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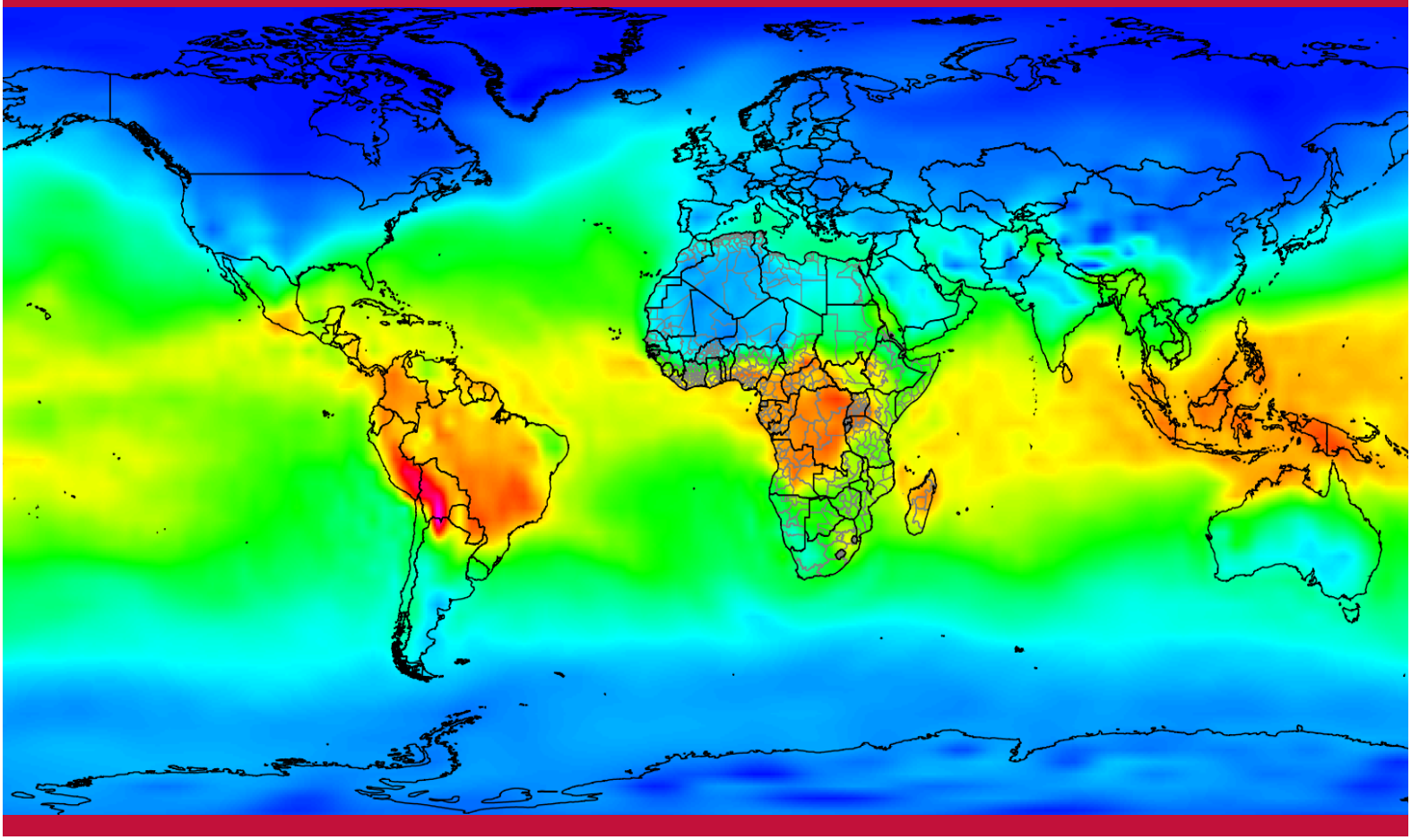
THE VALUE OF CLIMATE SERVICES ACROSS ECONOMIC AND PUBLIC SECTORS

A REVIEW OF RELEVANT LITERATURE



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Climate Services Partnership, Economic Valuation Working Group

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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. UNDERSTANDING THE VALUE OF CLIMATE SERVICES

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

[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.

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).

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

[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.

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 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.

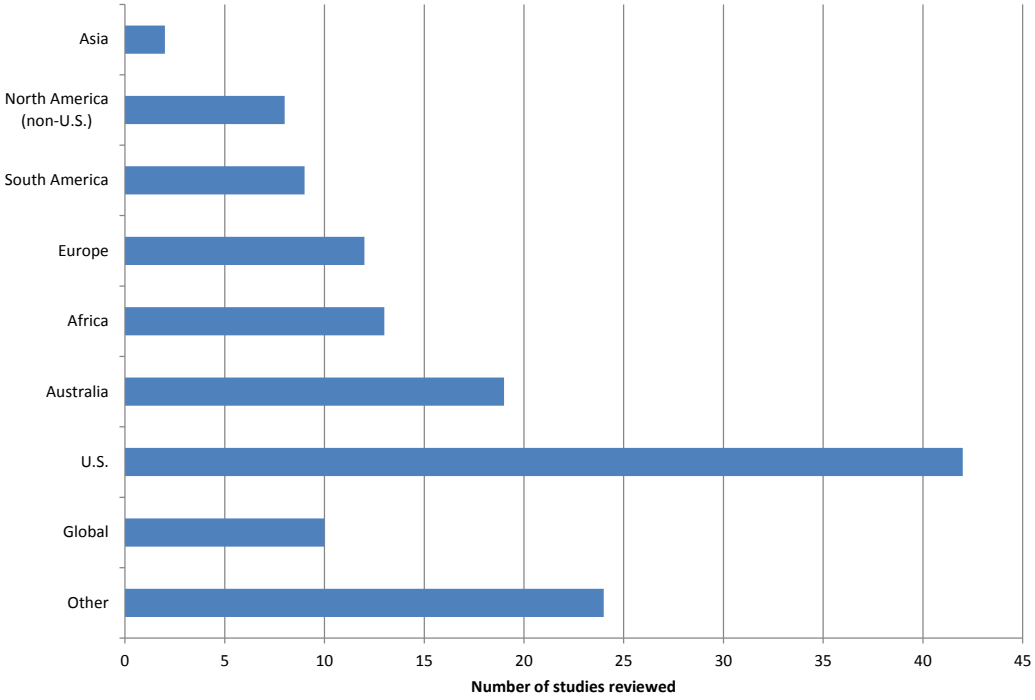
Exhibit 2 shows the distribution of studies reviewed by the project team by continent/geographic area. Exhibit 3 shows the number of studies reviewed in developed vs. developing countries, by sector. As shown, studies of the value of climate services in the agricultural sector are more equally distributed 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.

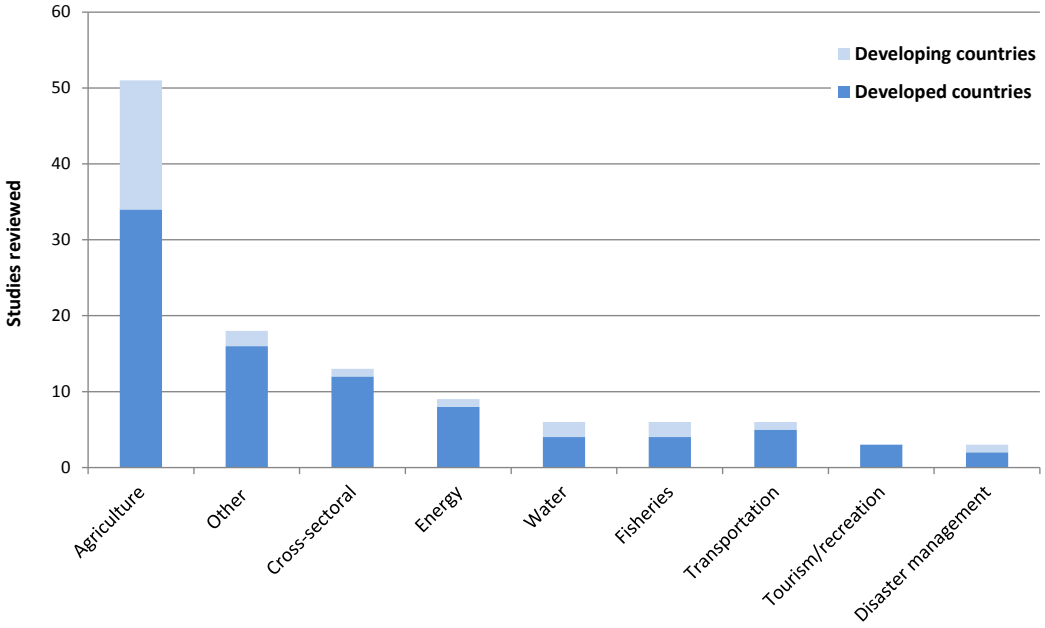
Some agricultural studies have examined the value of climate information at the aggregate (or sector) level, taking into account price response due to changing supply and demand, and providing estimates of consumer and producer surplus as a measure of the benefits to society (e.g., Adams et al., 1995, 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]

3.1.3.1. 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

[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.

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).

3.1.3.2. 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.

3.1.3.3. 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.

3.1.3.4. 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 ubas 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).

3.1.3.5. 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 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.

3.1.3.6. 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.*

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

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.

3.1.3.7. 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

Sector	Metrics
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.