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Data Validation of the NASA Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) Pathfinder Microwave Radiometer

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ABSTRACT

Launched in June 2021, the TROPICS Pathfinder CubeSat has a microwave radiometer payload sensitive to the frequencies for observing precipitation, humidity, temperature, and cloud ice. The observed brightness temperatures must be compared to a data set of ‘known’ quality to validate the measured data across all channels of the microwave radiometer. This research explores validating TROPICS Pathfinder data against reanalysis data to determine the quality of the provisional TROPICS Pathfinder data product, with an eye for the future of comparing against other microwave radiometer measurements. Validation involves comparing Pathfinder data to ERA5 reanalysis data by using the Community Radiative Transfer Model (CRTM) to calculate simulated radiances. The simulated radiances are then compared to the on-orbit Pathfinder data to determine biases, in a method known as single-differencing. The Pathfinder data presented here is at the provisional data maturity level and should be considered preliminary. This effort will be repeated when the TROPICS Pathfinder Level-1 radiances reach the validated data product maturity level late in the summer of 2022.

To effectively validate the Pathfinder mission, we have developed a process using MATLAB to read and match the TROPICS Pathfinder data for latitudes between -40° – 40° with desired data for comparison, which is ERA5 in this research. These latitude-longitude data match-ups are then filtered for data points without clouds, using cloud cover data from the GOES-16 satellite. Using data that is cloud-free and over-ocean ensures that single-differencing comparisons are made using like-data sets and will result in minimal error introduced by the reanalysis and radiative transfer models. After filtering the data, this validation process generates the input files required by CRTM to simulate the model, simulates these observations using the unique Pathfinder CRTM coefficients resulting in the most accurate data, and performs the necessary difference calculations. The end result is an automated process that performs data comparisons for researchers, and we present them as a summary for analysis. The provisional Level-1 radiances show good agreement with combined ERA5 and CRTM simulated radiances, and we expect even better agreement with the upcoming validated Level-1 radiances.

1 Introduction

The Time-Resolved Observations of Precipitation structure and storm intensity with a Constellation of Smallsats (TROPICS) mission is a NASA mission selected to provide nearly all-weather observations of the temperature and humidity structure of Earth's atmosphere over the tropics.[1] It will also provide observations of cloud ice and precipitation horizontal structure. TROPICS will collect observations of the atmosphere at a high temporal resolution, which is beneficial for monitoring the rapidly-evolving features of tropical cyclones (TCs).

1.1 TROPICS Mission Overview

TROPICS is comprised of a constellation of CubeSats paired in separate low-Earth orbital planes, allowing for median observation revisit rates of around 60 minutes. The constellation is designed to obtain measurements of TCs in the tropical latitudes using a passive microwave spectrometer. The constellation will provide rapid-refresh measurements to observe the thermodynamics of the troposphere and precipitation structure of storm systems,[1] which will lead to significant advances in storm track prediction.

The TROPICS constellation launches are planned to occur within a 60-day window of each other, with at least two CubeSats on each launch vehicle. The TROPICS Pathfinder space vehicle was launched on June 30, 2021 as a test for the full TROPICS mission and is currently observing in a sun-synchronous orbit with a local time of ascending node (LTAN) of 02:00:00 at launch.

1.2 TROPICS Observation Platform

The TROPICS observation platforms each host a passive microwave spectrometer developed at Massachusetts Institute of Technology (MIT) Lincoln Laboratory (LL). The Pathfinder mission, a precursor to the main TROPICS mission, has an identical payload to the TROPICS constellation. It is designed to test the microwave spectrometer and provide information in advance of the constellation. The main TROPICS mission is designed with 6 3U satellites. Each satellite pair will be flown in Low-Earth Orbit (LEO), in separate orbital planes for each pair, all at an orbital inclination of 30°.[1] The combination of multiple space vehicles and the geometry of the orbital planes will allow for rapid observation revisit rates.

The payload consists of a passive microwave spectrometer that measures spectral radiance in 12 channels over the cross-track direction of the satellite. The radiometers provide measurements in seven channels near 118.75 GHz (oxygen absorption band), three channels near 183 GHz (water vapor absorption line), one channel near 90 GHz (imagery for precipitation measurements), and one channel near 205 GHz (cloud-ice particle detection).[1] Channels and their respective frequencies and beamwidths are listed in Table 1.

Table 1: TROPICS Channels[2] and Corresponding Analysis Groups

Channel	Frequency (GHz)	Beamwidth (°) Down/Cross	Analysis Group
1	91.655 +/- 1.4	3.0/3.17	1
2	114.50	2.4/2.62	2
3	115.95	2.4/2.62	2
4	116.65	2.4/2.62	2
5	117.25	2.4/2.62	2
6	117.80	2.4/2.62	2
7	118.24	2.4/2.62	2
8	118.58	2.4/2.62	2
9	184.41	1.5/1.87	3
10	186.51	1.5/1.87	3
11	190.31	1.5/1.87	3
12	204.80	1.4/1.83	4

1.3 TROPICS Science Objectives

The mission has three science objectives with the overall goal of providing nearly all-weather observations of the 3-D temperature and humidity structure of the troposphere to investigate the lifecycles of TCs. The first objective is to establish relationships between the precipitation structure, upper-level warm-core evolution, and associated storm intensity changes of TCs. The second objective is to relate the evolution of TC precipitation structure and storm intensification to environmental humidity fields. The third objective is to determine the impact of TROPICS rapid-update observations on the numerical and statistical intensity forecasts of TCs.[1]

1.4 Microwave Radiometers

Each TROPICS payload will host a radiometer to collect the various data products. Microwave radiometers measure the thermally-emitted radiation from an object at microwave frequencies, usually expressed in terms of brightness temperature

(T_B). These frequencies are advantageous for Earth-weather monitoring due to their high atmospheric transmissivity.[3] Combining observations in multiple frequency bands also enables the investigation of the vertical atmospheric structure.

1.5 Radiative Transfer Models

To compare the quality of the data collected by the on-orbit instruments, observed brightness temperatures must be compared to data sets of "known" quality. To effectively validate the measurements collected by Pathfinder, we calculate simulated radiances with a radiative transfer model.

Radiation transfer describes the transfer of energy through a medium and can be described using the radiative transfer equation (RTE). Radiative transfer models use the RTE to numerically solve the propagation of radiation through the atmosphere and determine how radiation interacts with particles.

Line-by-line (LBL) radiative transfer models compute radiance by exactly accounting for the contribution of all individual absorption lines. LBL models are rigorous, but are computationally expensive. Fast radiative transfer models have been developed to reduce the computational time of calculating absorption and transmittance in the atmosphere. In this work, we use the Community Radiative Transfer Model (CRTM), developed by the Joint Center for Satellite Data Assimilation (JCSDA)[4] to simulate atmospheric observations. This model uses parameterizations and lookup tables to quickly calculate simulated radiances.

2 Calibration and Validation of Microwave Radiometers

Observing instruments require calibration and validation to ensure consistent measurements and an accurate data product. Typical calibration sources for warm calibration of microwave radiometers on large satellites are too big to be flown on CubeSats, so rather than using a blackbody calibration source, CubeSat-based radiometers employ noise diodes.[5,6] However, noise diodes can drift over time and introduce error into the measurements.[7] Therefore, we must correct for noise diode drift using calibration and validation methods.[8,9]

2.1 Calibration

While CubeSat instruments are calibrated prior to launch, re-calibration is required to account for any change in instrument performance over time. The TROPICS calibration sources involve deep space for the cold point and a weakly coupled noise source for the warm calibration point.[10] Calibration methods for the deep space and noise diode calibration points were determined prior to launch and are described in the TROPICS Algorithm Theoretical Basis Document (ATBD) version 2.0 for the provisional Level-1 radiance data,[10] but are beyond the scope of this paper.

2.2 Validation

Data validation compares satellite data to other measurements in order to determine the overall quality of the instrument data product. The TROPICS validation plan is similar to those used by other on-orbit passive microwave radiometers for validation, such as the MicroMAS-2A mission.[2,11] In this work, we will describe our steps toward the single differencing process, which involves comparing TROPICS data with simulated data from a radiative transfer model. We utilize the ERA5 Reanalysis data generated by the European Centre for Medium-Range Weather Forecasts (ECMWF) for our known quality data source for simulation.[12,13] We generate our simulated radiances in CRTM with TROPICS Spectral Response coefficients and compare the output to the TROPICS Pathfinder data.

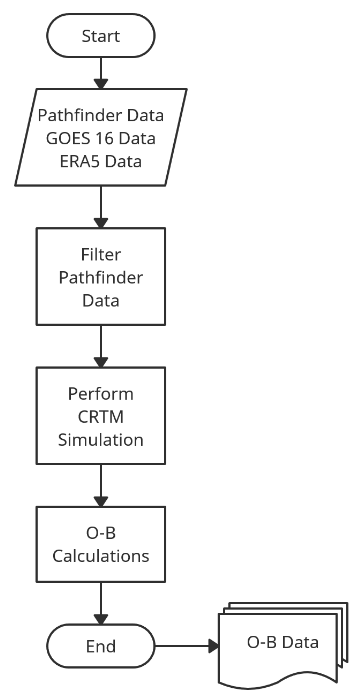

Figure 1: Overall view of the TROPICS data validation process

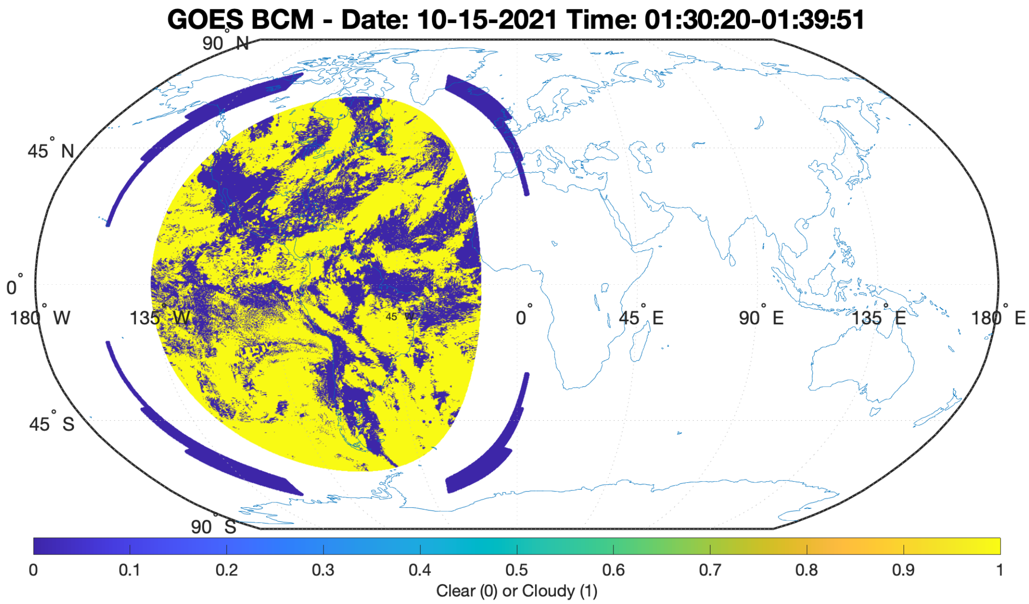

Figure 2: Example GOES-16 cloud observation data from 2021-10-15

3 Validation Architecture

Analyzing large quantities of data necessitates automation to some degree. The end result is to have Pathfinder observation data ingested into the process and have the single differences, or observation minus background (O-B), returned to data scientists for further analysis, as shown in Figure 1.

3.1 Purpose

To validate on-orbit microwave radiometer observations, the data must be compared with another data set of known quality to determine the difference. Comparisons must be across similar data sets, meaning that only like-frequencies, geographical matches, and close temporal observations may be considered suitable.

For the purposes of this research, we use the single differencing methodology described by Dr. Crews[9] as a foundation and build upon her research for higher resolution single differencing. Single differencing refers to the subtraction of on-orbit data and simulated data output by a radiative transfer model with the atmospheric conditions at the time of satellite observation, more commonly called Observation Minus Background or O-B. The result is the difference between the on-orbit observed data and corresponding simulated data.

To ensure that comparison across the data sets is accurate and to remove any points where error may be introduced, our analysis is limited to data in clear air and over open ocean, because land and clouds introduce additional brightness temperature information into the data that is not accounted for in the simulated comparison data set. We use cloud data from the Geostationary Operational Environmental Satellites (GOES) 16. Additionally, Pathfinder observations in this analysis were filtered for points that were collected near-nadir, because the projected surface area observed by the Pathfinder microwave radiometer drastically changes over the range of scan angles. By limiting the data set to scan angles near nadir, we can ensure that the scan spot sizes of each observation are roughly the same and the observation is being made through approximately the same line-of-sight distance through the atmosphere.

3.2 Data Inputs

3.2.1 TROPICS Pathfinder Data

TROPICS Pathfinder observations are read into MATLAB and include the following variables: observation latitude, observation longitude, time of observation, whether or not the observation is over land or sea, observation scan angle, observation zenith angle, observation brightness temperature, and data quality, which are respectively *losLat_deg*, *losLon_deg*, *timeE*, *LandFlag*, *losScan_deg*, *losZen_deg*, *tempBrightE_K*, and *calQualityFlag*.

3.2.2 GOES Cloud Observation Information

We have chosen to filter the data for clouds by using the GOES Clear Sky Mask Product. The clear sky mask is a GOES Level 2 product that contains a binary cloud mask, which identifies cloud coverage by labeling pixels as either “clear” or “cloudy”. The clear sky mask has a resolution of 2 km for the Advanced Baseline Imager (ABI) bands, which is the primary instrument for imaging Earth’s weather aboard GOES.

The GOES spacecraft reside in a geostationary orbit, meaning they remain stationary relative to Earth’s surface. This geostationary position provides the GOES spacecraft with a full disk view of the Earth, centered at a longitude of 75.2° West, which allows for full visibility of the contiguous United States in the Northern Hemisphere.[14] This full disk view provides us with access to cloud data for approximately half of the longitude range of the TROPICS observations.

The GOES ABI default scan mode (Scan Mode 6) takes a full disk image every ten minutes,[15] with approximately 30 seconds between observation files. From these files, we pull the latitude, longitude, binary cloud mask, the data quality flag, and the start and end times of observation. The data quality flag values range from 0-6, with points marked as 0 being the good quality data. We filter the binary cloud mask for those good quality points and then compare the geographical locations of the cloud mask points to the Pathfinder data.

3.2.3 ERA5 Reanalysis Data

While options for reanalysis data include MERRA-2 and ERA5, the ERA5 simulated reanalysis data was selected because of a higher number of data match-ups between reanalysis and satellite-observed data, due to ERA5’s finer temporal and spatial resolution. ERA5 surface and pressure level data is published on an hourly basis, globally, and with a spatial resolution of 0.25°.[16,17] From the surface data set, we utilize the variables 10 m u- and v-component of wind, mean sea level pressure, surface pressure, sea surface temperature, ice temperature layers 1-4, and sea-ice cover. From the pressure level data set, we use the variables for geopotential, specific humidity, ozone mass mixing ratio, specific cloud liquid water content and temperature.

3.3 Filtering TROPICS Pathfinder Data

The first portion of the automation is to filter the Pathfinder dataset for like-points for comparison. To automate this part of the single differencing process, we chose MATLAB as the data-formatting language due to its capability to handle large data sets and interface with CRTM. The filtering process is outlined in Figure 3.

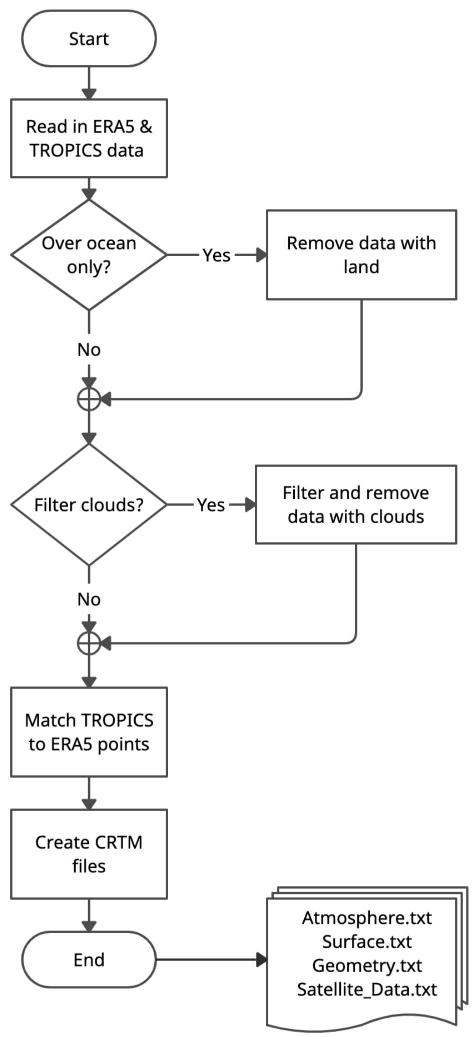

Figure 3: Filter Pathfinder Data portion of the TROPICS data validation process

3.3.1 Filtering Over-Ocean Data

The TROPICS data contains a calibration quality flag, *calQualityFlag*, which contains 8 bits of information, including a non-ocean point flag. This

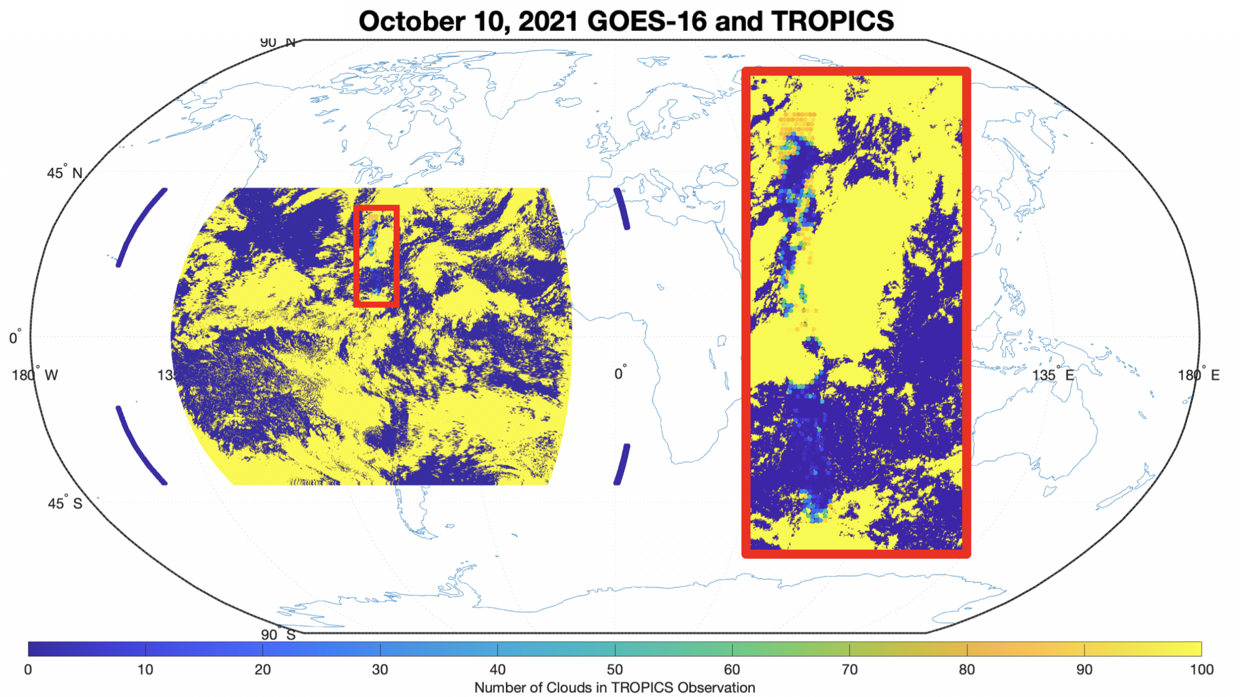

Figure 4: TROPICS Pathfinder observation matchups overlayed with respective GOES-16 data for one Pathfinder orbit

variable also contains a lunar/solar intrusion flag, a spacecraft maneuver flag, a cold calibration consistency flag, a hot calibration consistency flag, an ascending/descending scan position flag, a day/night flag, and a payload orientation in flight path flag. We use this data quality flag to separate the points that are over ocean in the TROPICS Pathfinder data for further analysis

3.3.2 Filtering Near Nadir Data

The indices for near-nadir observations are found using the *losScan_deg* variable in the TROPICS Pathfinder data. This variable describes the angle between local nadir at the satellite and the line-of-sight vector to the Earth's surface. Single differencing results discussed in this presentation fall within $\pm$ 10° of nadir. This range was selected to compare data points that observed similarly-sized geographical areas.

3.3.3 Filter Cloud Free Data

To ascertain if the observed data is clear of clouds, we determine the size of each observation point and then match each TROPICS point with the corresponding GOES cloud information. Due to the observation cadence of GOES-16 cloud information in Mode 6, each Pathfinder observation is matched with cloud information no more than 10 minutes in temporal separation.

Since the GOES cloud observations are recorded in a fixed-grid format and the TROPICS Pathfinder observations are oval-shaped and cover significantly more geographical area, we first must determine whether or not the GOES cloud data points fall within the area of a Pathfinder observation. We compare these points by re-defining the Pathfinder observation shape from an oval centered on the latitude and longitude of the observation to a square observation that has a set width and height. The size of the this rectangle is currently set at a constant 22 km, which corresponds to the average geometric mean of the scan spots within $\pm$ 10° of nadir across all TROPICS channels. Future work will incorporate true scan spot sizes for each scan spot and band in this calculation, which will provide a higher degree of accuracy to our cloud comparisons. Data match-ups between Pathfinder and the GOES-16 cloud information can then be made with this updated latitude and longitude window.

Each GOES cloud data point is marked either 1 indicating the presence of clouds or 0 indicating clear sky, as shown in Figure 2. All the cloud data match-ups for a single Pathfinder observation are summed. A summed result of greater than 1 indicates some number of clouds marked by GOES in the Pathfinder field of view, while a summed result of zero indicates that the TROPICS Pathfinder observation is clear of clouds and therefore a good candidate for single differencing. A cloud cover fraction can then be performed with this data for additional situational awareness. Figure 4 shows Pathfinder observation matchups with summed cloud data overlayed on the respective GOES-16 cloud data it is being compared against.

3.3.4 ERA5 Reanalysis Match-ups

ERA5 data is published hourly and with a spatial resolution of 0.25°. Because TROPICS Pathfinder data is observed nearly continuously in some data sets, a portion of the automation is to match the Pathfinder observation point with the nearest published ERA5 data point, both spatially and temporally. Spatially, this is accomplished by utilizing the haversine formula to find the nearest ERA5 point. For temporal match-ups, data points observed with times ending in less than 30 min past the hour are matched with data published on that hour (<30 minutes previous). Data points observed with times greater than 30 minutes past the hour are matched with ERA5 data published the following hour (<30 minutes later). In this way, Pathfinder data is matched with ERA5 data that is no more than 30 minutes in temporal separation.

3.4 CRTM

For this work, we utilize version 2.3.0 of CRTM to generate simulated radiances and perform radiance validation of TROPICS Pathfinder data. CRTM is a 1-D radiative transfer model written in Fortran that uses atmospheric profile data, surface data, satellite coefficients, and scan angles to calculate simulated brightness temperatures.[4] We have integrated updated sensor coefficients for the TROPICS Pathfinder instrument with CRTM, provided to us via the TROPICS program.[18] These coefficients will be standard in CRTM version 2.4.1, which is currently under development.

We generate the atmosphere, surface, and geometry profiles of the filtered data points in the previous step. CRTM uses these profiles to simulate the atmospheric conditions that we expect to see at the same time of the TROPICS Pathfinder observations. These simulations provide the "background" measurement in our O-B, or single difference, calculations. The outputs of the CRTM simulation are subtracted from the filtered Pathfinder data observations. This results in the single difference value.

4 Results

To obtain a strong estimate of instrument performance, we selected one full month of data on which to perform single differencing: October 2021. This data set was selected based on data availability for the month, and October 2021 had some of the most complete sets of data. Additionally this data set was limited to observations at -40° - 40° in latitude and the longitudes of the GOES-16 cloud coverage. This resulted in approximately 198,213 match-ups for consideration.

A histogram plot of single differences for all channels can be found in Figure 5. Histogram plots separated by channel, as well as plots comparing simulated to observed data, can be found in Appendix A. Ideal data should have a low standard deviation and kurtosis, indicating that the data is both accurate and precise.

Heatmaps of the observed vs simulated brightness temperatures can also be found in Appendix A. Ideally the heatmaps will have a 1:1 linear quality to them indicating that the observed temperature is the same as the simulated temperature.

5 Discussion

Based on the histogram in Figure 5, it is found that the average single difference across all channels is 0.671 K. Higher single differences are anticipated for channels sensitive to the surface and channels sensitive to water vapor, which are two areas that ERA5 and CRTM have the largest variability. Individual outliers are potentially due to cloud-impacted measurements included in the statistics.

5.1 Channel differences

When comparing the single differencing among the channels, we see variation in the standard deviation results across each channel. For example, channel 1 exhibits a standard deviation of 11.94 K compared to a standard deviation of 0.892 K for channel 6.

Indeed, channel 1 shows the largest deviation from 0 K of the 12 channels based on our simulations, with a mean of 0.62321 K and standard deviation of 11.94 K. This data spread may be due to surface emissivity model deficiencies and surface water temperature uncertainties. Channels 2-8 (114.5 - 118.58 GHz) exhibit means near 0 K and small

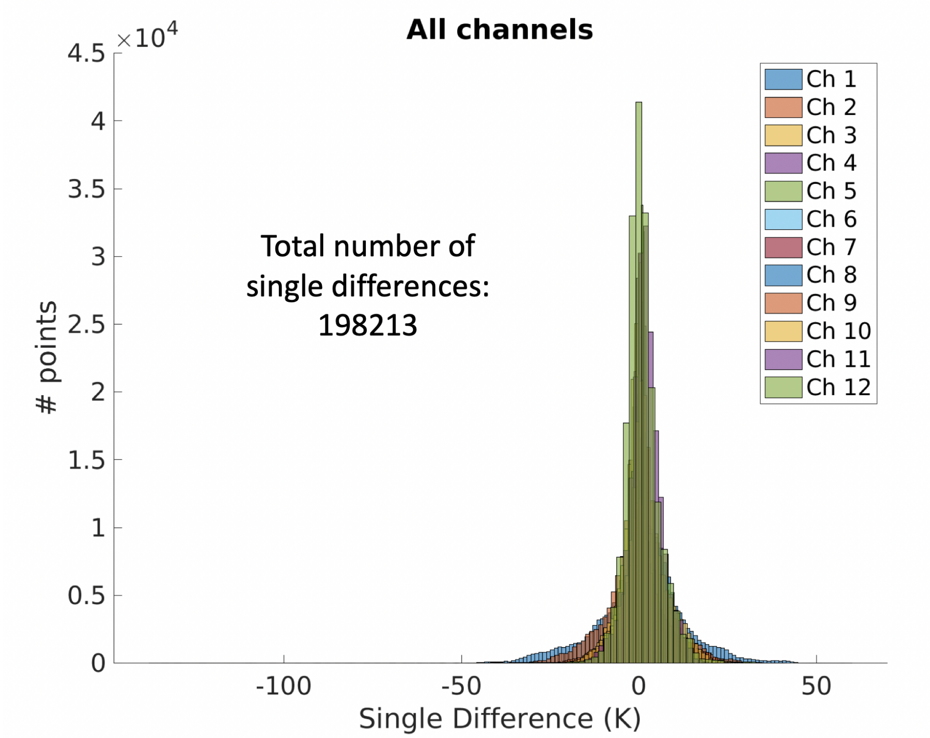

Figure 5: O-B histogram of data matchups for all channels in October 2021

standard deviations, reflecting high similarity between the ERA5 reanalysis data, the radiative transfer model, and the TROPICS observations. These channels are the typical non-surface-sensitive channels, which are best validated by the O-B technique. Channels 9-11 are of a similar frequency, and we see similar means and standard deviations as expected. These channels are sensitive to water vapor, which has higher uncertainties in the simulations. Channel 12 is another channel that is susceptible to extra variability in observations because it is sensitive to water vapor and light clouds that might be misidentified as clear-sky.

6 Summary/Conclusion

In summary, single differencing automation has allowed for the data analysis of the TROPICS Pathfinder microwave radiometer observations. To the extent of our simulation assessment, the calibration of the current data maturity is good. Automation of single differencing will allow for continued TROPICS data validation and can be used to re-calibrate measurements over time. The single differencing results indicate that a majority of the observation points have a small mean difference between the observed data and the simulated data, calculated using ERA5 reanalysis data and CRTM. Channels 6-8, with frequencies in the 117-119 GHz range, had particularly small means and low standard deviations across October 2021. Channel 1, a window channel with a larger bandwidth, resulted in a comparatively larger standard deviation.

6.1 Future Work

While the provisional Level-1 radiances used in this work show good agreement with the combined ERA5 and CRTM simulated radiances, we plan to repeat this effort with future TROPICS Pathfinder Level-1 radiances when they reach the validated data product maturity level in the summer of 2022.

We will incorporate GOES-17 data for future match-ups to increase the surface area coverage of our data match-ups. With more observations to analyze, we will be better able to capture the instrument performance aboard TROPICS Pathfinder and ultimately the full constellation.

We plan to implement additional features to the single differencing automation process in order to improve performance and reduce error in our simulations. One planned improvement includes restructuring cloud-data-observation match-ups. To better count the GOES cloud data as it overlaps with the TROPICS observation, channels in the same analysis group, shown in Table 1, will have their observation size tailored to their respective frequency and scan angle. Additionally, we are working toward incorporating ERA5 data point temporal and spatial interpolation. Since weather can exhibit great changes over the course of an hour (particularly with storms), interpolation of the ERA5 data between hourly publication and 0.25° intervals should yield more accurate CRTM results for comparison to the observed data.

The final iteration of this O-B script automation will also include double differencing of the observation data, which includes an O-B comparison of data from another satellite using a microwave radiometer at similar frequencies, such as the ATMS instruments aboard NOAA-20 and Suomi-NPP. As the TROPICS constellation is fully realized and operational, double differencing of satellite observations can also be compared among instruments within the constellation itself. The double difference method allows for inter-calibration between on-orbit sensors.

Acknowledgments

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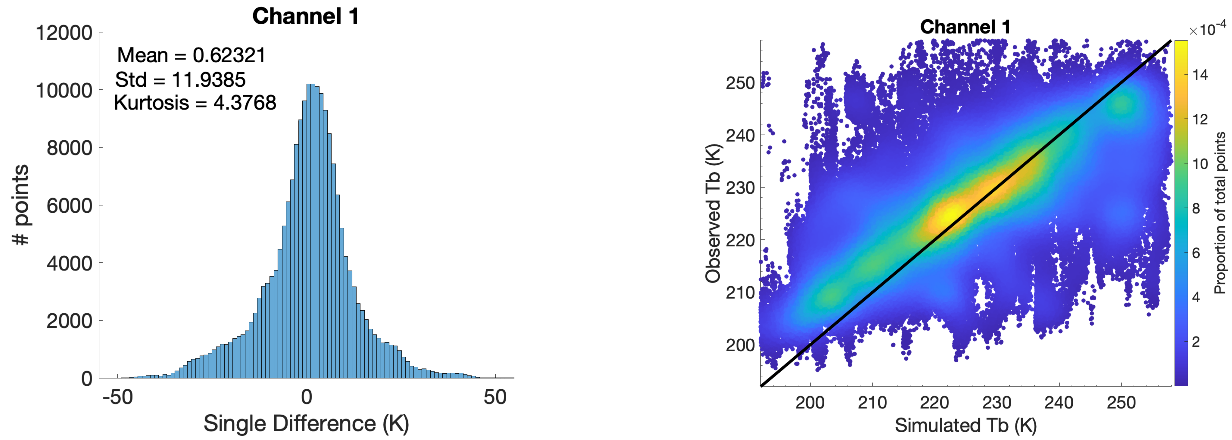
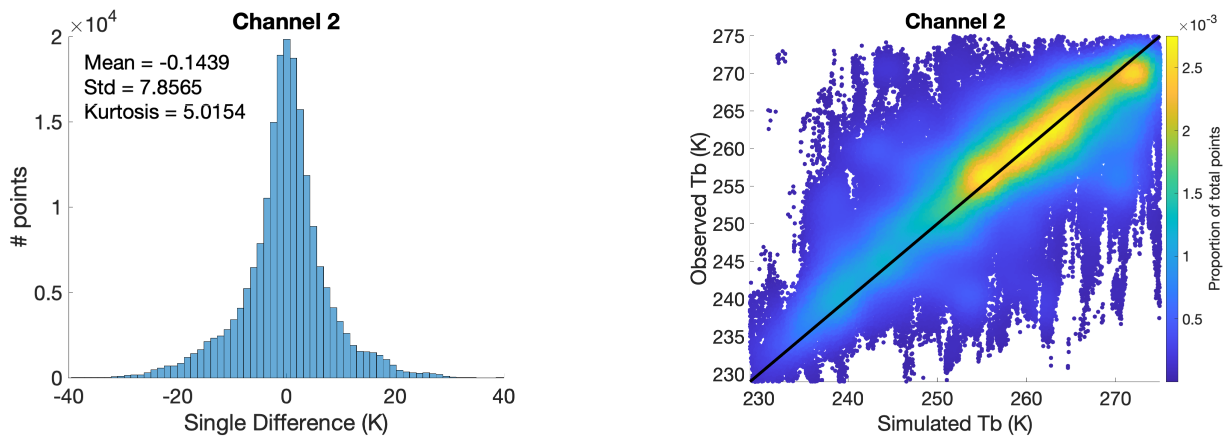
APPENDIX A: Channel Histograms of Errors For Comparison



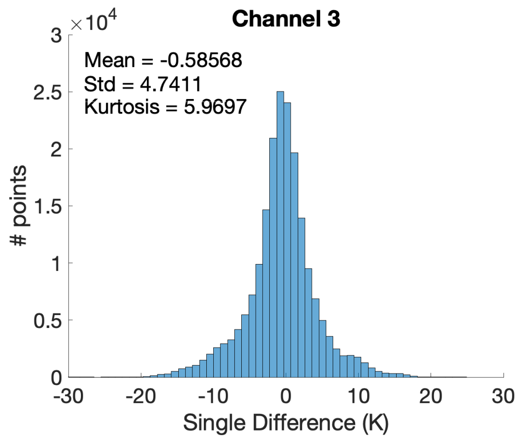
(a) O-B Histogram **(b) Heatmap**

Figure 6: Channel 1 - single differencing results, October 2021

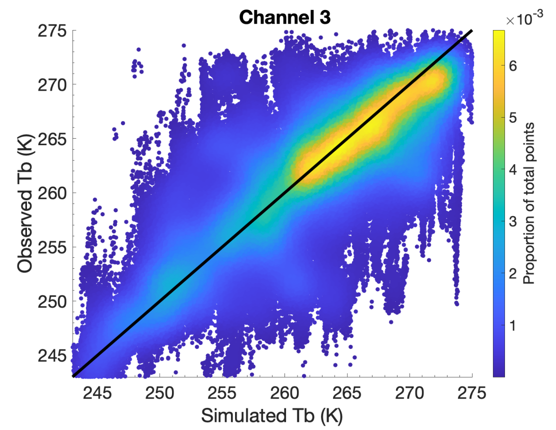


(a) O-B Histogram **(b) Heatmap**

Figure 7: Channel 2 - single differencing results, October 2021

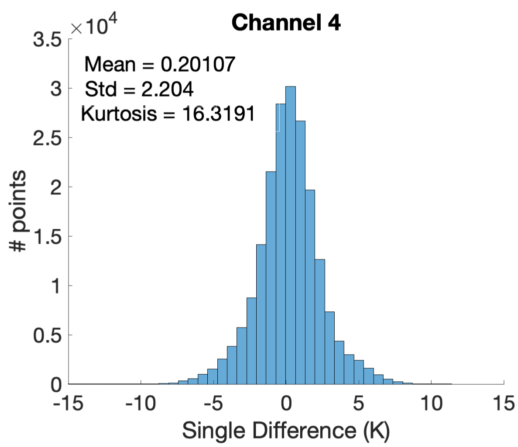


(a) O-B Histogram

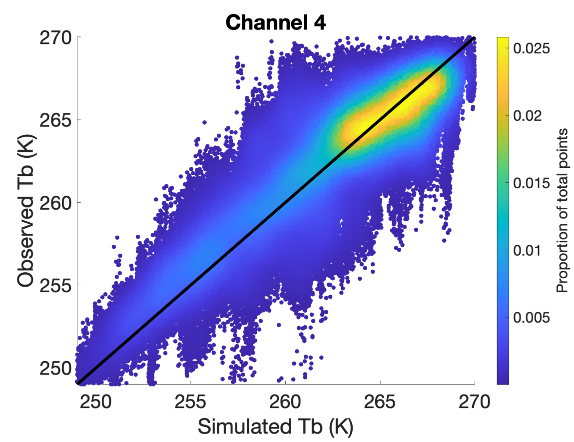


(b) Heatmap

Figure 8: Channel 3 - single differencing results, October 2021

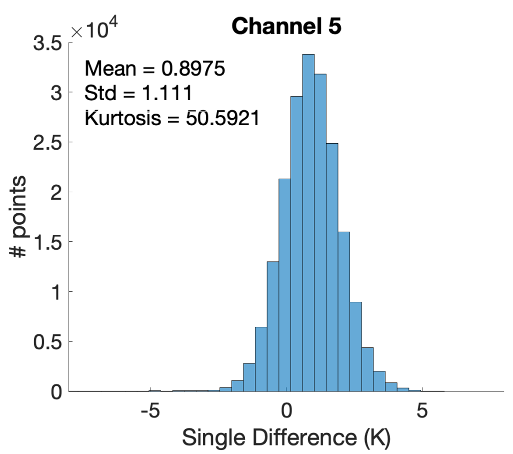


(a) O-B Histogram

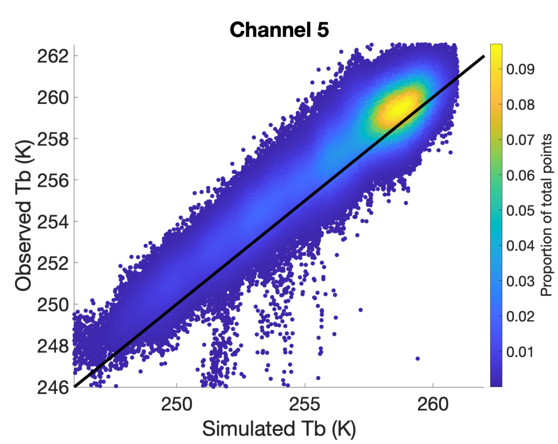


(b) Heatmap

Figure 9: Channel 4 - single differencing results, October 2021

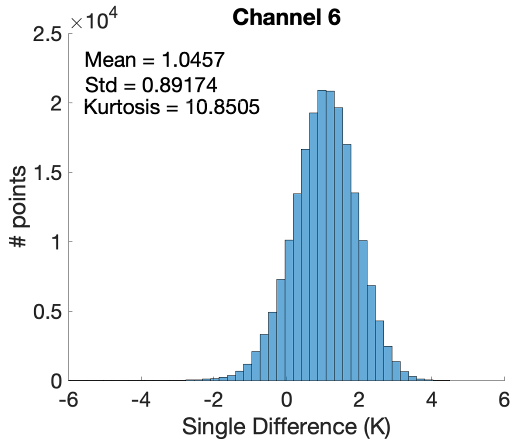


(a) O-B Histogram

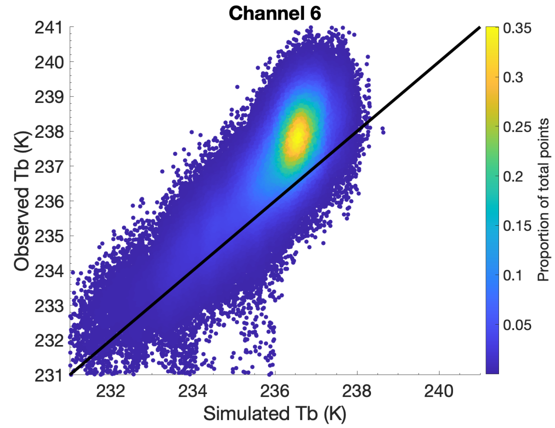


(b) Heatmap

Figure 10: Channel 5 - single differencing results, October 2021

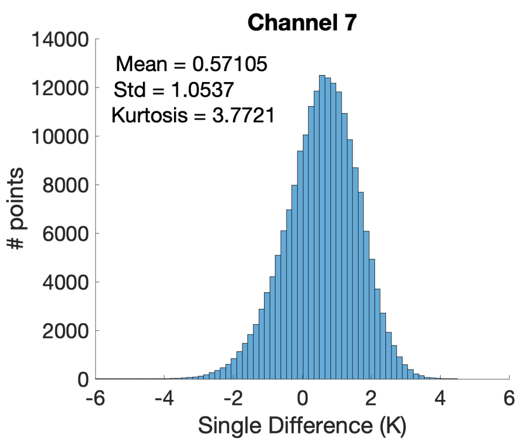


(a) **O-B Histogram**

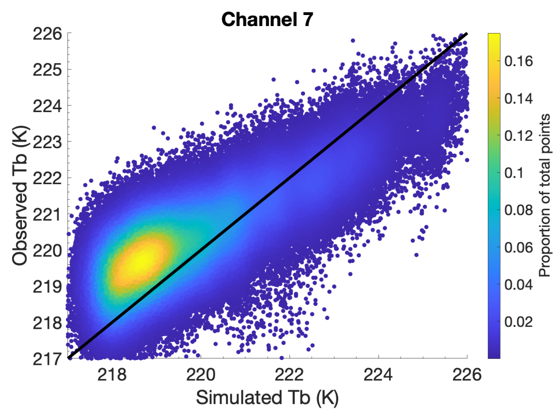


(b) **Heatmap**

Figure 11: Channel 6 - single differencing results, October 2021

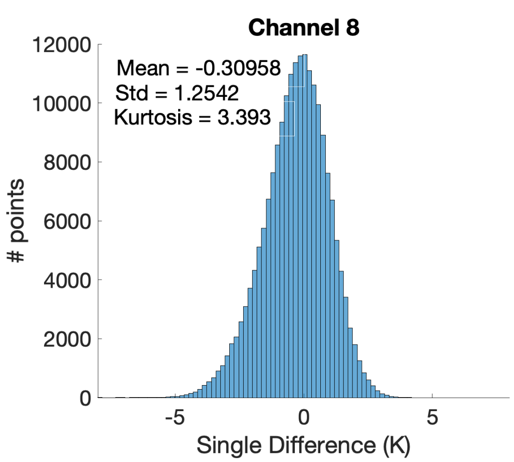


(a) **O-B Histogram**

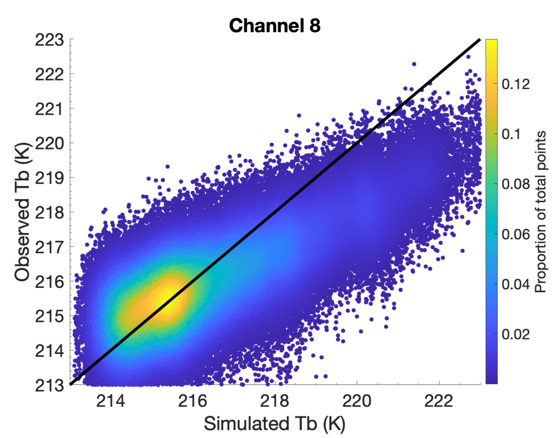


(b) **Heatmap**

Figure 12: Channel 7 - single differencing results, October 2021

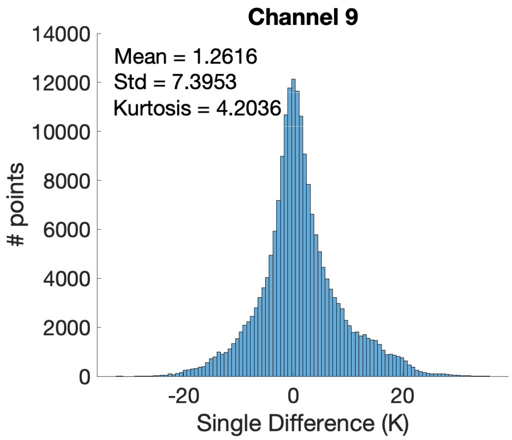


(a) **O-B Histogram**

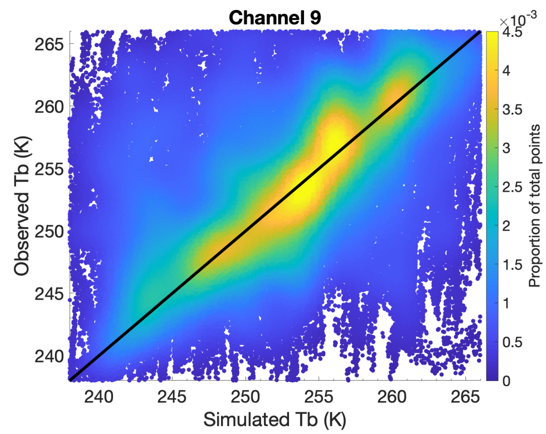


(b) **Heatmap**

Figure 13: Channel 8 - single differencing results, October 2021

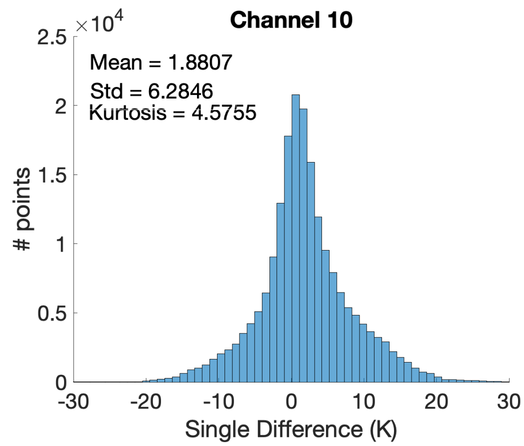


(a) O-B Histogram

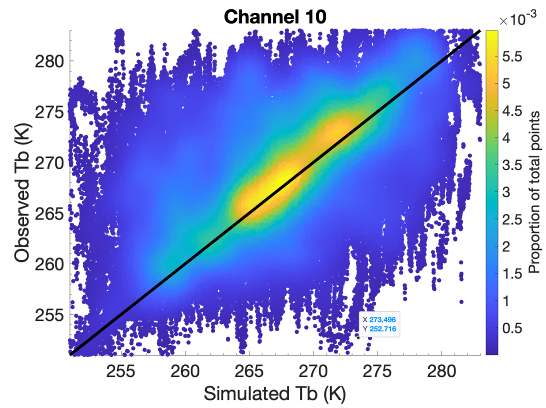


(b) Heatmap

Figure 14: Channel 9 - single differencing results, October 2021

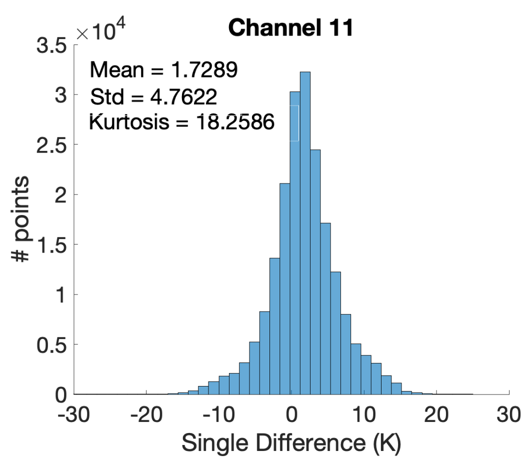


(a) O-B Histogram

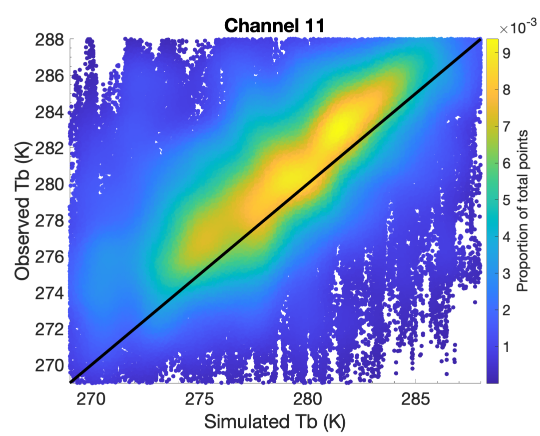


(b) Heatmap

Figure 15: Channel 10 - single differencing results, October 2021

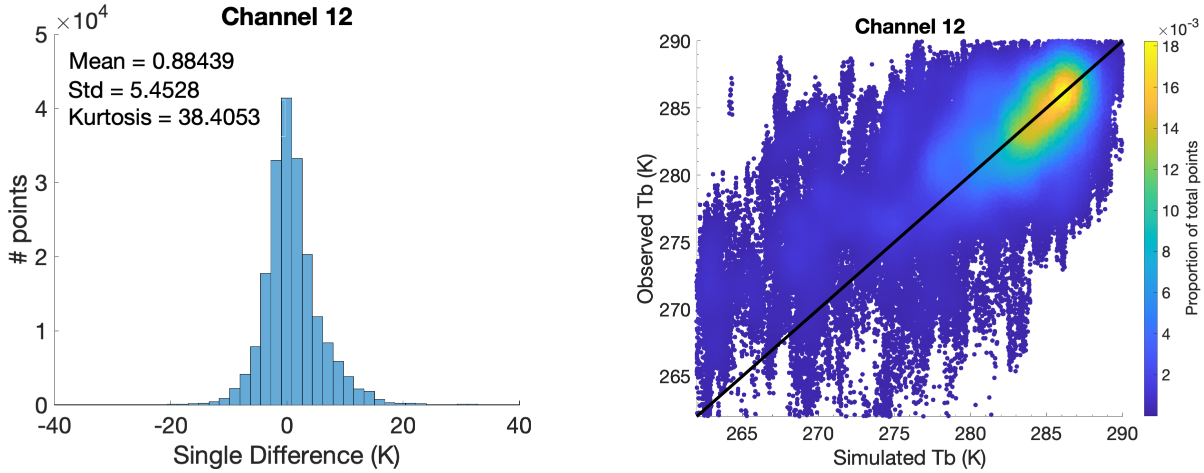


(a) O-B Histogram



(b) Heatmap

Figure 16: Channel 11 - single differencing results, October 2021



(a) O-B Histogram **(b) Heatmap**

Figure 17: Channel 12 - single differencing results, October 2021