Climate Data Record (CDR) Program

Climate Algorithm Theoretical Basis Document (C-ATBD)

IR Sounder Upper Tropospheric Humidity BT

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REVISION HISTORY

Rev.	Author	DSR No.	Description	Date
1	Lei Shi, NOAA/NCDC	DSR-348	Initial Submission to CDR Program	04/22/2013
2	Lei Shi, NOAA/NCDC	DSR-588	Changed the reference of v02r05 to v02r06	02/25/2014
3	Lei Shi, NOAA/NCEI	DSR-885	Updated inter-calibration description between NOAA-14 and NOAA-15. Changed the reference of v02r06 to v03r00. Replaced flowchart.	03/17/2015
4	Lei Shi, NOAA/NCEI	DSR-1436	Updated text for v03r01. Updated Fig. 3 and Table 2. Added Fig. 4.	5/5/2020
5	Lei Shi, NOAA/NCEI	DSR-1508	Updated text for v03r02. Changed the reference of v03r01 to v03r02. Updated description on inter-satellite calibration. Updated Table 2	2/28/2021
6	Lei Shi, NOAA/NCEI	DSR-1742	Updated text for v04r00. Added description on using IASI to simulate HIRS channels. Updated Fig. 4. Added Table 3.	4/17/2023
7	Lei Shi, NOAA/NCEI	DSR-1775	Changed the product name to IR Sounder Upper Tropospheric Humidity BT. Updated Fig. 4 with more recent years of data.	6/12/2023

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1. Introduction

1.1 Purpose

The purpose of this document is to describe the algorithm submitted to the National Centers for Environmental Information (NCEI) by Lei Shi from NOAA/NCEI that will be used to create the IR Sounder Upper Tropospheric Humidity Brightness Temperature Climate Data Record (CDR), using High-Resolution Infrared Radiation Sounder (HIRS) data from National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites and the Meteorological Operational Satellite Program (Metop) and Infrared Atmospheric Sounding Interferometer (IASI) data from Metop. The actual algorithm is defined by the computer program (code) that accompanies this document, and thus the intent here is to provide a guide to understanding that algorithm, from both a scientific perspective and in order to assist a software engineer or end-user performing an evaluation of the code.

1.2 Definitions

Following is a summary of the symbols used to define the algorithm.

Atmospheric parameters:

Tb = HIRS channel 12 brightness temperature

1.3 Referencing this Document

This document should be referenced as follows:

IR Sounder Upper Tropospheric Humidity Brightness Temperature - Climate Algorithm Theoretical Basis Document, NOAA Climate Data Record Program CDRP-ATBD-0309 Rev. 5 (2021). Available at https://www.ncei.noaa.gov/products/climate-data-records

1.4 Document Maintenance

This document is under version control in the CDR Program library. The information in this document applies to v04r00 of the archived data. Future versions of the product will be accompanied by an update to this C-ATBD and other documentation as needed.

2. Observing Systems Overview

2.1 Products Generated

The objective of this algorithm is to derive intersatellite calibrated HIRS and IASI simulated HIRS (IHIRS) clear-sky upper tropospheric humidity (UTH) brightness temperatures (BT) from measurements made by the NOAA and Metop satellite series. The data are cloud-cleared. Monthly files are generated at 2.5x2.5 degree latitude/longitude.

2.2 Instrument Characteristics

Since the launch of the Television Infrared Observation Satellite (TIROS-N) in 1978, more than 40 years of observations have been made by the HIRS instruments on board the NOAA polar orbiting satellite series (hereafter abbreviated as N#, where # is the satellite number) and the Metop satellites (abbreviated as M#). There are twenty channels in the HIRS instrument, in which channel 12 observes the upper tropospheric humidity. As a background information, Figure 1 displays the spectral response functions of HIRS channel 12 for a number of satellites. The approximate spectral ranges for the HIRS/2 series and the HIRS/3 and HIRS/4 series are marked at the top of Figure 1. The atmospheric transmittance for a typical tropical clear-sky atmosphere is also included as a reference (see (Shi; Bates 2011)).

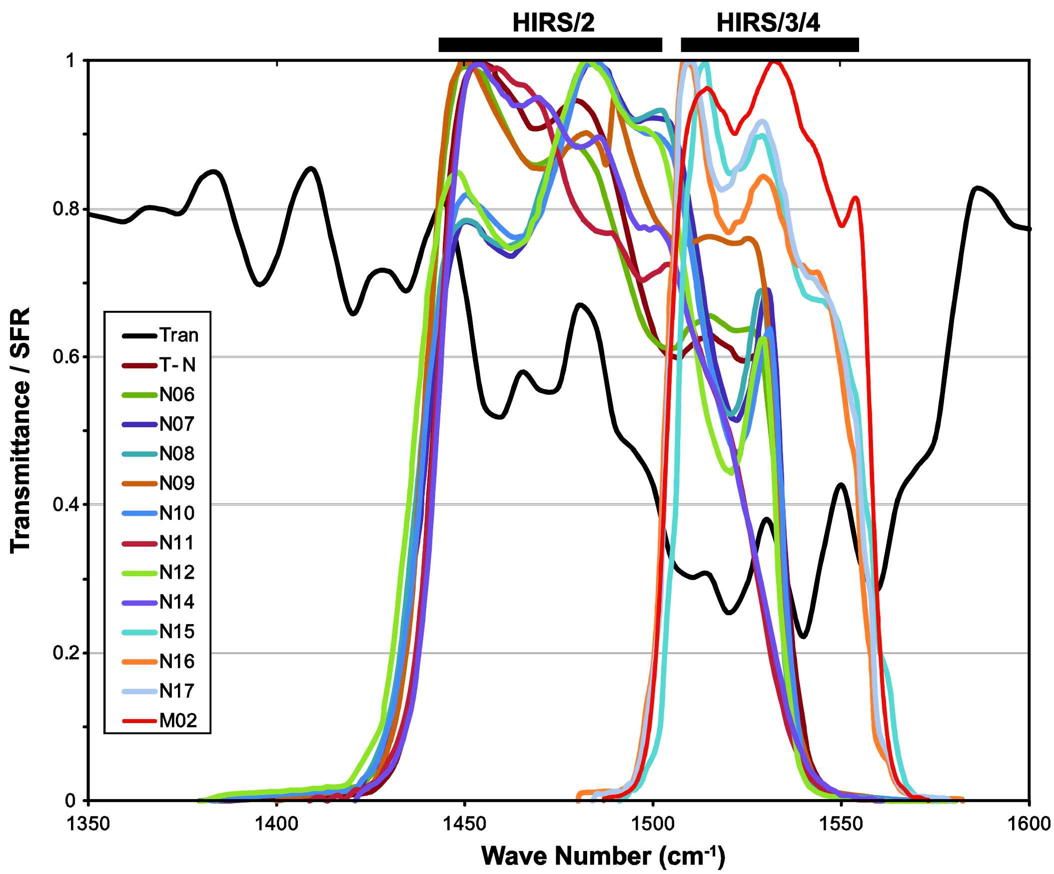

Figure 1: Spectral response functions of HIRS channel 12. As a reference, the atmospheric transmittance for a typical tropical clear-sky atmosphere is included (black line). The approximate spectral ranges for the HIRS/2 series and the HIRS/3 and HIRS/4 series are marked at the top (taken from Shi and Bates, 2011).

The IASI instrument is a cross-track scanning Michelson interferometer providing hyperspectral measurements in 8461 channels in the spectral range of 645 – 2760 cm^{-1} (3.6 – 15.5 μm) at 0.25 cm^{-1} resolution in a 2 x 2 array of circular footprints with a nadir spatial resolution of 50 x 50 km and a corresponding single footprint spatial resolution of roughly 12 km at nadir. The spectral range of HIRS channel 12 is completely covered by the IASI hyperspectral channels.

3. Algorithm Description

3.1 Algorithm Overview

There have been sixteen satellites carrying the HIRS instruments in the NOAA and Metop polar orbiting satellite series. Due to the independence in the calibration based on individual HIRS instrument's channel spectral response function along with other factors, biases exist from satellite to satellite. The measurement from HIRS channel 12 is a fundamental climate data record and is key to water vapor feedback. It is important that the intersatellite biases are corrected. Examination of the intersatellite biases shows that the biases are scene brightness temperature dependent. An algorithm is developed to account for this feature of varying biases with respect to brightness temperature. The bias correction data are derived from overlaps of monthly means of each 10-degree latitude belt from the equator to the poles. HIRS measurements from the NOAA and Metop series of polar orbiting satellites are calibrated to a reference satellite (NOAA-12). Measurements from IASI are convolved to HIRS channel 12, and calibrated to the same reference satellite.

3.2 Processing Outline

The processing outline of intersatellite calibrated IR Sounder UTH brightness temperature is summarized in Figure 2. The algorithm for data processing is written in C, FORTRAN, and C Shell scripts. Input data are HIRS level-1B in binary format and output data are written in netCDF format.

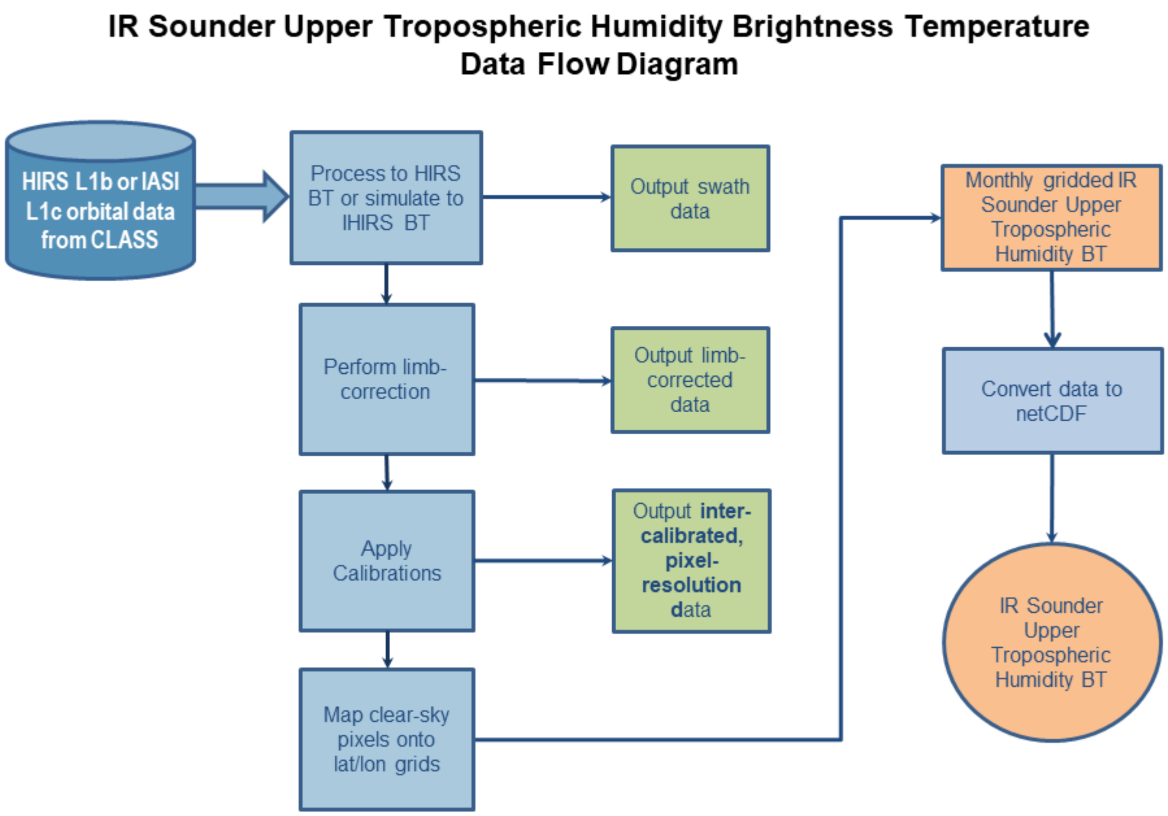

Figure 2: Flowchart of the intersatellite calibrated IR Sounder Upper Tropospheric Humidity BT processing.

3.3 Algorithm Input

3.3.1 Primary Sensor Data

The input data are HIRS Level 1B and IASI Level 1C data from the CLASS archive. The HIRS data include channel radiance, observation time, latitude, longitude, scan line number, position in a scan line, and satellite altitude. The IASI data also include cloud fraction information in addition to the variables in the HIRS dataset.

3.3.2 Ancillary Data

The algorithm requires three ancillary datasets: 1) Limb correction coefficients; 2) intersatellite calibration coefficients; and 3) inter-instrument calibration coefficients for calibrating IHIRS to HIRS. The limb correction coefficients were developed by Jackson et al. (2003) using a linear multivariate regression algorithm from multiple HIRS channels. The intersatellite calibration coefficients were developed by Shi and Bates (2011). The coefficients were derived based on zonal monthly means of overlapping satellites. The coefficients vary with respect to observed brightness temperature. The inter-instrument calibration coefficients were developed by Inamdar et al. (2023).

3.3.3 Derived Data

Not applicable.

3.3.4 Forward Models

Not applicable.

3.4 Theoretical Description

The production of the intersatellite calibrated clear-sky HIRS channel 12 brightness temperature is a sequential processing. The processing is done in the following sequence: HIRS Level 1B and IASI Level 1C data ingestion, limb-correction, intersatellite calibration, identifying and mapping of clear-sky data, and conversion of data to netCDF format.

3.4.1 Physical and Mathematical Description

Because of the independence in the calibration based on the individual HIRS instrument's channel spectral response function along with other factors, biases exist from satellite to satellite. The intersatellite biases for Television and Infrared Observation Satellite (TIROS-N), N06 to N19, M02 and M01 are shown in Figure 3. For the satellites processed, the biases are computed by subtracting the zonally matched brightness temperatures of each satellite from those of the previous satellite (for example, the bias between N16 and N17 is Tb(N16) − Tb (N17)).

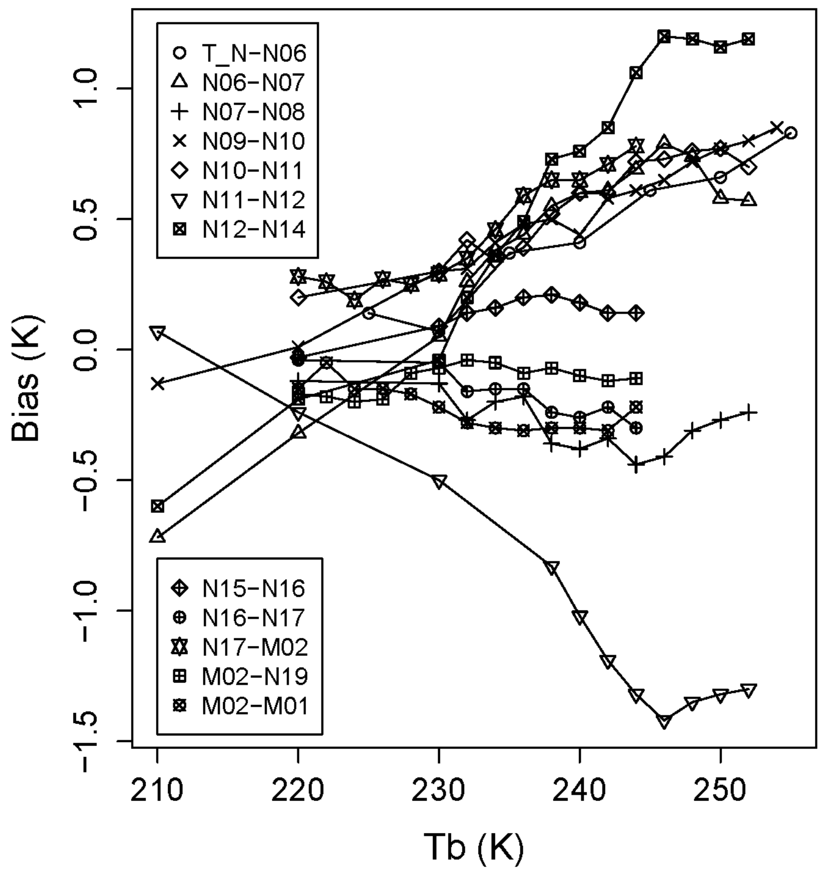

Figure 3: Sequential intersatellite biases of HIRS channel 12 brightness temperatures for 12 pairs of satellites as functions of the brightness temperature.

Bias values between N14 and N15 can be as large as 9 K at the warm end of the brightness temperatures (not shown). This is caused by the channel frequency change from about 1480 cm^{-1} on N14 and earlier satellites to 1530 cm^{-1} on N15 and later satellites. Because of the frequency change, the sensors on N14 and N15 essentially observed water vapor at different heights, which lead to the large bias of more than 9 K at the warm temperature observations. Examinations showed that due to large channel frequency change the biases between N14 and N15 not only vary with brightness temperature values, but also vary along latitude zones. Therefore, one additional component, latitude, is added to the derivation of inter-calibration coefficients for N14 and N15.

For other satellite pairs with similar channel response functions, the biases are within the range of ±1.2 K. Many satellite pairs have bias variations of more than 0.5 K across the scene temperature ranges. Small bias values are found at the low brightness temperature range. The patterns of the temperature bias variations are very similar to the bias variations of SNO measurements as shown by Shi et al. [2008]. Generally, the temperature-dependent biases shown in the low-temperature range of SNO measurements are extended by the bias variation curves derived in the current study into the warm temperature range with the continued increasing or decreasing patterns. At the observation temperature of 220 K, the differences of biases between a pair of data sets are within 0.2 K for almost all satellite pairs (except for N14-N15 because of large spectral change). However, the SNO measurements are limited to a much smaller temperature range over the polar regions, while the approach in the current study provides intersatellite bias data for the observations from 220 K to over 250 K.

The inter-satellite calibration coefficients are derived based on overlapping satellite pairs. The early satellites with HIRS/2 instruments before NOAA-14 often had shorter life spans compared to recent satellites. Intersatellite calibration coefficients derived from shorter overlapping times resulted in relatively large fluctuations due to smaller amounts of co-located data available. To achieve better homogeneity of the time series two more years of data before and after each pair of the overlapping periods are included in accessing the intersatellite differences.

The simulation of HIRS radiances with the IASI observed radiances is described in Inamdar et al. (2023). It involves the convolution of IASI radiances with the HIRS spectral response functions.

$$N_i^{HIRS}(\theta,\varphi) = \int N_v^{IASI}(\theta,\varphi) \cdot \Phi_i(v)\, dv \qquad (1)$$

Equation (1) states that the HIRS i^{th} channel radiances, N_i^{HIRS}, can be simulated by convoluting the observed IASI radiances, N_v^{IASI}, with the corresponding HIRS channel spectral response function, Φ_i, assuming that the IASI radiances sufficiently cover the spectral range of the HIRS SRF. For this CDR, i represent channel 12.

The accuracy of the integral in Equation (1) is affected by the resolution of the IASI radiances. In practice, this integral is computed numerically as a weighted summation between the IASI radiances and HIRS SRF function as

$$N_i^{HIRS}(\theta,\varphi) = \sum_{j=a}^{b} N_j^{IASI}(\theta,\varphi) \cdot \underline{\Phi}_{i,j} \qquad (2)$$

*w*here, N_j^{IASI} is the IASI j^{th} channel radiance and $\underline{\Phi}_{i,j}$ is the normalized spectral response function for the HIRS i^{th} channel averaged over the width of the IASI j^{th} channel. The summation over IASI channels [a,b] is performed over the extent of the spectral span of the given HIRS SRF.

The following lists the meanings of the symbols used in equations (1) and (2):

υ = *wavenumber (cm^{-1})*

θ = *view zenith angle or local zenith angle (degree)*

φ = *relative azimuth angle (degree)*

$\Phi_i(\upsilon)$ = *normalized spectral response function for the i^th^ channel (unit-less)*

$N_i^{HIRS}(\theta,\varphi)$ = *Top of the Atmosphere (TOA) radiance of HIRS i^th^ channel* (Wm^{-2} sr^{-1} $(cm^{-1})^{-1}$)

$N_v^{IASI}(\theta,\varphi)$ = *TOA radiance IASI at wavenumber* υ (Wm^{-2} sr^{-1} $(cm^{-1})^{-1}$)

N_j^{IASI} = *IASI j^th^ channel radiance*

$\underline{\Phi}_{i,j}$ = *normalized spectral response function HIRS i^th^ channel averaged over the frequency range of the IASI j^th^ channel*

The Metop satellite operated by EUMETSAT carries both the HIRS and the hyper-spectral IASI instrument with accurate spectral and radiometric calibration, providing a great opportunity to consistently calibrate the measurements. After the IASI radiances are convolved with the HIRS spectral response functions to produce IASI-simulated HIRS (IHIRS), IHIRS data are collocated and compared with HIRS observed radiances on Metop-A to develop a calibration table for each of the ascending/descending orbits and cloudy and clear categories. The resulting inter-instrument calibrated IHIRS data was found to agree with HIRS brightness temperatures within 0.04 K for channel 12 (Inamdar et al., 2023).

3.4.2 Data Merging Strategy

Not applicable for the pixel resolution dataset. For monthly mean data, data in each grid area are averaged to form monthly means.

3.4.3 Numerical Strategy

The limb correction and intersatellite calibration are performed to each individual pixel. If there are missing data, the value for a grid point is designated as 999.

3.4.4 Calculations

The HIRS channel 12 CDR production includes the following major steps:

1) Read Level 1B data

2) Perform cloud screening

3) Perform limb-correction on all longwave channels

4) Perform intersatellite calibration.

The IHIRS channel 12 production includes the following major steps:

1) Read Level 1C IASI data

2) Perform limb-correction on IHIRS channels 1-12

3) Perform inter-instrument calibration

4) Perform inter-satellite calibration

3.4.5 Look-Up Table Description

The look-up tables for intersatellite calibration coefficients are included as part of the source code package, developed based on the differences in zonal means of overlapping satellites (Shi and Bates, 2011). There is one look-up table for each pair of consecutive satellites with the following exceptions: (1) NOAA-18 is not included due to frequent sensor issues; and (2) Metop-01 is inter-calibrated to Metop-02. Near the time of the Metop-01 launch in 2013, N19 experienced a period of sensor issues, and therefore Metop-01 is calibrated to Metop-02, rather than to N19.

The inter-satellite biases are brightness temperature dependent. A look-up table contains a column of channel 12 brightness temperature at 2 K interval and the corresponding intersatellite bias at the ± 1 K range of the brightness temperature.

The look-up tables for inter-instrument calibration coefficients that calibrates IHIRS channel 12 to HIRS channel 12 on Metop-A are included as part of the source code package.

3.4.6 Parameterization

None.

3.4.7 Algorithm Output

Table 1: Output of the intersatellite calibrated clear-sky IR Sounder UTH brightness temperature dataset, including its content, file format, unit, and estimated sizes.

Name	Intersatellite calibrated clear-sky IR Sounder UTH brightness temperature
Content	Global monthly 2.5°x2.5° gridded time series from 1979 to the presently processed month.
File Format	NetCDF4
Physical Unit	Degrees K
Size	Pixel resolution data are stored in daily files of individual satellites with a size of approximately 38MB each. Monthly data are stored in yearly files with a size of 0.5MB each.

4. Test Datasets and Outputs

4.1 Test Input Datasets

There are no specific test data sets

4.2 Test Output Analysis

4.2.1 Reproducibility

Running the processing codes to the input datasets, users should recover same results except for rounding errors.

4.2.2 Precision and Accuracy

The precision of measurements depends on the noise equivalent differential radiance (NEΔN). The typical NEΔN value for HIRS channel 12 is 0.2 mW/(m2·sr·cm−1). The absolute accuracy cannot be determined as the product is inter-calibrated to a reference satellite. The relative averaged accuracy is approximately 0.1K.

4.2.3 Error Budget

The goal of the intersatellite calibration is to minimize the intersatellite differences. The remaining differences between each pair of overlapping satellites after the intersatellite calibration procedure are computed and listed in Table 2. The list shows that the averaged differences are mostly close to zero. It is important that the differences of individual pairs of satellites are closely clustered around 0 K. This ensures that the discontinuities among the uncorrected individual satellite series are minimized in the intercalibrated satellite series.

Table 2: Averaged remaining differences (K) of intersatellite calibrated monthly mean HIRS brightness temperatures between individual satellites for 30°S to 30°N latitudes.

Pairs	**T_N-N06**	**N06-N07**	**N07-N08**	**N09-N10**	**N10-N11**	**N11-N12**	**N12-N14**
Ave. Diff.	-0.118	0.004	0.052	0.119	-0.034	-0.134	0.062
Pairs	**N14-N15**	**N15-N16**	**N16-N17**	**N17-M02**	**M02-N19**	**M02-M01**	**N19-M01** (2020)
Ave. Diff.	0.087	-0.046	0.086	0.075	0.065	0.018	0.006

Table 3: Averaged remaining differences (K) of intersatellite calibrated monthly mean IHIRS brightness temperatures between individual satellites for 30°S to 30°N latitudes.

Pairs	**IHIRS M02-M01**	**IHIRS M01-M03**
Ave. Diff.	-0.093	0.088

5. Practical Considerations

5.1 Numerical Computation Considerations

None.

5.2 Programming and Procedural Considerations

None.

5.3 Quality Assessment and Diagnostics

Quality assessment and diagnostics are based on

a. HIRS sensor status provided by NOAA Office of Satellite Operations, available at https://www.ospo.noaa.gov/Operations/POES/status.html and https://www.ospo.noaa.gov/Operations/METOP/status.html.

b. IASI sensor status provided by EUMETSAT at https://www.eumetsat.int/metop-spacecraft-status

c. Comparison of output from overlapping satellites.

5.4 Exception Handling

When problems are found based on the quality assessment and diagnostics of 5.3, affected data are removed from the time series.

5.5 Algorithm Validation

The intersatellite calibration brings HIRS and IHIRS channel 12 brightness temperature data to the level of a reference satellite observation (NOAA-12 as the reference satellite). Validation is done to check the homogeneity between overlapping satellites. Analyses show that the remaining differences between overlapping satellite are generally less than 0.1 K (Shi and Bates, 2011). Inter-comparisons with upper tropospheric water vapor channel data from other satellites, including METEOSAT and from AMSU-B are also performed (see Yang 2014; Chung et al. 2016).

The upper panel of Fig. 4 shows an inter-comparison of monthly IR Sounder UTH brightness temperature (labeled as IR) anomalies averaged over the domain 30° S–30° N with two microwave sounder brightness temperature datasets derived from SSM/T-2, AMSU-B and MHS that measure upper tropospheric humidity near the layer of HIRS channel 12 weighting function peak. The microwave datasets are independently developed by scientists at University of Miami (labeled as MW1) and by the Fidelity and uncertainty in climate data records from Earth Observations (FIDUCEO) funded by the European Union (labeled as MW2). The lower panel displays the total values of monthly IR Sounder UTH brightness temperatures averaged over the same domain.

Similar to the study of Shi et al. (2022), despite the structural difference between infrared and microwave datasets, i.e., the infrared dataset is based on clear-sky, and the microwave datasets excludes only precipitating clouds, the anomaly comparison (upper panel) shows consistency in seasonal and interannual variability patterns among the three datasets. All three datasets show major peaks and dips along the time series in the same phases, though there are differences in the magnitudes of the fluctuations. In the FIDUCEO dataset, SSM/T-2 data before 1998 were often sparse or missing, causing a few data gaps and some uncertainty in monthly means. Despite different definitions and ways of computing UTH, the anomalies of the three datasets are close to each other. The differences between the anomalies of the IR dataset and MW1 are generally within 0.1 K.

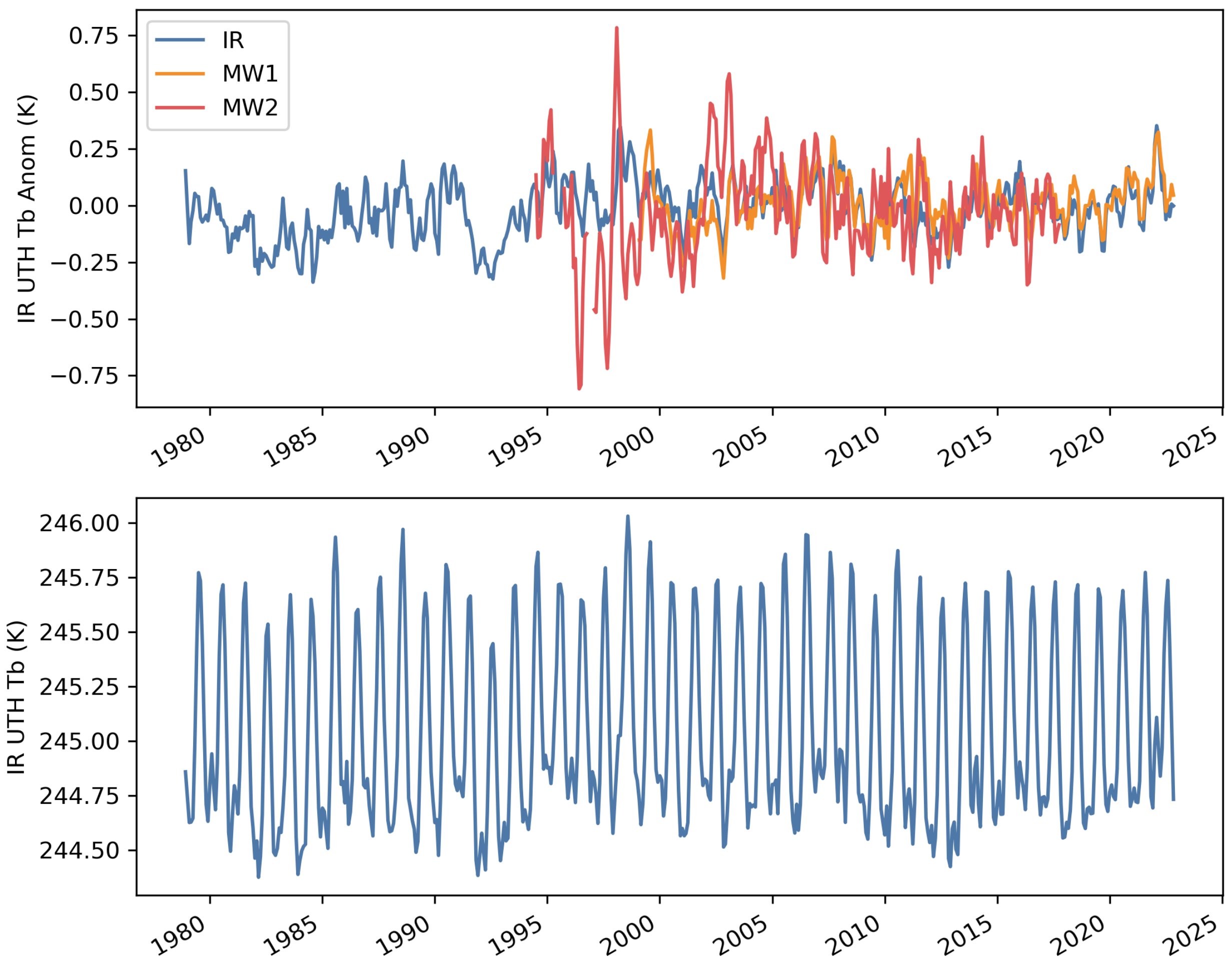

Figure 4: Anomaly (upper panel) and total value time series of brightness temperatures from infrared and microwave sounder measurements that measure upper tropospheric humidity. Labels: IR: HIRS and IHIRS data from NCEI; MW1: AMSU-B and MHS data from University of Miami; MW2: SSM/T-2, AMSU-B, and MHS data from Fidelity and uncertainty in climate data records from Earth Observations. A 3-month moving average is applied to the

time series to reduce short-term fluctuations.

5.6 Processing Environment and Resources

HIRS data are processed on a Linux machine with ~16GB memory. Programming languages include C, Fortran 77, and C Shell script. It takes about 10 hours to process one year of data. The processing needs ~15GB of disk space for one year's input data per satellite and needs about the same amount of disk space for intermediate outputs.

The programming languages for processing IHIRS data include C, Fortran 77, IDL, and C Shell script. It takes about 30 hours to process one year of data. The processing needs ~700GB of disk space for one month's input data per satellite and needs about twice amount of disk space for intermediate outputs.

6. Assumptions and Limitations

The time series is based on clear-sky data only.

6.1 Algorithm Performance

Not applicable.

6.2 Sensor Performance

HIRS and IASI sensor status are provided by NOAA Office of Satellite Operations and EUMETSAT, available at https://www.ospo.noaa.gov/Operations/POES/status.html, https://www.ospo.noaa.gov/Operations/METOP/status.html, and https://www.eumetsat.int/metop-spacecraft-status .

7. Future Enhancements

When improved intersatellite calibration algorithm becomes available, the entire time series will be re-processed.

8. References

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Yang, Q., (2014) Comparison of upper tropospheric humidity estimates from different instruments. EUMETSAT Satellite Application Facility on Climate Monitoring, CDOP2 VS Study: CM_AS13_02

Appendix A. Acronyms and Abbreviations

Acronym or Abbreviation	Meaning
BT	Brightness Temperature
C-ATBD	Climate Algorithm Theoretical Basis Document
CDR	Climate Data Record
FIDUCEO	Fidelity and uncertainty in climate data records from Earth Observations
HIRS	High-Resolution Infrared Radiation Sounder
IASI	Infrared Atmospheric Sounding Interferometer
IHIRS	IASI simulated HIRS
IR	infrared
Metop	Meteorological Operational Satellite Program
MW	microwave
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
SNO	Simultaneous Nadir Overpass
SSM/T-2	Special Sensor Microwave - Humidity
TIROS-N	Television Infrared Observation Satellite - N
UTH	Upper Tropospheric Humidity