2023 EARTH OBSERVATIONS ASSESSMENT REPORT: CLIMATE

Product of the

SUBCOMMITTEE ON U.S. EARTH OBSERVATION

COMMITTEE ON ENVIRONMENT

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About the Subcommittee on the United States Group on Earth Observations

The United States Group on Earth Observations (USGEO) is chartered as a Subcommittee of the NSTC Committee on Environment. The Subcommittee's purpose is to plan, assess, and coordinate Federal Earth observations, research, and activities; foster improved Earth system data management and interoperability; identify high-priority user needs for Earth observations data; and engage international stakeholders by formulating the United States' position for, and coordinating U.S. participation in, the intergovernmental Group on Earth Observations (GEO).

About this Document

In the area of climate, societal benefits accrue from Earth observations measurements that can inform both short- and long-term decisions made by policymakers, urban planners, disaster managers, research scientists, as well as watershed, natural resource, and land managers. Earth observations measurements of renewable resources and ecosystem conditions also support evidence-based decision-making by commodity markets, communities, and all levels of government. This report represents a summary of the societal benefit area elicitation results and associated findings. USGEO is making readily available, either through this report or through the online visualization services (https://usgeo.gov/eoa), those elements that are most valuable for agency and public analysis.

Copyright Information

Table of Contents

Introduction

The rapid changes underway in the climate system due to human activities underscore the importance of Earth observations to facilitate monitoring, prediction, and planning for the Nation. Earth observation systems are used to monitor the climate directly through measurements of important variables in the atmosphere, ocean, cryosphere, and land surface such as temperature, precipitation, ice cover, and water vapor (Figure 1). These observing systems also monitor environmental variables that are influenced by or can influence the climate system, such as ocean acidity, sea level, ozone concentrations, and seasonal vegetation cover.

Because the climate system and associated changes can have profound impacts on society, the societal benefits that accrue from investments in these Earth observing systems are potentially quite large. However, there are fundamental challenges associated with developing a comprehensive and cohesive observing systems strategy for the climate societal benefit area:

1. The need for consistent multi-year or multi-decade measurement time periods in order to robustly characterize the many climate variable states or to detect trends, and
2. The wide range of climate and climate-related variables that could be monitored but that are not part of a systematic or coordinated effort.

Because Earth's changing climate touches on so many aspects of society, such observational efforts are critical for adaptation and mitigation efforts in the relevant communities or environments.

Summary of Key Takeaways

1. Support a diverse portfolio of Earth observing systems, spanning from the ocean bottom to the top of the atmosphere.
2. Support a sustained portfolio of Earth observing systems to minimize risk of disruptions.
3. Leverage Earth observing systems to support the development of effective strategies and policies to limit human-caused climate change.
4. Leverage or deploy new Earth observing systems to improve short-term climate prediction in anticipation of accelerating climate trends.
5. Promote open, interoperable, and equitable access to climate observations and data.

This Earth Observations Assessment examined the state of observing systems related to the Climate Societal Benefit Area (SBA). This report represents a summary of the SBA elicitation results and associated findings. The United States Group on Earth Observations (USGEO) is making readily available either through this report or through the online visualization services (https://usgeo.gov/eoa) those elements that are most valuable for agency and public analysis.

Recognizing the evolution of the climate sciences since the 2016 Earth observation assessment, the Key Objectives (KOs) discussed highlight potential opportunities to enable future climate products and services. This will result in improved understanding of both the impact of Earth observation inputs (EOIs) on climate mitigation and adaptation strategies, and the incorporation of EOI data into socioeconomic cost calculations in addition to climate research.

Figure 1. ***Illustrating Four Sub-Areas Under the Climate Societal Benefit Area.***

Follow-on Analysis

USGEO and the Earth Observations Assessment Working Group (EOA-AWG) will continue to mine the elicited data to derive additional insights, particularly to identify EOI data and product dependencies and chokepoints (products that have a large influence in the societal benefit network) and obtain unique insights. Such information can further inform investment decisions at both agency and enterprise levels. Also, as additional SBA elicitations are completed over the coming years, USGEO and the AWG will be able to expand analyses beyond individual SBAs and assess across the entire network.

Assessment Results

The 2023 Earth Observing Assessment (EOA) of the Climate SBA is a follow-on to assessments conducted in 2016 and 2012. the latest IPCC report (IPCC 2023) states that:

> [W]idespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred. Human-caused climate change is already affecting many weather and climate extremes in every region across the globe. This has led to widespread adverse impacts and related losses and damages to nature and people (high confidence). Vulnerable communities who have historically contributed the least to current climate change are disproportionately affected (high confidence).

This third EOA updates and expands on the scope of the Climate SBA in prior assessments by developing a Value Tree[1] (see example in Table 1) that covers the breadth of climate change impacts and opportunities for adaptation and mitigation in response to a warming planet. This includes an assessment of observations and observing systems that are fundamental to understanding and predicting all aspects of the Earth's climate system, and importantly, for responding to the growing human influence on it. The Climate SBA

[1] A value tree is a hierarchical model containing top-level SBAs and Sub-Areas, and respective functionally aligned products and services. For more details see the EOA Methodology Report (https://usgeo.gov/eoa).

team took a broad view of the importance of observing systems, from basic research into the workings of the climate system and the connections to more fundamental Earth system processes, to applications related to mitigating, adapting to, and providing services in response to a changing climate. The assessment represents a snapshot in time of what the agencies are using and why. As in the 2016 Assessment, an international perspective and the U.S. role in leading global climate considerations was important when considering the societal benefits of Earth observing systems.

Four Sub-Areas were identified by the Climate SBA team that address societal objectives for understanding, predicting, and responding to Earth's changing climate. Because of the Administration's increased emphasis on assisting ongoing and new societal responses to climate change, the 2023 weights for each Sub-Area were distributed more evenly across the four Sub-Areas. This contrasts with the 2016 Assessment where weights were concentrated in the *Understanding, predicting, and projecting Earth's climate system* Sub-Area (Table 2). For the 2023 Assessment, two Sub-Areas, *The Earth's climate system and the changes occurring in it* (35% weight) and *Human and natural influences on the climate system* (5%) are similar in scope to the highest weighted Sub-Area from the 2016 Assessment and, for EOA 2023, when combined still had the highest overall weighting. In keeping with the emphasis on understanding and addressing the impacts of climate change, however, the Sub-Area *Climate change effects on human and environmental systems* was given an equally high weight (35%) as the first Sub-Area. Similarly, the weight for the Sub-Area *Facilitating societal responses to climate variability and change* (25%) had a relatively high weight to reflect the importance of Earth observing systems in developing climate services and developing domestic and international policies in response to human influence on the climate system.

Table 1. ***Table of value tree structure, descriptions, and examples.***

Value Tree	Elements	Description	Example
Top	SBA	Societal Benefit Area	Climate [CL]
Top	SBA Sub-Area	Natural thematic subdivisions of the parent SBA	The Earth's climate system and the changes occurring in it [CL-1]
Top	Key Objective (KO)	An activity within a Sub-Area that is clearly supported by and can be linked to Earth observing systems, data, and products	The Land Surface: Understand and model land surface variability and change with respect to the primary influences on the climate system and climate change [CL-1-4]
Top	Key Product, Service, or Outcome (KPSO) Group	A group of KPSOs that belong to the same category or class of information products or research outcomes	Land Cover Land Use [CL-1-4-1]
Bottom	KPSO	A primary or important information product, service, or outcome required to make progress toward or meet a Key Objective	Normalized Difference Vegetation Index — Climate Data Record
Bottom	Data Source (Surveyed Product and/or Earth Observations Input)	The data, information, and Earth observing systems needed to produce KPSOs	Polar Orbiter Surface Reflectance — Climate Data Record
Bottom	Earth Observations Input	An observing system or database that is the lowest level of disaggregation in the value tree	JPSS Polar Constellation Visible Infrared Imaging Radiometer Suite: Day-Night Band

Table 2. ***Sub-Area Assessment Weights for the 2016 and 2023 Earth Observation Assessments.***[2]

2016 Assessment		2023 Assessment	
Sub-Area	**Weight**	**Sub-Area**	**Weight**
Understanding, predicting, and projecting Earth's climate system	70	The Earth's climate system and the changes occurring in it	35
Assessing and adapting to impacts of climate variability and change	20	Human and natural influences on the climate system	5
Drivers and mitigation of climate variability and change	10	Climate change effects on human and environmental systems	35
		Climate change effects on human and environmental systems	25

2 There is not a clear one-to-one matching between the ideas encompassed within each of the 2023 Sub-Areas relative to those of the 2016 Sub-Areas, and thus the differences in the weighting in the two assessments are narratively but not quantitatively relevant.

Table 3 lists the KOs associated with each Sub-Area. KOs (5–8 per Sub-Area, 26 total) were established that represent critical components and goals within each Sub-Area. Within the scope of the effort and in support of the Climate KOs, a total of 509 KPSOs were identified, with 1,752 total products surveyed (e.g., Polar Orbiter Surface Reflectance — Climate Data Record [CDR] from Table 1) from input from 850 corresponding Subject Matter Experts (SMEs). In turn, 1,939 unique EOIs (e.g., Joint Polar Satellite System [JPSS] Polar Constellation Visible Infrared Imaging Radiometer Suite: Day-Night Band from Table 1) were identified as supporting the production of the KPSOs.

Table 3. ***Table of Climate Sub-Areas and Key Objectives.***

Sub-area	Key Objectives
The Earth's climate system and the changes occurring in it [CL-1]	• The Atmosphere: Understand and model atmospheric circulation variability and change, and the role of the atmosphere in climate change [CL-1-1] • The Ocean: Understand and model ocean variability and change, including the ocean's physical, biogeochemical, and dynamical conditions, and the role of oceans in climate change [CL-1-2] • The Cryosphere: Understand and model the Earth's cryospheric systems, including the sensitivity, feedbacks, and dominant processes controlling system variability, evolution and change, and the role of cryospheric systems in climate change [CL-1-3] • The Land Surface: Understand and model land surface variability and change with respect to the primary influences on the climate system and climate change [CL-1-4] • Climate Sensitivity and Climate Feedbacks: Understand and model feedbacks across the Earth's climate system, including changes in cloud cover, atmospheric water vapor, ocean circulation, and Arctic amplification (accelerated warming in the Arctic), and improve understanding of climate system sensitivity to external forcings including from human and natural sources [CL-1-5] • Past Climate: Improve understanding and quantification of past climate states and extremes, including abrupt changes in climate [CL-1-6]
Human and natural influences on the climate system [CL-2]	• Understand climate system forcings and improve their estimation [CL-2-1] • Assess, attribute, and project changes to sources and sinks of natural and anthropogenic atmospheric radiative forcing agents and pollution constituents [CL-2-2] • Monitor atmospheric greenhouse gas concentrations [CL-2-3] • Effectively validate greenhouse gas emissions inventories through enhanced cooperation with organizations such as the Global Climate Observing System and the Committee on Earth Observing Satellites [CL-2-4] • Monitor or predict the effects of potential climate intervention strategies [CL-2-5]
Understanding Climate change effects on human and environmental systems [CL-3]	• Understand, assess, predict, and project the impacts of climate change, including extreme events, on water resources [CL-3-1] • Understand, assess, predict, and project the impacts of climate change, including extreme events, on the built environment, including urban systems, energy systems, and transportation systems [CL-3-2] • Understand, assess, predict, and project the impacts of climate change, including extreme events, on human-driven changes to land cover and land-use [CL-3-3] • Understand, assess, predict, and project the impacts of climate change, including extreme events, on terrestrial ecosystems and agroforestry systems [CL-3-4] • Understand, assess, predict, and project the impacts of climate change, including extreme events, on coastal and marine resources and ecosystems [CL-3-5] • Understand, assess, predict, and project the impacts of climate change, including extreme events, on the air quality and human health [CL-3-6]

Sub-area	Key Objectives
	• Understand, assess, predict, and project the impacts of climate change, including extreme events, on Tribes and Indigenous Peoples [CL-3-7]
Facilitating societal responses to climate variability and change [CL-4]	• Evaluate the costs, benefits, risks, and effectiveness of climate change mitigation, including strategies to reduce anthropogenic greenhouse gas emissions or influence greenhouse gas sources, sinks, and concentrations [CL-4-1] • Evaluate the costs, benefits, risks, and effectiveness of climate change adaptation strategies and investments [CL-4-2] • Provide data needed to support national, regional and local impact assessments and the identification of highly vulnerable systems, regions, and populations [CL-4-3] • Provide communication services, stakeholder engagement, user education, and support tools to assist decision-making related to climate change adaptation efforts [CL-4-4] • Empower communities, in particular marginalized and traditionally underserved groups, to strengthen their adaptive capacity, increase resilience, and to prepare for and mitigate climate change impacts [CL-4-5] • Provide data management and information stewardship in service of climate change adaptation efforts [CL-4-6] • Enable the US to collaborate with national and international partners and provide leadership on the global stage to address climate change [CL-4-7] • Support the environmental stewardship activities of Tribes and Indigenous Peoples and their capacity to mitigate climate change impacts [CL-4-8]

The Climate KPSOs identified in this assessment are provided by a variety of government agencies and academic institutes' projects funded by governments, including:

- U.S. Geological Survey (USGS) (e.g., Coastal Change Impacts Project),
- National Aeronautics and Space Administration (NASA) (e.g., GISS Model-E Simulations, Agricultural Model Inter-comparison and Improvement Project—AgMIP),
- National Oceanic and Atmospheric Administration (NOAA) (e.g., National Temperature and Precipitation Maps—Climate Monitoring Services),
- Department of Energy (e.g., Observations for Model Intercomparison Project—Obs4MIPs),
- Environmental Protection Agency (e.g., National Emissions Inventory [NEI]),
- United States Department of Agriculture (e.g., Soil Climate Analysis Network [SCAN]), and
- Academic institutes (e.g., Community Climate System Model by National Center for Atmospheric Research (NCAR) and MODIS Land Surface Phenology: Seasonal Cycles of Vegetation Growth by Boston University).

From these inputs, the percent impact of each data input towards the overall SBA and each Sub-Area was calculated as described in the EOA Methodology Report. Several satellite-based systems stand out as being high impact data sources. The OLI sensor aboard Landsat, JPSS VIIRS, and the MODIS sensors aboard Terra and Aqua (Figure 2) were found to be the most impactful remote sensing observing systems providing observations to support objectives across the SBA.

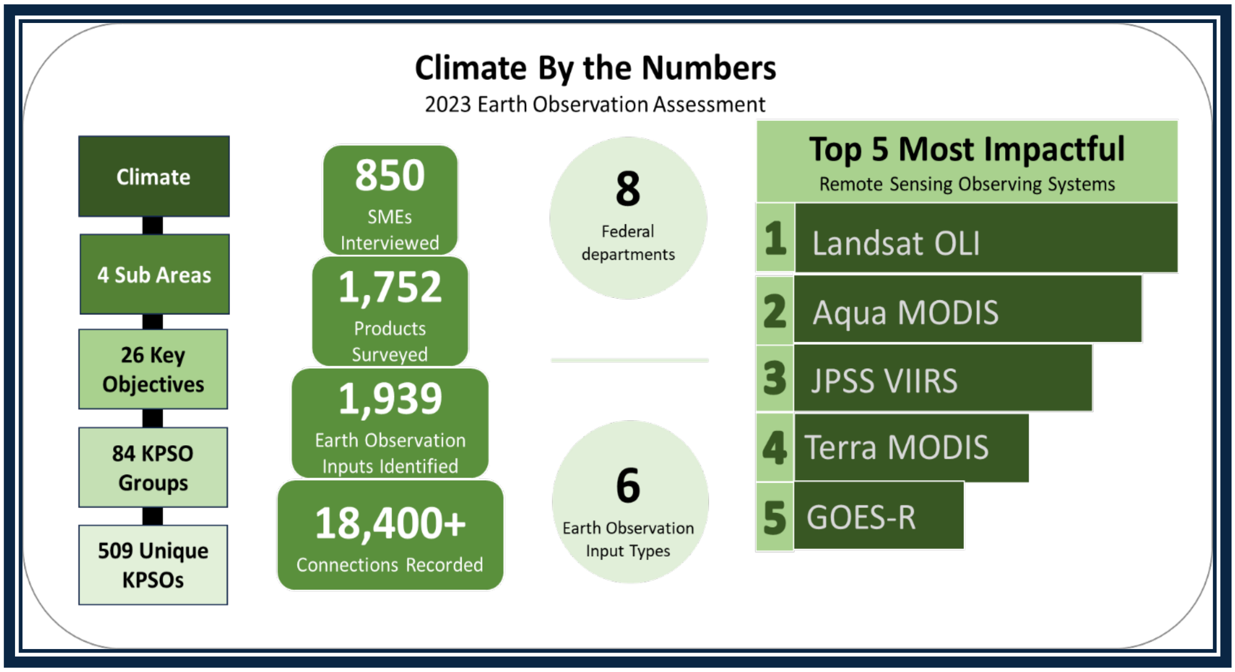

Figure 2. **Overview of Climate SBA Assessment Statistics.** Bar chart of Top 5 Most Impactful Remote Sensing Observing Systems is representative of the percent impact on the SBA.

A list of the top 20 earth observation inputs is shown in Table 4. Landsat, having the highest impact score, reflected this increased importance placed on the Sub-Areas associated with climate change impacts and societal efforts to respond to climate change compared to the 2016 EOA.

Table 4. ***Top 20 Earth Observation Inputs from the Climate SBA Ordered by Percent Impact on the SBA.***

Rank	Earth Observation Input	Observation Type
1	Landsat Operational Land Imager (OLI)	Satellite/Satellite Data
2	Aqua Moderate Resolution Imaging Spectroradiometer (MODIS)	Satellite/Satellite Data
3	JPSS Polar Constellation Visible Infrared Imaging Radiometer Suite	Satellite/Satellite Data
4	Commercial Airborne Lidar	Airborne Data
5	Terra Moderate Resolution Imaging Spectroradiometer (MODIS)	Satellite/Satellite Data
6	Landsat Thermal Infrared Sensor (TIRS)	
7	Geostationary Operational Environmental Satellite - R Series (GOES-R) Advanced Baseline Imager	Satellite/Satellite Data
8	National Water Level Observation Network (NWLON)	In Situ
9	NWS Cooperative Observer Program (COOP)	Other Reference Data
10	Polar-orbiting Operational Environmental Satellite Series (POES) Advanced Very High Resolution Radiometer	Satellite/Satellite Data
11	Global Argo Profiling Floats	In Situ
12	U.S. Climate Reference Network (USCRN)	In Situ
13	Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager Sounder	Satellite/Satellite Data

14	Digital Elevation Models Output - Shuttle Radar Topography Mission (USGS)	Elevation Dataset
15	Global Drifter Program	In Situ
16	Automated Weather Observing System (AWOS)	In Situ
17	Traditional Ecological Knowledge (TEK)	Other Reference Data
18	USGS Streamgages	In Situ
19	SNOwpack TELemetry (SNOTEL)	In Situ
20	Database: Global Land Survey Digital Elevation Model (GLSDEM)	Elevation Dataset

Summary of Key Findings

An important consideration when analyzing the overall ranking of EOIs is the potential for some inputs to have a relatively lower overall impact ranking, but to nevertheless provide significant impact to a limited number of KPSOs within one or more Sub-Areas. To assess the prevalence of this situation across the EOIs, two metrics were calculated and plotted in Figure 3. The *Impact on Climate* (vertical axis) is the impact of each EOI on the SBA as a whole. The *% of KPSOs Impacted* (i.e., applicability; horizontal axis) is the number of KPSOs impacted across the value tree (out of the total 509).

Shown in Figure 3, the EOIs in the 75th percentile and below of impact scores are light green. For systems in the top 25% of impact scores, the systems are further divided into groups based on the 99%, 95%, and 90% impact score thresholds. Those darker blue symbols are highly valued across the value tree. These systems can be seen as critical Earth observing infrastructure. The 10 systems with the highest percent impact scores are labeled in Figure 3.

The systems with the highest impact scores reflect a range of climate change risks and responses that are being considered by society. For example, the highest scoring input was Landsat OLI. The high ranking of this system resulted from its importance to monitoring climate change effects on water resources, ecosystems, and land use change. The long, uninterrupted time series likely contributes to this value given the time scales over which the Earth's climate is changing in response to human activities. Landsat was also ranked of high importance for achieving objectives related to facilitating international collaboration and providing tools to vulnerable communities that help increase climate resilience. These high rankings, which are notably paired with lower (but still overall very high) rankings for the 'traditional' aspects of climate-related observing systems, highlight the changes in the 2023 EOA Assessment that place increased emphasis on the wide breadth of activities that provide societal benefits related to climate and climate change.[3]

[3] The top four ranked systems in the 2016 Earth Observation Assessment for the Climate Sub-Area were: 1) Global Climate Observing System (GCOS) Surface Network (GSN), 2) Terra Moderate-Resolution Imaging Spectroradiometer (MODIS), 3) Aqua Moderate-Resolution Imaging Spectroradiometer (MODIS), and 4) Landsat Optical.

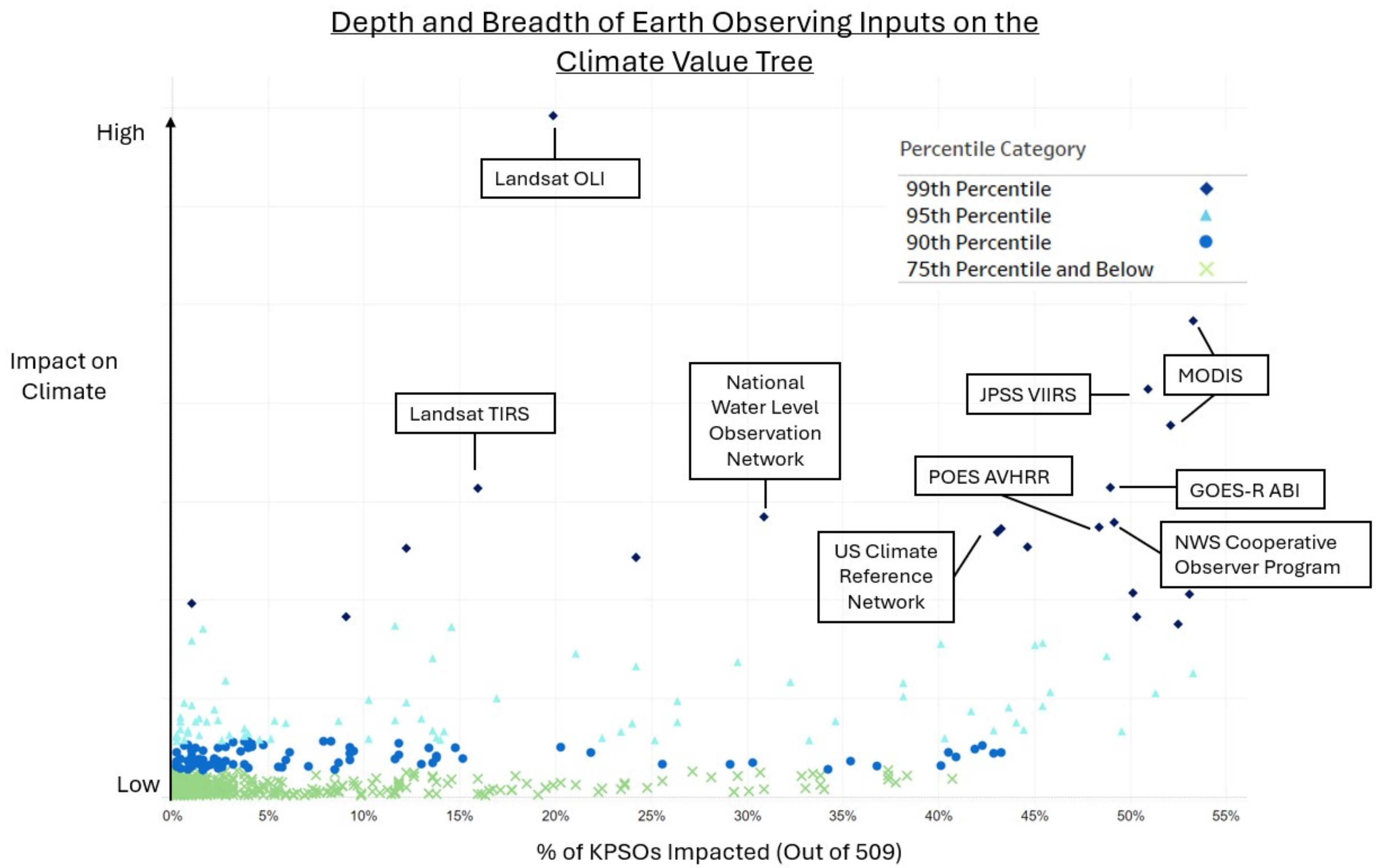

Figure 3. ***Graph of Earth Observations Inputs' Impact on the Climate SBA by the Number of KPSOs (out of 509) Impacted by 0.01% or Greater.*** *The top 100 Earth observations inputs that impact most Climate KPSOs can be found in Annex B. Data points in the table are disaggregated by their rank in the list of Earth observations impacts in Annex C. Data points towards the top right have the most impact and broadest applicability in the SBA. Those towards the bottom left have more niche value.*

Satellite Observing Systems

Eight of the highest contributing 20 inputs across the SBA are satellites. Terra and Aqua are ending their useable life (due to a lack of fuel reserves to maintain orbit) and are being at least partially replaced by the JPSS missions. The relative rankings for VIIRS and MODIS (Figure 4) indicate that while VIIRS is increasingly relied on for fundamental understanding of the climate system (CL1), it is less integrated into those KPSOs that are most connected to climate change mitigation and impacts (CL2, CL 3, & CL4). This indicates that more work needs to be done to prepare the applications communities for the imminent loss of the MODIS instrument on the Terra and Aqua satellites.

Key
99th Percentile
95th Percentile
90th Percentile
75th Percentile
50th Percentile
Below 50th Percentile
Blank Cells Indicate Input Does Not Contribute to Area

	Earth Observation Inputs	SBA: Climate [CL]	Sub-area: The Earth's climate system and the changes occurring in it [CL-1]	Human and natural influences on the climate system [CL-2]	Climate change effects on human and environmental systems [CL-3]	Facilitating societal responses to climate variability and change [CL-4]
1	Landsat Operational Land Imager (OLI)	3.45%	1.83%	3.74%	3.39%	5.87%
2	Aqua Moderate Resolution Imaging Spectroradiometer (MODIS)	2.43%	2.48%	3.04%	2.18%	2.58%
3	JPSS Polar Constellation Visible Infrared Imaging Radiometer Suite	2.07%	3.61%	1.57%	1.37%	0.92%
4	Commercial Airborne Lidar	1.99%	0.59%	2.47%	2.82%	2.76%
5	Terra Moderate Resolution Imaging Spectroradiometer (MODIS)	1.90%	1.37%	2.83%	2.02%	2.31%

Figure 4. ***Ranking of Landsat, MODIS, and JPSS.***

In Situ Observing Systems

In addition to satellite-borne sensors, observations from in situ networks (occupying 8 of the top 20 EOIs [Table 4]) also provide knowledge on many spatial and temporal scales for understanding the changes occurring in Earth's climate system. These observations also inform the development, calibration, and evaluation of numerical models of the Earth system being used in analyzing past changes in climate and for making projections of future climate. In situ observing systems remain a critically important element in monitoring the climate in near real time. In addition to providing observations far back in time, to provide the ability to track trends and long-term variability, they are also necessary for calibration of remotely sensed data. The Global Drifter Program (ranked 15th overall and 9th for CL1), for example, is an essential source of high-quality sea surface temperature (SST) data needed to validate satellite SST retrievals and to constrain blended satellite-in situ SST data products. Argo (ranked 11th overall, 13th for CL3), discussed further below, is a global network of approximately 4,000 profiling robotic floats that provides information on subsurface variability that cannot be observed remotely from space. The SNOTEL (ranked 19th overall) network, as another example, provides critical near real-time measurements of snowpack. NWS's Automated Surface Observing System and FAA's Automated Weather Observing System (ranked 16th overall) stations are crucial for accurate weather forecasting and airline safety.

Citizen Science

There are several observing systems that incorporate citizen science in the form of volunteer observers. The oldest is the U.S. Cooperative Observer Network (COOP) in NOAA's National Weather Service that was established in the late 1800s to describe the climate of the United States. The long record and relatively high sampling density make the COOP Network critical for detection of long-term climate variability and change. This is evidenced by its importance ranking in the analysis results, where it was ranked 9th overall and 4th for CL1. It is also the highest-ranked terrestrial non-satellite observing system in the analysis. The COOP Network has approximately 8,500 volunteer observers in all 50 States, Puerto Rico/USVI, and the Pacific Island territories. These volunteers are provided with standard equipment and take observations of maximum and minimum temperature and total precipitation once a day, typically at 7 am. These observations are then archived and incorporated into climate data sets by NOAA's National Centers for Environmental Information (NCEI). Another volunteer network is the Community Collaborative, Rain, Hail, and Snow Network (CoCoRaHS) precipitation observing network that was established in 1998 by Colorado State University. It is a network in all 50 States and Canada where observers take a precipitation observation once a day and send the observation into the CoCoRaHS system. The data also are archived at NCEI and used for precipitation data sets.

Role of Niche KPSOs Critical to Specific Objectives

In addition to widely used satellite missions like MODIS and Landsat, specific objectives commonly rely heavily on more niche EOIs. As an example of a system with a higher impact across a narrower set of KOs, the Indigenous Knowledge (IK) impact score was almost entirely due to very high rankings in just 3 KOs (out of 26 total) under two Sub-Areas (CL3-7, CL4-5, and CL4-8). IK refers to Indigenous Peoples' practices of learning, observing, recording, researching, and communicating, which are required to support the ability to flourish in an ecosystem, and the social adaptive capacity to prepare for and adjust to change. IK is becoming increasingly recognized as a critical source of information in developing response strategies to climate change.

Another example is commercial airborne LIDAR, which represents part of a rapidly growing commercial data corpus that allows much greater coverage and resolution that provides significant impact to KOs focused on human interaction and response to climate change (rather than core research). While these examples indicate narrower applicability, the high impact score also suggests that the smaller number of KOs represented in this group are more highly dependent on these systems. These high-scoring, narrowly applicable systems could represent potential chokepoints in the system.

Identifying Opportunities for Observing Systems and Key Objective Alignment

The assessment results point to potential opportunities for better alignment between the observing systems and societal benefits that accrue through the KPSOs and KOs. Overall, 1,939 EOIs were identified as contributing to the KPSOs and the 26 KOs across the four Climate Sub-Areas (Figure 2).

It would be expected, in general, that utilization of EOIs would decrease in line with their impact (i.e., impact across the SBA is correlated to use across the SBA). However, analysis has revealed that for a number of KOs this is not the case. Figure 5 highlights KOs where the utilization of EOIs differs from what might be expected *a priori*.

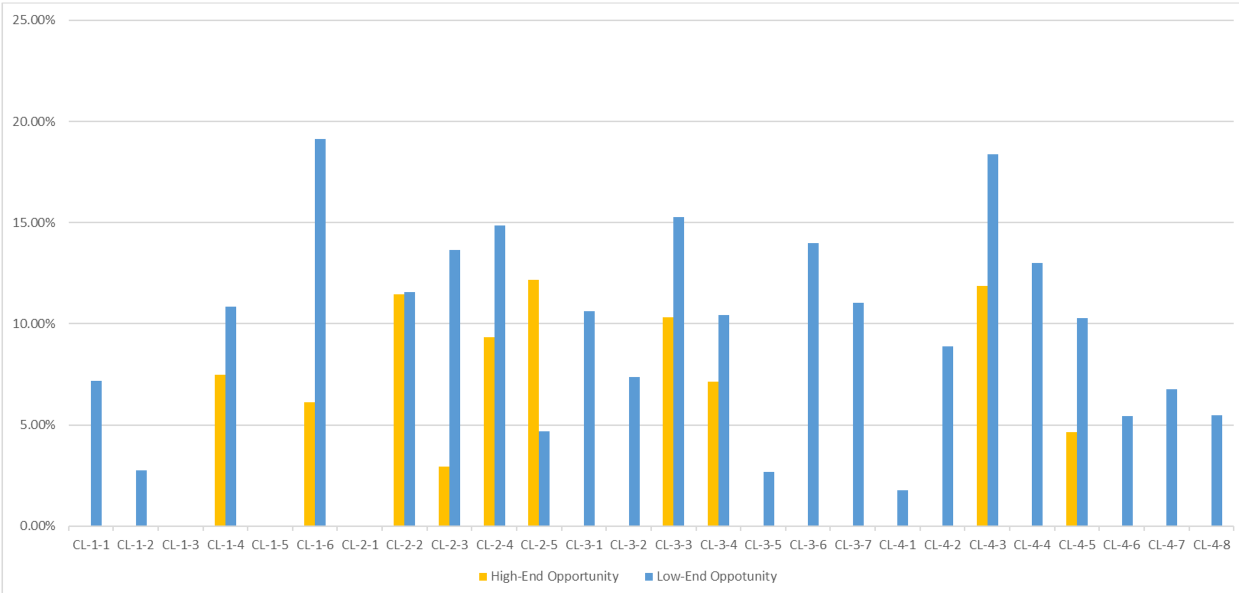

Figure 5. ***Potential Underutilization of EOIs.*** *The difference between the Sub-Area EOIs count and the KO EOIs count is assessed against the top ranked (impact >0.1%) and the bottom ranked (impact <0.01%) EOIs. The differences are identified as potential opportunities.*

The KOs for which more impact is derived from EOIs not in the top tier (contributing <0.1%) are highlighted as *High-End Opportunity)*, and the KOs for which there is more impact derived from less impactful sources (<0.01%) are highlighted as *Low-End Opportunity)*.

There are a number of potential reasons for underutilizing of high impact EOIs. High impact EOIs may not be as relevant for the KO[4], the KO may be focused on particular measurements[5], or high impact EOIs from another KO in the Sub-Area are relatively underutilized in the rest of the Sub-Area[6]. However, that does not account for all cases, and the potential for improved utilization of currently available high impact EOIs may provide additional benefit.

Similarly, each Sub-Area has a significant number of low-impact EOIs (between 40% and 50% of the total EOI count). However, these EOIs are often only leveraged by one or two KOs within the Sub-Area. Wider accessibility and interoperability of these low impact sources will likely raise their utility across the SBA.

Additional opportunities may exist for better alignment between observing systems and KOs. CL-2-5 (*Monitor or predict the effects of potential climate intervention strategies*), for example, is an emerging issue with national and international policy implications related to the types of strategies that may be employed to mitigate the harmful effects of human-caused global warming. Independent of which climate intervention strategies are adopted either nationally or globally, EOIs that can provide critical information about the sensitivity of the atmosphere and the climate system to such strategies are likely to be of high importance. Currently, the most impactful EOIs for this KO include indirect inputs such as the U.S. Census of Agriculture (highest-ranked EOI) and the National Agriculture Imagery Program (fifth highest-ranked

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4 For example, CL 1-6 (*Past Climate: Improve understanding and quantification of past climate states and extremes, including abrupt changes in climate*) does not depend on to major active EOIs (e.g. satellites)

5 For example, CL 2-4 (*Effectively validate greenhouse gas emissions inventories through enhanced cooperation with organizations such as the Global Climate Observing System and the Committee on Earth Observing Satellite*) is only focused on GHG monitoring EOIs

6 For example, CL 2-1 (*Understand climate system forcings and improve their estimation*) makes extensive use of field work EOIs that are essentially unused by the other KOs in the Sub-Area.

EOI). This suggests that other EOIs or new observation systems may be needed to achieve this KO more directly.

Ocean Observation Systems

The oceans take up 90% of the planetary radiative heat imbalance caused by rising greenhouse gas (GHG) concentrations in the atmosphere and roughly a quarter of the anthropogenic carbon produced by the combustion of fossil fuels and deforestation. Ocean observations enable better understanding of climate sensitivity to external forcings from human and natural sources and what role the ocean plays in these feedbacks due to changes in ocean circulation, surface fluxes of heat, moisture, momentum, and carbon across the air-sea interface, cloud-radiative feedbacks, and polar amplification.

Satellites provide spatial coverage for SST, sea surface height, surface salinity, surface vector and scalar winds, and ocean color, but they cannot measure below the ocean surface. The memory of the climate system resides in the ocean, so subsurface ocean data are required for a proper assessment of the planet's changing climate as well as for initializing weather forecasts, subseasonal to seasonal (S2S) climate forecasts, and decadal climate forecasts and projections. Consequently, although ~30% of the highest impact EOIs for ocean monitoring (CL-1-2) are satellites, the majority are in situ observations. As noted earlier, high quality in situ data are also crucial for validating measurements made at the ocean surface from space-borne satellite sensors, especially when trying to tie data from different satellite missions together into a long climate time series.

The Argo program,[7] (contributing to >40% of the KPSOs) managed by various agencies within the United States and internationally, collects key in situ data, but it is limited mostly to the upper 2000 m of the ocean. Recent expansions of the Argo program to measure the abyssal ocean below 2000 m ("Deep Argo"[8]) and biogeochemical Argo ("BGC Argo"[9]) are in the early stages of implementation. Unlike the U.S. collaboration with international partners for satellite observations, Argo is operated as a single system as opposed to separate systems contributing to an observing system-of-systems, and so the concerns about long-term data control and access do not apply. The combination of satellites, Argo (ranked 11th overall, and the Global Drifter Program [ranked 15th]) comprise a cornerstone of the Global Ocean Observing System (GOOS).

Regional- and Local-Scale Monitoring

The EOA highlighted the importance of regional EOIs (e.g., IOOS Regional Ocean observing and NOAA Regional Climate Center surface observations) in addition to state and local EOIs (e.g., fish surveys, air monitoring, stream & water quality monitoring etc.) for regional- and local-scale decision support. There are some areas where improving this linkage would be of benefit.

While long-term observations of GHGs today in remote regions of the world (e.g., from NOAA's observatories at Mauna Loa, HI; Barrow, AK; and the South Pole) continue to provide a global report card on society's emissions worldwide, the opportunity exists to enhance management of sources and sinks of GHGs and aerosols through denser and focused coverage, both of atmospheric amounts and Earth system fluxes. Similarly, models with improved transport, chemistry, and removal, and with better resolution could enhance analyses of key source and sink areas.

Additionally, many regions experiencing large changes in climate are not well monitored, such as Alaska, and even some areas in the western United States. Enhanced observations in these under-observed regions would allow model developers to improve the accuracy of both weather and climate models—as would

7 https://www.aoml.noaa.gov/argo/
8 https://oceantoday.noaa.gov/deepargo/
9 https://www.aoml.noaa.gov/biogeochemical-argo-program/

improving the accuracy and reliability of regional and local climate projections, particularly in predicting changes in precipitation.

The global tropical belt is a key region in which to ensure robust ocean observing systems for detection and prediction of severe tropical storms, the formation of atmospheric rivers, and year-to-year variations linked to ENSO events that affect weather and climate extremes over the United States and elsewhere through far-field teleconnections mediated by changes in the general circulation of the atmosphere and planetary scale waves processes. The pattern of trends in sea-surface temperatures in the tropical Pacific is particularly important for understanding how ENSO will change in the future. If temperatures warm faster in the western tropical Pacific, as has been the case since about 1980, ENSO becomes more La Nina-like. This impacts mid-latitude circulation with amplified Rossby Waves during La Nina, which even carries over to the Polar regions leading to a warmer Arctic and colder mid-latitude continental temperatures. Furthermore, La Nina impacts tropical cyclone formation in both the Atlantic and Pacific, with more tropical cyclones in the Atlantic and fewer in the eastern Pacific. Polar amplification of climate change signals likewise argues for robust ocean observing systems at high latitudes, though there are major challenges with building and sustaining observing systems in remote oceanic regions that are ice-covered for much of the year. It is critical to measure variability in western boundary current regions where meridional transports of ocean mass, heat, and salt affect the global energy balance; and in upwelling zones, both coastal and in the open ocean, where the upward transport of cold, nutrient-rich thermocline water towards the surface sustains thriving ecosystems and productive fisheries and where vigorous ocean-atmosphere exchanges take place that affect oceanic heat and carbon budgets.

Argo floats and Global Drifter Program buoys provide global coverage but in addition, there are many other types of measurement systems that can address regional in situ observational needs where specialized measurements are required to address specific phenomena as described above. Examples include moored buoy systems for studies of ocean circulation, tropical storms, and the dynamics of climate modes such as ENSO and the monsoons; island and coastal tide gauge stations for monitoring regional sea level rise; float and mooring-based ocean sampling technologies that are adapted to seasonal ice coverage in polar regions; and arrays designed to the study the Atlantic Meridional Overturning Circulation. Expanding, enhancing, and evolving these observing systems provide one way forward in addressing in situ ocean measurement needs in a changing climate.

Data Management

EOIs are the starting point of an extensive value chain of climate information and knowledge that the Federal Government provides both to Federal agencies and to other users. EOIs are used for a range of applications from national assessments and the understanding of long-term trends to planning mitigation and adaptation policies and strategies at the global, national, and local level. The value of EOI data for climate application has been sustained (and in many cases has increased) for decades, and so the management of the long-term data record is essential to ensure the continued integrity of climate analyses.

EOI data volumes are expected to increase by orders of magnitude with the next generation of observing systems. For example, the upcoming NISAR satellite mission alone will generate more than 30 petabytes of raw data per year—increasing NASA's total data holdings for all other current and previous satellite missions by more than a quarter in its first year. Similarly, the next generation of both Landsat and GOES (GeoXO) are expected bring a significant increase in data volume. Processing such large quantities of data and deriving meaningful insights from it can no longer be done efficiently using traditional on-premises methods. Agencies are actively exploring alternative data management approaches that use the cloud, along with massively parallel computational systems, so that the data do not need to be downloaded and staged locally, and so that a much larger global workforce and more representative community can access and analyze it from wherever they are, not just at elite facilities in high-resource nations. Pioneering cloudnative, open-source, internationally collaborative analysis platforms such as NASA's MAAP[10] look to address this need.

Making sure that this wealth of EOI data is discoverable and equitably accessible is essential. NOAA and NASA have been collaborating closely on data cataloguing, and efforts such as data.gov and the FGDC Geoplatform[11] attempt to capture a broad overview of Federal data.

Recommendations

1. ***Support a diverse portfolio of Earth observing systems, spanning from the ocean bottom to the top of the atmosphere.***

Because climate change effects can be pervasive throughout society, effective responses will require EOIs that can observe and detect changes throughout the climate system. These observations include those from both satellite and in situ platforms since satellite observations provide broad spatial coverage and in situ observations often provide long historical context and higher accuracy data at specific locations. Some of these platforms may be viewed as newly relevant and part of robust climate change response system (both for mitigation and adaptation activities). However, many in situ networks lack the systemization needed to develop the observational record of sensitivity and exposure to the climate change hazards. For example, extreme heat-related risks in urban areas due to the combined effects of global climate change and local urban heat islands was identified as a critical topic in the Fifth National Climate Assessment.[12] However, currently the only way to systematically measure this exposure risk is indirectly through satellite measurements of land surface (skin) temperature. Systematic in situ and high-density measurements of near surface air temperature and humidity across urban areas of the United States may be necessary to address the associated KOs (CL3-2, CL3-3, CL3-6, CL4-3). Similar examples of observation needs can be found across climate change-influenced phenomena such as wildfire risks (requiring high quality measurements of humidity, wind speed and direction, and solar radiation) and wildfire hazards (smoke monitoring, wind speed and direction), saltwater intrusion from sea level rise, invasive species monitoring, and forest stress due to long-term drought.

2. ***Support a sustained portfolio of Earth observing systems to minimize risk of disruptions.***

A common issue across this SBA is the need to sustain data and time series. Detection of long-term changes in any part of the climate system requires high-quality time series of observations that are considered homogeneous, meaning that variations and trends in the time series are solely a result of changes in the climate system and not artifacts due to issues such as changes in instrumentation, the observing station for in situ observations, or the introduction of new satellites without sufficient overlap with expiring satellites.

3. ***Leverage Earth observing systems to support the development of effective strategies and policies to limit human-caused climate change.***

Recent methodological advances and new EOIs deployments have increased the potential traceability of GHGs in the atmosphere to the original sources. The fusion of 'top-down' and 'bottom-up' observation and estimation methods is of critical importance for efforts such as the global stocktake[13] that form the core of national GHG inventory development and associated international GHG abatement policies. Deployment

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[10] https://www.earthdata.nasa.gov/esds/maap
[11] https://www.geoplatform.gov/
[12] Chu, E.K., M.M. Fry, J. Chakraborty, S.-M. Cheong, C. Clavin, M. Coffman, D.M. Hondula, D. Hsu, V.L. Jennings, J.M. Keenan, A. Kosmal, T.A. Muñoz-Erickson, and N.T.O. Jelks, 2023: Ch. 12. Built environment, urban systems, and cities. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH12.
[13] https://unfccc.int/topics/global-stocktake

of EOIs that can provide rapid GHG detection, particularly of 'easy to abate' emission sources, and integration into seamless data-modeling platforms such as the recently launched U.S. Greenhouse Gas Center, will help to accelerate national mitigation goals as well as international partnerships and agreements.

4. ***Leverage or deploy new Earth observing systems to improve short-term climate prediction in anticipation of accelerating climate trends.***

Rapid global warming poses significant risks to society. The recent string of record warm years (the warmest 10 years on record have all occurred in the last 10 years) has highlighted how extreme events most associated with global climate change can cause severe damage to people, property, and ecosystems. A more comprehensive portfolio of climate-observing platforms would help improve weather and climate prediction at short timescales (days to seasons) to facilitate appropriate preparedness and response activities. For short-term climate prediction, deployment of targeted in situ and remotely sensed EOIs can facilitate detection of near-term climate trends that pose significant risks (e.g., drought, extreme heat, increased rainy seasons), as well as precursors for the onset of important modes of climate variability such as ENSO. For the oceans where the rapid onset of extreme marine events is of growing concern, investment in adaptive sampling strategies can facilitate greater ability to observe such phenomena as they are developing. New and emerging climate services can benefit from ensuring modeling capabilities exist that are able to incorporate all relevant climate observations for this purpose.

5. ***Promote open, interoperable, and equitable access to climate observations and data.***

A significant trend that has emerged since EOA 2016 is the increasing use of EOIs beyond climate research. The EOI impact scores for CL-4 (*Facilitating societal responses to climate variability and change*) clearly indicate the need for access to EOI data by an ever-broadening user community. In addition to providing efficiency and equitable access to these increased volumes, continued development, implementation, and maintenance of global data standards is needed to help ensure interoperability among data sets and systems. Recent data policies, such as those being implemented as part of the Geospatial Data Act of 2018, can facilitate the assimilation of disparate EOIs across platforms and partners (e.g., public, private, regional, national) into the types of systems necessary for climate change adaptation. Best practice standards for data harvesting and management (such as those laid out in the FAIR principles)[14] lay the foundation for equitable access. However, new guidance, structures, partnerships, or recommendations are needed to promote leveraged EOIs that can respond directly to climate change adaptation needs. It should also be recognized that there are multiple constituencies with very different well-established data-to-decision-making workflows, some of which incorporate proprietary software. There is a need to work to move these workflows toward integration points as close to the original data as possible to avoid duplication, inefficiency, and the costs associated with it.

[14] https://www.go-fair.org/fair-principles/

Abbreviations and Acronyms

AgMIP	Agricultural Model Inter-comparison and Improvement Project
AWG	Assessment Working Group
AWOS	Automated Weather Observing System
CDR	Climate Data Record
CL	Climate (SBA)
CoCoRaHS	Community Collaborative Rain, Hail, and Snow Network
COOP	Cooperative Observer Program
ENSO	El Niño Southern Oscillation
EO	Earth observations
EOA	Earth Observations Assessment
EOI	Earth observation input
EOP	Executive Office of the President
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
ESA	European Space Agency
FAA	Federal Aviation Administration
FAIR	findable, accessible, interoperable, and reusable
FGDC	Federal Geographic Data Committee
GCOM-W	Global Change Observation Mission — Water
GEO	Geostationary Equatorial Orbit
GHG	greenhouse gases
GISS	Goddard Institute for Space Studies
GOES-R	Geostationary Operational Environmental Satellite-R Series
GOOS	Global Ocean Observing System
GOS	Global Observing System
IK	Indigenous Knowledge
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
JAXA	Japan Aerospace Exploration Agency
JPSS	Joint Polar Satellite System
KO	key objective
KPSO	key product, service, or outcome
LiDAR	light detection and ranging
MAAP	Multi-mission Algorithm and Analysis Platform

MODIS	moderate resolution imaging spectroradiometer
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEI	National Centers for Environmental Information
NEI	National Emissions Inventory
NISAR	NASA-ISRO SAR Mission [ISRO — Indian Space Research Organization]
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting Partnership
NSTC	National Science and Technology Council
NWLON	National Water Level Observation Network
NWS	National Weather Service
Obs4MIPs	Observations for Model Intercomparison Project
OLI	Operational Land Imager
OSTP	Office of Science and Technology Policy
POES	Polar-orbiting Operational Environmental Satellite Series
SBA	societal benefit area
SCAN	Soil Climate Analysis Network
SME	subject matter expert
SNOTEL	Snowpack Telemetry
SST	sea surface temperature
TEK	Traditional Ecological Knowledge
TIRS	Thermal Infrared Sensor
USCRN	U.S. Climate Reference Network
USGS	U.S. Geological Survey
USGEO	U.S. Group on Earth Observations
USVI	U.S. Virgin Islands
VIIRS	Visible Infrared Imaging Radiometer Suite
WMO	World Meteorological Organization