Received: 29 June 2017 | Revised: 30 November 2017 | Accepted: 12 March 2018 | Published on: 17 September 2018

DOI: 10.1002/qj.3290

ADVANCES IN REMOTE SENSING OF RAINFALL AND SNOWFALL

Quarterly Journal of the Royal Meteorological Society

An overview of the TROPICS NASA Earth Venture Mission

W. J. Blackwell[1] | S. Braun[2] | R. Bennartz[3,6] | C. Velden[3] | M. DeMaria[4] | R. Atlas[5] | J. Dunion[5] | F. Marks[5] | R. Rogers[5] | B. Annane[5] | R. V. Leslie[1]

[1]Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts, USA
[2]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
[3]Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin, Madison, Wisconsin, USA
[4]NOAA/NWS/NCEP – Technology and Science Branch of the National Center, Fort Collins, Colorado, USA
[5]NOAA/AOML/Hurricane Research Division, Miami, Florida, USA
[6]Vanderbilt University Earth and Environmental Sciences, USA

Correspondence
W.J. Blackwell, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts, USA.
Email: WJB@LL.MIT.EDU

Funding information
National Aeronautics and Space Administration (NASA, USA),

The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission was selected by NASA as part of the Earth Venture-Instrument (EVI-3) program. The overarching goal for TROPICS is to provide nearly all-weather observations of 3D temperature and humidity, as well as cloud ice and precipitation horizontal structure, at high temporal resolution to conduct high-value science investigations of tropical cyclones. TROPICS will provide rapid-refresh microwave measurements (median refresh rate better than 60 min for the baseline mission) which 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 six CubeSats in three low-Earth orbital planes. Each CubeSat will host a high-performance radiometer to provide temperature profiles using seven channels near the 118.75 GHz oxygen absorption line, water vapour profiles using three channels near the 183 GHz water vapour absorption line, imagery in a single channel near 90 GHz for precipitation measurements (when combined with higher-resolution water vapour channels), and a single channel near 205 GHz which is more sensitive to precipitation-sized ice particles. This observing system offers an unprecedented combination of horizontal and temporal resolution to measure environmental and inner-core conditions for tropical cyclones 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. Launch readiness is currently projected for late 2019.

KEYWORDS
data assimilation, microwave sounder, NWP, precipitation, temperature and moisture profiles, TROPICS, tropical cyclones

1 | INTRODUCTION

Close to 60 million Americans live within counties along the East and Gulf coasts (140 million total in East and Gulf coast states), exposing them to potential hazards caused by Atlantic landfalling tropical cyclones (TCs, known as hurricanes in the Atlantic and typhoons in the West Pacific). Many millions more are affected by TCs worldwide. Pielke *et al.* (2009) projected a doubling of US economic losses from TCs every ten years. Advances in airborne and satellite observing systems, numerical models and scientific understanding of TCs have led to significant advances in the predictions of storm track. However, improvements in forecasts of storm intensity and size (wind and precipitation structure) prediction have lagged behind those of storm track.

The need for improved observations and understanding of storm track, intensity, and associated precipitation has been underscored by the occurrence of recent major landfalling events such as hurricanes *Katrina* (2005), *Ike* (2008), *Sandy* (2012), *Irma* (2017), and *Maria* (2017) in the Atlantic and supertyphoons *Megi* (2010), *Bopha* (2012), and *Haiyan* (2013) in the West Pacific. The 2007 NASA Decadal Survey (National Research Council, 2007) recommended the Precipitation and All-weather Temperature and Humidity (PATH) mission as a means of obtaining three-dimensional (3D) temperature and humidity measurements as well as precipitation. PATH was envisioned primarily as a microwave instrument suite in geosynchronous orbit that would provide 15–30 min temporal refresh, but would by necessity be limited in sensor spatial resolution and overall coverage. Low-Earth orbit (LEO) sensors were viewed as impractical due to the large number of constellation members that would be needed to provide 15–30 min sampling. However, since that survey, new technologies have evolved which now make possible the formation of constellations of smallsat radiometers capable of delivering measurements that are directly relevant to PATH objectives with refresh rates of 30–60 min and near-global coverage at a small fraction of the cost of a geostationary sounder.

The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) CubeSat mission will provide rapid-refresh microwave measurements over the Tropics to observe the thermodynamics and precipitation structure of TCs over much of their life cycle. TROPICS comprises six CubeSats (dual-spinning, 6.0 kg, 3 units or 3U) spread across three 550 km altitude, 30° inclination orbital planes for up to one year. Each CubeSat contains a 2U spacecraft bus and hosts a 1U high-performance 12-channel microwave radiometer scanning across the satellite track at 30 revolutions per minute (RPM) to provide both sounding (temperature and humidity, 2–3 km vertical resolution) and imaging capabilities. The sensor will include seven channels near the 118.75 GHz oxygen absorption line for temperature, three channels near the 183 GHz water vapour absorption line for moisture, a single channel at 90 GHz (combined with temperature and moisture channels) for precipitation structure detection, and a single channel near 205 GHz for larger cloud/smaller precipitation ice measurements. The full swath of the radiometer observations will be fully programmable and extendable to ±60° from nadir, with a 1.5° cross-track sampling interval (81 spots/swath) and fields-of-view (FOVs) comparable to the scale of warm thermal anomalies associated with TC cores. Data latency (space-to-ground) will likely be at least several days, therefore TROPICS will be focused on data collection and science, rather than on operationally driven real-time mission objectives.

2 | THE TROPICS OBSERVATORY

TROPICS comprises a constellation of six identical space vehicles (SVs) conforming to the 3U CubeSat form factor and hosting a passive microwave spectrometer payload. The constellation members will be flown in a circular LEO in nearly equally spaced orbital planes, with multiple satellites populating each orbital plane. Each orbit inclination will be roughly 30°. The constellation will allow for rapid-revisit sampling of vertical temperature and moisture profiles of TCs. Figure 1 shows the median revist, the mean revisit, and the fraction of time measurements are observed with revisit rates greater than 2 hr as a function of the constellation orbital configuration. Three orbital planes are considered, with some number of satellites populating each orbital plane (up to four in each plane). The satellites are ejected upon deployment with unique velocities to virtually eliminate the possibility of multi-plane satellite conjunctions (satellites overlapping simultaneously in multiple orbital planes), even when the satellites are allowed to drift freely with no active control ("random phasing"). The revisit rate of the constellation is a function of latitude, and the historical frequency of named TCs is also a function of latitude. To create a scalar revisit metric, the constellation revisit rate as a function of latitude is weighted by the historical storm frequency as a function of latitude. The TROPICS baseline mission will fly six satellites (two in each of three planes), which will allow the baseline mission requirement of 1 hr median revisit to be achieved even with the failure of up to two satellites. Also shown in Figure 1 is a cumulative distribution function of the revisit rates.

An important consideration of the TROPICS constellation architecture is the presence of long gaps and the impact this could have on the value of the observations. To assess this, TROPICS swaths were simulated using an 11-day Weather Research and Forecasting (WRF) model Hurricane Nature Run (HNR) (Nolan *et al.*, 2013). The baseline TROPICS orbital configuration, denoted 2-2-2, uses two satellites in each of three equally spaced orbital planes with 30-degree inclination and 550 km altitude. As shown in Figure 2 for the baseline 2-2-2 configuration, there can be up to several relatively large gaps per day. However, many features in the storm are preserved, even in the presence of occasional gaps. Also shown for reference in Figure 2c is the temporal sampling of an alternate constellation with three satellites in each of two equally spaced planes. Long gap times are more frequent in this configuration, but useful temporal coverage is still obtained.

The passive microwave (PMW) spectrometer antenna is mounted on a rotating axis which will spin about the long axis of the SV. The long axis is aligned to the satellite velocity vector such that the spectrometer will record measurements along a line perpendicular to the satellite velocity in a "cross-track-scan" fashion which maximizes the area scan rate of the instrument. Each SV will record the raw passive microwave data and relay the raw data to the ground, where the data will be processed to produce the temperature and moisture profiles. Spatial resolution (averaged over the swath) is approximately 25 km for the moisture channels (183–206 GHz) and approximately 40 km for the temperature channels (90–118 GHz). Radiometric data are calibrated

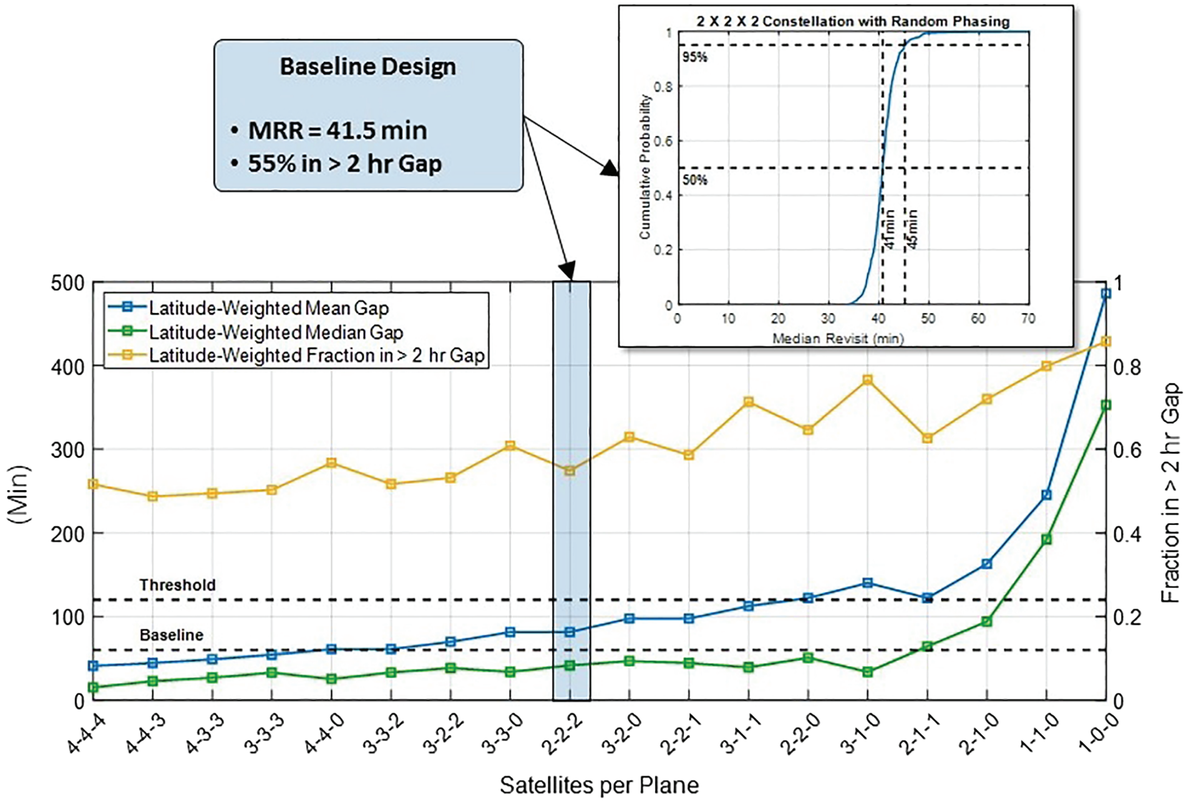

FIGURE 1 TROPICS constellation revisit statistics. The baseline mission case is shown shaded in blue. Other configurations are shown for comparison. The baseline requirement for median revisit of 60 min is indicated by a black horizontal dashed line, as is the 120 min threshold requirement. The upper panel shows a cumulative distribution function of revisit rates of the TROPICS baseline design

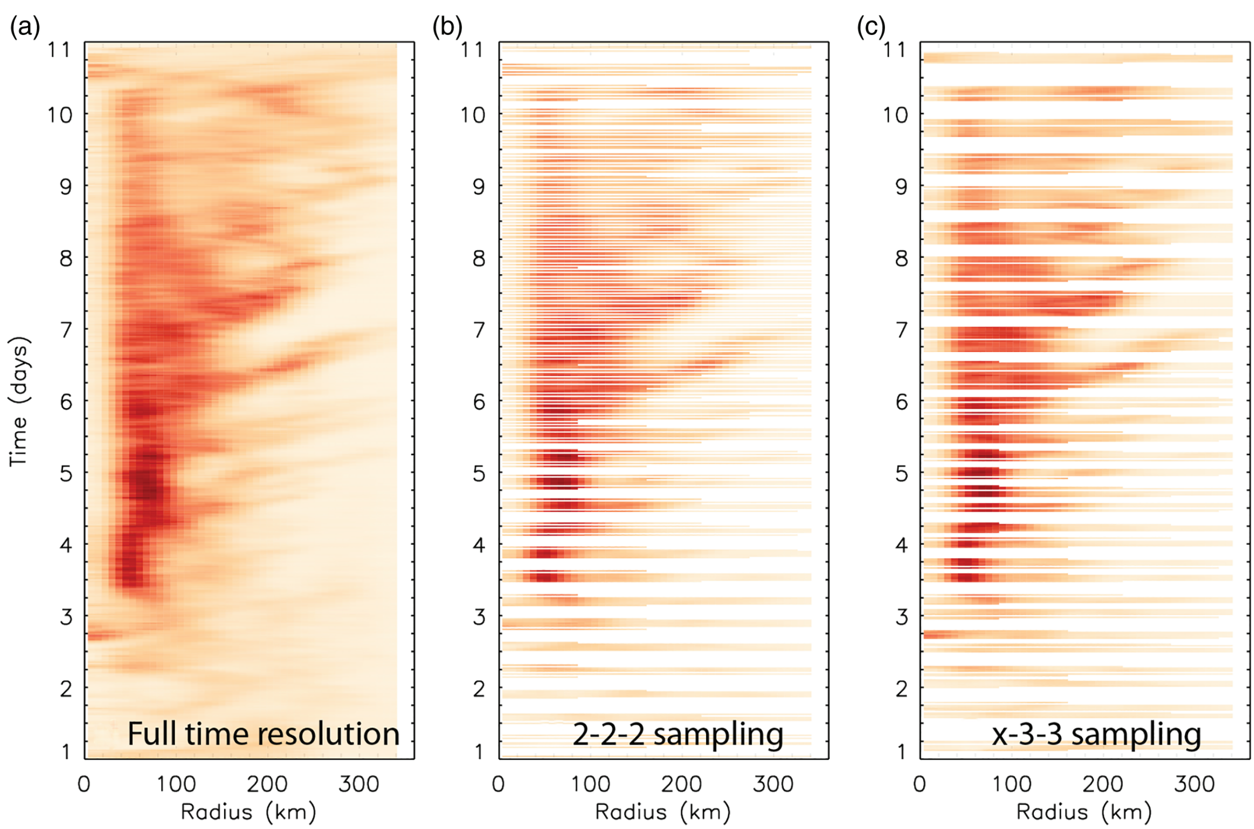

FIGURE 2 Hovmöller diagrams showing precipitation intensity as a function of time and radial distance from the centre of the storm for the WRF Hurricane Nature Run. (a) shows the continuous evolution of precipitation. (b) shows the temporal sampling as observed from the baseline 2-2-2 orbital configuration. (c) shows the temporal sampling as observed from a 3-3 orbital configuration

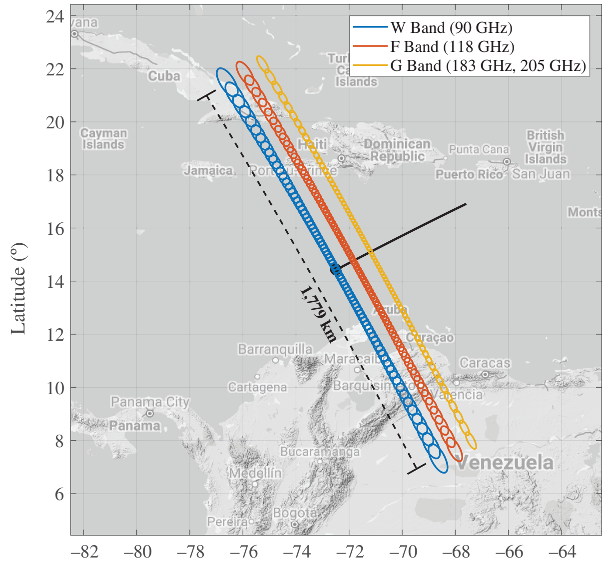

FIGURE 3 TROPICS ground scan pattern for supported frequency bands (shown for a 550 km altitude)

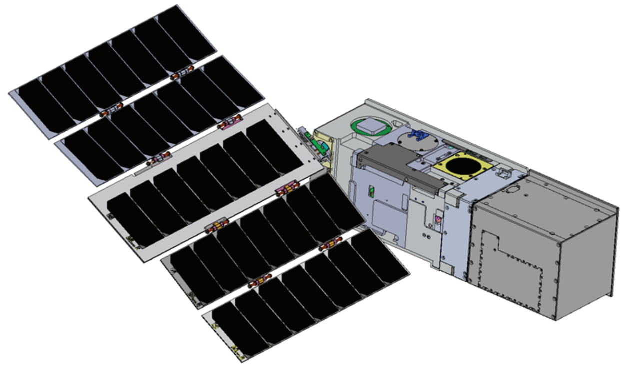

FIGURE 4 TROPICS space vehicle showing CubeSat bus, radiometer payload, and deployed articulated solar array

using an onboard noise diode referencewhich is turned on and off against the cold-sky background at least once per revolution (every 2 s). The earth-projected scan pattern is shown in Figure 3, and additional details on spatial resolution are provided in section 2.2.

The TROPICS observatory will provide a set of products as shown in Table 1, including raw (uncalibrated) radiances, calibrated and geolocated radiances, temperature and moisture profiles, rain rate, and intensity indicators. Details on these products and their use in the TROPICS science program is described below.

2.1 | Space vehicles

Each SV in the six-member TROPICS constellation is an identical 3U CubeSat consisting of a MIT Lincoln Laboratory (MIT LL) spectrometer payload integrated onto a commercially procured bus. The spectrometer payload consists of a rotating passive radio frequency (RF) antenna measuring spectral radiance as it rotates about the SV velocity vector. The payload is based upon a similar payload previously designed by MIT LL for the MicroMAS-2 mission (Micro-sized Microwave Atmospheric Satellite; Blackwell, 2017). The engineering team will modify the design in order to meet TROPICS performance and mission reliability requirements. The redesign includes:

- Antenna modification to optimize ground profile while minimizing side lobes
- Noise reduction in analogue front end
- Higher-dynamic-range analogue-to-digital converter
- Modifications to spectrometer channel centre frequencies and bandwidths
- Higher-reliability control electronics
- Higher-reliability and lower-power motor–scanner assembly

The redesign effort does not include any high-risk modifications, and should simplify the build and calibration of the payload relative to the MicroMAS-2 baseline design.

A notional SV including the bus and payload is shown in Figure 4. The MicroMAS-2 bus does not have sufficient pointing accuracy or power generation capability to meet TROPICS mission requirements. The TROPICS bus will match much of the functionality of the MicroMAS-2 bus, but will take advantage of recent commercial advances in CubeSat reliability and bus technology. In particular, making use of available GPS receivers for position knowledge and star

TABLE 1 TROPICS data products

Designation	Description	Requirement
Level 0	Raw CCSDS payload and telemetry from space vehicles	N/A
Level 1a	Timestamped, geolocated, calibrated antenna temperature	See Table 2
Level 1b	Timestamped, geolocated, calibrated brightness temperature with bias removed	See Table 2
Level 2a	Spatially resampled G-band brightness temperature to F-band resolution	N/A
Level 2b	Atmospheric vertical temperature profile (K)	2 K r.m.s. at 50 km scan-averaged spatial resolution
Level 2b	Atmospheric vertical moisture profile (g g^{-1})	25% at 25 km scan-averaged spatial resolution
Level 2b	Instantaneous surface rain rate (mm h^{-1})	25% at resoluton of 2.5° × 2.5° on weekly basis
Level 2b	TC Intensity: Minimum sea-level pressure (hPa)	10 hPa r.m.s.
Level 2b	TC Intensity: Maximum sustained wind (m s^{-1})	6 m s^{-1} r.m.s.

cameras for attitude knowledge will greatly enhance the data product geolocation accuracy.

The spacecraft bus will be procured from Blue Canyon Technologies and will provide power and power conditioning, communications, on-board processing, thermal management, and Attitude Determination and Control System (ADCS) to the satellite. The flight software will provide command and control of the payload, and will interface with the bus communications system to manage payload commands and prepare payload telemetry for downlink.

2.2 | Radiometer characteristics

TROPICS will continue a long history of microwave sounding/imaging missions targeted to the study of storms. For example, the Global Precipitation Measurement Mission (Hou *et al.*, 2014) and the Megha-Tropiques Mission (Desbois *et al.*, 2003) both observe storms and severe weather with very high measurement fidelity but very low temporal resolution. TROPICS will fly two total power radiometers that measure 12 channels spanning approximately 90–206 GHz. The "WF-band" radiometer comprises eight channels from 90 to 119 GHz, and the "G-band" radiometer comprises four channels from 183 to 206 GHz. The specific channel properties are shown in Table 2. The full-widths at half maximum antenna beamwidths are achieved using an offset parabolic reflector illuminated with two feed horns which are physically separated, and the beams are combined and colocated using a polarizing wire grid diplexer. Beam efficiencies for the temperature and water vapour sounding channels are designed to exceed 95%. Radiometer calibration is accomplished using weakly coupled noise diodes with known and stable noise output which are turned on and off against the cold space background. Satellite intercalibration is optimized using cross-comparisons (Biswas *et al.*, 2013) and daily calculated numerical model residuals (Saunders *et al.*, 2013) to derive and implement any needed bias corrections.

TABLE 2 Description of the TROPICS radiometer channels

Channel	Centre frequency (Ghz)	Bandwidth (MHz)	Beamwidth (°) Down/Cross	ΔT_{rms} (K)	Calibration accuracy (K)
1	91.655 ± 1.4	1000	3.0/3.17	0.7	2.0
2	114.50	1000	2.4/2.62	1.0	1.5
3	115.95	800	2.4/2.62	0.9	1.5
4	116.65	600	2.4/2.62	0.9	1.5
5	117.25	600	2.4/2.62	0.9	1.5
6	117.80	500	2.4/2.62	0.9	1.5
7	118.24	380	2.4/2.62	0.9	1.5
8	118.58	300	2.4/2.62	1.0	1.5
9	184.41	2000	1.5/1.87	1.0	1.0
10	186.51	2000	1.5/1.87	0.6	1.0
11	190.31	2000	1.5/1.87	0.6	1.0
12	204.80	2000	1.4/1.83	0.6	1.0

TABLE 3 TROPICS spatial resolution (in km) for W, F, and G-band channels are shown at nadir and averaged over the 81 footprints in the swath. Also shown is the "effective" spatial resolution which accounts for how often the footprints are revisited across the scan (see text for details)

Band	Nadir	Scan mean	Effective across scan
W (90 GHz)	29.6	42.9	50.7
F (118 GHz)	24.1	34.9	41.2
G (183 GHz)	16.1	23.3	27.5
G (205 GHz)	15.6	22.1	26.0

The radiometer operates in an "integrate-while-scanning" mode which results in elongated footprints in the cross-track direction. The spatial resolution is thus reported as the geometric mean of the minor and major axes of the ellipse projected on the Earth, also accounting for Earth curvature. As the constellation of six satellites scans the Earth, the footprints near the edge of the scan are revisited more often than the footprints near nadir. This effect is quantified by calculating an "effective" spatial resolution which weights the spatial resolution of each footprint by the relative frequency with which it is revisited. The nadir, mean-across-scan, and effective spatial resolutions are shown in Table 3. The satellite pointing accuracy and sensor mounting requirements are set to ensure geolocation errors are smaller than approximately 10% of the footprint size.

Temperature weighting functions for all 12 TROPICS channels are shown in Figure 5. Channel passbands are designed to span altitudes from the surface up to 20 km for temperature and 10 km for water vapour. Multiple temperature channels probe the upper troposphere to observe TC warm core anomalies.

2.3 | Ground station and data processing

The TROPICS SVs will interface with a ground station network to allow for SV command and control and downlink of bus and payload telemetry for each member of the constellation. Stored mission data will be downlinked at S-band. The data products will be made available to the data processing centre via a secured connection. University of Wisconsin (UW) Space Science and Engineering Center (SSEC) as the data processing lead will archive the data to an Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Center (DAAC) in a format approved by NASA Earth Science Data Systems (ESDS).

3 | SCIENCE OBJECTIVES

The overarching goal for the TROPICS mission is to provide nearly all-weather observations of 3D temperature and

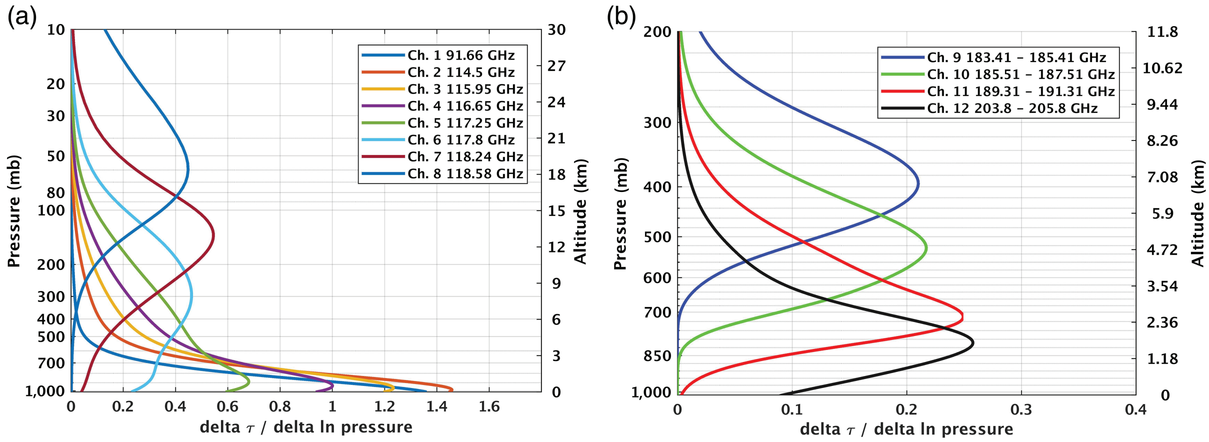

FIGURE 5 Weighting functions calculated at nadir incidence over a perfectly emissive surface for a standard tropical atmosphere for both (a) temperature/imaging and (b) water vapour/imaging channels

humidity, as well as cloud ice and precipitation horizontal structure, at high temporal resolution compared to current passive microwave (PMW) measurements, to conduct high-value science investigations of TCs including:

1. Relationships between rapidly evolving precipitation structure, upper-level warm-core evolution, and associated storm intensity changes;
2. The evolution of TC precipitation structure and storm intensification in relation to environmental humidity fields; and
3. The impact of TROPICS rapid-update microwave observations on numerical and statistical intensity forecasts of TCs.

While the mission chose to focus on TC applications, the proposed constellation can certainly address a much wider range of science goals including analysis of tropical mesoscale convective systems (MCSs), the Madden–Julian Oscillation (MJO), and monsoon weather.

The major limitations in predicting intensity change in TCs are an inadequate understanding of the processes that cause it, insufficient sampling of appropriate observations of the storm environment and internal processes, and inadequate representation of those processes in models (Rogers *et al.*, 2006). The challenge for TC intensity prediction is that storm strength depends on processes operating at spatial scales ranging from the cloud scale to synoptic scale and time-scales from 30 min to diurnal. The smaller-scale phenomena are more difficult to observe, tend to be more chaotic, and their interaction with larger scales is poorly understood.

Addressing these TC intensity science goals requires rapid-update quantitative observations of storm structure and environment, but current observing systems are inadequate for this purpose. Geosynchronous visible and infrared systems provide nearly continuous observations, but storm structure information is primarily limited to the evolution of cloud tops. Passive microwave observations from LEOs, in contrast, reveal the TC structure beneath the cloud tops, but are relatively infrequent with gaps in time of several hours. Proposed geostationary PMW systems remain an unproven technology and would only provide data over a portion of a single ocean basin. TROPICS is designed to bridge these gaps by providing high-resolution, rapid-update PMW measurements over all TC ocean basins which will increase our observations and knowledge of the processes that lead to significant, and sometimes rapid, changes in TC structure and intensity. TROPICS provides a relatively low-cost, high-impact means of addressing the following science questions.

3.1 | What are the relationships between upper-level warm-core evolution and storm intensity and structure change?

The formation of an upper-level warm core is a key indicator of TC development and the processes that lead to warm core formation are thus key to understanding how it is linked with the onset and continuation of intensification. The TC warm core has been the subject of numerous studies spanning decades of research (e.g. Velden, 1989; Velden *et al.*, 1991; Brueske and Velden, 2003; Demuth *et al.*, 2006; Halverson *et al.*, 2006; Bessho *et al.*, 2010; Stern and Nolan, 2012; Kieu *et al.*, 2016). However, mainly due to observing limitations, our understanding of how it evolves and relates to TC structure change is still incomplete. In order to improve TC intensity analyses and forecasts, the factors controlling warm-core evolution need to be better observed and understood.

PMW sounders operating in the 53–55 GHz and 115–118 GHz frequency bands are sufficiently transparent to cloud cover to allow a coarse mapping of the TC warm core in the ∼ 100–400 hPa layer (Figure 6) and coincident horizontal precipitation structure (Figure 7, from the Advanced Technology Microwave Sounder (ATMS) and having horizontal resolution comparable to that of the TROPICS mission). A robust relationship exists between these thermal anomalies and TC intensity as measured by reconnaissance

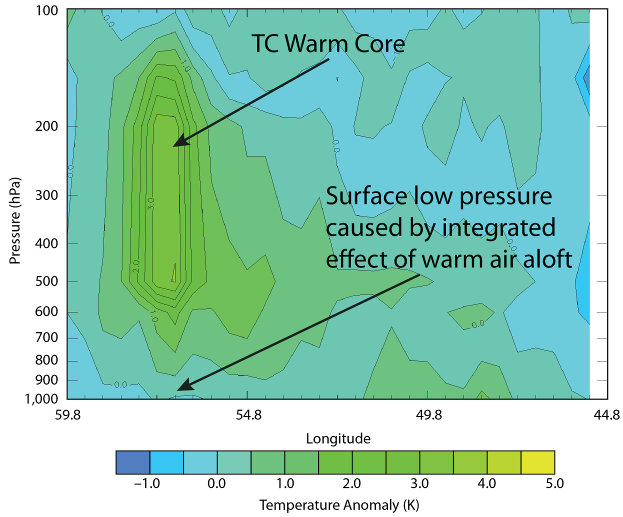

FIGURE 6 Vertical cross-section derived from AMSU during hurricane *Edouard* at 0529 UTC 15 September 2014. Storm intensity estimates are obtained in relation to the strength of the warm core using either measured brightness temperatures or retrieved thermal anomalies

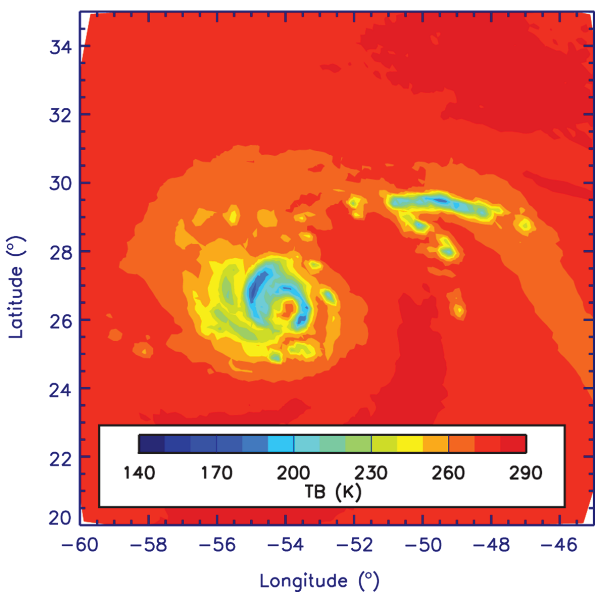

FIGURE 7 ATMS 183 ± 7 GHz brightness temperatures for hurricane *Edouard* at ∼ 0500 UTC September 15, 2014. The horizontal resolution of TROPICS data will be very similar to that of ATMS

aircraft. Since 1998, the Advanced Microwave Sounding Unit (AMSU) flown aboard the Polar-orbiting Operational Environmental Satellite (POES) series of spacecraft has been used to develop intensity estimation techniques which exploit a microwave sounder's ability to map upper-level temperatures in TCs and monitor the evolution of the warm-core anomaly. Since then, similar microwave sounders have become available (e.g. Special Sensor Microwave Imager/ Sounder – SSMIS – on Defense Meteorological Satellite Program – DMSP – satellites; ATMS on the Suomi National Polar-orbiting Partnership satellite – NPP).

The primary limitation of current PMW sounders for monitoring TCs is that they reside on polar-orbiting satellites. Views over weather systems in the Tropics are not continuous, and there can be gaps in coverage over a particular TC of up to 8–12 hr, even with the current constellation. Since rapid intensity changes can take place on the order of a few hours, this coverage is sub-optimal for monitoring the evolution of TC characteristics (i.e. warm-core anomaly, precipitation structure). TROPICS will bridge this temporal gap by providing more rapid refresh of these critical observations.

3.2 | What is the role of rapidly evolving storm structure in TC formation and intensity change?

Many TC observational and modelling studies have examined the role of precipitation in rapid intensification (RI) with an emphasis on the role of convective bursts (CBs), i.e. focused locations of deep, vigorous convection characterized by cold and expanding cloud tops, ice scattering in PMW imagery, lightning, and towers of high reflectivity (Cecil *et al.*, 2002) which are indicative of strong updraughts. Kelley *et al.* (2005) identified CBs from the TRMM Precipitation Radar (PR) and found that storms exhibiting deep (> 14.5 km altitude) convective towers in the eyewall intensified 71% of the time while storms with echo tops < 10 km weakened 87% of the time. The role that CBs play in intensification has been attributed to localized vortex stretching and aggregation in the boundary layer (Hendricks *et al.*, 2004; Montgomery *et al.*, 2006; Braun *et al.*, 2010), warming from upper-level subsidence around the periphery of the bursts (e.g. Heymsfield *et al.*, 2001; Zhang and Chen, 2012) and diabatic heating in a region of elevated inertial stability inside the radius of maximum wind (RMW; e.g. Vigh and Schubert, 2009; Rogers *et al.*, 2013).

In contrast to emphasizing the role of CBs, other studies have used PMW sensors to emphasize the importance of the azimuthal coverage of rainfall on RI. Using 85.5 GHz imagery, Harnos and Nesbitt (2011) showed that a symmetric ring of convection appeared in a climatological composite of RI events. A PMW-aided study by Jiang and Ramirez (2013) showed that RI is accompanied by greater spatial coverage of rain in the inner core. A TRMM PR study by Zagrodnik and Jiang (2014) showed that precipitation frequency and the coverage of rainfall increase in the inner core and become more symmetric over time in rapidly intensifying TCs.

In order to determine whether or not CBs play a critical role in RI, rapid-refresh microwave observations which allow for tracking the evolution of CBs (movement around the eye, azimuthal asymmetries about the centre, intermittency or tendency to form in clusters) will be necessary, as illustrated in Figure 8.

In the figure, Hovmöller diagrams illustrate the evolution of CBs in a simulated storm in a WRF model nature run (Nolan *et al.*, 2013) with data degraded to 30 km resolution. The abscissa represents azimuth (direction relative to the storm centre) while the ordinate is time (in days). Tracking of CBs within TCs rapidly degrades when gaps in sampling are

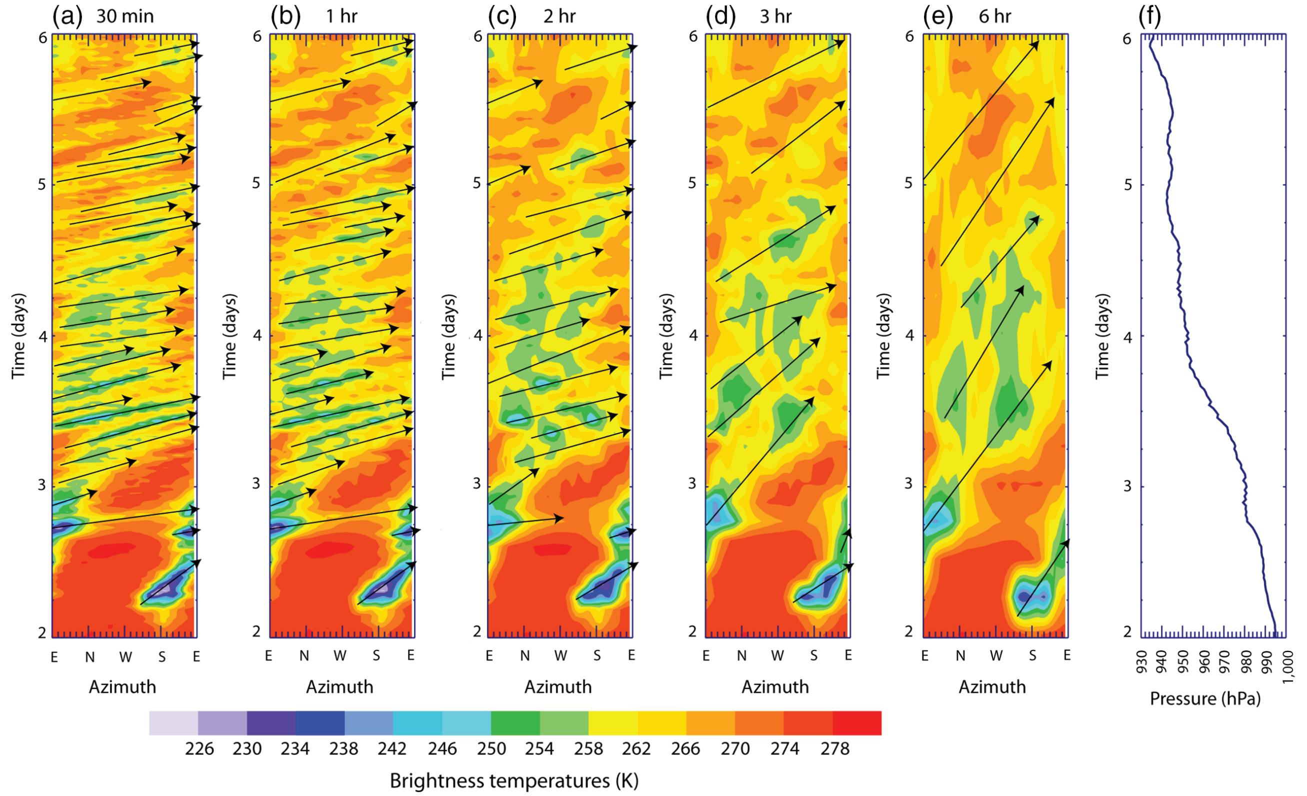

FIGURE 8 Azimuth versus time plots of simulated 114.85 GHz brightness temperatures from a WRF nature run, averaged over a circle extending from the simulated TC centre to 120 km radius, and sampled at the indicated time intervals (a) 30 min, (b) 1, (c) 2, (d) 3, and (e) 6 hr. Lower temperatures correspond to the movement of convective bursts (CBs) around the eyewall (black arrows). There is good tracking of individual CBs for sampling intervals ≤ 1 h; tracking rapidly degrades for sampling intervals > 2 h. The cluster of CBs between days 3 and 4 is associated with a rapid change of storm intensity during that time, as indicated by (f) the simulated minimum sea-level pressure

consistently > 2 h. TROPICS will provide a viable configuration for viewing TCs with median refresh rates (∼ 40 min) commensurate with the time-scales of evolving convection and gaps > 2 h occurring about 55% of the time. The TROPICS frequencies will provide a wealth of information on scattering by precipitation-sized ice particles in CBs, including information in the expanding upper-cloud shield (in the unique 205 GHz channel sensitive to small precipitation-ice particles). The data will be used to track the macrostructure of CBs in TCs across the globe for entire TC life cycles and will provide an unprecedented opportunity to investigate the importance of CBs in RI.

3.3 | How does environmental moisture impact TC structure, size, and intensity?

High relative humidity in the middle troposphere has long been recognized as an important factor in determining where TCs form (Gray, 1975; 1979; 1998; McBride, 1998). DeMaria *et al.* (2001) showed that their formulation of a TC genesis parameter, of which mid-level moisture is a part, can provide useful information on the probability of storm formation. Environmental humidity also exerts a significant impact on storms after development. Hill and Lackmann (2009) and Kimball (2006) examined the impact of dry environmental air in numerical simulations and found that higher environmental humidities led to increased outer rainband production, larger storms, and broader storm-force wind distributions, but not necessarily to stronger storms. Braun *et al.* (2012) showed that asymmetric ingestion of dry air (e.g. caused by dry air being located preferentially on one side of the storm) can lead to significant precipitation asymmetries, but found that, in the absence of significant wind shear, dry air had difficulty penetrating the core of storms, thereby limiting impacts on intensity.

In contrast, other studies have suggested that significant relationships exist between environmental humidity and storm intensity. (Kaplan and DeMaria, 2003) showed that high values of 700–850 hPa relative humidity generally favour RI of TCs. Shu and Wu (2009) suggested that, in weakening storms, dry air penetrates to smaller storm radius than in intensifying storms, usually in the quadrants to the left of the storm motion. Wu *et al.* (2012) found more moist conditions within 200–400 km of the storm centre in intensifying and RI storms compared to weakening storms. A major unknown is whether the dry air acts to potentially weaken TCs through modification of precipitation structure or overall convective activity (Braun *et al.*, 2012). TROPICS will provide coupled measurements of the more slowly varying environmental humidity around a TC and previously unresolvable short-term variations in vortex-scale horizontal precipitation structure over the lifetime of storms which will

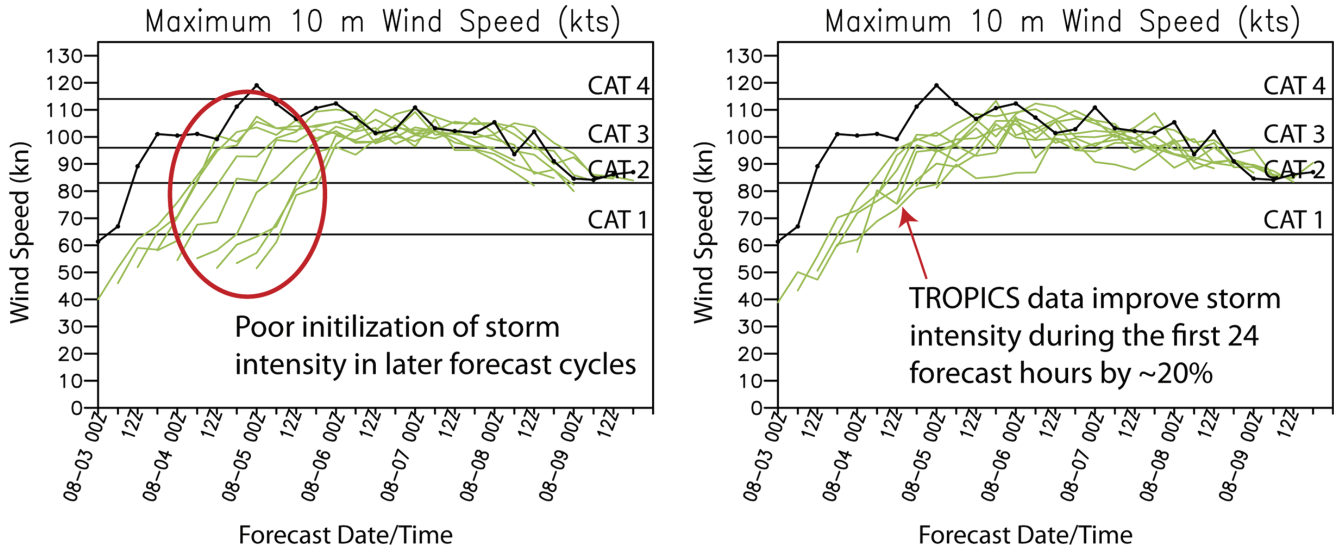

FIGURE 9 Maximum 10 m wind speeds (kts) from the NOAA Hurricane Research Division HWRF OSSE using the WRF nature run. (a) shows that the lack of a "bogus" TC vortex in the model initialization contributed to large initial intensity errors. (b) shows a marked reduction in the short-term intensity forecast errors from assimilating TROPICS data; thus better environmental analyses near TCs can improve subsequent TC forecasts

enhance our ability to determine the extent of environmental humidity control on TC precipitation and intensity.

3.4 | Can TC intensity forecasts be improved through utilization of rapid-update microwave information?

TROPICS data offer great potential for improving forecasts from numerical weather prediction (NWP) models. Data impact studies will utilize two state-of-the-art numerical models, the NOAA Hurricane WRF (HWRF) model and the NASA Goddard Earth Observing System (GEOS-5) model. Figure 9 shows a mesoscale Observing System Simulation Experiment (OSSE) performed with HWRF to quantify the potential improvement in the intensity forecast of a TC from a WRF HNR (Nolan *et al.*, 2013) when TROPICS temperature and moisture observations are added to a control that includes all routine operational observations. The data were spatially blurred to 30 km to approximate TROPICS resolution (23.3 km mean across scan for moisture and 34.9 km mean across scan for temperature), and included measurements at 30 min intervals throughout the HNR life cycle. Because the forecast system does not use a vortex initialization technique to correct for errors in the initial analysis, without TROPICS data the analyzed initial intensity becomes poorly represented (Figure 9a) as the storm intensifies. Simulated TROPICS data lead to significant improvements in the initial mean sea-level pressure (not shown) and maximum wind speed (Figure 9b) which are maintained through the first 27 hr of simulation. HWRF will be used to conduct pre-launch OSSEs and post-launch Observing System Experiments (OSEs) to evaluate the impacts of TROPICS data. Furthermore, simulations will be used to evaluate the relative impact of environmental moisture on TC structure and intensity, particularly in the context of dry air–shear–vortex interactions.

Once real TROPICS data become available, these data will be ingested by the GEOS-5 data assimilation system (DAS). It is expected that the GEOS-5 DAS will already have a 4D variational assimilation system implemented by then to better exploit the temporally frequent observations provided by TROPICS. Data impacts will be examined in the context of a diminished observing system, such as a future atmosphere-observing satellite gap. A variety of metrics will be considered, including general NWP scores and more specialized metrics concerning TC analysis and forecasts.

Statistical and dynamical models provide intensity forecasts of comparable accuracy. However, statistical models are still superior for anticipating rapid intensity changes (Kaplan *et al.*, 2015). Parameters derived from infrared imagery from geostationary satellites, and PMW data from LEO satellites, are important components of statistical RI models (Rozoff *et al.*, 2015). Rozoff *et al.* (2015) found that the relative skill improvements from including PMW-based predictors range from 10 to 45%. However, the low time resolution of current microwave data is a limitation of their use in RI prediction. In addition, the resolution of current microwave sounder data is fairly coarse relative to the size of the TC warm core, which introduces sensitivity to the satellite footprint location relative to the storm centre. The higher time resolution of TROPICS data makes it much more likely to obtain a satellite pass where the sounder footprint is aligned with the cyclone centre. A number of predictors from the TROPICS data will be evaluated as input to the statistical RI models, including eyewall organizational parameters and temperature and moisture parameters in the near-storm environment.

Statistical models for RI rely on classification methods such as linear discriminant analysis and logistic regression to separate RI and non-RI cases using predictors from the storm environment and inner core. Experimental versions of these models can be developed to assess the potential for improvement through new data sources, provided that a developmental data source is available for model training. Ideally, these models would be trained on TROPICS data. This would not be possible until near the end of the experiment, where one season of global TC cases might be marginally sufficient. However, new satellite data types have been successfully evaluated using statistical models trained on proxy data. For example, the Cooperative Institute for Research in the Atmosphere (CIRA) TC intensity and structure algorithm was developed from AMSU temperature retrievals, but implemented directly with ATMS retrievals when those first became available. The algorithm worked well and the bias that was introduced was correctable with only a short overlap period between ATMS and AMSU. This method does not capture all of the information available in new data sources since the statistical relationships with the proxy data usually are weaker than they would be with more accurate input, but this method can provide a lower-bound estimate of what can be expected from the new observations. For the TROPICS experiment, we will utilize ATMS data and possibly AMSU for the training, and then run the algorithm with the TROPICS input. When an overlap period is obtained, a bias correction will be investigated, followed by training with TROPICS data near the end of the experiment.

4 | SUMMARY AND CONCLUSIONS

A constellation of passive cross-track-scanning microwave radiometers in orbits that permit rapid sampling of the tropical cyclone belt at all longitudes is being developed with launch readiness expected in late 2019. Observations will be available in 12 channels from 90 to 205 GHz which will enable a host of new science questions to be addressed. All data will be publicly available through NASA.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the many helpful comments from the anonymous reviewers and Steven Michael (MIT LL) for producing the revisit statistics figure. This work was supported by the National Aeronautics and Space Administration (NASA, USA). Opinions, interpretations, conclusions, and recommendations are those of the authors and not necessarily endorsed by the US Government.

REFERENCES

Bessho, K., Nakazawa, T., Nishimura, S. and Kato, K. (2010) Warm core structures in organized cloud clusters developing or not developing into tropical storms observed by the Advanced Microwave Sounding Unit. *Monthly Weather Review*, 138, 2624–2643.

Biswas, S.K., Farrar, S., Gopalan, K., Santos-Garcia, A., Jones, W.L. and Bilanow, S. (2013) Intercalibration of microwave radiometer brightness temperatures for the global precipitation measurement mission. *IEEE Transactions on Geoscience and Remote Sensing*, 51, 1465–1477.

Blackwell, W.J. (2017) Technology development for small satellite microwave atmospheric remote sensing. In: *Proceedings of IEEE International Microwave Symposium*, Honolulu, HI. http://doi.org/10.1109/MWSYM.2017.8059079

Braun, S.A., Montgomery, M.T., Mallen, K. and Reasor, P. (2010) Simulation and interpretation of the genesis of tropical storm *Gert* (2005) as part of the NASA tropical cloud systems and processes experiment. *Journal of the Atmospheric Sciences*, 67, 999–1025.

Braun, S.A., Sippel, J.A. and Nolan, D.S. (2012) The impact of dry mid-level air on hurricane intensity in idealized simulations with no mean flow. *Journal of Atmospheric Sciences*, 69, 236–257.

Brueske, K.F. and Velden, C.S. (2003) Satellite-based tropical cyclone intensity estimation using the NOAA-KLM series Advanced Microwave Sounding Unit (AMSU). *Monthly Weather Review*, 131, 687–697.

Cecil, D.J., Zipser, E.J. and Nesbitt, S.W. (2002) Reflectivity, ice scattering, and lightning characteristics of hurricane eyewalls and rainbands. Part I: quantitative description. *Monthly Weather Review*, 130, 769–784.

DeMaria, M., Knaff, J.A. and Connell, B.H. (2001) A tropical cyclone genesis parameter for the tropical Atlantic. *Weather and Forecasting*, 16, 219–233.

Demuth, J., DeMaria, M. and Knaff, J.A. (2006) Improvement of advanced microwave sounding unit tropical cyclone intensity and size estimation algorithms. *Journal of Applied Meteorology and Climatology*, 45, 1573–1581.

Desbois, J., Roca, R., Eymard, L., Vitard, N., Viollier, M., Srinivasan, J. and Narayanan, S. (2003) The Megha–Tropiques mission. *Proceedings of SPIE, Atmospheric and Oceanic Processes, Dynamics, and Climate Change*, 4899, 172–183. https://doi.org/10.1117/12.466703.

Gray, W.M. (1975) *Tropical cyclone genesis*. Fort Collins, CO: Colorado State University. Department of Atmospheric Sciences Paper 234

Gray, W.M. (1979) Hurricanes: their formation, structure and likely role in the tropical circulation. In: Shaw, D.B. (Ed.) *Meteorology Over Tropical Oceans*. Reading, UK: Royal Meteorological Society, pp. 155–218.

Gray, W.M. (1998) The formation of tropical cyclones. *Meteorology and Atmospheric Physics*, 67, 37–69.

Halverson, J.B., Simpson, J., Heymsfield, G., Pierce, H., Hock, T. and Ritchie, L. (2006) Warm core structure of hurricane *Erin* diagnosed from high-altitude dropsondes during CAMEX-4. *Journal of Atmospheric Sciences*, 63, 309–324.

Harnos, D.S. and Nesbitt, S.W. (2011) Convective structure in rapidly intensifying tropical cyclones as depicted by passive microwave measurements. *Geophysical Research Letters*, 38, L07805. https://doi.org/10.1029/2011GL047010.

Hendricks, E.A., Montgomery, M.T. and Davis, C.A. (2004) The role of 'vortical' hot towers in the formation of tropical cyclone *Diana* (1984). *Journal of Atmospheric Sciences*, 61, 1209–1232.

Heymsfield, G.M., Halverson, J.B., Simpson, J., Tian, L. and Bui, T.P. (2001) ER-2 Doppler radar investigations of the eyewall of Hurricane *Bonnie* during the convection and moisture experiment-3. *Journal of Applied Meteorology*, 40, 1310–1330.

Hill, K.A. and Lackmann, G.M. (2009) Influence of environmental humidity on tropical cyclone size. *Monthly Weather Review*, 137, 3294–3315.

Hou, A.Y., Kakar, R.K., Neeck, S., Azarbarzin, A.A., Kummerow, C.D., Kojima, M., Oki, R., Nakamura, K. and Iguchi, T. (2014) The global precipitation measurement mission. *Bulletin of the American Meteorological Society*, 95, 701–722.

Jiang, H. and Ramirez, E.M. (2013) Necessary conditions for tropical cyclone rapid intensification as derived from 11 years of TRMM data. *Journal of Climate*, 26, 6459–6470.

Kaplan, J. and DeMaria, M. (2003) Large-scale characteristics of rapidly intensifying tropical cyclones in the North Atlantic basin. *Weather and Forecasting*, 18, 1093–1108.

Kaplan, J., Rozoff, C.M., DeMaria, M., Sampson, C.R., Kossin, J.P., Velden, C.S. and Cione, J.J. (2015) Evaluating environmental impacts on tropical cyclone rapid intensification predictability utilizing statistical models. *Weather and Forecasting*, 30, 1374–1396.

Kelley, O.A., Stout, J. and Halverson, J.B. (2005) Tall precipitation cells in tropical cyclone eyewalls are associated with tropical cyclone intensification. *Geophysical Research Letters*, 31, L24112. https://doi.org/10.1029/2004GL021616.

Kidder, S.Q., Goldberg, M.D., Zehr, R.M., DeMaria, M., Purdom, J.F.W., Velden, C., Grody, N.C. and Kusselson, S.J. (2000) Satellite analysis of tropical cyclones using the advanced microwave sounding unit. *Bulletin of the American Meteorological Society*, 81, 1241–1259.

Kieu, C., Tallapragada, V., Zhang, D. and Moon, Z. (2016) On the development of double warm-core structures in intense tropical cyclones. *Journal of Atmospheric Sciences*, 73, 4487–4506.

Kimball, S.K. (2006) A modeling study of hurricane landfall in a dry environment. *Monthly Weather Review*, 134, 1901–1918.

Marzano, F.S., Cimini, D., Memmo, A., Montopoli, M., Rossi, T., De Sanctis, M., Lucenti, M., Mortari, D. and Di Michele, S. (2009) Flower constellation of millimeter-wave radometers for tropospheric monitoring of pseudo-geostationary scale. *IEEE Transactions on Geoscience and Remote Sensing*, 47, 3107–3122.

Marzano, F.S., Cimini, D., Rossi, T., Mortari, D., Di Michele S and Bauer, P. (2010) High-repetition millimeter-wave passive remote sensing of humidity and hydrometeor profiles from elliptical orbit constellations. *Journal of Applied Meteorology and Climatology*, 49, 1454–1476.

McBride, J.L. (1998) Observational analysis of tropical cyclone formation. Part I: basic description of data sets. *Journal of Atmospheric Sciences*, 38, 1117–1131.

Montgomery, M.T., Nicholls, M., Cram, T. and Saunders, A. (2006) A 'vortical' hot tower route to tropical cyclogenesis. *Journal of Atmospheric Sciences*, 63, 355–386.

National Research Council Fellows, J.D. and Alexander, J.K. (Eds.) (2007) *Decadal Science Strategy Surveys: Report of a Workshop*. Washington, DC: The National Academies Press. https://doi.org/10.17226/11894.

Nolan, D.S., Atlas, R., Bhatia, K.T. and Bucci, L.R. (2013) Development and validation of a hurricane nature run using the joint OSSE nature run and the WRF model. *Journal of Advances in Modeling Earth Systems*, 5, 382–405.

Pielke, R.A., Gratz, J., Leadsea, C.W., Collins, D., Saunders, M.A. and Musulin, R. (2009) Normalized hurricane damages in the United States: 1900–2005. *Natural Hazards Review*, 9, 29–42.

Rogers, R., Aberson, S., Black, M., Black, P., Cione, J., Dodge, P., Dunion, J., Gamache, J., Kaplan, J., Powell, M., Shay, N., Surgi, N. and Uhlhorn, E. (2006) The intensity forecasting experiment: a multi-year field program for improving tropical cyclone intensity forecasts. *Bulletin of the American Meteorological Society*, 87, 1523–1537.

Rogers, R.F., Reasor, P.D. and Lorsolo, S. (2013) Airborne Doppler observations of the inner-core structural differences between intensifying and steady-state tropical cyclones. *Monthly Weather Review*, 141, 2970–2991.

Rozoff, C.M., Velden, C.S., Kaplan, J., Kossin, J.P. and Wimmers, A.J. (2015) Improvements in the probabilistic prediction of tropical cyclone rapid intensification with passive microwave observations. *Weather and Forecasting*, 30, 1016–1038. https://doi.org/10.1175/WAF-D-14-00109.1.

Saunders, R.W., Blackmore, T.A., Candy, B., Francis, P.N. and Hewison, T.J. (2013) Monitoring satellite radiance biases using NWP models. *IEEE Transactions on Geoscience and Remote Sensing*, 51, 1124–1138.

Shu, S. and Wu, L. (2009) Analysis of the influence of the Saharan air layer on tropical cyclone intensity using AIRS/Aqua data. *Geophysical Research Letters*, 36. https://doi.org/10.1029/2009GL037634.

Staelin, D.H. and Surussavadee, C. (2007) Precipitation retrieval accuracies for geo-microwave sounders. *IEEE Transactions on Geoscience and Remote Sensing*, 45, 3150–3159.

Stern, D. and Nolan, D. (2012) On the height of the warm core in tropical cyclones. *Journal of the Atmospheric Sciences*, 69, 1657–1680.

Velden, C. (1989) Observational analyses of North Atlantic tropical cyclones from NOAA polar-orbiting satellite microwave data. *Journal of Applied Meteorology*, 28, 59–70.

Velden, C., Goodman, B.M. and Merrill, R.T. (1991) Western North Pacific tropical cyclone intensity estimation from NOAA polar-orbiting satellite microwave data. *Monthly Weather Review*, 119, 159–168.

Vigh, J.L. and Schubert, W.H. (2009) Rapid development of the tropical cyclone warm core. *Journal of Atmospheric Sciences*, 66, 3335–3350.

Wu, L., Su, H., Fovell, G., Wang, B., Shen, J.T., Kahn, B.H., Hristova-Veleva, S.M., Lambrigtsen, B.H., Fetzer, E.J. and Jiang, J.H. (2012) Relationship of environmental relative humidity with North Atlantic tropical cyclone intensity and intensification rate. *Geophysical Research Letters*, 39, L20809. https://doi.org/10.1029/2012GL053546.

Zagrodnik, J.P. and Jiang, H. (2014) Rainfall, convection, and latent heating distributions in rapidly intensifying tropical cyclones. *Journal of Atmospheric Sciences*, 71, 2789–2809.

Zhang, D.-L. and Chen, H. (2012) Importance of the upper-level warm core in the rapid intensification of a tropical cyclone. *Geophysical Research Letters*, 39, L02806. https://doi.org/10.1029/2011GL050578.

How to cite this article: Blackwell WJ, Braun S, Bennartz R, *et al*. An overview of the TROPICS NASA Earth Venture Mission. *Q J R Meteorol Soc*. 2018;144 (Suppl. 1):16–26. https://doi.org/10.1002/qj.3290