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ARM

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Executive Summary

The U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility's Tethered Balloon System Merged Data (TBSMERGED) Value-Added Product (VAP) integrates data from instruments flown on ARM's tethered balloon system missions that collect in situ measurements of temperature, humidity, wind speed, wind direction, and aerosol properties with estimates of cloud base and boundary-layer height from a surface-based ceilometer to improve the ease of use of tethered balloon system (TBS) data sets. The TBSMERGEDINCLOUD VAP, a variation of TBSMERGED, includes supercooled liquid water content (tbsslwc) measurements collected within the cloud.

Acronyms and Abbreviations

ARM	Atmospheric Radiation Measurement
CPC	condensation particle counter
EMSL	Environmental Molecular Sciences Laboratory
GPS	Global Positioning System
netCDF	Network Common Data Form
OLI	Oliktok Point, Alaska
PNNL	Pacific Northwest National Laboratory
POPS	portable optical particle spectrometer
SGP	Southern Great Plains
TBS	tethered balloon system
TBSMERGED	Tethered Balloon System Merged Data Value-Added Product
TBSMERGEDINCLOUD	a version of TBSMERGED that includes supercooled liquid water content collected within clouds
UAV	unpiloted aerial vehicle
VAP	value-added product

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1.0 Introduction

Specific TBS data products included in TBSMERGED are: tbsground (surface temperature, pressure, wind speed, gust wind speed, and relative humidity), tbspops (airborne aerosol number concentration and size distribution from 140 nm-3 µm), tbscpc (airborne aerosol number concentration from 10 nm-1 µm), tbsimet and tbsimetxq (airborne temperature, pressure, relative humidity, and altitude), and tbswind (airborne wind speed, gust wind speed, and wind direction). Surface-based ceilometer estimates of cloud base and boundary-layer height are included. tbsslwc (airborne supercooled liquid water content) will be included in the TBSMERGEDINCLOUD product when tbsslwc data are available on ARM's Data Discovery.

TBSMERGED allows users to download and visualize multiple TBS datastreams within individual data files created for each TBS flight per date. Additionally, all datastreams are indexed to TBSIMET timestamps and altitudes, which eliminates this step from being performed by the user. The inclusion of airborne meteorological and aerosol observations within a single file per flight facilitates studies of vertically resolved profiles of aerosol concentration and size distribution, and the atmospheric conditions and processes that govern aerosol formation and transportation.

2.0 Algorithm and Methodology

Most data provided in the TBSMERGED VAP are in situ measurements collected by the TBS. The derived quantities include the cloud base and boundary-layer height estimates provided by the ceilometer, and the estimated supercooled liquid water content included in the TBSMERGEDINCLOUD product.

Vaisala CL-31 ceilometers deployed at ARM observatories are capable of detecting up to three cloud layers simultaneously between the surface and 7,700 m above the surface at 10 m vertical resolution. As described in Morris (2016), the cloud base height estimates from the ceilometer are based on Vaisala's built-in cloud-base detection algorithms, which report the altitude where the horizontal visibility is dramatically reduced. The CL-31 ceilometer BL-VIEW software also reports up to three candidate planetary boundary-layer heights between the surface and 4,000 m above the surface. TBSMERGED includes both candidate planetary boundary-layer heights and the quality index for each boundary-layer height candidate, which is based on gradient amount (a low gradient results in a high-quality index), detected cloud bases (clouds detected in the vicinity of a boundary layer reduce its quality index), and distance to other gradient minima (high distance results in high quality). An example of ceilometer-derived boundary-layer height, tbspops, and tbscpc data included in a TBSMERGED output file is shown below in Figure 1.

Estimates of supercooled liquid water content from the ARM observatory at Oliktok Point, North Slope of Alaska (OLI) in the TBSMERGEDINCLOUD product are calculated from the rate of change of a vibrating wire operated on an Anasphere supercooled liquid water content sonde within a cloud on the TBS. As detailed in Dexheimer et al. (2019), the calculation of supercooled liquid water content also requires the vertical speed of the TBS platform, horizontal wind speed, and estimates of mean droplet diameter and droplet collection efficiency.

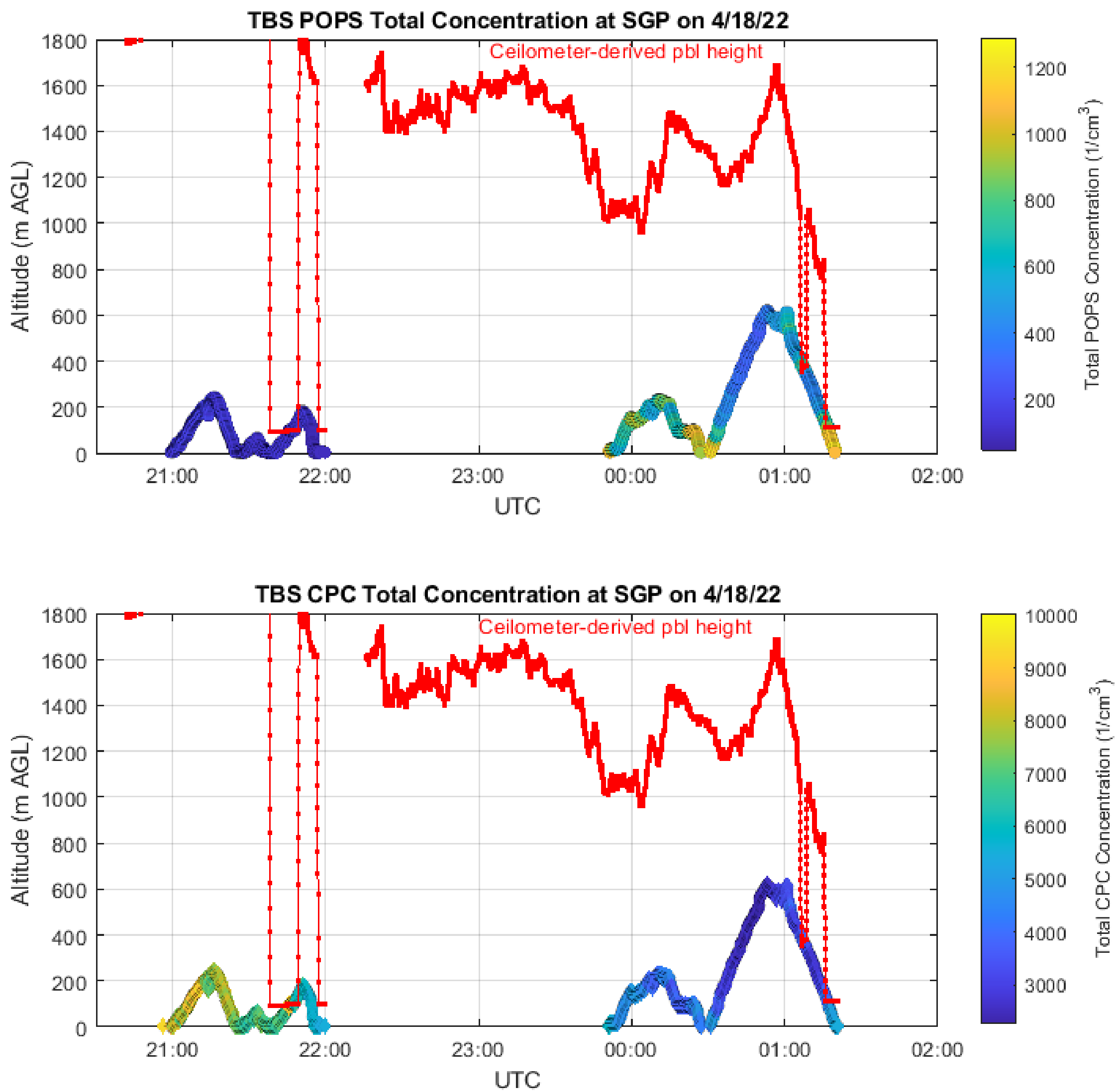

Figure 1. Aerosol total number concentration from the portable optical particle spectrometer (POPS) (top), and the condensation particle counter (CPC) (bottom), with the ceilometer-measured first boundary-layer height (red) from flights 3-5 of the TBS at ARM's Southern Great Plains (SGP) observatory on April 18, 2022. Note the different limits on the particle concentration color bars between the POPS and CPC plots.

3.0 Input Data

Input data are provided by six ARM datastreams: ceilpblht, tbscpc, tbsimet, tbsimetxq2, tbspops, and tbswind.

Cloud base and planetary boundary-layer height estimates are from Vaisala CL-31 ceilometer data included in the ceilpblht datastream.

Total aerosol number concentration from 0.01 µm to 1 µm is provided from six TSI CPC 3007 units, which provide data to the tbscpc datastream. More than one CPC may be operated from different locations on the tether during the same TBS flight. The calibrations for both the CPC and POPS units were performed before and after each deployment (Kuang and Mei 2016, Mei and Pekour 2020, Mei et al. 2020b, Bezantakos and Biskos 2022), and all flow rates were are periodically checked in the field.

iMet RSB-4 radiosondes are operated within 5 m of each CPC or POPS on the TBS and provide Global Positioning System (GPS) and geopotential height-based altitude data, as well as temperature, relative humidity, and pressure data, to the tbsimet datastream. More than one iMet RSB-4 may be operated from different locations on the tether during the same TBS flight. Multiple iMet RSB-4 radiosondes are bench-tested against each other and the tbsground instrumentation during each TBS deployment. The tbsground station consists of an NRG IceFree3 heated anemometer, Campbell Scientific EE-181 temperature and humidity probe, and Setra 278 barometer.

iMet XQ2 unpiloted aerial vehicle (UAV) sensors are operated on each TBS wind sensor and provide the same measurement outputs as iMet RSB-4 radiosondes. More than one iMet XQ2 UAV sensor may be operated from different locations on the tether during the same TBS flight. The tbsimetxq2 datastream functions as a redundant source of altitude and meteorological data in the event of an iMet RSB-4 radiosonde failure during a TBS flight. iMet XQ2 sensors are returned to interMet for calibration annually.

Six Handix Scientific POPS units measure aerosol size distribution and total number concentration from 140 nm to 3 µm. Each POPS is connected to an iMet RSB-4 radiosonde while in flight on the TBS, and the pressure, relative humidity, temperature, and altitude data from the iMet radiosonde are included with the aerosol size distribution data in the tbspops datastream. More than one POPS may be operated from different locations on the tether during the same TBS flight.

Eight wind sensors units are used on the TBS and provide 1-second airborne measurements of gust wind speed, average wind speed, vertical wind speed, and wind direction to the tbswind datastream. More than one wind sensor may be operated from different locations on the tether during the same TBS flight. Horizontal wind speed is measured by NRG 40C anemometers. Wind direction is measured using two Tallysman HC872 helical antennas coupled with a Vega 28 GNSS compass board. Vertical wind speed is measured by an RM Young 27106. The vertical wind speed measurement is corrected for the ascent rate of the TBS measured in the tbsimet datastream. NRG 40C and RM Young 27106 sensors are returned to the manufacturers for calibration annually. Wind direction data from the Vega 28 GNSS compass board are compared against an NRG 200P wind vane annually.

3.1 Flowchart

This TBSMERGED and TBSMERGEDINCLOUD VAPs do not apply any special algorithms or perform scientific analysis on the data they retrieve. Their purpose is to create a consolidated data product that simplifies a user’s ability to access and use the TBS data products. A flow diagram of the process is provided below.

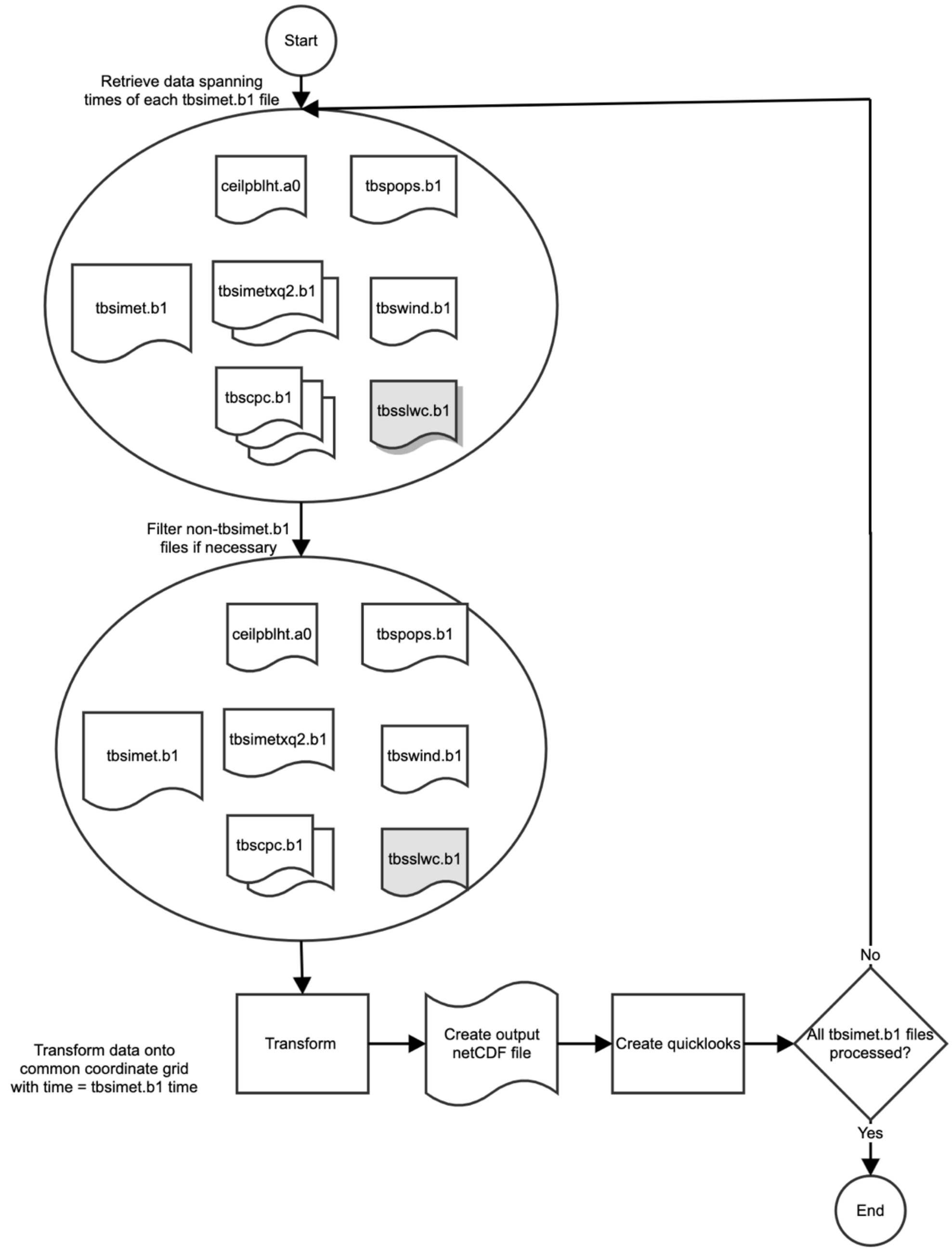

Figure 2. Process flow diagram of TBSMERGED VAP.

The process consists of retrieving, filtering non-tbsimet.b1 data that cannot be merged, consolidating all input data onto a common coordinate grid, creating quicklooks for a subset of variables, and writing the data to a netCDF file. For each tbsimet.b1 file found in a processing period that spans a given start and end time, each tbsimet.b1 file is retrieved from the files into memory as is, as well as portions of the input data products' data that overlap the times found in the tbsimbet.b1 file. The data retrieved from the non-tbsimet.b1 data may fall across one or more of the other input datastream files. If such 'extra' files are found, they are examined to determine whether for any of the common non-tbsimet.b1 input files, any of the non-time dimensions vary in size. If multiple files exist that cannot easily be merged, the shape of the non-tbsimet file that spans the longest time period of the tbsmet.b1 file is used, and extra non-tbsimet.b1 files with a different shape are deleted.

Quality checks are applied for 55 variables.

Primary output variables of TBSMERGED:

1. planetary boundary layer height
2. cloud base height
3. aerosol concentration
4. atmospheric temperature
5. atmospheric moisture
6. aerosol particle size distribution
7. vertical velocity
8. horizontal wind.

4.0 Output Data

The TBSMERGED VAP produces one output file, named:

SSStbsmergedXX.c1.YYYYMMDD.hhmmss

Where:

- SSS is the site of the instrument (e.g., SGP)
- XX is the facility (i.e., C1, C2, etc.)
- YYYY is the year
- MM is the month of the year
- DD is the day of the month
- hh is the hour of the day
- mm is the minute of the hour
- ss is the second of the minute.

The time stamps of the output files match those of the tbsimet.b1 input files because the output target time is the same as the tbsimet.b1 sample times. Thus, if there is no tbsimet.b1 data for a given period, there will be no tbsmerged data for that same period. A tbsimet file is produced for each flight of the TBS. Many TBS flights may occur over the course of a single day and a tbsmerged output file (tbsmerged.c1 or tbsmergedincloud.c1) will be produced for each of these files.

In addition to ARM's standard global attributes described in the ARM standards document, an additional global attribute of 'input_files_used' that comprises a list of all input files merged is provided to make clear what files remained following the filtering process described in section 3.1.

The specific variables in the tbsmerged.b1 output are listed below. Primary measurements are noted in bold. Quicklooks are produced for all primary variables.

base_time:
time_offset: [time]

time: [time]
bl_height_1: [time]
qc_bl_height_1: [time]
bl_height_2: [time]
qc_bl_height_2: [time]
bl_height_3: [time]
qc_bl_height_3: [time]
bl_index_1: [time]
qc_bl_index_1: [time]
bl_index_2: [time]
qc_bl_index_2: [time]
bl_index_3: [time]
qc_bl_index_3: [time]
first_cbh: [time]
qc_first_cbh: [time]
second_cbh: [time]
qc_second_cbh: [time]
third_cbh: [time]
qc_third_cbh: [time]
detection_status: [time]
tbscpc_total_concentration: [time,num_cpc]
qc_tbscpc_total_concentration: [time,num_cpc]
tbscpc_alt: [time,num_cpc]
qc_tbscpc_alt: [time,num_cpc]
tbscpc_lat: [time,num_cpc]
qc_tbscpc_lat: [time,num_cpc]
tbscpc_lon: [time,num_cpc]
qc_tbscpc_lon: [time,num_cpc]
tbsimet_air_temperature: [time,num_imet]
qc_tbsimet_air_temperature: [time,num_imet]
tbsimet_air_temperature_raw: [time,num_imet]
qc_tbsimet_air_temperature_raw: [time,num_imet]
tbsimet_ascent_rate: [time,num_imet]
qc_tbsimet_ascent_rate: [time,num_imet]
tbsimet_battery_volt: [time,num_imet]
qc_tbsimet_battery_volt: [time,num_imet]
tbsimet_frostpoint: [time,num_imet]
qc_tbsimet_frostpoint: [time,num_imet]
tbsimet_gps_ascent_rate: [time,num_imet]
qc_tbsimet_gps_ascent_rate: [time,num_imet]
tbsimet_gps_num_satellites; [time,num_imet]
qc_tbsimet_gps_num_satellites; [time,num_imet]
tbsimet_gps_pressure; [time,num_imet]
qc_tbsimet_gps_pressure; [time,num_imet]
tbsimet_imet_altitude; [time,num_imet]
qc_tbsimet_imet_altitude; [time,num_imet]
tbsimet_imet_file_name; [time,num_imet]
tbsimet_imet_internal_temperature; [time,num_imet]
qc_tbsimet_imet_internal_temperature; [time,num_imet]
tbsimet_pressure; [time,num_imet]
qc_tbsimet_pressure; [time,num_imet]

tbsimet_pressure_sensor_temperature; [time,num_imet]
qc_tbsimet_pressure_sensor_temperature; [time,num_imet]
tbsimet_rh; [time,num_imet]
qc_tbsimet_rh; [time,num_imet]
tbsimet_rh_sensor_temperature; [time,num_imet]
qc_tbsimet_rh_sensor_temperature; [time,num_imet]
tbsimet_theta; [time,num_imet]
qc_tbsimet_theta; [time,num_imet]
tbsimet_total_column_water; [time,num_imet]
qc_tbsimet_total_column_water; [time,num_imet]
tbsimet_vapor_mixing_ratio; [time,num_imet]
qc_tbsimet_vapor_mixing_ratio; [time,num_imet]
tbsimet_alt: [time,num_imet]
qc_tbsimet_alt: [time,num_imet]
tbsimet_lat: [time,num_imet]
qc_tbsimet_lat: [time,num_imet]
tbsimet_lon: [time,num_imet]
qc_tbsimet_lon: [time,num_imet]
tbsimet_xq2_air_temperature: [time,num_xq2]
qc_tbsimet_xq2_air_temperature: [time,num_xq2]
tbsimet_xq2_pressure: [time,num_xq2]
qc_tbsimet_xq2_pressure: [time,num_xq2]
tbsimet_xq2_rh: [time,num_xq2]
qc_tbsimet_xq2_rh: [time,num_xq2]
tbsimet_xq2_rh_sensor_temperature: [time,num_xq2]
qc_tbsimet_xq2_rh_sensor_temperature: [time,num_xq2]
tbsimet_xq2_sat_count: [time,num_xq2]
qc_tbsimet_xq2_sat_count: [time,num_xq2]
tbsimet_xq2_serial_number: [num_xq2]
tbsimetxq2_xq2_file_name: [num_xq2,strlen]
tbsimet_xq2_alt: [time,num_xq2]
qc_tbsimet_xq2_alt: [time,num_xq2]
tbsimet_xq2_lat: [time,num_xq2]
qc_tbsimet_xq2_lat: [time,num_xq2]
tbsimet_xq2_lon: [time,num_xq2]
qc_tbsimet_xq2_lon: [time,num_xq2]
tbspops_dn_135_150: [time,num_pops]
qc_tbspops_dn_135_150: [time,num_pops]
tbspops_dn_1380_1760: [time,num_pops]
qc_tbspops_dn_1380_1760: [time,num_pops]
tbspops_dn_150_170: [time,num_pops]
qc_tbspops_dn_150_170: [time,num_pops]
tbspops_dn_170_195: [time,num_pops]
qc_tbspops_dn_170_195: [time,num_pops]
tbspops_dn_1760_2550: [time,num_pops]
qc_tbspops_dn_1760_2550: [time,num_pops]
tbspops_dn_195_220: [time,num_pops]
qc_tbspops_dn_195_220: [time,num_pops]
tbspops_dn_220_260: [time,num_pops]
qc_tbspops_dn_220_260: [time,num_pops]
tbspops_dn_2550_3615: [time,num_pops]

qc_tbspops_dn_2550_3615: [time,num_pops]
tbspops_dn_260_335: [time,num_pops]
qc_tbspops_dn_260_335: [time,num_pops]
tbspops_dn_335_510: [time,num_pops]
qc_tbspops_dn_335_510: [time,num_pops]
tbspops_dn_510_705: [time,num_pops]
qc_tbspops_dn_510_705: [time,num_pops]
tbspops_dn_705_1380: [time,num_pops]
qc_tbspops_dn_705_1380: [time,num_pops]
tbspops_gps_pressure: [time,num_pops]
qc_tbspops_gps_pressure: [time,num_pops]
tbspops_imet_pressure: [time,num_pops]
qc_tbspops_imet_pressure: [time,num_pops]
tbspops_imet_temperature: [time,num_pops]
qc_tbspops_imet_temperature: [time,num_pops]
tbspops_pressure: [time,num_pops]
qc_tbspops_pressure: [time,num_pops]
tbspops_relative_humidity: [time,num_pops]
qc_tbspops_relative_humidity: [time,num_pops]
tbspops_temperature: [time,num_pops]
qc_tbspops_temperature: [time,num_pops]
tbspops_total_concentration: [time,num_pops]
qc_tbspops_total_concentration: [time,num_pops]
tbspops_alt: [time,num_pops]
qc_tbspops_alt: [time,num_pops]
tbspops_lat: [time,num_pops]
qc_tbspops_lat: [time,num_pops]
tbspops_lon: [time,num_pops]
qc_tbspops_lon: [time,num_pops]
tbswind_altitude_datastream: [num_anem,strlen]
tbswind_altitude_fname: [num_anem,strlen]
tbswind_altitude_offset: [num_anem]
tbswind_anem_file_name: [num_anem,strlen]
tbswind_serial_number: [num_anem,strlen]
tbswind_wind_direction: [time,num_anem]
qc_tbswind_wind_direction: [time,num_anem]
tbswind_wind_gust: [time,num_anem]
qc_tbswind_wind_gust: [time,num_anem]
tbswind_wind_speed: [time,num_anem]
qc_tbswind_wind_speed: [time,num_anem]
tbswind_vertical_wind: [time,num_anem]
qc_tbswind_vertical_wind: [time,num_anem]
tbswind_alt: [time,num_anem]
qc_tbswind_alt: [time,num_anem]
tbswind_lat: [time,num_anem]
qc_tbswind_lat: [time,num_anem]
tbswind_lon: [time,num_anem]
qc_tbswind_lon: [time,num_anem]

The tbsmergedincloud.c1output includes all variables listed for tbsmerged.c1 plus the variables from the tbsslwc.b1 datastream. As before, primary variables are in bold and quicklooks are created for these bolded variables.

tbsslwc_air_density
qc_tbsslwc_air_density
tbsslwc_air_temperature
qc_tbsslwc_air_temperature
tbsslwc_deriv_smooth_slwc_frequency
qc_tbsslwc_deriv_smooth_slwc_frequency
tbsslwc_droplet_collection_efficiency
qc_tbsslwc_droplet_collection_efficiency
tbsslwc_droplet_diameter
qc_tbsslwc_droplet_diameter
tbsslwc_dynamic_air_viscosity
qc_tbsslwc_dynamic_air_viscosity
tbsslwc_imet_altitude
qc_tbsslwc_imet_altitude
tbsslwc_imet_file_name
tbsslwc_inertia
qc_tbsslwc_inertia
tbsslwc_modified_inertia_param
qc_tbsslwc_modified_inertia_param
tbsslwc_pressure
qc_tbsslwc_pressure
tbsslwc_reynolds_number
qc_tbsslwc_reynolds_number
tbsslwc_slwc
qc_tbsslwc_slwc
tbsslwc_slwc_frequency
qc_tbsslwc_slwc_frequency
tbsslwc_smooth_slwc_frequency
qc_tbsslwc_smooth_slwc_frequency
tbsslwc_un_iced_slwc_frequency
qc_tbsslwc_un_iced_slwc_frequency
tbsslwc_wind_speed
qc_tbsslwc_wind_speed
tbsslwc_wire_diameter
tbsslwc_lat
qc_tbsslwc_lat
tbsslwc_lon
qc_tbsslwc_lon

5.0 Summary and Future Work

The TBSMERGED VAP allows users to retrieve data from five baseline TBS instruments in a single file for each flight, eliminating the need for the user to independently retrieve multiple datastreams and then map times and altitudes between each datastream. TBSMERGED also includes measurements of cloud base height and planetary boundary-layer height to aid users in evaluating relationships between vertical aerosol profiles, cloud processes, and the evolution of the boundary layer. TBSMERGEDINCLOUD is produced for OLI, where the TBS was able to fly instruments within clouds in Restricted Airspace, and includes in situ measurements of supercooled liquid water content.

The term baseline refers to standard ARM TBS instruments that are typically operated on each TBS flight. ARM plans to add datastreams to the TBSMERGED VAP as future TBS instruments are developed, validated, and transitioned into baseline operational status. Currently, PNNL's Environmental Molecular Sciences Laboratory (EMSL) microscopy, spectroscopy, and advanced mass spectrometry results are not available on ARM Data Discovery, but if they become available in the future, those data could be integrated into TBSMERGED.

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