Surface Atmosphere Radiation Budget (SARB) working group update

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CERES Science Team Meeting
May 14-16, 2024

Outline of this presentation

- Edition 4 data products
  - CRS
  - EBAF
  - MATCH (NOAA20 aerosol optical thickness consistent with Aqua)
- Edition 5 algorithm developments
  - CERES radiative transfer model
  - GEOS-IT temperature and humidity correction for EBAF
  - Aerosol transport model

Edition 4 products production and validation

- Edition 4 CRS (Seung-Hee Ham's presentation)
  - Instantaneous surface and in atmosphere irradiances (Level 2)
  - Gridded instantaneous irradiances (SYN1deg, Level 3)
  - January 2018 through December 2022 (Terra or Aqua) were released
- Edition 4.1 SYN
  - Produced through January 2024.
  - Edition 4B (MET-10 bug fix, 2-channel nighttime optical depth, and no twilight algorithm with TISA new interpolation) available soon.
- Edition 4.2 EBAF
  - Reprocessed and released revised Edition 4.2 surface fluxes and TOA total area clear-sky fluxes from March 2000 through June 2023 in December 2023
  - Produced and released through December 2023.
  - Reprocess clouds over the NOAA20 period (April 2022 onward) with MERRA-2 (summer 2024). Climatological adjustments to NOAA20 will be applied with Terra+Aqua using a common period from May 2018 through March 2022.
  - The revised product will be released late summer/early fall 2024
- Edition 4 MATCH
  - Consistency of aerosol optical thickness derived from MODIS and VIIRS
  - Working with the Dark Target and Deep Blue teams to mitigate the AOD differences
- CCCM D2 version
  - Produced with CALIPSO V4-51and CloudSat R05 data products.
  - Will be released soon.

CERES Cloud Radiative Swath (CRS) Update

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Collaboration with:

TISA Group: Joshua C. Wilkins, David Doelling and Pamela Mlynczak (TISA gridding for CRS1deg product)

Data Management: Walter Miller, Victor Sothcott, Joshua C. Wilkins, and Kathleen Dejwakh

ADM Group: Wenying Su (TOA fluxes)

Cloud group: Bill Smith Jr, Sunny Sun-Mack, and Ben Scarino (Cloud and skin temperature retrievals)

FLASHFLUX group: Paul Stackhouse (Parameterized surface fluxes in FLASHFLUX)

CRS Flux Algorithm

Inputs

Atmospheric Profiles	GMAO Reanalysis p(z), T(z), q(z), and O_3(z)
Surface	Surface Skin Temperature Surface Emissivity Surface Albedo
Clouds	MODIS Clouds
Aerosol	MODIS & CATM* Aerosol

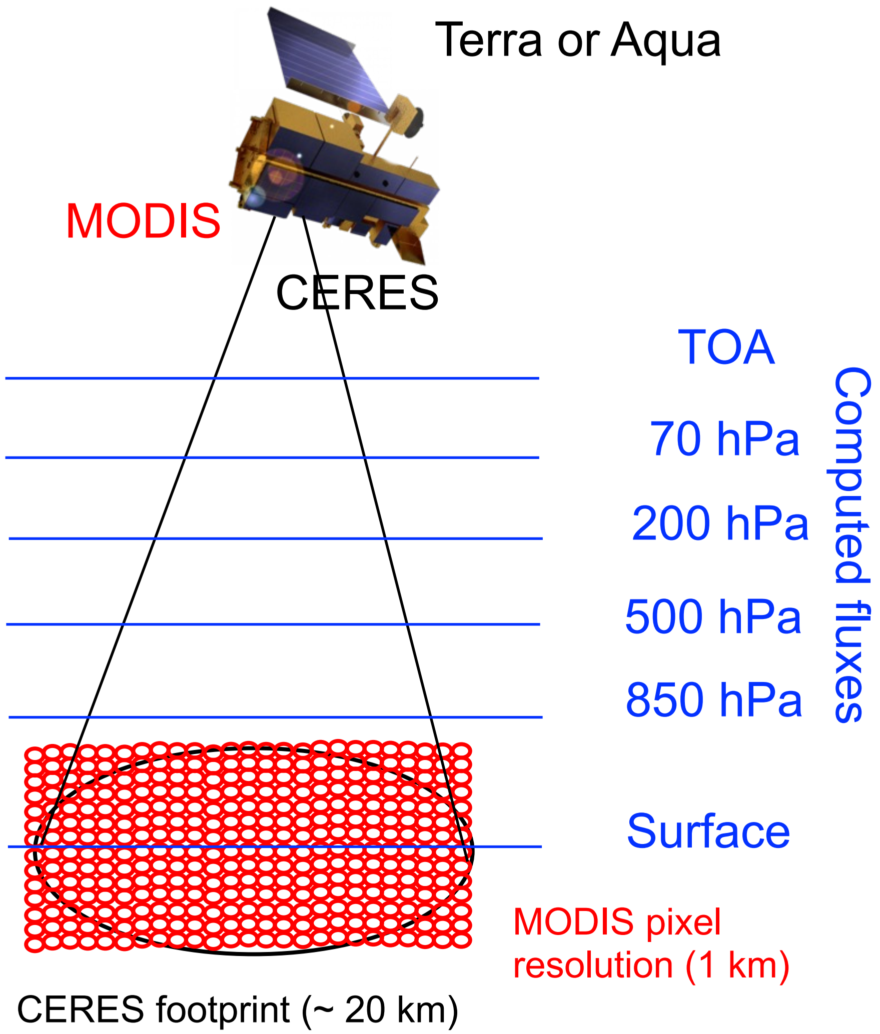
↓

Fu-Liou Radiative Transfer Model

Four Conditions:
- Total Sky (Aer + Cld)
- Clear Sky (Aer)
- No Aerosol (Cld)
- Pristine (-)

↓

Computed Instantaneous Fluxes at 6 vertical levels for every CERES footprint

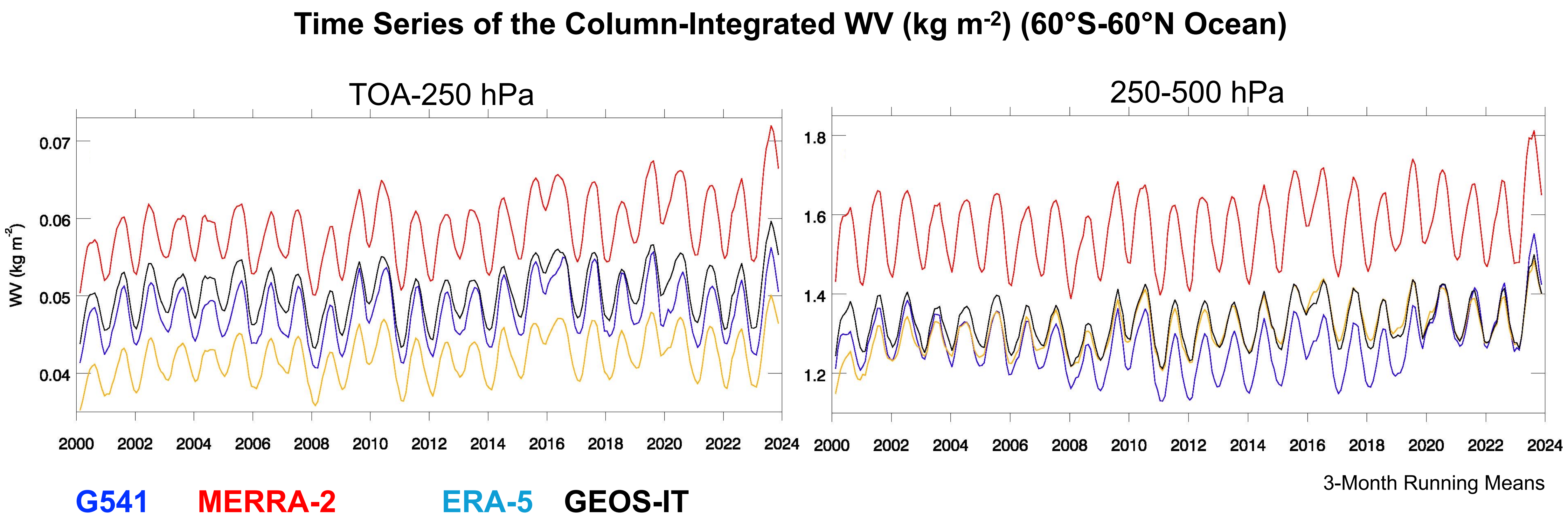


CATM : CERES Atmospheric Transport Model produced by CERES SARB group

Ongoing Ed5 Development for the CRS Flux Algorithm

- Switching of the reanalysis (GEOS-5.4.1 → GEOS-IT), which is used for describing T(z) and q(z) profiles
- Flexible configuration of Fu-Liou radiative transfer model
- Updating gas absorption subroutine in Fu-Liou by including more gases and new band structure
- Updating surface albedo history (SAH) map using Ed5 IGBP and SSF CERES/MODIS
- Evaluation of the CRS algorithm using surface validation sites
- New aerosol properties from CAM6 aerosol model

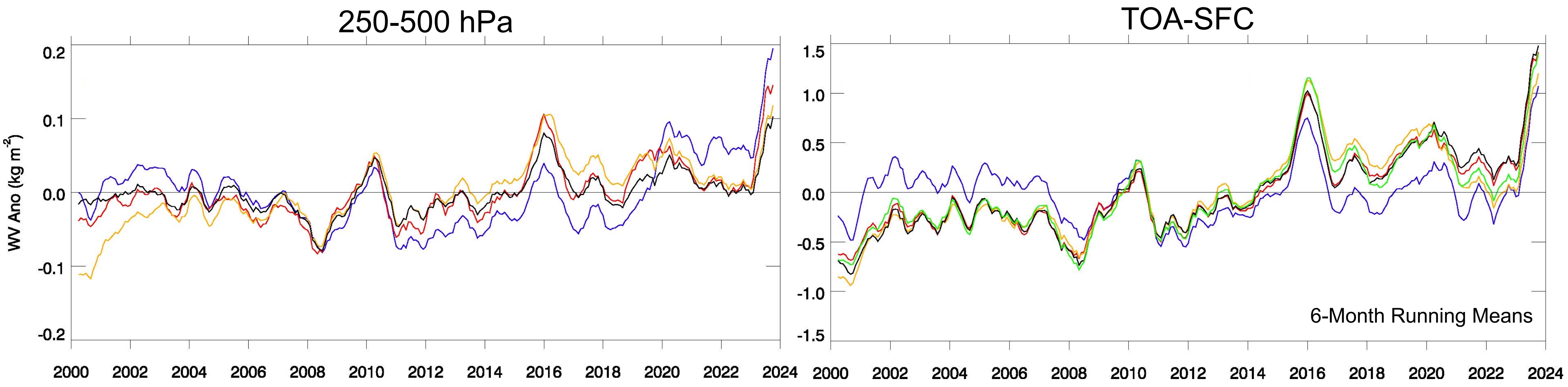
Better Upper-tropospheric Humidity (UTH) in GEOS-IT, compared to MERRA-2



- UTH in GEOS-IT is lower than MERRA-2, which are closer to other AIRS satellite observations.
- GEOS-IT UTH is comparable to G541 UTH but with a better anomaly time series (next slide).

Better GEOS-IT WV Anomaly Time Series compared to GEOS-5.4.1

Anomaly Time Series of the Column-Integrated WV (kg m^{-2}) (60°S-60°N Ocean)



G541 **MERRA-2** **ERA-5** **GEOS-IT** **REMSS (MW Obs)**

- MERRA-2, ERA-5 and GEOS-IT show quite consistent WV anomaly time series, while G541 is an outlier.
- However, after 2020, the PW anomaly time series of the three datasets (MERRA-2, ERA-5, and GEOS-IT) start to diverge, while Microwave observation (REMSS) is closest to ERA-5.
- **By using GEOS-IT T and q profiles, Ed5 LW flux time series will be improved, compared to the Ed4 LW flux time series from G541.**

Validation of the CRS Algorithm Using Polar Ground Measurements

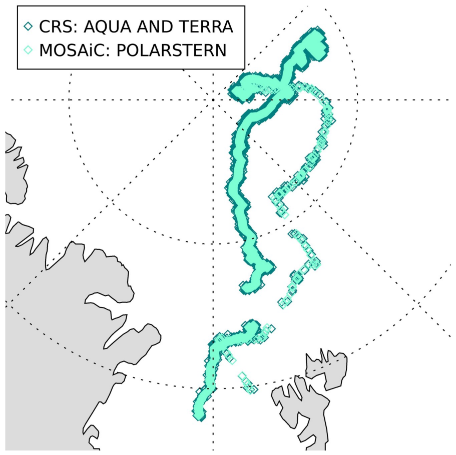
1. **Siple Dome over the West Antarctica:**
   (Lat 81.65°S, Lon 148.81°W, Elevation 720 m, Dec 2019 to January 2020)
2. **MOSAiC Ship Campaign over the Arctic Sea:**
   (September 2019 to October 2020)

Siple Dome Site

https://www.usap-dc.org/view/dataset/601540

- **Validation of the CRS inputs**
  - Atmospheric T(z) and q(z) profiles
  - Skin temperatures
  - Surface albedos
  - Cloud masks and optical properties
- **Validation of the CRS outputs**
  - Computed fluxes

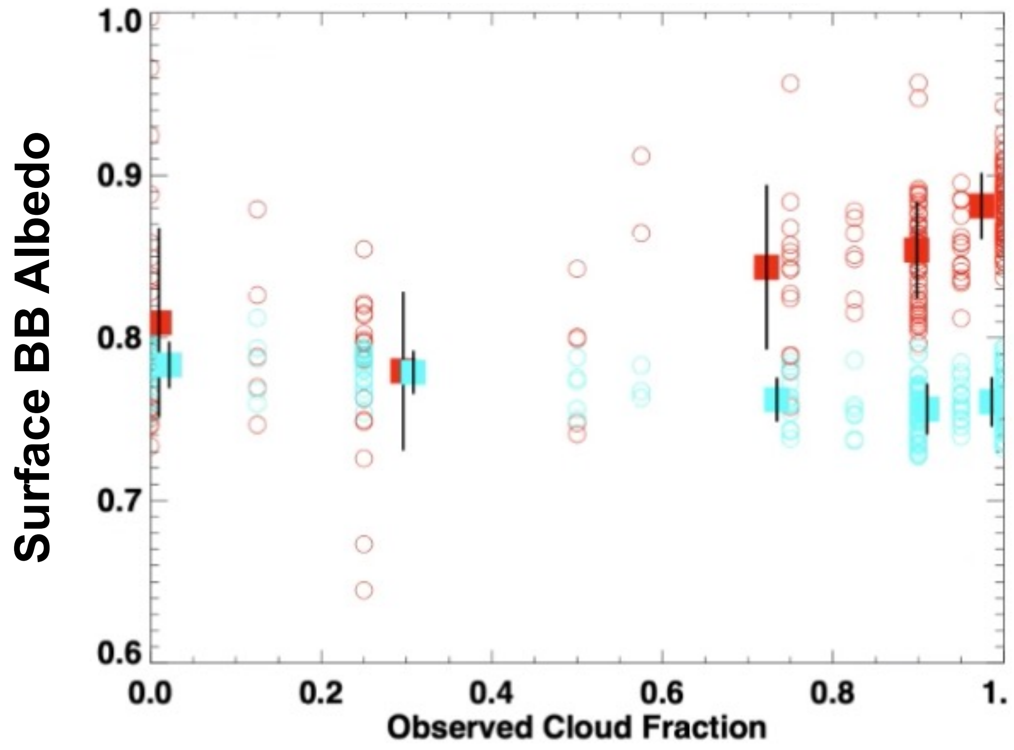
MOSAiC Campaign



Validation of the CRS Surface Broadband Albedo Using Ground Measurements

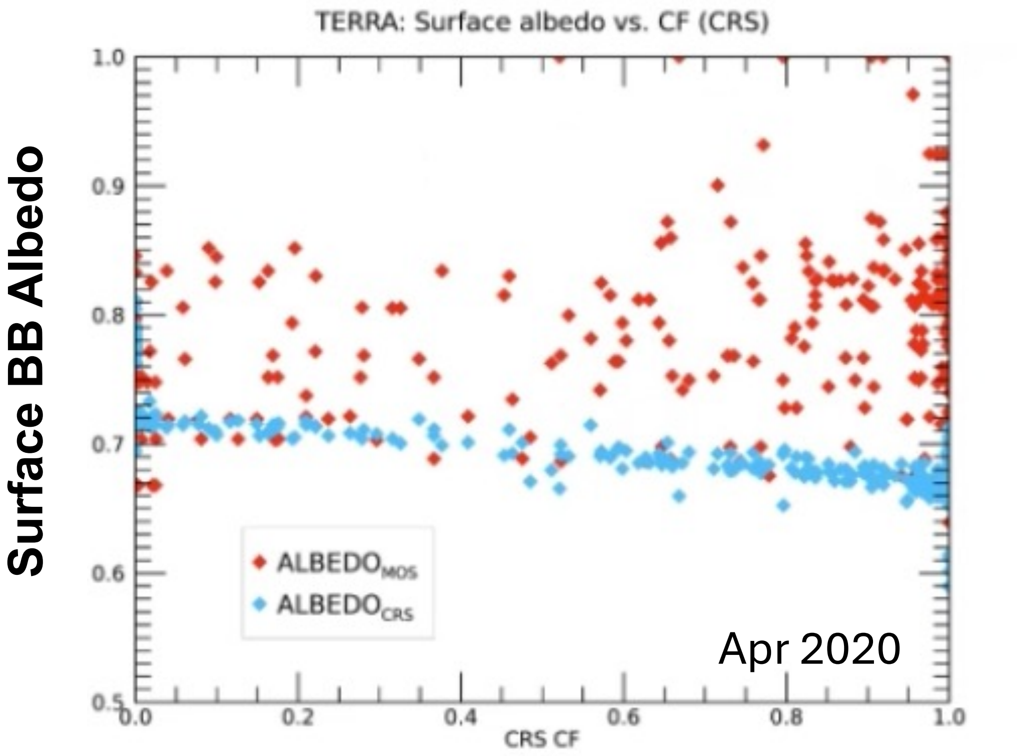
- CRS surface BB albedo is underestimated particularly for cloudy skies.
- Ground observation indicates increasing surface BB albedo with cloud fraction, but the CRS albedo does not increase with the cloud fraction.

Siple Dome Ground Site (Snow Surface)



Siple Dome (West Antarctica)
CRS surface albedo

MOSAiC Ship Campaign (Sea Ice Surface)



MOSAiC Ship (Arctic Sea)
CRS surface albedo

Why does a higher snow BB Albedo occur for cloudy skies compared to clear skies?

- Spectral shapes of snow albedo remain similar with changing cloud τ especially if the solar angle is close to the diffuse angle (only changing into solar diffuse angle as τ increases).
- Broadband albedo is a mean of spectral albedo weighted by a fraction of SW SFCDN.

$$\alpha_{BB} = \frac{\int_{\lambda_{min}}^{\lambda_{max}} F_{dn}(\lambda)\alpha(\lambda)d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} F_{dn}(\lambda)d\lambda} = \int_{\lambda_{min}}^{\lambda_{max}} w(\lambda)\alpha(\lambda)d\lambda \qquad \text{where } w(\lambda) = \frac{F_{dn}(\lambda)}{\int_{\lambda_{min}}^{\lambda_{max}} F_{dn}(\lambda)d\lambda}$$

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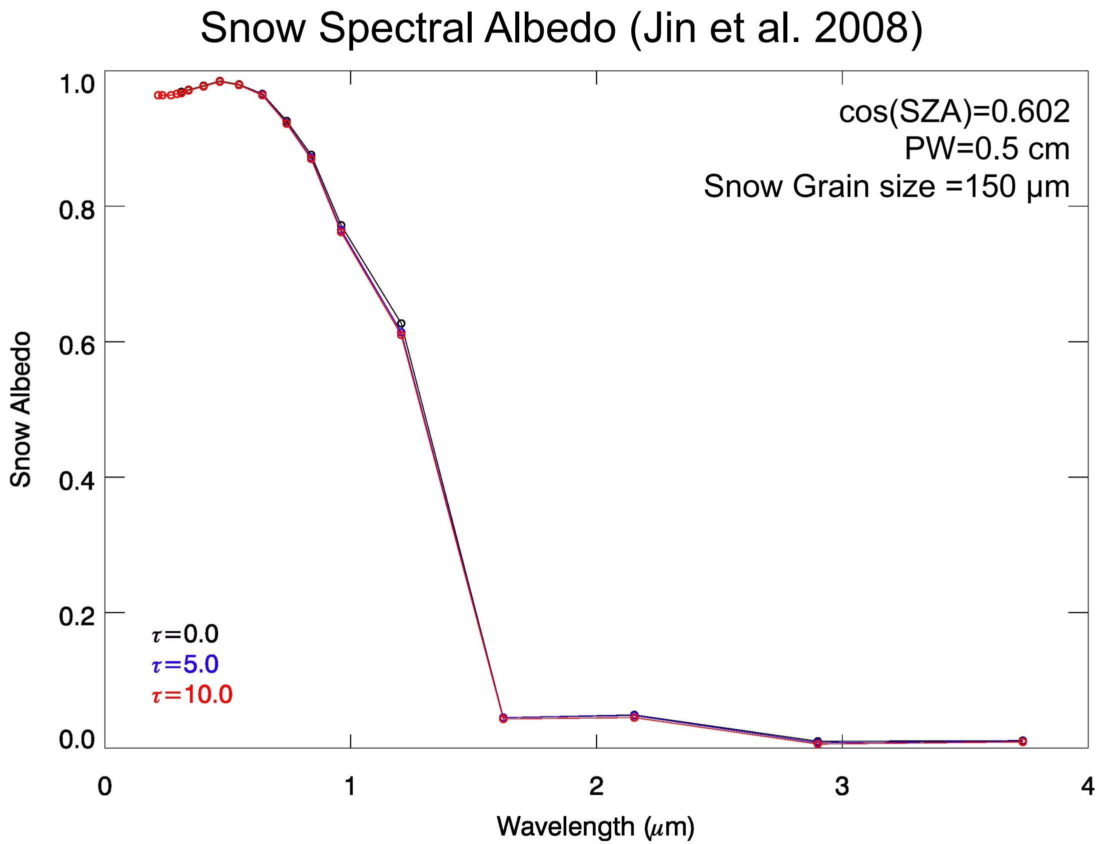
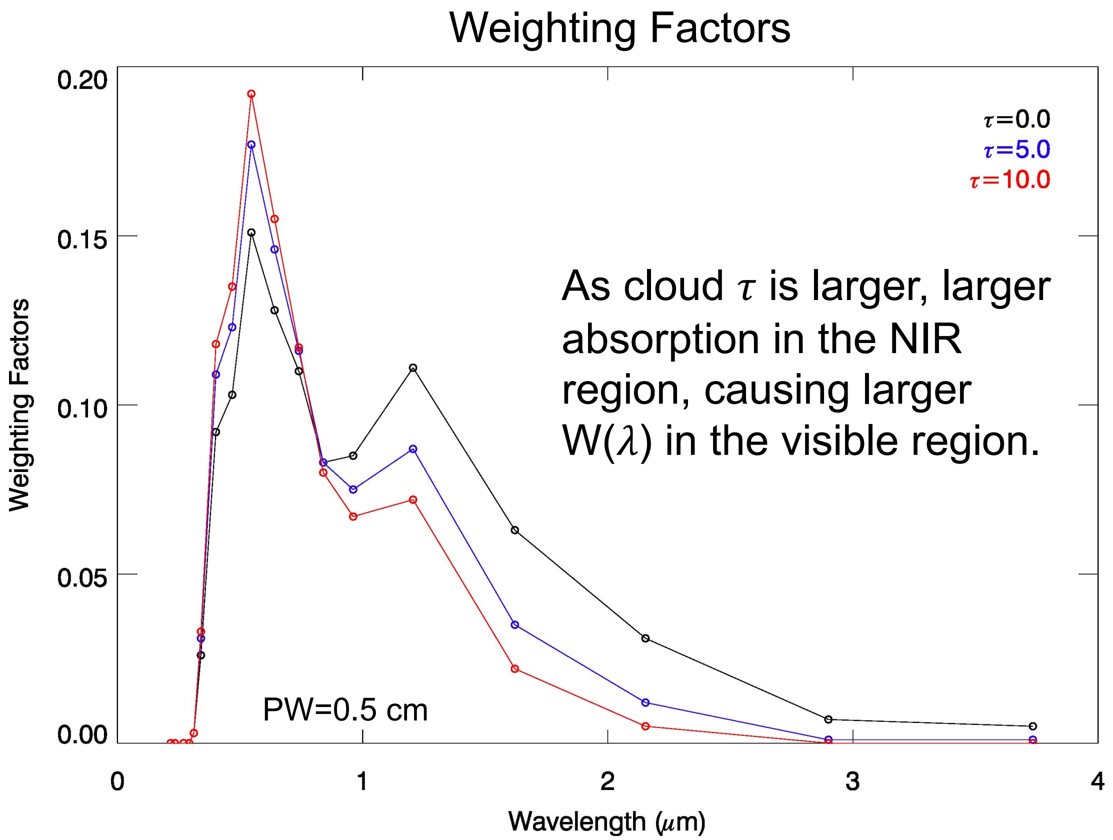
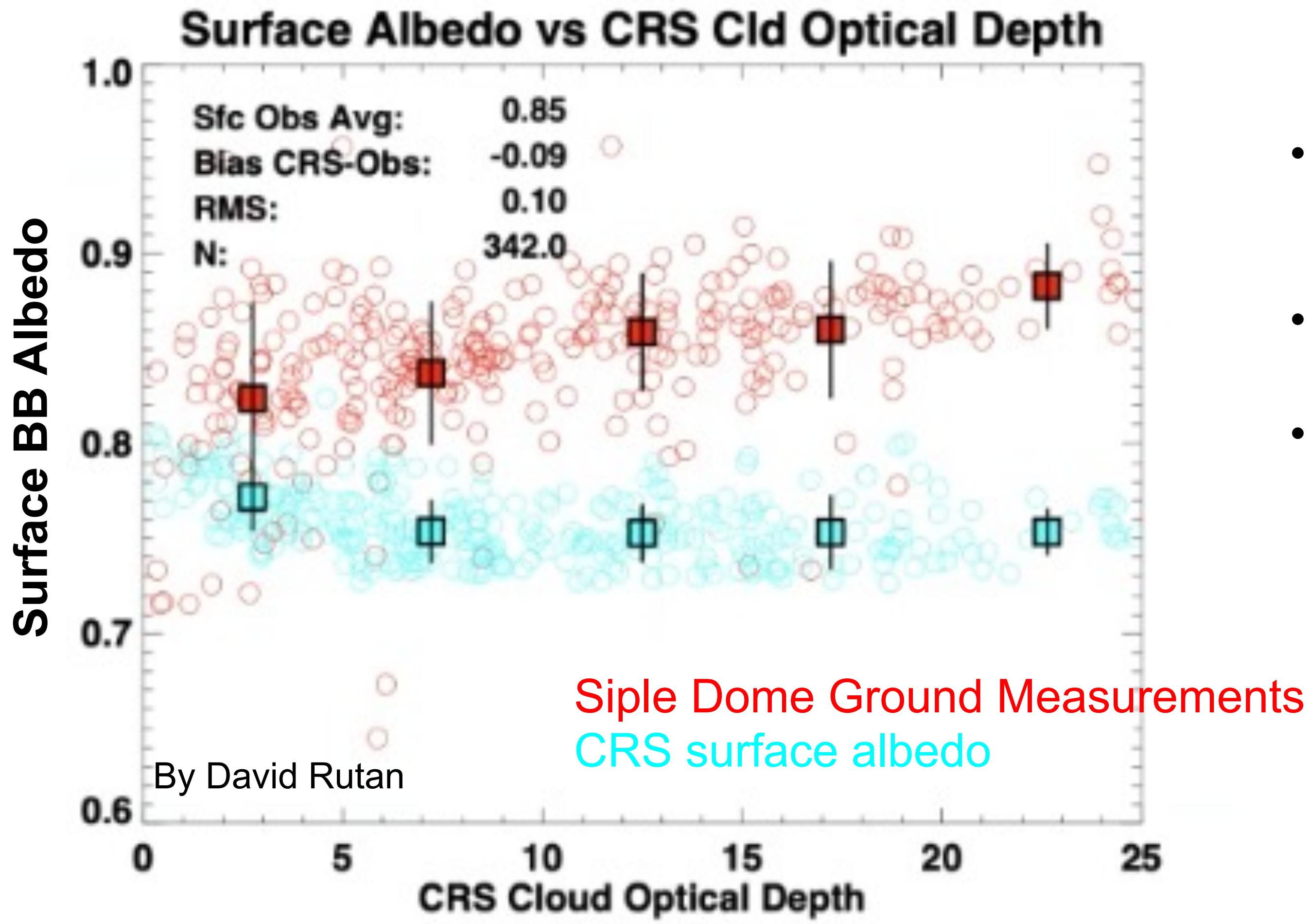




Underestimation of Snow Surface BB Albedo in CRS Calculations

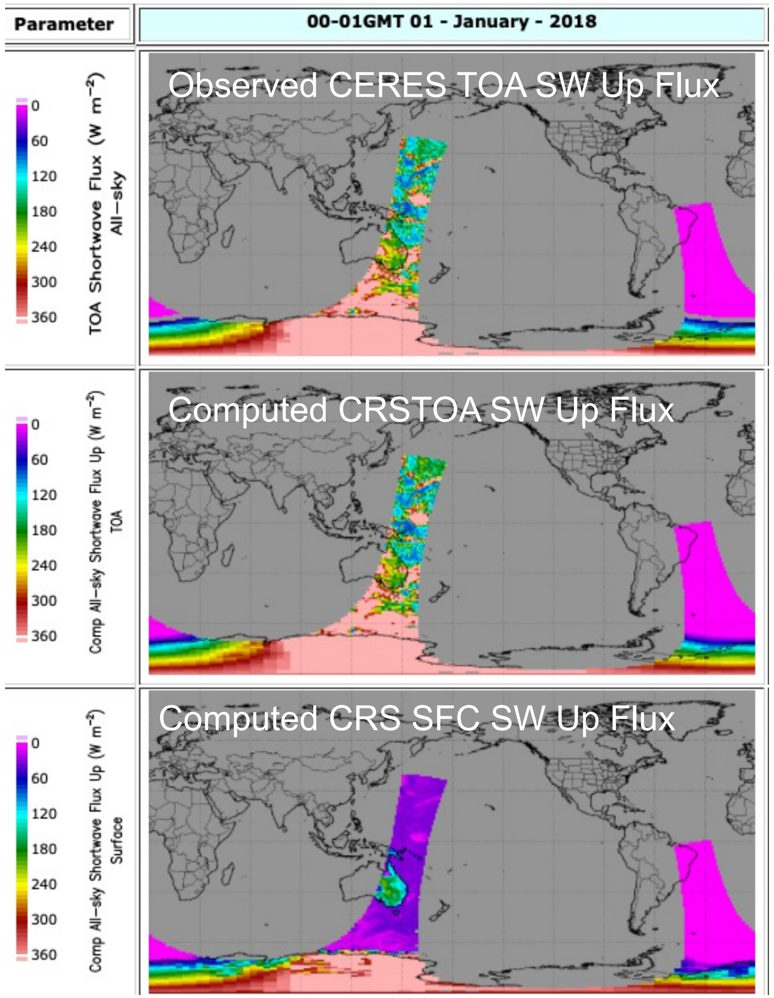
Siple Dome Site (Snow Surface)

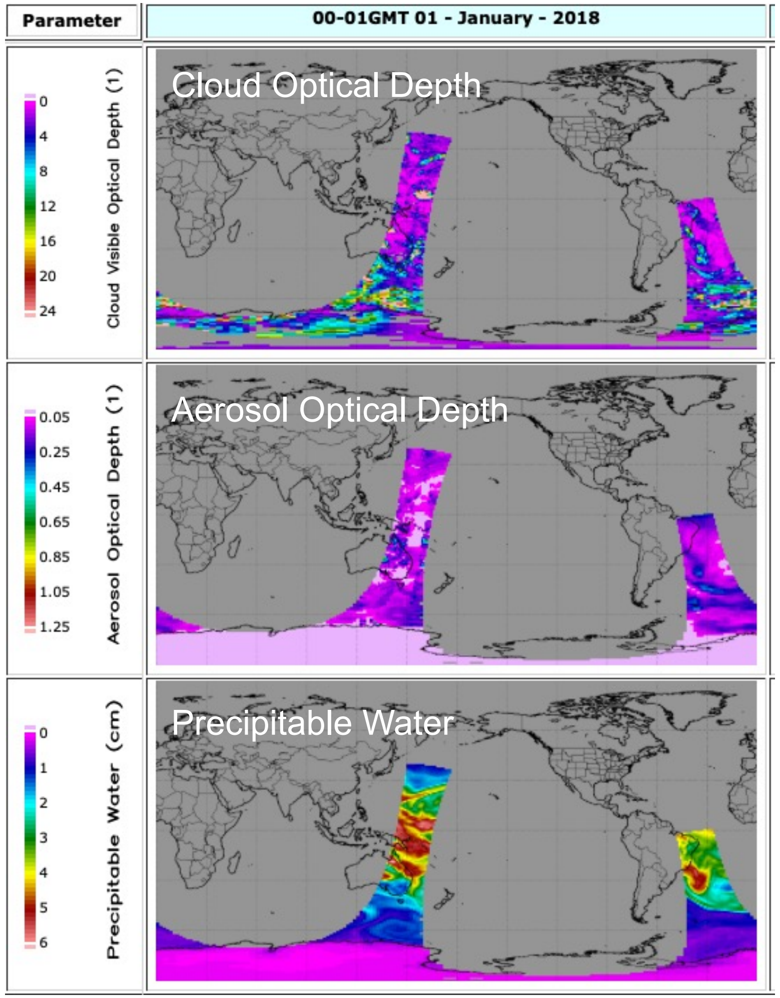


- Theoretical considerations and ground measurements indicate an increasing snow surface BB albedo with cloud optical depth.
- CRS snow BB albedo does not increase with cloud optical depth, and rather decreases.
- One of reason is to constraining process of snow spectral albedo from the SAH BB albedo, which only comes from clear-sky measurements.

Ed4 CRS1deg-1Hour Product Release (March 2024) (TISA & DMT Group)

- Available for 2018-2022 in the CERES ordering tool (https://ceres.larc.nasa.gov/data/) or ASDC (https://asdc.larc.nasa.gov).
- Hourly grided (1°) **instantaneous** (Terra or Aqua times) computed fluxes and RT inputs, which can be compared with other climate or satellite datasets





Summary

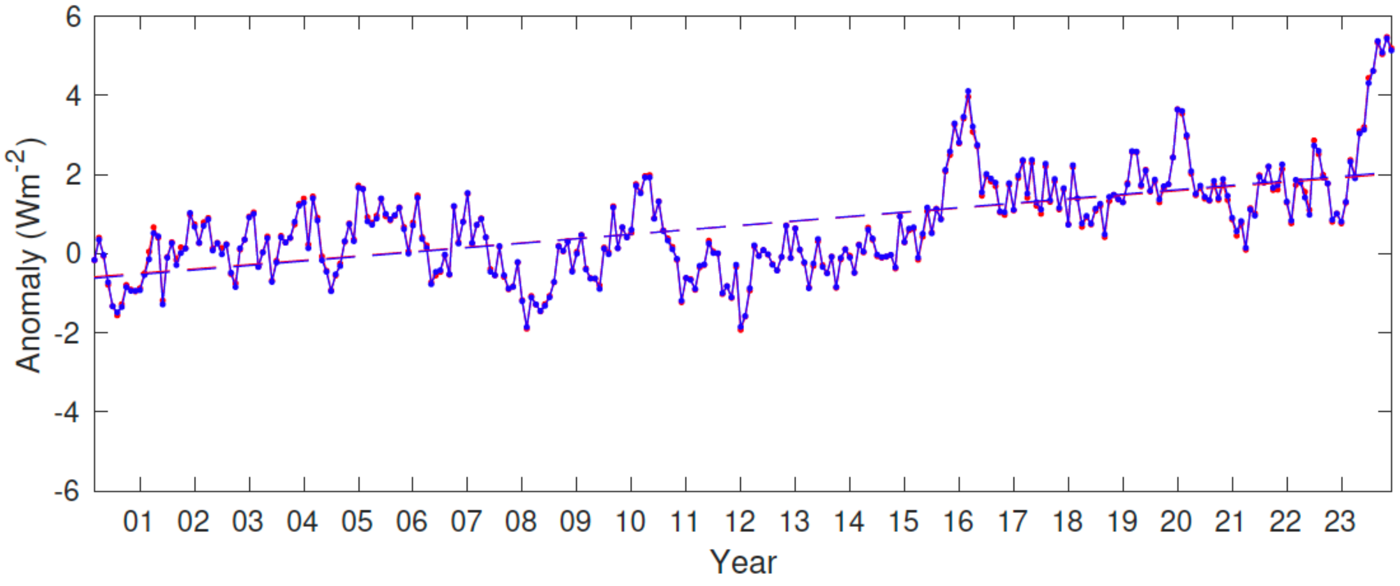
- By using GEOS-IT temperature and humidity profiles from product, better time series of the computed LW fluxes are expected, compared to those from GEOS-5.4.1.
- Comparison of the CRS surface SW fluxes with ground measurements at polar regions indicates that the CRS surface albedo is overestimated over snow or sea ice regions, particularly for cloudy skies. These are likely related to the constraining method we are using based on the clear-sky observations (i.e., SAH map).
- Terra/Aqua CRS1deg-1Hour Ed4 product was released in March 2024, for five-year periods (2018-2022).

Edition 4.2 EBAF

- Downward longwave irradiance increased significantly in 2023.
- Top-of-atmosphere (TOA) net irradiance is increasing at a rate of 0.50 ± 0.47 $Wm^{-2}dec^{-1}$. The increase is confirmed by ocean temperature measurements (Loeb et al. 2021).
- Atmospheric net irradiance is increasing at a rate of 0.4 ± 0.2 $Wm^{-2}dec^{-1}$
- Atmospheric net irradiance is TOA net irradiance minus surface net irradiance.
- Is the EBAF-surface product consistent with the TOA EBAF product?

Downward longwave and shortwave irradiance at the surface

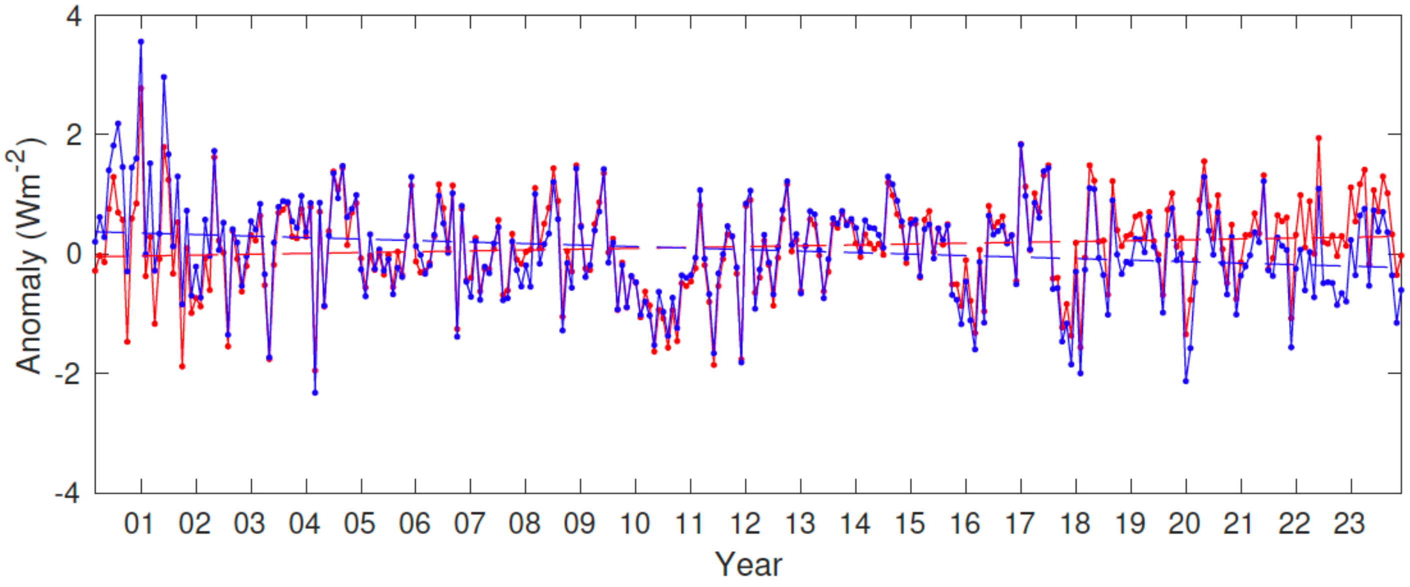
Downward longwave
Red: Ed4.2 EBAF
Blue: SYN noGEO



Standard deviation of anomalies is 0.46 Wm^{-2}.

Trend:
EBAF 1.10 Wm^{-2} dec^{-1}
SYN1deg noGEO 1.13 Wm^{-2} dec^{-1}

Downward shortwave
Red: Ed4.2 EBAF
Blue: SYN noGEO

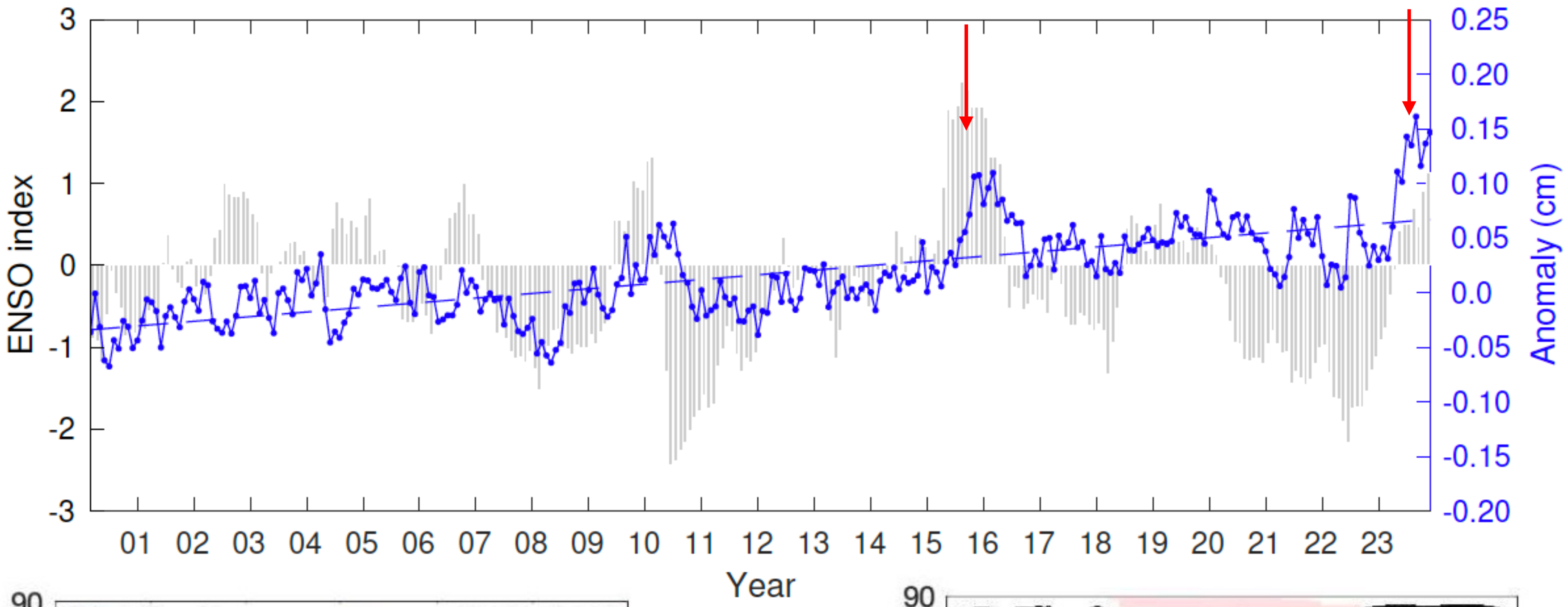


Standard deviation of anomalies is 0.53 Wm^{-2}.

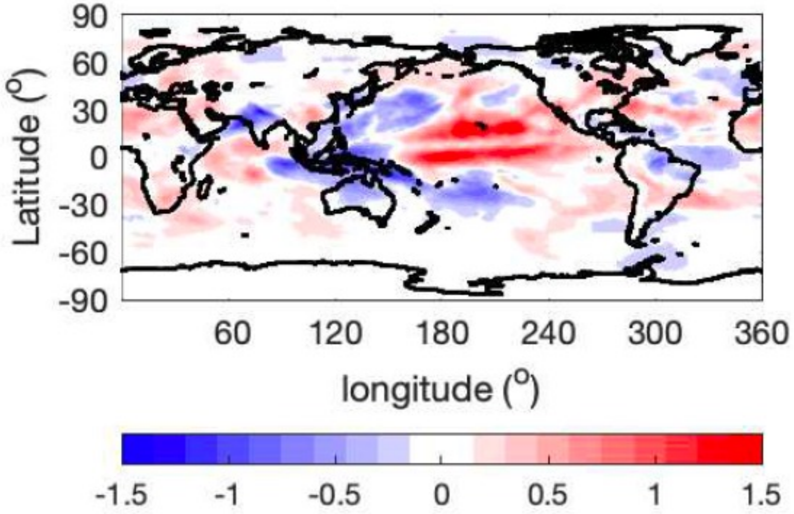
Trend:
EBAF 0.14 Wm^{-2} dec^{-1}
SYN1deg noGEO -0.25 Wm^{-2} dec^{-1}

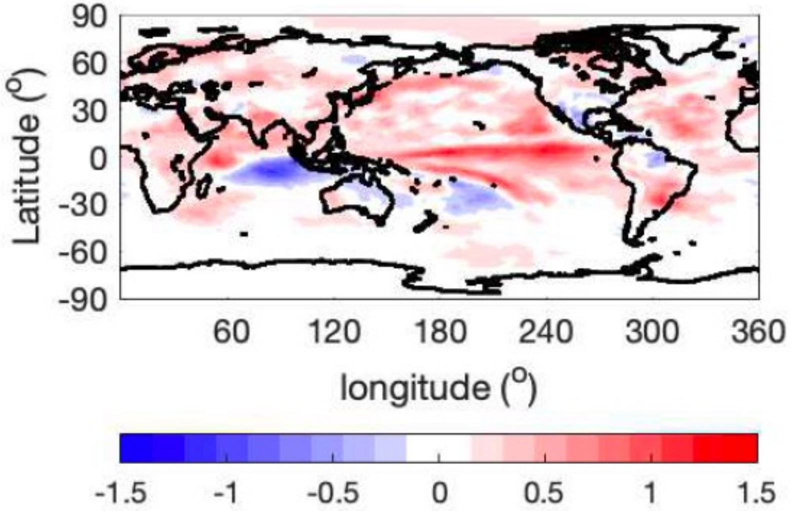
Water vapor in the atmosphere

Global monthly anomalies of MERRA-2 precipitable water in cm



September 2015

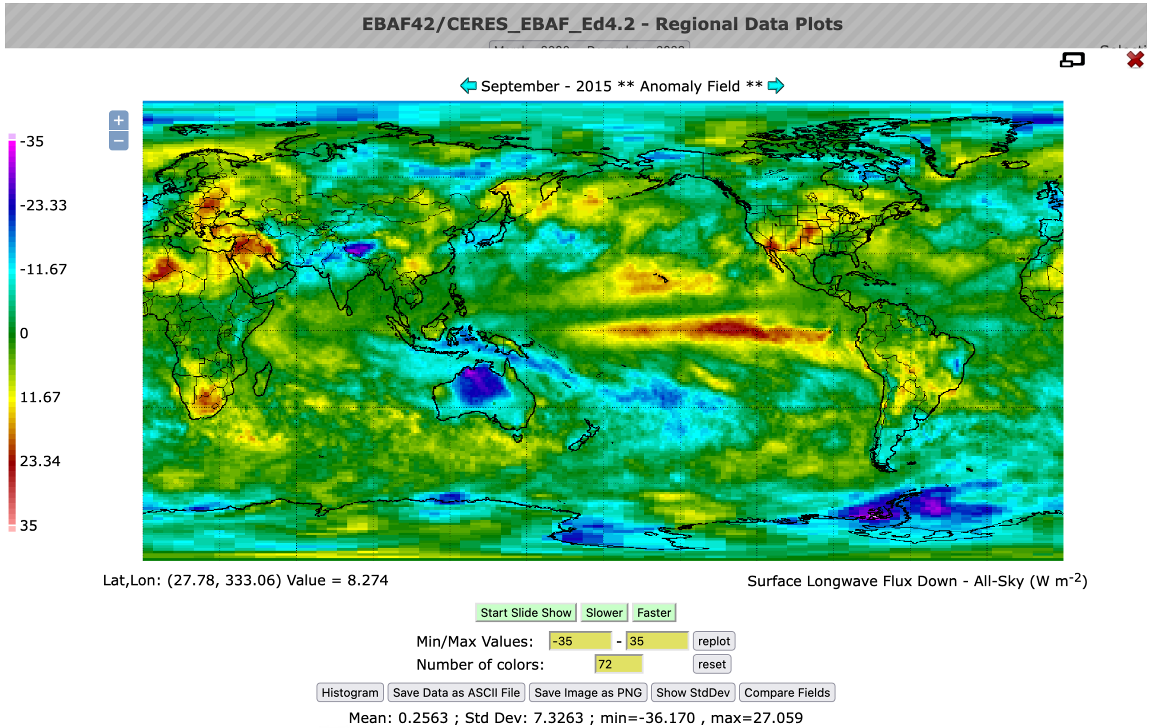


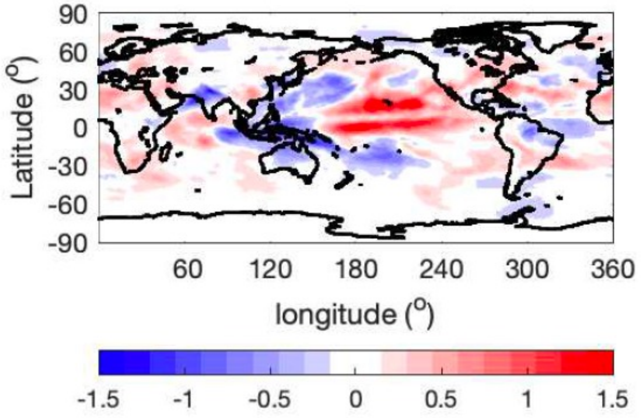


September 2023

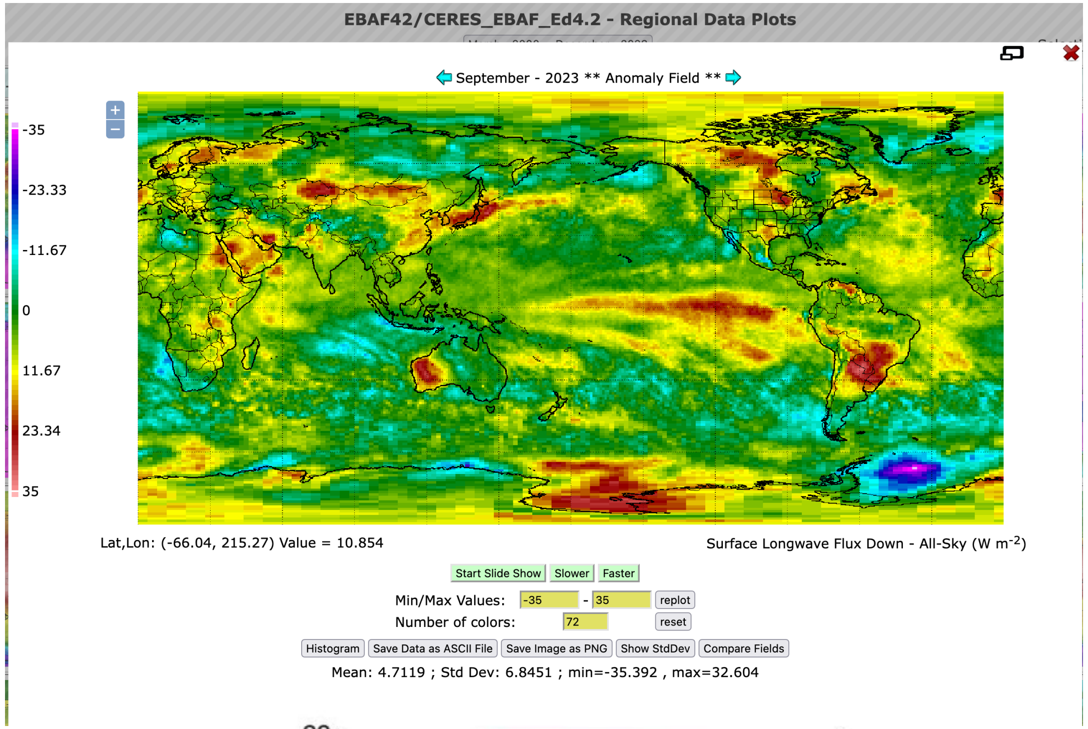
Downward longwave irradiance anomalies

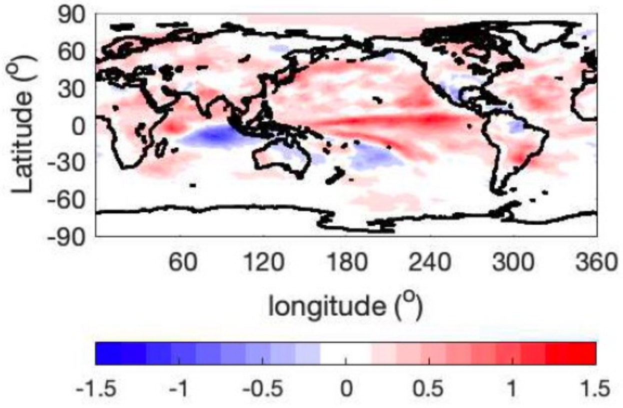
September 2015



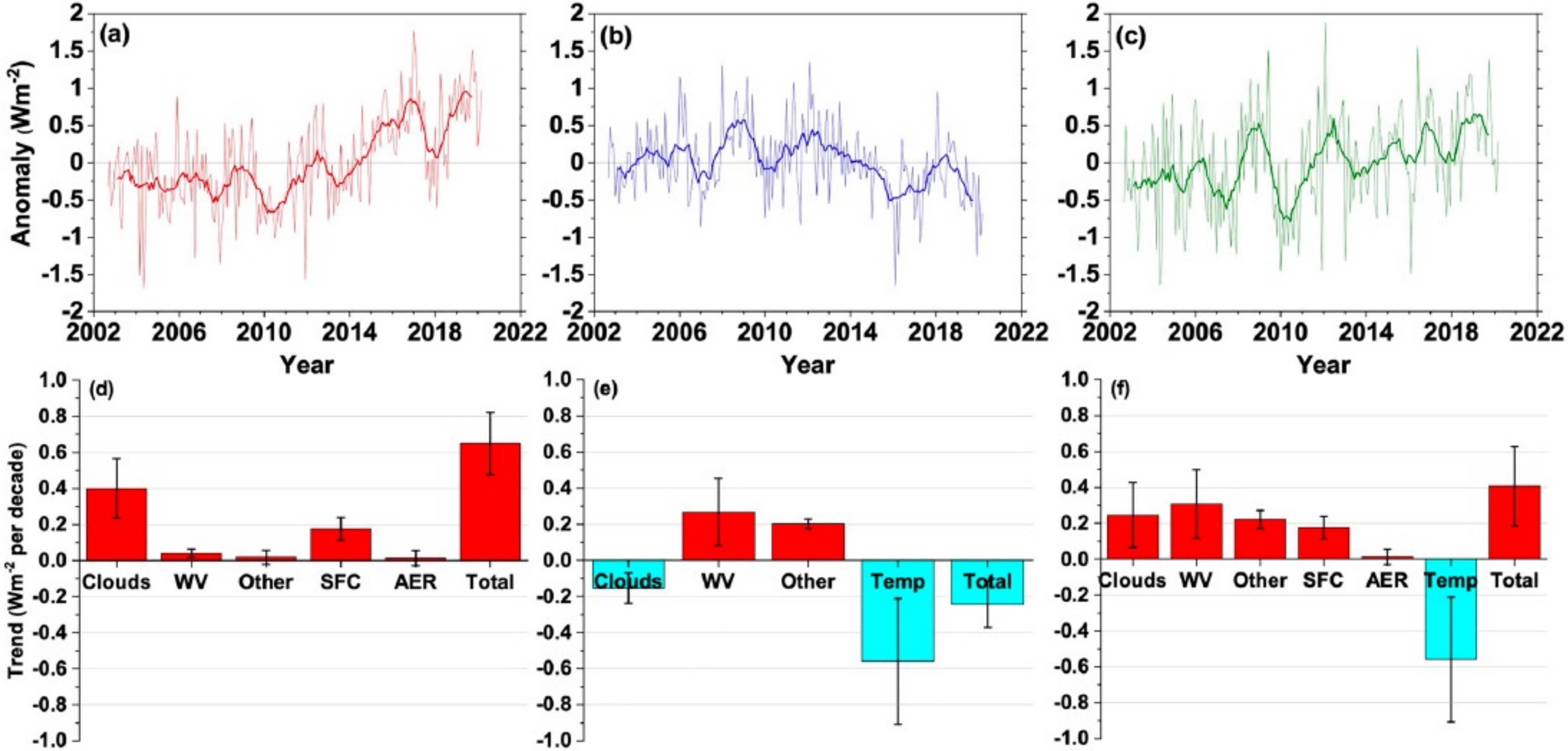


September 2023





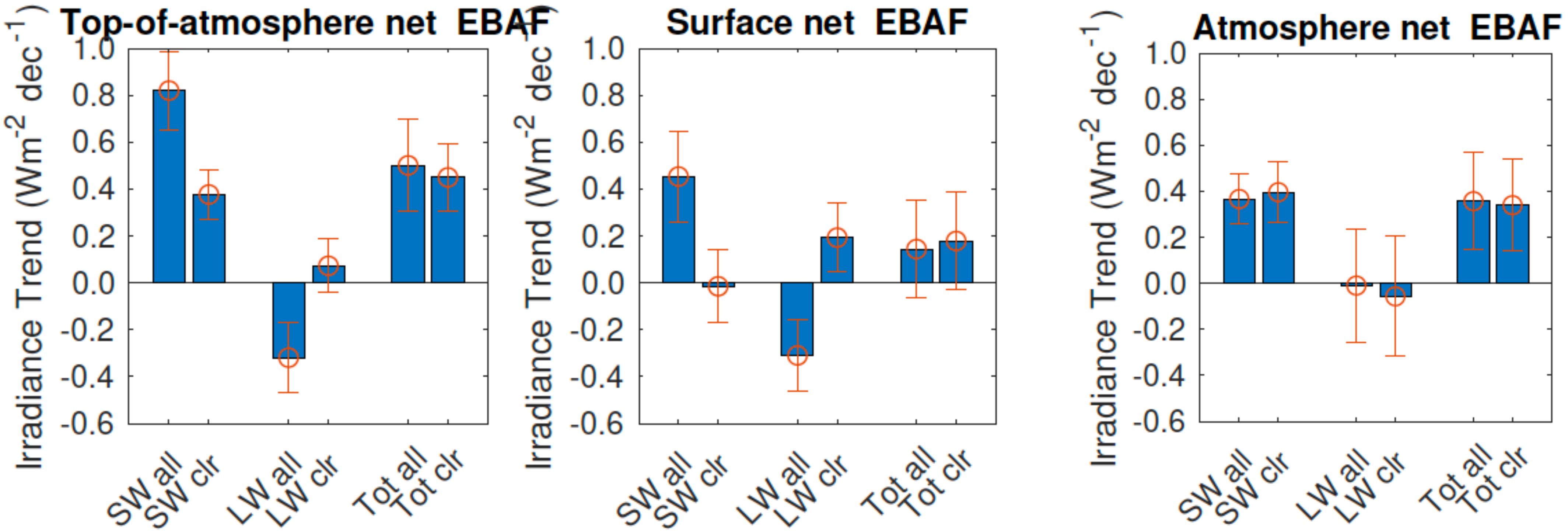
Contributions to Top of atmosphere trend



Loeb et al. 2021

Global TOA, surface and atmosphere irradiance trends

from March 2000 through December 2023



- A positive trend indicates energy inputs at TOA or surface
- Difference between all-sky and clear-sky is due to clouds
- A positive trend of net atmospheric irradiance is driven by shortwave absorption

Water vapor contribution to shortwave absorption

If we separate the net surface shortwave irradiance change by water vapor from the net surface shortwave irradiance change, increasing water vapor in the atmosphere reduces the contribution of water vapor to the net shortwave surface irradiance

$$\Delta F_{net,sw}^{sfc} = -\Delta F_{net,sw}^{sfc}(wv) + \Delta F_{net,sw}^{sfc}(other)$$

and increase shortwave absorption in the atmosphere

$$\Delta F_{net,sw}^{atm} = +\Delta F_{net,sw}^{atm}(wv) + \Delta F_{net,sw}^{atm}(other)$$

The sum of net surface and atmosphere is the net shortwave TOA irradiance change

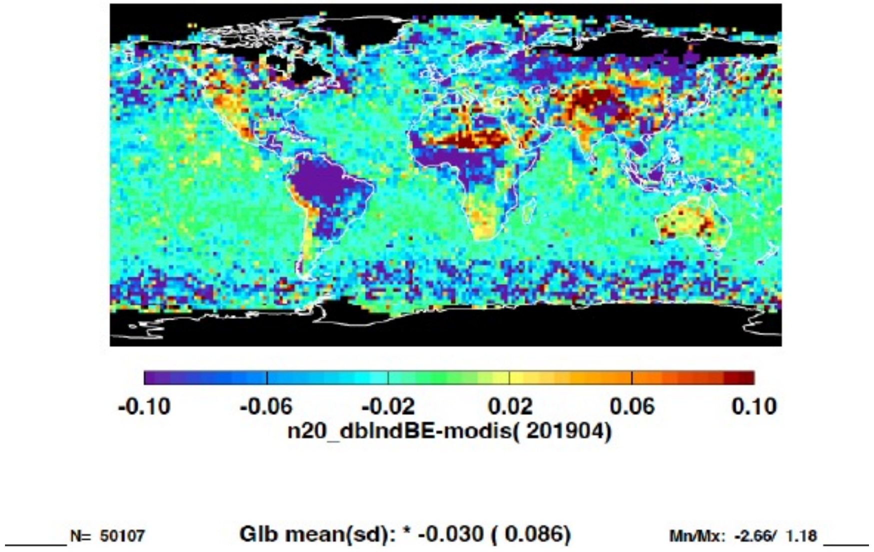
$$\Delta F_{net,sw}^{TOA} = \Delta F_{net,sw}^{atm} + \Delta F_{net,sw}^{sfc}$$

Therefore, the contribution of water vapor increase in the atmosphere to the net TOA shortwave irradiance can be small.

NOAA 20 VIIRS AOD correction

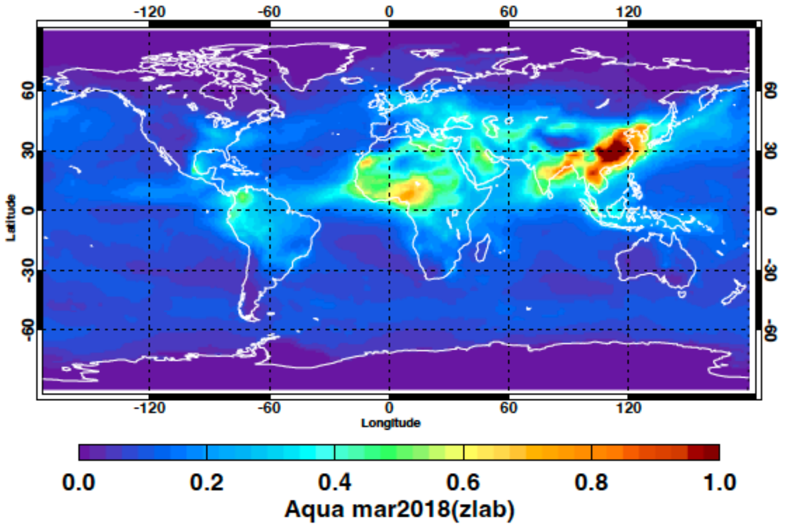
- Goal is to correct VIIRS aerosol optical thickness to agree with MODIS (Aqua) aerosol optical thickness
- Approach
  - Deep Blue: MODIS deep blue team (Jaehwa Lee) provided correction coefficients
  - Dark Target: VIIRS AODs are regressed with MODIS Aqua AODs land, ocean, polar separately.

NOAA20 VIIRS minus Terra+Aqua MODIS aerosol optical thickness for April 2019



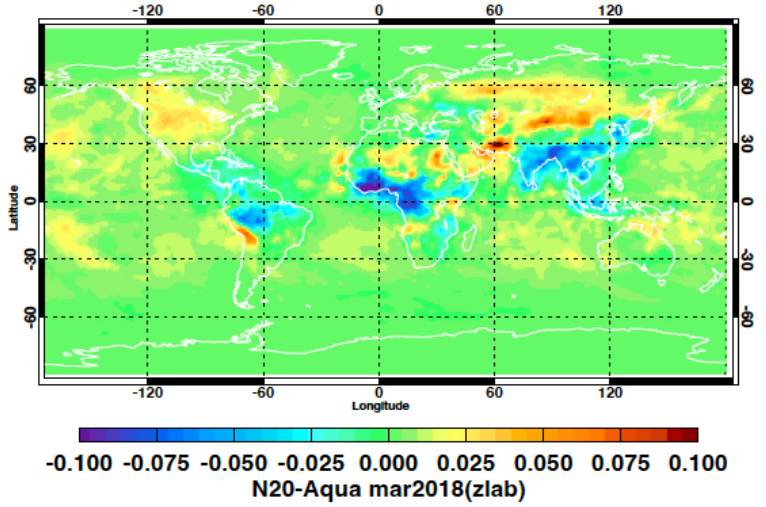
MATCH AOD with NOAA20 corrections for March 2018

Aqua MATCH (DT+DB) AOD



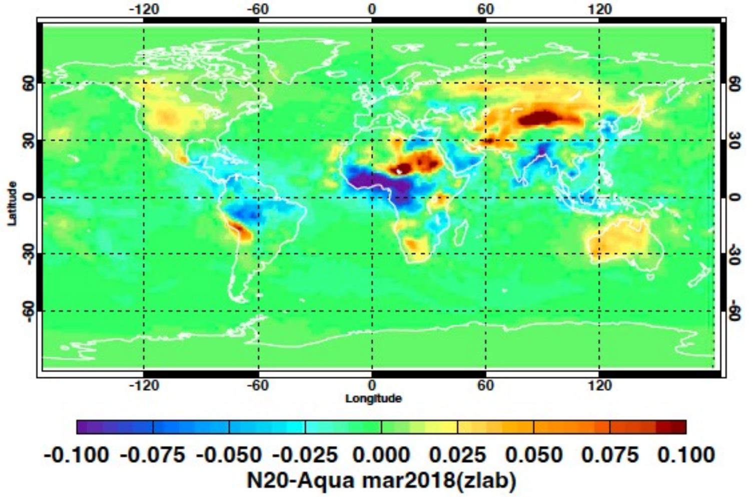
N= 64800 Glb mean(sd): 0.152 (0.130) Mn/Mx: 0.0002/ 1.25

With correction



N= 64800 Glb mean(sd): 0.0032 (0.012) Mn/Mx: -0.160/ 0.161

Without correction



N= 64800 Glb mean(sd): -0.0034 (0.017) Mn/Mx: -0.179/ 0.245

Edition 5 algorithm developments

- Fu-Liou code (Seung-Hee Ham's talk on Thursday)
  - New k-distribution coefficients
  - Total of 24 shortwave bands, increased from 20 bands.
- CERES aerosol transport model (CATM)
  - Better aerosol models with CAM6
- GEOS temperature and humidity profile correction algorithm.
  - Use averaged spectral radiances (a back-up plan for CLIMCAPS), using the algorithm developed by Bill Smith Sr. (dual-regression retrieval algorithm).

Monitoring biases in temperature and humidity profiles

- Bias correction in temperature and humidity profiles is needed in the EBAF process.
  - We are using CLIMCAPS because it has AIRS and CrIS Level 3 products.
- An alternative approach is to use mean spectral radiances.
- We tried to develop spectral radiative kernels to retrieve reanalysis temperature and humidity profiles.
  - Similarity of spectral radiative kernels for different heights makes the inversion an ill-conditioned.
- Dual-regression approach avoid this issue by making the retrieval by a forward model.
- Temperature and humidity profiles derived from mean spectral radiance need to agree with mean of temperature and humidity profiles derived from instantaneous spectral radiances.

Dual-regression algorithm

- Use forward computations to derive temperature and humidity profiles (Smith et al. 2012)

$$\mathbf{q}_{ret} = \mathbf{q}_0 + (\mathbf{r}_m - \mathbf{r}_0)\mathbf{C}$$

where

$\mathbf{q}_{ret}$: Retrieved atmospheric states and skin temperature

$\mathbf{q}_0$: Climatological (or ensemble) mean state

$\mathbf{r}_m$: Observed spectral radiance

$\mathbf{r}_0$: Ensemble mean spectral radiance

C: Statistical-regression coefficient matrix

Climate (CERES/SARB) application

- The algorithm that is primarily developed for tropics and mid-latitude convection to global climate application.
- Apply this algorithm to 16-day mean AIRS spectral radiances
- Derive biases and drifts (discontinuities) in reanalysis (GEOS-IT) temperature, humidity, and spectral radiance profiles

$$\mathbf{q}_{ret} = \mathbf{q}_0 + (\mathbf{r}_m - \mathbf{r}_0)\mathbf{C}$$
$$\Delta\mathbf{q} = \mathbf{q}_{reanalysis-}\mathbf{q}_{ret}$$

where

$\mathbf{r}_m$: Observed mean spectral radiance

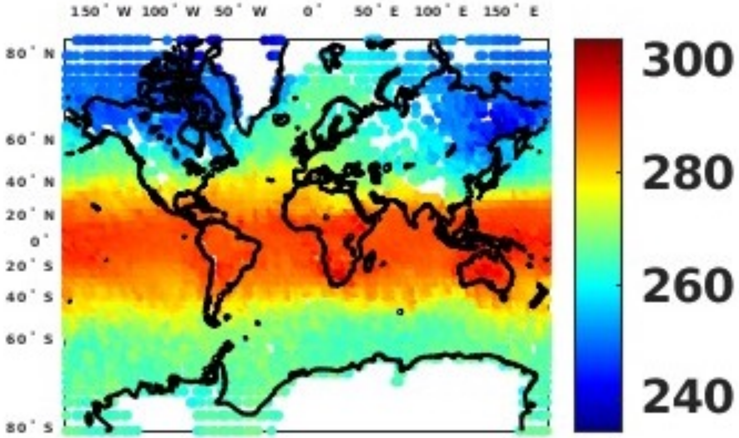
$\mathbf{q}_{reanalysis}$: Reanalysis temperature and humidity profiles and skin temperature

- Test:

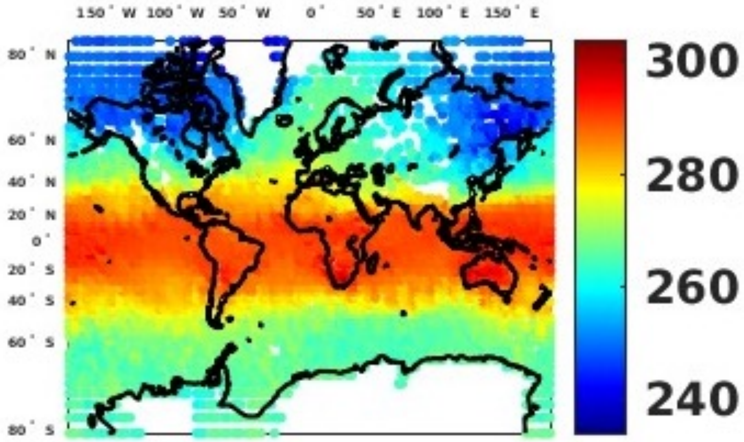
  Temperature and humidity profiles and skin temperature derived from mean spectral radiances AVE(RAD) are equal to the mean of temperature, humidity, and spectral radiance derived from instantaneous radiances AVE(DAT)

All-sky 850 hPa air temperature and water vapor mixing ratio retrieval
(Nadir: Descending and ascending 20070101 to 20070116)

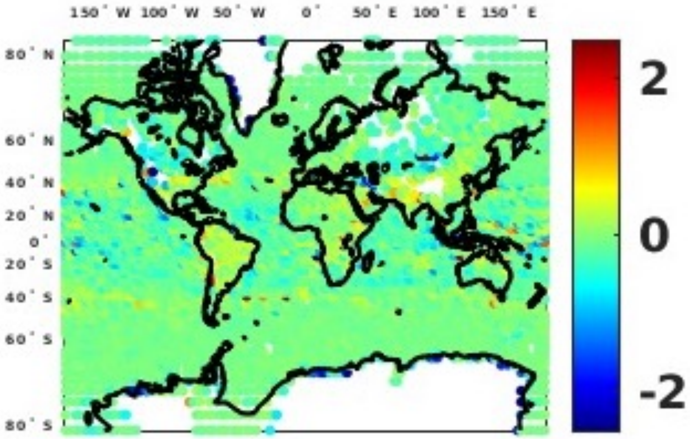
AVE(RAD) Temperature



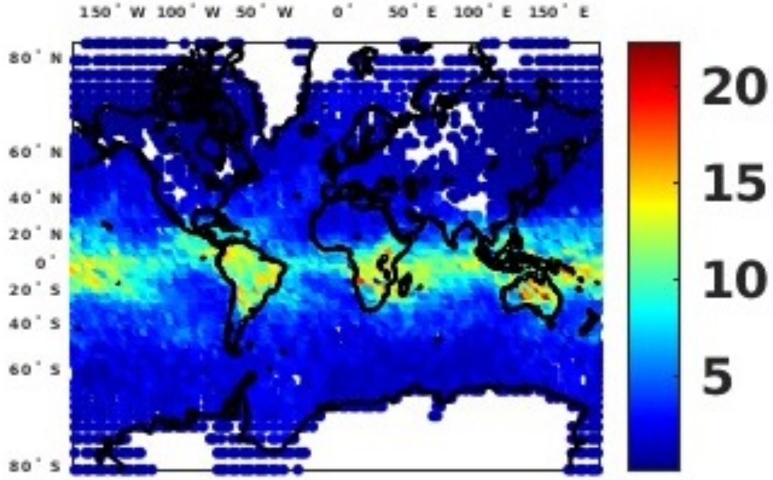
AVE(DAT) Temperature



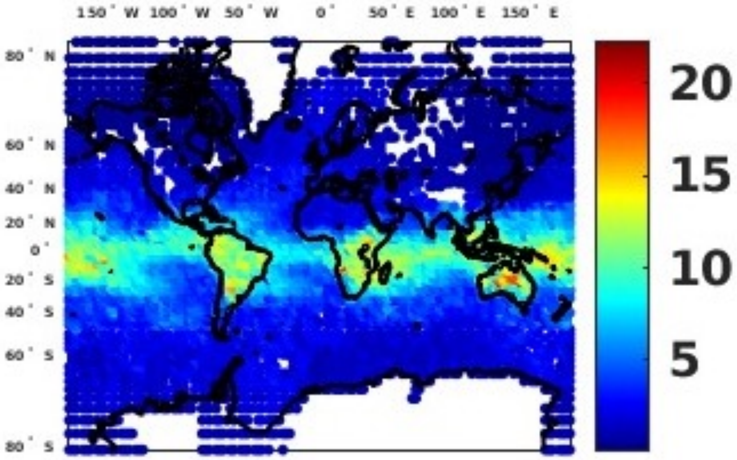
AVE(RAD)- AVE(DAT)



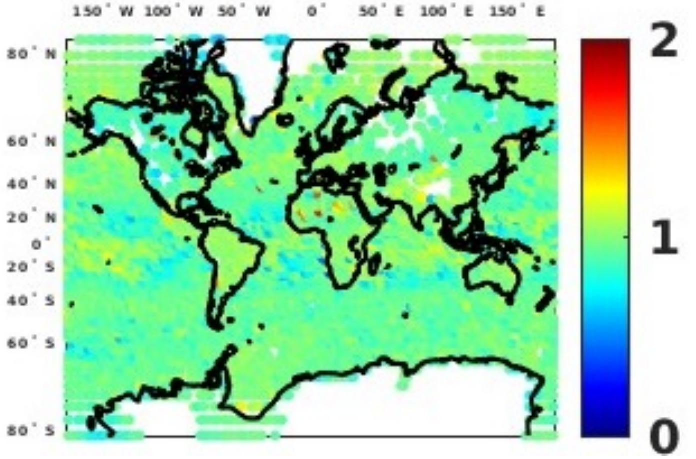
AVE(RAD) Mixing ratio



AVE(DAT) Mixing ratio

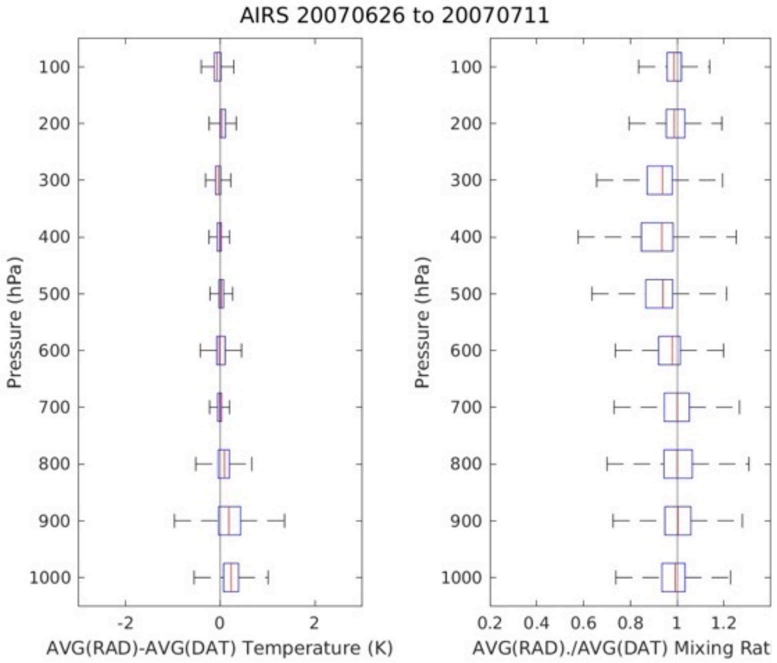


AVE(RAD) / AVE(DAT)

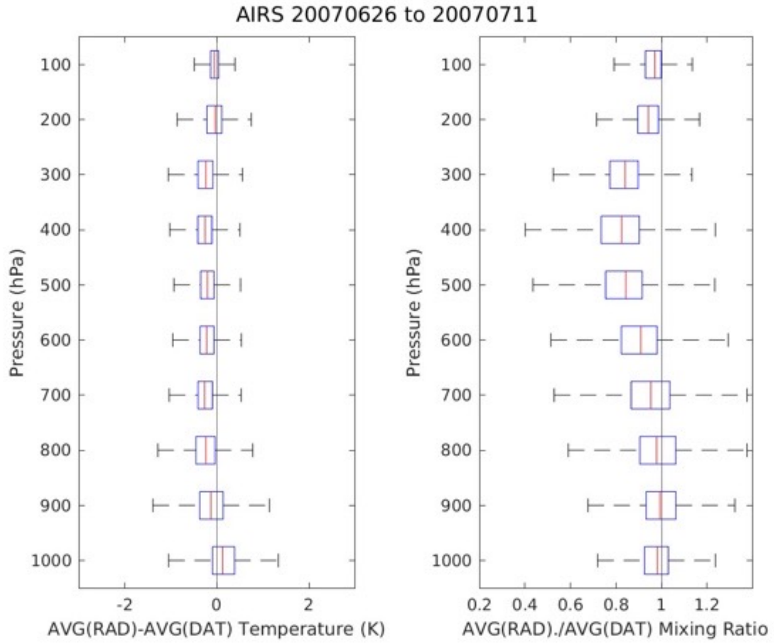


Viewing angle dependence (Clear-sky, ascending)

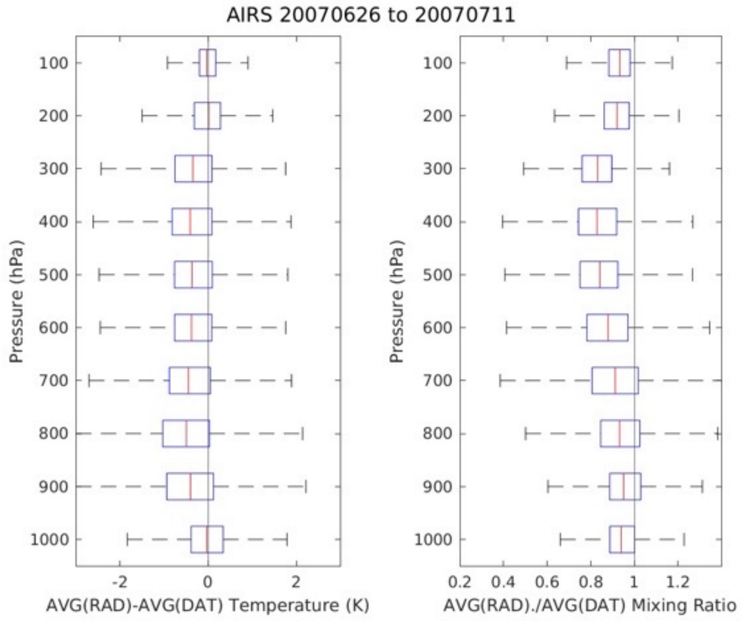
Nadir
(0 to 1.6 degree viewing zenith angles)



Near-nadir
(1.6 to 24.8 degree viewing zenith angles)



Oblique
(24.8 to 49.0 degree viewing zenith angles)



Edition 5 aerosol transport model
(D. Fillmore's presentation on Wednesday)

- Based on CAM6
  - Aerosols are internally mixed and size distribution is modeled
  - Better aerosol models (e.g. dusts) than Ed4 MATCH.
- Forcing aerosol optical thickness to match MODIS- and VIIRS-derived optical thickness
  - Modeled aerosol optical thickness for cloudy conditions
- Use temperature, specific humidity, and wind fields from GEOS-IT (currently using MERRA-2)
- Use biomass and volcano input files
  - https://wiki.ucar.edu/display/camchem/Emission+Inventories
- Global volcanic sulfur dioxide (SO2) emissions (VolcanEESM through 2015)
  - https://catalogue.ceda.ac.uk/uuid/a8a7e52b299a46c9b09d8e56b283d385
- Longwave optical property models (not included in CAM6)

Publications

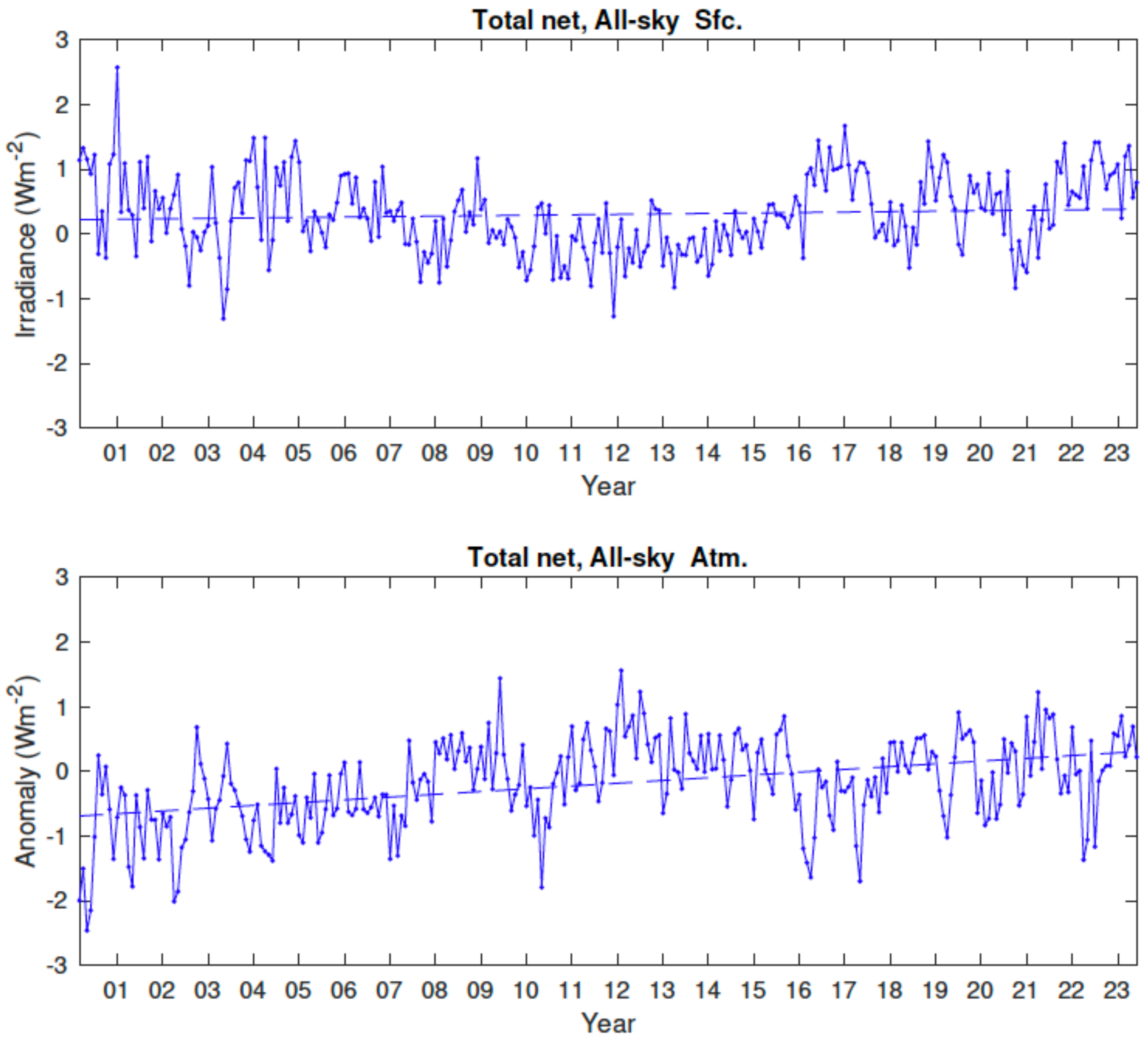
- Ham, S.-H., N. G. Loeb, S. Kato, T. J. Thorsen, A. Voigt, W. L. Smith Jr., and D. Winker, 2023: Zonal cloud trends observed by passive MODIS and active CALIPO and CPR sensors, Submitted to *J. Climate*.
- Kato, S., N. G. Loeb, F. G. Rose, S.-H. Ham, T. J. Thorsen, D. A. Rutan, W. F. Miller, T. E. Caldwell, D. R. Doelling, S. Sun-Mack, 2023: Seamless continuity in CERES Energy balanced and Filled (EBAF) surface radiation budget across multiple satellites, submitted *to J. Climate*.
- Riihimaki, L. D., M. F. Cronin, … D. Rutan,….. 2024: Ocean surface radiation measurement best practice, *Frontiers Marine Science*, Accepted.
- Loeb, N. G., D. R. Doelling, S. Kato, W. Su, P. E. Mlynczak, and J. C. Wilkins, 2024: Continuity in top-of-atmosphere earth radiation budget observations, Submitted to *J. Climate*.
- Loeb, N. G., S.-H. Ham, R. P. Allan, T. J. Thorsen, B. Meyssignac, S. Kato, G. C. Johnson, and J. M. Lyman, 2024: Observational assessment of changes in Earth's energy imbalance since 2000, *Surveys in Geophysics*, doi:10.1007/s10712-024-09838-8.
- Mayer M., S. Kato, M. Bosilovich, P. Bechtold, J. Mayer, M. Schröder, A. Behrangi, M Wild, S. Kobayashi, Z. Li, B. Roberts, and T. L'Ecuyer, 2023: Assessment of atmospheric and surface energy budget using observation-based data products, *Surveys in Geophysics*, doi:10.1007/s10712-024-09827-x.

Summary

- Edition 4.2 EBAF
  - NOAA-20 period (April 2022 onward) will be reprocessed with MERRA-2 clouds (data release will be in Fall 2024)
  - NOAA20 VIIRS AOD correction will be implemented in SYN1deg production for the EBAF reprocess.
- Edition 5
  - CRS and SYN1deg: Surface albedo over snow under cloud conditions will be revised
  - Radiative transfer mode: The ed5 code has a new band structure, and new k-tables.
  - Continue developing temperature and humidity correction with the dual-regression algorithm
  - Aerosol transport model is based on CAM6 (better aerosol models used for cloud conditions).

Back-ups

Timeseries of surface and net atmosphere anomalies



Global TOA, surface and atmosphere energy balance

TOA net irradiance change can be separated into changes occurred at the surface and within the atmosphere

$$F_{net,rad}^{TOA} = \Delta F_{net,rad}^{atm} + \Delta F_{net,rad}^{sfc} \qquad (1)$$

When kinetic energy change is ignored,
Surface energy balance is

$$\Delta F_{net}^{sfc} = \Delta F_{net,rad}^{sfc} - \Delta F_{LH} - \Delta F_{SH} = \Delta F_{net,rad}^{TOA} - \Delta MSE(T, wv) \qquad (2)$$

Moist static energy tendency ΔMSE is small for longer time scales so that global TOA net balances with surface net.
Atmosphere energy balance is

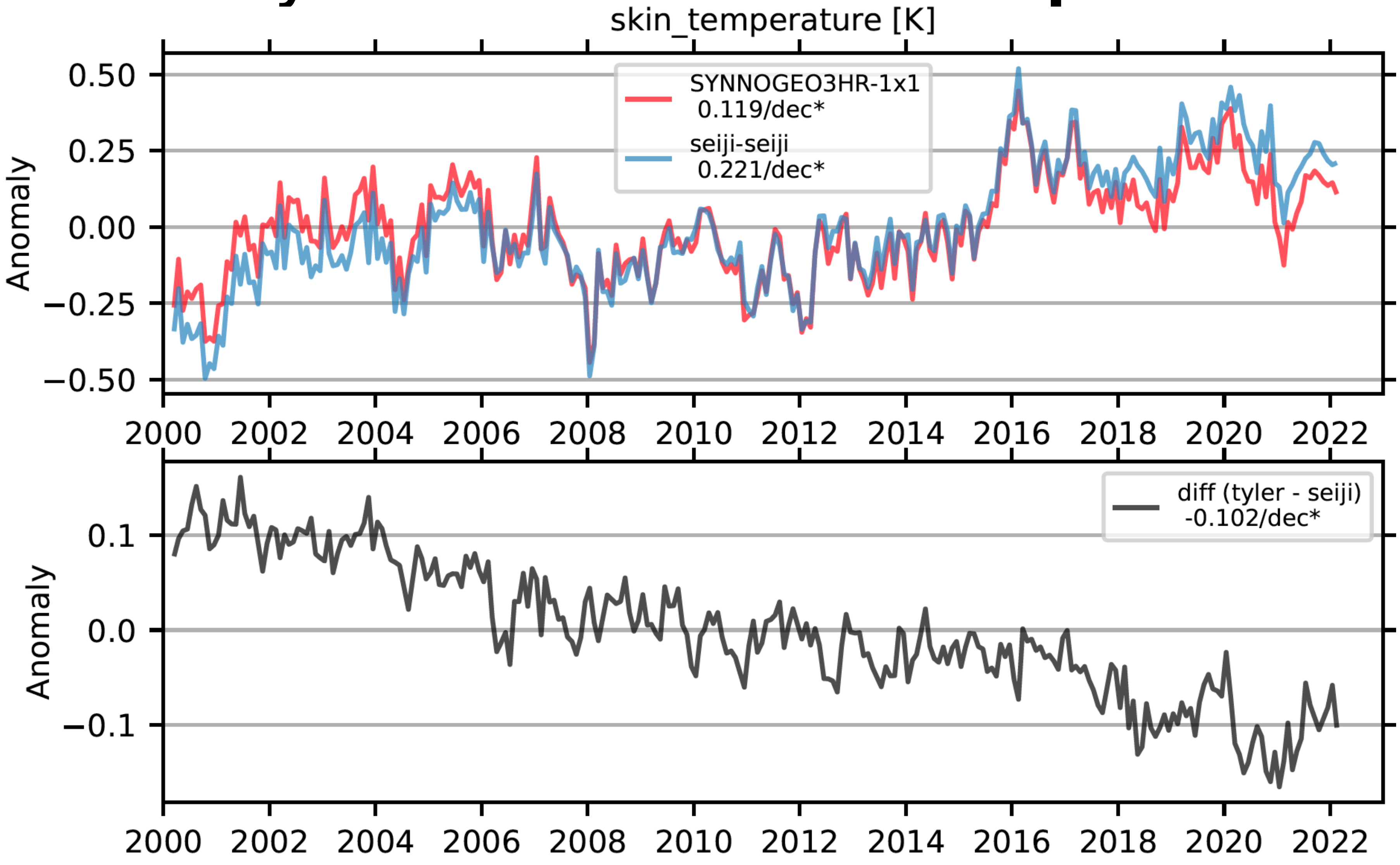
$$\Delta F_{net,rad}^{atm} + \Delta F_{precip} + \Delta F_{SH} = \Delta DSE(T) \qquad (3)$$

Subtracting (2) from (3) and substituting (1) lead to the water mass balance equation

$$\Delta MSE(T, wv) - \Delta DSE(T) = \Delta F_{LH} - \Delta F_{precip} \qquad (4)$$

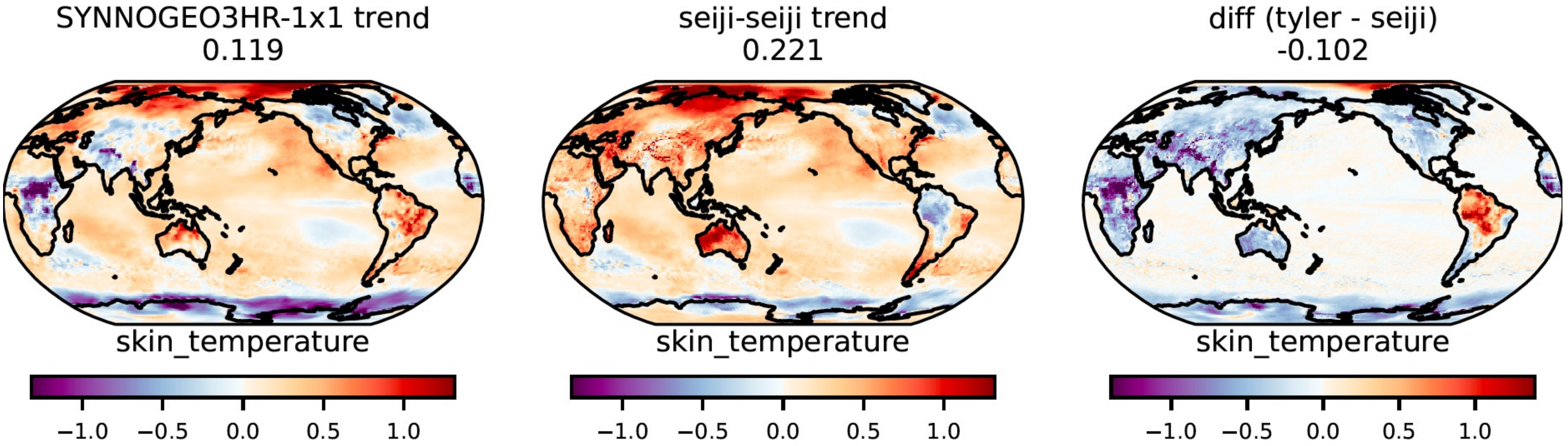
(3) Implies that precipitation can be inferred from non-precipitation terms.

Anomaly time series: **Skin Temperature**



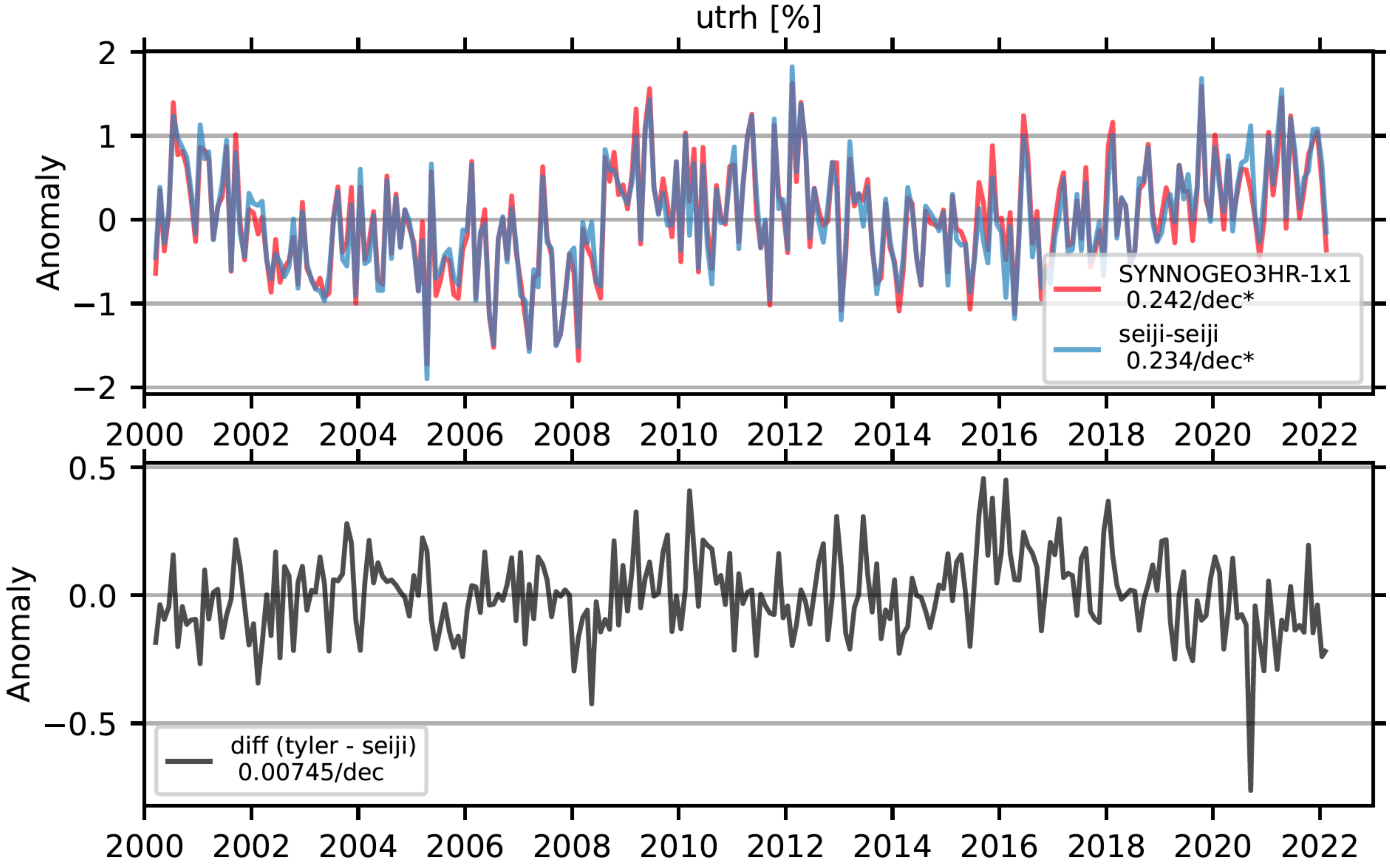
- Relatively large difference in Skin T trend, but time series are well correlated

Regional trends: **Skin temperature**

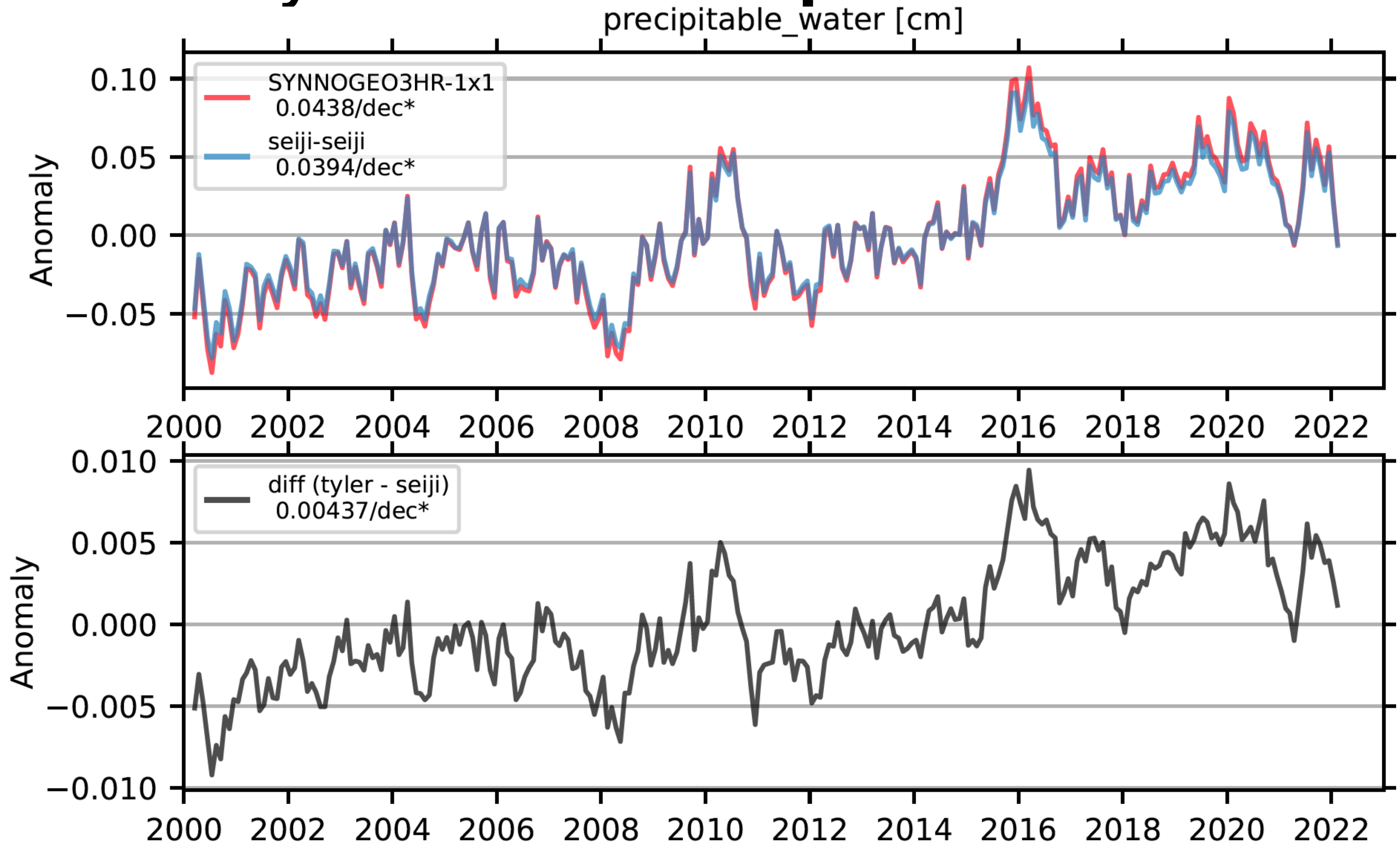


- Use different inputs here: Tyler = MERRA2; Seiji= GEOS5.4.1, MODIS-retrieved over land
- Skin temperature trends similar over ocean
- Largest difference over land: MODIS has more positive trends everywhere except for the Amazon
- Some differences from sea ice as well

Anomaly time series: **Inputs**



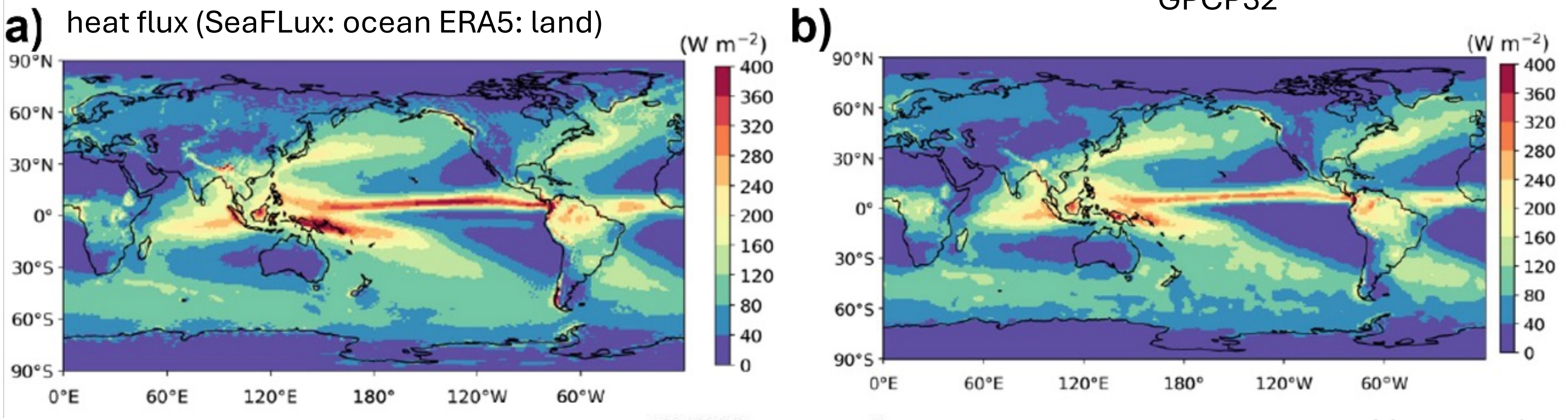
Anomaly time series: **Inputs**



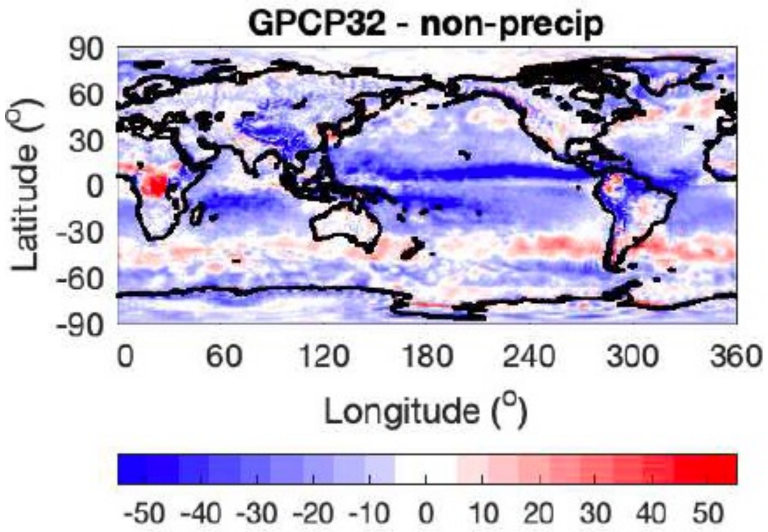
Diabatic heating by precipitation in Wm^{-2}

Inferred from TOA and surface net irradiances (EBAF), DSE divergence (ERA5) and sensible heat flux (SeaFLux: ocean ERA5: land)

GPCP32



Mayer et al. 2024



Moving toward closing surface and atmosphere energy balance under NASA energy water cycle study

Clear-sky temperature retrieval

AVG(RAD)	AVG(DAT)	AVD(RAD)-AVG(DAT)

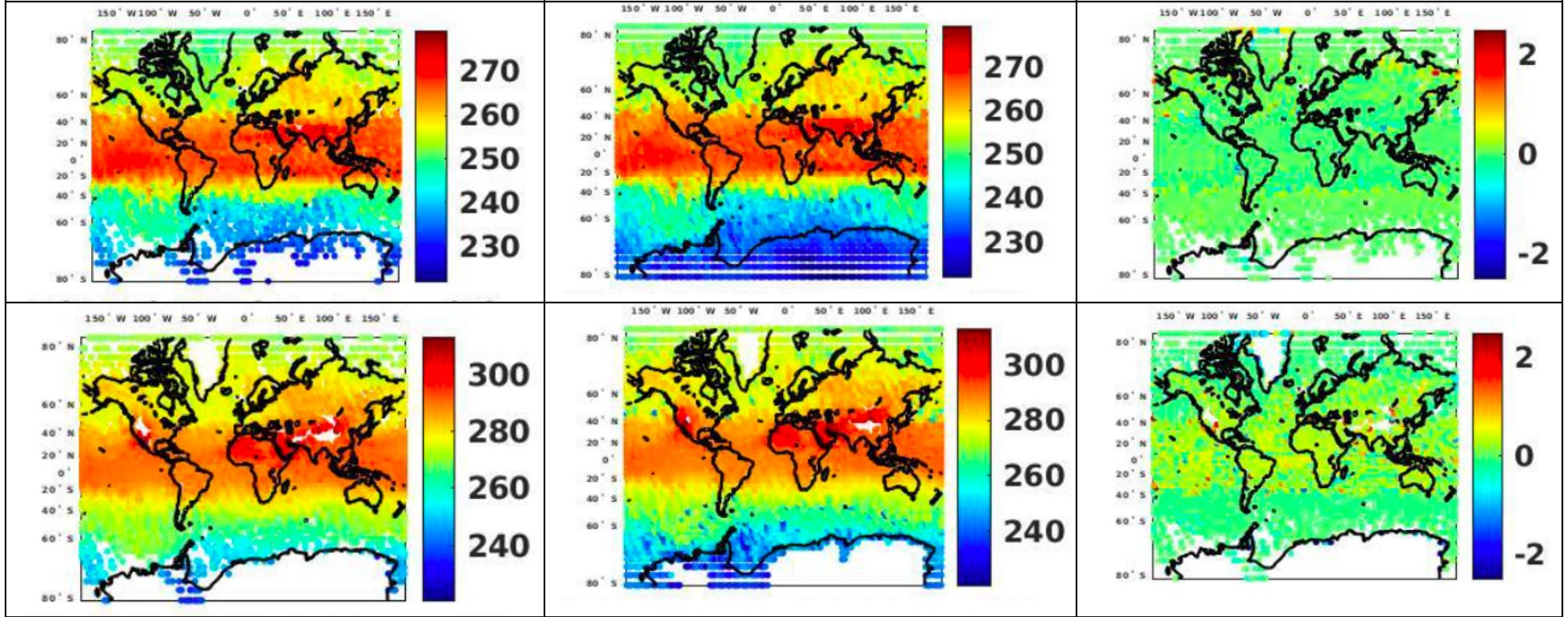


Figure 1: Retrieved temperature at (top) 500 hPa and (bottom) 850 hPa levels by the dual-regression algorithm using nadir-view AIRS clear-sky spectral radiance from June 26, 2007 through July 11 2007. The left column is retrieved with 16-day mean spectral radiance and middle column is mean of instantaneous retrievals. All radiances are from ascending orbits i.e. (daytime). The right column is the difference of AVG(RAD) and AVG(DAT).

Clear-sky water vapor mixing ratio retrieval

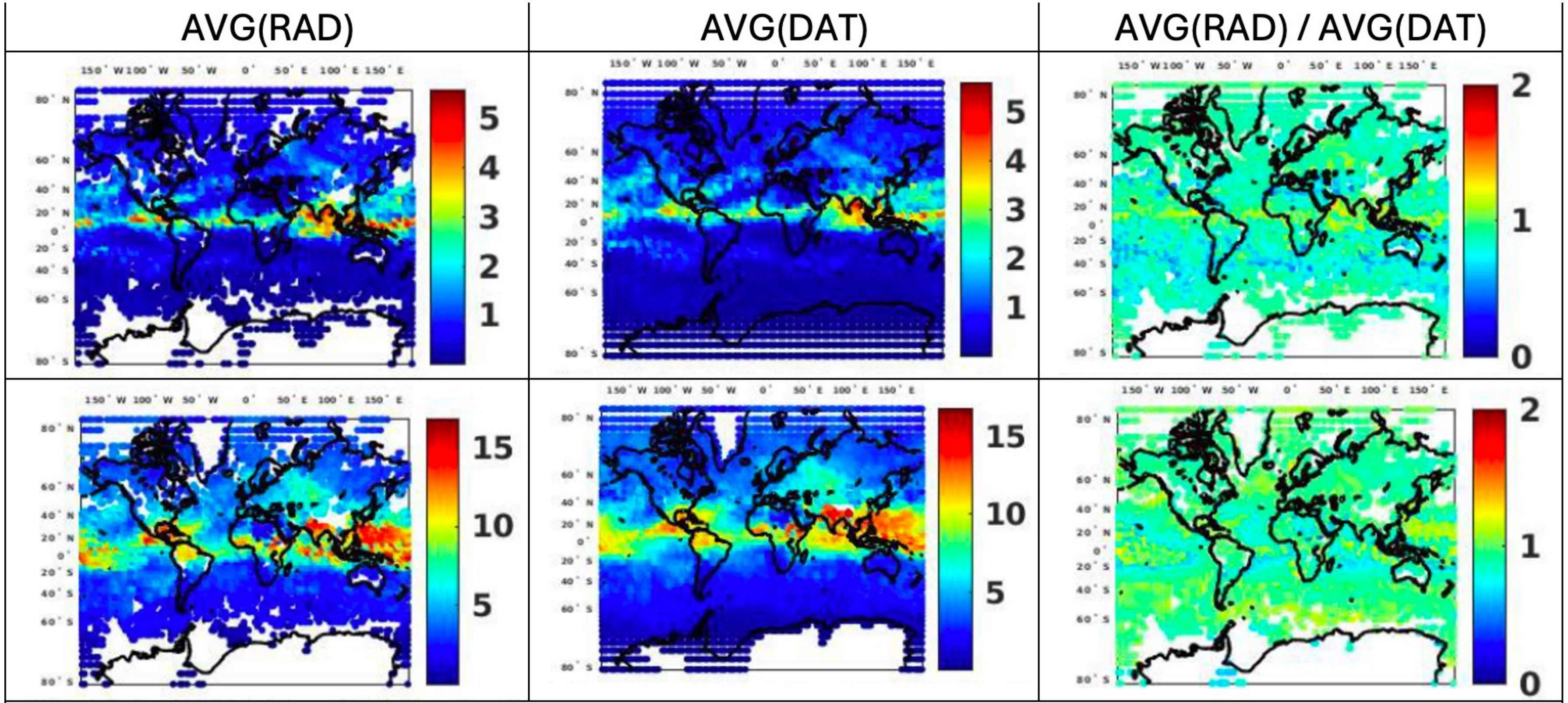


Figure 2: Retrieved specific humidity in g kg^{-1} at (top) 500 hPa and (bottom) 850 hPa levels by the dual-regression algorithm using nadir-view AIRS clear-sky spectral radiance from June 26, 2007 through July 11 2007. The left column is retrieved with 16-day mean spectral radiance AVG(RAD) and middle column is mean of instantaneous retrievals AVG(DAT). All radiances are from ascending orbit (i.e. daytime). The right column is the ratio of AVG(RAD) and AVG(DAT).