Applications for ICESat-2 Data

From NASA's Early Adopter Program

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NASA's Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) mission, scheduled to launch no later than April 2018 (and currently slated for October 2017), is being developed to continue the multiyear observations of the earth's surface elevation, ice, and clouds started by ICESat. To increase the use of the satellite data after launch, the ICESat-2 mission invested in an applications program aimed at innovatively applying the data in a variety of fields. The program provides a framework for building a broad and well-defined user community during the prelaunch period to maximize the use of data products after launch and to provide early insight into the range of potential uses of the mission data. Ideas and research on how altimetry data will be used for decision making arise from the end users; therefore, the ICESat-2 mission is extending itself through its applications program.

In this article, we provide a description of four case studies that demonstrate the breadth of the focus areas that have emanated from the program. These include sea-ice forecasting for maritime decision making, ecosystem monitoring in semiarid regions, water-level tracking for lakes and reservoirs, and volcanic and geohazard identification. These applications offer encouragement to both the end users and NASA to continue engaging a wide variety of decision makers before the launch of an Earth science satellite for societal benefit.

The first ICESat was developed in the 1990s and was primarily designed to measure elevation changes in the world's ice sheets. This system operated from 2003 to 2009 and provided the multiyear elevation data needed to determine changes in ice sheets, sea-ice thickness, land elevations, tree canopies, clouds, and aerosol profiles. The Geoscience Laser Altimeter System (GLAS) instrument aboard ICESat was the first space-borne lidar instrument for Earth science. This instrument collected data during approximately 33-day campaigns two or three times a year with consistent repeat coverage over the polar regions and at strategic locations requested by the user community at lower latitudes. ICESat fulfilled its mission objective of a five-year data record in 2008 and ceased measurement collection in October 2009.

THE ICESAT-2 MISSION

ICESat-2 is designed to continue measurements of changing ice sheets and sea ice and also to collect elevation measurements over oceans and land, allowing opportunities to study vegetation height, inland water elevation, atmospheric cloud heights, and ocean elevation through surface-specific data products.

ICESat-2 will make high-resolution, high-accuracy elevation measurements using the Advanced Topographic Laser Altimeter System (ATLAS) instrument. The ICESat-2 mission has an operational requirement of three years plus 60 days, a goal of five years of continuous operations, and fuel for seven years of operations, provided the mission continues to collect high-quality data. The ATLAS instrument is expected

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to provide elevation measurements with finer spatial resolution and accuracy than GLAS. ATLAS is a micropulse photon-counting lidar operating at a 532-nm wavelength. Unlike GLAS's single-beam, approximately 70-m footprint, full waveform recording technique using infrared light from a laser pulsed 40 times per second, the ATLAS instrument emits 10,000 laser pulses per second on each of its six beams, forming approximately 15-m-diameter circular footprints, and records the travel time of individual photons that are reflected back to the sensor from the surface of the earth. ATLAS measures the photon travel time, while the on-board global positioning system and the inertial measurement unit determine the location and pointing direction of the laser when a measurement is taken. These three pieces of data (i.e., the photon travel time, pointing direction, and position in space) are combined in ground processing to provide an accurate measurement of the surface elevation. Table 1 describes the NASA science requirements related to measurement accuracy. The measurement accuracy for any particular surface is a function of a number of factors, primarily the atmospheric transmission and the surface albedo. While snow and ice are reflective at the ATLAS wavelength, bare earth and oceans are less so. Consequently, these latter targets will have fewer signal photons over a given area compared with snow-covered areas, and they will have a correspondingly lower accuracy. This new approach to space-borne lidar will provide accurate global observations of elevation and enable high-quality data products that will have a wide variety of uses for societal benefit.

APPLICATIONS PROGRAM

In 2013, the ICESat-2 mission began an applications program modeled after the successful program from the Soil Moisture Active Passive (SMAP) mission. The applications program provides a framework for building a broad and well-defined user community during the prelaunch phases of the mission to maximize the use of data products after launch and to provide early insight into the range of potential uses of the mission data [1]. A multiscale communications approach is used to address the need for information at the local, national, and international scales in government, nongovernmental organizations, private entities, and academia to help provide several layers of information to the end user. The ICESat-2 Early Adopter Program facilitates the feedback loops between the mission and user communities that are necessary for a transparent understanding of the utility of ICESat-2 data products in different decision-making contexts.

Here, an application is defined as an innovative use of mission data products in decision-making activities for societal benefit [2]. This requires taking the science data products to stakeholders to ensure the data are actively being used to affect some change in policy, decision making, or reduction in risk [3]. To maximize the utility for societal decision making of data from scientific satellite missions, consideration should be given to the needs of potential applications during mission formulation and data product design [4]. For example, the measurements of reservoir heights can indicate the potential for flooding or low water levels that can be used by local governments to affect changes in reservoir management or to regulate water withdrawals.

An important part of the ICESat-2 applications effort is the Early Adopter Program, which promotes applications research that engages with specific institutions to provide a fundamental understanding of how ICESat-2 data products can be scaled and integrated into an organization's policy, business, or management activities to improve decision-making efforts [5]. Early Adopters are groups or individuals who have a direct or clearly defined need for data and who will invest their own time and resources in better understanding how ICESat-2 data will be used when they are available [1]. The Early Adopter designation provides individuals and groups an opportunity to engage with the mission and to demonstrate the utility of the data in their particular operational system or model before the launch of the sensor. Individuals who become Early Adopters commit to engaging in research, with specific support from the mission, to accelerate the use of the data when they become available. They also commit to providing valuable feedback on how ICESat-2 data can be used to support decision making in their communities [6].

This article provides an overview of ICESat-2 data products and their uses. In addition, summaries of four Early Adopter case studies demonstrate how ICESat-2 data can be integrated into the institutions' analyses and processes, and show how the data will be useful in the coming years.

ICESat-2 MISSION AND DATA PRODUCTS

The ICESat-2 mission was developed in response to the recommendations by the National Research Council [7] 2007 decadal survey for Earth science missions. The science objectives for ICESat-2 are to quantify changes in ice-sheet elevation and their contributions to sea-level rise, to estimate sea-ice thickness, to measure vegetation canopy height, and to enhance the utility of Earth-observation systems through the support of other measurements. Specific mission requirements and sensor design were developed based on the science objectives.

ICESat-2 IS DESIGNED TO CONTINUE MEASUREMENTS OF CHANGING ICE SHEETS AND SEA ICE AND ALSO TO COLLECT ELEVATION MEASUREMENTS OVER OCEANS AND LAND.

Table 2 shows the data products that will be developed from the mission, along with the required latency time for each product. Data from the ICESat-2 mission will be provided to the public in the Hierarchical Data Format 5 (HDF5) format (www.hdfgroup.org/HDF5). The HDF5 format has been adopted by a number of NASA mission data products [e.g., SMAP, among many other Earth-Observing System (EOS) satellite missions] as it provides a platform-independent open-source HDF. The mission plans many of the higher-level products to be in gridded format with a two-dimensional interpolation between observations to provide a data product comparable to other sensors for applications. Latency between data collection and the posting of the higher-level products is 30–45 days due to the data duration required (i.e., monthly products) and the need for ancillary data and processing time. An important focus of applied research is to understand the impact of the delay between data acquisition and delivery on applications.

TABLE 1: THE ATLAS INSTRUMENT MEASUREMENT ACCURACIES AND REQUIREMENTS.

LAND-ICE MEASUREMENT REQUIREMENTS:

- ice-sheet elevation changes to 0.4-cm/a accuracy on an annual basis
- annual surface elevation change rates on outlet glaciers to better than 0.25 m/a over areas of 100 km^2 for year-to-year averages
- surface elevation change rates to an accuracy of 0.4 m/a along 1-km track segments for dynamic ice features that are intersected by the ICESat-2 set of repeated ground tracks
- resolution of winter (accumulation) and summer (ablation) ice-sheet elevation change to 10 cm at 25-km × 25-km spatial scales.

SEA-ICE MEASUREMENT REQUIREMENT:

- monthly surface elevation measurements with a track spacing smaller than 35 km poleward of 70°, to enable the determination of sea-ice freeboard, when sea-surface references are available under clear sky conditions to an uncertainty of 3 cm along 25-km segments for the Arctic Ocean and southern oceans.

MABEL, THE ICESat-2 SIMULATOR

Due to the large differences between the GLAS and ATLAS instruments, the ICESat-2 project developed an airborne simulator called the *Multiple Altimeter Beam Experimental Lidar (MABEL)*, which is used to collect data that are similar to what will be produced by ATLAS [8]. The MABEL instrument is not a replica of the ATLAS instrument but incorporates many of the key features of ATLAS (i.e., multiple beams, photon-counting detection, data density, and thousands of laser pulses per second). MABEL data have been used to produce simulated ATLAS data with similar characteristics and responses, to assist scientists in the development of algorithms for ICESat-2 [9], and to characterize data flows and loads for ground systems. As is the case with ATLAS, the accuracy of MABEL-derived surface elevations depends on the surface characteristics and atmospheric transmission. For snow-covered surfaces, researchers have found that several of the MABEL beams have accuracies consistent with those projected for ATLAS [9].

MABEL's first flights were over the southwestern United States in late 2010. Then the instrument collected data over Greenland and its adjacent ice-covered oceans in March 2012. Subsequent campaigns focused on forest cover in the eastern United States and glaciers and mountains in Alaska. The existing data span a diversity of surface features, including land ice, sea ice, inland water, coastal ocean, deserts, and forested areas (Table 3). The data have been used to develop algorithms for ICESat-2 as well as to obtain a better understanding of the performance of ATLAS-like lidar data over different surfaces. Data from these flights are available for free to the general public through the ICESat-2 website (http://icesat.gsfc.nasa.gov/icesat2/data/mabel/mabel_docs.php). All are encouraged to explore these data.

USING ICESat-2 DATA IN APPLIED RESEARCH

Although ICESat-2 was designed primarily to address the critical-science need to understand rapidly changing polar ice and ocean responses to climate change, the especially diverse data products being developed offer an opportunity to enhance numerous Earth science applications. Recent history has shown that Earth-observing satellites provide data products that can inform decision making across a

TABLE 2. THE ICESat-2 SCIENCE DATA PRODUCT TABLE.

PRODUCT NUMBER	NAME	SHORT DESCRIPTION	LATENCY*
ATL00	Telemetry data	Raw ATLAS telemetry in packets with any duplicates removed by EOS Data Operations System.	Downlinked eight times/day
ATL01	Reformatted telemetry	Parsed, partially reformatted, HDF5 time-ordered telemetry.	Two days
ATL02	Science unit converted telemetry	Science unit converted time-ordered telemetry calibrated for instrument effects. All photon events per channel per shot. Includes atmosphere raw profiles. Includes housekeeping data, engineering data, space craft position, and pointing data.	Two days
ATL03	Global geolocated photon data	Precise latitude, longitude, and height above ellipsoid for all received photons determined using precision orbit determination and precision pointing determination. Along-track data, per shot per beam. Geophysical corrections applied. Classification of each photon (signal versus background) and into surface types (land ice, sea ice, ocean, etc.).	21 days
ATL04	Normalized relative backscatter	Along-track normalized relative backscatter profiles at full instrument resolution (25 times/s for ~30-m vertical bins). Includes calibration coefficient values calculated in the polar region.	21 days
ATL06	Land-ice height	Surface height for each beam, along- and across-track slopes calculated for beam pairs. All parameters are calculated at fixed along-track increments for each beam and repeat.	45 days
ATL07	Sea-ice height	Height of sea ice and open water leads (at varying length scale). Includes height statistics and apparent reflectance.	45 days
ATL08	Land-vegetation height	Height of ground and canopy surface at varying length scale. Where data permits, include estimates of canopy height, relative canopy cover, canopy height distributions, surface roughness, surface slope, and apparent reflectance.	45 days
ATL09	ATLAS atmosphere cloud layer characteristics	Along-track cloud and other significant atmosphere layer heights, blowing snow, integrated backscatter, and optical depth.	45 days
ATL10	Sea-ice freeboard	Estimates of freeboard using sea-ice heights and available sea-surface heights within kilometer-length scale; contains statistics of sea-surface samples used in the estimates.	45 days
ATL11	Land-ice height	Time series of the height at points on the ice sheet, calculated based on repeat tracks and/or crossovers.	45 days from receipt of last data in product
ATL12	Ocean-surface height	Surface height at varying length scales. Where data permits, include estimates of height distributions, surface roughness, and apparent reflectance.	45 days from receipt of last data in product
ATL13	Inland water-body height	Along-track inland water height extracted from land/water/vegetation product. Where data permits, include roughness, slope, and aspect.	45 days from receipt of last data in product
ATL14	Antarctic and Greenland gridded height	Height maps of each ice sheet for each year of the mission based on all available ICESat-2 elevation data.	45 days from receipt of last data in product
ATL15	Antarctic and Greenland height change	Height-change maps of each ice sheet, with error maps, for each mission year and for the whole mission.	45 days from receipt of last data in product
ALT16	ATLAS atmosphere weekly	Polar cloud fraction, blowing snow frequency, ground detection frequency.	45 days from receipt of last data in product
ATL17	ATLAS atmosphere monthly	Global cloud fraction, blowing snow and ground detection frequency.	45 days from receipt of last data in product
ATL18	Land-vegetation gridded height	Gridded ground-surface height, canopy height, and canopy cover estimates.	45 days from receipt of last data in product
ATL19	Gridded sea-surface height—open ocean	Gridded ocean height product, including coastal areas. To be determined (TBD) grid size. TBD merge with sea-ice /sea-surface height.	45 days from receipt of last data in product
ATL20	Gridded sea-ice freeboard	Gridded sea-ice freeboard. TBD length scale.	45 days from receipt of last data in product

* Latency is defined as the approximate time it takes from the data acquisition on a satellite until it reaches an individual in a usable format.

breadth of applications, even though these applications were not conceived prior to launch. These include, in particular, data from the Advanced Very-High-Resolution Radiometer sensor that have been used for many applications never envisioned by the original mission [10]. Landsat data have been used in an enormous number of

TABLE 3. A SUMMARY OF THE MABEL FLIGHTS BY TARGET AND YEAR.

TARGETS	2010	2011	2012	2013	2014
Calibration	0	0	2	1	8
Desert	2	3	0	3	0
Forests	1	2	10	5	3
Fresh water	1	4	4	0	5
Glaciers	0	0	4	0	3
Ice sheet	0	0	7	0	0
ICESat tracks	1	1	0	0	0
Mountains	3	4	6	4	5
Ocean	1	4	6	2	1
Salt flat	1	0	0	0	1
Sea ice	0	0	4	0	3
Snow	1	1	1	0	0
Volcano	0	0	0	0	1
Wildfire	0	0	0	0	1

(Note that flights can have more than one target. For complete MABEL flight information, please visit the NASA ICESat-2 website at http://icesat.gsfc.nasa.gov/icesat2/.)

applications [11], [12] during the past four decades. The Tropical Rainfall Monitoring Mission has been used to identify and correct problems with ground-based weather radar [13] while providing comprehensive information on precipitation extremes. More recently, NASA's SMAP has been a pioneer in developing applications programs for its data [2].

As a result of numerous outreach efforts, the ICESat-2 applications program has identified societal benefit areas that may have an interest in altimetry data from the Group on Earth Observations (GEO) applications, which include the following:

- disasters including sea-ice monitoring for improved shipping navigation, keeping an eye on volcanic hazards, and monitoring sea-level rise for anticipating storm surge impacts
- ecosystems including forest, canopy modeling, and vegetation mapping
- health including air quality and other atmospheric studies
- water including operational water resources planning; weather forecasting; and modeling of inland water, hydrological, and floods.
- climate including assessing, understanding, and predicting change
- biodiversity including monitoring the condition and extent of ecosystems
- agriculture including land-cover change, changes in the extent of land degradation and deforestation, and changes in irrigation water availability
- energy including renewable energy potential [14].

Encouraging the use of ICESat-2 data within each of these areas requires engaging with stakeholders who have a compelling need for highly accurate information in one of these areas but who lack familiarity with photon-counting lidar instruments or space-based approaches to product development [3]. Because of the new design of ATLAS compared to the GLAS instrument on the first ICESat mission, an exploration of the benefits of the photon-counting approach for applications is an important goal. Early Adopter projects are selected in the different societal benefit areas listed to improve the ability of the mission to understand the potential utility of ICESat-2 data, to provide a wider set of applications that benefit society, and to foster innovative use of the measurements to inform environmental decision making [1].

As of September 2015, there have been three calls for Early Adopters open to any individual or group interested in exploring the potential use of ICESat-2 data. The program, which hosts a total of 16 Early Adopter groups, has prelaunch research that covers most GEO societal benefit areas, as illustrated in Table 4. The majority of Early Adopter research is conducted for sea ice, vegetation, and hydrological studies. Four Early Adopter groups are exploring the utility of ICESat-2 data for prediction of the sea-ice environment in the Arctic with benefits to applications in the areas of disasters, climate, biodiversity, ecosystems, and water. Five Early Adopters are conducting research to measure the change in vegetation height on country, regional, and global scales with benefits to applications in the areas of ecosystems, biodiversity, and disasters. Additionally, four groups are assessing the feasibility of using ICESat-2 for hydrological research related to applications in the water, agriculture, hazards, and ecosystems areas.

Two Early Adopter groups are conducting research on the use of ICESat-2 to improve digital elevation models (DEMs) for volcanic and geohazard-related research and ice volume discharge studies with benefits to disaster applications. One Early Adopter group is looking at the potential to use ICESat-2 for deriving aerosol optical properties in the polar region with potential benefits to applications in the areas of health, ecosystems, biodiversity, and disasters. Additional work will be necessary to identify underrepresented potential applications for the mission as well as to expand the potential users in the energy, agriculture, and health areas.

Each of the four Early Adopter projects described below conducts applied-science analysis and studies that increase the knowledge of the mission about how ICESat-2 mission data will be used. These four projects demonstrate the breadth of the focus areas that have emanated from the program, and they include sea-ice forecasting for maritime decision making, semiarid ecosystem monitoring, water-level tracking for lakes and reservoirs, and volcanic and geohazard identification. Each requires investigation into how the data will be used, the decisions the system will influence, and the requirements of the system for satellite data.

VALIDATING THE U.S. NAVY'S ICE FORECASTING SYSTEM

ICESat-2's high-accuracy, dense observation data set over the Arctic regions will provide high-quality validation data points for the U.S. Navy's two ice forecasting systems that predict the changing ice environment for maritime decision makers, i.e., the Arctic Cap Nowcast/Forecast System (ACNFS) and the Global Ocean Forecast System (GOFS) 3.1. The Early Adopter project from the U.S. Naval Research Laboratory (NRL) seeks to assimilate ICESat-2 sea-ice observations in the ACNFS for improved accuracy of sea-ice thickness in navigable waters and the ice edge forecast.

The ACNFS is a geographic subset of the global domain of the GOFS 3.1, which is a fully coupled ice/ocean system model and is the focus of the applied research. ACNFS has undergone validation by the U.S. NRL [15], has been declared operational (September 2013), and runs daily at the Naval Oceanographic Office (NAVOCEANO). GOFS 3.1 was transitioned to NAVOCEANO on 26 September 2014 [16] and is undergoing the final operational testing by NAVOCEANO and the National Ice Center (NIC). The NIC presently uses ACNFS output and, in the near future (once declared operational), will use GOFS 3.1 output to improve the accuracy and resolution of the analyzed ice edge location.

To provide sufficiently accurate information for maritime operations, three critical components are necessary to predict the open ocean environment. The first is access to satellite observations that measure sea-surface height, sea-surface temperature, and ice concentration with in situ observations from public sources and ships. The second component is numerical models representing the dynamic processes capable of capturing the physics of the ocean and numerical methods for efficiently representing those physics. The third component is the technology to assimilate available observations into numerical models [17]. An improved ACNFS/GOFS 3.1 will benefit the U.S. Navy and its navigation and other tasks as well as external customers that include the NIC; the National Weather Service in Anchorage, Alaska; and the National Oceanic and Atmospheric Administration (NOAA). Thus, ICESat-2 observations fit within the needs of the system, and research to assimilate ICESat-2 data into the model or use them for model validation will accelerate the use of the data after launch.

The U.S. NRL will investigate how to improve the assimilation of the 45-day latency ice thickness product by running a twin hindcast of the operational system (ACNFS or GOFS 3.1) lagged by 45 days. Hindcasts are a way of testing a model against known or closely estimated inputs for past events to see how well the model matches the known results. Periodically, either seasonally or once per year, ice thickness observations will be assimilated into the ACNFS/GOFS 3.1 systems to create a more realistic forecast product. The U.S. NRL will use the April 2012 Arctic Campaign lidar data collected by the ICESat-2 airborne simulator MABEL as a proxy data set for the testing of assimilation techniques into ACNFS and GOFS 3.1. Derived products (such as sea-ice freeboard, snow depth, and ice thickness) created using lidar, radar, and imagery data from NASA's Operation IceBridge will be used by the U.S. Navy for model validation until ICESat-2 data become available. Although ice thickness fields are not currently assimilated into ACNFS or GOFS 3.1, work is ongoing to assimilate these data sources correctly into the model.

The end user of the improved ACNFS/GOFS 3.1 system is the U.S. Navy, NAVOCEANO, and the NIC. The NIC redistributes data products to a wide variety of private and government actors that manage and distribute navigational tools and products. For example, NOAA's Environmental Response Management Application for the Arctic includes many different products that originate with the ACNFS/GOFS 3.1, including ice edge, marginal ice zone, and sea-ice concentration maps. Sea-ice data products are of critical importance to improving safety in the Northwest Passage as multiyear ice recedes and ship traffic increases in regions that are inadequately surveyed and charted [18]. Interannual variability of sea-ice position and thickness will continue to pose navigation safety issues [19], increasing the importance of ICESat-2 data inputs into the ACNFS system.

ICESat-2'S HIGH-ACCURACY, DENSE OBSERVATION DATA SET OVER THE ARCTIC REGIONS WILL PROVIDE HIGH-QUALITY VALIDATION DATA POINTS FOR THE U.S. NAVY'S TWO ICE FORECASTING SYSTEMS.

With this Early Adopter project, the mission will have the opportunity to contribute improved sea-ice location and freeboard data to a critical maritime navigation system. By assimilating ICESat-2 data, an improvement in the overall ability of the ACNFS/GOFS 3.1 to provide marginal ice zone and sea-ice concentration maps to decision makers should improve, increasing the ability of the United States, Canada, and other nations to respond to sea vessel emergencies and improve sea safety for all vessels in the Arctic.

SATELLITE ALTIMETRY DATA FOR ECOSYSTEM MONITORING IN SEMIARID ECOSYSTEMS

Laser altimetry data have been shown to be well suited to mapping canopy structure and tree height [20]. There are significant needs for reliable estimates of the health and biomass of drylands, where 35% of the world's population resides. Drylands are particularly vulnerable to simultaneous changes in climate, fire, invasive species, and anthropogenic stressors [21], [22], and they can be difficult to monitor with remote sensing, given their sparse, heterogeneous structure [23]. Changes in dryland vegetation structure, such as in the semiarid Great Basin in the western United States, have resulted from invasion of exotic annuals such as cheatgrass (*Bromus tectorum*), resulting in an increase in fire frequency and spread at regional scales [24], [25]. Targeted fuel reduction and prevention of conversion to fire-prone grasslands in the Great Basin is a high priority for land management agencies such as the Bureau of Land Management (BLM), as demonstrated by the recent

TABLE 4. THE ICESat-2 EARLY ADOPTERS AS OF SEPTEMBER 2015.

EARLY ADOPTER PRINCIPAL INVESTIGATOR NAME	SCIENCE DEFINITION TEAM PARTNER	SCIENCE THEME	REGION(S)	EARLY ADOPTER TITLE	END-USER(S)	APPLICATION(S)	GEO SOCIETAL BENEFIT AREA(S)
Pamela G. Posey (U.S. NRL, NASA's Stennis Space Center)	Sinead L. Farrell (NASA's GSFC)	Sea ice	Full Arctic region	"Use of ICESat-2 Data as a Validation Source for the U.S. Navy's Ice Forecasting Models"	**U.S. Navy** (POC: Bruce McKenzie, Naval Oceanographic Office) **U.S. National/Naval Ice Center** (POC: Lt. j.g. David Keith)	Navigation; Arctic shipping	Water
Nancy F. Glenn (Boise State University, Boise Center Aerospace Laboratory)	Amy Neuenschwander (University of Texas)	Vegetation	Semiarid regions; western United States	"Improved Terrestrial Carbon Estimates with Semiarid Ecosystem Structure"	**USDA** (U.S. Forest Service and Agricultural Research Service; POC: Dr. Stuart Hardegree) **DOI** (BLM; POC: Anne Halford; including the Great Basin Landscape Conservation Cooperative and USGS; POC: Dr. Matt Germino) **DOD** (POCs: Charles Baun, Idaho Military Division; Carl Rudeen, Mountain Home Air Force Base) **Regional partners** (GBRMP and Joint Fire Sciences Program)	Long-term land management; using estimates of aboveground biomass to quantify carbon, fuel loads, and monitor change in semiarid regions	Ecosystems, biodiversity
Lucia Mona (Institute of Methodologies for Environmental Analysis of the National Research Council of Italy)	Steve Palm (NASA's GSFC)	Atmospheric sciences	Polar region	"APRIL (Aerosol optical Properties in polar Regions with ICESat-2 Lidar)"	NASA Policy makers at local (polar regions) and global (climate change) scale Examples: Aerocom, WMO	Climate; air quality (effects on health and environment); volcanic hazards	Climate, health, disasters
Greg Babonis (State University of New York at Buffalo)	Alex Gardner (NASA/JPL)	Ice sheets; solid earth	Subglacial volcanic events in areas such as Antarctica, Iceland, and in southern Andean ice fields	"Applications of ICESat-2 in Volcanic and Geohazards-Related Research"	Volcano observatories, Vhub user group, University of New York at Buffalo Geophysical Mass Flow Group	Volcanic hazard mitigation, monitoring, and forecasting	Disasters
Lynn Abbott and Randy Wynne, (both at Virginia Polytechnic Institute and State University)	Sorin Popescu (Texas A&M University)	Vegetation	Not specified (global)	"Detection of Ground and Top of Canopy Using Simulated ICESat-2 Lidar Data"	Researchers in forestry and governmental policy makers	Monitoring forest-related harvesting and land use	Ecosystems
Sudhagar Nagarajan (Florida Atlantic University)	Bea Csatho (University of Buffalo)	Ice sheets	Not specified (global)	"Incorporation of Simulated ICESat-2 (MABEL) Data to Increase the Time Series and Accuracy of Greenland/Antarctica Ice Sheet Dynamic DEM"	**Center for Environmental Studies**, (POC: Dr. Leonard Berry; works with local, national, and international government organizations on sea-level rise)	Sea-level rise monitoring/forecasting	Disasters, water
Andy Mahoney (UAF, Geophysical Institute)	**Sinead L. Farrell (NASA GSFC), Ron Kwok (NASA/JPL)**	Sea ice	Alaska's northern coastline; Arctic coastal system	"Repeat Altimetry of Coastal Sea Ice to Map Landfast Sea Ice Extent for Research and Operational Sea Ice Analysts"	**NOAA National Weather Service Ice Desk** [POC(s): James Nelson, meteorologist in charge, (james.a.nelson@noaa.gov); Rebecca Heim, ice forecaster, (Rebecca.Heim@noaa.gov)]	Operational ice charts/navigation; coastal deliveries; monitoring habitat of marine wildlife; offshore oil and gas industry roads; travel/transportation	Water, biodiversity

Charon Birkett (University of Maryland, Earth System Science Interdisciplinary Center)	**Mike Jasinski (NASA GSFC)**	Hydrology	Global (requirement: observations of lakes/reservoirs at least down to 10-km^2 target size)	"The Application of Altimetry Data for the Operational Water Level Monitoring of Lakes and Reservoirs"	Various water resources, agriculture, and regional security policy makers across the *.gov, *.org, *.com, *.mil groups; e.g., USDA/FAS.	Hydrological drought; agricultural drought; monitoring of high water (flood) levels; monitoring of crop condition and production	Agriculture, disasters, water
Guy J-P. Schumann (University of California at Los Angeles, Joint Institute for Regional Earth System Science and Engineering)	**Mike Jasinski (NASA GSFC)**	Hydrology	California Bay Delta; Niger Inland Delta	"Assessing the Value of the ATL13 Inland Water Level Product for the Global Flood Partnership (GFP)"	**GFP** (POCs: Dr. Florian Pappenberger; Global Flood Service and Toolbox Pillar; Dr. Guy Schumann, member of the GFP)	Prediction and managing of flood disaster impacts and global flood risk	Disasters
Kuo-Hsin Tseng (National Central University, Taiwan, Center for Space and Remote Sensing Research)	**Mike Jasinski (NASA GSFC)**	Hydrology	Ganges-Brahmaputra-Meghna river basin covering India, Nepal, China, Bhutan, and Bangladesh	"Using ICESat-2 Ground and Water Level Elevation Data Towards Establishing a Seasonal and Flash Flood Early Warning System in the Lower Ganges-Brahmaputra-Meghna River Basin"	**Institute of Water Modelling** (POC: Zahirul Haque Khan) **Bangladesh Water Development Board** (POC: Engr. Zahirul Islam) **Bangladesh Inland Water Transport Authority** (POC: Md. Mahbub Alam)	Water resource management; observation of freshwater storage change	Water, ecosystems
Andrew Roberts (Naval Postgraduate School) Alexandra Jahn (University of Colorado at Boulder) Adrian Turner (Los Alamos National Laboratory)	**Ron Kwok (NASA/JPL)**	Sea ice	Central Arctic analysis domain	"An ICESat-2 Emulator for the Los Alamos Sea Ice Model (CICE) to Evaluate DOE, NCAR, and DOD Sea Ice Predictions for the Arctic"	**DOE** (POC: Elizabeth Hunke) **National Center for Atmospheric Research** (POCs: Marika Holland, Jennifer Kay) **DOD** (POCs: Wieslaw Maslowski, Ruth Preller) **University of Colorado at Boulder** (POC: John Cassano)	Sea-ice forecasting; national defense environmental forecasting; coordinated disaster response: oil spill mitigation, field campaigns; improved climate projections at all latitudes	Water, climate, disasters
Stephen Howell (Environment Canada, Climate Research Division)	**Ron Kwok (NASA/JPL)**	Sea ice	Canadian Arctic	"Use of ICESat-2 Data for Environment Canada Observational Applications and Prediction Systems"	**Climate Research Division** (POC: Howell) **Canadian Meteorological Centre** (POC: Belair) **Canadian Ice Service** (POC: Arkett) **Canadian Centre for Climate Modelling and Analysis** (POC: Derksen)	Climate data records; operational sea-ice forecasting for Arctic shipping; sea-ice information for mariners; weather hazards; prevention/mitigation of atmospheric catastrophes	Climate, water, disasters
Wenge Ni-Meister (Hunter College of the City University of New York)	**Sorin Popescu**	Vegetation	Global	Mapping Vegetation with On-Demand Fusion of Remote Sensing Data for Potential Use of U.S. Forest Service Inventories and Fire Fuel Estimates	U.S. Forest Service	Forest inventories and fire fuel mapping	Ecosystems, biodiversity, disasters
Birgit Peterson (USGS)	**Amy Neuenschwander**	Vegetation	United States	Evaluation of ICESat-2 ATLAS Data for Wildland Fuels Assessments	**U.S. Forest Service's Wildland Fire Assessment System** [POC: W. Matt Jolly (mjolly@fs.fed.us), project manager]	Wildfire decisions; fire behavior modeling variables	Disasters

(continued)

TABLE 4. THE ICESat-2 EARLY ADOPTERS AS OF SEPTEMBER 2015. (CONTINUED)

EARLY ADOPTER PRINCIPAL INVESTIGATOR NAME	SCIENCE DEFINITION TEAM PARTNER	SCIENCE THEME	REGION(S)	EARLY ADOPTER TITLE	END-USER(S)	APPLICATION(S)	GEO SOCIETAL BENEFIT AREA(S)
G. Javier Fochesatto, (UAF, Geophysical Institute) Falk Huettmann (UAF, Institute of Arctic Biology)	**Lori Magruder (University of Texas)**	Vegetation	Arctic tundra and boreal forest; interior Alaska	Using ICESat-2 Prelaunch Data in High Latitude Terrestrial Ecosystems to Allow for Continuous Monitoring of Boreal Forests and Arctic Tundra	**USDA Forest Service PNW Research Station** (POC: Dr. Hans-Erik Andersen)	Land management and monitoring over large regions (Arctic tundra, boreal forest)	Ecosystems, biodiversity
Rodrigo C.D. Paiva (Federal University of Rio Grande do Sul, Brazil, Hydraulic Research Institute)	**Mike Jasinski**	Hydrology	Congo, Amazon, and Niger River Basins	Improved river hydrodynamics estimates from ICESat-2 for hydrology predictions	**Brazilian National Water Resources Agency** (POC: Adalberto Meller) **Brazilian Geological Survey** (POC: Daniel Medeiros Moreira) **International Commission for Congo Oubangui and Sangha Basin**	Flood monitoring	Disasters

GSFC: Goddard Space Flight Center; JPL: Jet Propulsion Laboratory; POC: point of contact; WMO: World Meteorological Organization; USGS: U.S. Geological Survey; DOI: Department of the Interior; GFP: Global Flood Partnership; DOD: U.S. Department of Defense; UAF: University of Alaska at Fairbanks; DOE: U.S. Department of Energy; PNW: Pacific Northwest.

Secretarial Order 3336 (2015). Lidar remote sensing offers the ability to map canopy characteristics needed for land management of the ecosystem [26], as metrics describing shrub canopy are critical inputs to quantifying fuels, productivity, and habitat quality.

The Great Basin is a large sagebrush-steppe eco-region and is bounded by the Wasatch Mountains on the east, the Sierra Nevada and Cascade Ranges on the west, and the Snake River Basin on the north. It includes most of Nevada and substantial portions of Utah, Oregon, California, and Idaho (Figure 1). This Early Adopter project focuses on integrating ICESat-2 data into management-driven projects in the Great Basin with the BLM and within the Joint Fire Sciences Program. These projects work to ensure the maximum integration of science into management decisions through partnerships and technology transfer. The projects are also part of the Great Basin Research and Management Partnership (GBRMP) and of associated consortia databases intended to reach a wide management-based audience.

This project tests prototype ICESat-2 data (MABEL) with airborne and terrestrial laser-scanning and optical remote sensing data that have previously been used to derive biomass, cover, and height information in the Great Basin. While previous work on vegetation analysis with ICESat-2 has focused on forests with a full canopy, this project seeks to determine the sensitivity of ATLAS data to derive key canopy characteristics that would allow mapping of semiarid ecosystem structure at landscape scales, such as the sagebrush steppe in the Great Basin.

MABEL-based simulations of ATLAS data were used to evaluate the potential of ATLAS to quantify shrub heights in two study areas in the Great Basin [27]. The study areas included the U.S. Department of the Interior's Morley Nelson Snake River Birds of Prey National Conservation Area (NCA) and the U.S. Department of Agriculture's (USDA's)Reynolds Creek Experimental Watershed (RCEW). The analyses demonstrated that simulated ATLAS data have the sensitivity to quantify height metrics of semiarid vegetation with minimum heights of 1 m and 30% canopy cover [26]. These results are compelling, especially with the potential to combine future ICESat-2 data with optical data such as Landsat 8 to improve both height and cover estimates (e.g., [28]–[30]). The synergistic use of Landsat 8 and ICESat-2 data may enable wall-to-wall estimates of vegetation community structure and carbon for semiarid ecosystems.

This Early Adopter activity continues to focus on improving the mission's understanding of how the data could be used for quantifying semiarid vegetation, and how the information could be incorporated into land management decision making. The BLM, the primary land manager for the Great Basin, relies on satellite remote sensing as the basis of quantitative, repeatable, and low-cost methods to measure indicators of ecosystem health, fuel loads, and habitat quality, particularly in huge, sparsely populated regions where the costs of monitoring and intervention are substantial [31]. This project has provided the mission with evidence of the potential usefulness of ATLAS data to land managers in semiarid ecosystems and with indications of the potential to apply ATLAS data globally in dryland ecosystems.

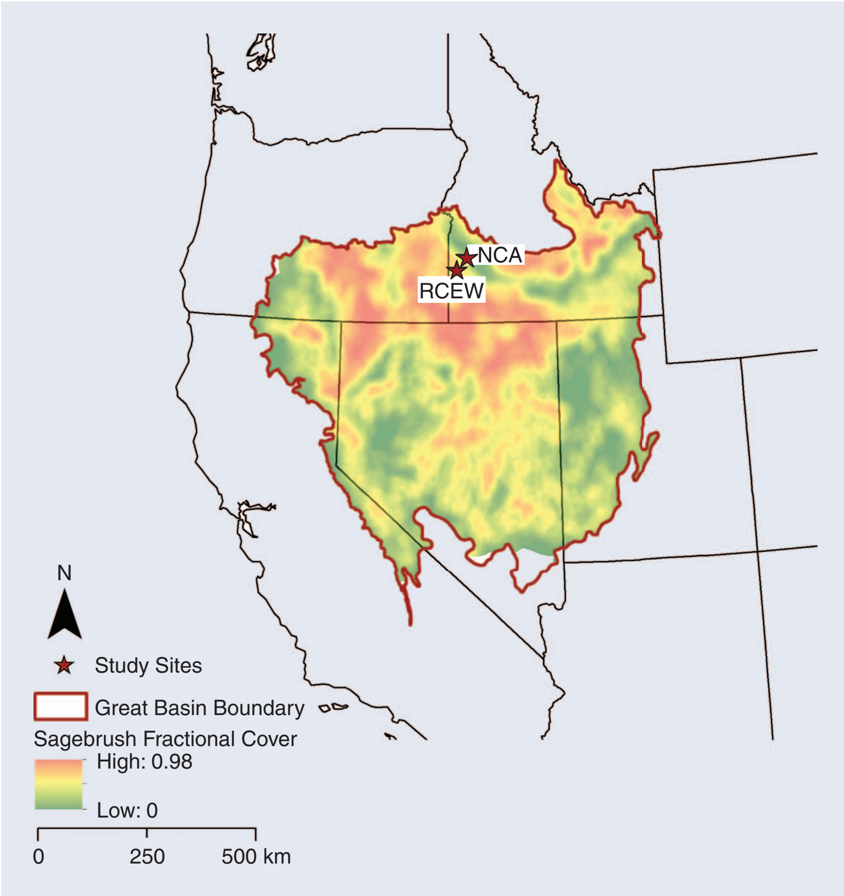

FIGURE 1. The Great Basin Landscape Conservation Cooperative with fractional sagebrush cover and study locations within the RCEW and the Morley Nelson Snake River Birds of Prey NCA.

ALTIMETRY DATA FOR WATER-LEVEL MONITORING OF LAKES AND RESERVOIRS

Altimetry data have long been a critical component of monitoring lake and reservoir heights in regions where elevation observations of change are restricted or absent. Current programs that monitor near real-time and/or archival lake and reservoir water levels are employed by the USDA/Foreign Agriculture Service (FAS) as an indicator of overall current or long-term water availability (Figure 2). Natural and man-made reservoirs are the primary way that water managers are able to reduce the effects of interseasonal and interannual streamflow fluctuations. They provide flood control and a means for hydroelectric power generation, and they offer a constant water supply for both recreation and irrigation [32]. This Early Adopter is researching the feasibility of incorporating ICESat-2 data into the Global Reservoir and Lake Monitor (G-REALM), a USDA/NASA–funded altimetric and operational water height monitoring system [33].

The USDA/FAS uses the G-REALM system for assessment of longer-term (decadal) hydrological drought and for near real-time assessment of agricultural (seasonal) drought and the detection of high water levels and floods [34]. Although the FAS does not use lake levels quantitatively in its assessment of global agricultural production, it is an additional tool within an array of models and remote sensing data products used during its monthly lock-up process, which produces global crop statistics, advisories, and warnings. Market agents use the information from these reports to make decisions regarding, for example, the purchase of grain, which influences international commodity prices [35]. The report development process is very time sensitive; thus, if the ICESat-2 lake height elevation data are to be used in the FAS process, at least one new lake-level observation needs to be made during each month, and the observation delivered within several days after satellite overpass. Given the limited coverage the instrument will have over lakes at low latitudes, many of these data points may be used only for validation, given the relatively long latency of these data sets.

ICESat-2 products, which will have a relatively long latency, can be used in two ways in this system:

- as primary data sources of the monitoring of high-latitude reservoirs, if repeat sampling of one month or less is available
- as secondary data sources for the validation of radar altimeter-based water level products for lakes and reservoirs.

Concerning the second use, research will be conducted that will link each ICESat-2 data observation location and value to an existing ground-based (in situ) observation and estimate the accuracy of the ICESat-2 elevations. Such validation exercises will focus on a variety of lakes and reservoirs in the United States and Canada. The utility of ICESat-2 data products within G-REALM for USDA/FAS, however, will depend on ICESat-2's temporal resolution and delay time. A low (seasonal) temporal resolution means that ICESat-2 can be used only as an archival validation source. Challenges to the use of ICESat-2 data in the system also include data loss via cloud cover and potential loss due to penetration effects in clear water.

This project aims to utilize the ICESat-2 inland water products that may impact decision making in the agriculture, water resources, and regional security sectors. Although the potential for significant contribution to inland water monitoring is evident, analysis and research are needed to estimate the temporal and spatial frequency of relatively accurate observations, which are expected to be better than 10 cm over lakes and reservoirs distributed across all latitudes. Existing MABEL data demonstrate that such accuracy is possible under clear-sky conditions over approximately 100-m averaging lengths, and we expect similar performance for ATLAS and the relevant ICESat-2 data products.

INTEGRATING ICESat-2 DATA WITH OTHER SOURCES OF HIGH-ACCURACY ELEVATION INFORMATION COULD SIGNIFICANTLY IMPROVE OUR ESTIMATION OF POTENTIAL VOLCANIC HAZARDS.

VOLCANIC AND GEOHAZARD IDENTIFICATION

Information about an imminent volcanic eruption can prevent catastrophic damage to life and property by estimating when an eruption might occur, the style of the eruption, and how volcanic debris may spread [36]. Recent use of thermal data from daily observations from the MODIS sensor in the MODVOLC system has greatly increased the ability of scientists to detect volcanic unrest in the form of increased surface temperatures, indicating near-surface magma [37]. Data from synthetic aperture radar (SAR) systems and sensors such as ICESat-2 are well suited for looking at other geologic changes that precede an eruption, such as changes in elevation around a volcano due to the intrusion of magma [38]. Topographic changes around an active volcano are also important to measure, as many volcanic hazards follow the surrounding topography [39]. In-filled valleys are less able to contain volcanic mass flows such as pyroclastic density currents (high-concentration avalanches of hot volcanic rock and gas) and lahars (fast-moving and deadly mudflows) [40], [41], and steep slopes can increase the mobility of volcanic debris [42].

DEMs derived from airborne altimetry flights, optical satellite platforms such as the Advanced Spaceborne Thermal Emission and Reflection or Satellite Pour l'Observation de la Terre, or SAR systems can be used together with ICESat-2 data, when available, to identify features of the landscape that can lead to loss of life or property [43]. Monitoring changes in topography around a volcano during an eruption, which can last for decades or longer, can yield information to determine potential hazards from pyroclastic density currents and lahars down flanks of the volcano. Pyroclastic density currents and lahars are the most deadly volcanic phenomena, causing the most deaths from volcanic eruptions [44]. Repeated high-accuracy elevation measurements are critical for hazard monitoring and forecasting.

ICESat-2's extremely accurate elevation data can improve analysis of volcanic hazards. The Surface Elevation Reconstruction and Change (SERAC) detection approach was developed to combine multiplatform laser altimetry data on ice sheets into time series of elevation changes from all observations within a surface patch using

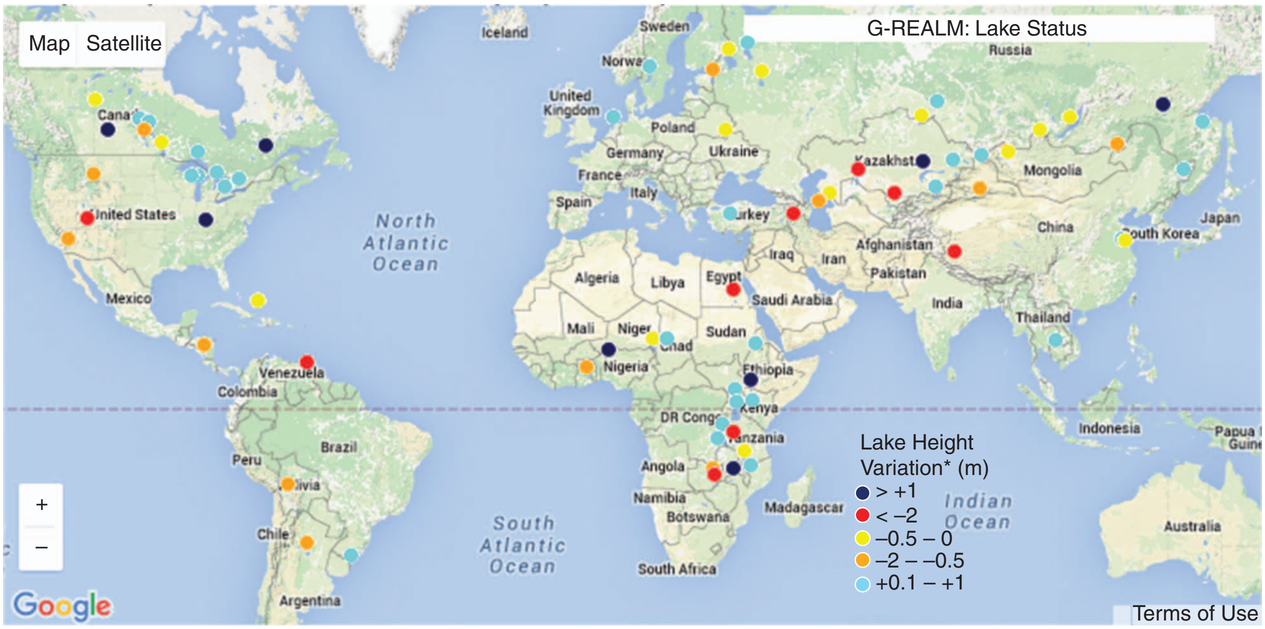

FIGURE 2. A lake status indicator map (courtesy of the USDA/NASA G-REALM program). Dot colors indicate the current status of water levels in lakes and reservoirs as compared to a long-term mean (1993–2002). Generally, a third of the monitored water bodies have current water levels 0.5 m or more below their longer term average.

least-squares adjustment [45]. Thickness changes over time are approximated by analytical curves to derive elevation change rates. Applied to volcanoes, this method could be used not only to detect volcanic edifice inflation for use in eruption forecasting but also to provide the spatiotemporal data necessary to model magma chamber processes. ICESat-2 data may be used to improve the elevation data around volcanoes that have not been monitored previously, reducing errors and uncertainty in the hazard models used to estimate the possible movement of volcanic mass flows across the landscape.

This Early Adopter research demonstrates the value of the data for monitoring and assessment of volcanic hazards and how the data can be incorporated into analysis of hazards, which should result in an improved early detection and societal response to volcanic hazards. Although research is needed to implement approaches such as SERAC for volcanic landscapes, by integrating ICESat-2 data with other sources of high-accuracy elevation information, these approaches could significantly improve our estimation of potential volcanic hazards.

CONCLUSION

Engagement with stakeholders early in the process of developing data products for a science mission is critical for ensuring the maximum societal benefit of the data. Particularly for missions where the life span of the instrument is likely limited to three to five years, the ability of the user community to use the data soon after launch is important. Increasing data awareness and demonstrating how the data can be used in different types of decision support systems is a critical part of the Early Adopter Program. For purposes of continuity, the buy-in of the stakeholder needs to occur as early as possible in any subsequent missions so the missions can be designed in a way that allows time for synergistic development of data products that are maximally useful for decision makers.

NASA and its applied sciences programs are committed to engaging users in the planning of future Earth-observing satellites by envisioning and planning applications of the data early on. This article has described four Early Adopter research projects from the ICESat-2 mission that demonstrate how the data can be used in four different thematic areas: 1) improved sea-ice modeling to improve sea safety and to better respond to emergencies, 2) ecosystem monitoring to provide height measurements that are relevant to monitoring ecosystem health for land management decision making, 3) lake and reservoir height tracking to impact decision making in the agriculture, water resources, and regional security sectors, and 4) providing early detection and societal response to volcanic hazards. The challenges in using the data, faced by each of these applications, are different, but the value of the information is similar. Once available, the data will provide important new sources of information that will enable these institutions to improve their ability to respond to changing environmental conditions.

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