A User-Driven Approach to Determining Critical Earth Observation Priorities for Societal Benefit

Erica Zell, Amy K. Huff, Adam T. Carpenter, and Lawrence A. Friedl

***Abstract*—In order to help data providers make informed decisions regarding the availability and accessibility of Earth observations for societal benefit, a cross-sectoral meta-analysis of observation priorities was conducted from the perspective of users. The analysis was organized around the Group on Earth Observations' (GEOs) societal benefit areas (SBAs): Agriculture, Biodiversity, Climate, Disasters, Ecosystems, Energy, Health, Water, and Weather. Users' needs for Earth observations were prioritized using a two-stage process. In the first stage, critical observations for each individual SBA were determined based on observation needs expressed in publicly available documents, such as scientific journal articles, scientific reports, and workshop summaries. In the second stage, an ensemble of four statistically robust methods was used to prioritize the observations identified in the individual SBA analyses, based on their criticality and commonality to multiple SBAs. The result of the meta-analysis is a ranking of 152 critical Earth observation priorities; the highest priority Earth observations are those that are considered critical for the largest number of SBAs. The 10 highest ranked observations are: (1) Precipitation, (2) Soil Moisture, (3) Surface Air Temperature, (4) Land Cover, (5) Surface Wind Speed (6) Vegetation Cover, (7) Surface Humidity, (8) Urbanization, (9) Vegetation Type, and (10) Surface Wind Direction and Sea Surface Temperature (tie). This study represents one viable method to assess the priority of Earth observations from the perspective of users. The list of critical Earth observation priorities from this study is a foundation for engagement between data providers and users in regard to observation priorities.**

***Index Terms*— Earth Observing System, environmental factors, international collaboration, geoscience, remote sensing, social factors.**

I. Introduction

USERS of Earth observations have a wide range of data requirements and priorities that depend on their specific applications. Some users need both basic datasets of directly observed phenomena and derived forecasts and products, while others utilize only a particular type of dataset. Users have varying technical sophistication levels, ranging from researchers who work with raw datasets, to intermediate users who utilize processed data products, to end users who employ highly processed products, tools, or forecasts. Earth observation users also span a wide range of sectors, including the public sector, the private sector, academia, and the media. Data users require information on a variety of observation timescales, from near real-time to historic archived data, for such applications as historical trend analysis, operational tactical decisions, and strategic planning and forecasting. Users also vary in their engagement with Earth observation organizations and in documentation of their data needs.

Understanding the diverse and evolving range of user needs is essential for creating a successful architecture to maximize Earth observation benefits for society. Data providers cannot make informed decisions regarding Earth observation systems without knowing users' observation requirements and associated priorities. Identifying critical Earth observation needs is essential for assessing the cost-effectiveness of investments in Earth observations as a whole and for determining Earth observation investment options.

Several researchers have conducted studies to assess the costs and benefits of investments in Earth observation systems, which support the need for prioritization assessments. Recent analyses have concentrated on the Global Earth Observation System of Systems (GEOSS), an international collaboration led by the Group on Earth Observations (GEO). GEO is a voluntary organization working to improve the availability, accessibility, and utility of Earth observations to benefit society [1]. GEO's initiatives are focused around its nine societal benefit areas (SBAs): Agriculture, Biodiversity, Climate, Disasters, Ecosystems, Energy, Health, Water, and Weather. GEOSS builds on national, regional, and international observation systems and data from thousands of instruments [2]. Fritz *et al.* [3] proposed a conceptual framework for assessing the incremental benefits of the increased international coordination being fostered by GEOSS compared to the associated costs, while Rydzak *et al.* [4] described a systems approach to measure and analyze the impacts of global Earth observations across the GEO SBAs. These studies noted that assessing the costs and benefits within a single SBA could help prioritize among Earth observation investment options, if costs and benefits can be detailed by the SBA. In fact, focused analyses have detailed the costs and benefits of Earth observations for tsunami disaster response and recovery in Banda Aceh, Indonesia [5] and for the Biodiversity SBA [6], [7]. Other remote sensing applications with a potential for high societal impact, such as assessments of urban sprawl and coastal storm surge inundation [8], [9], have not conducted cost-benefit assessment.

Previous attempts to assess Earth observation priorities have involved the identification of high-priority observations within

Manuscript received September 29, 2011; revised December 15, 2011 and March 23, 2012; accepted April 26, 2012. Date of publication July 03, 2012; date of current version December 28, 2012. This work was supported by GEO Task US-09-01a from NASA Applied Sciences Division (contract GS-23F-8167H) as well as from the U.S. Environmental Protection Agency and the German Federal Ministry of Transportation, Building and Urban Development.

E. Zell and A. K. Huff are with the Battelle Memorial Institute, Arlington, VA (corresponding author e-mail: zelle@battelle.org).

A. T. Carpenter is with American Water Works Association, Washington, DC.

L. A. Friedl is with NASA Applied Sciences Program, Earth Science Division, Washington, DC.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JSTARS.2012.2199467

a single subject area. The Integrated Global Observing Strategy Partnership (IGOS-P) utilized this type of approach to identify key observation needs for individual themes, such as the Water Cycle [10] and Geohazards [11], and a set of Essential Climate Variables was identified for the Global Climate Observing System to address the cross-cutting issue of climate change [12]. More broadly, many countries and organizations have written reports, held workshops, sponsored projects, conducted surveys, and produced documents that specify the needs and/or priorities of users of Earth observations. For example, the World Meteorological Organization (WMO) conducts a periodic Rolling Requirements Review (RRR) that compares user requirements for meteorological observations with the capabilities of present and planned observing systems [13]. In addition, the U.S. National Research Council periodically identifies key scientific questions to be informed by Earth observations, in order to assist U.S. government agencies, such as the National Aeronautics and Space Administration (NASA), the National Oceanographic and Atmospheric Administration (NOAA), and the United States Geological Survey (USGS), with program design [14]. These research efforts have been invaluable for assessing user needs with regard to specific topics or types of users.

Although previous studies have supported the need for prioritization of Earth observations through cost-benefit analyses of investments in observation systems and have assessed observation priorities within a single topic area, an effort to identify the priorities of users across all types of Earth observations and topic areas has not been made. In order to fill this gap, we have conducted a cross-sectoral meta-analysis of global Earth observation priorities from the perspective of users. The study was sponsored by GEO and was focused around GEO's nine SBAs. This paper discusses the methodology and results of the prioritization study, including a ranking of 152 critical Earth observation priorities based on the needs of users across multiple SBAs. Some of these observations are critical for a particular field, such as disasters or agriculture, while others support a broad range of societal benefits. The results of this study can support the development of a data architecture to maximize interoperability and provide societal benefits from the most critical Earth observations.

II. Methodology

Users' needs for Earth observations were identified and prioritized in this study using a two-stage process, illustrated in Fig. 1. All types of Earth observations were considered, regardless of measurement technology, including ground-based, satellite, and airborne measurements. Analysis concentrated on the observations needed by users, and included directly measured observations and combinations of direct measurements, as well as measurements that involve processing or modeling. Since the analysis focused on the needs of users, user terminology for Earth observations was retained; consequently, many of the required observation parameters discussed in this paper are phenomena of interest to a user rather than technical specifications of an observation as discussed in the remote sensing or in situ measurement communities.

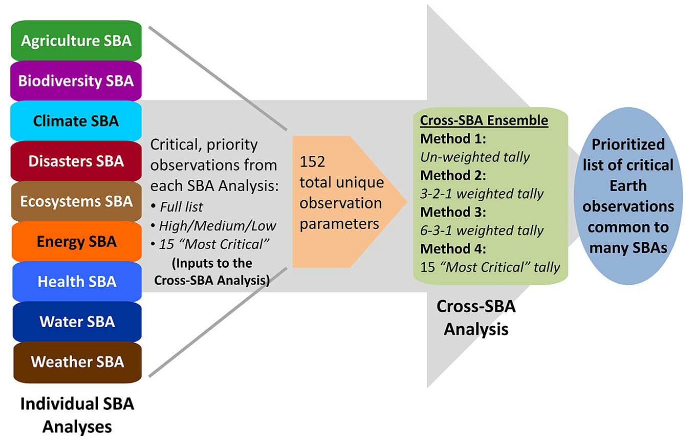

Fig. 1. Flowchart representing the sequence in the overall methodology for determining critical Earth observation priorities that are common to many SBAs.

A. Individual SBA Analyses

The first stage of the methodology involved the determination of critical Earth observation priorities for the individual SBAs. The analysis for each SBA was done in accordance with the GEO User Interface Committee's (UIC) designated 9-step process, described in this section, beginning with identification of an Analyst to lead each SBA analysis. Each Analyst worked with an ad hoc international Advisory Group. The SBA Advisory Groups each included 6–23 technical, scientific, management, and/or policy experts in their fields. Across all of the SBAs, 173 experts from 40 countries participated in the Advisory Groups, including representatives from 30 GEO Member Countries and 14 GEO Participating Organizations, as shown in Fig. 2. Advisory Group members were solicited through contacts of the Analysts, the GEO UIC network, GEO Communities of Practice, and from review of relevant literature. Some GEO organizations, such as the Committee on Earth Observation Satellites (CEOS) and WMO, provided members for several Advisory Groups. The selection of Advisory Group members was at each Analyst's discretion, based on the requirement to maximize breadth of expertise and geographic representation. Participants were from all geographic regions and from developed and developing countries, although there was a relative lack of Advisory Group members from Africa compared to other regions due to difficulty in recruiting appropriate technical experts.

Each Analyst worked with his or her Advisory Group to determine the scope of the prioritization analysis, including the sub-areas of focus, which helped organize and bound the study. In general, the Analysts and Advisory Groups selected sub-areas that represented either logical sub-topics within their SBA (e.g., types of disasters for the Disasters SBA), or different topics on which users may focus (e.g., famine early warning within the Agriculture SBA). The Analysts coordinated their efforts to minimize overlap between the analyses, given the related nature of many of the SBAs. For example, Weather SBA users include those in the disasters, health, agriculture, and energy sectors, among others, which could have resulted in overlap between the scope of the Weather SBA report and the scopes of the Disasters

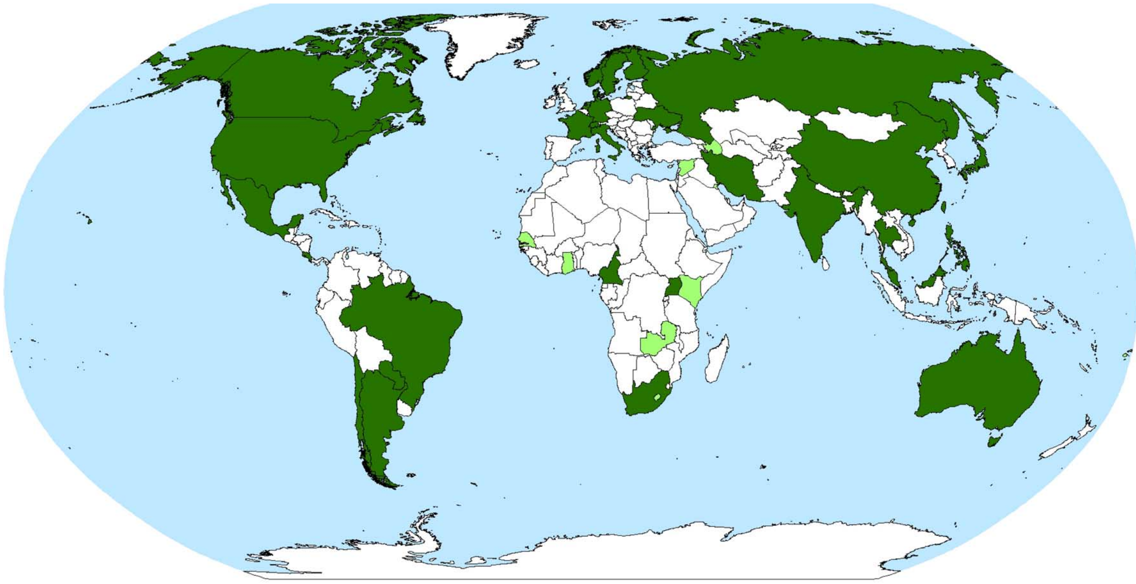

Fig. 2. Countries represented by the SBA Advisory Groups.

SBA, Health SBA, Agriculture SBA, and Energy SBA reports. The sub-areas of focus for each SBA report are listed in Table I.

The 9-step process developed by the GEO UIC for the prioritization analysis was based on the premise that a great deal of work has already been conducted on prioritizing Earth observations [15]. To that end, the Analysts relied on stated user needs in existing, publicly available documents, such as scientific journal articles, international reports, workshop summaries, conference proceedings, and national- and international-level reports. With the help of their Advisory Group, the Analysts identified appropriate documents and extracted stated user needs that were relevant to their SBA sub-areas of focus. The number of relevant documents used for each SBA analysis is shown in Table I. Documents were drawn from around the world, including from developed and developing countries, to ensure that the needs of users from all geographic regions were included in the analyses. Documents had to contain one or both of the following types of information in order to be included in the individual SBA analyses: (1) specification of Earth observation parameters *needed by users* (preferred), or (2) reference to Earth observation parameters *currently in use*, with some indication of the *adequacy* of the observation parameter characteristics as currently available. Most of the identified documents were written in English, although some documents written in languages other than English were consulted. The relative lack of non-English language documents was a limitation of the study, but Analysts relied on their international Advisory Groups to provide information on user needs that are not stated in English language documents.

After extracting information on critical Earth observations from relevant documents, the Analysts prioritized the observations using priority-setting methods developed in conjunction with their respective Advisory Group. In order to obtain the most relevant list of priority Earth observations for each SBA, all Analysts were not required to utilize the same priority-setting methods. Instead, they used a range of methods that were specific to their SBAs, including a combination of quantitative and qualitative approaches. For example, the Disasters SBA Analyst weighted observations based on the frequency with which they were mentioned in documents, cross-cutting applications within the Disasters SBA, and document type, where international or consensus documents were given a greater weight, since these documents represent the viewpoints of organizations and users from a broad range of geographic locations and specialties. The Disasters SBA Analyst also incorporated the risk of specific types of disasters (e.g., tropical cyclones, volcanic eruptions) to human life and property in the priority-setting analysis. In contrast, the Health SBA Analyst utilized a Disability Adjusted Life Year (DALY) metric to prioritize observations that support decision-making related to diseases.

Each Analyst prioritized the resulting list of critical Earth observations in three ways. These lists were used as input to the overall cross-SBA analysis (discussed in Section II-B).

1) Full List: Each Analyst submitted the entire list of critical Earth observation priorities for their SBA. No restrictions were made on the total number of priority Earth observations that could be identified for each SBA. The average number of observation priorities was 42; the Ecosystems SBA had the largest number of priority observations (77), and the Energy SBA had the lowest (15).

2) High/Medium/Low List: Each Analyst assigned a ranking of “high,” “medium,” or “low” priority to the Earth observations in their full list, based on the recognition that some observations have greater priority than others. These terms are relative, with the understanding that even “low” priority observations may be critical for many users.

3) 15 Most Critical List: Each Analyst submitted a list of the 15 “most critical” observations from their full list. This list re-

TABLE I
SUB-AREAS OF FOCUS AND NUMBER OF DOCUMENTS USED FOR INDIVIDUAL SBA ANALYSES

SBA Analysis	Sub-Areas of Focus	Number of Documents
Agriculture	Famine Early Warning Agriculture Production Seasonal/Annual Agriculture Forecasting and Risk Reduction Aquaculture Production Timber, Fuel, and Fiber Management (Forests) Forest Perturbations and Protection Carbon and Biomass (Forests)	85
Biodiversity	Freshwater Marine Terrestrial	64
Climate	Atmosphere Ocean Lands	40
Disasters	Earthquakes Floods Landslides Tropical Cyclones Volcanic Eruptions Wildfires	85
Ecosystems	Coastal and Near-Shore Marine Systems Forests Inland/Fresh Water Oceanic Islands and Archipelagos Tundra Watersheds	115
Energy	Hydropower Wind power Bioenergy (Including Transportation Biofuels) Solar Power Geothermal Power	54
Health	Aeroallergens Air Quality Infectious Diseases	1,093
Water	Surface Waters Sub-Surface Waters Forcings (on the Terrestrial Waters) Water Quality/Water Use	200
Weather	Global Numerical Weather Prediction Regional Numerical Weather Prediction Synoptic Meteorology Nowcasting and Very Short Range Forecasting Seasonal and Inter-annual Forecasts Aeronautical Meteorology Atmospheric Chemistry Ocean Applications Agricultural Meteorology Hydrology	25
TOTAL		**1,761**

stricted the number of priority observations to an equal number for each SBA and thus limited the bias toward those SBAs that had a larger number of priority observations.

From the full lists of priorities taken collectively across the SBAs, 152 unique critical Earth observations were identified. The complete individual SBA reports can be found on the GEO Task US-09-01a website [16].

B. Cross-SBA Analysis

In the second stage of the methodology, an ensemble of four statistically robust methods was used to prioritize the 152 Earth observations based on their criticality and commonality to multiple SBAs. The cross-SBA analysis focused on prioritizing Earth observations common to the nine SBAs (Agriculture, Biodiversity, Climate, Disasters, Ecosystems, Energy, Health, Water, and Weather). The cross-SBA analysis methodology was developed collectively through consultation with the SBA Analysts, the GEO UIC, and expert statisticians, and it was designed to produce nuanced results that reflect sensitivity to the selected analysis methods, with the recognition that many possible analysis methods could be valid in addition to those selected. The cross-SBA ensemble methods are four variations of frequency analysis of the critical Earth observations identified for each of the SBAs, corresponding to the three types of prioritization lists prepared by the individual SBA Analysts (discussed inSection II-A).

Method 1: Unweighted Tally: This method is an un-weighted sum of the number of SBAs for which a given observation is considered critical, based on the full list of priority observations for each SBA. The total number of critical Earth observations for each SBA varied, as described in Section II-A. For this method, the critical Earth observations were ranked according to the number of SBAs that specified a given observation as a priority. For example, Precipitation was identified as a critical observation for all nine SBAs, making it a top priority.

Method 2: 3-2-1 Weighted Tally: This method is a weighted sum of the number of SBAs for which a given observation is considered critical, based on the high/medium/low list of critical observations for each SBA. A weight of 3 for was assigned for "high" priority observations, 2 for "medium," and 1 for "low." The values for these numerical weights were agreed upon by the SBA Analysts. For example, Precipitation was ranked as a "high" priority by all nine SBAs, making it a top priority with a weighted "score" of 27 from Method 2.

Method 3: 6-3-1 Weighted Tally: Similar to Method 2, Method 3 is also a weighted sum of the number of SBAs for which a given observation is considered critical, based on the high/medium/low list of critical observations for each SBA. For Method 3, a weight of 6 was assigned for "high" priority observations, 3 for "medium," and 1 for "low." This scheme was suggested by the SBA Analysts to give added emphasis to observations of "high" and "medium" priority. For example, since Precipitation was ranked as a "high" priority by all nine SBAs, it is a top priority with a weighted "score" of 54 from Method 3.

Method 4: "15 Most Critical" Tally: This method is an un-weighted sum of the number of SBAs, if any, for which a given observation was among the 15 "most critical" observations. This scheme was suggested by the SBA Analysts as an option to equalize SBA representation and avoid bias from SBAs that had a larger number of priority observations.

For each of the 152 observations, the scores from cross-SBA ensemble methods 1 through 4 were converted to ordered ranks (1, 2, 3...) and then averaged to obtain an average rank and a range of ranks across the four ensemble methods. Using this approach, the highest priority Earth observations are those that are considered most critical for the largest number of SBAs, and thus have the highest average rank (i.e., rank closest to 1). Observations that have the same average rank are considered to be tied.

Several "pre-processing" steps were necessary to facilitate incorporation of observations from the individual SBA analyses into the cross-SBA analysis, such as standardizing the categories of the specified critical Earth observations across the SBAs. As a result, most Earth observations incorporated into the cross-SBA analysis include several related measurements. For example, Precipitation incorporates solids and liquids; observations on the phase, amount, frequency, and duration of precipitation; precipitation in thunderstorms; and extreme precipitation events. Similarly, Soil Moisture includes surface and sub-surface soil moisture observations. In addition, pre-processing ensured that the underlying datasets required for calculating derived observations were also included as priorities. This step was necessary because some Earth observation parameters are measured or sensed directly, whereas some are derived indirectly from other observations or models. For example, the observation parameter Land Cover is derived from underlying topography and other data sets, so indication of Land Cover as a priority necessitates consideration of topography and the other associated underlying data sets as observation priorities as well. The linkages between derived observations and directly measured observations were established through consultation with the SBA Analysts.

The complete Cross-SBA report can be found on the GEO Task US-09-01a website [17].

III. Results

The primary result of the cross-SBA analysis was an overall ranking of the 152 Earth observation priorities based on their criticality and commonality to multiple SBAs. Fig. 3 shows the top 25 Earth observations from the cross-SBA analysis in priority order. The error bars indicate the range of ranks from cross-SBA ensemble methods 1 through 4. For illustration purposes, the priority observations in Fig. 3 are listed by their observation score, which is the inverted average rank. For example, Precipitation has the highest average rank (1), so its corresponding observation score is 152.

In order of priority, the top 10 observation priorities are: (1) Precipitation, (2) Soil Moisture, (3) Surface Air Temperature, (4) Land Cover, (5) Surface Wind Speed (6) Vegetation Cover, (7) Surface Humidity, (8) Urbanization, (9) Vegetation Type, and (10) Surface Wind Direction and Sea Surface Temperature (tie). Fig. 3 illustrates that the top 10 observations have relatively low variability (smaller error bars) across cross-SBA ensemble methods 1 through 4, compared to lower ranked observations. This result suggests that the top 10 observations are high priorities regardless of the analysis method, while lower ranked observations appear to be more sensitive to the specific cross-SBA ensemble methods.

Fig. 4 lists the top 25 Earth observations in order of priority, based on their average rank from the cross-SBA analysis, and the corresponding SBAs for which the observation was considered critical. Fig. 4 conveys both the criticality and commonality of the top 25 observations. The dark blue squares indicate that the observation is considered a priority for a particular SBA, while the gray squares indicate that the observation is not considered a priority for a particular SBA. Although some observations may be relevant or critical to some users associated with a particular SBA, if an observation was not identified as a priority in the individual SBA analysis, then it is not shaded dark blue in Fig. 4.

In this study, priority is determined by criticality and commonality among the SBAs. As shown in Fig. 4, three of the four highest ranked observations, Precipitation, Soil Moisture, and Surface Air Temperature, are critical for all nine SBAs. Land Cover, the fourth highest ranked observation, is critical for seven SBAs. The 15 highest ranked observations are critical for five or more SBAs, and the 46 highest ranked observations, which represent 30% of the total 152 observations, are critical for three or more SBAs.

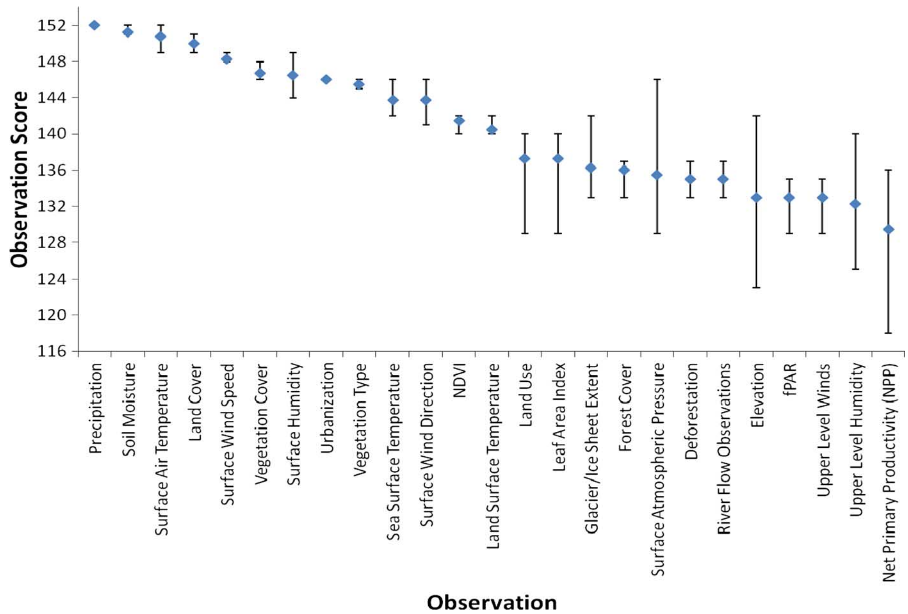

Fig. 3. Top 25 Earth observations from the cross-SBA analysis in priority order, based on the observation score, which is the inverted average rank. The error bars indicate the range of ranks for each observation from the four cross-SBA ensemble methods described in the text.

IV. Discussion

This study represents one valid approach to summarize global Earth observation priorities from the perspective of users, with a focus on societal benefit areas. As explained in the Introduction, establishing observation priorities is important for making the most cost-effective investments in Earth observation technologies and ensuring that the needs of the greatest number of users are met. This study identified Earth observation priorities across a full geographic range and spectrum of user types associated with each SBA. The results of the study were shaped in part by the methodology developed by the GEO UIC, in which SBA Analysts relied primarily upon stated user needs in publicly available documents as the basis of determining critical Earth observation priorities. Although other prioritization methods may be viable, this approach was adopted to provide a quantitative, objective foundation for the individual SBA analyses of critical Earth observations.

The methodology for determining the critical Earth observations for the individual SBAs had some important limitations, however. Although the SBA Analysts collectively reviewed more than 1,700 relevant documents with broad geographic coverage in an effort to ensure adequate geographic representation of users' observation needs, some regions were more represented than others in available documents. For example, the Disasters SBA Analysts found no relevant documents that focused specifically on Earth observation priorities for Africa or South America, although many documents covered user needs for these continents in general. More broadly, the Weather SBA Analyst noted that mechanisms to gather requirements across weather applications are mature, but there is a lack of documentation on regional and national needs. These gaps in documentation of user needs may be partially due to the primary focus on English language documents, the limited availability on the internet of documents from developing countries, and the inadequate scientific institutional capacity to ascertain and catalog regional to national Earth observation priorities in specific regions. The lack of complete geographic representation in the documents likely introduced some bias into the prioritization process. In cases where the paucity of documents for a given region seemed particularly limiting (e.g., Disasters SBA, Agriculture SBA), the respective Analysts utilized expert opinion from their Advisory Group to augment observation priorities identified from stated user needs in documents. In this way, the Analysts attempted to balance a purely objective approach that was limited in some cases (identifying observation needs in documents) with potentially more representative but subjective input from their expert Advisory Groups.

Furthermore, the SBA Analysts used different priority-setting methods to identify Earth observation priorities for their respective SBAs, which may have also influenced the overall cross-SBA prioritization process. Requiring all of the Analysts to use identical priority-setting methods would have ensured consistency for the individual SBA analyses, but it would have sacrificed the accuracy of having Analysts utilize priority-setting methods that were most suited for their particular SBAs, such as DALYs for the Health SBA analysis.

Despite the limitations of the prioritization methodology, several important outcomes have emerged from the analysis. The results of this study reinforce the need for a cross-sectoral approach to cataloging Earth observation requirements for societal benefit, and ultimately for designing interoperable systems, since the three highest ranked critical Earth observations are priorities for all nine SBAs. The study also provides unique examples of the many different types of users and the variety of purposes for which users require Earth observations. For example, wind speed information is needed by users affiliated with the Health and Ecosystems SBAs, in addition to the perhaps more obvious needs for meteorological monitoring and forecasting by users affiliated with the Weather and Disasters SBAs. Some

Health SBA users require wind speed data to monitor and forecast the spread of infectious diseases and to study aerobiological processes, including emission and dispersion of pollen, while some Ecosystems SBA users require wind speed data to assess storm impacts on ecosystems.

The relative agreement on the top 10 critical observations by the four cross-SBA ensemble methods (Fig. 3) demonstrates that these Earth observations represent the most critical observations required by users, based on their commonality to multiple SBAs; their rankings are not a function of the type of prioritization methodology employed. Also of interest in Fig. 3 is the mix of types of measurements in the top 25 observations, including direct observations, such as Precipitation, and parameters derived from multiple Earth observations, such as Urbanization. This mix in types of observations reflects the spectrum of users whose needs were considered as part of the study. Users employ Earth observations for a variety of applications, such as historical trend analysis, operational tactical decision-making, strategic planning, and forecasting, with various organizations providing data or information products across the spectrum. This study found that users can be viewed as a spectrum—a "chain of users"—from researchers to intermediate users to end users. For example, weather forecasters are intermediate users, who analyze and interpret Earth observations and typically produce forecasts or warnings. End users, such as government officials and public health managers, take the forecasts and warnings and act on them, making decisions for societal benefit. Many SBA Analysts developed lists of users or frameworks to characterize this flow of data among users to capture appropriately user needs across the broad range of user types. Incorporating the needs of the entire "chain of users" added complexity to the analysis but was essential to ensure that the needs of all types of users were captured in the prioritization process.

The prioritization analysis focused on the commonality and criticality of observations by SBA, rather than by region. Thus, users' priority needs that are unique to a single region, when documented, are not likely to be among the highest ranked observations in the overall cross-SBA analysis. Likewise, some user needs identified as high-priority in the cross-SBA analysis may not be a priority for certain regions. For example, the Ecosystems SBA included marine ecosystems as a sub-area, but user needs related to marine ecosystems are not likely to be priorities for users in land-locked regions. Furthermore, some needs were found to be priorities for developing countries, because, for example, of their agriculture-dependent economies and focus on developing biofuels as a source of energy and revenue. Such developing country needs were incorporated into the individual SBA analyses during the document-gathering stage, but they were not separately analyzed or otherwise called out in the study results. A prioritization analysis focused on developing country observation needs and needs for development in general could be a useful angle for future studies.

The results of this study are not meant to be a static list of Earth observation priorities that are valid indefinitely, since users' needs will change in the coming years for a variety of reasons. For example, users' Earth observation priorities are likely to evolve as climate shifts and weather becomes more variable

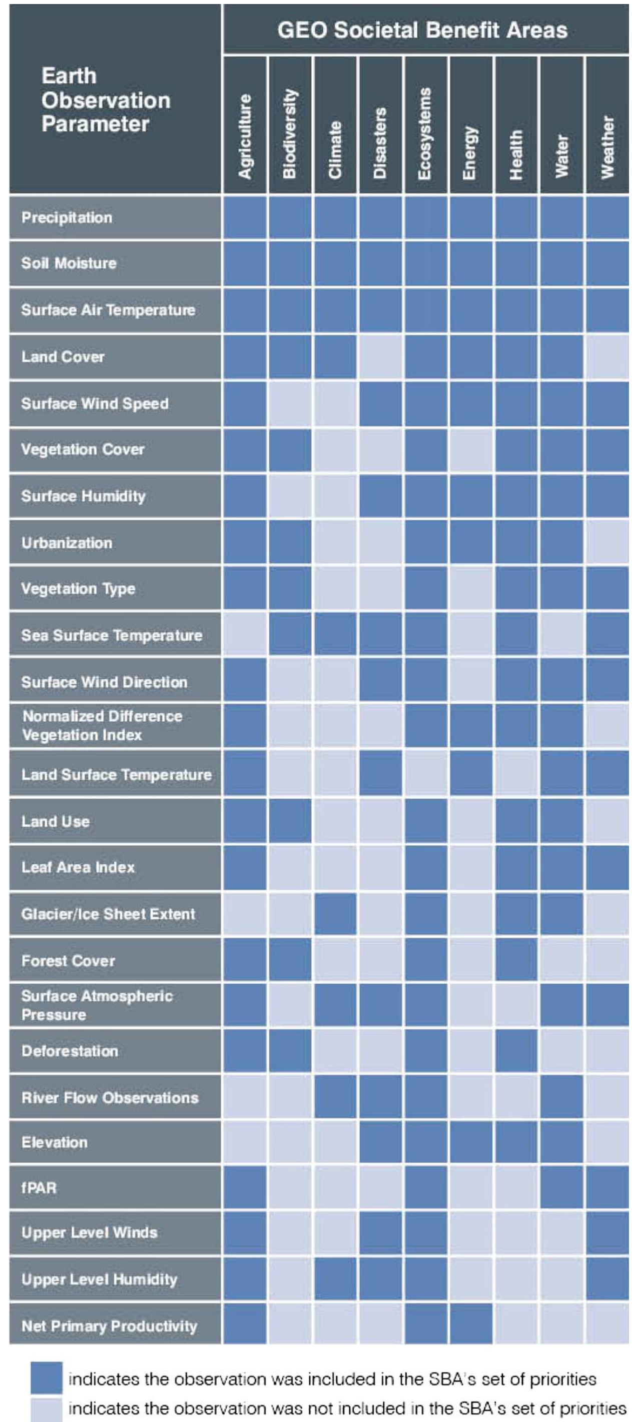

Fig. 4. Top 25 Earth observation priorities listed according to their average rank in the cross-SBA analysis, and the associated SBAs. The dark blue squares indicate that the observation was identified as a priority for the particular SBA using cross-SBA ensemble method 1. This figure conveys both the criticality and commonality of the observations to many SBAs. Some observations may be relevant or even critical to some users associated with an SBA, but they were not included in the SBA's overall set of priorities in the cross-SBA analysis (i.e., are not shaded dark blue) because the observations did not rise to the level of criticality established by the relevant SBA Analyst and Advisory Group.

due to anthropogenic climate change. The Climate SBA Analyst captured the Essential Climate Variables specified by the Global Climate Observing System and its supporting agencies, but also noted the lack of regional and national priority accorded atmospheric observations of carbon dioxide and methane [12]. Furthermore, measurement of terrestrial carbon (storage, uptake, and fluxes) was identified as a critical priority observation for the Agriculture and Ecosystems SBAs, but was not one of the overall highest ranked observations in the cross-SBA analysis due to its designation as a critical priority for only two SBAs. Given the cross-cutting implications of climate change for all SBAs, future prioritization analyses could include a factor to account for the cascading impacts of certain phenomena such as climate change.

An initial aspect of this study was to document specific observation parameter characteristic needs, such as the required accuracy, precision, and latency of observations. Many of the documents reviewed during the course of the study did not include quantitative information on the required characteristics of critical observations, however. In addition, required observation characteristics vary widely depending on the user and application. As a result, the SBA Analysts focused primarily on user observation needs in general, with only a secondary focus on required observation characteristics. Recognizing that information on needed observation characteristics is important for maximizing societal benefit, the authors are conducting a follow-on study to document the specific required characteristics of Precipitation observations, primarily through outreach to GEO Communities of Practice and other relevant communities of users. Precipitation is the focus of this additional analysis because it is the highest ranked parameter in the cross-SBA analysis, and it is a priority for all nine SBAs. The authors are also conducting an additional follow-on study to assess the availability of current and planned satellite-based observations for the top 35 observations in the cross-SBA analysis.

Despite some of the constraints of the analysis methodology, this study has established a process for collecting and prioritizing Earth observations using statistically robust analyses of user needs documented in publicly available sources. This study is a breakthrough in documenting critical Earth observation priorities. It is the first cross-sectoral meta-analysis of worldwide user needs, and it represents one feasible method to assess user needs for societal benefit.

V. Summary and Conclusions

By providing a measure of Earth observation priorities across multiple areas of societal benefit, this study builds a foundation for successful architecture and interoperability to support a broad range of users of Earth observation data. The results of this study can benefit data providers, user communities, and institutions with a mandate for improving the availability, accessibility, and utility of Earth observations for decision-making. The list of 152 critical Earth observation priorities is also a basis for further engagement between data providers and users in regard to observation priorities and needs. By identifying critical Earth observation priorities, users of similar observations can connect and benefit from each other, and data-providing organizations can maximize the efficient use of their limited resources.

The results of this study have many specific applications in the GEO community. GEO can use the Earth observation priorities to determine, prioritize, and communicate gaps in current and future Earth observations and to help ensure that interoperable systems are in place to meet users' needs. GEO Member Countries and Participating Organizations can use the results to determine priority investment opportunities for Earth observations, identify key opportunities to serve their users' needs, partner with other members to provide key observations for broad societal benefit, and register data and information to support users across many SBAs. GEO Committees can identify key gaps in current and planned availability of priority observations, examine access to the observations through GEOSS, build capacity in use of high-priority observations, assess maturity of science and technology to serve priority needs, and engage users on needed characteristics of key observations. GEO Communities of Practice can engage users and organizations with common interests, identify linkages with other Communities of Practice, and broaden their communities across user types. GEO users can compare their needs and priorities to those of others, identify linkages with other SBAs, and discover observations of possible use and benefit.

This study broadly assessed critical Earth observation priorities from the perspective of users, regardless of measurement technology. Additional studies could assess the current and planned availability of priority Earth observations, building on the analysis currently being conducted by the authors on the availability of satellite-based observations for the top 35 priority observations identified in the cross-SBA analysis. Complementary studies could determine priorities for specific types of measurements, such as near real-time observations, or measurements made using a particular technology, such as ground-based measurements. Other studies could focus on regional or national level needs, specific developing country needs, the needs of under-represented user types in the literature, and/or rapidly evolving needs, such as those related to climate change. Each of these follow-on studies would further enhance the baseline provided by this study for engaging user communities on critical observation needs and meeting those needs with interoperable systems.

Acknowledgment

The authors thank the SBA Analysts who contributed to GEO Task-US-09-01a: Allan Sommer (Agriculture SBA); Glynis Lough (Agriculture SBA/Forests Sub-report and Ecosystems SBA); Michele Walters and Greg Susanke (Biodiversity SBA); Molly Macauley (Climate SBA); Stephanie Weber (Disasters SBA); Tom Gulbransen and Harry Stone (Ecosystems SBA); Hillel Koren, Rudy Husar, and Pietro Ceccato (Health SBA); Sushel Unninayar (Water SBA); and Michael Nyenhuis (Weather SBA). The authors also thank Amy Jo Swanson for providing logistics and coordination among the SBA Analysts. Special thanks to Vince Brown and three anonymous reviewers for comments that significantly improved the manuscript.

References

[1] About GEO, the Group on Earth Observations (GEO). [Online]. Available: http://www.earthobservations.org/about_geo.shtml, Sep. 20, 2011.

[2] The Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan, February 2005 Group on Earth Observations. [Online]. Available: http://www.earthobservations.org/documents/10-Year%20Implementation%20Plan.pdf, Sep. 23, 2011.

[3] S. Fritz, R. J. Scholes, M. Obersteiner, J. Bouma, and B. Reyers, "A conceptual framework for assessing the benefits of a global earth observation system of systems," *IEEE Systems J.*, vol. 2, no. 3, pp. 338–348, 2008.

[4] F. Rydzak, M. Obsersteiner, and F. Kraxner, "Impact of global earth observation—Systemic view across GOESS societal benefit areas," *Int. J. Spatial Data Infrastructure Research*, vol. 5, pp. 216–246, 2010.

[5] I. McCallum, R. Kidd, S. Fritz, F. Kraxner, and M. Obersteiner, "Banda Aceh—The Value of Earth Observation Data in Disaster Recovery and Reconstruction: A Case Study," International Institute for Applied Systems Analysis, Interim Report IR-08-048, Nov. 27, 2008.

[6] E. Leyequien, J. Verrelst, M. Slot, G. Schaepman-Strub, I. M. A. Heitkonig, and A. Skidmore, "Capturing the fugitive: Applying remote sensing to terrestrial animal distribution and diversity," *Int. J. Appl. Earth Observ. Geoinform.*, vol. 9, no. 1, pp. 1–20, 2007.

[7] D. M. Muchoney, "Earth observations for terrestrial biodiversity and ecosystems," *Remote Sens. Environ.*, vol. 112, no. 5, pp. 1909–1911, 2008.

[8] A. Rahman, S. P. Aggarwal, M. Netzband, and S. Fazal, "Monitoring urban sprawl using remote sensing and GIS techniques of a fast growing urban centre," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens. (JSTARS)*, vol. 4, no. 1, pp. 56–64, 2011.

[9] E. Ramsey, L. Zhong, Y. Suzuoki, A. Rangoonwala, and D. Werle, "Monitoring duration and extent of storm-surge and flooding in Western Coastal Louisiana marshes with Envisat ASAR data," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens. (JSTARS)*, vol. 4, no. 2, pp. 387–399, 2011.

[10] Cryosphere Theme Report for the Monitoring of our Environment from Space and from Earth 2007 Integrated Global Observing Strategy (IGOS). [Online]. Available: http://cryos.ssec.wisc.edu/docs/cryos_theme_report.pdf, Sep. 26, 2011.

[11] Geohazards Theme Report for the Monitoring of our Environment from Space and from Earth, April 2004 Integrated Global Observing Strategy (IGOS). [Online]. Available: http://www.geohazcop.org/library/documents/igos_geohazards_report.pdf, Sep. 26, 2011.

[12] World Meteorological Organization and Intergovernmental Oceanographic Commission, Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update), GCOS-138, GOOS-184, GTOS-76, WMO-TD/No. 1523, August 2010. [Online]. Available: http://www.wmo.int/pages/prog/gcos/Publications/gcos-138.pdf, Nov. 15, 2011.

[13] The Rolling Requirements Review Process, World Meteorological Organization (WMO). [Online]. Available: http://www.wmo.int/pages/prog/sat/rrr_en.php, Sep. 26, 2011.

[14] National Research Council, Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, 2007. [Online]. Available: http://www.nap.edu/catalog.php?record_id=11820, Nov. 15, 2011.

[15] Description of 9-Step Process for Task US-09-01a, the Group on Earth Observations (GEO) User Interface Committee (UIC). [Online]. Available: http://sbageotask.larc.nasa.gov/GEO_UICUS0901a_Process.pdf, Sep. 25, 2011.

[16] GEO Task US-09-01a Individual SBA Reports, the Group on Earth Observations (GEO) and the National Aeronautics and Space Administration (NASA), October 2010. [Online]. Available: http://sbageotask.larc.nasa.gov/, Sep. 25, 2011.

[17] GEO Task US-09-01a Cross-SBA Report, Second Edition, the Group on Earth Observations (GEO) and the National Aeronautics and Space Administration (NASA), March 2012. [Online]. Available: http://sbageotask.larc.nasa.gov/docpres.html, Mar. 20, 2012.

Erica Zell is a Principal Research Scientist at Battelle, and she has 16 years of experience with air quality and climate change applications in developing countries, analysis of renewable energy technologies, satellite remote sensing, and geographic information systems analysis. Her recent projects include serving as the climate change specialist for USAID staff training worldwide, initiating inclusion of air quality data into the SERVIR Program in Mesoamerica, and piloting the application of satellite remote sensing data in global environmental indicators. Ms. Zell served as the Cross-SBA Analyst, lead Energy SBA Analyst, and supporting Climate SBA Analyst for GEO Task US-09-01a. She earned an M.S. in Environmental Engineering from the University of California at Berkeley in 1997.

Dr. Amy K. Huff has been a Research Scientist at Battelle since 2007. She earned a Ph.D. in Chemistry from the University of California, San Diego in 1998 and an M.S. in Meteorology from Pennsylvania State University in 2007. She has 18 years of experience in atmospheric chemistry and meteorology. Recently, she has worked on projects for NASA, NOAA, and USEPA on air quality, environmental science, remote sensing, and climate change. Dr. Huff was the co-Disasters SBA Analyst for GEO Task US-09-01a and supported the cross-SBA analysis.

Adam T. Carpenter is currently a Regulatory Analyst at the American Water Works Association, focusing on climate change impacts to the drinking water sector, water quality issues related to hydraulic fracturing, and other issues affecting drinking water quality and water utilities. Formerly, he was an Environmental Researcher at Battelle, where his work focused on two main areas: supporting the Earth observations community and performing research for toxics programs. After earning a B.S. in biology from George Washington University in 2007 and an M.S. in environmental sciences and policy at Johns Hopkins University in 2008, he is currently pursuing a Ph.D. in environmental science and public policy from George Mason University. Mr. Carpenter provided support to the Analysts for the Agriculture, Energy, Ecosystems, and Disasters SBA reports, and he also supported the cross-SBA Analysis.

Lawrence A. Friedl is the Director of the NASA Applied Sciences Program within the Earth Science Division. Mr. Friedl served on the Group on Earth Observations User Interface Committee, and is the co-lead for GEO Task US-09-01a (Identification of Critical Earth Observation Priorities). Mr. Friedl joined NASA in 2002. He holds a degree in Aerospace Engineering from Princeton University and an M.S. in Public Policy from Harvard University.