National Aeronautics and
Space Administration

Advancing NASA's **Climate Strategy**

2023

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Executive **Summary**

NASA's climate mission is to observe, understand, and address climate change through science, exploration and innovation for the benefit for all.

NASA uses the vantage point of space and its expertise in aeronautics to innovate, inform, and inspire for the benefit of all. NASA is a leader and trusted partner in providing climate and Earth system observations, modeling, research, applications, technology, and actionable information to scientists, decision-makers, and the public. NASA's free and open data powers research across the federal government, academia, and the private sector. The agency also works alongside international, federal, state, and local partners to advance understanding of and response to our changing planet.

NASA's climate portfolio is varied, extensive, and covers multiple missions and focus areas. To help assess and advance NASA's climate strategy, a Climate Strategy Working Group (CSWG) was created and now falls under the guidance of the Office of the Chief Scientist. The CSWG found:

- With more than two dozen satellites and instruments observing key climate indicators, NASA, in coordination with its domestic and international partners, remains the world's leading agency for observing and understanding changes to the Earth system;
- NASA has decades of experience developing technologies that contribute to reducing emissions and enhancing sustainability; and
- NASA delivers climate-related information and resources to a wide range of government and university partners as well as the public.

The breadth of NASA's climate efforts presents challenges in, and opportunities for, intra-agency coordination. In addition, there are many other governmental and non-governmental entities engaged in climate-related research and technology development that present partnering opportunities and a need to clearly articulate NASA's role. There is also a need to continue to improve the discoverability, accessibility, and usability of NASA's climate information and technology. Finally, climate is changing, which impacts research needs and our own operations (including mission safety and timely attainment of milestones).

To address these challenges and achieve our climate mission, the CSWG identified four major priorities and several needs within each priority. These priorities are to innovate, inform, inspire, and partner.

Priorities

Priority 1
INNOVATE

1.1. Advance climate and Earth science through novel observations, including the Earth System Observatory, associated research and modeling, and the creation of societally useful applications.
1.2. Advance the development and use of aeronautics and space technologies that enable us to understand, mitigate, and adapt to climate change.
1.3. Promote Earth-based applications of technologies developed for space exploration, space operations, and aviation for climate adaptation and mitigation.
1.4. Ensure sustainability of NASA centers and facilities, including reducing agency greenhouse gas (GHG) emissions and increasing resiliency to climate variability and change.

Priority 2
INFORM

2.1. Increase discoverability, accessibility, and usability of climate and Earth science information.
2.2. Support communities and stakeholders in preparing for and responding to climate change by enhancing information, tools, applications, and resources that draw on NASA observations, models, and people to improve societal resilience.
2.3. Address climate change impacts in underserved and vulnerable communities by promoting equity in the collection and use of climate and Earth science information.

Priority 3
INSPIRE

3.1. Help humanity understand and prepare for climate change by improving stakeholder and public awareness of and access to NASA climate discoveries, information, and technology.
3.2. Enhance and support climate literacy of the NASA workforce and those who work with NASA.
3.3. Inspire and educate the next generation of climate researchers and citizens.

Priority 4
PARTNER

4.1. Facilitate coordination and partnerships with other federal agencies, international entities, and state, local, and tribal governments to deliver actionable climate information to stakeholders, and ensure the broadest applicability of NASA climate information and technologies.
4.2. Expand ongoing successful partnerships and determine the appropriate role for NASA in collaborating with the growing number of commercial entities and non-profit organizations conducting climate observations, research, and applications.
4.3. Increase coordination and collaboration among NASA centers and mission directorates with respect to climate research and climate-related technology development.

The CSWG has sought to better understand the agency's current climate portfolio, articulate challenges, and identify opportunities to advance NASA's climate efforts. The result, "Advancing NASA's Climate Strategy," outlines priorities and needs that can enable the continuation and expansion of a legacy of robust contributions to understanding the Earth's changing climate, providing actionable information to those who need it, and innovating for the benefit of humanity.

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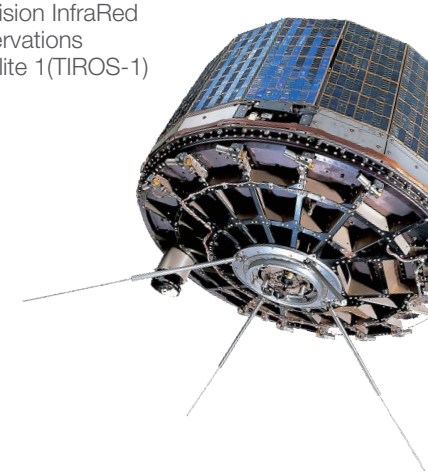
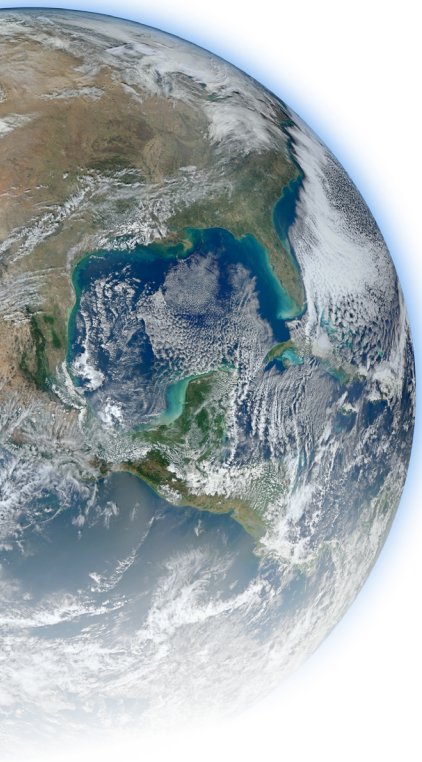
Background and Context

NASA

Background **and Context**



Television InfraRed Observations Satellite 1(TIROS-1)



Climate is changing. Earth's average surface temperature in 2022 was tied for the fifth warmest on record, with the nine most recent years being the warmest since modern record keeping began. Along with increases in temperature, there are other changes in the Earth system, including declines in Arctic sea ice, increases in sea level, and increases in extreme events. For example, the number of record high temperature events in the United States has been increasing since 1950; and the U.S. has also witnessed increasing numbers of intense rainfall events.

NASA is the U.S. space agency that provides end-to-end research about our home planet, including observations, models, decision support, and technology development. NASA has a long history of Earth observations and climate research, beginning with the Television InfraRed Observations Satellite (TIROS) in the 1960s. While NASA has traditionally focused on researching the Earth system, including changes in climate, its centers and facilities are also impacted by climate change.

By statute, NASA is the lead agency for civil aeronautics research and conducts aeronautics research and development to "increase the efficiency of the Nation's air transportation system" and "protect the environment" (51 U.S.C. § 40102). NASA has also been tasked with performing scientific research that can be productively studied from space, including "Earth Science research and research on the Sun-Earth connection through the development and operation of satellites and other means" (51 U.S.C. § 20301(a)(3)(B)). Specifically, NASA shall "pursue a program of Earth observations, research, and applications activities to better understand the Earth, how it supports life, and how human activities affect its ability to do so in the future" (51 U.S.C. § 60501). Additionally, the law acknowledges that "securing practical benefits for society will be an important measure of [the success of these programs] in addition to securing new knowledge about the Earth system and climate change." NASA is also tasked with ensuring that the climate-related data generated from its grant awards is made available to be shared among other researchers "to enhance and facilitate their availability and widest possible use to ensure public access to accurate and current data on global warming" (51 U.S.C. § 60506).

NASA

NASA is one of many U.S. Government Agencies that researches climate. There are several interagency coordination efforts related to climate change, including the National Climate Task Force and the U.S. Global Change Research Program (USGCRP). In addition, the National Space Council identified climate as a priority topic. There are also several climate-related Executive Orders (E.O.) that affect NASA, including:

EO14008: Tackling the Climate Crisis at Home and Abroad (January 27, 2021), which mandated the development of the Agency Climate Action Plan (CAP);

EO14057: Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability (December 8, 2021), which directs the federal government to reduce emissions from federal operations and invest in clean energy industries; and

EO13985: Advancing Racial Equity and Support for Underserved Communities Through the Federal Government (January 20, 2021), which led to the development of NASA's Equity Action Plan which includes an action on climate and Earth science information.

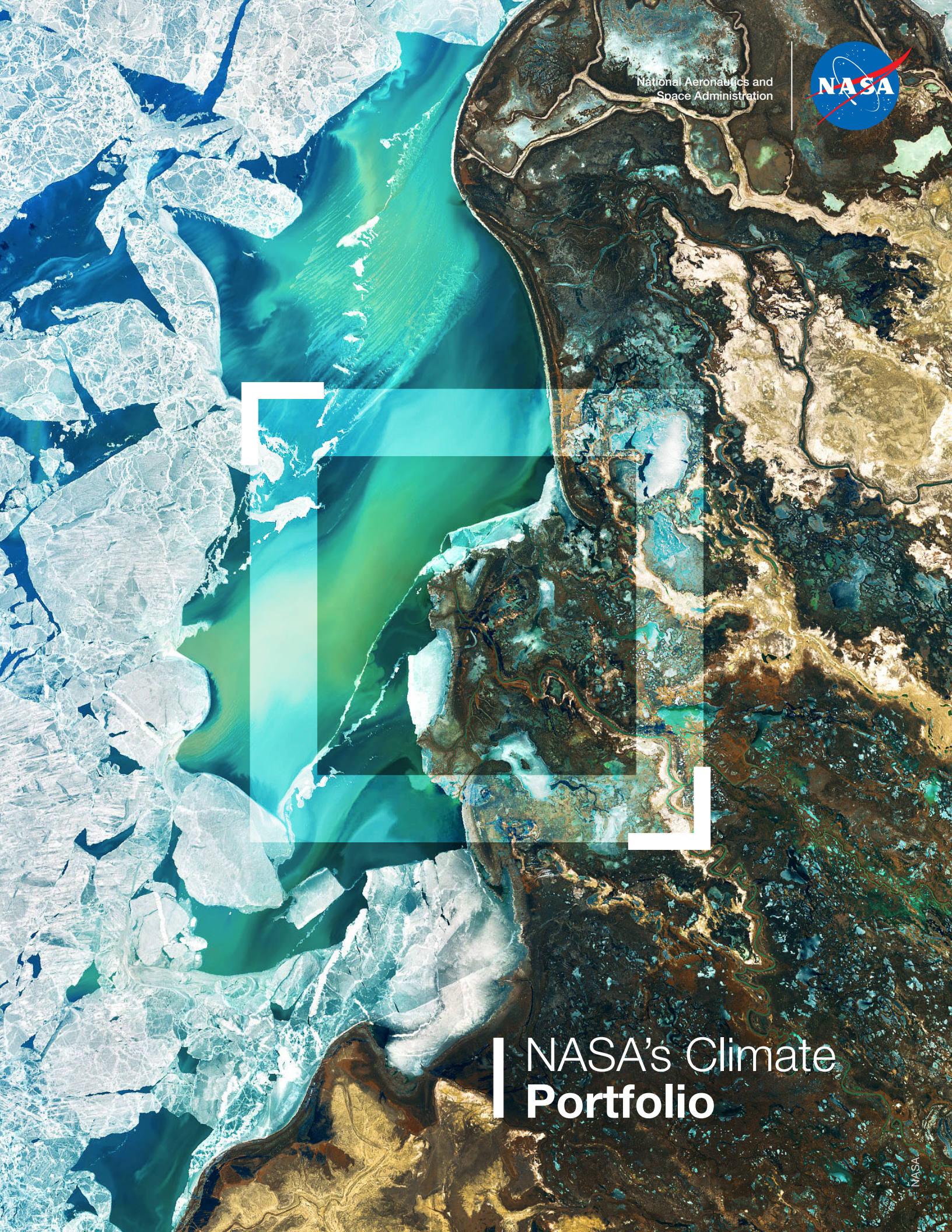
The CSWG was created under the leadership of the Senior Climate Advisor to help navigate the intra- and inter-agency climate landscape and develop a NASA-wide strategy for climate. The motivating questions that the CSWG is addressing in this report include:

- What is NASA's current portfolio in climate-related research?
- Where is NASA leading in climate change observations, research, and technology?
- Where are there opportunities to strengthen NASA's climate portfolio?
- What is NASA's role in climate-related research and technology development, relative to other federal agencies, international agencies, and other actors (e.g., non-profit organizations, private industry)?

This report is intended to help coordinate and advance NASA's climate efforts internally, as well as facilitate communication of NASA's portfolio externally.

Artemis I Flight Day 13: Orion, Earth and Moon

NASA



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NASA's Climate **Portfolio**

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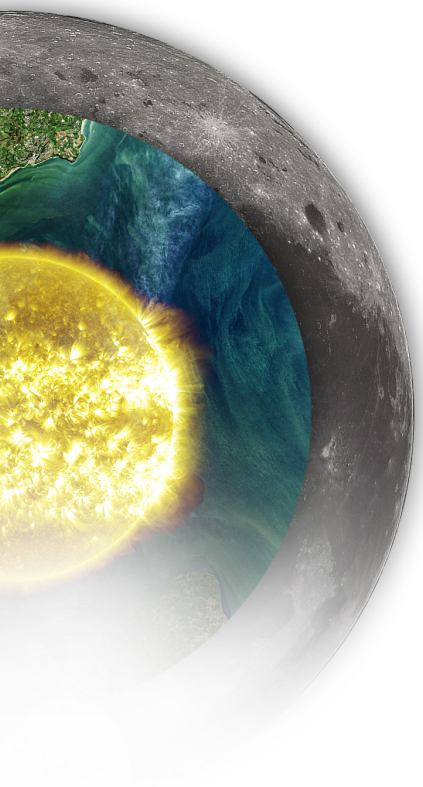
NASA's Climate **Portfolio**

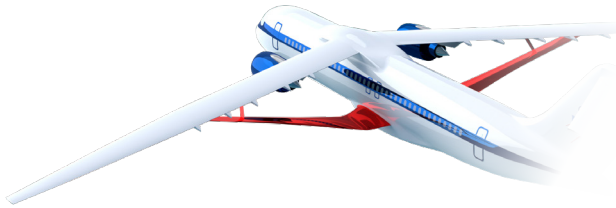


NASA's climate portfolio is varied, extensive, and covers multiple missions and focus areas. Research in climate processes and long-term trends is conducted mainly, but not exclusively, through the Science Mission Directorate (SMD) in the Earth Science Division (ESD). Broadly, the ESD implements the current and future Earth observing missions, including the mission science and applications teams, modeling and analysis, and technology development to maximize the science and applications potential. This encompasses the development of new Earth observing instruments, monitoring of long-term climate trends, observing the climate processes that are essential to understanding and predicting climate changes, supporting observation-led model development, supporting the use of these models and observations in applications, and provision of data to user communities. Additionally, through ESD's Commercial Smallsat Data Acquisition Program, NASA is leveraging commercial capabilities through the purchase of data from several commercial remote-sensing companies.

In the other SMD divisions, the Heliophysics Division (HPD) supports research into the impacts of the Sun on Earth's climate, while the Planetary Science Division (PSD) and Astrophysics Division (APD) investigate habitability on Earth throughout its 4.5 billion-year history through the Astrobiology Program. These divisions also study climate conditions on solar system bodies and newly characterized exoplanets (planets beyond the solar system), looking at signs of habitability and climate systems in general on distant worlds. This research often uses climate models that were initially developed for modern Earth conditions and expanded to encompass this increasingly broad range of environments.

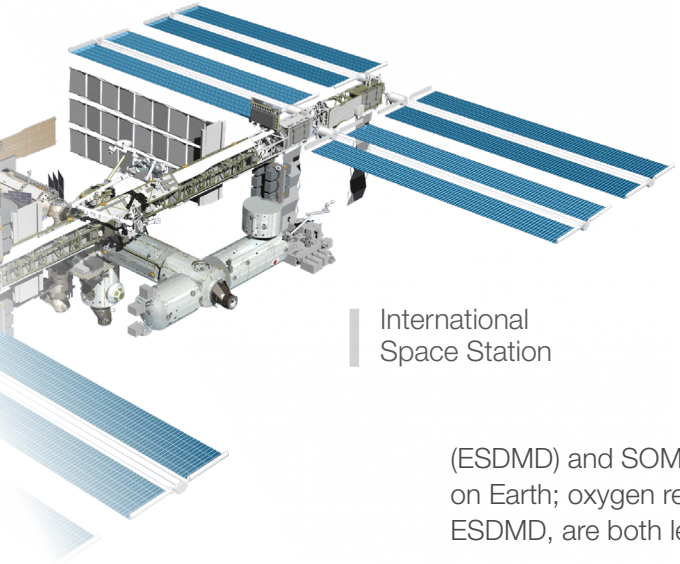
NASA's climate portfolio also encompasses research and technology development in aeronautics and space technology, focused on clean energy, environmental monitoring, and sustainable aviation. The Aeronautics Research Mission Directorate (ARMD) supports U.S. leadership in global aviation by advancing the state of the art to dramatically improve the efficiency of civil aircraft and engines and develop new operational concepts for aviation. This includes research and

An artist's concept of the transonic truss-braced wing aircraft configuration.



technology development for sustainable aviation through increasing fuel efficiency, reductions in other pollutants, aircraft operations research, and the development of new hybrid and fully electric powertrains for aircraft.[1]

The Space Technology Mission Directorate (STMD) seeks to transform NASA space missions and ensure American leadership in the space economy by rapidly developing, demonstrating, and transferring revolutionary, high-payoff space technologies driven by diverse ideas. Climate-relevant investments include technology development across the breadth of NASA's missions, including: clean energy creation (e.g., solar, small-scale nuclear, and bioenergy, higher efficiency battery and energy storage, cryogenic storage and transfer enabling a hydrogen economy); mitigation solutions (e.g., conversion of carbon dioxide to oxygen, carbon dioxide regulation technology in space environments); sensor and spacecraft platform development for improved Earth observations in situ and from space; software to improve modeling, simulation, assimilation; and decision support for prediction and climate mitigation, as well as increased aircraft efficiency and electric aircraft propulsion. In addition to conducting technology development projects with a diverse group of awardees from early stages to technology demonstrations, STMD also advances NASA's mission and enhances connections with the public through open innovation tools, and approaches, markets, and licenses NASA's patent portfolio to create commercial products to benefit the nation.



International Space Station

The International Space Station (ISS), under the purview of the Space Operations Mission Directorate (SOMD), has become a significant Earth observation platform, with numerous science instruments aboard. Many of the Earth observing instruments on the ISS are sponsored by SMD/ESD. Other Earth observation payloads have been developed by external partners (e.g., other U.S. Government Agencies, or international partners such as the Japanese Aerospace Exploration Agency, or JAXA) and sponsored by SOMD. The ISS also advances sustainability technology that benefits Earth, including water and air recycling, and food production. Water recycling technology, sponsored by the Exploration Systems Development Mission Directorate (ESDMD) and SOMD, has been used in rural and disaster relief applications on Earth; oxygen recovery and food production technology, sponsored by the ESDMD, are both leveraging from and contributing to terrestrial applications.

The Mission Support Directorate (MSD) and specifically the Office of Strategic Infrastructure (OSI) work to both assess the agency's carbon footprint, support center sustainability plans, and track the resilience of NASA infrastructure in the face of climate change.

1 See here for more details: https://www.nasa.gov/aeroresearch/nasa-aims-for-climate-friendly-aviation; https://www.nasa.gov/aeroresearch/nasa-plans-for-subsonic-flight-demonstrator; https://www.nasa.gov/aeroresearch/solicitations; https://sam.gov/opp/6c070678508b4897a48270073da7edfe/view

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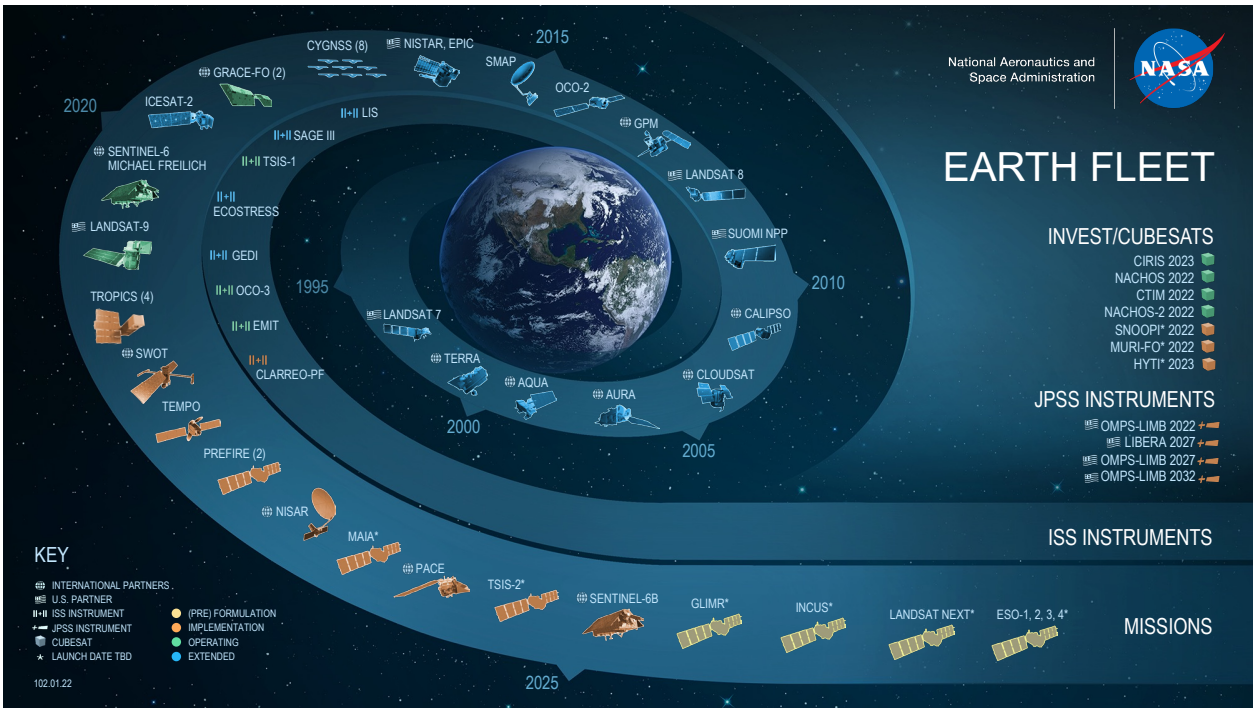


NASA's Earth Fleet is the global leader in surveying climate change and climate process from space

NASA's communications and outreach efforts are committed to informing, inspiring, and involving the public. Through media engagement, communication campaigns, press releases, web feature stories, video and audio storytelling, a robust web presence, social media and partnerships, NASA informs the public about climate-related research, applications, and technology, and engages people of all ages in learning about climate and the Earth system. NASA's Office of STEM Engagement (OSTEM) plays an important role in preparing a diverse workforce and bringing NASA climate-related knowledge to students, by engaging students in authentic learning experiences with NASA's people, content, and facilities, and attracting diverse groups of students to STEM. NASA mission directorates also support these objectives through individual and collaborative activities.

Additionally, NASA's federated organization through different field centers has allowed for independent development of climate-related expertise and connections to stakeholders across the country and internationally.

Status and Challenges

The inventory of current activities reveals an impressive array of efforts across the agency, demonstrating how NASA is paving the way on many aspects of climate-related research and applications (see box above). To support this strategy, the CSWG assessed the status of NASA's climate portfolio and found:

- With more than two dozen satellites and instruments observing key climate indicators, and with the upcoming Earth System Observatory (ESO), NASA, in coordination with its domestic and international partners, remains the world's leading agency for observing and understanding changes to the Earth system;

- NASA has decades of experience developing technologies that contribute to reducing emissions and enhancing sustainability; and
- NASA delivers climate-related information and resources to a wide range of government and university partners as well as the public.

In assessing the efficacy and impact of the agency's current activities, the CSWG identified several challenges that this strategy aims to address:

- Climate change involves or touches almost the entire agency, including every mission directorate. Agency activities go beyond climate research to significant investment in climate-related technology in aeronautics, clean energy, environmental monitoring, and applications. Furthermore, the agency has key infrastructure at risk from climate change and has begun to consider GHG emissions and climate in its planning and sustainability processes. This breadth presents challenges in, and opportunities for, intra-agency coordination;
- There are many other governmental and non-governmental actors engaged in climate-related research and technology development that present partnering opportunities and a need to clearly articulate NASA's role in climate;
- There is a need to continue to improve the discoverability, accessibility, and usability of NASA's climate information and technology; and
- Climate is changing, which impacts research needs and NASA's operations (including mission safety and timely attainment of milestones).

Selected Highlights of the Breadth and Quality of NASA's Climate Portfolio

NASA's climate portfolio is varied, extensive, and covers multiple missions and focus areas. This box highlights a small set of examples for six different focus areas.

Sea level rise and coastal impacts

Observations: NASA has several satellites and field campaigns focused on ocean, ice, and sea level rise. For example, NASA, together with NOAA, the European Space Agency (ESA), the French Space Agency (CNES), and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), have measured sea level rise for ~30 years using a series of satellite altimeters. Additionally, the GRACE and GRACE-FO missions, a partnership with the German Aeospace Center (DLR) and the German Research Center for Geosciences (GFZ) have provided powerful evidence for ice sheet and glacier loss. The Oceans Melting Greenland field campaign helped scientists understand the role of ocean warming in ice sheet loss.

Research, Analysis, and Applications: The Sea Level Change Portal provides for sea level information based on satellite observations, climate models, and projected scenarios of future sea level change, including the latest Intergovernmental Panel on Climate Change (IPCC) report, National Climate Assessment, and high-tide flood estimates (https://sealevel.nasa.gov).

Implementation: NASA periodically performs shoreline restoration and beach renourishment efforts at Wallops Flight Facility and Kennedy Space Center.

Selected Highlights of the Breadth and Quality of NASA's Climate Portfolio *(continued)*

Health and Air Quality

Observations: The Dutch-Finnish Ozone Monitoring Instrument (OMI) on the Aura satellite is one of a number of space-based instruments that measure ozone and air pollutants from space.

Research, Analysis, and Applications: The Earth Observing Dashboard, developed by NASA, JAXA, and ESA, provides information on air quality globally (https://eodashboard.org/).

Wildfires

Observations: NASA has several satellites and instruments in orbit that provide information on wildfires, including active fires, burn perimeters, and fuel for fire. For example, the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument provides information on active fires.

Research, Analysis, and Applications: The Fire Information for Resource Management System (FIRMS) provides near real-time information on active fires (https://firms.modaps.eosdis.nasa.gov/).

Technology and Innovation: The Scalable Traffic Management for Emergency Response Operations (STEReO) tests the use of NASA technology, like Unmanned Aircraft Systems, in responding to wildfires and other emergencies.

Greenhouse Gases

Observations: NASA has satellites (e.g., Orbiting Carbon Observatory (OCO)-2), instruments on the ISS (e.g., OCO-3), and field campaigns (e.g., Arctic-Boreal Vulnerability Experiment or ABoVE) that provide information on GHGs and the carbon cycle.

Research, Analysis, and Applications: The Carbon Monitoring System is a portfolio of projects that develop capabilities to support stakeholder needs for monitoring, reporting, and verification of carbon stocks and fluxes (https://carbon.nasa.gov/).

Technology and Innovation: The CO_2 Conversion Challenge is a competition that sought to create a carbon dioxide-based manufacturing system that can be used in space and on Earth. It took place in two phases and awarded $750,000 in prize money.

Selected Highlights of the Breadth and Quality of NASA's Climate Portfolio *(continued)*

Energy and Power for Efficient Communities

Research, Analysis, and Applications: NASA POWER provides solar and meteorological data sets from NASA research for support of renewable energy, building energy efficiency and agricultural needs (https://power.larc.nasa.gov).

Technology and Innovation: The Sustainable National Flight Partnership (SNFP) will demonstrate the first-ever high-power hybrid-electric propulsion on a large transport aircraft, ultra-high efficiency long and slender aircraft wings, new large-scale manufacturing techniques of composite materials, and advanced engine technologies based on breakthrough NASA innovation.

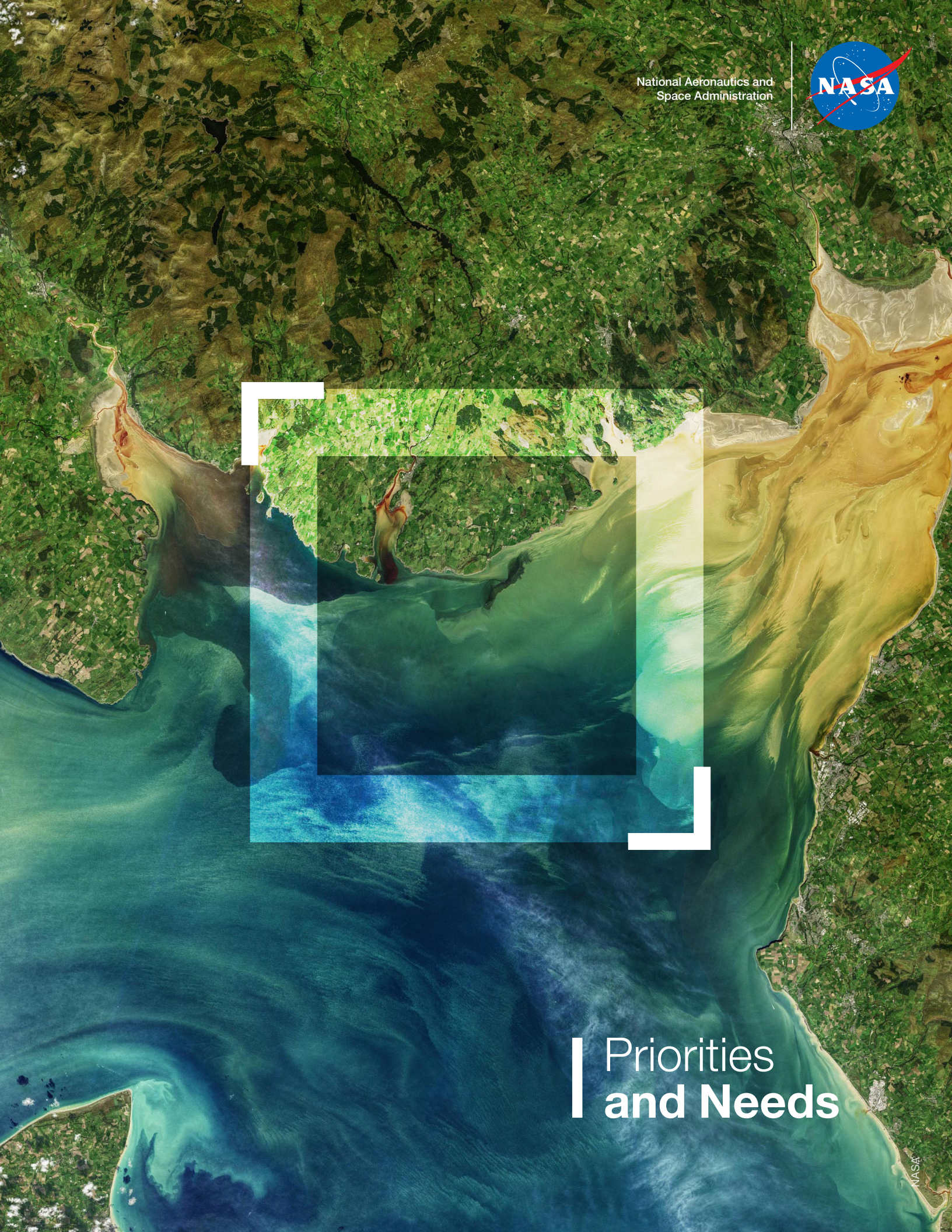
Agriculture

Observations: NASA has several satellites and instruments in orbit that provide information about agriculture and land use. For example, the NASA-U.S. Geological Survey (USGS) Landsat program has provided 50 years of continuous observations of land use and land cover, including crops and agriculture.

Research, Analysis, and Applications: NASA Harvest is a consortium of actors, including public, private, and universities, focused on using satellite information for agricultural applications.

Technology and Innovation: The Vegetable Production System (Veggie) is a plant growth unit on the ISS, which helps NASA study plant growth in microgravity to support the crew's food consumption. Research into growing crops on ISS has led to improvements in LED lighting and fertilizers used on Earth.

In addition to studying individual areas, NASA also studies the Earth as a system, including the development and use of two Earth system models. NASA's Goddard Institute for Space Studies' ModelE is NASA's key modeling contribution to domestic and international assessment efforts, including the IPCC 6th Assessment Report and the upcoming 5th National Climate Assessment. The Goddard Earth Observing System Model (GEOS) represents dynamical, physical, chemical, and biological processes across a wide range of space and time scales.



National Aeronautics and
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Priorities and Needs

Priorities **and Needs**

To address these challenges and achieve the agency's climate mission, the CSWG identified four major priorities and several needs within each priority. These priorities are to innovate, inform, inspire, and partner.

NASA's Climate Mission and Description

Mission: To observe, understand, and address climate change through science, exploration, and innovation for the benefit of all.

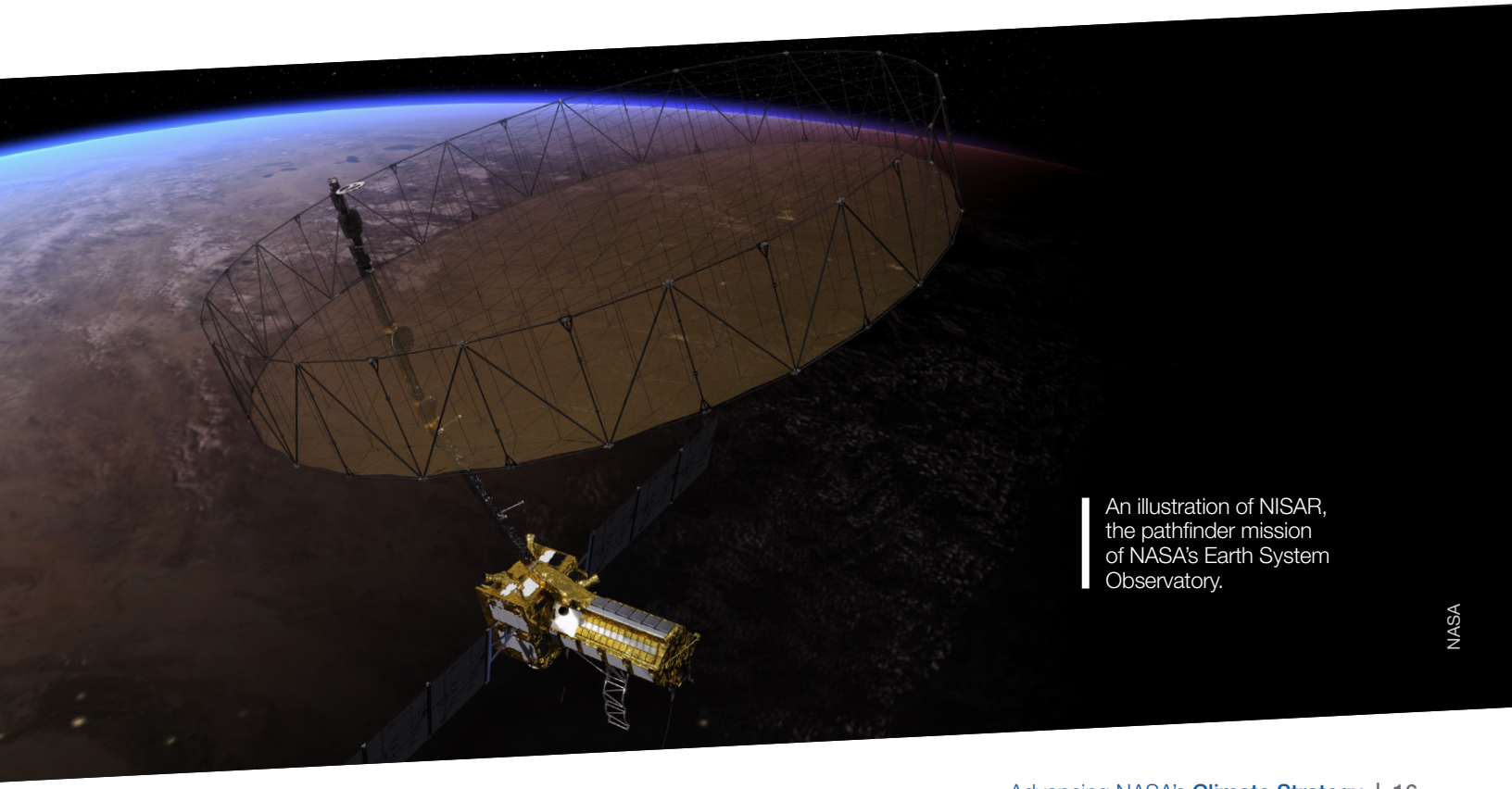
Description: NASA uses the vantage point of space and its expertise in aeronautics to innovate, inform, and inspire for the benefit of all. NASA is a leader and trusted partner in providing climate and Earth system observations, research, applications, technology, and actionable information to scientists, decision-makers, and the public. NASA's free and open data powers research across the federal government, academia, and the private sector. The agency also works alongside international, federal, state, tribal and local partners to advance understanding of and response to our changing planet.

Priority 1
INNOVATE

1.1: Advance climate and Earth science through the initiation of novel observations, including the Earth System Observatory, associated research and modeling, and the creation of societally useful applications.
NASA is a world leader in observing and understanding the Earth system. NASA's existing satellite and instrument fleet provides measurements of changes in vegetation, carbon dioxide, Earth's energy budget, clouds and precipitation, the mass of ice sheets, oceans, and much more that are integral to our current understanding of the Earth's climate. NASA integrates these observations into scientific discovery and models to provide a more complete picture of the Earth system and its changes. NASA's observations, models, and research are global in scope and integrate both human-induced and naturally-occurring changes to the Earth system. NASA's contributions to Earth observations and modeling have fundamentally improved our understanding of climate and the Earth system.

There are still many questions and uncertainties remaining that require new and innovative observations to answer. Some of these questions have been identified in the National Academies Earth Science Decadal Survey, while others emerge from broader initiatives and scientific efforts. To help address these questions and continue the agency's leadership in observing and understanding the Earth system, there is a need to continue to provide innovative observations, applications, and associated modeling. As part of that effort, NASA will be developing and launching the ESO. The ESO suite of satellites will be designed to complement each other, working in tandem to create a three-dimensional, holistic view of Earth. In addition, there is a need to consider new technology, architectures, and partnerships for climate-relevant missions to spur new science and applications capabilities that increase societal value.

While most of the Earth observation and modeling efforts reside in NASA's ESD, there are many opportunities for cross-NASA engagement and innovation. Technologies and sensors developed for other missions could help improve our ability to observe the Earth, just like the sensors used in the James Webb Space Telescope (JWST) informed development of the sensors used in the OCO missions. Improving our understanding and modeling of other planets, whether in our solar system or beyond, could improve our understanding and modeling of Earth. To help spur innovation in Earth observation and modeling, there is a need to facilitate engagement between ESD, other parts of SMD, and STMD (see also 4.3). In the post-ISS era, commercial low-Earth orbit (LEO) destinations could have the capability to host Earth observing instruments. The Commercial LEO Development Program under SOMD is working with SMD/ESD and HPD to identify and integrate their future needs for these next generation platforms. Continued collaboration between SMD and SOMD is needed to ensure a smooth transition post-ISS.



An illustration of NISAR, the pathfinder mission of NASA's Earth System Observatory.

NASA

1.2: Advance the development and use of aeronautics and space technologies that enable us to understand, mitigate, and adapt to climate change.
NASA has a long history of advancing the state of the art in several technology areas critical to U.S. leadership in aviation, science, and exploration. NASA's current climate and clean energy technology investments are spread across multiple mission directorates, in several technology focus areas, including:

- GHG emissions mitigation and reduction;
- Clean energy (production, distribution, conversion, management, storage, transmission, etc.);
- Sustainable aviation;
- New observation paradigms, technologies for observation platforms, and instruments for climate relevant science; and
- New approaches for application, fusion, and integration of relevant data and technologies.

The X-57 project is the agency's first all-experimental electric aircraft, and an early part of NASA's work to develop sustainable aviation solutions.

NASA's approach to technology development for climate-related challenges must be strategic to focus on the most critical challenges, leverage limited resources to have the greatest impact, and avoid duplication. There is a need to increase coordination and cross-directorate efforts to address climate technology investments (see also 4.3). The mission directorates could incorporate climate and clean energy priorities into the agency's strategic technology (STAR) framework to prioritize technology gaps and future investments. There is a need to use the full set of tools at its disposal to develop technology, including, but not limited to, leveraging Small Business Innovation Research/Small Business Technology Transfer programs to engage small businesses and entrepreneurs, using grants to support early-stage research at universities, and public challenges and prize competitions to engage innovators across the globe.

Cross-directorate coordination should prioritize the transition and infusion of new and innovative technologies with clear pathways for new technology inclusion in flight hardware and missions. This is particularly relevant as new technologies and architectures can spur new capabilities in science and application value including, for example, visualization and decision support. For example, the FireSense working group leverages a coordinated approach across multiple directorates to address wildland fire challenges.

NASA also recognizes that in some technology areas the innovation is happening outside the walls of government, such as in small businesses and venture-backed companies. Capabilities in artificial intelligence, machine learning, robotics, and autonomy are advancing quickly in response to market demands. There is also a need to engage with the entrepreneurial community, and the funders that support them (see also 4.2), that are developing solutions with an eye towards sustainable commercial space and aeronautics markets. Advancing a culture that embraces risk and experimentation, advancing technology not only for new capabilities but also for national advantage, is paramount to NASA's ability to support the space economy and combat the climate crisis.

NASA

Astronaut Serena Auñón-Chancellor harvests red Russian kale and dragoon lettuce from Veggie on Nov. 28, 2018, just in time for Thanksgiving. The crew got to enjoy a mid-afternoon snack with balsamic vinegar, and Auñón-Chancellor reported the lettuce was "delicious!"

1.3: Promote Earth-based applications of technologies developed for space exploration, space operations, and aviation for climate adaptation and climate mitigation.

NASA has developed and improved numerous technologies that could have applications on Earth for reducing emissions, increasing energy efficiency, and enhancing sustainability. For example, to support astronauts living on the ISS and in research for space exploration missions, NASA has developed and improved several technologies that have applications on Earth, such as water processing, oxygen recovery from carbon dioxide, and crop and other food production technologies. The ISS National Lab is also sponsoring initiatives in partnership with commercial companies, with a goal of advancing sustainability research, such as addressing the problem of plastic waste and enabling scientific and technological advances that improve Earth's environment. NASA's investments are also resulting in technologies that have sustainability impacts in space and on Earth, including sustainable food production and clean power and propulsion, such as solar.

NASA has a long history of promoting the transfer of NASA-developed technologies into non-NASA applications for public benefit, including for climate and sustainability. Spinoffs include sustainable farming methods that increase crop yield with fewer resources, clean energy production, and tools or technologies that provide risk assessment models or other capabilities to address flooding and other climate-related natural disasters. There is a need to continue to promote Earth applications of technologies developed for exploration by identifying and protecting NASA's intellectual property and marketing and licensing NASA's patent portfolio to create commercial products to benefit the nation. There is also a need to continue to promote startup company formation to leverage NASA's technology investments, making NASA-developed software available to industry, entrepreneurs, academia, and the public.

1.4: Ensure sustainability of NASA centers and facilities, including reducing agency GHG emissions and increasing resiliency to climate variability and change.

Climate change will have significant impacts on NASA's ability to fulfill its mission. NASA has made it mandatory to integrate climate considerations into the agency's policies, strategies, master plans, and partner engagements. At the same time, NASA, like all businesses and agencies, is a source of GHG emissions. Recognizing both the importance of proactively addressing climate change and risks to mission due to climate change, and in compliance with E.O. 14008, NASA prepared a Climate Action Plan to provide NASA's vision for adapting to climate change effects on its mission, facilities, infrastructure, natural lands, and other assets, now and in the future. NASA also has an ongoing effort, the Climate Adaptation Science Investigators (CASI) working group, that provides updated climate science and information for use in planning and risk analysis at NASA centers. NASA has also tracked agency GHG emissions since 2008 and has seen a consistent downward trend in emissions.

ESA/Alexander Gers

While NASA has incorporated climate considerations into agency planning and reduced agency emissions over time, continued work is needed to address continued climate change. Thus, there is a need to ensure the sustainability of its missions, centers, and facilities. There is also a need to periodically review existing efforts to integrate climate adaptation risks and mitigation planning into NASA risk management and budget development processes to ensure they reflect the latest knowledge on climate change. There is also a need to identify and implement specific actions to further reduce the agency's carbon footprint, in line with E.O. 14057.

NASA facilities are managed by OSI. However, the information and tools developed by ESD can be used to support this analysis. Existing projects, like CASI, can help facilitate the exchange of scientific and infrastructure information to improve the resilience of NASA centers.

Priority 2
INFORM

2.1: Increase discoverability, accessibility, and usability of climate and Earth science information through newly developing information delivery technologies.

Through the NASA Distributed Active Archive Centers (DAACs), the NASA Earth Science Data Systems Program, and the NASA Applied Sciences Program, NASA has demonstrated international leadership in providing free public access to climate and Earth science information. NASA has continued to innovate in the use of open data services and cloud-based data archives and processing systems. NASA has made important progress in using tools to catalogue and organize Earth science datasets to improve discoverability and accessibility for the Earth science community.

Earth observation satellite Landsat 9

While NASA's climate and Earth science information is publicly available, there are still barriers to its use and a need to increase discoverability, accessibility, and usability of this information. Recent advances in cloud computing, powerful browser-based visualization tools, and the growing adoption of a common open data service specification (OpenAPI) provide opportunities to increase broad access to NASA climate and Earth science information, following Findability, Accessibility, Interoperability, and Reuse (FAIR) data access principles. However, further work is needed to organize this information into coherent, actionable information products for specific climate change planning and response activities for diverse user and stakeholder communities. In addition, these efforts, in coordination with other federal agencies, need to consider the importance of ensuring the long-term continuity and reliability of information products and data services that support climate change planning and response.

A further challenge is that many potential users do not have access to sufficient computing resources to process and use the large volumes of data generated by NASA missions. NASA has been moving data into the cloud to facilitate its use by a broad user community and has identified climate data accessibility as a priority in its recent Equity Action Plan, with plans to move more data into the cloud

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(see also 2.3). There is a need to manage climate and Earth science datasets using both cloud-based and dedicated compute infrastructure. As more users incorporate NASA information into their planning and response efforts, there is a need to ensure users understand how to use the information provided by NASA, including considerations related to data accuracy and uncertainty. Additional trainings, enhanced metadata, and continued development of measures and standards for data accuracy and uncertainty could help address challenges with data accessibility and usability.

2.2: Support communities and stakeholders in preparing for and responding to climate change by enhancing information, tools, applications, and resources that draw on NASA observations, models, and people to improve societal resilience.

NASA has supported the use of climate insights from Earth science to benefit the economy, health, quality of life, and environment. These activities include project and program-level collaborations with local, state, and tribal governmental and non-governmental organizations to develop and demonstrate the use of Earth observation data for climate-related decision making. NASA also supports efforts to enhance the capacity of these organizations to use Earth observation data. Internationally, NASA makes important contributions to national climate change information repositories and visualization tools developed for the public. Activities such as the NASA-U.S. Agency for International Development (USAID) SERVIR program have also established a pathway for increasing use of NASA data by international partners to improve capacity to respond to natural disasters and manage natural resources in the face of climate change. Various NASA activities, such as the NASA Sea Level Projection Tool, the NASA FIRMS, and OpenET, demonstrate how NASA data can be integrated into both long-term climate change planning and short-term response to the emerging impacts of climate change, such as intensifying wildfire events, increasing drought severity and duration, and declines in streamflow. NASA capabilities such as the NASA Advanced Supercomputing Division and NASA Earth Exchange, based at Ames Research Center, and the

Participants of NASA's Student Airborne Science Activation inaugural class and some of their mentors pose in front of NASA's P-3 aircraft, which they used to collect Earth science data needed for their research studies.

TEMPO, a UV-visible spectrometer instrument will be the first ever space-based instrument to monitor air pollutants hourly across the North American continent during daytime

NASA Global Change Data Center, based at Goddard Space Flight Center, have also made important contributions to the production and distribution of key climate change datasets that are broadly used in climate response planning.

Building upon these examples of success, there are important opportunities to broaden both the types of NASA observational and modeled datasets that can be used to prepare for and respond to climate change, as well as the diversity of ways that people and communities can access and use this information. Nearly all upcoming Earth observing satellite missions enable key opportunities to provide new information to support climate response planning. The 2018 National Academies' Decadal Survey for Earth Science and Applications from Space highlights the importance of utilizing data from these satellite missions to both support advances in scientific understanding and to improve our collective ability to respond to climate change. There is a need to continue to enhance information, tools, applications, and resources that support efforts by communities and stakeholders in preparing for and responding to climate change. Such efforts could include providing climate change data and information, as well as efforts to engage communities in co-developing resources. The newly announced Earth Information Center provides an opportunity to do both.

2.3: Address climate change impacts in underserved and vulnerable communities by promoting equity in the collection and use of climate and Earth science information.

NASA's climate data is used by many researchers and stakeholders. However, for historical and cultural reasons, many communities and organizations have not had equitable and sufficient resources to fully leverage NASA capabilities. In addition, using NASA data and tools can require large computing resources and significant technical knowledge, which can present challenges for many people and communities. NASA's existing efforts on transforming to open science aim to ensure tools and resources are open and accessible. In addition, NASA's Equity Action Plan includes an effort to move some Earth science data to the cloud and provide trainings in Spanish language to improve equity and accessibility of Earth science information.

While NASA has initiated efforts to advance equity and accessibility of climate and Earth science information, there are still barriers to its use. There is a need to promote equity and environmental justice in the collection and use of climate information. Such efforts could include:

- Developing information, resources, and tools to help under-resourced organizations evaluate their climate risks (see also 2.2);
- Increasing the accessibility of climate information provided (see also 2.1); and
- Partnering with organizations working in communities most impacted by climate change and identify ways in which NASA can contribute towards environmental and climate justice initiatives (see also 4.2).

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Priority 3
INSPIRE

3.1: Help humanity understand and prepare for climate change by improving stakeholder and public awareness of and access to NASA climate discoveries, information, and technology.

NASA has a broad portfolio of climate research and climate-related technology development. NASA's brand provides a powerful pull for other agencies to partner with NASA on these projects to capture the imagination of the public and seek their involvement. Yet, many are not aware of or have incomplete knowledge of NASA's climate activities. NASA's Global Climate Change website, climate.nasa.gov, is the top-rated website in the world for users searching for "climate change." However, thus far, it has focused predominantly on NASA's Earth science research. Information on climate-related technology development at NASA is sprinkled throughout other NASA websites and does not have a consolidated home online.

While many are aware of a few aspects of NASA's climate portfolio, few are aware of the breadth of the Earth and climate-related research and technology development at NASA. To help researchers and the public understand and address climate change, there is a need to improve stakeholder and public awareness of the full extent of the agency's climate portfolio. Communication products should be designed to engage a broad audience through different media and platforms (e.g., print, social media, podcasts, videos, etc.), with messages designed to showcase NASA's full climate portfolio. In addition, developing a single website for all of NASA's climate-related activities, encompassing the agency's entire climate portfolio, could help facilitate these efforts.

While the Office of Communications leads all communications efforts for NASA, much of the work is accomplished through mission directorate and center communication strategies and teams. There is opportunity to improve coordination among these organizations to ensure a consistent and impactful voice and messaging strategy.

3.2: Enhance and support climate literacy of the NASA workforce and those who work with NASA.

Climate variability and climate change impact all NASA centers and therefore NASA's ability to fulfill its mission. Recent Executive Orders related to climate (e.g., E.O. 14008 and E.O. 14057) provide direction to NASA with respect to the agency's climate actions. NASA's climate portfolio will involve a broad swath of the agency's workforce beyond traditional climate scientists, including those in mission support organizations, technical mission directorates, and centers. Many of those involved in these activities have limited training in or awareness of climate change, or of the extent of the agency's climate activities.

There is a need to enhance and support climate literacy within the agency's workforce. Such climate literacy efforts would provide resources for NASA employees to learn and understand climate change and how it impacts NASA's mission, the vulnerability of NASA centers and facilities, and what NASA is doing in response to climate change. A variety of means could be used to enhance and support climate literacy, including webinars, trainings, and surveys.

NASA's SpaceX Crew-2 NASA astronaut Megan McArthur speaks to students during a visit to Arlington Science Focus Elementary School, Friday, June 10, 2022, in Arlington, Virginia.

There are several existing efforts within NASA to provide education and training materials related to climate, including resources for K-12 students and educators (e.g., the Global Learning and Observations to Benefit the Environment (GLOBE) program), training material on NASA's Earth Science data and applications (e.g., the Applied Remote SEnsing Training Program, or ARSET), and projects connecting climate scientists to mission support organizations who need climate information (e.g., CASI). In addition, climate literacy efforts are also being pursued by other federal agencies as part of their climate action plans. NASA's climate literacy efforts could bring together information and insights from ESD, OSTEM, and other federal agencies (where appropriate).

3.3: Inspire and educate the next generation of climate researchers and citizens.

NASA has a wide variety of activities designed to inspire and educate researchers and the public, including public prize competitions, challenges, crowdsourcing, and citizen science activities, many of which relate to climate. These activities are designed for all ages, and include resources for K-12 students and educators, research opportunities for high school, undergraduate, and graduate students, and science education activities for the public.

While existing efforts have had a broad reach, there remains a need to continue to inspire and educate the next generation of climate researchers and citizens, including across all demographic and socioeconomic groups. These efforts could include expanding STEM and public engagement products, and opportunities to learn about climate and NASA's portfolio; adding a climate focus to more agency-supported STEM programs; creating additional climate-related materials to be used by teachers/educators; and integrating STEM activities into major climate science and technology agency initiatives.

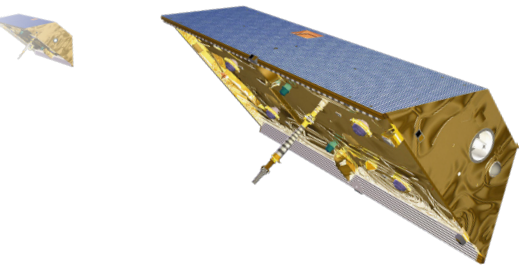
There are many different offices at NASA engaged in educating and inspiring the public with respect to climate, including OSTEM, ESD, SMD, STMD, and the Office of Communications.

Priority 4
PARTNER

4.1: Facilitate coordination and partnerships with other federal agencies, international entities, and state, local, and tribal governments to deliver actionable climate information to stakeholders, and ensure the broadest applicability of NASA climate information and technologies.

NASA is one of many federal agencies conducting climate-related research. NASA currently participates in a broad range of federal interagency working groups (e.g., USGCRP). These groups span a broad range of activities, including observations, climate research, and meteorological services, as well as specific topics, including the ocean, the Arctic, and resilience. NASA also works with other federal agencies in bilateral and multilateral efforts, including partnerships on satellite missions (e.g., with USGS for Landsat) and projects (e.g., with USAID on SERVIR).

NASA's observations and research are global in scope. NASA works with international partners, including participating in international working groups (e.g., the Committee on Earth Observation Satellites and the Group on Earth Observations), partnering on satellite missions (e.g., with DLR/GFZ on GRACE/GRACE-FO), and co-developing information dissemination portals (e.g., with JAXA and ESA on the Earth Observing Dashboard). NASA scientists also contribute to a variety of national and international assessments, including the IPCC and the National Climate Assessment. NASA also works with state, local, and tribal governments in understanding and responding to climate change.



GRACE Follow-On (GRACE-FO) measures Earth's surface mass and water changes

While there are many existing collaboration and coordination efforts, strategic sustained and enhanced collaboration is needed to ensure the broadest applicability and use of NASA climate information and technologies. NASA's climate research is complementary to the efforts at other agencies. Furthermore, each agency has its own set of stakeholders and user groups. Continued and enhanced coordination and collaboration with other agencies is needed to meet user needs, ensure a broader reach of all U.S. Government climate information, and provide sustained and innovative observations and information. Similarly, continued collaboration with international partners is needed to provide sustained and innovative observations and information. Since most NASA missions are not planned with successors, balancing the extended operations of NASA missions, planning for new missions that continue the records of current observables, and coordination with other federal agencies and international partners, are all needed to address continuity of data and information products. Finally, as climate changes, the needs of users and researchers for climate information and technology will also change. Such changes may necessitate evolving contributions to existing interagency and international efforts, or engagement with additional interagency and international activities to complement existing efforts.

NASA

4.2: Expand ongoing successful partnerships and determine the appropriate role for NASA in collaborating with the growing number of commercial entities and not-for-profits conducting climate observations, research, and applications.

There are an increasing number of commercial and not-for-profit entities engaging in Earth observations, climate research, and climate-related technology development. NASA has been introducing commercial small satellite capability into its programs through the purchase of data via the Commercial Smallsat Data Acquisition program. This program provides access to commercial satellite data for scientific use by NASA-funded researchers (and other federal partners in some instances). NASA also has collaborations with non-profits and commercial entities for climate research, including projects, partnerships, consortia, and Space Act agreements. For example, NASA Harvest is a consortium of actors, including public, private, and universities, focused on using satellite information for agricultural applications. For space technology and aviation, NASA is heavily invested in cost-sharing partnerships and collaborative research with U.S. industry to research and demonstrate technology advancements. For example, NASA worked with Electric Power Systems to design and develop the batteries for the X-57 experimental electric flight plane. Additionally, NASA's University Leadership Initiative supports universities pioneering next-generation technologies for a net-zero carbon emissions aviation future.

NASA's X-57 is an all-electric experimental aircraft designed to demonstrate multiple leading-edge technologies.

While NASA has several successful engagements with commercial and not-for-profit entities, there continue to be new entities and new products emerging. There is a need to expand ongoing successful partnerships and the community NASA engages with on climate. There is also a need to identify new opportunities for collaboration and consider when and how NASA engages with new entities.

The opportunities for partnership span many mission directorates and centers. For example, SMD runs the Commercial Smallsat Data Acquisition program and engages in research and application partnerships. ARMD works closely with industry on aviation research and technology demonstrations. STMD works closely with industry and academia on space technology research and technology demonstrations and the commercialization of those inventions through NASA's technology transfer program. To enhance the engagement with these commercial and not-for-profit entities, NASA could facilitate closer coordination among mission directorates (including mission support) and centers to explore these opportunities.

4.3: Increase coordination and collaboration among NASA centers and mission directorates with respect to climate research and climate-related technology development.

NASA's climate research and climate-related technology development spans the agency, with involvement from all mission directorates and centers. While there are many examples of cross-directorate and/or cross-center collaboration efforts on climate, the CSWG has also identified a need for greater integration across the agency's climate portfolio. Climate change itself involves almost every aspect of the atmosphere-ocean-land-cryosphere system, and human impacts upon it

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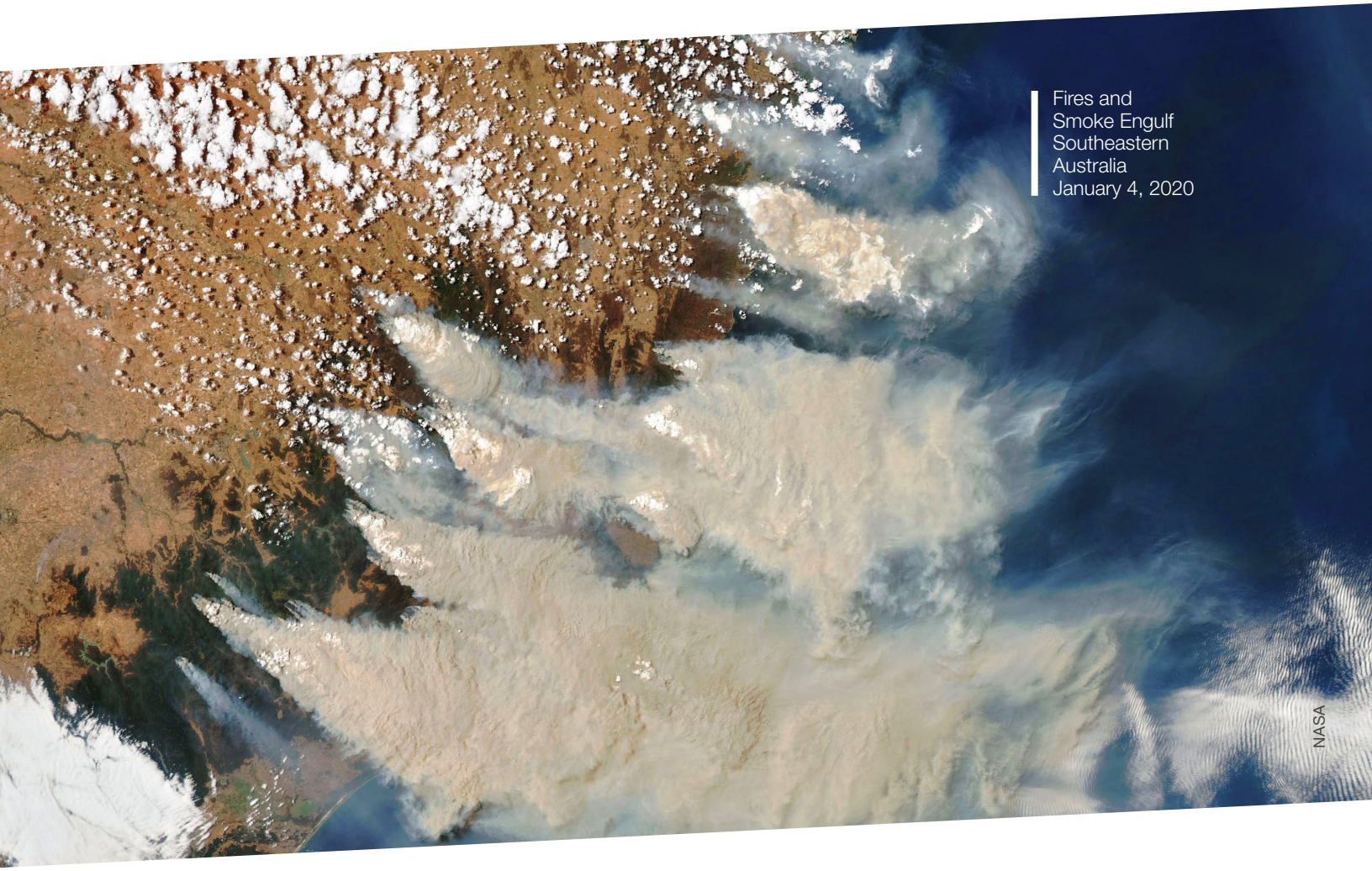
involve almost every aspect of global society (power generation, transportation, agriculture, industry, urban design, etc.). Therefore, research into monitoring and understanding that change, developing necessary technologies, and responding to climate change, will all be more impactful through greater integration and enhanced collaboration across the agency. To facilitate that integration and collaboration, NASA could consider organizing and facilitating periodic focused climate summits to share information about NASA's climate portfolio with others in the agency, identify opportunities for potential future collaborative activities, and identify opportunities for more targeted discussions on intra-agency collaborations on climate.

Since climate research and climate-related technology development are spread throughout the agency, there are many opportunities for collaborations between the mission directorates and centers. NASA could consider maintaining a small working group under the Office of the Chief Scientist and Senior Climate Advisor, bringing together representatives from all mission directorates and centers to discuss, inform, and advise on potential climate-related initiatives across the agency.



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Advancing NASA's **Climate Strategy**

NASA's CSWG has sought to better understand the agency's current climate portfolio, identify existing gaps, make connections, and present recommendations for consideration to enable the agency to become more effective in its approach to tackling the climate crisis. The result, "Advancing NASA's Climate Strategy," outlines priorities and needs that will enable the continuation and expansion of a legacy of robust contributions to understanding the Earth, its changing climate, and the impacts to our planet and those who live on it.

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NP-2023-03-3112-HQ