NASA/CP–20210010046

Second Time-Resolved Observations of Precipitation Structure and Storm Intensity With a Constellation of Smallsats (TROPICS) Mission Applications Workshop

E.B. Berndt
Marshall Space Flight Center, Huntsville, Alabama

J.P. Dunion
NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida

E.L. Duran
University of Alabama in Huntsville, Huntsville, Alabama

P.T. Duran
Marshall Space Flight Center, Huntsville, Alabama

W.J. Blackwell
Massachusetts Institute of Technology, Cambridge, Massachusetts

S.A. Braun
Goddard Space Flight Center, Greenbelt, Maryland

D.S. Green
NASA Headquarters, Washington, DC

Proceedings of a Workshop held at the University of Miami Rosenthal School of Marine and Atmospheric Studies Auditorium, Miami, Florida,
Hosted by the Cooperative Institute for Marine and Atmospheric Studies, University of Miami,
Organized by the NASA Earth Science Division
Applied Science Program, February 19–20, 2020

February 2021

The NASA STI Program…in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results…even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>

- E-mail your question via the Internet to <help@sti.nasa.gov>

- Phone the NASA STI Help Desk at 757–864–9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681–2199, USA

NASA/CP—20210010046

Second Time-Resolved Observations of Precipitation Structure and Storm Intensity With a Constellation of Smallsats (TROPICS) Mission Applications Workshop

E.B. Berndt
Marshall Space Flight Center, Huntsville, Alabama

J.P. Dunion
NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida

E.L. Duran
University of Alabama in Huntsville, Huntsville, Alabama

P.T. Duran
Marshall Space Flight Center, Huntsville, Alabama

W.J. Blackwell
Massachusetts Institute of Technology, Cambridge, Massachusetts

S.A. Braun
Goddard Space Flight Center, Greenbelt, Maryland

D.S. Green
NASA Headquarters, Washington, DC

Proceedings of a Workshop held at the University of Miami Rosenthal School of Marine and Atmospheric Studies Auditorium, Miami, Florida,
Hosted by the Cooperative Institute for Marine and Atmospheric Studies, University of Miami,
Organized by the NASA Earth Science Division
Applied Science Program, February 19–20, 2020

February 2021

Available from:

NASA STI Information Desk
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681–2199, USA
757–864–9658

This report is also available in electronic form at
<http://www.sti.nasa.gov>

TABLE OF CONTENTS

1. BACKGROUND 1

2. WORKSHOP PURPOSE AND OBJECTIVES 3

3. WORKSHOP ORGANIZATION 4

4. WORKSHOP ATTENDEES 6

5. WORKSHOP SUMMARY 7

   5.1 Mission Status and Summary 7
   5.2 Mission Latency and Summary of Findings 9
   5.3 Summary of Proxy Data Analysis and Needs 14
   5.4 Summary of Community Needs 17
   5.5 Summary of Application Area Findings 18
      5.5.1 Tropical Cyclone Analysis and Forecasting 18
      5.5.2 Terrestrial/Disasters/Severe Weather 20
      5.5.3 Tropical Cyclone Modeling and Data Assimilation 23
   5.6 Synergy With Other Missions 26
   5.7 Summary of Strengths/Limitations of Smallsats 28

6. MEETING ACTIONS/TAKEAWAYS 30

APPENDIX A—ORGANIZING COMMITTEE 33

APPENDIX B—MEETING AGENDA 34

APPENDIX C—ATTENDEE LIST 38

APPENDIX D—BREAKOUT SESSION QUESTIONS 40

REFERENCES 42

LIST OF FIGURES

1. The Moderate Resolution Imaging Spectroradiometer onboard NASA's Terra satellite captured Hurricane Florence on 13 September 2018 which brought devastating flooding to the Carolinas as it made landfall the next day 2

2. Group photo of the TROPICS workshop attendees 6

3. Example of the TROPICS proxy data from the HNR. A simulated overpass is demonstrated with the 205-GHz channel, with cooler brightness temperatures indicating the structure of convective clouds, and warmer colors indicating the ocean surface. Image credit: NASA SPoRT 8

4. The noise equivalent differential temperature from the payload thermal-vacuum calibration including all calibration error sources: (a) The atmospheric vertical temperature profile (AVTP) and (b) the atmospheric vertical moisture profile (AVMP). The average error (K) is displayed in blue for each TROPICS smallsat unit and the baseline and threshold requirements are noted by the green and red lines, respectively. Image credit: MIT LL 9

5. Locations of three KSAT-Lite Ground Stations under contract for the TROPICS Mission. The primary ground station is at Hartebeesthoek, South Africa, with backup sites in Dubai and Singapore. Image credit: MIT LL 10

6. Locations of three KSAT-Lite Ground Stations under contract for the TROPICS Mission plus additional ground stations for CONOP 2 or CONOP 3. Expanded coverage includes ground stations in Hawaii, Panama, Cordoba, and Mauritius. Image credit: MIT LL 11

7. Examples of applied research, applications, and types of decisions enabled by latency. Image credit: NASA SPoRT 12

8. (a) Examples of FY-3C TROPICS proxy dataset and (b) number of TC overpasses per tropical storm by intensity category. Image courtesy of Vince Leslie, MIT LL 15

9. Comparison of rainfall from the (a) full HNR simulation with the (b) HNR-derived TROPICS proxy data. Image courtesy of Erin Munsell, NASA Goddard Space Flight Center (GSFC)/Earth System Science Interdisciplinary Center (ESSIC) 16

10. Tropical storm Arthur on July 3, 2014. Collocated images from the (a) GOES-13 (IR) and (b) Global Change Observation Mission First-Water (GCOM-W1) (89 GHz) satellites are shown. Images courtesy of Jack Beven, NOAA NHC 19

LIST OF FIGURES (Continued)

11. PRPS rainfall accumulation over the 13-day HNR simulation period. This is a prelaunch simulation to demonstrate the potential of TROPICS. Image courtesy of Chris Kidd, University of Maryland/ESSIC, NASA GSFC 21

12. Modeled brightness temperature and rain rate relationships for TROPICS channels. These are prelaunch simulations to demonstrate the potential of TROPICS: (a) Observations—Tb depression c.200→179 K, (b) TROPICS MM2—Tb depression c.200→170 K, (c) TROPICS MM2—too much Tb depression, and (d) TROPICS MM2—Tb depression c.200→185 K. Image courtesy of Chris Kidd, University of Maryland/ESSIC, NASA GSFC 22

13. COAMPS-TC forecasts of 20E (a) minimum sea level pressure and (b) maximum wind speed for Hurricane Patricia at 1800 UTC, October 21, 2015. Red and blue lines indicate forecasts with and without all-sky radiance data assimilation, respectively, and the black lines represent intensities from the NHC best track. Images courtesy of Zhao et al. 2020 (NRL) 24

14. COAMPS-TC forecasts of 10-m wind speed (ms^{-1}) and sea level pressure (hPa) (a) without and (b) with all-sky data assimilation. Horizontal wind speed (contours) and vertical wind speed (colors) (c) without and (d) with all-sky data assimilation. Images courtesy of Hao Jin, NRL 25

15. All-sky GMI (Control 31) TROPICS: Root-mean-square error difference ($\times10^{-3}$) for forecasts of (a) specific humidity, (b) temperature, and (c) meridional wind between a GEOS forecast employing clear-sky radiance assimilation and a control run without clear-sky assimilation. Images courtesy of Min-Jeong Kim of NASA's GMAO/ Morgan State University/Goddard Earth Science (GES) Technology and Research 26

LIST OF TABLES

1. Comparison of HNR and FY-3C MWHS-2 TROPICS proxy datasets. Image courtesy of Vince Leslie, MIT LL 15

2. The NOAA NHC forecast cycle. Courtesy of Jack Beven, NOAA NHC 19

3. List of members of the Second TROPICS Applications Workshop organizing committee. 33

4. List attendees for the Second TROPICS Mission Applications Workshop detailed in appendix B. 38

LIST OF ACRONYMS

3U	three-unit (reference to size of CubeSats)
AMSU	Advanced Microwave Sounding Unit
AMSR-2	Advanced Microwave Scanning Radiometer 2
AOML	Atlantic Oceanographic and Meteorological Laboratory
ARCHER	Automated Rotational Center Hurricane Eye Retrieval
ARPEGE	Action de Recherche Petite Echelle Grande Echelle
ATMS	Advanced Technology Microwave Sounder
AVMP	atmospheric vertical moisture profile
AVTP	atmospheric vertical temperature profile
AWIPS	Advanced Weather Interactive Processing System
BUFR	Binary Universal Form for the Representation of meteorological data
CIMAS	Cooperative Institute for Marine and Atmospheric Studies
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CIRA	Cooperative Institute for Research in the Atmosphere
COAMPS-TC	Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones
CONOP	concept of operations
CPHC	Central Pacific Hurricane Center
CPTEC	Centro de Previsão de Tempo e Estudos Climáticos
CRTM	Community Radiative Transfer Model
CYGNSS	Cyclone Global Navigation Satellite System

LIST OF ACRONYMS (Continued)

DBNet	Direct Broadcast Network
DISC	Data and Information Services Center
DoD	Department of Defense
DPC	Data Processing Center
ECMWF	European Center for Medium-Range Weather Forecasts
ESD	Earth Science Division
ESSIC	Earth System Science Interdisciplinary Center
FY-3C	FengYun-3 C series
GCOM-W1	Global Change Observation Mission-Water
GEOS	Goddard Earth Observing System
GeoTIFF	Georeferenced Tagged Image File Format
GES	Goddard Earth Science
GLM	Geostationary Lightning Mapper
GMAO	Global Modeling and Assimilation Office
GMI	global precipitation measurement Microwave Imager
GOES	Geostationary Operational Environmental Satellite
GOES-R	Geostationary Operational Environmental Satellite-R series
GPM	global precipitation measurement
GPROF	Goddard profiling algorithm
GSFC	Goddard Space Flight Center
HNR	Hurricane Nature Run

LIST OF ACRONYMS (Continued)

HRD	Hurricane Research Division
HQ	Headquarters
IMERG	Integrated Multi-satelliE Retrievals for global precipitation measurement
INPE	National Institute for Space Research
IR	infrared
JPL	Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
JTWC	Joint Typhoon Warning Center
KSAT	Kongsberg Satellite Services
MHS	Microwave Humidity Sounder
MicroMAS-2	Micro-sized Microwave Atmospheric Satellite-2
MiRS	microwave integrated retrieval system
MIT LL	Massachusetts Institute of Technology Lincoln Laboratory
M-PERC	Microwave-based Probability of Eyewall Replacement Cycle
MSFC	Marshall Space Fight Center
MTS	Mission Tools Suite
MW	microwave
MWHS-2	second-generation Microwave Humidity Sounder
NetCDF	Network Common Data Form
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration

LIST OF ACRONYMS (Continued)

NPP	NASA Postdoctoral Program
NRL	Naval Research Laboratory
NWP	numerical weather prediction
NWS	National Weather Service
PATH	Precision and All-Weather Temperature and Humidity
PI	Principal Investigator
PMW	passive microwave
PRPS	precipitation retrieval and profiling scheme
RSMAS	Rosenthal School of Marine and Atmospheric Studies
RSMC	Regional Specialized Meteorological Center
SAL	Saharan Air Layer
SAPHIR	Sounder for Probing Vertical Profiles of Humidity
SATCON	Satellite Consensus
SNPP	Suomi National Polar-orbiting Partnership
SPoRT	Short-term Prediction Research and Transition
SSEC	Space Science and Engineering Center
SSMI/S	Special Sensor Microwave Imager/Sounder
STI	Scientific and Technical Information
Tb	brightness temperature
TC	tropical cyclone
TRMM	Tropical Rainfall Measuring Mission

LIST OF ACRONYMS (Continued)

TROPICS	Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of Smallsats
UAH	University of Alabama in Huntsville
UM	University of Miami
UMD	University of Maryland
UW	University of Wisconsin
WMO	World Meteorological Organization
WRF	weather research and forecasting

CONFERENCE PUBLICATION

SECOND TIME-RESOLVED OBSERVATIONS OF PRECIPITATION STRUCTURE AND STORM INTENSITY WITH A CONSTELLATION OF SMALLSATS (TROPICS) MISSION APPLICATIONS WORKSHOP

1. BACKGROUND

The NASA Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission is a constellation of state-of-the-science observing platforms that will measure temperature and humidity soundings and precipitation with spatial resolution comparable to current operational passive microwave (PMW) sounders but with unprecedented temporal resolution (Mission Website).[1] TROPICS is a cost-capped ($30.2 million), Venture-class mission funded by the NASA Earth Science Division (ESD) and led by Principal Investigator Dr. William Blackwell from the Massachusetts Institute of Technology Lincoln Laboratory (MIT LL). The mission consists of a constellation of six, three-unit (3U) CubeSats (approximately $10 \times 10 \times 34$ cm), each hosting a 12-channel PMW spectrometer based on the Micro-sized Microwave Atmospheric Satellite-2 (MicroMAS-2) developed at MIT LL, but with a substantially improved design. TROPICS will provide imagery near 91 and 205 GHz, temperature sounding near 118 GHz, and moisture sounding near 183 GHz. Spatial resolution at nadir will be around 27 km for temperature and 17 km for moisture and precipitation with a swath width of approximately 2,000 km from a 550-km orbit altitude. Both the spatial resolution and swath width are similar to the Advanced Technology Microwave Sounder (ATMS) that is being flown as part of the Suomi National Polar-orbiting Partnership (SNPP) and National Oceanic and Atmospheric Administration (NOAA) Joint Polar Satellite System (JPSS). In addition, TROPICS meets many of the requirements outlined in the 2007 Decadal Survey for the Precision and All-Weather Temperature and Humidity (PATH) mission, which was originally envisioned as a microwave instrument in geostationary orbit. TROPICS enables temporal resolution approaching that of geostationary orbit but at a much lower cost, demonstrating a technology that could impact the design of future Earth-observing missions. The satellites for the TROPICS mission were delivered to NASA in 2019 for launches planned in the 2021–2022 timeframe. The primary mission objective of TROPICS is to relate temperature, humidity, and precipitation structure to the evolution of tropical cyclone (TC) intensity.

The TC community has a long legacy of using space-based observations from visible and infrared satellite imagery (e.g., Geostationary Operational Environmental Satellite (GOES) imagers, Moderate Resolution Imaging Spectroradiometer (MODIS), and Visible Infrared Imaging Radiometer Suite (VIIRS)) for situational awareness of TC position, structure, and intensity and from microwave sounders and imagers (e.g., multiple Special Sensor Microwave Imager/Sounder (SSMI/S), Advanced Microwave Sounding Unit (AMSU), Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), Global Precipitation Measurement (GPM) Microwave Imager

(GMI)) for better understanding of storm dynamics and precipitation and for assimilation into numerical weather prediction (NWP) models (fig. 1). However, most previous passive microwave instruments have flown aboard satellites in polar or high-inclination orbits, reducing the revisit time of the instruments. The GPM satellite constellation has improved the satellite sampling frequency, but each satellite has different hardware and measures at different channel frequencies. Thus, TROPICS represents a potentially game-changing mission that will allow for revisit times of identical sensors that are between 30 and 60 minutes. This rapid-refresh rate will allow for better measurement of quickly evolving changes within TCs over their entire lifecycles.

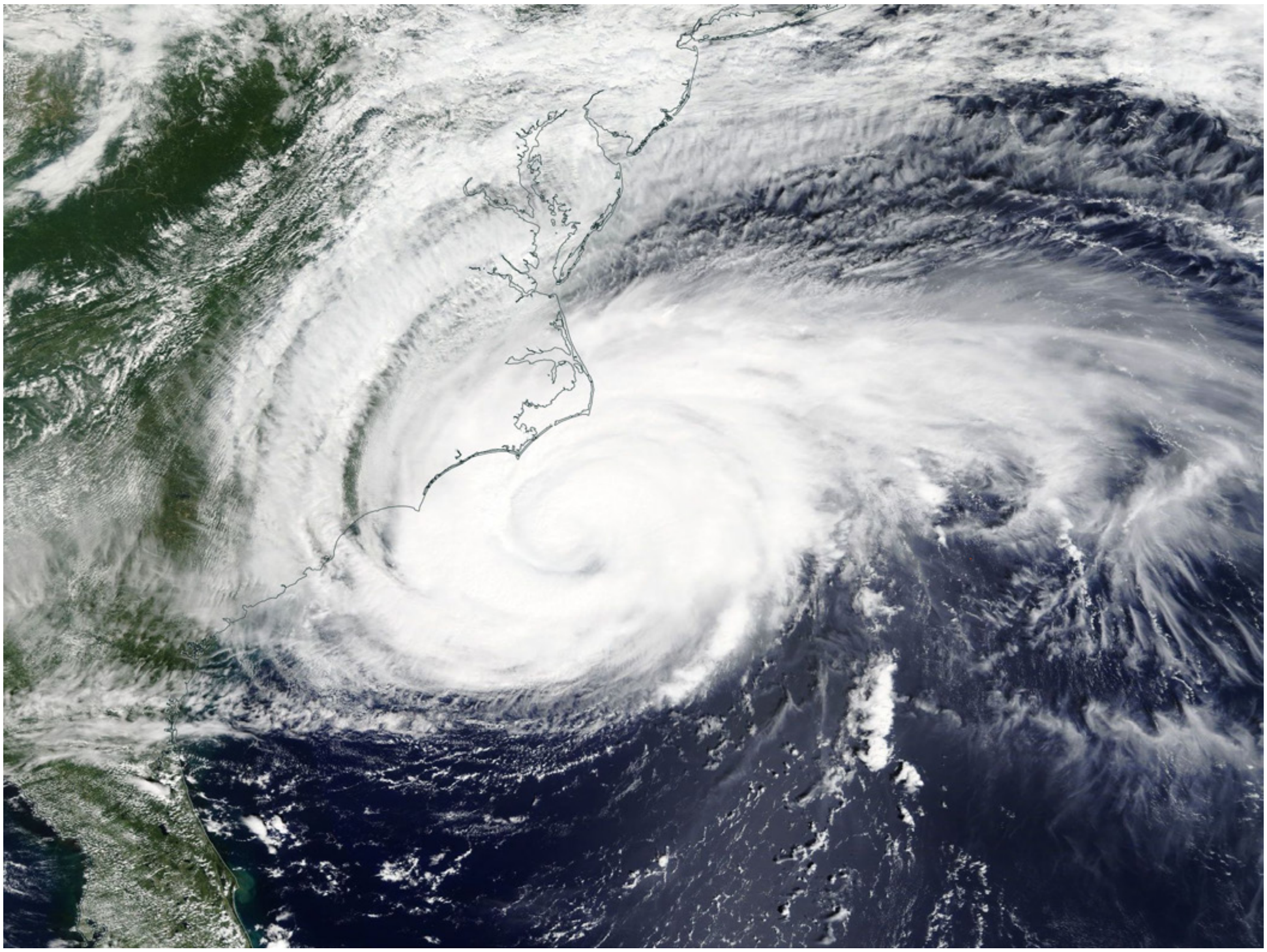


Figure 1. The Moderate Resolution Imaging Spectroradiometer onboard NASA's Terra satellite captured Hurricane Florence on 13 September 2018 which brought devastating flooding to the Carolinas as it made landfall the next day.

2. WORKSHOP PURPOSE AND OBJECTIVES

On February 19–20, 2020, the NASA ESD Applied Sciences Program convened the Second TROPICS Applications Workshop to enable conversation between the mission developers/science team and the end-user/application community. By fulfilling these specific objectives before final mission formulation and prior to the expected mission launch date, the TROPICS science team is demonstrating a commitment to maximize return on investment for NASA by pushing for impact on application end-user decisions. While the primary mission objective for TROPICS is related to observing environmental and internal factors that relate to TC intensity, there are other application areas where observations from TROPICS may be valuable to assess hazards related to disasters and severe weather.

Outcomes of the First TROPICS Applications Workshop (May 8–10, 2017) included the establishment of four main application focus areas and potential solutions to improve mission latency to make data more accessible in near real time. In addition, an Early Adopter program[2] was established in 2018 and proxy datasets[3] have since become more widely available. Thus, the Second TROPICS Applications Workshop focused on the following specific objectives:

- Introduce end-users to the expected value of TROPICS by reviewing mission specifications and status.

- Engage the end-user community to learn how TROPICS observations could be used by their organizations and identify barriers to data use.

- Provide an opportunity for the early adopter community to share results using current and/or proxy data, and communicate challenges, successes, and future needs to the science team.

- Identify technical and visualization needs that can be addressed by the science and applications community (e.g., data assimilation, Level 3/Level 4 products, visualization tools) to accelerate broad utilization of TROPICS data post-launch.

3. WORKSHOP ORGANIZATION

The organizing process of the Second TROPICS Applications Workshop was facilitated through a broad representation from the mission and applications/end-user community (members of the organizing committee are shown in app. A). The workshop organizing committee provided inputs about the program format and focus areas. Members of the organizing committee volunteered to act as session chairs and breakout discussion leads. The chairs were responsible for identifying and inviting speakers for their sessions.

With a community of end-users established and beginning to use the mission proxy data from simulations and instruments such as the Feng-Yun 3C (FY-3C) Micro-Wave Humidity Sounder-2 (MWHS-2), the meeting was organized to first update the applications community on the TROPICS mission status and then have a focused session on applied research and analysis with proxy datasets. These presentations were provided by mission scientists, operational agencies, and applied researchers. This session set the foundation for the attendees to be familiar with the mission, capabilities, and current datasets to guide discussions during the remainder of the meeting. The remainder of the 1½-day workshop consisted of applications presentations and breakout sessions to capture end-user perspectives. The applications community presented applied research and operational decision making being done with current PMW observations in order to educate the mission Principle Investigator (PI) and the science team on expected applications and limitations to potential use of TROPICS data by the applied research, applications, and operational communities. The breakout sessions focused on latency, community needs, and strengths and limitations of smallsats.

A comprehensive 1.5-day workshop agenda was assembled by the organizing committee that encompassed five sessions and two breakout sessions. The agenda is shown in appendix B and also on the agenda page on the meeting website.[4] A list of attendees is also detailed in appendix C.

Workshop presentations focused on applied research or operational uses of TROPICS data related to the core science team measurements and products: (1) terrestrial/disasters/severe weather, (2) TC nowcasting, and (3) modeling and data assimilation. Presenters summarized their current research and/or operational activities, ways that they currently use satellite observations, and ideas for how their organization could/would use TROPICS data. Additional sessions on proxy data and synergy with other missions provided opportunities to present the value of TROPICS observations with preliminary data and in conjunction with the capabilities of other missions such as the Cyclone Global Navigation Satellite System (CYGNSS), Geostationary Operational Environmental Satellite-R (GOES-R) Series imagery and lightning observations, JPSS Series polar-orbiting capabilities, and the current PMW constellation observations, (i.e., GPM).

The three breakout sessions were planned to capture the end-user perspective related to latency, community needs for products, visualizations, new tools, and potential strengths and limitations of integrating smallsats into research and applications. During each breakout session, the attendees self-divided into groups related to: (1) terrestrial/disasters/severe weather, (2) tropical cyclone analysis/forecasting, and (3) TC modeling and data assimilation. The first breakout session focused on latency and was preceded by an update on mission latency to inform users on current mission requirements and potential solutions to providing more timely observations. The objective of this breakout was to identify needs for latency and data coverage to maximize utility of TROPICS data and discuss limitations of current mission specifications.

The second breakout on products, visualization, tools, and community needs immediately followed. The foundation of presentations in the morning of the first day on mission status, expected products, and proxy data allowed for an afternoon dedicated to discussion. The objective of this second breakout was to identify needs for additional products including Level 3 (gridded products) or Level 4 (assimilated products), visualizations, data formats, or tools related to data assimilation that would further enable the use of TROPICS data. The last breakout session was aimed at discussing the strengths and limitations of integrating smallsats in applied research, applications, and operations. As only a few smallsat missions have been demonstrated (e.g., CYGNSS and Temporal Experiment for Storms and Tropical Systems-Demonstration (TEMPEST-D)) and may become more common in the coming decade, this discussion was a first step toward capturing user feedback on the potential benefits and challenges with integrating new technology. Therefore, the objective of this breakout was to identify questions, concerns, and exciting potential benefits of utilizing this new technology. The breakout was preceded by a presentation on the challenges and advantages of exploiting smallsat data in NWP as a lead-in to the breakout discussion. Additional details, outcomes, and conclusions related to the sessions and breakout sessions can be found in the following sections.

4. WORKSHOP ATTENDEES

The 40 registered attendees for the workshop underscored interest in the TROPICS mission and the number of potential end-users for the data. Workshop attendees included federal employees and contractors from NASA, NOAA, and the Department of Defense (DoD) with applied research and operational responsibilities for TC analysis and prediction and terrestrial applications. Members of the international research-to-operations community attended to share interest in the mission data. The academic community from universities and NOAA cooperative institutes participated to describe their applied research activities. The broad range of backgrounds and interests among the workshop attendees highlighted the potential use of TROPICS data for a number of application areas. A complete list of registered attendees (pictured in fig. 2) can be found in appendix C.

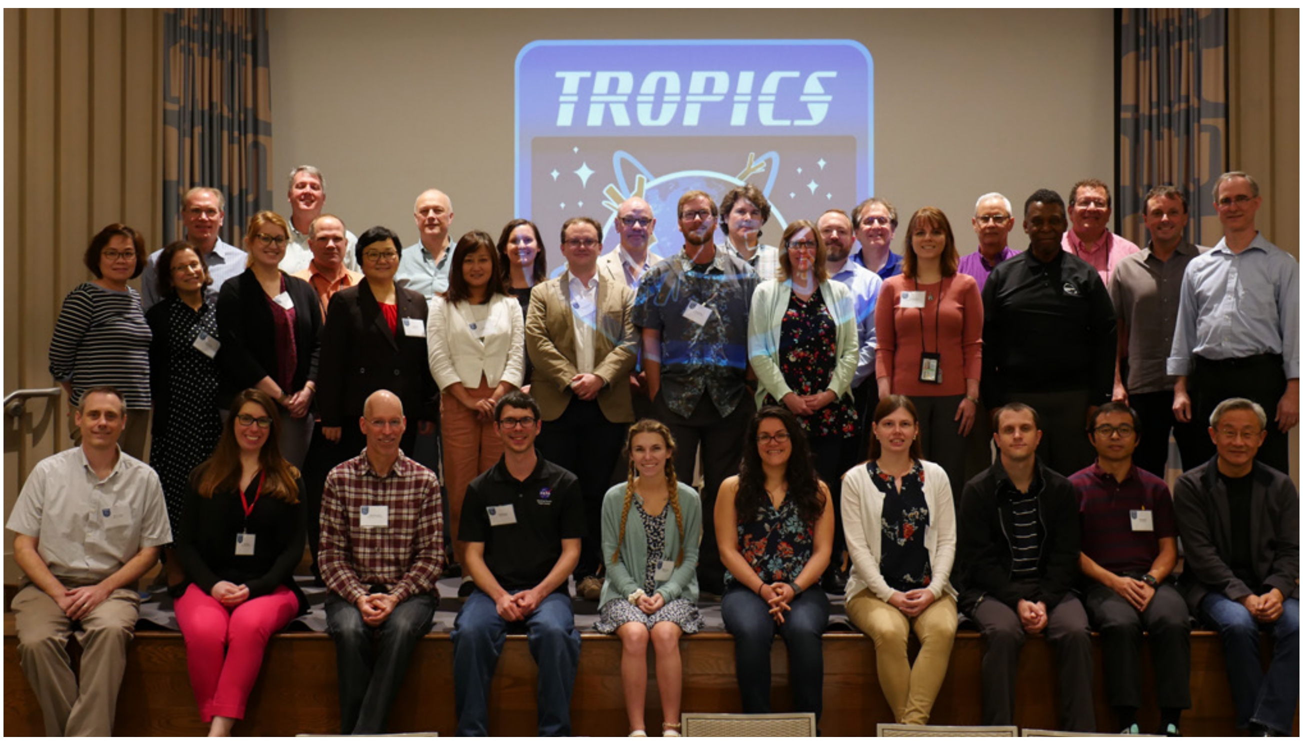


Figure 2. Group photo of the TROPICS workshop attendees.

5. WORKSHOP SUMMARY

The following sections summarize key discussions, end-user inputs, and conclusions for each of the meeting sessions.

5.1 Mission Status and Summary

TROPICS data will address critical science questions related to TCs, whereby measurements of 4-dimensional (4-D) temperature, humidity, and precipitation will enable better understanding of hurricane science and therefore improve the forecasts and forecast models. CubeSat sounders such as the MicroMAS-2a are a key enabling technology. The millimeter wave receiver hardware for TROPICS enables a compact, low-power, high-performance mission for the purpose of determining thermodynamic relationships in rapidly evolving storms at a high refresh rate through a constellation of smallsats. TROPICS will provide observations with a median revisit rate better than 60 minutes over all ocean basins. The CubeSats will be in three orbital planes and provide state-of-the-art temperature and moisture soundings. Mission specifications state a 6- to 12-hr average latency with the primary ground station in Hartebeesthoek, South Africa. Each payload includes an ultra-compact W/F/G radiometer with W band at 92 GHz, F band with 7 channels from 114 to 119 GHz, and G band with 3 channels near 183 GHz and another at 205 GHz. The swath width is approximately 2,000 km with temperature sounding horizontal resolution near 27 km and moisture sounding near 17 km. More specifics on the mission can be found in Blackwell et al. (2018)[5] and the First TROPICS Applications Workshop Summary Report (cf. app. D).[6]

This past year, the science team also released proxy datasets from the Weather Research and Forecasting (WRF) model Hurricane Nature Run (HNR) described by Nolan et al. 2013[7] (fig. 3) and the FY-3C MWHS-2 instrument. The HNR is a simulated dataset that matches the spatial, temporal, and spectral frequency of planned satellite architectures in TROPICS mission format and was used to test key components of the ground system including testing of algorithms at the Data Processing Center (DPC). The FY-3C dataset is a collection of measured TC radiances from MWHS-2 that has similar bands (90, 118, and 183 GHz) to TROPICS, but slightly different spatial, noise, and spectral characteristics. The two proxies complement each other by balancing simulation errors and differences in hardware performance. The proxy datasets[3] were evaluated by the science team and then released to the public and the applied-sciences community through the NASA Applied Sciences TROPICS Applications Early Adopter Program.[2]

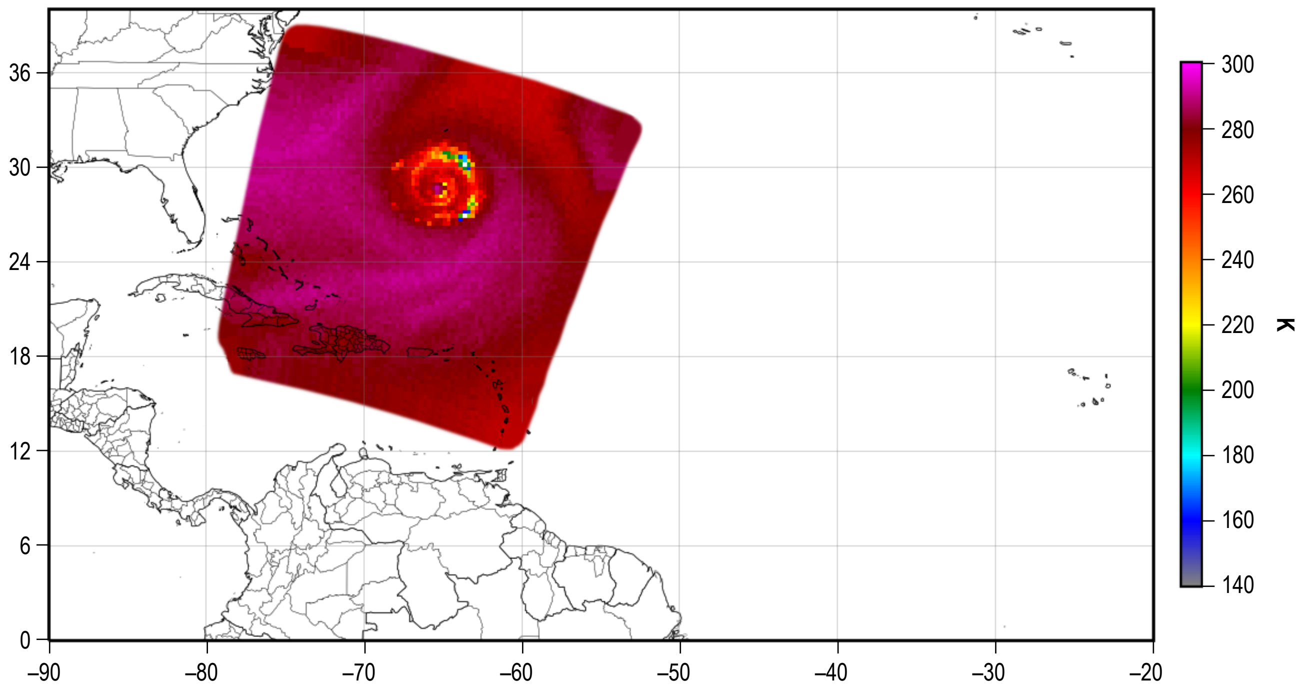


Figure 3. Example of the TROPICS proxy data from the HNR. A simulated overpass is demonstrated with the 205-GHz channel, with cooler brightness temperatures indicating the structure of convective clouds and warmer colors indicating the ocean surface. Image credit: NASA SPoRT.

Currently, seven flight units are in storage and ready for flight. The flight units show consistent performance as Thermal-Vacuum Calibration was completed in 2019 (fig. 4) and prelaunch testing shows excellent stability when evaluating the noise diodes for on-orbit calibration. A series of payload, space vehicle, and ground segment testing over the last year indicated that all Level 1 Science Requirements are met within margin, the space system works as expected, and the communications and data-product generation have been prepared and tested. For example, key components of the ground segment (i.e., Ground Station Network, Missions Operations Center (MOC), Science Operations Center (SOC), and Data Processing Center (DPC)) have passed key milestones.

After key testing was completed in 2019, all seven units were delivered with excellent performance and are currently in storage. NASA is in the process of procuring launches, with the possibility of obtaining launches by the end of 2021. At the time of the workshop, initial discussions for the early launch of the seventh unit as a pathfinder mission had begun. Since the workshop convened, more definitive actions are in process to launch the pathfinder mission in 2021.

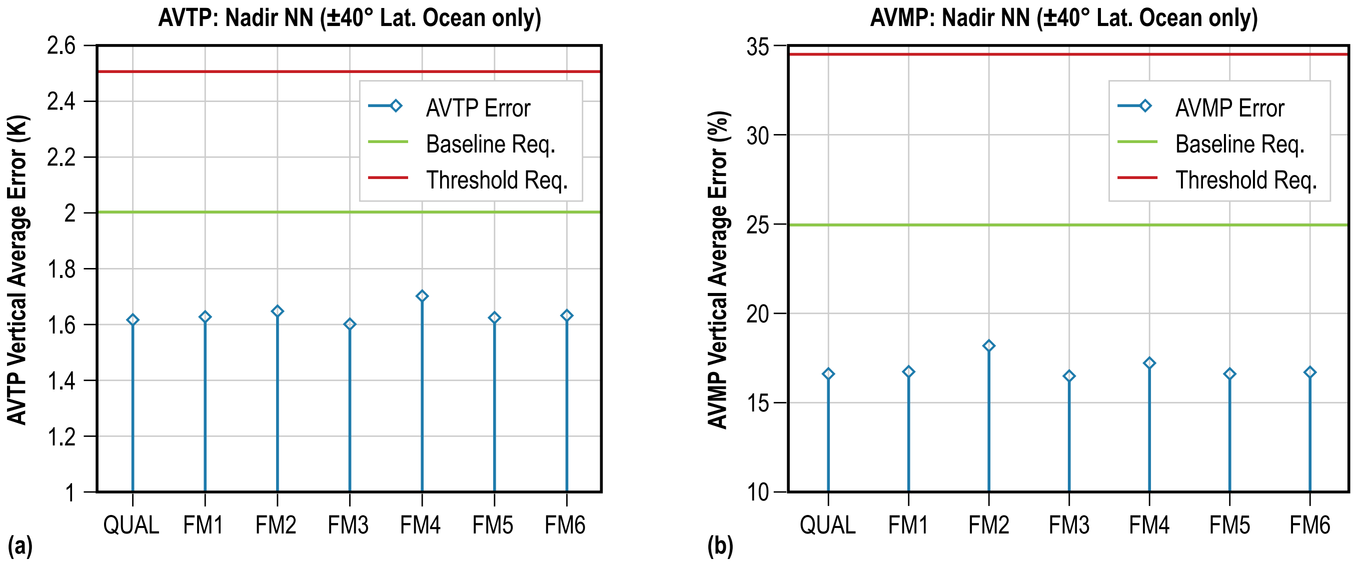


Figure 4. The noise equivalent differential temperature from the payload thermal-vacuum calibration including all calibration error sources: (a) The atmospheric vertical temperature profile (AVTP) and (b) the atmospheric vertical moisture profile (AVMP). The average error (K) is displayed in blue for each TROPICS smallsat unit, and the baseline and threshold requirements are noted by the green and red lines, respectively. Image credit: MIT LL.

5.2 Mission Latency and Summary of Findings

A major outcome of the First TROPICS Applications Workshop in 2017 was the need to optimize data latency given that the TROPICS mission holds much potential benefit to the applications community. Here, data latency is defined as the amount of time between when an observation is made by a satellite and when the data become available for use by the scientific community. The mission latency requirements (e.g., 4 days from downlink time) for TROPICS in the original mission proposal were not designed for use by the operational community. Therefore, any optimization of data latency is performed on a best-effort basis or with external funding, given the constraints of the fixed-price mission.

Average latency over a 1-month period with two contacts per day at the primary ground station is about 6.5 hours. TROPICS will pass over the South Africa ground station immediately after traversing the Atlantic. Besides the primary Kongsberg Satellite Services (KSAT)-Lite ground station and the two secondary backup stations in Dubai and Singapore, there are additional ground stations that can be utilized to optimize TROPICS latency. Three 'concepts of operations' (CONOPs) were presented as potential ways to reduce latency for the TROPICS mission. CONOP 1 is to use the planned mission implementation (fig. 5) but to spend additional funding to optimize data processing to facilitate low-latency passes coming in over the Atlantic. TROPICS does have scheduling priority at the Hartebeesthoek antenna, which enables storm prioritization and the achievement of ≈1-hr latency through some data processing optimization (fig. 5). The second and third CONOP options involve utilizing additional KSAT-Lite ground stations (fig. 6) but reducing latency for select time periods. Additional ground station time/priority and data processing optimization could be funded to reduce latency. CONOP 2 is summarized by reducing latency to about 120 minutes for 8 months of the year and 90 minutes during 4 months of the year to facilitate expedient observations during the Northern Hemisphere hurricane season. CONOP 3, the most expensive option, is to utilize all seven ground stations in figure 5 and operate with 60- to 90-minute latency during the full year.

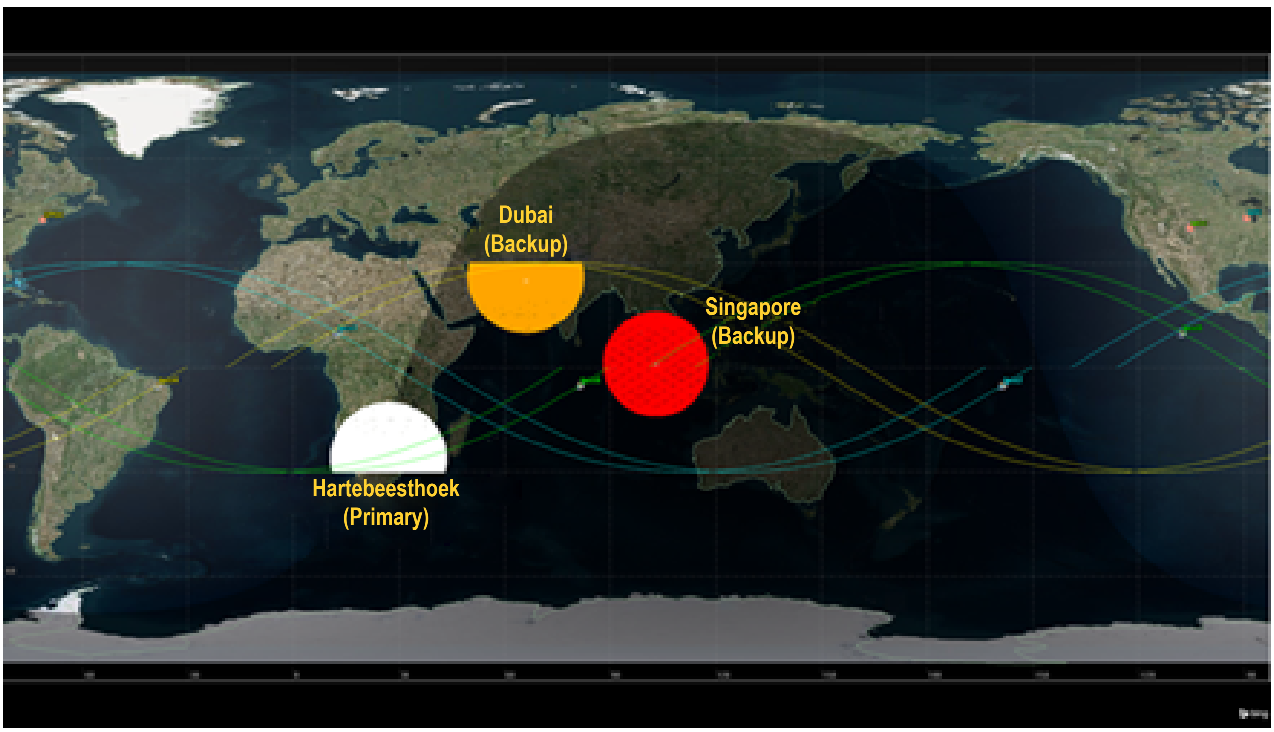


Figure 5. Locations of three KSAT-Lite Ground Stations under contract for the TROPICS mission. The primary ground station is at Hartebeesthoek, South Africa, with backup sites in Dubai and Singapore. Image credit: MIT LL.

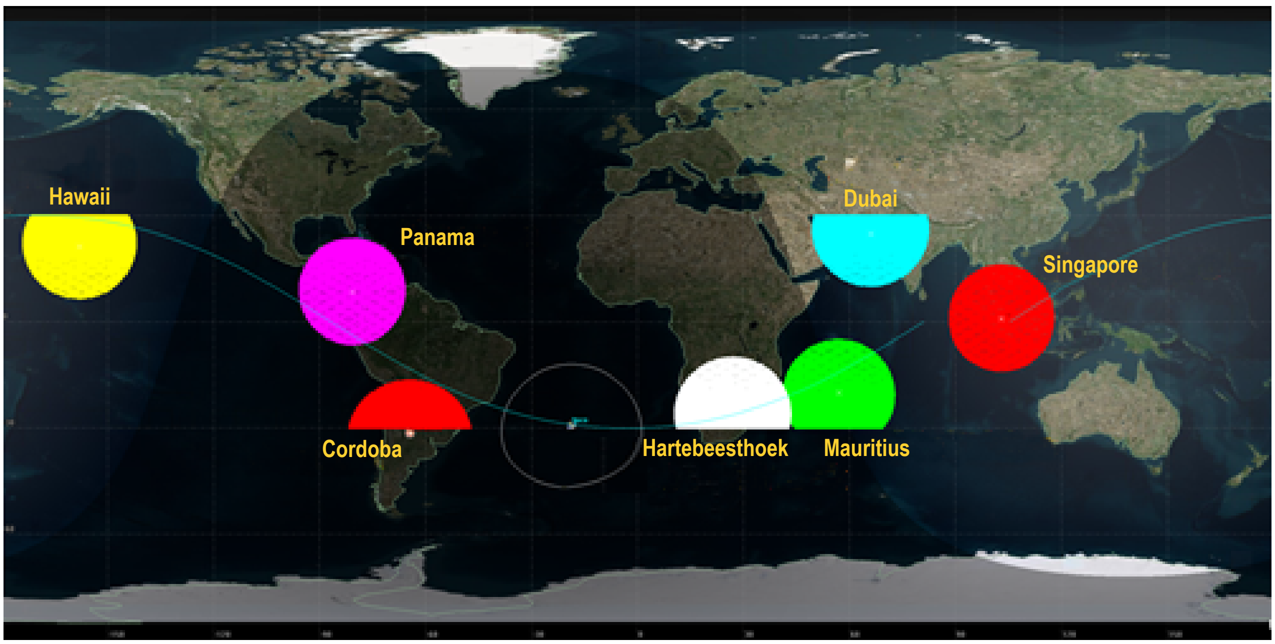


Figure 6. Locations of three KSAT-Lite Ground Stations under contract for the TROPICS mission plus additional ground stations for CONOP 2 or CONOP 3. Expanded coverage includes ground stations in Hawaii, Panama, Cordoba, and Mauritius. Image credit: MIT LL.

During the latency breakout session, attendees had the opportunity to discuss the latency requirements of the mission and how it relates to their applied research or operations. Eight questions (see app. D, page 40) were given to the groups but groups were not limited to discussing these questions. Workshop attendees agreed that real-time data with a latency better than 3–6 hours is ideal, with most users stating 30 minutes to 1 hour as an optimal latency to facilitate operational use of the data. Figure 7 summarizes how improving TROPICS latency would enable a hierarchy of applications and broader community use. The nominal mission latency of 6–12 hours would enable applied research studies related to weather and socioeconomic impacts, and applications that are concerned with time-independent decisions or analysis. By reducing the latency to 3–6 hours, operational analysis to support hurricane and weather forecasting, including data assimilation in operational models would be enabled. The data would be accessible and available for short-term analysis and decisions, enabling use by a wide range of U. S. national and international operational centers. Making TROPICS observations available with a 1-hr latency would facilitate use of the data for time-critical decisions including weather and disaster warnings, hurricane field campaigns, and ingesting into rapid update models. In addition, users agreed that data coverage over the Atlantic, West Pacific, and Eastern Pacific are important, and latency should be prioritized for these regions. Having the data accessible on a global scale with a very-short latency could increase the socioeconomic benefit by informing and potentially improving time-critical, lifesaving decisions made by the operational weather community, emergency response, and nongovernmental organizations.

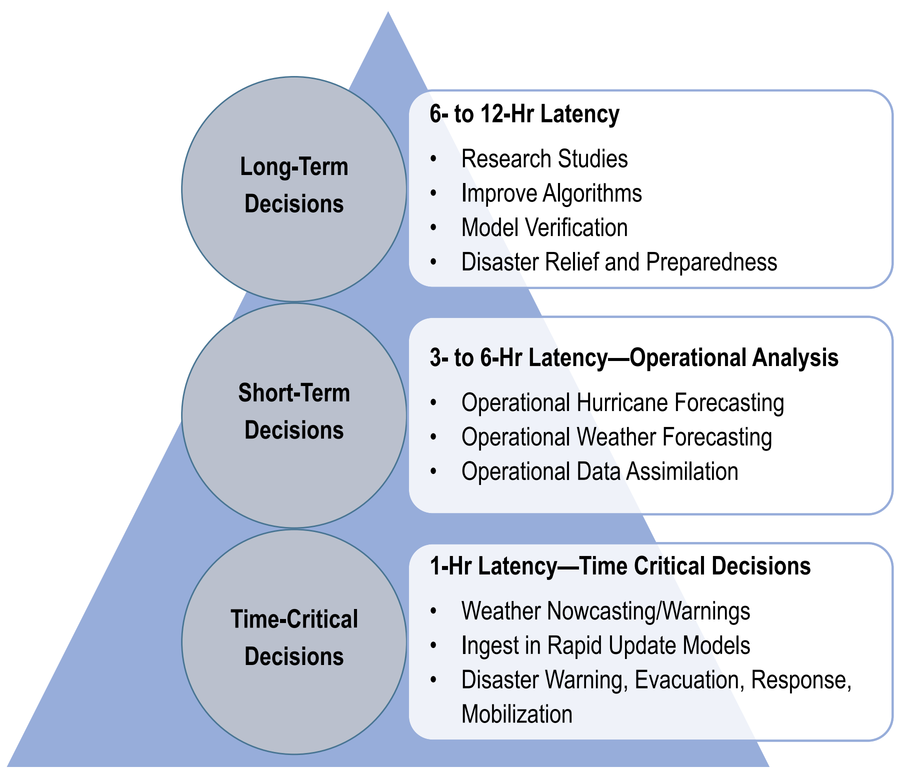


Figure 7. Examples of applied research, applications, and types of decisions enabled by latency. Image credit: NASA SPoRT.

Mitch Goldberg gave an overview of the NOAA Direct Broadcast Real Time Network. NOAA JPSS has funded the Cooperative Institute for Meteorological Satellite Studies/Space Science and Engineering Center (CIMSS/SSEC) to install and operate a network of polar-orbiting satellite receiving stations across North America and the Pacific. There are a total of 16 receiving stations (e.g., Orbital Systems X/L-band antennas), providing near-global coverage when combined with the worldwide Direct Broadcast Network (DBNet)[8] which is coordinated by the World Meteorological Organization (WMO) Space Program. The goal is to deliver advanced sounder data to NWP centers with low latency for rapid refresh data assimilation. Data are acquired real time at NOAA and partner sites, processed centrally at CIMSS/SSEC to Level 1B, and delivered to NWP centers in Binary Universal Form for the Representation of meteorological data (BUFR) format. When analyzing data delivery, the average latency for ATMS during August 2019 at the SSEC site was <15 minutes with all files delivered in <20 minutes. U.S. and European operational centers have been ingesting the BUFR data for NWP assimilation. Currently, the network is preparing for the JPSS-2 launch in 2022, migrating processing to the cloud, and adding more partner sites. The antenna sites are preparing to update for Metop-Second Generation and adding FY-3C/D and Advanced Microwave Scanning Radiometer-2 (AMSR-2) processing in the future. As the X/L-band network upgrades to add S-band to accommodate AMSR-2, it may be possible to also upgrade to K-band to support TROPICS. Following the workshop, discussions will continue between JPSS and the TROPICS PI to discuss a NOAA partnership to improve data latency, provide data in BUFR format, and disseminate data in real time, consistent with WMO DBNet best practices.

During the breakout session, users also answered the question about ways to mitigate latency. The ideas listed below include anything from prioritizing Level 1B processing to partnering with military or international organizations to obtain funding for optimal latency:

- Prioritize processing and release of Level 1B at low latency.

- Consider an ‘intermediate’ data release with minimal processing (e.g., Integrated Multi-satelliE Retrievals for GPM (IMERG) Early and Late products).

- Increase processing centers beyond Wisconsin.

- Streamline processing (e.g., data goes to Colorado, then Wisconsin).

- Install a receiver and/or data process at operational centers/locations (e.g., National Hurricane Center (NHC), Joint Typhoon Warning Center (JTWC), Brazil’s National Institute for Space Research (INPE)).

- Conduct a cost-benefit analysis to demonstrate the $2M for optimal latency may be small relative to the benefit of preparedness and disaster mitigation and improvements to NWP and forecasting.

- Request international support to cover the extra costs; leverage international data sharing agreements.

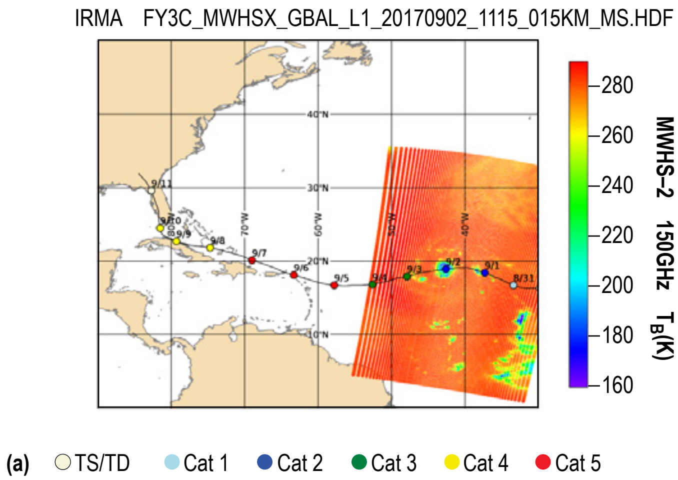
- Engage with the TC Operations and Research Forum.
- Partner with the military branches for support and funding.
- Demonstrate value with launching the 7th Qualification Unit.

5.3 Summary of Proxy Data Analysis and Needs

Prior to launch, synthetic (or proxy) datasets provide value to the community by allowing for prelaunch research and analysis. Currently, there are two TROPICS proxy datasets available to the community for prelaunch activities: simulated TROPICS data from the HNR and remote sensing observations from the FY-3C satellite. The latest version of the HNR is available in the final mission format to facilitate integration of TROPICS data into a variety of existing operational systems prior to launch.

The second (official) release of the HNR proxy dataset contains synthetic TROPICS data derived from a single highly realistic Atlantic TC simulated in the WRF model (Nolan et al. 2013).[7] TROPICS brightness temperatures are simulated using the Community Radiative Transfer Model (CRTM 2.2.3) over the 13-day lifecycle of the HNR TC. This dataset is derived for the baseline, six-satellite architecture, and assumes idealized TROPICS payload characteristics, including an idealized antenna pattern and spectral response (i.e., boxcar channel set). More information on mission specifications can be found in Blackwell et al. (2018).[5] Output is in the TROPICS Level 1B Network Common Data Form (netCDF) (i.e., netCDF data format), and now also includes Level 2 Microwave Integrated Retrieval System (MiRS) temperature and moisture profiles.

The FY-3C MWHS-2 proxy dataset is a large collection of actual TC radiance measurements with frequencies similar to TROPICS (e.g., 90, 118, 183 GHz). Measurements are taken from the MWHS-2 instrument, which has slightly different spatial, radiometric, and spectral characteristics as compared to TROPICS. While not an exact match, TROPICS channels can be simulated by differencing MWHS-2 channels. This dataset includes 2,475 global overpasses from 2013 to 2017, covering ≈900 TCs of varying strengths (fig. 8). These overpasses were matched with the Automated Tropical Cyclone Forecasting (ATCF) [9] System hurricane track files, which is included in the netCDF filename, along with the name of the storm. By simulating differences in hardware performance and providing different estimates of errors, the HNR and FY-3C TROPICS proxy datasets complement one another (table 1).



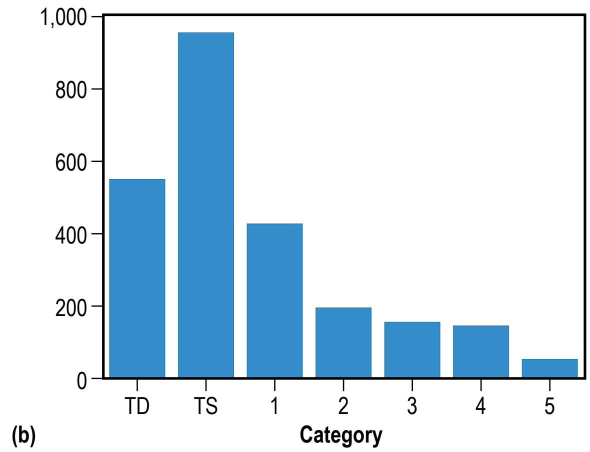


Figure 8. Examples of (a) FY-3C TROPICS proxy dataset and (b) number of TC overpasses per tropical storm by intensity category. Image courtesy of Vince Leslie, MIT LL.

Table 1. Comparison of HNR and FY-3C MWHS-2 TROPICS proxy datasets. Image courtesy of Vince Leslie, MIT LL.

Characteristic	HNR Proxy	FY–3C MWHS–2 Proxy
Radiances	Simulated	Actual measurements
TC diversity	Single TC from genesis to Cat 4	2475 global cases from TD to Cat 5; ≈900 from Cat. 1 to Cat. 5
Spectral	Idealized boxcar passbands meeting TROPICS specifications	Different passbands than TROPICS, but similar vertical altitude (i.e., weighting functions)
Spatial	Idealized TROPICS horizontal cell size and spacing	Larger spatial resolution than TROPICS
Temporal	Idealized constellation of six CubeSats	Single satellite in SSA orbit (i.e., no temporal continuity)
Radiometric Sensitivity	Expected TROPICS performance	Higher sensitivity than TROPICS

Workshop participants presented preliminary results using both the HNR and the FY-3C TROPICS proxy datasets. Validation of the HNR TROPICS proxy data against the full HNR numerical simulation demonstrates that TROPICS proxy data capture similar TC structure, but underestimate precipitation amounts (fig. 9). This appears to be caused by a warm bias of the synthetic brightness temperature data.

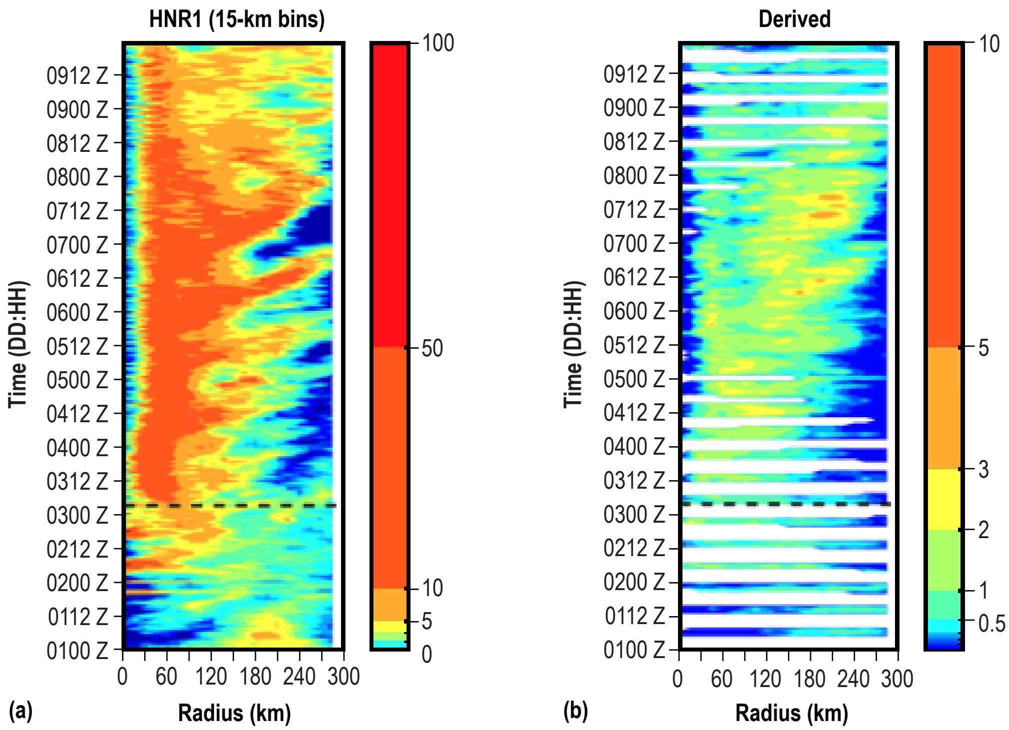


Figure 9. Comparison of rainfall from the (a) full HNR simulation with the (b) HNR-derived TROPICS proxy data. Image courtesy of Erin Munsell, NASA Goddard Space Flight Center (GSFC)/Earth System Science Interdisciplinary Center (ESSIC).

Using Hövmoller diagrams and proxy data imagery (simulated Channel 10; 187 GHz), TROPICS proxy data demonstrate similar TC convective structures, including eye/eyewall development and diurnal variability. Near the edge of the swath, however, data quality appears to deteriorate. The spatial resolution of TROPICS may limit the ability to track individual convective cores; however, the HNR and other model simulations similar to the HNR suggest that the frequency of TROPICS overpasses can capture the evolution of the TC diurnal cycle. Analysis of the impact of PMW sounding data in the European Centre for Medium-Range Weather Forecasts (ECMWF) system demonstrates that continued benefit is observed with the addition of each new PMW sensor, and that this benefit is statistically significant. There is also clear benefit for TC forecasting, showing improvement of track forecasts and short-term intensity when PMW data are included. Data from the FY-3C satellite have been assimilated in the ECMWF system since April 2019. Results indicate that the clearest benefit is observed from the 183-GHz channels, and the main impact of the 118-GHz channels is through the improved short-range forecasts of clouds (for the full observing system). Overall, strong positive impacts are observed from incorporating PMW sounding data, and TROPICS will add coverage where there are current gaps in the existing constellation.

Participants expressed the importance of prelaunch instrument characterization and stable in-orbit performance, as well as quality control and bias correction. For the HNR proxy data, participants indicated that the brightness temperatures and precipitation estimates appear underestimated. This caused difficulty in TC analysis with proxy data and suggestions were made to improve the data through tuning of parameters in the Community Radiative Transfer Model (CRTM). Additional proxy data over land and outside TCs for use in other applications was also of interest.

5.4 Summary of Community Needs

TROPICS observations will be useful to diverse users in the meteorology and climatology communities. To facilitate widespread and efficient access to TROPICS products, attendees stressed that a variety of data types and visualization tools should be provided, along with training resources that describe the utility and interpretation of different products. Appendix D (see page 40) outlines the questions workshop attendees considered during the breakout session.

TROPICS provides a new source of temperature, humidity, and layer total precipitable water products, which will be highly useful for forecasting TCs and rainfall. For large-scale tropical research and forecasting, participants expressed a need for monthly aggregated products of rainfall, moisture, and temperature. These aggregates could be compared to those provided by the existing GPM constellation, especially IMERG. For product validation, there was great interest in a 'match-up database' between TROPICS and other existing missions for ease of comparison. Multiple attendees expressed a desire for the creation of a 37-GHz channel proxy, which is particularly valuable in TC analysis. It was not immediately clear how such a product could be produced with the instruments included onboard TROPICS, but participants would like this to be investigated.

For operational forecasters at the National Weather Service (NWS) and the NHC, distribution of products through the Local Data Manager (LDM) feed for visualization in the Advanced Weather Interactive Processing System (AWIPS) is preferred. Since some other operational centers and other end-users do not have access to AWIPS workstations, attendees also expressed a need for open-source tools for product visualization. TROPICS products will be useful for field campaigns, and a capability to display them in NASA's Mission Tools Suite (MTS) is of interest, although the frequency of overpasses could be challenging. An orbital navigation tool to view upcoming TROPICS overpasses during a given period of time also could enhance situational awareness. Attendees also favored making TROPICS datasets available in NASA's Earth Observing System Data and Information System (EOSDIS) Worldview online tool. For research purposes, a framework that combines TROPICS overpasses with other satellite overpasses to track the lifecycle of convective systems (or even individual precipitation features) would be highly valuable. For operational modeling and data assimilation, participants expressed a strong preference for data files in BUFR format with metadata, whereas netCDF4 was preferred for research purposes.

Attendees expressed the need for training material, particularly relating to individual channels and derived products that were previously unavailable. TROPICS will include a 205-GHz channel with which the community has little experience using in applied research and operations. It is possible that such a channel can be used to track low-level moisture or ice-laden cloud tops, but much more investigation and training is necessary to determine how useful such a product is to operational forecasters. Representatives from NHC expressed interest in training for the 118- and 183-GHz channels. Such training will need to be highly focused so that forecasters can very quickly garner the information they need from these products. The potential launch of a pathfinder mission could facilitate the development of these trainings by providing an initial view of how these products behave. Overall, participants expressed a need for short training materials to be made available online that describe how to use TROPICS imagery, in addition to detailed seminars geared toward operational users.

5.5 Summary of Application Area Findings

5.5.1 Tropical Cyclone Analysis and Forecasting

Operational forecast centers such as the NOAA NHC, NOAA Central Pacific Hurricane Center (CPHC), and the JTWC rely extensively on satellite observations to support their analyses and forecasts of TCs. Even in the North Atlantic where aircraft reconnaissance missions into TCs are routinely flown, aircraft observations are only available for ≈30% of all forecast cycles. The reliance by TC forecast centers on satellite observations is even more pronounced in other oceanic basins where reconnaissance and research missions are rarely flown. PMW imagery represents an important component of these remotely sensed observations, and at JTWC, it is used in more than half of the forecast cycles. Forecasters routinely use PMW imagery to aid in the determination of TC location/motion, strength (i.e., maximum sustained surface winds), and structure (e.g., size of the tropical storm and hurricane-force wind fields). Although the TC upper-level cirrus canopy often obscures details of storm structure in traditional satellite imagery (e.g., visible and infrared (IR)), PMW imagery can be used to ‘see’ through this layer of clouds. Figure 10 shows Tropical Storm Arthur on July 3, 2014, and emphasizes the advantage of PMW imagery over IR imagery in detecting storm features such as the eye, eyewall, and outer rainbands.

For applications of TC analysis and forecasting, the TROPICS mission offers both promise and challenges. TROPICS will provide more frequent views of TC structure (e.g., warm core evolution and eyewall replacement cycle evolution), center finding, and intensity estimation than is available in the current constellation of PMW satellites. However, data latency of more than 3 hours rapidly decreases the real-time utility of the data as forecasters are already moving into the next advisory cycle (table 2). Regardless of latency, TROPICS data will still be useful for post-analysis and preparing final TC reports. It is anticipated that other Regional Specialized Meteorological Centers (RSMCs) such as Fiji, Darwin, La Reunion, Tokyo, and New Delhi could also benefit from near real-time TROPICS data. Like NOAA NHC, NOAA CPHC, and JTWC, these forecast centers would also require timely access to TROPICS data for nowcasting applications.

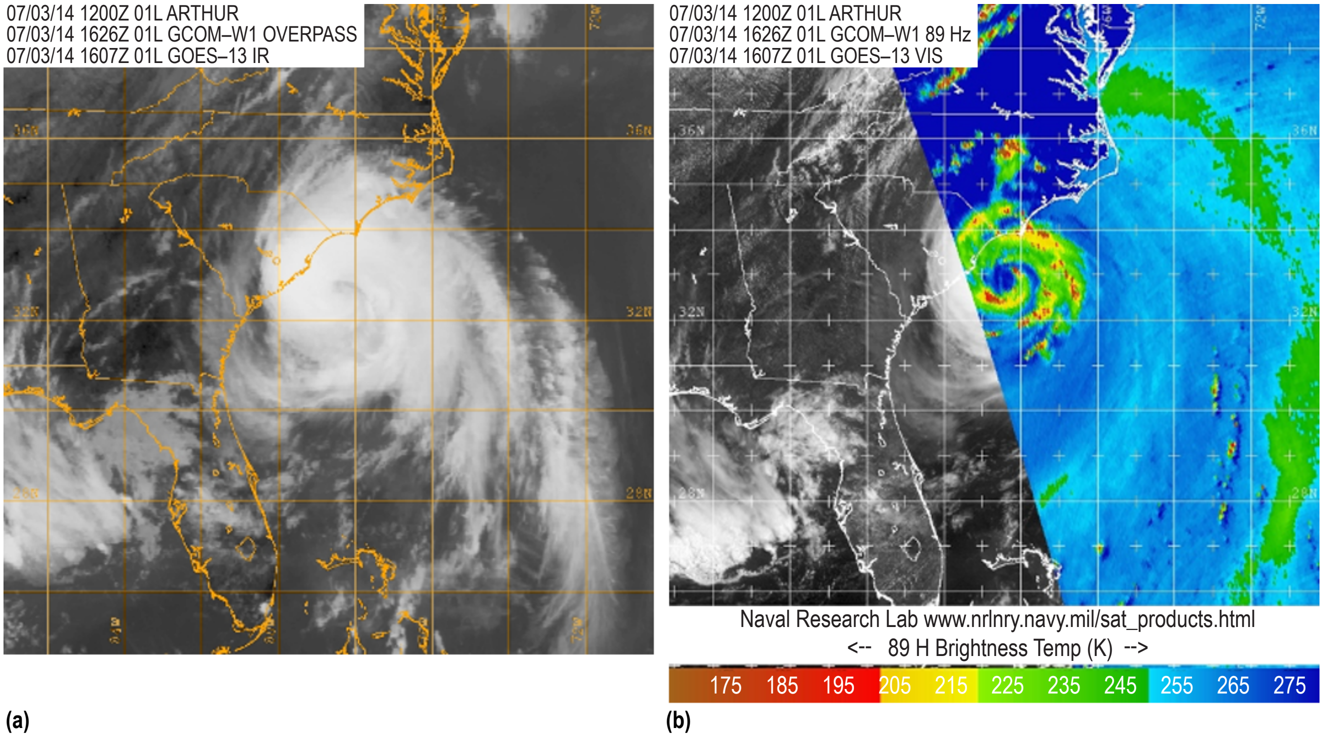


Figure 10. Tropical storm Arthur on July 3, 2014. Collocated images from the (a) GOES-13 (IR) and (b) Global Change Observation Mission First-Water (GCOM-W1) (89 GHz) satellites are shown. Images courtesy of Jack Beven, NOAA NHC.

Table 2. The NOAA NHC forecast cycle. Courtesy of Jack Beven, NOAA NHC.

Time (hr:min)	Event
00:00	Issue Tropical Weather Outlook Issue Intermediate Public Advisory (if necessary) Synoptic time/cycle begins
00:45	Receive satellite fix data
01:00	Initialize models
01:10	Receive model guidance and prepare forecast
02:00	NWS/DoD hotline coordination
03:00	Advisory deadline
03:15	FEMA conference call
06:00	New cycle begins

The TC Analysis and Forecasting session also included presentations highlighting TROPICS-related research with potential forecasting applications. Efforts at NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) Hurricane Research Division (HRD) have involved conducting Observing System Simulation Experiments (OSSEs) using synthetic TROPICS radiance observations (TROPICS Proxy Data) in an HNR model simulation. Simulated TROPICS radiances show positive impacts on Hurricane-WRF (HWRF; v3.6) model initial conditions for moisture, TC position correction, short-term TC track forecasts, and TC track and intensity forecasts beyond 2 days. Future work will involve continuing to optimize the assimilation of TROPICS radiances to assess impacts on numerical model forecasts. The results of these efforts have potential implications on operational models that assimilate data from the TROPICS constellation.

Other research efforts have focused on using TROPICS data to improve the real-time estimation of TC intensity. The University of Wisconsin-Madison/CIMSS (UW/CIMSS) seeks to leverage the robust relationship between microwave sounder-derived brightness temperature (Tb) anomalies associated with the TC warm core and its relationship to TC intensity. UW/CIMSS has already developed an operational radiance-based algorithm for estimating TC intensity that uses data from AMSU flying on NOAA-15, -16, and -17 satellites, SSMI/S, and the ATMS flying on the NOAA-20 and SNPP satellites. AMSU data (channel 6 (54.4 GHz) and Channel 8 (55.5 GHz)) for TCs from 1998–2015 is being used to develop a database of estimated equivalent brightness temperature anomalies from TROPICS (channel 6 (117.8 GHz) and Channel 7 (118.3 GHz)). This database will provide a training dataset for developing a statistical relationship between TROPICS Tb anomalies and TC intensity and will be independently tested using TROPICS proxy data. The goal of this work is to develop a new TC intensity estimation algorithm that uses Tb from the TROPICS satellite constellation. The Naval Research Laboratory (NRL) in Monterey plans to incorporate TROPICS data into machine learning analyses of TC structure to analyze and predict TC rapid intensification. TROPICS measurements of environmental and inner core moisture, precipitation, ice water path, liquid water path, and tropopause temperature could all serve as inputs to the machine learning models that are being developed.

5.5.2 Terrestrial/Disasters/Severe Weather

As TROPICS will observe both land and ocean in the tropical latitudes, TROPICS Early Adopters with a Terrestrial/Disasters/Severe Weather focus seek to use TROPICS data to improve the monitoring, modeling, and forecasting of atmospheric phenomena pertaining to precipitation and the Earth's surface. In particular, the high temporal frequency of TROPICS will supplement precipitation data in tropical regions that lack ground-based radar coverage. As a result, there are a number of terrestrial and severe weather end-user applications that can incorporate these data into decision-making processes.

Preliminary results generated from the TROPICS HNR proxy data processed through the Precipitation Retrieval and Profiling Scheme (PRPS) demonstrate that the overall structure of precipitation is captured well, but the magnitudes tend to be underestimated (fig. 11). PRPS is similar to the Goddard Profiling Algorithm (GPROF) which will be used with TROPICS, but uses a different database for validation. Modeled TROPICS brightness temperature and rain rate relationships for the 91- and 183-GHz channels demonstrate an increase in rain rates with decreasing brightness temperature (fig. 12). Moreover, modeling of the oxygen channels (114.5–118.58 GHz), which are not typically used for this purpose, also demonstrate useful information.

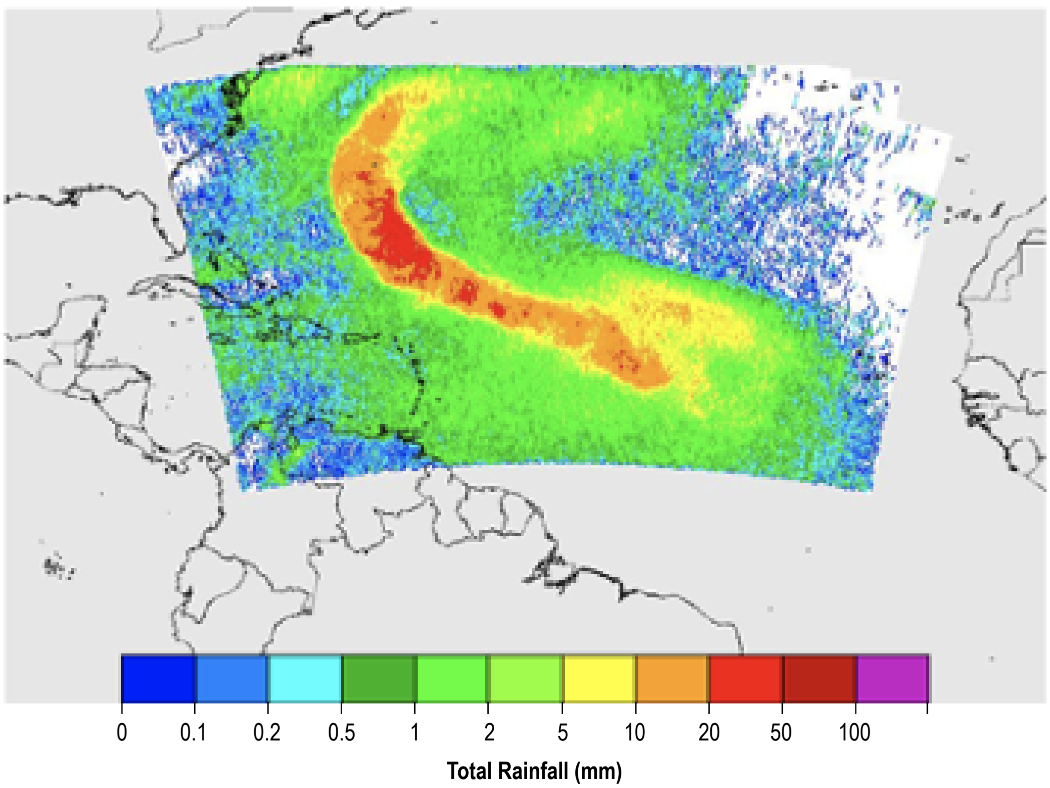


Figure 11. PRPS rainfall accumulation over the 13-day HNR simulation period. This is a prelaunch simulation to demonstrate the potential of TROPICS. Image courtesy of Chris Kidd, University of Maryland/ESSIC, NASA GSFC.

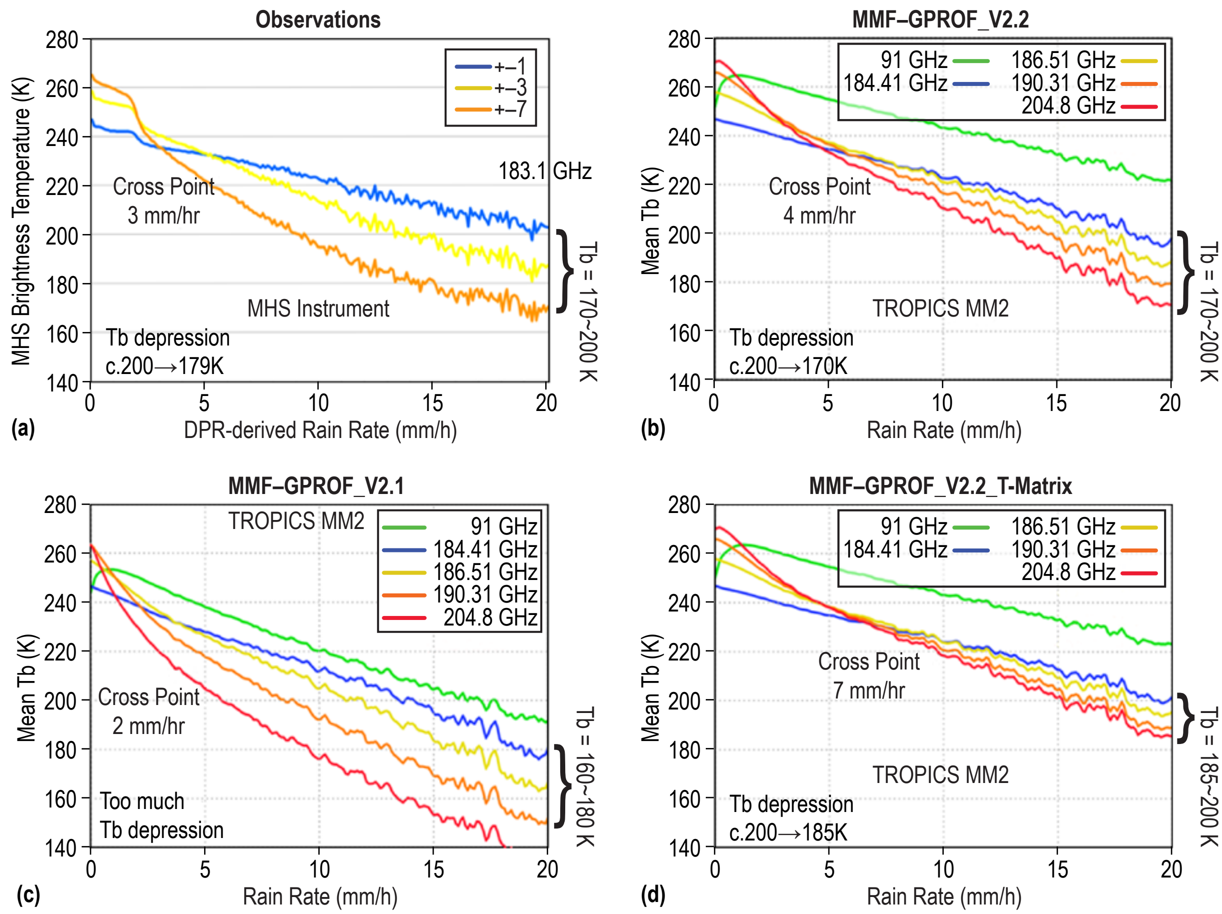


Figure 12. Modeled brightness temperature and rain rate relationships for TROPICS channels. These are prelaunch simulations to demonstrate the potential of TROPICS: (a) Observations—Tb depression c.200→179 K, (b) TROPICS MM2—Tb depression c.200→170 K, (c) TROPICS MM2—too much Tb depression, and (d) TROPICS MM2—Tb depression c.200→185 K. Image courtesy of Chris Kidd, University of Maryland/ESSIC, NASA GSFC.

Other participants noted that TROPICS has the potential to help improve rainfall estimates over land. In particular, the use of TROPICS data in real time with low latency (<30–60 minutes) would be valuable for disaster monitoring and response, particularly for flooding and for severe weather. TROPICS PMW data will provide additional information beyond geostationary infrared imagery, and low latencies would allow for monitoring and analysis with the combination of these two datasets. Participants also demonstrated that a differential brightness temperature analysis can improve the precipitation retrievals over both snow/ice-covered land and in TCs, and the availability of data at the frequent revisit rate of TROPICS may further improve this performance.

The value of pairing TROPICS datasets with existing missions, such as GPM, for severe storm tracking and analysis was also considered. The frequent data products available with TROPICS allow for the rapid detection of storms when combined with data from GPM. Since the current constellation can have long gaps in coverage, many severe thunderstorms are entirely missed. Participants suggest that, although TROPICS may detect a greater number of storms, it likely will have lower confidence with regard to the severity of these detected storms. However, using the temporal trend from TROPICS to refine GPM-based estimates of a storm's severity may be useful.

Some outstanding research questions raised by participants include the following: Can TROPICS assess the rate of weakening or intensification of a storm? Can retrievals of temperature and moisture profiles measure storm inflow thermodynamics? A TROPICS proxy dataset of severe storms or over land could be valuable for exploring these questions.

5.5.3 Tropical Cyclone Modeling and Data Assimilation

Advances in numerical modeling over the past two decades have led to marked improvements in TC track forecasts. Although intensity forecast accuracy also has increased, these advances occur more slowly, largely due to uncertainties in the initial conditions and in the dynamics that govern the TC inner core. Improving the representation of inner-core processes in mesoscale TC models is an important key to better intensity forecasts. Data assimilation also exerts a large influence on TC forecasting through accurate depiction of the TC circulation and its environment. The high spatial and temporal resolution of TROPICS offers an opportunity to improve representations of TC structure and evolution in both the research and operational modeling environments.

The global coverage and high temporal resolution of TROPICS provides an opportunity to improve global operational models through enhanced data assimilation. Representatives from Météo-France indicated that by the time TROPICS data are available, the four-dimensional variational system of their global Action de Recherche Petite Echelle Grande Echelle (ARPEGE) model will be able to assimilate all-weather microwave sounder observations. Experiments using the Megha-Tropiques Sounder for Probing Vertical Profiles of Humidity (SAPHIR) cloudy radiances suggest that assimilation of these observations reduces ARPEGE TC track forecast errors by about 6%. Impediments to operational assimilation include the time needed to test the impact of new observations after launch (about 7 months) combined with the short planned lifetime of the mission.

At the NRL, prelaunch activities include the acquisition of spectral response functions (SRF) and validation of radiative transfer models using these SRFs. After launch, a series of calibration/validation activities are performed prior to full operational assimilation. Assimilation of all-sky radiances into NRL's Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TCs) model shows promise to improve both TC track and intensity forecasts through better representation of TC structure. Experiments with all-sky assimilation of water vapor infrared radiances reduced intensity forecast errors by up to 58% for Hurricane Patricia (2015), with improved intensification trends relative to a control simulation without all-sky radiances (fig. 13). The improved TC track and intensity forecasts for Hurricane Patricia appeared to be related to a better representation of Patricia's very compact, intense inner core (fig. 14). These results suggest that assimilation of TROPICS radiances could be of significant benefit to COAMPS-TC, although testing is ongoing.

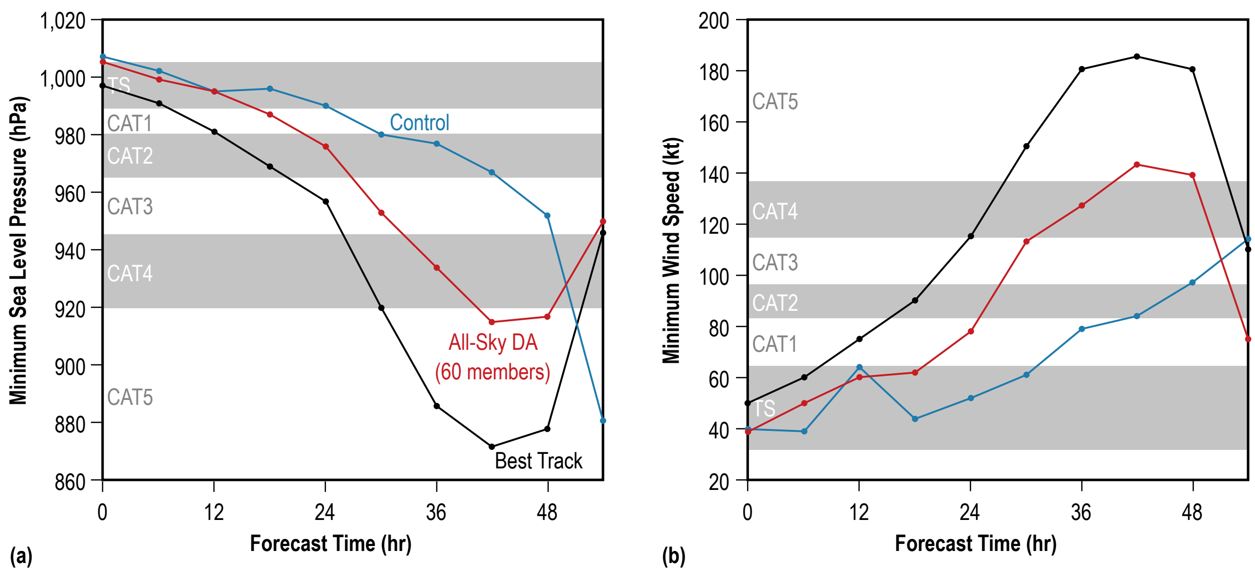


Figure 13. COAMPS-TC forecasts of 20E (a) minimum sea level pressure and (b) maximum wind speed for Hurricane Patricia at 1800 UTC, October 21, 2015. Red and blue lines indicate forecasts with and without all-sky radiance data assimilation, respectively, and the black lines represent intensities from the NHC best track. Images courtesy of Zhao et al. 2020 (NRL).

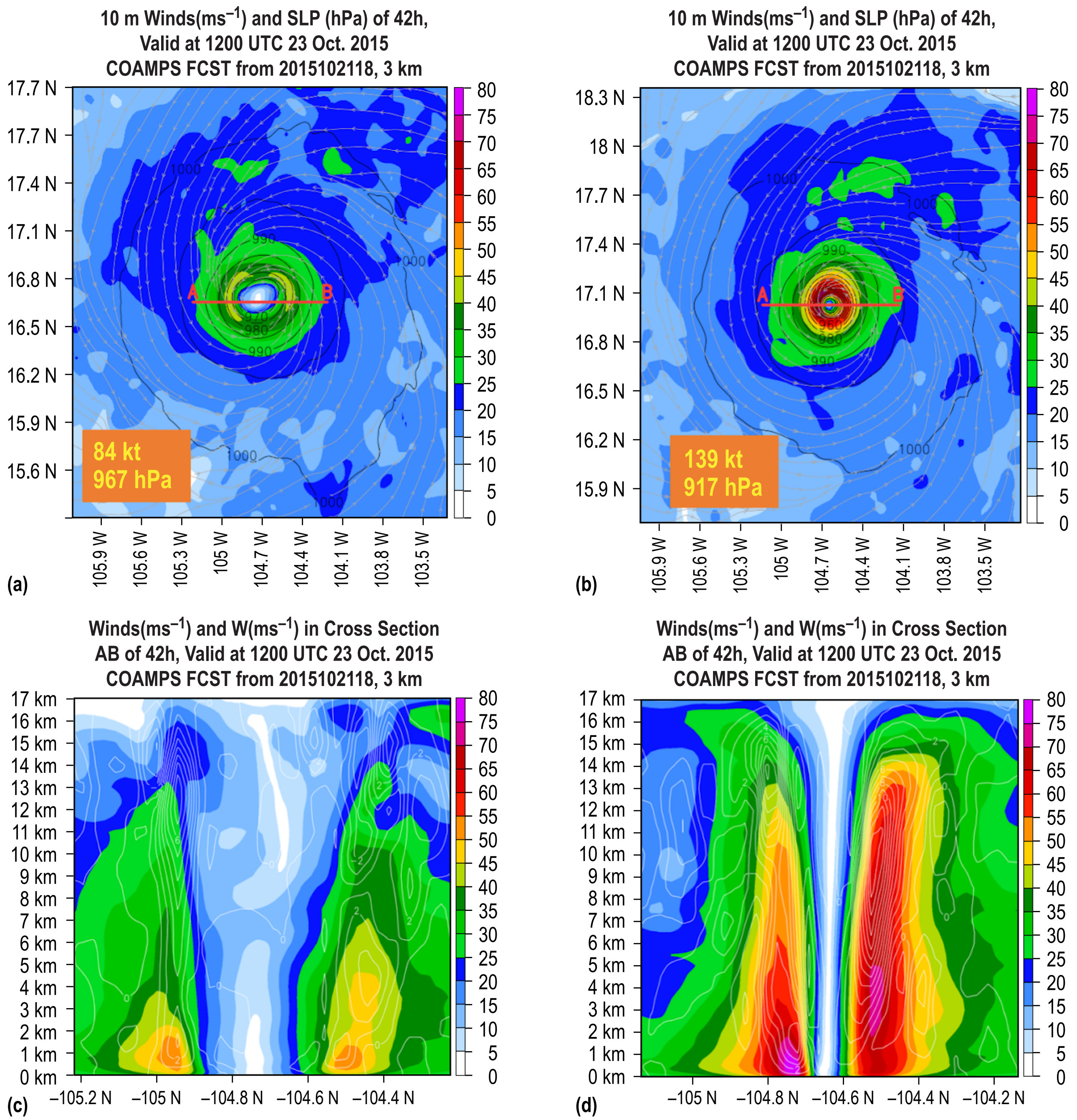


Figure 14. COAMPS-TC forecasts of 10-m wind speed (ms^{-1}) and sea level pressure (hPa) (a) without and (b) with all-sky data assimilation. Horizontal wind speed (contours) and vertical wind speed (colors) (c) without and (d) with all-sky data assimilation. Images courtesy of Hao Jin, NRL.

Recent advances at NASA's Global Modeling and Assimilation Office (GMAO) have enabled the near-real-time assimilation of all-sky radiances from the GPM constellation since 2018. Upon model physics changes and assimilation of all-sky radiances, Goddard Earth Observing System (GEOS) forecasts of specific humidity, temperature, and wind in the tropics exhibited considerably smaller error throughout the troposphere (fig. 15). GMAO is working to incorporate data from other microwave sensors such as the Microwave Humidity Sounder (MHS), ATMS, SSMI/S, and SAPHIR, and can apply similar techniques to assimilate TROPICS data when it becomes available.

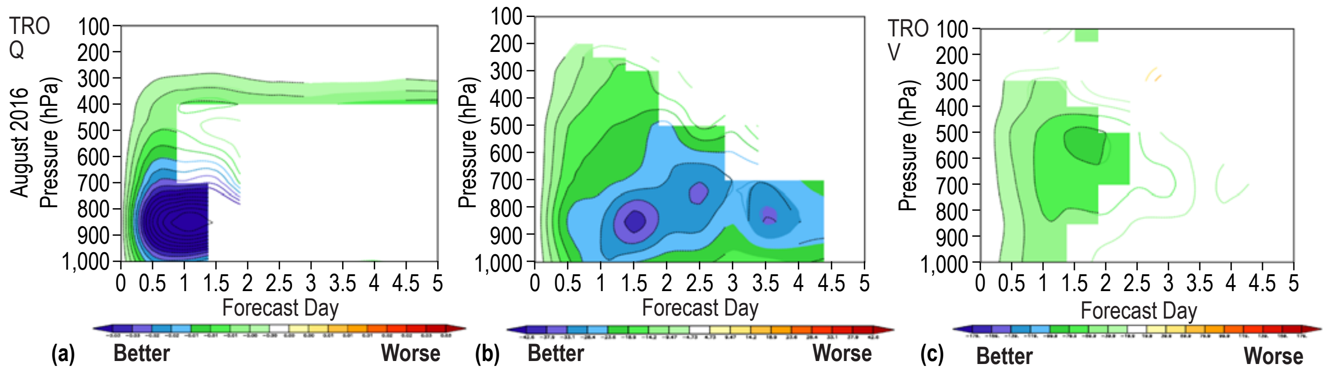


Figure 15. All-sky GMI (Control 31) TROPICS: Root-mean-square error difference ($\times 10^{-3}$) for forecasts of (a) specific humidity, (b) temperature, and (c) meridional wind between a GEOS forecast employing clear-sky radiance assimilation and a control run without clear-sky assimilation. Images courtesy of Min-Jeong Kim of NASA's GMAO/Morgan State University/Goddard Earth Science (GES) Technology and Research.

Overall, results presented by operational modeling groups show great promise that assimilation of all-sky radiances from TROPICS could further improve TC track and intensity forecasts. The groups also highlighted, however, that latency is a primary limitation in the successful operational assimilation of TROPICS data, with a latency of less than 4 hours ideal for Météo-France. Attendees also noted that data quality flags, uncertainties, and biases are necessary to facilitate assimilation of TROPICS data into operational and research models.

5.6 Synergy With Other Missions

NASA, NOAA, and DoD have multiple ongoing or planned satellite missions focused on observing TCs and their surrounding environment, which have potential synergy with the TROPICS mission. The CYGNSS mission is a space-based satellite constellation that uses GPS signals scattered by the ocean surface to measure ocean surface wind speed in most naturally occurring precipitating conditions, including those experienced in the TC eyewall. CYGNSS can also measure ocean surface wind speed in the TC inner core with sufficient frequency to resolve genesis and rapid intensification. Potential overlap of the TROPICS and CYGNSS missions will provide a unique opportunity to collect collocated thermal (TROPICS) and surface wind (CYGNSS) information in the inner core (R≤150 km), near environment (R=150–300 km), and peripheral environment (R≥300 km) of TCs at a relatively high temporal frequency. This will allow for detailed analyses of the evolution of TC structure over the complete lifecycle of a storm. There are also opportunities for lessons learned from CYGNSS as this mission is also comprised of a constellation of smallsats.

The GOES-R satellites (i.e., GOES-16 and -17) represent a significant leap forward for the GOES satellite series with faster image scanning and higher spatial and spectral resolution with the Advanced Baseline Imager (ABI). There are several application synergies between GOES-R and TROPICS, where observations from the TROPICS satellites could enhance the visible and IR observations and products that are available from the GOES-R satellites:

- Tropical Cyclone Center Fixing: The TROPICS microwave imager (≈90 GHz) could improve TC center-fixing when the storm center is obscured by clouds in the IR.

- Tropical Cyclone Intensity Estimation: TROPICS TC intensity estimates could complement the IR-based Advanced Dvorak Technique (ADT) and could also be entrained into the UW/CIMSS SATCON (Satellite Consensus) technique for estimating TC intensity.

- Atmospheric Motion Vectors (AMVs): TROPICS PMW imagery could be used to track convective cell motions with a relatively high temporal refresh rate, which could lead to improved 3-D winds in the TC inner core.

- Saharan Air Layer (SAL): TROPICS moisture channels could aid in the detection of the SAL's low to mid-level dry air (≈500–850 hPa), especially in the environment of TCs that are interacting with the SAL.

- Geostationary Lightning Mapper (GLM): TROPICS rain-rate data could augment GOES-R GLM data and be used to diagnose and possibly predict TC rapid intensification events, relate precipitation structure evolution to the evolution of the TC upper-level warm core anomaly (intensity change), relate the occurrence of intense convective cores in the TC vortex (i.e., convective bursts) to TC intensity change, and examine the evolution of the TC diurnal cycle.

There are also several application synergies between TROPICS and PMW applications developed by UW-CIMSS that are currently being used for TC analysis around the globe:

- Automated Rotational Center Hurricane Eye Retrieval (ARCHER): ARCHER is designed to aid TC forecasters in objectively identifying key TC characteristics such as center position, eye diameter, and presence of an eye. TROPICS data could be used to supplement the PMW imagery that is currently used as input for the ARCHER algorithms.

- Satellite Consensus (SATCON): The SATCON product blends TC intensity estimates derived from multiple objective algorithms to produce an ensemble estimate of TC intensity for storms worldwide. TROPICS data could be used to supplement the PMW data that is currently used in SATCON (e.g., AMSU, SSMI/S, and ATMS).

- Microwave-Based Probability of Eyewall Replacement Cycle (M-PERC) Model: M-PERC is a statistical model for predicting the onset of TC eyewall replacement cycles

(ERCs) that can affect storm intensity and structure. TROPICS data could be used to supplement the PMW data that are currently used as input in M-PERC.

The TROPICS mission offers a unique capability for providing rapid refresh PMW observations in the TC environment and has numerous potential synergies with existing satellite missions. Data from TROPICS have many potential applications that can provide enhanced capabilities for examining TC track (location), intensity change, and structure, as well as the larger scale environment surrounding storms.

5.7 Summary of Strengths/Limitations of Smallsats

As smallsat technology is developed, demonstrated, and matured, it presents new opportunities for satellite observations but also presents strengths and limitations that will be uncovered as users integrate this new technology into applied research and applications. A breakout session on the strengths and limitations of smallsats was an opportunity for users to discuss questions related to using this new technology. The breakout session was preceded by a presentation about the challenges and advantages of exploiting smallsat data in NWP. Smallsats present advantages for more agile, cost-effective solutions to complement existing satellite architectures but introduce challenges related to maturity, design life, stability, reliability, and data quality. Operational assimilation requires high availability and reliability and tools/data assimilation systems need to adapt to evolving observing system architectures to facilitate rapid research-to-operations. For example, a mature observation type can be promoted to operational data assimilation 6 months after launch with a focus on prelaunch activities, leveraging sensor heritage, and interagency coordination. Integration of known heritage sensors can be characterized by low post-launch effort and low risk of sensor failure because the technology is mature. In contrast, new observations can take as long as 20 months post-launch to be promoted to operational data assimilation. The post-launch effort and risk of sensor failure are high since the technology may be less mature with more knowns that need to be characterized such as expected age and on-orbit performance. With the limited design life of smallsats, it is important to identify and mitigate potential challenges prelaunch to determine if operational data assimilation is feasible. The challenges related to smallsats (e.g., checkout, calibration/validation, stable data quality, continuous data for observing system experiments, integration and testing, and research-to-operations bottlenecks) can potentially be overcome by technology maturation, development of tools to accelerate the assessment of sensor/data performance, address latency requirements through ground-station planning, prelaunch development, tools to accelerate impact assessments, and agile development and operations strategies. Addressing challenges related to forward operator development, assessment, and improvement, error characterization, and quality control are important aspects of the process to consider.

During the breakout, workshop attendees gave their perspective on strengths and limitations of integrating smallsats into their research or application as well as an opportunity to comment on the enabling aspects of TROPICS (see questions in app. D). Attendees agreed that the coverage and temporal frequency of TROPICS are exciting attributes of the mission, noting the advantage of some familiar frequencies and the ability to use the data for validation of NWP output, physics schemes, or other satellite products such as IMERG. Although the vertical resolution may be limited, the temporal resolution is an unprecedented attribute of the mission. The temporal resolution is the greatest strength that users foresee for integrating a constellation of smallsats in their research and/or application, allowing for rapid updating for data assimilation systems (including improved vortex initialization and the fidelity for cloud tracking and winds) and improved operational analysis (e.g., assessing the tropical environment, TC genesis, and TC evolution). Overall, the greatest limitations that users foresee with integrating a constellation of smallsats in applied research and applications are calibration, short mission life and limited longevity of hardware, and the amount of time to ingest new data into data assimilation systems and user applications. Given a short mission life, indepth calibration is not feasible, noting that calibration or instability between platforms will impact microwave intensity and precipitation retrieval, while noise will create undesired anomalies where errors of 1–5 K impact applications. In addition, concerns were raised about ice scattering and the need to do training for the higher frequency channels.

Attendees noted the need to have good prelaunch data and documentation of bias corrections. To mitigate the challenges with the short mission life and the time it takes to integrate data into assimilation systems and user applications, the attendees strongly recommended launching the 7th TROPICS unit as an early pathfinder mission to allow preliminary integration into algorithms, end-user applications, and data assimilation systems as an opportunity to create the needed infrastructure for the full mission. Given the complexity of using smallsats in tandem, users were asked to comment on potential requirements for metadata that would facilitate their use of TROPICS data. The modeling and data assimilation attendees noted the need for covariance for instrument noise, antenna correction (if applied), reflection and scan bias, quality flags including Moon in view or whether a lower sample of calibration was used, and instrument temperature. Attendees noted the advantage of including any and all metadata to allow them to analyze and correlate attributes. Another limitation that attendees noted was the need to begin planning a TROPICS mission follow-on. In the event data are successfully transitioned to end-users for disaster, forecasting applications, or operational data assimilation, how will users deal with the sudden loss of data? Last, the attendees recommended funding for post-mission data analysis be prioritized.

6. MEETING ACTIONS/TAKEAWAYS

Since the first TROPICS Applications Workshop in 2017, there has been continued momentum within the community of applied-science and operational end-users to understand TROPICS capabilities and prepare to integrate these unprecedented observations within existing science and applications frameworks. The inputs from the second TROPICS Application Workshop will be considered by the science team and NASA applications leads as possible actions to continue to build capacity for utilization of TROPICS data and to maximize the benefit to society. Similar to the first workshop, the desire for improved data latency (e.g., <3 hours; optimally <1 hour) beyond mission requirements is strongly desired and viewed as attainable given the required cost and high potential return on investment. Given the short mission life, complexities with integrating smallsats in existing systems, the need to characterize error and bias, and deficiencies with current proxy datasets, the community strongly recommends launching the 7th TROPICS qualification unit prior to the full constellation. Such a pathfinder mission will enable preliminary integration into algorithms, end-user applications, and data assimilation systems and help build the needed infrastructure for the full mission and accelerate post-launch activities. Finally, users recommended a variety of data formats (e.g., netCDF, Georeferenced Tagged Image File Format (geoTIFF), BUFR, AWIPS-compatible) to accelerate the integration of TROPICS data into a variety of applied research and applications that span forecasting, disaster response, and operational modeling. In addition to data formats, users requested targeted training to understand new capabilities such as the value of the 205-GHz channel for operational TC forecasting.

The following meeting actions/takeways are documented here as potential areas where the TROPICS science team, NASA TROPICS Early Adopter Program, and the applied-science community could make additional investments into the mission to enhance and accelerate TROPICS applications for the benefit of society:

- **Seek external funding and/or partnership with NOAA or international organizations to optimize mission latency to the greatest extent possible to facilitate operational application of data for time-sensitive decisions and increase societal benefit.** There is a strong preference to increase the availability of TROPICS observations—for low latency data on a global scale. While current mission specifications are suitable for applied research and time-independent end-user decisions, optimal latency would expand the utility for operational decision making related to weather forecasting, NWP, and disaster response, increasing the societal benefit. In addition, users strongly request low latency capabilities expanded to the Pacific Ocean basin. Without augmentations to existing mission specifications, there could be a missed opportunity to maximize the potential of NASA data and prepare the community for future missions of value that are likely to be comprised of smallsat technology.

- **There is a need for refinement and expansion of the HNR proxy data or additional datasets.** Refinement and expansion of the HNR proxy data is needed to correct for limb-effects and underestimation of brightness temperatures. These issues caused difficulty in TC analysis with proxy data and suggestions were made to improve the data through tuning of parameters in CRTM. Precipitation proxy data are not widely available and initial algorithm assessments indicate either an underestimation of precipitation estimates from the retrieval algorithm or a warm bias in the proxy brightness temperatures. Additional proxy data over land and outside TCs for use in other applications were of high interest, indicating the need for more nature runs with a variety of phenomena/structures.

- **Launch the 7th TROPICS unit to prepare for full mission capabilities before launch.** Given the shortcomings of existing proxy datasets and restricted access to the FY-3C data, the pathfinder would provide a more encompassing proxy dataset without the above identified shortcomings. Launch of a pathfinder mission would provide rich opportunities for applied research, development of training materials, preparation of algorithms, and understanding of error characteristics, bias, and on-orbit performance prior to launch of the full mission. The community would be able to take initial steps to deal with complexities of integrating smallsats in existing systems. In addition, development of the infrastructure and preparation of observations for operations prior to launch would accelerate use of the full TROPICS mission quickly after launch, maximizing the short mission life and benefit to society.

- **Participants expressed the importance of prelaunch instrument characterization and stable in-orbit performance, as well as quality control and bias correction, and requested these metrics from the science team.**

- **Establish a working group on requirements for operational data assimilation to discuss and develop requirements for BUFR format, forward operators, data assimilation tools, prelaunch testing and error/anomaly characterization, and best practices for data assimilation of smallsat data and assessment of the impact on forecasts.** A recommendation was made for interested data assimilation centers to assign a point of contact for TROPICS data assimilation and interaction with the science team on prelaunch activities, questions, and feedback. In addition, the NWP community can easily uncover anomalies and relay findings to the mission calibration/validation team.

- **A recommendation for the science team and applications community to develop a variety of data types and visualization tools to facilitate use of TROPICS data and to accelerate integration within operational systems, given the short duration mission.** For example, given the experience of UW/SSEC, the recommendation was made for the mission DPC to create and distribute BUFR-formatted data. The experience of NASA's Short-term Prediction Research and Transition (SPoRT) Center can be leveraged to develop formats and display capabilities for NWS display systems (AWIPS and National Centers-AWIPS). The GES Data and Information Services Center (DISC) has experience with development of GeoTIFF-formatted files and necessary experience with Common Metadata Repository (CMR) requirements to enable integration of TROPICS in NASA's Worldview display and Geospatial Information Systems, enabling broader use by end-users who rely on these capabilities for access to remote sensing observations such as those in the disaster and emergency response community. Other frameworks of interest include NASA's MTS, commonly used during field campaigns, and the Jet Propulsion Laboratory's (JPL's) Tropical Cyclone Information System.

- **Applied research or 'proof of concept' studies are necessary to discover the advantages and limitations of new TROPICS channels and the benefit to science and applications.** Understanding the thermodynamic and microphysics features these channels detect and the relationship to TC structure, intensity, and evolution is integral to use in operations. Although TROPICS is a mission with a focus on TCs, how do these features relate to thunderstorm structure, intensity, and resulting hazards? Understanding of the relationships between the remote-sensing characteristics, detected atmospheric features, and associated phenomena can be used to create targeted training material for the community of end-users to demonstrate capabilities relevant to the operational environment and decision making. Considering NHC forecasters have relied on passive microwave 37- and 89-GHz observations, there is a need to understand how TROPICS observations provide similar or enhanced capabilities beyond the program of record. Similarly, understanding and training regarding precipitation estimates and biases is critical for effective use by operational organizations. Leveraging the experience of NASA SPoRT to create applications-based training to prepare users for satellite datasets, it is recommended that the applications community and subject matter experts collaborate on proof-of-concept studies and development of training resources that describe the utility and interpretation of different products. NASA Applied Remote Sensing Training (ARSET) is also a resource to leverage for training development and seminars. In addition, a future NASA ROSES TROPICS Science Team solicitation could include a section on key science questions related to process studies with TROPICS data to understand the thermodynamic and microphysical processes related to tropical convection, TCs, and precipitation systems, as well as development of new algorithms, techniques, and products with an emphasis on the cross-benefit of research and applications (i.e., TROPICS Applied Science Team).

The inputs from the Second TROPICS Application Workshop will be considered by the TROPICS science team and the TROPICS application leads as possible actions to continue to build capacity for utilization of TROPICS data in applications and to maximize the benefit to society, but much of the effort will require community involvement and active engagement with applied researchers, operational end-users, and TROPICS Early Adopters. Since the workshop convened, more definitive plans are in process to launch the pathfinder mission in 2021, which will provide a robust opportunity for the community to make progress on the recommendations herein and further prepare for the TROPICS mission prior to launch of the full constellation.

APPENDIX A — ORGANIZING COMMITTEE

Table 3. List of members of the Second TROPICS Applications Workshop organizing committee.

Name	Affiliation
Emily Berndt*	NASA Marshall Space Flight Center (MSFC) / TROPICS Deputy Program Applications Lead
William Blackwell	MIT LL / TROPICS Principal Investigator
Neils Bormann	ECMWF
Scott Braun	NASA GSFC / TROPICS Project Scientist
Michael Brennan	NOAA NWS National Hurricane Center
Joshua Cossuth	NRL
Jason Dunion*	University of Miami (UM) / CIMAS - NOAA/HRD
Erika Duran	The University of Alabama in Huntsville / SPoRT
Patrick Duran	NASA MSFC / SPoRT
David Green	NASA HQ / CYGNSS & TROPICS Program Applications Lead
Derrick Herndon	University of Wisconsin / CIMSS / SSEC
Dalia Kirschbaum	NASA GSFC
John Murray	NASA Langley Research Center (LaRC) / CYGNSS Deputy Program Applications Lead
Daniel Vila	INPE

*Meeting co-conveners

APPENDIX B—MEETING AGENDA

Second Time-Resolved Observations of Precipitation Structure and Storm Intensity With a Constellation of Smallsats (TROPICS) Mission Applications Workshop

February 19-20, 2020
Rosenstiel School of Marine & Atmospheric Science Auditorium,
University of Miami
4600 Rickenbacker Causeway, Miami, FL 33149-1031

Tuesday, February 18:

6:00p – 7:30p	Optional Cocktail Hour at Above Mayfair

Wednesday, February 19:

7:15a	UM shuttle departs Mayfair Hotel & Spa for UM/RSMAS
7:30a – 8:00a	Registration/Light Refreshments
8:00a – 8:05a	Welcome and Logistics, **Jason Dunion**, UM/CIMAS – NOAA/AOML/HRD
8:05a – 8:10a	UM Welcome, **Benjamin Kirtman**, Director, UM/CIMAS
8:10a – 8:15a	Summary of Workshop Objectives, **Emily Berndt**, Deputy Program Applications Lead TROPICS, NASA/MSFC
8:15a – 8:30a	NASA HQ and Applied Sciences Welcome, **John Murray**, Associate Program Manager, Disasters, NASA Applied Sciences
8:30a – 9:00a	*TROPICS Mission Overview and Status*, **William Blackwell**, TROPICS Principal Investigator, MIT Lincoln Laboratory

<u>Proxy Data Presentations</u>: (Session Chair: William Blackwell)

9:00a – 9:15a	*Hurricane Nature Run*, **Vince Leslie,** MIT LL
9:15a – 9:30a	*Impact of passive MW data in the ECMWF system and experience with MWHS-2*, **Niels Bormann**, ECMWF
9:30a – 9:45a	*Exploring TC Structure and Rainfall with TROPICS Proxy Data,* **Erin Munsell**, NASA GSFC/University of Maryland (UMD) ESSIC
9:45a – 10:00a	*Analysis of the Tropical Cyclone Diurnal Cycle using TROPICS Proxy Data*, **Erika Duran**, UAH/NASA SPoRT
10:00a – 10:15a	Morning Break (registration payment desk will be open)

<u>Application Presentations 1</u>: TC Analysis and Forecasting
(Session Chair: Jason Dunion)

10:15a – 10:30a	*NHC Perspective*, **Jack Beven**, NOAA/NHC
10:30a – 10:45a	*JTWC Perspective*, **James Darlow**, JTWC
10:45a – 11:00a	*HRD Perspective*, **Hui Christopherson**, UM/CIMAS – NOAA/AOML/HRD
11:00a – 11:15a	*Level 2 TROPICS Tropical Cyclone Intensity Products*, **Derrick Herndon,** UW-Madison/CIMSS
11:15a – 11:30a	*Using Machine Learning of TC Structures for Rapid Intensification Forecasting*, **Hui Su**, JPL
11:30a – 12:30p	Lunch at RSMAS Commons: SALT Waterfront Restaurant

<u>Application Presentations 2</u>: Terrestrial/Disasters/Severe Weather
(Session Chair: Daniel Vila)

12:30p – 12:45p	*TROPICS Precipitation Products*, **Chris Kidd**, NASA GSFC/UMD
12:45p – 1:00p	*NASA Disasters Overview*, **Andrew Molthan**, NASA MSFC
1:00p – 1:15p	*TROPICS – Potential for a Step-Change in Operational Hydrology*, **Ana Barros**, Duke University
1:15p – 1:30p	*MCS Tracking and Nowcasting,* **Daniel Vila**, Centro de Previsão de Tempo e Estudos Climáticos (CPTEC)/INPE
1:30p – 1:45p	*How Do TROPICS Frequencies Respond to Large Hail*, **Dan Cecil** (NASA MSFC) & **Sarah Bang** (NASA Postdoctoral Program; NPP)
1:45p – 2:00p	*Improving Precipitation Retrieval with Brightness Temperature Temporal Variation: Add a Time Dimension*, **Yalei You**, UMD
2:00p – 2:15p	Afternoon Break

<u>Breakout Discussions/Capture End-User Perspectives</u>

2:15p – 2:30p	Update on Mission Latency, **William Blackwell**, MIT LL
2:30p – 3:15p	Breakout Discussions No. 1: Latency (led by session chairs; local scribes) (1) Terrestrial/Disasters/Severe Weather (2) Tropical Cyclone Analysis/Forecasting (3) Tropical Cyclone Modeling and Data Assimilation
3:15p – 3:45p	Breakout Leads Report Out (10 minutes each)
3:45p – 4:30p	Breakout Discussions No. 2: Products, Visualization, New Tools, Needs (led by session chairs; local scribes) (1) Terrestrial/Disasters/Severe Weather (2) Tropical Cyclone Analysis/Forecasting (3) Tropical Cyclone Modeling and Data Assimilation

4:30p – 5:00p	Breakout Leads Report Out (10 minutes each)
5:00p – 5:15p	**Wrap up for the day**
5:15p – 6:15p	Optional Ice Breaker: RSMAS Commons
6:30p	UM shuttle departs UM/RSMAS for Mayfair Hotel & Spa

Thursday, February 20:

7:15a	UM shuttle departs Mayfair Hotel & Spa for UM/RSMAS
7:30a – 8:00a	Registration/Light Refreshments

Application Presentations 3: Tropical Cyclone Modeling and Data Assimilation
(Session Chair: Scott Braun)

8:00a – 8:15a	*Tropical Modeling Activities at Météo-France and Potential Applications of TROPICS Data*, **Philippe Chambon**, Météo-France
8:15a – 8:30a	*NOAA's Hurricane Modeling and Data Assimilation Efforts Under the Unified Forecast System Framework*, **Xuejin Zhang**, NOAA/AOML/HRD
8:30a – 8:45a	*All-Sky Radiance Assimilation for COAMPS-TC at NRL,* **Allen Zhao**, NRL Monterey
8:45a – 9:00a	*Impact of Satellite Microwave Radiance Data Assimilation on GEOS Atmospheric Analysis and Forecasts in Tropics,* **Min-Jeong Kim**, NASA GSFC/GMAO
9:00a – 9:15a	*Assimilation of Satellite Radiances and Retrieved Data Products for Improved Numerical Prediction of Tropical Cyclones: Promises, Challenges, and Trade-offs,* **Zhaoxia Pu**, University of Utah

Breakout Discussions/Capture End-User Perspectives

9:15a – 9:30a	*Challenges With Smallsats*, **Kevin Garrett**, NOAA NESDIS
9:30a – 10:15a	Breakout Discussions No. 3: Potential Strengths and Limitations of Integrating Smallsats in Research and Applications (led by session chairs; local scribes) (1) Terrestrial/Disasters/Severe Weather (2) Tropical Cyclone Analysis/Forecasting (3) Tropical Cyclone Modeling and Data Assimilation
10:15a – 10:45a	Breakout Leads Report Out (10 minutes each)
10:45a – 11:00a	Morning Break (registration payment desk will be open)

<u>Synergy With Other Missions:</u>
(Session Chair: Patrick Duran)

11:00a – 11:15a	*Optimizing the Utilization of CYGNSS Wind Observations for Numerical Prediction of Tropical Cyclones*, **Bachir Annane**, UM/CIMAS – NOAA/AOML/HRD
11:15a – 11:30a	*Application Synergy With JPSS and TROPICS*, **Mitch Goldberg**, NOAA JPSS
11:30a – 11:45a	*GOES-R ABI Applications to Hurricanes*, **Jason Dunion**, UM/CIMAS – NOAA/AOML/HRD & **Chris Velden**, UW-Madison/CIMSS
11:45a – 12:00a	*GOES-R GLM*, **Stephanie Stevenson**, Cooperative Institute for Research in the Atmosphere (CIRA)/Colorado State University – NOAA/NHC
12:00a – 12:15p	*Hurricane Intensity and the PMW Constellation*, **Derrick Herndon**, UW-Madison/CIMSS

12:15p – 12:30p	**Workshop Final Thoughts/Adjourn Meeting**
12:45p	UM shuttle departs UM/RSMAS for Mayfair Hotel & Spa
1:30p – 3:30p	Closed-Door TROPICS Science Team Meeting: CIMAS Conference Room
3:45p	UM shuttle departs UM/RSMAS for Mayfair Hotel & Spa

APPENDIX C—ATTENDEE LIST

Table 4. List of attendees for the workshop detailed in appendix B.

Last Name	First Name	Affiliation	E-mail Address
Alvey	Trey	UM/CIMAS and NOAA/AOML/HRD	george.alvey@noaa.gov
Atlas	Robert	NOAA Retired	robert.atlas@noaa.gov
Bang	Sarah	NASA NPP/MSFC	sarah.d.bang@nasa.gov
Barros	Ana	Duke University	barros@duke.edu
Bates	David	NOAA/AOML	dbates47@gmail.com
Berndt	Emily	NASA MSFC	emily.b.berndt@nasa.gov
Bill	Blackwell	MIT LL	wjb@ll.mit.edu
Bormann	Niels	ECMWF	n.bormann@ecmwf.int
Braun	Scott	NASA GSFC	scott.a.braun@nasa.gov
Cecil	Dan	NASA MSFC	daniel.j.cecil@nasa.gov
Christophersen	Hui	NOAA/AOML/HRD and UM	hui.christophersen@noaa.gov
Dahl	Brittany	UM/CIMAS-NOAA/AOML/HRD	brittany.dahl@noaa.gov
DeMaria	Mark	NHC	Mark.DeMaria@noaa.gov
Dunion	Jason	UM/CIMAS-NOAA/HRD	jason.dunion@noaa.gov
Duran	Erika	UAH/NASA SPoRT	erika.l.duran@nasa.gov
Duran	Patrick	NASA MSFC/SPoRT	patrick.t.duran@nasa.gov
Freeman	Ronald	Journal of Space Operations	ronhfreeman@yahoo.com
Herndon	Derrick	UW-Madison/CIMSS	dherndon@ssec.wisc.edu
Holley	Kenward	UAH/NASA SPoRT	hek0003@uah.edu
James	Darlow	JTWC	james.darlow@noaa.gov
Kidd	Christopher	UMD/ESSIC and NASA GSFC	chris.kidd@nasa.gov
Kim	Min-Jeong	Morgan State University	min-jeong.kim@nasa.gov
Leslie	Vince	MIT LL	lesliev@ll.mit.edu
Loeser	Carlee	NASA GES DISC	carlee.f.loeser@nasa.gov
Marks	Frank D.	NOAA/AOML/HRD	frank.marks@noaa.gov

Last Name	First Name	Affiliation	E-mail Address
Molthan	Andrew	NASA MSFC	andrew.molthan@nasa.gov
Munsell	Erin	NASA GSFC	erin.b.munsell@nasa.gov
Murray	John	NASA Disasters	john.j.murray@nasa.gov
Nolan	David	UMiami	dnolan@miami.edu
Philippe	Chambon	Météo-France	philippe.chambon@meteo.fr
Pu	Zhaoxia	University of Utah	Zhaoxia.Pu@utah.edu
Stevenson	Stephanie	CIRA/NHC	stephanie.stevenson@noaa.gov
Stock	Christopher	United States Space Force	christopher.stock.1@us.af.mil
Su	Hui	JPL	Hui.Su@jpl.nasa.gov
Vila	Daniel	CPTEC/INPE	daniel.vila@inpe.br
Wei	Jennifer	NASA GSFC	jennifer.c.wei@nasa.gov
Worku	Lakemariam	UM / CIMAS	lakemariam.y.worku@noaa.gov
Xuejin	Zhang	NOAA/AOML/HRD	xuejin.zhang@noaa.gov
You	Yalei	UMD	yyou@umd.edu
Zawislak	Jon	UM/CIMAS, NOAA/AOML/HRD	jonathan.zawislak@noaa.gov

APPENDIX D—BREAKOUT SESSION QUESTIONS

Breakout Session No. 1: Latency

- What are the latency requirements (optimal latency) for your application or applied science?
- Over what regions do you need data the most?
- What applications would result if latency were optimal?
- How is your proposed application of the data limited by the expected latency?
- How is your application or applied science enabled by the expected latency?
- What approaches could be explored to mitigate latency concerns?
- Reliability vs latency: are users willing to sacrifice quality to receive the data more quickly?
- Timing of data and forecasting process: when are the optimal times to receive data to issue products or assimilate the data in models?

Breakout Session No. 2: Community Needs

- Are there any needs for Level 3, Level 4, or derived products that are not planned by the mission? Over what temporal and spatial scales should Level 3 products be aggregated?
- How do you use MiRS products now and are there any strengths or limitations?
- Are there MiRS products you would like to have from TROPICS?
- How do you envision TROPICS being used with MiRS products from the current PMW constellation?
- Are there any GPM imagery and precipitation (swath rain rate or IMERG) products you use now?
- How do you envision TROPICS imagery or precipitation being used with GPM imagery or precipitation?
- Are there current visualization tools, software, or portals that TROPICS data should be added?
- What types of visualization tools are needed to enable use of TROPICS data?
- What types of tools/code need to be developed to prepare for and use TROPICS data?
- What needs are related to CRTM or other radiative transfer tools?
- Are there needs for further development of forward operators or other data assimilation tools?

- Are there particular data formats that are needed for your application or research?
- Is there a need for BUFR or WMO header/standards?

Breakout Session No. 3: Strengths and Limitations of Smallsats

Given the community has limited experience with smallsats:

- What is exciting?
- What questions do you have about using smallsats?
- What do you view as potentially limiting?
- How important is it for your application/research that calibration is stable or that the satellites have nearly identical calibration characteristics?
- How does TROPICS spatial resolution help or hinder your application or research?
- How does TROPICS temporal resolution help or hinder your application or research?
- What are potential requirements for metadata (i.e., individual noise, sensor temperature, quality flags, bias, etc.) that would enable use of the data?
- What strengths do you foresee with integrating smallsats in your application/research?
- What limitations do you foresee with integrating smallsats in your application/research?

REFERENCES

1. Blackwell, W.J.; and Braun, S.A.: “TROPICS: Mission Overview,” <https://tropics.ll.mit.edu/CMS/tropics/>, 2015.

2. Berndt, E.B.; Jedlovec, G.; and Meyer, P.: “Mission Overview: Early Adopter Program,” <https://weather.msfc.nasa.gov/tropics/>, 2018.

3. Berndt, E.B.; Jedlovec, G.; and Meyer, P.: “Proxy Data,” <https://weather.msfc.nasa.gov/tropics/products_proxy.html>, 2017.

4. Berndt, E.B.; and Dunion J.P.: TROPICS 2020 Meeting Archive: Agenda," <http://tropics.ccs.miami.edu/agenda/>,2020.

5. Blackwell, W.J.; Braun, S.A.; Bennartz, R.; et al.: “An Overview of the TROPICS NASA Earth Venture Mission,” *Quarterly Journal of the Royal Meteorological Society*, Vol. 44, No. S1, doi:10.1002/qj.3290, <https://doi.org/10.1002/qj.3290>, September 2018.

6. Zavodsky, B.; Dunion, J.P.; Blackwell, W.J.; et al.: “First Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of SmallSats (TROPICS) Mission Applications Workshop Summary Report, <http://tropics.ccs.miami.edu/2017-tropics-meeting/#tab-id-6>, 2017.

7. Nolan, D.S.; Atlas, R.; Bhatia, K.T.; and Bucci, L.R.: “Development and Validation of a Hurricane Nature Run Using the Joint,” *Journal of Advances in Modeling Earth Systems*, Vol. 5, pp. 382–405, doi:10.1002/jame.20031, <https://doi.org/10.1002/jame.20031>, June 2013.

8. World Meteorological Organization (WMO): “DBNet,” <https://community.wmo.int/activity-areas/wmo-space-programme-wsp/dbnet>, 2019.

9. Sampson, C.R.; and Schrader, A.J.: “The Automated Tropical Cyclone Forcasting System (Version 3.2),” *Bulletin of the American Meteorological Society*, Vol. 81, No. 6, pp. 1231–1240, doi:10.1175/1520-0477, <https://doi.org/10.1175/1520-0477(2000)081<1231:TATCFS>2.3.CO;2>, 2000.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 01–02–2021	**2. REPORT TYPE** Conference Publication	**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE Second Time-Resolved Observations of Precipitation Structure and Storm Intensity With a Constellation of Smallsats (TROPICS) Mission Applications Workshop		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) E.B. Berndt, J.P. Dunion, E.L. Duran, P.T. Duran, W.J. Blackwell, S.A. Braun, and D.S. Green		**5d. PROJECT NUMBER**
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) George C. Marshall Space Flight Center Huntsville, AL 35812		**8. PERFORMING ORGANIZATION REPORT NUMBER** M–1518
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546–0001		**10. SPONSORING/MONITOR'S ACRONYM(S)** NASA
		11. SPONSORING/MONITORING REPORT NUMBER NASA/CP–20210010046

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 43
Availability: NASA STI Information Desk (757–864–9658)

13. SUPPLEMENTARY NOTES
Prepared by the Earth Sciences Branch, Science Mission Directorate

14. ABSTRACT
The NASA Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission is a constellation of observing platforms that will enable passive microwave observations with unprecedented temporal resolution. The primary mission objective is to relate temperature, humidity, and precipitation to the evolution of tropical cyclone intensity. The NASA Earth Sciences Division convened the Second TROPICS Applications Workshop in February 2020 to foster interaction between the community of end users and the science team. An overview and outcomes of the workshop are presented, including recommended actions for the community to take to accelerate TROPICS mission applications.

15. SUBJECT TERMS
remote sensing, smallsats, hurricanes, precipitation, severe weather, disasters

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	60	STI Help Desk at email: help@sti.nasa.gov / STI Help Desk at: 757–864–9658

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

National Aeronautics and
Space Administration
IS02
George C. Marshall Space Flight Center
Huntsville, Alabama 35812