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NASA REPORT ON THE STATUS OF CURRENT AND FUTURE EARTH SATELLITE SYSTEMS

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Executive Summary

NASA currently supports the operations of 23 Earth Science missions. Since CGMS-46 (June 2018), NASA's Earth Science program launched the Ice, Cloud, and Land Elevation (ICESat-2) satellite, two instruments to the International Space Station (ISS) including the ECOsystem Spaceborne Thermal Radiometer Experiment (ECOSTRESS) and the Global Ecosystems Dynamics Investigation (GEDI), and one CubeSat for research technology demonstration (Compact Spectral Irradiance Monitor). The Earth Science program also prepared an additional instrument for launch to the International Space Station (ISS), the Orbiting Carbon Observatory-3 (OCO-3), scheduled to launch no earlier than (NET) April 30, 2019 (between the due date for working paper drafts and the CGMS meeting). During this time, significant effort was put into the early operations of the US-German Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) satellites launched on May 22, 2018. The CALIPSO satellite exited the A-Train in September 2018 and now orbits in close proximity to CloudSat; together they now constitute what is called the "C-Train." Finally, the QuikScat satellite completed its service in October 2018 after 19 years of operations.

Although all NASA operated missions discussed in this report were conceived as research missions, the efficiency of the communications and ground data handling systems has supported operational and near-real-time applications. NASA has also continued to support the development and deployment of direct operational application Earth sensing missions with the Landsat series for the USGS and the GOES and JPSS series for NOAA.

NASA's Earth Science Division (ESD) is implementing a balanced and robust plan to accomplish a broad set of critical Earth observation measurements from space for advancing Earth sensing science research. The program advances

knowledge of the integrated Earth system, the global atmosphere, oceans (including sea ice), land surfaces, ecosystems, and interactions between all elements, including the impacts of humans. A balance of satellite measurements, science research, technology development and applications are all needed to address and observe a complex global Earth system. NASA plans to launch 9 missions and 5 instruments (on host missions) in the future, along with two additional CubeSats from our technology program.

In the last year, the National Academies of Science, Engineering, and Medicine released the updated final version of their decadal survey for Earth Sciences, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. NASA’s Earth Science Division has already been in the process of responding to the survey, including the initiation of study plans for the Designated Observables called for in the report and releasing an Announcement of Opportunity for the first Earth Venture-Continuity mission, which is focused on Earth Radiation Budget measurements.

NASA Report on the status of current and future satellite systems

1 INTRODUCTION

NASA currently supports the operations of 23 Earth Science missions (see Tables 1 to 3). Since CGMS-46 (June 2018), NASA's Earth Science Division launched the ECOsystem Spaceborne Thermal Radiometer Experiment (ECOSTRESS) and Global Ecosystems Dynamics Investigation (GEDI) as hosted payloads on the International Space Station (ISS), the Ice, Cloud, and Land Elevation Satellite (ICESat-2), and the Compact Spectral Irradiance Monitor (CSIM) 6U-class technology demonstration satellite. During this time, the QuikScat satellite, came to an end after ~19 years of operation. The CALIPSO mission was moved out of the A-Train constellation to fly in close coordination with CloudSat, which had moved to an orbit slightly below that of the A-Train (Aura, Aqua, OCO-2, Japan's GCOM-W) in what is now called the C-Train. The SORCE mission continues to show significant signs of aging and its instruments are operating in reduced data collection mode. An Announcement of Opportunity (AO) was released for the first Earth Venture Continuity Mission; this will be focused on measurements of the Earth's Radiation Budget. An AO was also released for the fifth installment in the Earth Venture Instrument (EV-I) program, under which proposals are currently undergoing evaluation. Although all missions were conceived as research missions, the efficiency of the communications and ground data handling systems has supported operational and near-real-time applications.

In addition, NASA's Earth Science Technology Office (ESTO) continues to support the development of U-class satellites as technology demonstrations. The satellites that are most relevant to CGMS include the previously deployed ICECube, RainCube, and TEMPEST-D satellites, which continue to operate. Development has also begun on two new missions selected in response to the most recent call of the In-Space Validation of Earth Science Technology program.

NASA's Earth Science Program is implementing a balanced and robust plan to accomplish a broad set of critical Earth observation measurements from space. The program advances knowledge of the integrated Earth system, the global atmosphere, oceans (including sea ice), land surfaces, ecosystems, and interactions between all elements, including the impacts of humans. A combination of satellite measurements, science research, technology development and applications are needed to address a complex global Earth system. NASA's plans include the launch of 9 missions and 5 instruments (on host missions) in the future.

In the past year, the National Academies of Science, Engineering, and Medicine released the updated final version of their decadal survey for Earth Sciences, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*, which provides guidance to the program on scientific questions to be addressed and observations to be made over the coming decade. NASA's Earth Science Division (ESD) has made significant efforts towards responding to the Survey. In particular, ESD created study teams to address the Designated Observables called for in the survey (Aerosols and Clouds, Convection and

Precipitation; Surface Biology and Geology; Mass Change; and Surface Deformation and Change) and released an Announcement of Opportunity (AO) for the first Earth Venture-Continuity mission, which is focused on measurements of the Earth's Radiation Budget. Significant efforts at informing the Earth science community have been made about these responses, including scheduling community fora every four months.

NASA has also begun to implement its first Commercial Satellite Data Buy Pilot program. After soliciting Requests for Information (RFI) from potential providers, NASA has entered into agreements with three private entities (DigitalGlobe, Planet Lab, Spire) to purchase Earth observation data, and has augmented the tasks of approximately 30 current research or application investigators to allow them to assess the efficacy of the purchased data in achieving their research and/or applications objectives.

Note that this working paper focuses on the missions developed and/or operated by and for NASA's Earth Science Division (ESD); some of these missions are operated by NASA's partners, but are included here given ESD's significant leadership in their development. Two other divisions within NASA's Science Mission Directorate (SMD) have missions within their portfolios that may be of interest to CGMS members. The Heliophysics Division (HPD) studies the Earth's upper atmosphere, the sun, and the interactions between them, and is extensively involved with measurements that contribute to the knowledge of Earth's charged particle and magnetic environment, and thus all aspects of Space Weather. These activities are reported through the CGMS Space Weather Task Team. NASA's Joint Agency Satellite Division (JASD) builds satellites for the National Oceanic and Atmospheric Administration (NOAA) on a reimbursable basis. Since NOAA holds the requirements and resources for these missions, NOAA will report on them as part of its inputs to CGMS. Readers interested in those programs should consult the relevant working papers.

2 CURRENT SATELLITE SYSTEMS

The following tables summarize ESD's satellite systems:

Table 1: Current ESD LEO Satellites
Table 2: Current ESD HEO (or other) Satellites
Table 3: Current ESD Research and Development (R&D) Satellites

Table 1 - Current NASA LEO Satellites

Satellite	Operating Agency	ECT / Inclination	Mean Altitude	Launch Date	Data Access	Instruments and Details
Landsat-7	* USGS (support from NASA)	10:00 (D)	705 km	15-Apr-1999	EROS	**Science:** High-resolution image information of the Earth's surface (Follow on to Landsat series) **Instruments:** ETM+
Jason-2 (Op) (Ocean Surface Topography Mission)	* NOAA (support from NASA, EUMETSAT and CNES)	66-deg Non Sun-Sync	1336 km	20-Jun-2008	Handbook	**Science:** Sea surface topography (Follow on to Jason-1) **Instruments:** LRA, DORIS, POSEIDON-3, AMR, GPSP
Suomi-NPP (Op)	* NOAA (support from NASA)	13:30 (A)	833 km	28-Oct-2011	Suomi Data Direct Broadcast	**Science:** Atmospheric dynamics, water and energy cycle, clouds and aerosols, radiation, GHG, air/sea fluxes; also supporting operational weather forecasting & ozone monitoring **Instruments:** CrIS, CERES, VIIRS, ATMS, OMPS
Landsat-8	* USGS (support from NASA)	10:11 (D)	705 km	11-Feb-2013	EROS	**Science: High-resolution image information of the Earth's surface (Follow on to Landsat series)** **Instruments: OLI, TIRS**

** Although NASA does not officially "operate" these missions, NASA supports operations through the science instrumentation.*

Table 2 - Current NASA HEO (or other) Satellites

Satellite	Operating Agency	Orbit	Launch Date	Data Access	Instruments	Details: Applications
DSCOVR	* NOAA (support from NASA)	Lagrange (L1)	11-Feb-2015	PlasMag (NOAA) EPIC	PlasMag, EPIC, NISTAR	Solar Wind Plasma, Interplanetary 3-D magnetic field vectors UV and VIS radiance for derived total ozone, clouds, aerosols, and vegetation indices

** Although NASA does not officially "operate" these missions, NASA supports operations through the science instrumentation.*

Table 3 - Current NASA Research and Development (R&D) Satellites

Satellite	Operating Agency	ECT / Inclination	Mean Altitude	Launch Date	Data Access	Instruments	Details: Applications
Terra (EOS AM-1)	NASA	10:30 (D)	705 km	18-Dec-1999	Terra Data Direct Broadcast	ASTER, MODIS, MOPITT, MISR, CERES	Atmospheric dynamics and chemistry, water and energy cycle, clouds, aerosols, radiation, GHG, carbon and water, air-land exchange
Aqua (EOS PM-1)	NASA	13:30 (A)	705 km	4-May-2002	EOSDIS Direct Broadcast	MODIS, AIRS, CERES, AMSU-A, AMSR-E, HSB	Atmospheric dynamics, water and energy cycle, clouds and aerosols, radiation, GHG, air/sea fluxes, precipitation

SORCE	NASA	40-deg Non Sun-Sync	640 km	25-Jan-2003	GES DISC	SIM, SOLSTICE, TIM, XPS	Total and spectral solar irradiance
Aura	NASA	13:45 (A)	705 km	15-Jul-2004	GES DISC	MLS, TES, HIRDLS, OMI	Chemistry and dynamics of atmosphere, O_3, GHG, aerosols
CALIPSO†	NASA (support from CNES)	13:30 (A)	705 km (689 km)	28-Apr-2006	ASDC	CALIOP, IIR, WFC	Aerosols and clouds vertical profiling
CloudSat†	NASA	13:30 (A)	705 km (689 km)	28-Apr-2006	CloudSat DPC	CPR	Cloud vertical profiling
GPM Core	NASA (support from JAXA)	65-deg Non Sun-Sync	407 km	27-Feb-2014	PMM Data	GMI, DPR	Global precipitation, evaporation, water cycle
OCO-2	NASA	13:30 (A)	705 km	02-Jul-2014	GES DISC	Spectrometer	Carbon dioxide sources and sinks and solar-induced fluorescence
SMAP	NASA	18:00 (A)	685 km	31-Jan-2015	ASF (radar) NSIDC (cryosphere and land microwave)	L-Band Radar, L-Band Radiometer	Soil moisture, freeze-thaw state
CYGNSS (8 small satellites)	NASA	35-deg Non Sun-Sync	500 km	15-Dec-2016	PO.DAAC	GPS	Ocean surface winds for tropical storms and hurricanes

SAGE-III-ISS Intl. Space Station Instrument only	NASA	51.6-deg Non Sun-Sync	407 km	19-Feb-2017	ASDC	Spectrometer	Stratospheric ozone, aerosols, and water vapor
LIS-ISS Intl. Space Station Instrument only	NASA	51.6-deg Non Sun-Sync	407 km	19-Feb-2017	GHRC	Optical Imager	Lightning
TSIS-1-ISS Intl. Space Station Instrument only	NASA	51.6-deg Non Sun-Sync	407 km	15-Dec-2017	GES DISC	SIM, TIM	Total and spectral solar irradiance
GRACE-FO (Follow-On)	NASA	89-deg Non Sun-Sync	490 km	22-May-2018	PO.DAAC	MWA, LRI, Accelerometers, GPS RO	Earth mass distribution, with application to ground water, ocean currents and ice sheets; vertical temperature and humidity profiles of the atmosphere.
ECOSTRESS-ISS Intl. Space Station Instrument only	NASA	51.6-deg Non Sun-Sync	407 km	29-Jun-2018	LP.DAAC	Thermal radiometer	Plant-water dynamics

ICESat-2	NASA	92-deg Non Sun-Sync	500 km	15-Sep-2018	NSIDC	ATLAS	Ice-sheet thickness, sea-ice thickness, vegetation height, carbon and biomass
GEDI-ISS Intl. Space Station Instrument only	NASA	51.6-deg Non Sun-Sync	407 km	5-Dec-2018	LP.DAAC (L1,L2) ORNL DAAC (L3,L4)	LIDAR	Forest vertical structure

† CloudSat exited the A-train constellation in February 2018 by lowering its altitude from 705 km to ~689 km. CALIPSO also exited the A-train constellation and joined CloudSat in formation flying at this lower altitude in September 2018. Although both orbits were initially sun-synchronous, the equator crossing times are being allowed to drift.

Failed / Decommissioned Instruments

** HSB and AMSR-E on Aqua*
** HIRDLS and TES on Aura*
** L-Band Radar on SMAP*

Reduced Function Instruments

** ASTER on Terra (SWIR module not functioning)*
** AMSU on Aqua (channels-1, 2, 4, 5 and 7 failed)*
** SORCE - Battery degradation, Instruments turned off during orbit night*
** CloudSat - Battery degradation, Instruments turned off during orbit night*

3 STATUS OF CURRENT LEO SATELLITE SYSTEMS

In July 2018, **Jason-2** completed its first geodetic cycle in the long-repeat orbit. A few days after it completed the cycle, the satellite moved to an "interleaved" long-repeat orbit to fill in the grid established during the first cycle. The gyro anomalies that began in 2017 continued in 2018, and a decision was made in March 2019 to prolong the most recent safehold mode to allow the gyros to undergo annealing. Recovery will be initiated in late May 2019 when the gyros will be swapped periodically in an effort to avoid future safeholds, and the satellite will maneuverer to "rewind" the ground track so that data collection resumes where it left off in February 2019. The **Jason-3** satellite continues to operate nominally, extending the ocean topography measurements initiated with the TOPEX mission in 1992 and continued through the Jason-1 and Jason-2 missions. The **Suomi-NPP** Cross-track Infrared Sounder (CrIS) experienced the loss of its windwave range band in March 2019. Engineering studies are underway to determine whether this capability can be restored by switching to redundant electronics.

4 STATUS OF CURRENT HEO (OR OTHER) SATELLITE SYSTEMS

The Deep Space Climate Observatory (**DSCOVR**) was launched on February 11, 2015 to the Sun-Earth Lagrange-1 (L1) point, 1.5 million kilometers from Earth towards the Sun, to provide continuous solar wind measurements for accurate space weather forecasting, and to observe the full, sunlit disk of Earth from a unique vantage point. The DSCOVR mission is a joint venture among NOAA, NASA and the U.S. Air Force. NASA built the spacecraft and operates the two Earth science instruments, the Earth Polychromatic Imaging Camera (**EPIC**) and the NIST Advanced Radiometer (**NISTAR**).

EPIC produces RGB color images of the sunlit disk of Earth, typically at least 11 times per day. The DSCOVR vantage point at L1 has afforded opportunities for some unique images, including the passage of the Moon in front of the sunlit disk of Earth, and the passage of a total solar eclipse passing across the Pacific Ocean. All EPIC color images are publicly available through the web page http://epic.gsfc.nasa.gov.

In addition to the RGB images, numerous science products are derived from EPIC, including total column ozone and erythemal irradiance. Aerosol products include UV aerosol index, aerosol optical depth, single scattering albedo, and aerosol and cloud optical depth of aerosol layers above clouds. Two volcanic SO2 algorithms have been developed to retrieve volcanic SO2 columns from EPIC UV radiances. EPIC cloud products include Cloud Mask (CM), Cloud Effective Pressure (CEP), Cloud Effective Height (CEH), and Cloud Optical Thickness (COT). Surface Reflectance products include spectral bidirectional reflectance factors (BRF, aka surface reflectance) and bidirectional reflectance distribution function (BRDF). Vegetation products include Leaf Area Index (LAI) and diurnal courses of Normalized Difference Vegetation Index (NDVI), Sunlit Leaf Area Index (SLAI) and Fraction of incident Photosynthetically Active Radiation (FPAR) absorbed by vegetation.

NISTAR is designed to measure the absolute irradiance reflected and emitted from nearly the entire sunlit face of Earth seen from the L1 point. An accurate measurement of the irradiance provides insight into Earth radiation balance and helps quantify any changes in the radiation budget over time. Level 2 products from both EPIC and NISTAR are currently available at the NASA Langley Atmospheric Science Data Center (https://eosweb.larc.nasa.gov/).

5. STATUS OF CURRENT R&D SATELLITE SYSTEMS

Four new Earth science missions launched in 2018, including two polar orbiting satellites, the Gravity Recovery and Climate Experiment Follow-On (**GRACE-FO**) and the Ice, Cloud and land Elevation Satellite-2 (**ICESat-2**). Two instruments were also deployed on the ISS: the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (**ECOSTRESS**) and the Global Ecosystem Dynamics Investigation (**GEDI**).

GRACE-FO and ECOSTRESS both experienced anomalies that interrupted their data collection. GRACE-FO commissioning was suspended for nearly three months, after the GRACE-FO 2 (GF2) satellite suffered a failure of its primary Instrument Processing Unit (IPU). After recovering on its redundant side, the commissioning resumed in November 2018, and was successfully completed in January 2019. Preliminary Level 1 data products are expected to be released in May 2019. ECOSTRESS lost both the primary and redundant sides of the Mass Storage Unit (MSU), where data were being recorded and stored prior to downlinking via the ISS. The mission is currently testing a method to bypass the MSU and stream the science data files directly. Nevertheless, Level 1B data products were made publicly available in March 2019, at the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/).

Other science data sets continue to be extended with many satellites operating well beyond their design life. Signs of battery aging have been observed on CloudSat and SORCE, both of which require intensive battery management and/or duty-cycling of instruments, which can reduce both quality and spatial/temporal coverage of the datasets. Furthermore, following the failure of one of its reaction wheels (RW #1) in 2017, CloudSat exited the A-train constellation in February 2018, lowering its altitude from 705 km to ~689 km. In September 2018, CALIPSO also exited the A-train and joined CloudSat in formation flying at this lower altitude to resume their coincident measurements. SORCE is currently planned to be decommissioned in January 2020.

QuikSCAT ended its long and noteworthy mission on October 2, 2018, with the final passivation of the spacecraft. During its more than 19-year mission, QuikSCAT established one of the longest climate data records by a single spaceborne instrument, providing crucial ocean vector winds data. The data enabled discoveries of new mechanisms of air-sea interaction, improved forecasting of tropical hurricanes and cyclones, including early detection of the location, direction, structure and strength of tropical and extra-tropical storms. QuikSCAT measurements were instrumental in monitoring ongoing changes of the Earth's systems, including sea ice, land and snow cover, urban extent, carbon biomass, and ocean productivity. The long duration of the QuikSCAT mission also enabled the development of the first global climatologies of winds over the ocean at high spatial resolution.

Instruments with reduced capability (noted in RED, Table 3) are Terra's ASTER (the SWIR module is no longer functional), and Aqua's AMSU (channels 1, 2, 4, 5, and 7 are no longer operational). Other instruments that no longer provide data (also noted in RED, Table 3) are Aqua's HSB and AMSR-E, Aura's HIRDLS and TES, and SMAP's L-Band Radar. All other sensors are fully functional and are producing standard products that meet or exceed specifications.

5.1 Formation Flying

Several of the satellites in Table 3 fly in close proximity to each other at ~705 km altitude and ascending equator crossing times of ~13:30. Known as the A-train, this constellation was built up over more than a decade from the initial launch (Aqua in 2002) through the launches of PARASOL (2004, decommissioned 2013), Aura (2004), CloudSat (2006, exited 2018), CALIPSO (2006, exited 2018), the Japanese GCOM-W1 "SHIZUKU" satellite (2012), and the Orbiting Carbon Observatory-2 (2014). The constellation is actively managed to ensure appropriate separation even in the presence of collision avoidance maneuvers (see section 5.2). This proximity provides nearly-simultaneous measurements even though they are spread across multiple platforms from multiple providers. The broad range of complementary techniques used across these platforms, with different wavelengths and viewing geometries, are particularly valuable in studying atmospheric chemistry and physics because of the need to comprehensively measure physical state and trace gas and particle composition. The value of such coincident measurements was highlighted by the CALIPSO team's decision to follow CloudSat out of the A-train, after the latter's reaction-wheel failure. Despite the exit of these two missions, there remains a strong emphasis in the NASA research program to make synergistic use of the A-train instruments.

5.2 Collision Avoidance Monitoring

Once new missions are launched, NASA must continually monitor their positions to avoid collisions with other satellites. Changing solar activity has led to more uncertainty in collision analysis calculations and consequently intensified analysis and planning activities to determine collision avoidance maneuvers. A history of collision avoidance maneuvers is shown in Figure 1. Active monitoring of close approach events has steadily increased since 2008. In addition, potential conjunctions between operational, maneuverable satellites have increased, necessitating communication between the satellite operators in order to coordinate avoidance maneuver planning. In addition to increasing the resources dedicated to collision assessment, NASA continually improves the agency's orbital debris procedures, and invests in analysis tool improvements.

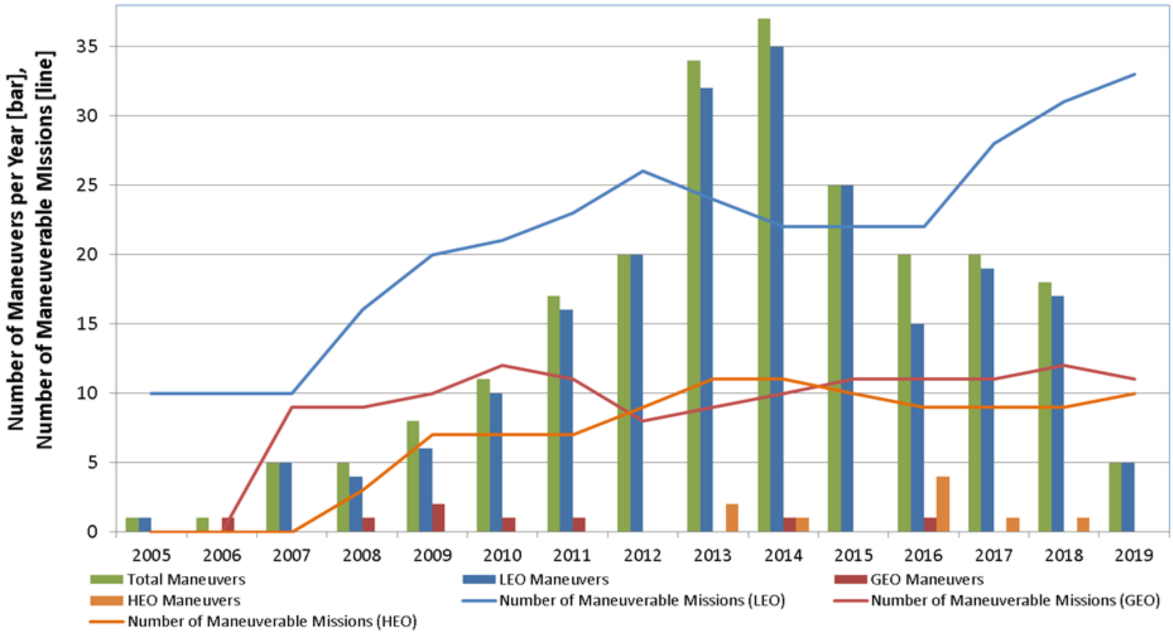

Figure 1: *History of collision avoidance maneuvers.*

5.3 Cyclone Global Navigation Satellite System (CYGNSS)

The CYGNSS constellation of eight satellites was successfully launched on December 15, 2016 into a low inclination (tropical) Earth orbit. Each satellite carries a four-channel bistatic radar receiver that measures GPS signals scattered by the ocean. Measurements of ocean wind speed can be made under all levels of precipitation due to the low frequency at which GPS operates, and frequent sampling of tropical cyclone intensification and of the diurnal cycle of winds is made possible by the large number of satellites.

The mission transitioned to Phase E (continuous on-orbit science operations) in March 2017 and completed its prime mission in March 2019. During the prime mission, data products were continuously delivered to NASA's PO.DAAC data distribution center. Science data quality meets the mission requirements for temporal sampling, spatial resolution and coverage, performance in extreme precipitating conditions, and wind speed retrieval uncertainty below 20 m/s. Between 20 and 60 m/s, retrieval uncertainty is assessed to be 10% above the mission requirement but still adequate to support its scientific investigations of tropical cyclones. In addition, new investigations using measurements over land have begun to study retrieval of soil moisture and flood inundation mapping. CYGNSS was approved to begin extended Phase E operations in March 2019.

5.4 ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)

ECOSTRESS, one of NASA's Earth Venture Instrument (EVI-2) series of missions, was successfully launched from Cape Canaveral Air Force Station in Florida onboard the SpaceX Dragon cargo spacecraft on June 29, 2018. ECOSTRESS was powered on July 6, 2018 aboard the ISS. Perched aboard the ISS, ECOSTRESS uses a multispectral thermal infrared radiometer to provide some of the most detailed temperature images of the Earth's surface ever acquired from space - down to an individual farmer's field - through an optimal combination of thermal infrared (TIR) measurements with high spatiotemporal resolution (<100 m; every few days at varying times of day) (Figure 5).

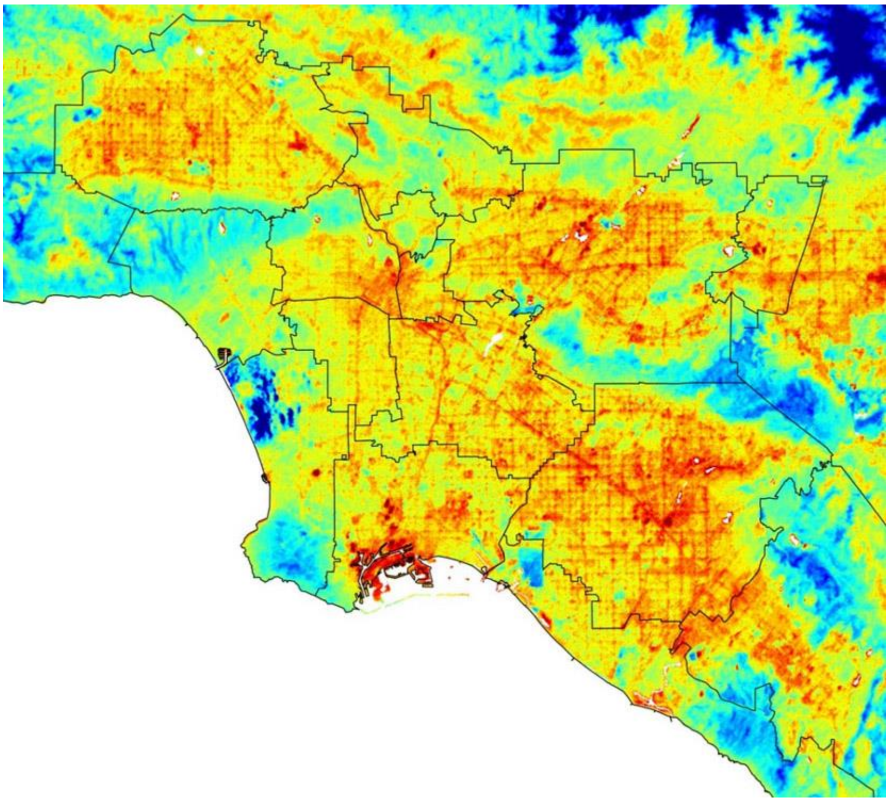

Figure 5: Surface temperature variations in Los Angeles, CA in the early morning hours of July 22, 2018. Hot areas are shown in red, warm areas in orange and yellow, and cooler areas in blue. Credits: NASA/JPL-Caltech.

Taken at varying times throughout the daylight cycle, these high spatiotemporal thermal infrared measurements enable ECOSTRESS to answer several key science questions related to changes in water availability, how changes in daytime vegetation water stress may impact the global carbon cycle, and how agricultural vulnerability may be reduced through advanced monitoring of water use and improved drought estimation. One of the core products produced is the Evaporative Stress Index (ESI) for selected regions of the globe and the contiguous United States.

All data is freely available through the Early Adopter Program. Sign up via the ECOSTRESS website at: https://ecostress.jpl.nasa.gov.

5.5 Global Ecosystem Dynamics Investigation (GEDI)

The Global Ecosystem Dynamics Investigation (GEDI) launched in 2018 will provide precise three-dimensional measurements of Earth's vegetation and topography, data critical for developing an improved understanding the Earth's carbon cycle and the biodiversity of terrestrial ecosystems. The GEDI instrument is a geodetic-class light detection and ranging (lidar) laser system comprised of 3 lasers that produce 8 parallel tracks of observations. GEDI observations quantify forest canopy height, canopy vertical structure, and surface elevation.

GEDI was competitively selected as a NASA Earth Ventures Instrument (EVI) mission in 2014. Cost-capped at $94 million, GEDI is led by the University of Maryland in collaboration with NASA Goddard Space Flight Center. GEDI was successfully launched to the ISS on December 5, 2018 and was integrated onto the ISS JEM-EF (Japanese Experiment Module-External Facility). GEDI was commissioned and transitioned to science operations on March 25, 2019. At the time of this report, a full assessment of data quality is unavailable. However, all systems are working within expected ranges. Lower-level GEDI data products will be available from NASA's Land Processes DAAC within six months of commissioning. Approximately one year after initial data collection, the Oak Ridge National Laboratory Distributed Active Archive Center (DAAC) will begin distributing higher-level data products from GEDI, including forest canopy height metrics and measurements of aboveground biomass and model outputs.

GEDI contains three Nd:YAG lasers, emitting 1064 nm light. These lasers pulse 242 times per second with a power of 10 mJ, firing short pulses of light (14 ns) down towards the Earth's surface with a beam divergence of 56 mrad, resulting in footprints averaging 25 m in diameter. Two of the lasers are full power, and one is split into two beams, producing a total of four beams. Beam Dithering Units (BDUs) rapidly change the deflection of the outgoing laser beams by 1.5 mrad, shifting them by 600 m on the ground. This produces eight ground tracks; four power and four cover tracks. Footprints are separated by 60 m along-track and 600 m across track.

Given the ISS's precessing orbit, GEDI measurements are made over the Earth's surface between 51.6° N and 51.6° S. GEDI can be rotated on the JEM by up to 6°, allowing the lasers to be pointed up to 40 km on either side of the ISS ground track. This capability is used to sample the Earth's land surface as completely as possible, filling in gaps due to clouds. During GEDI's two-year mission life, about 10 billion cloud-free observations of the Earth's surface will be acquired. These observations can then be gridded into regular coverages of varying resolution, such as 1 km grid cells.

5.6 Measurement Continuity and Transition to Follow-on Missions

5.6.1 Solar Spectral Irradiance (SORCE / TSIS-1-ISS / CSIM-FD / CTIM)

NASA continues to explore and support new approaches and technologies to measure the solar spectral irradiance (SSI) at a higher level of accuracy than the Solar Radiation and Climate Experiment (SORCE) and equal to or better than the Total and Spectral Solar Irradiance Sensor on the ISS (TSIS-1-ISS) mission. The **Compact Spectral Irradiance Monitor (CSIM)** instrument, designed for accommodations on a CubeSat or micro-bus, will acquire the same SSI measurements currently being made by the SORCE Spectral Irradiance Monitor (SIM) and the TSIS SIM (Figure 2).

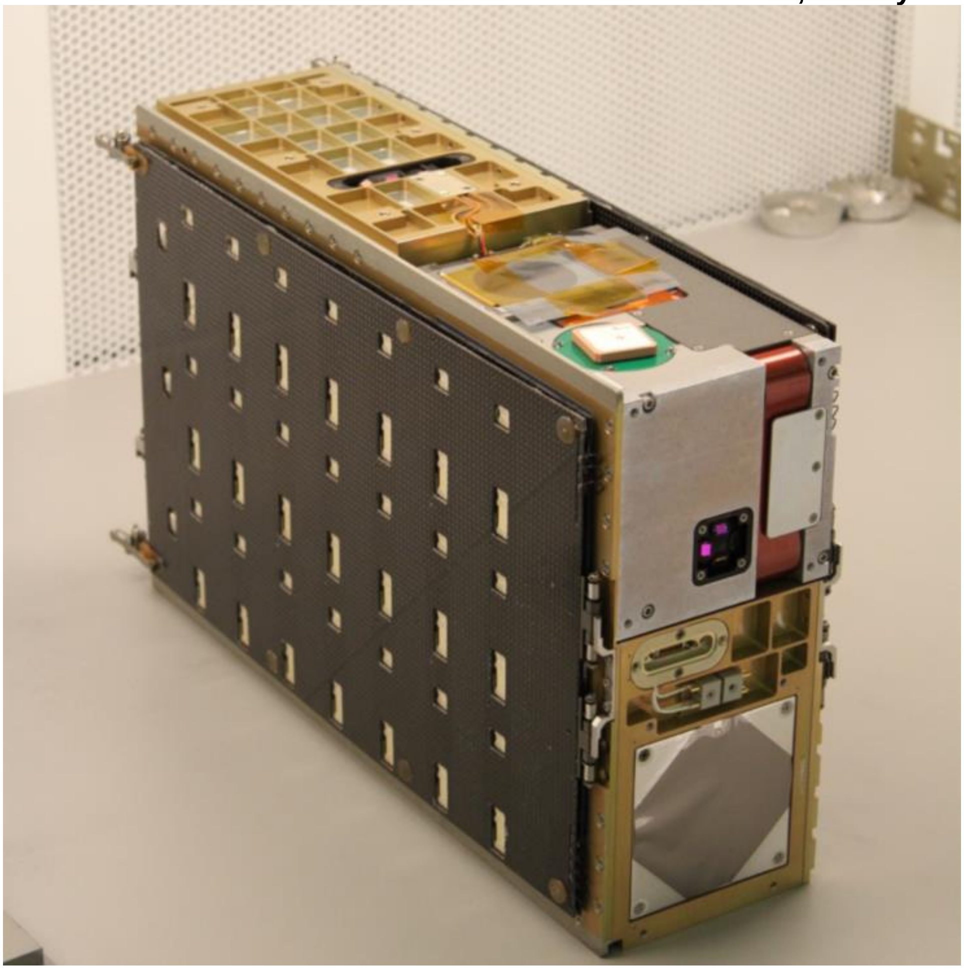

Figure 2: CSIM CubeSat flight hardware prior to launch (Credit: Erik Richard, LASP)

CSIM was launched into a sun-synchronous orbit on December 3, 2018 onboard a SpaceX Falcon 9 rocket as part of a ride-share mission (Spaceflight SmallSat Express). Designed, built, and operated by the University of Colorado’s Laboratory for Atmospheric and Space Physics (LASP), the CSIM instrument marks a significant departure from the previous SIM instruments, achieving large reductions in mass, volume, and power requirements, and enabling a flight-qualified instrument in a 6U CubeSat package, and with performance requirements identical to those for the TSIS SIM.

In early March 2019, the Compact Spectral Irradiance Monitor (CSIM) CubeSat obtained first light results across its full scanning range: a continuous wavelength range of 200-2400 nm (Figure 3).

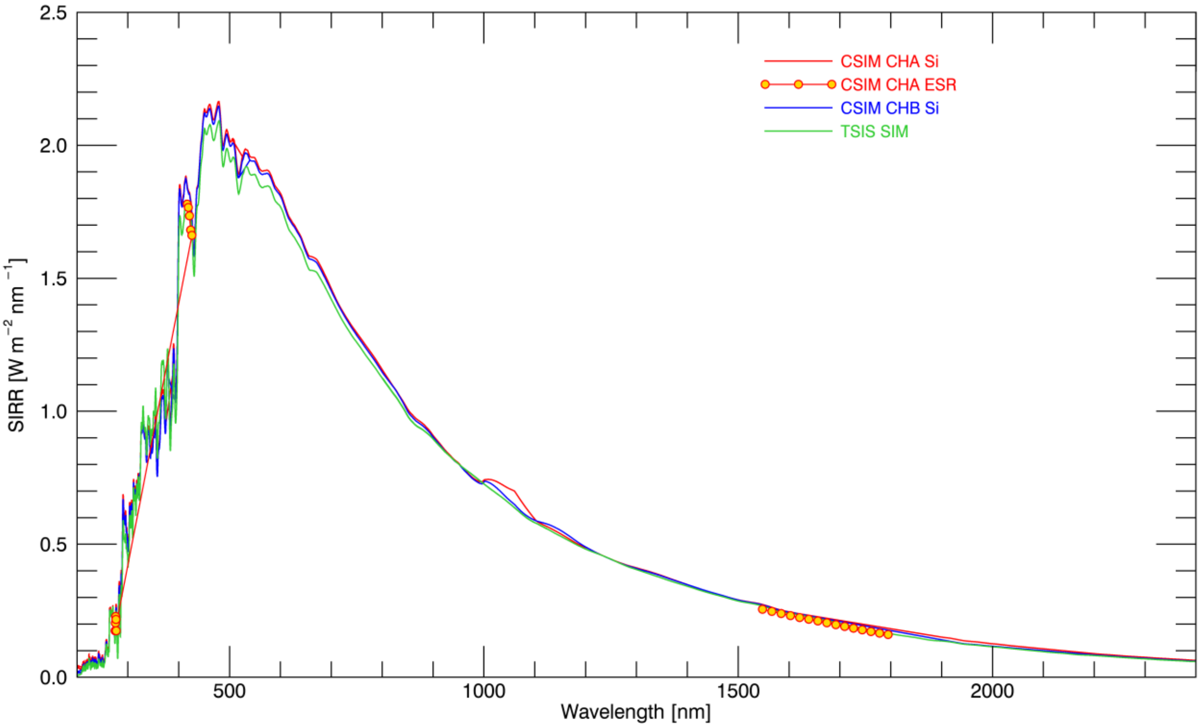

Figure 3: Uncorrected CSIM data showing the full scan range (200-2400) compared to TSIS data. CSIM channel A is shown in red, CSIM channel B is shown in blue, and TSIS SIM data is shown in green. Data from the CSIM's electronic substitution radiometer, which uses carbon nanotubes for onboard calibration, is shown in yellow circles. (Credit: Erik Richard, LASP)

Like TSIS SIM, CSIM underwent extensive radiometric absolute spectral calibrations in the LASP Spectral Radiometry Facility (SRF) in early 2017 to achieve the same calibration and stability performance of TSIS SIM (see Table 3). Like the SORCE and TSIS TIM and SIM, CSIM SIM uses redundant channels to track and correct the solar-exposure related degradation. While TSIS SIM is a three-channel instrument designed to maintain on-orbit long-term stability through full inter-channel cross calibrations activities, CSIM is a two-channel instrument (like SORCE SIM) for which analysis has shown the long-term stability can be maintained for several years. The primary measurement channel is used to obtain the twice-daily solar spectral irradiance. The secondary channel will then be used less frequently (~10% duty cycle) to correct the solar exposure degradation in the primary channel.

CSIM will produce a number of advances in future satellite SSI measurements. First, CSIM will demonstrate the viability of a 6U CubeSat SSI monitor to benefit the long-term SSI climate data record by providing short development cycles at reduced costs that can offer rapid response to augment larger missions where the risk of launch delays and measurement gaps are real (Figure 4).

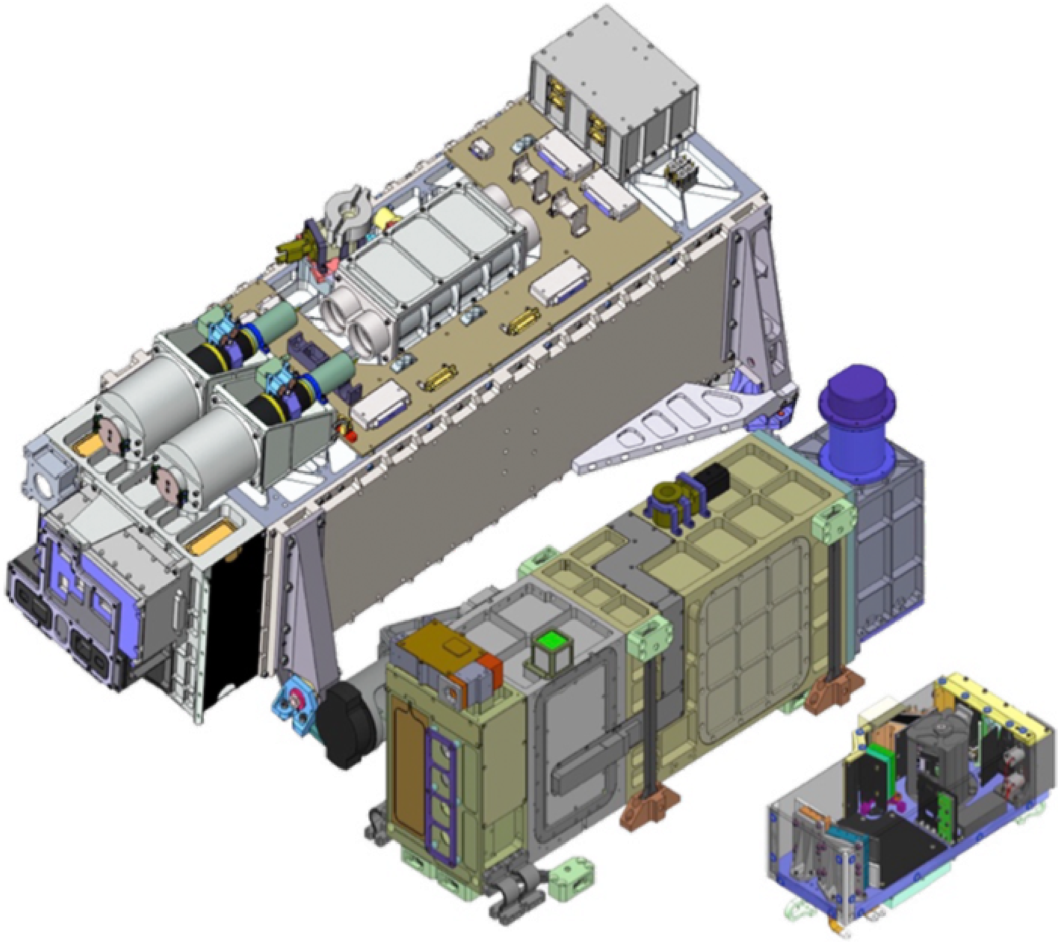

Figure 4: Relative size comparison between (left to right) SORCE, TSIS, and CSIM (Credit: NASA)

Second, it will raise the Technology Readiness Level (TRL) of several new technologies that can be applicable to other instruments. Third, the timing of this flight overlaps with the SORCE SIM instrument and the TSIS SIM instrument resulting in improved accuracy of the SSI climate record and providing an end-of-mission calibration for SORCE SIM. Operational overlap between the TSIS SIM and CSIM instrument is particularly interesting because the calibration of both instruments is tied to the same calibration facility. With more than 6 months of operational overlap, the data trends for each instrument can be compared, providing a unique opportunity to validate the technique for degradation tracking using redundant channels. Finally, CSIM can mitigate a potential data gap between SORCE and TSIS SIM instruments should a significant delay occur in the TSIS program.

As noted in section 6.4, the In-Space Validation of Earth Science Technologies (InVEST) program has also recently selected the Compact Total Irradiance Monitor (**CTIM**) project, a companion to the CSIM CubeSat. The CTIM effort will build and fly a next-generation total solar irradiance (TSI) instrument onboard a 6U CubeSat.

5.7 Additional Successful CubeSat Technology Satellite Demonstrations

Several additional technology demonstration satellites that may be of interest to CGMS members are currently in Earth orbit or are planned to launch in the near future. Two were selected in response to the 2015 solicitation from the In-Space Validation of Earth Science Technologies (InVEST) program under NASA's Earth Science Technology Office (ESTO), and one was selected for technology demonstration in response to the Earth Venture Instrument (EVI-2) call in 2014.

The **IceCube** 3U CubeSat, launched in April 2017 on a ULA Atlas V 401 rocket carrying Orbital ATK's seventh contracted commercial resupply services mission (OA-7) to the ISS, performed the space validation of an 883 GHz submillimeter wave radiometer for ice cloud remote sensing. Global cloud ice and properties are critical for quantifying the role of clouds in the Earth system. Submillimeter wave remote sensing has the capability to penetrate clouds and measure ice mass and microphysical properties. Following deployment from ISS in May 2017, IceCube spun continuously around the axis to the Sun at ~1.2 degrees per second, allowing for maximum solar power reception and periodic Earth and space views for instrument calibration. IceCube operated in LEO for over one year and produced the first map of the global distribution of atmospheric ice in the 883-Gigahertz band (Figure 6). IceCube deorbited in October 2018.

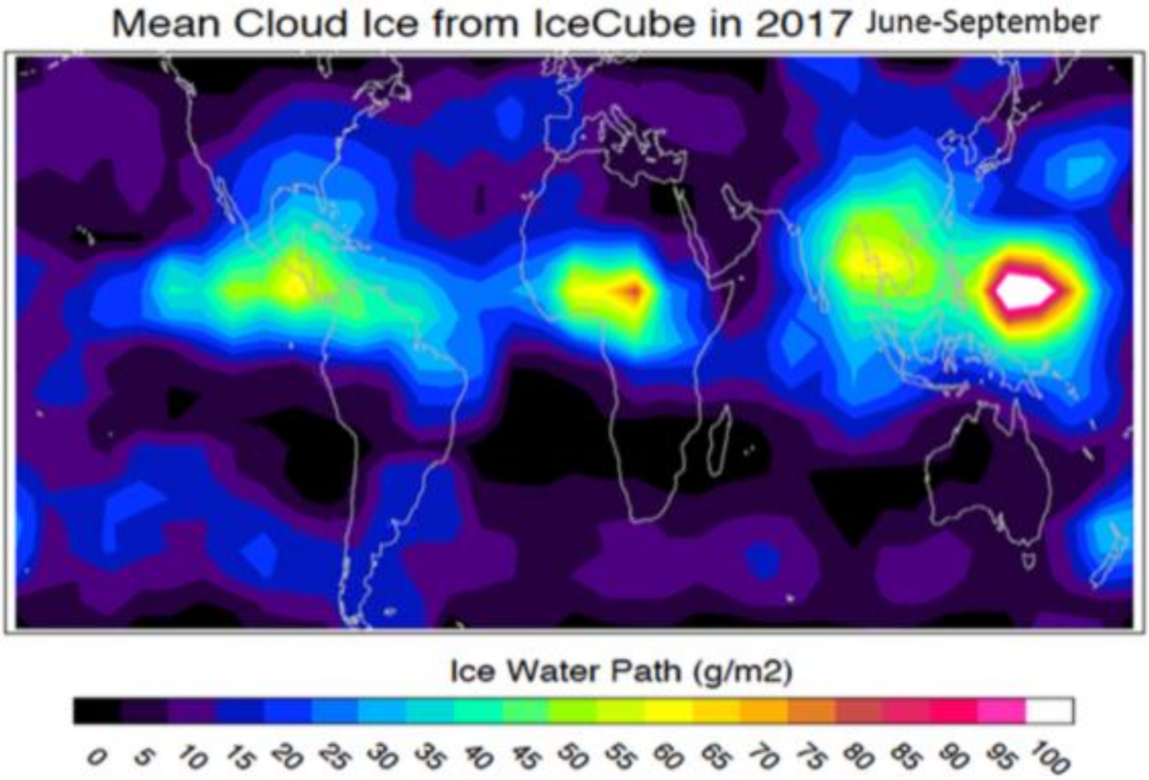

Figure 6: The first ever 883-GHz Cloud Ice Map (Credit: Dong Wu-APL)

The Radar-in-a-CubeSat (**RainCube)** consists of a miniaturized Ka-band precipitation radar within a 6U CubeSat platform. The RainCube radar has a performance defined to emulate the nadir azimuth of the Ka-band channel of GPM's DPR: for the InVEST technology demonstration the requirements are 250 m vertical resolution, 10 km horizontal resolution, and sensitivity of 20 dBZ. RainCube adopts a novel system architecture, high purity pulse compression and a highly constrained lightweight deployable antenna to achieve these performance goals within the mass, volume and power constraints imposed by the 6U class form factor. Launched in May 2018 to the ISS as part of the Cygnus OA-9 resupply payload, and subsequently deployed from ISS in July 2018, RainCube has captured data of numerous rain events, including tropical cyclones in the Atlantic and Pacific during the 2018 storm season (Figure 7).

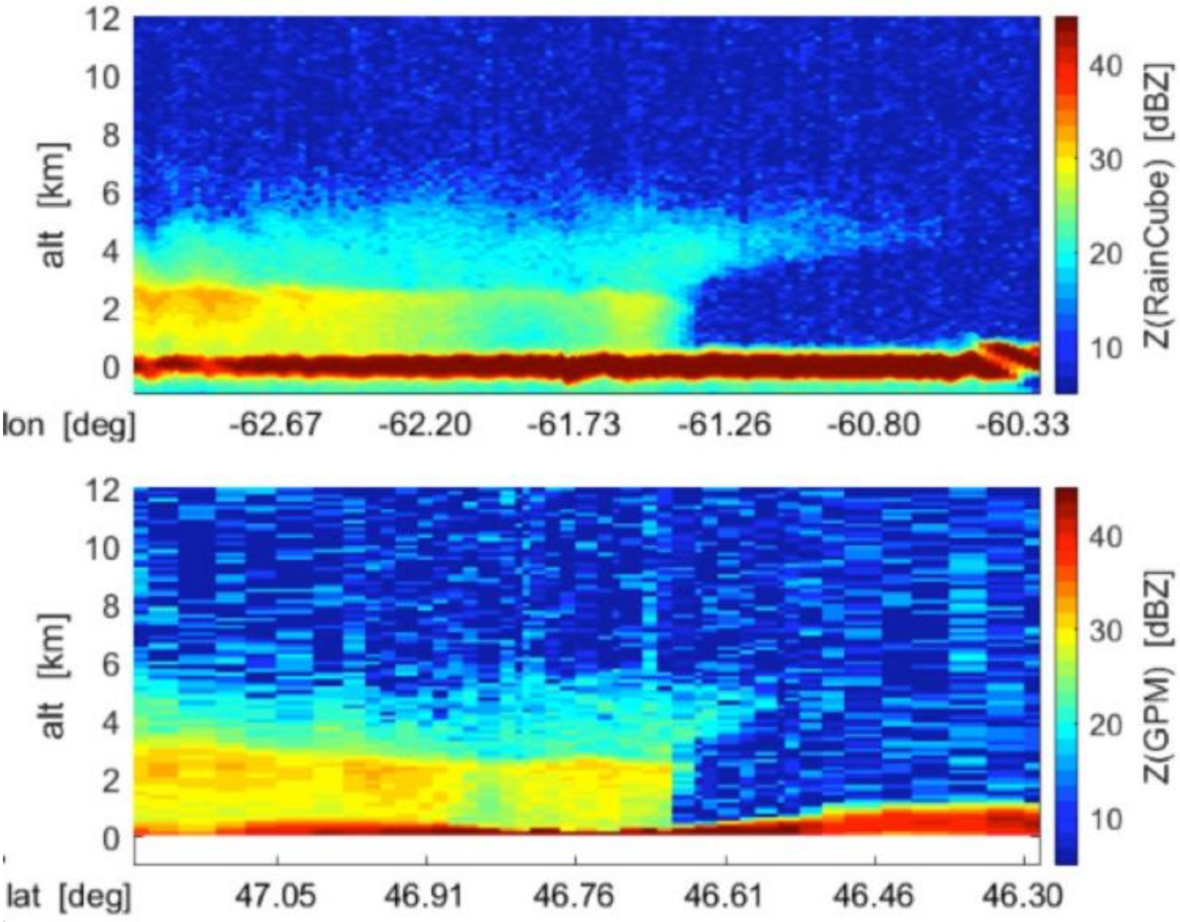

Figure 7: Collocated measurements of vertical rain reflectivity profiles acquired by RainCube (top panel) and GPM's Ka-band radar (bottom panel) on January 25, 2019.

Finally, the Temporal Experiment for Storms and Tropical Systems Technology Demonstration (**TEMPEST-D**), a NASA Earth Venture Instrument project, is demonstrating technology on orbit to reduce the risk, cost and development time for a potential future TEMPEST mission. The TEMPEST-D radiometer provides observations at five millimeter-wave frequencies from 89 to 183 GHz using a single instrument on a 6U platform. TEMPEST-D was launched to the ISS in May 2018 as part of the Cygnus OA-9 resupply payload and was subsequently deployed from the ISS in July. Shortly after achieving first light in September 2018, TEMPEST-D captured data of Hurricane Norman off the coast of Hawaii as well as its first full swath image of Hurricane Florence in the Atlantic Ocean (Figure 8).

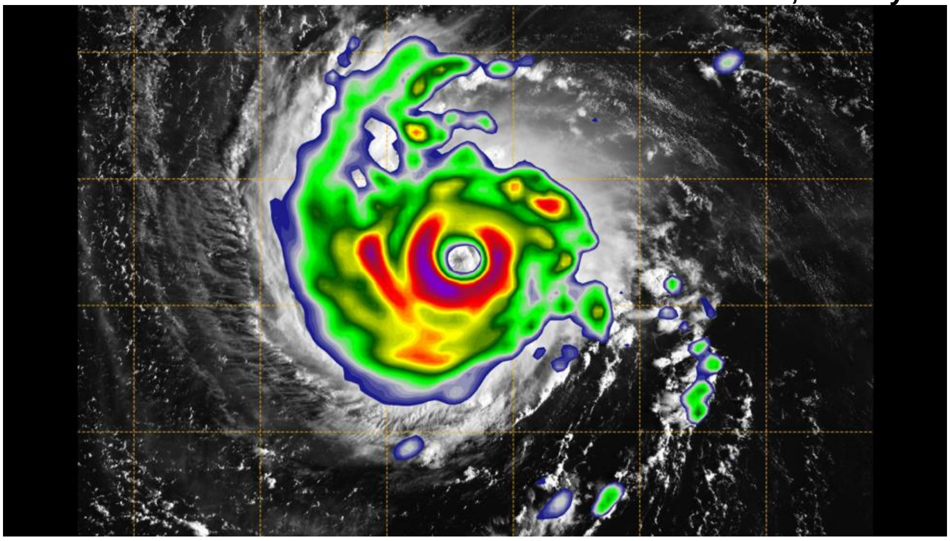

Figure 8: This image was taken by TEMPEST-D as it flew over Hurricane Florence on Sept. 11, 2018. The colors reveal the eye of the storm, surrounded by towering, intense rain bands. The green areas highlight the extent of the rain being produced by the storm, with the most intense rain shown in the yellow and red areas.

The key objectives of the TEMPEST-D are to demonstrate cross-calibration with at least one other orbiting radiometer to 2 Kelvin inter-satellite precision or better and to demonstrate feasibility of orbital drag maneuvers to control a 6U-class spacecraft altitude to 100 m or better.

6. FUTURE SATELLITE SYSTEMS

6.1 Earth Systematic Missions (ESM)

NASA's ESM includes a broad range of multi-disciplinary science investigations aimed at developing a scientific understanding of the Earth system and its response to natural and human-induced forces and changes. The ESM program develops Earth observing research satellite missions, manages the operation of NASA facility research missions once on orbit, and produces standard mission products in support of NASA and national research, applications, and policy communities. The formulation and development of the 2007 Decadal Survey missions have been led by the ESM program. The remaining mission most relevant to CGMS members is the Surface Water Ocean Topography (**SWOT**) mission. Others include: the NASA-ISRO Synthetic Aperture Radar (**NISAR**); the Plankton, Aerosol, Cloud, ocean Ecosystem (**PACE**[1]) mission, and the Climate Absolute Radiance and Refractivity Observatory Pathfinder instrument on the ISS (**CLARREO PF-ISS**[1]). NASA is also continuing its partnership with the U.S. Geological Survey (USGS) to extend the Landsat series with **Landsat-9**.

[1] Development continues through FY19 consistent with the Consolidated Appropriations Act 2019. Identified for termination in FY20 in the President's FY20 Budget Proposal released March 11, 2019.

6.2 Earth System Science Pathfinder (ESSP)

ESSP provides an innovative approach to Earth science research by providing frequent, regular, competitively selected opportunities that accommodate new and emerging scientific priorities and measurement capabilities. These opportunities represent a series of relatively low-to-moderate cost, small-to-medium sized missions[2]. They are competitively selected, principal investigator led missions that focus on scientific objectives to support a selected subset of studies of the atmosphere, oceans, land surface, polar ice regions, or solid Earth. NASA currently funds the Earth Venture-class (EV) missions, and several other missions and instruments in pre-formulation under ESSP. The EV missions are part of a competitive program to select small instruments, small satellites, or airborne science campaigns to complement the strategic NASA Earth science missions.

The first Earth Venture Instrument investigation (EVI-1), selected in 2012, the Tropospheric Emissions: Monitoring of Pollution (**TEMPO**) mission, will be the first space-based sensor to monitor major chemical air pollutants across North America hourly during daytime. It will share a ride on a commercial communications satellite in geostationary orbit as a hosted payload.

The EVI-3 selection in 2016 included the Multi-Angle Imager for Aerosols (**MAIA**) and the Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (**TROPICS**) missions, which are both low-Earth orbit investigations. Observations of small atmospheric aerosols from MAIA will be combined with health information to determine the toxicity of different particulate matter types in airborne pollutants over the world's major cities. The TROPICS mission will develop and launch a constellation of CubeSats to study the development of tropical cyclones through rapid-revisit sampling.

The most recent selections (EVI-4) made in early 2018 were the Polar Radiant Energy in the Far Infrared Experiment (**PREFIRE**) and the Earth Surface Mineral Dust Source Investigation (**EMIT**). PREFIRE will fly a pair of small CubeSat satellites to probe a little-studied portion of the radiant energy emitted by Earth for clues about Arctic warming, sea ice loss and ice-sheet melting. EMIT will be mounted to the exterior of the ISS to determine the mineral composition of natural sources that produce dust aerosols around the world and help answer the essential question of whether these types of aerosols warm or cool the atmosphere.

An announcement of opportunity was released for the fifth installment of the Earth Venture instrument program, and proposals are currently under evaluation.

The second mission selected under the Earth Venture Mission (EV-M) program, GeoCARB, selected in late 2016, continues to make progress towards future launch NET early 2020's. GeoCARB will be in a geostationary orbit and will measure column amounts of carbon dioxide, methane, carbon monoxide, and Solar Induced Fluorescence (SIF) over much of the Western Hemisphere.

6.3 2nd Decadal Survey for Earth Science and Applications from Space

The US National Academies of Science, Engineering, and Medicine issued its second decadal survey for Earth sciences in 2018. This report, entitled *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*, came out in preliminary form in early 2018 and in final form in the spring of 2019. This report is available from the National Academies Press (https://www.nap.edu/download/24938) and may be downloaded for free as a PDF file. This report was requested jointly by NASA, NOAA, and the US Geological Survey (USGS), and includes both general and agency-specific recommendations. In this summary, a small subset of the recommendations and findings relevant to NASA and of interest to the CGMS community are summarized. Readers are encouraged to consult the full report for more information.

In the interval between the release of the preliminary version of the report in early 2018 and the present, NASA has already taken several steps towards implementing the recommendations in the report. Those steps will also be summarized in this summary. A fuller report on the status of these activities may be found at https://science.nasa.gov/earth-science/decadal-surveys. Note that every four months, NASA hosts a community forum that allows for participation from all members of the Earth Science community (including international participation). Information about the schedule for those fora may be found at https://science.nasa.gov/earth-science/decadal-survey-community-forum.

The survey contained a strong endorsement of the “program of record” (the series of existing or previously planned observations) that was in place as of the release of the survey. This includes satellites or instruments that have launched within the past year (including GRACE-FO, ECOSTRESS, ICESat-2, and GEDI), as well as many others, including both directed missions and those selected as part of NASA’s Earth Venture program. For future measurements, the survey described several classes, emphasizing the types of observations that were needed rather than specific missions (as had been called for in the first decadal survey for Earth Science (*Earth Science and Applications From Space (ESAS): National Imperatives for the Next Decade and Beyond* released in 2007 – see https://www.nap.edu/catalog/11820/earth-science-and-applications-from-space-national-imperatives-for-the).

The classes of observations and steps taken by NASA so far include the following:

- ***Designated***: *“A program of cost-capped medium and large-size missions to address observables essential to the overall program, directed or competed at the discretion of NASA.”* Five such observables were defined (Aerosols; Clouds, Convection, and Precipitation; Mass Change; Surface Biology and Geology; and Surface Deformation and Change). NASA has begun a series of implementation studies using the combined resources of several NASA centers, as well as involving community members. These studies began in the fall of 2018 and will last for approximately two years and should help define potential implementation approaches and also identify potential partnership relationships and contributions. For the purposes of these studies, a single integrated study was initiated that combined the aerosol and clouds, convection, and precipitation observables that were identified in the survey.

- ***Earth System Explorer***: *"A new program element involving competitive opportunities for cost-capped medium-size instruments and missions serving specific ESAS-priority observations."* The survey identified seven such observations (greenhouse gases; ice elevation; ocean surface winds and currents; ozone and trace gases; snow depth and snow water equivalent; terrestrial ecosystem structure; and atmospheric winds). NASA has not yet begun implementation of this element, but will do so when budget flexibility allows.

- ***Incubation***: *"A new program element, focused on investment for priority observation capabilities needing advancement prior to cost-effective implementation, including an innovation fund to respond to emerging needs."* The survey identified three types of observations – atmospheric winds (also in the Explorer category above), planetary boundary layer, and surface topography and vegetation. NASA decided to focus its early work for Incubation on the latter two (given that atmospheric winds was also in the Explorer category). NASA is planning to engage the community through an open solicitation currently being finalized to support the development of reports for each that can inform NASA's future research and technology investments in this area in the future (when released, that solicitation may be found at https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=660372/solicitationId=%7BABB576B8-F844-25E0-AD23-9E94AAC04AE1%7D/viewSolicitationDocument=1/Table%203%202019_amend3.html). Such investments may be made through a mix of competitive and directed processes.

- ***Earth Venture***: *"Earth Venture program element, as recommended in ESAS 2007, with the addition of a new Venture-continuity component to provide opportunity for low-cost sustained observations."* The first Earth Venture Continuity (EV-C) solicitation was released on December 19, 2018 and subsequently amended for proposals to be due on July 26, 2019. The focus for this solicitation was limited to measurements of the Earth's radiation budget, specifically "for cost-capped activities resulting in the design, implementation, on-orbit characterization and scientific exploitation of observations from a capable observing system, to measure top of the atmosphere (TOA) short wave (SW), long wave (LW), and total radiative fluxes (SW plus LW)."

6.4 In-Space Validation of Earth Science Technologies (InVEST) Program

The HyperAngular Rainbow Polarimeter (**HARP**) CubeSat was selected in response to the 2012 solicitation from the In-Space Validation of Earth Science Technologies (InVEST) program under NASA's Earth Science Technology Office (ESTO). HARP is scheduled to launch to the ISS in late 2019 or early 2020 and will perform a technology validation of a wide field of view (FOV) imaging polarimeter for characterizing aerosol and cloud properties as required by the Aerosol-Cloud-

Ecosystem (ACE) mission concept. HARP uses modified Philips prisms to split 3 identical images into 3 independent imaging detector arrays. This technique achieves simultaneous imagery of the 3 polarization states and is the key innovation to achieve high polarimetric accuracy with no moving parts. The spacecraft consists of a 3U CubeSat with 3-axis stabilization designed to keep the polarimeter pointing nadir.

In July 2018, NASA selected four new proposals in response to the 2017 solicitation from the InVEST program. The 2017 InVEST solicitation was targeted to small instruments and instrument subsystems that can advance technology to enable relevant Earth science measurements and was limited to in-space validation utilizing the CubeSat platform. One of these selections is relevant for the CGMS, as follows:

The Compact Total Irradiance Monitor (**CTIM**) project, a companion to the CSIM CubeSat discussed in section 5.6.1, will build and fly a next-generation total solar irradiance (TSI) instrument onboard a 6U CubeSat. This instrument will meet the measurement requirements of the previous generation instruments while being compact enough to fit on a CubeSat platform. To accomplish this, CTIM will utilize new technologies, including silicon-based vertically aligned carbon nanotube (VACNT) bolometers. This compact, lower-mass instrument has shorter fabrication times and lower costs which should provide more flight opportunities, helping reduce the risk of future TSI-measurement data gaps. With launch planned for no earlier than 2020, the one-year mission will test the on-orbit performance of the CTIM directly against the Total and Spectral Solar Irradiance Sensor (TSIS) Total Irradiance Monitor (TIM) currently operating on the ISS in order to test initial measurement accuracy as well as long-term stability of the measurements over the mission life.

Table 4 - Future NASA Research and Development (R&D) Satellites

Satellite	Space Agency	Orbit Information	Launch Date (NET)	Instruments	Details: Applications
OCO-3-ISS Intl. Space Station Instrument only	NASA	51.6-deg inclination Non Sun-Sync 407 km	2019	Spectrometer	Carbon dioxide sources and sinks and solar-induced fluorescence
TROPICS	NASA	LEO constellation	2020	Microwave radiometer	Precipitation, temperature, humidity, imagery, cloud ice
Landsat-9	NASA/USGS	98.2-deg inclination Sun-Sync, 10:00 (D) 650 km	2020	OLI-2, TIRS-2	High-resolution imagery of the Earth's surface (follow-on in the Landsat series)
TEMPO Hosted Payload Instrument only	NASA	Geosynchronous	>2020	UV and VIS spectrometer	Atmospheric pollution over the Americas; tropospheric ozone, ozone precursors, aerosols, and clouds
SWOT	NASA/CNES	77.6-deg inclination Non Sun-Sync 891 km	2021	Ka-Band Radar Interferometer, AMR, GPSP, LRA, Poseidon Altimeter	Oceanography (wide swath ocean surface topography) and hydrology (lake levels, river discharge)
PREFIRE	NASA	Near-polar 470-650 km	2021	Grating spectrometer	Energy exchange between surface and atmosphere in the Arctic
EMIT-ISS Intl. Space Station Instrument only	NASA	51.6-deg inclination Non Sun-Sync 407 km	2021	Imaging spectrometer	Mineral composition of natural dusts; thermal impacts on atmosphere

NISAR	NASA/ISRO	98-deg inclination Sun-Sync, 6AM-6PM 747 km	2022	L-band, S-band SAR (repeat-pass interferometry, polarimetry)	Earth surface deformation, ecosystems and biomass change, ice motion
MAIA Hosted Payload Instrument only	NASA	Sun-Sync 740 km	2022	Multi-angle imager	Atmospheric aerosols
GeoCarb Hosted Payload Instrument only	NASA	Geosynchronous	2022	Grating spectrometer	Concentrations of carbon dioxide, methane, and carbon monoxide and solar-induced fluorescence
PACE	NASA	98-deg inclination Sun-Sync 676.5 km	2022	OCI, Polarimeters	Aerosols, clouds, ocean color
TSIS-2	NASA	TBD	2022	Absolute ESR detector (NiP bolometer)	Solar spectral irradiance
CLARREO PF-ISS Intl. Space Station Instrument only	NASA	51.6-deg inclination Non Sun-Sync 407 km	2023	Spectrometer	Reflected solar Earth radiance

7. ADDITIONAL TOPICS OF RELEVANCE TO CGMS

7.1 Commercial Satellite Data Buy

NASA has begun to implement a Commercial Satellite Data Buy Pilot program designed to determine whether Earth science data from commercial small-satellite constellations offer a cost-effective means to supplement the suite of Earth observations acquired directly by NASA, other U.S. government agencies, and international partners. On September 28, 2018, following release for a Request for Information (RFI) to potential participants, NASA awarded sole-source contracts to acquire test data sets from three private entities:

- **DigitalGlobe**, a Maxar Technologies company headquartered in Westminster, Colorado, has five very high-resolution Earth imaging satellites (GeoEye-1, WorldView-1, WorldView-2, WorldView-3, WorldView-4) capable of collecting 30-centimeter resolution imagery.

- **Planet Lab**, headquartered in San Francisco, has three satellite constellations (SkySat, Dove, RapidEye) with more than 150 satellites supplying imagery and derived products over the entire Earth at medium and high resolution with high repeat frequencies.

- **SPIRE**, headquartered in San Francisco, operates a constellation of over 60 satellites collecting radio occultation soundings, aircraft location information and ship reports. GPS radio occultation measurements can be used to sound the atmosphere for temperature, water vapor, and atmospheric pressure.

These contracts represent the first time that NASA has engaged with commercial small-satellite constellation operators to purchase their data for scientific evaluation. They establish a way for NASA to acquire and examine the data products during the next 12 months. Each contract includes an option for NASA to extend the agreement for an additional four years, for a total value of up to $7 million for each of the three agreements. To be considered for participation in this pilot program, companies had to demonstrate they were currently operating a small satellite constellation of no fewer than three satellites in non-geostationary orbit and producing consistent global coverage. Companies also were asked to supply a comprehensive catalog of their data, describing areal coverage, data latency, pricing, and other factors.

NASA has augmented tasks of approximately 30 current research or application investigators to allow them to assess the adequacy of the purchased data in achieving their research and/or applications objectives. These researchers, whose activities span a range of research and application areas (e.g., land cover land use change, oceanography, atmospheric science, cryospheric science, health and air quality, natural disasters), have only recently begun their assessment activities. Preliminary reports are to be provided at an investigator meeting on April 30, 2019, with more complete responses due in late 2019.

7.2 Competed Research and Suborbital Investigations

7.2.1 U.S. Participating Investigator (USPI-18)

NASA solicits proposals for the U.S. Participating Investigator (USPI) investigations on a foreign space mission that address the Earth Science Research Program objectives listed in the NASA Science Plan every 2 years. This research contributes and facilitates access to foreign space agencies' assets. Investigators may serve as a member of a foreign space mission science or engineering team and participate in science team activities such as mission planning, mission operations, data processing, data analysis, and data archiving. In response to its 2018 research announcement, NASA received 26 proposals and selected six, reflecting the foci described above.

The following selected investigations will expand scientific links with future European, Asian, and South American space missions:

- **Polar IST**: Polar Ocean and Land-ice Assessments with Radar Altimetry from the Polar Ice and Snow Topography mission
- **SABIA-Mar**: Algorithm development (photosynthetically available radiation, atmospheric correction) in support of the SABIA-Mar ocean-color mission
- **EnMAP**: Cryosphere physical properties from the DLR EnMAP imaging spectrometer
- **HISUI**: L2 reflectance and L3 plant functional trait retrieval for HISUI
- **EarthCARE**: Cloud, convection and precipitation radar products - algorithm development and product calibration and validation
- **Sentinel-2**: Adapting a new ocean color algorithm to enhance water quality and validation capabilities for the future Sentinel constellation

The total funding for these investigations, over a period of five years, is approximately $4.9 million.

7.2.2 Earth Venture Suborbital (EVS-3) Investigations

Five new NASA Earth science campaigns will take to the field starting in 2020 to investigate a range of pressing research questions, from what drives intense East Coast snowfall events to the impact of small-scale ocean currents on global climate.

These studies will explore important, but not-well-understood, aspects of Earth system processes and were competitively selected as part of NASA's Earth Venture-class program. This is NASA's third series of Earth Venture suborbital investigations, which are regularly solicited, sustained observation projects first recommended by the National Research Council in 2007. The first set of five projects was selected in 2010, and the second in 2014.

The five newly selected Earth Venture investigations are:

- **Aerosols changing clouds** – Aerosol Cloud Meteorology Interactions over the Western Atlantic Experiment (ACTIVATE) will identify how aerosol particles change cloud properties in ways that affect Earth's climate system. The investigation will focus on marine boundary layer clouds over the western North Atlantic Ocean that have a critical role in our planet's energy balance. Two NASA research aircraft, an HU-25 Falcon and a B-200 King Air, will fly from NASA's Langley Research Center in Hampton, Virginia, to gather measurements from above, below, and within the marine boundary layer clouds.

- **Impact of strong storms on stratosphere** –Dynamics and Chemistry of the Summer Stratosphere (DCOTSS) project will investigate how strong summertime convective storms over North America can change the chemistry of the stratosphere. These storms regularly penetrate deep into the lower stratosphere, carrying pollutants that can change the chemical composition of this atmospheric layer, including ozone levels. Flights of NASA's ER-2 high-altitude aircraft will be based out of Salina, Kansas (Figure 9).

- **Intense snowfall events** – Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) project will study the formation of snow bands in East Coast winter storms. Better understanding of the mechanisms of snow band formation and the factors that influence the location of the most intense snowfall will help improve forecasts of these extreme weather events. This study will involve flights of NASA's ER-2 and P-3B research aircraft over the northeastern United States (Figure 9).

- **Ocean heating of the atmosphere** – Submesoscale Ocean Dynamics and Vertical Transport (S-MODE) investigation will explore the potentially large influence that small-scale ocean eddies have on the exchange of heat between the ocean and the atmosphere. The project will collect a benchmark data set of climate and biological variables in the upper ocean that influence this exchange. Measurements will be collected by research aircraft and shipborne instruments 200 miles off the coast of San Francisco.

- **River deltas and sea level rise** – Delta-X investigation will better understand the natural processes that maintain and build land in major river deltas threatened by rising seas. The project will improve models that predict loss of coastal land from sea level rise by improving estimates of how deltas add land—a process that involves trapping sediments and creating organic soils as plants grow. Delta-X will focus on the Mississippi River Delta using instruments on three NASA research aircraft (Figure 10).

A total of six NASA centers and 27 educational institutions are participating in these five Earth Venture projects. The five-year investigations were selected from 30 proposals. The Delta-X project is funded at a total cost of no more than $15 million; each of the other projects is funded at no more than $30 million.

Competitively selected orbital missions and field campaigns in this program provide innovative approaches to address Earth science research with frequent windows of opportunity to accommodate new scientific priorities. The agency's observations of Earth's complex natural environment are critical to understanding how our planet's natural resources and climate are changing now and could change in the future.

Figure 9: NASA's high-altitude ER-2 research aircraft will be used in two new projects to study the impact of strong summer storms on the stratosphere and intense snowfall events along the U.S. East Coast. Credits: NASA

Figure 10: The new Delta-X project will study parts of the Mississippi River Delta and the processes that build and maintain land in deltas threatened by rising seas. Credits: NASA