions need to be adequately characterized to develop a defensible measure of the change in socioeconomic outcomes with any system adjustment or investment.

apply an "objective-resources-constraints" approach to understanding potential gaps and opportunities for improving communication in the hurricane information process in the United States.

We note that "resources" and "constraints" largely determine a system's, household's, or institution's vulnerability and thus the "economic" approach could also be tied more directly to vulnerability studies. Blaikie et al. (1994) discuss vulnerability in much greater detail in terms of societal structures and institutions that create and maintain vulnerability including root causes, dynamic pressures and unsafe conditions that are primarily societal determinants of vulnerability that interact with hydro-meteorological (and other) hazards to create risk. In evaluating the weather information value process, it is important to consider that these "other" factors may well be much more important in driving the socioeconomic impacts or hydro-met events than changes in hydro-met information.[9]

The weather information value chain can also be used to detail the potential contributions of other social sciences to evaluating the chain and to enhancing value. Studies from other social sciences on information creation (Daipha 2015), communication (Morrow et al. 2015), decision-making (Morss et al. 2010), risk perceptions (Lazo et al. 2015), impacts (Lazo et al. 2011), risk outcomes (Mills et al. 2020), etc. can further improve our understanding of the overall process and identify priorities for improvements. The project referred to in Figure 2 [Warning Decisions in Extreme Weather Events (WDEWE)] used mental modeling methods to "map" the forecast and warning process and to identify potential information gaps among forecasters, emergency managers, broadcasters, and the public.[10] A valuation component was tied to this mental modeling approach to examine economic measures of important factors that affect decision-making based on the quality of the hurricane forecast and warning information.

Finally, the weather information value chain could be used as a tool to explicate how user-relevant information can drive product and service research and development (R&D), providing an essential link back to the "left hand" side of the generic value chain introduced in Figure 1.[11] Having valid measures of efficacy (e.g., lives saved, injuries or damage avoided) and economic value of different information products and services—tied to common metrics of hydro-met information quality such as skill scores—provides quantitative evaluation evidence from the end

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[9] See Appendix B: Preliminary Thoughts on Some Value Chain Related Concepts for further examples of alternative value chain configurations

[10] See Morgan et al. (2002). Mental model approaches have been used elsewhere in the meteorology literature (Trafton 2004; Kuonen et al. 2019).

[11] We note that it would also be fruitful to further discuss the relationship between socio-economic measures of the value of hydro-met information and methods to evaluate or verify hydro-met information. This could tie closely to the concept and methods in "user-relevant verification" (e.g., see Barbara Brown, Laurie Wilson, and Beth Ebert's work at https://www.researchgate.net/profile/Barbara_Brown7/publication/266178943_User-Relevant_Verification/links/54c2bb860cf256ed5a8f720f.pdf; https://ams.confex.com/ams/88Annual/techprogram/paper_134304.htm; and https://opensky.ucar.edu/islandora/object/articles%3A22230/datastream/PDF/download/citation.pdf).

user's perspective that can guide identification and prioritization of future information enhancements.

3 *VOICE* : The "Value of Information Characterization and Evaluation" Model

To begin to formalize a process for building and evaluating value chains we propose the "Value of Information Characterization and Evaluation," or ***VOICE*** approach. "Value of Information," or **VOI**, is a primary conceptual and theoretical framework for economic analysis of the socioeconomic value of information—including the ***VOICE*** template. VOI is the primary conceptual framework for economic analysis of the socioeconomic benefits of hydro-met information.[12]

We use the term "Characterization" to indicate the important, yet considerable effort needed to identify the various actors; establish what their objectives, resources, and constraints are; and determine how they obtain, interpret, modify, and act upon information. For most applications, we see this as largely a qualitative exercise. The nature, context, and quality (broadly defined as in Stvilia et al. 2007) of information is also characterized qualitatively and quantitatively. We use the term "Evaluation" to indicate that quantitative methods can be used to measure and assess, for instance, the quality of information as well as estimating behavioral response, determining societal outcomes, or using economic methods to assess benefit or costs.[13]

Table 1 proposes an initial template for explicating the components of a weather information value chain.[14] The categories in the left column are initial ideas about aspects of the chain to be characterized and assessed. The use of a more formal or methodical approach to developing value chains would require a wide range of disciplines and methods to appropriately distinguish and describe the diversity of forms that information may take along any single production and utilization process. In addition, there are more dimensions to characterizing the quality, usability, relevance, format, and content (and other dimensions) of information than generally addressed in most of the extant literature on the value of hydro-meteorological information (see Stvilia et al. 2007 for a range of concepts and measures applicable to characterizing information).

Future work should identify the full range of relevant categories to characterize a value chain for economic analysis. For instance, the role of R&D either within NMHS (e.g., NOAA's Office of Atmospheric Research and its related laboratories[15]), other governmental or nongovernmental

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[12] There is a relatively large literature on the VOI in economics both theoretical and applied. While the topic covers a range of concepts and applications several references are directly relevant to understanding VOI in decision-making as related to the use of weather information (see Ganderton 2006; Katz and Murphy 1997; Katz and Lazo 2012; Lawrence 1999; Laxminarayan and Macauley 2012; Wilson 2015).

[13] There is not a distinct line separating qualitative and quantitative methods and there is significant variation of methods within in each. We feel that a "mixed methods" approach is likely necessary in developing a value chain for any given objective. See, e.g., Harwell (2011).

[14] See Appendix C: Developing a Framework for Value Chain Explication for examples of questions to pose to populate and inform different elements of ***VOICE*** and information value chains more generally.

[15] See https://research.noaa.gov/Labs-Programs.

institutions (e.g., the National Center for Atmospheric Research[16]), or private-sector organizations could be incorporated as needed in the development of specific value chains.

At this time, the ***VOICE*** approach to articulating information value chains is a very preliminary design and should be further refined, developed, and tested through applications to enable and broaden the use of the value chain concept. Toward this end, a related effort to establish value chain guidance by the WMO HIWeather and WMO WWRP/SERA Working Group[17] may undertake an exercise to implement the ***VOICE*** framework building in part on the work described here. With respect to the ***VOICE*** concept and framework, we thus encourage and recommend follow-on focused efforts including developing a framework white paper on this approach.

16 See https://ncar.ucar.edu/.

[17] http://www.hiweather.net/.

Table 1: VOICE—Value of Information Characterization and Evaluation

Process	Observations	Modeling	Forecasting	Dissemination	Communication	Perception/ Interpretation	Decisions [18]	Outcomes [19]	Economic Valuation
Features	• Satellites • Radar • Ground stations • Cars, planes and boats with built-in observation systems, • Social media, • Phone calls, • Traffic	• Numerical Weather Prediction • Nowcasting • Climate models • Impact models	• Weather forecast • Seasonal forecasts • Climate forecasts • Watches and warnings • Relevant hazards • Impacts • First-order responses	• Internet • Television • Radio • Telephone • Smartphone • Newspapers • Sirens • Word of mouth • Indirect (actions of others)	• Format • Content • Detail • Uncertainty • External sources/noise	• Threat • Impacts • Probability • Reliability/ trust	• Run/hide • Buy/sell • Sunglasses/coat • Defer/ reschedule • Substitute • Ignore	• Live/die • Happy/sad • Cold/wet • Profit/loss • Attributes (immediate, lagged, acute, chronic, secondary/ tertiary/ derived/ induced…)	• Reduction in economic impacts of weather • Willingness to pay for information • Increased profits in production processes
Agent/actor									
Objective									
Resources									
Constraints									
Information Characteristics									
Value Added									
Other Process Characteristics									

[18] *ex ante*—before actualization of weather—we note as well that this could be taken to include intentions, behaviors, practices, and habits as well as models, constructs, and concepts from social psychology, behavioral geography, and sociology communities and other disciplines.

[19] *ex post*—with actualization of weather.

4 What to Value?

With respect to economic values, we note that valuation is at the end of the chain, so valuation methods ultimately depend on the decisions and potential outcomes being evaluated. The VOI lies in potential changes in outcomes based on decisions made or potentially made using the information prior to the realization of the weather event. Alternatively, once a decision has been made, examining the economic value of the outcome given the realization of the weather is an evaluation of the economic impact of weather. Some of the types of outcomes that may be evaluated include the following:

- Morbidity/mortality
- Reduced costs of production
- Reduced damages from weather events
- More efficient responses to weather events
- Increased profits (e.g., from investments or weather derivatives)
- Improved welfare [e.g., measured through willingness to pay (WTP)]

Economic values are the result of the complex process of information creation, communication, interpretation, use, and decision-making. Ultimately VOI is a function of the ability of decision-makers to receive, understand, and act on information on uncertain future events. To derive valid benefit estimates, the research must be able to tell the story of the weather information chain end to end or explain explicitly how the information relates to decisions, outcomes, and values. We note also that value of an impact or information is measured as a difference between two states of the world—with the impact or information compared to some "baseline" or "counterfactual." Thus, the researcher needs to be able to characterize both states of the world to measure the impact of weather (usually done implicitly by assuming "normal" weather as the nonimpact state) or the value of the weather information (often done assuming continuing of the current information regime compared to an improved or different information context).

In studying economics and weather there is a range of topics for the value of "weather" and "weather information." The economic impact of weather (as discussed further below) is fundamentally different than the value of weather information and there is not a necessary relationship between the two. In some sectors there may be significant economic impacts from weather, water, or climate but if there are few or no behavioral response options, weather information may have little value.[20] On the other hand, in a sector or activity with a small economic impact but significant opportunity to mitigate those impacts, weather information may have significant value. The relative extent of economic activity in any given sector or enterprise that may be subject to influence is constantly changing with shifts in technology, production processes, and consumer demand that in many cases allows for better discretization and management of risks and opportunities, but in others may significantly lessen the weather-

[20] If the information is of poor quality or more commonly miscommunicated or misinterpreted, and these lead to bad decisions and outcomes, it can lead to negative value.

related sensitivity. The dynamic nature of social processes thus argues for "continuous valuation" efforts to appropriately evaluate societal preferences and values and help prioritize ongoing investments in ESOSS.

Lazo et al. (2011) is an example of a study of the economic impact of weather. Using historical weather and economic data and empirical analysis methods from economics, Lazo et al. estimated the variability of economic output related to weather variability in the United States of up to $485 billion (in 2008) a year (about 3.6% of GDP).[21] On the other hand, Dutton (2002) using entirely subjective estimation states that "some one-third of the private industry activities, representing annual revenues of some $3 trillion, have some degree of weather and climate risk. This represents a large market for atmospheric information" (Dutton 2002, p. 1306). Given the significant differences in these results, the economic impact of weather is an important and currently inadequately researched topic of interest.[22] We consequently encourage a strong research effort in this area as there are potentially important policy implications, such as those related to anthropogenic climate change, of having good measures of the impact of weather (in the United States as well as internationally).

When considering meteorological information, VOI studies can endeavor to estimate the benefits of:

- current weather forecasts,
- improved weather forecasts, or
- research to improve forecasts.

Each may have different policy purposes and involve different theoretical or methodological issues. For instance, valuing current information may be more difficult to assess than valuing an improvement in information as a counterfactual for "current information" is difficult to determine. Without "current information," it is unclear if the baseline should be "no information" or more likely persistence or climatological averages. The comparison baseline for the value of current information may therefore be dependent on the end user's perceptions and understanding of meteorological processes. On the other hand, the alternative to no "current information" from the local NMHS may well be information online from other agencies or private-sector providers. There also may be other ways of "cutting this up" including looking at different actors in the value chain or looking at different weather/water/climate phenomena.

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[21] Applying the same 3.6% factor to projected 2021 U.S. GDP of $21.921 trillion would indicate current sensitivity of $789 billion. It is unknown if this sensitivity is increasing or decreasing although there are broad assertions that it is increasing in part due to climate change. This is an empirical question that should be examined with valid and reliable economic analysis.

[22] We reference Dutton (2002) here as the assertion that "some one-third of the private industry activities, representing annual revenues of some $3 trillion, have some degree of weather and climate risk" (Dutton 2002, p. 1306) is very widely cited in the weather community as an indication of the importance of weather information. For instance, see https://www.noaa.gov/weather—in this case, this number is cited without reference to the source or acknowledgement of the lack of economic validity or reliability of this assessment.

In addition, "current information" may imply a "right" in the status quo and the correct value measure may be a willingness-to-accept (WTA) a reduction in products and services as opposed to willingness to pay (WTP) for better information. There is literature (mainly from environmental economics) on potential differences in WTA and WTP for essentially the same change in products and services depending on the framing of the property rights in the commodity.[23]

Lazo et al. (2009) is one of the few empirical studies of the value of current information. Other studies, often applying a "benchmarking approach" largely due to data and resource constraints (e.g., Rogers and Tsirkunov 2013), offer important "first guess" value estimates but are less reliable. Using a simple but sound and transparent method to scale results from a national sample survey of WTP results, Lazo et al. estimate the average household value of current information in the United States to be about $286 per household per year (in 2006). Given that there were over 114 million U.S. households, this translated to a value of current (2006) information of over $31 billion per year. Comparing this to a $5.1 billion per year estimate of current costs for meteorological information in the United States (including research and public and private-sector provision) generated a 6.2 to 1.0 benefit-cost ratio.[24]

Many of the studies funded by NHMS are of the actualized (*ex post*) or potential (*ex ante*) value of improved forecasts to justify expenditures for new forecasting capabilities (e.g., observation systems or new products or services). For instance, the case study described Section 6.8 on the "GOES-R Socio-Economic Benefits Study" quantifies the value of improved hurricane forecasts to the U.S. public attributable to the GOES-R satellite series as compared to the GOES-N-O-P satellites (which serve as the baseline or "counterfactual" in the analysis). The study derived a baseline estimate of $9.27 billion in benefits from improved hurricane forecasting to the U.S. hurricane-prone public (with a 90% confidence interval of $5.39 to $13.14 billion).

A limited number of studies have looked at the value of research to improve forecasts. See the case study in Section 6.7 on "A Public-Private-Academic Partnership to Advance Solar Power Forecasting" for an example of research to improve forecasts for utility-scale solar power that included an economic valuation component. The analysis included an implementation of the utility's production cost model (PCM) under different scenarios of the error in solar forecasting to estimate how much costs will be lowered under improved forecasts. This was then extrapolated nationally over time to generate a benefit estimate of over $450 million. Also looking at the value of research, Lazo et al. (2010a) used expert elicitation and benefits transfer to quantity the value of potentially purchasing a supercomputer to be used in weather forecasting research. Attributing benefits to aviation (reductions in fatalities), households (willingness to pay for improved information), and agriculture (improved crop production) indicated a present value (in 2003) of $104.6 million or an internal rate of return of 21.8%.

Valuation studies can also examine value added in the weather information value chain irrespective of changes in the accuracy or precision of "geospatial" information provided by an

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[23] See, e.g., Tunçel and Hammitt (2014).

[24] We recommend undertaking more and better studies of the current value of weather information as the method used in Lazo et al. (2009) is not "economically rigorous."

NMHS. There are benefits (or value added) related to current or potentially improved dissemination, comprehension, use, and decision-making steps in the value chain. For instance. Hosterman et al. (2019) and Lazo et al. (2020) discuss the socioeconomic benefits of impact-based decision support (IDSS). These benefits arise mainly from an improved communication process rather than any specific improvement in the quality of the hydro-met information itself.

The ***VOICE*** framework encourages one to consider the relative merits of investing in different areas of the value chain, not just those associated with improvements in prediction quality attributes. Investments in communication aspects as highlighted above may yield higher payoffs than improving on the accuracy and precision of hydrological, meteorological, and climate information (see Williamson et al. 2002).

Sources of economic value often extend beyond the short-term influence of weather forecasts and the same ***VOICE*** framework can be used to identify and explore a range of other potential benefits. For instance, improved rainfall and flood information can help improve the design of flood control infrastructure or improve climate modeling for climate change policy analysis, and historical weather information can help inform decision-making on designing insurance programs or emergency response needs.

5 Valuation Methods—Using Existing Resources

In any given analysis, the appropriate economic valuation method to use is dependent on the nature of the outcomes to be evaluated. Figure 3 (adapted from WMO 2015, pp. 64–65) shows a categorization of a range of benefit assessment methods from the economic toolkit. We have purposely excluded the benchmarking methods contained in the original publication (WMO 2015) from Figure 3 even though it has been used in several economic studies of the value of weather information. Also not included are expert elicitation methods that may not really be considered valuation methods but instead are methods for deriving estimates on specific parameters that may be part of a valuation study (see the case study in Section 6.8). We encourage the adoption of theoretically based economic methods listed in Figure 3 unless there are limited reliable data or resources available—in these cases "back-of-envelope" benchmarking and expert elicitation methods may be appropriate.[25]

[25] Chapter 6 in WMO (2015) provides some additional information on the application of the methods listed in Figure 3. For each of these methods there is extensive literature in the economic profession on the theoretical basis as well as the appropriate methods and application and strengths and weaknesses of each. Future work expanding the current white paper could begin to detail some of this information to guide noneconomists on appropriate approaches. See, e.g., https://www.cgms-info.org/documents/SETT_GuidanceDocument.pdf or https://www.nasa.gov/sites/default/files/files/SocioeconomicImpactsPrimer.pdf.
as examples of developing guidance on socioeconomic methods for the environmental observations and hydro-meteorological community.

	Method	Description
Non-market valuation – Stated preference	Contingent valuation (CV)	– Survey-based elicitation of individuals' preferences and values (for example, WTP)
	Conjoint analysis	– Similar to CV, except respondents are surveyed about a set of choices instead of a single WTP question
Non-market valuation – Revealed preference	Averting behaviour	– Determines values based on expenditures that would have been made to reduce impacts of weather or climate events, but were avoided because of improved met/hydro information
	Travel cost or expenditure modelling	– Uses observed tourist and recreational trip-taking behaviour to determine whether people pay more to visit sites for which forecasts are available – Can rely on other expenditures or costs incurred to search for or obtain met/hydro information
	Hedonic analysis	– Uses observed housing, property, or labour market behaviour to infer values for quality changes
Economic modelling	Decision analysis	– Analyses decisions and resulting values when people have access to met/hydro services and when they do not – Typically paired with business or production models
	Equilibrium modelling	– Examines changes in supply and demand, and price effects associated with use of met/hydro services – Measures resulting gains/losses for producers and consumers
	Econometric modelling	– Examines statistical relationships to determine specific outcomes associated with the use of met/ hydro services – Regression analysis is the most common form of econometric modelling
Avoided-cost assessment		– Evaluates benefits based on avoided costs of weather and climate events due to better met/hydro information, including avoided asset losses, lives saved, and avoided morbidity impacts
Benefit transfer		– Applies results of existing valuation studies and transfers them to another context (for example, a different geographic area or policy context)

Figure 3: Economic Valuation Methods

(Source: modified from WMO 2015, pp. 64–65; Table 6.2. Valuation methods)

We encourage anyone interested to use the WMO 2015 guide as an introduction to economic theory, methods, and applications for understanding and measuring the economic value of weather, water, and climate information. The document provides a summary of 12 benefits studies across several different countries indicating benefit-cost ratios for hydro-met services ranging from 2-to-1 to over 2,000-to-1 (WMO 2015, p. 8). It further contains 10 case studies of the value of weather, water, and climate information. The book is structured along a value chain framework to "to address the connections between the production and delivery of met/hydro services and the various user communities and to highlight important features of the value generation process." The value chains developed and used in WMO (2015) are shown in Figure 4 and Figure 5. Figure 4 shows the model of service delivery as commonly implemented by NMHS and Figure 5 shows the broader model of socioeconomic value in which the NMHS service delivery is embedded.

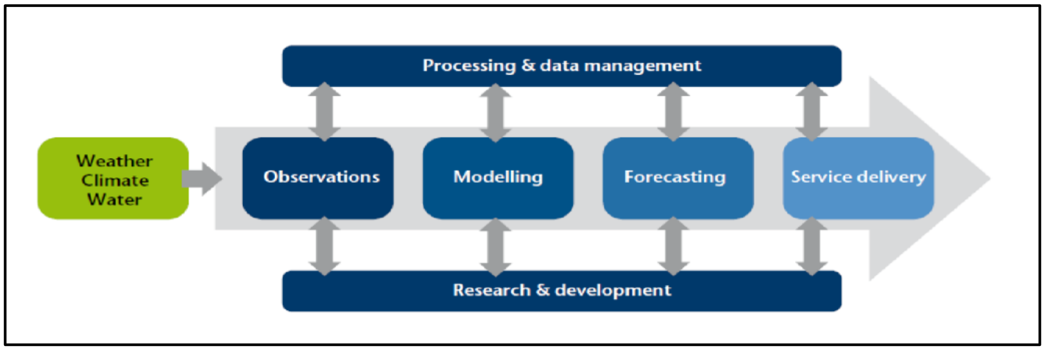

Figure 4: Weather-Water-Climate Service Production Model (WMO 2015, p. 47)

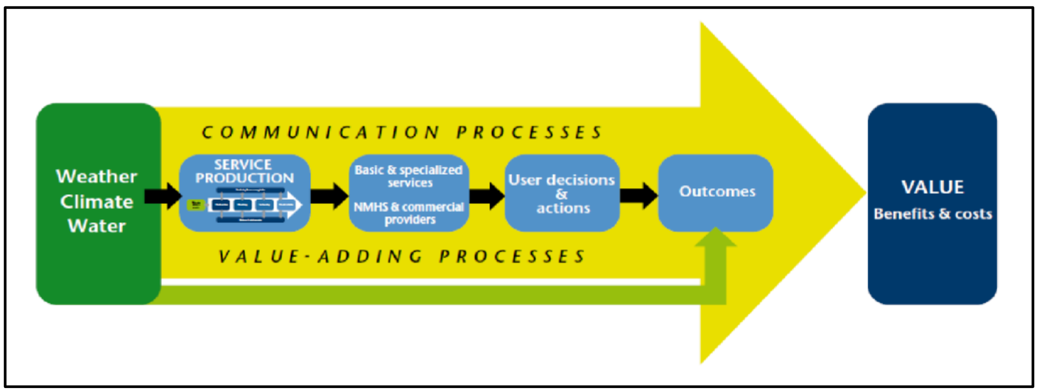

Figure 5: Value Chain Model (WMO 2015, p. 47)

Several other resources cover similar material on economic evaluation of hydro-met information, including Socioeconomic Benefits Tiger Team (2016), Lazo et al. (2008), and NASA (2013).

NASA (2013) includes "Table 1. Socioeconomic Impact Assessment Methods" as shown in part in Figure 6 below. The document discusses each method in detail, including information on the strengths and weaknesses of each approach.

We also note that the primary purpose of these documents is not to make the reader an expert in economic valuation or to prescribe specific methods and procedures to conduct a valid and reliable economic study. The documents largely provide the noneconomist reader with information to help them design a study to meet their needs, work with economists to implement the study, and to understand and interpret study results (e.g., for a policy decision or program evaluation).

Approach	Focus	Considerations
Impact Assessment		
Time-Series/ Statistical Analysis	Comparing historical trends before and after project completion	Retrospective; based primarily on objective data; therefore data-intensive and dependent upon availability of data
Expert Opinion	Using expert judgment or prior analyses to estimate project impacts	Can be retrospective or prospective; feasible in situations with limited data, but based on subjective or proxy data
Value of Information	Analyzing decisions under uncertainty with and without information from project	Usually prospective; requires availability and cooperation of decision maker; mix of subjective and objective basis
Cost-Based Assessment		
Benefit-Cost Analysis	Comparing monetized impacts with financial costs of project	Allows financial comparison of projects with different objectives; requires both impact and cost analyses; monetizing impacts can be difficult and controversial
Cost-Effectiveness Analysis	Comparing costs of achieving desired impacts	Allows financial comparison of projects with similar objectives; requires both impact and cost analyses; does not require monetizing impacts
Impact Monetization		
Market Valuation	Using prices paid in open markets for goods and services related to project impacts	Objective; requires market data; applicable only if markets exist for goods and services related to the project impact
Standards-Based Valuation	Using standardized prices from government or industry for project impacts in lieu of market data	Can be controversial, depending on standardizing source; simplifies monetization process; available for only a limited number of impacts
Benefits Transfer from Prior Research	Adapting existing studies to monetize impacts similar to those from the project	Can be controversial, depending on relative similarity of project benefits to those in prior research
Stated Preferences Valuation	Using surveys, augmented by analysis, to estimate stakeholders' willingness to pay for project impacts (e.g., conjoint analysis)	Tendency for biased responses by stakeholders who are only conceptually spending money for the impacts; requires survey development and analysis
Revealed Preferences Valuation	Using stakeholder behavior to estimate willingness to pay for project impacts (e.g., travel cost analysis, hedonic analysis)	Based on actual behavior rather than conceptual surveys; relationship between priced item and project impact may be indirect and thus controversial

Figure 6: Valuation methods NASA Table 1

6 Case Studies

6.1 Overview and Discussion of Case Studies

We elicited input from several authors on their use of the information value chain in research and analysis. The case studies are presented not as perfect examples of the application of the weather information value chain but rather to illustrate the range of topics and methods that have been adopted. In doing so, readers will appreciate the varying extent to which the value chain is explicitly or implicitly part of each study.

Table 2 presents summary information on the case studies. They represent a range of uses and means of implementing the value chain concept for research projects and empirical analysis; weather and climate analysis; developed and developing countries; qualitative frameworks and detailed quantitative applications.

Table 2: Value Chain Case Study Summary				
Case Study	**Primary Contributor**	**Value Chain Model**	**Use of the Value Chain**	**Type of Study**
Weather-Economics Literature Review	Lou Nadeau Eastern Research Group	Identify stages in the process from the occurrence of weather events/hazards to potential benefits from the information process as well as interconnections	Categorize a set of 450 studies during the literature review	Literature review
Kazakhstan Climate Resilient Wheat	Glen Anderson Winrock International	Analytical framework linking value chains for climate services and crop production	Guide the planning of project activities for the first two goals	Applied development project
Impact-Based Decision Support Services and the Impacts of Winter Storms	Heather Hosterman Abt Associates	Model showing the place of IDSS in the communication and decision-making process and types of outcomes in three sectors evaluated	Tool to understand how IDSS works and how it can benefit or provide value to decision-makers	Applied benefits study for strategic efforts for National Hydro-Met Service (NWS).
NOAA Fleet Societal Benefit Study	Jeffery E. Adkins NOAA Contractor	Individual descriptive value chains for 12 products that are highly dependent on the NOAA fleet	Demonstrate the societal benefits associated with NOAA fleet data collection activities	Conceptual model used throughout applied benefits study
WMO High Impact Weather (HIWeather) Value Chain	Brian Golding Met Office and WMO	Representation of the end-to-end connectedness of the warning production and delivery chain	Tool for project participants to bring together multidisciplinary research elements across all stages of the preparation and delivery of weather-related warnings	Framework to integrate across activities in international research program (WMO)
A Public-Private-Academic Partnership to Advance Solar Power Forecasting	Sue Ellen Haupt NCAR	Solar forecasting value chain concluding with utility decision-maker optimizing outcomes of day-ahead unit allocation and real-time operational decisions	Tool for visioning how to develop a system to generate value	Framework to integrate across activities in focused research program and indicate activities and contributions of research efforts
GOES-R Socio-Economic Benefits Study	Michael Jamilkowski The Aerospace Corporation	Value chain for hurricane information from GOES-R data sources	Used in discussions with NWS forecasters, NCAR researchers, and NOAA experts to guide discussions and develop a protocol for eliciting information on the portion of hurricane forecast improvements attributable to GOES-R	Applied benefits study of operational observing system

6.2 Weather-Economics Literature Review[26]

As part of a project to estimate the value of IDSS for National Weather Service (NWS), Eastern Research Group, Inc. (ERG) developed a value chain that was used to categorize a set of 450 studies during the literature review phase of the project (Figure 7).

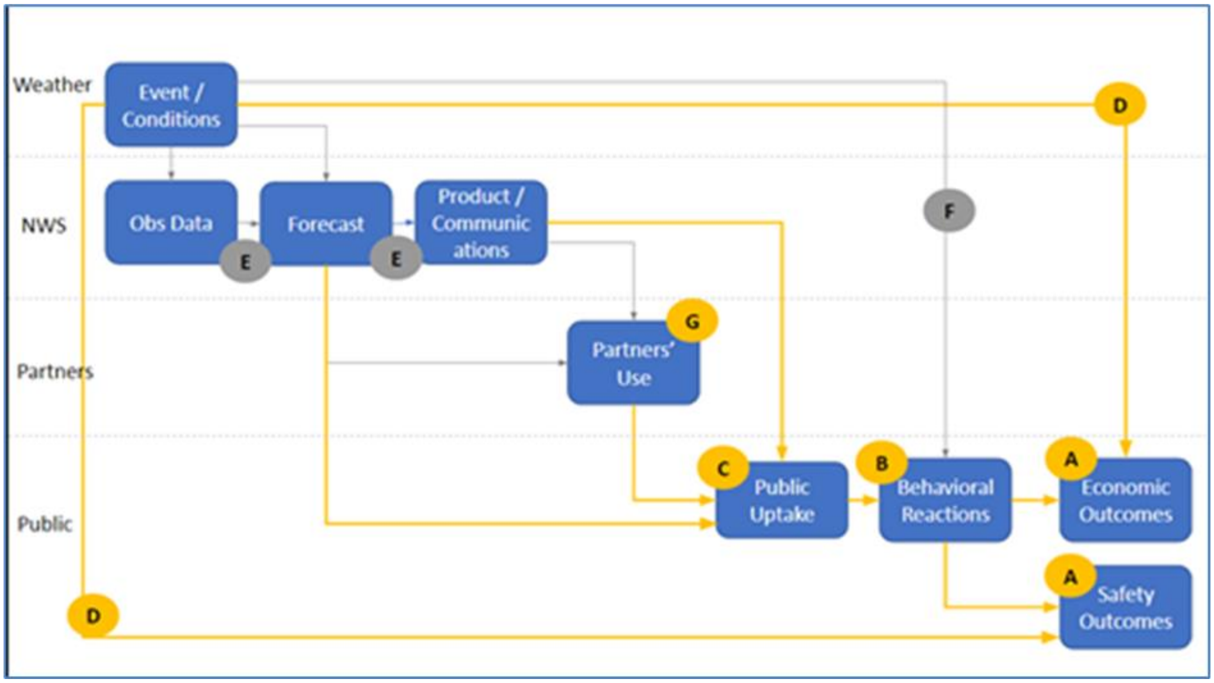

Figure 7: "Swim Lane" Value Chain Model for ERG Weather-Economics Literature Review

The value chain ERG developed identified all stages in the IDSS process from the occurrence of weather events/hazards to the potential benefits that could result from the IDSS process, as well as the interconnections between the stages. The chain was also organized into "swim lanes" depicting the actor in the process who performed the step. This set up allowed ERG to categorize each study based on the stages or interconnections it addressed. The value chain depicted in the figure consists of boxes, representing stages in the process, and gold or gray lines representing connections between the stages. Letter coding was used to categorize studies that were found by ERG, with gold letters/connections being most relevant for ERG's project and those in gray less relevant. This categorization allowed ERG to focus its resources on reviewing the most relevant literature for the project.

[26] This case study was provided by Lou Nadeau, Vice President, Sr. Economist, Eastern Research Group, Inc. (Lou.Nadeau@erg.com).

6.3 Kazakhstan Climate Resilient Wheat [27,28]

USAID[29] funded a Global Climate Change Initiative in Kazakhstan, "Improving the Climate Resiliency of Kazakhstan Wheat," implemented by the United Nations Development Programme (UNDP) during the period 2012–16. With technical assistance support from the USAID-funded Climate Change Resilient Development (CCRD) project, UNDP implemented activities to advance three goals: 1) improve monitoring and information sharing for climate resilient wheat production; 2) develop climate resiliency through mainstreaming of adaptation measures; and 3) support a regional dialogue on wheat, climate change, and regional food security.

To guide the planning of project activities for the first two goals, CCRD staff developed an analytical framework linking value chains for climate services and crop production (see Figure 8). The elaboration of the value chain also was useful in understanding the full range of information that could be considered by decision-makers in the wheat value chain. UNDP and CCRD conducted a series of stakeholder meetings with farmers and agricultural extension and research staffs to understand the types of information products (climate, market, and production) available to and used in farm-level decision-making. In addition, a climate services roundtable was organized to enable producers and institutional users of climate services in the agriculture and food security sector to present on current services, gaps, and areas for improvement in production and delivery of services.

[27] This case study was provided by Glen Anderson, Senior Development Economist, Winrock International (glen.anderson@winrock.org).
[28] Additional information on the case study is available in the report Compendium: The USAID Climate-Resilient Development Project - Final Report | Global Climate Change (climatelinks.org).
[29] United States Agency for International Development.

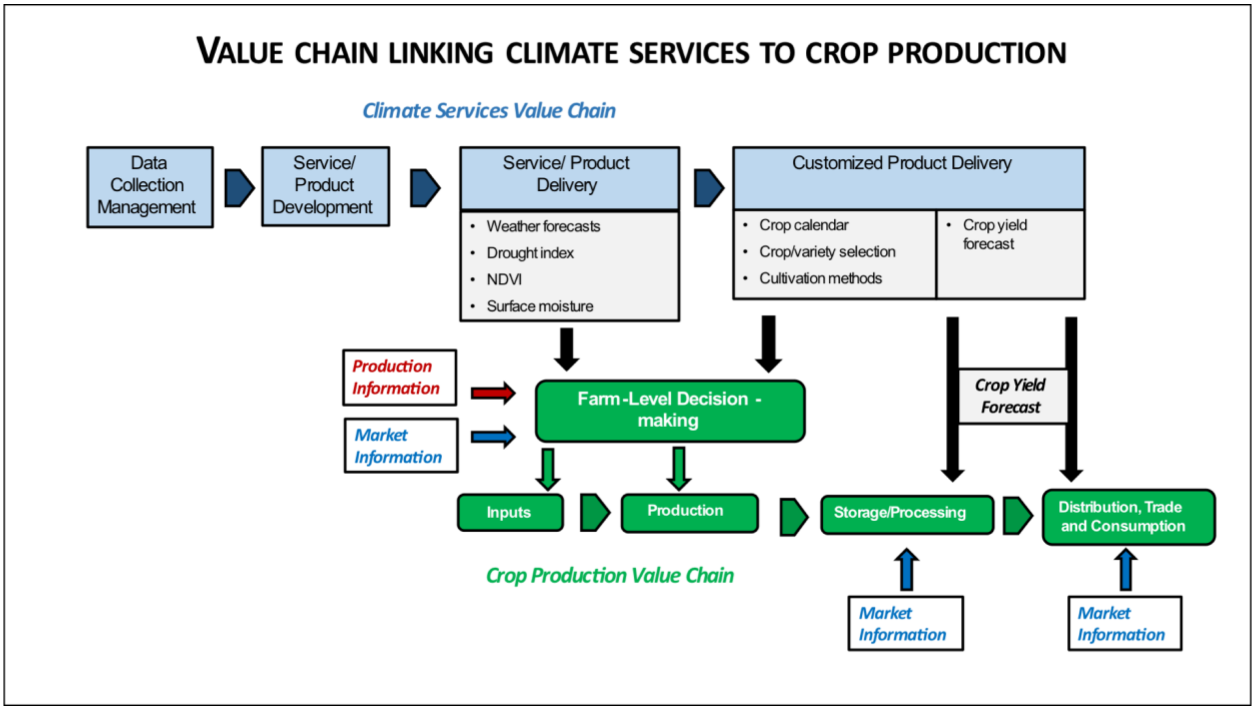

Figure 8: Analytical Framework Linking Value Chains for Climate Services and Crop Production

UNDP also contracted with a local consultant to develop a report on agrometeorological support of agriculture in Kazakhstan. On the basis of these meetings and the report, CCRD implemented a series of climate services activities and UNDP collaborated with two Kazakh research institutes to demonstrate alternative management practices related to the crop calendar, selection of crops and cultivation methods. CCRD support on climate service product development and delivery included the following:

- CCRD partner the International Research Institute for Climate and Society (IRI) conducted a back-casting exercise of the forecasts for wheat-producing areas applying a range of alternative forecasting methods to the analog methodology used in Kazakhstan and provided training on monthly and seasonal forecasting. IRI also helped KAZHYDROMET automate updates of the monthly drought index and provided permanent access to IRI's vast climate information database.
- CCRD consultants worked with the National Space Research Institute (NSRI) in Almaty to consider the use of remotely sensed data to augment soil moisture forecasts (based at the time on field data at selected monitoring sites) and improve crop yield forecasts based on NDVI[30] satellite imagery and monthly/seasonal forecasts. CCRD also supported the creation of a geoportal to facilitate sharing of NSRI forecasts and weather and climate products produced by KAZHYDROMET.

[30] NDVI is the normalized difference vegetation index.

During the summer of 2013, UNDP organized a series of field demonstrations, during which farmers were able to view experiments conducted by research institutes in Shortandy and Kostanay and by one large commercial farmer in Petropavlovsk to demonstrate the impacts on yields of alternative planting dates, crop and variety selection, and alternative tillage practices.

While these assistance efforts were praised by Kazakh partners, dissemination of climate services products has been hampered by a number of structural issues:

- All but the most basic services are only available at a cost considered too high for small farmers. In part, KAZHYDROMET sells data and information to partially defray the costs of salaries, equipment, and other expenses. NSRI faced similar constraints in developing and operationalizing the geoportal.
- Confidence in the monthly and seasonal forecasts produced by KAZHYDROMET is not strong among farmers, with some farmers relying on information produced by Russia. Also, while the agricultural research centers communicate with farmers on planting dates, it appeared in the summer of 2013 that growers deviated from the recommended planting date of the third or fourth week in May. Wheat was planted earlier than the recommended date and yields were significantly depressed in the region, suggesting that other factors influenced planting decisions, such as traditional knowledge on soil conditions and planting dates and concerns that there would be insufficient storage capacity for late harvested wheat.
- The crop yield forecast has been improved and is an important source of information along with market information for the Government of Kazakhstan in ensuring there is adequate storage for the harvested crop and maintaining wheat reserves, and for international traders.

6.4 Impact-Based Decision Support Services and the Impacts of Winter Storms[31]

Building on existing U.S. NWS efforts to provide consistent messaging to the meteorological community and as part of the NWS Roadmap's focus on Building a Weather-Ready Nation,[32] NWS increased their efforts to provide decision support services to core partners. In 2011, NWS formalized their approach to IDSS.[33] IDSS moves beyond traditional forecast creation and dissemination to provide relevant information and interpretative services that enable partners to prepare for and respond to, as planned, extreme weather, water, and climate events for the protection of life and property (Uccellini and Ten Hoeve 2019).[34] The fundamental purpose of

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[31] This case study was provided by Heather Hosterman (Abt Associates), Jeff Lazo (Jeffrey K. Lazo Consulting LLC), Jennifer Sprague-Hilderbrand (NWS), and Jeffery Adkins (NOAA Contractor).
[32] https://www.weather.gov/news/192203-strategic-plan.
[33] https://www.weather.gov/about/idss.
[34] https://journals.ametsoc.org/view/journals/bams/100/10/bams-d-18-0159.1.xml.

IDSS is to better connect forecasts and warnings to critical decision points of core partners "for the protection of life and property and enhancement of the national economy."[35]

The study posits that formal IDSS provides core partners with better information and supports decisions that reduce socioeconomic impacts during extreme winter storms. The researchers compare two storms in the New York City area with similar characteristics but differing in their implementation of IDSS: the December 2010 storm occurred before the implementation of formal IDSS, whereas the January 2016 storm occurred after the implementation of formal IDSS. The comparison of the storm events indicates that IDSS and mitigating actions reduce flight cancellations, improve recovery time in the ground transportation sector, and reduce the duration and number of customers affected by power outages.

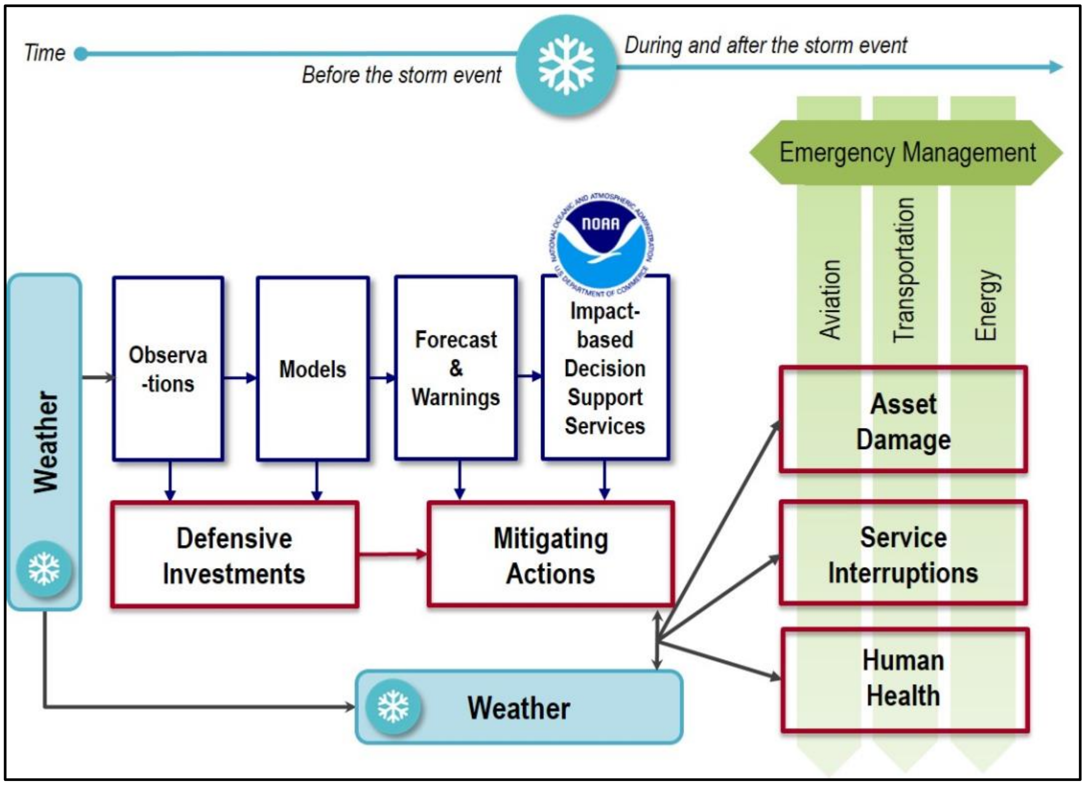

Figure 9: Value Chain of IDSS Information

The researchers present a weather information value chain as a tool to understand how IDSS works and how it can benefit or provide value to decision-makers (Figure 9). In this value chain, weather is shown as "pre-event" conditions that are observed and modeled, leading to forecasts and warnings of impending winter storm events. Prior to IDSS, forecasts and warnings were disseminated through conventional channels. With the advent of the IDSS, additional capabilities and procedures are implemented to improve the dissemination and communication of forecasts and warnings to core partners. With IDSS, processes are put in place well before the forecast such

[35] https://www.weather.gov/about/.

that the forecast and warnings will connect to the decision process in a collaborative way. This ensures the information is more relevant to decision-makers to enhance the protection of property and health and safety.

At the bottom of the value chain, weather is shown again as the actualization of the event. The actual weather outcome occurs within the context of the defensive investments and mitigating actions that are designed to lead to improved social and economic outcomes. Based on prior mitigating actions and procedures, and event-specific information from NWS, the interaction of defensive investments and mitigating actions with the actualization of the weather event results in social and economic impacts with potential asset damages, service interruptions, and human health impacts in all sectors. Presumably, these impacts are less with the defensive investments guided in part by IDSS than they would be without such actions. The focus of the study was on the aviation, ground transportation, and energy sectors, as indicated in the value chain.

Actual impacts in each sector are highly dependent on the structure of the sector and the decision processes. For instance, the researchers expect a larger portion of the impacts in aviation to be in service interruptions than in human health impacts, whereas in road transportation there may be a significant component of human health impacts if extreme winter weather leads to more traffic accidents. Emergency management cuts across all sectors as a core partner and as an intermediary in communicating and implementing public responses to extreme weather events. To simplify the figure, the researchers do not include other intermediaries, such as broadcast and private-sector meteorologists; however, these intermediaries also play critical roles in forecast, warning, and decision processes.

The value chain developed in this study helped the researchers identify where IDSS enters the value chain process and how it changes the way weather information is disseminated to decision-makers and emergency managers. It also assisted the researchers as they conducted interviews with stakeholders along the value chain—such as emergency managers, transportation managers, and energy providers—to identify stakeholder relationships with weather information providers and to characterize and quantify improvements in decision-making and enhanced socio economic outcomes with IDSS. Using the value chain and case study comparison of two extreme winter storms in the NYC region, the researchers find strong indications that IDSS has improved decision-making, enhanced communication between the NWS and core partners, and reduced societal and economic impacts of extreme winter weather events. The comparison of the storm events indicates that IDSS and mitigating actions reduce flight cancellations, improve recovery time in the ground transportation sector, and reduce the duration of power outages and the number of customers affected by them.

6.5 NOAA Fleet Societal Benefit Study[36]

Data collected by NOAA's fleet of research vessels are used in more than 600 products and services across the full spectrum of the agency's mission, more than 80% of which address climate, weather, and fisheries issues. To demonstrate the societal benefits associated with fleet data collection activities, this study developed descriptive value chains for 12 products that are highly dependent on the fleet and/or have a relatively large societal benefit, meaning they affect decisions made in important sectors of the economy and/or result in significant savings or increased well-being for U.S. households.

These value chains describe the linkages within NOAA from data collection and management to analysis and the production and dissemination of products and services. They also describe the linkages from NOAA to society and the creation of societal benefits, identifying the users of the products and services, the manner in which they are used, and the manner in which they and society at large benefit from their use.

Other linkages that are distinctive of NOAA were identified in the value chains, showing the role of research that adds value to the use of data in analyses and the creation of final products and services; the roles of other agencies, organizations, and stakeholders in product dissemination and communication (e.g., local weather forecasters providing information from the National Weather Service to viewers); and the role of intermediaries who use information from NOAA to create value-added products and services (e.g., private companies who generate weather forecast information and disseminate this to the public). A general value chain from the final report is shown Figure 10.

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[36] Case study provided by Jeffery E. Adkins, NOAA Contractor, Performance, Risk, and Social Science Office. Study conducted by Abt Associates, Incorporated and Corona Environmental Consulting for the NOAA Office of Marine and Aviation Operations (https://www.omao.noaa.gov/sites/default/files/documents/Final%20Societal%20Benefit%20Study%20Report%203.19.2018.pdf).

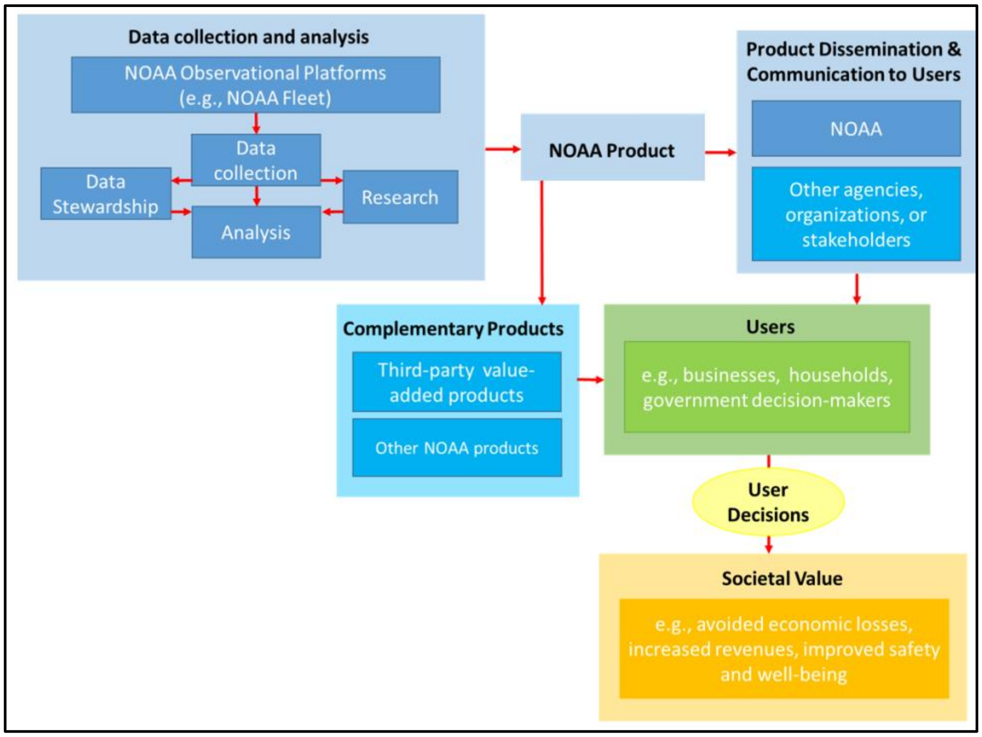

Figure 10. Simplified Value Chain for NOAA Products and Services

Each of the narratives describing value chains for the 12 products that were selected for assessment in this study (no services were selected in this study) describes:

- the NOAA product,
- the product's use of data from NOAA research vessels,
- other critical inputs to the product,
- the users of the product and the manner in which they use the product (e.g., the decisions that are informed by the use of the product), and
- the manner in which users and society as a whole benefit from the use of the product and information about the economic magnitude of the decisions that are being informed (e.g., the value chain narrative for NOAA's Sea Level Rise Viewer provides general information on the number and value of homes at risk from flooding from a commercial database, and estimates by the U.S. Environmental Protection Agency of the cumulative costs of sea level rise through 2100).

This study also identified five of the 12 products for which quantitative estimates of value were estimated. These five products were selected using the following criteria:

- the product likely has significant benefits for society,
- the product has a significant dependency on data from the NOAA Fleet,
- data are available to robustly quantify/monetize the societal benefits of the product within the scope of this contract, and

- information is available for independent verification of results [i.e., information confirming that (a) the product is critical in the use case that is evaluated and (b) outcomes will improve with the use of improved products].

All 12 products for which descriptive value chains were developed satisfied the first two criteria, so the selection of the five products for further evaluation was based on the last three criteria. The following five products were selected for quantification of benefits:

- Coral Reef Status and Trends Reports (used to inform investments in coral reef protection),
- Sea Level Rise Viewer (used to provide first-order indicators of vulnerability to sea level rise, providing a starting point for adaptation planning),
- Nautical Chart Products (used to support safe and efficient marine navigation),
- El Nino Southern Oscillation Outlook (seasonal forecast used by government agencies and farmers and other businesses to mitigate the negative effects of short-term climate variations), and
- National Marine Sanctuary Condition Reports (used to inform the development of management plans to ensure the continued delivery of benefits provided by the Sanctuaries).

The development of more detailed value chains was necessary for the quantification of benefits. Figure 11 shows the detailed value chain that was developed for the Sea Level Rise Viewer. This value chain contains additional details that provide a conceptual model that illustrates the relationships that are quantified in the analysis, allowing the estimation of benefits associated with the final product and attribution of a portion of the benefit to the data provided by the NOAA fleet (attribution of value to the data reflects NOAA's estimates of the degree of degradation in the final product if the data were not available).

Value chains provide a framework for organizing information on the production and use of products and services to guide assessments of their value. Their use helps to ensure that valuation studies and other research reflect an accurate understanding of the connection between NWS products and services, the necessary inputs, and the means by which societal outcomes are improved. Value chain diagrams and narratives are also valuable story-telling tools, providing a rich context for understanding and interpreting the results of studies.

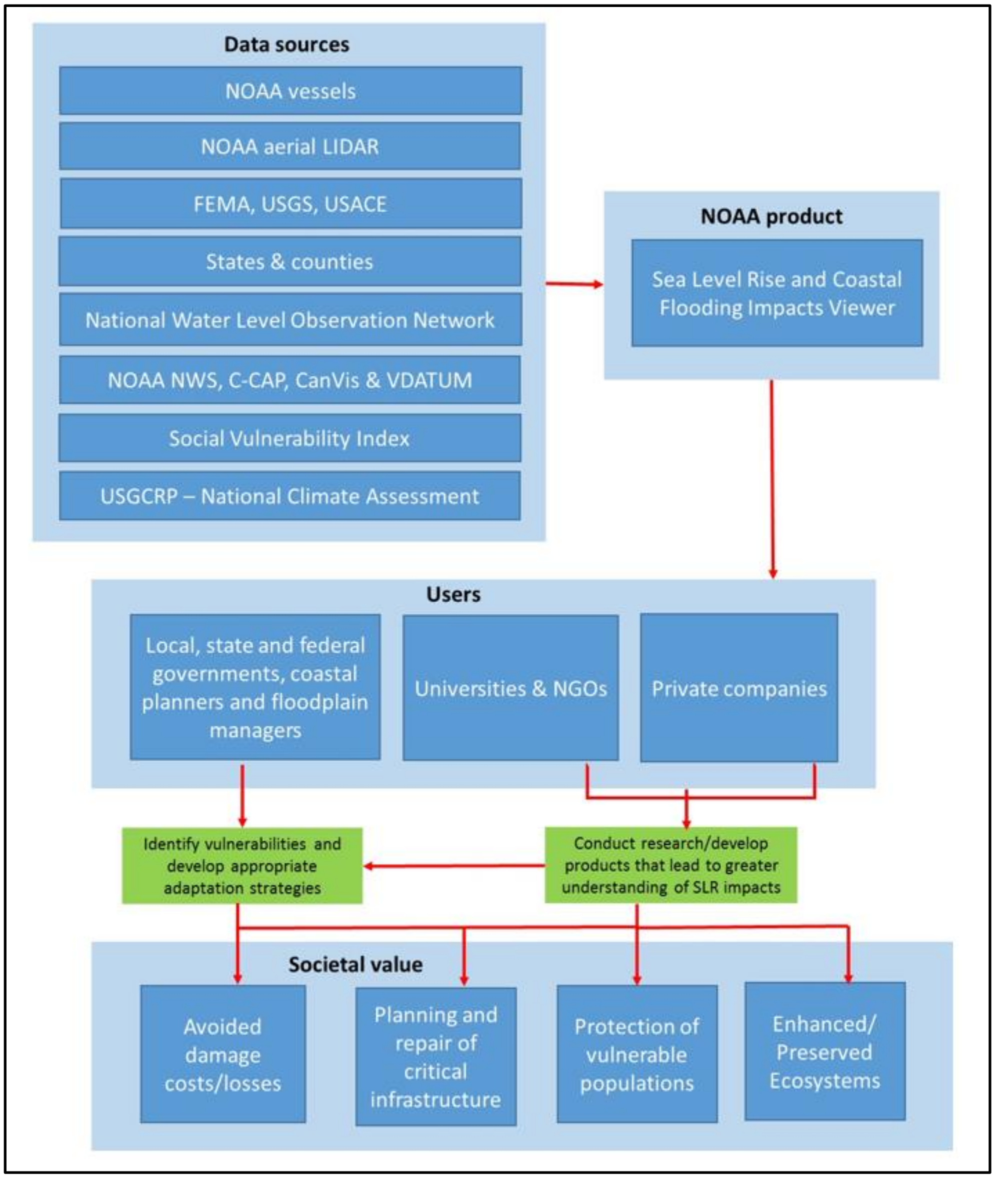

Figure 11: Detailed Value Chain for NOAA's Sea Level Rise Viewer

6.6 WMO High Impact Weather (HIWeather) Value Chain[37]

The World Meteorological Organization (WMO) World Weather Research Programme (WWRP) High Impact Weather (HIWeather) project was initiated in 2015 to carry out research that would lead to better weather-related hazard warnings throughout the world. The HIWeather project

[37] Case study provided by Brian Golding, Met Office, and co-chair of the World Meteorological Organisation's 10-year high impact weather research project, HIWeather.

plan identified many and varied areas of physical and social science needing further research at all stages of the preparation and delivery of weather-related warnings. Subsequent to project initiation, workshop discussions among project participants focused on how the multidisciplinary research elements could be brought together.

These discussions crystalized around a representation of the end-to-end connectedness of the warning production and delivery chain, which was captured in the "five valleys of death" concept (Figure 12). Here each mountain represents the expertise in a specific organization or discipline, the valleys represent the potential loss of information between organizations or disciplines arising from different viewpoints, technical languages, digital capabilities, etc., and the bridges represent the effectiveness of working practices that reduce these losses. Rather than focusing individually on the multiple inhibitors to communication, this conceptual value chain represents the aggregate effect of communication inhibitors between multiple pairs of actors in a multiactor chain, ending with the final user of the information. This is, of course, a grossly over-simplified representation of the warning production and delivery chain, which in reality is more like a web of multiple users and multiple information sources. However, it served the purposes of the project, by providing a mapping to connect the disparate disciplines and areas of research, as well as highlighting aspects of connectedness that needed to be brought into the project.

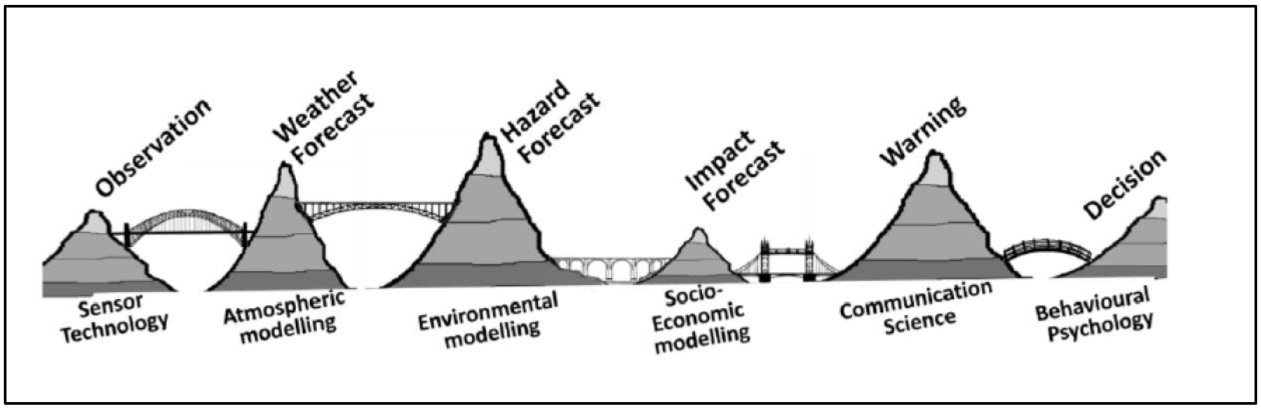

Figure 12: Conceptual Value Chain for a Weather-Related Hazard Warning

Figure 3 from Golding et al. (2019).[38]

Having adapted the value chain concept, the objectives of the project have evolved toward optimizing the value of a warning chain as a connected system, rather than continuing to pursue specific disciplinary challenges. This has manifested itself in three cross-cutting activities of the project that are ongoing.

The first activity is to draw together the disciplinary good practices already identified into a textbook on the end-to-end warning chain. The implications of the conceptual value chain in this activity have led us to focus on the bridges connecting the actors and so as to make partnership

[38] Caption from Figure 3 in Golding et al. "The peaks of expertise, valleys of death and bridges of communication between them, in a conceptual value chain for a weather-related hazard warning. Each peak adds value to the process, but value is lost in each valley and the value of warning lead time is lost at every stage of the process."

the unifying theme of the book. A corollary to this is that every bridge must enable effective information flow in both directions if the end-to-end chain is to be effective. Each of the "valleys of death" presents a different set of drivers that inhibits effective communication, and the benefits of partnership working contribute differently to the end value of the warning, but the underlying principles of building a partnership remain the same.

The second activity addresses a specific research methodology that may have application across the whole warning chain. Citizen science is an approach to data gathering and analysis that complements the centralized modelling studies at the heart of weather prediction. Along with the use of artificial intelligence tools, it offers potential ways to create and communicate information about hazards, their impacts, and the ways people respond to forecasts and warnings.

The third activity aims directly at the end-to-end value problem. Current attempts to understand the relationship between the performance of specific parts of the chain and the eventual value of the warning are inhibited by a lack of data on overall performance of the end-to-end warning chain. Our aim is to bring together weather and hazard forecast verification data, post-event warning assessments, and disaster impact studies to create an interrogable database. Ultimately, we aim for a capability that can identify the sensitivity of warning value to changes in any part of the warning chain, and that can be used to attribute value. Such a capability would form the basis for investment to optimize warnings.

In summary, the use of the HIWeather value chain has created a conceptual simplification of the highly complex set of information flows and inhibitors typically present in a warning system. It highlights the connectedness of the expert actors in the chain, the shared responsibility for the end value and the critical role of communication at every stage. Use of the value chain has enabled the identification and initiation of key areas of interdisciplinary research that will contribute to better warning systems in the future. These three elements: multiple expert actors; shared contribution to end value; and loss of information between actors; are common to many situations where use of a value chain may help to organize and simplify the problem.

6.7 A Public-Private-Academic Partnership to Advance Solar Power Forecasting[39]

In 2012, the U.S. Department of Energy (DOE) awarded $4.1 million to NCAR to lead a collaborative project to design, develop, build, deploy, test, assess, and value new methods to forecast solar power output (see Haupt et al. 2016[40]). The private-public-academic partnership assembled by NCAR included three other national laboratories, six universities, and 14 private-sector partners, including forecasting companies, utilities, and grid-balancing authorities. The output of solar arrays depends critically on the cloud and aerosol distribution, which changes dynamically. Some of these changes can be readily forecast while others are more challenging. As solar power becomes more widely deployed, the variability of its output can make it difficult

[39] Case study provided by Sue Ellen Haupt, Research Application Laboratory, NCAR, Boulder, CO.
[40] https://opensky.ucar.edu/islandora/object/technotes%3A539.

for utilities and balancing authorities to blend it into the grid to meet their electricity demand. When expected solar power is not available, reserve units must provide power. Confidence in improved forecasts can directly reduce operating costs by only allocating nonrenewable units when solar power is not fully available. Using the maximum amount of available clean solar energy has the added benefit of reducing emissions of CO_2 and other pollutants.

Once the project was awarded, the first challenge was to bring the collaborators together to develop a shared vision and detailed project plan that would drive the research toward improving the forecast of solar power output. At a team workshop held in March 2013, the value chain approach was presented as a tool for visioning how to develop a system to generate value. A first step in filling in a value chain was understanding the decision process of the end users, in this case the utilities and balancing authorities that decide when to use the solar power versus when to rely on alternative sources of energy to assure that electric load is met. Because solar power is less expensive to operate once installed, it is economically preferred to fossil fuels. The research scientists needed to understand the objectives, resources, and constraints that the decision-makers face on a daily basis; that is, to fully understand the right side of the value chain in order to design a system to optimize value added through forecasting. To that end, the workshop began with a panel of end users discussing their decision process and the impact that those decisions, and error in the decisions, had on operations. The meteorologists then explained the physics of the processes that cause the clouds and aerosols to vary spatially and temporally (the left side of the value chain) and the difficulty in forecasting them. Understanding these two extremes of the chain (the boundary conditions) set the stage for a mental modeling exercise on how to get from the left side (weather happens) to the right side where value is added. The participants were invited to first build an individual mental model of how to progress from left to right along the chain, then to explain their model to a small group of colleagues with differing expertise. The small groups were then challenged to integrate the work of the individuals to build a more comprehensive model that incorporated multiple points of view. Each small group presented its model to the full group to consider before the full team brainstormed on what a final project-specific value chain would look like. This hierarchical approach to mental modeling was quite effective at building a collaborative team that could understand the importance of the work of each of the subteams to produce a forecasting system capable of providing value.

The resulting solar forecasting value chain is depicted in Figure 13. The decision-maker on the right wishes to optimize the outcomes of day-ahead unit allocation and real-time operational decisions by running the reserve units more effectively. The first step in forecasting at the left is observing the clouds and aerosols at the solar array using both remote (satellite) and in situ instruments (such as pyranometers and sky imagers). Those observations feed into building and running the models that comprise the next step, with various models being tested for forecasting at different time ranges to match the decision points of the end users—AI methods for the very short range and tailored numerical weather prediction (NWP) models for the longer ranges. The models are blended using a software-engineered system to provide point and area forecasts of the solar irradiance. But the end user requires that solar irradiance be translated into information that they can use; that is, power. That conversion was accomplished using another AI algorithm plus the uncertainty is quantified to provide added decision-support information. This information is then perceived by the user in terms of projected power production, which is compared to actual power production, leading to more optimal load balancing, both on the day-ahead and real-time basis.

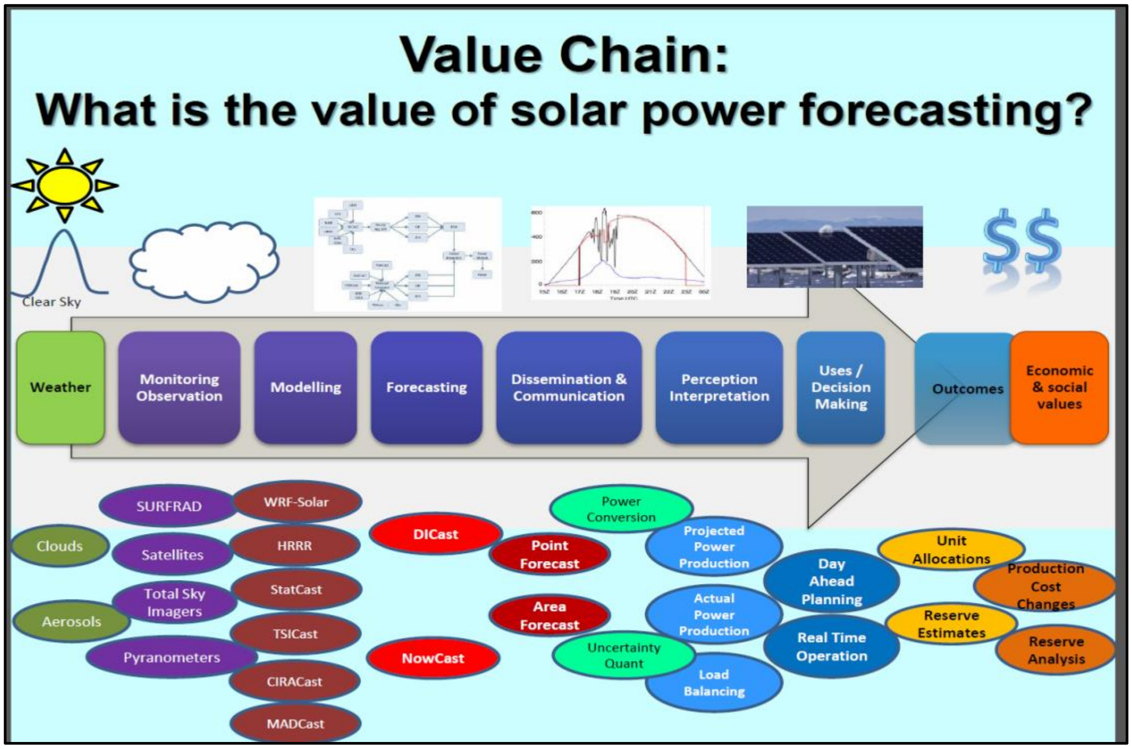

Figure 13: Solar Power Forecasting Value Chain

(Source: Haupt et al. 2018)

Working along this value chain better enabled project assessment and valuation. By defining steps in adding value, the team could design appropriate metrics and valuation methodologies. Toward the end of the project, the project economist collaborated with a utility partner to quantify the value of the improved forecast. For that utility's service area, the forecast improved over the course of the project by about 50% over a baseline of simply using publicly available NWP model output. Using production cost modeling, Xcel Energy was able to compute the value of the reduction in forecast error at $819,000 for a year 2024 scenario. The project economist then applied econometric tools to project those findings to an aggregate U.S. national basis, computing an estimated savings in production costs of $455 million over a 26-year period if the improved forecast were available to all authorities balancing electric systems that include solar plants (Haupt et al. 2016).

6.8 GOES-R Socio-Economic Benefits Study[41]

NOAA's Geostationary Operational Environmental Satellites (GOES), known as the GOES-R Series, is the United States' fleet of advanced geostationary weather satellites circling Earth in geosynchronous orbit. GOES satellites are designated with a letter prior to launch and renamed with a number once they reach geostationary orbit.[42] The GOES-R Series is a four-satellite program including GOES-R, GOES-S, GOES-T, and GOES-U. GOES-R has an impressive array of advanced-technology instruments including the Advanced Baseline Imager (ABI), Geostationary Lightning Mapper (GLM), and a suite of space environment sensors.

Commissioned by the NASA/NOAA GOES-R Program Office in 2020, a team consisting of an engineer and a meteorologist from The Aerospace Corporation and an economist undertook a study to monetize the socioeconomic improvements of the GOES-R Series System over the previous GOES N-O-P Series System. The team recently completed Phase 1 (of 2) to demonstrate and make credible the methodologies needed to perform such a valuation to the public using several NWS hurricane products as a Pathfinder.

Building on prior value chain work and on the NOAA September 2017 Fleet Societal Benefit Study,[43] as a model, the GOES-R study team tailored a generalized weather value chain into a value chain specific to hurricane information from GOES-R data sources.

A draft model of the value chain was used in discussions with NWS forecasters, NCAR researchers, and NOAA experts and researchers to help guide discussions and to develop a protocol for eliciting information from NWS forecasters on the portion of hurricane forecast improvements attributable to GOES-R. The value chain model as shown in Figure 14 was refined and finalized based on feedback from forecasters from NWS Weather Forecast Offices (WFOs) as part of an expert elicitation. The value chain model was used in this project to

- characterize the chain or process in general from the GOES-R observing system to end users and decision-makers and ultimately to the monetary value,
- help characterize the value chain beyond the public benefits that result from GOES-R-based data to other potential benefits areas,
- indicate the importance of appropriately evaluating difficult-to-assess elements in the valuation exercise including
    - the percent contribution of any observing system to an improvement in any particular forecast product or service, and
    - the actual monetary value of an improvement in any particular forecast product or service.

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[41] The initial draft for this case study provided by Michael "Jammer" Jamilkowski from The Aerospace Corporation (see Lubar et al. 2021).

[42] See https://www.goes-r.gov/mission/mission.html.

[43] See https://www.omao.noaa.gov/find/media/documents/noaa-fleet-societal-benefit-study. See Case Study 6.5 NOAA Fleet Societal Benefit Study.

As noted in the study, the weather information value chain "is a conceptual model of the creation, communication, use, and value of hydrometeorological information used in the current analysis to articulate the process from GOES-R observations through to end-user benefits. This model is used to frame and discuss value creation across project participants to ensure consistency and enhance the validity and reliability of economic benefit estimation" (Lubar et al. 2021; ES-1).

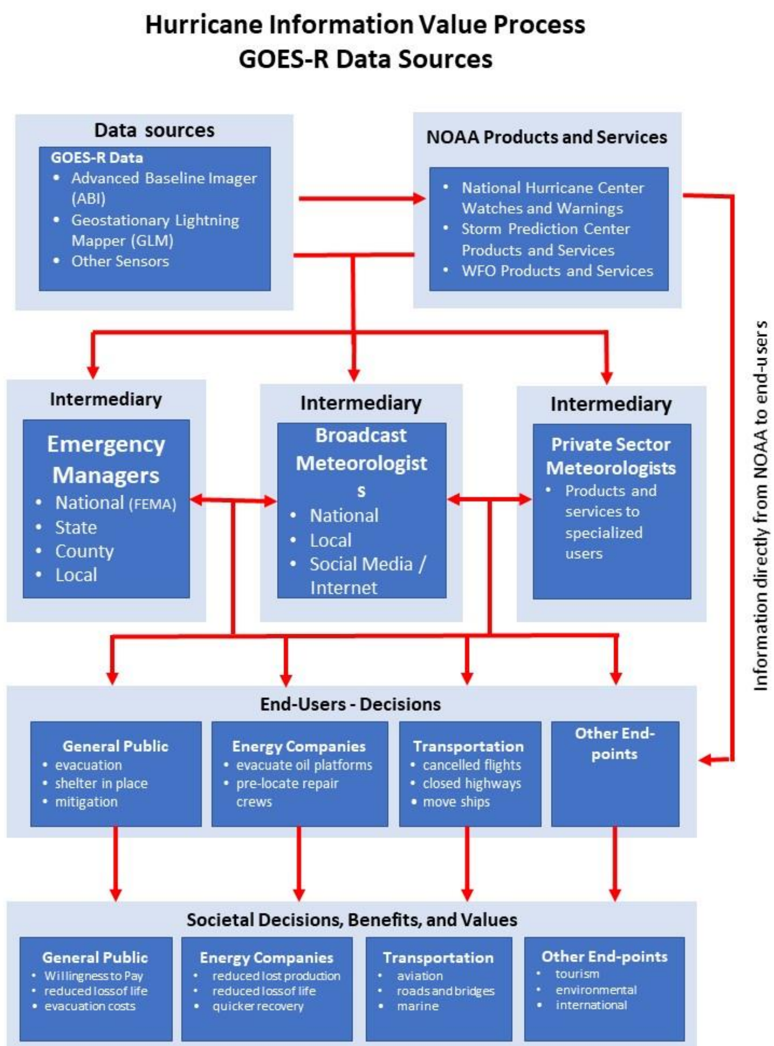

Figure 14: GOES-R Hurricane Information Value Chain

Based on an expert elicitation of weather forecasters, the researchers derived an estimate of the percentage of GOES-R contributions to specific hurricane products. The researchers then used an average of estimates from three existing economic studies to derive a baseline estimate of per household willingness-to-pay (WTP) value for improved hurricane forecast products. This average was multiplied by the percent attributable to GOES-R derived from the WFO interview protocol to derive a WTP for improved forecasts attributable to GOES-R. Using this per household GOES-R attributable WTP an aggregate Present value benefits was then derived, taking into account 1) coastal and inland counties population, 2) number of households, 3) rate of coastal and inland population increases, 4) rate of increase of per capita GDP, 5) real prices, 6) real rate of discount, and 7) a GOES-R mission lifetime. As a baseline estimate, over its lifetime, GOES-R will generate $9.27 billion in benefits from improved hurricane forecasting to the U.S. hurricane-prone public (with a 90% confidence interval of $5.39 to $13.14 billion related to uncertainty in attribution of benefits to GOES-R from the interview protocol results).

7 Ideas for Developing and Enhancing the Value Chain Approach

During the development of the current white paper, considerable discussion and correspondence among the AMS Policy Program Valuation Project participants, authors, and case study contributors raised questions and ideas to build on and enhance the value chain approach. We list several of these areas as focal points for future work.

1. Three areas that could assist in the future use of the value chain concept include
    - identify and describe social science research methods for eliciting, characterizing, populating and measuring value chains;
    - building on Figure 3, identify and describe economic theories and robust methods for undertaking benefit studies; and
    - compile a glossary of relevant terms and concepts, building on existing glossaries such as those compiled in WMO (2015), Socioeconomic Benefits Tiger Team (2016), NASA (2013).
2. The WMO HIWeather Project and WMO/WWRP SERA Working Group are beginning a value chain effort that extends many of the concepts discussed in this white paper and proposes to undertake case studies implementing value chain approaches. They also are developing a bibliography of value chain studies. The white paper will be provided to this group to incorporate and adapt into their work. The AMS Policy Program Valuation Project would benefit from continued interaction with these WMO efforts.
3. There are many efforts underway in the weather community to integrate artificial intelligence (AI) approaches in weather forecast systems. There are also efforts underway to develop agent-based models (ABM) of weather forecasting and societal response systems. As these efforts develop, it seems worthwhile to consider the relationship between these and the value chain concept as well as economic analysis of value chains incorporating AI or ABM methods.
4. There are a multitude of “concepts” relevant to the communication, use, and value of environmental information, any one of which constitutes significant theoretical and applied research efforts. It would be useful to consider these topics and their relationship to characterizing and improving the ESOSS information value process. Some of these “concepts” include
    - Trust

- Communication
- Experience
- Complexity
- Vulnerability[44]
- Information
- Information Quality

5. In our discussions we identified several of the "actors" in the information value process. Each of these could be considered in greater depth and efforts undertaken to better characterize their contributions to the information process. Future work could elicit their perspectives on the information process as well as potentially use the ***VOICE*** template to populate value chain processes from their perspectives as participants and stakeholders. This could include
   - Forecasters
   - Researchers
   - Emergency Management
   - Broadcast Meteorology
   - Private-Sector Meteorology
   - Private-Sector End Users
   - Public End Users
6. Economics as a study of value is built on specific ethical and philosophical perspectives.[45] While economics is a social science and the value chain is primarily a conceptual model of an information process, there are important underlying philosophical issues and questions that have received very little attention in the hydro-meteorological community. At the least there are potentially important ethical questions about the equitable distribution of information and differential impacts of weather on different segments of society. We feel there is more attention to ethical/equity issues in the climate literature (e.g., Anthoff et al. 2009; Islam and Winkel 2017). We also feel it could be useful to bring in philosophical perspectives on how different people may conceive of nature and science and knowledge (e.g., metaphysical and epistemological perspectives) as this may be reflected in how they interpret and respond to information.

8 Discussion and Recommendations

Based on our overview of the economics of weather information and prior work we recommend several actions to improve the integration of socioeconomic analysis to meet the needs of the hydro-met community and, by extension, the welfare of society. We emphasize that these "recommendations" need significant discussion and further integration with the weather

[44] See Appendix B: Preliminary Thoughts on Some Value Chain Related Concepts for a preliminary discussion of some concepts related to "vulnerability" and "information quality."

[45] Adam Smith, the "father of economics" and the author of *The Wealth of Nations* (1776), was first and foremost a philosopher (his book *The Theory of Moral Sentiments* preceded *The Wealth of Nations* by 17 years).

information value chain. They have been retained at this time as “plausible pathways” to start some discussion on what the contents of the recommendations could be from this effort.

First, we recommend that all major investments or changes in hydro-met services should be subject to economics analysis. Many countries require some sort of benefit-cost analysis for major investments of public funds but often do not actually carry these out or use them in the decision-making policy process. The ***process*** of undertaking a socioeconomic analysis of major investments in and of itself helps inform project advocates, actual and potential end users, and policy makers of the broader implications of a project including potential improvements or changes in products and services, costs to achieve those, and possible societal outcomes and their benefits (or costs). We believe that the value chain approach and ***VOICE*** template provide a useful framework to organize such an undertaking.

Second, in relation to our first recommendation above, we recommend a critical review of the use of economics in national hydro-met service policy making. Such a review would identify where the use of economics has been helpful or where it could have been helpful (and where it has not been helpful) in policy making. A clear understanding of the use of socioeconomic benefits studies in policy making will lend credence to the call for more and better studies to support policy decision-making. Some of the other tasks within the current AMS Policy Program project may serve this need or begin to lay the groundwork for such a review.

Third, there is a critical need for more and better primary studies on the value of hydro-met information across a broad range of hydro-met phenomena, information products and services, stakeholders, and end users. Little of the existing literature is of adequate quality or documented sufficiently to be used in benefits transfer applications and therefore new primary studies will support future broader policy analysis using benefits transfer (which is less expensive and much quicker than primary analysis).

Fourth, with the need for primary studies in mind, we also advocate that there be a comprehensive critical review and consolidation of the existing economic literature on hydro-met services. Such a review would help identify needs and priorities for future primary studies and provide support, where literature is available, for current policy questions. Such a review should be well structured and publicly available as a web-based database so future researchers can build on this knowledge. We note that there is a GEOValue initiative led by USGS that could serve this purpose at least partially and a repository of valuation studies for Earth observations is being developed. The Environmental Valuation Reference Inventory (EVRI) might also serve as a useful template.[46]

Fifth, we recommend that those funding new studies require them to be well designed and implemented and well documented based on criteria recommended for the evaluation of studies for use in benefits transfer (Rosenberger and Loomis 2003; Johnston et al. 2015). Meeting such criteria would ensure quality and transparency of the study and enhance the value of studies as resources in future benefits transfer applications. This would also reduce the costs of

[46] https://www.evri.ca/en/content/about-evri.

socioeconomic benefit studies in the long run by preventing future studies from "reinventing the wheel" with each new study.

Sixth, we recommend researchers begin to evaluate the potential contributions of behavioral economics more thoroughly to understanding and improving weather information processes. This recommendation can be extended to recommend incorporating studies from all the different social sciences in understanding the information value process as each brings multiple different perspectives, theories, and methods that can enhance our understanding of the inherently complex information process.

Seventh, we recommend discussing the input of approaches and concepts from philosophy and their relationship to the weather information value chain and the provision of hydro-met information in general. For instance, there are important ethical issues in the creation and distribution of hydro-met information including potential social biases and distributional issues. There are also likely interesting philosophical considerations of the different approaches and capacities of the physical sciences, social sciences, and humanities that may help frame discussions of the information process.

And finally, we recommend that future studies of the value of hydro-met information attempt to fully characterize the weather information value chain as a fundamental part of such benefits studies. Further developing and using the concept of the weather information value chain and the ***VOICE*** template proposed in Table 1 will help researchers fully map out the relationships between the creation and value of hydro-met information to enhance the validity and reliability of their economic analysis.

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Appendix A: The Concept of Conceptual Models [47]

Taking the value chain as a "conceptual mode" it is worth considering what conceptual models are and any research on how they work and how they have and can be used. The abstract from Thalheim (2011) states:

> Conceptual modelling is a widely applied practice and has led to a large body of knowledge on constructs that might be used for modelling and on methods that might be useful for modelling. It is commonly accepted that database application development is based on conceptual modelling. It is, however, surprising that only very few publications have been published on a theory of conceptual modelling. Modelling is typically supported by languages that are well-founded and easy to apply for the description of the application domain, the requirements and the system solution. It is thus based on a theory of modelling constructs. Modelling is ruled by its purpose, e.g., construction of a system, simulation of real-world situations, theory construction, explanation of phenomena, or documentation of an existing system. Modelling is also an engineering activity with engineering steps and engineering results. It is thus engineering.

From this abstract alone we could identify several purposes for modeling including

- construction of a system
- simulation of real-world situations
- theory construction
- explanation of phenomena
- documentation of an existing system
- an engineering activity with engineering steps and engineering results

From the various discussions and examples of value chains in this paper it seems likely that in different applications all of these "purposes" have been the motivations of value chains in the hydro-meteorological community.

A quick search of the literature found several resources on the use and analysis of conceptual models in research (Thalheim 2011; vom Brocke and Buddendick 2006; Van der Waldt 2020), in education (Mayer 1989), and in ecology and environmental sciences (Fortuin et al. 2011; Hersperger et al. 2010; Heemskerk et al. 2003).

There is also literature on conceptual models of information including Järvelin and Wilson (2003) and Verelst (2005). There is likely a considerably richer literature on conceptual models and information that could help in the current discussion. In addition, there is a literature on conceptual models from a philosophical perspective that likely relates to our discussion

[47] We have not fully reviewed the references in this section but assembled these based on preliminary literature searches mainly on the term "conceptual models." This therefore deserves further evaluation and development as a concept as well as determining the relevance of the cited literature.

elsewhere in this white paper on the integration of philosophy with the hydro-meteorological community (Guarino et al. 2019; Guizzardi 2005).

There are also several examples where conceptual models have been used in weather, water, and climate sciences as well as broader environmental and natural resource sciences (see Schultz and Doswell 1999; Panteli and Mancarella 2015; Wedawatta and Ingirige 2016; Perch-Nielsen 2004; Browning 1986; Doswell and Burgess 1993; Marzetta 2017; Patterson et al. 2010; Warren 2005; Edwards 2011) Several of these references include graphical representations of weather, water, or climate systems including observing, modeling, and forecasting that could represent the left side of value chains as considered in this paper.

Appendix B: Preliminary Thoughts on Some Value Chain Related Concepts

With respect to further developing the concepts mentioned in Section 7 on "Ideas for Developing and Enhancing the Value Chain Approach" we note some preliminary concepts as a suggestion to the type of issues related to these topics.

With respect to the concept of vulnerability, the pressure and release (PAR) model of vulnerability as shown in Figure 15 highlights a broad range of social, economic, cultural, and natural factors affecting how individuals, families, and communities can "create" vulnerability and how this thus affects how they respond to risks.

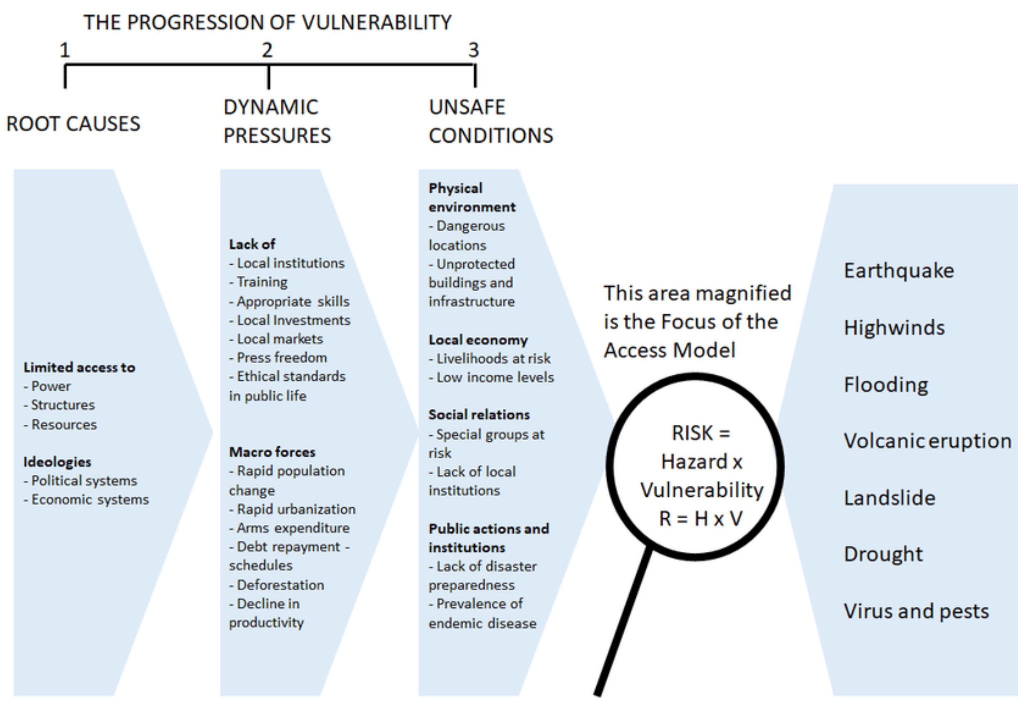

Figure 15: Pressure and Release Model

From Blaikie et al. (1994)

From an economic perspective value is usually assessed taking a given social, cultural, and institutional framework and evaluating how changes in information alter socioeconomic outcomes. Equally valid would be taking a given information set and seeing how changes in the social, cultural, and institutional framework may improve socioeconomic outcomes.

There are certainly several different, and perhaps conflicting, models of vulnerability and risk that could be considered and may even lead to different approaches to creation and communication of ESOSS to achieve desired socioeconomic outcomes. Having an understanding of how decisions are made in the face of risk and the "construct" of risk is an integral part of the weather information value chain and in part determines or defines the value of such information.

In a similar manner, as shown in Figure 16, Stvilia et al. (2007) present a "framework for information quality assessment that is considerably broader and more nuanced than information quality measures generally used in the hydro-met literature.

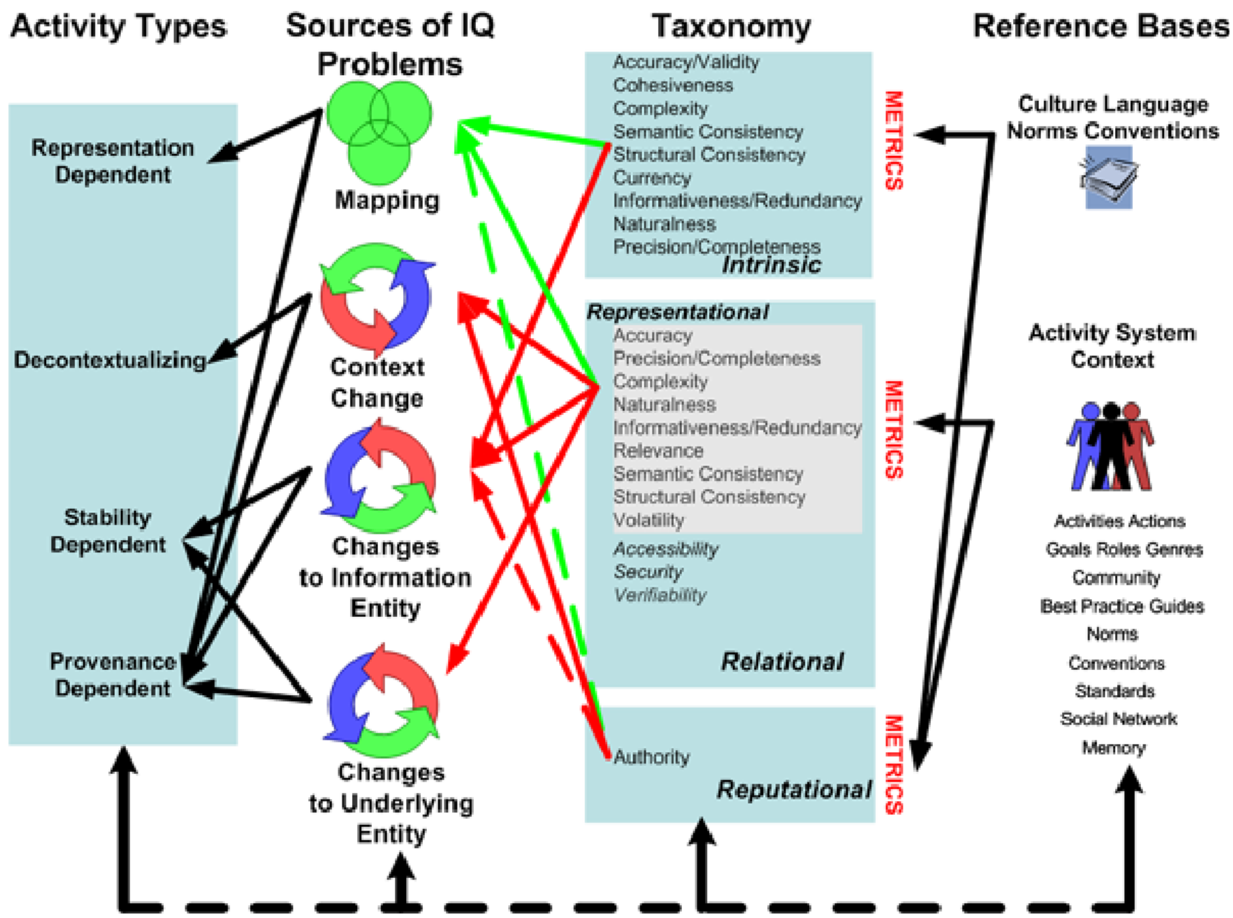

Figure 16: Information Quality Assessment

(Figure 3: Conceptual model of IQ measurement from Stvilia et al. 2007)

It seems likely useful to map methods for measuring the quality of forecast information (as well as climate and hydrological information) such as verification methods to the framework proposed by Stvilia et al. The types of quality measured used in the meteorological community seem very limited compared to the broad and comprehensive Stvilia et al. framework. Potentially expanding concepts of information quality in the hydro-met sciences may identify information characteristics important to decision-making and societal values that shift the focus from "scientifically accurate" to societally relevant.

From an initial consideration of the Stivila et al. model we also note that the "Activity System Context" noted on the right side of Figure 16 is related to the framework presented in the Blaikie et al. pressure and release model of vulnerability shown in Figure 15. Understanding and connecting in-depth conceptual, theoretical, and applied models from many different perspectives may greatly enhance the understanding of the weather information value chain as well as identify opportunities for improving societal outcomes.

For each of the concepts noted above as well as many more there are likely relevant theoretical and applied studies from across the physical and social sciences and humanities that can help inform our understanding of the information/value process both to better characterize and evaluate it and to improve it.

Appendix C: Developing a Framework for Value Chain Explication

The following is a very preliminary, brief, and incomplete outline of issues and questions to address is characterizing a value chain. We present this as a "strawman" for others to adapt, revise, or build upon (or reject and start from scratch) with the idea that while there is no one correct way to "populate" a value chain, it would be useful for some work be focused on developing and evaluating ways to do so.[48]

<u>Characterizing the Objective and Participants in the Value Chain Exercise</u>

1. What is the objective of the value chain?
    a. Develop research team coordination
    b. Undertake economic analysis
    c. Assess information gaps or opportunities
    d. Undertake other policy analysis
    e. Show benefits to potential stakeholder
2. Who can best help identify/characterize the value chain at each step?
3. At each step can we identify
    a. For each stakeholder (related to ***VOICE*** Approach)
        i. Their objectives
        ii. Their resources
        iii. Their constraints
        iv. How they use the information input and change it to an information output
4. At each step between actors can we identify
    a. For link between each stakeholder
        i. What the information is
        ii. How to measure or characterize information "quality"/content at each step (e.g., see Stvilia et al. 2007)
        iii. How it is "transmitted" (Channels?)
5. What is the theoretical basis for this analysis?
    a. Economic theory
    b. Behavioral economics
    c. Communication theories
    d. Grounded theory
    e. Risk theory
    f. Decision theory
    g. Etc. …

[48] It is our understanding that the HiWeather Value Chain working group is developing a more comprehensive approach and testing with specific applications. We suggest the reader refer to that effort as well.

Characterizing the Value Chain

1. What is the observation/data/forecast system to be evaluated?
    a. What instrument and what data are involved?
    b. What existing literature identifies an explains this?
    c. Are there processes for measuring this (e.g., NOSIA, NWS verification …)?
2. What model or information system uses this input?
    a. Numerical prediction models for weather forecasting?
    b. Nowcasting?
    c. Climate models?
    d. Hydrological models for flooding?
3. What is the NWS (or other) product or service?
    a. Flash flood warnings
    b. Volcanic ash advisory?
4. How has this been improved/changed compared to baseline (e.g., GOES N-O-P vs GOES-R)?
    a. What is the counterfactual?
    b. What is the new quality measure?
    c. What is the timeline of these improvements?
    d. Are there other improvements not attributable to the subject (e.g., improved communication, modeling, or theory as opposed to observations)?
5. Who uses the product?
    a. Who are the intermediaries?
        i. Emergency managers
        ii. Broadcast meteorologists
        iii. Private-sector meteorologists
        iv. Government agencies
    b. Who is the end stakeholder?
        i. Specific economic sector
        ii. Members of the public
        iii. Local, state, national, international?
6. How is it communicated? (possibly at each step in the process)
    a. Data provided
    b. Forecast, warnings
7. Decision-making/use of the information by end users
    a. What decisions are made with the product?
    b. How have/could decisions be improved with the improved product?
    c. How has this/would this change socioeconomic outcomes?
    d. How do we measure this improvement qualitatively?
    e. How do we measure this improvement quantitatively?
8. Monetization
    a. How can this be monetized?
    b. Are there existing studies to monetize this?

        i. Can benefits transfer be applied to this
    c. Are there existing models to monetize this?
        i. Could production cost modeling be used to monetize improvements in energy production?
        ii. Are there crop models that could be applied to monetize this in agriculture?
        iii. Are there transportation models that could be run to monetize reductions in traffic disruptions?
    d. Are there existing metrics to monetize this?
        i. VSL
        ii. Value of time lost
        iii. Reduction in air traffic delays
    e. How is this benefit aggregated across space/time/users?
        i. What is the lifetime of the improvement?
        ii. What is the population affected that this is aggregate to?
        iii. What other parameters change over time to affect aggregation?
        iv. Are costs to be evaluated as part of the aggregation (i.e., BCA versus benefits only)?
        v. What discount rate is applicable?
        vi. What sensitivity analysis is needed?
        vii. What internal/external review is best for assessing the analysis?

9. What future research could improve the value chain characterization?
10. What literature is relevant to this analysis?
11. How to communicate this analysis [see WMO (2015) Chapter 9, "Socioeconomic Benefit Study Step 10: Communicating the Results of Socioeconomic Benefit Studies"]
    a. Report
    b. Peer review article
    c. Webinar
    d. Video recording
    e. White paper
    f. Conference presentation

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