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THE VALUE OF CLIMATE SERVICES ACROSS ECONOMIC AND PUBLIC SECTORS: A REVIEW OF RELEVANT LITERATURE

June 10, 2013

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THE VALUE OF CLIMATE SERVICES ACROSS ECONOMIC AND PUBLIC SECTORS: A REVIEW OF RELEVANT LITERATURE

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Prepared for:

United States Agency for International Development
Climate Change Resilient Development Project
Climate Services Partnership, Economic Valuation Working Group

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EXHIBITS

ACRONYMS

CCRD	Climate Change Resilient Development
CDD	Canadian dollars
CSP	Climate Services Partnership
CV	Contingent valuation
EGU	European Geosciences Union
ENSO	El Niño-Southern Oscillation
GDP	Gross domestic product
GFCS	Global Framework for Climate Services
GOES	Geostationary operational environmental satellites
HAB	Harmful algal blooms
ICCS	International Conference on Climate Services
NOAA	National Oceanic and Atmospheric Administration
PDO	Pacific Decadal Oscillation
SOI	Southern Oscillation Index
SSTA	Sea surface temperature anomaly
TAFs	Terminal aerodrome forecasts
USAID	U.S. Agency for International Development
USD	U.S. dollars
WMO	Word Meteorological Organization
WTP	Willingness to pay

1. INTRODUCTION

Weather services (including current meteorological information and forecasts for hours and days ahead) and basic climate services have been available in most parts of the world for more than half a century. However, it is only over the last few decades that a full suite of climate services (including provision of comprehensive historical observational data, climate system monitoring, monthly, seasonal and inter-annual climate predictions, and long-term climate change projections) have become available in many countries.

Climate services have been developed and implemented rather quickly for public and private sector users in developed countries, but developing countries have been slower to use these tools for several reasons, including: (1) a lack of awareness of the opportunities and benefits of climate services, (2) an unreliable record of managing local weather and climate data, and (3) limited resources for building and sustaining capacity to provide climate services.

In 2009, the World Climate Conference-3, attended by more than 2,500 participants from more than 150 countries, including 13 Heads of State and Government and 81 Ministers, decided to establish a Global Framework for Climate Services (GFCS) to strengthen the production, availability, delivery, and application of science-based climate prediction and services.

The Climate Services Partnership (CSP) was formed during the International Conference on Climate Services (ICCS) in October 2011 with the goal of improving the provision and development of climate services worldwide. During the ICCS, three working groups were formed to carry out the work program of the CSP. One of these groups, the Economic Valuation of Climate Services Working Group, is collaborating on several activities to demonstrate the benefits of climate services and help providers prioritize opportunities for expanding their use.

KEY TERMS AND CONCEPTS

The Word Meteorological Organization (WMO) defines ***climate forecasts*** as forecasts for a one-month period or longer. ***Weather forecasts*** are typically thought of as forecasts for less than one month.

When predicting climate, ***long-range forecasts*** are generally considered to range from one month to two years while ***climate predictions*** typically include forecasts of more than two years in advance (WMO).

The WMO defines ***climate services*** as the dissemination of climate information to the public or a specific user.

The Climate Services Partnership expands on this definition, stating that ***climate services*** involve the production, translation, transfer, and use of climate knowledge and information in climate-informed decision making and climate-smart policy and planning.

For the purposes of this analysis, climate services involve the dissemination of all types of climate and climate-related information, including information on individual weather conditions or events.

The goals of this working group include:

- Synthesize current work on economic valuation
- Encourage the valuation of climate services by providing users and providers with guidance on appropriate methodologies for valuing their own activities
- Advance the current state of knowledge on climate services valuation

As a first step to meeting these goals, the working group initiated a review of literature related to the use and value of climate services across economic and public sectors. This report summarizes the findings of the literature review and provides a summary of key issues associated with studies conducted to date.

1.1 METHODS

Through the U.S. Agency for International Development (USAID)-funded Climate Change Resilient Development (CCRD) Project, Stratus Consulting was tasked to conduct the bulk of this research. As part of this effort, Stratus Consulting, in coordination with key working group members, reviewed 183 studies related to the use and value of climate services. Based on this review, we identified 139 primary studies that provide quantitative value estimates or are otherwise directly related to the value of climate services (e.g., literature reviews or other qualitative assessments).

During the first phase of this research, the project team identified and reviewed 105 relevant studies, most of which focused on the use and value of climate services within the agricultural sector. The geographic focus of these studies was relatively evenly divided between developed and developing countries. Key findings from the first phase of this research were presented at the European Geosciences Union (EGU) annual conference held in Vienna in April 2012. Following the EGU conference, Stratus Consulting performed a second literature search, focusing on articles conducted within sectors other than agriculture. We also tried to identify as many studies as possible that were conducted in developing countries.

The results of these efforts are summarized below. One caveat to this discussion is that the studies included in this research are primarily peer-reviewed journal articles. The project team had a difficult time locating articles in the grey literature (e.g., unpublished government reports, technical reports, white papers). It is likely that many reports exist in the grey literature, and that they would provide additional (and more recent) insights on the value of climate services in more applied settings.

1.2 ORGANIZATION OF REPORT

The remainder of this report is organized as follows:

- **Section 2** briefly summarizes the importance of increasing knowledge related to the value of climate services.
- **Section 3** provides an overview of the characteristics of the studies reviewed as part of this research.
- **Section 4** describes factors that have been found to affect the value of climate services in different sectors.
- **Section 5** reviews some of the barriers that have been identified in the use of climate services.
- **Section 6** provides a summary of findings, including the limitations associated with studies conducted to date.
- **Section 7** identifies potential next steps for the Economic Valuation of Climate Services Working Group.

2. WHY IS THE VALUE OF CLIMATE SERVICES IMPORTANT?

Studies of the social and economic benefits of climate information and services date back to the 1960s, with much of the early work brought together in a series of WMO conferences (e.g., WMO, 1990, 1994) and publications (e.g., Nicholls,1996), and a widely referenced text on valuation methodologies (Katz and Murphy, 1997). However, there is still relatively little known about the value of climate services for public and private sector users, especially in developing countries. A more complete understanding of the benefits of climate services is important for several reasons, including:

- **Fostering awareness and increasing the use of climate services.** The value of climate services can serve as an important communication tool in increasing the adoption and use of climate services. Valuation studies express benefits in terms that decision-makers can easily understand (e.g., increased revenues, avoided costs, water savings). This can result in an increased likelihood of adoption and use of climate services, thereby increasing total value to a given community or sector.
- **Enhancing the value of and improving climate services**. It is important that climate service providers have a clear understanding of the use and value associated with climate services. Understanding on-the-ground conditions and outcomes will allow providers to modify and tailor climate services in order to further maximize the value obtained from their use. This feedback loop should continue to evolve over time.
- **Pricing and charging for services.** Both the public and private sector provide climate services. Private sector providers charge for their services, and in some cases it may be necessary for the public sector to charge marginal incremental fees for value-added services (e.g., where the public sector provides tailored climate services for use by a small group of specialized users). Thus, it is necessary to establish an economic framework for funding, pricing, and charging for services (Zillman, 2007). Valuing climate services can support this.
- **Justifying implementation and/or obtaining funding for specific programs and services.** In most countries, the competition for scarce public funds is intense. Thus, it is important that National Meteorological Services and other providers of climate services conduct rigorous benefit-cost analyses to ensure that the services implemented generate maximum returns on investments (Zillman, 2007).
- **Helping to form public policy in relation to climate services**. According to the World Meteorological Organization (WMO, 2007), the global costs of weather-, climate- and water-related disasters may exceed 100,000 deaths and $100 billion U.S. dollars (USD) of damage in a single year (worldwide). However, participants taking part in a WMO-sponsored conference on the social and economic benefits of climate services[1] stressed the difficulty of integrating weather and climate services into national development strategies (WMO, 2007). A clear understanding of the value and opportunities associated with climate services can help national governments and organizations guide priorities and better manage the impacts of weather and climate across economic sectors (e.g., through natural disaster mitigation strategies, drought relief, and related policies and programs; Zillman, 2007).

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[1] The International Conference on Secure and Sustainable Living: Social and Economic Benefits of Weather, Climate and Water Services was held in Madrid, Spain in March 2007.

3. STUDY CHARACTERISTICS

This section summarizes the studies reviewed by the project team, including the economic sectors evaluated, the geographic distribution, the level of analysis, and the types of benefits quantified.

3.1 SECTOR ANALYSIS

Most of the studies analyzed examine the benefits of climate services (especially forecasts) within the agricultural sector. These studies have focused mainly on the value of climate forecasts (primarily seasonal) for managing rain-fed cropping systems. However, some studies have examined the value of climate services for irrigated crops (Susnik et al., 2006; Cai et al., 2011), livestock (Luseno et al., 2003; Boone et al., 2004; Sheriff and Osgood, 2008), and other agricultural enterprises (Cyr et al., 2010; Osgood and Shirley, 2010). The level of production evaluated in most of these studies generally represents commercial agriculture; however, the project team reviewed several studies related to subsistence agriculture.

In addition to agriculture, the project team identified and reviewed a number of studies focusing on the value of climate services within the water resource management (e.g., Ritchie et al., 2004; Broad et al., 2007; Liao et al., 2010), energy (e.g., Hertzfeld et al., 2004; Graham et al., 2006; Block, 2011), aviation/transportation (e.g., Stewart et al., 2004; Graham et al., 2006), fisheries (e.g., Orlove et al., 2004; Kaje and Huppert, 2007), and tourism/recreation (e.g., NOAA, 2002; Kaiser and Pulsipher, 2004) sectors. Several studies reviewed also examined the effects of weather and/or the value of climate services across economic sectors, and the resulting impact at the aggregate sector, state, and national levels. Others have assessed the avoided costs associated with the use of forecasts for disaster management and response.

Exhibit 1 provides a summary of the 139 primary studies reviewed for this analysis by economic sector/industry area. Examples of specific applications for climate services within each sector (for the studies evaluated) are also provided.

Exhibit 1. Summary of studies reviewed, by sector/industry

Sector/industry	Studies reviewed[a]	Examples of specific applications
Agriculture	64	• Crop management (e.g., timing of planting/harvest, selection of crops) • Irrigation decisions • Product marketing • Input use (e.g., fertilizer application) • Herd management (e.g., when and how many animals to sell) • Changes in commodity prices • Implications for global trade market
Energy	10	• Planning purchases of gas and electric power • Managing responses in emergency situations • Managing capacity and resources (e.g., grid/distribution management, electricity production/pricing) • Optimizing reservoir/hydropower operations • Commercial/residential consumption decisions
Fisheries	6	• Responding to threat of harmful algal blooms (HAB) • Harvest management
Transportation	5	• Reducing wait times on runways • Fuel purchasing • Accident reduction • Snow preparation/removal • Canal management
Water resources management	7	• Storage/release decisions by reservoir managers • Water pricing/allocation • Adoption of conservation measures
Tourism/ recreation	3	• Marine forecasts/warnings • Event management
Disaster management	3	• Hurricane preparedness • Early warning systems (e.g., heat watch, flooding)
Cross-sector	17	• Weather impacts on national economy • Willingness to pay by consumers for weather information • Multi-sector studies including value of forecasts for transportation, water, construction, energy, fisheries, forestry, and other sectors
Other[b]	30	• Pricing of weather derivatives/other financial products • Pricing of insurance products • Forecasting extreme weather events

a. Total number of studies adds to greater than 139 due to studies that included the evaluation of climate services in more than one sector.
b. Studies in this category are not necessarily relevant to a specific study (e.g., theoretical models of forecast value).

Although fewer studies have explored the value of climate services in sectors other than agriculture, those that have been conducted demonstrate the value of these services in many areas. The water resource management studies reviewed as part of this research, for example, demonstrate the benefits of climate services associated with urban, agricultural, and environmental water use and reservoir management. Ritchie et al. (2004) found that the use of streamflow forecasts would significantly increase the amount of water available for instream flows/environmental purposes in the Murray-Darling River Basin in Australia, while maintaining the amount of water needed by irrigators. Steinemann (2006) examined the use of seasonal precipitation forecasts by water resource managers in Georgia to decide whether to pay farmers to suspend irrigation in forecasted drought years. Economic benefits associated with the use of these forecasts included $100–350 million in mitigated agricultural losses in state-declared drought years and $5–30 million in savings to the state in non-drought years.

In the energy sector, studies have demonstrated the value of short-term and seasonal forecasts (e.g., for temperature, wind speed, stream flow) for fuel purchasing decisions, demand forecasting, and system planning. Temperature forecasts allow managers to more accurately forecast peak loads and optimally schedule electric generating plants to meet demands at a lower cost (Weiher et al., 2005). Hydropower operations benefit from daily, weekly, and seasonal precipitation and streamflow forecasts, which can help to optimize operations. Hamlet et al. (2002) found that the use of streamflow forecasts would increase energy production from major Columbia River hydropower dams by 5.5 million MWh/year, resulting in an average increase in annual revenue of approximately $153 million per year. Block (2011) found that the use of forecasts to manage hydropower operations in Ethiopia produces cumulative decadal benefits ranging from $1 to $6.5 billion, compared to a climatological (no forecast) approach.

In the transportation sector, the use of climate services can result in increased revenues and avoided costs for transportation industries and/or public agencies. Climate services can also reduce delays and improve safety for travelers. The majority of the transportation-related studies reviewed as part of this research examine the value of climate services for road and air transportation. Frei et al. (2012) found that the use of meteorological information by the road transportation sector in Switzerland generates an economic benefit of $56.1 to $60.1 million per year in reduced government spending, and an additional $14.2 to $25.3 million per year in value added.[2] Stewart et al. (2004) found that improved short-term precipitation forecasts can help road supervisors improve their allocation of resources and their efficiency in snow removal activities on the New York Thruway. Weiher et al. (2005) summarized a number of studies that estimate the benefits of weather and climate services for air transportation, which include reductions in accidents (Paull, 2001; NOAA, 2002), fuel costs (Leigh, 1995; Williamson et al., 2002), and flight delays (Rhoda and Weber, 1996; Evans et al., 1999; Alan et al., 2001; Sunderlin and Paull, 2001; NOAA, 2002).

In the commercial fishing industry, short-term (i.e., daily/weekly) forecasts can be important for the safety of fishermen, while long-term (i.e., seasonal) forecasts can enhance fishery management decisions (Weiher et al., 2005). However, the project team found only a few studies that valued climate services for this sector. One of these studies is by Costello et al. (1998), who estimated the value of perfect and imperfect El Niño-Southern Oscillation (ENSO) forecasts for the Coho salmon fishery in the Pacific Northwest. The authors found that perfect ENSO forecasts would result in an annual welfare gain of approximately $1 million in consumer and producer surplus (e.g., profits for producers, consumer surplus for recreational fishing), but that imperfect forecasts would lead to smaller gains. In another study, Jin and Hoagland (2008) estimated the value of harmful algal blooms (HAB) forecasts for the New England near-shore commercial shellfish fishery. The net present value of the HAB predictions over 30 years was found to range from $0.9 to $51.3 million, depending on HAB frequency, accuracy of the predictions, and response to the forecast.

The use of climate services for improved disaster management can help lower the social and economic costs of extreme events, including floods and hurricanes. Few studies, however, have estimated the value

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[2] All values are reported as USD. For studies that reported foreign currencies, values were adjusted to USD using the value of that currency on January 1 in the study's year of publication. Historical exchange rates were accessed from www.xe.com. If local currency was expressed in a particular year that was different from the study's publication date, those figures were converted to USD in the original year.

of climate services for this purpose. Hallegatte (2012) estimated that in Europe, hydro-meteorological information and early warning systems save several hundreds of lives per year, and avoid between $596 million and $3.5 billion of disaster asset losses per year. The authors estimated that in developing countries, the potential benefits of upgrading hydro-meteorological information production and early warning capacity would range from $300 million to $2 billion in avoided asset losses, and an average of 23,000 saved lives per year. Two studies included in this review estimated the value of improved hurricane forecasts: Regnier and Harr (2006) estimated avoided hurricane preparation costs and asset losses for Galveston, Texas and Norfolk, Virginia, while Considine et al. (2004), examined benefits to the energy sector due to reduced foregone oil drilling time in the Gulf of Mexico.

A few studies have examined the value of climate services in the tourism, sports, and leisure sector, finding the potential for significant economic benefits for this sector. Costello et al. (1998), Kaiser and Pulsipher (2004), and Wieand (2008) estimated the value of forecast information (including improved ocean observation systems and ENSO forecasts) for recreational fishing. The National Oceanic and Atmospheric Administration (NOAA) (2002) estimated values associated with improvements to its geostationary operational environmental satellites (GOES) system for recreational boating, golfing, and ocean fishing (the GOES satellites allows for better monitoring of storm development and movement). Anderson-Berry et al. (2004) assessed the benefits of a forecast demonstration project that provided enhanced weather information to a variety of users, including the 2000 Sydney Olympic Organizing Committee. Although no value was estimated, Olympic committee interviewees said that the forecasts helped them make decisions on whether to conduct events.

Finally, the project team reviewed a number of studies that explored the use of forecasts and climate information in predicting high incidences/outbreaks of various diseases, especially vector-borne diseases, such as malaria and dengue fever. These studies were conducted primarily in developing countries to explore the feasibility and usefulness of early warning systems. These studies found correlations between specific diseases and various climate variables, and resulted in the development of models for prediction of outbreaks. We did not find any studies that attempted to value the use of these models.

3.1.1 GEOGRAPHIC DISTRIBUTION

Although we specifically searched for studies conducted in developing countries, the majority of the studies we analyzed examined the value of climate services within the United States and/or Australia. Those that examined the value of climate services in developing countries were generally either conducted in Africa or South America, and included only a handful of countries (e.g., Ethiopia, Kenya, Burkina Faso, Mozambique, Malawi, South Africa, Argentina, Peru, Brazil, Panama, and Chile). The project team also reviewed two studies that focused on cities and regions in Asia.

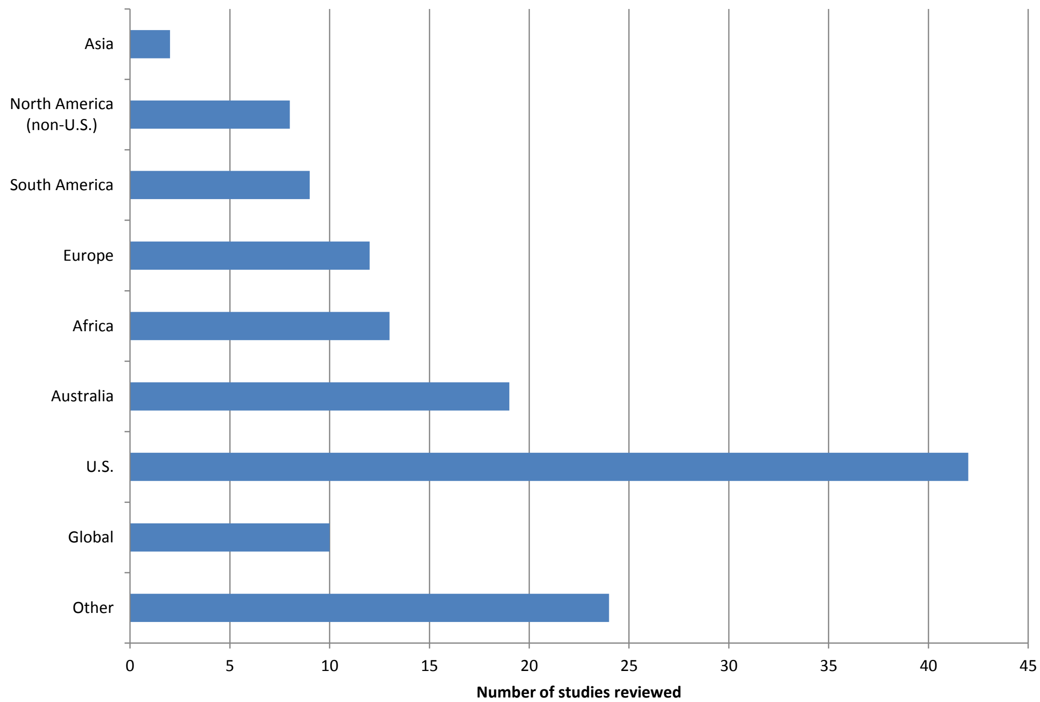
Exhibit 2 shows the distribution of studies reviewed by the project team by continent/geographic area. Exhibit 3 shows the number of studies reviewed in developed vs. developing countries, by sector. As shown, studies of the value of climate services in the agricultural sector are more equally distributed with regard to their focus on developed and developing countries, compared to studies in other sectors.

3.1.2 LEVEL OF ANALYSIS

In the agricultural sector, the most common type of assessment examines the value of seasonal climate forecasts at the crop/enterprise level, where value is obtained as a function of changes in management for an individual crop (or group of crops). Other studies (e.g., Messina et al., 1999; Jones et al., 2000, Letson et al., 2009) have estimated the value of climate forecasts at the farm level, allowing land allocation to vary between crop types.

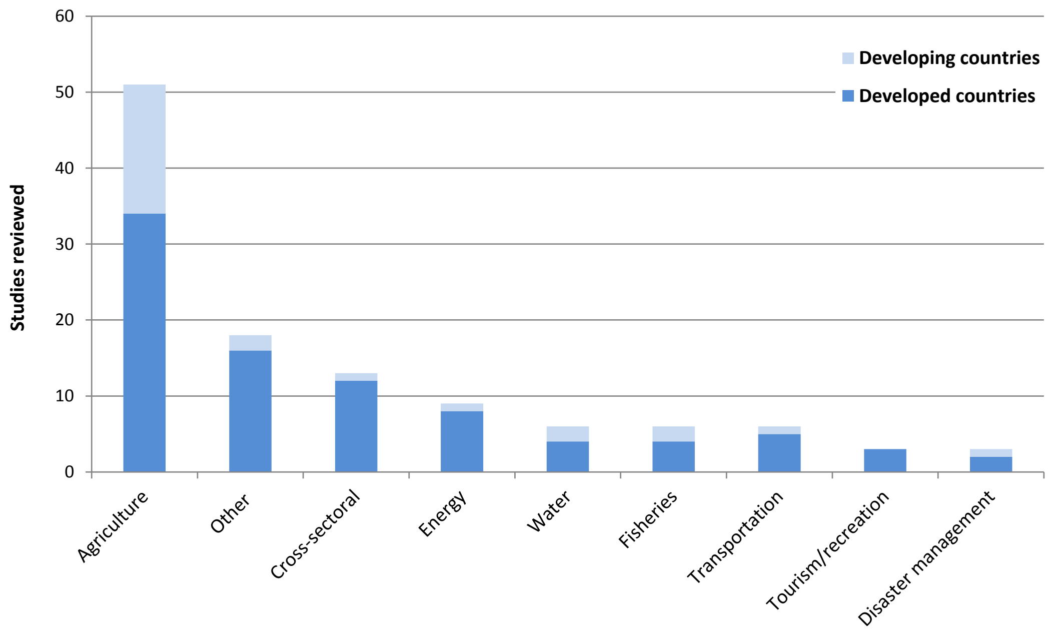
Some agricultural studies have examined the value of climate information at the aggregate (or sector) level, taking into account price response due to changing supply and demand, and providing estimates of consumer and producer surplus as a measure of the benefits to society (e.g., Adams et al., 1995, 2003; Hill et al., 2004, Chen and McCarl, 2000, Chen et al. 2001). Some of these studies estimated the value of forecasts at the multinational scale (e.g., Rubas et al., 2008).

Exhibit 2. Studies reviewed by region



Note: "Other" category refers to theoretical studies that were not applied to a specific geographic area.

Exhibit 3. Studies conducted in developed and developing countries by sector



In sectors other than agriculture (e.g., energy, water management, transportation), aggregate-level studies are much more common. Most of these studies estimate the potential value of climate services for a specific sector(s) in terms of avoided costs, increased revenues, or other metrics. Others extended this analysis to estimate impacts at the national level, including producer and consumer surplus, or impacts to gross domestic product (GDP) (Liao et al., 2010; Frei et al., 2012). A few aggregate-level studies (e.g., Larsen, 2006; Lazo et al., 2011) examined the impact of climate variability or weather on past economic performance across sectors.

Mjelde (1999) and Hill and Mjelde (2002) warned that aggregate-level studies must be carefully reviewed and interpreted. For example, in the agricultural sector, some studies have aggregated field-level results without consideration of price and acreage responses. Price effects of large-scale responses to forecasts may either benefit or harm producers, depending on the direction of the shift in the aggregate supply curve and the price elasticity of demand (Mjelde, 1999). In addition, at the aggregate level, interrelationships between other commodities and sectors, such as input and financial sectors, become relevant, but relationships to other economic sectors are often not evaluated. Although Mjelde (1999) and Hill and Mjelde (2002) discussed these issues within the context of studies related to agriculture, many of these concerns exist for studies of other sectors as well.

3.1.3 VALUATION METHODS

The studies included in this literature review used a variety of methods to quantify the value of climate services, including: decision theory, avoided cost calculations, partial equilibrium models, game theory, contingent valuation, benefits transfer, and econometric models. These different methods, and how they have been applied across different studies, are described below.[3]

[3] Rubas et al., 2006 provides a more comprehensive discussion of decision theory, general equilibrium concepts, and game theory as applied to the valuation of climate services.

DECISION THEORY

Decision theory typically involves a single agent or entity who must make decisions to maximize (or minimize) an objective (e.g., represented by a utility function, production function, cost-loss model of two alternatives, or other economic model). The application of decision theory assumes that the decision maker makes decisions based solely on the effect of the decisions on his or her payoffs. Institutional factors and the choices of other decision makers are assumed to be fixed (Rubas et al., 2006).

In the context of climate services, decision theory often assumes that decision makers have some level of prior climate knowledge. Without updated climate information, the decision maker uses his or her prior knowledge to make decision(s). If updated climate information is provided, the decision maker will use this information to make optimal choices. The value of climate information is then equal to the difference between the payoff when the information (i.e., updated knowledge) is used, relative to when prior knowledge or no forecast is used (Rubas et al., 2006).

Decision theory is appropriate when the choice of a decision maker or entity cannot affect an outcome for another decision maker. For example, a single agricultural decision maker interested in adopting seasonal forecasts would have little impact on supply or demand and would therefore have little impact on price (Rubas et al., 2006). Studies based in decision theory are typically paired with business or production models (i.e., crop growth simulation models, fisheries management models) to identify optimal decisions under alternative climate scenarios.

The majority of studies included in this review have applied some form of decision theory (broadly defined) to estimate the value of climate services. In the agricultural sector, Meza & Wilks (2004) estimate the value of perfect SSTA forecasts for fertilizer management in Chile to be $5 to $22 per hectare for potato farmers, compared to a no forecast approach. In the transportation sector, Berrocal et al. (2010) found that the use of probabilistic weather forecasts for predicting ice conditions reduced costs for the Washington State Department of Transportation by 50% relative to the use of deterministic forecasts.

In the energy sector, Hamlet et al. (2002) evaluated the use of long-lead stream flow forecasts in the management of hydroelectric dams on the Columbia River. The authors found that use of these forecasts could increase energy production by $5.5 million MWh per year, resulting in a US$153 million increase in net revenues (compared to shorter lead time snowpack forecasts). For this study, the authors assume that monthly prices are "… unaffected by the relatively small shifts in energy production from spring to fall examined here" (Hamlet et al. 2002, p. 98 as cited in Rubas et al. 2006). Several studies in the fisheries sector make similar assumptions (e.g., Costello et al., 1998, Kaje and Huppert, 2007).

While assuming away price effects may be appropriate when considering a single economic agent or small sector/region, it is inappropriate when considering a large number of producers or a large impact on the supply and demand conditions of the process. In these cases, other methodologies must be used (Rubas et al. 2006).

AVOIDED COSTS

Several studies have calculated avoided costs associated with the use of climate services. These studies are often based in decision theory because there is optimization that occurs in the use of the climate service being valued.

For example, Considine et al. (2004) used a probabilistic cost-loss model to estimate the incremental value of hurricane forecast information to oil and gas producers in Gulf of Mexico. Results showed the value of a 48-hour forecast amounted to $8.1 million annually in terms of avoided costs and foregone drilling time. Frei et al. (2012) found that the use of meteorological (weather) services by the transportation sector in Switzerland would result in $56.1 to 60.1 million in avoided governmental spending. Several studies have also (mostly qualitatively) evaluated the avoided costs associated with the use of early warning systems for disaster management. For example, Ebi et al. (2004) determined that the use of early warning systems during extreme heat events in the city of Philadelphia prevented 117 premature deaths from 1995 through 1998. The dollar benefit of these prevented deaths was estimated to be $468 million.

EQUILIBRIUM MODELS

General equilibrium models recognize that the choices of different decision makers are interlinked. For example, in the agricultural sector, if one producer uses climate forecasts, prices will not change because the production of a single producer is very small relative to total(e.g., regional) production. But, as the number of producers using climate forecasts increases, the change in total production will cause price changes (which will result in changes in supply and demand – and prices – for related goods and services). Producers who do not anticipate this change may not make optimal choices (Rubas et al., 2006). General equilibrium models take these effects into account, providing estimates of consumer and producer surplus as a measure of the benefits to society.

To our best knowledge, whole general equilibrium models have not been used to value climate services, likely due to their complexity and extensive information requirements. However, studies have used general equilibrium concepts to develop partial equilibrium models, sector models, and trade models to examine the effects of climate forecast use (Rubas et al. 2006). For studies related to agriculture, crop-growth simulation models have generally been used in conjunction with decision theory models to obtain producers' production responses from forecast use. The models then develop aggregate supply relationships. Changes in aggregate supply caused by the use of climate forecasts affect price, which is taken into account by individual producers (represented in the model) when making decisions (Rubas et al. 2006).

As reported by Rubas et al. (2006), a series of related studies have examined the effect of ENSO-based climate forecasts on the agricultural sector using a previously developed model of U.S. agricultural production (Chen & McCarl, 2000, Chen et al. 2001, 2002). Chen & McCarl (2000) and Chen et al. (2001) report that producer surplus decreases by using ENSO-based forecasts (due to decreased prices associated with increased production), but consumer surplus increases enough that overall social welfare increases. Inclusion of rest-of-the-world ENSO effects was found to have little impact on the overall value of ENSO-based forecasts. Overall, foreign surplus gains were found to be minor compared to US surplus gains. Chen et al. (2002) report that using the five-phase ENSO definition almost doubles social welfare gains compared to the more standard three-phase definition (Rubas et. al. 2006).

Using a similar model, Adams et al. (2003) report the value of an ENSO-based system to be $10 million annually for Mexican agriculture. Mjelde et al. (2000) use a previously developed dynamic model to show that use of seasonal forecasts in the production agricultural sector will affect machinery manufacturers, food processors and retailers, and the financial sector (Rubas et al., 2006).

In the water sector, Liao et al. (2010) developed a (partial equilibrium) regional water economic model to evaluate the economic impacts of ENSO events on a regional water market with and without the use of ENSO information. Results showed that a water management strategy based on transferring water among different groups could potentially increase social welfare by as much as $11.6 million when ENSO information was provided.

GAME THEORY

Game theory is a study of strategic decision making. More formally, it is "the study of mathematical models of conflict and cooperation between intelligent rational decision-makers." (Myerson, 1991). "Game theory is concerned with the actions of individuals who are conscious that their actions affect each other" (Rasmusen, 1992 pg. 21, as cited in Rubas et al. 2006). Payoffs in game theory are often obtained through decision theory and/or equilibrium modeling.

Game theory has not been widely used to value climate services, most likely due to its extensive information and knowledge requirements necessary to develop and solve games (Rubas et. al. 2006). One application is Rubas et al. (2008), which used an updated version of Hill et al.'s (2004) international wheat trade model, to develop a three-player game between the United States, Canada, and Australia. Producers in each country were assumed to either use climate forecasts or not use them. Because of economic linkages, payoffs (i.e., increases in expected producer surplus) were found to vary based on which country(ies) adopted the forecasts.

For example, results show that if only Australia adopted the use of climate forecasts, Canada's producers lose, whereas if either Canada or the United States adopted the forecasts, Canadian producers gain. Canadian producers were found to gain the most if both the U.S. and Canada adopted, and Australia did not adopt. Regardless of the other countries' decisions, each country's highest payoff was found to be when it chose to use climate forecasts. The U.S. gains the most when it alone adopts climate forecasts, whereas Australia gains the most when all three countries adopt. Canadian and U.S. losses associated with Australia adopting are not as large as the gains from adopting. Results suggest that cooperation between countries can increase worldwide gains from climate forecast use (Rubas et al., 2006).

CONTINGENT VALUATION

Values for non-market goods (e.g., weather and climate services that are not typically paid for by the public in an established market) can be estimated using techniques called "stated preference" methods. Contingent valuation (CV) is a commonly used stated preference method for estimating the value of non-market goods and services. In its simplest terms, CV is a survey-based technique used to elicit the maximum amount (in dollar terms) that an individual, household, or business would be willing to pay for a non-market good or service of a specified quality. Stated preference methods for conducting economic analysis are so named because values are obtained based on the stated preferences of individual survey respondents.

In the context of climate services, several studies have assessed household willingness to pay (WTP) using CV methods. For example, Anaman and Lellyett (1996a) conducted a survey in the Sydney metropolitan area to estimate the economic value householders attach to basic public weather forecasts and warnings. Results indicate that the average annual WTP for these services was about $18. In a similar study, Lazo and Chestnut (2002) found the median household WTP for current weather forecasts in the United States to be $109 per year.

Several studies have also assessed WTP for climate services by businesses or sectors. Rollins and Shaykewich (2003) used CV to estimate benefits generated by an automated telephone-answering device that provides weather forecast information to commercial users in Toronto, Canada. Average value per call varied by commercial sector from $1.58 for agricultural users to $0.44 per call for institutional users with an overall mean of $0.87 per call.[4] With roughly 13,750,000 commercial calls annually, benefits were estimated to be about $11,960,000 per year. Anaman and Lellyett (1996 b, c) also surveyed cotton producers to determine WTP for an enhanced weather information service tailored to the cotton

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[4] Values converted from Canadian dollars to U.S. dollars based on an average 2003 exchange rate of 1.375 CAD.

industry. At the time of the survey (a drought period), average WTP for the service was about $175. In addition, producers indicated they were willing to pay an average of $204 annually for the use of the service during a period of good rainfall. Makaudze (2005) investigated the value of seasonal forecasts to farmers in Zimbabwe via CV surveys. Results showed that WTP for improved seasonal forecasts ranged from $0.44 to $0.55. Households in wet districts revealed consistently lower WTP than those in drier districts.

BENEFITS TRANSFER

Original studies to estimate stated preferences, avoided costs, or other values associated with the use of climate services can require a significant amount of time and financial resources. For this reason, researchers often use the *benefits transfer* approach to estimate these values. Bergstrom and De Civita (1999, p. 79) offer the following definition of benefits transfer:

> Benefits transfer can be defined practically as the transfer of existing economic values estimated in one context to estimate economic values in a different context ... benefits transfer involves transferring value estimates from a "study site" to a "policy site" where sites can vary across geographic space and or time.

Benefits transfer is commonly used in economics, and there is a well-developed literature on how to correctly apply this method (e.g., Rosenberger and Loomis, 2003). Federal guidelines for economic analysis discuss how and when benefits transfer should be applied (U.S. EPA, 2000; U.S. OMB, 2003).

A limited number of studies included in this literature used benefit transfer techniques to estimate values associated with climate services. Most notably, Hallegatte (2012) estimated the potential benefits of providing early warning systems in developing countries based on a study of benefits for similar services in Europe. Taking into account differences in population, increased hazard risk due to climate and geography, as well as increased exposure to weather due to the state of infrastructure, the author estimated that upgrading early warning capacity in all developing countries would result in between $300 million and $2 billion per year of avoided asset losses due to natural disasters. In addition, early warning systems would save an average of 23,000 lives per year (valued between $700 million and $3.5 billion per year using the Copenhagen Consensus guidelines) and would add between $3 and $30 billion per year in additional economic benefits.

Other studies have used benefits transfer to evaluate specific benefits. For example, Weiand (2008) estimated the value of improved ocean observing data to recreational fishermen in Florida using estimates of WTP for recreational fishing (per fish caught) from existing literature. Costello et al (1998), also used estimates from the literature to determine the value associated with improved in-stream fishing in the Pacific Northwest due to improved fishery (Coho salmon) management with the use of ENSO-based forecasts.

ECONOMETRIC MODELS

Econometric models are used to specify statistical relationships between socioeconomic (or other) variables pertaining to a particular economic phenomenon. Econometric models typically model the effect of a series of independent variables (e.g., price, age or income of individual) on a dependent variable (e.g., the value of a climate service). Regression analysis is the most common form of econometric modeling.

Few studies have used econometric models to determine the value of climate services. One example is Anaman and Lellyett (1997), who conducted an econometric analysis of the effect of aviation weather forecasts on operating costs of Qantas Airways Limited for its international operations. Based on annual data from 1971/72 to 1993/94, the authors evaluated the use of terminal aerodrome forecasts (TAFs) and upper atmosphere wind forecasts available to Qantas Airways Limited and other international airlines. The authors estimated long run and short run total fuel cost functions using multiple regression techniques, where total fuel cost was the dependent variable. Independent variables included the price of aviation fuel, output of the airline, capitalization of the airline measured by the depreciation of aircraft, alternate fuel policy concerning use of TAFs, and quality of upper atmosphere wind forecasts. The short run fuel cost function also involved a pulse dummy variable for a fuel policy change involving TAFs that occurred in 1985. This fuel policy change allowed pilots the discretion not to add alternate fuel to the total fuel load if the weather forecasts contained in the TAFs at the destination airport are not severe. Before 1985, the alternate fuel load was added to the total fuel load regardless of the predicted weather conditions at the destination airport.

Results indicated that the airline fuel consumption was strongly related to the price of aviation fuel and airline output. In addition, increased capitalization involving the acquisition of more fuel-efficient planes led to reduced fuel consumption. The abandonment by the airline of mandatory requirement for pilots to carry alternate fuel in 1985, in favor of carrying such extra fuel based on weather forecasts, saved between $19 to $30 million per year in reduced fuel consumption (in 1993/1994 dollars).

Several studies have also examined the sensitivity of private sector output to weather variability (but not how this was impacted by the use of climate services). For example, Lazo et al. (2011) developed econometric models for 11 sectors in the United States to estimate the effect of weather variability on economic output. The authors used 24 years of state-level economic data and historical weather observations to develop a nonlinear regression analysis of economic output by sector (dependent variable). Results showed that the aggregate variation in U.S. economic activity due to weather variability could be $485 billion per year. Sectors such as communications, construction, retail trade, services, transportation, and wholesale trade were found to have a relatively low sensitivity to weather variability (less than 5%), while fire, manufacturing, and utilities showed intermediate sensitivity (between 5% and 10%). Agriculture was found to be one of the most sensitive sectors at 12.1%, even though it is one of the smallest in absolute terms (less than 1.5% of total GDP). Mining was the most sensitive sector at 14.4%.

3.1.4 EX ANTE VS. OBSERVED STUDIES

The majority of the quantitative studies analyzed include ex ante predictions of the value of climate services based on models developed using historical climate data. Only a handful of studies are based on observations of actual changes in management (and associated economic impacts) that occurred as a result of climate forecasts. In ex ante studies, it is typically assumed that baseline management decisions are based on perfect knowledge of historical climate data or on the forecast available at the time. The value of baseline management is then compared to the value of perfect (and sometimes imperfect) forecast models in which decisions are simulated based on the observed (i.e., retrospective) conditions. The effects of climate change have generally not been taken into account, as most studies are based on a seasonal average of past conditions.

In agriculture, the majority of ex ante studies have used crop-growth simulation models to estimate crop yields under different climate conditions. The main reason for this is that almost no real-world data exist on how producers would change production practices in response to climate forecasts (Hill et al., 2002 as cited in Hill and Mjelde, 2002). "Crop-growth models generate simulated data that can be used to determine optimal production practices and associated yields under the producer's assumed prior knowledge and climate forecast scenarios with a fixed technology" (Hill and Mjelde, 2002 p. 615). Variations of this approach (i.e., model simulations) have been used to examine benefits in other sectors.

Exceptions to ex ante assessment include Changnon (2002), who examined costs associated with the NOAA's zero failed drought forecast in 2000 based on surveys, interviews, and focus groups of

Midwestern farmers. In the water management sector, Steinemann (2006) estimated the value of seasonal precipitation forecasts in Georgia based on their actual use by water managers in deciding whether to pay farmers to suspend irrigation in forecasted drought years. In the energy sector, Changnon et al. (1999) found that the actual use of an ENSO forecast by a heating plant manager resulted in more than $500,000 in savings in natural gas purchases over the course of the 1997–1998 winter season (based on predictions of a warm winter, the plant manager chose to purchase natural gas on the spot market, rather than lock in a price.)

Reviews of literature related to the value of climate services indicate that several studies have used surveys and other data collection techniques to qualitatively assess the use of climate services in various sectors. For example, Luseno et al. (2003) explored the value of climate forecast information to pastoralists in southern Ethiopia and northern Kenya using survey data. Orlove et al. (2004) surveyed almost 600 people in Peru regarding responses to and use of climate forecasts for the 1996–1997 El Niño phenomenon.

3.1.5 FORECAST TYPES

In the agricultural sector, almost all the studies considered a discrete type of seasonal forecast (e.g., three- or five-phase ENSO forecasts), with ENSO-based phase forecasts being the most frequently analyzed forecast type. Other studies considered discrete forecasts for categories of seasonal precipitation (e.g., above normal, normal, below normal) or for total precipitation. According to Meza et al. (2008), the use of discrete categories simplifies the assessment of the expected economic value of climate information, because the relative frequencies of the forecasted events can be easily computed from historical records." (p. 1274). The authors also noted a failure to incorporate state-of-the-art developments (i.e., dynamic models of global climate) in seasonal forecasting into economic valuation studies.

In the water management and fisheries sectors, most studies valued the use of seasonal forecasts, including ENSO- and streamflow-based forecasts. In other sectors (e.g., transportation, energy, tourism/recreation), the use and valuation of short-term forecasts is more common. For example, Barthelmie et al. (2008) estimated the impact of using short-term wind speed forecasts on the price of electricity in Scotland. Berrocal et al. (2010) compared the use of 12-hour probabilistic and deterministic weather forecasts for predicting ice conditions on roads. Numerous cross-sector studies have evaluated the impact of weather forecasts (or past weather conditions) on national economies and consumers.

A number of studies assumed a perfect forecast scenario, while others valued climate services using probability-based or "imperfect" forecasts. With a perfect phase forecast, average conditions (and optimal management) for that phase are typically assumed. In most cases, the value of perfect and imperfect forecasts is compared to the economic impacts associated with optimal management under historical climatological conditions. Imperfect forecasts are typically portrayed as capturing some percentage of the value of a perfect forecast. As discussed in Section 4, several studies focused on how different forecast characteristics influence the ultimate value of the forecast.

3.1.6 BENEFITS QUANTIFIED

The preceding sections mention different metrics that have been used to demonstrate the value of climate services in various sectors. Exhibit 4 summarizes these metrics for the studies evaluated as part of this research (thus, not all benefit metrics important to these various sectors are listed, e.g., avoided property loss, as this was not valued in any of the articles reviewed as part of this research).

Exhibit 4. Benefit metrics, by sector

Sector	Metrics
Agriculture	• USD per hectare or acre (e.g., increased revenues per hectare) • Total welfare gains (producer and consumer surplus) • Avoided revenue losses • Increase in total farm revenue • Change in crop prices • Growth in GDP • Producer surplus • Reduction in insurance prices • Willingness to pay for forecasts
Energy	• Increase in electricity prices (benefit for electric industry) • Cost savings due to more efficient energy purchasing • Increased sales/revenue from hydro-power dams • Increased mean weekly income in wind energy sector • Cost savings from more efficient building operations • Consumer gains from reduced energy costs
Water resources management	• Water savings • Total welfare gains • Avoided agricultural production losses • Savings to the state from reduced compensation to irrigators
Transportation	• Avoided costs • National economic benefits
Disaster management	• Avoided evacuation costs • Reduced asset losses • Reduced foregone drilling time (oil and gas industry)
Tourism/recreation	• Consumer welfare • Increased recreational fishing days • Value of recreational fishing day (contingent valuation)
Other sectors	• Household willingness to pay for weather services • Impact of weather variability as a percent of GDP • Avoided costs • Increased revenues

Although most of the studies have expressed the value of forecasts in monetary terms, a few have also considered the environmental benefits associated with the use of forecasts. Hill et al. (1999), Dailey et al. (2006), and Yu et al. (2008) all considered how forecast information provides producers with a method for using nitrogen more efficiently, resulting in positive environmental consequences. Ritchie et al. (2004) quantified the amount of additional streamflow that would be available for environmental restoration purposes under alternative forecast schemes. For the most part, however, environmental benefits have not been quantified.

3.1.7 VALUE ESTIMATES

In general, studies show a positive value for climate services, although results are very site-specific. Given the significant variation in study parameters (e.g., geographic region, level of analysis, types of climate services and benefits evaluated), value estimates from the different studies included in this literature review are difficult to compare. However, it is useful to examine values from the literature in order to gain a broader understanding of the type and magnitude of values that have been assessed.

Exhibits 5 and 6 provide examples of value estimates from studies reviewed as part of this research, and the context in which the values were developed. Exhibit 5 provides a summary of values from selected studies related to agriculture, while Exhibit 6 offers examples from studies of other sectors. Both exhibits are organized by the level of analysis conducted, including studies of value at the farm/firm or individual level, the sector level, and the regional or national level.

Exhibit 5. Climate service value estimates from selected agricultural studies, by geographic location and level of analysis

Developed countries	Developing countries	Global
Farm level • $13,812 increase (27%) in annual cash flow for grazing farm in Australia with use of SST-based forecast (McIntosh et al., 2005) (2001USD[a]). • $16,567 increase in annual after-tax cash flow of U.S. farms with use of perfect forecast under existing government programs (Mjelde et al., 1996). • $7.69 per hectare increase in gross margins for Australian wheat farmers with use of Southern Oscillation Index (SOI)-phase information for nitrogen management (Wang et al., 2008). • $57 per hectare for Australian wheat farmers with use of perfect ENSO forecast for nitrogen management (Yu et al., 2008). • $2.90 per hectare with use of ENSO-phase information by Florida peanut-cotton-corn farmer, under existing farm policies (Cabrera et al., 2007). • $17.95-28.46 increase in annual value per acre for Illinois corn farmers with perfect seasonal climate information, depending on prior knowledge (Mjelde et al., 1988). **Sector** • $36 million in benefits to Canadian hay production with daily precipitation forecast (Fox et al., 1999). • $1.1 billion in losses to U.S. agriculture from incorrect 2000 drought forecast (Changnon, 2002). • $145-265 million in social welfare benefits for southeast United States agriculture with perfect ENSO information, depending on farm programs (Adams et al., 1995). **Regional/national** • $1.1 million in annual benefits for Australian farmers in Merredin region with forecasting technology that provides 30% decrease in seasonal uncertainty (Petersen and Fraser, 2001).	**Farm level** • $17.7 – 41.9 per hectare for farmers in Southern Kenya with use of global circulation model-based seasonal precipitation forecasts for maize planting and fertilizer management (Hansen et al., 2009). • $0.44 – 0.85 in willingness-to-pay by households in Zimbabwe for improved seasonal forecasts (Makaudze, 2005). • $9-35 in benefits per acre by adjusting crop mix to ENSO phase in Argentina (Jones et al., 2000). • $20 per hectare for Chilean potato farmers with use of perfect sea surface temperature anomaly (SSTA) information (Meza and Wilks, 2004). • $1.80 (landowners) and $15 (tenants) per hectare for Argentinian farmers with use of ENSO forecasts (Letson et al., 2009). **Regional/national** • $1 billion in annual GDP growth with use of ENSO-based long-range forecasts by farmers in South Africa (Jury, 2002). • $10 million in annual benefits to Mexico economy with use of ENSO early warning system by farmers (Adams et al., 2003) (2002 USD).	**International/global** • Global annual value of ENSO phase information in agriculture estimated to range from $399 million (Chen and McCarl, 2000) to $556 million (Chen et al., 2001) to $1,390 million (Chen et al., 2002). • Global value of climate prediction estimated to be approximately $900 million (Hallstrom, 2004).

a. Values have not been adjusted for inflation. The year of the dollar value reported in the study is included for those studies for which it is available. Otherwise, values are assumed to be reported as the year of the study publication. All values are reported as USD. For studies that reported values in foreign currencies, values were adjusted using the exchange rate on January 1st of the year the study was published unless otherwise noted. .

Exhibit 6. Climate service value estimates from selected non-agricultural studies, by sector and level of analysis

Energy	Transportation	Fisheries
Firm/individual • 100% increase in net weekly income for wind energy producers in Europe with medium-range forecasts. (Roulston et al. 2003). • $500,000[a] in savings on natural gas purchases for Northern Illinois University with ENSO-based winter temperatures forecast (Changnon et al. 1999) (1998 USD). • $6,881/building in annual energy savings (24% cost reduction) for commercial building with 24-hour forecast (Zavala et al., 2009). **Sector** • $8.1 and $10.5 million in average annual savings for offshore oil and gas producers in Gulf of Mexico with 48- and 24-hour hurricane forecasts. Perfect forecasts would have increased savings to $207.5 and $238.7 million (Considine et al., 2004) (1999 USD). • $153 million increase in average annual revenue for Columbia River hydropower dams with perfect ENSO and Pacific Decadal Oscillation (PDO)-based stream flow forecasts (Hamlet et al., 2002) (1998 USD). **Regional/national** • $1 to $6.5 billion in decadal hydropower benefits for Ethiopia with perfect ENSO-based precipitation forecast (Block, 2011). • $136 and $79 million in average annual benefits for California (reduced energy costs) and Pacific Northwest (increased revenues) due to potential electric power transfers based on ENSO and PDO forecasts (Voisin et al. 2006) (2000 USD).	**Firm/individual** • Annual benefits of terminal wind information for reducing flight delays: $25.7 million at Los Angeles, $16.7 million at Seattle, and $119 million at San Francisco airports (Evans et al., 1999). • $11 million in avoided costs of carrying extra fuel for Qantas Airlines at the Sydney Airport in Australia due to improvements in terminal aerodrome forecast information (Weiher et al., 2005) (2004 USD). **Sector** • $20 million increase (~ 3%) in annual average income for canal transit and power generation sectors in the Panama Canal with use of perfect ENSO forecast (Graham et al., 2006). • $58 million in annual benefits to U.S. aviation sector in reductions in accidents and flight delays with NOAA's GOES (NOAA, 2002). • $580 million in annual delay reductions at U.S. airports with use of Federal Aviation Administration's Terminal Convective Weather Forecast (6% of U.S. weather delay costs in 2001) (Sunderlin and Paull, 2001). **Regional/national** • 50% reduction in anti-icing and road closure losses for State of Washington with use of 12-hour probabilistic forecast, compared to deterministic forecast (Berrocal et al., 2010). • $56.1–60.1 million in avoided costs and $14.2–25.3 million in value-added to the Swiss economy with use of weather services in the transportation sector (Frei et al. 2012).	**Sector** • $0.9 to $51.3 million in benefits over 30 years to New England near-shore commercial shellfish fishery with HAB forecasts, depending on HAB frequency, prediction accuracy, and response measures (Jin and Hoagland, 2008) (2005 USD). • 2.2% to 24% increase in total value for Coho salmon fishery in State of Washington with perfect short-term climate information (Kaje and Huppert, 2007). • $91 million in welfare benefits for boat-based recreational anglers in the Gulf of Mexico with NOAA's Integrated Ocean Observation System (Wieand 2008) (2000 USD). **Regional/national** • $902,000 in average annual total welfare benefits related to Pacific Coho salmon fishery with use of perfect ENSO forecast. (Costello et al., 1998). • $85 to $126 million in average annual benefits for marine transportation, commercial fishing, recreational fishing, and other sectors with ocean observation system in Gulf of Mexico (2004).

Exhibit 6. Climate service value estimates from selected non-agricultural studies, by sector and level of analysis (cont.)

Water management	Multi-sector
Sector • 2% reduction in losses for rice producers in the Ebro River Basin in Spain with use of water management strategies based on drought forecasts under climate change (Quiroga et al., 2011). **Regional/national** • $100-350 million in annual benefits to the state in drought years (2001, 2002) with use of water management strategies based on tailored precipitation index forecast in Georgia. $5–30 million in savings in non-drought years (Steinemann, 2006). • Up to $11.6 million in annual welfare benefits with use of perfect ENSO forecasts in the Northern Taiwan regional water market (Liao et al., 2010).	**Business/household** • $109 per year is the median household value for current weather forecasts. Average household willingness to pay to have forecast quality improved to the maximum level is $16 per year (Lazo and Chestnut, 2002) (2001 USD). • Household willingness to pay of $18 per year for public weather forecasts in Australia (Anaman and Lellyett, 1996). • Households willing to pay (homeowners) $25–41 per year for tropical cyclone service in Australia (Anaman et al., 1997). **Sector** • $28 million in marginal annual benefits to the U.S. commercial trucking industry with use of weather information provided by NOAA's GOES satellite system (NOAA, 2002). **Regional/national** • Potential annual socioeconomic benefits of weather services in Eastern Europe range from $13.8–29.1 million in Bosnia-Herzegovina to $58.2–73.0 million in Croatia for transport, construction, energy production, flood protection, and agricultural sectors (Hautala et al., 2008) (2005 USD). • $468 million in benefits from Philadelphia's heat watch/warning system over 1995 to 1998 in terms of prevented deaths (Ebi et al., 2004).

a. Values have not been adjusted for inflation. The year of the dollar value reported in the study is included for those studies for which it is available. Otherwise, values are assumed to be reported as the year of the study publication. All values are reported as USD. For studies that reported values in foreign currencies, values were adjusted using the exchange rate on January 1st of the year the study was published unless otherwise noted. .

4. FACTORS AFFECTING THE VALUE OF CLIMATE SERVICES

The valuation studies included in this review have provided important insights on some of the different factors that affect the use and value of climate services. This section reviews factors that have been discussed and tested in the literature, including forecast characteristics, decision-maker characteristics, decision-maker environment, and the flexibility of management decisions. The uncertainty of forecast value estimates is also addressed.

4.1 FORECAST CHARACTERISTICS

Forecast characteristics that influence the value of climate services:

- Forecast accuracy
- Lead time
- Forecast type (e.g., probabilistic vs. deterministic)
- Specificity
- Spatial resolution

Hill and Mjelde (2002) described several design characteristics that can affect the use and/or value of forecasts, including: accuracy, lead time, categorical vs. probabilistic, specificity, spatial resolution, and weather parameters reported. Of these design characteristics, accuracy has received the most attention in the literature (Hill and Mjelde, 2002; Meza et al., 2008). In general, studies across sectors have shown that more accurate forecasts typically generate more value (e.g., Katz et al., 1987; Mazzaco et al., 1992; Adams et al., 1995; Costello et al., 1998; Meza and Wilks, 2004; Vizard and Anderson, 2009; Liao et al., 2010). Studies comparing the value of perfect and imperfect forecasts have typically found that imperfect forecasts capture a percentage of the value that a perfect forecast would provide. The use of an imperfect forecast typically results in a higher value than the use of a climatological-based approach (i.e., historical climate data); in some cases, however, the increased value has been found to be very small, or even zero (e.g., Block, 2011).

Many studies have concluded that the relationship between forecast accuracy and value is not one-to-one. Murphy and Ehrendorfer (1987) showed that increases in forecast accuracy (as judged by the meteorological community) can actually decrease forecast value because quality cannot be defined by a single parameter. Mjelde et al. (1988) demonstrated a trade-off between forecast accuracy and lead time (i.e., a less accurate forecast with more lead time is typically preferred to a highly accurate forecast that does not allow much time for adoption of alternative management practices).

In the electric utility industry, Hertzfeld et al. (2004) noted that improved forecast quality from satellites (including temperature and precipitation data) will improve demand-based market decisions as well as the reliability of the electricity supply. As noted by the California Energy Commission, the reliability rating of certain power system elements "will improve in direct relationship to improvements in the accuracy of short-term weather forecasts" (Hertzfeld et al., 2004, p. 799).

In a survey of subscribers to NOAA's Monthly and Seasonal Weather Outlook, Easterling (1986) found that the most important factor in distinguishing between users and non-users of climate forecasts is lack of lead time, which is often cited as a barrier to the use of forecasts in the agricultural sector (e.g., Changnon, 1997). On the other hand, if decision-makers are able to adapt management strategies in response to updated forecast information, shorter lead times can increase value (e.g., Mjelde et al., 1988). This is true across sectors. For example, Considine et al. (2004) found that updated 24-hour hurricane forecasts provided greater value to oil and gas producers in the Gulf of Mexico than 48-hour forecasts.

Benefits of the 24-hour forecast included reduced foregone drilling time and avoided evacuation costs because of increased accuracy.

Despite the importance of lead times in many applications, increased values associated with increased lead times may be relevant only within certain periods. For example, Costello et al. (1998) found that in relation to the Coho salmon fishery in the State of Washington, lengthening the ENSO forecast horizon from one year to two years had only a small effect.

Several studies have found that probabilistic and ensemble forecasts have a higher value than deterministic or categorical forecasts (Murphy, 1977; Richardson, 2000; Zhu et al., 2001; Palmer, 2002; Buizza, 2007; Berrocal et al., 2010). Buizza (2007) demonstrated that probabilistic forecasts are more valuable than single forecasts because they can be used not only to identify the most likely outcome, but also to assess the probability of occurrence of extreme and rare events. Zhu et al. (2001) showed that ensemble forecasts provide greater potential economic benefits than a traditional control forecast run at a higher resolution due to the fact that (1) the ensemble provides a more detailed forecast probability distribution, allowing users to tailor their weather forecast-related actions to their particular cost/loss situation, and that (2) the ensemble has an ability to differentiate between high- and low-predictability cases. For a specific application in the transportation sector, Berrocal et al. (2010) found that in the State of Washington, the use of probabilistic forecasts for predicting ice conditions on roads can reduce operational costs by about 50% compared to deterministic forecasts.

Other studies have attempted to estimate the effect of specificity (i.e., the number of categories within the forecast system) on forecast value. Chen et al. (2002) found significant potential gains from releasing five-phase as opposed to three-phase ENSO information in a global, multi-commodity agricultural setting. However, in a study of wheat production at multiple sites within the United States and Canada, Hill et al. (2000) found that the value of three-phase vs. five-phase forecasts varied by region and commodity price. Hansen et al. (2006, as cited in Meza et al., 2008) warn that "comparisons of forecast systems with differing numbers of categories are problematic unless precautions are taken to control for the artificial skill that tends to increase as the number of categories increases" (Meza et al., 2008, p. 1275).

Improved spatial resolution may also increase forecast value, although few studies have evaluated this effect. Hansen et al. (2009) compared the value of a simple ENSO seasonal forecast to a method that perfectly predicts whether regional growing season precipitation will be categorically dry, normal, or wet. Results show that although the regional forecast had a higher level of accuracy, this did not translate to more value at the farm level.

Finally, the forecast valuation literature has generally not estimated the value of advanced forecasting techniques. In locations and seasons where more advanced climate forecast models are available, a failure to incorporate the best climate science could lead to an underestimation of forecast value (Meza et al., 2008).

4.2 DECISION-MAKER CHARACTERISTICS

Several studies have examined the influence of decision-maker characteristics on the value of climate forecasts. One example is the role of risk aversion, which has been examined in many studies. In agriculture-related studies, the general finding is that forecast value tends to be higher for slightly risk-averse decision makers than for those who are risk-neutral (Marshall et al., 1996; Jones et al., 2000;

Decision-maker characteristics that influence the value of climate services:

- Risk aversion
- Prior knowledge/beliefs
- Access to resources
- Lack of ability to interpret forecast information
- Relationship to asset

Cabrera et al., 2007; Tena and Gomez, 2011). This suggests that ignoring risk aversion where it is present can lead to an undervaluation of forecast information (Meza et al., 2008).

In a study of forecast value for agricultural decision-makers in the Pampas region of Argentina, Letson et al. (2005) found that forecast value generally increases within increasing levels of risk aversion, although only to a point. At very high levels of risk aversion, forecast value was found to start decreasing. One reason for this is that highly protective risk management strategies constrain the decision set (i.e., a highly risk-averse farmer may not be able to bear the uncertainty inherent in the forecast) (Meza et al., 2008).

Several studies have found that different forecast outcomes can have varying levels of value to decision-makers with different risk preferences (Messina et al., 1999; Letson et al., 2005; Cabrera et al., 2007). Letson et al. (2005) found that forecasts of adverse climatic conditions were most valuable to risk-neutral farmers because they used them primarily to avoid risk associated with adverse conditions (i.e., defensive response). Forecasts of favorable conditions became more valuable at increasing levels of risk aversion because these farmers were more likely to seek additional profits by taking advantage of favorable conditions (i.e., offensive response). Meza et al. (2008) reasoned that risk-averse farmers tend to manage all years using low-return, protective strategies in case any year turns out to be extremely bad (i.e., they always implement defensive response strategies). A favorable forecast enables risk-averse farmers to relax some of their defensive strategies in favorable years, thus increasing average annual earnings. At the same time, they are able to retain protective strategies when adverse years are anticipated (Meza et al., 2008).

The role of risk aversion may also depend on the selection of management strategies available for use under a given forecast. For example, in studying the value of perfect ENSO phase forecasts for selected rain-fed agricultural locations in Chile, Meza et al. (2003) found that levels of risk aversion did not generally produce important changes in the selection of optimal management alternatives. The authors reasoned that the use of forecasts in this region resulted in relatively small changes in decision variables, which would produce only a modest impact on realized yields. Thus, the choice is not between a high-risk decision and a cautious one.

In sectors other than agriculture, only a few studies have explored the effect of decision-maker characteristics. One of these is Quiroga et al. (2011), who evaluated the effect of risk aversion on forecast value for water managers in the Ebro River Basin in Spain. The objective of this study was to estimate the value of drought forecasts in making water allocation decisions under various climate change scenarios. The authors found a negative relationship between forecast value and risk aversion of water managers (i.e., the value of the forecast decreased as risk aversion increased). The risk-averse water managers were more likely to reduce water allocations to agriculture in response to a forecast of drought in order to obtain satisfactory water supply reliability (as opposed to maintaining allocations and exposing farmers to drought risk later in the season). However, the reduction in water allocation would result in a production loss greater than that expected under the alternative scenario.

Other decision-maker characteristics evaluated include prior beliefs (e.g., knowledge of historical climate data) and access to resources. With regard to prior beliefs, most studies have assumed that forecast users possess accurate and complete knowledge of prior climate probabilities. To test the impact of this assumption on forecast value predictions, Sherrick et al. (2000) conducted a survey of large agricultural producers in midwestern United States, and found that producers systematically misrepresented the probabilities of climate events that would affect their well-being. In particular, producers had a tendency to overstate the likelihood of adverse events and understate the likelihood of favorable events. As a result, the authors concluded that common methods for valuing forecast information are likely to understate the true value when recipients began with inaccurate prior beliefs.

Mjelde et al. (1988) studied the impact of prior knowledge on forecast value for agricultural decision-makers in Illinois (corn production). The authors evaluated the impact of reacting to different baseline climate expectations, including the most recent year's sequence (myopic), the best year in the range of historical climate data (optimistic), and the worst year in the range (pessimistic). Forecasts were found to have the same value as historical prior knowledge and optimistic prior expectations, probably because of favorable corn-growing conditions in Illinois. However, the forecasts provided higher value to those with both pessimistic and myopic prior expectations.

Access to resources can also affect the use, and thus the value, of climate forecasts. Ingram et al. (2002) studied production systems in three agro-eco zones of Burkina Faso to evaluate farmers' ability to use forecasts. The farmers interviewed in all three areas strongly emphasized that their ability to respond adequately to forecasts is hindered by resource limitations, especially the lack of available labor and productive land. Most of the farmers also mentioned that they are constrained by a lack of access to credit, capital, or agricultural technologies. Because rapid crop establishment is a key factor in coping with a shortened rainy season, farmers stated that access to tractors, plows, and other technologies that could expedite crop establishment is critical.

Another limitation may arise from a decision-maker's lack of ability to interpret forecast information. Broad et al. (2001) identified misinterpretation of forecast information as a serious problem for forecast users within the Peruvian fisheries sector during the 1997–1998 El Niño season. However, most studies assumed that the forecast user is statistically sophisticated, with perfect knowledge and understanding of forecast performance (Millner, 2009). Millner (2009) demonstrated that if users react to forecasts according to whether previous ones were accurate (i.e., reinforcement learning rather than perfect knowledge/understanding), the value of the forecasts to those users is severely reduced. Value scores were found to vary based on the users' cost-loss ratio, forecast accuracy, and the climatological probability of the adverse event.

The relationship of the decision-maker to the asset (e.g., a plot of land or herd of livestock) also can affect the use and value of climate services. Boone et al. (2004) studied the use of forecasts by livestock ranchers in South Africa. The authors found differences in the use of information between communal and commercial livestock operations. Communal ranchers were less likely than commercial ranchers to sell livestock in response to a drought forecast. The authors attribute this difference to a different set of goals and values held by communal ranchers. Letson et al. (2009) examined the impact of land tenure (i.e., ownership vs. short-term lease) on the value of ENSO predictions for farmers in Argentina. The authors found that the expected value of information is three to five times higher for tenants than for owners. They suggest this difference stems from owners' limited ability to respond to climate forecasts. These cases illustrate the importance of context in determining the use and value of climate information.

4.3 DECISION-MAKER ENVIRONMENT

The environment in which a decision-maker operates also influences the use and value of climate services. Government programs and policies (e.g., subsidized insurance, restrictions on crops or areas, and various tax schemes), community norms and behavior, the credibility of the forecast and/or forecasting institutions, and the level of vulnerability to climate impacts all have consequences for the use of forecast information.

Decision-environment characteristics that influence the value of climate services:

- Government programs and policies
- Community norms
- Credibility of climate service provider
- Sensitivity to climate variation

Decision-makers act within an environment that includes incentives and constraints created by government policies and programs. Farm policies that reduce income variability and the riskiness of farm enterprises also reduce the value of climate information. Cabrera et al. (2007) found that federal farm policies in the United States, specifically the Commodity Loan Programs and the Crop Insurance Programs, reduced the overall value of forecast information to peanut, cotton, and corn farmers in north Florida. Mjelde et al. (1996) reached a similar conclusion in a study of dry-land corn and sorghum producers in east central Texas. The authors examined the effects of federal crop insurance and acreage reduction programs, and found that crop insurance programs reduce the value of improved climate forecasts by mitigating potential losses. Acreage reduction programs reduce this value because the producer then has less acreage for which to adjust input decisions. The increased use of climate information can, however, lower insurance premiums by reducing the risk of crop loss (Osgood and Shirley, 2010).

Decision-makers do not always act alone; the norms and behavior of the community can influence the use and value of climate services. Artikov et al. (2006) studied the use of weather information and forecasts by Nebraska farmers, and found that community norms regarding the use of weather information had a positive significant impact on the use of short- and long-term forecasts in agronomic decisions. The Orlove et al. (2004) study of the response of fishermen to ENSO forecasts in Peru found that the likelihood of them using the forecasts was dependent, in part, on the town in which the fishermen lived. The authors also found that those who responded were more likely to belong to unions, neighborhood associations, and nongovernmental associations. The timing of adoption of other producers is another factor affecting the value of forecasts for individual decision-makers. Rubas et al. (2006, 2008) demonstrated in a study of North American wheat producers that early adopters of the use of forecasts benefit more than later adopters (see also Hill and Mjelde, 2002).

The use of weather information and the value that decision-makers place on forecasts are also influenced by the credibility of the forecast and the institutions providing the information (Hill and Mjelde, 2002). Changnon (2002) studied the impact of inaccurate drought forecasts in the U.S. Midwest in 2000, and found that the inaccuracy of the forecast led to a loss of credibility in climate predictions and a reluctance on the part of agricultural producers and water officials to use similar forecasts in the future. The credibility of forecasts and forecasting institutions is also important in non-western contexts: two studies of the use of forecasts by pastoralists in Kenya and Ethiopia (Luseno et al., 2003; Lybbert et al., 2007) found that confidence in the forecasts was a determining factor in their use.

The value of climate information can also depend on the sensitivity of the decision-maker to climate variability (Meza et al., 2008). A study of farmers and pastoralists in Africa (Ingram et al., 2002) found that forecasts had greater value for farmers, as they could not move their operations. Pastoralists, on the other hand, were partly insulated from climate variation by the ability to move their herds. They therefore placed lower value on climate information.

4.4 AVAILABLE MANAGEMENT OPTIONS

In studies related to agriculture, management decisions are generally limited to a narrow range of crop management options (e.g., planting date, fertilizer application rate, choice of crop). Several studies have also considered the impact of land allocation decisions in response to forecast information (Messina et al., 1999; Jones et al., 2000; Carberry et al. 2000; Ritchie et al., 2004; Cabrera et al., 2007). Others have considered the implementation of both crop management and land allocation decisions (Mjelde et al., 1997; Petersen and Fraser, 2001; Hill et al., 2004; Letson et al., 2005).

Management options can influence the value of climate services due to :

- Range of options available
- Relevance of options
- Flexibility of options
- Decision-maker characteristics and environment

Meza et al. (2008, p. 1280) noted that most studies "consider a narrow range of decisions with little or no evidence that they are relevant or feasible from the standpoint of farmers." Hansen (2002) reported that analysts who use crop simulation models understandably tend to focus on the subset of decision variables that are built into available crop models, potentially overlooking important decisions such as crop selection, water management and allocation, pest management, input supply, or marketing.

Further, most studies fail to take into account management decisions that are not directly relevant to the sector being studied. For example, in a study of the value of the 1996–1997 ENSO-based forecast in Peru for the fisheries sector, Orlove et al. (2004) found that responses to forecasts went beyond fishing activities, with a high percentage of individuals taking some form of action to protect their houses (and few changed their fishing activities). This suggests that sectorally limited studies may overlook a range of decisions, whether at the household level or at other levels.

As stated by Hill and Mjelde (2002), flexible strategies allow for the reevaluation of management strategies as the decision environment (including available information) changes. However, in the agricultural sector, only a few studies allowed for continued management based on a series of forecasts provided throughout the year (e.g., Mjelde et al., 1988). Most management options considered are implemented at the beginning of a growing season, and cannot be changed if new information is received. However, evidence suggests that farmers do adapt management strategies in response to climate conditions throughout the growing season. Studies in some of the other sectors allow for more flexibility in management options because they include responses to more short-term forecasts.

Decision-maker characteristics and the decision-maker environment may also influence the management options available, as well as the flexibility of options. For example, Letson et al. (2009) evaluated the effect of land ownership on forecast value for agriculturalists in the Pampas region in Argentina. Results showed that the forecast value is three to five times higher for tenants than for owners, because owners abide by crop rotations and have less flexibility to respond to climate forecasts. As discussed above, government policies and programs can also influence the decision set.

4.5 UNCERTAINTY

As with most economic studies, there is a level of uncertainty surrounding the value estimates presented in the literature. As described above, failure to account for differences in decision-maker characteristics (e.g., risk aversion), the decision-maker's environment (e.g., existence of relevant government policies or programs, crop prices and other market characteristics), or to include realistic management options, can result in the underestimation or overestimation of value. Despite these uncertainties, the studies of forecast value included in this review provide very useful indications of the magnitude of forecast benefits and how climate services can be developed to maximize this value.

Perhaps the most significant factor affecting the uncertainty of forecast value is the ex ante nature of most studies conducted and their associated assumptions. For example, in studies related to agriculture, crop simulation models are assumed to match on-the-ground conditions and do not account for many aspects of human behavior. In reality, even if a farmer does adopt a specific management strategy, it may take several years before he or she begins to see returns. The farmer may also choose to implement a different strategy, or may not have the resources to change farming techniques at all. He or she may also decide to pursue other means of income for the season. These types of behavioral effects are not included in most models and studies.

Resolving this issue completely would require extensive ex post studies conducted after forecasts have been widely communicated and adopted for a sufficient period to allow for learning and widespread adoption (Meza et al., 2008). However, ex post studies are often very expensive and time consuming to conduct. Studies that combine qualitative social science methods for understanding the determinants of the use of forecasts and value with modeling approaches that can realistically incorporate this information can help to reduce the uncertainty associated with ex ante studies (Meza et al., 2008). Other studies may be able to make use of existing data to conduct ex post studies of specific programs or policies.

5. BARRIERS TO THE USE OF CLIMATE SERVICES

This section discusses findings from a small subset of studies we reviewed that examined or summarized barriers to the use of forecasts in different sectors. This topic was not the focus of our review and the following discussion represents only a small sample of the literature on this subject.

Several studies have examined barriers in agricultural settings. Hill and Mjelde (2002) noted that most surveys of agricultural decision-makers have indicated that they believe the use of improved climate forecasts would have value, but that there are impediments to implementation. The impediments most frequently cited include problems with the forecasts themselves, as well as institutional constraints associated with the decision-makers or their environments.

Forecast-related barriers include low levels of accuracy, lack of lead time, lack of spatial resolution, and forecast parameters that do not meet the decision-makers' needs. Institutional constraints include the lack of credit availability and access to resources, lack of appropriate models to apply to the decision-making process when using climate forecasts, lack of knowledge concerning the forecasts, lack of knowledge concerning climate variability impacts and associated decision responses, skepticism about the scientific credibility of forecasting, and government policies that limit how seasonal forecasts can be used (Changnon et al., 1997; Hill and Mjelde, 2002). Changnon et al. (1997) also noted that data on previous years in which the weather patterns were similar to the forecasts are needed for reference purposes, and that future weather predictions should include variables other than precipitation and mean temperatures. Studies examining the use of forecasts in the agricultural sector have generally concluded that user education and interactions among climate forecasters, modelers, and decision-makers are critical.

Ingram et al. (2002) studied agricultural production systems in three agro-eco zones of Burkina Faso to determine: (1) farmers' interest in and ability to use forecasts, (2) forecast information requested by farmers, (3) the lead time required for the greatest forecast value, and (4) the need for forecast dissemination, interpretation, and application. It was found that while farmers in all three agro-eco zones expressed a strong interest in receiving seasonal precipitation forecasts, they were much more interested in receiving forecasts predicting when the rains would start and end, and whether there would be interruptions in the rains. The authors concluded that if seasonal precipitation forecasts are disseminated, they should be part of an extension package that includes discussion of the probabilistic nature of the forecasts, potential response strategies, and risk management. Furthermore, it was noted that farmers may need greater access to basic agricultural technologies, such as plows, new crop varieties, and fertilizers, before they can benefit fully from precipitation forecasts.

Similar findings have been reported for the water management sector. Ritchie et al. (2004) maintained that the use of seasonal information by water resource managers has generally been extremely limited, and that impediments to using climate forecast information for water management include both forecast characteristics and institutional factors. Using a case study approach from eastern Australia, the authors showed that a forecast, which is acceptable from a climatological perspective, does not necessarily transfer into a useable forecast for decision-makers.

O'Connor et al. (2005) explored factors affecting the use of forecasts in the water sector based on a survey of community water systems managers in South Carolina and the Susquehanna River Basin of Pennsylvania. The author revealed that the strongest determinant of the use of forecasts is risk perception (i.e., if extreme climate conditions are anticipated in the near future, the consideration of a forecast is more likely). Water managers who expect to face problems from weather events in the next decade are much more likely to use forecasts than those who expect few problems. Also, their expectations of future problems are closely linked with experience: water managers who have had problems with specific types of weather events (e.g., flood emergencies) in the last five years are likely to expect to experience problems in the next decade. Managers of larger systems as well as systems depending on surface water were also found to be more likely to use forecasts.

In reporting findings from other studies, Block (2011) noted that the lack of forecast use by water resources managers is often ascribed to the following factors: their tendency to act in a risk-averse manner (i.e., maintain status quo), "poor" forecast skills, difficulty in integrating forecasts into existing decision support systems, a lack of focus on specific user needs, management and political disincentives, individual and institutional inflexibility, behavioral effects, and informational constraints.

With regard to the electric power industry, Hertzfeld et al. (2004) discussed several impediments to the use of forecasts, noting that forecast quality and spatial resolution are key factors. The authors also reported that problems of utilization are magnified when technology and knowledge transfer occur across borders and cultures. For example, 60% of Central American power comes from hydropower, which is sensitive to precipitation. Yet power companies in the region often rely on weather information available on the Internet, rarely using the commercially tailored models used by U.S. companies (Hertzfeld et al., 2004). Changnon et al. (1995) conducted a survey of decision-makers at electric utilities with responsibilities in load forecasting, fuel acquisition, power trading, and systems planning, and found that their use of climate forecasts is minimal. However, survey respondents generally believed that climatological data would be valuable to their work if it were made more user-friendly.

In the fisheries sector, Broad et al. (2001) examined the use and non-use of climate forecasts in the Peruvian fishery during the 1997–1998 El Niño event, concluding that societal benefits of forecasts are limited due to limitations of the forecasts themselves as well as societal/institutional constraints. The latter include: (1) a lack of access to forecast information, (2) difficulties in making productive use of probabilistic information, (3) the stifling of information dissemination and distortion of informational content, and (4) producers' and other actors' individual reactions to forecasts (e.g., layoffs or increased resource extraction), which may be inconsistent with what the provider has defined as societal benefit.

Based on the existing literature, it is clear that there are many barriers to the use of forecasts. In general, these can be attributed to problems with the forecasts themselves or to the institutional/social constraints of the decision-maker. Although this review does not focus on studies designed to specifically address barriers, it is clear that efforts to foster the effective use of climate information and forecasts must be grounded in a firm understanding of the goals, objectives, and constraints of decision-makers. Interaction and feedback between suppliers of meteorological data/forecasts and the end users of such information is critical.

6. SUMMARY OF FINDINGS, INCLUDING STUDY LIMITATIONS

The overwhelming majority of the studies reviewed estimate the value of climate services in the agricultural sector. These studies generally examine the benefits of management options adopted in response to seasonal climate forecasts (e.g., ENSO phase forecasts). The most common type of assessment examines the value of climate forecasts at the crop/enterprise or farm level. Several studies also examine aggregate- (or sector-) level benefits, taking into account price response due to changing supply and demand.

The project team reviewed several studies focused on the value of climate services within the energy, water management, fisheries, and other sectors. These studies typically examine benefits at the sector or national level, and have been conducted mostly in developed countries. Studies in sectors other than agriculture include a wider range of forecast types, including seasonal forecasts and short-term forecasts of various weather parameters.

The majority of reviewed studies include ex ante predictions of the value of climate services based on models developed using historical climate data. Very few studies are based on observations of actual changes in management that occurred as a result of climate forecasts. In ex ante studies, it is typically assumed that baseline management decisions are based on perfect knowledge of historical climate data or on the forecast available at the time. The value of baseline management is then compared to the value of management under perfect (and sometimes imperfect) forecast conditions.

Studies conducted to date have provided important insights on the value of climate services, including an understanding of the factors that influence their use and value. However, there are some limitations and issues that must be considered, which follow.

Limited system and geographic range. With regard to agricultural studies, Meza et al. (2008) argued that the quantitative forecast valuation literature does not provide a realistic picture of the value of seasonal forecasts because of its limited representation of farming systems and locations. For example, the authors reported that published quantitative studies are not available for many parts of the world that show the highest current predictability of precipitation at a seasonal lead time. In addition, the highest published values of ENSO-based seasonal forecasts are for high-value horticultural crops and irrigated crops, which have not been studied to a great extent. The authors maintained that additional studies of horticultural crops, livestock systems, and irrigated agriculture are necessary before robust generalizations about the value of climate forecasts can be made for the agricultural sector (Meza et al., 2008).

Studies in other sectors have focused largely on water, energy, and/or transportation systems in developed countries. These studies vary greatly in the methodology employed and the benefits evaluated. Thus, it is difficult to draw conclusions about the value of climate services for these sectors.

Aggregate-level assumptions. Many aggregate-level studies assume complete adoption of management options in response to a given forecast. However, adoption of climate forecasts by decision-makers occurs over time, and some producers may never adopt (Rubas et al., 2006). Early adopters may be able to increase profits by increasing efficiency, while causing only small price changes, if any. At the aggregate level, adoption of information may cause changes in total supply, which would have an impact on price in a competitive market. Price changes will then impact both consumers and producers (Mjelde, 1999). Rubas et al. (2008) demonstrated the effect of adoption rates on the value of seasonal climate forecasts in multiple countries using an international wheat trade model. The authors found that early adopters benefit the most, and that after 60–95% adoption, there is no further incentive for producers to incorporate seasonal climate forecasts into their production system.

Perfect knowledge. Most studies have assumed that forecast users possess accurate and complete knowledge of historical climate conditions and probabilities. However, evidence suggests that agricultural decision-makers systematically misrepresent the probabilities of climate events that affect their wellbeing (Sherrick et al., 2000). In particular, producers were found to have a tendency to overstate the likelihood of adverse events and understate the likelihood of favorable events. As a result, the assumption that producers have perfect knowledge of historical conditions is likely to result in the underestimation of forecast value if recipients began with less-than-accurate beliefs.

Perfect forecasts. The majority of studies reviewed assume a perfect forecast scenario. With a perfect phase forecast (e.g., ENSO), average conditions (and optimal management) for that phase are typically applied (i.e., intra-phase climatic variations are not taken into account). Although a perfect forecast scenario provides useful insights and an upper bound for the value of climate services, it can also change the set of decision options that would be selected in the face of more uncertainty. In some studies, the value of a perfect forecast is compared to the value of a more realistic imperfect forecast. Imperfect forecasts are typically portrayed as capturing some percentage of the value of a perfect forecast.

Limited management options. Quantitative valuation studies have generally targeted a limited subset of potential management responses. With regard to studies of the agricultural sector, Meza et al. (2008) note that most studies consider a narrow range of crop management decisions, with little or no evidence that they are relevant or feasible for farmers in the study area. With the exception of a few studies, most of the alternatives considered in agricultural studies are related to decisions made at the beginning of the growing season (e.g., sowing date, plant density, land allocation) without the possibility of further revision.

In addition, most studies fail to take into account management decisions that are not directly relevant to the sector being studied. In relation to agriculture, Meza et al. (2008) argued that the effective management of climate risk can include fundamental changes to the farming system, or regime shifts, that could move poor farmers onto a different livelihood trajectory altogether. This suggests that studies limited to one sector may overlook a range of decisions, whether at the household level or other levels.

Lack of observed data. One reason for the limited set of management options presented in most studies is the failure to incorporate observed data into models of forecast value. The integration of quantitative valuation studies with qualitative research approaches (e.g., surveys, focus groups, ethnographic research) to elicit a more complete set of promising management responses would greatly improve the understanding of the value of climate services (Meza et al., 2008). Hansen (2002) suggests a participatory, co-learning approach for combining the best elements of descriptive and modeling methods for evaluating decision options. The author maintains that since farmers and researchers each offer information and perspective that the other lacks, this promises to produce insights that neither group has alone.

Environmental and social benefits. As noted previously, most studies estimate the value of climate services based on increased revenues, avoided costs, or consumer and producer surplus associated with their use. Only a few studies have estimated the environmental and social benefits of climate services. Potential benefits may include reduced fertilizer use (agriculture), increased water use for instream purposes (water management), lives saved (disaster mitigation), and increased welfare associated with improved recreational fishing experiences (recreation/tourism), among others. Standard economic techniques can be used to value these benefits.

Climate change implications. The majority of studies reviewed estimate the value of seasonal or short-term forecasts, and the forecasts analyzed are typically based on historical climate data. Thus, the implications of climate change (e.g., increased variation in weather patterns, extreme events) have generally not been taken into account.

Advances in forecast technologies. The forecast valuation literature generally has not incorporated advanced forecasting techniques. In areas and seasons where advanced climate forecast models are available, a failure to incorporate the best climate science could lead to underestimating the forecast value (Meza et al., 2008).

7. NEXT STEPS

This literature review has provided important insights on the value of climate services, and serves as a starting point for future work. Key outcomes of this research include the identification of suitable methods that can be used for valuation, as well as an assessment of the limitations of the existing research (e.g., ex post studies, studies related to sectors other than agriculture, especially in developing countries). The Economic Valuation of Climate Services Working Group can build upon the findings of this research to expand the current knowledge of the value of climate services. Potential next steps include the following:

- **Developing guidelines for valuing climate services.** As noted above, a key outcome of this research includes the identification of suitable methods for valuing climate services. Given that little is known about the value of existing or potential climate service programs, a logical next step includes the development of guidelines (or a series of guidelines) that can be used by policymakers and national and/or state governments and organizations to assess the benefits of climate services.

  The guidelines would be focused on the assessment of policy programs and outcomes (as opposed to most of the studies included in the literature review, which are more academic in nature), and would be designed to help decision-makers assess the value of climate services within the context of their local region or country. Guidance for the use of benefits transfer (discussed above) could be included as one aspect of the guidelines, in addition to guidance for developing original studies. Guidance for the assessment of environmental and social benefits associated with climate services would also be incorporated.

- **Evaluating the potential for benefits transfer based on studies already conducted.** As noted previously, ex post studies can be expensive and time consuming to conduct. For this reason, researchers often use the *benefits transfer* approach to estimate economic values for non-market goods and services (see section 3.1.3 for additional detail on benefits transfer). Benefits transfer is commonly used in economics, and there is a well-developed literature on how to correctly apply this method (e.g., Rosenberger and Loomis, 2003). Given the extensive amount of literature reviewed as part of this research, it would be instructive to assess the potential for the use of benefits transfer in different contexts and sectors.

- **Exploring existing data sources to apply to new studies.** As part of the guidelines, or as a separate research project, the project team could also develop original studies of the value of climate services based on existing data and programs. This would entail exploring and finding potential case studies where information already exists, and could build upon some of the well-developed case studies that have already been conducted for the Economic Valuation of Climate Services Working Group.

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