Global Clear-Sky Skin Temperature From Geostationary and Polar-Orbiting Satellites Using a Single-Channel Algorithm With Viewing Zenith Angle Correction

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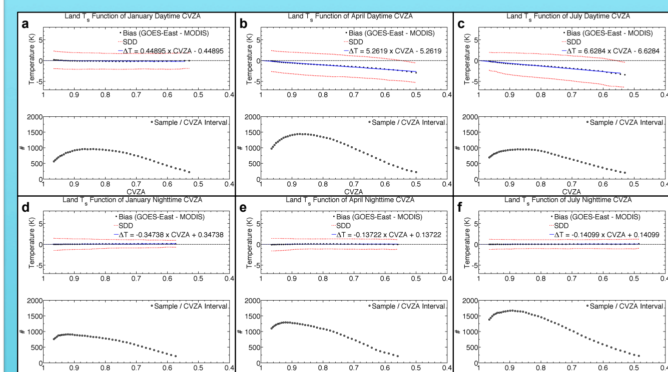
Introduction

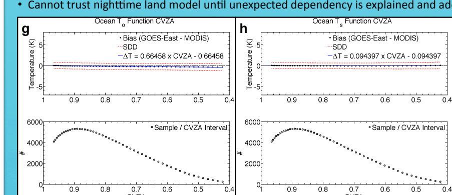
NASA Langley provides historic and near-real-time (NRT) land and ocean clear-sky skin temperature (T_s) derived from high-resolution 11-µm brightness temperatures (*T11*) measured from geostationary (GEO) satellites and the Advanced Very High Resolution Radiometer (AVHRR) sensors. The combined GEO satellites offer continuous hourly observations of the near-global diurnal T_s cycle, while the higher-resolution AVHRR imagers complement the GEO sensors with polar retrievals. The NRT merged global estimates of T_s, with accompanying cloud and surface data, are valuable as input for modelers and for monitoring Earth surface processes. Deriving T_s from single-channel *T11* data is limited to clear-sky conditions, requires correction for atmospheric absorption, and is subject to viewing angle effects. Therefore, T_s validation with established references is essential. Presented here are improvements to the NASA Langley GEO satellite and AVHRR *T11*-based T_s product, derived using a single-channel technique. The resulting clear-sky T_s values are validated with ground references and the independent Moderate-resolution Imaging Spectroradiometer (MODIS) Land Surface Temperature product (LST). Furthermore, an empirical method is developed to correct for the daytime viewing-angle dependency of T_s. Results of a nadir-normalized empirical correction model show improved accuracy and precision in T_s relative to MODIS LST, the Surface Radiation Budget Network (SURFRAD), and an Atmospheric Radiation Measurement (ARM) Program ground station. The immediate availability and extensive coverage of these enhanced T_s observations should prove valuable for assimilation into and validation of weather and climate models.

Nadir Normalization Model



Figs 2a-f. GOES-East *T11*-derived T_s mean bias relative to the same for nadir-looking MODIS over land, as a function of cosine of the viewing zenith angle (CVZA). Simple linear regression yields T_s correction value *ΔT* (see **Applying Correction Model *ΔT*** section):

- Note: x-axes are reversed to preserve origin (CVZA=1) on left side. Slope of *ΔT* is relative to increasing CVZA
- Day (**a-c**): GOES-East becomes "colder" relative to nadir retrievals as VZA increases (CVZA decreases). *ΔT* dependent on season
- Night (**d-f**): Unintuitive VZA dependency, i.e., GOES-East becomes "warmer" with increasing VZA
- Cannot trust nighttime land model until unexpected dependency is explained and addressed



Figs 2g-h. Comparison of T_o- and T_s-based nadir-normalized models over ocean:

- Over ocean, T_s is derived from ε_s that is produce from a VZA- and wind-speed-dependent surface emissivity model
- Fact that T_o-based model shows dependency whereas T_s-based model shows virtually none demonstrates that ocean emissivity model adequately accounts for T_s VZA dependency
- Because ocean T_o dependency is much more consistent diurnally and seasonally compared to land, boundary layer influence might contribute to reversed VZA dependency over nighttime land

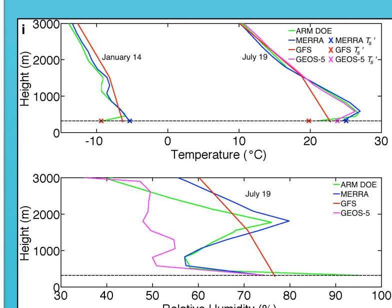


Fig 2i. Comparison of ARM Department of Energy (DOE) 12:00 UTC sounding observations with MERRA, GFS, and GEOS-5 model temperature (top) and relative humidity (bottom) profiles at the ARM Central Research Facility:

- GFS poorly represents the boundary layer
- Higher-resolution MERRA performs better, but fails to resolve January nocturnal inversion
- MERRA better characterizes July temperature and humidity inversion, but underestimates magnitude
- GEOS-5 (July only) temperature profile is similar to MERRA, although with less warm bias at the surface; humidity is poorly characterized compared to MERRA
- Need to investigate if inability to resolve nocturnal inversion can explain the unintuitive VZA dependency in the nadir-normalized T_s bias model at night/weak dependency in winter

Applying Correction Model *ΔT*

Normalize to nadir (Example: ARM IRT)	$T_{s,sat}(VZA_{nadir}) = T_{s,sat}(VZA_{sat}) - \Delta T(VZA_{sat})$
Normalize to off-nadir VZA (Example: MODIS)	$T_{s,sat}(VZA_{modis}) = T_{s,sat}(VZA_{sat}) - [\Delta T(VZA_{sat}) - \Delta T(VZA_{modis})]$
Normalize to wide FOV (Example: SURFRAD)	$T_{s,sat}(VZA_{53°}) = T_{s,sat}(VZA_{sat}) - [\Delta T(VZA_{sat}) - \Delta T(VZA_{53°})]$

Table 1. Correction equations for satellite-retrieved T_s:

- **Correct to nadir:** Nominal scenario. Given satellite-retrieved $T_{s,sat}(VZA_{sat})$, subtract the correction value determined as a function of satellite viewing angle $\Delta T(VZA_{sat})$. Yields nadir-normalized satellite skin temperature $T_{s,sat}(VZA_{nadir})$
- **Correct to MODIS VZA:** Start with $T_{s,sat}(VZA_{sat})$, subtract the difference of $\Delta T(VZA_{sat})$ and the correction value at the MODIS VZA, $\Delta T(VZA_{modis})$. Yields MODIS-normalized satellite skin temperature $T_{s,sat}(VZA_{modis})$
- **Correct to SURFRAD:** Given $T_{s,sat}(VZA_{sat})$, subtract the difference of $\Delta T(VZA_{sat})$ and the correction value at VZA=53°, $\Delta T(VZA_{53°})$. Yields SURFRAD-normalized satellite skin temperature $T_{s,sat}(VZA_{53°})$. (see **Validation** section for further discussion)

Background

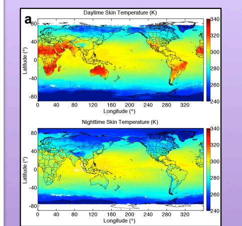


Fig 1a. AVHRR October T_s average

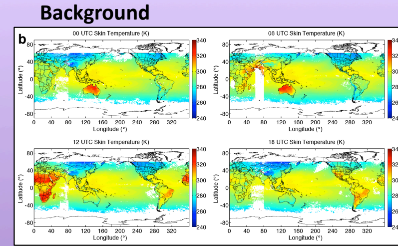
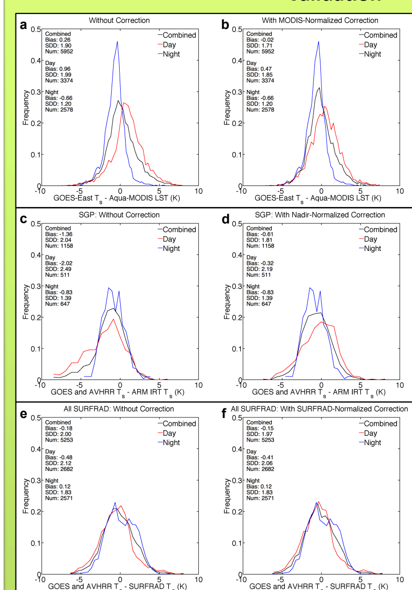


Fig 1b. Merged GEO T_s: INSAT-3D replaces FY-2E over Indian Ocean in 2015

Single-channel (LaRC) T_s retrieval algorithm overview[1]

- Start with modeled skin temperature T_s' from MERRA gridded **tile** data
- Using T_s' and surface emissivity ε_s, compute a surface-leaving IR temperature T_o' and top-of-atmosphere (TOA) brightness temperature *T11'* via absorption/emission correction using correlated *k*-distribution method
- Adjust T_s' and temperature/humidity profiles such that *T11'* equals observed *T11*
- Compute radiance ratio, $R_t = L(T_o) / L(T11)$, for each tile
- For each clear pixel *i* within the tile, $L_{si} = R_t \times L(T11_i)$
- **Result:** The pixel-level surface radiance L_{si} is converted, via inverse Planck Function B^{-1}, to $\mathbf{T_{si}}$ using ε_s model or observations (CERES or MODIS values[2,3]) and downwelling radiant energy at the surface L_{DWi}: $T_{si} = B^{-1}\left\{\frac{[L_{si} - (1-\varepsilon_s)L_{DWi}]}{\varepsilon_s}\right\}$

Validation



Figs 3a-b. Mean bias and standard deviation of the differences (SDD) of GOES-East T_s relative to the Aqua-MODIS Land Surface Temperature and Emissivity product (MYD11_L2), without and with application of the daytime VZA correction (**Table 1: Correct to MODIS**):

- Comparison performed on pixel-averaged 1°x1° grid
- Both GOES-East and MODIS are using the MYD11_L2 ε_s values
- A spectral band difference adjustment factor is applied

Figs 3c-d. Mean bias and SDD of combined GOES-East, GOES-West, and NOAA-18-AVHRR T_s relative to ARM Southern Great Plains (SGP) Infrared Thermometer (IRT) ground-based radiation pyrometer, without and with daytime VZA correction (**Table 1: Correct to nadir**):

- IRT provides upwelling and downwelling contributions
- All T_s retrievals use CERES ε_s values
- Using MODIS ε_s for all retrievals amounts to a 0.57-K increase in absolute bias (**Figs 4a-b**)

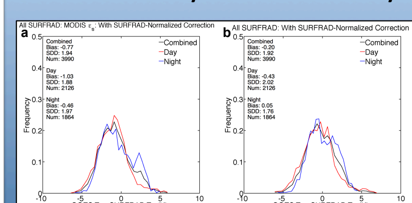
Figs 3e-f. Mean bias and SDD of combined GOES-East, GOES-West, and NOAA-18-AVHRR T_s relative to the seven combined SURFRAD ground stations, without and with daytime VZA correction (**Table 1: Correct to SURFRAD**):

- SURFRAD pyrometers measure radiation hemispherically, thus satellite T_s is normalized to a view equivalent to radiation measured at all angles (~53°)
- SURFRAD pyrometers are broadband radiometers, thus CERES broadband ε_s values are used

		BON		DRA		FPK		GWN		PSU		SXF		TBL	
		Orig	Corr	Orig	Corr	Orig	Corr	Orig	Corr	Orig	Corr	Orig	Corr	Orig	Corr
Combined	Bias	0.99	0.89	-1.18	-1.17	-0.31	0.12	0.54	0.35	0.85	0.70	0.03	0.20	-0.90	-0.85
	SDD	1.88	1.86	1.61	1.46	1.70	1.58	1.92	2.11	2.05	2.17	2.08	2.05	1.70	1.67
Day	Bias	1.41	1.18	-1.00	-0.97	-0.41	0.25	-1.02	-1.46	-0.30	-0.65	-0.10	0.22	-1.16	-1.06
	SDD	2.15	2.15	1.91	1.67	1.72	1.54	1.48	1.55	1.91	2.01	2.45	2.40	1.88	1.83
Night	Bias	0.66	0.66	-1.40	-1.40	-0.13	-0.13	1.80	1.80	1.65	1.65	0.17	0.17	-0.66	-0.66
	SDD	1.56	1.56	1.11	1.11	1.63	1.63	1.17	1.17	1.74	1.74	1.52	1.52	1.48	1.48

Table 2. Mean bias and SDD (K), before (Orig) and after (Corr) daytime VZA correction, of combined GOES-East, GOES-West, and NOAA-18-AVHRR T_s relative to the SURFRAD ground stations: Bondville, Desert Rock, Fort Peck, Goodwin Creek, Penn State, Sioux Falls, and Table Mountain. Note: no correction applied to night data.

Sensitivity to Surface Emissivity: CERES vs. MODIS



Figs 4a-b. Mean bias and SDD of combined GOES-East and GOES-West T_s relative to the seven combined SURFRAD ground stations, comparing the use of MODIS ε_s (**a**) with CERES ε_s (**b**):

- Using MODIS ε_s instead of CERES ε_s for the satellite-based T_s retrievals amounts to a 0.57-K increase in absolute bias on average
- SURFRAD pyrometers use CERES broadband ε_s values

Summary/Future Work

- Daytime CVZA dependency of T_s is evident, especially in the summer, and can be characterized with an empirical model
- Relative to ARM (MODIS), VZA correction reduces daytime absolute bias by 1.7 K (0.5 K) and SDD by 0.3 K (0.1 K)
- Relative to all SURFRAD stations, VZA correction reduces daytime absolute bias and SDD by about 0.1 K
- Need to determine if unintuitive CVZA dependency during night/winter is related to problems with resolving boundary layer inversions in modeled atmosphere. Will employ radiative transfer model to assess influence of inversion at varying VZA

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[1]Scarino, B., P. Minnis, R. Palikonda, R. H. Reichle, D. Morstad, C. Yost, B. Shan, Q. Liu, 2013: Retrieving clear-sky surface skin temperature for numerical weather prediction applications from geostationary satellite data. Remote Sensing, 5(1), 342-366.
[2]Chen, Y., S. Sun-Mack, P. Minnis, D. F. Young, and W. L. Smith, Jr., 2004: Seasonal surface spectral emissivity derived from Terra MODIS data. Proc. 13th AMS Conf. Satellite Oceanogr. and Meteorol., Norfolk, VA, Sept. 20-24, CD-ROM, P2.4.
[3]Z. Wan and Z.-L. Li, 1997: A physics-based algorithm for retrieving land-surface emissivity and temperature from EOS/MODIS data. IEEE Trans. Geosci. Remote Sens., 35(4), 980-996.