Towards a U.S. Framework for Continuity of Satellite Observations of Earth's Climate and for Supporting Societal Resilience

Study Co-Chairs

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NASA Jet Propulsion Laboratory
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Keck INSTITUTE FOR SPACE STUDIES

These Charts Submitted Paper

NASEM CESAS Fall Meeting
November 29, 2023

Presented on behalf of the **KISS Study Team**

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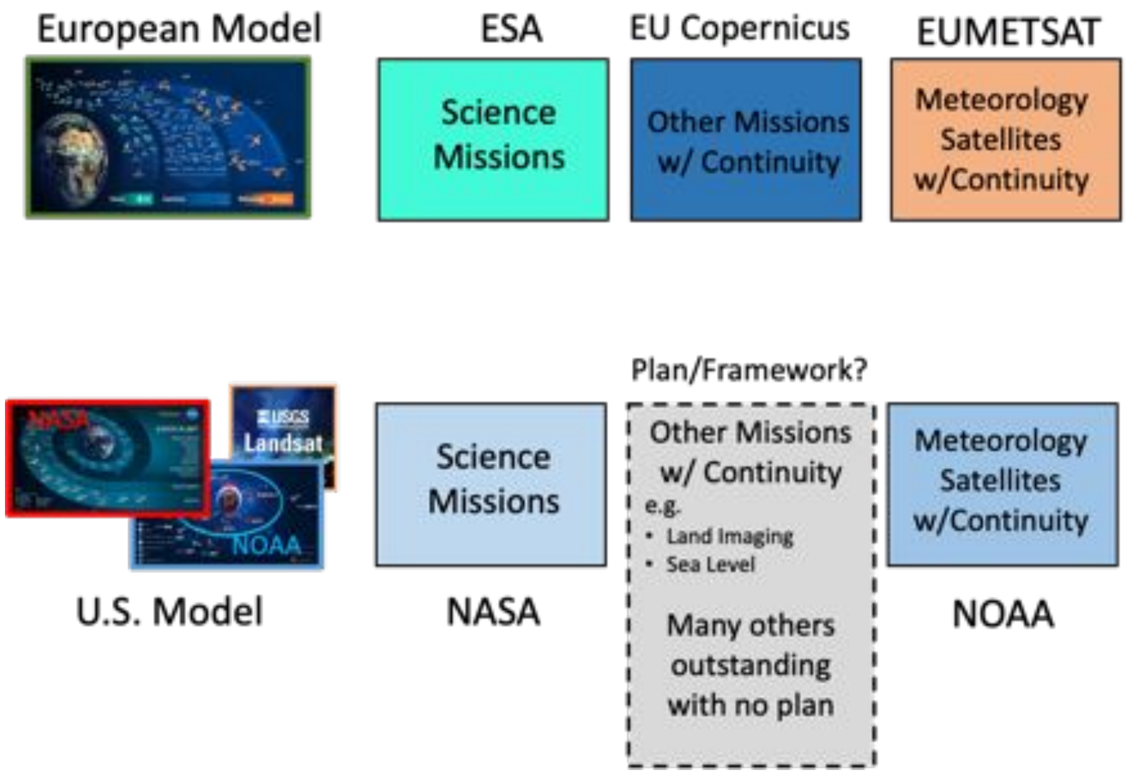
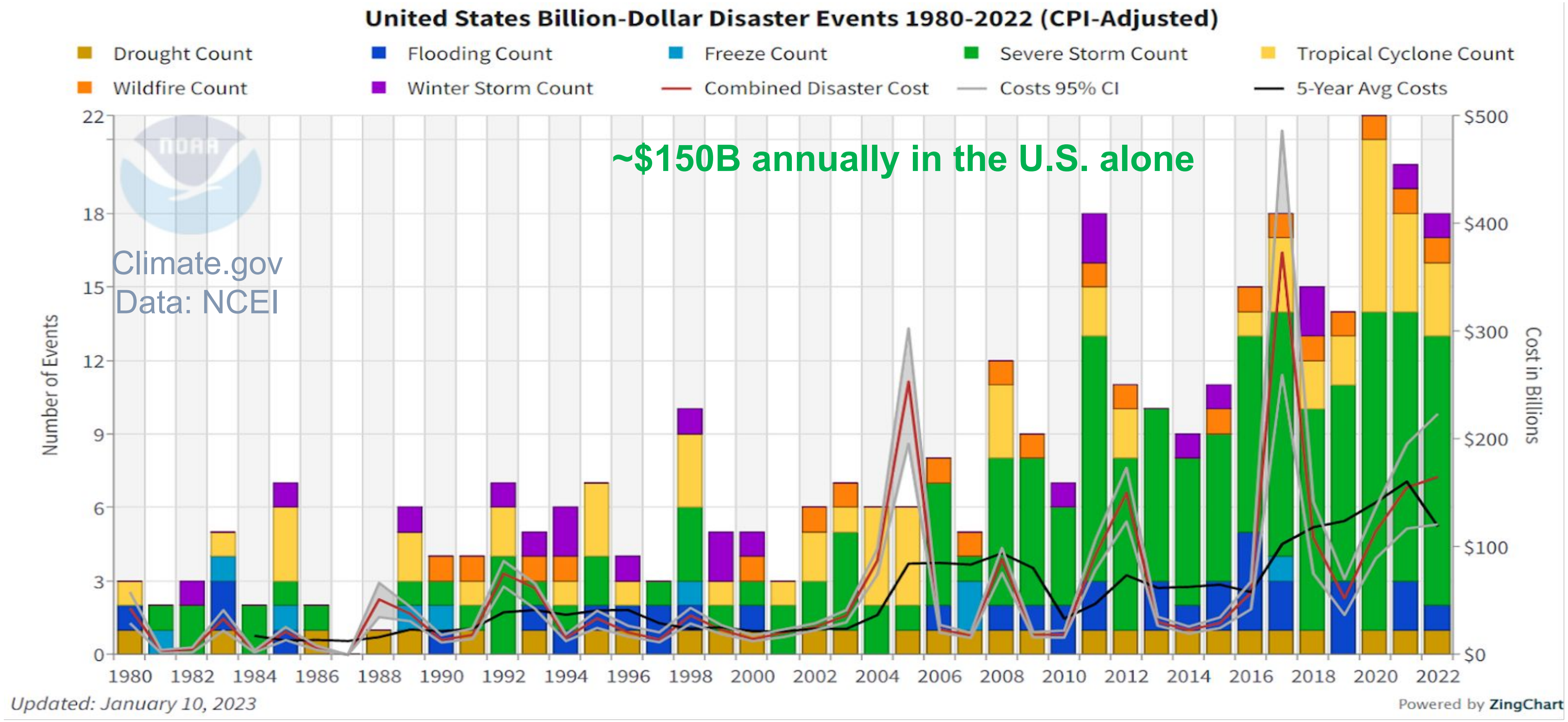
Questions for the U.S. Concerning Sustained Observations



- Apart from weather, what are our national priorities for sustained Earth observations?
- What paradigm will the U.S. use as the basis for setting these national priorities?
- What organization or body will be chartered to develop these priorities for the U.S.?
- What is our national approach to implementing sustained Earth observations that meet these priorities, including the information production and delivery services?

Damages From Climate-related Disasters Have Quadrupled Between 1980's And 2010's

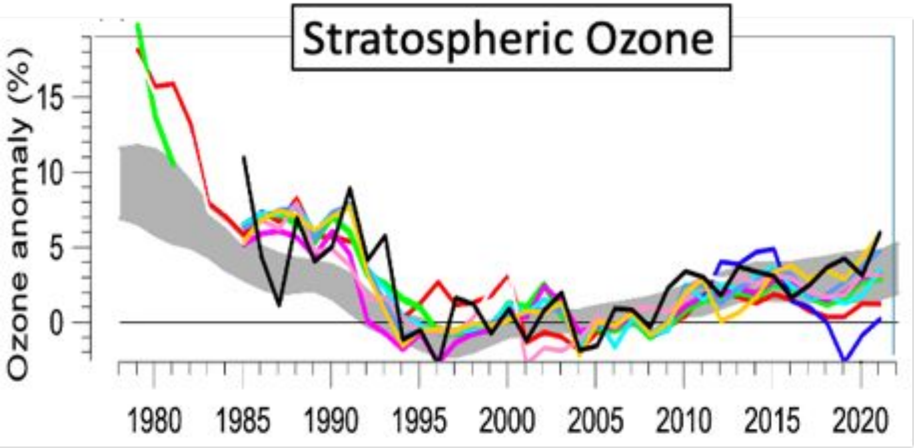


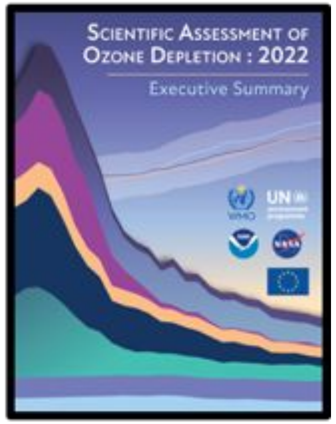
There is growing urgency for improved public and commercial services to support a resilient, secure, and thriving U.S. population and economy, particularly in the face of mounting decision-support needs for environmental stewardship and hazard response, and for climate change adaptation and mitigation actions.

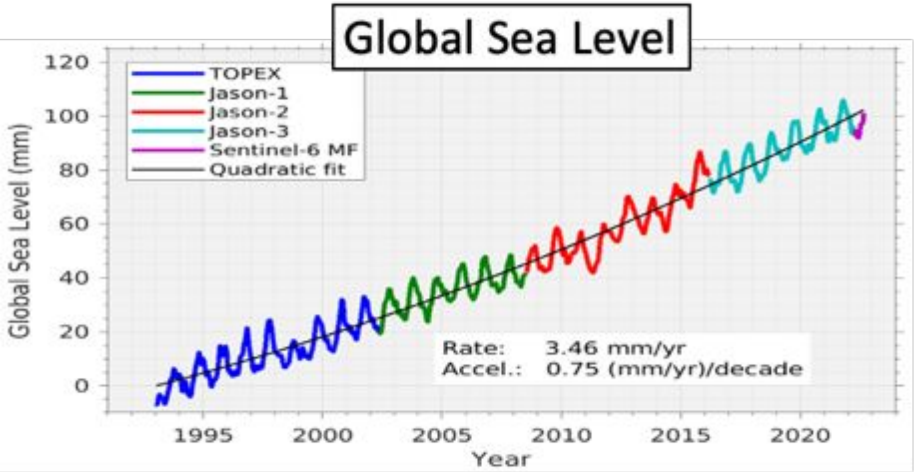
As with weather, significant science and societal benefits have been demonstrated from other long-record, satellite observations of the Earth

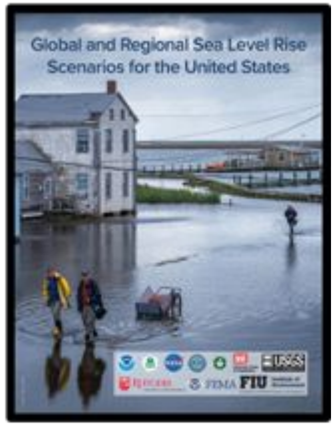
Many quantities measurable from satellites that have been shown to have scientific and/or decision-support value do not have a plan for sustained observations.*

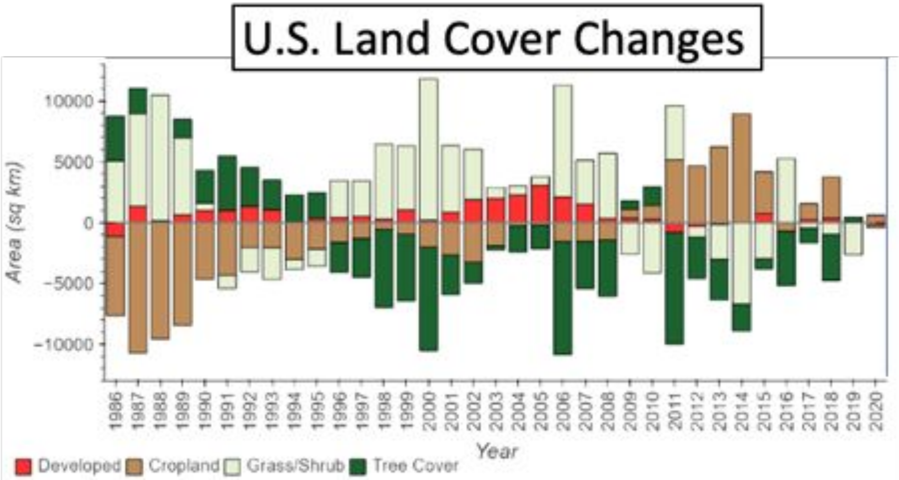
*Examples include but are not limited to (in no particular order): precipitation, soil moisture, streamflow, snowpack, greenhouse gas concentrations and emissions, stratospheric ozone, radiation budget, aerosol/cloud profiles, ocean salinity and surface winds.











KECK INSTITUTE FOR SPACE STUDIES

The Keck Institute for Space Studies (KISS) was established at Caltech in Jan 2008 with a $24 million grant over 8 years from the W. M. Keck Foundation.

The Institute is a "think and do tank," whose primary purpose is to bring together a broad spectrum of scientists and engineers for sustained technical interaction aimed at developing new space mission concepts and technology.

The Institute is centered on the intellectual, instrumentation, and research strengths of the Caltech Campus and JPL — and augments those by inviting external experts from academia, government, and industry to engage in its programs.

Annual Call for Studies
Support ~5 Studies Per Year
~ 24 non-EC, 6 EC Participants
2 Full Week, In-Person Workshops

Study Participants

1. **Waleed Abdalati** - University of Colorado Boulder
2. **Nancy Baker** - Naval Research Laboratory
3. **Stacey Boland** – Jet Propulsion Laboratory/Caltech/NASA
4. **Michael Bonadonna** - National Environmental Satellite, Data, and Information Service, NOAA
5. **Carol Anne Clayson** - Woods Hole Oceanographic Institution
6. **Belay Demoz** - University of Maryland, Baltimore County
7. **Kelsey Foster** – Stanford University
8. **Christian Frankenberg** - Caltech
9. **Maria Hakuba** – Jet Propulsion Laboratory/Caltech/NASA
10. **Therese Jorgensen** - NASA Ames Research Center
11. **Ryan Kramer** - University of Maryland, Baltimore County/NASA Goddard Space Flight Center
12. **Daniel Limonadi** – Jet Propulsion Laboratory/Caltech/NASA
13. **Anna Michalak** - Carnegie Institution for Science/Stanford University
14. **Asal Naseri** - Space Dynamics Laboratory
15. **Pat Patterson** - Space Dynamics Laboratory
16. **Peter Pilewskie** - University of Colorado Boulder
17. **Steven Platnick** - NASA Goddard Space Flight Center
18. **Charlie Powell** – University of Michigan / NOAA
19. **Jeff Privette** - NOAA's National Centers for Environmental Information
20. **Chris Ruf** - University of Michigan
21. **Tapio Schneider** - Caltech
22. **Jörg Schulz** - European Organization for the Exploitation of Meteorological Satellites (EUMETSAT)
23. **Paul Selmants** - U.S. Geological Survey
24. **Rashmi Shah** – Jet Propulsion Laboratory/Caltech/NASA
25. **Qianqian Song** – University of Maryland, Baltimore County
26. **Graeme Stephens** – Jet Propulsion Laboratory/Caltech/NASA
27. **Timothy Stryker** - USGS National Land Imaging Program
28. **Wenying Su** - NASA Langley Research Center
29. **Mathew Van Den Heever** – University of Colorado
30. **Anna Veldman** – UCLA
31. **Duane Waliser** – Jet Propulsion Laboratory/Caltech/NASA
32. **Elizabeth Weatherhead** - Jupiter Intelligence and University of Colorado Boulder

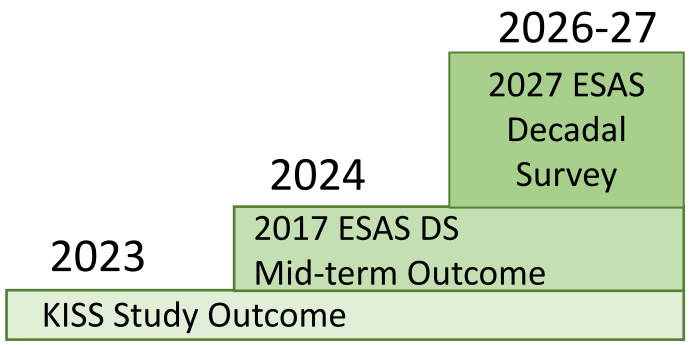
- *9 on or previously on CESAS and/or 2017 ESAS Decadal Survey*
- *7 Early Career members*
- *4 NASA Centers, 3 NOAA, 2 USGS, Navy, Universities, EUMETSAT, GCOS/CEOS, small sats, etc.*
- ***SEE BACKUP CHART FOR MORE DETAILS ON STUDY PARTICIPANTS***

Selected for the 2022 KISS Study Program

Towards a U.S. Framework for Continuity of Satellite Observations of Earth's Climate and for Supporting Societal Resilience

KISS Study Proposal

The goal of this study program is help accelerate discussions and plans for a greater and more impactful U.S. contribution to the global climate observing system. *In this context, "climate" includes observations that support climate science and process understanding, as well as monitoring for situational awareness, climate services, impact response, adaptation, and mitigation assessments.*



Aspiration: *Aid/support the anticipated upcoming NASEM discussions regarding satellite-based climate observing system*

KISS Proposal : Figure 2

Study Website
https://kiss.caltech.edu/programs.html#satellite_observations

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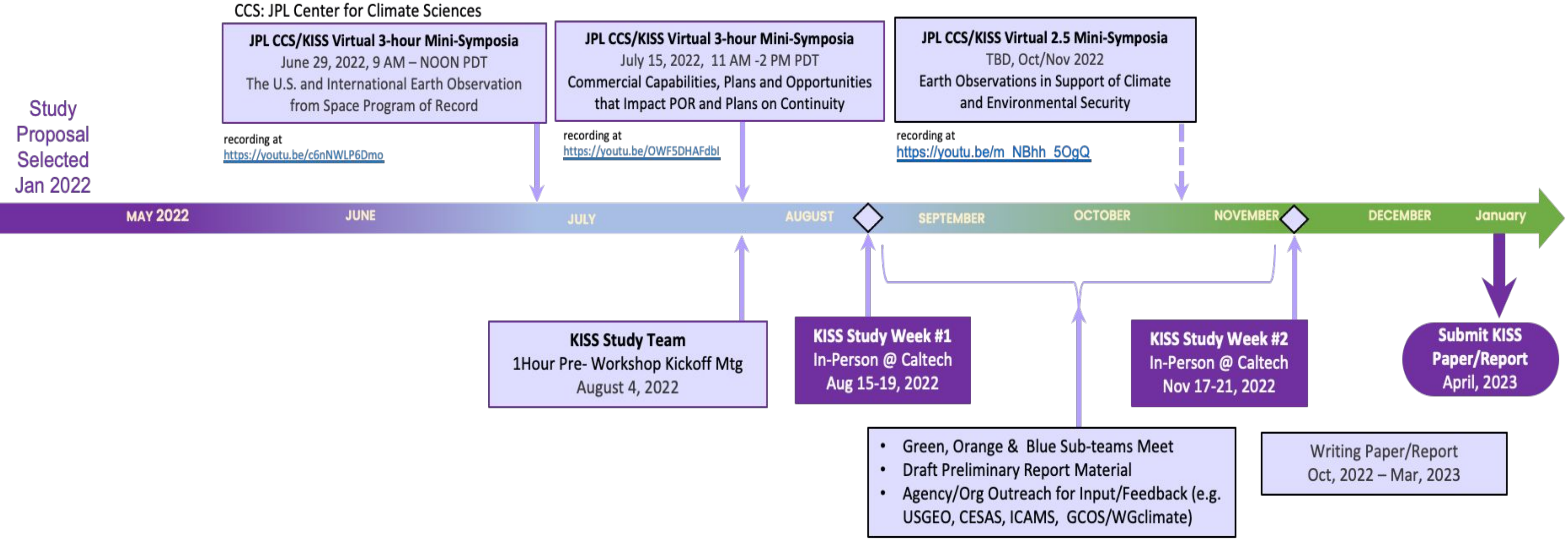
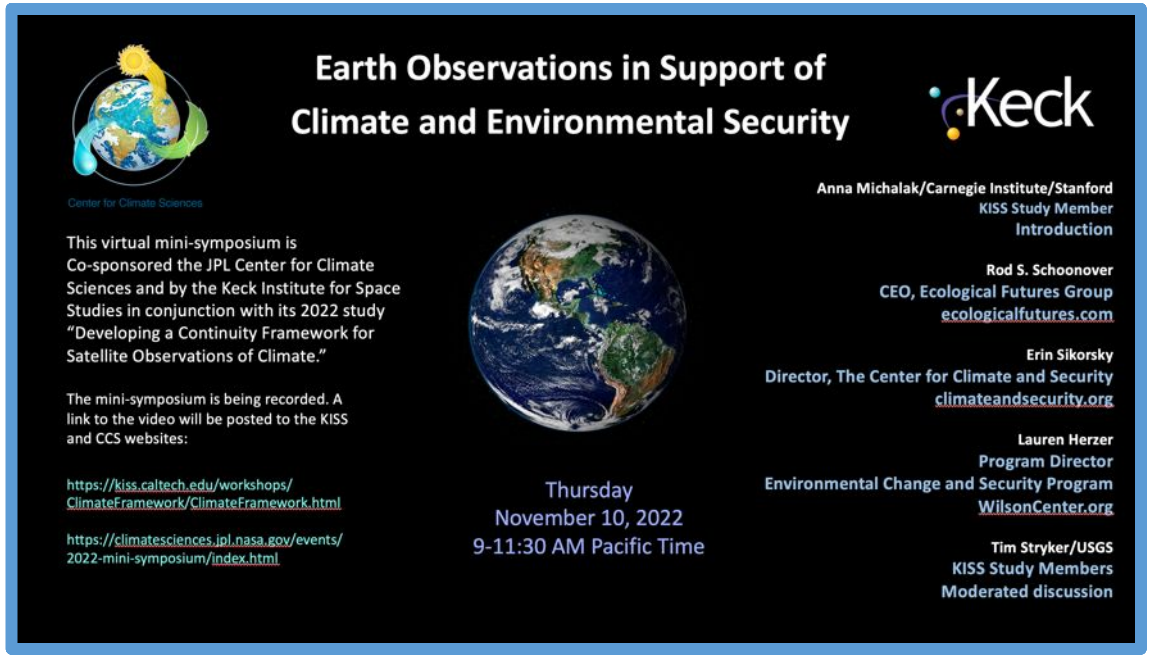
Study Activities & Timeline



Center for Climate Sciences

Three Supporting Mini-Symposia: POR, NGO, Climate Security

(recorded, links available)




EXIT




AED

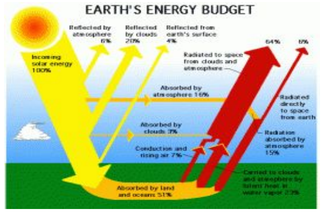
EXIT


AED

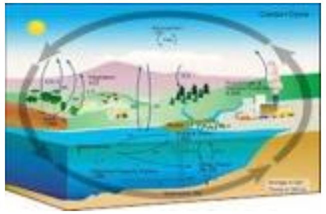
KISS Study 3 Pillar – Left to Right - Approach

Keck Institute for Space Studies

Energy Cycle & Resources



Carbon Cycle & Resources



Water Cycle & Resources

?

+

?

+

?

t

t+10 yrs

t+20 yrs

1What to include?

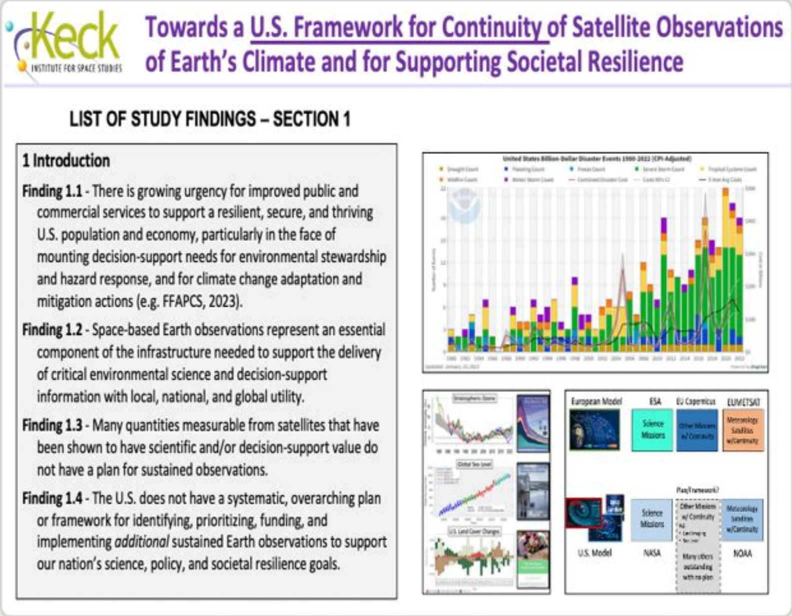
Observation Priorities Consider approaches to identify and prioritize satellite observables that should be sustained to support Science and Decision Support

2) How to include?

Architecture Approaches/Configurations: Consider approaches to architecture design and development, including "new space" and technology advances, commercial data, and international considerations.

3) How to sustain & impact?

Stewardship and Implementation: Consider data flow infrastructure and operations, calibration & validation, uncertainty quantification and traceability, data stewardship best practices, dissemination.



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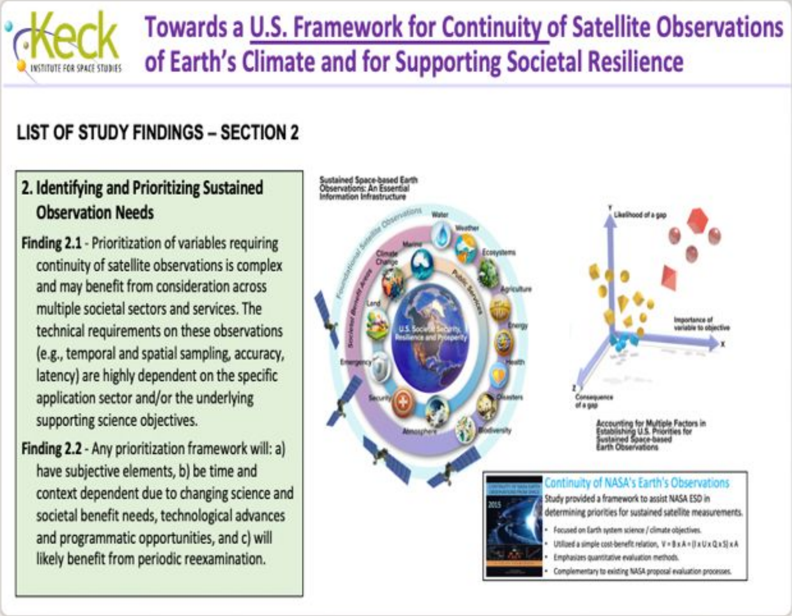
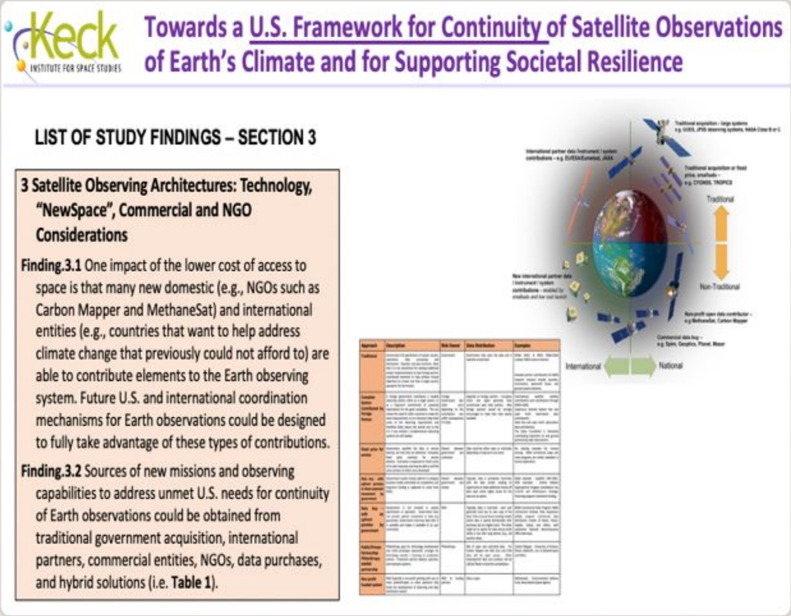


2

SEE BACKUP SLIDES



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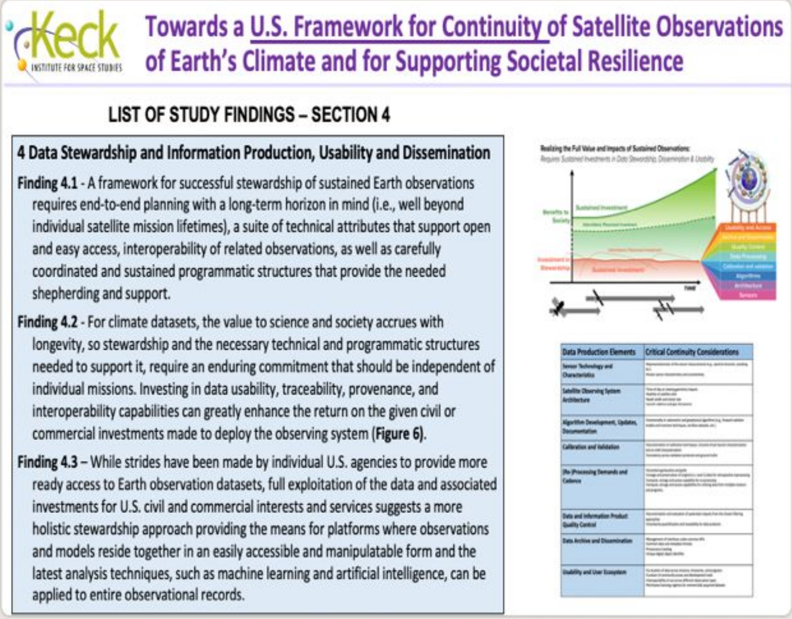

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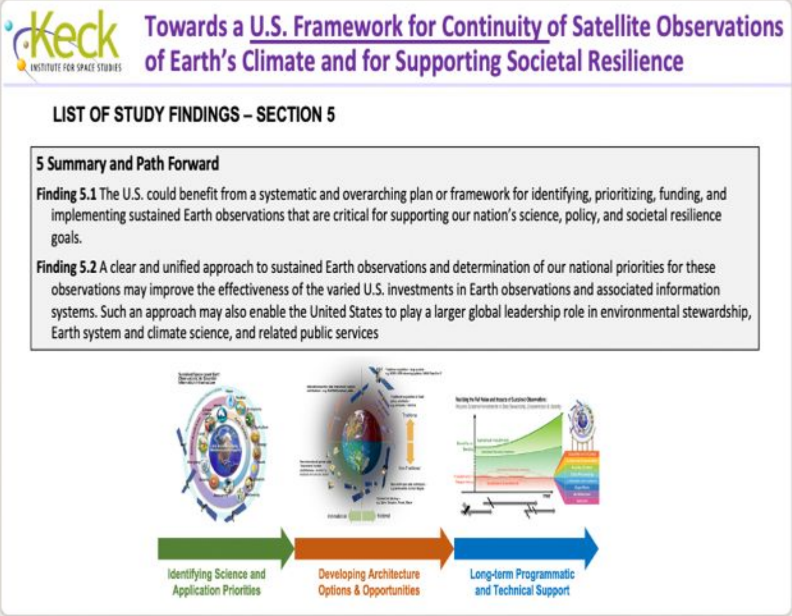
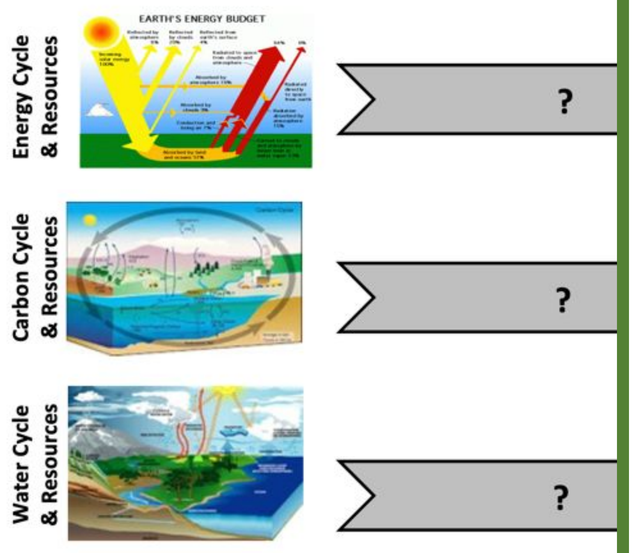


5

KISS Study
13 Findings
Across 5 Sections

***KISS Continuity Study Team**, Towards a U.S. Framework for Continuity of Satellite Observations of Earth's Climate and for Supporting Societal Resilience, **Earth's Future**, American Geophysical Union, Submitted with minor revisions 10/25/2023*

Green Team – What to Include? How to Identify/Prioritize?



1What to include?

Observation Priorities Consider approaches to identify and prioritize satellite observables that should be sustained to support Science and Decision Support


Waleed Abdalati
U of Colorado/CIRES


Stacey Boland
JPL/Caltech/NASA


Carol Anne Clayson
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Kelsey Foster –
Stanford University


Christian Frankenberg
Caltech


Maria Hakuba –
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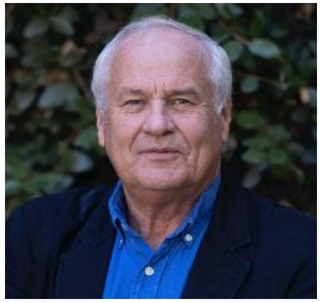
Anna Michalak
Stanford/CIS


Paul Selmants
USGS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JPL/Caltech/NASA


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NASA Langley


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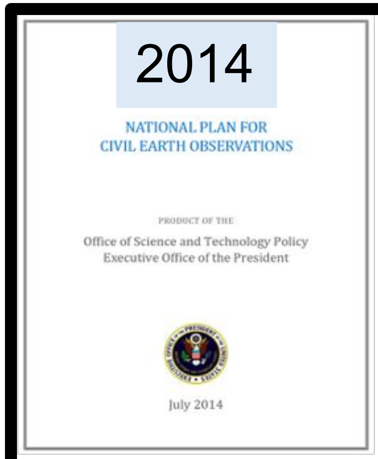
QMUL/UCLA/Columbia

Start with Identifying and Prioritizing Sustained Observation Needs for the U.S.


2014

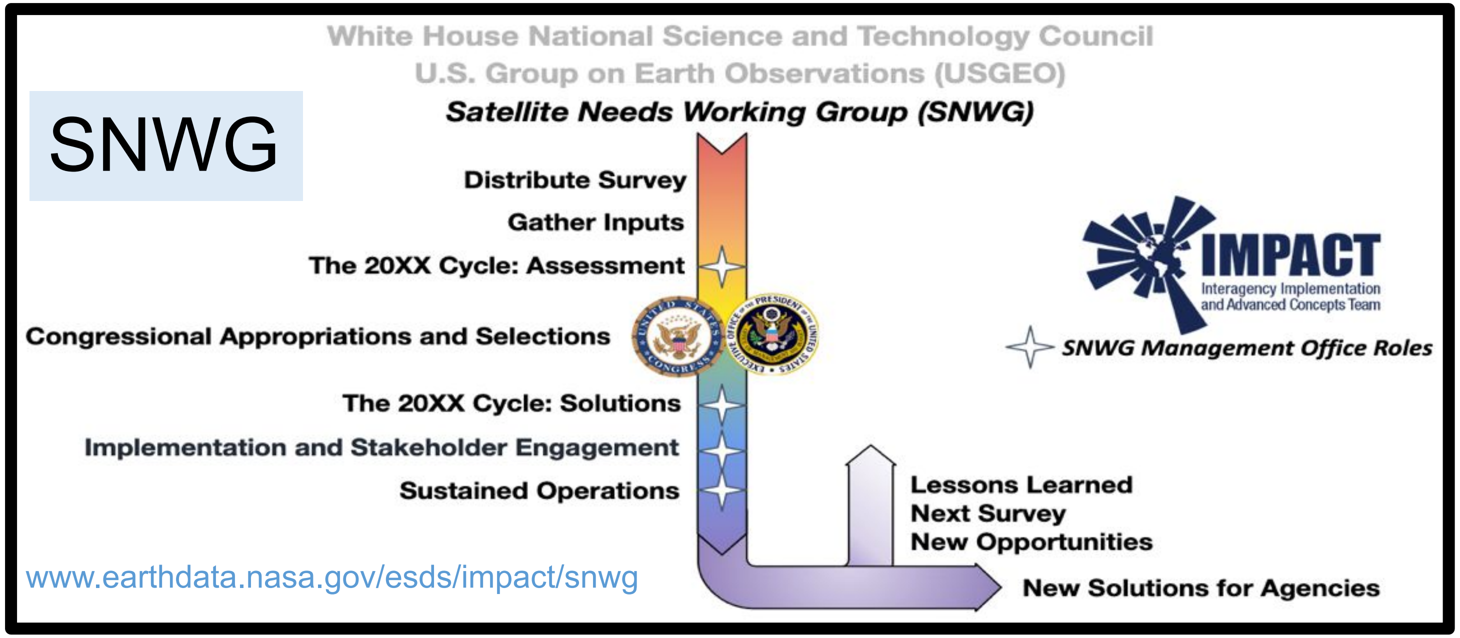
NATIONAL PLAN FOR
CIVIL EARTH OBSERVATIONS

PRODUCT OF THE
Office of Science and Technology Policy
Executive Office of the President

July 2014

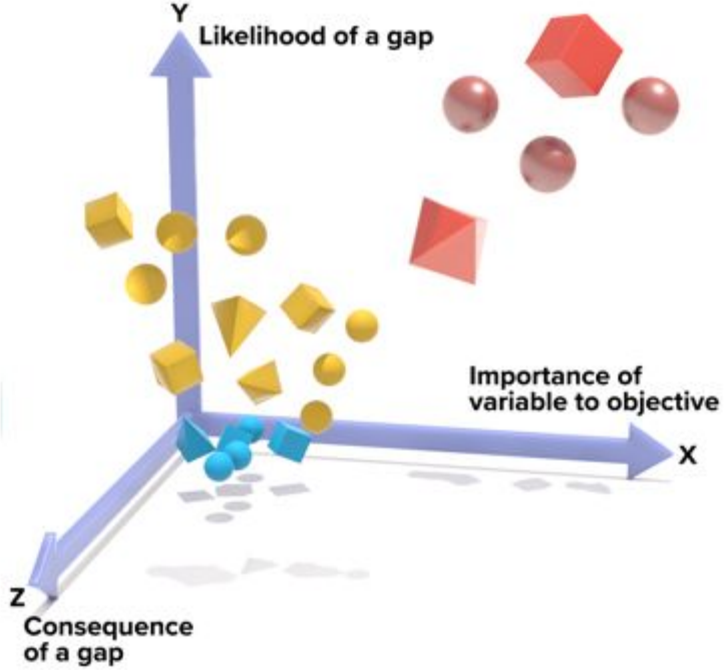
12 Societal Benefit Areas (SBAs)

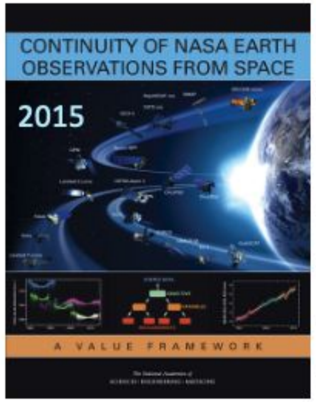
- **Agriculture and Forestry**
- **Biodiversity**
- **Climate**
- **Disasters**
- **Ocean and Coastal Resources**
- **Energy and Mineral Resources**
- **Ecosystems**
- **Human Health**
- **Space Weather**
- **Transportation**
- **Water Resources**
- **Weather**



Start with Identifying and Prioritizing Sustained Observation Needs for the U.S.

Example Framework To Highlight Multi-Dimensional Considerations for Sustained Observation Priorities





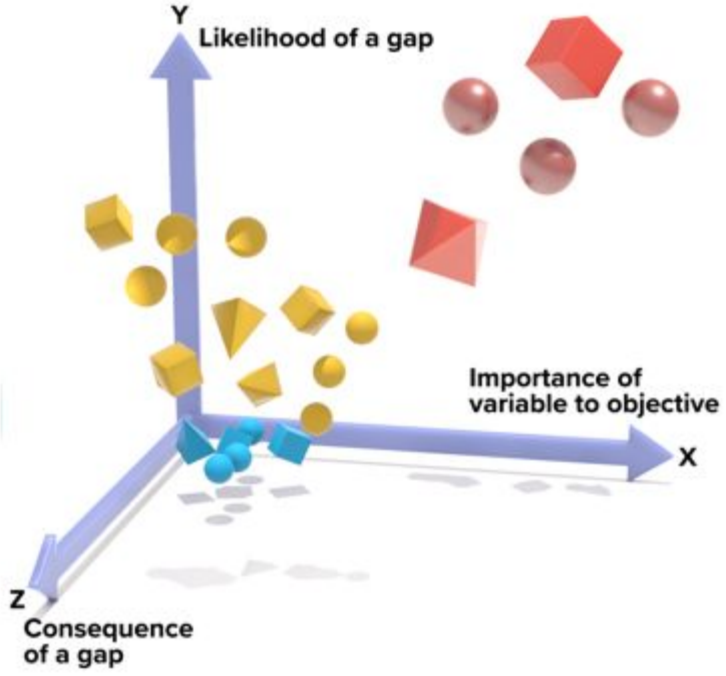
Continuity of NASA's Earth's Observations

Study provided a framework to assist NASA ESD in determining priorities for sustained satellite measurements.

- Focused on Earth system science / climate objectives.
- Utilized a simple cost-benefit relation, $V = B \times A = (I \times U \times Q \times S) \times A$
- Emphasizes quantitative evaluation methods.
- Complementary to existing NASA proposal evaluation processes.

Start with Identifying and Prioritizing Sustained Observation Needs <u>for the U.S.</u>

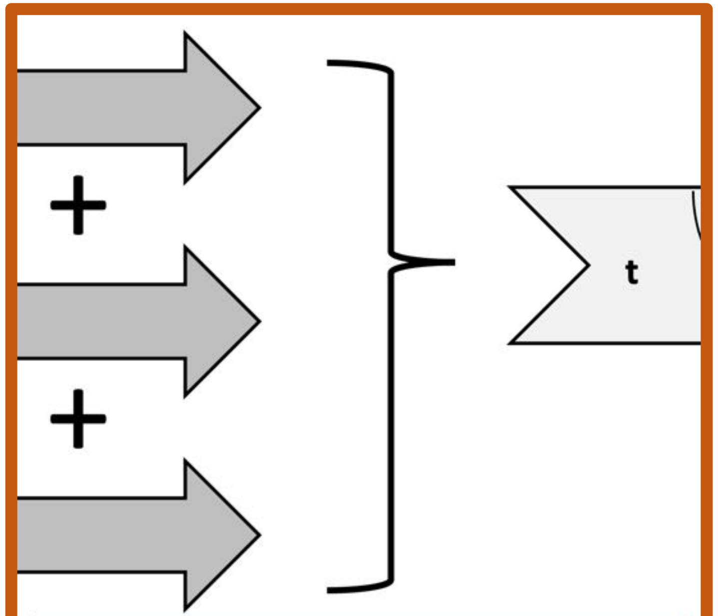
Example Framework To Highlight Multi-Dimensional Considerations for Sustained Observation Priorities



Prioritization of variables with U.S. needs in mind will:

- require a mix of objective and subjective considerations across multiple societal sectors, public services and Earth/climate science areas.
- depend on changing societal needs, technology advances and programmatic opportunities – and thus need to be periodically revisited

Orange Team – How to include? Architecture options?



2) How to include?

Architecture Approaches/Configurations: Consider approaches to architecture design and development, including “new space” and technology advances, commercial data, and international considerations.

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NESDIS/NOAA

Therese Jorgensen
NASA AMES

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JPL/Caltech/NASA

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Space Dyn. Lab./U. Utah

Pat Patterson –
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Chris Ruf
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Rashmi Shah
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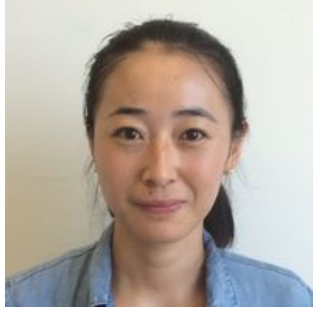
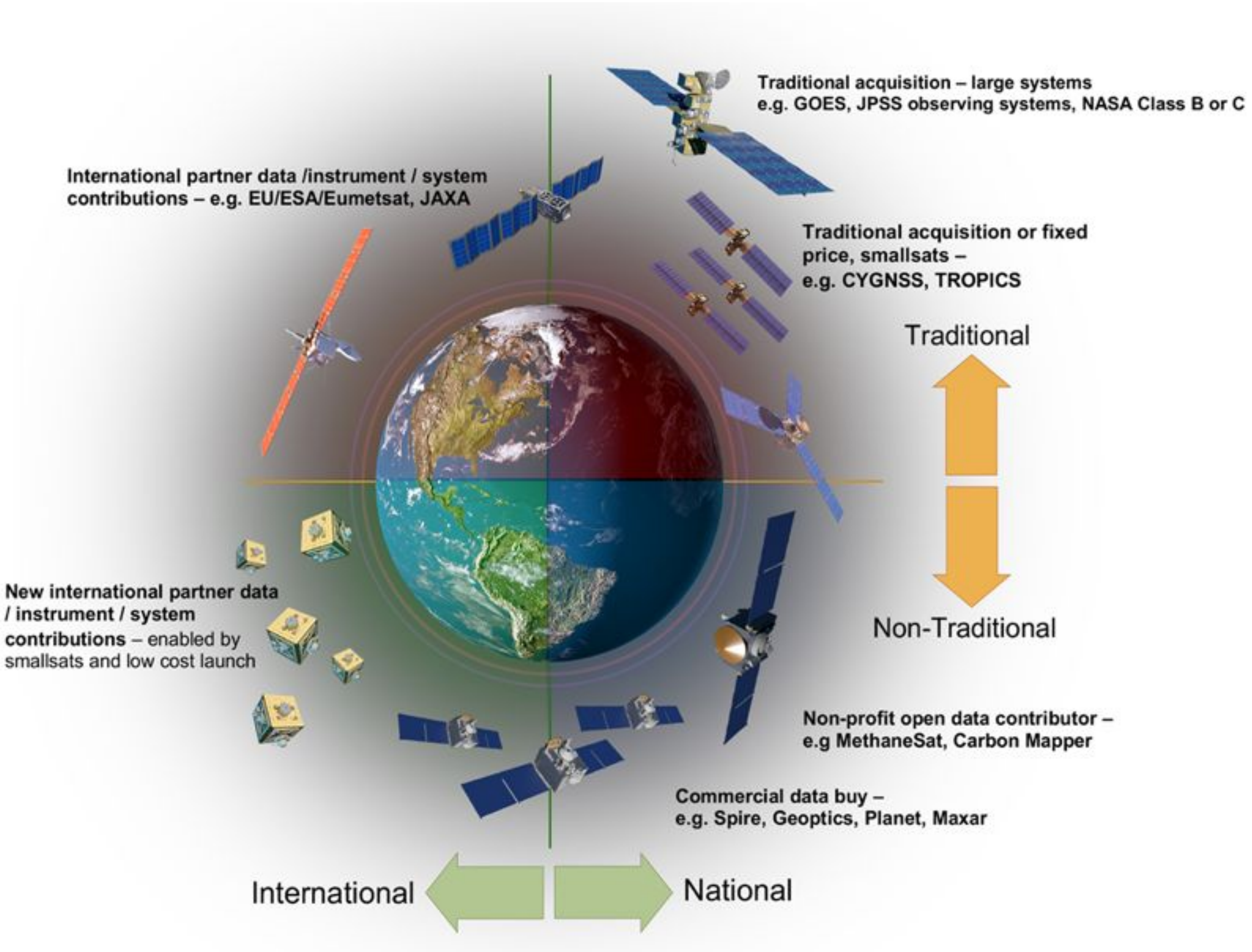


Qianqian Song
U Maryland/BC

Expanding Opportunities for Contributing to and Sustaining Earth Observations

Lower cost of access to space is increasing the sources able to contribute elements to the Earth observing system.

- traditional government agencies
- international partners
- commercial entities with data buys
- NGOs and non-profit
- hybrid solutions



Leveraging "NewSpace", the Latest Technologies, Commercial and NGO Opportunities

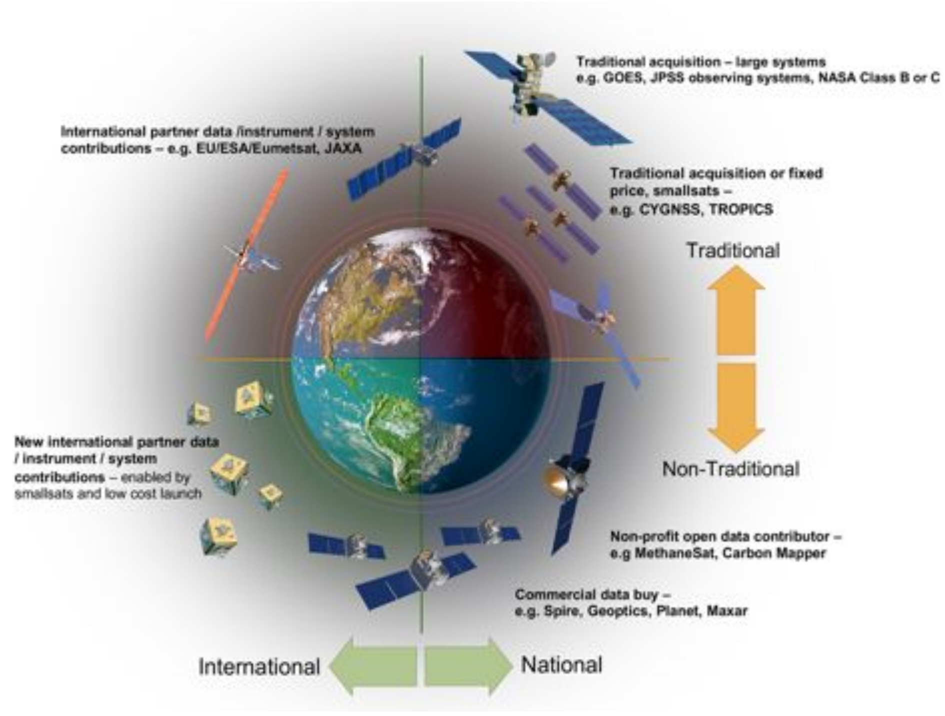
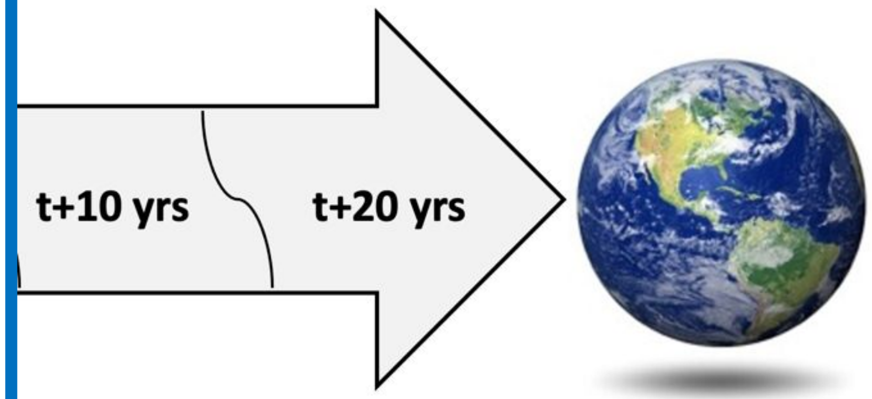


Table 1. Summary of current and potential future acquisition & support models

Approach	Description	Risk Owner	Data Distribution	Examples
Traditional	Government full specification of system, launch, operations, data processing and distribution. Typically, cost-plus contracts. Note that it is not uncommon for existing traditional project implementations to have foreign partner contributed elements to help achieve mutual objectives at a lower cost than a single country paying for the full mission.	Government	Government fully owns the data and is typically unrestricted	NOAA GOES, & NPSS; NASA-USGS Landsat; NASA science missions Example partner contributions for NASA research missions include launches, instruments, spacecraft buses, and ground system elements.
Complete System Contributed by Foreign Partner	A foreign government contributes a needed observing system, either as a single system, or as a long-term commitment of sustained observations for the given variable(s). This can relieve the need for other countries to make the same measurement, or at a minimum help meet some of the observing requirements and therefore likely reduce the overall cost to the U.S. if any residual / complementary observing systems are still needed.	Foreign Government (but other users depending on this contribution also suffer consequences if it fails)	Depends on foreign partner – European Union and Japan generally have unrestricted open data policies. New foreign partners would be strongly encouraged to make their data openly available.	International weather satellite contributions and coordination through WMO-CGMS. Copernicus Sentinel System free and open Earth observation data contributions. JAXA free and open Earth observation data contributions. The Qatar Foundation is interested contributing important ice and ground penetrating radar observations.
Fixed price for service	Government specifies the data or service desired, not how they are delivered. Competes fixed price contracts for service delivery. Contractor is expected to invest some of its own resources and may be able to sell the same services to others once developed.	Shared between government and contractor	Data could be either open or restricted, depending on long term cost share.	No existing example for remote sensing. NASA commercial cargo and crew programs are similar examples in human exploration.
Data buy - with upfront promise or down payment investment by government	Government invests money upfront in company business model, potentially via competition, but long-term funding is expected to come from NGOs.	Shared between government and vendor	Typically, data is somewhat restricted, with the data vendor needing an opportunity to make additional money off data sales unless higher prices for the data are an option.	NASA example - SeaWiFS 1997-2007; DOD examples - Orbital Sidekick hyperspectral imaging constellation has In-Q-Tel and AFVentures's Strategic Financing program investment funding.
Data buy – with no upfront promise by government	Government is not involved in system specification or operation. Government does not provide upfront investment or data buy guarantees. Government only buys data after it is available and makes it available to its user community.	NGO	Typically, data is restricted - each user generally must buy its own copy of the data; There may be future funding models where data is openly distributable after purchase, but at a higher price. The latter might be an option for data whose profit utility is low after long latency (e.g., old weather data).	NOAA Commercial Data Program; NASA Commercial Smallsat Data Acquisition (CSDA) program commercial data distribution models of Maxar, Planet, Capella, IceEye, and others, with substantial National Reconnaissance Office data buys.
Public/Private Partnership: Philanthropy-seeded partnership	Philanthropy pays for technology development and initial prototype spacecraft, arranges for technology transfer / licensing to production partner. Production partner deploys, operates, and maintains systems.	Philanthropy	Mix of open and restricted data. For Carbon Mapper the GHG (Co2 and CH4) data will be open access. Other hyperspectral data and products will be sold by Planet to fund the constellation.	Carbon Mapper - University of Arizona, Planet, NASA/JPL, mix of philanthropies and NGOs.
Non-profit funded system	NGO (typically a non-profit working with one or more philanthropies or other partners) fully funds the development of observing and data distribution system.	NGO & funding partners	Data is open.	MethaneSat - Environmental Defense Fund, New Zealand Space Agency.

Blue Team – How to sustain and make needed impacts?



3) How to sustain & impact?

Stewardship and Implementation: Consider data flow infrastructure and operations, calibration & validation, uncertainty quantification and traceability, data stewardship best practices, dissemination.

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Ryan Kramer
NASA GSFC - NOAA

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Charlie Powell
U. Michigan - NOAA

Jeff Privette
NCEI/NOAA

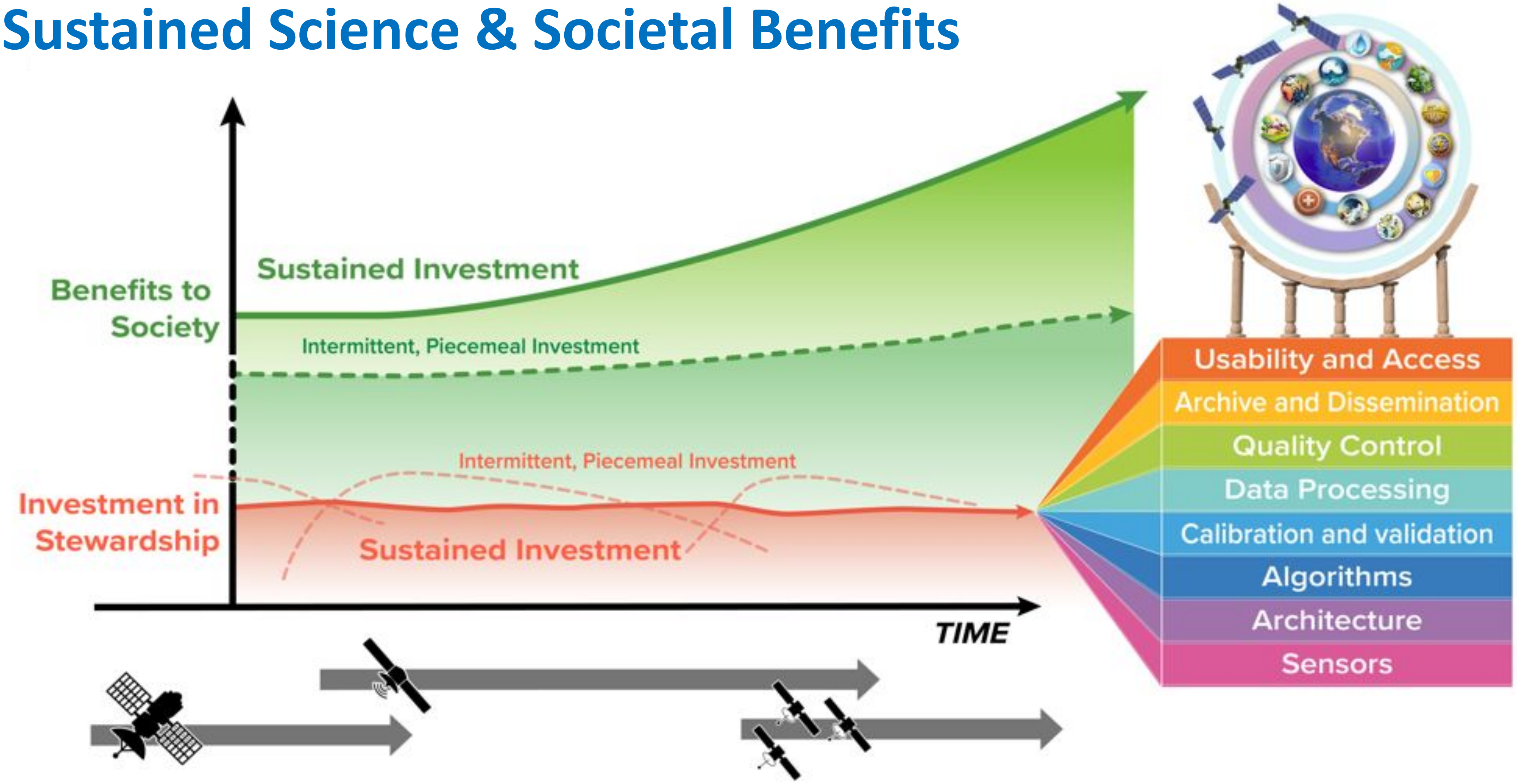
Tapio Schneider
Caltech

Jörg Schulz
EUMETSAT

Timothy Stryker
USGS

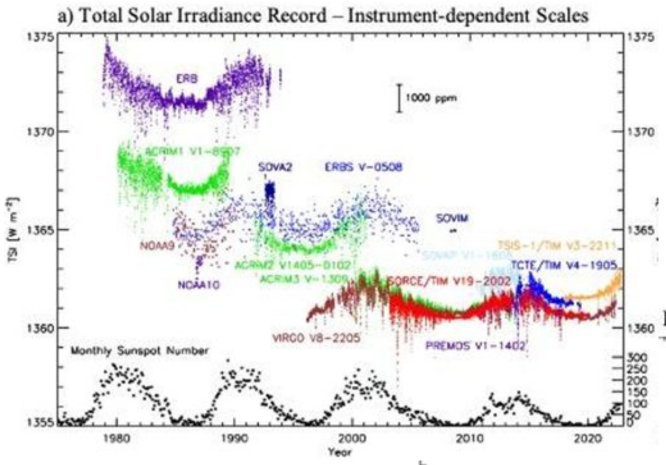
Betsy Weatherhead
- Jupiter Intelligence

Sustained Observing Systems Yield Sustained Science & Societal Benefits



A framework for successful stewardship of sustained Earth observations requires: **a)** end-to-end planning with a long-term horizon in mind, **b)** a suite of technical attributes and platforms that support open and easy access, **c)** interoperability of related observations, **d)** carefully coordinated and sustained programmatic structures that provide the needed shepherding and support, etc.

Data Stewardship, Information Production, Dissemination & Use



Example highlighting Importance of Data Production Elements of Stewardship

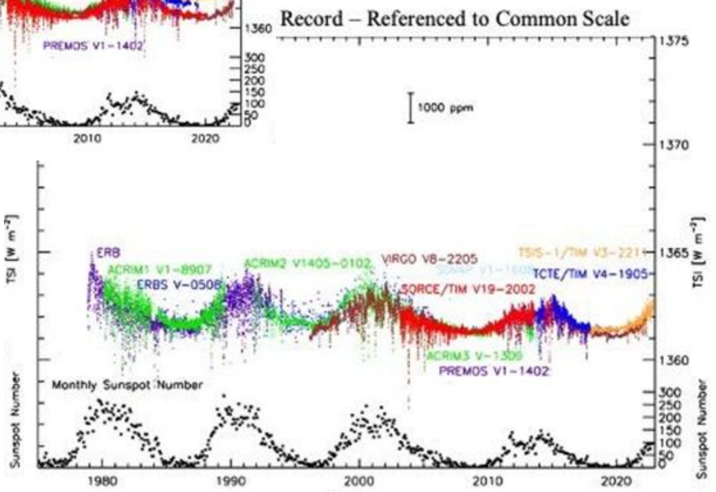
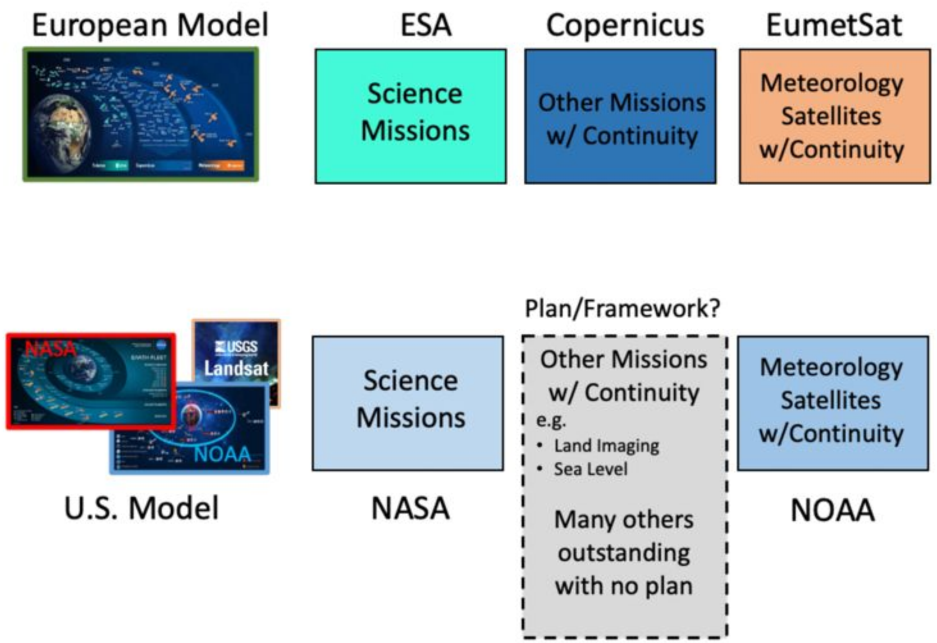


Figure 4.2. *An example of the importance of climate observation continuity. The figure on the left shows incoming radiative energy from the Sun, a fundamental climate data record, from the set of space-based measurements since 1978. The measurements are shown at each instrument's native calibration scale. Because the individual observation records overlap, it enables the construction of the composite record on the right where all measurements are on a common scale. This helps reveal trends in the long-term data record that may have impacts on climate. Figure from G. Kopp (https://spot.colorado.edu/~koppg/TSI/),*

Table 4.1. *Key elements of the data production value chain of satellite-based Earth observations.*

Data Production Elements	Critical Continuity Considerations
Sensor Technology and Characteristics	•Representativeness of the sensor measurements (e.g., spectral channels, sampling, etc.) •Known sensor characteristics and uncertainties
Satellite Observing System Architecture	•Time-of-day or viewing geometry impacts •Stability of satellite orbit •Swath width and revisit rate •Launch cadence and gap risk posture
Algorithm Development, Updates, Documentation	•Commonality in radiometric and geophysical algorithms (e.g., forward radiative models and inversion techniques, ancillary datasets, etc.)
Calibration and Validation	•Documentation of calibration techniques, inclusive of pre-launch characterization and on-orbit characterization •Consistency across validation protocols and ground truths
(Re-)Processing Demands and Cadence	•Consistent geolocation and grids •Lineage and preservation of original (i.e. Level 1) data for retrospective reprocessing •Compute, storage and access capability for re-processing •Compute, storage and access capabilities for utilizing data from multiple missions and programs.
Data and Information Product Quality Control	•Documentation and evaluation of systematic impacts from the chosen filtering approaches •Uncertainty quantification and traceability for data products
Data Archive and Dissemination	•Management of interfaces under common APIs •Common data and metadata formats •Provenance tracking •Unique digital object identifier
Usability and User Ecosystem	•Co-location of data across missions, timeseries, and programs •Curation of community access and development tools •Interoperability of use across different observation types •Permissive licensing regimes for commercially acquired datasets

Study Status & Summary

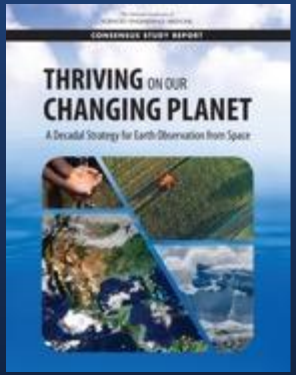


The U.S. could benefit from a systematic and overarching plan or framework for identifying, prioritizing, funding, and implementing sustained Earth observations that are critical for supporting our nation's science, policy, and societal resilience goals.

A clear and unified approach to sustained Earth observations and determination of our national priorities for these observations may improve the effectiveness of the varied U.S. investments in Earth observations and associated information systems. Such an approach may also enable the United States to play a larger global leadership role in environmental stewardship, Earth system and climate science, and related public services

- Formal KISS Study Completed in the Summer of 2023
- ***KISS Continuity Study Team***, Towards a U.S. Framework for Continuity of Satellite Observations of Earth's Climate and for Supporting Societal Resilience, ***Earth's Future***, *American Geophysical Union, Submitted with minor revisions 10/25/2023*
- *The team is organizing 'Continuity' sessions at AGU'22 and AMS'23.*

Earth Science and Applications from Space Decadal Surveys



2017 Recommendation 2.2: NASA—with NOAA and USGS participation—should engage in a formal planning effort with international partners (including, but not limited to ESA, EUMETSAT, and the European Union via its Copernicus Program) to agree on a set of measurements requiring long-term continuity and to develop collaborative plans for implementing the missions needed to satisfy those needs. This effort to institutionalize the sustained measurement record of required parameters should involve the scientific community, and build on and complement the existing domestic and international Program of Record.

2017 Recommendation 4.6: NASA ESD should employ the following guidelines for maintaining programmatic balance:

- New Measurements versus Data Continuity. Lead development of a more formal continuity decision process (as in NASEM, 2015) to determine which satellite measurements have the highest priority for continuation, then work with U.S. and international partners to develop an international strategy for obtaining and sharing those measurements.

2017 Recommendation 4.7: NASA should make the following scope changes to its program elements:

- Technology Program. Establish a mechanism for maturation of key technologies that reduce the cost of continuity measurements.

2007 Recommendation: The Office of Science and Technology Policy, in collaboration with the relevant agencies and in consultation with the scientific community, should develop and implement a plan for achieving and sustaining global Earth observations.

National Plan for Civil Earth Observations

The purpose of the National Plan for Civil Earth Observation is to help coordinate Federally-supported Earth observations and investments, identify opportunities to advance Earth observations, and achieve national Earth observation policy objectives. This plan serves as a resource to assist Federal departments and agencies (hereafter, "agencies") in their planning, coordination, identifying high-leverage research and development opportunities, and avoiding unnecessary duplication and redundancy. This plan should help inform the normal budget process through which resources are allocated. Under the NSTC which has the responsibility to ensure R&D is coordinated across Federal departments and agencies, the USGEO Subcommittee will use this plan to coordinate implementation of the recommended actions.

2014

NATIONAL PLAN FOR CIVIL EARTH OBSERVATIONS

PRODUCT OF THE
Office of Science and Technology Policy
Executive Office of the President

July 2014

2019

2019 NATIONAL PLAN FOR CIVIL EARTH OBSERVATIONS

A Report by the
U.S. Group on Earth Observations Subcommittee
Committee on the Environment

of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

December 2019

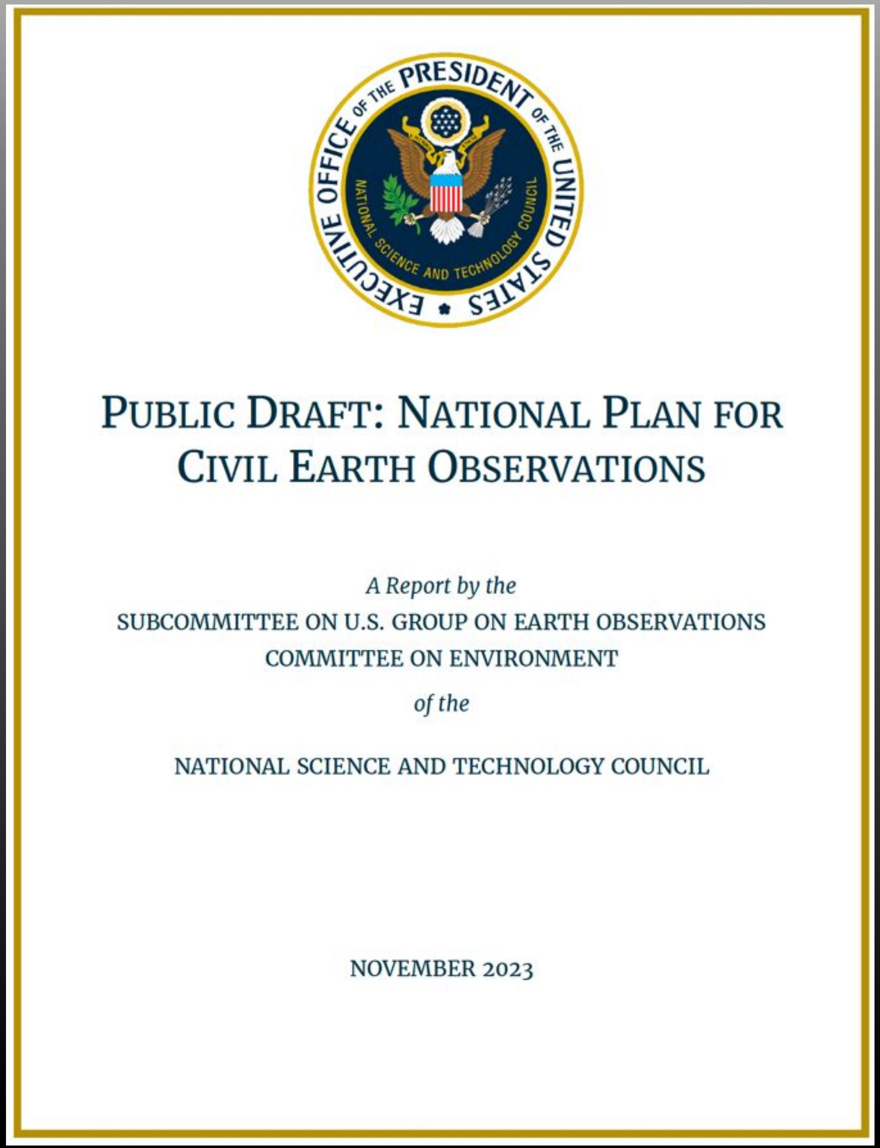
FYI
The 2014 NP referred to the 2008 DS
The 2018 DS referred to the 2014 NP.
The 2019 NP made no reference to the 2018 DS

National Plan for Civil Earth Observations

RFI FOR REVIEW OF 2023 PLAN AVAILABLE NOW

DRAFT Language: Page 17

"Earth Observations Continuity Framework: This National Plan calls for the formation of a national Earth Observations Continuity Framework. OSTP, working through USGEO as the organizing entity, will work with stakeholders and the EOE to develop this Framework. The Framework is to provide the structure for scoping, governance, and other factors toward ensuring continuity for the Sustained Observations. Observations, The Framework will initially apply to the Sustained Observations for Public Services identified in the 2014 National Plan… "



PUBLIC DRAFT: NATIONAL PLAN FOR CIVIL EARTH OBSERVATIONS

A Report by the

SUBCOMMITTEE ON U.S. GROUP ON EARTH OBSERVATIONS

COMMITTEE ON ENVIRONMENT

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

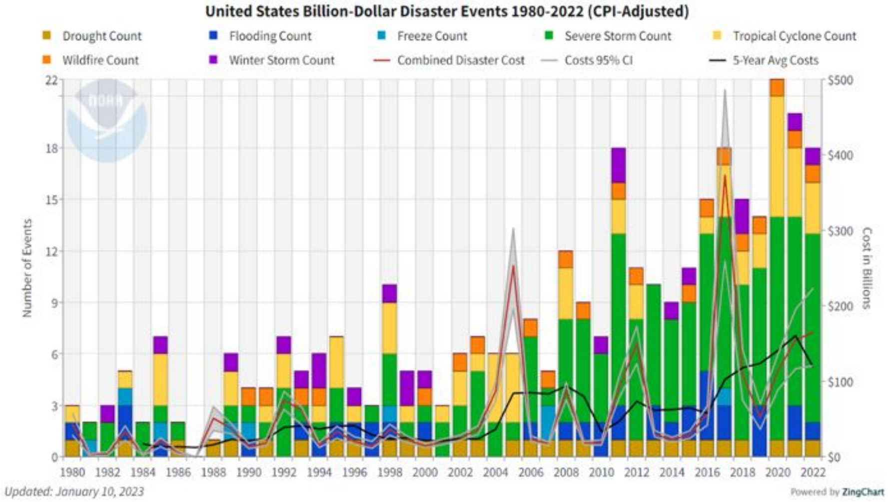
NOVEMBER 2023

https://www.regulations.gov/document/OSTP_FRDOC_0001-0013

RFI Comment Due Date
Dec 31, 2023

Additional Considerations and Next Steps

- Consider plan for our future (e.g. 2040) sustained observing system for science and services
- Aid U.S. leadership and interagency and commercial/NGO coordination
- Add structure or a framework in the “gray zone” e.g., priorities, decision-tree, roadmap, org or wiring structure.
- Apply System (of Systems) Engineering to the Program architecture in addition to the technical architectures (obs & info sys)
- To get started - Green and Orange Steps require relatively small investments

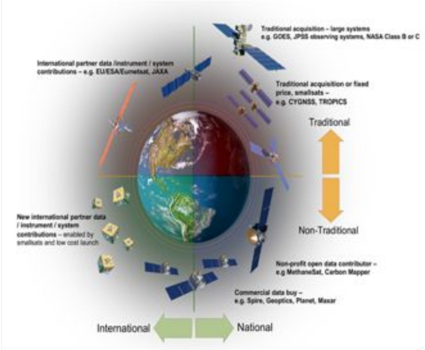


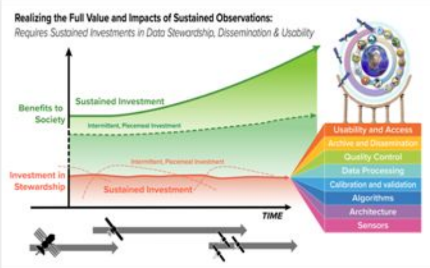
European Model

ESA	Copernicus	EumetSat
Science Missions	Other Missions w/ Continuity	Meteorology Satellites w/Continuity

U.S. Model

NASA	Plan/Framework?	NOAA
Science Missions	Other Missions w/ Continuity e.g. • Land Imaging • Sea Level Many others outstanding with no plan	Meteorology Satellites w/Continuity





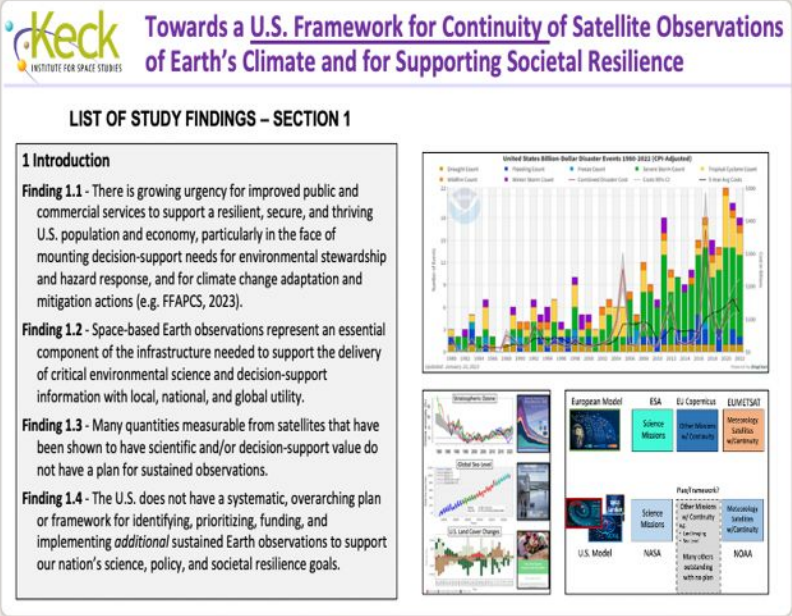
Identifying Science and Application Priorities

Developing Architecture Options & Opportunities

Long-term Programmatic and Technical Support

Towards a U.S. Framework for Continuity of Satellite Observations of Earth's Climate and for Supporting Societal Resilience

BACKUP SLIDES



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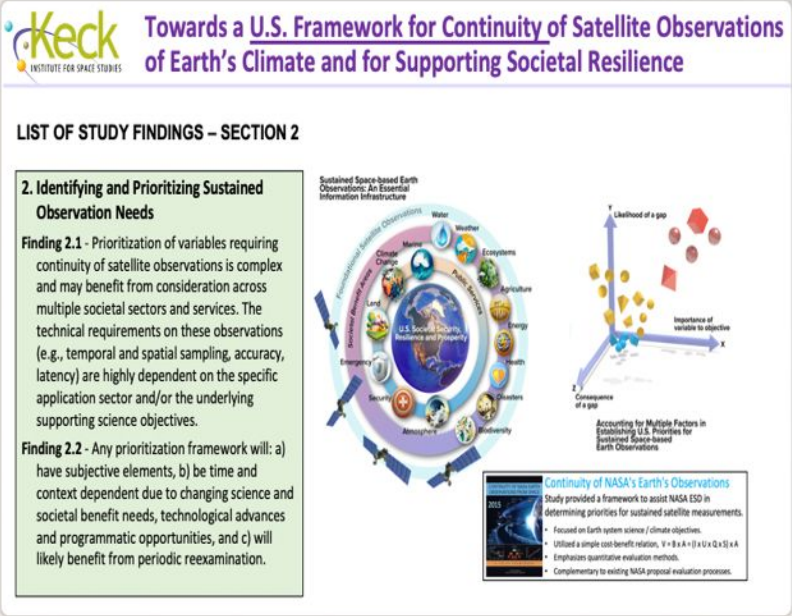

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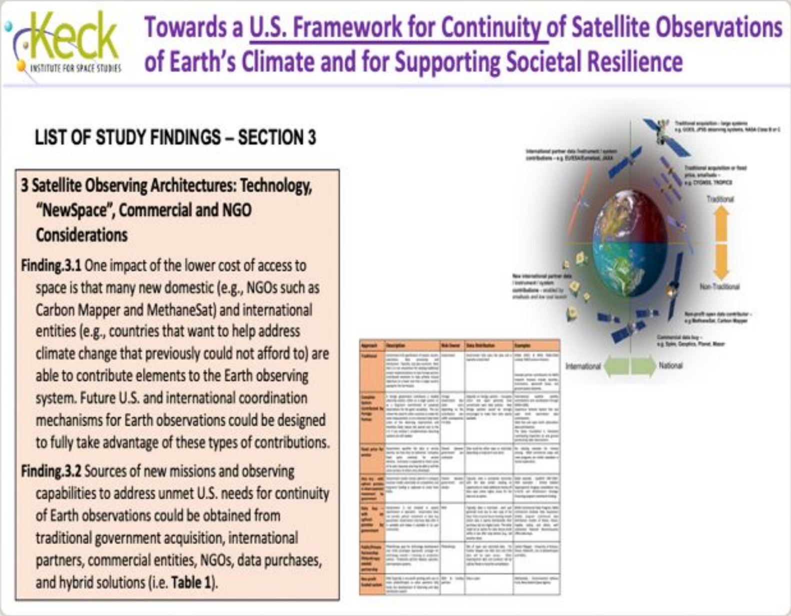

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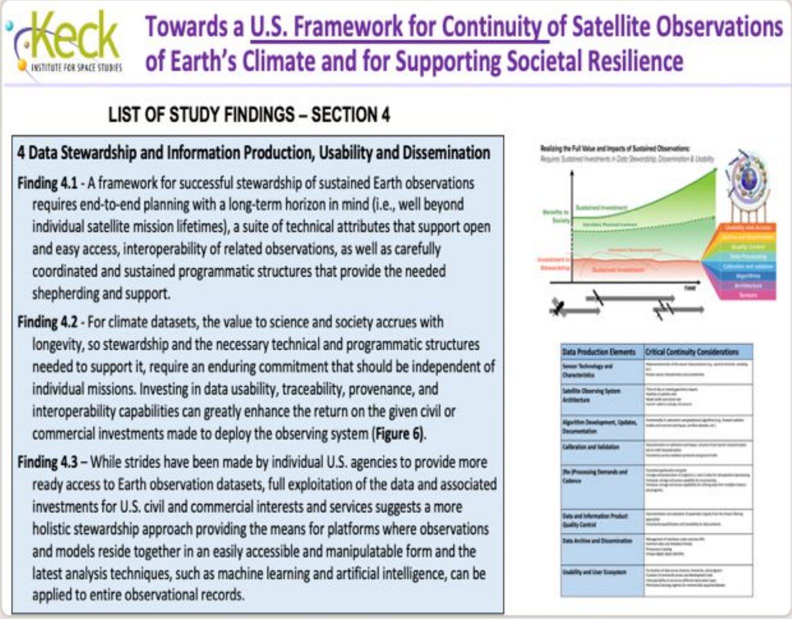

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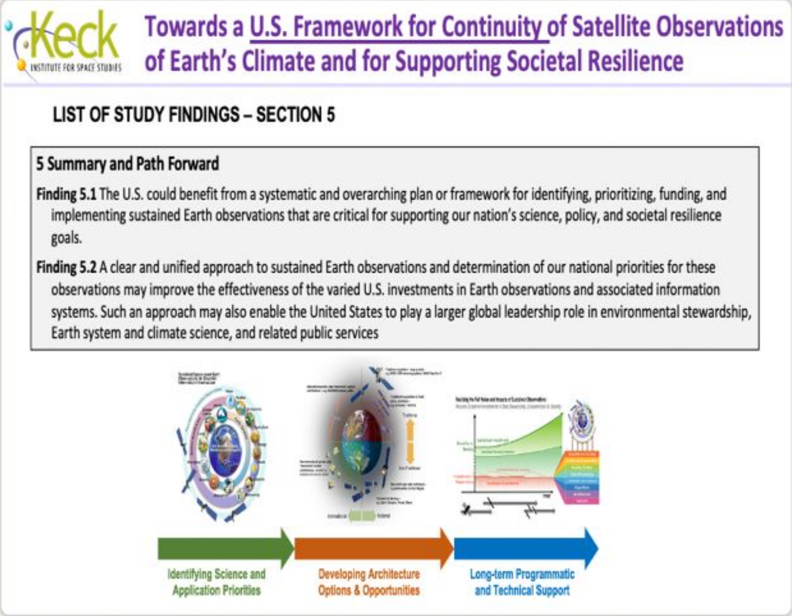
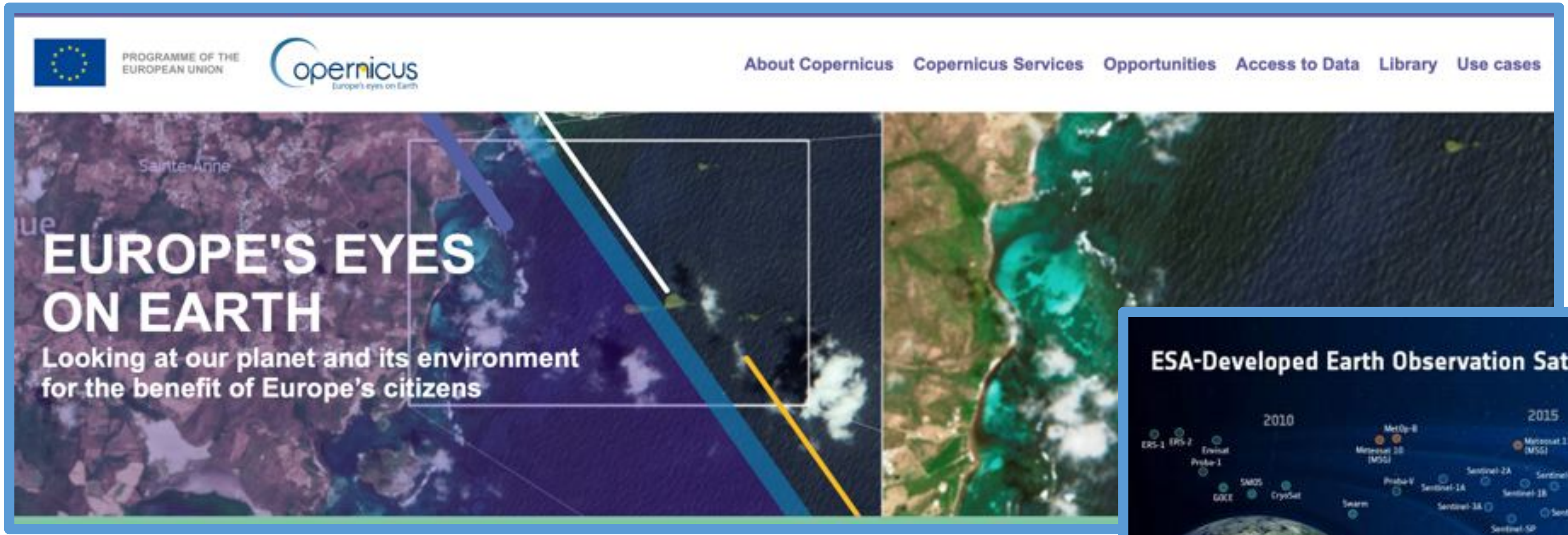


5

KISS Study 13 Findings Across 5 Sections

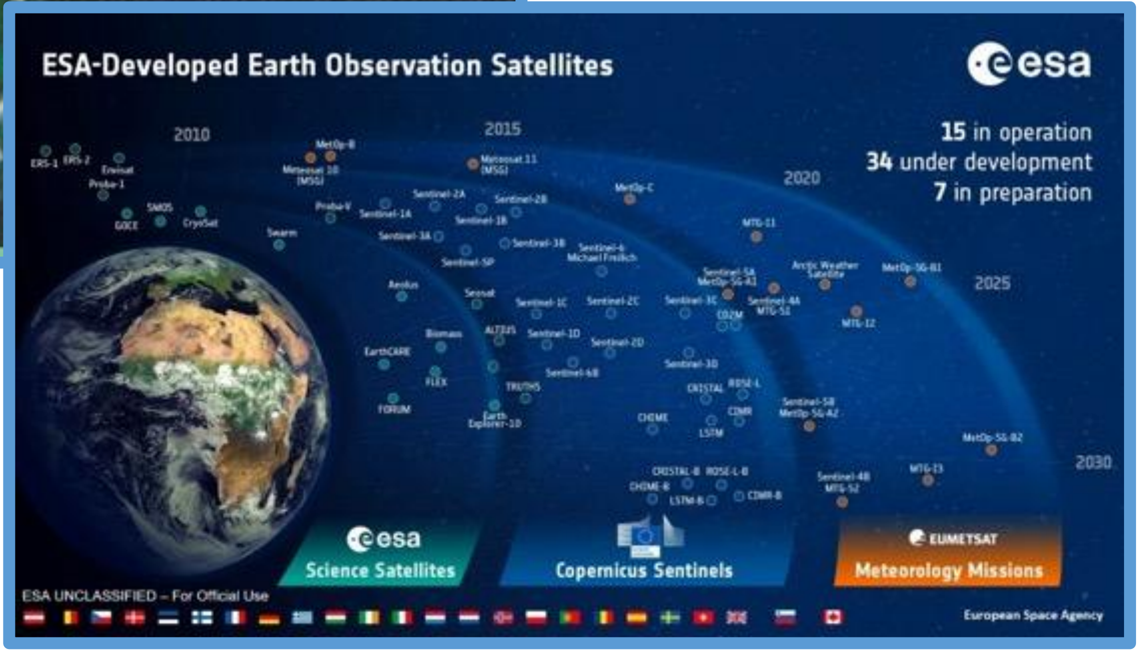
KISS Continuity Study Team, *Towards a U.S. Framework for Continuity of Satellite Observations of Earth's Climate and for Supporting Societal Resilience*, ***Earth's Future***, *American Geophysical Union, Submitted with minor revisions 10/25/2023*

European Union’s Answer



opernicus

The European Earth Observation Programme



Copernicus is the EU’s Earth observation program that looks *“at our planet and its environment to* ***<u>benefit all European citizens. It offers information services that draw from satellite Earth Observation</u>*** *and in-situ data…to help service providers, public authorities, and other international organizations* *<u>improve European citizens' quality of life and beyond</u>*.

The satellite component of Copernicus is based on a series of “Sentinel” missions which are developed to provide the observations needed to deliver the public benefits of the Copernicus Programme – which are provided in the form of Atmosphere, Marine, Land, Emergency, Climate, and Security Services.

Towards a U.S. Framework for Continuity of Satellite Observations of Earth's Climate and for Supporting Societal Resilience

LIST OF STUDY FINDINGS – SECTION 1

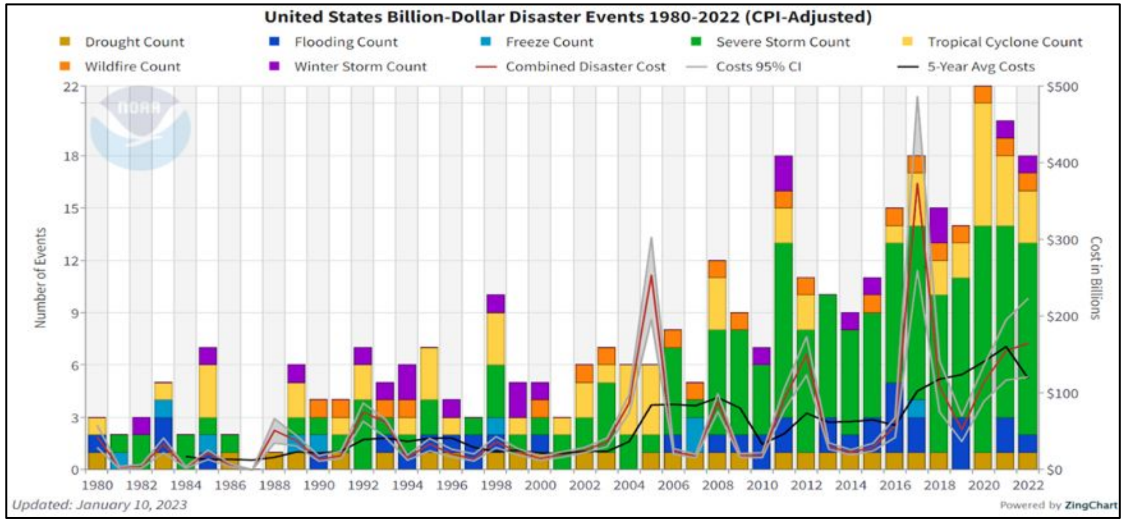
1 Introduction

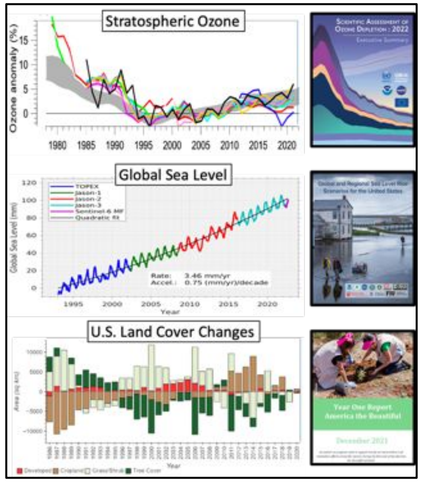
Finding 1.1 - There is growing urgency for improved public and commercial services to support a resilient, secure, and thriving U.S. population and economy, particularly in the face of mounting decision-support needs for environmental stewardship and hazard response, and for climate change adaptation and mitigation actions (e.g. FFAPCS, 2023).

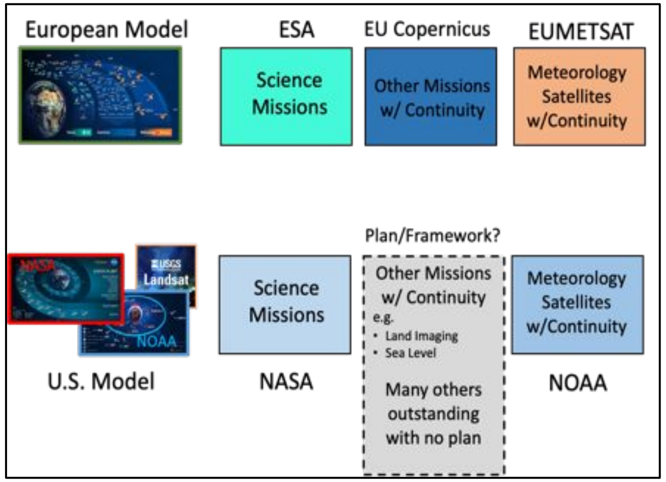
Finding 1.2 - Space-based Earth observations represent an essential component of the infrastructure needed to support the delivery of critical environmental science and decision-support information with local, national, and global utility.

Finding 1.3 - Many quantities measurable from satellites that have been shown to have scientific and/or decision-support value do not have a plan for sustained observations.

Finding 1.4 - The U.S. does not have a systematic, overarching plan or framework for identifying, prioritizing, funding, and implementing *additional* sustained Earth observations to support our nation's science, policy, and societal resilience goals.







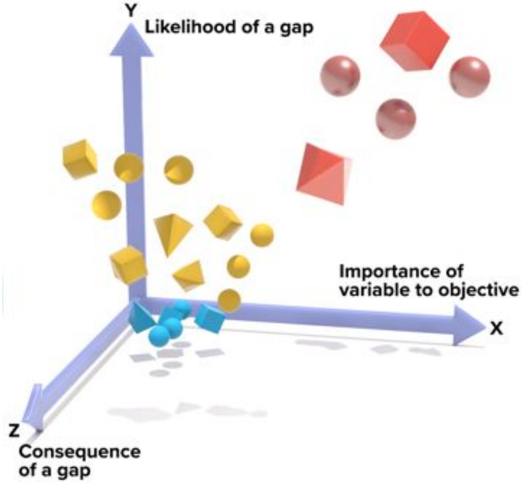
LIST OF STUDY FINDINGS – SECTION 2

2. Identifying and Prioritizing Sustained Observation Needs

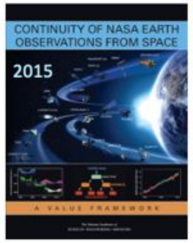
Finding 2.1 - Prioritization of variables requiring continuity of satellite observations is complex and may benefit from consideration across multiple societal sectors and services. The technical requirements on these observations (e.g., temporal and spatial sampling, accuracy, latency) are highly dependent on the specific application sector and/or the underlying supporting science objectives.

Finding 2.2 - Any prioritization framework will: a) have subjective elements, b) be time and context dependent due to changing science and societal benefit needs, technological advances and programmatic opportunities, and c) will likely benefit from periodic reexamination.

Sustained Space-based Earth Observations: An Essential Information Infrastructure



Accounting for Multiple Factors in Establishing U.S. Priorities for Sustained Space-based Earth Observations



Continuity of NASA's Earth's Observations

Study provided a framework to assist NASA ESD in determining priorities for sustained satellite measurements.

- Focused on Earth system science / climate objectives.
- Utilized a simple cost-benefit relation, $V = B \times A = (I \times U \times Q \times S) \times A$
- Emphasizes quantitative evaluation methods.
- Complementary to existing NASA proposal evaluation processes.

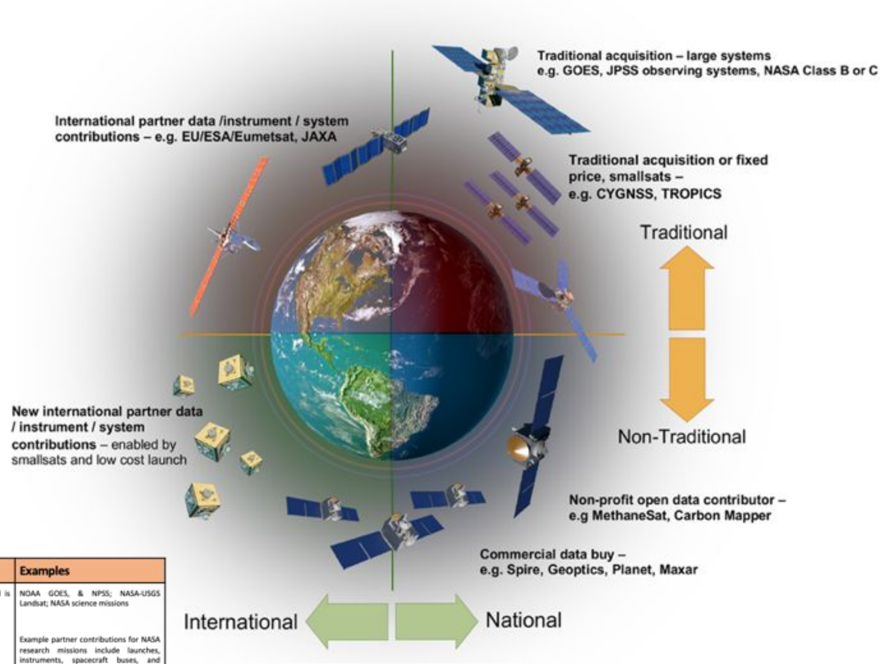
Towards a U.S. Framework for Continuity of Satellite Observations of Earth's Climate and for Supporting Societal Resilience

LIST OF STUDY FINDINGS – SECTION 3

3 Satellite Observing Architectures: Technology, "NewSpace", Commercial and NGO Considerations

Finding.3.1 One impact of the lower cost of access to space is that many new domestic (e.g., NGOs such as Carbon Mapper and MethaneSat) and international entities (e.g., countries that want to help address climate change that previously could not afford to) are able to contribute elements to the Earth observing system. Future U.S. and international coordination mechanisms for Earth observations could be designed to fully take advantage of these types of contributions.

Finding.3.2 Sources of new missions and observing capabilities to address unmet U.S. needs for continuity of Earth observations could be obtained from traditional government acquisition, international partners, commercial entities, NGOs, data purchases, and hybrid solutions (i.e. **Table 1**).



Approach	Description	Risk Owner	Data Distribution	Examples
Traditional	Government full specification of system, launch, operations, data processing and distribution. Typically, cost-plus contracts. Note that it is not uncommon for existing traditional project implementations to have foreign partner contributed elements to help achieve mutual objectives at a lower cost than a single country paying for the full mission.	Government	Government fully owns the data and is typically unrestricted	NOAA GOES, & NPSS; NASA-USGS Landsat; NASA science missions Example partner contributions for NASA research missions include launches, instruments, spacecraft buses, and ground system elements.
Complete System Contributed by Foreign Partner	A foreign government contributes a needed observing system, either as a single system, or as a long-term commitment of sustained observations for the given variable(s). This can relieve the need for other countries to make the same measurement, or at a minimum help meet some of the observing requirements and therefore likely reduce the overall cost to the U.S. if any residual / complementary observing systems are still needed.	Foreign Government (but other users depending on this contribution also suffer consequences if it fails)	Depends on foreign partner – European Union and Japan generally have unrestricted open data policies. New foreign partners would be strongly encouraged to make their data openly available.	International weather satellite contributions and coordination through WMO-CGMS. Copernicus Sentinel System free and open Earth observation data contributions. JAXA free and open Earth observation data contributions. The Qatar Foundation is interested contributing important ice and ground penetrating radar observations.
Fixed price for service	Government specifies the data or service desired, not how they are delivered. Competes fixed price contracts for service delivery. Contractor is expected to invest some of its own resources and may be able to sell the same services to others once developed.	Shared between government and contractor	Data could be either open or restricted, depending on long term cost share.	No existing example for remote sensing. NASA commercial cargo and crew programs are similar examples in human exploration.
Data buy - with upfront promise or down payment investment by government	Government invests money upfront in company business model, potentially via competition, but long-term funding is expected to come from NGOs.	Shared between government and vendor	Typically, data is somewhat restricted, with the data vendor needing an opportunity to make additional money off data sales unless higher prices for the data are an option.	NASA example - SeaWiFS 1997-2007; DOD examples - Orbital Sidekick hyperspectral imaging constellation has In-Q-Tel and AFVentures's Strategic Financing program investment funding.
Data buy – with no upfront promise by government	Government is not involved in system specification or operation. Government does not provide upfront investment or data buy guarantees. Government only buys data after it is available and makes it available to its user community.	NGO	Typically, data is restricted - each user generally must buy its own copy of the data; There may be future funding models where data is openly distributable after purchase, but at a higher price. The latter might be an option for data whose profit utility is low after long latency (e.g., old weather data).	NOAA Commercial Data Program; NASA Commercial Smallsat Data Acquisition (CSDA) program commercial data distribution models of Maxar, Planet, Capella, IceEye, and others, with substantial National Reconnaissance Office data buys.
Public/Private Partnership: Philanthropy-seeded partnership	Philanthropy pays for technology development and initial prototype spacecraft, arranges for technology transfer / licensing to production partner. Production partner deploys, operates, and maintains systems.	Philanthropy	Mix of open and restricted data. For Carbon Mapper the GHG (Co2 and CH4) data will be open access. Other hyperspectral data and products will be sold by Planet to fund the constellation.	Carbon Mapper - University of Arizona, Planet, NASA/JPL, mix of philanthropies and NGOs.
Non-profit funded system	NGO (typically a non-profit working with one or more philanthropies or other partners) fully funds the development of observing and data distribution system.	NGO & funding partners	Data is open.	MethaneSat - Environmental Defense Fund, New Zealand Space Agency.

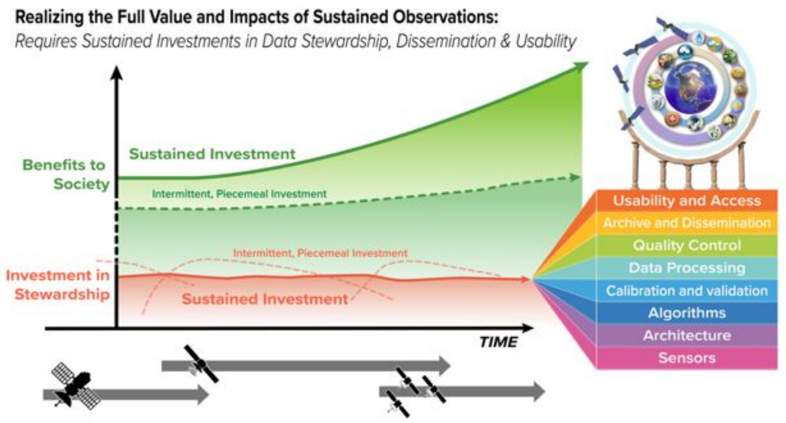
LIST OF STUDY FINDINGS – SECTION 4

4 Data Stewardship and Information Production, Usability and Dissemination

Finding 4.1 - A framework for successful stewardship of sustained Earth observations requires end-to-end planning with a long-term horizon in mind (i.e., well beyond individual satellite mission lifetimes), a suite of technical attributes that support open and easy access, interoperability of related observations, as well as carefully coordinated and sustained programmatic structures that provide the needed shepherding and support.

Finding 4.2 - For climate datasets, the value to science and society accrues with longevity, so stewardship and the necessary technical and programmatic structures needed to support it, require an enduring commitment that should be independent of individual missions. Investing in data usability, traceability, provenance, and interoperability capabilities can greatly enhance the return on the given civil or commercial investments made to deploy the observing system (**Figure 6)**.

Finding 4.3 – While strides have been made by individual U.S. agencies to provide more ready access to Earth observation datasets, full exploitation of the data and associated investments for U.S. civil and commercial interests and services suggests a more holistic stewardship approach providing the means for platforms where observations and models reside together in an easily accessible and manipulatable form and the latest analysis techniques, such as machine learning and artificial intelligence, can be applied to entire observational records.



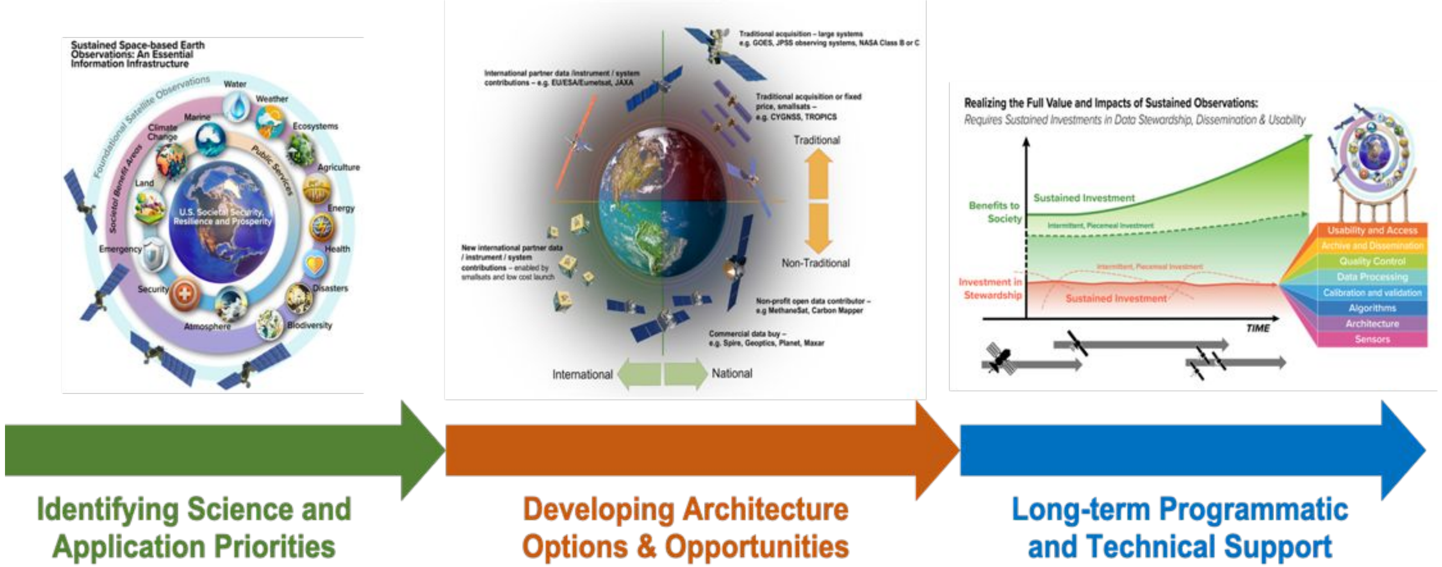
Data Production Elements	Critical Continuity Considerations
Sensor Technology and Characteristics	•Representativeness of the sensor measurements (e.g., spectral channels, sampling, etc.) •Known sensor characteristics and uncertainties
Satellite Observing System Architecture	•Time-of-day or viewing geometry impacts •Stability of satellite orbit •Swath width and revisit rate •Launch cadence and gap risk posture
Algorithm Development, Updates, Documentation	•Commonality in radiometric and geophysical algorithms (e.g., forward radiative models and inversion techniques, ancillary datasets, etc.)
Calibration and Validation	•Documentation of calibration techniques, inclusive of pre-launch characterization and on-orbit characterization •Consistency across validation protocols and ground truths
(Re-)Processing Demands and Cadence	•Consistent geolocation and grids •Lineage and preservation of original (i.e. Level 1) data for retrospective reprocessing •Compute, storage and access capability for re-processing •Compute, storage and access capabilities for utilizing data from multiple missions and programs.
Data and Information Product Quality Control	•Documentation and evaluation of systematic impacts from the chosen filtering approaches •Uncertainty quantification and traceability for data products
Data Archive and Dissemination	•Management of interfaces under common APIs •Common data and metadata formats •Provenance tracking •Unique digital object identifier
Usability and User Ecosystem	•Co-location of data across missions, timeseries, and programs •Curation of community access and development tools •Interoperability of use across different observation types •Permissive licensing regimes for commercially acquired datasets

LIST OF STUDY FINDINGS – SECTION 5

5 Summary and Path Forward

Finding 5.1 The U.S. could benefit from a systematic and overarching plan or framework for identifying, prioritizing, funding, and implementing sustained Earth observations that are critical for supporting our nation's science, policy, and societal resilience goals.

Finding 5.2 A clear and unified approach to sustained Earth observations and determination of our national priorities for these observations may improve the effectiveness of the varied U.S. investments in Earth observations and associated information systems. Such an approach may also enable the United States to play a larger global leadership role in environmental stewardship, Earth system and climate science, and related public services



Study Participants

1. **Waleed Abdalati** - University of Colorado Boulder, CIRES director, cryosphere and Earth System scientist, previous NASA Chief Scientist and co-chair of the 2018 DS
2. **Nancy Baker** - Naval Research Laboratory, meteorologist, satellite data assimilation, part of the weather panel of the 2017 Decadal Survey and a previous member of CESAS.
3. **Stacey Boland** – JPL/Caltech/NASA, system engineer, member of the 2007 and 2017 Decadal Surveys, previous member of CESAS, contributions to NASA's OCO-2/3 and MAIA missions.
4. **Michael Bonadonna** - NESDIS/NOAA, acting Chief of the Architecture Planning, Products & Services Division, within the Office of Systems Architecture and Engineering; helped with the establishment of more sustained space weather observations.
5. **Carol Anne Clayson** – Woods Hole Oceanographic Institute, Senior Scientist, expertise in remote sensing, oceanography, air sea interaction, and climate; 2018 Decadal Survey and previous member of cCESAS.
6. **Belay Demoz** – U. Maryland, Baltimore County, Professor, Director for their Joint Center for Earth Systems Technology, leads research at intersection of atmospheric physics, remote sensing and ground observation assets.
7. **Kelsey Foster** – Early Career, PhD student at Stanford University, working with Professor Michalak in the areas of carbon cycle, flux determination and ecosystems.
8. **Christian Frankenberg** – Caltech, Professor, expertise in atmospheric and ecosystem science, remote sensing of GHGs and carbon cycle processes; co-developed the measurement of solar induced fluorescence (SIF) from space.
9. **Maria Hakuba** – JPL/Caltech/NASA, remote sensing scientist, expertise in the Earth's Radiation Budget and its imbalance, Deputy PI of Libera, NASA's first EV-C mission to measure components of the Earth Radiation budget.
10. **Therese Jorgensen** - NASA Ames, was the Chief Scientist for NASA's Small Spacecraft Virtual Institute, and now Director of their New Opportunities Center; previously the head of NSF's Geospace Sciences Section, and helped start and run their CubeSat program.
11. **Ryan Kramer** – Early Career, previously at GSFC's Climate and Radiation Laboratory and recently moved to a research scientist position at NOAA/GFDL, expertise with radiation & climate forcing.
12. **Daniel Limonadi** – JPL/Caltech/NASA, Chief System Engineer for Earth Sciences, involved in the formulation and implementation efforts of a number of NASA missions – including flagships to Mars and the Surface Water and Ocean Topography mission - SWOT.
13. **Anna Michalak** - Carnegie Institute for Science at Stanford University, Professor, expertise with climate, GHGs, Carbon Cycle, Ecosystems and Global Ecology; previous member of CESAS.

Study Participants

14. **Asal Naseri** – Previously, Space Dynamics Laboratory, University of Utah, Head of Satellite Technology Branch. Recently, Asal became a Program Executive within the Heliophysics Division, Science Mission Directorate at NASA.
15. **Pat Patterson** - Space Dynamics Laboratory, University of Utah, Director of Advanced Concepts; Chair of the annual Small Satellite Conference, and a member of the Air Force's Science Advisory Board.
16. **Peter Pilewskie** - University of Colorado, Professor, also affiliated with their Laboratory for Atmospheric and Space Physics, expert in earth radiation and remote sensing, PI of the Libera mission, NASA's first EV-C, and current member of CESAS.
17. **Steven Platnick** – NASA GSFC, Deputy Director for Atmospheres, Earth Science Division, head of the EOS Project Science Office since 2008, expertise in atmospheric remote sensing, clouds, radiation; closely involved with NASA's MODIS, PACE and Suomi-NPP missions.
18. **Charlie Powell** – Early Career, PhD student at University of Michigan, working with Professor Chris Ruf, also served as a NOAA program analyst and policy advisor.
19. **Jeff Privette** - National Center for Environmental Information (NCEI)/NOAA, Acting Chief of the NOAA Climate Science and Services Division; chair of WGclimate under the Committee on Earth Observation Satellites (CEOS).
20. **Chris Ruf** –University of Michigan (UM), Professor, and Director of UM's Space Institute, PI NASA's CYGNSS Earth Venture mission, an advisor to the commercial enterprise - Muon Space, and a previous member of CESAS.
21. **Tapio Schneider** – Caltech, Theodore Y. Wu Professor of Environmental Science and Engineering, expert in climate dynamics of Earth and other planets, cloud dynamics, climate modeling, and PI of the CLIMA climate model development effort.
22. **Jörg Schulz** – EUMETSAT, head of Operations and Services to Users Department, previous chair of CEOS' Wgclimate, contributor to the Copernicus Climate Services element.
23. **Paul Selmants** – USGS, Western Geographic Science Center, Research Ecologist, expertise on the impact of human activities on terrestrial ecosystems at regional to continental scales.
24. **Rashmi Shah –** JPL/Caltech/NASA, Associate Chief Technologist for Earth Science, expertise in remote sensing technology and architecture development for earth missions.
25. **Qianqian Song** – Early Career, PhD student at University of Maryland, Baltimore County, under Professor Zhibo Zhang, studying processes related to radiation and aerosols/dust, supported via a NASA's FINEST graduate student research award.

Study Participants

26. **Graeme Stephens** – JPL/Caltech/NASA, Senior Research Scientist, co-Director Center for Climate Sciences, PI of NASA's Cloudsat mission, presently on CESAS, member of the 2017 Earth Science Decadal Survey, and a member of the National Academy of Engineers.
27. **Timothy Stryker** – USGS, National Land Imaging Program, Chief of Outreach and Collaboration Branch, Program Director of US Group on Earth Observations – a subcommittee of the National Science and Technology Council.
28. **Wenying Su** – NASA Langley Research Center, Senior Research Scientist, expert in Earth's energy budget, US member to the Committee on Earth Observation Satellites (CEOS), and it's subgroups Working Group Climate (WGClimate) and Coordination Group for Meteorological Satellites (CGMS).
29. **Mathew Van Den Heever** – Early Career, University of Colorado, Boulder, Graduate Student, working with Professor Peter Pilewskie at LASP, involved in the NASA's Libera mission and developing remote sensing expertise with radar, precipitation and earth radiation.
30. **Anna Veldman** – Early Career, previously a UCLA summer intern working at JPL while as an undergraduate student at Queen Mary University of London, now a graduate student Masters in Public Administration at Columbia University.
31. **Duane Waliser** – Jet Propulsion Laboratory/Caltech/NASA, Chief Scientist for Earth Sciences, expertise in climate dynamics, global modeling, prediction and predictability.
32. **Elizabeth Weatherhead** - former senior scientist at U. Colorado, now works at Jupiter in climate risk analysis and information, former NOAA Science Advisor Board member; Betsy also led one of the first WGCRP Grand Challenge papers on Continuity and the establishment of a climate observing system in 2018

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