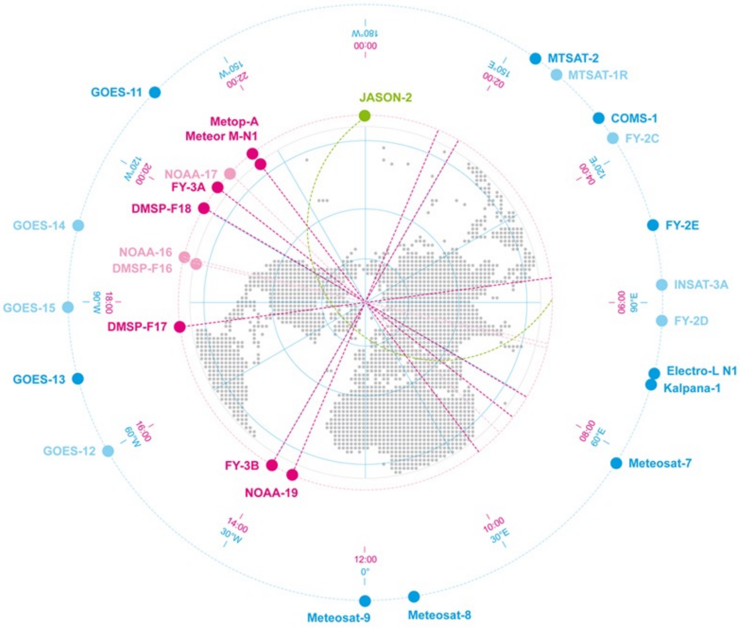


NASA Report on Current & Future Satellite Systems

Presented to CGMS-50 Plenary Session, Agency Interventions/Reports, Agenda Item 2

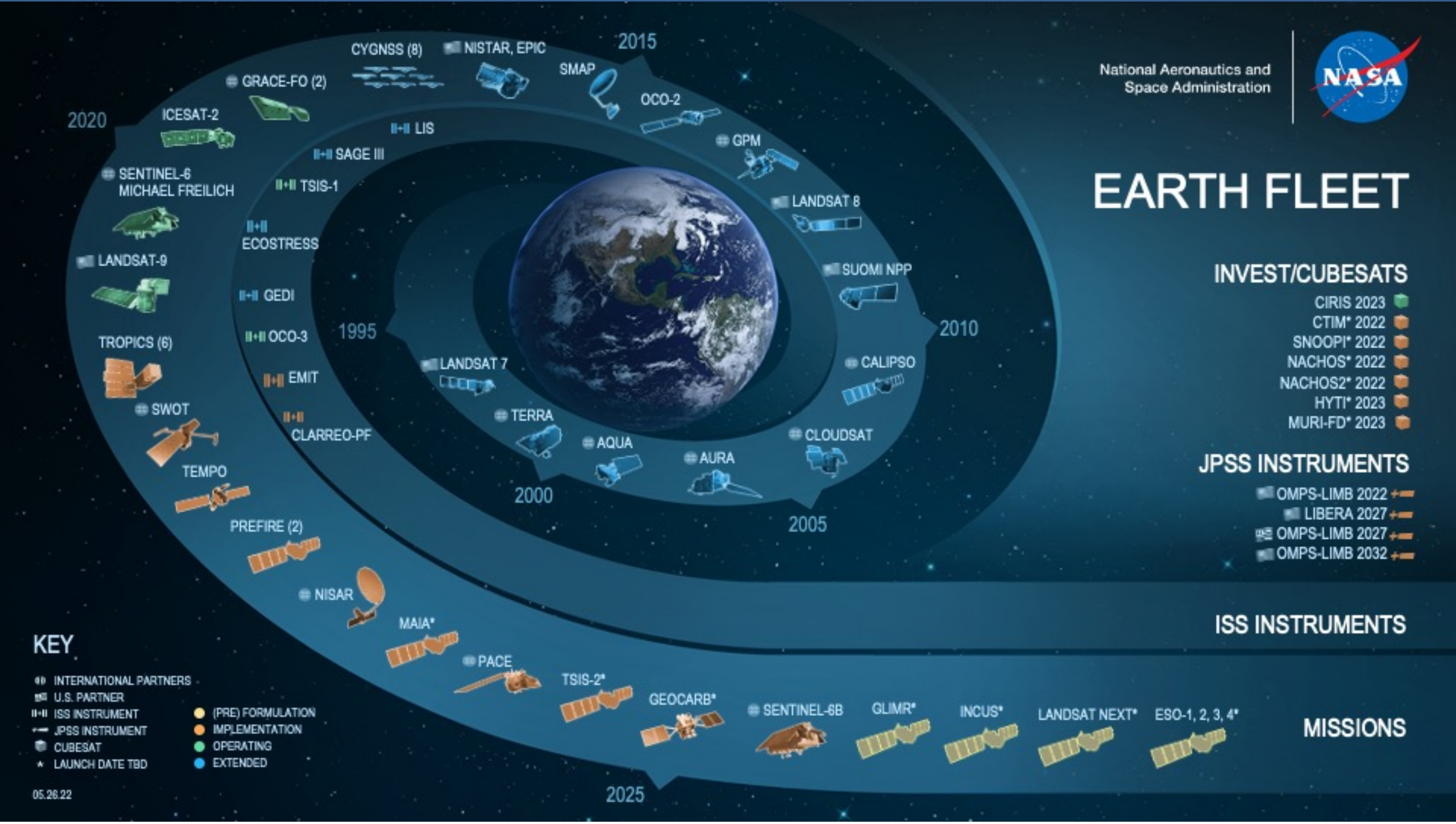
Presenter: Jack Kaye, NASA Headquarters

Report prepared based on inputs from numerous colleagues at NASA HQ, NASA Centers, and the broader research community

Coordination Group for Meteorological Satellites

OUTLINE

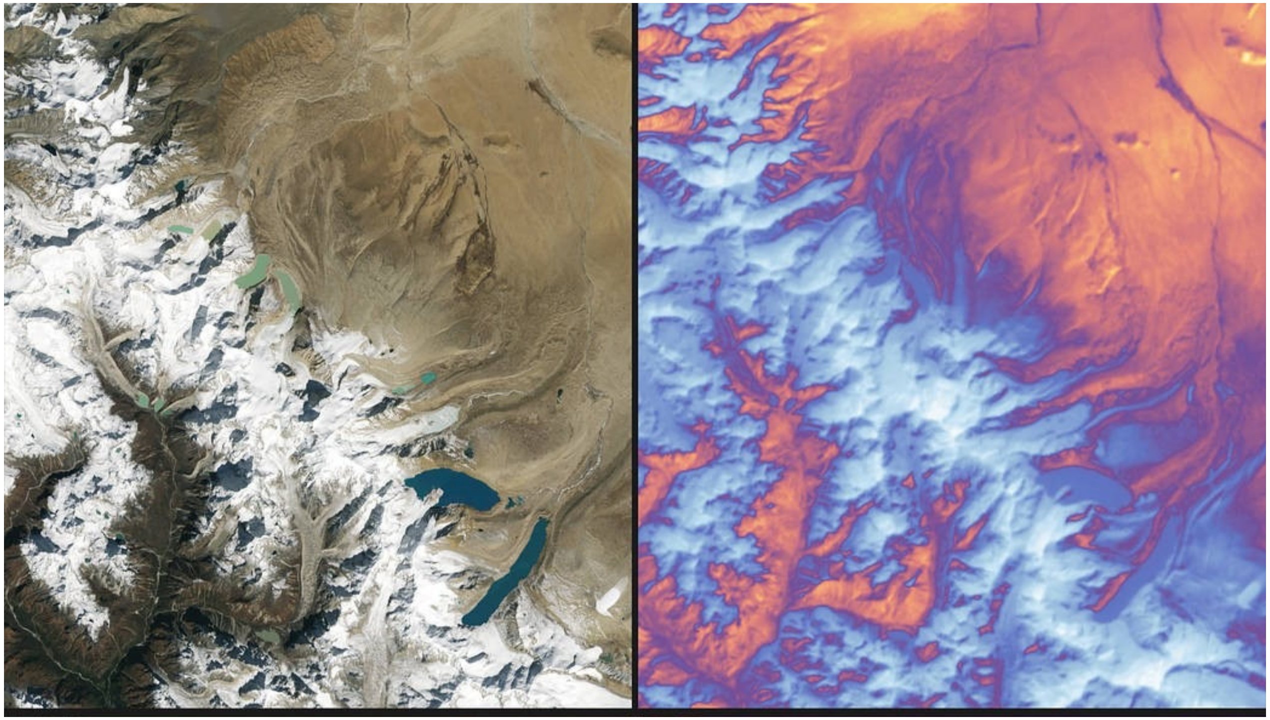
- Status of NASA's spaceborne fleet
- Launch highlights
- Upcoming missions
  - Earth Venture
  - Technology demonstrations
  - Earth Systematic
- Status of NASA response to 2017 Earth Science Decadal Survey
  - Designated
  - Incubation
  - Explorer
- Key highlights
  - Field campaigns
  - Research & Data products
  - Global Monitoring of Greenhouse Gasses
  - Open science



Coordination Group for Meteorological Satellites

LANDSAT-9

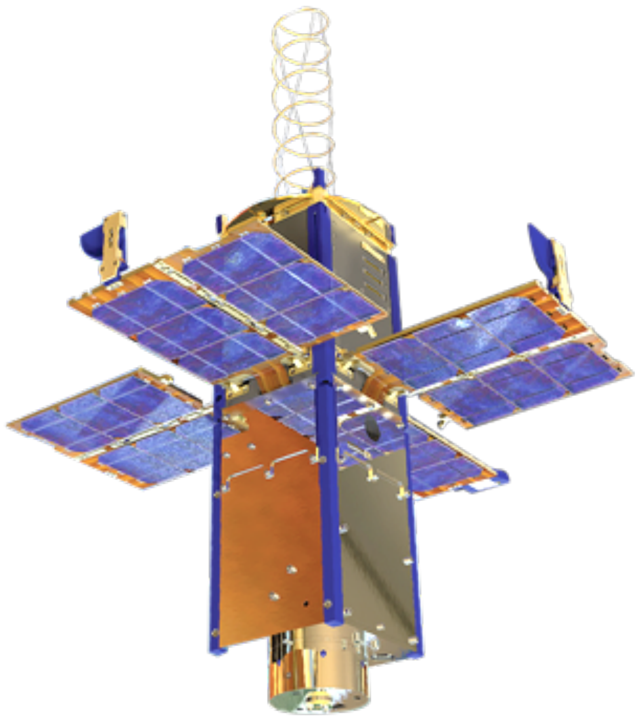
- Continuing the 50-year Landsat legacy of monitoring the Earth's land and coastal areas, NASA and USGS successfully launched Landsat 9 from Vandenberg Space Force Base in California on September 27, 2021.
- It carries the Operational Land Imager 2 (OLI-2) and the Thermal Infrared Sensor 2 (TIRS-2)
- While similar to its predecessors, Landsat 9 can transmit data with higher radiometric resolution, which allows it to detect subtle differences on the Earth's surface.



(Left) Snow and glaciers in the Himalayan mountains, leading to the flat Tibetan Plateau to the north from the OLI instrument. (Right) The same area from the (thermal) TIRS-2 instrument.

Nanosat Atmospheric Chemistry Hyperspectral Observation System (NACHOS)

- On 19 February 2022, NACHOS-1 was launched as part of Northrop Grumman's 17th resupply mission to the International Space Station from NASA's Wallops Flight Facility on Wallops Island, Virginia.
- It is an ultra-compact (3U) is a hyperspectral imager for measuring atmospheric trace gases (NO_2, SO_2, O_3, HCHO, and more). It will operate in the 290-500 nm spectral region, with f/2.9 optics, 1.3 nm resolution, 0.6 nm sampling, 350 contiguous spectral channels, and 350 across-track spatial pixels.
- Streamlined hyperspectral gas retrieval algorithms pre-process data in situ, addressing the issue of limited telemetry bandwidth by reducing large data cubes down to a set of small 2D images and spectral sample sets.
- NACHOS-1 is expected to deploy in June 2022
- NACHOS-2 is expected to launch in September 2022



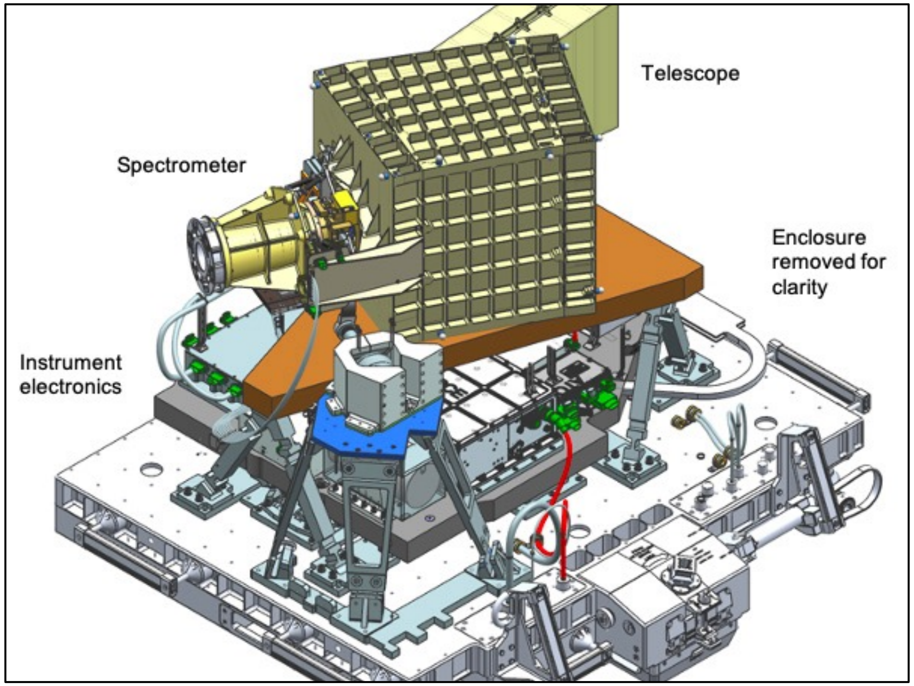
UPCOMING MISSIONS

2022-2023 EARTH VENTURE INSTRUMENTS

Earth Surface Mineral Dust Source Investigation (EMIT)

Imaging spectrometer operating in the Visible to Shortwave Infrared (VSWIR) range (380 – 2500 nm) sampling at 7.4 nm.

https://earth.jpl.nasa.gov/emit/

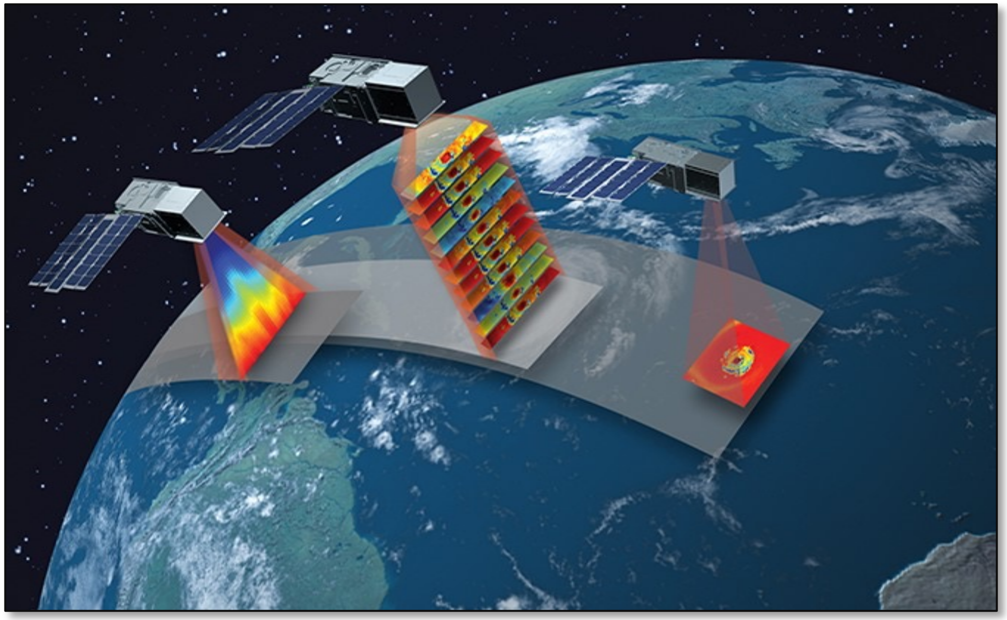


2022-2023 EARTH VENTURE INSTRUMENTS

Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS)

Six dual-spinning 3U CubeSats equipped with a 12-channel passive microwave spectrometer providing imagery near 90 and 205 GHz, temperature sounding near 118 GHz, and moisture sounding near 183 GHz.

https://tropics.ll.mit.edu/CMS/tropics/Mission-Overview



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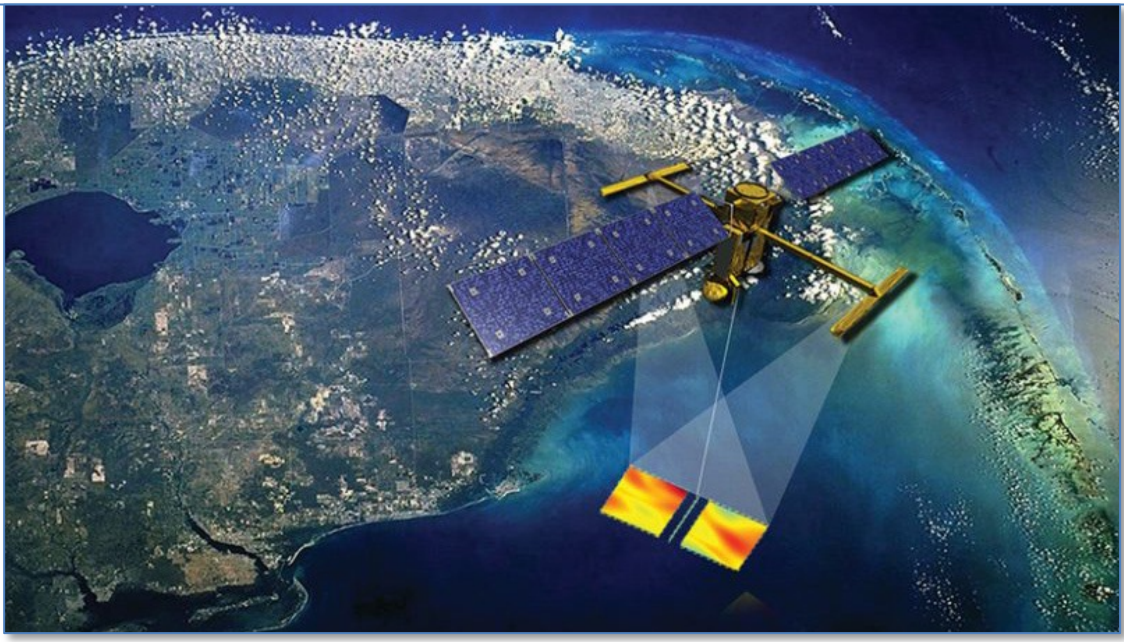
2022-2023 EARTH SYSTEMATIC MISSIONS

Surface Wind and Ocean Topography (SWOT)

Radar interferometry (KaRIn), Jason-class Altimeter, DORIS Antenna, Microwave Radiometer, X-band Antenna, Laser Reflector Assembly, and GPS Receiver

https://swot.jpl.nasa.gov/

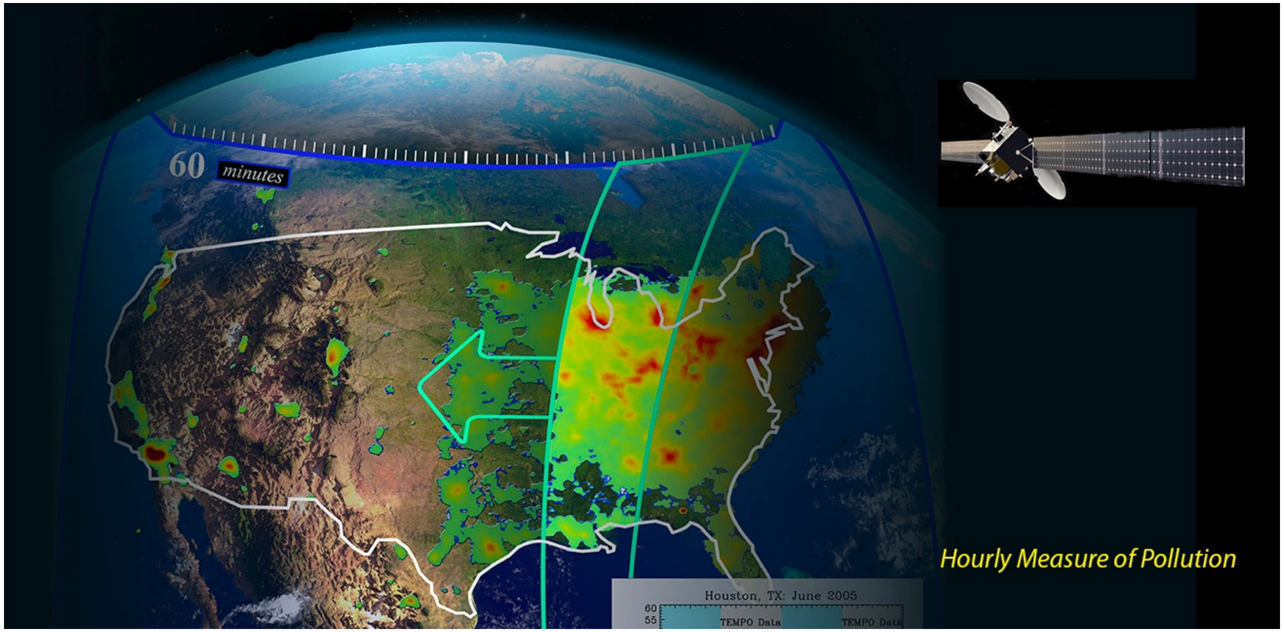


2022-2023 EARTH VENTURE INSTRUMENTS

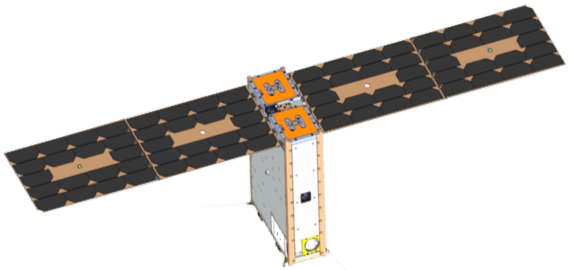
Tropospheric Emissions: Monitoring Pollution (TEMPO)

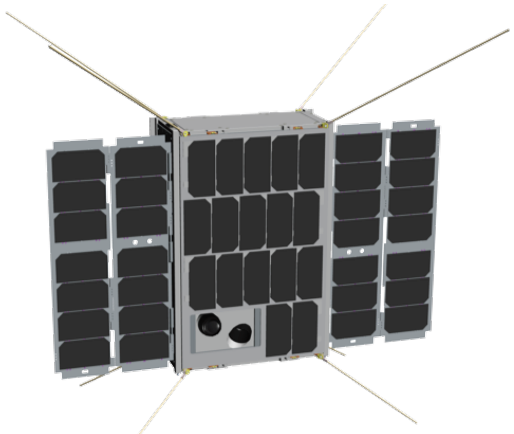
Scanning Ultraviolet and Visible range (290–740 nm) spectrometer, sampling at 0.2 nm and at 0.6 nm spectral resolution stationed as a hosted payload in geostationary orbit

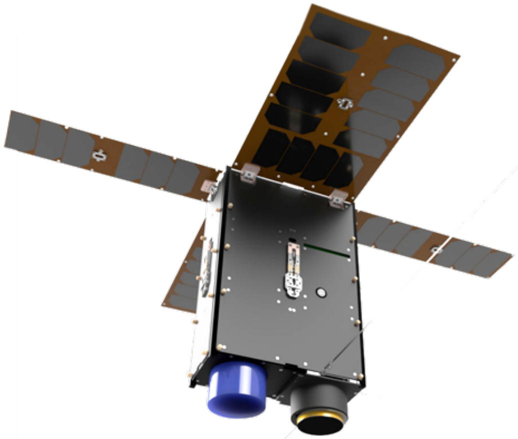
http://tempo.si.edu/overview.html



2022-2023 TECHNOLOGY DEMONSTRATION







Compact Total Irradiance Monitor – Flight Demonstration (CTIM-FD)

8 channel 6U CubeSat reflectometer that uses P-band signals of opportunity

https://esto.nasa.gov/invest/ctim/

Signals Of Opportunity P-band Investigation (SNOOPI)

6U CubeSat reflectometer capable of using P-band signals of opportunity

https://esto.nasa.gov/invest/snoopi/

Hyperspectral Thermal Imager (HyTI)

6U Thermal Imaging Cubesat with 25 channels between 8-10.7 ɥm, at 13 1/cm, and at a ground sampling distance of approximately 60 meters

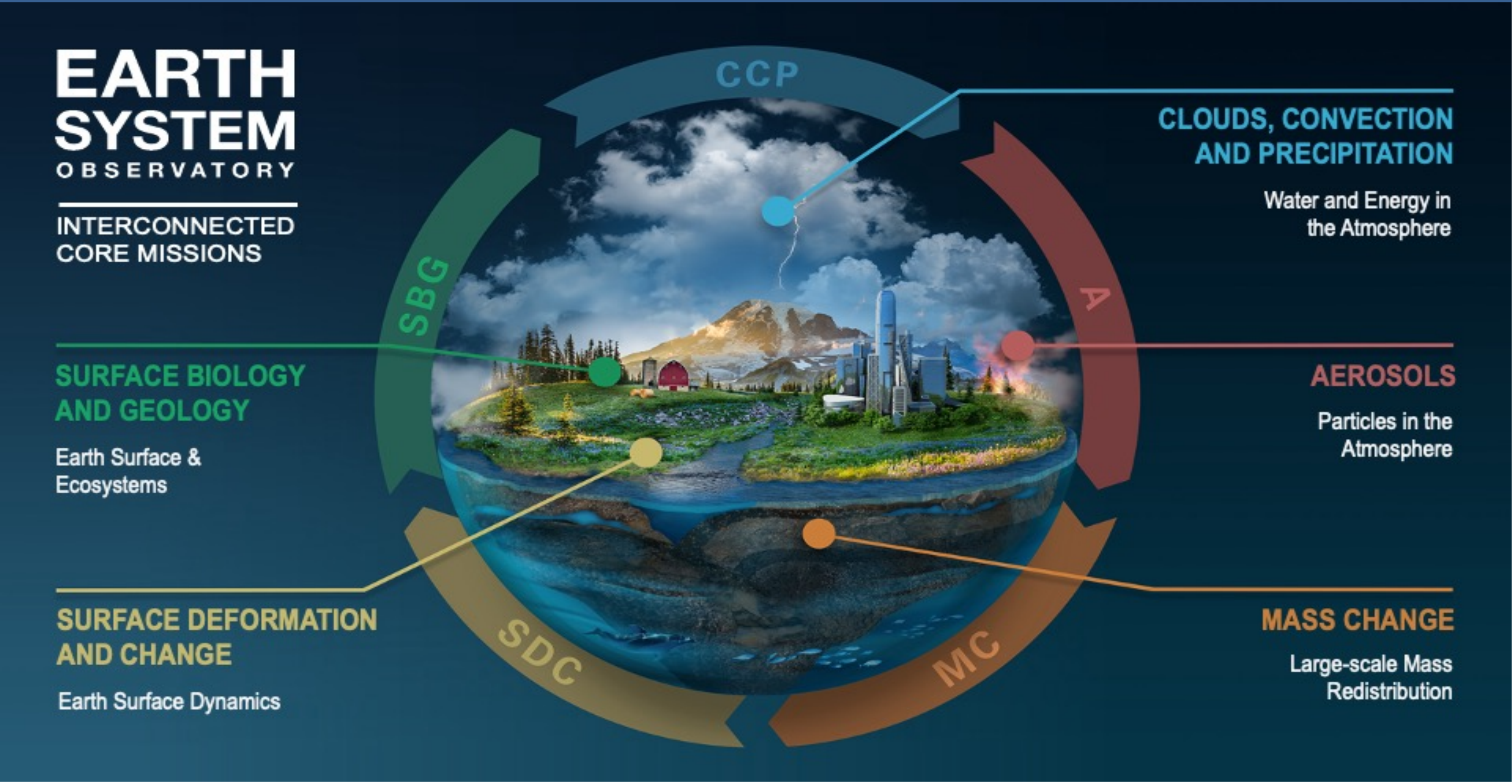
https://esto.nasa.gov/invest/hyti/

DECADAL SURVEY MISSIONS

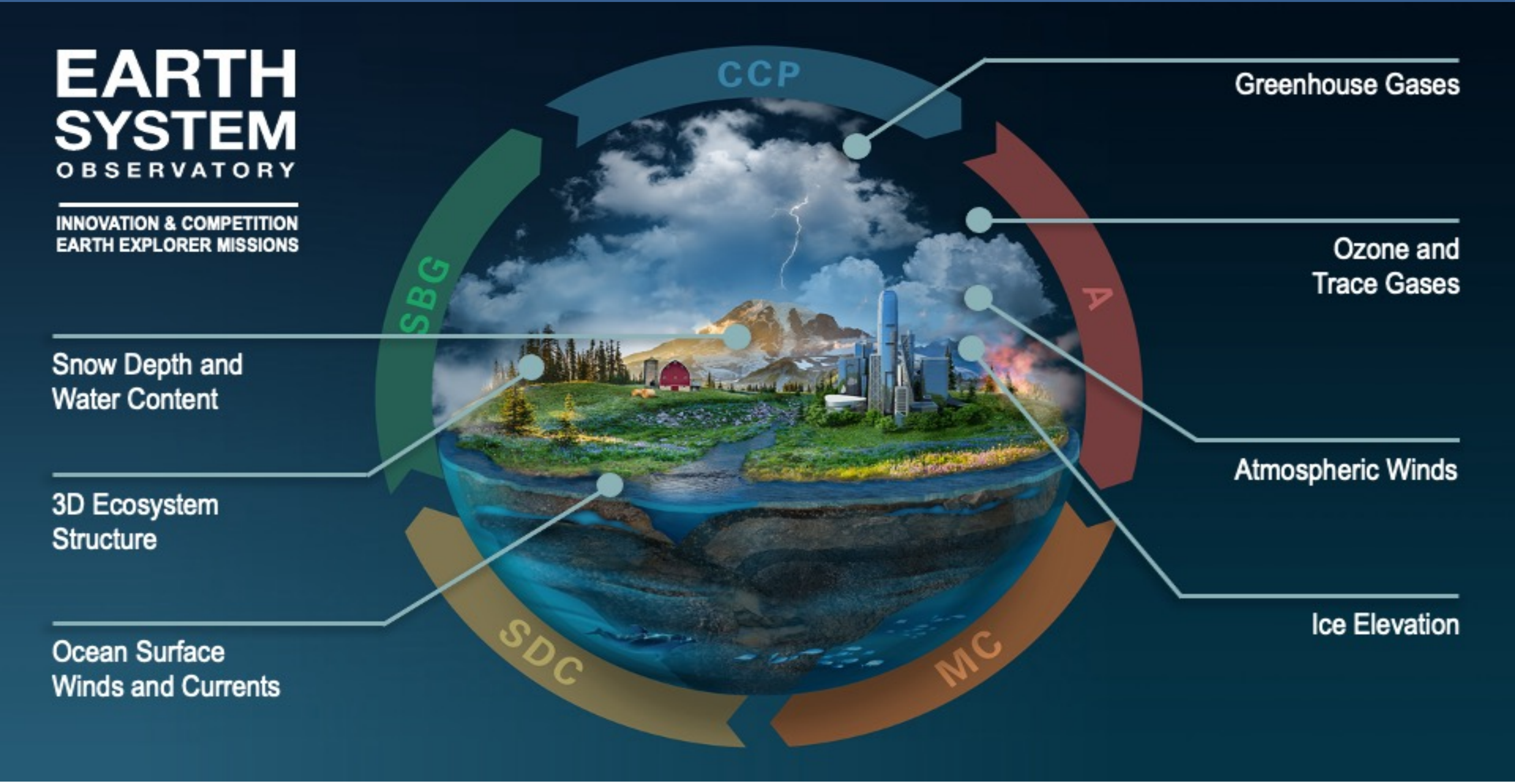
2017 EARTH SCIENCE DECADAL SURVEY

- The *2017 Earth Science Decadal Survey: Thriving on a Changing Planet*, contained a strong endorsement of the Program of Record (POR), which comprises satellites or instruments currently on orbit, as well as those already in formulation and implementation.
- The DS recommended building on this observing system, identified observations needed to address key science and application objectives, and allocated them to three new program elements:
  - Designated - focused on the highest-priority observations;
  - Explorer - a competed program to address the *Explorer* targeted observables;
  - Incubation - intended to accelerate the readiness of cost-effective flight implementations not yet mature enough to deploy to capture other high-priority observables.
- Following release of the Decadal Survey (DS) report in early 2018, ESD initiated studies to explore implementation options for observing systems to address the DS's five Designated Observables (DO):
  - Aerosols (A); and Clouds, Convection, and Precipitation (CCP);
  - Mass Change (MC);
  - Surface Biology and Geology (SBG); and
  - Surface Deformation and Change (SDC).

NASA RESPONSE TO 2017 EARTH SCIENCE DECADAL SURVEY



NASA RESPONSE TO 2017 EARTH SCIENCE DECADAL SURVEY



NASA RESPONSE TO 2017 EARTH SCIENCE DECADAL SURVEY

DECADAL SURVEY INCUBATION

- Decadal Survey Incubation (DSI) activities were initiated in 2019 to focus on investments for priority observation capabilities that need to be advanced prior to cost-effective implementation in the next decade. The program is focused on the Planetary Boundary Layer (PBL) and Surface Topography and Vegetation (STV) Targeted Observables.
- Two selected study teams – one each for PBL and STV – completed reports to inform program strategy and decisions. A solicitation was subsequently released in July 2021 to enable science and technology advancements.
- NASA received a total of 76 proposals in response to the solicitation. In April 2022, it selected 35 proposals for funding.
- The total first year of funding to be provided for these investigations is approximately $9.5 million.
- Information regarding the awarded proposals is available at: https://esto.nasa.gov/project-selections-for-dsi-21/

FIELD CAMPAIGNS

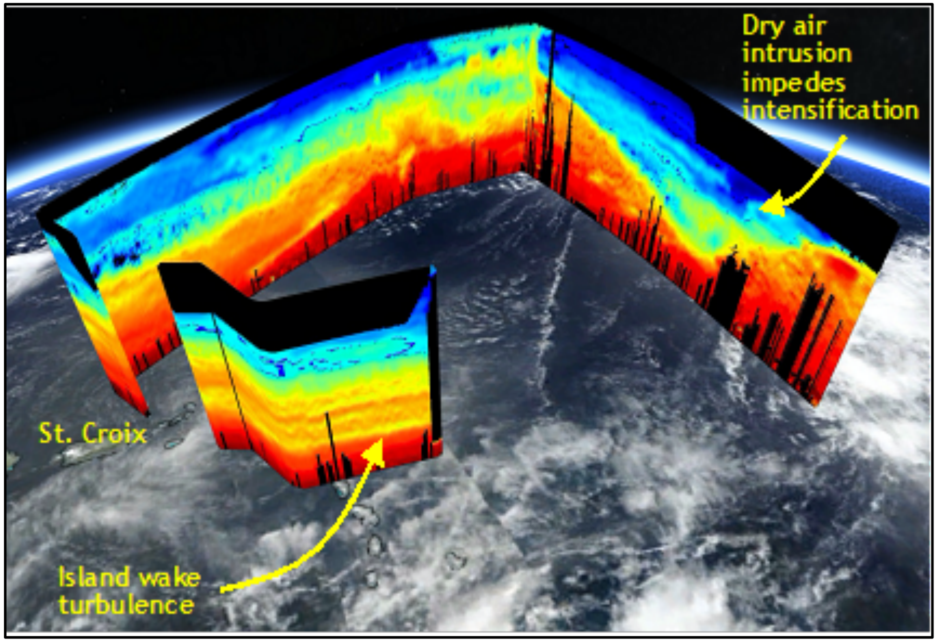
2021 Convective Process Experiment for Aerosols and Winds (CPEX-AW)

The 2021 Convective Processes Experiment for Aerosols and Winds (CPEX-AW) was aimed at collecting observations using the NASA DC-8 for the study of dynamics and microphysics related to the Saharan Air Layer (SAL), African easterly waves and jets, and deep convection within the Intertropical Convergence Zone (ITCZ) in the Caribbean and tropical North Atlantic regions. A primary goal of CPEX-AW was the calibration and validation activity in support of ESA's Aeolus wind lidar, the first spaceborne wind profiler.

Originally planned to fly from Cabo Verde, the campaign was relocated to Saint Croix, U.S. Virgin Islands. Because of the shift from the eastern to western Atlantic, many of the DC-8 flight missions were in the vicinity of Atlantic tropical cyclones.

The CPEX-AW team coordinated six DC-8 flights (49 flight hours), under-flying Aeolus over 5,836 km.

Instruments: Advanced Vertical Atmospheric Profiling System (AVAPS) dropsondes; Doppler Aerosol Wind Lidar (DAWN), High-Altitude Lidar Observatory (HALO); third generation Airborne Precipitation Radar (APR-3), and High-Altitude Monolithic Microwave Integrated Circuit Sounding Radiometer (HAMSR); surface-launched radiosondes



Research flight number 5, 28 August 2021 near the Leeward Islands. A vertical curtain of water vapor measurements from HALO shows vertical moisture gradients—warmer colors indicate moist air while cooler colors indicate dry air. On the right side of the figure, dry air intrusion into lower altitudes suggest inhibition of convective growth also shown by other instruments on the DC-8 (not shown here).

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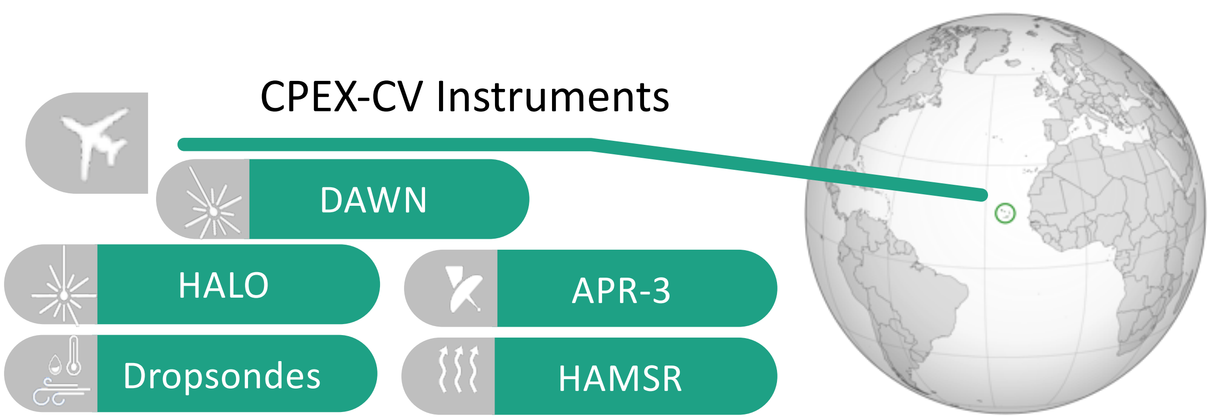
2022 Convective Process Experiment at Cabo Verde (CPEX-CV)

Analysis of CPEX-AW flight data is ongoing in 2022, NASA plans to complete the flight portion of the program in September 2022 from Sal Island, Cabo Verde – the campaign is named CPEX-CV. The Cabo Verde location will allow for process studies consistent with the original CPEX-AW objectives, including observing the two-way interactions between deep convection and large-scale weather phenomena in the tropical East Atlantic—this includes the SAL and associated midlevel easterly jet, African easterly waves, and the ITCZ.

There are also plans to conduct more underflights of Aeolus and other international satellites to continue the originally planned calibration and validation activities. NASA will also overfly surface-based stations deployed by European partners from Greece and Slovenia out of Mindelo Island, Cabo Verde.

While objectives of studying tropical convection and cloud-aerosol interactions will remain the same across CPEX-AW and CPEX-CV, the CPEX-CV campaign based out of Cabo Verde will provide easy access to ITCZ, coastal dynamics, and early stages of dust interaction with storms that was not accessible during CPEX-AW.



Coordination Group for Meteorological Satellites - CGMS

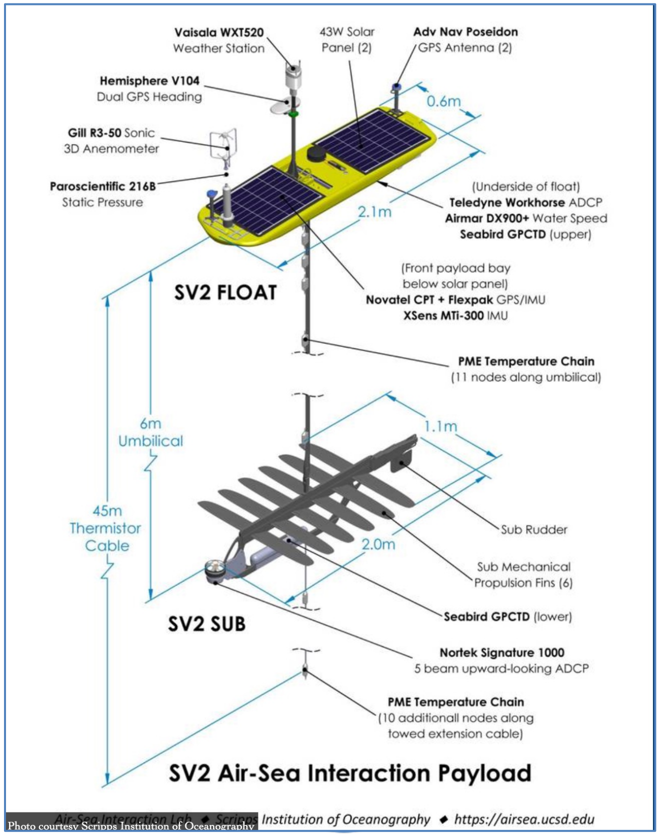
Sub-Mesoscale Ocean Dynamics Experiment (S-MODE)

S-MODE is a six-year (2019-2025) NASA airborne science investigation aimed at testing the hypothesis that sub-mesoscale ocean dynamics make important contribution to vertical exchange of climate and biological variables in the upper ocean. Scientists suspect that kilometer-scale eddies and fronts have a significant impact on ocean-atmosphere heat exchange. The S-MODE campaign will address the need of building and maintaining a comprehensive benchmark dataset on sub-mesoscale motions and help minimize an important source of uncertainty in simulating the global ocean.

S-MODE conducted a reduced-scope pilot campaign offshore of California in October 2021.

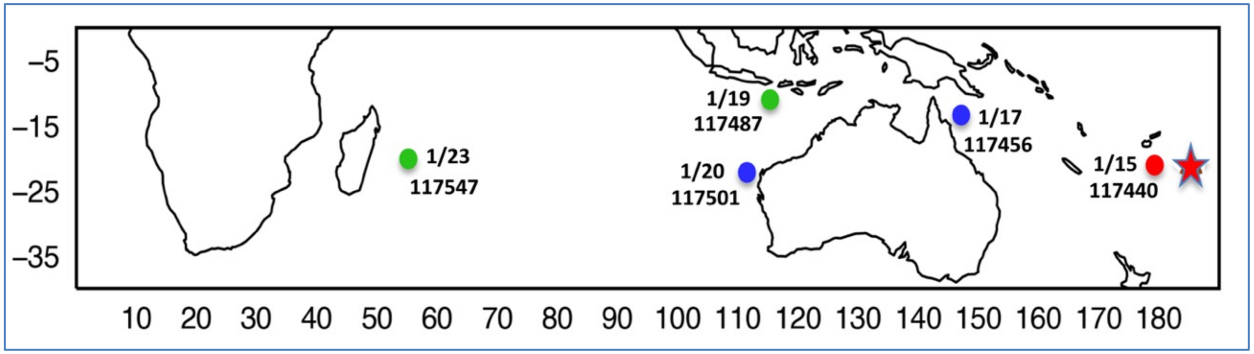
Observations acquired by King Air B-200 and Twin Otter aircraft were augmented with in situ data recorded by surface drifters, wave-propelled autonomous surface vehicles (Wave Gliders, Saildrone), Lagrangian floats, vertically profiling autonomous underwater gliders, and R/V Oceanus owned by NSF.

Airborne Instruments: DopplerScatt; Multiscale Observing System of the Ocean Surface (MOSES); and Modular Aerial Sensing System (MASS)

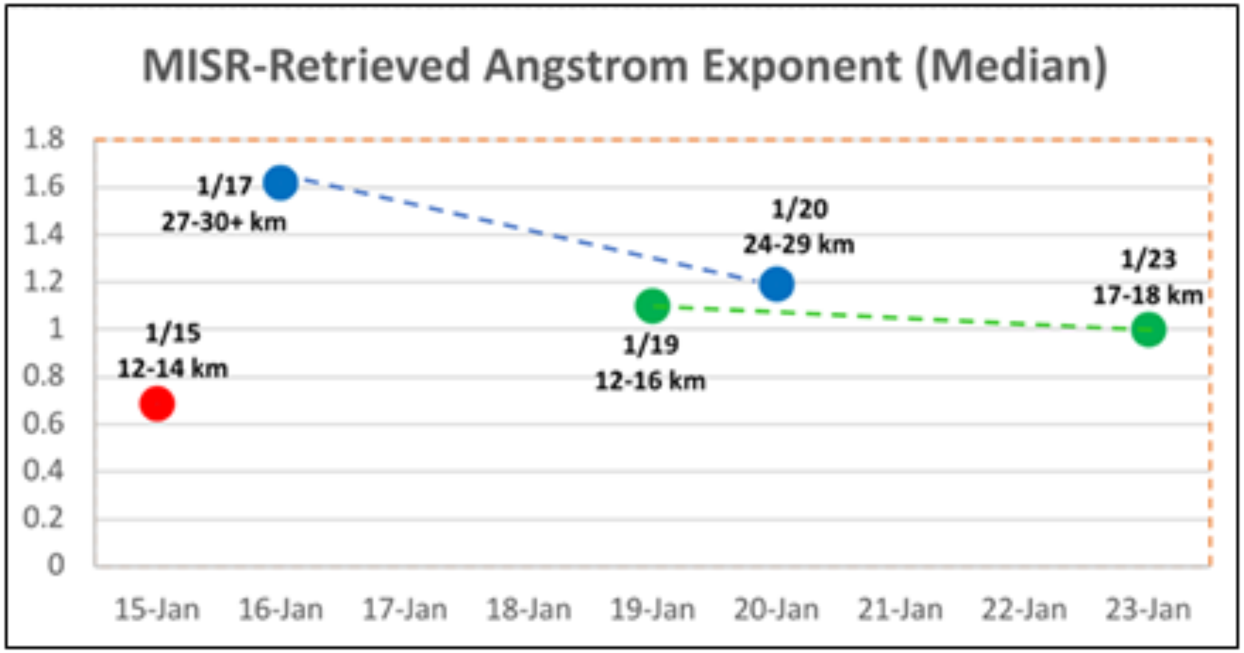


RESEARCH & DATA PRODUCT HIGHLIGHTS

RESEARCH HIGHLIGHT - Satellite Tracking of Hunga-Tonga Hunga-Ha'apai Volcanic Plume



Shown in the figure are January 2022 MISR HTHH volcano plume observation locations, dates, and Terra satellite *Orbit numbers*, the volcano is indicated with a red star. Observations of the layer at ~24-30+ km are shown in blue, those at ~13 to 20 km are shown in green, and one at 10-14 km is in red.



Retrieved MISR-retrieved Ångström Exponent of plume (inversely proportional to particle size) as it traveled westward. The particles were largest on the 15th (red dot near plume). Particle size within the plume observed above 24 km increased between 17th and 20th January 2022.

HTHH was a "wet" eruption, and other instruments showed that significant water was injected to these elevations. The most likely explanation for the observed particle growth is particle hydration, either by adsorption or ice deposition.

Credit: Ralph Kahn, GSFC

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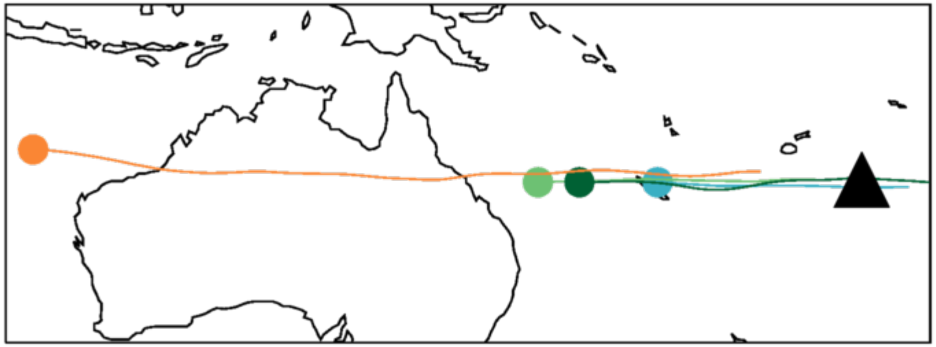
Coordination Group for Meteorological Satellites - CGMS

RESEARCH HIGHLIGHT - Hunga-Tonga Hunga-Ha'apai Hydration of the Stratosphere

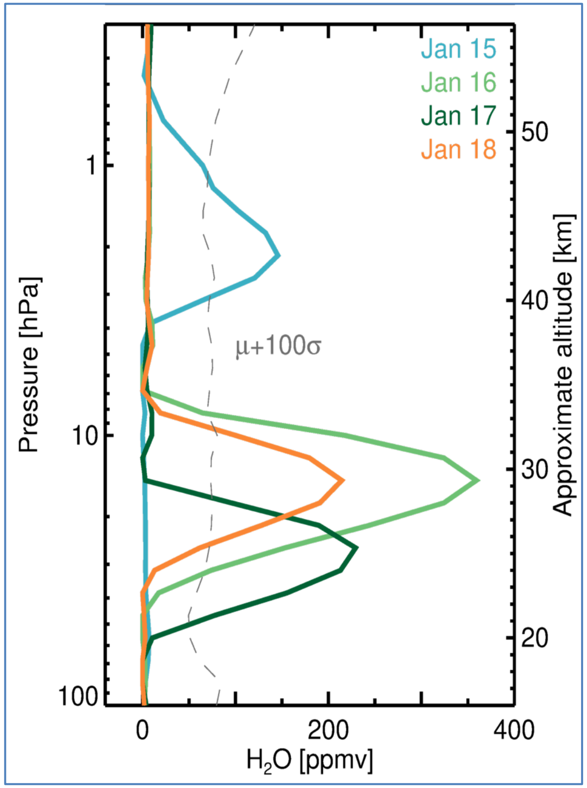
- Observations recorded by **Microwave Limb Sounder (MLS) onboard the Aura** spacecraft revealed that HT-HH injected an unprecedented amount of water vapor (H_2O_v) penetrating into the mesosphere.
- Millán et al. (2022) (accepted for publication) estimates that mass of H_2O_v injected into the stratosphere to be 146 ± 5 Tg, approximately 10 percent of the global stratospheric burden.
- Particle growth observed by MISR, if due to H_2O condensation or adsorption, could account for some of the MLS-observed decrease in H_2O_v as the plume ages.
- It may take several years for this H_2O plume to dissipate. The eruption could impact climate through surface warming due to the radiative forcing from the excess stratospheric H_2O_v; surface cooling due to sulfate aerosols is likely to be negligible.



Color-coded locations of daily MLS H2O observations

MLS vertical distribution of H_2O_v on Jan 15-18th. After the HT-HH eruption, MLS reports 150ppmv at 45km (15 Jan) and 350ppmv at 30km (16 Jan and subsequent days). For reference, H_2O_v in the middle atmosphere is usually 3-8 ppmv. The eruption injected H_2O over a large vertical extent encompassing most of the stratosphere. However, on 15 January MLS captured only the outer edge of the plume at 45 km, as strong winds advected the lofted H_2O to locations sampled by MLS.

Credit: Ralph Kahn Millan Luis F. Valle, Hugh Pumphrey, and Nathaniel J. Livesey



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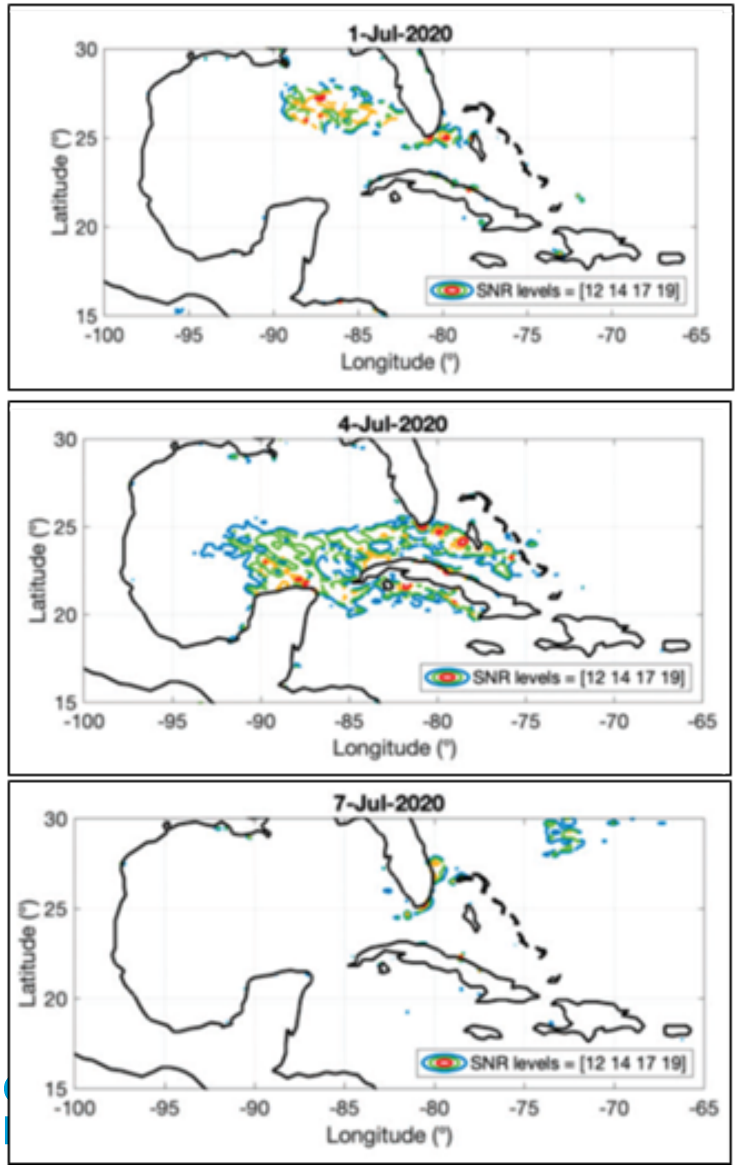
RESEARCH HIGHLIGHT - Detection and Mapping of Phytoplankton Outbreaks Using CYGNSS



A massive dust storm formed over the Sahara Desert in June 2020, which traveled and resulted in the highest aerosol optical thickness (AOT) observed in the past two decades. Dust particles are deposited on the ocean surface, impacting the ocean biogeochemistry through the supply of nutrients.

Nutrients trigger the phytoplankton (algae) blooms, which form a film on the ocean surface and affect the ocean surface tension. The change in ocean surface tension causes a local decrease of ocean surface roughness over the areas covered with phytoplankton.

Rodriguez-Alvarez and Oudrhiri (2021) demonstrated that CYGNSS can detect changes in the ocean surface roughness, expressed as an increase in reflectivity when the surface becomes smoother

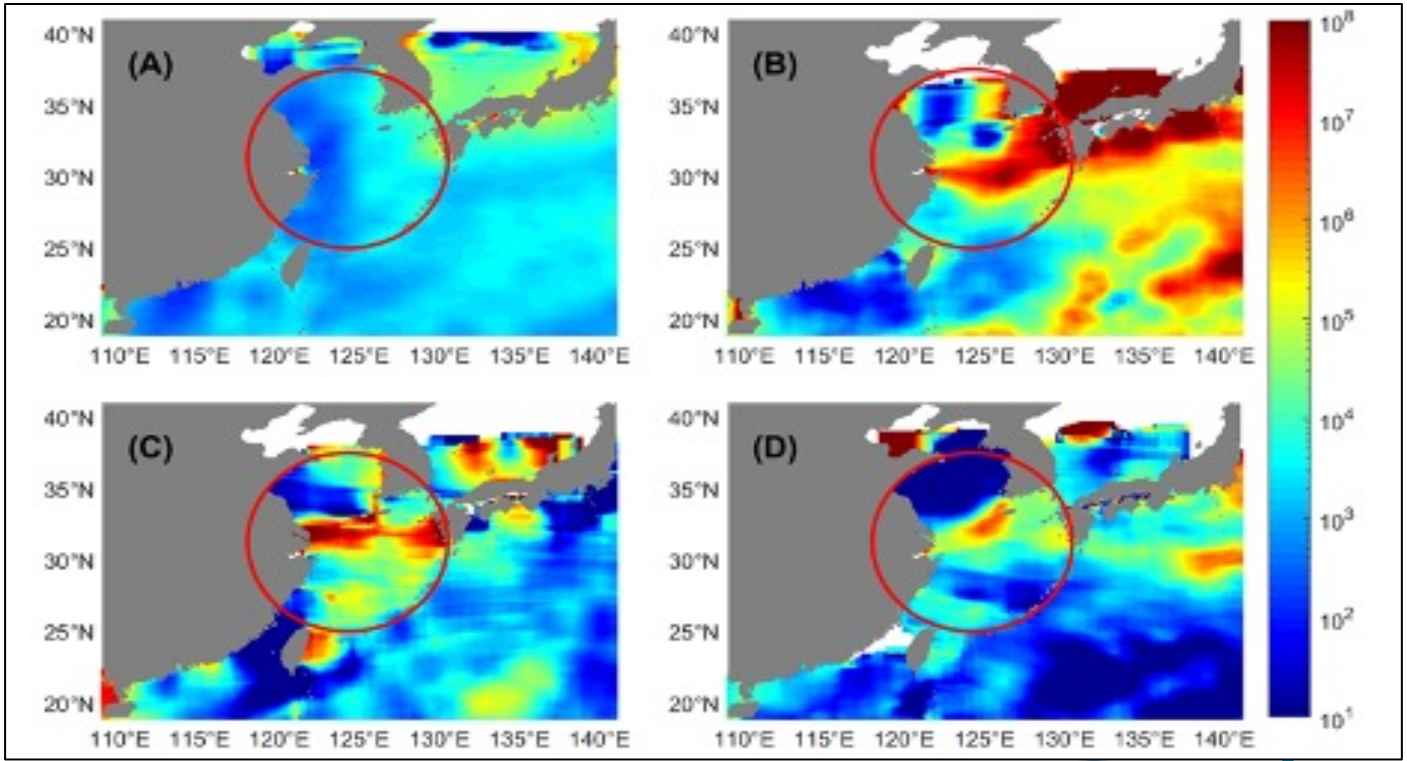
CYGNSS reflectivity maps before (1 July), during (4 July) and after (7 July 2020) a phytoplankton outbreak in the Gulf of Mexico triggered by a massive Saharan dust storm in June 2020. (Rodriguez and Oudrhiri, 2021).

CYGNSS MICROPLASTICS CONCENTRATION DATA PRODUCT

A method presented in Evans and Ruf (2021) is able to detect the global distribution of ocean microplastics from space. The method uses CYGNSS measurements of ocean surface roughness and relies on a reduction in responsiveness to wind-driven roughening caused by surfactants that act as tracers for microplastics near the surface.

Panel (A) shows the average microplastic concentration number density (#/km2) over an entire year. It serves as a background reference.

Individual one-week averages within that year are shown in Panels (B) 22–28 Jun 2017, (C) 27 Oct – 2 Nov 2017, and (D) 2–8 Dec 2017. They reveal short lived bursts of high microplastic concentration emerging from the Yangtze River mouth (highlighted by red circles) and dispersing into the East China Sea.



https://podaac.jpl.nasa.gov/announcements/2021-11-24-CYGNSS-Ocean-Microplastic-Concentration-V1.0-Release

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Slide: 25

GLOBAL MONITORING OF GREENHOUSE GASES AND OPEN SCIENCE INITIATIVE

Coordination Group for Meteorological Satellites - CGMS

GLOBAL GREENHOUSE GAS MONITORING - NASA CONTRIBUTION

- **Surface-based greenhouse and trace gas measurements**: **Advanced Global Atmospheric Gases Experiment (AGAGE)** and **Total Carbon Observing Network (TCCON)**
- **NASA airborne instruments: Airborne Visible InfraRed Imaging Spectrometer – Next Generation (AVIRIS-NG)** and **Hyperspectral Thermal Emissions Spectrometer (HyTES)**
- **NASA's spaceborne systems:**
  - **OCO-2 (Orbiting Carbon Observatory)** launched in July 2014, and **OCO-3** that was built from OCO-2 flight spare materials and launched to the ISS in May 2019;
  - **MODIS, ECOSTRESS**, and others allow accurate characterization of land surface type, state and properties (moisture, temperature, albedo, etc.), enabling documentation of regional changes (e.g., fires, droughts), as well as the underlying processes
  - **Geostationary Carbon Cycle Observatory (GeoCarb)** expected to launch in the next couple of years will observe GHG concentrations from a geostationary orbit
- **NASA's Carbon Monitoring System** project aim is to prototype development of capabilities necessary to support stakeholder needs for Monitoring, Reporting, and Verification (MRV) of carbon stocks and fluxes.
- **International, inter-agency, and commercial partnerships**:
  - Retrieval algorithm intercomparison and instrument calibration/validation – **GOSAT** and **TROPOMI** with JAXA and ESA respectively;
  - Research on understanding carbon sources (biological versus fossil fuel combustion) and sinks);
  - Support to CEOS/CGMS working group on climate and its subgroup on carbon
  - Support to WMO's Integrated Global Greenhouse Gas Information System (IG3IS) in partnership with National Institute of Standards and Technology (NIST)
  - Support of Arctic Methane and Permafrost Challenge (AMPAC) with the ESA
  - Commercial Smallsat Data Acquisition (CSDA) is planning to acquire data from **GHGSat** and evaluate its usefulness for Earth system science research & application

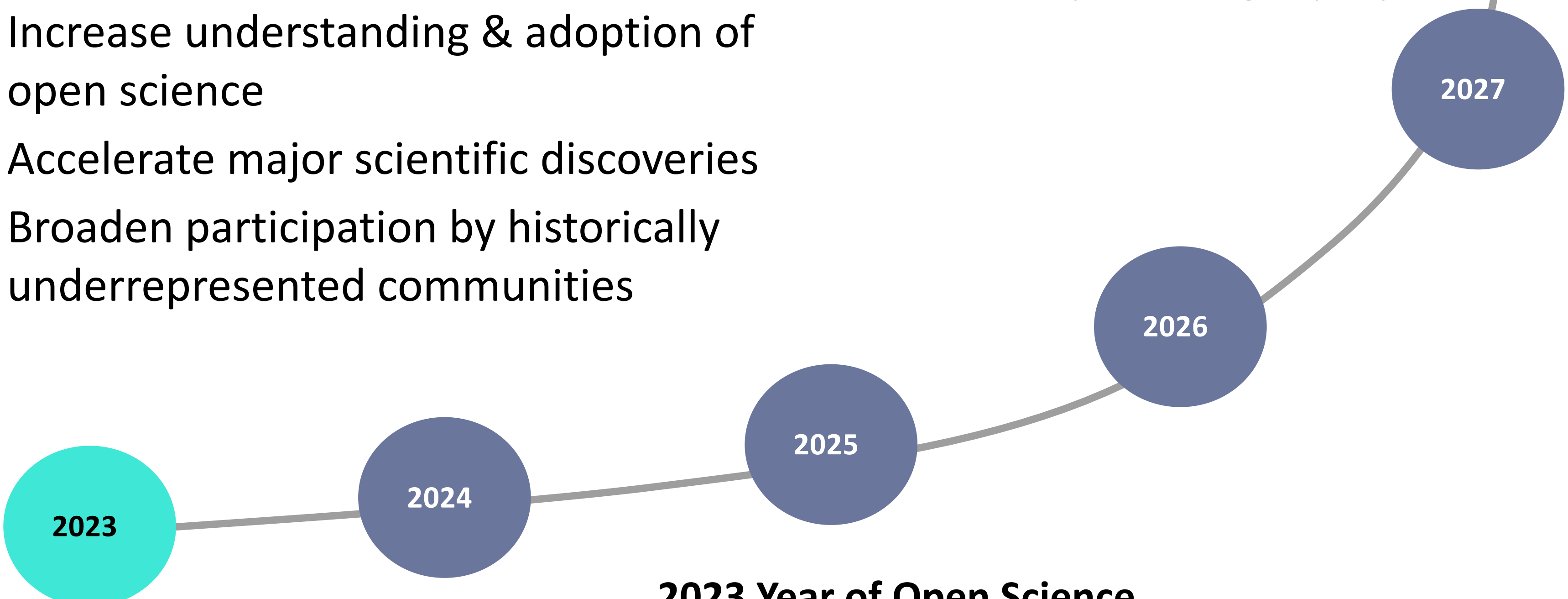
TRANSFORM TO OPEN SCIENCE (TOPS)

Transform to Open Science (TOPS) is a 5-year NASA Science Mission Directorate mission with the following objectives:

- Increase understanding & adoption of open science
- Accelerate major scientific discoveries
- Broaden participation by historically underrepresented communities

2027 Goals

- 20K earn Open Science Badge
- 5+ major discoveries
- Increase participation of underrepresented groups by 2x



2023 Year of Open Science

- Recognizing open science practices
- Holding open meetings
- Sharing hidden knowledge
- Inclusive collaborations

THANK YOU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NASA EARTH
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BACKUP

FIELD CAMPAIGN HIGHLIGHT – Ocean Melting Glaciers (1)

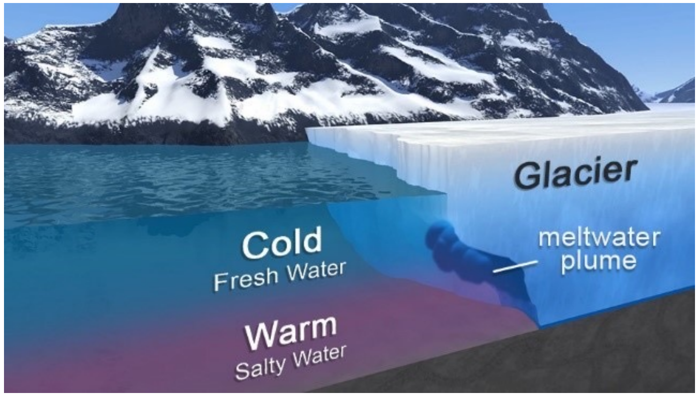
Description: The six-year (2015-2021) Earth Venture Investigation was aimed at measuring changes in ocean temperatures surrounding Greenland, along with the thinning and retreat of the glaciers that drain the ice sheet.

Significance: Greenland contains enough ice to raise global sea levels by 25 feet, and current predictions are dramatically underestimating how quickly Greenland's ice is disappearing.

Results: 1) The investigation's primary hypothesis was confirmed - that the oceans drive a large fraction of Greenland's ice loss;

2) The warm water that affects Greenland's glaciers sits deeper than 200 m below the ocean surface on Greenland's continental shelf and cannot be measured remotely; and

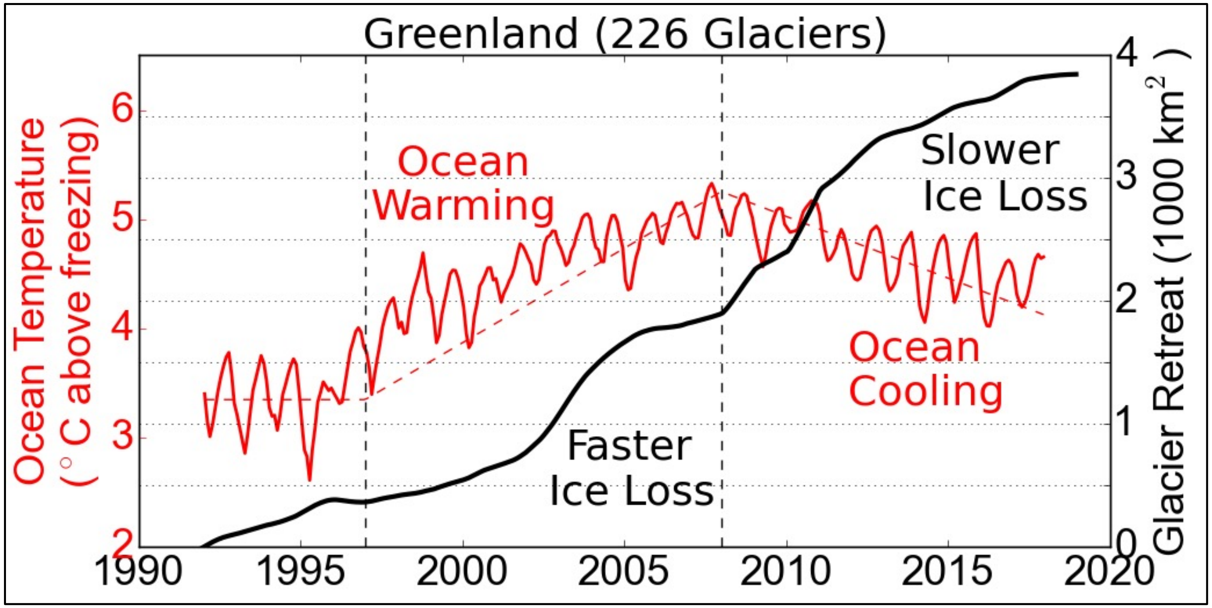
3) OMG demonstrated that floats, much like those used by Argo, can operate in the shelf region and provide measurements of these important waters year-round.

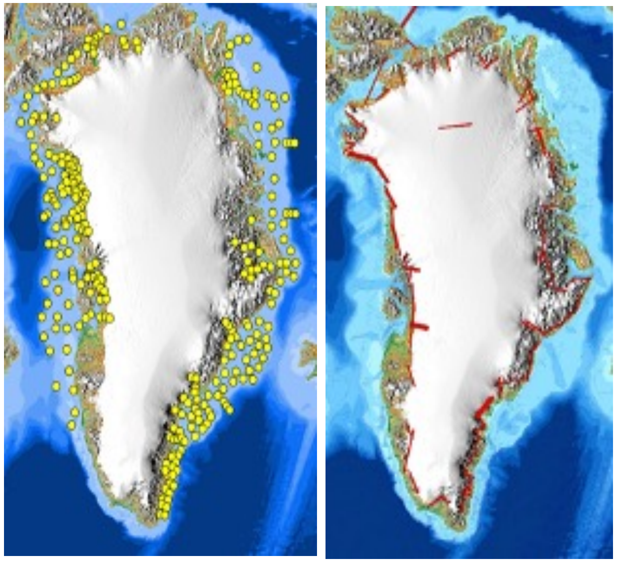


An illustration of the warm, salty layer of ocean water that threatens Greenland's glaciers.


Helheim Glacier in 2019, as seen over the wing of Ocean Melting Glacier (OMG) ocean survey aircraft (a DC-3 Turbo Prop leased from Kenn Borek Air). The brown pool of water is a plume of meltwater rising up the glacier's face. The plume mixes with warm water from the ocean to eat away at the glacier from the bottom.

FIELD CAMPAIGN HIGHLIGHT – Ocean Melting Glaciers (2)

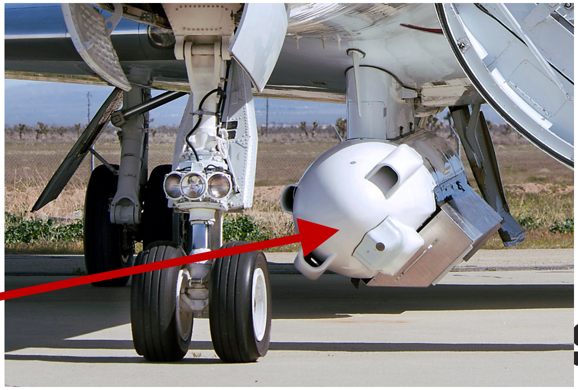




(Left): Each yellow dot is one of the 250 locations where OMG measures water temperature and salinity each year. (Right): OMG's ice survey. Red lines show where glacier elevations were measured by the GLISTIN-A.

The analysis by OMG Team Member Mike Wood/JPL combines OMG data with historical data and ocean simulation results. It shows that period of ocean warming drove faster ice loss over all of Greenland, and the period of ocean cooling slowed down ice loss. This confirmed OMG's central hypothesis that the oceans play a major roll in Greenland ice loss. It also found that if ocean warming is ignored, projections of ice loss from Greenland will be too small, by a factor of 2.

The GLISTIN-A instrument is a radar interferometer that provided elevation maps of the last 5-10 km of the glaciers where they meet the ocean.



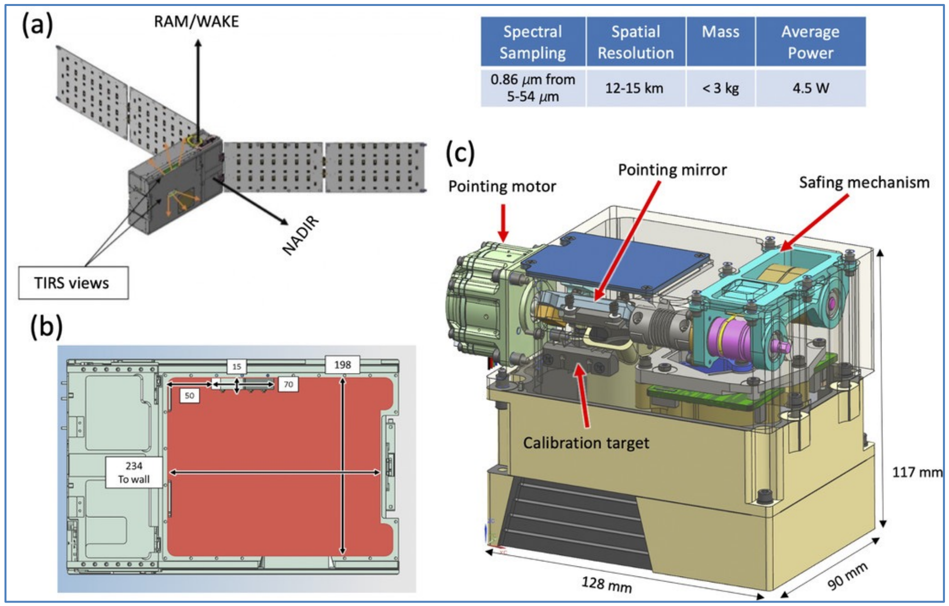
Coordination Group for Meteorological Satellites

2022-2023 EARTH VENTURE INSTRUMENTS

Polar Radiant Energy in the Far-InfraRed Experiment (PREFIRE)

Two 6U CubeSat spacecraft in two different 470-650 km altitude, near-polar (82°-98° inclination) orbits, each with a Heritage miniaturized IR spectrometer, covering the 0-54 mm region at 0.84 µm spectral resolution

https://prefire.ssec.wisc.edu/



Spectral Sampling	Spatial Resolution	Mass	Average Power
0.86 µm from 5-54 µm	12-15 km	< 3 kg	4.5 W

(a) Approximate form of the PREFIRE 6U CubeSat and (b) corresponding interior layout and dimensions. The total dimensions of each CubeSat are 300 mm long, 200 mm wide, and 100 mm deep. (c) The TIRS instrument will occupy just over half of this space.

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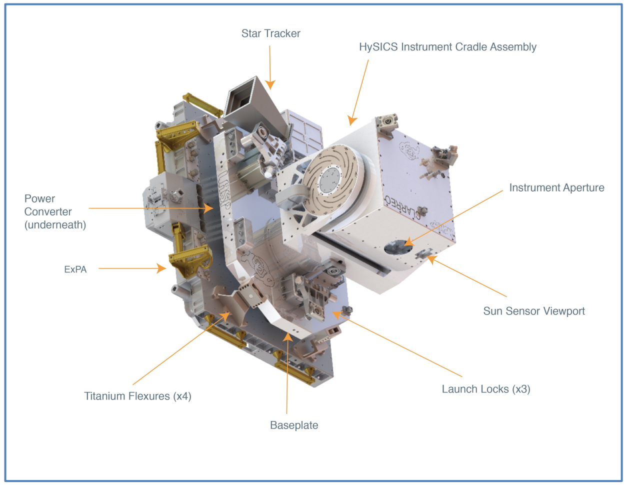
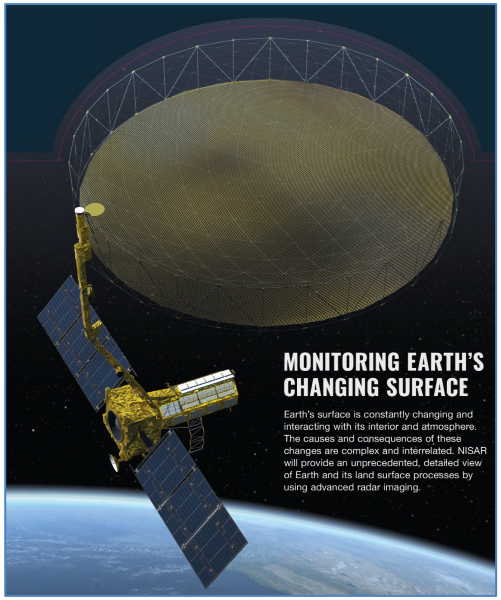
2022-2023 EARTH SYSTEMATIC MISSIONS



Climate Absolute Radiance and Refractivity Observatory (CLARREO-PF)

Hyper-Spectral Imager for Climate Science (HySICS)

https://clarreo-pathfinder.larc.nasa.gov/



NASA-ISRO Synthetic Aperture Radar (NISAR)

L- and S-band Synthetic Aperture Radar (SAR)

https://nisar.jpl.nasa.gov/

NASA RESPONSE TO 2017 EARTH SCIENCE DECADAL SURVEY

DESIGNATED OBSERVABLES – THE EARTH SYSTEM OBSERVATORY

- In the spring of 2021, under the name **Earth System Observatory (ESO)**, NASA initiated pre-Phase A activities for four of the five Designated Observables: A, CCP, MC, and SBG.
- The fifth Designated Observable study team, SDC, will continue its study of potential architectures through launch of the NISAR mission.
- Project offices have been established to further define the mission concepts, execute trade studies related to architecture(s) identified during the study phase, and continue to develop opportunities for collaboration with international partners.
- Through 2022, the ESO missions in pre-Phase A will undergo Mission Concept Reviews in preparation to enter Phase A, where they will develop a baseline mission concept, validate requirements, and establish mission architecture.

FIELD CAMPAIGNS

Campaign	Scope	Platforms
AVIRIS-NG 2021 flight campaigns	Use of imaging spectroscopy to assess vegetation type and productivity; quantify water quality and suspended sediment concentrations that influence wetland soil accretion in the Mississippi delta (Delta-X campaign). Campaign in Europe focused on the development of automated vicarious validation methods to allow comparison between AVIRIS-NG reflectance data and field spectroradiometer measurements.	ER-2; UAVSAR
EXPORTS (Export Processes in the Ocean from Remote Sensing)	Acquire observations critical to developing a predictive understanding of the export and fate of carbon transformed by global ocean net primary production (NPP) and its implications for the Earth's carbon cycle in present and future climate.	Global and ocean class research vessels and autonomous platforms
air-LUSI (Airborne Lunar Spectral Irradiance)	High accuracy radiometric measurements of the moon that can serve as a benchmark to specify the absolute lunar spectral irradiance, which has been identified as an essential to improving the lunar calibration system and advancements in on-orbit sensor calibration capabilities.	ER-2

GLOBAL GREENHOUSE GAS MONITORING – NASA Space and Airborne Systems

Surface-based Greenhouse gas measurement network

- **Advanced Global Atmospheric Gases Experiment (AGAGE)** is a network of 13 monitoring stations set up around the world to measure 40 atmospheric gases that contribute to warming and ozone depletion. These include Methane (CH_4) and CO (Carbon Monoxide), among others

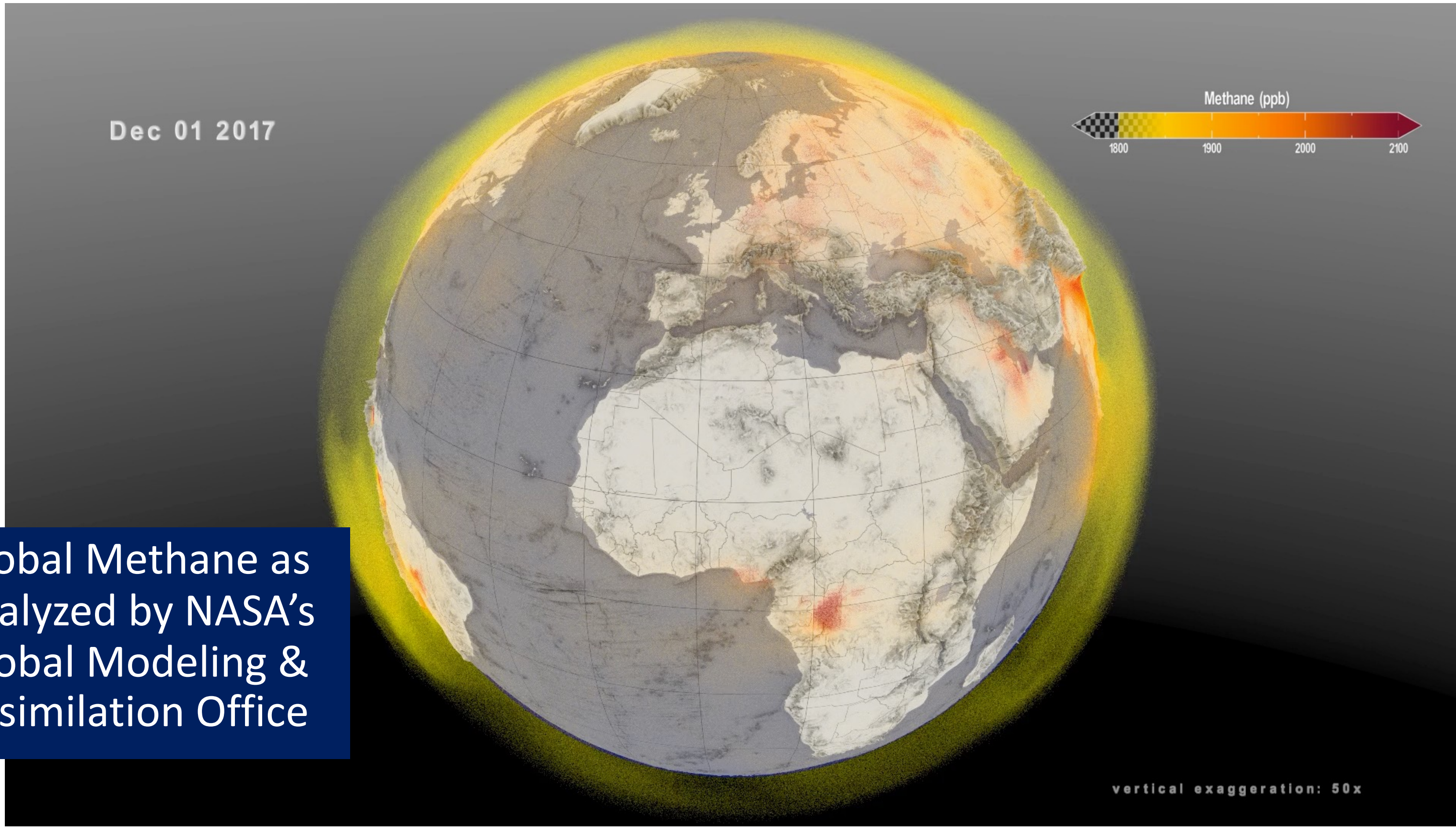
Satellite measurements of carbon dioxide (CO_2) and Methane (CH_4)

- **OCO-2** (Orbiting Carbon Observatory) was launched in July 2014, and observes CO_2 on regional scales (>100 km)
- Built from OCO-2 flight spare materials, NASA launched **OCO-3** in May 2019 to the Japanese Equipment Module Exposed Facility (JEM-EF) on the ISS. The ISS orbit can see daily variations in release and uptake of CO_2 in rain forests and urban areas

Airborne systems

- **NASA's Airborne Visible InfraRed Imaging Spectrometer – Next Generation (AVIRIS-NG)** measures reflected solar radiance from 380 nm to 2510 nm with 5 nm sampling for monitoring of methane (CH_4) and carbon dioxide (CO_2)
- **Hyperspectral Thermal Emissions Spectrometer (HyTES)** is an airborne imaging spectrometer with 256 spectral channels between 7.5 and 12 micrometers in the thermal infrared part of the electromagnetic spectrum.

GLOBAL GREENHOUSE GAS MONITORING – Modeling and Analysis



Global Methane as Analyzed by NASA's Global Modeling & Assimilation Office

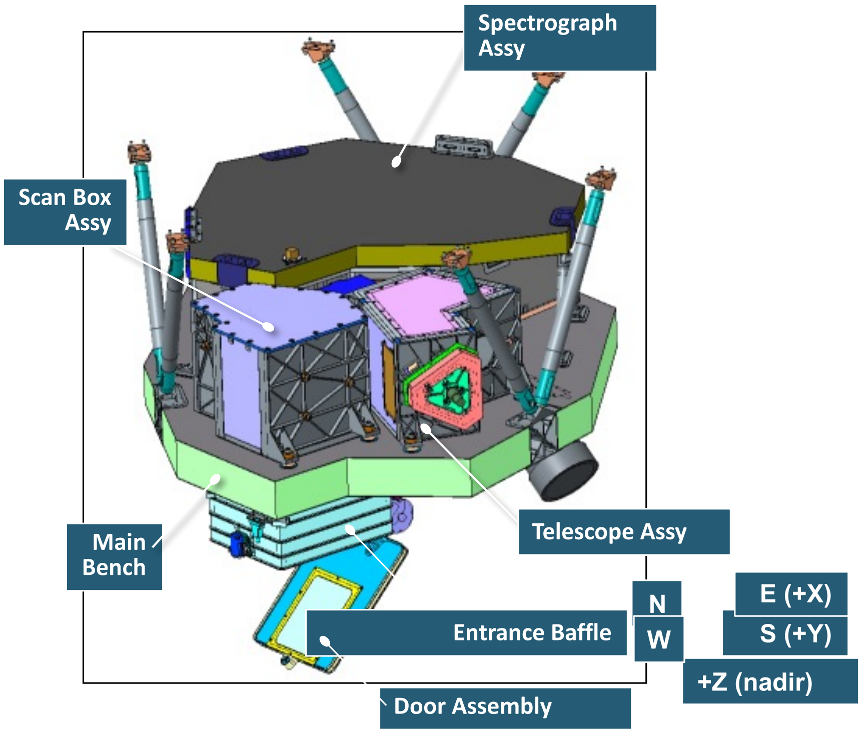
https://svs.gsfc.nasa.gov/4799

GLOBAL GREENHOUSE GAS MONITORING - Future NASA Mission

Geostationary Carbon Observatory (GeoCarb) is a single-slit, 4-Channel infrared scanning spectrometer that will be hosted on a commercial satellite flying in a geostationary orbit.

It will allow retrievals of total atmosphere column of carbon dioxide, methane, carbon monoxide and solar-induced fluorescence (SIF) at a spatial resolution of about 5 to 10 kilometers.

The primary goals of GeoCarb are to monitor plant health and vegetation stress throughout the Americas and to probe the natural sources, sinks and exchange processes that control carbon dioxide, carbon monoxide and methane in the atmosphere.



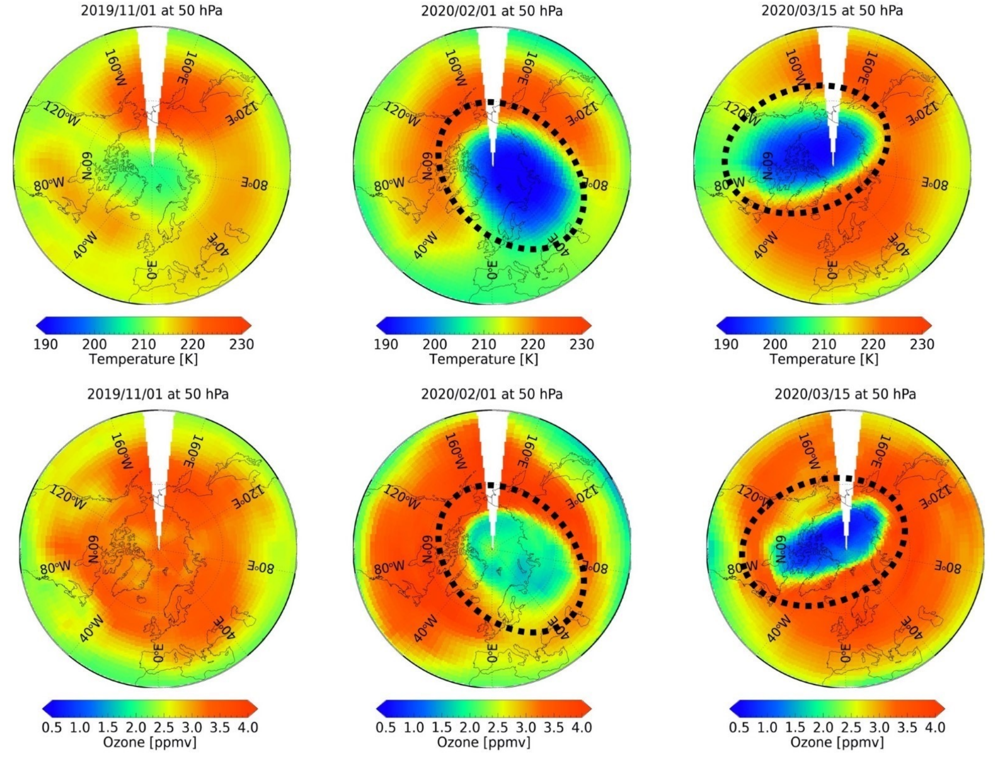
Community Long-term Infrared Microwave Combined Atmospheric Product System (CLIMCAPS)

CLIMCAPS is a multi-instrument, multi-platform system that uses observations provided by modern-era hyperspectral infrared instruments to retrieve profiles of temperature, water vapor, and ozone, as well as a series of trace gases (CO, CO_2, CH_4, SO_2, HNO_3, N_2O), together with cloud top pressure, cloud fraction, surface temperature, and emissivity.

Cross-track Infrared Sounder (CrIS) and Advanced Technology Microwave Sounder (ATMS) extend the 20-year record of the Atmospheric Infrared Sounder (AIRS) and Advanced Microwave Sounding Unit (AMSU) instruments.

The CLIMCAPS algorithm concept benefits from decades of research funded by NASA and NOAA.

A CLIMCAPS sibling algorithm, NOAA-Unique Combined Atmospheric Processing System (NUCAPS), is operational at NOAA and provides real-time information to weather forecast offices.



CLIMCAPS-Aqua retrievals of temperature (top row) and ozone (bottom row) at 50 hPa from (left) 1st Nov 2019, (middle) 1st Feb 2020 and (right) 15th Mar 2020. The black oval outlines an Arctic Vortex event. These maps are CLIMCAPS Level 2 observations averaged onto a grid, with each grid cell representing an area of 3˚ latitude by 20˚ longitude.

GLOBAL GREENHOUSE GAS MONITORING – Future Non-US Government Missions

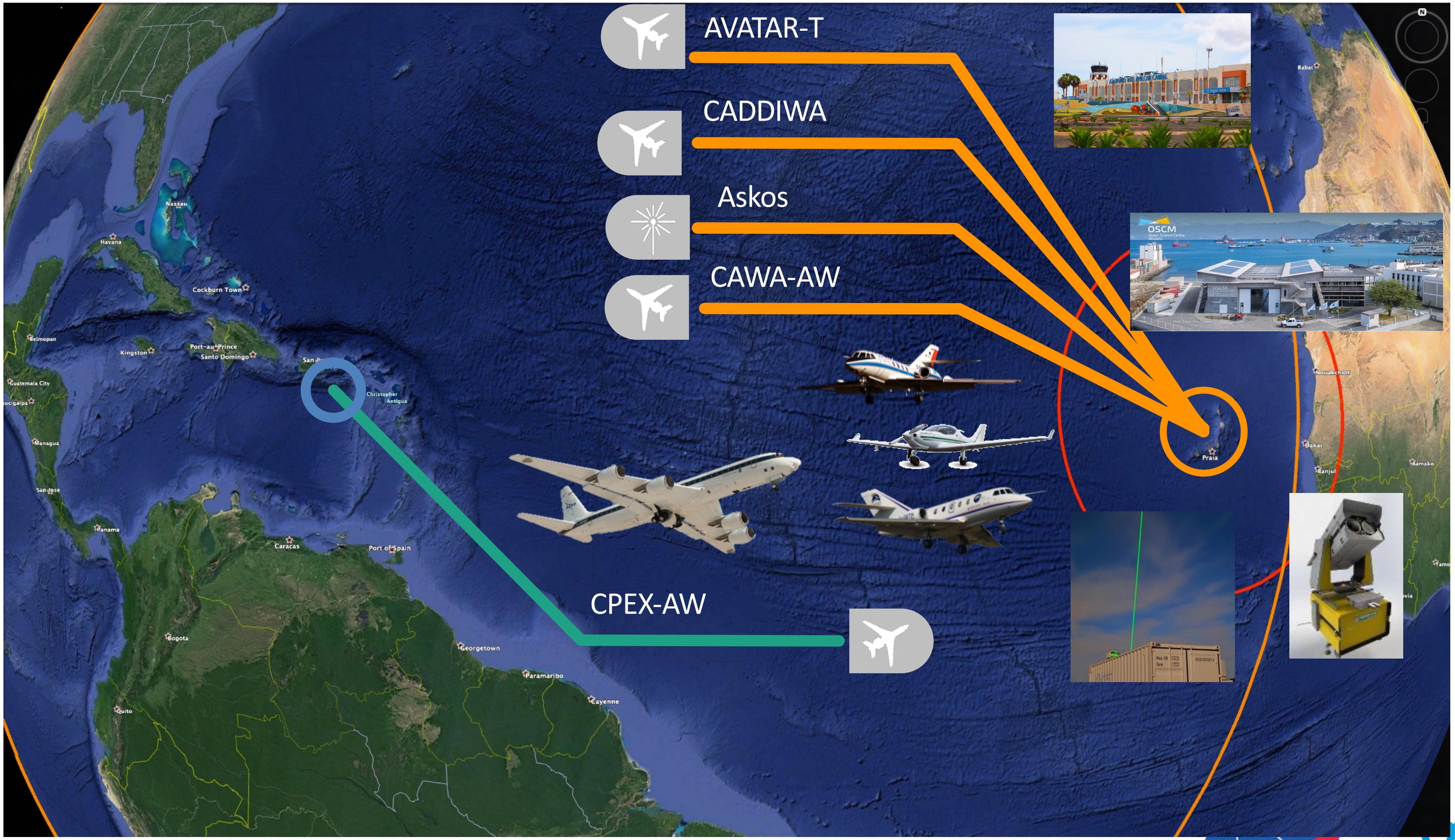
GHGSat Inc. plans to have a constellation of 10 microsatellites in orbit by the end of 2022, with 6 already in orbit. The first satellite (GHGSat-D) was launched in 2016. The satellites measure CO_2 and CH_4 abundances at a spatial resolution of less than 50 m and a 14 day repeat cycle. The payload includes a 2D Wide-Angle Fabry-Perot short-wave infrared imaging spectrometer (1600-1700 nm), and a the visible and near-infrared Clouds & Aerosols sensor (400-1000 nm) with 325 bands at 1.9 nm spectral resolution.

MethaneSAT, LLC is a wholly owned subsidiary of Environmental Defense Fund, Inc., and plans to launch in the 2022-2023 timeframe a shortwave infrared imaging spectrometer that will detect methane concentrations as low as two parts per billion and high spatial resolution.

Carbon Mapper, Inc. is a non-profit 501c3 organization to deploy a hyperspectral satellite constellation with the ability to pinpoint, quantify and track point-source methane and CO_2 emissions. Phase 1 is underway to develop and launch of the first two satellites by 2023. Phase 2 will encompass expansion to an operational multi-satellite constellation starting in 2025. Partnership with NASA JPL signed in April 2021 for payload development.

Coordination Group for Meteorological Satellites - CGMS

International Collaboration for Convective Process Experiment for Aerosols and Winds (CPEX-AW)



Coordination Group for Meteorological Satellites

NASA

CGMS