National Aeronautics and
Space Administration

NASA/CP—2017–219705

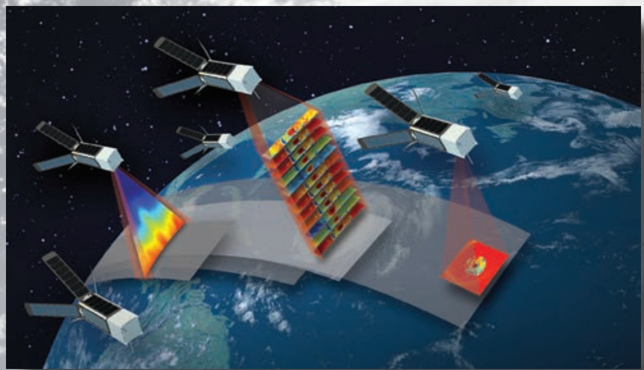
First Time-Resolved Observations of Precipitation Structure and Storm Intensity With a Constellation of SmallSats (TROPICS) Mission Applications Workshop Summary Report

University of Miami Rosenthal School of Marine
and Atmospheric Studies (RSMAS) Auditorium

Sponsored by
NASA Earth Science Division Applied Science Program

Hosted by the Cooperative Institute for Marine
and Atmospheric Studies (CIMAS),
University of Miami, Miami, Florida

May 8–10, 2017



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B. Zavodsky, J. Dunion, W. Blackwell, S. Braun, C. Velden, M. Brennan, and R. Adler

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Marshall Space Flight Center • Huntsville, Alabama 35812

October 2017

Front Cover Photo Credits:

Background image: Hurricane Irma (2017) prior to landfall in Southwest Florida as seen by the NASA/NOAA Visible Infrared Imaging Radiometer Suite. Image from NASA EOSDIS WorldView.

Bottom left image: TROPICS Mission Overview. Image from the Massachusetts Institute of Technology Lincoln Laboratory (MIT LL).

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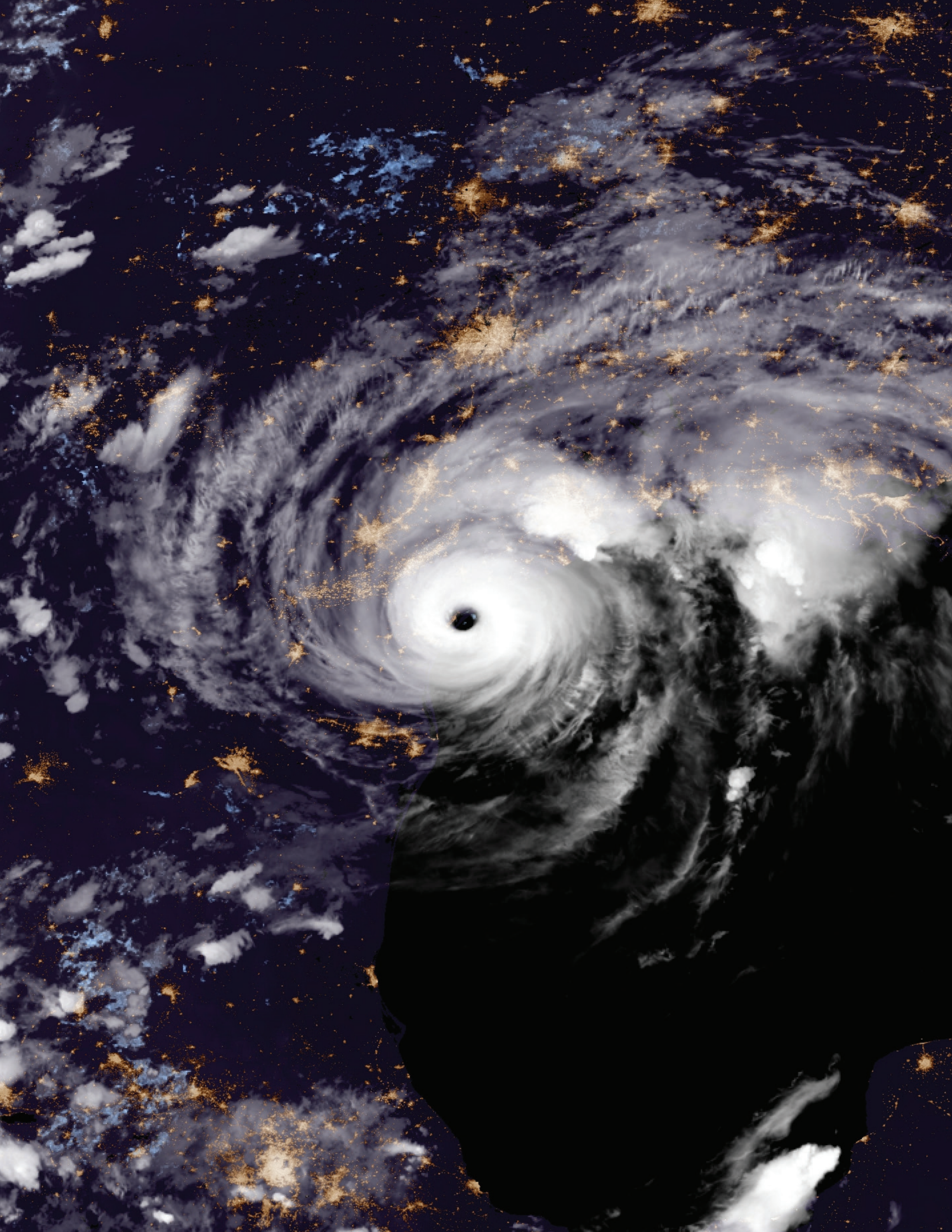
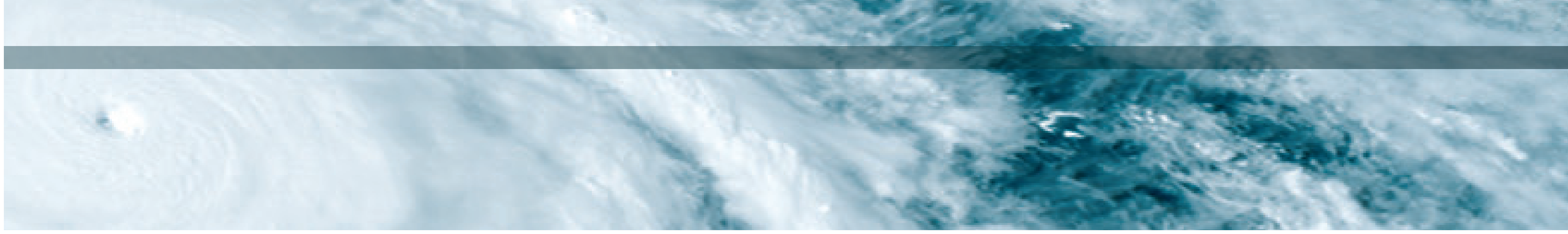


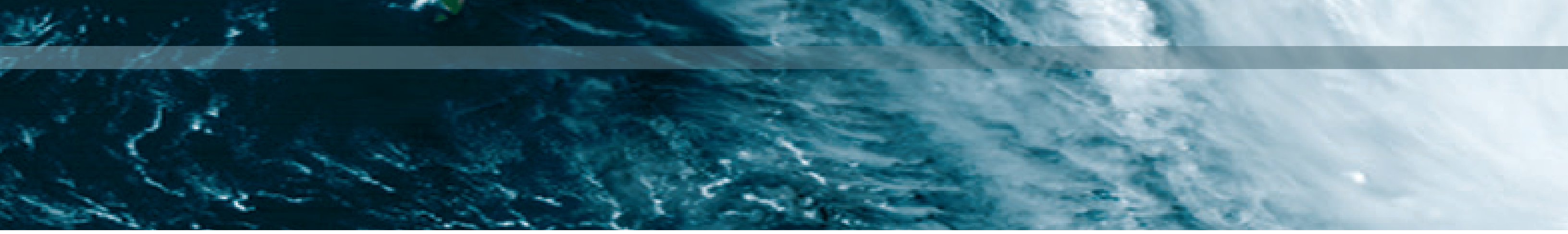


Background

The National Aeronautics and Space Administration (NASA) Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of SmallSats (TROPICS; Mission web site) 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 sounders but with unprecedented temporal resolution. TROPICS is a cost-capped ($30M) 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 is comprised of a constellation of six, three-unit (3U) CubeSats (approximately 10×10×34 cm), each hosting a 12-channel passive microwave spectrometer based on the Micro-sized Microwave Atmospheric Satellite 2 (MicroMAS-2) developed at MIT LL. TROPICS will provide imagery at frequencies 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. 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 and will fly starting in 2017 on the 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 mission, which was originally envisioned as a microwave instrument in geostationary orbit. TROPICS enables temporal resolution similar to 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 are slated for delivery to NASA in 2019 for launches planned no earlier than 2020. 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 Satellites (GOES), Moderate Resolution Imaging Spectroradiometer, and Visible Infrared Imaging Radiometer Suite, for situational awareness of TC position, structure, and intensity and from microwave sounders and imagers, e.g., multiple Special Sensor Microwave Imager/Sounder, Advanced Microwave Sounding Unit (AMSU), Tropical Rainfall Measuring Mission Microwave Imager, and Global Precipitation Measurement (GPM) Microwave Imager (GMI), for better understanding of storm dynamics and precipitation and for assimilation into numerical weather prediction (NWP) models. 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 temporal 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 life cycles.

Photo Left: Hurricane Harvey just before landfall along the Texas coast as seen by the NOAA GOES-16 Advanced Baseline Imager GeoColor product overlaid on a static image of nighttime lights from NASA/NOAA Visible Infrared Imaging Radiometer Suite. Image Courtesy of NOAA/Cooperative Institute for Research in the Atmosphere (CIRA).



Workshop Purpose and Objectives

From May 8–10, 2017, the NASA ESD Applied Sciences Program convened the 1st TROPICS Applications Workshop to enable a conversation between the mission developers/science team and the end-user/applications community. By fulfilling these specific objectives before final mission formulation and 2–3 years 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 TC intensity, there are other application areas where observations from TROPICS may be valuable. Thus, the TROPICS Applications Workshop focused on the following specific objectives:

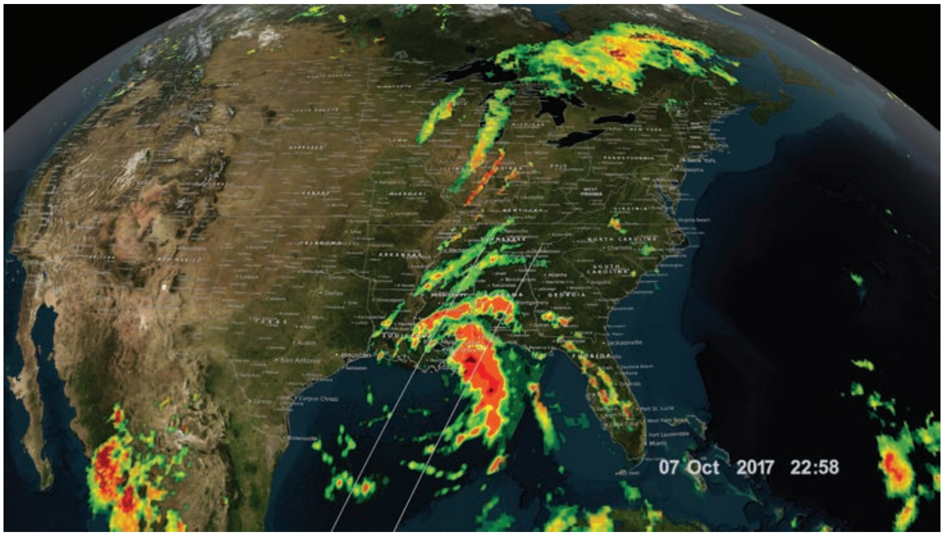
- Introduce a broad community of potential end users to the expected value of TROPICS by reviewing mission specifications and status.

- Review TROPICS data applications through presentations and breakout discussions.

- Provide a forum for applied researchers and operational decision makers to share insight into how observations from TROPICS can be used in their organizations and challenges to their application.

- Begin establishment of a user community that can highlight potential TROPICS applications and accelerate postlaunch applications.

GeoColor image from the NOAA GOES-16 Advanced Baseline Imager of Hurrican Maria prior to landfall in Puerto Rico. Image courtesy of NOAA/Cooperative Institute for Research in the Atmosphere (CIRA).



Precipitation rates from GPM IMERG as Hurricane Nate makes its first landfall.

Workshop Organization

The organizing process of the 1st 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 appendix 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 for each of four applications areas. The chairs were responsible for identifying and inviting speakers for their sessions.

The meeting was organized to first educate the applications community on the TROPICS mission design and requirements through a mission overview and status presentation that was followed directly by a discussion on challenges associated with low-latency for SmallSat missions. This discussion worked to set the expectations and focus areas for the remainder of the meeting related to the strengths and limitations of the mission design/concept. Then, the applications community presented current applied research and operational decision making being done with current passive microwave observations in order to educate the mission principal investigator and science team on expected applications and limitations to potential use of TROPICS data by the applications and operations community.

A comprehensive 2½-day workshop agenda was assembled by the organizing committee that encompassed two panel discussions, four applications-focused sessions, and two breakout sessions. The agenda is shown in appendix B and also on the agenda page on the meeting web site.

Panel discussions focused on learning about how TROPICS can leverage lessons learned from other NASA missions and how TROPICS fits into the broader Earth satellite community. The first panel addressed challenges with obtaining low-latency data and was convened to seek guidance from other satellite missions about downlink solutions that can provide potential solutions for reducing the latency of data from TROPICS (Panel Discussion 1, Data Latency). A second panel focused on synergies with other satellite missions and agencies to discuss how TROPICS may fill observing gaps in the coming years and to determine if there are proxy datasets that can be generated using current mission datasets (Panel Discussion 2, Synergies With Other NASA Missions).

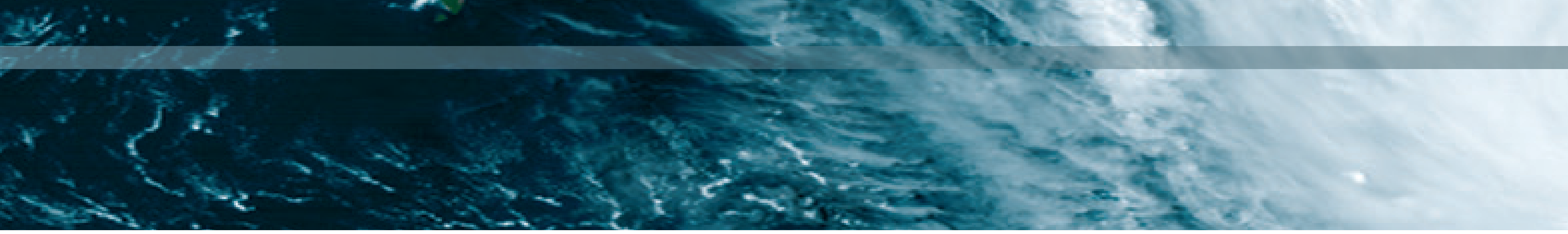
Workshop presentations focused on potential operational or application areas of TROPICS data related to the core science team measurements and products: (1) Terrestrial, (2), TC Nowcasting, (3) Modeling and Data Assimilation, and (4) Tropical Dynamics. Prior to the meeting, the presenters were asked to summarize their current research and/or operations activities, ways that they currently use satellite observations, and ideas for how they or their organization could/would use TROPICS data. The following four specific questions were also asked of the presenters:

(1) What constraints would be applied to your project/organization with reduced latency? How would you use real-time data (0–2 hours latent)? How about near real-time data (<6 hours latent)? What about beyond real-time (6–12 hours latent)? If data were up to a week latent, would the data still be useful to you?

(2) The mission plans to provide the following products temperature profiles (27-km resolution at nadir; 40-km resolution average), moisture profiles (17-km resolution at nadir; 24-km resolution average), and precipitation (17-km resolution at nadir; 24-km resolution average). Are there other products that can be derived from the passive microwave channels on TROPICS that would be valuable for your applications?

(3) What data formats are most useful for your applications?

(4) What do you view as the required accuracy for your applications?



The second morning of the meeting focused on two breakout sessions. The meeting attendees self-divided into four groups related to the four applications areas for which presentations were made: (1) Terrestrial, (2) TC Nowcasting, (3) Modeling and Data Assimilation, and (4) Tropical Dynamics. The objectives of the breakout sessions were to collect broader inputs on strengths and limitations of the mission concept for applications and to identify potential new applications areas where TROPICS data could be used for applied research and operational decision making. The panels were asked to provide inputs on the following seven questions:

(1) What are the discipline or focus area applications science questions and challenges that can be addressed with TROPICS data?

(2) TROPICS could provide first-of-its-kind revisit times with a spatial resolution similar to current operational passive microwave sounders. How are science questions and applications impacted if the revisit time is decreased to 30–60 minutes, 3 hours, or once per day? What is the longest gap period where the data loses its value and begins to look like other current datasets?

(3) For the application challenges listed in question (1), what is the required data latency? Consider real-time data (0–2 hours latent), near real-time data (<6 hours latent), and beyond real-time (>6 hours latent). Is there a certain latency where the data would no longer be useful for your operations/applications?

(4) The TROPICS Science Team will be providing a suite of standard data products, including temperature and moisture profiles and precipitation. Given what you have learned about TROPICS over the last 2 days, what additional or higher level data products might be useful in your science or applications tasks? Include the characteristics of the product and other requirements, e.g., resolution, accuracy, data latency, data format. Rank them in importance.

(5) A variety of current and future partners exists in the community. Who are your key partners or end-user organizations on tasks, projects, or processes that use NASA satellite data? Who are additional potential users?

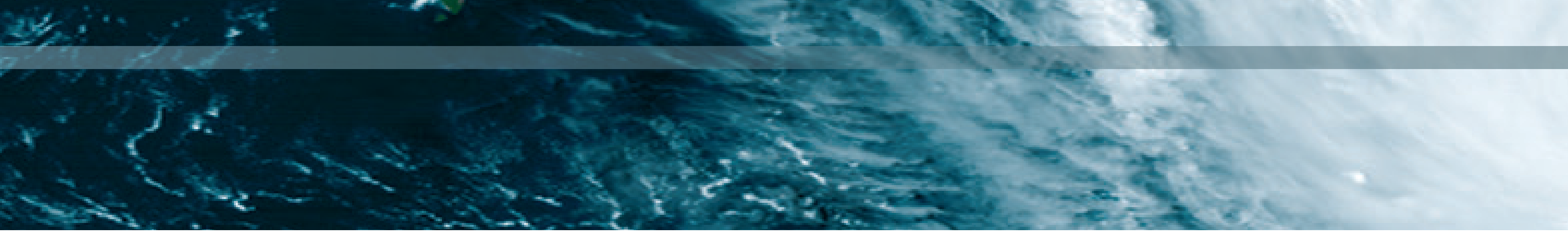
(6) Within your organization, what are the biggest impediments limiting your use of new satellite data and products?

(7) What data formats, e.g., Network Common Data Form (NetCDF), Hierarchical Data Format (HDF), geographic information system (GIS) compatible, etc., do you need for your science or applications tasks?

Additional details, outcomes, and conclusions related to these discussion points and questions can be found in the following sections.

Workshop Attendees

The 57 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. Private sector partners from the broadcast, reinsurance, and data visualization community provided a vision for how TROPICS data could benefit the products that they develop for their customers. The academic community from universities and NOAA cooperative institutes participated to describe their applied research activities. Hosting at the University of Miami (UM) also allowed for a handful of graduate students from UM and Florida International University to participate. The broad range of backgrounds and interests among the workshop attendees highlighted the potential use of TROPICS data for a number of potential application areas. A complete list of registered attendees can be found in appendix C.



Workshop Summary

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

Mission Status and Summary

The TROPICS mission was selected by NASA in 2016 as part of the Earth Venture-Instrument-3 program. The overarching goal for TROPICS is to provide nearly all-weather observations of three-dimensional (3-D) temperature and humidity, as well as cloud ice and precipitation horizontal structure, at high temporal resolution to conduct high-value science investigations of TCs, including: (1) relationships of rapidly evolving precipitation and upper cloud structures to upper-level, warm-core intensity and associated storm intensity changes, (2) the evolution of precipitation structure and storm intensification in relationship to environmental humidity fields, and (3) the impact of rapid-update observations on numerical and statistical intensity forecasts of TCs. TROPICS will provide rapid-refresh microwave measurements (median refresh rate better than 60 minutes for the baseline mission) over the tropics that can be used to observe the thermodynamics of the troposphere and precipitation structure for storm systems at the mesoscale and synoptic scale over the entire storm life cycle. TROPICS comprises a constellation of at least six CubeSats in three low-Earth orbital planes (two satellites per plane). The number of CubeSats in the constellation and their plane are the main factors driving the temporal resolution of the data (fig. 1; table 1). Trade studies are ongoing to determine the optimal number of satellites based on science, reliability, and cost.

Table 1. Summary of temporal resolution impacts based on number of satellites in constellation. The current baseline configuration is six satellites.

	Average (min)	Median (min)	Frequency of Gaps <2 hr (%)
8 satellites	60	30	55
6 satellites	75	40	45
4 satellites	120	70	25

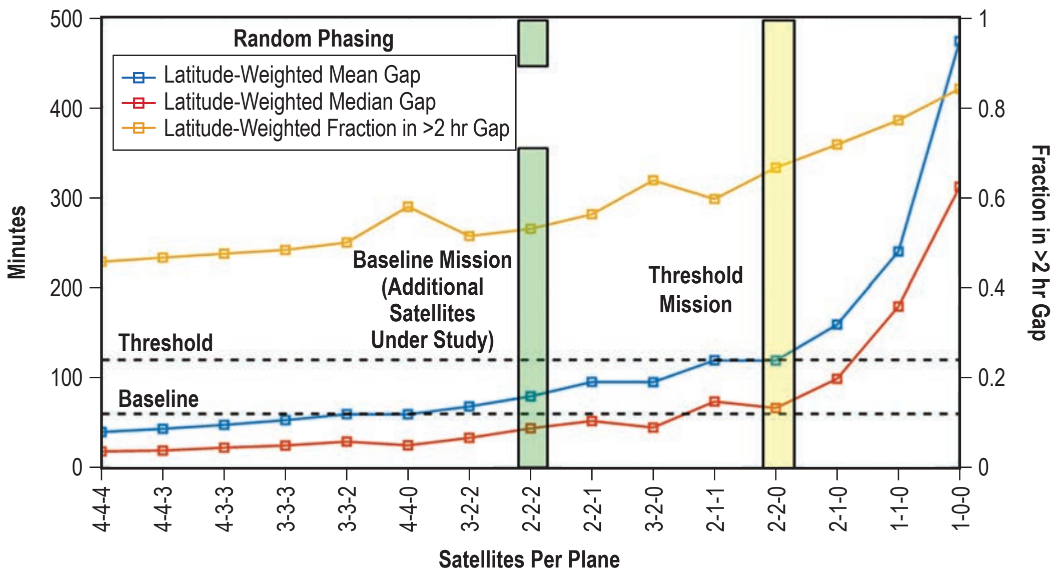


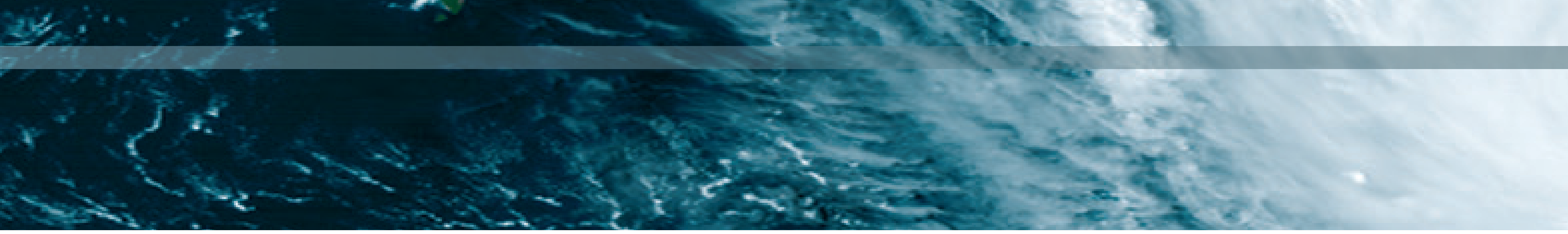
Figure 1. Temporal resolution of TROPICS data using different constellation configurations. The current baseline configuration is shown in the green bar.

Each SmallSat will host a high-performance radiometer to provide temperature profiles using seven channels near the 118.75 GHz oxygen absorption line, water vapor profiles using three channels near the 183 GHz water vapor absorption line, imagery in a single channel near 90 GHz for precipitation measurements (when combined with higher resolution water vapor channels), and a single channel near 205 GHz that is more sensitive to precipitation-sized ice particles and low-level moisture. This observing system offers an unprecedented combination of horizontal and temporal resolution to measure environmental and inner-core conditions for TCs on a nearly global scale and is a major leap forward in the temporal resolution of several key parameters needed for assimilation into advanced data assimilation systems capable of utilizing rapid-update radiance or retrieval data. The mission is on track to deliver flight-ready CubeSats to the launch provider in 2019. The System Requirement Review and Mission Definition Review have been completed, and the Preliminary Design Review is scheduled for late 2017. More specifics on the mission can be found in appendix D.

Panel Discussion on Latency Challenges

Data latency has been identified as a primary limitation for the application of satellite datasets in operational decision making (NASA Low Latency Workshop). Typically, data latency is defined as the amount of time between when an observation is made by a satellite and when that data becomes available for use by a scientific user community. The latency requirements for TROPICS in the original mission proposal were not designed for use by the operational community; therefore, optimization of data latency is performed on a best-effort basis given the constraints of the fixed-price mission. TROPICS will rely on two ground stations to downlink science mission data via S-band frequencies. This small number of ground stations limits the availability of downlinked data resulting in an average of 6 hours latency in data delivery to the user community. However, the TROPICS team recognizes that this mission holds much potential benefit to the applications community and is attempting to reduce data latency.

Latency for both TROPICS and its sibling mission, Cyclone Global Navigation Satellite System (CYGNSS), are driven by the number of homogeneous ground stations and staffing at these stations. However, simply adding heterogeneous ground stations is usually not a good solution because of the overhead involved in folding these stations into the network and the Mission Operations Center (MOC). Additionally, there is efficiency lost in managing a constellation of satellites at the MOC, so having additional ground stations with the higher number of satellites results in higher costs. For example, at least one commercial provider has been identified that could provide 15-minute average, space-to-ground latency, but the additional cost to the mission (relative to the NASA Near Earth Network currently baselined) would be approximately $1M. Considerations for government sharing of homogeneous ground sites, leveraging new commercial technologies, and partnering with the university community were discussed as methods for increasing the number of ground stations. The university and business approaches may introduce too much added cost for the ground system due to the heterogeneity of site types. However, the idea for government sharing was introduced as a potential option that may allow for limited areas of low latency data. Dr. Mitch Goldberg, the program scientist for the NOAA/NASA JPSS mission, proposed a partnership for NASA and NOAA to jointly fund a couple of S-band receiving stations (total cost was estimated at around $100K per antenna) in order to generate line-of-sight, real-time data downlink and processing that could be used for regionally specific operations. Placing one of these sites in Hawaii and one in Miami would give forecasters in the Central Pacific and Western Atlantic/Caribbean/Gulf of Mexico access to real-time data that could be used to better understand the value of the added temporal resolution of the data on forecast operations.



Panel Discussion on Mission Synergies

NASA, NOAA, and DoD have multiple currently operating or near-future satellite missions that measure TCs, which could benefit or be benefitted by TROPICS.

The GPM constellation of satellites provides good global precipitation coverage; however, there are some spatial gaps, especially over the tropics, where TROPICS data may be able to help fill. TROPICS will provide context of what is seen in GPM imagery by filling gaps in the GPM constellation and also providing vertical thermodynamic data that is not captured by the GMI. TROPICS will be measuring different spectral channels than GMI, so opportunities for direct comparisons may be limited; however, there should be opportunities to integrate the TROPICS data into the GPM Integrated Multi-satellitE Retrievals for GPM (IMERG) level-3 product. More details on the need for this capability from an applications perspective are outlined in the next section. TROPICS and CYGNSS provide unique and complementary data in deep convection. It is expected that there will be some overlap between the CYGNSS and TROPICS missions as there seems to be nothing that should hinder extension of CYGNSS out 4 to 6 years beyond its primary mission. As a result, there will be opportunities to provide unique and complementary data in deep convection to couple the thermal environment to the wind environment to address science questions related to the boundary layer and convection from the surface through the atmosphere. There are also opportunities for lessons learned from CYGNSS as this mission is also comprised of a constellation of SmallSats.

NOAA is interested in the temporal resolution improvements that will be offered by TROPICS and would complement the ATMS sensors that will be part of the JPSS operational satellite system. Potential NOAA contributions include engagement by the NOAA Office of Oceanic & Atmospheric Research and the NOAA National Weather Service (NWS) for integration of data products into operational forecasting. NOAA has also developed the Microwave Integrated Retrieval System algorithm, which is a fast, radiative transfer algorithm that could be used to generate level-2 products, and could also aid in limb corrections for the observations given the scanning nature of both ATMS and TROPICS. NOAA has mechanisms in place to convert TROPICS outputs to formats needed for data assimilation and to investigate radiative transfer applications that can be used to assimilate these data. ATMS data would also be available to develop proxy products for TROPICS. Precipitation products derived from TROPICS would be beneficial to operational rain rate level-2 products developed for the NOAA GOES-16 Advanced Baseline Imager. The high temporal resolution of the TROPICS measurement could be used to validate quantitative precipitation estimates from geostationary orbit.

DoD was represented by the United States Air Force and noted that TROPICS might be able to help bridge the gap between the Defense Meteorological Satellite Program fleet that will reach its end of life around 2023 and its next generation meteorological satellite programs. Additionally, the design of the TROPICS mission as a constellation of satellites offers a strategic proof-of-concept for the development of a more resilient satellite fleet to reduce risk for defense purposes related to potential space weather impacts or adversarial anti-satellite device.

Summary of Application Area Findings

Through a series of presentations and breakout sessions at the 1st TROPICS Applications Workshop, end users were able to communicate their potential applications for TROPICS data and potential limitations to its use. Appendix B shows the agenda for the meeting with each speaker and their title. The following section provides a summary of some of the key take-aways from each session. For more in-depth details of each application presentation and breakout discussion, please visit the Presentations section of the meeting web site.

1. *Terrestrial*

Because TROPICS will measure precipitation locations and rates, there are a number of terrestrial end-user applications that can incorporate these data into decision-making processes. High temporal resolution precipitation measurements can potentially be used to supplement the lack of ground-based radar observations in regions outside the contiguous United States. In current high temporal resolution precipitation products, infrared measurements from geostationary satellites are used to fill in gaps between observations from passive microwave instruments. It is expected that there will be some improvements to precipitation products even with the lower spatial and spectral resolution of TROPICS. TROPICS data can be used to develop, test, and improve:

- Detection, monitoring, forecasting, and warning of floods and landslides (fig. 2).
- Monitoring and forecasting for water accounting, agriculture, human consumption, and ecosystems.
- Regional hydrometerological forecasting through data assimilation of moisture and temperature profiles into atmospheric models that drive hydrological and crop models with high temporal resolution.

Each of the aforementioned applications has a different data latency and temporal resolution requirement. For quickly evolving applications, such as floods and landslides, having data at a temporal resolution of between 30 and 60 minutes is required in order to provide updates on rapidly-changing conditions. Data latencies for this application are desired to be less than 30 minutes but could be up to 2 hours. For water availability applications, a revisit time of 3 hours would be acceptable because the land surface is not evolving as quickly for these applications. Desired latency is 1 hour, but up to 6 hours would be acceptable for these more slowly-evolving applications. The modelers who want to improve the atmospheric forcing in their hydrologic and crop models could live with data at 1- to 2-hour temporal resolution and as latent as 6 hours with a desire for 1-hour latency.

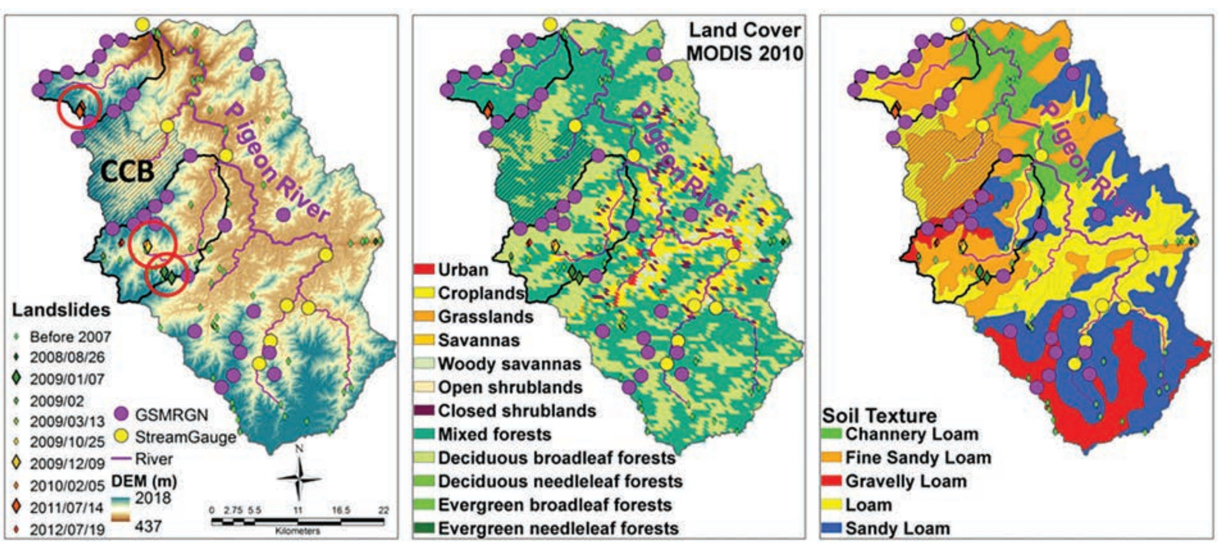
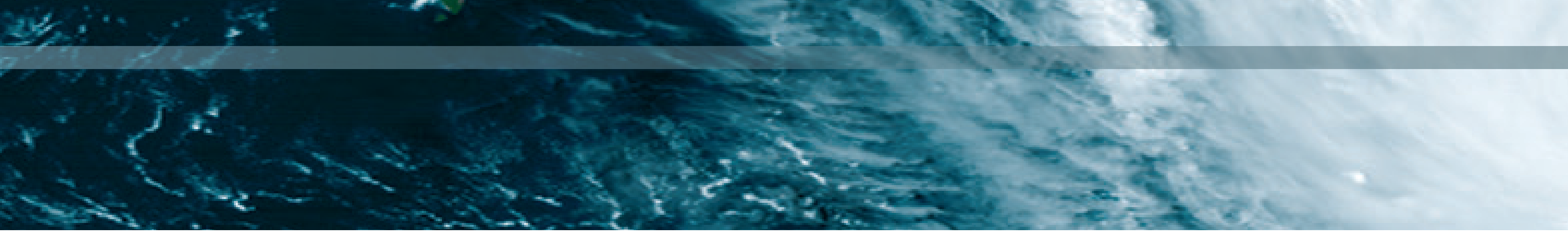


Figure 2. Overview of potential flood, debris flow, and landslide application for TROPICS. Images show the location of landslides (left), land cover from NASA MODIS (center), and soil texture (right) in southwestern North Carolina. Precipitation from TROPICS would provide high temporal resolution precipitation information as input to this model. Image from Ana Barros, Duke University.



Throughout the discussions of terrestrial applications, participants expressed a desire to see TROPICS rainfall products integrated into other precipitation analysis datasets—such as the IMERG product developed for the GPM mission—for use in international hydrology and land surface modeling applications. The increased temporal resolution from passive microwave may yield improvements in the temporal evolution of precipitation in these products, which currently relies on advection derived from geostationary satellite data to obtain higher temporal resolutions. However, it was noted that there have been challenges with incorporating rain rates from microwave sounders like ATMS into IMERG, which may need to be resolved if a heavier reliance is placed on TROPICS. Some participants also described a need for a gridded column-integrated moisture product, which could be used for detection of atmospheric river features generally associated with heavy precipitation that can result in flood and landslide disasters.

The terrestrial applications have a large and diverse set of potential end users. There were representatives at the meeting from the United States Army Corps of Engineers (USACE), international agriculture, hydrologic modeling, and reinsurance companies. During the breakout discussions, a number of humanitarian and international partners were identified, including the Global Flood Partnership, United States Agency for International Development, the World Bank, various United Nations agencies, and the Red Cross. These groups communicated that GIS-formatted datasets, e.g., Georeferenced Tagged Image File Format (GeoTIFF), Keyhole Markup Language (KML), etc., and NetCDF were the preferred data formats for their applications. There is also the potential to partner with international agriculture universities in developing nations. Many of these universities have faculty who have studied in the United States and have a working knowledge of remote sensing tools. Direct engagement with these universities or working with NASA SERVIR in areas where they have hubs are two approaches for increasing the discoverability and use of data from TROPICS by local governments in these nations. The NASA Applied Remote Sensing Training (ARSET) group could help address training needs, which was expressed as a key hurdle to data application.

2. Tropical Cyclone Analysis and Nowcasting

Operational TC forecasters, such as those at the NOAA NWS National Hurricane Center (NHC), NOAA NWS Central Pacific Hurricane Center (CPHC), and DoD Joint Typhoon Warning Center (JTWC), rely heavily on satellite observations for TC and environmental analysis because TCs develop in traditionally data-void regions over the open ocean. Tropical cyclone analysts often use passive microwave satellite observations to diagnose storm intensity and dynamics since other types of satellite imagery, e.g., visible and infrared, may not easily reveal the convective structure/organization under the cirrus canopy. For example, figure 3 shows vertical cross sections of a TC using passive microwave sounder observations to diagnose warm core anomalies that are linked to intensity estimation. In the figure, the thermal anomaly in the warm core of Typhoon Bopha is better captured by the higher spatial resolution ATMS instrument, which can serve as a proxy for the TROPICS sensor. Forecasters also use the passive microwave data to get fixes on the center location of TCs, especially when a cloud-covered eye is present (fig. 4). Feedback from these forecasters also suggests that integration of new satellite datasets into operational decision support systems, e.g., the Advanced Weather Interactive Processing System (AWIPS) and National Centers for Environmental Prediction (NCEP) AWIPS (NAWIPS) systems used by NOAA operational forecasters, increases the likelihood of operational use.

From the perspectives of operational analysis and nowcasting applications, the TROPICS mission offers both promise and challenges. The ability to provide more frequent views of TC structure, e.g., warm core evolution, eyewall replacement cycle evolution, intensity estimates and trends, than is currently available is a definite plus. However, the lack of higher spatial resolution microwave imaging channels (especially at 37 and 85/91 GHz) to complement the proposed sounding channels will limit

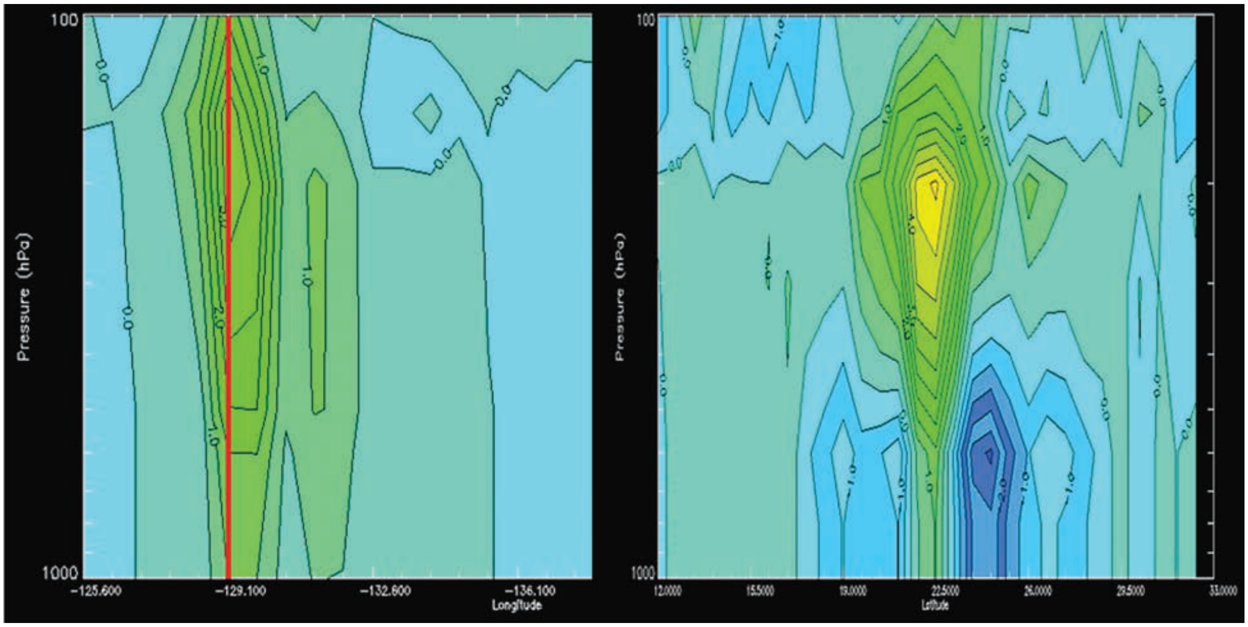


Figure 3. Example of the observed thermal (i.e., warm core) anomaly during Typhoon Bopha (2012) from AMSU (left) and ATMS (right) around the same time. More of the warm core anomaly is captured in the higher resolution ATMS (proxy for TROPICS), which should translate to improved intensity estimations of the TC central pressure and maximum winds. Image courtesy of Derrick Herndon, University of Wisconsin CIMSS.

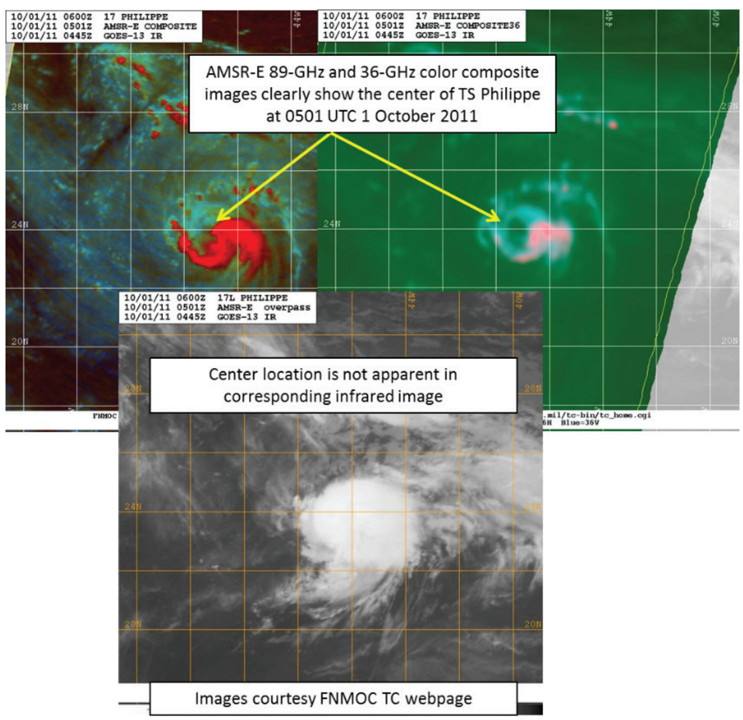


Figure 4. Application of passive microwave observations by operational forecasters to obtain a fix on a TC center. Image by Michael Brennan, NOAA/NWS/NHC.

the qualitative usefulness. Data latency is the biggest challenge for nowcasting use. Latency requirements of less than 1 hour are desired, and anything delayed by more than 3 hours becomes much less useful to nowcasting applications given the 6-hour cycle on which forecasts are issued (table 2). Regardless of latency, TROPICS data would still be useful for post-analysis and best-track analysis duties.

Table 2. NOAA/NWS/NHC forecast cycle demonstrating the data latency needs (from Michael Brennan (NOAA/NWS/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

Breakout discussions focused on other attributes of TROPICS that could impact analysis/nowcasting applications. Nontraditional spectral bands to be primarily used for the temperature and moisture retrievals may also provide qualitative information in the form of signatures of rapid intensity fluctuations, moisture/dry air penetrations, and perhaps rain rate estimates. The capabilities and applications of the new channel at 205 GHz are largely unexplored and may offer new insights regarding the TC inner core and its surrounding environment. The rapid refresh of the TROPICS satellite constellation should allow for improved animations of the imagery and derived products, such as from the Cooperative Institute for Meteorological Satellite Studies (CIMSS) Morphed Integrated Microwave Imagery at CIMSS TC and total precipitable water tools. It is hoped that TC-centric products such as those currently done on the Naval Research Laboratory (NRL) web site will be made available, perhaps via the NASA Jet Propulsion Laboratory (JPL) TC Information System portal.

In terms of end users, it is apparent that the potential nowcasting applications of TROPICS extend well beyond just the NHC/CPHC/JTWC forecast units. Other TC analysis centers around the world, e.g., Regional Specialized Meteorological Centers at Fiji, Australia, Reunion, Tokyo, and Delhi, could also benefit from real-time TROPICS data, as well as other national centers around the globe. The trick will be to get the data to these remote sites in a timely manner to be useful. The other potential user group is social media—whether it be through television stations or Web-based data providers. The ability to show the public a TC threat through the lens of TROPICS data has great potential. However, this capability would involve an important educational element not only for awareness of the data, but also how to interpret the data, as the current culture of the media makes it hard to utilize/display new, esoteric data types, especially for research-type missions.

3. Tropical Cyclone Modeling and Data Assimilation

Operational TC forecasters rely heavily on numerical model guidance to produce their forecasts. Assimilation of clear-sky passive microwave observations has been shown to have the largest positive impact on NWP (fig. 5), and work is underway to develop techniques for assimilating all-sky radiances. As a result, having these data at higher temporal frequencies has the potential to provide significant improvements not only to hurricane forecasts but also to general global NWP. Over the last 20 years, NWP models have been able to reduce errors in forecast track, but they are still not able to fully capture TC intensity or rapid changes in intensity. Much of this can be attributed to challenges of obtaining observations related to TC dynamics with enough temporal resolution to capture processes that drive the intensification. Use of data from TROPICS will allow researchers and operational modelers to potentially improve NWP forecasts of TC track and intensity. The higher temporal frequency is also attractive for regional models where more rapid cycling can better take advantage of this improvement over current satellite sensors.

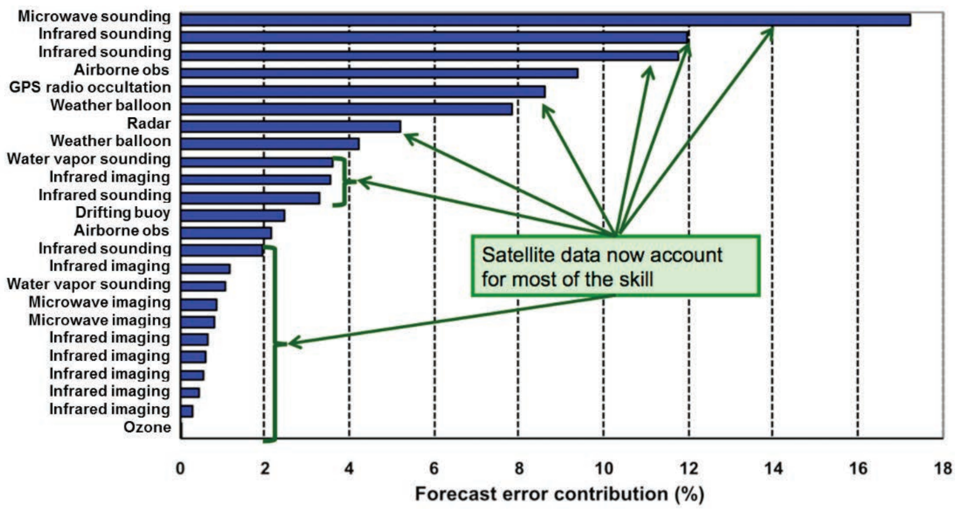


Figure 5. Impact of various observations on 24-hour ECMWF Global Forecast Skill. In the figure, larger values constitute larger impacts on reducing forecast error. Figure by Erik Andersson, ECMWF.

Many users are hesitant to invest resources to prepare for assimilating data from short-lived satellite missions, so it is imperative that these users are able to obtain proxy datasets as early as possible. In order to accelerate the use of the observations from TROPICS, NOAA's Hurricane Research Division (HRD) is planning to develop Observing System Simulation Experiments (OSSEs). An idealized set of TROPICS data demonstrated that when TROPICS data are included in the model, they result in stronger initial intensity—in better agreement with the Nature Run—especially for a strong hurricane case (fig. 6). OSSEs are valuable for new observing systems in a prelaunch setting by evaluating expected impacts of a proxy data set on hurricane track and intensity predictions, design tradeoffs, and methodologies for data assimilation tuning. A hurricane nature run will be used to create a set of OSSEs for TROPICS that will provide feedback to the mission and attempt to develop forward operators, bias corrections, error covariances, quality controls, and data thinning approaches. Similarly, technology demonstration launches of the MicroMAS-2 and Microwave Radiometer Technology Acceleration (MiRaTA) systems in 2017 and 2018 will also allow for development of some proxy products.

Different latency requirements are needed for different modeling systems. For regional/mesoscale NWP operations, the analysis cycling is much more rapid, so observations would need to arrive for assimilation into the models within 2 to 3 hours of observation. Global models tend to have less frequent cycles and, in some cases, perform a spin-up prior to the analysis and forecast time resulting in an acceptable latency of 3 to 6 hours for these systems. If the data are not available in these timeframes, application impacts will be limited, but they will still be extremely valuable for reanalysis products and scientific investigations using models by university researchers. Revisit times of 30 minutes are desired by a number of global modeling centers; however, it was noted that current data assimilation systems may not benefit from fast revisit times unless employing four-dimensional variational approaches to remove any spatial or temporal observation thinning. The higher temporal resolution will also be of benefit for instances in which data are removed from the assimilation process when differences between the background model and observations are sufficiently large. Universally, the data assimilation community relies on data to be in Binary Universal Form for the representation of meteorological data format for ingest, so it will be important to ensure that TROPICS data are available in this format for NWP applications.

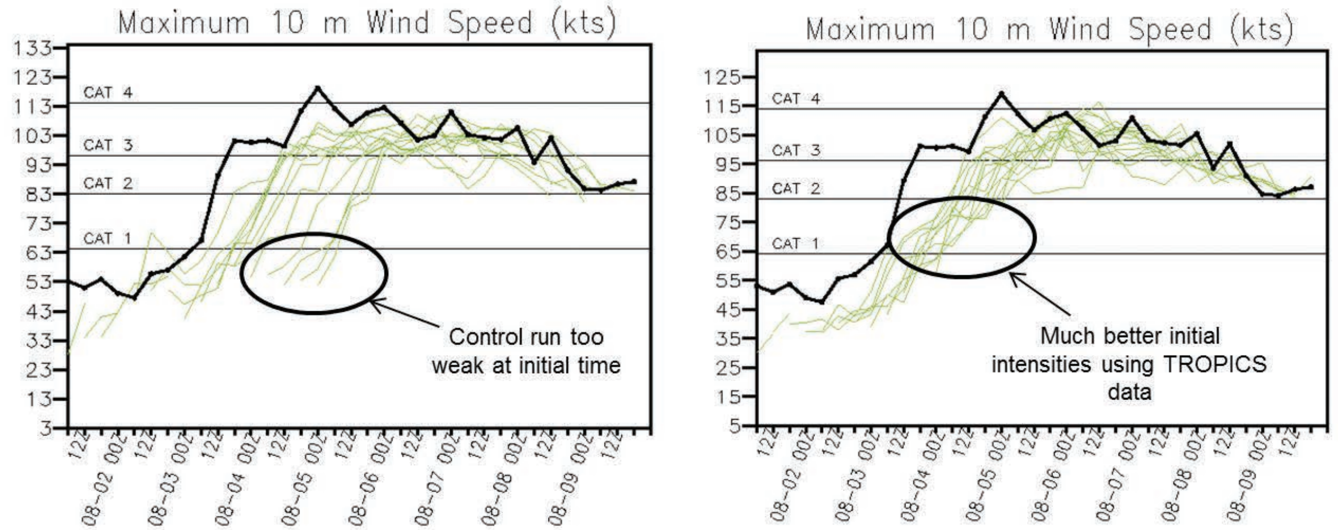


Figure 6. Two sets of intensity forecasts (defined as peak winds at 10-m altitude) for the control run where no TROPICS data were assimilated (left) and a set of runs where TROPICS temperature and moisture fields were assimilated (right). Green lines in both cases show TROPICS-enhanced runs compared with Nature Run intensity (black line). Figure by Bachir Annane, Florida International University/NOAA/Atlantic Oceanographic and Meteorological Laboratory (AOML).

A number of potential users were identified during the meeting. The NOAA/NCEP Environmental Modeling Center, which runs the Global Forecasting System and regional Hurricane Weather Research and Forecasting (HWRF) system, is currently the primary operational modeling center employed by the NWS. Additionally, there is interest in the data from the NASA Global Modeling and Assimilation Office, and from a number of international modeling groups, including MeteoFrance, United Kingdom Met Office, and European Center for Medium range Weather Forecasting (ECMWF). The global models are more prepared to handle satellite radiance data, so faster implementation of the data may occur in those systems. Currently, the HWRF system is undergoing initial development of data assimilation capabilities with expectations of having a more mature system by the time TROPICS launches.

4. Tropical Cyclone Dynamics

Tropical dynamics refers to a broad range of phenomena that encompasses TCs, convection, and modes of variability including Equatorial Kelvin and Rossby waves, and the Madden-Julian Oscillation (MJO, fig. 7). One of the largest areas of potential impact from TROPICS will be on the occurrence of convective extremes related to the phenomena described above given that these events can evolve over relatively short time scales and are often missed by current observing systems. It is expected that TROPICS will aid in addressing the following scientific questions:

(1) When, where, and with what frequency do extreme damaging storms occur?

(2) Given the previous poor temporal sampling of current and past missions, what is the life cycle of extreme events undersampled by these other missions?

(3) How do moisture and precipitation co-evolve to precondition the convective environment to lead to the onset of mesoscale convective systems (MCS) and extreme precipitation, particularly on the margins of moist regions?

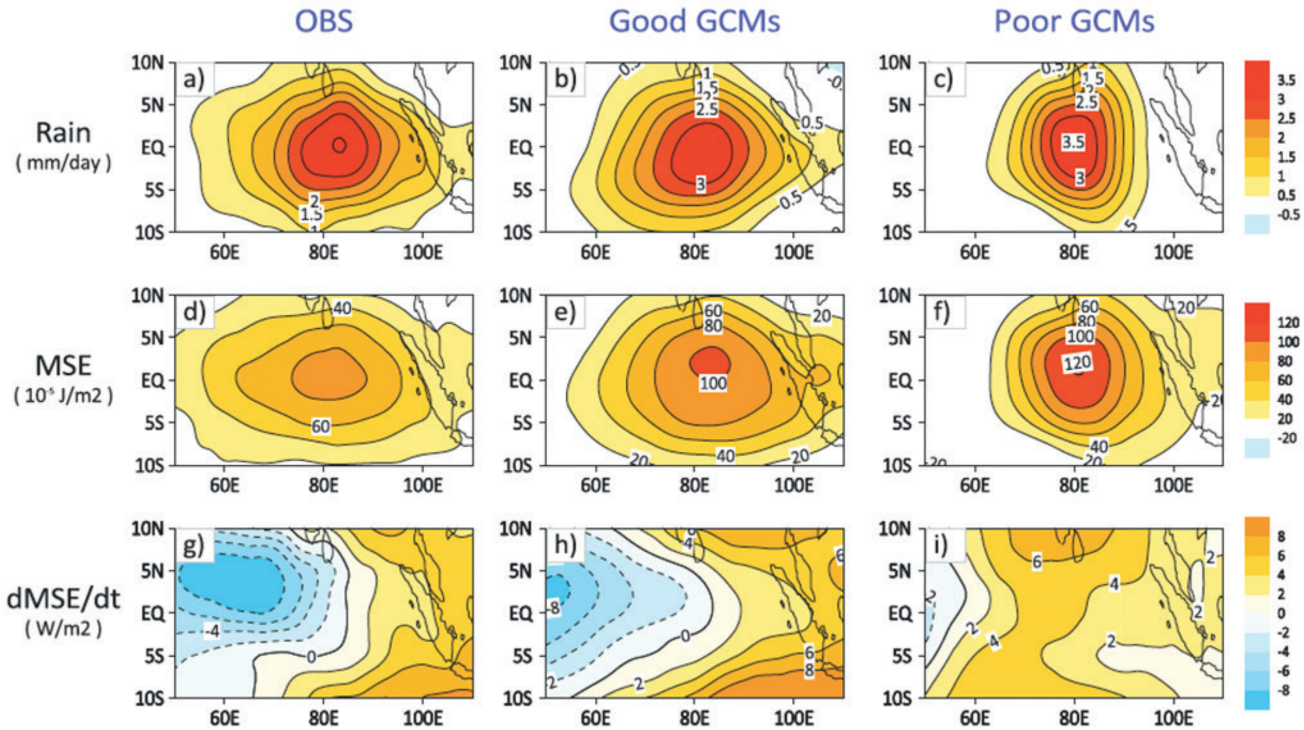


Figure 7. Representation of moist static energy (MSE) and its advection as it relates to prediction of the eastward propagation of MJO. TROPICS vertical moisture sounding will be used to improve representation of MSE. Image from Jiang et al. (2017) http://dx.doi.org/10.1002/2016JD025955.

(4) What predictors related to rapid changes in the thermodynamic environment (3-D structure) and precipitation structure can be derived related to the onset of extreme precipitation, particularly tropical cyclogenesis and intensification?

(5) How does the thermodynamic structure in the vertical layers observed by TROPICS allow forecasters to characterize the intensity and motion of the Saharan Air Layer (SAL)?

The ability to address these five scientific questions will be impacted by any reductions in satellite revisit rate, with smaller convective storms requiring the finest temporal resolution, and larger MCSs (evolving on time scales of 1 to 6 hours) and the thermodynamic environment of convection having less strict requirements. For smaller-scale intense convection, the typical life cycle of convective cells will be up to 1 hour, so a revisit rate of approximately 5 to 10 minutes might be considered ideal. However, given the coarse spatial resolution of the TROPICS rainfall product (~17 km at nadir, 24 km average across the swath), and the fact that extreme events are often made up of a series of convective cells, 30- to 60-minute temporal resolution will likely be adequate for tracking these smaller convective systems, with 1 hour representing an upper limit. For MCSs, system evolution can be up to 6 hours or longer. A median revisit rate of 1 hour is expected to be adequate for MCSs, but will degrade significantly as it approaches 3 hours, considered the upper limit for MCSs. The thermodynamic environment evolves over longer time scales than the convection, particularly above the boundary layer, so revisit rates less than 3 hours will still be valuable. Beyond 3 hours, the revisit rate would be approaching current capabilities (except that current capabilities may rapidly degrade by launch).

Data latency requirements will vary by application. Tracking extreme convection will likely require data in real time given the life cycle of short-lived convection. Larger-scale or longer-lived events (atmospheric rivers, synoptically forced events) and variations in environmental thermodynamic conditions, e.g., the SAL, can be tracked in near real time (3–6 hours). Storm postmortem analysis for emergency response likely would also require near real-time availability. It is anticipated that users in the insurance industry, or anyone else interested in risk assessment, would not require data in or near real time. Latency is not a factor for these latter groups.

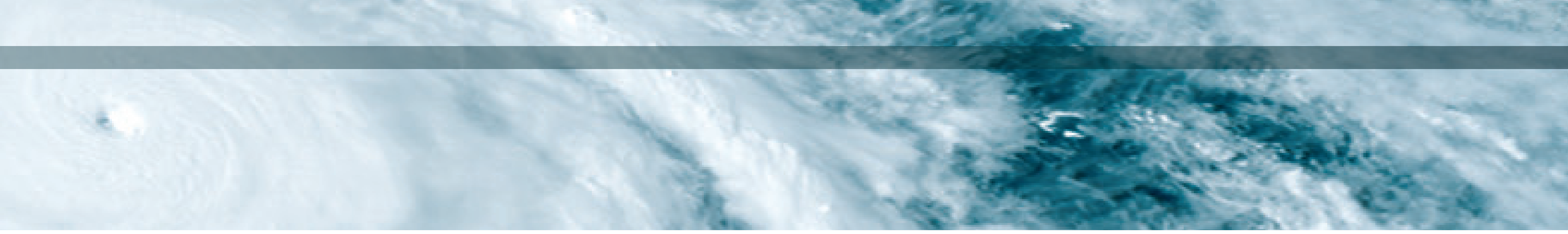
In addition to the expected level-1 calibrated brightness temperatures and level-2 orbital derived products (temperature, humidity, and rainfall), the group suggested the following higher level products:

- Level-3 gridded products at the highest possible spatial resolution for brightness temperatures, relative humidity (total precipitable water), and precipitation. The time interval could be less than the median revisit rate, allowing users to average or accumulate data over longer time periods, as desired. Some individuals were interested in having gridded fields include all observations going into each grid box in order to dive deeper into the samples.

- Products that use morphing to fill gaps in time. There was particular interest in the impact of TROPICS data on multisatellite precipitation products such as IMERG and the NOAA/NCEP Climate Prediction Center MORPHing technique (CMORPH).

- Error estimates.

The 1st TROPICS Applications Workshop presentations and breakout discussions focused more on applied research that will be enabled in the government and university communities than specific end-user applications. It is anticipated that these applied research concepts will be communicated to the operational community through continued engagement by a TROPICS applications community that will be built off of this meeting. Key partners to work with users would be the SERVIR and Short-term Prediction Research and Transition programs at NASA Marshall Space Flight Center (MSFC). New data sets can be difficult for users to adopt for a number of reasons. Important steps for facilitating data usage include holding user training meetings through either workshops or programs like ARSET or University Corporation for Atmospheric Research/COMET; providing documentation of products, uncertainties, caveats about data usage, and README files; and provision of code to read all products. For NWS users, implementation of data within operational data analysis systems (NAWIPS, AWIPS, or equivalent systems) is important. Online visualization and analysis tools may be ideal for some users since data would not need to be downloaded or code written. Spatial, temporal, and parameter subsetting tools, e.g., Open-source Project for a Network Data Access Protocol, are also highly desirable. Because users may utilize a variety of software systems, data formats should be flexible (NetCDF, HDF, GIS, e.g., GeoTIFF, shape, KML), and Gridded Binary version 2, to the extent possible.



Meeting Actions/ Take-Aways

TROPICS principal investigator William Blackwell noted that the inputs provided during this applications workshop would be used to help finalize some of the mission implementation decisions in preparation for Preliminary Design Review. In particular, the desire for improved data latency was very clearly expressed, and it may be possible to provide latencies down to 60–120 minutes at least some of the time for tropical storms that occur near the ground stations.

The following meeting actions/take-aways were documented as potential areas where NASA could make additional investments into the mission to increase the usability of data from the mission:

- End users in real-time tropical marine weather applications and operations communities need data with the least amount of latency possible. Ideally, data would be less than 1 hour latent, but the maximum latency for use in operations is ~3 hours. Any data more latent than that leads to less impact on real-time forecast products. Terrestrial applications have varied latency requirements between 1 hour for flood/landslide applications to upwards of a day for agriculture and water use applications. The applied research community plans to use these data to better understand TC dynamics and intensification; however, they do not have data latency requirements. A government partnership between NASA and NOAA to invest in a couple of S-band downlink sites (perhaps at Hawaii and Miami, Florida) at a relatively minimal cost of $100K per site would enable a more comprehensive demonstration of the SmallSat concept in operations, perhaps leading to future lower-cost, lower-risk operational missions for collecting passive microwave observations. Another option is to leverage commercially available ground networks that could be used to downlink TROPICS data. A recent study found that existing commercial sites could be used to achieve approximately 15-minute average data latency at a total cost of less than $1M.

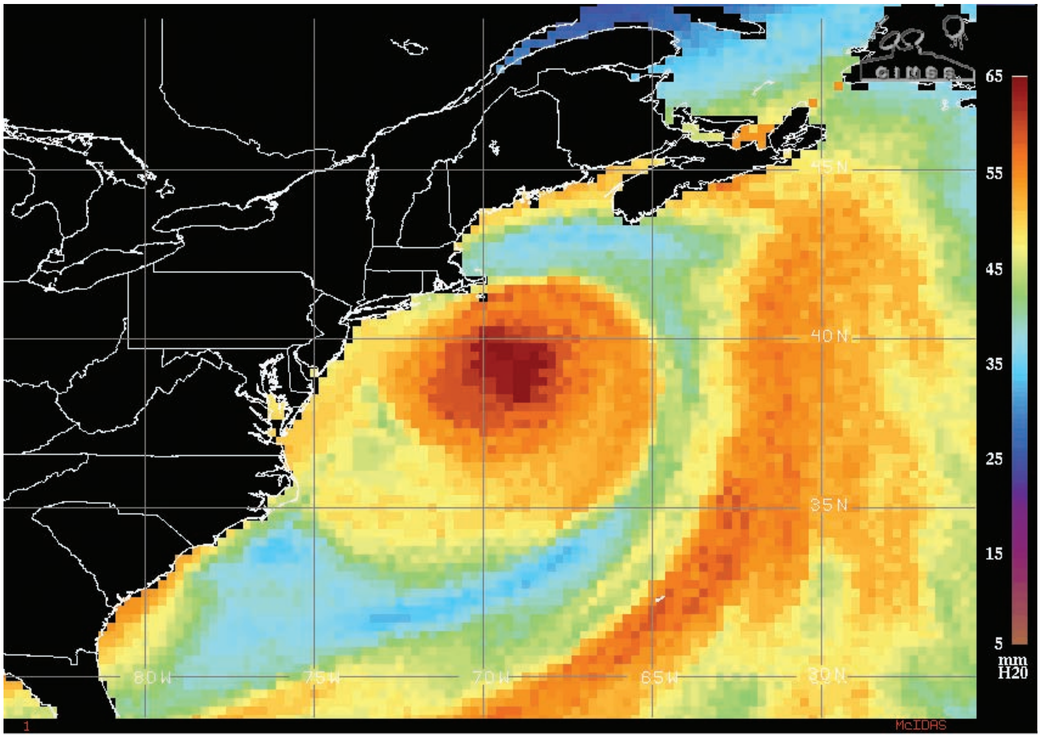
- For most of the applications presented and discussed at the meeting, 30 minutes was presented as the ideal temporal resolution in order to most aptly capture dynamic processes within TCs and precipitation features associated with flooding and landslides. However, temporal resolutions of 60 minutes are still acceptable for most applications. Thus, it is recommended that the mission retain enough satellites in the constellation to support at least 60-minute temporal frequency. If temporal frequencies approach 3 hours, then these observations lose their added value and begin to look like other currently flying satellite missions.

- To enable a greater chance for successful application of TROPICS data, the mission data needs to be provided to users in their desired data format and/or integrated into their decision support systems, e.g., format data for viewing in NAWIPS for NHC users.

- Many workshop users were disappointed that TROPICS will not have high spatial resolution passive microwave imager channels to support the sounding channels, as such imager data provide the ability for applications like TC center fixes and structure analysis. There was strong advocacy for potential follow-on TROPICS missions to include additional traditional MW imager channels with the same temporal resolution as TROPICS but with increased spatial resolution.

- Development of proxy products from the upcoming MicroMAS-2 launch in Fall 2017 and OSSEs will allow for prelaunch testing of proposed TROPICS product algorithms. These proxy products can be used to accelerate this new technology into operations/applications. The 205-GHz channel has never been used for an Earth science satellite mission. There was interest expressed in how this channel might be useful for TC and other applications, especially for processes that involve ice-cloud features. Also, there is a need for development of various data assimilation tools, e.g., forward operators, bias corrections, error covariances, quality controls, and data thinning approaches, in order to incorporate near-real-time observations shortly after TROPICS launch. A proxy dataset would also enable the applications community to create data products formatted for ingest into expected user decision support systems, as key to doing operational demonstrations of experimental products. Some of these science activities could be addressed through a NASA proposal solicitation to fund science applications beyond the role of the TROPICS Science Team.

- In order to maintain continued engagement with the applications community, the participants in this meeting agreed to participate in periodic activities that will provide updates on mission status and new application opportunities. Through interactions with the meeting attendees and their collaborators, a roster of 'Early Adopters' of TROPICS data will be built to help capture potential mission impacts on applications/operations.
- Establish an unfunded international science team/working group to improve synergy with current and emerging missions from outside the United States, such as Megha-Tropiques and the MetOp Ice Cloud Imager.



Tropical Storm Jose (2017) shown in the Morphed Integrated Microwave Imagery at CIMSS - Total Precipitable Water product. Image courtesy of CIMSS.

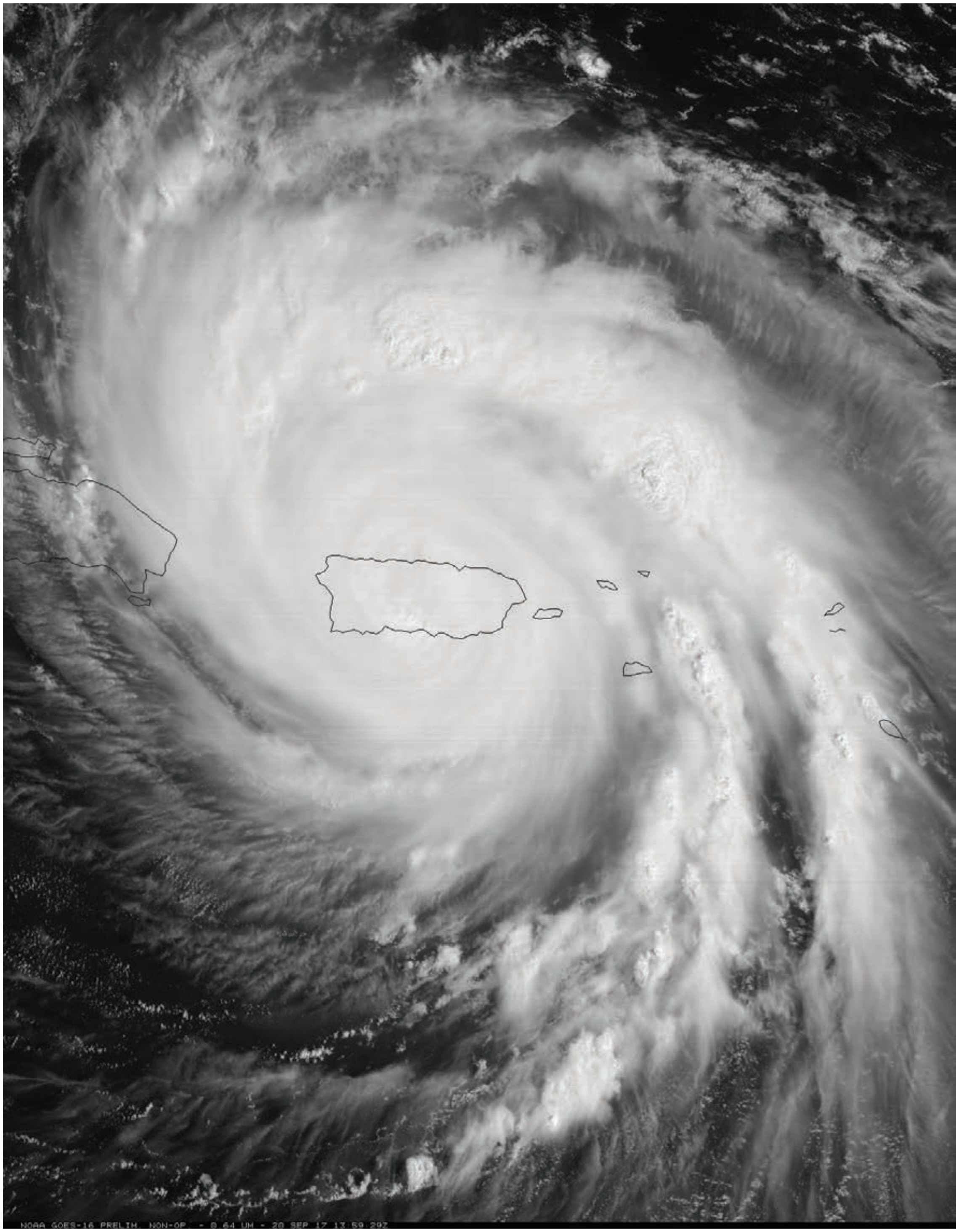
APPENDIX A—ORGANIZING COMMITTEE

The 1st TROPICS Applications Workshop organizing committee is given in table 3.

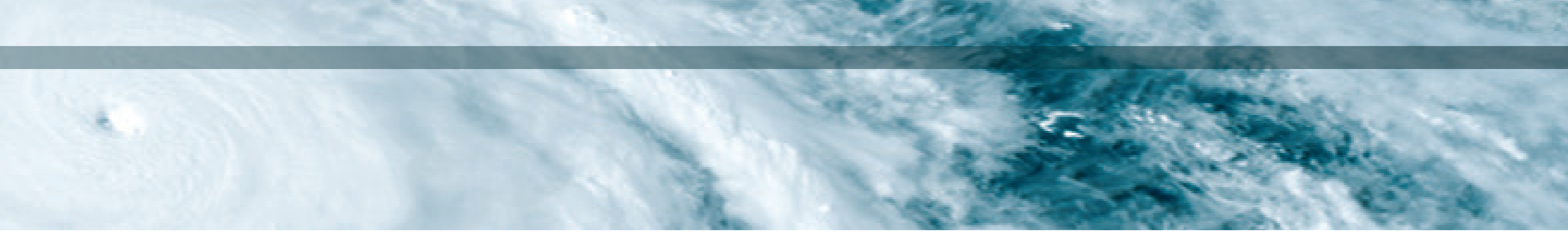
Table 3. Members of 1st TROPICS Applications Workshop organizing committee.

Name	Affiliation
Robert Adler	University of Maryland
William Blackwell	MIT LL / TROPICS Principal Investigator
Michael Brennan	NOAA NWS National Hurricane Center
Scott Braun	NASA GSFC / TROPICS Project Scientist
Joshua Cossuth	NRL
Jason Dunion*	UM/CIMAS - NOAA/HRD
David Green	NASA HQ / CYGNSS & TROPICS Program Applications Lead
John Murray	NASA LaRC / CYGNSS Deputy Program Applications Lead
Chris Velden	University of Wisconsin - CIMSS
Bradley Zavodsky*	NASA MSFC / TROPICS Deputy Program Applications Lead

*Meeting co-conveners



Hurricane Maria (2017) following landfall in Puerto Rico as seen by the NOAA GOES-16 Advanced Baseline Imager. Image courtesy of NASA Marshall Space Flight Center Short-term Prediction Research and Transition (SPoRT).



APPENDIX B—MEETING AGENDA

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

May 8–10, 2017

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

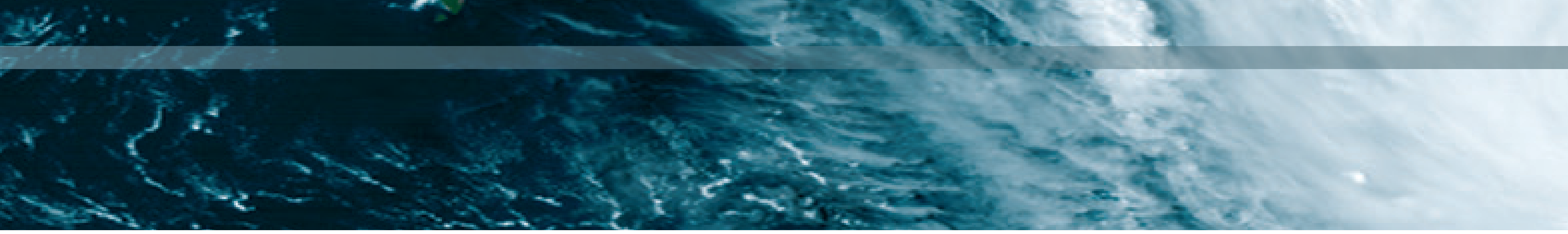
Sunday, May 7

5:00p – 6:30p	Optional Cocktail Hour at Above Mayfair*

Monday, May 8

7:15a	UM Shuttles Depart Conference Hotels for UM/RSMAS
7:30a – 8:00a	Registration/Light Refreshments
8:00a – 8:05a	UM Welcome **Dr. Benjamin Kirtman**, Director, University of Miami-CIMAS
8:05a – 8:15a	NASA Applied Sciences Welcome **David Green**, Program Applications Lead TROPICS, NASA HQ
8:15a – 8:25a	NASA HQ Welcome **Tsengdar Lee**, Weather Focus Area Lead, NASA HQ
8:25a – 8:30a	Summary of Workshop Objectives **Bradley Zavodsky**, Deputy Program Applications Lead TROPICS, NASA MSFC
8:30a – 9:00a	TROPICS Mission Overview and Status **William Blackwell**, TROPICS Principal Investigator, Massachusetts Institute of Technology, Lincoln Laboratory

* http://www.mayfairhotelandspa.com/above-mayfair-rooftop-lounge/



Panel Discussion 1— Data Latency

(Session Moderator, William Blackwell)

9:00a – 10:00a Panelists:
Mitch Goldberg, JPSS Program Scientist
Darren McKague, Research Scientist, Calibration/Validation Lead for Cyclone Global Navigation Satellite System (CYGNSS), University of Michigan
Tim Neilsen, Civil Space Satellite Technologies Program Manager, Space Dynamics Laboratory, Utah State University

10:00a – 10:30a Morning Break (registration payment desk will be open)

Application Presentations 1—Terrestrial

(Session Chair, Robert Adler)

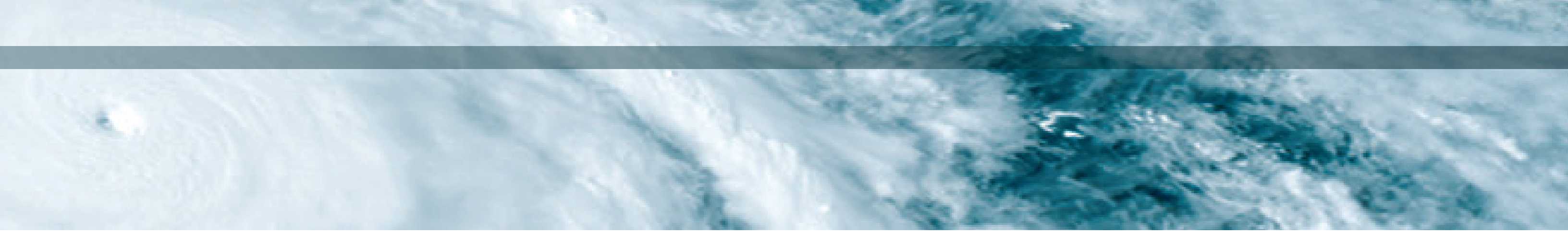
10:30a – 10:50a Using Remote Observations of Precipitation to Support Army Terrain Analysis in a Geospatially-Enabled System of Systems Model
John Eylander, Program Manager/Army Terrestrial-Environmental Modeling and Intelligence System (ARTEMIS) USACE Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, Hanover, NH

10:50a – 11:10a Potential Benefits of TROPICS Data to the Insurance Industry
Joshua Woodbury, Natural Catastrophe Specialist: Flood, Swiss Region

11:10a – 11:30a Quenching the Thirst in the Middle East North Africa Region
Rachel McDonnell, Head of Climate Change Modeling and Adaptation, International Center for Biosaline Agriculture, Dubai, United Arab Emirates

11:30a – 11:50a From Precipitation to Water and Health, Security and Resilience—Science and Application Challenges and Opportunities in Tropical Hydrology
Ana Barros, Professor of Earth and Ocean Sciences, Duke University

11:50a – 12:50p Lunch at UM Dining Room



Application Presentations 2—Tropical Cyclone Analysis and Nowcasting

(Session Chair, Chris Velden)

12:50p – 1:10 p — The Use of Microwave Satellite Data at NHC
Michael Brennan, Senior Hurricane Specialist NOAA/NWS/NCEP National Hurricane Center

1:10p – 1:30p — Nowcasting and Analysis at National Weather Service, San Juan
Ernesto Rodriguez, Science Operations Officer, San Juan, Puerto Rico, National Weather Service Weather Forecast Office

1:30p – 1:50p — Satellites and Storytelling
Matt Sitkowski, Executive Weather Producer, The Weather Channel

1:50p – 2:10p — Microwave Sounding Nowcasting at NRL, CIMSS, and JTWC
Joshua Cossuth, Meteorologist, Naval Research Laboratory

Application Presentations 3—Tropical Cyclone Modeling and Data Assimilation

(Session Chair, Joshua Cossuth)

2:10p – 2:30p — Radiance Assimilation in HWRF: Status and Relevance to the TROPICS Mission
Jason Sippel, Meteorologist, NOAA/AOML/HRD

2:30p – 2:50p — TC OSSEs and the Potential Uses of CubeSat Microwave Sounding Data
Robert Atlas, Director, NOAA/AOML

2:50p – 3:10p — Assimilation of Satellite-Derived Temperature and Moisture Profiles and Precipitation for Improved Prediction and Understanding of Tropical Cyclone Genesis and Intensity Changes: Applications and Data Quality Requirements
Zhaoxia Pu, Professor, Department of Atmospheric Sciences, University of Utah

3:10p – 3:40p — Afternoon Break

Application Presentations 4—Tropical Cyclone Dynamics

(Session Chair, Scott Braun)

3:40p – 4:00p — Interests of JPL Scientists in TROPICS Data
Hui Su, Research Scientist, NASA Jet Propulsion Laboratory, Caltech

4:00p – 4:20p — Application of 183 GHz Humidity Measurements for Tropical Cyclone Research
Brian Soden, Professor of Atmospheric Science, University of Miami

4:20p – 4:40p — Mechanisms Maintaining the Moist Mode of Column Water Vapor
Brian Mapes, Professor of Atmospheric Science, University of Miami

4:40p – 5:00p — Temporal Evolution and Mapping of Intense Convective Systems Using TROPICS
Dan Cecil, Research Physical Scientist, NASA MSFC

5:00p – 6:00p — Optional Ice Breaker; GPM Virtual Reality Demonstration

6:15p — UM Shuttles Depart UM/RSMAS for Conference Hotels

Tuesday, May 9

7:15a — UM Shuttles Depart Conference Hotels for UM/RSMAS

7:30a – 8:00a — Registration/Light Refreshments

Breakout Discussions/Capture End-User Perspectives

8:00a – 8:10a — Introduction and Goals
David Green, Program Manager, NASA HQ

8:10a – 9:30a — Breakout Discussions No. 1 (led by session chairs; local scribes)
– Terrestrial (Lead, Robert Adler)
– Tropical Cyclone Nowcasting (Lead, Chris Velden)
– Tropical Cyclone Modeling and Data Assimilation (Lead, Joshua Cossuth)
– Tropical Dynamics (Lead, Scott Braun)

9:30a – 9:50a — Morning Break (registration payment desk will be open)

9:50a – 11:10a — Breakout Discussions No. 2 (led by session chairs; local scribes)
– Terrestrial (Lead, Robert Adler)
– Tropical Cyclone Nowcasting (Lead, Chris Velden)
– Tropical Cyclone Modeling and Data Assimilation (Lead, Joshua Cossuth)
– Tropical Dynamics (Lead, Scott Braun)

11:10a – 11:40a — Breakout Leads Prepare Reporting; General Networking

11:40a – 12:40p — Lunch

12:40p – 2:00p	Breakout Leads Report Back (~20 minutes each)
2:15p	UM Shuttles Depart for Conference Hotels or the Optional Group Tour at the National Hurricane Center
4:15p/4:30p	UM Shuttles Depart National Hurricane Center and Return to Conference Hotels
6:30p – ?	Optional Group Dinner at Greenstreet Café†

Wednesday, May 10

7:15a	UM Shuttles Depart Conference Hotels for UM/RSMAS
7:30a – 8:00a	Registration
8:00a – 9:00a	Mission Design Impacts on Applications Discussion **Christine Bonniksen**, Program Executive for TROPICS, NASA HQ

Panel Discussion 2—Synergies With Other NASA Missions

(Session Moderator, Bradley Zavodsky)

9:00a – 10:30a	Panelists: – S-NPP/JPSS, **Mitch Goldberg**, JPSS Program Scientist – CYGNSS, **Sharan Majumdar**, Professor and Associate Dean of Graduate Studies, RSMAS/UM – GPM, **Scott Braun**, TROPICS Project Scientist, NASA Goddard Space Flight Center – U.S. Air Force, **Brian Kabat**, Chief, Environmental Monitoring Branch, Air Force Space Command – GOES-R, **Bob Kuligowski**, Meteorologist, NOAA/NESDIS Center for Satellite Applications and Research (STAR)
10:30a – 11:00a	Morning Break
11:00a – 12:00n	Concluding Remarks; Meeting Summary and Take-Aways
12:00n	Adjourn Meeting
12:15p	UM Shuttles Depart UM/RSMAS for Conference Hotels

† http://www.greenstreetcafe.net/

APPENDIX C—ATTENDEES LIST

The 1st TROPICS Applications Workshop registered participants is shown in table 4.

Table 4. Registered participants at the 1st TROPICS Applications Workshop.

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APPENDIX D—MISSION DETAILS

Details of 12 TROPICS channels are given in table 5.

Figures 8 and 9 give the weighting functions for TROPICS channels for temperature and moisture soundings, and the swatch geometry for the TROPICS mission compared to ATMS, respectively.

Table 6 lists the spatial resolution of each of the TROPICS L2 products.

Table 5. Details of 12 TROPICS channels are given in table 5.

TROPICS Channel	W-band Channel	Center Frequency (GHz)	Bandwidth (GHz)	RF Span (GHz)
1	W1	91.655±1.4	1.000	89.756–90.756, 92.556–93.556
TROPICS Channel	**F-band Channel**	**Center Frequency (GHz)**	**Bandwidth (GHz)**	**RF Span (GHz)**
2	F1	114.50	1.000	114.00–115.00
3	F2	115.95	0.800	115.55–116.35
4	F3	116.65	0.600	116.35–116.95
5	F4	117.25	0.600	116.95–117.55
6	F5	117.80	0.500	117.55–118.05
7	F6	118.24	0.380	118.05–118.43
8	F7	118.58	0.300	118.43–118.73
TROPICS Channel	**G-band Channel**	**Center Frequency (GHz)**	**Bandwidth (GHz)**	**RF Span (GHz)**
9	G1	184.41	2.000	183.41–185.41
10	G2	186.51	2.000	185.51–187.51
11	G3	190.31	2.000	189.31–191.31
12	G4	204.8	2.000	203.8–205.8

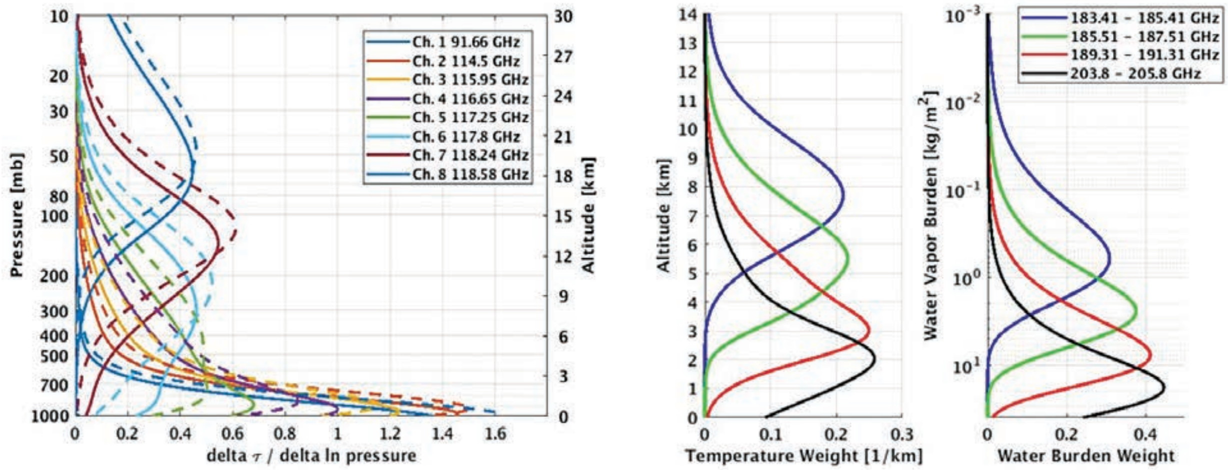

Figure 8. Weighting functions for TROPICS channels for temperature (left) and moisture (right) soundings. Solid lines in the temperature represent nadir; dashed lines represent 50° scan angle. Lines in moisture figure represent nadir. Weighting functions in both figures use the U.S. 1976 Tropical Standard Atmosphere.

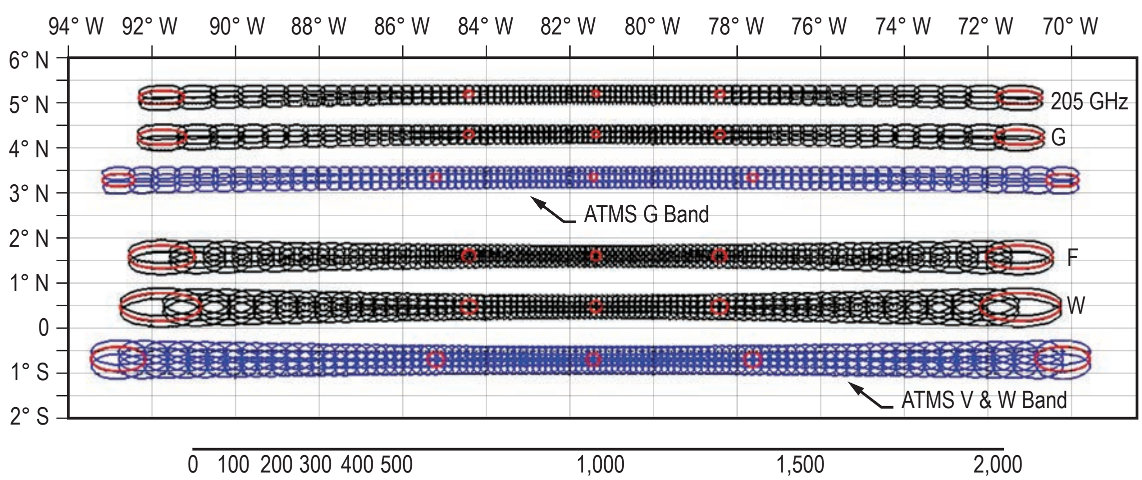

Figure 9. Swath geometry for TROPICS mission compared to ATMS.

Table 6. Spatial resolution of each of the TROPICS L2 products.

	ATMS Nadir/Avg (km)	TROPICS Nadir/Avg (km)
Temperature	33/44	27/40
Moisture and precipitation	17/24	17/24
90-GHz imaging	33/44	35/52
Swath width	2,250 (±50.5°)	2,025 (±56°)

APPENDIX E—LIST OF ACRONYMS

3-D	three-dimensional
AMSU	Advanced Microwave Sounding Unit
AOML	Atlantic Oceanographic and Meteorological Laboratory
ARSET	Applied Remote Sensing Training
ATMS	Advanced Technology Microwave Sounder
AWIPS	Advanced Weather Interactive Processing System
CIMAS	Cooperative Institute for Marine and Atmospheric Studies
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CMORPH	Climate Prediction Center MORPHing technique
CPHC	Central Pacific Hurricane Center
CYGNSS	Cyclone Global Navigation Satellite System
DoD	Department of Defense
ECMWF	European Center for Medium Range Weather Forecasting
ESD	Earth Science Division
GCM	General Circulation Model
GeoTIFF	Georeferenced Tagged Image File Format
GIS	geographic information system
GMI	GPM Microwave Imager
GOES	Geostationary Operational Environmental Satellite
GPM	Global Precipitation Measurement
HDF	Hierarchical Data Format
HQ	Headquarters
HRD	Hurricane Research Division
HWRF	Hurricane Weather Research and Forecasting
IMERG	Integrated Multi-satelliE Retrievals for GPM
JPL	Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
JTWC	Joint Typhoon Warning Center

KML	Keyhole Markup Language
MCS	mesoscale convective systems
MicroMAS-2	Micro-sized Microwave Atmospheric Satellite 2
MIMIC	Morphed Integrated Microwave Imagery at CIMSS
MIT LL	Massachusetts Institute of Technology Lincoln Laboratory
MJO	Madden-Julian Oscillation
MOC	Mission Operations Center
MSE	moist static energy
MSFC	Marshall Space Flight Center
N-AWIPS	NCEP AWIPS
NCEP	National Centers for Environmental Prediction
NASA	National Aeronautics and Space Administration
NetCDF	Network Common Data Form
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NWP	numerical weather prediction
NWS	National Weather Service
OSSE	Observing System Simulation Experiment
RSMAS	Rosenthal School of Marine and Atmospheric Studies
SAL	Saharan Air Layer
Sat	satellite
SERVIR	acronym in Spanish for Mesoamerican Regional Visualization and Monitoring System
TC	tropical cyclone
TROPICS	Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of SmallSats
U	unit (reference to size of CubeSats)
UM	University of Miami
USACE	United States Army Corps of Engineers

REPORT DOCUMENTATION PAGE						Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 01–10–2017	2. REPORT TYPE Conference Publication	3. DATES COVERED *(From - To)* May 8–10, 2017

4. TITLE AND SUBTITLE First Time-Resolved Observations of Precipitation Structure and Storm Intensity With a Constellation of SmallSats (TROPICS) Mission Applications Workshop Summary Report	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) B. Zavodsky, J. Dunion,* W. Blackwell,** S. Braun,*** C. Velden,† M. Brennan,‡ and R. Adler§	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–1441
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546–0001	10. SPONSORING/MONITOR'S ACRONYM(S) 11. SPONSORING/MONITORING REPORT NUMBER NASA/CP—2017–219705

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified-Unlimited
Subject Category 47
Availability: NASA STI Information Desk (757–864–9658)

13. SUPPLEMENTARY NOTES

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14. ABSTRACT

The NASA Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of SmallSats (TROPICS) mission will provide temperature, humidity, and precipitation measurements every 30–60 minutes to help the weather community improve understanding of tropical cyclone development and intensification. This Conference Publication summarizes the outcome of the 1st TROPICS Applications Workshop, which introduced a broad community of potential applied researchers and operational decision makers to the expected value of TROPICS and provided a forum for these end users to share insight into how TROPICS could be used in their organizations.

15. SUBJECT TERMS

meteorology, tropical cyclones, applications, remote sensing

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	40	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

P-3 flight into eye of Hurricane Irma (2017). P-3 data will provide validation information for TROPICS intensity. Image used with permission from Jonathan Zawislak, University of Miami CIMAS-NOAA/AOML Hurricane Research Division.

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