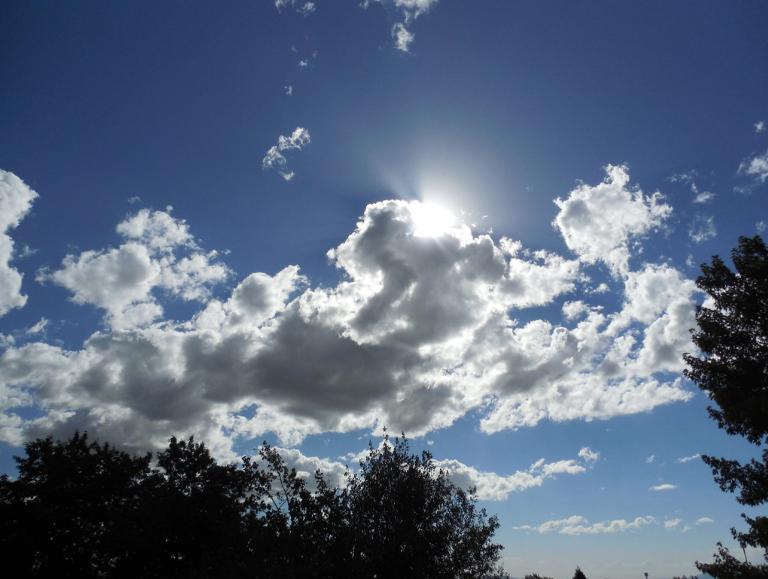
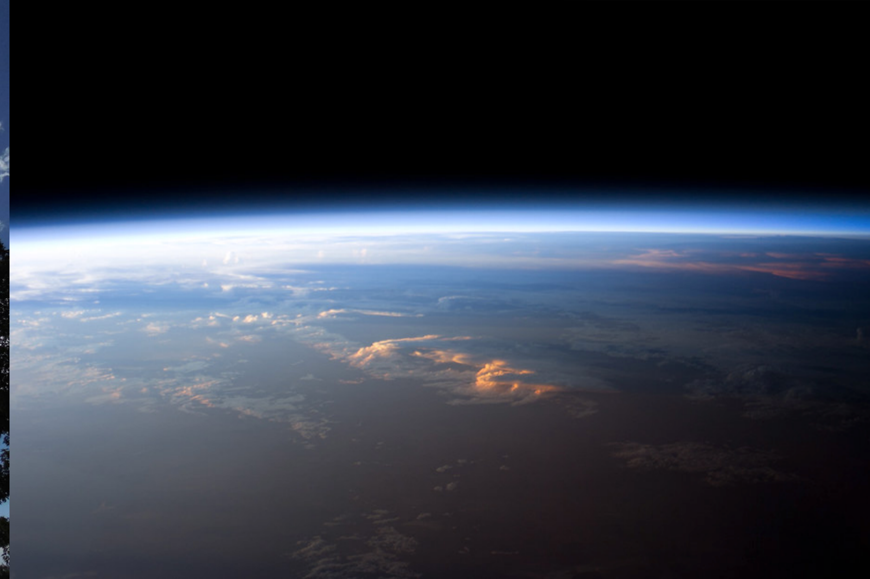
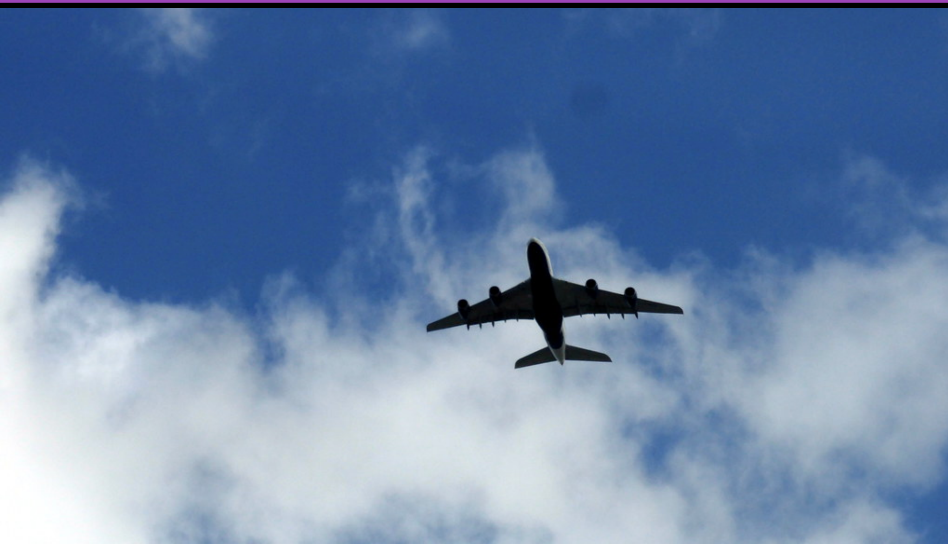
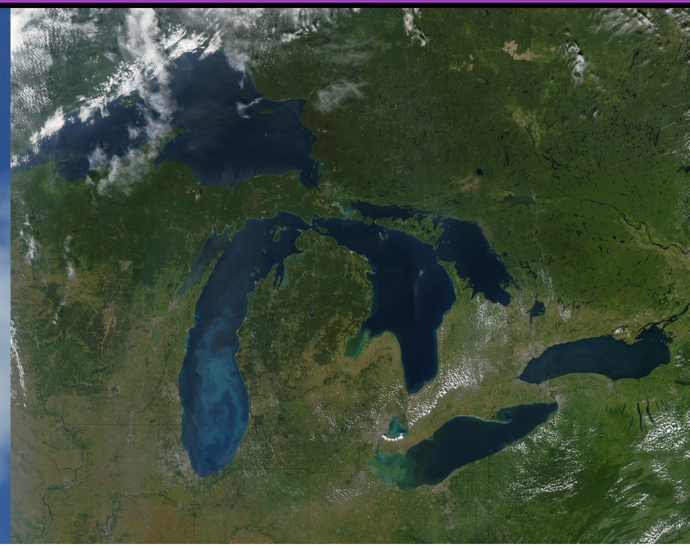




Societal Benefits in Weather, Water, and Climate: Understanding, Communication, and Enhancement





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Societal Benefits in Weather, Water, and Climate: Understanding, Communication, and Enhancement

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American Meteorological Society

Policy Program Study

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Foreword

This AMS Policy Program study explores the role of Earth system observations, science, and services (OSS) in modern society, particularly as they relate to weather, water (fresh and salt), and climate (WWC). In the broadest sense, the study has two overarching goals: 1) to improve understanding of the societal benefits of Earth system OSS and 2) to enable the enhancement of the societal benefits of Earth system OSS.

To support both goals, the study provides the background information necessary for understanding, communicating, and subsequently extending the societal benefits that result from OSS. We explore through broad qualitative examples ways that humanity uses Earth system OSS and provide a non-technical description of several economic concepts that enable systematic consideration of societal benefits. This also helps to develop a common vocabulary for internal and external partners and stakeholders. We then explore ways that societal benefits may be enhanced.

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

The complementary project components include **a study to characterize the value chain of WWC information and services** from observations, research (basic and applied), modeling, forecasting, dissemination, decision support, and other services through market transactions and the provision of non-market goods and services. This value chain study uses case studies to illustrate different ways that the value chain concept can help understand, communicate, and enhance societal benefits of Earth system OSS.

We have also begun **a study of policy issues** that could enhance or diminish the value of the WWC enterprise. This policy emphasis is critical because policy choices help to determine whether, when, and how information matters; how benefits and costs are distributed (who pays, who benefits, and how much); and a wide-range of additional factors that influence the advancement and use of information and services. As a result, the policy framework is hugely influential in determining the societal benefits that result from Earth system OSS.

Two policy areas have been particularly important for the WWC enterprise over the last half century and will require emphasis over at least the next decade: 1) policies that shape the distribution of roles and responsibilities among public, private, academic, and NGO communities within the enterprise and 2) policies that shape international collaboration through data sharing, particularly as we increasingly consider data from new sources and from different disciplines within the Earth system sciences. This study and the policy study explore aspects of these issues, but both are sufficiently complex to merit more focused attention as is the need for more comprehensive and sustained assessments of the enterprise's value.

Taken together, these studies will highlight the societal benefits that result from Earth system OSS and help identify unmet and emerging user needs in OSS. The studies will also provide a strong and overarching emphasis on public–private partnerships; most notably, the studies will help to refresh aspects of the 2003 Fair Weather report by the National Academies of Science, which has been foundational to the weather enterprise over the past two decades.

The final project element is to both draw on and build capacity within the enterprise itself (particularly that contained within the AMS community) to understand and enhance the societal benefits of OSS. We are working within the AMS meeting structure to engage the community (e.g., by helping to organize sessions on valuation in AMS annual and specialty meetings). We will also continue to actively engage the AMS community with working group discussions, by soliciting feedback on draft manuscripts, and through the distribution of completed studies. All of these approaches are intended to help draw on the considerable collective wisdom of the AMS community. The approaches can also work to empower valuation efforts within the broader AMS community, most notably the volunteer-driven efforts of the past decade.

The primary audience for this study is members of the WWC enterprise, but the study is accessible to external audiences that wish to have a more detailed understanding of the issues relating to OSS and societal well-being. We intend to develop a slightly modified version of the executive summary (~2 pages) that is intended for external partners.

Widespread understanding of the enterprise's value is critical because it has the potential to enable new opportunities to apply OSS for societal benefit, help determine public investments in OSS, and guide future investments in OSS to help ensure that they confer the largest possible benefit to society.

Executive Summary

Humanity is experiencing a period of rapid global change—defined here broadly to encompass the separate and combined impacts of technological, societal, and environmental changes occurring throughout the world. Meeting the challenges and opportunities associated with these global changes will depend on understanding, communicating, and enhancing the societal benefits of Earth system observations, science, and services (OSS).

Earth system OSS inform and guide the activities of innumerable institutions underlying modern civilization and virtually every social and economic sector. OSS are a foundational component of efforts to meet basic human needs, including having access to food, shelter, energy, and health and safety, among others. This makes OSS a basic building block for virtually all infrastructure nationally and globally. At the same time, the opportunities for societal benefit from OSS are increasing dramatically.

This study seeks to 1) characterize broadly the societal benefits of OSS, 2) identify the factors that limit the societal benefits of OSS, 3) develop approaches to enhance those societal benefits, and 4) communicate this information to internal audiences (i.e., the providers of OSS) and external partners (i.e., decision-makers, information users, the media, and the public).

Modern systems and physical infrastructure are built around capabilities in Earth system OSS. This allows cost savings and the realization of benefits that would otherwise not be possible. For example, the agricultural sector uses Earth system OSS to determine what crops to plant, which varieties to use, when to plant and harvest, and when to apply fertilizers, pesticides, and water. Water resource management relies on OSS to determine water availability, quality, and need. The energy sector relies on forecasts of summer heat and winter cold to predict consumer demands for energy and to avoid blackouts and heating fuel shortages. The transportation sector uses OSS to improve safety, reduce delays, and strengthen supply chains by optimizing routes for surface and airborne travel. Public health uses OSS to recognize when environmental conditions may lead to disease outbreaks or cause weather-related health impacts due to floods, heat waves, and extreme events. Disaster preparedness and response efforts rely on OSS for advance warning and ongoing assessments as extreme events occur (e.g., winter storms, droughts, hurricanes, tornados, floods, heat waves, singular environmental catastrophes like the Deepwater Horizon oil spill, and accumulating environmental damage and degradation). National security depends on OSS domestic safety and for strategic and tactical decisions involving the timing of military operations and the resource needs for troops. The Blue Economy—goods and services from the oceans and coasts—is critical to human needs but would be greatly diminished without OSS.

As a result, Earth system OSS comprise an asset that supports the whole of the national and global agenda. These capabilities are distributed across all levels of government (federal, state, local, and internationally), throughout an extensive and growing private sector, and in university research laboratories. Enhancements to Earth system OSS have

great potential to create new opportunities and to help overcome societal and environmental challenges.

Efforts to quantify these societal benefits—economic valuation—contribute to two critical yet somewhat distinct goals: 1) to promote deeper understanding of value and 2) to assist in decision-making. As a result, economic valuation is central to efforts to understand, communicate, and enhance the societal benefits of Earth system OSS.

There are a wide range of valuation tools and approaches that support these two goals, and it is important to understand what each can offer and how they may be constrained. Notably, different metrics or "numeraires" are more and less capable of capturing different aspects of value. For example, we might hope to understand connections to economic well-being, environmental quality, sustainability, social progress, societal well-being, quality of life, fairness, diversity and inclusion, aesthetic beauty, and so on.

In focusing on different aspects of value to society, each numeraire offers unique strengths and limitations. This is because the choice of any numeraire emphasizes and obscures different aspects of what matters to us. Of course, we all may value different things differently as well. Nevertheless, valuation inspires consideration of what matters to us, contributes to informed decision-making, and helps us systematically weigh trade-offs when we face them.

Valuation efforts are particularly useful for accounting simultaneously for market and non-market goods and services. Notably, physical and biological systems throughout the world provide both types of goods and services. "Ecosystem services" or "nature's contributions to people" often include basic life support services such as relatively stable weather patterns and climate; fresh water; purification of air, water, and soil; flood and drought control; and pollinators for crops, among others. Without valuation efforts, even critical goods and services are easy to overlook.

Valuation is also particularly helpful for identifying and addressing market failures—cases when market transactions lead to suboptimal outcomes. Addressing market failures is an opportunity for policies to enhance public well-being at no net cost overall.

Efforts to enhance the societal benefits of Earth system OSS are most effective when they recognize and account for linkages that permeate weather, water (fresh and salt), and climate (WWC) information and services. For example, benefits emerge from the combination of observations, science, and services—like a car's steering wheel or engine, each part is necessary, but the true value emerges from the whole of the vehicle. Additional linkages include those among observing systems (e.g., remotely sensed and in situ measurements); across planetary systems (e.g., oceans, atmosphere, hydrology, biological systems, the cryosphere, the lithosphere, space weather, and human systems); through partnerships involving the public, private, academic, and NGO sectors; in collaborations among nations throughout the world; and over weather and climate time scales that span seconds and minutes to days, weeks, months, decades, and centuries. Recognizing and accounting for these linkages is central to efforts to enhance societal benefits from OSS.

Linkages among public, private, academic, and NGO institutions are particularly important for the societal benefits of Earth system OSS. Each component of the enterprise contributes to societal well-being, albeit in very different ways, with different motivations, and with different limitations. Public investments are often foundational to goods and services provided by the private sector and to the advances that occur through academic research. At the same time, private, academic, and NGO communities contribute substantially to public well-being, often in ways that go beyond any possible contribution from another sector.

Valuation efforts reveal great potential to enhance the societal benefits from Earth system OSS. This potential can be realized through efforts to 1) provide actionable information; 2) prepare and empower information users; 3) create decision-support products and services that harness scientific advances for societal benefit; 4) build strong partnerships among stakeholders, practitioners, and information providers; 5) develop the next generation workforce; 6) recognize and account for linkages; 7) provide an effective policy framework for enhancing both the availability of information and society's ability to use it; 8) create, strengthen, and evolve partnerships among public, private, academic, and NGO communities; 9) engage and empower the public to demand, understand, use, and contribute to water information and services; and 10) reduce or eliminate market failures, when they occur.

The ongoing expansion in capabilities of and needs for Earth system OSS create tremendous opportunity that will benefit from careful management in the decades ahead. As one illustration, efforts to provide a truly integrated and digitally accessible understanding of the Earth system are evolving quickly and offer tremendous potential to leverage existing capabilities and serve increasing user needs.

Finally, periodic assessments of opportunities and challenges in the WWC enterprise will be needed. Here we suggest that AMS serve as a neutral convener for a rolling assessment process (e.g., a "septennial assessment") that brings together the public, private, academic, and NGO communities on a subdecadal time scale. This approach would seek to contribute to rather than duplicate ongoing and future assessment efforts.

1. Introduction

Humanity is going through a period of rapid global change, defined here broadly to encompass the individual and combined impacts of technological, social, and environmental changes now occurring throughout the world. Meeting the challenges and opportunities associated with these global changes will depend on efforts to understand, communicate, and enhance the societal benefits of Earth system observations, science, and services (OSS).

Earth system OSS inform and guide the activities of innumerable institutions underlying modern civilization and virtually every social and economic sector (AMS Policy Program 2012; Kull et al. 2021). Increasingly, OSS are a foundational component of efforts to meet basic human needs, including ensuring access to food, shelter, energy, and health and safety, among others. At the same time, the opportunities for societal benefit from OSS are increasing dramatically.

Earth system intelligence guides decisions in every social and economic sector of modern civilization

Finding: Measuring, understanding, and communicating the societal benefits (i.e., valuation) of Earth system OSS is challenging but critical for future advancements in capabilities and public service.

Earth system observations reveal a wide range of characteristics and functions of our planet and how humanity is causing environmental change throughout the world. The observing system consists of ground, oceanic, aerial, and satellite-based resources. We observe physical systems (e.g., weather events, the land surface, and coastal areas), biological resources (e.g., terrestrial and aquatic ecosystems), and social institutions (e.g., agriculture, the built environment, and urban areas) like never before. These systems, resources, and institutions underpin social and economic well-being.

Earth system sciences consist of basic and applied experiments conducted in the lab, field, or computer models that increase our knowledge and understanding of the Earth system. This knowledge and understanding alerts us to societal risks, informs risk management decisions, and creates new opportunities for societal advances.

Earth system services synthesize our knowledge and understanding of the Earth system (based on observations and science) and apply that knowledge to improve social and economic well-being. Services include weather forecasts of routine conditions and extreme events, assessments of fire risk, flood and drought monitoring and prediction, tsunami modeling and forecasting, natural hazard preparedness and response, public health warnings, disease prevention and control, identifying and understanding global environmental change (e.g., climate change), and decision support for policy-makers in water resources, agriculture, transportation, health, environmental sustainability, and to all other social and economic aspects of modern life. People working in the public, private, academic, and non-governmental organization (NGO) communities contribute to these services.

OSS enhance social and economic well-being. For example, the *agricultural sector* uses OSS to determine what crops to plant; which varieties to use; when to plant and harvest; and when to apply fertilizers, pesticides, and water. The *energy sector* relies on forecasts of summer heat and winter cold to predict consumer demands for energy and to avoid blackouts and heating fuel shortages. OSS also help decision-makers identify and ameliorate harmful unintended consequences of energy production and use, such as the public health consequences associated with air pollution and climate change.

Water resource management relies on OSS to determine water availability, quality, and need. Observations of temperature, precipitation, humidity, soil moisture, and streamflow provide a basis for flood warnings, operation of water management systems, water quality protection, floodplain mapping, and the design of critical infrastructure (e.g., bridges, levees, and dams).

Humanity is experiencing a period of rapid global change due to large shifts in technology, society, and the environment

Disaster preparedness and response efforts rely on OSS for advance warning of impending extreme events (e.g., winter storms, droughts, hurricanes, tornados, floods, and heat waves) and for the assessment of the extent and duration of natural and human-induced disasters. The *public health sector* uses Earth system OSS to recognize when environmental conditions may lead to disease outbreaks or cause weather-related health impacts due to floods, heat waves, and extreme events.

The *transportation sector* uses OSS to improve public safety, reduce travel delays, and strengthen supply chains by optimizing routes for surface and airborne travel. For example, aviation is a multi-billion-dollar industry worldwide. Delays, cancellations, and diversions cost commercial airlines hundreds of millions of dollars a year in the United States alone. Weather forecasts increase efficiency and safety of flights. For example, advance notification of convection allows aircrews to reroute around storms. This reduces the need for inefficient, last-minute rerouting, which saves fuel and thereby reduces costs and emissions.

National security depends on OSS for strategic and tactical decisions involving the timing of military operations and the resource needs for troops. Furthermore, national security issues arise in parts of the world where weakened or failing states experience acute weather events, natural disasters, and climate variability and change. OSS help spot these troubled regions and allow targeted efforts to provide humanitarian aid or otherwise manage conflicts with potential to spread.

Goods and services connected to the *oceans and coasts*—the Blue Economy—also contribute critically to human society and well-being (Spalding et al. 2016). The dynamic nature of ocean environments means that much of the economic activity related to the oceans depends on information and understanding derived from ocean observations, science, and services (R. Raynor 2021, unpublished manuscript). Furthermore, the benefits from ocean OSS often extend far inland because prediction of routine and extreme weather events, particularly extended forecasts, depends on information of oceanic conditions.

Modern systems and physical infrastructure are often built around current capabilities in OSS. This allows cost savings and the realization of benefits that would otherwise not be possible. As a result, OSS comprise an asset that supports the whole of the national and global agenda. These capabilities are distributed across all levels of government (federal, state, local, and international), throughout an extensive and growing private sector, and in university research laboratories. Enhancements to OSS have great potential to create new opportunities and to help meet growing societal needs.

Earth system intelligence is an asset that supports the whole of the national and global agenda

Finding: Earth system observations, science, and services guide decisions in every social and economic sector of modern civilization.

This study and its key findings (Figure 1) and recommendations (Figure 2) seek to 1) characterize broadly the societal benefits of OSS, 2) identify the factors that limit the societal benefits of OSS, 3) develop approaches to enhance those societal benefits, and 4) communicate this information to internal audiences (i.e., the providers of OSS) and external partners (i.e., decision-makers, information users, the media, and the public).

Figure 1. Key Findings

1) Earth system observations, science, and services (OSS) guide decisions in every social and economic sector of modern civilization.
2) Measuring, understanding, and communicating the societal benefits (i.e., valuation) of Earth system OSS is challenging but critical for future advancements in capabilities and public service.
3) Societal benefits of Earth system OSS depend on complex linkages and interdependencies, including those among
    a) observations, data assimilation, research, modeling, and services;
    b) scientific disciplines (physical, natural, and social) involved in understanding the Earth system and humanity's interactions with it;
    c) weather, water (fresh and salt), and climate opportunities and challenges;
    d) time scales spanning from seconds and minutes to decades and centuries;
    e) the public, private, academic, and NGO communities; and
    f) the international community.
4) Basic economic principles related to valuation are well established but not widely understood. Economic analysis is not always incorporated sufficiently or systematically into efforts to advance OSS capabilities.
5) A wide range of stakeholders depend on and contribute to Earth system OSS capabilities. These include providers of OSS, decision-makers who enable and fund OSS, users of OSS, and the public. All are key partners in the enhancement of societal benefits, but each audience requires information tailored for their specific backgrounds and needs.
6) A range of approaches are needed to engage with different audiences. This range almost certainly spans qualitative descriptions (e.g., compelling storytelling), and rigorous quantitative economic analyses.
7) Efforts to enhance societal benefits of OSS sometimes involve difficult trade-offs, uncertain futures, and value-laden preferences over which people can disagree and for which information is critical but not an exclusive determining factor.
8) Four types of goods and services contribute to public well-being (public, private, common resources, and natural monopolies). There can be overlap among them.
9) Society has some control (often limited) over which types of goods and services are which (e.g., public vs private goods and services). These choices involve trade-offs that need to be considered carefully and will likely evolve over time as capabilities, needs, and interests shift.
10) Market failures are instances when the private interests of a decision-maker are at odds with overall societal well-being (e.g., the decision-maker benefits but with net benefits that are less than the net cost to someone else).
11) Correcting market failures is a major opportunity to advance societal well-being because the cumulative benefits of doing so exceed the cumulative costs.
12) Identifying and correcting market failures, when deemed appropriate, is a central role of the public sector.
13) Views and interests about when correcting market failures "is appropriate" and how to do so can vary even while benefits exceed costs. This is because distributional consequences are often uneven (i.e., there will be winners and losers) and because the pursuit of economic efficiency (i.e., maximizing net economic benefit) is one of many subjective values over which people may disagree.
14) Public, private, academic, and NGO institutions all contribute to societal well-being, albeit in very different ways, with different motivations, and with different limitations or constraints. For illustration (simplified here as roles do overlap):
    a) The public sector corrects market failures; provides long-term vision, infrastructure, and resources; helps to recognize and enable key linkages; and invests in high-risk, broadly beneficial outcomes.
    b) The private sector provides goods and services efficiently through market transactions.
    c) The academic community advances knowledge and understanding and builds workforce capabilities.
    d) The NGO community enables social change and humanitarian efforts beyond those provided by the public sector.
15) There is no single "best" way to distribute roles among the public, private, academic, and NGO communities. Any distribution involves trade-offs and value judgments over which interests and preferences will often vary.
16) Roles and responsibilities among public, private, academic, and NGO communities will almost certainly shift over time as capabilities, interests, and needs continuously evolve.

2. Types of Goods and Services

Societal benefits, like those described above, can be aggregated and categorized in several different ways. Two categories of goods and services are particularly useful for considering societal benefits (value): those that are bought and sold (*market* goods and services) and those that are not for sale (*non-market* goods and services) but that provide benefits to people nevertheless.

Market goods and services include anything that can be purchased with money—food, energy, transportation services (bikes, cars, taxis, and on buses, trains, and planes), durable goods, housing and household appliances, and so on.

Non-market goods and services include anything that is not exchanged in market transactions. Examples include clean air, a scenic view, environmental stability, and sustainable resource stocks (e.g., fish and timber).

Physical and biological systems throughout the world provide a vast range of both market and non-market goods and services (Daily 1997; National Research Council 2005; Kadykalo et al. 2019; Chan and Satterfield 2020; R. Raynor 2021, unpublished manuscript). These goods and services (often called ecosystem services or nature's contributions to people) can be particularly relevant to the valuation of Earth system OSS. Market goods and services include natural resources, food, energy, fiber, and building materials. Non-market goods and services include numerous basic life support services such as relatively stable weather patterns and climate; fresh water; purification of air, water, and soil; flood and drought control; and pollinators for crops, among others.

Valuation is foundational to understanding, communicating, and enhancing societal benefits

In many cases, these physical and biological resources would be either difficult or impossible to replace but, paradoxically, are also relatively easy to take for granted because they are foundational, are readily available, and can seem inexhaustible (National Research Council 2005). We do not always recognize or account for the value of these goods and services and, too often, incentives for individuals and the broader society can be misaligned (see discussion of market failures below). As a result, when they are lost or exchanged to produce market goods and services, there can be severe economic harm.

Valuation efforts can help address this "economic invisibility of nature," the tendency to disregard the economic importance of naturally occurring goods and services provided freely. To illustrate, when mangroves in Indonesia are replaced by shrimp aquaculture farms, a seemingly profitable business for the region, valuation efforts reveal that this is economically harmful. The benefits of non-market services provided by mangroves, including coastline protection, prevention of saltwater intrusion, fish breeding grounds, and carbon sequestration far outweigh the economic benefit of shrimp harvesting (Malik et al. 2015). When mangroves are removed, expensive alternatives for coastline protection become necessary to replace the lost service. Similarly, costly substitutes for the prevention of saltwater intrusion become necessary and potable drinking water must be supplied to local communities when mangroves are disturbed or removed.

Valuation efforts often have two related but somewhat distinct goals: 1) to promote deeper understanding of value and 2) to assist in decision-making (Chan and Satterfield 2020). These apply to both market and non-market goods and services. Importantly, the effectiveness and applicability of different approaches to valuation depends on the goal.

Generally speaking, non-market valuation is often an attempt to bring the importance of public goods into the discussion of policy choices in ways that combine both objectives (i.e., to improve understanding of benefits that could otherwise be easily overlooked and to assist with decisions that can result in their preservation or enhancement).

Economists have a wide range of tools for the valuation of non-market goods and services (Kriström and Johansson 2015; WMO et al. 2015; Lazo and Mills 2021, unpublished manuscript), though a detailed exploration of these tools is beyond the scope of this study. Nevertheless, it is useful to recognize that stated and revealed preferences (and the interpretation of them) can be influenced by the framing of questions, method of valuation, the underlying assumptions or goals of the valuation effort, and the cognitive challenge needed in considering values comprehensively—i.e., based on all of its potential forms and contributions (Fischhoff 1991; Gregory et al. 1993; Chan and Satterfield 2020).

Finding: Basic economic principles related to valuation are well established but not widely understood, and economic analysis is not always incorporated sufficiently or systematically into efforts to advance OSS capabilities.

Recommendation: Engage economists and other social scientists as true partners in the weather, water (fresh and salt), and climate enterprise to develop rigorous quantitative analyses that inform, correct, and build on qualitative descriptions of value.

At first glance, quantifying the value of market goods and services may seem relatively straightforward because an exchange occurs and that exchange is measured in a metric of valuation (e.g., currency such as U.S. dollars) that is widely understood. However, there are two challenges that economic analyses work to address and that are useful to consider when trying to understand value or make decisions among competing options.

First, the total value of any good or service is generally not well captured by the price of an exchange for it (i.e., the market transaction). Rather, the price captures only the value of the last unit exchanged—the marginal value, which is the lowest price at which any seller is willing to provide the good or service and the highest price for which any buyer is willing to pay for the good or service. The price of each unit of the good or service is set to this marginal value. Therefore, the value of each previous unit exchanged is generally expected to be higher than the price.

The total value of a good or service is the summation of the cost that any buyer would pay for each unit of the good or service (i.e., the price that anyone would be willing to pay for every unit exchanged). The price of drinking water, as opposed to the value of drinking water, illustrates this point. The first few liters of water are exceedingly valuable because life could not exist without them. Each of us would be willing to pay an inordinate amount for those first few liters because they are the difference between life and death for us and anything living that we care about. However, water is relatively abundant in developed countries and the price is determined by the value of the last liter exchanged, not the first. Consumers are willing to pay much less for a liter of water after already consuming hundreds of liters because the value of that additional liter is much less when it will be used to water a houseplant, wash the car, or spend an extra minute in the shower. Note also that, in this example, the willingness to pay is bounded by an individuals' net worth and/or future earning potential, which touches on potentially important philosophical and ethical questions with respect to valuing basic life-support services among people whose wealth differs.

Modern systems and physical infrastructure are often built around capabilities in weather, water, and climate

Nevertheless, the total value of water to the consumer includes those exceedingly valuable first few drops. Therefore, the total value is not directly measurable by market transactions and may be challenging to estimate in some cases. The total value of a good or service is generally much higher than the sum of all market exchanges for that good or service, and additional valuation methods are needed to understand, assess, and communicate value.

Note that the importance of this distinction between marginal value and total value may be more important when the goal of the valuation effort is to promote understanding and may be less critical when the goal is to facilitate decision-making among competing options. This is because decision-making often involves trade-offs at or close to the margin (e.g., whether we want more of one good or service or another) rather than an all or nothing decision as is implicit for total value.

A second issue is that the unit of measure we use, particularly but not exclusively for market transactions (e.g., U.S. dollar or other currencies in most cases), is only one of the possible measures of value, and any measure of value likely captures some of what people care about more effectively than others. It is certainly possible to convert, to a large degree, among measures of value, but not perfectly. While useful in many respects (particularly for allowing quantitative comparisons among different people and enabling the consideration of trade-offs), there are diverse conceptions of value (Pascual et al. 2017), and currency is not the only metric for capturing what matters to people. This becomes particularly evident when we consider non-market goods and services.

Currency is meaningful to people because we have experience exchanging it in market transactions. It is particularly valuable for considering trade-offs in decision-making because we use it that way routinely. On the other hand, currency is unrelated to many of the things that people value greatly, such as loving relationships and friendship, membership in a community, possession of a sense of meaning, a connection to one's ancestors and future generations, knowledge and understanding, capability and talent, equity, fairness, access to opportunity, self-determination, appreciation of natural beauty, etc. It is not entirely intuitive or straightforward to convert these valuables into dollar equivalents, though many tools are at least partly able to address this issue for some conceptions of value (WMO et al. 2015).

There are also limits and trade-offs with aggregated metrics used to measure economic well-being and their application to assessments of societal well-being more broadly. For example, gross domestic product (GDP) is often used as a proxy of societal well-being, as it generally captures economic development, which is a reasonably effective predictor of societal progress, particularly for nations with lower per capita income (SPI 2020). However, GDP is also limited, in part, because it measures only economic activity (i.e., how much is exchanged in markets). This can obscure some components relating to value or emphasize market goods and services relative to non-market goods and services (Bagstad and Shammin 2012; SPI 2020; Stern et al. 2020; Raworth 2012; Stiglitz et al. 2009).

The choice of metric can emphasize or obscure aspects of value that are important to people

For illustration, GDP generally increases with natural disasters because expenditures of money occur when communities rebuild. What cannot be captured by GDP is the cost of the destruction and damage to property, lives, livelihoods, relationships, and physical and natural systems—not all of which is captured completely in market transactions (or incorporated into aggregated measures such as GDP). Similarly, GDP increases even when an extremely valuable non-market good or service (e.g., clean air, sustainable fish stocks, a stable climate, the goods and services provided by biological systems, and so on) is converted into something that can be exchanged in a market transaction. A loss in value of non-market goods and services could exceed any gain in value of market goods and services, but GDP would still increase as a result.

Metrics for measuring value might include (or try to capture) economic well-being (e.g., currency, GDP, employment); environmental quality/sustainability (willingness to pay for environmental protection; species richness; biodiversity; habitat quality or its opposite: habitat destruction, degradation, and fragmentation); social progress (SPI 2020) or specific indicators of quality of life (income inequality, measures of development, lives saved, opportunity for personal growth, connection to community, happiness); culture, diversity, or connection with cultural heritage or ancestry; aesthetic beauty; societal well-being (e.g., democratic rule, the rule of law, interdependence, fairness); and so on. All such "numeraires" have limitations, and the choice of any numeraire can emphasize or obscure aspects of value that may or may not be important to some people. Of course, people are also individuals and will almost certainly value different things in different amounts and different ways (Pascual et al. 2017). Therefore, the choice of numeraire is dependent on the question being asked or the purpose of the use of the metric.

Recommendation: Integrate multiple perspectives of value and use a hierarchy of valuation methods to understand and describe the societal benefits of Earth system OSS, including rigorous quantitative analysis and qualitative descriptions, anecdotes, or stories. All such efforts should inform one another and provide an accurate, consistent, harmonized, and compelling understanding of the value of Earth system OSS. They are likely to be most effective for enhancing public good when focused on public interest.

Different metrics or "numeraires" are more and less capable of capturing different aspects of value

It is also important to recognize that any approach to valuation necessarily incorporates subjective judgments that may not be equally relevant in all cases. For example, choices relating to the appropriate distribution of costs and benefits across generations, methods of pricing non-market goods and services, and the approach to calculating social welfare all embed value judgements that might be no better (or worse) than alternative options that produce different results (DeCanio 2003; Ackerman et al. 2009; Higgins 2014). On the other hand, valuation efforts provide a rigorous framework that enables us to better understand the benefits of goods and services and to make thoughtful, if imperfect, choices involving trade-offs among competing options.

Finding: A wide range of stakeholders depend on and contribute to Earth system OSS capabilities. These include providers of OSS, decision-makers who enable and fund OSS, users of OSS, and the public. All are key partners in the enhancement of societal benefits, but each audience requires information tailored for their specific backgrounds and needs.

Finding: A range of approaches are needed to engage with different audiences. This range almost certainly spans qualitative descriptions (e.g., compelling storytelling), and detailed, rigorous, quantitative economic analyses.

Finding: Efforts to enhance societal benefits of OSS sometimes involve difficult trade-offs, uncertain futures, and value-laden preferences over which people can disagree and for which information is critical but not an exclusive determining factor.

Recommendation: When faced with difficult choices and uncertain futures, use approaches that combine many pilot projects, rapid detection of success and failure, iterative processes that allow for updating, and dissemination of lessons learned so that successes can be replicated and failures avoided.

Relatedly, market and non-market goods and services can also be categorized into four types based on “rivalry” and “excludability.” These four types of goods are public goods, private goods, common resources, and natural monopolies.

Rival and non-rival

A good or service is “rival” if its use by one entity makes it unavailable for another. For example, seafood is a rival good because once it is eaten by a person it is unavailable to anyone else. A good or service is non-rival if its use by one entity leaves it unchanged and equally available for another. For example, a weather forecast on television or radio is not used up by any one person who watches or hears it.

Excludable and non-excludable

Public goods are often foundational for the availability of private goods

A good or service is “excludable” if it is possible to prevent someone from using it (e.g., those who do not pay for something cannot benefit from it). For example, a watchmaker can provide watches only to those who pay for them, thereby excluding anyone who does not buy a watch from having one. Similarly, private companies can restrict access to observations or forecasts to those who purchase them. A good or service is non-excludable if anyone can benefit from it whether or not they pay to have it. For example, a public clock tower provides information about time for everyone to see. Similarly, publicly accessible observations or data are available to everyone. In this case, the access to time information from the clock tower or weather observations is non-excludable. Similarly, severe weather advisories provided by the National Weather Service are available to everyone (i.e., are non-excludable) whereas private sector forecasts can be restricted to those who pay for them.

Public goods are both non-rival and non-excludable. Those who use them do not prevent others from using them and no one can be prevented from doing so. For example, air; FM/AM radio broadcasts; network TV; and publicly available scientific research, knowledge, and understanding are partly or completely public goods (note: patents partly convert knowledge and understanding into other types of goods as opposed to publicly available information). A key issue about public goods discussed below is that private companies and market forces will not provide them in sufficient supply (i.e., that maximizes economic well-being) because the full value of public goods and services cannot be collected through market transactions. This is another important type of market failure—the inability of unregulated markets to provide maximum economic benefit because some of the benefits (or costs) associated with the good or service are external to the entities who participate in the transaction (see discussion of externalities below).

Public goods are often foundational for rival and excludable goods (i.e. private goods and services). For example, public data such as Earth system observations from satellites or in situ measurements are routinely incorporated into private weather forecasts. Public investments in scientific research lead to advances in knowledge and understanding that get incorporated into new products and services. This foundational role of public goods is often easily overlooked. The incentive for private companies is to underinvest in public goods and services because the benefits are broadly distributed and not monetized by those who participate in market transactions. At the same time, private entities have diminished incentives to provide goods or services that are already provided as a public good.

Private goods are both rival and excludable. Those who use them must pay for what they use and those who provide them can prevent anyone who does not pay from using it. Examples include food, clothing, housing, and the opportunity to attend a particular college or university. Private companies in the weather sector provide specific forecasts that can create competitive advantage for those who purchase them. Critically, there is a financial incentive for private companies to provide these forecasts when there are buyers for them. Note, however, that the availability of some public forecasts diminishes the potential for private entities to sell forecasts and this reduces the incentive for doing so. As a result, any attempt to maximize public well-being involves a complex balancing act of the public and the private provision of goods and services.

Environmental intelligence alerts us to danger, informs risk management choices, and creates new opportunities for societal advancement

Note also that goods can simultaneously have private and public components. For example, the knowledge a person gains through attending a college or university benefits them personally (a private good) while also creating public goods in the form of the increase in that individual's capacity to provide benefits to the broader society. This public good constitutes a positive externality of education and job training (see market failures discussion below). The person who chooses to pursue that education and training benefits directly from the future earnings and career enhancement that follows, but much of the societal benefit of increased worker capacity is external to the individual. As a result, we would expect public investments in education and training to be effective at enhancing public interest.

Common resources are rival and non-excludable. Those who use them prevent others from doing so, but no one can be prevented from using whatever good or service exists. This includes unregulated natural resources (fish in the ocean, timber, and, possibly, fossil fuels). Common resources are prone to overexploitation because individual decision-makers have incentives that conflict with the public overall (see split-incentive market failures discussion).

Natural monopolies are non-rival and excludable. Those who use them do not prevent others from using them, but those who provide them can exclude those who do not pay for them from use. Examples include, satellite or subscription television, tourism at private nature reserves, and private weather forecasts.

As already alluded to, there can be hybrids and exceptions among these four types of goods. For example, the U.S. Postal Service provides a combination of public and private goods, as do the U.S. healthcare and education systems. Regulation can also alter the type of good that something is. For example, regulated utilities and national flood insurance programs set or control prices and/or business practices on goods and services provided by private companies. Regulation of natural resources (e.g., fishing) through quotas also shifts an ocean fish stock from being a common resource toward being a private good.

Critically, there is no single approach to the provision of goods and services that will be most effective in serving public interest in all cases. The provision of public goods can help to ensure widespread access among all people. However, provision of public goods reduces the financial incentive for private sector entities to provide similar or enhanced services. In some cases, public provision of goods and services increases their availability and enhances what the private sector is able to provide, and in other cases it can prevent or diminish what the private sector makes available.

There is no single approach to the provision of goods and services that will be most effective in serving public interest in all cases

This also illustrates that policy choices can determine a type of good or service. For example, a society that provides universal education has determined that education will be non-rival and non-excludable (at least for the publicly available option). A society that leaves education entirely to the private sector ensures that educational services will be excludable. Note that the services provided by individual teachers, schools, and school districts are rival to the extent that classes, schools, or counties are limited in the number of students that can participate. Online courses may, to a degree, make individual teachers and classes non-rival.

Finding: Four types of goods and services contribute to public well-being (public, private, common resources, and natural monopolies). There can be overlap among them.

Finding: Society has some control (often limited) over which types of goods and services are which (e.g., public vs private goods and services). These choices involve trade-offs that need to be considered carefully and will likely evolve over time as capabilities, needs, and interests shift.

3. Market Failures and the Value of Earth System OSS

As described above, the concept of market failures is particularly relevant to discussions of societal benefit from Earth system observations, science, and services. Market failures result when individual decisions that optimize well-being from the perspective of the individual making the decision lead to suboptimal economic outcomes for the larger society. Correcting market failures is one of the unique roles of the public sector that can enhance the societal benefits associated with OSS.

Six market failures are particularly noteworthy for OSS (Higgins 2010):

1. Externalities, where the full costs or benefits associated with an activity are not entirely reflected in the price paid (or benefit received) by the agent who decides whether to engage in a particular activity. For example, the return on investments in research, education, infrastructure, and environmental protection include the contributions they make to non-market goods and services. A profit-maximizing entity would not consider these returns and will therefore be expected to underinvest.

2. Split incentives, in which the narrow interests of a decision-maker are maximized when creating higher costs (or lower benefits) for someone else. For example, the incentive for a contractor to minimize the cost of capital equipment could result in the selection of equipment with higher operating costs, a short lifespan, or diminished capabilities even if the savings to the contractor are small by comparison.

3. Imperfect information, in which decision-makers do not know or understand their options and the implications of their choices. For example, we cannot know the full spectrum of societal benefits that will result from investments in OSS infrastructure. As a result, there is a tendency for investments to be suboptimal in magnitude and for investment decisions to be imperfect.

4. Monopoly power, which limits consumer choices for potentially desirable alternatives. For illustration, people might demand additional capabilities associated with larger investments in geostationary observations, but we cannot know that in the absence of those observations.

5. Long-lived (fixed or immobile) factors of production, which lock in technologies or infrastructure because the existing capital stock reduces responsiveness to market signals.

6. Nonexistent markets for public goods (e.g., climate stability) because the private sector simply cannot provide and price public goods.

Physical infrastructure is built around our capabilities in Earth system observations, science, and services

It is also important to recognize that the discussion of market failures (and more generally with the choice to use economic tools or to emphasize economic concepts) implicitly embeds value judgments. Implicit in the choice to use market-based mechanisms is that economic efficiency is an overarching goal (Higgins 2010). This can make sense because economic efficiency generally promotes overall economic well-being—assuming that "economic well-being" is defined comprehensively and recognizing that distributional consequences must also be considered. In short, economic efficiency means that no one can be made better off without making anyone else worse off. As a result, efforts that improve economic efficiency can increase overall economic well-being (i.e., by realizing greater benefits in aggregate than losses and assuming those benefits are distributed equitably).

Improving economic efficiency can increase overall economic well-being but there may be winners and losers

However, other values matter to people and, as described above, measures can only capture portions of what people value. For example, people care greatly about, but rarely agree on, issues of fairness, equity, and justice; the importance of cultural heritage; ethical standing of non-human species; and how to balance interests of people from different locations or future times or across social and economic status. These issues and the different perspectives people have on them can be overlooked by efforts to correct market failures and thereby improve economic efficiency.

On the other hand, correcting market failures does mean that more resources are available to a society, and those resources could be used to address a range of issues. This is because market mechanisms are, in principle, the most economically efficient approaches (i.e., they can be expected to result in the greatest amount of benefit for the least cost or, equivalently, the most benefit for a given cost).

Finding: Market failures are instances when the private interests of a decision-maker are at odds with overall societal well-being (e.g., the decision-maker benefits but with net benefits that are less than the net cost to someone else).

Finding: Correcting market failures is a major opportunity to advance societal well-being because the cumulative benefits of doing so exceed the cumulative costs.

Finding: Identifying and correcting market failures, when deemed appropriate, is a central role of the public sector.

Finding: Views and interests about when correcting market failures "is appropriate" and how to do so can vary even while benefits exceed costs. This is because distributional consequences are often uneven (i.e., there will be winners and losers) and because the pursuit of economic efficiency (i.e., maximizing net economic benefit) is one of many subjective values over which people may disagree.

Figure 2. Key Recommendations

Valuation and Communication of Societal Benefits:

1) Integrate multiple perspectives of value and use a hierarchy of valuation methods to understand and describe the societal benefits of Earth system OSS, including rigorous quantitative analysis and qualitative descriptions, anecdotes, or stories. All such efforts should inform one another and provide an accurate, consistent, harmonized, and compelling understanding of the value of Earth system OSS. They are likely to be most effective for enhancing public good when focused on public interest.
2) Engage economists and other social scientists as true partners in the weather, water (fresh and salt), and climate enterprise to develop rigorous quantitative analyses that inform, correct, and build on qualitative descriptions of value.
3) Recognize the need to combine humility and confidence with complex and value-laden endeavors such as understanding, communicating, and working to enhance societal benefits of OSS.
4) Create decision-making processes for providing Earth system OSS that incorporate the best available information while recognizing that all such choices cannot be determined by information alone as they involve interests and values.
5) When faced with difficult choices and uncertain futures, use approaches that combine many pilot projects, rapid detection of success and failure, iterative processes that allow for updating, and dissemination of lessons learned so that successes can be replicated and failures avoided.
6) Develop integrated, digitally accessible syntheses of Earth system observations and understanding.

Partnerships among Public, Private, Academic, and NGO Sectors:

7) Enable careful consideration of roles and collaboration among the enterprise sectors (i.e., as called for in the National Research Council's 2003 Fair Weather Report).
8) Strengthen and enhance discussions among the sectors that promote the exchange of perspectives, understanding, and trust.
9) Enable long-term and iterative engagement with periodic updating of roles and responsibilities among public, private, academic, and NGO communities.

International Collaboration:

10) Recognize that interests, incentives, and approaches for the provision and use of Earth system OSS among nations will not always align.
11) Promote international collaborations that recognize and embrace complexity associated with differing interests, priorities, capabilities, and perspectives and the importance of continuously revisiting interests and preferences over time.
12) Maintain and enhance international dialog for coordination and collaboration on the full range of disciplines involved in Earth system OSS.

Community Leadership and Empowerment:

13) Foster mechanisms to discuss, revise, and update roles and responsibility throughout the enterprise.
14) Seek ways to promote adaptive capacity in the face of rapid global changes associated with technological development, societal change, and environmental degradation.
15) Promote a shared sense of urgency, vision, and opportunity to extend Earth system OSS capabilities and to enhance the resulting societal benefits. Enable updating over time.
16) AMS should facilitate a periodic (e.g., septennial) community assessment that brings together members of the enterprise for discussions of options, needs, opportunities, and priorities to enhance OSS and the societal benefits that result.

4. Societal Well-Being and the Public, Private, Academic, and NGO Communities

There is an important distinction between *public goods and services* (non-rival and non-excludable goods and services) and the contribution that all goods and services make to societal well-being. Critically, each of the four types of goods and services contributes to societal well-being, and each of the four types of goods and services has value.

Finding: Public, private, academic, and NGO institutions all contribute to societal well-being, albeit in very different ways, with different motivations, and with different limitations or constraints.

The public sector provides goods and services that would not be available (or that would be less available) based on market forces alone. This includes investments in research and observations or providing public goods and services. For example, the cost of some satellite observing systems is a barrier to provision by the private sector. Similarly, user demand for such data may initially be insufficient for private sector investment. Once made available through public investments, such data can enable a wide range of private sector uses.

The public sector is also unique in being able to establish limits on market transactions (e.g., allowing, prohibiting, and regulating market transactions based on ethical, pragmatic, or efficiency concerns) and in correcting market failures like those described in the previous section. In many instances, including with respect to OSS, the public sector provides foundational infrastructure, information, and services that support all other sectors within the enterprise.

The private sector contributes to societal well-being by creating and providing goods and services (at least cost) that people purchase through market transactions. As described above, these goods and services provide value to consumers, and the total value of such goods and services almost invariably exceeds the aggregated price of all exchanged goods and services. Provision of goods and services by the private sector is generally economically efficient (barring the occurrence of market failures—which is a large caveat). In the event that a good or service could be provided more efficiently (at higher quality or lower cost), another private sector company would be expected to do so and to outcompete those who cannot. On the other hand, the private sector has no incentive to provide goods or services (even those of great value) that cannot be fully accounted for through market transactions.

The academic community increases knowledge and understanding through research and helps to educate members of society at a variety of scales (e.g. students, communities, practitioners, and professionals) and to develop workforce capability. Of course, other sectors also contribute directly (e.g., employee training in the private sector and national labs) and indirectly (through grant funding and by providing jobs for those with skills). Universities are hubs of collaboration and innovation, and the incentives are often aligned to enhance public good. This includes a broad tendency to enable the open exchange of ideas and information and to promote engagement and cooperation across disciplines, enterprise sectors, and the public.

The NGO community contributes to societal well-being by providing social, humanitarian, educational, and environmental services and other charitable functions, and by providing resources and encouraging social change. As before, this role can be identified in activities of the other sectors, but it is a primary emphasis of the NGO community. NGO work can be both independent of political or for-profit efforts or done in partnership. NGOs can also play a neutral role in challenging discussions involving other enterprise sectors.

Of course, partnerships among these sectors routinely occur (National Research Council 2003), such as government investments in academic research and teaching, and partnerships between governments and NGOs, through regulation, procurement, and the establishment of rules and regulations governing practices throughout the sectors. Furthermore, the roles and responsibilities of each of the sectors can (and almost certainly will need to) shift over time as capabilities, interests, opportunities, and challenges shift.

This is best illustrated by considering the range of roles that the public sector takes under different conditions. In some instances, the public sector provides goods and services directly either because there is no incentive for other sectors to do so, because public interest makes the public provision of goods and services imperative, or because society has deemed access to specific goods and services a basic right (e.g., life-threatening hazard warnings, healthcare services, mail delivery, etc.).

This role is particularly important when profit-seeking organizations lack an incentive to provide valuable goods and services equitably or at all. In other instances, the public sector regulates those who provide services. There are no public restaurants, for example, as governments do not seek to compete with private entities but instead regulate them; create and enforce laws related to health, hygiene, labor, and advertising; and oversee their activities.

Additional examples can round out the range of roles the public sector can have. Universal access to K–12 education, emergency healthcare and universal access to vaccines, investments in scientific research, and public libraries represent instances in which the country has decided that goods and services that might be provided exclusively by the private sector should instead be available as public goods.

Those decisions do have potential implications for what goods and services may be available. For example, it becomes more difficult to create a business that will provide goods and services if those goods and services are provided for free by the public sector. Under different conditions (at different times or places) different roles for the public sector can most effectively enhance (or inhibit) societal well-being. As a result, a key opportunity for enhancing the societal benefits of OSS will be to navigate partnerships over time as opportunities and challenges shift.

A perpetual challenge in collaboration is that the members of the enterprise have differing perspectives on the most appropriate and effective distribution of roles and responsibilities (National Research Council 2003). This will almost certainly remain true even as the optimal configurations of roles for the purposes of advancing public interest shift over time as capabilities and interests shift among the sectors.

Notably, many of the conclusions from the National Research Council's Fair Weather Report (National Research Council 2003) continue to apply today. For example, the report recognized that it would be "counterproductive and diversionary to establish detailed and rigid boundaries for each sector outlining who can do what and with which tools. Instead, efforts should focus on improving the processes by which the public and private providers of weather services interact."

Over the last 15 years, these words have been verified with the continuing evolution of the enterprise. New businesses have entered and begun to provide a wider range of services. They will almost certainly continue to apply for the foreseeable future as a rapid period of technological, societal, and environmental change continues or even accelerates.

One area where the conclusions of the Fair Weather Report may need further attention based on subsequent events is with respect to commercially available data. New capabilities and business opportunities lead to rapid changes in what the private sector is able to provide. For example, recent increases in small satellite capabilities, opportunities through commercial data purchases, and legislation requiring or enabling these data buys are creating a rapidly shifting landscape that brings complex challenges and opportunities.

Notably, this issue of commercial data has implications for partnerships among public, private, academic, and NGO communities, and for international collaboration (described in the next section). Free access to data (i.e., public data) is a foundation for numerous private and academic sector activities and advances. However, making data freely available can increase the cost of data acquisition for public entities or reduce the incentive for commercial providers to enter the market (and thereby limit the data that is available). A shift away from data sharing could also reduce the availability of data from patterns, particularly internationally. Issues also arise with quality assurance and quality control as the approaches to data acquisition change.

A second area where the conclusions of the Fair Weather Report may need updating is with the expanding areas of interest among private sector companies across the entire value chain. Private sector roles and capabilities are considerably more varied and advanced than they were two decades ago. For example, the Report focused primarily on weather, but information and services relating to water (fresh and salt) and climate are increasingly attracting private sector attention. Services related to the oceans, hydrology, and climate will almost certainly grow in significance over the next several decades as global technological, societal, and environmental opportunities and challenges unfold. As a result, there is an expanding need for communication and collaboration among the public, private, academic, and NGO communities.

Public, private, academic, and NGO organizations all contribute to public well-being often in complex and inter-dependent ways

The issues associated with data commercialization and the potential for a refresh of the Fair Weather Report are complex and merit focused studies themselves. As a result, a detailed exploration of these issues is beyond the scope of this study. We anticipate that the next study in this project will delve into them in more detail as part of a larger effort to explore policy dimensions involved in enhancing societal benefits. These issues will almost certainly remain important to recognize and consider carefully over a sustained period.

Finding: There is no single "best" way to distribute roles among the public, private, academic, and NGO communities. Any distribution involves trade-offs and value judgments over which interests and preferences will often vary.

Finding: Roles and responsibilities among public, private, academic, and NGO communities will almost certainly shift over time as capabilities, interests, and needs continuously evolve.

Recommendation: Enable careful consideration of roles and collaboration among the enterprise sectors (i.e., as called for in the National Research Council's 2003 Fair Weather Report).

Recommendation: Strengthen and enhance discussions among the sectors that promote the exchange of perspectives, understanding, and trust.

Recommendation: Enable long-term and iterative engagement with periodic updating of roles and responsibilities among public, private, academic, and NGO communities.

5. International Dimensions of Earth System OSS

This study has emphasized issues and experiences in the United States. In many cases, these issues apply to other nations, and there are numerous connections between the United States and other nations with respect to Earth system OSS. Other nations also constitute new and emerging markets for U.S. companies, and international companies provide goods and services that benefit the people of the United States.

The weather, water (fresh and salt), and climate (WWC) enterprise has a strong history in international collaboration, with the long-standing WMO Resolution 40 affirming free and unrestricted international exchange of data as a fundamental principle of the WMO. There is also a history of cooperation among nations in providing one another with aid in times of crisis. Collaborations on hydrometeorological services have, in the past, also contributed to easing tensions among nations.

International collaboration on hydrometeorological services has helped to ease tensions among nations

This is an area of active consideration, as discussions within the WMO are exploring whether and how Resolution 40 may be updated to account for increasing potential of commercial data and with growing incorporation of disciplines in the Earth system sciences into the provision of meteorological services.

The advantages of data sharing are compelling: it expands the availability of information among nations, promotes collaboration, and reduces the need for redundancy in investments. However, there are also challenges with sharing: most notably, public availability diminishes the financial incentive for private entities to provide data and increases the cost of data for those who procure it.

As with the distribution of roles throughout the enterprise, careful consideration of these complex issues is needed for all efforts to maximize public well-being. Efforts to maximize public well-being often constitute complex choices without unambiguous solutions. Even when optimal solutions (to the extent they exist) are clear, they will continue to shift over time as opportunities and needs evolve.

Market failures can take on additional dimensions when international issues are considered. For example, there can be positive externalities associated with providing international stability or humanitarian benefits—split incentives such that individual countries maximize their interests suboptimally (i.e., even when small additional investments could lead to large returns globally).

Many of the issues with valuation efforts described earlier apply internationally as well. For example, different nations have different interests and values. Furthermore, nations vary in their structural approaches to WWC information and services. In most instances, the respective roles of the public, private, academic, and NGO communities are specific to each country. In some cases, public sector institutions provide for-profit services that make the development of a private sector unlikely.

Recommendation: Recognize that interests, incentives, and approaches for the provision and use of Earth system OSS among nations will not always align.

Different nations can have different interests and values

Recommendation: Promote international collaborations that recognize and embrace complexity associated with differing interests, priorities, capabilities, and perspectives and the importance of continuously revisiting interests and preferences over time.

Finally, rapid global changes with respect to technology, society, and the environment will create great needs for improved coordination and collaboration globally. Efforts in isolation are unlikely to be sufficient to meet the challenges and opportunities facing the Earth system OSS community.

Recommendation: Maintain and enhance international dialog for coordination and collaboration on the full range of disciplines involved in Earth system OSS.

6. Linkages and Their Integration Underlie Societal Benefits

In examining the societal benefits of Earth system OSS, an overarching need is to recognize and account for the importance of the linkages that permeate almost all aspects of WWC information and services. Most notably, the value of observations, science, and services similarly cannot always be fully separated or disaggregated because the societal benefits they provide result from the goods and services that emerge only from their combination.

Multiple vantage points enable understanding of all that matters: economic well-being; environmental quality; societal progress; fairness; and quality of life

These "emergent properties" of linkage also occur separately for observations, science, and services themselves. For example, observations consist of remotely sensed (e.g., satellite) and in situ measurements. Each of these can relate to a wide range of systems within and beyond the planet, including Earth systems such as the atmosphere, ocean, biosphere, cryosphere, and lithosphere in addition to the sun and a wide range of human activities. Some of the value of any observation results from capabilities that emerge only with the full suite of complementary observations. This is also true for advances in research and the provision of services.

Improved integration across Earth system OSS disciplines can provide leverage for the advancement of science and services. Environmental processes and characteristics often involve multiple components of the Earth system (e.g., the oceans, atmosphere, biological systems, and ice and snow). These integrated systems often exhibit complex behaviors that only emerge as a result of interactions between subunits. As a result, the identification of new opportunities and vulnerabilities and the management of challenges associated with a planet that is increasingly small in comparison to the scale of human activity depends on a combination of continuing disciplinary advancement and systems integration. One need is to aggregate environmental information in ways that enable integrated and comprehensive (to the extent possible) understanding.

Recommendation: Develop integrated, digitally accessible syntheses of Earth system observations and understanding.

Linkages among the public, private, academic, and NGO components of the enterprise also enable societal benefits of Earth system OSS to emerge. Without public investments, advances in research and observing capabilities would not be possible and private sector services would be cost prohibitive.

The advancement of Earth system OSS has both depended on international cooperation and contributed to improved relationships internationally. As described in the previous section, the present rapid period of global change (societal, technological, and environmental) almost certainly means that finding ways for nations to work together will be central to the advancement of societal benefits in the future. Differences in how countries approach the provision of WWC goods and services create the potential for advancement if they combine 1) a wide range of pilot projects, 2) early detection of success and failure, and 3) rapid dissemination of lessons learned so other nations can emulate successes and avoid failures.

Progress depends on: having many pilot projects; early detection of success & failure; & rapid dissemination of lessons learned

Finally, capabilities across weather and climate time scales are often highly linked from seconds and minutes to weeks, months, decades, and centuries. Advances in capabilities at any one time scale contribute to understanding and advances at other time scales.

Recognizing and accounting for these linkages and the emergent benefits they make possible is critical for efforts to enhance societal benefits from OSS.

Finding: Societal benefits of Earth system OSS depend on complex linkages and interdependencies, including those among

1. **observations, data assimilation, research, modeling, and services;**
2. **scientific disciplines (physical, natural, and social) involved in understanding the Earth system and humanity's interactions with it;**
3. **WWC opportunities and challenges;**
4. **time scales spanning from seconds and minutes to decades and centuries;**
5. **the public, private, academic, and NGO communities;**
6. **the international community.**

The relationships between societal benefits and each of these linkages is complex. For example, societal benefits have a very different relationship to the linkage between different time scales than to the linkage between the different sectors of society. This prohibits a single or straightforward approach to managing linkages. Nevertheless, recognition of each of these linkages is central to any approach to advance societal benefits.

7. Opportunities to Enhance Societal Benefits through Earth System OSS

Societal benefits depend, in the broadest sense, on the comprehensiveness of Earth system OSS and the capacity to make effective use of the OSS that is available. Valuation has great potential to enhance the societal benefits from Earth system OSS by improving understanding of the societal benefits of OSS, identifying unmet needs for OSS, and supporting systematic consideration of choices involving OSS.

U.S. Federal efforts empower & promote community resilience

The American Meteorological Society is actively working to enhance societal benefits across ten opportunity areas (Figure 3) through a combination of internal activities, studies, and external engagement (AMS 2020).

Figure 3. The Potential to Improve Weather, Water (Fresh and Salt), and Climate Information and Services

Enhancement of the societal benefits of Earth system OSS is possible through efforts to

1) provide actionable information;
2) prepare and empower information users;
3) create decision-support products and services that harness scientific advances for societal benefit;
4) build strong partnerships among stakeholders, practitioners, and information providers;
5) develop the next generation workforce;
6) recognize and account for linkages;
7) provide an effective policy framework for enhancing both the availability of information and society's ability to use it;
8) create, strengthen, and evolve partnerships among public, private, academic, and NGO communities;
9) engage and empower the public to demand, understand, use, and contribute to water information and services; and
10) reduce or eliminate market failures, when they occur.

A key challenge is to navigate roles and responsibilities as well as partnerships and collaborations among public, private, academic, and NGO communities regarding the enhancement of social benefits of OSS. This can be done by building upon opportunities to promote cooperation and ensure productive dialogue and communication in order to increase awareness of challenges and opportunities throughout all components of the enterprise.

It is particularly important to recognize that roles and responsibilities can be distributed in a variety of ways, each of which creates opportunities and challenges for the provision of societal benefits. Services provided by the public sector to all people can diminish the incentive for private sector organizations to create products and services that consumers may want. Conversely, the public sector is able to provide goods and services that strongly benefit people but that would not be available from market forces or that that would be provided in amounts that are economically suboptimal. The public sector has specific responsibility for promoting fairness; regulating markets; seeking to provide, protect, or enhance non-market goods and services; correcting market failures; and creating a foundation for private, academic, and NGO communities to function effectively.

Recommendation: Recognize the need to combine humility and confidence with complex and value-laden endeavors such as understanding, communicating, and working to enhance societal benefits of OSS.

Recommendation: Create decision-making processes for providing Earth system OSS that incorporate the best available information while recognizing that all such choices cannot be determined by information alone as they involve interests and values.

8. Toward a Septennial Assessment for Earth System Observations, Science, and Services

Finally, the ongoing expansion in capabilities of and needs for Earth system OSS during this period of rapid global change ensures that efforts to enhance societal benefits will continue to evolve in the decades ahead. Regular, periodic assessments of opportunities and challenges in the WWC enterprise will be needed. Here we suggest that these be provided through a "septennial assessment" process that brings together the public, private, academic, and NGO communities on a subdecadal time scale. The AMS Policy Program intends to facilitate this capability within the enterprise through periodic workshop-based studies that convene and synthesize community and stakeholder discussions relating to OSS.

Societal benefits depend on the comprehensiveness of Earth system OSS and the capacity to make effective use of the OSS that is available

We anticipate that each iteration of the assessment would include

- a description of what Earth system observations science and services are, particularly relating to weather, water (fresh and salt), and climate;
- a description of why Earth system science observations and services matter to the broader Society;
- a snapshot of the enterprise (i.e., the roles and relationships among public, private, academic, and NGO communities within the enterprise);
- a summary of challenges, opportunities, and needs for the advancement of OSS over the next decade;
- options and alternatives for advancing OSS along with an assessment of pros and cons of those options/alternatives (i.e., an update for Figure 3);
- a conception of a community-based vision for OSS over the next decade;
- an updated implementation plan for achieving that vision;
- a description of what benefits might be expected from advancements in OSS over short and medium terms; and
- identification of longer-range planning needs (i.e., more distant horizon mapping).

The period for reassessment should be long enough to provide time for implementation, to reduce the burden for the assessment process itself, and to allow time for new opportunities and challenges to emerge. At the same time, the period between assessments should be short enough to account for rapidly changing technological, societal, and environmental conditions; to enable the establishment and maintenance of a supporting infrastructure for the assessments; and to account for timing needs of key external partners.

We suspect the ideal periodicity is somewhere between five and ten years, with ten years likely too long and five years likely too short. For these reasons, we propose a "Septennial Assessment" in Earth system OSS. This would allow a three-year assessment phase followed by a three-year implementation phase, with an additional year to set up the subsequent assessment, including revising or adapting the approach as needed.

The AMS Policy Program intends to facilitate this capability within the enterprise by continuing to develop the idea and to work with external partners on structural options for it. AMS is prepared to serve as a neutral convener for this effort, to assist another entity in a leading role, or to be part of a collaborative structure.

Recommendation: Promote a shared sense of urgency, vision, and opportunity to extend Earth system OSS capabilities and to enhance the resulting societal benefits. Enable updating over time.

Recommendation: Foster mechanisms to discuss, revise, and update roles and responsibility throughout the enterprise.

Recommendation: Seek ways to promote adaptive capacity in the face of rapid global changes associated with technological development, societal change, and environmental degradation.

Recommendation: AMS should facilitate a periodic (e.g., septennial) community assessment that brings together members of the enterprise for discussions of options, needs, opportunities, and priorities to enhance OSS and the societal benefits that result.

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