GSICS Global Space-based Inter-Calibration System

NOAA Satellites and Information
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GSICS Contribution to WGCV CEOS:

Reference Datasets, Recalibration, Climate Data Record, and Broader Impact on Climate Monitoring

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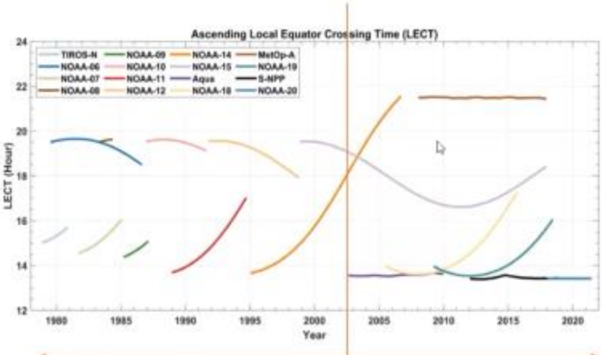
Two Periods of Satellite Microwave Sounder Observations

- NASA Aqua, MetOp series, SNPP, and JPSS series are all in stable sun-synchronous orbits. No diurnal drifting sampling errors
- NOAA satellites before NOAA-19 all had orbital drifts, causing diurnal sampling drifting errors. Contain diurnal sampling drifting errors

LECTs of POES, MetOp-A, Aqua, and JPSS satellites



Period with all satellites having orbital drifts

Period with satellites in stable orbits

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Requirement on Reference Measurements

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- **Requirements for reference measurements are different for weather prediction and climate change detection**
- Weather Requirement: absolute accuracy better than 0.1~0.2 K is required for satellite data to be assimilated into NWP models without a bias correction
  - Unless biases are absolutely zero, unstable small biases are no good for climate change detection--unstable bias of ±0.1K may still give a large non-climate trend signal of 0.2K/Dec.
- Climate Requirement: stability is the primary requirement for climate change detection
  - large bias is not a big concern as long as it is stable
  - Temperature measurement stability requirement (Ohring et al. 2005):
    0.04K/Decade for tropospheric temperature
    0.08K/Decade for stratospheric temperature (Observations can do better than this)

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Examples of Reference Satellites: SNPP/ATMS, Aqua/MetOp-A/AMSU-A

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- Diurnal sampling difference is absent – diurnal sampling biases are naturally removed by satellites with stable orbits of the same overpass time
- Time series from different satellites match with each other nearly perfectly without applying any diurnal drift corrections or time-dependent inter-calibration
- Calibration drifts could be estimated quite accurately
- Small trend differences suggest absolute stability on either instruments
- Radiometric stability within 0.004K/Year for SNPP/ATMS and Aqua/AMSU-A for all analyzed channels

Monthly global mean anomaly time series of brightness temperatures for AMSU-A channel 8 onboard Aqua (blue, top panel) versus ATMS channel 9 onboard SNPP (red, top panel) and their difference time series (green, top and lower panels). The AMSU-A and ATMS data are respectively from June 2002 and December 2011 to April 2018. The AMSU-A anomaly time series are overlaid by ATMS during their overlapping period with their differences shown as nearly a constant zero line in the same temperature scale. Amplified scale of temperature is used in the bottom panel to show detailed features in the anomaly difference time series. Both ATMS and AMSU-A data are from limb-adjusted views and averaged over ascending and descending orbits (plot from Zou et al. 2018).

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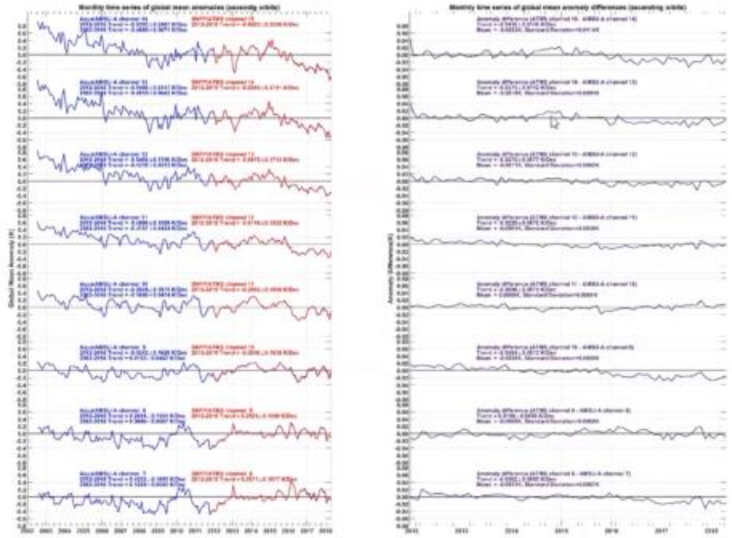
All analyzed channels Achieved High Radiometric Stability Performance



Radiometric stability achieves 0.004K/Year for most channels

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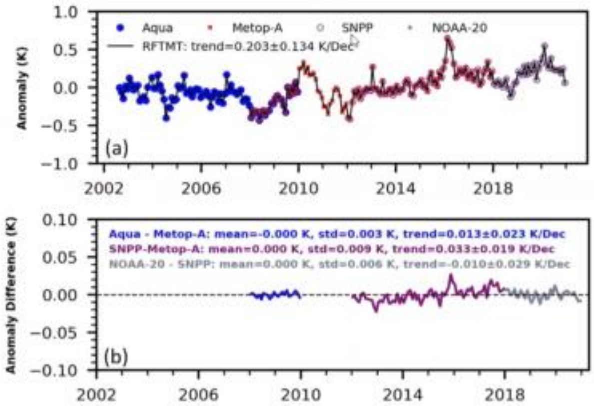
Reference Time Series for Climate Monitoring

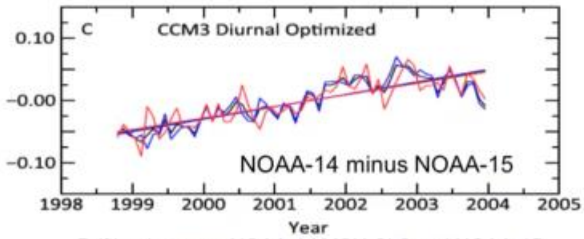
- Maximum relative drift between satellite pairs: 0.033 K/decade
- RFTMT is an average of available satellite observations which gives a trend of 0.203 K/decade during 2002-2021
- Small sampling theory gives a trend uncertainty= $\pm\frac{\Delta}{2\sqrt{N}} =$ $0.01\ \mathrm{K/decade}$; here Δ=0.033 K/decade, N=2 is the overlapping satellite number
- Accuracy in trend detection is better than the required 0.02 K/decade given in GCOS (2016)



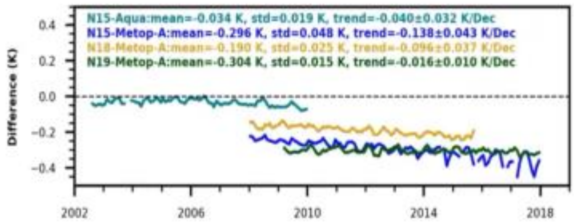
(a) Monthly global mean anomaly time series for temperatures mid-troposphere (TMT) from Aqua, MetOp-A, S-NPP, and NOAA-20 and the reference TMT (RFTMT) time series merged from these satellites; (b) inter-satellite difference time series before the merging. Anomalies are relative to a monthly climatology of RTMT for the MetOp-A period from January 2008 to December 2017. Uncertainties in trend calculations represent 95% confidence intervals with autocorrelation adjustments (Plots are from Zou et al. 2021)

Recalibration Requirement

- Cooling drifts up to 0.14 K/decade in NOAA-15 was found when compared to MetOp-A
- Warming drifts up to 0.2 K/decade in NOAA-14 was found when compared to NOAA-15
- Climate signals were 0.2 K/decade
- These drifts need to be removed to develop reliable CDR



Drifting between NOAA-14 MSU Ch2 and NOAA-15 AMSU-A Ch5 (Plot from Mears et al. 2016)



Drifts in NOAA-15 and NOAA-18 (AMSU-A Ch5) relative to MetOp-A (Plot from Zou et al. 2023)

Recalibration to Remove Bias Drift

- Instrument calibration equation:

$$R_e = R_c + G^{-1}(C_e - C_c) + \mu G^{-2}(C_e - C_c)(C_e - C_w) \quad (1)$$

$$G = \frac{(C_w - C_c)}{(R_w - R_c)} = Gain \quad (2)$$

- Assuming errors incur for warm target, cold target, and instrument nonlinearity:

ΔR_w → Warm target temperature measurement error
ΔR_c → Cold target temperature measurement error
$\Delta\mu$ → nonlinearity error

- One obtain the error free calibration equation (Zou et al. 2006):

$$R_e' = -\delta R + R_c + G^{-1}(C_e - C_c) + (\mu - \delta\mu)G^{-2}(C_e - C_c)(C_e - C_w) \quad (3)$$

$$\delta R = a\Delta R_w + (1 - a)\,\Delta R_c \quad (4)$$

$$\delta\mu = \Delta\mu + b\,(\Delta R_w - \Delta R_c) \quad (5)$$

Here: *a* and *b* → Unknown constants

Possible Mechanisms Causing Calibration Drifts

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- Possible mechanisms causing calibration drifts (Zou et al. 2023):

➢ Degradation in blackbody emissivity: A change of emissivity from 0.9999 to 0.999 in ten years with a blackbody temperature of 300K would cause calibration drift of 0.27 K/decade

➢ Side-lobe effect (efficiency 2%-4%): Assuming effective satellite temperature of 190K, then a 0.1%-0.2% change in side-lobe efficiency due to degradations in reflector or antenna materials would cause calibration drift of 0.19-0.38 K/decade

➢ Detector or amplifier degradation (changes in the nonlinearity coefficient λ over time). Also caused calibration bias drift but had a cancellation effect with drifts in the target measurement errors. *It also causes warm target related seasonal variability in* brightness temperatures.

Recalibration Results

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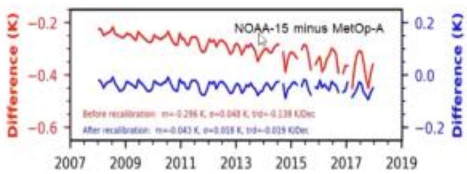
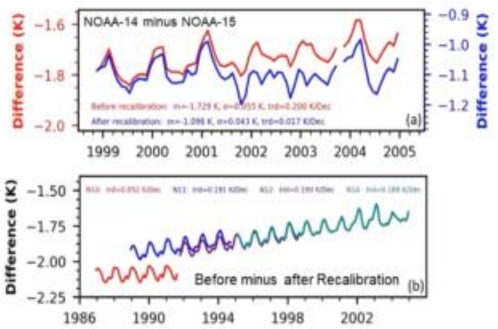


Inter-satellite TB differences between NOAA-15 and MetOp-A for before and after recalibration (Plot from Zou et al. 2023)

- NOAA-15 AMSU-A Ch5 drifts were nicely removed relative to MetOp-A by recalibration
- Relative drifts between NOAA-15 AMSU-A Ch5 and NOAA-14 MSU Ch2 were nicely removed by recalibration
- Spurious warming drifts on NOAA-11 to NOAA-14 were nicely removed by recalibration



(a) Global ocean mean difference time series of brightness temperatures between the recalibrated NOAA-15 AMSU-A channel 5 and NOAA-14 MSU channel 2 for before (red) and after (blue) recalibration of NOAA-14. Note the mean difference between NOAA-14 and NOAA-15 is still non-zero after the recalibration, due to their channel frequency differences. (b) Global mean differences for before minus after recalibration for NOAA-10 to NOAA-14, showing their spurious warming drifts before recalibration. (plot from Zou et al. 2023)

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Recalibration Impact on Climate Data Records

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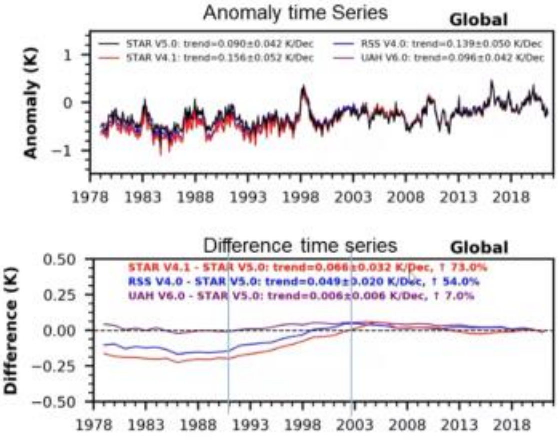
- Compare the recalibrated dataset, STAR V5.0 CDR with other existing CDRs developed by different research groups
- Major differences incurred during 1991-2002, where spurious calibration drifts in NOAA-11 through NOAA-14 were removed
- This also caused trend differences during the entire observation period



Upper panel: Global-mean TMT monthly anomalies; Lower Panel: Global annual mean anomaly difference time series between existing data sets and STAR V5.0. Time series are plotted so that their mean differences during 01/2020–06/2021 are zero. Vertical lines on the lower panel represent the end of NOAA-10 near 1991 and start of RTMT on August 2002, respectively. (Plot from Zou et al. 2023)

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Broader Impact on Climate Change Assessment and Climate Change Modeling

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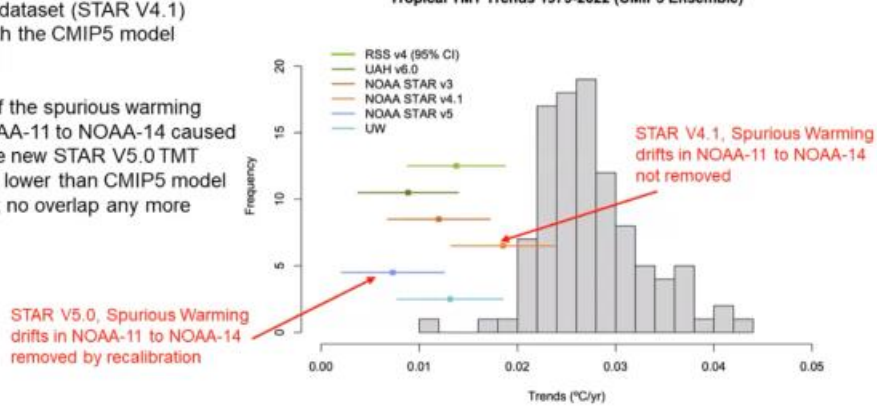
- Trends from the earlier version of the STAR TMT dataset (STAR V4.1) overlaps with the CMIP5 model simulations
- Removal of the spurious warming drifts in NOAA-11 to NOAA-14 caused trends in the new STAR V5.0 TMT significantly lower than CMIP5 model simulations; no overlap any more



Mid-troposphere satellite products from UAH, RSS, NOAA STAR (v3, v4.1 and v5) and UW. Model values use synthetic MSU/AMSU-TMT weightings, spread is 95% envelope of simulations (plot from Gavin Schmidt, RealClimate.org, https://www.realclimate.org/index.php/climate-model-projections-compared-to-observations/

Summary

•Satellite microwave sounders in stable sun-synchronous orbits (Aqua, MetOp-A, SNPP, NOAA-20) were identified as reference observations because they achieve high radiometric stability performance

• These reference satellites can be merged together quite straightforward to develop reference atmospheric temperature time series from 2002-present with high accuracy in trend detection

• The reference time series were used to identify with high confidence on the calibration drifts in old satellites with satellite overlaps. These include spurious cooling drift in NOAA-15 and spurious warming drifts in NOAA-14, NOAA-12, and NOAA-11

• The calibration drifts in NOAA-11 to NOAA-15 were removed by a recalibration approach based on simultaneous nadir overpasses using the reference satellites as a Reference

•A new version (STAR V5.0) of the mean layer temperature CDR, covering the period from November 1978 to the present (44 years) with three generations of satellite microwave sounders, was developed using a backward merging approach

• The new CDR includes three atmospheric layers: mid-troposphere (TMT), upper troposphere (TUT), and lower-stratosphere (TLS), which measure layer temperatures peaking roughly at 5 km, 10 km, and 17 km, respectively, above the Earth's surface.

• The new version of the TMT time series shows a much lower global warming trend than previous versions, suggesting that trends from the climate model simulations by CMIP5 are too warm