High Revisit-Rate Tropical Cyclone Observations from the NASA TROPICS Satellite Constellation Mission

W. J. Blackwell, *Fellow, IEEE*, S. Braun, G. Alvey, R. Atlas, R. Bennartz, J. Braun, K. Cahoy, R. Chen, G. Chirokova, B. Dahl, J. Darlow, M. DeMaria, M. Diliberto, J. Dunion, P. Duran, T. Greenwald, S. Griffin, Z. Griffith, D. Herndon, J. Hawkins, S. Kalluri, C. Kidd, M. J. Kim, R. V. Leslie, *Senior Member, IEEE*, F. Marks, T. Matsui, W. McCarty, A. Milstein, G. Perras, M. Pieper, R. Rogers, C. Velden, Y. You, and N. Zorn

***Abstract*—New satellite constellations to provide high-resolution atmospheric observations from microwave sounders operating in low-earth orbit are now coming online and are providing operationally useful data. The first of these missions, the NASA TROPICS (Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats) Earth Venture (EVI-3) mission, was successfully launched into orbit on May 7 and May 25, 2023 (Eastern Daylight Time, two CubeSats in each of the two launches). TROPICS is now providing nearly all-weather observations of 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 tropical cyclones. TROPICS is providing rapid-refresh microwave measurements (median refresh rate of better than 60 minutes early in the mission with four functional CubeSats, and now approximately 70-90 minutes with three functional CubeSats) 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 lifecycle. Hundreds of high-resolution images of tropical cyclones have been captured thus far by the TROPICS mission, revealing detailed structure of the eyewall and surrounding rain bands. The new 205-GHz channel in particular (together with a traditional channel near 92 GHz) is providing new information on the inner storm structure, and coupled with the relatively frequent revisit and low downlink latency, is already informing tropical cyclone analysis at operational centers. Here we present an overview of the TROPICS mission after two years of successful science operations with a focus on the suite of geophysical (Level 2) products (atmospheric vertical temperature and moisture profiles, instantaneous surface rain rate, and tropical cyclone intensity) and the science investigations that have been enabled by these new measurements.**

***Index Terms*—TROPICS, tropical cyclones, microwave sounder, smallsat, CubeSat, constellation, calibration.**

I. Introduction

THE tropical cyclone (TC) community has for many years used space-based observations from visible and infrared imagers for situational awareness of TC position, structure, and intensity and from microwave sounders and imagers for better understanding of storm dynamics and precipitation and for assimilation into numerical weather prediction (NWP) models [1], [2]. Some examples of the most commonly used (past and present) sensors are the Geostationary Operational Environmental Satellite (GOES) Advanced Baseline Imager (ABI) [3], the Moderate Resolution Imaging Spectroradiometer (MODIS) [4], the Visible Infrared Imaging Radiometer Suite (VIIRS) [5], the Special Sensor Microwave Imager/Sounder (SSMIS) [6], the Advanced Microwave Sounding Unit (AMSU) [7], the Advanced Technology Microwave Sounder (ATMS) [8], the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) [9], the Advanced Microwave Scanning Radiometer (AMSR-E and AMSR2) [10], and the Global Precipitation Measurement (GPM) Microwave Imager (GMI) [11]. However, most previous passive microwave instruments have flown aboard satellites in high-inclination orbits, reducing the revisit time of the observations for events that occur near tropical and subtropical latitudes. The TRMM satellite and GPM satellite constellation have improved the satellite sampling frequency for severe storm observation, but each satellite has different hardware and measures at different channel frequencies.

There has been considerable recent work to develop miniaturized microwave sounders and fly them on smaller satellites that are relatively less expensive to build, launch, and operate than conventional operational sounders. The MicroMAS-2A nanosatellite (a three-unit or "3U" CubeSat) provided the first demonstration of passive microwave atmospheric sounding from a Cubesat in April 2018 [12]–[15]. Other successful missions followed, including the TEMPEST-D 6U CubeSat [16], [17] and the GEMS1 3U CubeSat [18], which is a pathfinder for a planned future constellation [19]. More recently, Tomorrow.io has launched six 6U microwave sounding CubeSats based on TROPICS technology that has been updated for improved performance and calibration stability as part of a planned 18-unit constellation [20].

The NASA TROPICS mission [21] provided the first demonstration of a passive microwave sounder CubeSat constellation. TROPICS comprises four identical 3U CubeSats (in addition to a precursor "TROPICS Pathfinder" CubeSat, which launched in June 2021 and operated successfully until December 2023 and deorbited in July 2024) and is now providing rapid-refresh measurements of quickly evolving processes within TCs over their entire lifecycles [22]–[28]. The radiometer payload provides observations in 12 channels spanning approximately 90 to 206 GHz (see Table I for basic channel characteristics). Eighty one footprints are measured in a swath subtending ± 60 degrees from nadir across the satellite track as the payload rotates at 30 RPM. From an initial altitude of approximately 550 km, this results in a swath width of almost 2000 km. The calibration of the radiometer is achieved by injecting noise (generated by a weakly coupled noise diode) into the radiometer front end to provide a hot calibration

TABLE I: Description of the TROPICS channels, with on-orbit NEDT's measured at 300 K. TROPICS-5 channel 2 failed prior to launch, and the TROPICS-2 and TROPICS-4 satellites were lost due to a launch failure in 2022.

Channel	Center Frequency (GHz)	Bandwidth (MHz)	Resolution at nadir (km)	TROPICS-1 NEDT (K)	TROPICS-3 NEDT (K)	TROPICS-5 NEDT (K)	TROPICS-6 NEDT (K)	TROPICS-7 NEDT (K)
1	91.7 ± 1.4	1000	30	0.78	0.81	0.62	0.63	0.60
2	114.5	1000	24	0.58	0.59	xx	0.45	0.57
3	116.0	800	24	0.55	0.54	0.53	0.46	0.48
4	116.7	600	24	0.66	0.69	1.41	0.70	0.70
5	117.3	600	24	0.61	0.63	0.95	0.68	0.65
6	117.8	500	24	0.71	0.65	0.95	0.65	0.70
7	118.2	380	24	0.72	0.77	1.27	0.74	0.75
8	118.6	300	24	0.83	0.76	1.12	0.61	0.64
9	184.4	2000	17	0.50	0.54	0.59	0.43	0.48
10	186.5	2000	17	0.51	0.46	0.56	0.47	0.46
11	190.3	2000	17	0.46	0.35	0.39	0.35	0.36
12	204.8	2000	15	0.51	0.40	0.44	0.39	0.47

point and by measuring the cold cosmic background radiation to provide a cold calibration point. These calibrations are performed once per radiometer scan. Initial assessments of TROPICS radiance calibration performance have been published previously [26], [29], where it has been demonstrated that departures from ERA5-simulated radiances have generally been less than 1 K, exhibit Gaussian distributions, and are stable in time. Scan biases are less than 1 K for almost all scan angles. Recent calibration work has focused on reducing channel mixing and latitudinal biases in the 118-GHz temperature sounding channels. Updated calibration processing algorithms are currently under development that are expected to reduce these errors to facilitate the inclusion of these channels in data assimilation systems, and the excellent results that are presented in the subsequent sections for regression-generated products indicate that channel information content is high and there is therefore hope to derive effective corrections for the biases that remain.

The TROPICS median revisit rate is shown in Figure 1. A "latitude weighted" revisit rate is calculated by taking the dot product of the revisit rate versus latitude and the historical tropical cyclone storm frequency (normalized) versus latitude. The Pathfinder satellite is included in the statistics when available, but it contributes negligibly to the revisit rate due to its high-inclination, sun-synchronous orbit (the constellation satellites are all in orbits that are inclined by approximately 33 degrees with respect to the equator – thus providing latitudinal coverage to approximately ±40° – to optimize the likelihood of TC observation). Prior to Aug 2023, with four functional constellation satellites, a median latitude-weighted revisit rate better than one hour was achieved.

TROPICS is a science research mission with no requirements or design drivers associated with operational use. Nevertheless, given the broad interest of future systems like TROPICS to address at least some operational objectives, an early emphasis was placed on designing the mission to demonstrate some operational aspects on a best-effort basis while adding negligible risk to the baseline science mission. One example of this approach is the provision of a "near-real-time" (NRT) downlink mode, whereby the commercial ground network provided by Kongsberg Satellite Services for satellite downlinks was operated with more frequent downlinks and

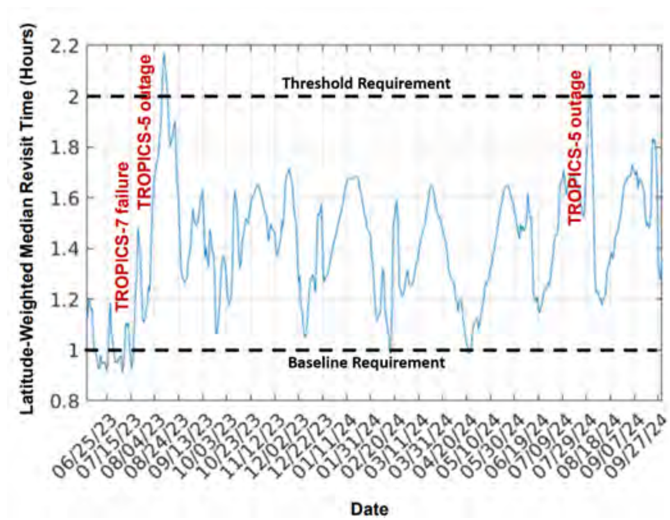


Fig. 1: TROPICS latitude-weighted median revisit rate, with mission threshold and baseline requirements indicated with horizontal dashed lines. Occasional satellite outages cause brief spikes in the plot (some example spikes are labeled above, with the label immediately left of the spike), and the cyclical nature of the plot is caused by the intraplane phasing of the satellites, which drift freely with respect to each other.

supplemented by additional downlinks from the ATLAS Space Operations ground network. These additional downlinks were funded by the Office of Naval Research, NOAA, and NASA, and no funds from the cost-capped NASA TROPICS EVI-3 mission budget were used for this activity. The provision of TROPICS data with NRT latencies was used to maximize the operational impact of TROPICS data and to permit effective evaluation of the operational utility to help inform the specification and design of future systems and facilitate the use of these data in operational centers. The latency for NRT mode and nominal mode is shown in Figure 2, where latency is defined as the time from when a data granule is written to spacecraft memory to the time it is downlinked to the ground. NRT latencies are generally better than one hour, whereas nominal mission latencies are approximately 12 hours. The tri-modal characteristic of the NRT distributions (all below

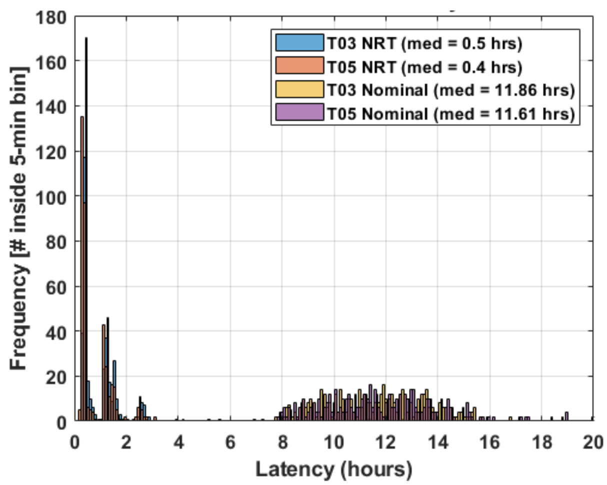


Fig. 2: TROPICS latency for TROPICS-3 and TROPICS-5 for "Near-real-time" (NRT) mode (three distributions centered near 50, 100, and 150 minutes) and for nominal mode (one distribution centered near 12 hours). The y-axis shows the number of downlinks that were collected with a given latency (shown on the x-axis).

three hours) arise due to the geographical spacing of the ground stations around the surface of the earth. The latencies demonstrated by TROPICS could be further improved by using additional ground stations with more uniform geographical coverage.

II. Radiance Calibration and Geolocation Performance

TROPICS has four radiance data products: 1) antenna temperature (L1a), 2) brightness temperature (L1b), 3) unified brightness temperature that spatially averages the water-vapor channels to match the spatial resolution of the temperature-sensitive channels (L2a), and 4) regularized scan pattern and limb-adjusted brightness temperature (L1c) [30]. All of the TROPICS data products and more details can be found at Goddard Earth Sciences Data and Information Services Center (GES DISC) [31], and additional details can be found for the various data products in their respective Algorithm Theoretical Basis Documents at the GES DISC. The GES DISC data product version used in the analysis presented in this paper was 1.0 for TROPICS-1, TROPICS-3, and TROPICS-6, and version 0.2 for TROPICS-5 and TROPICS-7.

Figure 3 and Figure 4 show validation of L1b brightness temperatures against the calibration reference simulation system [32]. Anchoring the calibration through the simulation system is required to remove any calibration drift or intra-satellite differences. The system simulates clear-sky ocean brightness temperatures using a non-scattering line-by-line radiative transfer model [33], the SURFEM ocean surface emissivity model [34], and the GEOS-5 Numerical Weather Prediction model's near-real-time reanalysis [35]. Clear-sky conditions were determined using the NOAA GOES Binary Cloud Mask data product [36]. Figure 3 shows histograms of the difference between the observed and the simulated brightness temperature for all five TROPICS satellites. Data is limited to near-nadir scan angles ($\pm 15°$) and latitudes of the lower-inclination constellation satellites ($\pm 40°$). The μ and σ above the histograms plots indicate the mean and standard deviation of the differences, with the lowest and highest one percent of the distribution removed to account for outliers in either the simulations or radiometer observations. Data from TROPICS-3, -5, and -6 used to produce this figure span June 2023 to December 2024, TROPICS-7 data span June and July 2023, and TROPICS-1 (Pathfinder) data span August 2021 to December 2023. Data used in the calculations consists of five days chosen randomly from each month, and every other orbit is retained. Each plot indicates the channel NEDT for a 300 K scene derived from the two calibration sectors, and the average value across the five satellites is shown. Figure 4 shows scatterplots of simulated versus observed brightness temperatures using the same dataset. The color indicates the density of the data points.

The TROPICS geolocation algorithm combines on-orbit measurements with pre-flight alignment measurements, including: antenna beam offsets, component mounting alignments, payload scan-angle, and satellite attitude and location. Performance is evaluated using the Coastline Inflection Method (CIM) which uses instrument data (Channel 1, 91.7 GHz) to detect coastlines [37]. The analysis presented here uses 371,482 coastline crossings from eight coastline regions that can be seen in Figure 5. The instrument-detected coastlines are compared with known actual coastlines provided by the global, self-consistent, hierarchical, high-resolution shoreline (GSHHS) database [38]. A correspondence between the measurement and the truth that considers the shape of the coastlines is established to determine the errors [39]. The correspondence is established using an iterative closest point (ICP) algorithm with an inlier threshold of 200 km. Geolocation error is reported as the distance between corresponding points. The geolocation errors shown in Figure 5 have been bias adjusted by subtracting the mean error for each satellite.

The data used for geolocation error determination is carefully quality controlled to include cloud-free and near-nadir ($\pm 15°$) measurements strictly when the satellite bus reports high confidence in the measured attitude and GPS location. Cloud-free measurements are identified using the CIM techniques described in [37] and [39], and by thresholding the difference of upper and lower atmosphere G-band measurements as described in [40]. Geolocation biases are approximately $1/30^{\text{th}}$ of a footprint diameter and RMS uncertainty is approximately $1/10^{\text{th}}$ of a footprint diameter in cross-track and along-track dimensions. There are ocassional large outliers due to outages of the GPS receivers. Future versions of the Level-1 geolocation algorithm will use an empirical correction to largely eliminate the mean error and reduce the standard deviation of the error using improved processing of the GPS and propagation data, further improving the geolocation uncertainty.

III. Imagery of Tropical Cyclone Structure

High-fidelity tropical cyclone intensity investigations require rapid-update quantitative observations of three-

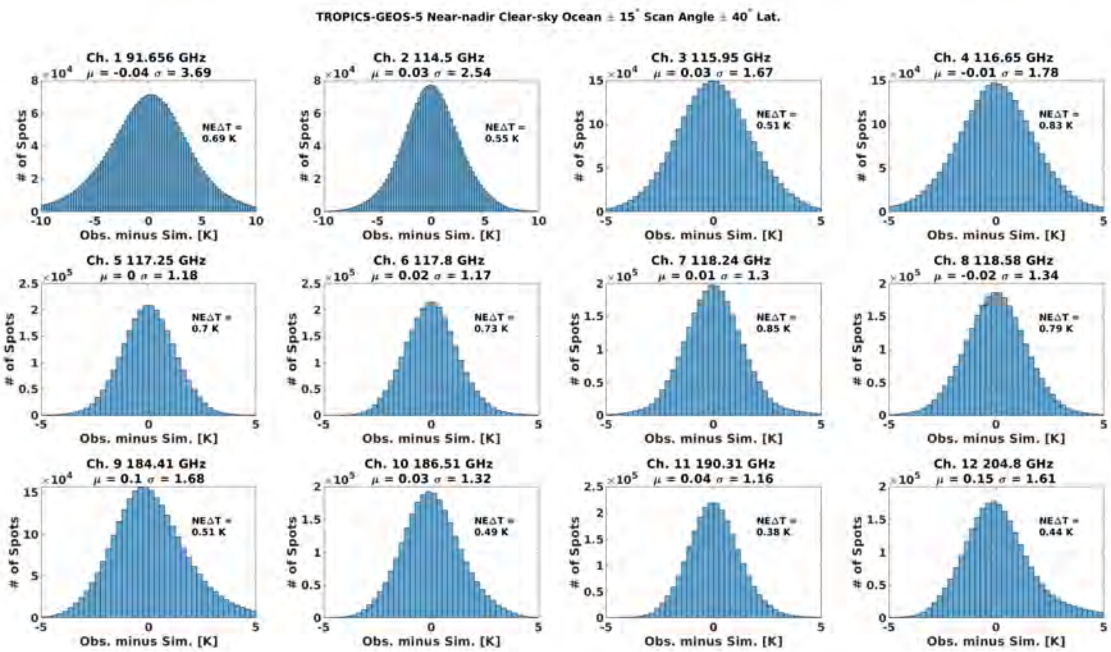


Fig. 3: Histogram of differences between the observed and simulated brightness temperatures for all five TROPICS satellites. Simulations were computed using GEOS5 matchups over clear-sky ocean.

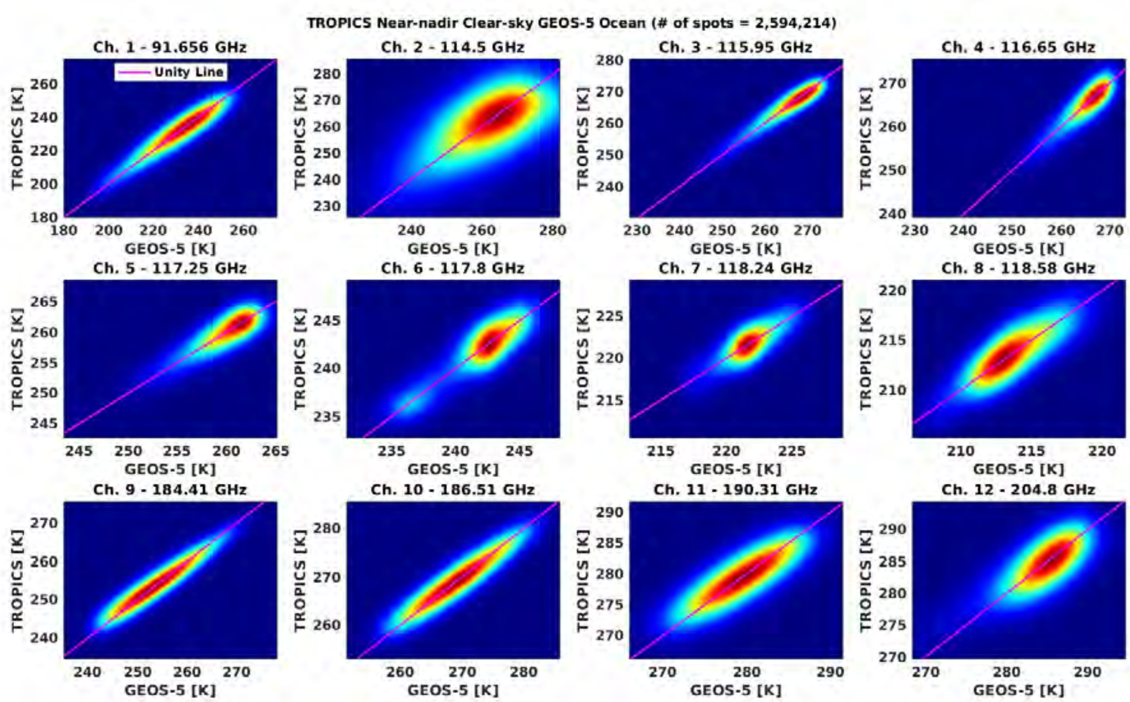


Fig. 4: Scatterplots of the observed versus simulated brightness temperatures for all five TROPICS satellites. Simulations were computed using GEOS5 matchups over clear-sky ocean. Color indicates the density of data points, with red indicating the highest density.

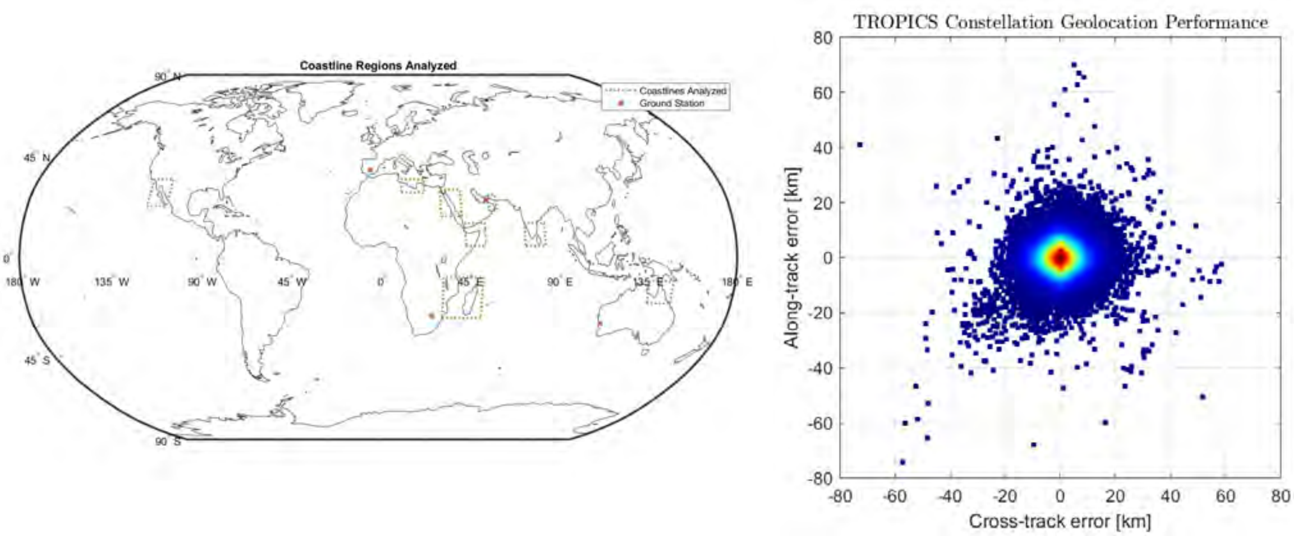


Fig. 5: TROPICS geolocation performance was assessed using 371,482 coastline crossings in eight different regions (left image) to calculate bias-adjusted geolocation errors in the cross-track and along-track dimensions (right image). The four TROPICS ground station locations are also indicated in the left image.

dimensional storm structure, 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 TROPICS, in contrast, reveal TC structure beneath the cloud tops and provide more rapid revisits than currently operational polar-orbiting sounders. One example of this new capability is shown in Fig 6, showing high-resolution imagery collected over Typhoon Kong-rey on Oct. 29, 2024 in one channel near 116 GHz (left image) and in one channel near 205 GHz (right image). Typhoon Kong-rey was a Category 5 storm when these images were taken, and the large, distinct eye is characteristic of its high intensity. The warm core anomaly (13 K) observed by a TROPICS temperature sounding channel for Kong-rey was among the highest ever recorded for a cross-track-scanning microwave sounder.

IV. Atmospheric Vertical Temperature and Moisture Profile Retrievals

The formation of an upper-level warm core is a key indicator of TC development, and the processes that lead to its 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. TROPICS is now providing atmospheric vertical temperature profile (AVTP) estimates to help characterize the upper-level warm core with revisit rates that are necessary to capture storm intensity evolution. TROPICS AVTP estimates are provided by a neural network technique that is trained using ERA5 reanalysis data co-located to TROPICS observations over a training set. The TROPICS AVTP and atmospheric vertical moisture profile (AVMP) products have been globally validated over ocean using high-quality radiosonde observations. The 33-degree inclination orbit of the four constellation satellites allowed for 12346 radiosonde matches released within 1 hour and 50 km of TROPICS collections from June 2023 to August 2024. The TROPICS AVTP bias and root-mean-squared uncertainty performance statistics as a function of altitude are shown in Figure 7, and the baseline mission requirement of 2 K RMS uncertainty is met.

High relative humidity in the middle troposphere has long been recognized as an important factor in determining where TCs form [41]–[44]. It has been shown that the formulation of a TC genesis parameter, of which mid-level moisture is a part, can provide useful information on the probability of storm formation [45]. Environmental humidity also exerts a significant impact on storms after development. A number of researchers have 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 [46], [47]. Other investigations confirmed an influence on storm size, but found that, in the absence of significant wind shear, dry air had difficulty penetrating into the core of storms, thereby limiting impacts on intensity [48]. The use of TROPICS atmospheric vertical moisture profile (AVMP) estimates at high revisit are an essential tool to further refine and evaluate these findings. The TROPICS AVMP bias and root-mean-squared uncertainty performance statistics as a function of altitude are shown in Figure 8, and the baseline mission requirement of 25% RMS uncertainty is met. To express water vapor bias and root-mean-squared (RMS) uncertainty as percentages, the normalizing conventions given in [49] are followed here to conform to AIRS/JPSS sounder science team practices, where W^1 weighting is used for bias calculations and W^2 weighting is used for RMS uncertainty calculations.

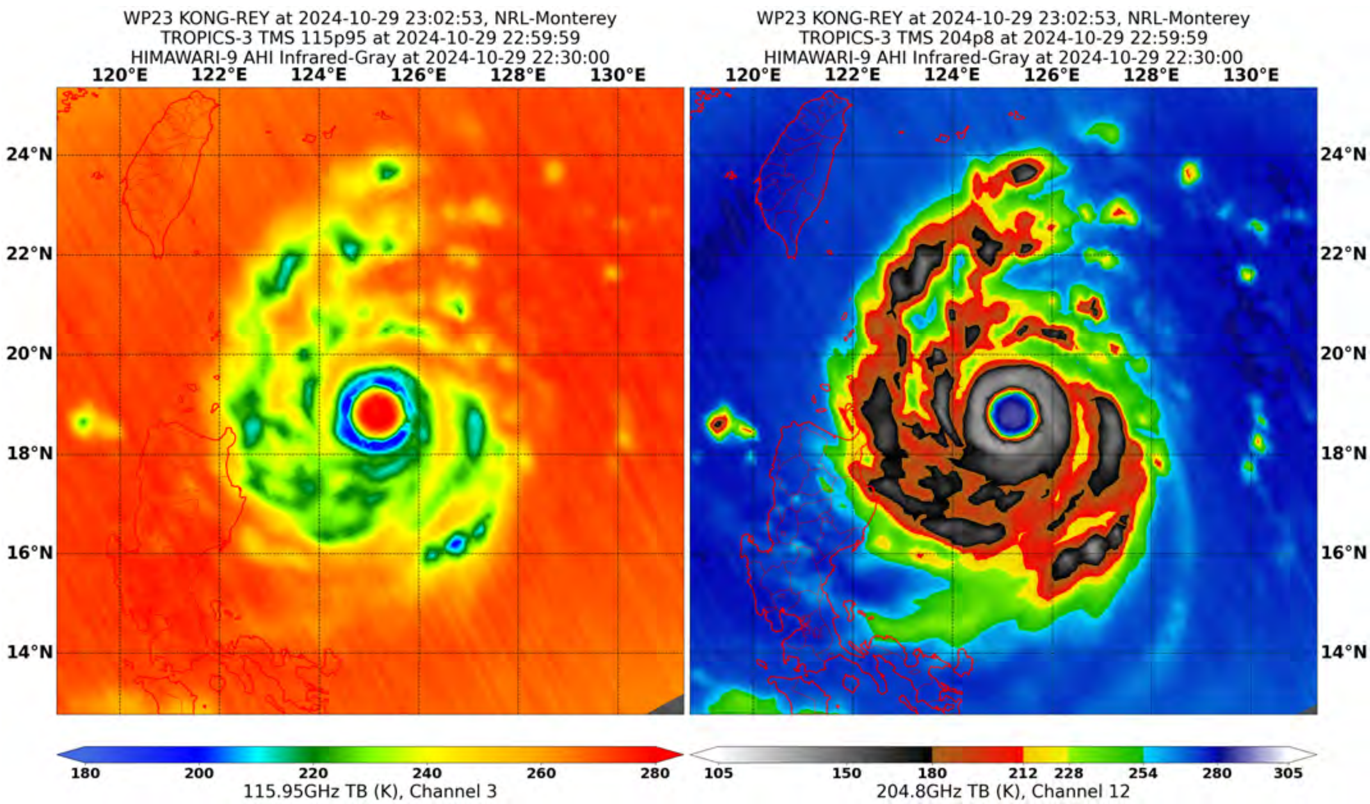


Fig. 6: TROPICS-3 imagery of Typhoon Kong-rey observed on Oct. 29, 2024 near 116 GHz (left image) and near 205 GHz (right image). Note the large and well-defined eye. Image credit: US Naval Research Laboratory.

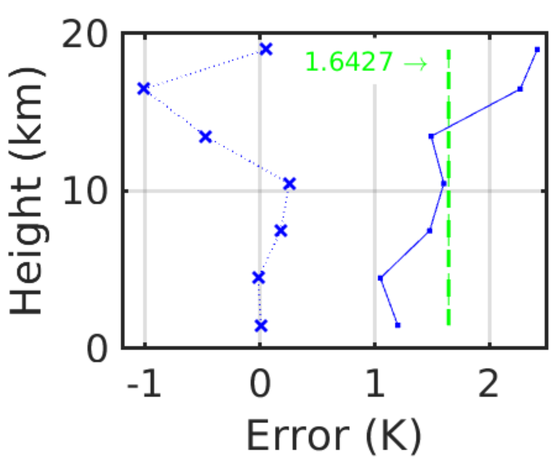


Fig. 7: TROPICS neural network temperature profile retrieval bias (blue dotted line) and RMS uncertainty (blue solid line) as computed from 12346 radiosondes launched over ocean. The RMS uncertainty averaged over all altitudes is 1.64 K (meeting the 2.0 K baseline mission requirement).

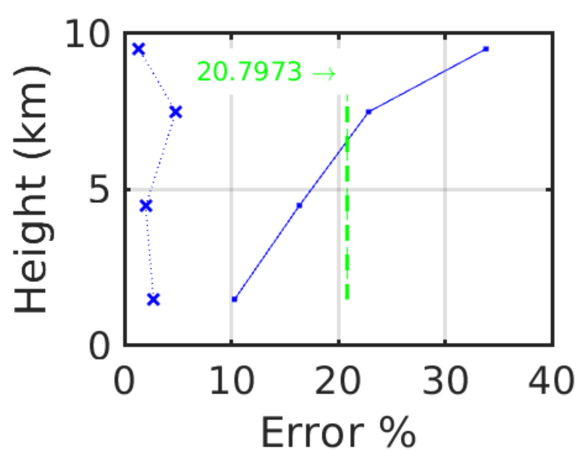


Fig. 8: TROPICS neural network moisture profile retrieval bias (blue dotted line) and RMS uncertainty (blue solid line) as computed from 12346 radiosondes launched over ocean. The RMS uncertainty averaged over all altitudes is 20.8 % (meeting the 25 % baseline mission requirement).

V. Ice Water Path Retrievals

The ice water path (IWP) quantifies the total mass of ice present in a vertical column of the atmosphere. Many research studies have indicated that accurate estimation of IWP is essential for characterizing the structure and intensity of tropical cyclones, as it is directly related to latent heating, which significantly influences tropical cyclone intensity [50]–[52]. Additionally, numerical hurricane model simulations have shown that incorporating ice-phase microphysics plays a crucial role in the evolution of simulated hurricanes [53]. Tropical cyclones with greater amounts of ice water content are likely to intensify faster, which suggests that observations

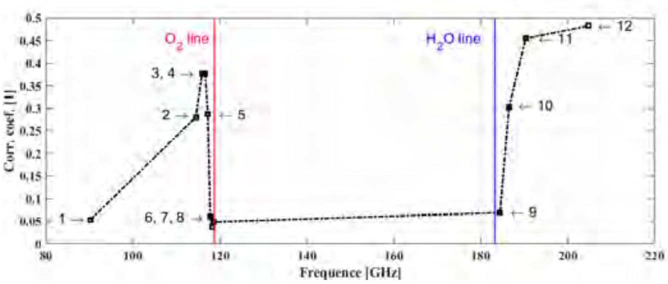


Fig. 9: Correlation coefficients between TB depressions (ΔTB) and precipitation ice water path (PIWP) for TROPICS-1.

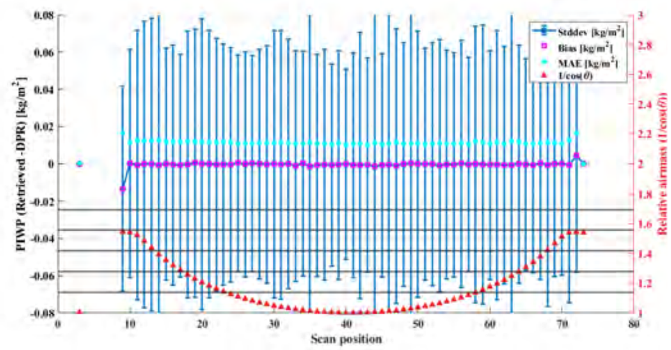


Fig. 10: Statistics of retrieved PIWP compared to DPR PIWP, for testing data from TROPICS-1 observations, based on kd-tree models developed from training data. The statistics include bias (magenta dots), mean absolute error (MAE, mint green dots) and standard deviation of the bias (blue line). The brick-red dots are for relative air mass, which is used to stratify the training data when creating the four k-d trees and to determine which k-d tree is used in neighbor-searching for testing data.

of ice water content may be used to improve the performance of hurricane forecast models [54].

In addition to the more traditional channels around 89, 118, and 183 GHz, TROPICS is the first spaceborne sensor equipped with a 205-GHz channel that is more sensitive to precipitation-sized ice particles, which makes it particularly advantageous for retrieving IWP. It is important to note that neither TROPICS nor the GPM Dual-frequency Precipitation Radar (DPR) are sensitive to small ice particles like those found in cirrus clouds. Therefore, the focus herein is on the precipitation ice water path (PIWP).

The algorithm employed to retrieve PIWP utilizes the K-Dimensional tree (k-d tree), an efficient data structure for organizing and searching high-dimensional datasets. It is particularly well-suited for analyzing TROPICS observations that consist of 12 channels. Previous studies have successfully applied k-d trees to retrieve atmospheric variables from microwave observations, for instance the work by Chen and Bennartz, who used the k-d tree to retrieve surface rain rates from the MicroWave Humidity Sounder 2 (MWHS-2) instrument aboard the FY-3C satellite [55]. In this context, the k-d tree structure is applied to a TROPICS dataset containing approximately 10 million collocated data points over a period of two years (2022 & 2023). Each data point includes TROPICS observations (TB) and scattering-induced brightness temperature depressions (ΔTB) across 12 channels, as well as matched PIWP derived from GPM DPR (2BCMB product).

Using clear-sky radiative transfer simulations as the background, the ΔTB is calculated by the equation:

$$\Delta \mathrm{TB} = \mathrm{TB}_{\mathrm{obs}} - \mathrm{TB}_{\mathrm{sim}}. \tag{1}$$

The radiative transfer simulations were implemented by running the Community Radiative Transfer Model (CRTM) with environmental data from the GEOS-5 Numerical Weather Prediction model's near-real-time reanalysis [35]. These ΔTBs reflect how strongly each channel responds to ice particle scattering. The correlation coefficients between ΔTB and PIWP for TROPICS are then calculated, and the results are shown in Figure 9. The lower peaking channels around 118 GHz oxygen absorption line (Channels 3 & 4) and 183 GHz water vapor absorption line (Channel 11) exhibit strong sensitivity to ice particle scattering. Notably, the highest correlation coefficient for TROPICS-1 is observed at Channel 12 around 205 GHz, which is most sensitive to smaller ice particles. On the other hand, the lowest correlation coefficients are found at Channels 6, 7, and 8, which are peaking at higher altitudes in the atmosphere and are thus less sensitive to ice particles.

To efficiently manage this complex dataset, the data were split into two subsets: 70% for training and 30% for testing. Moreover, the training dataset is stratified as a function of the TROPICS viewing angle, θ, expressed as a relative air mass factor, calculated as $1/\cos(\theta)$. This stratification ensures that the model accounts for the impact of the slant path on the observations. The 24-dimensional space for each subset is recursively partitioned to form four distinct k-d trees, which are then used for PIWP estimation during the search phase.

The k-d tree structure allows for efficient partitioning to find nearby data points. With a predefined radius (or hypersphere) around a query point, all points within this radius are considered neighbors. The PIWP corresponding to these neighboring points are then used to estimate the PIWP for the query point, with the final prediction being the average of the neighboring PIWPs. Using the same set of indexes, surface rain rate and hydrometeor water path (HWP, the accumulation of both ice and liquid water in the atmospheric column) can also be retrieved. A notable advantage of using the k-d tree is its ability to estimate the probability of precipitation based on the density of non-zero rain rates among the neighbors.

The evaluation of PIWP retrievals from the TROPICS observations demonstrates a high degree of accuracy and consistency, as shown in Figure 10. Over the testing dataset, the average bias is 0.01 g/m^2, with an error of 58 g/m^2. These metrics remain stable across the scanlines. It is worth noting that data from approximately 8 to 9 scan positions on each side are largely excluded through a rigorous screening process adapted from a previous study [55]. While retrievals near the scan edges are still technically feasible using this algorithm, their quality is compromised. When compared to the GPM DPR product globally, the PIWP retrievals from

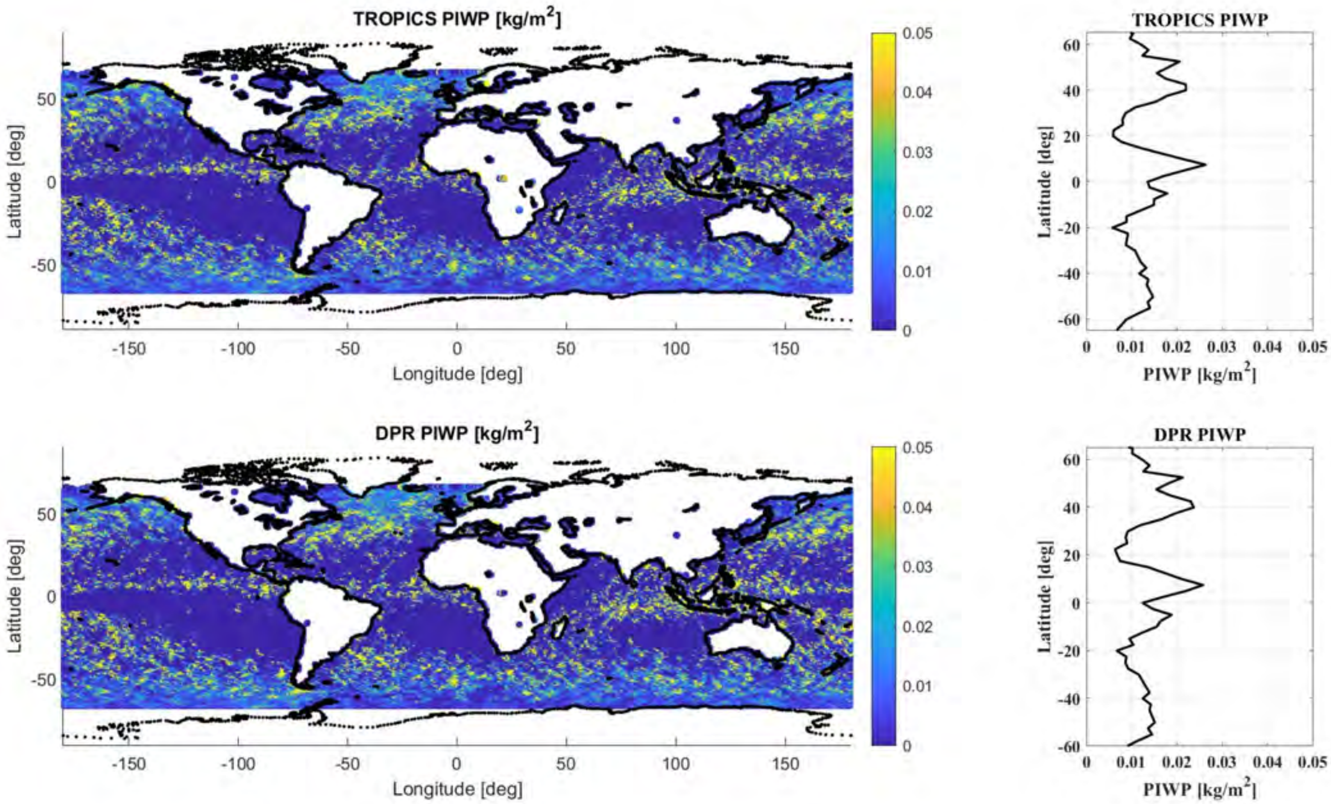


Fig. 11: Global PIWP retrievals derived from TROPICS (upper panel) are compared to those from GPM DPR (lower panel) on the left. The corresponding comparison of the averaged PIWP along latitude is shown on the right.

TROPICS align closely, as shown in Figure 11, indicating strong agreement between the two datasets. This alignment is further validated through case studies over hurricanes, where TROPICS observations correspond well with known storm characteristics. As an example, Figure 12(b) illustrates PIWP retrievals over Super Typhoon Mindulle on September 26, 2021, at 05:37 UTC. Notably, these data were not included in the development or testing phases of the k-d trees, highlighting the model's predictive capability. The retrieved PIWP patterns closely match TROPICS observations shown in Figure 12(a), demonstrating the model's robustness in new scenarios. A similar pattern is observed in the HWP and surface rain rate data presented in Figures 12(c) and 12(d). Additionally, the estimated probability of precipitation reflects realistic patterns, with higher chances of rainfall corresponding to areas of increased rain intensity. Figure 12 also demonstrates that while retrievals are available near the scan edges, they are less reliable than those in the central scan regions.

These findings underscore the effectiveness of this kd-tree algorithm in accurately retrieving PIWP from TROPICS observations, offering valuable insights into tropical cyclone dynamics and enhancing our understanding of storm development and intensity.

VI. Instantaneous Surface Rain Rate and Tropical Cyclone Intensity Retrievals

The TROPICS Precipitation Retrieval and Profiling Scheme (PRPS) [56] is designed to provide a best estimate of precipitation based upon a priori Tb-to-precipitation relationships. A fundamental design of the PRPS is the independence from any dynamic ancillary datasets (e.g., atmospheric or surface temperature from model reanalysis and other satellite products); that is, the retrieval is based solely upon the satellite radiances linked to precipitation rates through a static a priori database and associated index file. This independence is advantageous when generating products across time scales from near real-time (inaccessibility to dynamic ancillary data, such as model data) to climatological scales (circumventing possible changes or trends in the ancillary data). TROPICS rain rate retrieval compared against 2BCMB, a precipitation product that combines data from the Global Precipitation Measurement (GPM) Microwave Imager (GMI) and Dual-frequency Precipitation Radar (DPR), is shown in Figure 13. The statistical metrics (correlation, root-mean-square-error, and bias) for all four TROPICS satellites are listed in Table II. Specifically, the correlation coefficients vary from 0.51 to 0.60 for the four TROPICS sensors, which are generally as good as or better than ATMS onboard NOAA-20 and NOAA-21 [57]. The root-mean-square-error (RMSE) values are about 3.0 mm/hr for all four sensors. For the relative bias, all four sensors show a clear tendency of underestimation, which is primarily caused

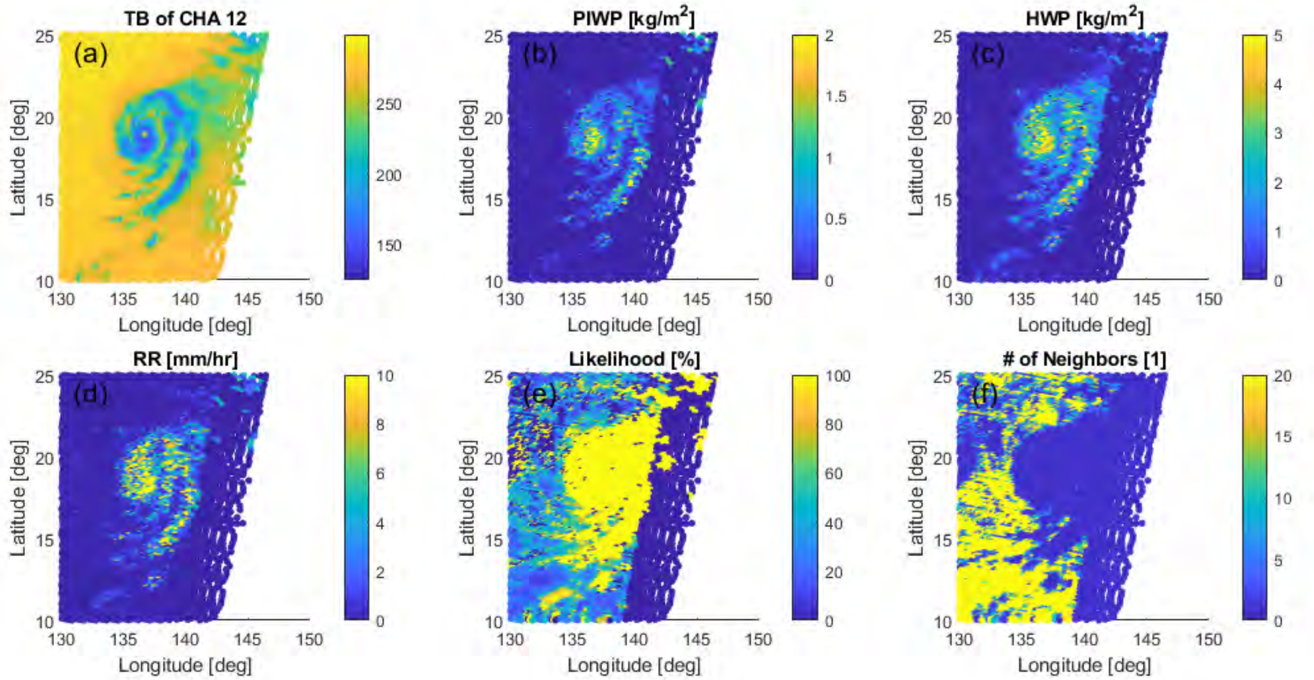


Fig. 12: A hurricane case study: Super Typhoon Mindulle on September 26, 2021, at 05:37 UTC. (a) Brightness temperature from TROPICS-1 at 205 GHz. (b-d) Retrievals of PIWP, HWP, and surface rain rate, respectively. (e) Likelihood of precipitation. (f) Number of neighbors found in k-d trees for each query point.

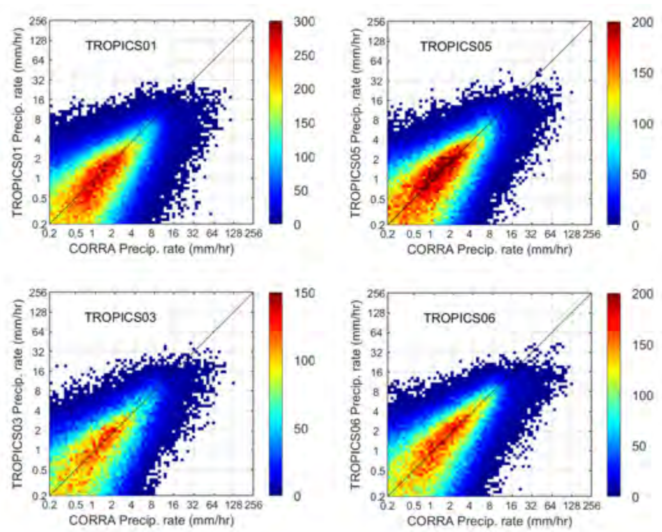


Fig. 13: TROPICS rain rate retrieval (V04-02) compared against 2BCMB (V07), a precipitation product that combines data from the Global Precipitation Measurement (GPM) Microwave Imager (GMI) and Dual-frequency Precipitation Radar (DPR).

by the underestimation of heavy precipitation events ($>$ 16 mm/hr). TROPICS-1 performs slightly worse than the other three satellites in terms of correlation and bias, which is most likely caused by the prior database used by TROPICS-1.

The accurate estimation of TC intensity (TCI) is crucial for real time warnings, initializing numerical models and predicting future impacts. This attribute is primarily derived from satellite-based remote sensing methods [58]. TROPICS offers both heritage and novel microwave spectral information along with high revisit rates that can significantly contribute to TC intensity monitoring. To examine this, a novel deep learning approach [59] is employed to estimate TCI that features TROPICS microwave imagery near 183 GHz. This algorithm, the Deep Multispectral Intensity of TCs (DMINT) estimator (henceforth "D-MINT183" to highlight the use of 183-GHz observations), was originally trained on 183 $\pm$ 1 GHz and 183 $\pm$ 3 GHz channel images from instruments onboard past and current operational low-earth-orbiting (LEO) satellites (AMSU-B, SSMIS, ATMS and MHS) [60]. Since the TROPICS microwave sounder does not explicitly have the 183 ± 1 GHz and 183 ± 3 GHz channels, the mixed-polarized 184.41-GHz and 186.51-GHz are used as respective proxies for input into D-MINT183. A schematic of the D-MINT183

TABLE II: Correlation, root-mean-square-error (RMSE), and bias between 2BCMB and four TROPICS sensors. The observation period for TROPICS-1 is from August 2021 to December 2023. For the other three satellites, the observation period is from June 2023 to May 2024.

	Correlation	RMSE (mm/hr)	Bias (%)
TROPICS-1	0.51	2.98	-25.89
TROPICS-3	0.55	2.95	-18.04
TROPICS-5	0.55	3.08	-20.09
TROPICS-6	0.60	3.26	-16.61

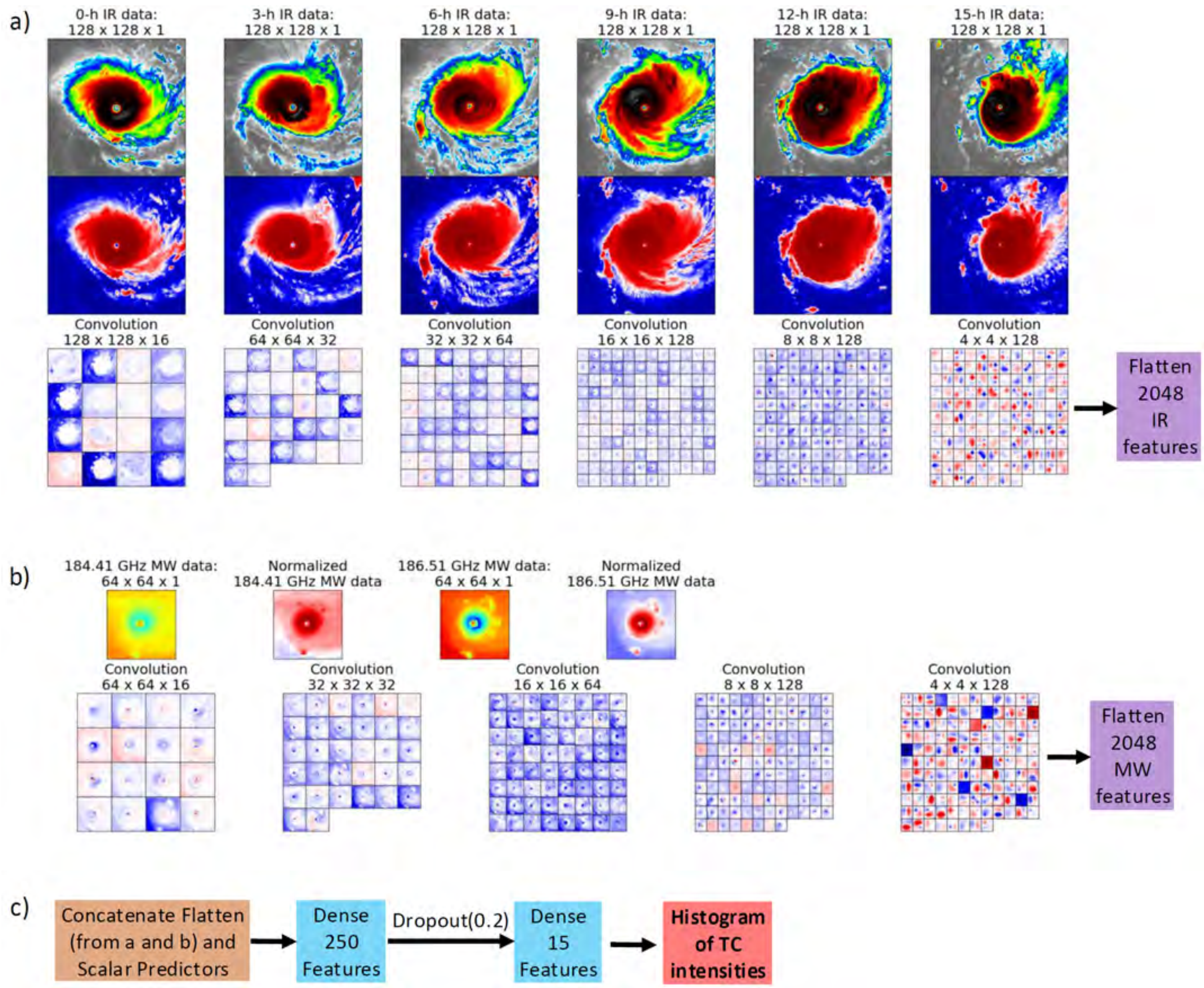
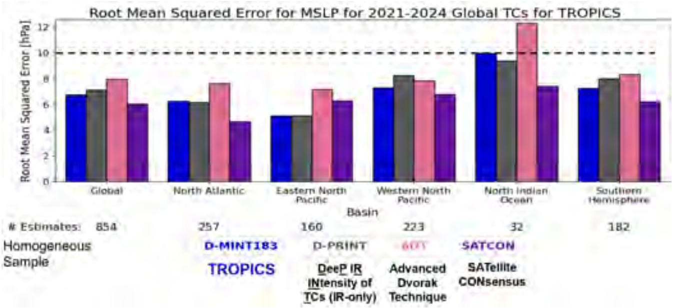


Fig. 14: Architecture of the D-MINT183 convolutional neural network model to estimate TC intensity. The inputs are normalized infrared (IR) brightness temperature (BT) data (a) and satellite microwave (MW) BT data (b), where red (blue) indicates normalized imagery with BTs that are higher (lower) than the respective image average BT, and (c) selected scalar predictors, leading to a probability distribution of TC intensity. For the feature maps produced in a) and b) by convolution and pooling layers, red indicates the presence of a dominant feature, while blue values indicate the absence of a dominant feature.

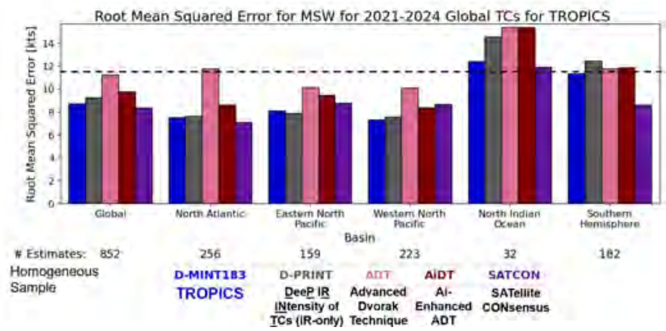
model is shown in Figure 14. The model configuration starts with six normalized infrared (IR) satellite images centered on agency-identified TC locations over the previous 15 hours as inputs, which are passed through convolution and activation layers to produce output "feature" maps (Figure 14a). The final map is flattened into a 1-D vector with 2048 elements. This procedure is then repeated for the MW satellite features (Figure 14b). Finally, the flattened IR feature map, flattened MW feature map, and selected input scalar features are concatenated together (Figure 14c). This encoded data is then transformed into estimations of current TC intensity at analysis time, producing a probability distribution of intensities for a given TC. The D-MINT183 single-value intensity is the average of the 30th to 70th probability quantiles. Further details are given in [59].

D-MINT183 was run on a large sample of global TC cases during 2021-2024 when TROPICS data were available. The TROPICS TCI RMS errors for Minimum Sea Level Pressure (Figure 15a) and Maximum Sustained Wind Speed (Figure 15b) show excellent performance and easily meet the mission baseline requirements (indicated by dashed horizontal lines on both figures) on a global basis. Most notable, the TROPICS TCI estimates are comparable to current state-of-the-art satellite-based approaches [58].

It is also informative to assess the skill of TCI estimates from TROPICS with that of heritage instruments with 183 GHz band sensing capability. TCI estimates from both TROPICS and near-coincident ATMS/MHS images (within 2 hours of each other) are compared in Table III. For both MSWS and MSLP estimates, the RMSE is similar, if not slightly lower, for



(a) TROPICS TCI performance for MSLP.



(b) TROPICS TCI performance for MSWS.

Fig. 15: Results for estimating TC intensity (TCI) with the D-MINT183 model using TROPICS data for a) TC Minimum Sea Level Pressure (MSLP) and b) TC Maximum Sustained Wind Speed (MSWS). Also shown are comparisons with the performance from existing state-of-the-art satellite-based TCI estimation methods on a homogeneous sample of global TCs from 2021-2024, verified with TC agency best track data. TROPICS baseline mission requirements are indicated by horizontal dashed lines.

TABLE III: Comparison of near-coincident (image times within 2 hours of each other) D-MINT183 TCI estimate uncertainties (RMSE) from TROPICS and ATMS/MHS on a homogeneous sample of global TCs from 2021-2025, verified with TC agency best track data. MSLP is the estimated TC minimum sea-level pressure.

	TROPICS	ATMS and MHS
Max Sustained Winds RMSE (kt)	8.81	8.84
MSLP RMSE (kt)	6.61	6.95

TROPICS than ATMS/MHS. Thus, D-MINT183 can be used to provide skillful TCI estimates with the 184.41-GHz and 186.51-GHz imagery provided by TROPICS, and at a much-improved refresh rate over that of current operational polar orbiters.

VII. An Overview of the TROPICS Mission Science Objectives and Accomplishments

A. Hurricane Field Program Observations to Support TROPICS Research and Validation

Each year, NOAA conducts its Advancing the Prediction of Hurricanes Experiment (APHEX) to improve the understanding and prediction of hurricane track, intensity, structure, and associated hazards [61]. Observations collected from a NOAA Gulfstream IV (G-IV) aircraft are used to aid in the improvement of current operational hurricane models and the development of the next-generation operational hurricane models, test new measurement strategies and technologies, and improve understanding of physical processes in tropical cyclones. As part of the 2024 APHEX Hurricane Field Program, the TROPICS science team designed a new TROPICS Satellite Validation Module to calibrate and validate temperature, moisture, and precipitation measurements obtained from the TROPICS satellites using coincident observations from NOAA Hurricane Hunter aircraft. As an example, as Hurricane Ernesto (2024) tracked over the central North Atlantic, it provided an ideal target for this new APHEX flight module.

Two NOAA G-IV missions were flown to sample the environment and near the inner core of Ernesto on 15 and 16 August when it was located 500 and 200 n mi (926 and 370 km) southwest of Bermuda, respectively. The Atlantic Oceanographic and Meteorological Laboratory (AOML)/Hurricane Research Division (HRD)/University of Miami Cooperative Institute for Marine and Atmospheric Studies (UM/CIMAS) team used satellite predictor tools to temporally and spatially align the G-IV take-off times and flight tracks with overpasses from the TROPICS-5 and -6 satellites, and GPS dropsonde and tail Doppler radar data were collected during each mission (see Table IV). Several National Hurricane Center (NHC) forecast discussions mentioned potential dry air interactions/intrusions that made for a difficult intensity forecast: “While the shear near Ernesto remains low, a large dry slot continues to wrap near the core, preventing anything other than slow intensification so far” [62]. The TROPICS overpasses and dropsondes shown in Figure 16 helped demonstrate these large moisture gradients near Ernesto’s inner core. These combined observations will be used in future research to assess the interactions between the environmental and inner-core thermodynamics of the storm.

B. Characterization of storm lifecycle using TROPICS observations

Hurricane Franklin formed on 19 August 2023, to the west of the Lesser Antilles. It remained a weak system as it slowly moved westward from 20-21 August and then northward from 22-24 August, crossing over the Dominican Republic late on 22 August and early on the 23 August. Franklin began steady intensification on 26 August and underwent a period of rapid intensification from 12 UTC 27 August to 00 UTC 29 August, during which time the intensity increased 50 kt (25.7 m s^{-1}). During this event, three of the TROPICS constellation satellites were collecting data, and their sampling of the storm over its lifecycle is shown in Figure 17, left image (“panel a”).

Because of the nature of the TROPICS inclined orbits, sampling was more sporadic when Franklin was equatorward of 20°N but became more frequent as it moved into latitudes where the revisit rate of the constellation satellites is maximum (near 30°N). At these later stages, the sampling of the rainfall evolution better captured the intensification of rainfall in the

TABLE IV: TROPICS satellite overpass details for the NOAA G-IV validation module on 15 and 16 August, 2024.

Mission ID YYYYMMDDN1	Mission Duration (h)	Time in Pattern	Flight Level (k ft)	NASA Dropsondes	NOAA Dropsondes	TROPICS Satellite (# of Overpasses)
20240815N1	7.4	1315-1803 UTC	41-45	37	0	TROPICS 5 & 6 (6)
220240816N1	7.7	1406-1848 UTC	41-45	13	22	TROPICS 5 & 6 (7)

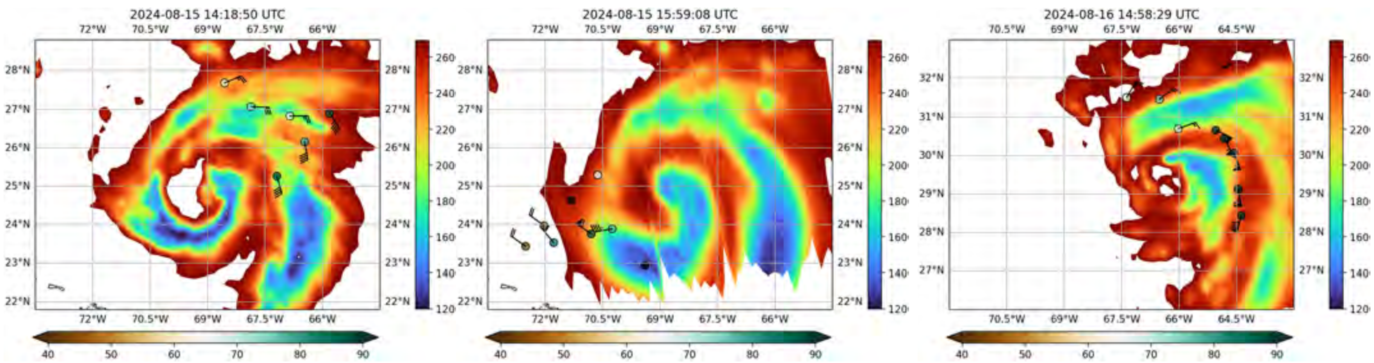


Fig. 16: TROPICS-5 and TROPICS-6 205-GHz brightness temperatures (K) for Hurricane Ernesto (2024) on 15 and 16 August coincident with the TROPICS Satellite Validation Module flown by the G-IV. Missions included under flights of TROPICS-5 (right image) and TROPICS-6 (left and center image). Shaded circles denote 850–700 hPa relative humidity (%) and wind barbs are 850-700 hPa layer averaged winds (kt). Only dropsonde data within 30 minutes of the TROPICS overpass times are plotted.

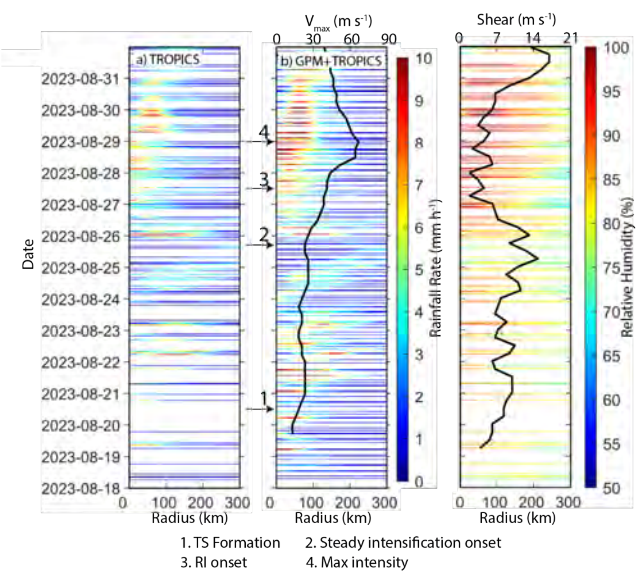


Fig. 17: Hovmoller diagrams showing the radial distribution of estimated surface precipitation rate (left image, "panel a" and center image, "panel b") and 800-700 hPa layer averaged relative humidity (right image, "panel c"). Panels (a) and (c) show TROPICS data only while panel (b) shows TROPICS data combined with GPM constellation precipitation estimates. In (b), the black line indicates Franklin's maximum wind speed from the NHC Tropical Cyclone Report [63], with the velocity scale at the top of the figure. In (c), the black line shows the Statistical Hurricane Intensity Prediction System (SHIPS) estimates of 850-200 hPa vertical wind shear (with vortex removed prior to shear calculation; product available at [64]), with the scale shown at the top of the panel.

inner core and the eventual outward shift of the rainfall when secondary bands or partial outer eyewalls formed [63]. To enhance the sampling of rainfall during Franklin's life cycle, TROPICS data are combined with a constellation of 11 passive microwave satellites that make up the Global Precipitation Measurement (GPM) mission constellation (Figure 17, panel b). Superimposed on the rainfall Hovmoller diagram is the time series of storm intensity from the NHC Tropical Cyclone Report for Franklin [63]. Although less frequent sampling prior to 24 August complicates interpretation, heavier precipitation was more variable in terms of storm radius. The period prior to 21 August tended to have precipitation within 100-km radius while the following period prior to 24 August had convection occasionally extending to 200-km radius. This was a period of moderate wind shear (black line in Figure 17, panel c) that, combined with drier environmental air (colors in Figure 17, panel c), likely prevented intensification.

From 00 UTC 24 August to 06 UTC 25 August, wind shear magnitude approximately doubled. Rainfall weakened as convection near the center moved southeastward (downshear to downshear right of the storm center), resulting in outward propagation in the Hovmoller diagram. A break in precipitation occurred during the latter part of 25 August as the shear caused the low-level center to become exposed in satellite imagery and dryer air to move in above the low-level center (Figure 17, panel c). Just prior to weakening of the wind shear, a burst of convection occurred near 00 UTC 26 August in the downshear to downshear-left region that quickly dissipated. However, wind shear dropped to just a few meters per second and sustained convection began near the center to mark the onset of intensification and later rapid intensification. The formation of secondary rainbands produces the outward shift of precipitation and a gradual weakening of the storm.

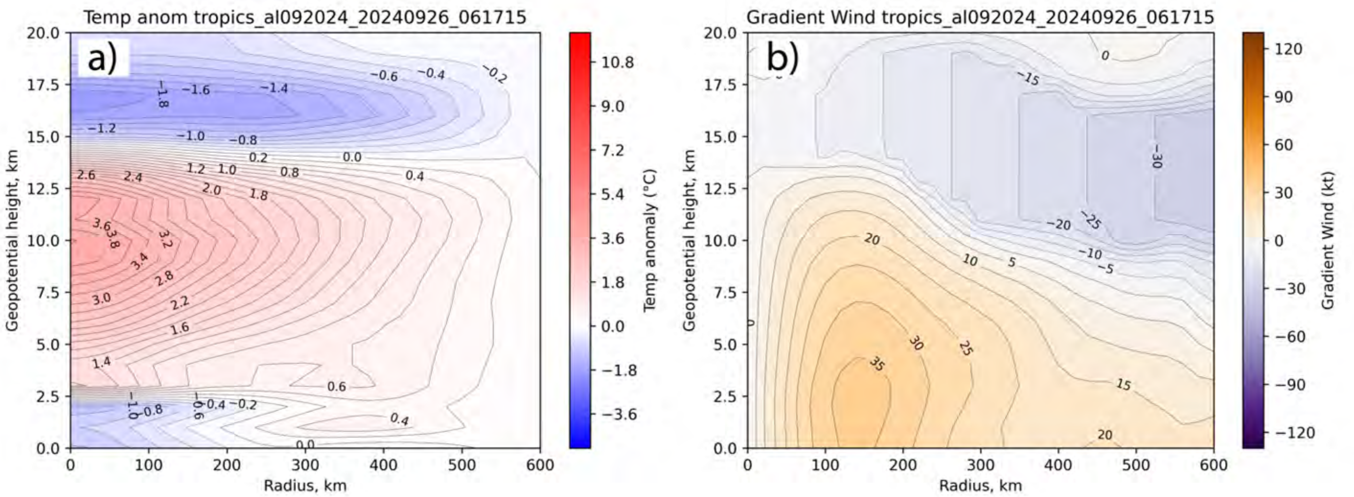


Fig. 18: Radial-height cross section of the (a) temperature anomaly and (b) gradient wind from a TROPICS-3 overpass at 0617 UTC on 26 September 2024 for Hurricane Helene. The temperature anomaly is the departure of the temperature at a radius of 600 km at each height level.

C. Determining tropical cyclone intensity and wind structure from TROPICS vertical profile data

The temperature and moisture retrievals described in Section IV can be combined with dynamical constraints to provide quantitative information on the TC structure. The CIRA Hurricane Intensity and Structure Algorithm (HISA) uses a modified version of the procedure described in [65] and [66] to estimate geopotential height and horizontal winds from the temperature retrievals. HISA is run operationally at the National Environmental Satellite, Data, and Information Service (NESDIS) using input from AMSU and ATMS Microwave Integrated Retrival System (MiRS) [67] retrievals and was adapted for the TROPICS machine learning vertical profile retrievals (discussed in Section IV). The temperature retrievals are used as input to the hydrostatic equation, which is integrated downward from 100 hPa to the surface using an upper boundary condition from a Global Forecast System (GFS) analysis to provide geopotential height. Then the gradient wind and nonlinear balance equations are used to estimate horizontal winds from 100 hPa to the surface. HISA also estimates maximum wind (intensity), minimum sea level pressure, and the radial extent of 34, 50 and 64 kt (17.5, 25.7 and 33 m s^{-1}) winds using a statistical method with physical parameters from the retrieved wind and height fields as input. The evaluation of the intensity and wind radii estimates using this approach with TROPICS input is in progress, although the primary TROPICS intensity estimation algorithm is D-MINT, as described above.

Figure 18 shows an example of the azimuthally averaged temperature anomaly and gradient wind retrievals as a function of height and radius from the TC center for Hurricane Helene at 0617 UTC on 26 September 2024 when it was just north of the Yucatan Peninsula. The warm core structure is easily seen, and the retrieved gradient winds extend through the depth of the troposphere. Although the gradient wind of the inner core of Helene is not well resolved, these analyses can be used to monitor changes in the vertical structure due to the high temporal resolution of TROPICS. DesRosiers [68] showed that the vortex depth measured in a symmetrically averaged wind field relative to a low-level center is an indirect measure of vertical tilt, which is usually caused by environmental wind shear. The TROPICS analyses for a large sample are being analyzed to determine if the changes in the vertical depth can be used to measure the TC response to vertical shear and as predictors of future intensity changes.

Figure 19 shows the horizontal wind and geopotential height fields for Hurricane Helene at the same time as in Figure 18. These analyses show that Helene was a very large TC and had very little vertical tilt since there is little displacement of the circulation center with height. The 250-hPa wind field shows an upper-level trough to the northwest of Helene that helped to steer Helene to the north over the next two days. A large sample is being examined to determine if the 2-D horizontal winds can also be used as a measure of vertical tilt and to estimate the environmental wind shear directly by averaging the horizontal winds around the TC center at each pressure level.

D. Assimilation experiments with TROPICS data

The assimilation of space-borne microwave sounding data, such as from the TROPICS mission, can significantly enhance Numerical Weather Prediction (NWP) forecasts by providing high-temporal and high-spatial resolution observations to constrain analysis fields. Efforts to assimilate all-sky TROPICS L1B data into operational systems are currently underway. To understand the potential contribution of TROPICS measurements to global NWP analysis, the sensitivity of atmospheric profiles to each of the 12 TROPICS channels is examined. These calculations were performed using the Community Radiative Transfer Model (CRTM) and short-term forecasts from the Goddard Earth Observing System (GEOS) [69] for clear-sky, non-precipitating cloudy, and precipitating conditions. The analysis focused on subtropical latitudinal bands

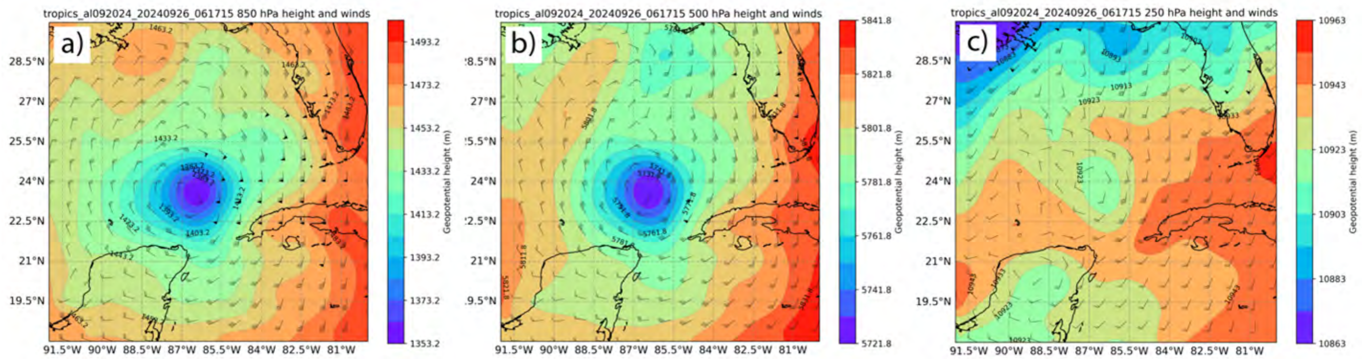


Fig. 19: Geopotential height and horizontal wind analyses at (a) 850, (b) 500 and (c) 250 hPa from a TROPICS-3 overpass on 0617 UTC on 26 September 2024 for Hurricane Helene.

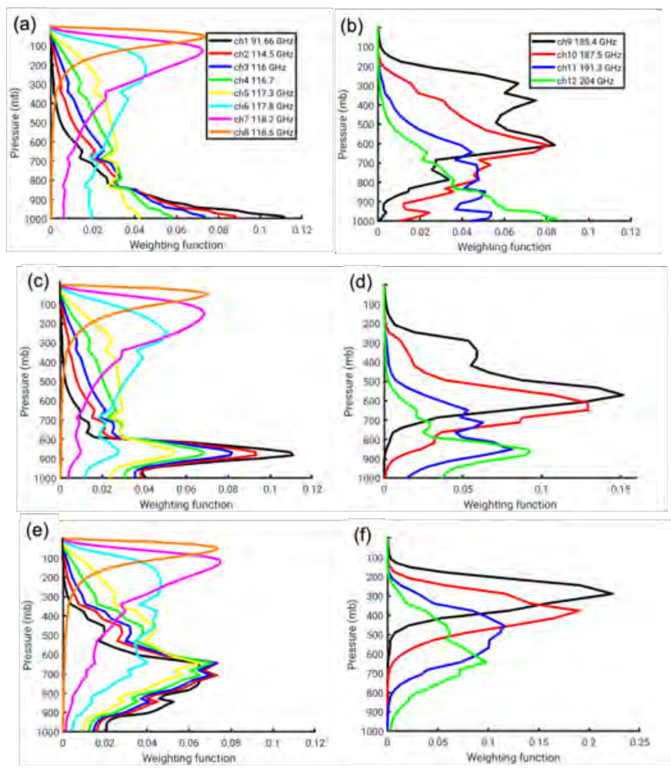


Fig. 20: Weighting functions calculated with CRTM 2.4.0 using the GEOS-FP short-term forecasts and averaged for subtropics on 27 August 2023. (a) and (b): clear-sky condition, (c) and (d): non-precipitating cloudy sky, and (e) and (f): precipitating sky condition.

$(23.26^\circ \leq |\text{latitude}| < 35^\circ)$ on 18 UTC 18 August 2023. For clear-sky conditions, observations where the vertically integrated liquid water (ql), ice cloud water (qi), rain (qr), and snow (qs) in the background profiles were less than 0.001 kg/m^2 were selected. Similarly, for non-precipitating cloudy conditions, profiles were chosen where ql > 0.1 kg/m^2 and qr+qs < 0.01 kg/m^2, while for precipitating conditions, profiles were chosen where ql > 0.1 kg/m^2 and qr+qs > 0.3 kg/m^2. Figure 20 presents the average weighting functions for the subtropical latitudes. Results for clear skies indicate that channels 1, 2, 3, 4, and 5, along with channels 11 and 12, show significant surface contributions. Channels 6, 7, and 8 have their weighting function peaks at approximately 200 hPa, 150 hPa, and 50 hPa, respectively. Humidity-sensitive channels 9, 10, and 11 show contributions from the upper, middle, and lower troposphere, respectively. In non-precipitating cloudy sky conditions, channels 5 through 10 provide information from altitudes above 600 hPa, while channels 1–5 exhibit similar weighting function profiles with peaks around 850 hPa. Channels 7 and 8 show peaks at 150 hPa and 50 hPa, respectively. For humidity-sensing channels (9, 10, 11, and 12), peaks are found in the lower to middle troposphere at 550 hPa, 630 hPa, 850 hPa, and 880 hPa, respectively. In precipitating conditions, channels 1–5 exhibit similar weighting functions with peaks near 700 hPa, while channels 6–8 peak at 250 hPa, 150 hPa, and 50 hPa, respectively. Humidity-sensing channels 9, 10, 11, and 12 show peak weighting functions at 300 hPa, 380 hPa, 470 hPa, 650 hPa, respectively. Overall, channels 1–5 exhibit similar weighting functions under different sky conditions, peaking at the surface, 850 hPa, and 700 hPa for clear, cloudy, and precipitating conditions, respectively. On average, sensitivity to the surface decreases by 50 % in cloudy conditions and by 75–85% in precipitation conditions compared to clear sky conditions. Temperature-sounding channels 6–8 show upper-troposphere contributions. Humidity channels 9, 10, and 11 display distinct vertically separated weighting function peaks across the upper, middle, and lower troposphere in all-sky conditions. The 12 TROPICS channels capture the vertical structure of atmospheric phenomena, such as tropical storms, with detailed information from the surface up through the upper troposphere. This capability is especially beneficial for improving the representation of storm dynamics and their associated vertical profiles in NWP systems.

To assess the potential benefits of TROPICS data for TC analysis and prediction, NWP experiments were performed using the GEOS model during August 2023. The atmospheric data assimilation system in GEOS is based on a Hybrid 4DEnvar algorithm assimilating various observation types every 6-hour analysis cycle [70]–[72]. The control run assimilated all available observations currently processed by the GEOS-Forward Processing (GEOS-FP) system, including conventional data (e.g., sondes, buoys, aircraft, GNSS-RO, radiance

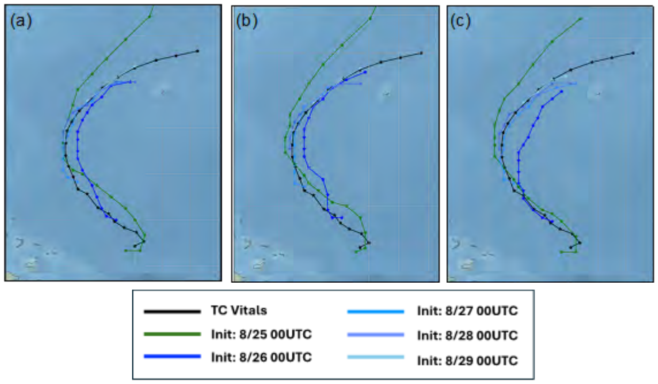


Fig. 21: GEOS forecasts of the 2023 Hurricane Franklin track: (a) control experiment, which assimilated all observations currently used in GEOS-FP; (b) experiment that included TROPICS-Pathfinder L1B radiance data in addition to all the observations used in the control; and (c) experiment that incorporated TROPICS-Pathfinder, TROPICS-3, and TROPICS-6 L1B radiance data, along with all the observations used in the control. The black line represents the observed true track, while the colored lines show forecasted tracks initialized at various forecast dates and times.

data from IASI, AIRS, CrIS, AMSU-A, ATMS, MHS, GMI, AVHRR, HIRS, and SSMIS). The first experiment incorporated TROPICS-Pathfinder L1B radiance data, while the second experiment included TROPICS-Pathfinder, TROPICS-3, and TROPICS-6 data. The tropical cyclone track forecasts for Hurricane Franklin (2023) were compared across these experiments. Figure 21 compares the control run, control + TROPICS-Pathfinder, and control + three TROPICS satellites. The true track of Hurricane Franklin is shown in black, while the forecasted tracks are represented in different colors, reflecting forecasts made on various dates. The results demonstrate that the assimilation of data from all three TROPICS satellites significantly improved the TC track forecasts, particularly for the first few days after the analysis time.

Data impact studies have also shown TROPICS to be valuable for improving prediction of TCs in regional forecast models. An observing system simulation experiment (OSSE) with NOAA's Hurricane Weather Research and Forecasting (HWRF) model using simulated data from the original six-satellite TROPICS constellation design demonstrated the potential for all-sky TROPICS radiances to improve TC thermodynamic structure and forecasts of track and intensity [23]. The OSSE results presented here provide a basis for real-data observing system experiments (OSEs) performed with NOAA's next-generation Hurricane Analysis and Forecasting System (HAFS), which offers an advanced 4D Ensemble Variational (4DEnVar) data assimilation (DA) system and the ability to perform fully online satellite radiance bias correction [73]. Preliminary assessments of the impact of TROPICS radiances in HAFS have shown promising results. In a case study of Hurricane Lee (2023), TROPICS Level 1B all-sky radiances from TROPICS-1, -3, and -6 were assimilated into HAFS over four six-hourly cycles leading up to 06 UTC 6 September. TROPICS radiances strengthened the warm core and shifted the maximum temperatures closer to the center compared to the control run with only the standard operational datasets assimilated (Figure 22). In addition, the kinematic structure of the TC was strengthened, with stronger radial outflow aloft and stronger radial inflow and tangential winds at low levels. This led to an overall reduction in the intensity and minimum sea level pressure (MSLP) forecast error (not shown). Further evaluation of the impact of TROPICS radiances in HAFS with additional case studies, as well as an investigation of how that impact may be enhanced when assimilated alongside ocean surface wind retrievals from the NASA Cyclone Global Navigation Satellite System (CYGNSS) satellites [74], are currently underway.

E. *TROPICS Applications*

1) The TROPICS Early Adopters Community: Throughout the mission's lifetime, the TROPICS team has worked closely with operational weather forecasters and other stakeholders to enhance the value of TROPICS data. Formed in 2018, the TROPICS Early Adopters program was established to connect the mission science team to stakeholders interested in using TROPICS data for research, forecasting, and decision making. Collaboration with early adopters in the forecasting and data assimilation fields revealed the need for low-latency data to better diagnose and predict tropical cyclones. This demand led to additional funding provided by NASA, NOAA, and the Office of Naval Research to lower the latency of the mission's Level-1 products to approximately one hour during the Atlantic hurricane season. This low latency, combined with the mission's efforts to incorporate TROPICS data into the decision support systems at the U.S. Joint Typhoon Warning Center (JTWC) and the NHC, led to the use of TROPICS data in forecasting of typhoons in the Western Pacific Ocean soon after the mission's launch. Collaboration with early adopters also revealed the potential for TROPICS data to be used in a variety of other applications, including analysis of extreme rainfall events [75] and correction of diurnal drift in climatological temperature records [76]. A joint workshop held in 2023 with the NASA CYGNSS mission highlighted the combined utility of the two missions, with CYGNSS providing information on surface winds and sea state and TROPICS providing information on atmospheric characteristics. For example, assimilation of both TROPICS and CYGNSS data into the Weather Research and Forecasting (WRF) model produced a better forecast of Hurricane Ida (2021) than assimilation of each of the data products alone [77]. This initial research opens up potential avenues for enhanced utility of commercial GNSS-R and millimeter-wave sounder constellations operated, for example, by Spire Global and Tomorrow.io, respectively.

2) Use of TROPICS Data by Tropical Cyclone Forecast Centers: TROPICS data have been made available for the NHC and the JTWC for evaluation and feedback since 2023. The operational centers currently access TROPICS data via the Naval Research Laboratory (NRL) web page [78], the Automated Tropical Cyclone Forecast System (ATCF) [79], and the National Weather Service AWIPS2 [80]. JTWC forecasters specifically cited timely TROPICS data for a dozen

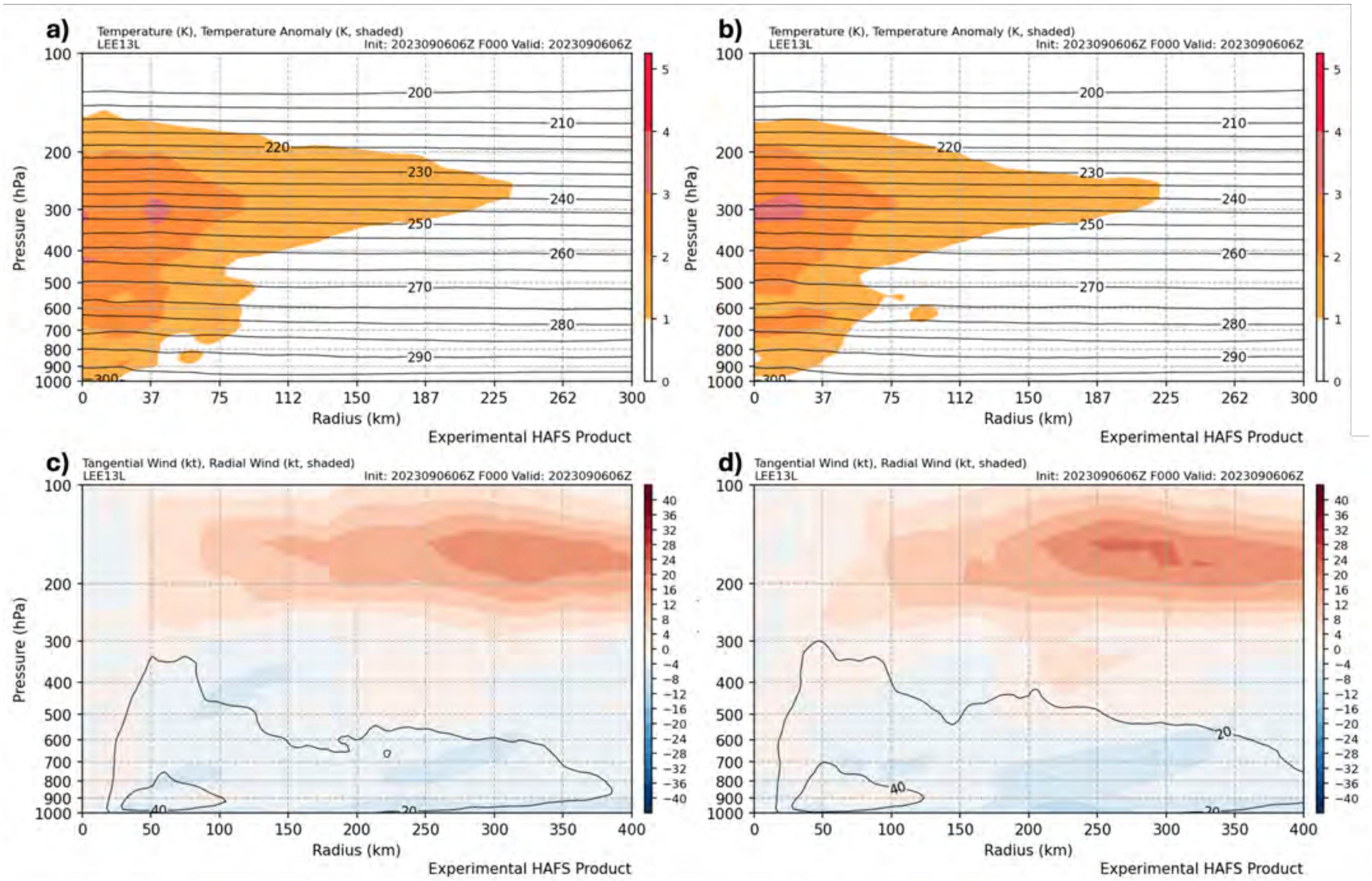


Fig. 22: HAFS analysis of 2023 Hurricane Lee showing azimuthally averaged temperature anomaly (K; a and b) and radial (shading) and tangential (contours) wind (kt; c and d) at 06 UTC 6 September 2023 for control (a and c) and TROPICS (b and d) experiments.

storms in the Western Pacific, Southern Hemisphere and Indian Ocean between Dec 2023 and Dec 2024. NHC forecasters found that TROPICS seems to perform best in cases where the tropical cyclone is very mature, large in size, and well-defined, showing eyes and other inner core structures well. They also found that the new TROPICS channel at 204.8 GHz is best for capturing TC convective structure, followed by the more traditionally used 91-GHz channel. The JTWC has been using TROPICS data to center-fix tropical cyclones and identify cloud formations which may indicate pre-development TC areas. The JTWC found the 91-GHz channel most useful to evaluate upper atmospheric tropical cyclone cloud structure and analyse the Low-Level Circulation Center position within a vertically stacked tropical system. The 204.8 GHz channel was evaluated for future use in subjective evaluation techniques. Both NHC and JTWC mentioned the TROPICS high revisit rate. In the example shown in Figure 23, TROPICS observations helped NHC track different stages of the eyewall replacement for Major Hurricane Kristy (2024) in the eastern Pacific. The high revisit rate, offered by a low-inclination orbit over the tropics, allowed for numerous fixes in the Indian and Pacific Oceans covered by the JTWC Area Of Responsibility when integrated into their NRT decision support system (see Figure 24). NHC forecasters also noted that it will be beneficial for future systems to have higher spatial resolution, especially near the edges of the swath where TROPICS has significant distortion. Currently, a TC needs to be closer to the center of the swath to capture the storm structure. Both NHC and JTWC expressed interest in having TROPICS data available in operations. Feedback from both NHC and JTWC is preliminary and does not represent a formal endorsement by NHC or JTWC.

VIII. Summary

The NASA TROPICS constellation mission has achieved all of its science mission baseline requirements, and has produced a high-quality aggregate data record spanning approximately 10 billion observations and 10 satellite-years. All data (Level 1 radiances and Level 2 geophysical products) are available to the general public via the GES DISC [81]. Multiple investigators have reported significant positive impact on hurricane track forecasting when using TROPICS data over multiple storms, and TROPICS data have been used by forecasters at multiple operational tropical cyclone centers. The TROPICS mission has provided a unique opportunity to assess relatively low-cost microwave sounder constellations for future earth observing use, and multiple commercial constellations are coming online now and are planned to come online soon,

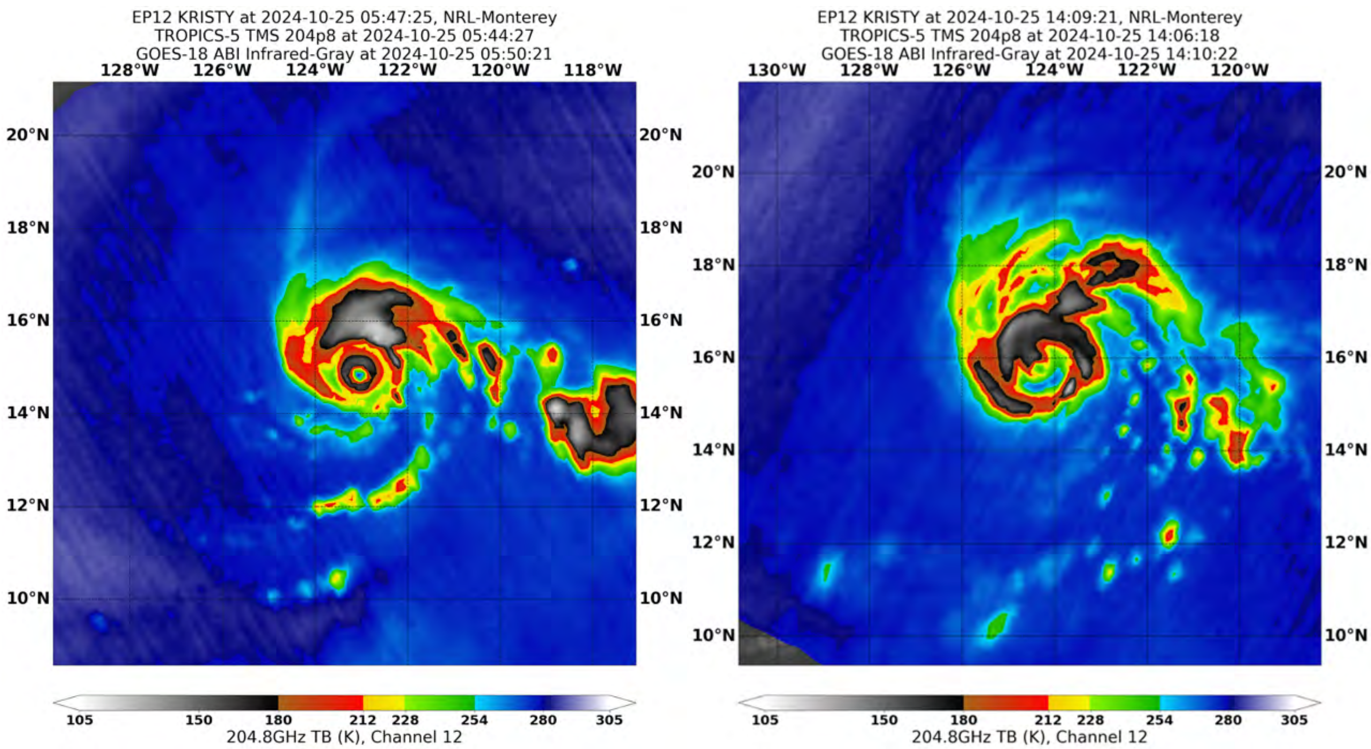


Fig. 23: TROPICS-5 204.8-GHz channel data for 2024-10-25 at 0547 UTC and at 1409 UTC. The figures show the east Pacific major Hurricane Kristy (ep122024) undergoing an eyewall replacement cycle. Image credit: US Naval Research Laboratory.

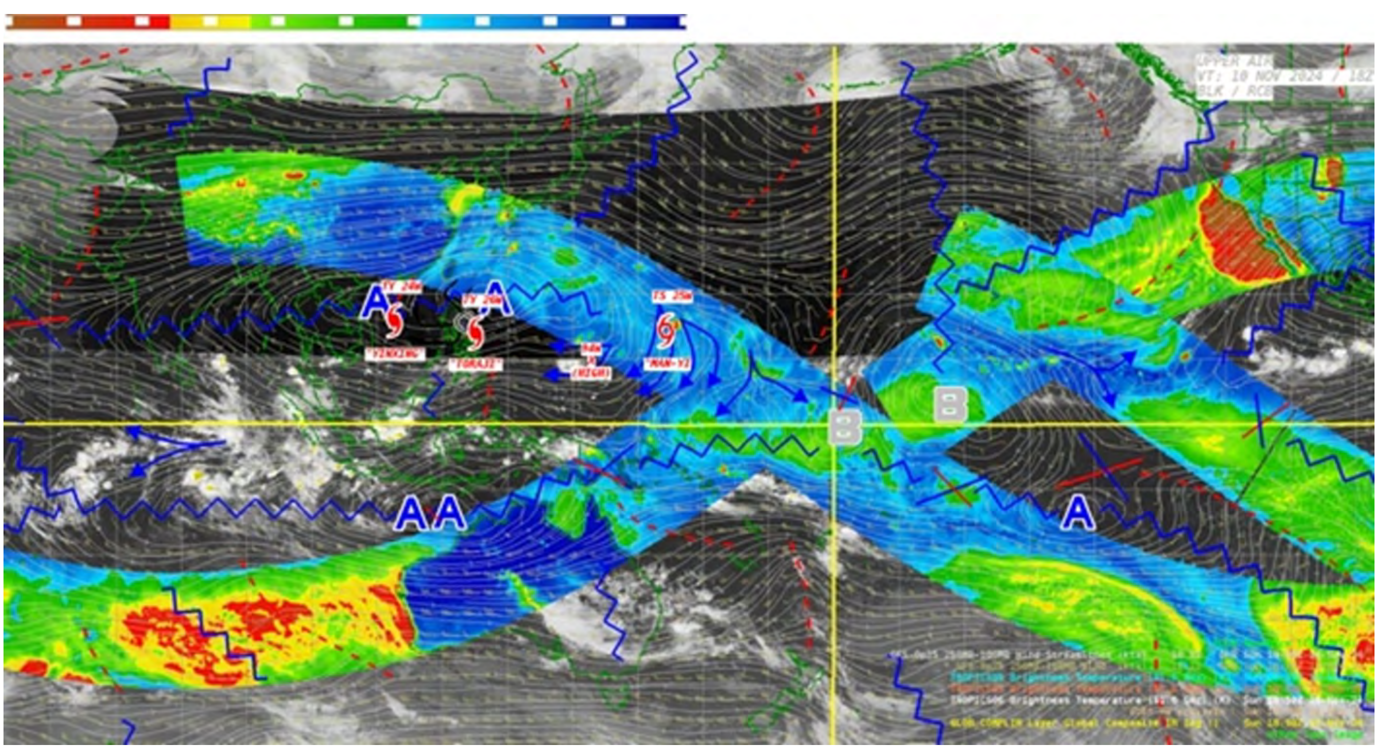


Fig. 24: TROPICS 91-GHz brightness temperature (filled contours) overlaid on other situational awareness products in the Joint Typhoon Warning Center's decision support system on 19 November 2024.

some of which are using technology directly derived from the TROPICS mission and are already showing improvements in revisit rate and performance relative to TROPICS [20], [82].

IX. Acknowledgments

The authors gratefully acknowledge the outstanding work of the MIT Lincoln Laboratory TROPICS Engineering and Mission Support teams, the University of Wisconsin Data Processing Center, Blue Canyon Technologies, Kongsberg Satellite Services, ATLAS Space Operations, Rocket Lab, and NASA ESSP, Headquarters, and GES DISC for their support. Funding for the near-real-time downlinks was provided by the Office of Naval Research, NOAA NESDIS, and the NASA Earth in Action program. This material is approved for public release and is based upon work supported by the National Aeronautics and Space Administration under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

References

[1] C. Velden, J. Knaff, D. Herndon, A. Mouche, J. Hawkins, G. Panegrossi, A. Stoffelen, J. Courtney, T. Tsukada, and A.-C. Fontan, "Recent innovations in satellite-based applications and their impacts on tropical cyclone analyses and forecasts," *Journal of the European Meteorological Society*, vol. 2, p. 100011, 2025.

[2] L. Ricciardulli, B. Howell, C. R. Jackson, J. Hawkins, J. Courtney, A. Stoffelen, S. Langlade, C. Fogarty, A. Mouche, W. Blackwell *et al.*, "Remote sensing and analysis of tropical cyclones: Current and emerging satellite sensors," *Tropical Cyclone Research and Review*, vol. 12, no. 4, pp. 267–293, 2023.

[3] T. J. Schmit, P. Griffith, M. M. Gunshor, J. M. Daniels, S. J. Goodman, and W. J. Lebair, "A Closer Look at the ABI on the GOES-R Series," *Bulletin of the American Meteorological Society*, vol. 98, no. 4, pp. 681 – 698, 2017. [Online]. Available: https://journals.ametsoc.org/view/journals/bams/98/4/bams-d-15-00230.1.xml

[4] V. Salomonson, W. Barnes, P. Maymon, H. Montgomery, and H. Ostrow, "MODIS: advanced facility instrument for studies of the Earth as a system," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 27, no. 2, pp. 145–153, 1989.

[5] D. Hillger, T. Kopp, T. Lee, D. Lindsey, C. Seaman, S. Miller, J. Solbrig, S. Kidder, S. Bachmeier, T. Jasmin, and T. Rink, "First-Light Imagery from Suomi NPP VIIRS," *Bulletin of the American Meteorological Society*, vol. 94, no. 7, pp. 1019 – 1029, 2013. [Online]. Available: https://journals.ametsoc.org/view/journals/bams/94/7/bams-d-12-00097.1.xml

[6] D. B. Kunkee, G. A. Poe, D. J. Boucher, S. D. Swadley, Y. Hong, J. E. Wessel, and E. A. Uliana, "Design and evaluation of the first special sensor microwave imager/sounder," *IEEE Transactions on Geoscience and Remote sensing*, vol. 46, no. 4, pp. 863–883, 2008.

[7] S. Q. Kidder, M. D. Goldberg, R. M. Zehr, M. DeMaria, J. F. Purdom, C. S. Velden, N. C. Grody, and S. J. Kusselson, "Satellite analysis of tropical cyclones using the Advanced Microwave Sounding Unit (AMSU)," *Bulletin of the American Meteorological Society*, vol. 81, no. 6, pp. 1241–1260, 2000.

[8] X. Zou, F. Weng, B. Zhang, L. Lin, Z. Qin, and V. Tallapragada, "Impacts of assimilation of ATMS data in HWRF on track and intensity forecasts of 2012 four landfall hurricanes," *Journal of Geophysical Research: Atmospheres*, vol. 118, no. 20, pp. 11–558, 2013.

[9] T. F. Lee, F. J. Turk, J. Hawkins, and K. Richardson, "Interpretation of TRMM TMI images of tropical cyclones," *Earth Interactions*, vol. 6, no. 3, pp. 1–17, 2002.

[10] K. Imaoka, M. Kachi, M. Kasahara, N. Ito, K. Nakagawa, and T. Oki, "Instrument performance and calibration of AMSR-E and AMSR2," *International archives of the photogrammetry, remote sensing and spatial information science*, vol. 38, no. 8, pp. 13–18, 2010.

[11] Z. Pu, C. Yu, V. Tallapragada, J. Jin, and W. McCarty, "The impact of assimilation of GPM microwave imager clear-sky radiance on numerical simulations of Hurricanes Joaquin (2015) and Matthew (2016) with the HWRF model," *Monthly Weather Review*, vol. 147, no. 1, pp. 175–198, 2019.

[12] W. Blackwell, G. Allen, C. Galbraith, T. Hancock, R. Leslie, I. Osaretin, L. Retherford, M. Scarito, C. Semisch, M. Shields *et al.*, "Nanosatellites for earth environmental monitoring: The MicroMAS project," in *Microwave Radiometry and Remote Sensing of the Environment (MicroRad), 2012 12th Specialist Meeting on*. IEEE, 2012, pp. 1–4.

[13] W. Blackwell, G. Allen, C. Galbraith, R. Leslie, I. Osaretin, M. Scarito, M. Shields, E. Thompson, D. Toher, D. Townzen *et al.*, "MicroMAS: A first step towards a nanosatellite constellation for global storm observation," in *2013 Small Satellite Conference Proceedings*, 2013.

[14] Z. Li, J. Li, T. J. Schmit, P. Wang, A. Lim, J. Li, F. W. Nagle, W. Bai, J. A. Otkin, R. Atlas *et al.*, "The alternative of CubeSat-based advanced infrared and microwave sounders for high impact weather forecasting," *Atmospheric and Oceanic Science Letters*, vol. 12, no. 2, pp. 80–90, 2019.

[15] A. Crews, W. J. Blackwell, R. V. Leslie, M. Grant, I. A. Osaretin, M. DiLiberto, A. Milstein, S. Leroy, A. Gagnon, and K. Cahoy, "Initial radiance validation of the Microsized Microwave Atmospheric Satellite-2A," *IEEE Transactions on Geoscience and Remote Sensing*, 2020.

[16] Y. V. Goncharenko, W. Berg, S. C. Reising, F. Iturbide-Sanchez, and V. Chandrasekar, "Design and analysis of cubesat microwave radiometer constellations to observe temporal variability of the atmosphere," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 14, pp. 11 728–11 736, 2021.

[17] W. Berg, S. T. Brown, B. H. Lim, S. C. Reising, Y. Goncharenko, C. D. Kummerow, T. C. Gaier, and S. Padmanabhan, "Calibration and validation of the TEMPEST-D CubeSat radiometer," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 59, no. 6, pp. 4904–4914, 2020.

[18] R. Belter, R. Delf, G. Sasaki, M. Marques, M. Hurowitz, R. Carter, D. Kraft, B. Sanders, and A. Gasiewski, "Correction of Geolocation Error in GEMS1 Passive Microwave Data," in *IGARSS 2024 - 2024 IEEE International Geoscience and Remote Sensing Symposium*, 2024, pp. 6709–6712.

[19] R. Carter, B. Sanders, A. Gasiewski, M. Hurowitz, D. Gallaher, W. Hosack, R. McAllister, F. McAllister, D. Kraft, R. Belter *et al.*, "The Global Environmental Monitoring Systems (GEMS) Constellation of Passive Microwave Satellites," in *AGU Fall Meeting Abstracts*, vol. 2019, 2019, pp. A13J–2955.

[20] F. Cannon, S. Pfreundschuh, B. Taylor, S. J. Munchak, E. Nelson, J. L'heureux, C. Owens, L. Conibear, S. Flampouris, and A. Chawla, "Deep Learning for Multi-Satellite Precipitation Retrievals: Impact of Tomorrow.io's Microwave Sounders," *Authorea Preprints*, 2024.

[21] W. Blackwell, S. Braun, R. Bennartz, C. Velden, M. DeMaria, R. Atlas, J. Dunion, F. Marks, R. Rogers, B. Annane *et al.*, "An overview of the TROPICS NASA Earth Venture mission," *Quarterly Journal of the Royal Meteorological Society*, 2018.

[22] P. G. Buzzi, D. Selva, N. Hitomi, and W. J. Blackwell, "Assessment of constellation designs for earth observation: Application to the TROPICS mission," *Acta Astronautica*, vol. 161, pp. 166–182, 2019.

[23] H. W. Christophersen, B. A. Dahl, J. P. Dunion, R. F. Rogers, F. D. Marks, R. Atlas, and W. J. Blackwell, "Impact of TROPICS radiances on tropical cyclone prediction in an OSSE," *Monthly Weather Review*, 2021.

[24] J. X. Yang, Y.-K. Lee, C. Grassotti, K. Garrett, Q. Liu, W. Blackwell, R. V. Leslie, T. Greenwald, R. Bennartz, and S. Braun, "Atmospheric humidity and temperature sounding from the cubesat TROPICS mission: Early performance evaluation with MiRS," *Remote Sensing of Environment*, vol. 287, p. 113479, 2023.

[25] A. B. Milstein, M. Pieper, and W. J. Blackwell, "Techniques for geophysical parameter retrievals," *Signal and Image Processing for Remote Sensing*, p. 25, 2024.

[26] A. Gagnon, S. N. Hasler, J. Chew, W. Blackwell, R. V. Leslie, M. DiLiberto, and K. Cahoy, "An initial validation of the NASA TROPICS Pathfinder microwave radiometer observations," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 2024.

[27] J. X. Yang, Y.-K. Lee, S. Liu, C. Grassotti, Q. Liu, W. Blackwell, R. V. Leslie, T. Greenwald, R. Bennartz, and S. Braun, "Evaluating rainfall and graupel retrieval performance of the NASA TROPICS Pathfinder through the NOAA MiRS system," *Remote Sensing of Environment*, vol. 318, p. 114570, 2025.

[28] E. B. Munsell, S. A. Braun, T. Greenwald, R. Bennartz, and W. J. Blackwell, "Examining tropical cyclone thermodynamic structure with TROPICS observations," *Monthly Weather Review*, 2025.

[29] R. V. Leslie, W. J. Blackwell, and M. DiLiberto, "NASA TROPICS mission: microwave radiometer calibration using machine learning," in *Sensors, Systems, and Next-Generation Satellites XXVIII*, vol. 13192. SPIE, 2024, p. 1319212.

[30] R. V. Leslie, M. DiLiberto, and S. Hazard, *User Guide for TROPICS Data Products*, NASA Langley Research Center, https://ntrs.nasa.gov/citations/20210018318, September 2023.

[31] W. J. Blackwell, "TROPICS L1B Orbital Geolocated Native-Resolution Brightness Temperatures, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC)," MIT Lincoln Laboratory, https://disc.gsfc.nasa.gov/, Tech. Rep.

[32] R. V. Leslie, W. J. Blackwell, and M. DiLiberto, *TROPICS Level-1 Radiance Algorithm Theoretical Basis Document*, NASA Langley Research Center, https://ntrs.nasa.gov/citations/20210018919, July 2021, version 2.0.

[33] P. W. Rosenkranz, "Line-by-line microwave radiative transfer (non-scattering)." [Online]. Available: http://cetemps.aquila.infn.it/mwrnet/lblmrt_ns.html

[34] L. Kilic, C. Prigent, C. Jimenez, E. Turner, J. Hocking, S. English, T. Meissner, and E. Dinnat, "Development of the SURface Fast Emissivity Model for Ocean (SURFEM-Ocean) Based on the PARMIO Radiative Transfer Model," *Earth and Space Science*, vol. 10, no. 11, 2023. [Online]. Available: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022EA002785

[35] "The GEOS data used in this study/project have been provided by the Global Modeling and Assimilation Office (GMAO) at NASA Goddard Space Flight Center through the online data portal in the NASA Center for Climate Simulation," https://gmao.gsfc.nasa.gov/GMAO_products/NRT_products.php.

[36] A. Heidinger and W. Straka, "Algorithm theoretical basis document: ABI cloud mask," NOAA NESDIS Center for Satellite Applications and Research, https://www.star.nesdis.noaa.gov/goesr/documents/ATBDs/Enterprise/ATBD_Enterprise_Cloud_Mask_v1.2_2020_10_01.pdf, Tech. Rep.

[37] L. H. Hoffman, *Calculation and accuracy of ERBE scanner measurement locations*. National Aeronautics and Space Administration, 1987, vol. 2670.

[38] P. Wessel and W. H. Smith, "A global, self-consistent, hierarchical, high-resolution shoreline database," *Journal of Geophysical Research: Solid Earth*, vol. 101, no. B4, pp. 8741–8743, 1996.

[39] J. Liu, W. Li, J. Peng, L. Shen, H. Han, P. Zhang, and L. Yang, "Geolocation error estimation and correction on long-term MWRI data," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 59, no. 11, pp. 9448–9461, 2021.

[40] S. Buehler, M. Kuvatov, T. Sreerekha, V. O. John, B. Rydberg, P. Eriksson, and J. Notholt, "A cloud filtering method for microwave upper tropospheric humidity measurements," *Atmospheric Chemistry and Physics*, vol. 7, no. 21, pp. 5531–5542, 2007.

[41] W. M. Gray, "Tropical cyclone genesis," Atmospheric Science Paper No. 234, 1975, Department of Atmospheric Science, Colorado State University, Fort Collins, CO, Tech. Rep.

[42] ——, "Hurricanes: Their formation, structure and likely role in the tropical circulation. meteorology over the tropical oceans," *Roy. Meteor. Soc.*, pp. 155–218, 1979.

[43] ——, "The formation of tropical cyclones," *Meteorology and atmospheric physics*, vol. 67, no. 1, pp. 37–69, 1998.

[44] J. L. McBride, "Observational analysis of tropical cyclone formation. part i: Basic description of data sets," *Journal of atmospheric sciences*, vol. 38, no. 6, pp. 1117–1131, 1981.

[45] M. DeMaria, J. A. Knaff, and B. H. Connell, "A tropical cyclone genesis parameter for the tropical Atlantic," *Weather and Forecasting*, vol. 16, no. 2, pp. 219–233, 2001.

[46] S. K. Kimball, "A modeling study of hurricane landfall in a dry environment," *Monthly weather review*, vol. 134, no. 7, pp. 1901–1918, 2006.

[47] K. A. Hill and G. M. Lackmann, "Influence of environmental humidity on tropical cyclone size," *Monthly Weather Review*, vol. 137, no. 10, pp. 3294–3315, 2009.

[48] S. A. Braun, J. A. Sippel, and D. S. Nolan, "The impact of dry midlevel air on hurricane intensity in idealized simulations with no mean flow," *Journal of the Atmospheric Sciences*, vol. 69, no. 1, pp. 236–257, 2012.

[49] N. R. Nalli, C. D. Barnet, A. Reale, D. Tobin, A. Gambacorta, E. S. Maddy, E. Joseph, B. Sun, L. Borg, A. K. Mollner, V. R. Morris, X. Liu, M. Divakarla, P. J. Minnett, R. O. Knuteson, T. S. King, and W. W. Wolf, "Validation of satellite sounder environmental data records: Application to the Cross-track Infrared Microwave Sounder Suite," *Journal of Geophysical Research: Atmospheres*, vol. 118, no. 24, pp. 13,628–13,643, 2013. [Online]. Available: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2013JD020436

[50] G. V. Rao and P. D. Macarthur, "The SSM/I Estimated Rainfall Amounts of Tropical Cyclones and Their Potential in Predicting the Cyclone Intensity Changes," *Mon. Wea. Rev.*, vol. 122, no. 7, pp. 1568–1574, 1994.

[51] D. J. Cecil and E. J. Zipser, "Relationships between Tropical Cyclone Intensity and Satellite-Based Indicators of Inner Core Convection: 85-GHz Ice-Scattering Signature and Lightning," *Mon. Wea. Rev.*, vol. 127, no. 1, pp. 103–123, 1999.

[52] H. Jiang and E. M. Ramirez, "Necessary Conditions for Tropical Cyclone Rapid Intensification as Derived from 11 Years of TRMM Data," *J. Climate*, vol. 26, no. 17, pp. 6459–6470, 2013.

[53] S. J. Lord, H. E. Willoughby, and J. M. Piotrowicz, "Role of a Parameterized Ice-Phase Microphysics in an Axisymmetric, Nonhydrostatic Tropical Cyclone Model," *J. Atmos. Sci.*, vol. 41, no. 19, pp. 2836–2848, 1984.

[54] S.-N. Wu, B. J. Soden, and G. J. A. Jr, "Ice water content as a precursor to tropical cyclone rapid intensification," *Geophys. Res. Letters*, vol. 47, no. 21, p. e2020GL089669, 2020.

[55] R. Chen and R. Bennartz, "Rainfall Algorithms Using Oceanic Satellite Observations from MWHS-2," *Adv. Atmos. Sci*, vol. 38, no. 8, pp. 1367–1378, 2021.

[56] C. Kidd, T. Matsui, W. Blackwell, S. Braun, R. Leslie, and Z. Griffith, "Precipitation estimation from the NASA TROPICS mission: Initial retrievals and validation," *Remote Sensing*, vol. 14, no. 13, p. 2992, 2022.

[57] Y. You, G. Huffman, C. Kidd, S. Braun, W. Blackwell, J. X. Yang, and C. Da, "Evaluating and improving TROPICS millimeter-wave sounder's precipitation estimate over ocean," *Journal of Geophysical Research: Atmospheres*, vol. 128, no. 16, p. e2023JD038697, 2023.

[58] C. S. Velden and D. Herndon, "A Consensus Approach for Estimating Tropical Cyclone Intensity from Meteorological Satellites: SATCON," *Wea. Forecasting*, vol. 35, p. 1645–1662, 2020.

[59] S. M. Griffin, A. Wimmers, and C. S. Velden, "Predicting Short-Term Intensity Change in Tropical Cyclones Using a Convolutional Neural Network," *Wea. Forecasting*, vol. 39, pp. 177–202, 2024.

[60] S. M. Griffin, A. Wimmers, D. C. Herndon, and C. S. Velden, "Estimating Current Tropical Cyclone Intensity from 183-GHz Microwave Satellite Observations using a Convolutional Neural Network," *Wea. Forecasting*, vol. 40, 2025, in review.

[61] J. Zawislak and Coauthors, "Accomplishments of NOAA's airborne hurricane field program and a broader future approach to forecast improvement," *Bull. Amer. Meteor. Soc.*, vol. 103, 2022.

[62] E. Blake, "AL05 Forecast Advisory: Hurricane Ernesto Discussion 15," 2024. [Online]. Available: https://www.nhc.noaa.gov/archive/2024/al05/al052024.discus.015.shtml

[63] J. L. Beven, "Hurricane franklin (al082023)," *Tropical Cyclone Report*, 2024.

[64] [Online]. Available: https://hurricanes.ral.ucar.edu/realtime/plots/northatlantic/2023/al082023/

[65] J. L. Demuth, M. DeMaria, J. A. Knaff, and T. H. Vonder Haar, "Evaluation of Advanced Microwave Sounder Unit tropical cyclone intensity and size estimation algorithms," *J. Appl. Meteor*, vol. 43, pp. 282–296, 2004.

[66] K. Bessho, M. DeMaria, and J. A. Knaff, "Tropical cyclone wind retrievals from the Advanced Microwave Sounder Unit (AMSU): Application to surface wind analysis," *J. Appl. Meteor*, vol. 45, pp. 399–415, 2006.

[67] S.-A. Boukabara, K. Garrett, W. Chen, F. Iturbide-Sanchez, C. Grassotti, C. Kongoli, R. Chen, Q. Liu, B. Yan, F. Weng *et al.*, "Mirs: An all-weather 1dvar satellite data assimilation and retrieval system," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 49, no. 9, pp. 3249–3272, 2011.

[68] A. DesRosiers, M. M. Bell, P. Klotzbach, M. Fischer, and P. Reasor, "Observed relationships between tropical cyclone vortex height, intensity, and intensification rate," *Geophys. Res. Letters*, vol. 50, no. 8, pp. 282–296, 2023.

[69] A. Molod, L. Takacs, M. Suarez, and J. Bacmeister, "Development of the GEOS-5 atmospheric general circulation model: evolution from MERRA to MERRA2," *Geosci. Model Dev.*, vol. 8, p. 1339—1356, 2015.

[70] M. M. Rienecker, M. J. Suarez, R. Todling, J. Bacmeister, L. Takacs, H.-C. Liu, W. Gu, M. Sienkiewicz, R. D. Koster, R. Gelaro, I. Stajner, and J. E. Nielsen, "The GEOS-5 Data Assimilation System - Documentation

of Versions 5.0.1, 5.1.0, and 5.2.0," *Technical Report Series on Global Modeling and Data Assimilation*, vol. 27, pp. 1–118, 2008.
[71] R. Todling and A. E. Akkraoui, "The GMAO Hybrid Ensemble-Variational Atmospheric Data Assimilation System: Version 2.0," *NASA Technical Report Series on Global Modeling and Data Assimilation. NASA/TM-219-104606*, vol. 50, 2018.
[72] M. Kim, J. Jin, A. E. Akaroui, W. McCarty, R. Todling, W. Gu, and R. Gelaro, "The Framework for Assimilating All-Sky GPM Microwave Imager Brightness Temperature Data in the NASA GEOS Data Assimilation System," *Mon. Wea. Rev.*, vol. 148, pp. 2433–2455, 2020.
[73] J. Knisely and J. Poterjoy, "Implications of self-contained radiance bias correction for data assimilation within the Hurricane Analysis and Forecasting System (HAFS)," *Wea. Forecasting*, vol. 38, p. 1719–1738, 2023.
[74] C. S. Ruf and Coauthors, "New ocean winds satellite mission to probe hurricanes and tropical convection," *Bull. Amer. Meteor. Soc.*, vol. 97, pp. 385–395, 2016.
[75] J. X. Yang, Y.-K. Lee, S. Liu, C. Grassotti, Q. Liu, W. Blackwell, R. V. Leslie, T. Greenwald, R. Bennartz, and S. Braun, "Evaluating rainfall and graupel retrieval performance of the NASA TROPICS pathfinder through the NOAA MiRS system," *Remote Sensing of Environment*, vol. 318, p. 114570, 2025.
[76] S. Po-Chedley, T. J. Thorsen, and Q. Fu, "Removing Diurnal Cycle Contamination in Satellite-Derived Tropospheric Temperatures: Understanding Tropical Tropospheric Trend Discrepancies," *J. Climate*, vol. 28, pp. 2274–2290, 2015.
[77] Z. Pu, C. Feng, W. J. Blackwell, and C. S. Ruf, "Assimilation of TROPICS and CYGNSS Satellite Data for Improved Numerical Prediction of Tropical Cyclones," in *AGU Fall Meeting Abstracts*, vol. 2023, Dec. 2023, pp. A52F–03.
[78] [Online]. Available: https://www.nrlmry.navy.mil/tcweb/active/
[79] C. R. Sampson and A. J. Schrader, "The Automated Tropical Cyclone Forecasting System (Version 3.2)," *Bull. Amer. Meteor. Soc.*, vol. 81, pp. 1231–1240, 2000.
[80] AWIPS2 Technical Library, Virtual Lab. [Online]. Available: https://vlab.noaa.gov/web/awips-technical-library/home
[81] [Online]. Available: https://disc.gsfc.nasa.gov/datasets?keywords=TROPICS%20(EVI-3)
[82] R. Honeyager, J. Guerrette, J. Munchak, and S. Flampouris, "The Tomorrow Microwave Sounder program: early observations and forecasting applications," *AGU24*, 2024.

X. Biography Section

William J. Blackwell (Fellow, IEEE) received the B.E.E. degree in electrical engineering from the Georgia Institute of Technology in 1994 and the S. M. and Sc.D. degrees in electrical engineering and computer science from MIT, Cambridge, MA, USA, in 1996 and 2002, respectively. He is currently a Laboratory Fellow in the Applied Space Systems Group at MIT Lincoln Laboratory, where he leads a number of projects involving atmospheric remote sensing, including the development and calibration of airborne and space-borne microwave sensors, the retrieval of geophysical products from remote radiance measurements, and the application of electromagnetic, signal processing, and estimation theory. He has served as associate editor of the Institute of Electrical and Electronics Engineers (IEEE) Transactions on Geoscience and Remote Sensing and the IEEE Geoscience and Remote Sensing Society (GRSS) Magazine, co-chair of the IEEE GRSS Remote Sensing Instruments and Technologies for Small Satellites working group, member of the NASA Aqua science team, and member of the National Academy of Sciences Committee on Radio Frequencies. He is the principal investigator on the NASA TROPICS Earth Venture mission and was previously the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office sensor scientist for the Advanced Technology Microwave Sounder on the Suomi National Polar Partnership launched by the National Oceanic and Atmospheric Administration (NOAA) and the Atmospheric Algorithm Development team leader for the NPOESS Microwave Imager/Sounder.

Dr. Blackwell received the MIT Lincoln Laboratory Technical Excellence Award in 2019 for his "innovative contributions to the science and practice of environmental monitoring." He was selected as a 2012 recipient of the IEEE Region 1 Managerial Excellence in an Engineering Organization Award "for outstanding leadership of the multidisciplinary technical team developing innovative future microwave remote sensing systems." In 2009, he was presented with the NOAA David Johnson Award for his work in neural network geophysical parameter retrievals and microwave calibration and is co-author of *Neural Networks in Atmospheric Remote Sensing* (Artech House, 2009) and *Microwave Radar and Radiometric Remote Sensing* (Artech House, 2015). Blackwell has also been an author of more than 200 publications related to atmospheric remote sensing and is currently the Editor of the Artech House Remote Sensing book series. He is a Fellow of the IEEE and an Associate Fellow of the American Institute of Aeronautics and Astronautics.

Scott A. Braun received his PhD in atmospheric sciences from the University of Washington, Seattle, in 1995. He is a research meteorologist at NASA's Goddard Space Flight Center and is the project scientist for NASA's Atmosphere Observing System (AOS) and TROPICS mission. He was previously project scientist for the TRMM and GPM satellites and Principal Investigator for the Hurricane and Severe Storm Sentinel (HS3) Earth Venture Suborbital investigation. He is a fellow of the American Meteorological Society.

George (Trey) Alvey received a B.S. degree in meteorology from the University of South Alabama in 2012, and M.S. and Ph.D. degrees in atmospheric science from the University of Utah in 2015 and 2019, respectively. He currently is an Associate Scientist with the Cooperative Institute for Marine and Atmospheric Studies (CIMAS). His primary research foci are using observational platforms like satellites (e.g., TROPICS) and radar and modeling systems like the Hurricane Analysis and Forecast System (HAFS) to better understand processes responsible for tropical cyclone vortex alignment and rapid intensification.

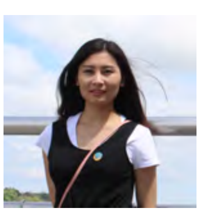
Robert Atlas received his Ph.D. in Meteorology and Oceanography in 1976 from New York University. Prior to receiving the doctorate, he was an operational weather forecaster in the U.S. Air Force where he maintained greater than 95 percent forecast accuracy. In 1978, Dr. Atlas joined NASA as a research scientist. He served as head of the NASA Data Assimilation Office from 1998-2003, and as Chief meteorologist at NASA GSFC from 2003-2005, in addition to serving as an Adjunct Professor for the University of Maryland. From 2005-2019, he served as the Director of NOAA's Atlantic Oceanographic and Meteorological Laboratory. He was a key member of the team that first demonstrated the significant impact of quantitative satellite data on numerical weather prediction and is a leading expert on Observing System Simulation Experiments. He is a recipient of the NASA Medal for Exceptional Scientific Achievement, and the American Meteorological Society's Banner I. Miller Award. In 2019, just prior to his retirement from NOAA, he was honored by the National Hurricane Center for Enduring Contributions to the nation's hurricane forecast and warning program, and by the U.S. House of Representatives for his service to the nation.

Ralf Bennartz received the Ph.D. degree in 1997 from the Free University of Berlin and the M.S. degree in atmospheric physics from the University of Hamburg, in 1994. From 2002 to 2013, he was with the faculty of the Atmospheric and Oceanic Sciences Department at the University of Wisconsin-Madison and principal investigator at the University of Wisconsin's Space Science and Engineering Center. Since 2013, he has been a Full Professor of Earth and Environmental Sciences at Vanderbilt University. His research interests include satellite remote sensing and atmospheric radiative transfer in the near-infrared and microwave spectral range. Prof. Bennartz is also past editor (2006–2010) of the American Meteorological Society's Journal of Applied Meteorology and Climatology.

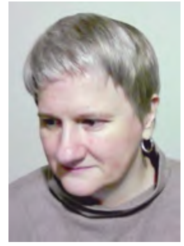
Jessica Braun received a B.S. and M.S degree in Atmospheric and Oceanic Science from the University of Wisconsin-Madison in 2004 and 2007, respectively. She is currently the Project Manager for the TROPICS Data Processing Center (DPC) and the National Weather Service (NWS) Geostationary Weather Satellite Antenna Systems (GWSAS) CSPP Geo Software Operations and Maintenance project at the Space Science and Engineering Center at the University of Wisconsin-Madison. She previously worked for SSAI Inc. on the NOAA Operations and Maintenance Contract, managing the Atmosphere Physics group creating and distributing geophysical products from geostationary and polar orbiting satellites to the National Weather Service.

Kerri Cahoy (Member, IEEE) received the B.S. degree in electrical engineering from Cornell University, Ithaca, NY, USA, in 2000, and the M.S. and Ph.D. degrees in electrical engineering from Stanford University, Stanford, CA, USA, in 2002 and 2008, respectively.

She previously worked at Space Systems Loral, as a Post-Doctoral Fellow at NASA Ames, Mountain View, CA, and currently leads nanosatellite atmospheric sensing, optical communications, and exoplanet technology demonstration missions. She is a Professor and of Aeronautics and Astronautics with MIT, Cambridge, MA, USA, and leads the Space Telecommunications, Astronomy, and Radiation (STAR) Laboratory.



Ruiyao Chen received the B.S. degree in Electrical Engineering from Wuhan University of Science and Technology, Wuhan, China in 2012. She received her M. S. and Ph.D. degrees in Electrical Engineering from the University of Central Florida in 2014 and 2018, respectively. She is currently a research scientist in the Department of Earth and Environmental Sciences at Vanderbilt University. Her work focuses on ice particle scattering, precipitation algorithm development and instrument calibration. Her research interests include satellite remote sensing, atmospheric radiative transfer and machine/deep learning.



Galina Chirokova is a research scientist at the Cooperative Institute for Research in Atmosphere (CIRA) in Fort Collins, CO. Galina joined CIRA in 2012, and her work at CIRA has been focused on three main areas: (1) Development of tropical cyclone (TC) applications from satellite microwave retrievals and polar-orbiting and geostationary satellite imagery using machine learning and other techniques; (2) Improvement to statistical TC analysis and forecast models using quantitative parameters from satellite and other data, with an emphasis on intensity forecasting; and (3) Transition of analysis and forecast methods to operational forecast centers. Galina has extensive experience working with JPSS and GOES satellite data and she is the principal investigator and managing multiple CIRA TC projects. She developed the night-time ProxyVis Imagery that provides geostationary (GOES and Himawari) full-disk animated visible-like imagery at night, and has extensive experience in developing and transitioning to operations TC satellite products and operational statistical models used at the National Hurricane Center, Joint Typhoon Warning Center, and other operational centers.

Brittany Dahl received B.S. and M.S. degrees in meteorology from the University of Oklahoma in 2011 and 2014, respectively. She is currently a Senior Research Associate with the Cooperative Institute for Marine and Atmospheric Studies (CIMAS) at the University of Miami, Miami, FL, USA, where she has been on staff since 2015. Her research centers around improving numerical prediction of tropical cyclones through data assimilation, including crewed and uncrewed reconnaissance aircraft, land-based radar, and satellite observations.

James (Jim) Darlow served 20 years in the U.S. Air Force as a Weather Technician at multiple locations across the globe. He earned his M.S. in Geosciences from Mississippi State University in 2011. He has been at the Joint Typhoon Warning Center since 2007 and works as a Meteorological Technician in the Technical Services Department as a qualified tropical cyclone Satellite Analyst. James was instrumental in sharing operational requirements with the TROPICS Early Adopters team, allowing consideration for exploring Near-Real-Time opportunities vital to operational Tropical Cyclone Warning Centers and collaborating researchers. James worked extensively with Cooperative Institute for Research in the Atmosphere (CIRA) Colorado State University, to implement AWIPS2 display of TROPICS and other new satellite imagery.

Mark DeMaria received a B.S. degree in Meteorology from Florida State University in 1977 and M.S. and Ph.D. degrees from Colorado State University in 1979 and 1983, respectively. He is currently a senior research scientist at the Cooperative Institute for Research in the Atmosphere at CSU and spent most of his career at NOAA working in research and operations. He is a Fellow of the American Meteorological Society (AMS) and received the AMS Banner Miller Award five times for development of tropical cyclone forecast applications. He has authored or co-authored more than 100 refereed journal articles on tropical cyclones, satellite meteorology, and numerical weather prediction.

Michael DiLiberto received a B.S. degree in electronic engineering technology from Wentworth Institute of Technology, Boston, MA in 2008 and a M.S. degree in electrical engineering from Tufts University, Medford, MA in 2012.

He has been a member of the Technical Staff at MIT Lincoln Laboratory in the Applied Space Systems Group since 2008 and has contributed to a number of remote sensing projects focusing on measuring Earth and its atmosphere. His research interests include radiometer calibration and satellite sensor geolocation.

Jason P. Dunion received his B.A degree from the University of New Hampshire in geography and geology in 1992. For the next 3 years, he worked as a social worker in Connecticut and Miami, Florida while also completing his graduate school prerequisite courses. He earned his M.S. degree in atmospheric and oceanic sciences at the University of Wisconsin-Madison in 1999 and his Ph.D. in atmospheric science at the University at Albany-SUNY in 2016. Jason specializes in satellite remote sensing of hurricanes and has led the development of several new satellite products for monitoring tropical cyclones and Saharan dust storms as well as a scheme for predicting tropical cyclone genesis. He has served as Director of NOAA's Hurricane Field Program since 2021, acted as chief scientist on several Hurricane Hunter research missions using NOAA's G-IV high altitude jet and P-3 Orions, and has flown on over 50 Hurricane Hunter flights. He is also a member of NOAA and NASA science teams that study Atlantic and Pacific hurricanes with high altitude drone aircraft and Office of Naval Research and NASA teams studying tropical cyclone rapid intensification, hurricane upper-level outflow layers, and tropical convection.

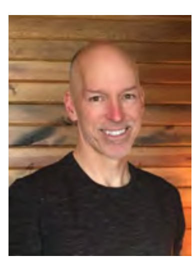
Patrick Duran received a B.S. degree in meteorology from the Florida Institute of Technology in 2012 and a Ph.D. in atmospheric science from the University at Albany, State University of New York, in 2018. He is a research scientist at NASA's Marshall Space Flight Center (MSFC) and the tropical meteorology team lead at NASA's Short-Term Prediction Research and Transition (SPoRT) Center. He leads the operation of MSFC's Geostationary Operational Environmental Satellite (GOES) receiving station and is the TROPICS mission applications lead.

Thomas J. Greenwald received the B.S. degree in physics from the University of Minnesota, Minneapolis, MN, USA, in 1983, the M.S. degree in Meteorology from the University of Wisconsin-Madison, WI, USA, in 1985, and the Ph.D. degree in Atmospheric Science from Colorado State University, Fort Collins, CO, USA, in 1994. He is a senior scientist at the Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin-Madison, specializing in radiative transfer theory and passive microwave remote sensing. His research includes radiative transfer modeling in satellite data assimilation and the GOES-R/GEOXO programs, and the development and application of microwave observations of atmospheric moisture and temperature, clouds, precipitation, and ocean/sea ice properties.

Sarah Griffin received a B.S. degree and M.S. degree in Atmospheric and Oceanic Sciences from the University of Wisconsin-Madison, Madison, WI, in 2009 and 2011, respectively. She has been a Research Scientist at the Cooperative Institute for Meteorological Satellite Studies since 2011, with research interests including tropical cyclones and machine learning.

Zachary Griffith received the B.S. degree in physics from the University of Northern Iowa in 2013 and the Ph.D. degree in physics from the University of Wisconsin-Madison in 2019. Since 2019, he has been a Data Engineer at the University of Wisconsin-Madison Space Science and Engineering Center and is a member of the TROPICS Data Processing Center.

Jeffrey D. Hawkins received his B.S. and M.S. degrees in Meteorology from Florida State University in 1976 and 1979. He spent three seasons working at NOAA'S Hurricane Research Division (HRD) in Miami, FL. His work focused on air-sea interaction as tropical cyclones (TC) routinely create a "cold wake" via upwelling. He also did calibration flights under NASA's SEASAT satellite focusing on the SFMR and scatterometer (SCAT) while flying radial legs through and around TCs ranging from depressions to hurricanes. Due to the SEASAT work, Jeff began work at the Naval Research Laboratory's Oceanography Division located at Stennis Space Center, MS (NRL-SSC, 1980-1992). As a satellite oceanographer, he helped create and transition new capabilities to the Navy's operational centers dealing with sea surface temperatures (SST), altimeter derived sea surface heights (fronts and eddies), and passive microwave measured sea ice edge, thickness, and age. From 1992-2015 he worked at NRL's Marine Meteorology Division, Monterey, CA where he led a team that created novel satellite visible, infrared, and passive microwave imager and sounder products. The sensors used included more than 30 instruments on NOAA, NASA, ESA, EUMETSAT, and JMA polar orbiters and geostationary satellites. Applications ran the gamut from dust detection via MODIS and Meteosat to TC location, structure, and intensity via PMW imagers/sounders such as SSM/I, SSMIS, TMI, and SSMIS, AMSU, and ATMS while collaborating with multiple academic institutions. Jeff is an AMS Fellow and received the Navy's Meritorious Civilian Service Award for his accomplishments. Since retirement, he has been a member of TROPICS Standing Review Board (SRB), the TROPICS Science Team, while consulting with Northrop Grumman and now part-time with the U. of Wisconsin/CIMSS.



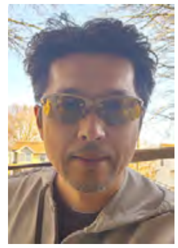
Derrick Herndon served in the Navy for eight years as a tactical weather forecaster/oceanographer before getting his B. S. degree in meteorology from Florida State University, Tallahassee, FL in 2000. He previously worked for WorldWinds LLC at Stennis Space Center, MS where he helped develop and evaluate mesoscale weather models for commercial and Navy applications. He has been a member of the Cooperative Institute for Meteorological Satellite Studies (CIMSS) Tropical Cyclone (TC) Group at the University of Wisconsin since 2002. His research focuses on satellite remote sensing applications of TCs and their environment in addition to serving as a member of the CIMSS outreach and education team.

Satya Kalluri received his Ph.D. from the University of Maryland at College Park in 1994 and M.Sc. from Osmania University in Hyderabad, India in 1990. He is the senior scientist for NOAA's Low Earth Orbit (LEO) observations, and is responsible for mission science from current and future LEO satellites including data evaluation and exploitation for operational applications. He has over 30 years of experience working on several missions including NOAA POES, GOES-R, JPSS, Landsat, Terra, Aqua, and Metop; and worked at the University of Maryland at College Park, NASA Goddard Flight Center, The Aerospace Corporation and Raytheon.

Min-Jeong Kim earned her Ph.D. from the University of Washington in 2014 and is currently a Research Physical Scientist at NASA's Goddard Space Flight Center. Specializing in atmospheric data assimilation and satellite data applications, she integrates satellite observations into global weather and climate models. Dr. Kim contributes to advancing NASA's Earth Science objectives, focusing on enhancing data assimilation techniques and exploiting new observations for Earth system modeling and analysis.

R. Vincent Leslie (Senior Member, IEEE) received the B.S. degree in electrical engineering from Boston University, Boston, MA, USA, and the M.S. and Ph.D. degrees in electrical engineering from the Massachusetts Institute of Technology (MIT), Cambridge, MA, in 1998, 2000, and 2004, respectively. He was a Graduate Research Assistant with Remote Sensing and Estimation Group, Research Laboratory of Electronics, MIT, specializing in passive microwave radiometry. He is a member of the Technical Staff with Applied Space Systems Group, MIT Lincoln Laboratory, Lexington, MA, and the TROPICS Instrument Scientist.

Frank Marks was a meteorologist with the Hurricane Research Division at the Atlantic Oceanographic and Meteorology Laboratory for NOAA from 1980-2024, and director from 2003-2023. He led the development of the NOAA Hurricane Forecast Improvement Program (HFIP) from 2007-2024. He also served as an Adjunct Professor in the Department of Meteorology and Physical Oceanography at the University of Miami, as well as a Fellow of marine and atmospheric research at the University of Miami's Cooperative Institute for Marine and Atmospheric Studies. He is a member of the American Meteorological Society, becoming a fellow in 2000, and serving on the Council from 2013-2016. Marks' research interests include analyzing meteorological remote sensing data sets (e.g., microwave radar and radiometer), particularly in tropical cyclones. He received a B.S. in Meteorology from Belknap College and both an M.S. and Sc.D. in Meteorology from the Massachusetts Institute of Technology.



Toshi Matsui received a B.E. degree in civil engineering from Kobe University, Kobe, Japan, in 1999, an M.S. in Earth and Environmental Resources Management from the University of South Carolina, Columbia, SC, USA, in 2002, and a Ph.D. in atmospheric science from Colorado State University, Fort Collins, CO, USA, in 2007. He is currently a Research Scientist at NASA Goddard Space Flight Center (GSFC) through the Earth System Science Interdisciplinary Center (ESSIC), University of Maryland, College Park. His research focuses on convection and precipitation processes, integrating theoretical studies, process modeling, remote sensing, and instrument simulation.

Adam Milstein has led and contributed to a variety of projects related to remote sensing and Earth science. He currently serves as PI of the NASA Decadal Survey Incubation science investigation, "AI-Enhanced Infrared Sounding of the Planetary Boundary Layer". Recently, he has served as PI for "Computational Reconfigurable Imaging Spectrometer (CRISP)", a new imaging spectrometer concept funded under a NASA ESTO's Advanced Component Technology award. He has also recently served as PI of "Improved Sounding of Boundary Layer Inversions", a science investigation funded by NASA as a "Science of Terra, Aqua, and Suomi NPP" award. Dr. Milstein is also currently PI of development efforts on the AIRS V7 Level 2 sounding retrieval neural network first guess. He has led attitude control system development and geolocation algorithm development for the successful MicroMAS-2A CubeSat mission. For the GOES-R series, he supported systems engineering and validation of the image navigation and registration systems for the Advanced Baseline Imager and the Geostationary Lightning Mapper instruments. Dr. Milstein's research has also included modeling and algorithm development efforts for laser radar remote sensing, scattering of light from aerosols, and Bayesian methods for solving ill-posed inverse problems.

Glenn Perras received a B.S. degree in meteorology from Lyndon State College, Lyndonville, VT in 1994 and began his career at MIT Lincoln Laboratory that same year. He participated in aviation weather research in support of FAA-funded programs until 2009 when he began focusing on satellite operations for various government sponsors. He currently serves as the TROPICS mission operations manager.

Michael L. Pieper is a technical staff member of the Applied Space Systems Group at MIT Lincoln Laboratory. He received a Ph.D of electrical engineering from Northeastern University in 2017. Research interests related to this paper include atmospheric profile retrievals using neural networks with microwave radiometers. Additional interests include atmospheric compensation, detection, identification, and temperature-emissivity separation of hyperspectral imagery in the VNIR-SWIR and LWIR. Projects of significance have included implementing a neural network profile retrieval algorithm for the NASA AIRS program, and military utility assessments (MUA) of several VNIR-SWIR hyperspectral sensors, including the TacSat-3 Advanced Responsive Tactically-Effective Military Imaging Spectrometer (ARTEMIS) and Airborne Cueing and Exploitation System-Hyperspectral (ACES-Hy) sensor.

Robert (Rob) Rogers is the Science Director and Chief Scientist for Typhoon Observations and Research at the Asia-Pacific Typhoon Collaborative Research Center in Shanghai, China. His main areas of research involve studying the role of convective- and vortex-scale processes in tropical cyclone (TC) structure and intensity change, primarily using in situ and remotely-sensed aircraft and satellite observations and numerical models. Prior to his current position, Dr. Rogers worked at the Hurricane Research Division within the National Oceanic and Atmospheric Administration, where he participated in many hurricane hunter missions, experiencing a wide range of conditions ranging from lightning strikes in outer rainbands to periods of zero gravity during eyewall penetrations of rapidly-intensifying hurricanes. He received his Bachelor's degree in Environmental Science from University of Virginia and his M.S. and Ph.D in Meteorology from The Pennsylvania State University. He has received funding from NOAA, NASA, ONR, and NSF for his research. He has been interviewed for Science Magazine and The New York Times and he has appeared on the Today Show, Fox News, and MSNBC to discuss his research. He received the Banner I. Miller Award, which is an AMS award for outstanding contribution to the science of hurricane and tropical weather forecasting in a publication with international circulation.

Christopher Velden received his B.S. degree in Geography and Natural Science from the University of Wisconsin-Stevens Point in 1979, and M.S degree in Atmospheric Science from the University of Wisconsin-Madison in 1982. His current position is Senior Research Scientist and PI at the University of Wisconsin Space Science and Engineering Center (UW-SSEC), Cooperative Institute for Meteorological Satellite Studies (CIMSS). He is Lead PI for the CIMSS Satellite Winds Research Group and founded the Tropical Cyclone Research Team. He was elected Fellow of the American Meteorological Society (AMS) in 2008, and his major accomplishments include two AMS Banner Miller Awards (2001 and 2018), two AMS Special Awards (1998 and 2015), a NASA Agency Honor Award (2017), an Office of the Federal Coordinator for Meteorology Hagemeyer Award (2003), and the U. of Wisconsin Chancellors Research Excellence Award (2012). He has lead-authored over 30 refereed publications and coauthored 250+ scientific conference papers since 1983. Major Field and Professional Experience includes Chairing of several AMS and World Meteorological Society (WMO) committees, working groups and workshops, and a member of several prominent National Academy of Sciences committees including the TRMM/GPM Study, the NPOESS/GOES-R Study, and the NASA Decadal Survey. He served as a long-term subject matter editor for the Bulletin of the AMS, and has been a participant in 15+ major atmospheric field programs since 1986. His research interests include satellite applications to weather phenomena with a focus on tropical cyclones.

Yalei You received the B.S. and M.S. degrees in atmospheric science from Yunnan University, Kunming, Yunnan, China, in 2005 and 2008, respectively, and the Ph.D. degree in meteorology from Florida State University, Tallahassee, FL, USA, in 2013. He is an assistant professor at the Department of Earth and Ocean Sciences, University of North Carolina, Wilmington, NC, USA. His research interests include passive microwave precipitation algorithm development and microwave instrument calibration. Dr. You served as an Associate Editor for the Journal of Hydrometeorology.

Nick V. Zorn earned BSEE and MSEE degrees from University of Pittsburgh in 2000 and 2003. Since joining MIT Lincoln Laboratory in 2003, he has written real-time control software for electro-optical and passive microwave payloads operating from satellite and airborne platforms. He develops algorithms to process and exploit data from EO and microwave sensors and is experienced in satellite anomaly investigation and resolution.