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Challenges to developing a global satellite climate monitoring system

By Mariel Borowitz

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Center for International and Security Studies at Maryland
4113 Van Munching Hall, School of Public Policy
University of Maryland
College Park, MD 20742
(301) 405-7601

Abstract

Satellites are critical to the ability to understand and address climate change, due to their unique ability to provide comprehensive global monitoring of the environment. More than 30 nations have been involved in satellite Earth observations, with more than 200 satellite instruments operating in 2014 alone. However, gaps remain in the ability to adequately monitor global climate change, due in part to a lack of international consensus on the definition of an adequate monitoring system.

This paper examines ongoing international efforts to identify the requirements of a global satellite climate monitoring system, including high-level efforts by the Global Climate Observing System (GCOS), the World Meteorological Organization (WMO), and the Committee on Earth Observing Satellites (CEOS), as well as efforts to define more detailed technical requirements being undertaken by GCOS, WMO, and the European Space Agency (ESA). Comparing the distinct processes and interim results of these groups highlights the lack of international consensus on the definition of an adequate global climate monitoring system. Developing such a system is a complex, multifaceted challenge, which requires expert technical knowledge of climate science and satellite capabilities as well as attention to political concerns for sovereignty and long-term international cooperation.

The paper examines the adequacy of the current satellite monitoring capabilities by developing a comprehensive dataset including all unclassified Earth observation satellites operating or planned between 1990 and 2020. This analysis shows that within each international effort, gaps in the type of data collected are present. Even when some data is collected on a particular variable, it is not necessarily done in a way that meets technical requirements for climate assessment and forecasting. A lack of free and open data sharing compounds this challenge, further decreasing the amount of data contributing to international climate monitoring efforts. The lack of consensus on the requirements of a global climate monitoring system makes it difficult for nations to use international coordination mechanisms to plan and prioritize future satellite systems.

The paper concludes by providing a series of recommended steps to improve harmonization among international efforts. This includes coordinating the bottom-up method used within GCOS with the top-down method used at WMO to identify concrete recommendations that will allow nations to prioritize investments that improve climate monitoring and/or improve the efficiency of the existing system. It recommends consolidating international efforts to define technical requirements to avoid duplication and facilitate prioritization among user groups with regard to which variables should be collected and what technical requirements must be met. A more systematic and integrated approach to system definition will make it possible for nations to shift and/or increase investments in satellite technology to better address agreed-upon needs and priorities.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, released in October 2013, stated that “warming of the climate system is unequivocal” and “human influence on the climate system is clear.”¹ This assessment is based on research drawing on a wide variety of observations of the Earth, many of which make use of remote sensing satellites. Adequately monitoring changes in the climate system is crucial to making well-informed climate mitigation and adaptation policies. This data is needed not only for designing policies, but also for policy evaluation to ensure successful implementation.

In 2014, there were hundreds of Earth observation satellite instruments in orbit with the potential to contribute toward a global climate monitoring system. However, despite the importance of understanding and monitoring climate change; many experts argue that key measurements are not being taken by these existing systems; accuracy and resolution of existing measurements are often not adequate for climatic uses; and stable, long-term collection of data is not assured. To evaluate these claims, it is necessary to define the elements of an adequate climate monitoring system. Thus, this paper first looks at existing efforts to define such a system, then assesses the ability of existing measurements to meet these requirements. It concludes by identifying future steps needed to both refine definitions and improve global climate monitoring.

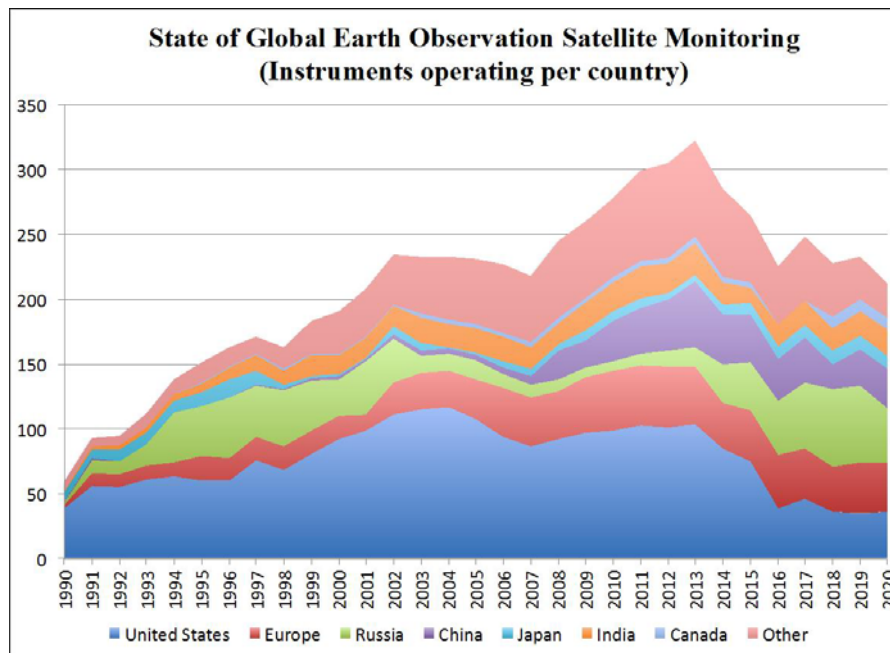


Figure 1: More than 30 nations are involved in satellite Earth observations, participating in the ownership or operation of at least one Earth observation satellite. However, a small number of nations and regional organizations account for the vast majority of all satellite instruments: the United States, Europe, Russia, China, Japan, India, and Canada. The total number of instruments operating is likely to decrease in future years as older satellites reach the end of their lifespans before new instruments are launched.

¹ "Summary for Policymakers." A Report of Working Group I of the Intergovernmental Panel on Climate Change. Fifth Assessment Report. IPCC, n.d. Web. 30 Jan. 2014.
<http://www.ipcc.ch/report/ar5/wg1/docs/WGIAR5_SPM_brochure_en.pdf>.

This paper addresses the following questions:

1. What types of measurements or systems would constitute an adequate satellite climate observation system? To what extent do current or planned future systems meet these requirements?
2. What specific technical requirements must each of these measurements meet to be useful for observation of climate change? To what extent do current and future planned satellites meet these requirements?
3. What are the policies governing data access? To what extent is data collected from current and future planned satellites actually made available to the international community?
4. What actions would be required to develop an adequate satellite climate observation system, given the current, and planned future, system?

1.0 High-level Efforts to Define a Global Satellite Climate Monitoring System

Numerous national, regional, and international organizations are trying to define climate-monitoring requirements, document current capabilities, and promote increased coordination and development to meet these requirements. While they have different roles and focus areas, in many cases these organizations are closely related and are coordinating their efforts, with many of the same nations and regional organizations belonging to multiple groups.

The World Meteorological Organization (WMO) is a specialized agency of the United Nations that provides the framework for international cooperation in the collection and exchange of data needed to monitor and understand weather, climate, hydrology, and geophysical sciences.² The WMO worked with a number of other UN programs to create the Global Climate Observation System (GCOS), which aims to identify the full range of national and international requirements for climate-related observations and provide comprehensive information on the climate system.³ The space-based components of GCOS are coordinated by the Committee on Earth Observing Satellites (CEOS). Coordination of these climate-relevant satellites is only one component of CEOS's broader mission, which is to ensure international coordination in data collection and sharing across civil space-based Earth observation programs of all kinds.⁴

A fourth prominent international organization encouraging the coordination of Earth observation efforts is the Group on Earth Observations (GEO). GEO's goal is to coordinate efforts to build a Global Earth Observation System of Systems (GEOSS), which encompasses both space and in-situ measurements across nine societal benefit areas.⁵ In addition to coordinating with WMO directly, GEO is affiliated with many of the same organizations in this area: CEOS helps to develop the space segment of GEOSS, and GCOS represents the climate component of GEOSS – one of the nine societal benefit areas.

As shown above, WMO, GCOS, CEOS, and GEO all have different driving missions – weather, climate, satellites, Earth observations – each of which relates to the others and to the development of a satellite

² "WMO in Brief." *World Meteorological Agency*. N.p., n.d. Web. 19 Apr. 2014. <http://www.wmo.int/pages/about/index_en.html>.

³ "About GCOS." *Global Climate Observing System*. N.p., n.d. Web. 19 Apr. 2014. <<http://www.wmo.int/pages/prog/gcos/index.php?name=AboutGCOS>>.

⁴ "CEOS Home." *Committee on Earth Observation Satellites*. N.p., n.d. Web. 19 Apr. 2014. <<http://www.ceos.org/>>.

⁵ "About GEO." *Group on Earth Observations*. N.p., n.d. Web. 19 Apr. 2014. <http://www.earthobservations.org/about_geo.shtml>.

climate monitoring system. The size and political or technical expertise of each organization vary significantly as well. WMO has 185 member states, each represented by its national director of meteorological services, an important and politically influential role.⁶ GEO's membership, while smaller at 89 countries and the European Commission, includes regular meetings of agency representatives as well as summits bringing together ministerial-level political decision makers every three to four years. CEOS and GCOS are considerably smaller organizations with more technical, rather than political, focus and expertise. These differences in missions, member nations, and expertise, drive the various ways that each organization has addressed the issue of satellite climate monitoring.

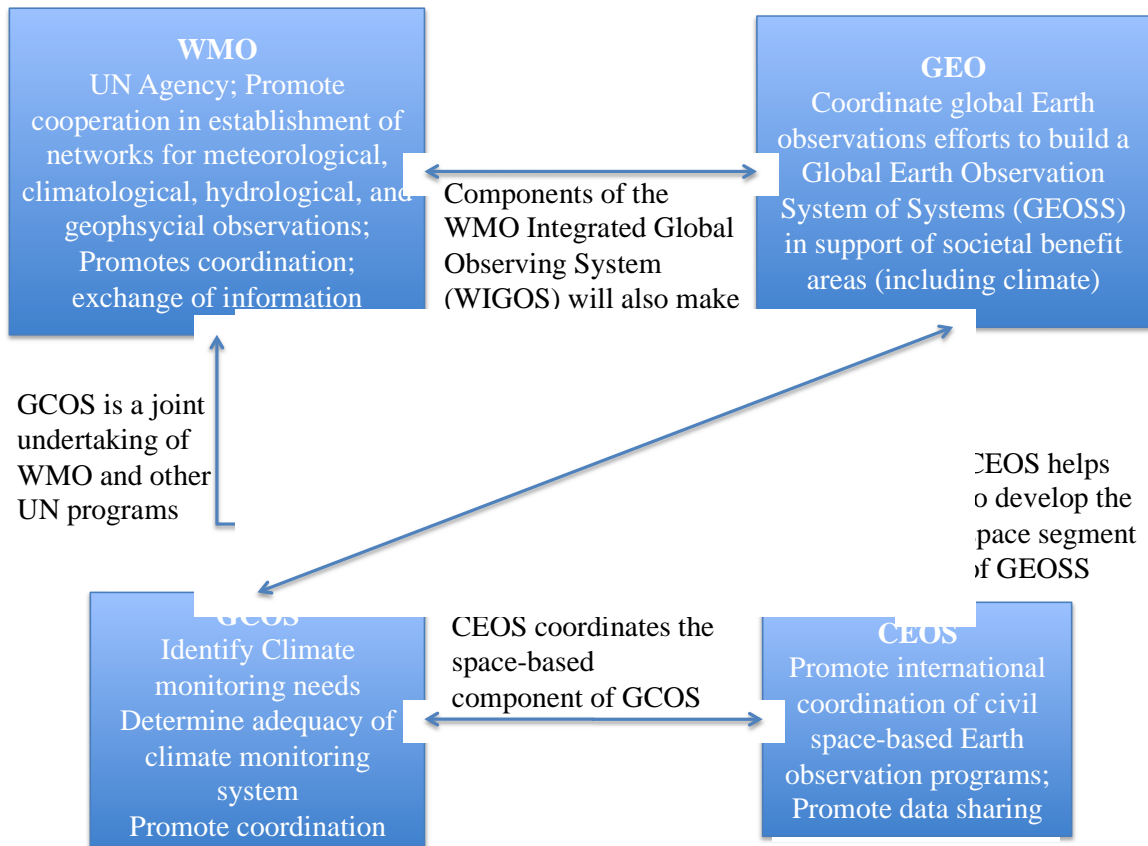


Figure 2: Four international organizations active in defining climate-monitoring requirements, documenting current capabilities, and promoting increased coordination and development to meet these requirements. Though they have different objectives, they are closely connected.

⁶ "Permanent Representatives." *World Meteorological Agency*. N.p., n.d. Web. 23 Jul. 2014. <http://www.wmo.int/pages/members/pr/index_en.html>.

1.1 GCOS Essential Climate Variables

The most comprehensive effort to define the needs of a global climate monitoring system was undertaken by the aptly named “Global Climate Observing System” (GCOS) group. GCOS is a joint undertaking of the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational Scientific and Cultural Organization (UNESCO), the United Nations Environment Programme (UNEP) and the International Council for Science (ICSU).⁷

In 2003, in collaboration with subject-area experts and members of the IPCC, GCOS developed a list of approximately 50 essential climate variables (ECVs) required to support the work of the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC). These variables cover the atmospheric, oceanic, and terrestrial domains, and no prioritization is provided among them. All of the essential climate variables were determined to be technically and economically feasible for systematic observation, and updates have been made to the list to adjust for changes in needs and capabilities over time. About half of the variables were identified as “largely dependent on satellites.”⁸

To examine the extent to which existing and planned satellites are able to observe these ECVs, this paper uses a dataset based on the CEOS Mission, Instrument, and Measurement (MIM) Database, with adjustments made to improve consistency and accuracy. The dataset includes every unclassified Earth observation satellite that operated from 1967 to 2013, as well as those planned for 2014 to 2031, and allows a direct mapping of each satellite instrument to the specific types of measurements it collects and the ECVs it supports.

There are a number of factors that influence the reliability of information regarding systems expected to launch or operate in the future, so projections for 2014 to 2020 are only notional. It is always possible for satellites to last longer, or to stop functioning earlier, than originally planned. Planned satellite launch dates may be delayed, and notional satellites with more distant launch dates may never be developed at all. Acting in the other direction, there are likely satellites that would have the ability to contribute to a global system but have not yet been conceptualized or announced, and thus are not included here. However, these estimates provide the best available baseline estimate for future global activity.

⁷ "About GCOS." *Global Climate Observing System*. N.p., n.d. Web. 30 Jan. 2014.

<<http://www.wmo.int/pages/prog/gcos/index.php?name=AboutGCOS>>.

⁸ *Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC*. Rep. no. GCOS-82. Global Climate Observation System, n.d. Web. 20 Dec. 2011. <http://www.wmo.int/pages/prog/gcos/Publications/gcos-82_2AR.pdf>.

⁸*Systematic Observation Requirements for Satellite-based Products for Climate Supplemental Details to the Satellite-based Component of the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC*. Rep. no. GCOS-107. Global Climate Observation System, Sept. 2006. Web. 20 Dec. 2011.

<<http://www.wmo.int/pages/prog/gcos/Publications/gcos-107.pdf>>.

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Aerosols	3	4	3	3	4	5	10	11	10	14	17	21	30	33	31	32	33	31	31	35	37	38	38	33	31	31	25	34	37	41	36
Albedo	7	9	11	14	20	27	36	32	34	41	42	47	53	57	55	62	66	65	77	76	76	79	80	81	75	74	65	69	70	62	49
Biomass	6	7	7	8	7	7	7	7	7	10	12	14	18	18	17	17	17	17	17	21	21	23	23	23	21	23	20	21	22	23	22
Carbon Dioxide, Methane, and GHGs	9	15	15	16	17	15	18	18	14	14	16	18	24	24	27	26	21	20	21	22	23	24	25	23	17	18	12	15	19	22	21
Cloud Properties	29	39	33	40	52	57	55	63	62	68	73	81	93	96	95	91	92	89	98	100	106	109	112	113	92	91	69	74	71	78	58
Earth Radiation Budget	14	20	20	25	28	29	27	30	27	34	39	40	51	53	52	55	51	50	54	58	66	71	75	80	58	59	41	46	40	40	34
FAPAR	2	2	2	3	2	4	4	4	4	6	7	10	11	17	19	19	20	20	22	25	26	28	28	29	20	20	19	16	13	16	18
Fire Disturbance	10	11	12	14	13	15	15	15	15	16	21	25	26	26	25	25	26	26	26	29	29	32	33	35	38	41	38	42	44	41	33
Glaciers and Ice Caps, and Ice Sheets	2	3	4	4	3	5	5	5	5	5	7	6	9	10	10	10	11	15	21	22	24	25	23	23	22	20	20	22	23	21	14
Gravidity and Magnetic Fields	5	6	9	11	12	13	14	15	16	19	22	25	31	32	33	32	33	33	34	40	41	41	41	48	40	40	34	32	33	30	29
LAI	2	2	2	2	1	1	2	2	2	5	6	7	10	10	9	9	9	9	9	11	11	12	12	13	12	13	11	11	9	10	12
Lakes	0	1	1	1	1	3	3	3	3	3	3	2	3	3	3	3	3	4	4	4	4	4	3	2	2	3	2	2	5	6	6
Land Cover	12	18	21	25	33	44	52	52	53	61	66	75	89	95	92	100	104	104	123	126	134	141	147	150	137	136	121	131	124	121	102
Ocean Color	8	10	10	11	15	23	23	20	21	27	29	31	36	34	34	35	37	34	37	39	44	46	44	42	36	37	29	36	35	40	21
Ocean Currents	1	2	6	7	9	12	14	12	13	15	13	15	18	17	18	18	18	14	18	18	18	19	20	16	14	20	13	15	15	15	20
Ocean salinity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	2	2	2	1	1	1	0	1	1
Ozone	12	21	21	24	27	24	26	27	23	24	28	33	41	39	41	42	36	34	36	40	43	45	46	45	36	39	26	30	34	34	30
Precipitation	8	13	12	15	22	26	27	35	38	41	43	47	55	56	55	56	58	54	55	58	62	67	69	70	56	56	46	51	43	47	40
Sea Ice	7	14	15	20	32	40	40	35	40	41	45	50	57	49	50	51	52	53	60	62	66	71	72	69	65	65	57	67	63	71	58
Sea Level	0	1	3	3	3	4	5	5	5	5	4	7	10	10	10	10	8	14	14	15	17	16	15	12	16	10	10	8	3	8	
Sea State	0	3	4	4	6	11	12	11	11	12	11	10	12	11	12	12	11	13	13	13	14	11	8	9	13	10	11	11	10	12	
Sea Surface Temperature	7	11	11	15	20	24	25	29	28	31	32	38	47	46	44	46	45	43	46	48	54	58	58	60	51	56	48	51	45	51	45
Snow Cover	13	22	21	25	35	39	37	41	42	40	47	51	58	57	55	52	53	55	61	63	67	71	75	75	68	62	53	58	58	60	47
Soil Moisture	2	5	4	4	4	7	10	13	14	16	16	15	22	22	21	20	24	27	29	32	34	35	36	35	32	25	22	26	22	24	25
Surface Temperature	7	11	11	15	20	24	25	29	28	31	32	38	47	46	44	46	45	43	46	48	54	58	58	60	51	56	48	51	45	51	45
Surface Wind Speed and Direction	3	7	7	7	11	17	17	18	18	22	23	23	28	27	27	26	28	25	27	27	28	35	34	33	32	36	32	38	30	31	31
Upper Air Temperature	19	30	28	32	36	34	33	36	31	33	39	46	53	54	57	53	50	49	54	56	61	61	65	67	52	40	29	35	29	39	35
Upper-air Wind	5	7	8	10	13	15	12	16	17	21	23	23	27	29	26	28	26	23	22	24	27	28	25	26	22	26	20	22	21	22	18
Water Vapour	17	29	28	31	39	43	43	47	46	50	54	58	71	71	72	72	75	72	77	79	85	90	92	96	83	79	62	70	57	67	66

Figure 3: This table shows the number of satellite instruments collecting each ECV each year. If the ECV is not collected in a given year, that cell is shown as red. Yellow represents an ECV that is collected by one to five instruments in a given year. Green cells are ECVs collected by more than five instruments in a year. One instrument can (and often does) contribute to the collection of more than one ECV.

Examining time-series data is important in studying climate, because continuity in the data record is essential for climate change studies. Overlap in satellite instruments collecting the same data is necessary to allow cross-calibration, ensuring that measurements taken by two different instruments are equivalent and can be used to study long-term trends. Gaps in the data record can significantly hinder the ability of climate scientists to confidently identify minor changes occurring over very long time periods.

At first glance it appears that nearly all of the ECVs largely dependent on satellites have been adequately collected in the three decades stretching from 1990 to 2020. Simply counting the number of instruments collecting each ECV, however, obscures the complexity of climate monitoring, because the Essential Climate Variables are defined at a relatively high level (e.g. “ozone” and “snow cover”). In reality, almost every essential climate variable requires the collection of multiple, more specific types of measurements.

Recognizing this, GCOS developed a list of about 150 specific types of measurements that need to be taken to support the ECVs.⁹ Examples of the connection between specific measurements and ECVs are shown in table 1.

When these more specific requirements are considered, deficiencies in data collection are more apparent, as shown in figure 4. Though collection of measurements on this expanded list has been increasing over time, only about two-thirds of the specific measurements are expected to be collected by more than five instruments from 2010-2020. About 10% of the measurements needed to support the ECVs are not collected at all during this period.

⁹ *Systematic Observation Requirements for Satellite-based Products for Climate*. Rep. no. GCOS-107. Global Climate Observation System, Sept. 2006. Web. 20 Dec. 2011. <<http://www.wmo.int/pages/prog/gcos/Publications/gcos-107.pdf>>.

ECV	Specific Measurement
Aerosols	Aerosol absorption optical depth (column/profile)
	Aerosol effective radius (column/profile)
	Aerosol Extinction / Backscatter (column/profile)
	Aerosol optical depth (column/profile)
	Volcanic ash
Glaciers and Ice Caps, and Ice Sheets	Glacier cover
	Glacier motion
	Glacier topography
	Ice sheet topography
Ocean salinity	Ocean salinity
Ocean Currents	Ocean dynamic topography
	Ocean surface currents (vector)
Precipitation	Lightning detection
	Precipitation index (daily cumulative)
	Precipitation Profile (liquid or solid)
	Precipitation rate (liquid) at the surface
	Precipitation rate (solid) at the surface

Table 1: Each ECV can be broken down into one or more specific types of measurements that can be collected by satellites. The table above shows the specific measurement types that support five selected ECVs.

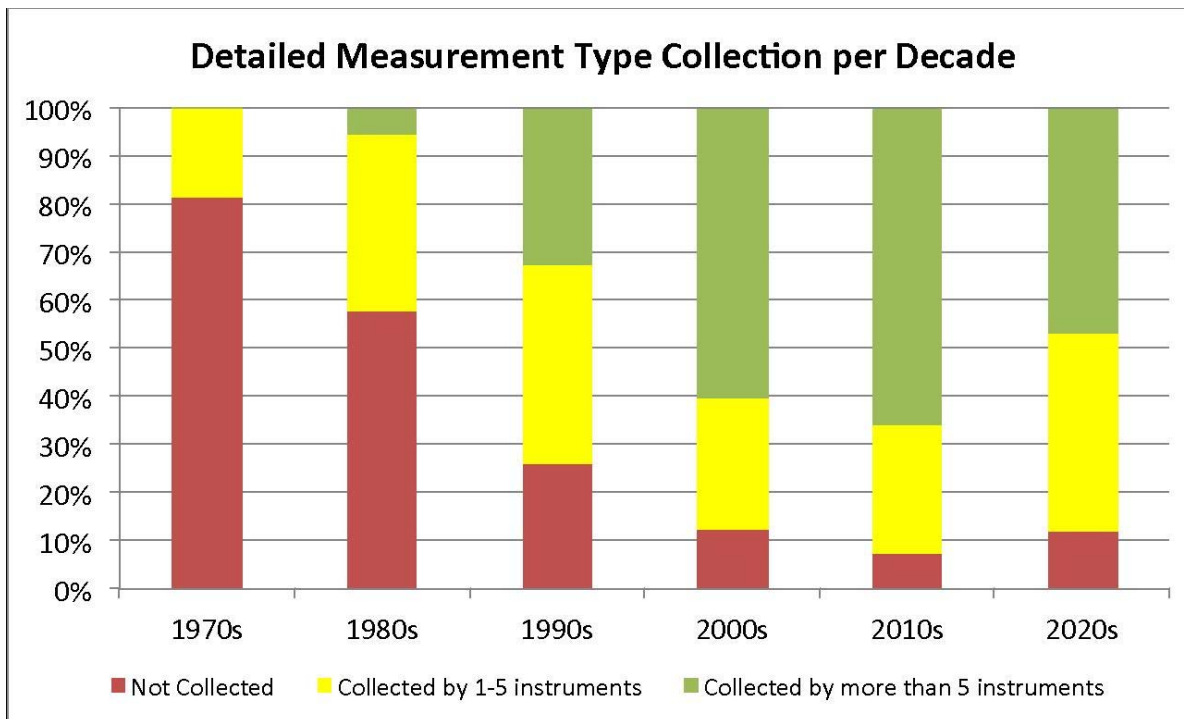


Figure 4: This chart shows the percentage of specific types of measurements each decade that were not collected, collected by one to five instruments, or collected by more than five instruments. Measurement collection after 2013 includes the addition of satellites planned for future launch. Data for 2020-2030 likely underestimates data collection, as many countries do not announce satellite development plans extending this far into the future.

GCOS developed the essential climate variables and, in cooperation with CEOS, identified which satellite instruments are relevant to each of these ECVs. While this allows an analysis of data continuity useful for identifying gaps in data collection, it does not address the ability of the systems to provide adequate temporal and geographic coverage, so it is difficult to determine exactly how many satellites are needed. GCOS also does not provide guidance on the ideal architecture of a global climate monitoring system in terms of specific satellites and instruments in particular orbits. This type of analysis could help to clarify high-priority system needs globally, helping states close gaps, improve capabilities, and avoid duplication of effort.

1.2 WMO Global Observing System 2025

The WMO has addressed the issue of physical system architecture through the definition of the WMO Integrated Global Observing System (WIGOS). The Global Observing System (GOS) is made up of in-situ and space-based systems that make environmental observations in support of WMO programs. These systems are owned and operated by WMO member states. The current space component of GOS includes four operational near-polar-orbiting satellites, six operational geostationary environmental observation satellites, and several research and development satellites.¹⁰

In addition to the existing Global Observing System, WMO hopes to coordinate future data collection via its “Vision for the Global Observing System in 2025.” The goal of this effort is to identify the systems and configurations needed to meet future requirements for weather and climate observation. It explicitly includes an expansion of the current GOS system to include observations that support the ECVs, though publicly available planning documents do not provide a full account of how each ECV will be addressed by the notional system.¹¹

The WMO Vision for GOS in 2025 includes six geostationary satellites carrying infrared and visible images and sounders, similar to the existing system, and aims to add lightning imaging instruments, as well. The operational polar-orbiting system would be expanded to six satellites, distributed among three orbital planes (as opposed to two orbital planes in the current model). As with existing meteorological systems, these satellites would carry both imagers and sounders, covering infrared, visible, and microwave spectra.¹²

¹⁰ "Observation Components of the Global Observing System." *WMO*. N.p., n.d. Web. 30 Jan. 2014. <<http://www.wmo.int/pages/prog/www/OSY/Gos-components.html>>.

¹¹ *Vision for the GOS in 2025*. Rep. no. Recommendation 6.1/1 (CBS-XIV). WMO Commission for Basic Systems Fourteenth Session, Apr. 2009. Web. 30 Jan. 2014. <<http://www.ioccg.org/groups/ecv.html>>.

¹² *Vision for the GOS in 2025*. Rep. no. Recommendation 6.1/1 (CBS-XIV). WMO Commission for Basic Systems Fourteenth Session, Apr. 2009. Web. 30 Jan. 2014. <<http://www.ioccg.org/groups/ecv.html>>.

Selected GOS 2025 Instruments	
<i>Operational geostationary satellites. At least 6, separated by no more than 70 deg longitude</i>	
High-resolution multi-spectral visible/infr	Cloud amount, type, top height/temperature; wind (through tracking cloud and water vapour features); sea/land surface temperature; precipitation; aerosols; snow cover; vegetation cover; albedo; atmospheric stability; fires; volcanic ash
Infrared hyper-spectral sounders	Atmospheric temperature, humidity; wind (through tracking cloud and water vapour features); rapidly evolving mesoscale features; sea/land surface temperature; cloud amount and top height/temperature; atmospheric composition
Lightning imagers	Lightning (in particular cloud to cloud), location of intense convection.
<i>Operational polar-orbiting sun-synchronous satellites distributed within 3 orbital planes (~13:0, 17:30, 21:30 ECT)</i>	
Infrared hyper-spectral sounders	Atmospheric temperature, humidity and wind; sea/land surface temperature; cloud amount, water content and top height/temperature; atmospheric composition
Microwave sounders	Atmospheric temperature, humidity and wind; sea/land surface temperature; cloud amount, water content and top height/temperature; atmospheric composition
High-resolution multi-spectral visible/infr	Cloud amount, type, top height/temperature; wind (high latitudes, through tracking cloud and water vapour features); sea/land surface temperature; precipitation; aerosols; snow and ice cover; vegetation cover; albedo; atmospheric stability

Table 2: This chart shows the expanded operational space-based components envisioned for WMO’s Global Observing System in 2025. The Vision for GOS in 2025 also includes additional operational missions in a variety of orbits that have not traditionally been a part of the WMO Integrated Global Observing System.

In addition to these traditional meteorological systems, the Vision for GOS in 2025 foresees a need for additional operational missions or constellations, including microwave imagers needed for measurements of sea ice and precipitation, scatterometers measuring sea surface wind speed; a radio occultation constellation of at least eight satellites to contribute to temperature and humidity measurements, and synthetic aperture radar to provide data on wave height and icebergs. In all, there are 11 new operational missions or constellations proposed. A further six missions are identified as contributing to the system through operational path finding and technology demonstration.¹³

The fact that so many new systems will be required – in addition to maintaining already existing satellite constellations – suggests that there are significant gaps in current data collection, and WMO recognizes that implementing the vision will require both an expanded number of contributing space agencies and increased collaboration.¹⁴ However, there are challenges in more precisely enumerating these gaps. WMO aims to assess progress towards meeting the requirements laid out in the GOS through its Observing Systems Capabilities Analysis and Review (OSCAR) tool, which documents current satellite

¹³ *Vision for the GOS in 2025*. Rep. no. Recommendation 6.1/1 (CBS-XIV). WMO Commission for Basic Systems Fourteenth Session, Apr. 2009. Web. 30 Jan. 2014. <<http://www.ioccg.org/groups/ecv.html>>.

¹⁴ *WIGOS: WMO Integrated Global Observation System: Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP)*. Rep. no. No. 2013-4. WMO, 2013. Web. 30 Jan. 2014. <<http://www.wmo.int/pages/prog/www/OSY/Publications/EGOS-IP-2025/EGOS-IP-2025-en.pdf>>.

capabilities. However, there is no clear explanation of how these currently operating satellite systems will be integrated into the WMO GOS framework. Though not part of the ideal system, they may still collect relevant information. Further, in the past, nations have developed satellite constellations to meet their own purposes, with minimal international input, later making them available for international coordination through WMO. It is not clear whether nations will agree to develop and contribute elements of the future system in accordance with the architecture envisioned by WMO, nor how departures from the architecture would affect the adequacy of the system. The disconnect between existing infrastructure and an ideal system architecture is still too great.

1.3 CEOS Virtual Constellations

Rather than focusing exclusively on a set of variables or physical system architecture, CEOS has used a more integrated method in its development of virtual constellations. The virtual constellations are sets of existing or planned space and ground segment capabilities that together could provide adequate coverage for particular Earth observation requirements. Each constellation is designed around a specific area of interest, focusing on one or more observational requirements and one or more measurement technologies.

Virtual Constellation	Focus	Parameter	Measurement Technique
Atmospheric Composition	Changes in the ozone layer, air quality, and climate forcing associated with changes in the environment	Various parameters (radiative and chemically active gases, aerosol, etc.)	Multiple
Land Surface Imaging	Land surface image data	Various parameters (related to land use/cover, fire, volcanic eruptions, etc.)	Multiple
Ocean Surface Topography	Observe the topography of, and the significant wave height on, the surface of the global oceans ranging from basin-scale to mesoscale; relevant to global sea level rise, the role of the oceans in climate, and operational oceanography	Ocean surface topography	Altimetry
Precipitation	Coordinate continued advancements of multi-satellite global precipitation missions	Precipitation	Rain radar supplemented with microwave radiometry
Ocean Colour Radiometry	Develop long time series of calibrated ocean color radiance (OCR) at key wavelength bands	Ocean color radiometry	Optical measurements of colour
Ocean Surface Vector Winds	Improve operational marine warnings and forecasts through the use of ocean surface vector winds from satellite scatterometry; ensure climate-quality records, facilitate research related to the influence of wind forcing on the circulation of the oceans	Ocean surface vector winds	Microwave scatterometry
Sea Surface Temperature	development and improvement of sea surface temperature products	Sea surface temperature	Infrared and passive microwave imaging radiometers

Table 3: This chart describes the primary focus of the CEOS Virtual Constellations. Each constellation is defined by one or more parameters and one or more measurement techniques. The constellations are not associated with specific ECVs, though there is significant overlap.

Organizing around specific substantive issues makes it easier to clarify requirements for particular uses or user-groups. Within this framework, it is possible to compare existing capabilities to these requirements and identify global observational gaps. CEOS also hopes to use virtual constellations to sustain routine collection of critical observations, by making the role of each contributing system or organization more clear.¹⁵

¹⁵ Kajii, Makoto. "CEOS Virtual Constellation Status and Issues." *CEOS*. N.p., Oct. 2010. Web. 30 Jan. 2014. <http://www.dpi.inpe.br/ceos/apresentacoes/Item_14_8_CEOS.pdf>.

These constellations are relevant to the GCOS ECVs, but are not explicitly tied to them, being instead designed to support the GEOSS Societal Benefit Areas (of which climate is one).¹⁶ The CEOS Climate Working Group has expressed an interest in determining which ECVs are covered by existing virtual constellations, but does not believe a unique virtual constellation is needed for each ECV (or each detailed measurement).¹⁷

1.4 Evaluation of Progress on High-level System Definition

Research Question 1: What types of measurements or systems would constitute an adequate satellite climate observation system? To what extent do current or planned future systems meet these requirements?

As illustrated above, GCOS, WMO, and CEOS have all made important progress in defining the measurements or systems needed to adequately monitor climate change. However, the variety of major efforts in itself demonstrates the lack of consensus in the international community on how to define an adequate global climate monitoring system, and this lack of consensus remains a fundamental challenge.

GCOS has focused on the types of measurements needed, WMO on the ideal physical architecture, and CEOS on the needs and existing capabilities relevant to particular user groups. Though each of these efforts shows promise, any one of these efforts on its own is unlikely to be successful in developing an actionable definition of an adequate global satellite climate monitoring system. GCOS is missing critical information on geographic and temporal coverage, WMO has not yet developed a pathway from the current technical and political system to its ideal architecture, and CEOS's user-focused efforts do not provide the comprehensive view needed for climate monitoring as a whole. A fully defined satellite climate monitoring system will need to include an understanding of the types of measurements needed, the technical systems necessary to collect these measurements, and the satellite architecture that will ensure adequate coverage. Each of the three major international efforts discussed above addresses a portion of this puzzle, but none provides a fully formed vision. Rather than continuing to elaborate each unique vision, resulting in overlapping and sometimes contradictory requirements and recommendations, these organizations should integrate the work that they've done, enabling a robust system definition that takes into account all of these elements.

Given the variety of definitions for a global satellite climate observation system, it is difficult to precisely evaluate the adequacy of current capabilities. However, within each of the three frameworks for defining a global system, capability gaps seem to be present. There are multiple ECVs that do not seem to have sufficient coverage, and additional systems identified as part of the WMO GOS Vision for 2025 that do not currently exist. Future gaps in data collection may be even more pronounced. Data

¹⁵"CEOS Virtual Constellations Process Paper." *CEOS*. N.p., Nov. 2013. Web. 30 Apr. 2014.

<<https://www.ghrsst.org/files/download.php?m=documents&f=130702183229-CEOSVirtualConstellationsProcessPaper2013updatev01a.docx>>.

¹⁶ "CEOS Virtual Constellations." *CEOS*. N.p., n.d. Web. 30 Jan. 2014.

<http://www.ceos.org/index.php?option=com_content&view=article&id=275>.

¹⁷ Dowell, Mark, and John Bates. "CEOS Working Group on Climate." *GCOS*. N.p., n.d. Web. 30 Jan. 2014.

<http://www.wmo.int/pages/prog/sat/meetings/documents/ARCH-WK-1_Doc_02-06_CEOS-WGC-climate.ppt>.

¹⁷"Ocean Colour Essential Climate Variable (ECV) Assessment." *IOCCG Working Groups*. N.p., n.d. Web. 30 Jan. 2014.

<<http://www.ioccg.org/groups/ecv.html>>.

suggests that the total number of Earth observation instruments is declining, largely due to a reduction in investment in the United States, the largest contributor to global Earth observations.¹⁸ This trend may put even the continuity of existing measurements in jeopardy as older satellites reach the end of their lives and are not replaced by new systems.

2.0 Technical Requirements for Global Climate Monitoring

Regardless of whether they focus on general variables or physical systems, the efforts discussed above all remain too broad to fully evaluate the adequacy of the existing global climate monitoring system. In order for satellite systems or the data they collect to be useful for climate-related research and operations, they must also meet a number of technical requirements in areas such as accuracy, stability, spatial resolution, and temporal resolution.

Accuracy and Stability: Changes in the climate are often very small, occurring over very long time periods. While the temperature in one city may fluctuate 20 degrees in the span of one day, the global average temperature has increased just one degree Celsius in the last 100 years.¹⁹ Therefore, to be useful for climate studies, observations often must be significantly more accurate than those for weather, i.e. the uncertainty in the measurement must be very low. Because climate measurements often require data collection on time scales much longer than the typical lifespan of a satellite, it is necessary to have overlap between old and new sensors, allowing for cross-calibration. This helps to ensure that the measurements are stable, i.e. the level of uncertainty does not increase over time.²⁰

Geographic Coverage and Temporal Coverage: Climate is a worldwide phenomenon, and therefore, it is important to have sufficient data from all areas of the globe. For satellite-collected data, geographic coverage depends on the orbital inclination of the satellite, its altitude, the swath width of the instrument, and the number of satellites collecting the same types of data. The inclination of the satellite determines which areas of the Earth are visible to the instruments onboard. A satellite in a polar orbit (90 degree inclination) will be able to view every part of the Earth as it progresses along its orbit. A satellite with a lower inclination, for example, 20 degrees, will only be capable of monitoring tropical regions (those within 20 degrees, north or south, of the equator).

Combined with the inclination, the orbit determines how frequently a satellite will revisit each point on the Earth. A satellite in a polar, low Earth orbit will monitor each point on the Earth twice a day. A satellite in geostationary orbit will circle the Earth at a rate that allows it to remain stationary over one area of the Earth. Land cover measurement gives an example of the relation between geographic coverage and temporal coverage. For many parts of the globe, twice-daily flyovers may be sufficient to produce enough cloud-free images to monitor land use change over long time periods. However, in the tropics, where it is often cloudy, it may be much more difficult to get cloud-free images. Therefore,

¹⁸ National Research Council. *Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey*. Washington, DC: The National Academies Press, 2012.

¹⁹ "Observed Changes in Climate and Their Effects." *AR4 Synthesis Report Summary for Policymakers*. N.p., n.d. Web. 30 Jan. 2014. <http://www.ipcc.ch/publications_and_data/ar4/syr/en/spms1.html>.

²⁰ *Guideline for the Generation of Datasets and Products Meeting GCOS Requirements, May 2010*. Rep. no. GCOS-143. Global Climate Observation System, Jan. 2014. Web. <<http://www.wmo.int/pages/prog/gcos/Publications/gcos-143.pdf>>.

²⁰ *Systematic Observation Requirements for Satellite-based Data Products for Climate, 2011 Update*. Rep. no. GCOS-154. Global Climate Observation System, Dec. 2011. Web. Jan. 2014. <<http://www.wmo.int/pages/prog/gcos/Publications/gcos-154.pdf>>.

supplementing a polar-orbiting land imaging satellite with a similar satellite in a lower inclination may result in more consistent global cloud-free images. In general, additional satellites carrying the same instruments can be used to increase temporal resolution – the frequency with which each area is monitored.

Swath Width and Spatial Resolution: The swath width of the instrument refers to the cross-section of the area it is able to monitor as it passes by. This depends in part on the altitude – a satellite close to the Earth may have a swath width covering a few kilometers, but a geostationary satellite can view the entire disc of the Earth at one time. Swath width is also generally inversely related to spatial resolution. A large swath can be monitored at a relatively low resolution while increasing the resolution may require reducing the total area (swath width) viewed.

The spatial resolution required for climate purposes depends to a large extent on the type of measurement being taken and its intended purpose. For example, land change studies can often be done using medium resolution data, such as the Landsat system’s 30-meter resolution imagery. However, other analyses, such as identifying water puddles on ice sheets, may require very high-resolution data – imagery that allows features less than 1 meter to be distinguished.

2.1 GCOS Satellite Observation Requirements

Again, GCOS is the source of one of the most comprehensive and authoritative documents on these data-quality requirements. A 2006 GCOS report provided specific requirements for accuracy, stability, spatial resolution, and temporal resolution for each ECV.²¹ This report was updated and expanded in 2011.²² In addition to the technical requirements for each ECV, GCOS provides an explanation of its importance to climate, relevant technologies, a qualitative assessment of the adequacy of current holdings, and recommendations for future action – typically about two pages of information per ECV.

The requirements were developed based on an assessment of user needs for a variety of climate applications and are set such that the datasets will have the maximum benefit for climate if they are met. The report does not address thresholds below which data would not be considered useful (minimum requirements), due to the difficulty of establishing such values for data to be used many years in the future and for unknown purposes. The report notes that the requirements were meant to act as the basis for discussion and must be kept under review by expert groups.²³

An added complication is introduced due to the fact that data from multiple sources, or data that has been reprocessed or calibrated, can sometimes meet more stringent requirements than the original instrument on its own. This is particularly relevant to requirements for temporal resolution (e.g. multiple satellites collecting the same type of data and operating as part of a constellation will have a shorter revisit time than one satellite on its own and will thus, as a group, be able to meet more stringent temporal resolution requirements) and stability (e.g. multiple satellites operating at the same time can be cross-calibrated, allowing greater stability over time), but can also apply to requirements for accuracy or

²¹ *Systematic Observation Requirements for Satellite-based Products for Climate*. Rep. no. GCOS-107. Global Climate Observation System, Sept. 2006. Web. Jan. 2014. <<http://www.wmo.int/pages/prog/gcos/Publications/gcos-107.pdf>>.

²² *Systematic Observation Requirements for Satellite-based Data Products for Climate, 2011 Update*. Rep. no. GCOS-154. Global Climate Observation System, Dec. 2011. Web. Jan. 2014. <<http://www.wmo.int/pages/prog/gcos/Publications/gcos-154.pdf>>.

²³ Ibid.

spatial resolution. Therefore, GCOS warns that the requirements for products provided in the report cannot be directly mapped to individual instruments.

2.2 WMO Rolling Requirements Review

The GCOS requirements provide one input to the WMO Rolling Requirements Review (RRR) process, which WMO uses to set priorities for the GOS.²⁴ The RRR process allows a variety of users with expertise in a particular application area to provide recommendations for requirements. These requirements are regularly reviewed by groups of experts within WMO programs. Like the GCOS requirements, the WMO's requirements address horizontal and vertical resolution, observing cycle, timeliness, and uncertainty (accuracy). However, unlike GCOS, RRR includes a minimum (or threshold) requirement below which data are not useful and a breakthrough requirement, which, if met, results in a significant improvement for the targeted application. The RRR equivalent of the GCOS requirement is the goal requirement, above which further improvements are not necessary. Observing requirements for space systems were added to the OSCAR system in September 2012, and are expected to be updated with additional information as part of the ongoing RRR process.²⁵ This also means that, unlike GCOS, requirements are available in a searchable, standardized format. However, they are not accompanied by explanatory material, as in the case of the GCOS report.

2.3 ESA Climate Change Initiative

The ESA Climate Change Initiative began in 2010 with the goal of developing standardized, high-quality satellite-based climate records to support 13 selected ECVs. One of the first steps in undertaking this task was to determine the requirements of climate scientists and other users for the satellite-based data for each ECV. This has resulted in the generation of a user requirement document for each variable, generally running 30 pages or more. This very detailed document includes information on the importance of the variable to climate, the users of the particular variable, analysis of existing requirements (including those developed by GCOS), and detailed analysis of the feedback collected via user surveys. In addition to providing goal and threshold-level spatial resolution, temporal resolution, and accuracy requirements for a variety of specific measurements and/or users, these documents also address issues such as data format, access, and priorities.²⁶

2.4 Technical Requirements Examples

Assessing the ability of current and future planned systems to meet the technical requirements identified by each of the efforts described above is complex. Though all three provide requirements relevant to the ECVs, they often break down the variable into different subsets of detailed measurements and provide

²⁴ Ibid.

²⁵ "Rolling Review of Requirements and Statements of Guidance." *WMO*. N.p., n.d. Web. 30 Jan. 2014. <<http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html>>.

²⁵ "RRR Database." *WMO*. N.p., n.d. Web. 30 Jan. 2014. <<http://www.wmo.int/pages/prog/www/OSY/RRR-DB.html>>.

²⁵ *Manual on the Global Observing System Volume I – Global Aspects*. Rep. no. WMO-No. 544. World Meteorological Organization, 2010. Web. 30 Jan. 2014. <http://library.wmo.int/pmb_ged/544_Vol_I_2010_en.pdf>.

²⁵ "WMO Observing Systems Capability Analysis and Review Tool (OSCAR)." *WMO*. N.p., n.d. Web. 30 Jan. 2014. <<http://www.wmo-sat.info/oscar/>>.

²⁶ "Climate Change Initiative." *ESA*. N.p., n.d. Web. 30 Jan. 2014. <<http://www.esa-cci.org/>>.

²⁶ Hollman, R., and C. J. Merchant. "The ESA Climate Change Initiative: Satellite Data Records for Essential Climate Variables." *Bulletin of the American Meteorological Society* 94.10 (2013): n. pag. Web. 30 Jan. 2014. <<http://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-11-00254.1>>.

requirements specific to a variety of different user groups. Further, as mentioned in the GCOS requirements document, direct comparison of individual systems to these requirements may not be practical, as reprocessing or combining multiple data sources may allow the creation of higher quality data records than one satellite on its own. This is particularly true for temporal resolution and stability requirements, which are directly affected by the number of satellites operating in a given period and their specific attributes. Furthermore, a prerequisite to carrying out the analysis involves determining which of the nearly one thousand Earth observation satellite instruments operating from 1990 to 2020 are relevant to the collection of each variable, a question on which current databases do not have full agreement.

Despite these challenges, the next section provides an analysis of the ability of current and future planned systems to meet technical requirements for measurements related to four ECVs: ice sheets, ocean color, precipitation, and ocean salinity. It demonstrates the complexities involved with identifying quantitative requirements through analysis of documents from each of the three programs. It then relies on the adjusted CEOS MIM Database and the WMO OSCAR database to identify relevant satellite instruments to carry out the analysis.

Ice Sheets

Data on the current state of, and changes in, ice sheets is important to the study of climate, because ice sheets contribute to sea level rise and changes in ocean circulation.²⁷ Ice sheets also play an important role in climate tipping points – large, abrupt changes – and are believed to have caused rapid sea level rise during past episodes of climate change.²⁸ Uncertainty regarding the contribution of ice sheets to sea level rise was an issue called out in the IPCC Fourth Assessment Report, and the inclusion of improved ice-sheet information was key to higher confidence levels in the Fifth Assessment Report.²⁹

The GCOS, WMO, and ESA programs have each examined the ice sheets variable, but they have broken it down into different sub-variables, each of which relies on different types of instruments. All three include ice sheet topography (also referred to as surface elevation change), and WMO includes two different sets of requirements for this variable.³⁰ GCOS and ESA also include requirements for ice velocity. Only GCOS includes the requirements for ice sheet mass change. ESA includes requirements for ice sheet grounding line location and calving front location – specific attributes of the glacier topology not included by GCOS or WMO.³¹

²⁷ Systematic Observation Requirements for Satellite-based Data Products for Climate, 2011 Update.

²⁸ Systematic Observation Requirements for Satellite-based Data Products for Climate, 2011 Update.

²⁹ "Uncertainties." *NASA Climate Change*. N.p., n.d. Web. 29 Apr. 2014. <<http://climate2.jpl.nasa.gov/uncertainties/>>.

²⁹ "Summary for Policymakers." *A Report of Working Group I of the Intergovernmental Panel on Climate Change*. Fifth Assessment Report. IPCC, n.d. Web. 30 Jan. 2014. <http://www.ipcc.ch/report/ar5/wg1/docs/WGIAR5_SPM_brochure_en.pdf>.

³⁰ Ibid.

³¹ *Ice Sheets (IS) Essential Climate Variable (ECV) User Requirements Document Version 1.5*. Rep. no. ST-DTU-ESA-ISCCI-URD-001. ESA Climate Change Initiative (CCI), 3 Aug. 2012. Web. 29 Apr. 2014. <http://esa-icesheets-cci.org/?q=webfm_send/19>.

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Ice Sheet Topography (Surface Elevation Change)			
	Horizontal Resolution	Temporal Resolution	Accuracy
GCOS	0.1 km	30 days	0.1 m/yr
	Climate and Cryosphere Project (WCRP) Goal: 0.1 km Breakthrough: 0.171 km Threshold: 0.5 km	Climate and Cryosphere Project (WCRP) Goal: 30 days Breakthrough: 43 days Threshold: 90 days	Climate and Cryosphere Project (WCRP) Goal: 0.05 m Breakthrough: 0.063 m Threshold: 0.1 m
	Terrestrial Observation Panel for Climate (GCOS) Goal: 0.01 km Breakthrough: 0.015 km Threshold: 0.05 km	Terrestrial Observation Panel for Climate (GCOS) Goal: 365 days Breakthrough: 2 years Threshold: 10 years	Terrestrial Observation Panel for Climate (GCOS) Goal: 0.1 m Breakthrough: 0.15 m Threshold: 0.2 m
WMO	Minimum: 1-5 km Optimum: <0.5 km	Minimum: annual Optimum: monthly	Minimum: 0.1-0.5 m/yr Optimum: <0.1 m/yr

Table 3: GCOS, WMO, and ESA have all developed requirements related to ice sheets, but they have broken the variable down into different components, and identified different values for the each type of measurement. Requirements related to ice sheet surface elevation change are shown here.

Looking at the requirements for surface elevation change only, it is clear that there is still a broad range in the requirements defined by each group. Minimum requirements for horizontal resolution range from ESA's 5-kilometer minimum to WMO's 10-meter goal – a two orders of magnitude difference. Similarly, the temporal resolution ranges from requiring updates of ice-sheet topography every ten years to having this update available each month. Accuracy requirements are in the same general range – on the order of 10 cm.³²

Determining the ability of existing assets to meet these requirements is a challenge due to the lack of agreement on relevant instruments across these programs. The WMO OSCAR Database does not list any instruments in its gap analysis for this variable; it is likely the analysis has not yet been completed.³³ The adjusted CEOS MIMS database lists four instruments as contributors to the ice sheet topography measurement – HRS, PRISM-2, ATLAS, and the VHR PAN/MS Camera.³⁴ However, the GCOS requirements document notes that Envisat's ASAR and Cryosat-2's SARAL could also contribute to the collection of this variable.³⁵ Most of these instruments are high-resolution visible imagers, synthetic aperture radars (SAR), or radar altimeters. It therefore seems likely that other instruments of this type, such as the high-resolution imagers found on the RapidEye constellation or the SAR instrument on the RADARSAT series of satellites, could also contribute to collection of this variable. The ESA CCI

³² "Requirements Defined for Ice Sheet Topography." *OSCAR (version 0.9.4.2)*. WMO, n.d. Web. 29 Apr. 2014. <<http://www.wmo-sat.info/oscar/variables/view/85>>.

³² Systematic Observation Requirements for Satellite-based Data Products for Climate, 2011 Update.

³² Ice Sheets Essential Climate Variable." *ESA CCI*. N.p., n.d. Web. 29 Apr. 2014. <<http://esa-icesheets-cci.org/>>.

³³ "Gap Analyses by Variable." *OSCAR (version 0.9.4.2)*. WMO, n.d. Web. 29 Apr. 2014. <<http://www.wmo-sat.info/oscar/gapanalyses?view=85>>.

³⁴ "Timelines - Measurement: Ice Sheet Topography." *MIMS Database*. CEOS, 2014. Web. 29 Apr. 2014. <<http://database.eohandbook.com/timeline/timeline.aspx>>.

³⁵ Systematic Observation Requirements for Satellite-based Data Products for Climate, 2011 Update.

project mentions that Landsat data may also be used, suggesting that even medium-resolution imagers may be able to contribute to collection of this variable.³⁶

Despite these challenges, five of the six instruments identified as relevant by CEOS and GCOS are capable of collecting data with resolutions of 10 meters or less – sufficient to meet even the most stringent resolution requirements. However, it is difficult to determine whether temporal resolution or accuracy requirements are met, as these depend not only on the orbits of the satellites, but also on the total number of satellites operating during a given period, the number of cloud-free images collected, and the effects of cross-calibration and reprocessing.

Past, Current, and Planned Future Instruments Contributing to Ice Sheet Topography					
Satellite	Instrument	Country	Launch Year	End of Life Year	Horizontal Resolution
SPOT-5	HRS (High Resolution Stereoscope)	France	2002	2014	Panchromatic: 10 m, Altitude: 15 m
Envisat	ASAR (Advanced synthetic aperture radar)	Europe	2002	2012	Image, wave and alternating polarisation modes: approx 30 x 30 m
					Wide swath mode: 150 x 150 m
Cryosat-2	SARAL (SAR Interferometer Radar Altimeter)	Europe	2010	2014	Range resolution 45 cm
					Along-track resolution 250 m
ALOS-3	PRISM-2 (Panchromatic Remote-sensing Instrument for Stereo Mapping-2)	Japan	2015	2020	0.8 m (nadir)
ICESat-II	ATLAS (Advanced Topographic Laser Altimeter System)	United States	2016	2019	66 m spots separated by 170 m
OPSIS	VHR PAN Camera and MS Camera (Very High Resolution Panchromatic Camera and Multi-Spectral Camera)	Italy	2017	2022	PAN = 0.5 m; MS = 2 m

Table 4: Selected satellite instruments that collect data relevant to the ice sheet topography ECV.

Ocean Color

Measurements of ocean color (the spectral distribution of water-leaving radiance) provide data on the concentration of chlorophyll-a – an indirect way of measuring the concentration of phytoplankton in the water. This is important, because phytoplankton play a key role in the global carbon cycle, removing an estimated 50 gigatons of carbon per year. They also play an important role in the ocean heat budget. However, because the light reflected by the ocean that reaches satellites has traveled through the atmosphere, inferring the ocean component of the signal is challenging. Small errors in the calibration of instruments or atmospheric corrections can create large errors in the inferred ocean signal.³⁷

While GCOS, WMO, and ESA all include chlorophyll concentrations as a key measurement related to ocean color, GCOS and ESA also identify a variety of additional variables. GCOS and ESA both note the importance of measuring water-leaving radiance. ESA also includes phytoplankton functional types, particle size distribution, and a variety of other measurements. WMO and ESA also both give multiple sets of requirements reflecting the needs of different user groups. The horizontal resolution requirements vary from a threshold of 100 kilometers identified by WMO forecasters and climate scientists to a goal of 100 meters from ESA scientists and modelers – three orders of magnitude difference. Temporal resolution requirements vary from 30 days to 1 day. Accuracy requirements not only vary widely (50%

³⁶ "Ice Sheets Essential Climate Variable." *ESA CCI*. N.p., n.d. Web. 29 Apr. 2014. <<http://esa-icesheets-cci.org/>>.

³⁷ Systematic Observation Requirements for Satellite-based Data Products for Climate, 2011 Update.

³⁷ *Ocean Colour Climate Change Initiative (OC_CCI) User Requirements Document (URD) Issue 1.11*. Rep. no. AO-1/6207/09/I-LG. ESA Climate Change Initiative (CCI), 29 June 2011. Web. 29 Apr. 2014. <http://www.esa-oceancolour-cci.org/?q=webfm_send/60>.

to less than 10% just within ESA requirements), but they are also given in different units by different programs (WMO provides accuracy requirements in terms of milligrams per cubic meter, rather than as a percentage).³⁸

Ocean Color (Ocean chlorophyll concentration)				
	Horizontal Resolution	Temporal Resolution	Accuracy	Stability
GCOS	30 km	Weekly averages	30%	3%
	Seasonal and Inter-Annual Forecasts (WMO) Goal: 25 km Breakthrough: 40 km Threshold: 100 km		Seasonal and Inter-Annual Forecasts (WMO) Goal: 0.05 mg/m ³ Breakthrough: 0.1 mg/m ³ Threshold: 0.2 mg/m ³	
WMO	Ocean Observation Panel for Climate (GCOS) Goal: 1 km Breakthrough: 5 km Threshold: 100 km	Goal: 1 day Breakthrough: 1.5 days Threshold: 3 days	Ocean Observation Panel for Climate (GCOS) Goal: 0.05 mg/m ³ Breakthrough: 0.1 mg/m ³ Threshold: 0.25 mg/m ³	NA
ESA	Modelers: Goal: 0.1-1 km Breakthrough: 1-10 km Threshold: 1-10 km EO Scientists Goal: 0.1-1 km Breakthrough: 0.1-1 km Threshold: 1-10 km	Goal: 1 day Breakthrough: 7 days Threshold: 30 days	Modelers: Goal: <10% Breakthrough: 10-25% Threshold: 10-25% EO Scientists Goal: <10% Breakthrough: 10-25% Threshold: 10-50%	Modelers: Goal: 1% Breakthrough: 1% Threshold: 10% EO Scientists Goal: 1% Breakthrough: 1-2% Threshold: 5%

Table 5: GCOS, WMO, and ESA have all developed requirements related to ocean chlorophyll concentration.

The adjusted CEOS MIMS Database lists 39 satellite instruments operating between 1990 and 2020 capable of contributing to the measurement of ocean chlorophyll concentration.³⁹ All of these instruments are capable of meeting WMO's threshold requirement of 100 kilometers spatial resolution. All but three of these are also capable of measurements at or below 1 kilometer, but only four have the capability to collect data at a resolution of 100 meters or less. Once again, temporal resolution, accuracy, and stability are difficult to determine without further analysis, though ESA does note that inter-calibration for this variable has been a challenge, and that no two identical ocean-color satellites have been launched into space.⁴⁰

³⁸ Systematic Observation Requirements for Satellite-based Data Products for Climate, 2011 Update.

³⁸ *Ocean Colour Climate Change Initiative (OC_CCI) User Requirements Document (URD) Issue 1.11*. Rep. no. AO-1/6207/09/I-LG. ESA Climate Change Initiative (CCI), 29 June 2011. Web. 29 Apr. 2014. <http://www.esa-oceancolour-cci.org/?q=webfm_send/60>.

³⁸ "Requirements Defined for Ocean Chlorophyll Concentration." *OSCAR (version 0.9.4.2)*. WMO, n.d. Web. 29 Apr. 2014. <<http://www.wmo-sat.info/oscar/variables/view/110>>.

³⁹ "Timelines - Measurement: Ocean Chlorophyll Concentration." *MIMS Database*. CEOS, 2014. Web. 29 Apr. 2014. <<http://database.eohandbook.com/timeline/timeline.aspx>>.

⁴⁰ *Ocean Colour Climate Change Initiative (OC_CCI) User Requirements Document (URD) Issue 1.11*. Rep. no. AO-1/6207/09/I-LG. ESA Climate Change Initiative (CCI), 29 June 2011. Web. 29 Apr. 2014. <http://www.esa-oceancolour-cci.org/?q=webfm_send/60>.

For this variable, the WMO has also conducted a gap analysis. Focusing on the period from 2010 to 2020, it identifies 30 satellites with the potential to contribute to ocean chlorophyll concentration measurement. As part of its gap analysis, WMO has also classified each instrument's degree of relevance on a scale of one (excellent) to five (marginal). Seven of the thirty instruments (23%) are identified as "excellent," one is ranked as "good," 14 are ranked as "fair," and the remaining 8 are either "significant" or "marginal." The seven potentially "excellent" satellites are sufficient to avoid gaps in data collection over the decade examined, though it is not clear whether there is sufficient overlap to produce the temporal resolution or stability desired.⁴¹

Precipitation

In its requirements document, GCOS suggests that precipitation (rainfall and snowfall) may be "the most important climate variable directly affecting mankind," and "one of the most critical data records for the climate modeling community."⁴² Measurements of precipitation can focus on the intensity, accumulation, or type. GCOS and WMO both provide requirements related to accumulation, while only WMO provides additional recommendations related to intensity. Neither provides requirements related to identifying precipitation type (referred to as hydrometer type by WMO). Precipitation is not one of the variables selected for inclusion in the ESA Climate Change Initiative, so ESA does not provide any guidance on requirements in this area.

Even among the requirements defined solely by GCOS and WMO, there is a fair amount of variation – requirements for horizontal resolution range from a threshold value of 500 kilometers for climate observations to a goal of 0.5 kilometers for numerical weather prediction. Similarly, temporal resolutions vary from monthly to every 6 hours, and accuracy ranges from 2 millimeters to 0.05 millimeters.⁴³

Precipitation				
	Horizontal Resolution	Temporal Resolution	Accuracy	Stability
GCOS	25 km	Monthly (resolving diurnal cycles and with statistics of 3 hourly values)	Max: 10% of daily totals; 0.1mm	5% of daily totals (regional scale)
	High Resolution Numerical Weather Prediction (WMO) Goal: 0.5 km Breakthrough: 2 km Threshold: 10 km	High Resolution Numerical Weather Prediction (WMO) Goal: 6 hours Breakthrough: 9 hours Threshold: 24 hours	Seasonal and Inter-Annual Forecasts (WMO) Goal: 0.05 mm Breakthrough: 2 mm Threshold: 5 mm	
	Atmospheric Observation Panel for Climate (GCOS) Goal: 100 km Breakthrough: 200 km Threshold: 500 km	Atmospheric Observation Panel for Climate (GCOS) Goal: 24 hours Breakthrough: 3 days Threshold: 12 days	Ocean Observation Panel for Climate (GCOS) Goal: 1 mm Breakthrough: 1.3 mm Threshold: 2 mm	
WMO				
ESA	Not Addressed			

⁴¹ "Gap Analyses by Variable: Ocean Chlorophyll Concentration." *OSCAR (version 0.9.4.2)*. WMO, n.d. Web. 29 Apr. 2014. <<http://www.wmo-sat.info/oscar/gapanalyses?view=110>>.

⁴² Systematic Observation Requirements for Satellite-based Data Products for Climate, 2011 Update.

⁴³ "Requirements Defined for Accumulated Precipitation (over 24h)." *OSCAR (version 0.9.4.2)*. WMO, n.d. Web. 29 Apr. 2014. <<http://www.wmo-sat.info/oscar/variables/view/1>>.

⁴³ Systematic Observation Requirements for Satellite-based Data Products for Climate, 2011 Update.

Table 6: Only GCOS and WMO have developed requirements related to precipitation.

The adjusted CEOS database identifies 11 satellite instruments operating between 1990 and 2020 that are capable of collecting data relevant to measurement of daily cumulative precipitation, many of which are hosted on operational geostationary weather satellites. All of these satellites are capable of meeting the 25 kilometers requirement provided by GCOS. Seven instruments are also capable of meeting the goal requirement of 0.5 kilometers identified by WMO as useful for numerical weather forecasting.⁴⁴

Past, Current, and Planned Future Instruments Contributing to Precipitation Measurement					
Satellite	Instrument	Lead Country	Launch Year	End of Life Year	Horizontal Resolution
ADEOS-II	AMSR (Advanced Microwave Scanning Radiometer)	Japan	2002	2003	5 - 50 km (dependent on frequency)
Aqua	AIRS (Atmospheric Infra-red Sounder)	United States	2002	2015	1.1 degree (13 x 13 km at nadir)
MTSAT-1R	JAMI (Japanese Advanced Meteorological Imager)	Japan	2005	2015	Visible: 1 km, TIR: 4 km
MTSAT-2	Imager	Japan	2006	2017	Visible: 1 km, TIR: 4 km
Himawari-8	AHI (Advanced Himawari Imager)	Japan	2014	2029	0.5 km in 0.64 μ m band; 1.0km in 0.46 μ m, 0.51 μ m and 0.86 μ m band, 2.0 km in all others
GOES-R	ABI (Advanced Baseline Imager)	United States	2015	2025	0.5 km in 0.64 μ m band; 2.0 km in long wave IR and in the 1.378 μ m band; 1.0 km in all others
Himawari-9	AHI (Advanced Himawari Imager)	Japan	2016	2031	0.5 km in 0.64 μ m band; 1.0km in 0.46 μ m, 0.51 μ m and 0.86 μ m band, 2.0 km in all others
GOES-S	ABI (Advanced Baseline Imager)	United States	2017	2028	0.5 km in 0.64 μ m band; 2.0 km in long wave IR and in the 1.378 μ m band; 1.0 km in all others
PCW-1	PCWMP (PCW Meteorological Payload)	Canada	2018	2028	Band dependent, varies from 0.5 km GSD (goal) for some of the VNIR bands to 2 km GSD for TIR bands.
PCW-2	PCWMP (PCW Meteorological Payload)	Canada	2018	2028	Band dependent, varies from 0.5 km GSD (goal) for some of the VNIR bands to 2 km GSD for TIR bands.
GOES-T	ABI (Advanced Baseline Imager)	United States	2019	2033	0.5 km in 0.64 μ m band; 2.0 km in long wave IR and in the 1.378 μ m band; 1.0 km in all others

Table 7: The CEOS MIM Database identifies 11 satellites that contribute to measurement of the daily cumulative precipitation index.

By contrast, WMO has identified 73 satellite instruments operating between 2010 and 2020 with the potential to provide information relevant to precipitation accumulation over 24 hours. However, according to the WMO OSCAR system, the relevance of these systems to the collection of the precipitation variable is generally very low. Only three of the 73 instruments are listed as providing an “excellent” or “good” level of relevance, a further eight are listed as “fair,” and the remaining 62 satellites (83%) provide only “significant” or “marginal” relevance.

According to the WMO analysis, the only currently operating instrument capable of providing “excellent” data for precipitation is the Dual-frequency Precipitation Radar on the Global Precipitation Measurement Mission (GPM). GPM’s precursor, Tropical Rainfall Measuring Mission carries the Precipitation Radar listed as a “good” source of data. The third instrument in this category is a Ku and

⁴⁴ "Timelines - Measurement: Precipitation Index (Daily Cumulative)." *MIMS Database*. CEOS, 2014. Web. 29 Apr. 2014. <<http://database.eohandbook.com/timeline/timeline.aspx>>.

Ka band Precipitation Radar on the Chinese FY-3 weather satellite, expected to launch in 2019.⁴⁵ Again, while these three satellites should make it possible to avoid gaps in data collection, without an assessment of geographic and temporal coverage, it is not clear whether they allow for adequate monitoring of this variable.

Sea Surface Salinity

Sea surface salinity affects the density and stability of the surface water of the oceans, and thus is important to understanding ocean circulations. It also contributes to climate models and has the potential to improve estimates of precipitation over the ocean. GCOS and WMO both provide requirements related to this variable, with WMO providing a set of requirements identified by each of eight different user groups. Sea surface salinity was not included as one of the ESA Climate Change Initiative variables, so no requirements are available from that program. Again, requirements vary widely, from a threshold requirement of 500 kilometers identified by WMO for climate uses to a goal of 1 kilometers identified by WMO for ocean applications. Temporal resolution requirements vary from 30 days to 3 days.

Sea Surface Salinity			
	Horizontal Resolution	Temporal Resolution	Accuracy
GCOS	100 km	Weekly	0.05 psu
	Ocean Applications (WMO) Goal: 1 km Breakthrough: 5 km Threshold: 10 km	Ocean Applications (WMO) Goal: 3 days Breakthrough: 12 days Threshold: 24 days	Ocean Applications (WMO) Goal: 0.05 psu Breakthrough: 0.07 psu Threshold: 0.1 psu
	Ocean Observation Panel for Climate (GCOS) Goal: 100 km Breakthrough: 170 km Threshold: 500 km	Ocean Observation Panel for Climate (GCOS) Goal: 7 days Breakthrough: 11 days Threshold: 30 days	Ocean Observation Panel for Climate (GCOS) Goal: 0.05 psu Breakthrough: 0.1 psu Threshold: 0.3 psu
WMO			
ESA	Not Addressed		

Table 8: GCOS and WMO both provide requirements related to sea surface salinity

The adjusted CEOS database only lists three satellite instruments operating between 1990 and 2020 capable of contributing to the measurement of this variable. WMO has also carried out a gap analysis, listing only three satellite instruments, as well. However, it includes the Soil Moisture Active-Passive (SMAP) satellite, which is not in the CEOS database, and omits the Sentinel-5 satellite, which is present in the CEOS list. All of these satellites are capable of meeting the 100 kilometers spatial resolution requirement identified by GCOS. Only one, the Sentinel-5 multispectral imager, is capable of meeting the most stringent requirement of 1 kilometer, though the resolution of this instrument is only notional at

⁴⁵ "Gap Analyses by Variable: Accumulated Precipitation (over 24 h)." *OSCAR (version 0.9.4.2)*. WMO, n.d. Web. 29 Apr. 2014. <<http://www.wmo-sat.info/oscar/gapanalyses?view=1>>.

this time.⁴⁶ In its gap analysis, WMO identifies the other three instruments as providing just a “fair” level of relevance for sea surface salinity.⁴⁷

Past, Current, and Planned Future Instruments Contributing to Sea Surface Salinity Measurement					
Satellite	Instrument	Lead Country	Launch Year	End of Life Year	Horizontal Resolution
SMOS	MIRAS (Microwave Imaging Radiometer using Aperture Synthesis)	Europe	2009	2014	33 - 50 km depending on the position in the swath - resampled to 15 km grid
SAC-D/Aquarius	Aquarius L-Band radiometer	Argentina	2011	2017	100 km
SMAP	SMAP (Soil Moisture Active-Passive)	United States	2014	2017	Radiometer: 40 km; SAR: 30 km (unprocessed, real aperture), 1-3 km
Sentinel-5	METImage (Multispectral imager)	Europe	2019	2026	250 - 500 m (TBD by EUMETSAT Post-EPS MRD)

Table 9: Satellites capable of providing data relevant to sea surface salinity.

2.5 Evaluation of Progress on Technical Requirements

What specific technical requirements must each of these measurements meet to be useful for observation of climate change? To what extent do current and future planned satellites meet these requirements?

There has been collaboration and awareness among the three major international efforts to identify technical requirements for climate-relevant measurements made by satellites. The high-level variables examined in each of these efforts are largely the same, primarily centering on the GCOS ECVs, but there is still significant variation in the relevant detailed measurements, user groups, and resulting technical requirements. The progress by these groups has been impressive, but examples discussed above demonstrate that there remains a lack of international consensus on the technical requirements for each variable.

This may be due in part to the higher level of complexity inherent in providing more specific guidance. Different user groups may legitimately differ on technical requirements for their work. The choice of a specific cut-off, or even of multiple levels of requirements (basic, threshold, goal, etc.) are matters of expert opinion and may never gain full consensus. Despite these challenges, better harmonization of efforts is needed to define the technical requirements of an adequate global satellite climate monitoring system.

Given the range of technical requirements for each variable, summarizing the ability of existing and planned systems to meet these requirements is challenging. As seen in the examples above, adequacy can vary significantly from variable to variable. In general, the least stringent requirements seem to be met – which is perhaps not surprising, since the satellites were presumably built with specifications that make them relevant to at least some user groups. Significantly fewer of the existing and planned systems are able to meet the more stringent goal requirements, suggesting that additional improvements would be beneficial, though these benefits are difficult to quantify.

An important, and somewhat surprising, finding from the analysis above is that CEOS and WMO often provide different assessments of which satellite instruments have the potential to contribute to a given

⁴⁶ "Timelines - Measurement: Ocean Salinity." *MIMS Database*. CEOS, 2014. Web. 29 Apr. 2014. <<http://database.eohandbook.com/timeline/timeline.aspx>>.

⁴⁷ "Gap Analyses by Variable: Sea surface salinity." *OSCAR (version 0.9.4.2)*. WMO, n.d. Web. 29 Apr. 2014. <<http://www.wmo-sat.info/oscar/gapanalyses?view=133>>.

variable, regardless of the adequacy with which they can do so. Further efforts are needed to examine the reason for these differences and better align future efforts. It will be impossible to identify technical shortcomings in data collection if there is not agreement on which instruments should even be included in the analysis.

3.0 International Earth Observation Satellite Data Sharing

Section 1 outlined efforts to identify high-level variables and more specific types of measurements that are needed to adequately monitoring climate. Section 2 demonstrated that developing an adequate climate monitoring system must also take into account the technical requirements for data quality on each of those variables, raising the bar for achieving adequate global monitoring. However, even if the appropriate measurements, meeting all technical requirements, were collected, their impact on global efforts to understand and address climate change would still be limited if they are not accessible to users. Therefore, Section 3 examines the issue of data sharing.

Satellite data sharing policies are typically developed on the domestic agency level, so that one nation may have greatly varying policies across its satellite assets. Also, within each agency, data sharing policies often identify different sharing procedures for specific satellite instruments. As agencies adapt to changing political circumstances, technical capabilities, and experience, data sharing policies change as well. Over the past thirty years, there have been broad international trends towards more free and open data sharing. The United States has led in this area, with NASA adopting a free and open data sharing policy in the 1990s, and the NOAA and USGS following suit in the mid-to-late 2000s. In recent years, Europe has also been opening up more of its data for free and open access, though some data, particularly high-resolution imagery and SAR data, remains restricted to allow data sales. Japan, Russia, China, and other nations that make major contributions to satellite climate monitoring also generally have more restrictive policies. Previous research suggests that data from about 40% of the unclassified government instruments that operated between 2000 and 2012 are provided freely and without restrictions.⁴⁸

Free and open sharing of data helps to maximize its use, which in turn maximizes its value in terms of climate-relevant research and products. Even relatively minimal restrictions or costs can have a significant impact on data use. Limits on data redistribution or uncertainties caused by restrictive policies can hamper data integration and sharing among researchers, industry, and others in the climate community. For example, if data from a satellite with a restrictive data-access policy is integrated into a long-term climate data record to provide continuity or improve quality, this could limit the ability of researchers to broadly distribute that climate data record, significantly decreasing its usefulness. GEOSS and WMO have both been particularly active in promoting satellite data sharing.

3.1 GEOSS Data Sharing Principles

The Group on Earth Observations (GEO) has been active in addressing the issue of data sharing, officially adopting the GEOSS Data Sharing Principles in 2005. These principles call for “full and open exchange of data, metadata, and products,” and promote the provision of this data free of charge,

⁴⁸ Borowitz, Mariel. *International Cooperation in Climate Monitoring via Satellite: Incentives and Barriers to Data Sharing*. Rep. N.p., Sept. 2013. Web. 29 Apr. 2014. <http://www.cissm.umd.edu/papers/files/borowitz_policy_brief__92413.pdf>.

particularly to research and education users.⁴⁹ The GEOSS Data Sharing Working Group has begun efforts to identify data sets that meet these principles and to provide access to this data through its GEOSS Data Collection of Open Resources for Everyone (GEOSS Data-CORE) program.

3.2 WMO Resolution 40

The World Meteorological Organization has defined guidelines for its members with regard to data sharing. WMO Resolution 40 calls on members to “provide on a free and unrestricted basis essential data and products.” These essential data and products are those that are seen to be most relevant to the protection of life and property and are outlined in an annex to the resolution. The resolution also commits WMO to “broadening and enhancing the unrestricted international exchange of meteorological and related data and products.”⁵⁰ There have been suggestions by the WMO Global Framework on Climate Services that a similar resolution be developed for climate data.

3.3 Data Access Policy Examples

Unique data sharing policies are generally written by each satellite operating agency within a country. In many cases, these policies will distinguish different data sharing procedures on the level of individual instruments. Therefore, to understand the extent to which data is available to the international climate community, it is necessary to examine the effect of these policies on each individual instrument. This section carries out this analysis for two of the variables discussed above: ice sheet topography and ocean chlorophyll concentration.

Ice Sheet Topography

Data from three of the six instruments contributing to the measurement of ice sheet topography is available for free without any restrictions. However, data from the other three missions will likely be more difficult to access. Though France recently announced plans to make archived SPOT satellite data available to noncommercial users free of cost, this only applies to data that are more than five years old, so the SPOT-5 data being collected now will not be available to researchers for another five years. The policy also excludes SPOT-5 data with resolutions sharper than 10 meters, though this is sufficient to meet the ice sheet topography spatial resolution requirements as currently defined. However, even accessing the older, lower resolution data will involve some restrictions, since access is limited to non-commercial use. Ensuring compliance with these restrictions can complicate efforts at data sharing and integration within the research community, with questions and complications arising in a variety of situations. For example, it may not be clear whether data may be shared with a commercial organization if that group is using the data for research, rather than commercial, purposes. A further complication is that the data archive is being made available as raw data (level 0 processing). The French space agency has agreed to process the first 100,000 images requested, but after that, those requesting data will have to pay a nominal fee.⁵¹

Two of the relevant systems have not yet been launched, so inferring data access policies is more difficult. However, there is reason to believe that both systems will be subject to restrictions and

⁴⁹ "GEOSS." *Group on Earth Observations*. N.p., n.d. Web. 30 Jan. 2014. <https://www.earthobservations.org/geoss_dsp.shtml>.

⁵⁰ "Resolution 40 (Cg-XII)." *WMO*. N.p., n.d. Web. 30 Jan. 2014. <http://www.wmo.int/pages/about/Resolution40_en.html>.

⁵¹ De Selding, Peter B. "France To Make Older Spot Images Available to Researchers for Free." *Space News*. N.p., 23 Jan. 2014. Web. 30 Apr. 2014. <<http://www.spacenews.com/article/civil-space/39234france-to-make-older-spot-images-available-to-researchers-for-free>>.

potentially high costs. Japan's ALOS-3 system is a high-resolution optical imagery satellite. In August 2013, Japan announced a change to its satellite data sharing policy that would differentiate between data with low or medium resolution, which would be distributed under a "full and open" policy, and those with high resolution, which would be subject to additional restrictions, including limited release for research and market pricing for commercial users.⁵² Information on the data sharing policy for Italy's OPSIS satellite, which is not scheduled to launch until 2017, are not yet available. However, the OPSIS satellite is a very high-resolution imaging system being developed for military and civil applications. Italy's existing dual-use system, Cosmos-SkyMed, is subject to restrictions, including application requirements for research users and market pricing for commercial users.⁵³ As mentioned above, these types of restrictions, even though they are aimed primarily at commercial users, can greatly hinder research use of the data as well.

Ocean Chlorophyll Concentration

Looking at the satellites relevant to ocean chlorophyll concentration measurement, about half provide data freely without restrictions – primarily instruments on systems operated by the United States and Europe, as well as some Japanese research satellites and Chinese meteorological satellites. Access to data from Russian and Indian satellite instruments, and Chinese hydrological satellite instruments, is generally more restricted.

With 18 of the satellites yet to be launched, it is possible that data access policies will change. While broad trends have pointed towards increased data sharing, there is always a possibility this trend will be reversed. In June 2013, the European Commission agreed to provide free access to data collected by the Sentinel series of environmental satellites.⁵⁴ This series, which is currently under development, includes a number of satellites with the potential to contribute to the collection of the ECVs, including ocean chlorophyll concentration. However, the European Commission has indicated that the data access policy will be adjusted if it is seen to be forcing private-sector satellite operators out of business.⁵⁵

3.4 Evaluation of Progress on Data Sharing

What are the policies governing data access? To what extent is data collected from current and future planned satellites actually made available to the international community?

About 40% of the unclassified government instruments that operated between 2000 and 2012 are covered by free and open data share policies.⁵⁶ The examples discussed above demonstrate that data

⁵² Ishida, Chu. "JAXA's Data Policy for Earth Observation Satellites." *Group on Earth Observations*. N.p., 14 Jan. 2013. Web. 30 Apr. 2014. <http://www.earthobservations.org/documents/se/124_jaxa_eo_data_policy.pdf>.

⁵³ "FAQ." *COSMO-SkyMed*. N.p., n.d. Web. 30 Apr. 2014. <<http://www.cosmo-skymed.it/en/index.htm>>.

⁵⁴ De Selding, Peter B. "Taking a Cue from U.S. Landsat and GPS Programs, Europe Permits Free Access to Sentinel Earth Observation Data." *Space News*. N.p., 30 July 2013. Web. 30 Apr. 2014. <<http://www.spacenews.com/article/civil-space/39234taking-a-cue-from-us-landsat-and-gps-programs-europe-permits-free-access-to>>.

⁵⁵ De Selding, Peter B. "France To Make Older Spot Images Available to Researchers for Free." *Space News*. N.p., 23 Jan. 2014. Web. 30 Apr. 2014. <<http://www.spacenews.com/article/civil-space/39234france-to-make-older-spot-images-available-to-researchers-for-free>>.

⁵⁶ Borowitz, Mariel. *International Cooperation in Climate Monitoring via Satellite: Incentives and Barriers to Data Sharing*. Rep. N.p., Sept. 2013. Web. 29 Apr. 2014. <http://www.cissm.umd.edu/papers/files/borowitz_policy_brief__92413.pdf>.

access remains a significant challenge, despite international efforts to encourage data sharing and a trend towards increasingly open data policies. About half of the instruments providing data relevant to ice sheet topography and ocean chlorophyll concentration are subject to restrictions or costs for research use. Barriers to data access complicate the challenges of developing an adequate global climate monitoring system. Even if needed variables are defined, technical requirements agreed upon, and systems to collect this information are developed and launched, barriers to data access can result in gaps that undermine the adequacy of the system.

4.0 Defining and Developing an Adequate Climate Monitoring System: Recommendations

What actions would be required to define and develop an adequate satellite climate observation system, given the current and planned future, system?

The above sections have demonstrated that though significant progress has been made in identifying the requirements of a global climate monitoring system, there is still a lack of global consensus on a single, concrete definition of what is needed to adequately monitor climate change. This lack of consensus makes it difficult or impossible for nations to plan or prioritize investments in satellite technology to meet global climate-monitoring needs. The final section of this paper provides a number of recommended steps that should be taken to improve the prospects of defining and developing an adequate climate monitoring system.

4.1 Improve Coordination of International System Definition Efforts

The efforts currently being undertaken by GCOS, WMO, and CEOS to define high-level requirements for a global system should be more closely coordinated. It is useful that these organizations have addressed the challenge of defining an adequate system from different angles, but it is now time for those efforts to be integrated. Without such integration, nations will not know which guidelines to use to inform future investments, and international coordination will be much more difficult, leading to inadequate and inefficient monitoring.

GCOS has defined a list of essential climate variables, but without explicitly addressing how those variables could most efficiently be met by a constellation of physical systems, and how well each is addressed by current systems (in terms of both continuity over time and adequate global coverage), it will be difficult to make concrete steps towards a better system. WMO has defined an ideal physical architecture and has the benefit of using a holistic view that provides guidance on the most efficient way to collect all relevant data with the fewest number of systems (and hence the lowest possible investment). However, it has not verified that the system would be capable of adequately monitoring the ECVs, and thus is not able to leverage existing consensus within the climate community. The CEOS Virtual Constellations have provided a good framework for analyzing the ability of current systems to meet the needs of particular user groups, a step necessary to identify gaps in global coverage and data continuity, as well as concrete steps forward to address these issues. However, like the WMO effort, CEOS is not leveraging existing consensus around the ECVs.

These issues could be addressed by integrating the efforts of these groups. GCOS, in cooperation with CEOS, should carry out a virtual-constellation-like analysis for each of the 25 ECVs largely dependent on satellites. Through this process, they can clarify the extent to which existing and planned future systems contribute to each ECV (which must be broken down into detailed measurements). They should

then take the additional step of identifying gaps in global coverage and data continuity over time, and suggesting modifications to future plans that could help to address these issues.

The WMO should carry out an analysis to demonstrate the extent to which the Global Observing System Vision for 2025 would be capable of providing adequate coverage of the ECVs. If the system can be shown to provide adequate coverage, it can be used as a model of the most efficient global architecture. Further analysis could identify the steps that could be taken to modify future development plans to get closer to this ideal system.

In this way, the GCOS and WMO efforts would begin to address the issue of adequate global climate monitoring in a clear, cohesive way. GCOS would focus on a bottom-up approach: how well do current systems meet the ECVs, and what systems are needed to fill gaps? Meanwhile, WMO would take a top-down approach: what would the most efficient data collection system look like, and what modifications to the current system could bring us closer to this ideal? Through coordination, GCOS and WMO could then identify where their recommendations would overlap: what systems can be modified or added to eliminate gaps in the collection of ECVs and/or improve the efficiency of data collection?

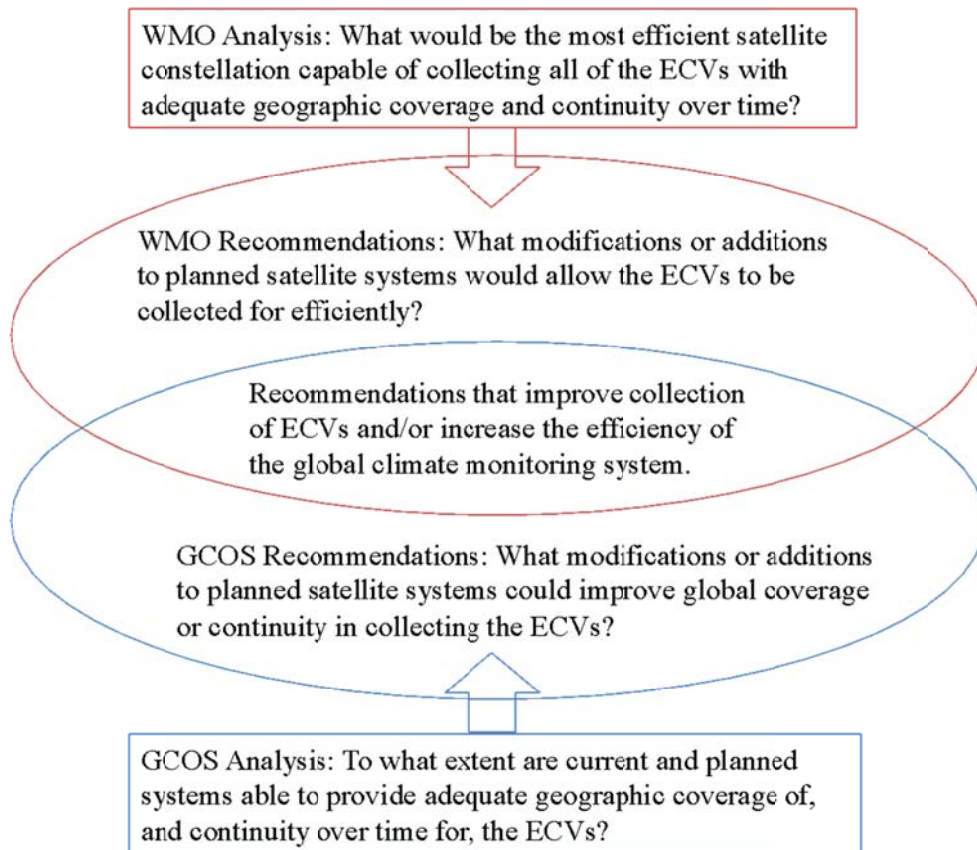


Figure 6: This diagram shows how the top-down WMO efforts and bottoms-up GCOS efforts could be coordinated to provide synergistic recommendations to improve global climate monitoring.

4.2 Combine International Technical Requirement Efforts

The efforts being undertaken by GCOS, WMO, and ESA regarding the definition of technical requirements already overlap to a significant degree – requirements developed as part of ESA’s Climate Change Initiative provided input to GCOS’s 2011 update of its requirements document and working groups within GCOS participate in the WMO Rolling Requirements Review. Because the variables that these groups are interested in are the same, the experts and user-groups relevant to these efforts overlap as well. Rather than continuing parallel requirement definition efforts, these groups should coordinate to develop one central repository for technical requirements. This should build on the ESA CCI methodology of close coordination with interest groups focused around each of the ECVs, and use the WMO RRR process and associated OSCAR database, which is continuously updated and maintained, to document and manage requirements. Supporting documentation related to user requirements development, such as the in-depth documents produced by the ESA CCI groups and the shorter analysis written up in the GCOS requirements document, should be referenced and made easily accessible as part of the WMO RRR.

Collecting all of these requirements in one central database will help to illuminate the breadth of user groups interested in each measurement. Comparison of the technical requirements of each of these groups will be simplified through the use of WMO’s standardized format comparing threshold, breakthrough, and goal requirements. Easy access to supporting documentation providing the reasoning behind the choice of technical requirements will promote better understanding among user groups and decision makers. The identification of user groups and easily comparable information will directly benefit the necessary next step: prioritization.

4.3 Prioritize Investments

Even with more than 30 nations involved in the development or operation of at least one Earth observation satellite, the cost and complexity of satellite systems means it is unlikely that all desired climate measurements can be taken with the desired technical attributes: it will be necessary to prioritize the requirements in the climate monitoring system. There is currently no prioritization among the 25 essential climate variables largely dependent on satellites, or the 150 specific measurement types needed to support them. Within each of these measurement types, there is little guidance on which technical requirements are most important – e.g. should spatial resolution be sacrificed to ensure better geographic coverage?

With so many important measurements, and so many diverse user groups interested in each of them, prioritization will likely be exceedingly difficult. However, through outreach to the climate science community and integration of expert assessment, GCOS, WMO, CEOS, and ESA have made important progress in identifying the relevant user groups for each variable and in outlining the efforts to which each of the variables contributes. A coordination procedure that works with these user groups, or examines the impact of each of the measurement on the identified uses, should make some prioritization possible.

As a first step, it may be useful to categorize measurements into general categories, such as high, medium, and low priority, to help to focus global investment and improve efficiency of the system. For example, as it works with climate data users, ESA’s Climate Change Initiative may be able to determine which data are most critical to various types of users. The data requirements that score highly across multiple user groups could be considered higher priority measurements overall.

WMO has already moved in the direction of prioritization with its definition of detailed requirements, and its identification of threshold, breakthrough, and goal requirements. Building on this type of information, it may be possible to make tradeoffs between, for example, having two satellites meeting a threshold requirement or just one that collects data at the goal level. Already, WMO has suggested that the breakthrough requirement may be the most cost-efficient option, rather than attempting to achieve the goal requirement in all cases.

GEOSS brings together a collection of Earth observation data users focused on non-climate related issues. It may be possible to leverage this connection to identify opportunities in which incremental improvements to systems designed for these other communities could allow them to meet the stringent requirements of the climate community. Many WMO members have already recognized this opportunity and some are adjusting weather satellite systems to make them more useful for climate purposes. Whichever international organization decides to take the lead, it will be important for all user groups to coordinate in a holistic analysis of these issues.

4.4 Shift Investments

As agreement on priority requirements starts to form and the ability to meet these requirements under current plans can be assessed, nations can begin to shift their investments towards the highest priority areas. In fact, these investments do not need to wait for a fully articulated, prioritized system to be evaluated. For example, even a rudimentary analysis shows that there is significant overlap in the number of land imaging satellites, but gaps in collection of some of the greenhouse gases. Shifting global resources from investment in redundant land imaging satellites to satellites designed to study atmospheric components may help to improve the global monitoring system without a significant change in the level of investment.

New entrants to the space field often begin their programs by procuring relatively simple, medium-resolution imaging satellites, likely because these systems are less expensive while still providing some value both in gaining technical expertise working with a satellite system and in data usefulness. Encouraging these nations or organizations to instead develop small satellites focused on an unmet need in the global system may be one method of improving efficiency. Such a policy would be much more feasible if the requirements of an adequate global climate monitoring system were well defined, providing clear guidance on these needs. International forums such as GEOSS and WMO could help coordinate efforts and provide encouragement to do so, perhaps through facilitating member partnerships, technology transfer programs, or explicit recognition of the importance of these contributions. In addition to the broad benefit to the global community, nations with relatively small space programs would likely experience greater prestige from these strategic contributions, as they would gain a place as a critical participant in international efforts. Officials from the Argentinian space agency have indicated that this rationale already plays a role in strategic planning for their Earth observation satellite program.⁵⁷

Similar reasoning may apply to non-state actors, particularly given the trend towards increasingly complex and capable small satellite systems. University programs wishing to give students hands-on

⁵⁷ Meeting attended by author, United Nations/ International Astronautical Federation Workshop on Space Technologies Applied to the Needs of Humanity, Naples, Italy, 28-30 September 2012.

experience building a small satellite may choose to increase the impact of their efforts by developing a sensor with the ability to contribute to a global need. Start-up companies that develop innovative systems to address gaps in the climate monitoring system that also have commercial applications may be able to sign on the government as a customer. It may not be practical for all, or even many, student projects or entrepreneurial efforts to make meaningful contributions to climate change. However, the better defined the priorities and gaps in the climate monitoring system are, the more likely it will be that actors large and small will take steps to try and fill them.

4.5 Increase Investment

Finally, in order to improve the global climate monitoring system, it will be necessary to increase global investment in satellite Earth observation systems. The GCOS Implementation Plan suggests that implementation of an adequate global observation system would be possible at an additional annual cost of \$2.5 billion above current investment levels, \$1 billion of which would be for developing additional satellite missions. However, these estimates are necessarily rough, and there are reasons to believe that this may be an underestimate, as satellite programs have a long history of going over budget. Even if this estimate is accurate, the increase in satellite investment would be significant. For NASA, the agency with the largest Earth observation satellite budget in the world, a \$1 billion supplement would require the Earth science budget increase by 70%.⁵⁸ For ESA, an additional \$1 billion would require nearly doubling the Earth observation budget, already the highest funded segment within ESA.⁵⁹

While more than 30 nations have been involved in satellite Earth observation activities, seven space agencies account for 80% or more of the instruments operating each year. Even if the \$1 billion investment were distributed among these nations, it would require permanent increases of 10% or more in their annual Earth observation budgets; a much more reasonable amount, though still not a simple task to achieve. The WMO Vision for the Global Observing System (GOS) in 2025 anticipated increasing involvement in satellite Earth observation activities. It is possible that additional participants in this effort will help to increase overall investment, though it seems unlikely that these nations, new to space activity, would significantly increase global investment levels. Overall, increased investment is likely to be necessary, but is unlikely to be the sole solution.

4.6 Increase Free and Open Data Sharing

One of the low-hanging fruit in improving the global climate monitoring system is to increase the amount of data that is freely shared. This can be done immediately in parallel with the other recommended steps discussed here. Making available data that has already been collected, or committing to providing data from planned future satellites for free, improves the global climate monitoring system without any need for international coordination or prioritization and without any change or increase in financial investments. Additional data can fill gaps where other satellite data is not available, or improve quality when integrated with data collected by other satellites. Commitments to provide data for free in the future can help to avoid redundant investments that might be planned if nations must collect the data on their own.

⁵⁸ United States. NASA. Earth Science. *NASA Earth Science Budget Estimates FY 2012*. N.p., 2011. Web. 30 Jan. 2014. <http://www.nasa.gov/pdf/516645main_NASAFY12_Budget_Estimates-Science_Earth-508.pdf>.

⁵⁹ "Funding." *European Space Agency*. N.p., n.d. Web. 30 Jan. 2014. <http://www.esa.int/About_Us/Welcome_to_ESA/Funding>.

GEO should continue to highlight the importance of data sharing and encourage nations to adopt free and open policies. WMO should take steps to formalize the practice of making essential climate data freely available among its members, just as it has done with essential weather data. These efforts have the potential to provide a rapid, significant increase in the amount of data available for global climate studies.

Conclusions

This paper has outlined the many ongoing efforts to define the needs of a global climate monitoring system, demonstrating that although there has been significant progress and laudable coordination among a number of organizations, this work is not complete. There is still a lack of global consensus on the concrete requirements for global climate monitoring, and nations and relevant international organizations should agree on a single set of requirements. The most promising start for this would be to coordinate the efforts of the GCOS, which already has widespread support and acceptance for its essential climate variables, and WMO, which is developing the Global Observing System to identify the ideal physical architecture. Efforts to develop detailed requirements for each of the essential climate variables should be consolidated, or at least fully coordinated, among these organizations as well.

A fully defined set of requirements will allow these organizations to agree on the gaps in the climate monitoring system, making recommendations more concrete, and action by individual nations more likely. Without a clear definition of what is required, it is nearly impossible to discuss tradeoffs among various items. Once there is agreement on where critical gaps in the system exist, it will also be easier for experts to assess the relative priority of filling these gaps, or to carry out tradeoffs among all parts of the system. It will be easier for nations or subnational actors to make the case for adopting free and open data sharing policies, prioritizing projects that fill key gaps, or increasing investments in Earth observation satellites if the need for such changes is well documented and agreed upon internationally. Development of even an adequate monitoring system is likely to be a complex and lengthy task, but it is an achievable one, and one that is essential to the ability to understand and address climate change.

About the Author

Mariel Borowitz is an assistant professor in the Sam Nunn School of International Affairs at Georgia Tech. Dr. Borowitz earned a PhD in Public Policy at the University of Maryland. Her research dealt with international cooperation in climate monitoring via satellite, focusing on the incentives for and barriers to data-sharing. Her research and teaching specializations include technology policy and space policy. Dr. Borowitz earned a Master's degree in International Science and Technology Policy from the George Washington University and a Bachelor of Science degree in Aerospace Engineering from the Massachusetts Institute of Technology. She has also worked as a research analyst at the Space Foundation in Washington, DC.

Acronyms

CEOS - Committee on Earth Observing Satellites

GCOS - Global Climate Observation System

ECV – Essential Climate Variable

ESA – European Space Agency

GEO - Group on Earth Observations

ICSU - International Council for Science

IOC - Intergovernmental Oceanographic Commission

IPCC - Intergovernmental Panel on Climate Change

JAXA – Japan Aerospace Exploration Agency

NASA – National Aeronautic and Space Administration

NOAA – National Oceanic and Atmospheric Administration

RRR - Rolling Requirements Review

UN – United Nations

UNEP – United Nations Environment Programme

UNESCO – United Nations Educational Scientific and Cultural Organization

UNFCCC - United Nations Framework Convention on Climate Change

USGS – United States Geological Survey

WMO - World Meteorological Organization