TEXAS A&M UNIVERSITY

Improved ice crystal optical properties and radiative transfer simulation capabilities in support of satellite remote sensing

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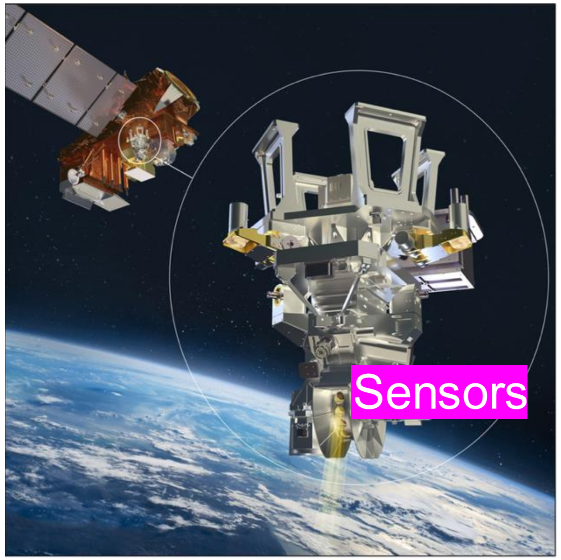
Background

❑ *The Legacy of the CERES Satellite Mission in Monitoring Earth's Energy Budget*

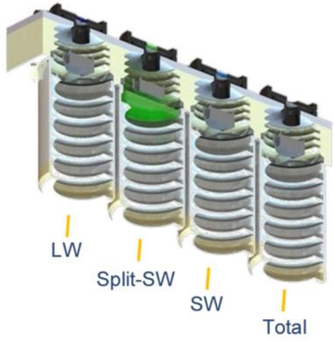
- *The CERES has provided the climate research community with almost three decades of global radiation data extending from observations at TOA (Loeb et al., 2018) to surface flux calculations **via a radiative transfer model (NASA LaRC Fu-Liou model)** (Kato et al., 2018).*

❑ *The Upcoming LIBERA Mission: The Successor to CERES and the Continuation of the Earth Radiation Budget Record*

- *LIBERA defines three overarching goals:*
  - ➢ *Provide **seamless continuity** of the CERES Earth Radiation Budget (ERB) Climate Data Records*
  - ➢ *Develop a self-contained, innovative and affordable observing system*
  - ➢ *Provide **new and enhanced capabilities** that support extending ERB science goals*



Total: 0.3 ~ 100.0+ µm
SW: 0.3 ~ 5.0 µm
Split-SW (new): 0.7 ~ 5.0 µm
LW: 5.0 ~ 50 µm



https://lasp.colorado.edu/libera/

A Potential Further Step Toward Improved Radiative Transfer Modeling

❑ *Current state of the CERES satellite mission*

- *The current CERES operational products mainly include*
  - ➢ *Broadband: SW (0.3 ~ 5.0 μm) & LW (5.0 ~ 200 μm)*

    WIN (8.0 ~ 12.0 um) on Aqua/Terra/NPP FM1~FM5

    replaced with LW (5.0 ~ 35.0 μm) on NOAA-20 FM6

- *While NASA LaRC Fu-Liou model continues its legacy, it is possible to **further improve radiative transfer computations associated with CERES and LIBERA.***
- *Objectives related to LIBERA*

  Specify spectral bands in a new radiative transfer model** tailored for the LIBERA satellite mission, **which precisely align with the LIBERA spectral bands.

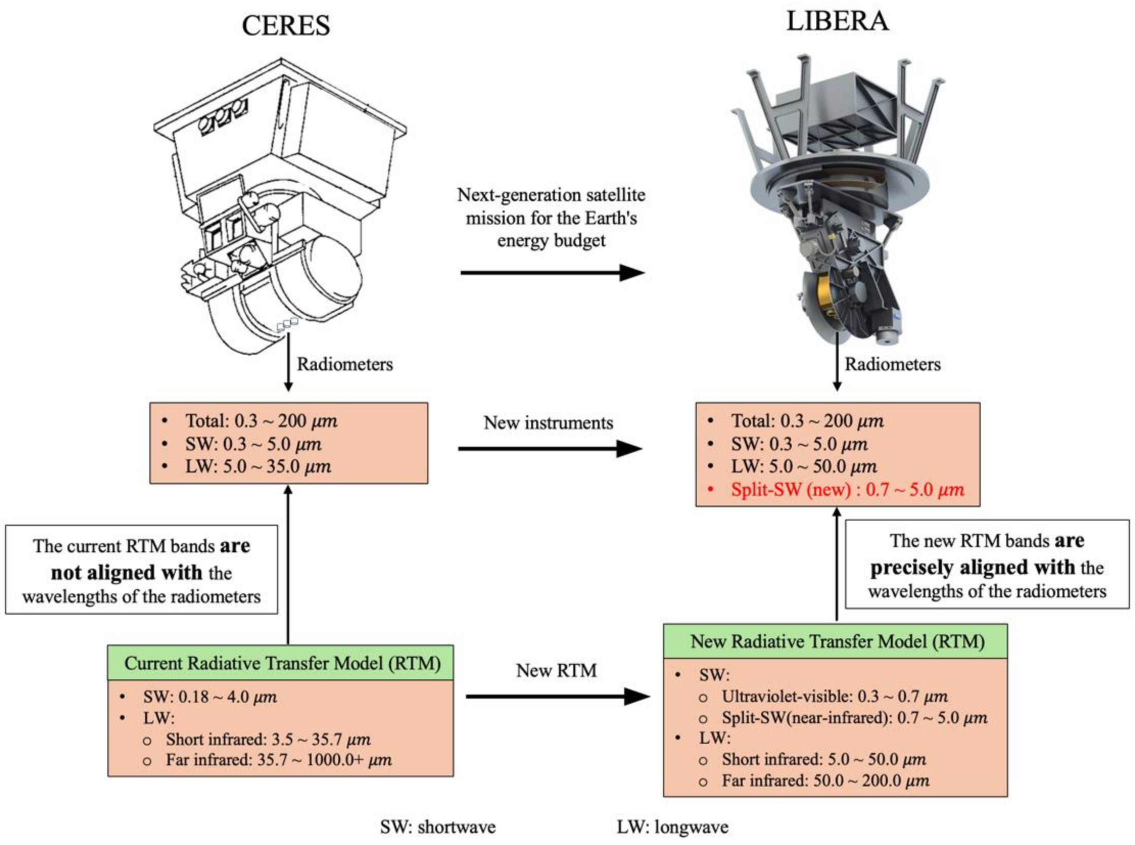


Figure. Observational channels and the radiative transfer models employed (or will be developed) in current and upcoming satellite missions (structures are from https://ceres.larc.nasa.gov/ and https://lasp.colorado.edu/libera/).

Radiative Transfer Model for LIBERA (RTML)

❑ *RTML Band Structure: SW*

	Wavenumber(cm-1)		Wavelength (um)	
No	Begin	End	Begin	End
1	820	2000	5.0000	12.1951
2	2000	2600	**3.8462**	**5.0000**
3	2600	3250	3.0769	3.8462
4	3250	4000	2.5000	3.0769
5	4000	4650	2.1505	2.5000
6	4650	5150	1.9417	2.1505
7	5150	6150	1.6260	1.9417
8	6150	7700	1.2987	1.6260
9	7700	8050	1.2422	1.2987
10	8050	14285	**0.7000**	1.2422
11	14285	16000	0.6250	**0.7000**
12	16000	22650	0.4415	0.6250
13	22650	25000	0.4000	0.4415
14	25000	31745	0.3150	0.4000
15	31745	33330	**0.3000**	**0.3150**
16	33330	35715	0.2800	0.3000
17	35715	38000	0.2632	0.2800
18	38000	50000	0.2000	0.2632

Split-SW (Bands 2–10); SW (Bands 2–16); Total

- *Potential Data Product types within SW*
  - ➢ *Broadband: SW (0.3 ~ 5.0 um): Band 2 ~ Band 15*
  - ➢ *Channels: UVB (0.280 ~ 0.315 um); Band 15 ~ Band 16*
    UVA (0.315 ~ 0.400 um); Band 13 ~ Band 14
    PAR (0.400 ~ 0.700 um); Band 11 ~ Band 13
  - ***(new capability)** Split-SW (0.70 ~ 5.0 um); Band 2 ~ Band 10*

❑ *LIBERA Goals* **https://lasp.colorado.edu/libera/**

- ➢ *Provide **seamless continuity** of the CERES ERB Climate Data Records*
- ➢ *Provide **new and enhanced capabilities** that support extending ERB science goals*

❑ *LIBERA Sensors*

- *SW: 0.3 ~ 5.0 μm*
- *Split-SW: 0.7 ~ 5.0 μm*
- *Total: 0.3 ~ 100+ μm*

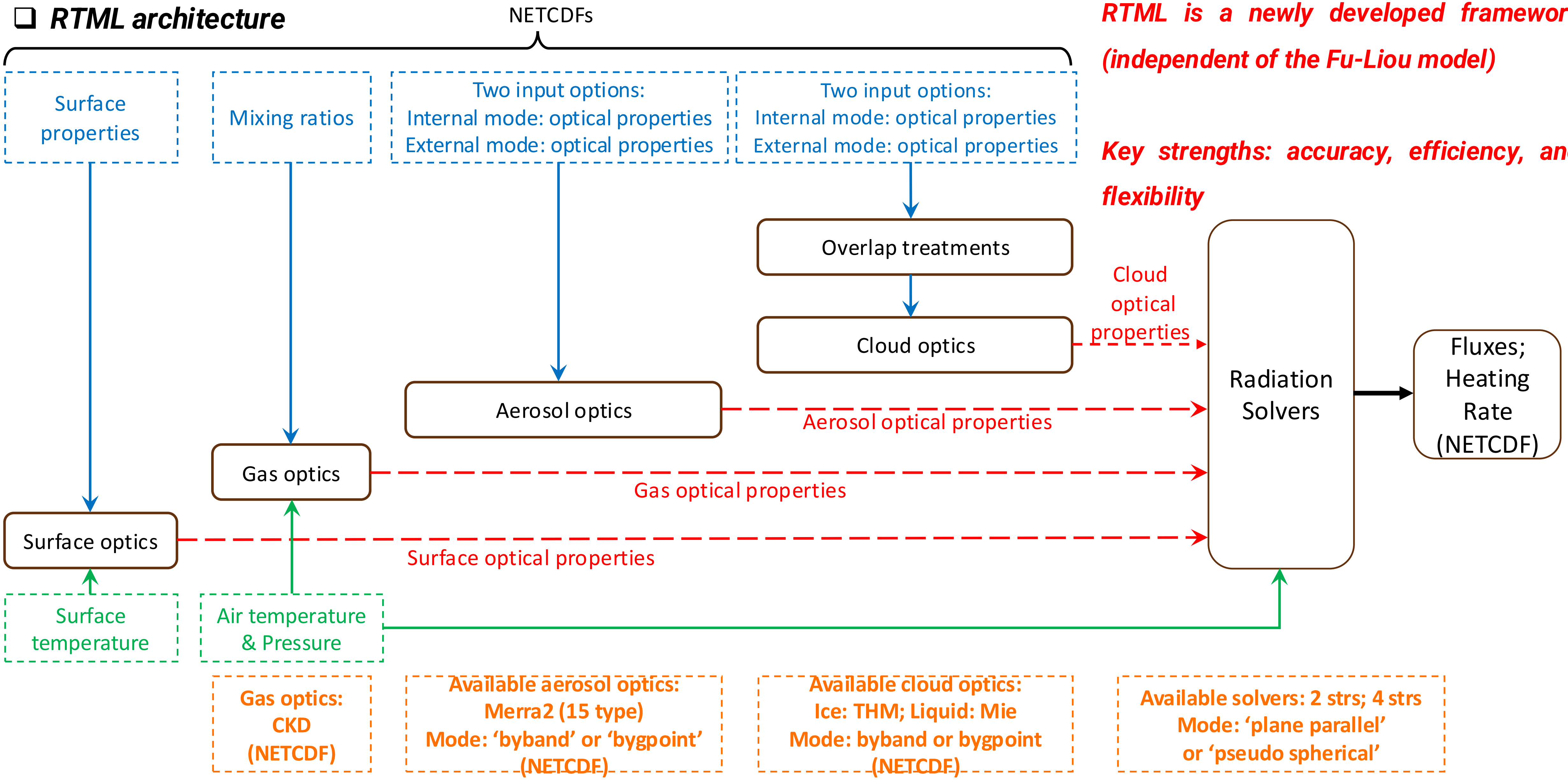
✓ ***The RTML SW band structure precisely aligns with the LIBERA radiometer bands.***

Radiative Transfer Model for LIBERA (RTML) – continued

❑ *RTML architecture*

RTML is a newly developed framework (independent of the Fu-Liou model)

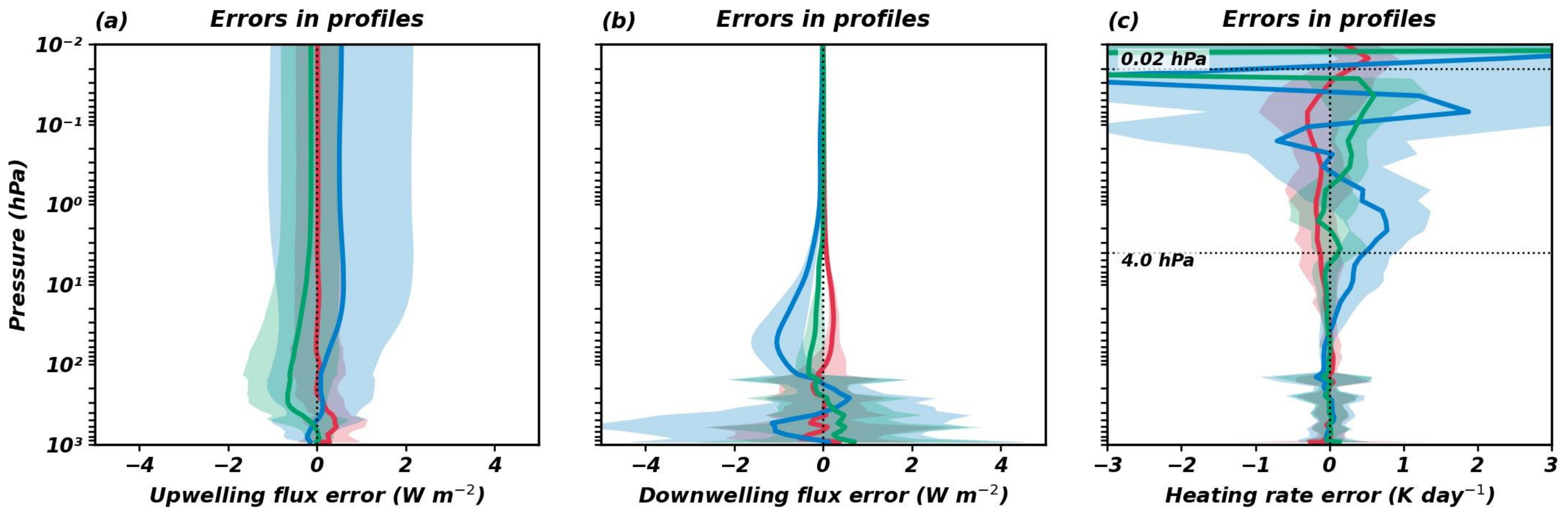
Key strengths: accuracy, efficiency, and flexibility

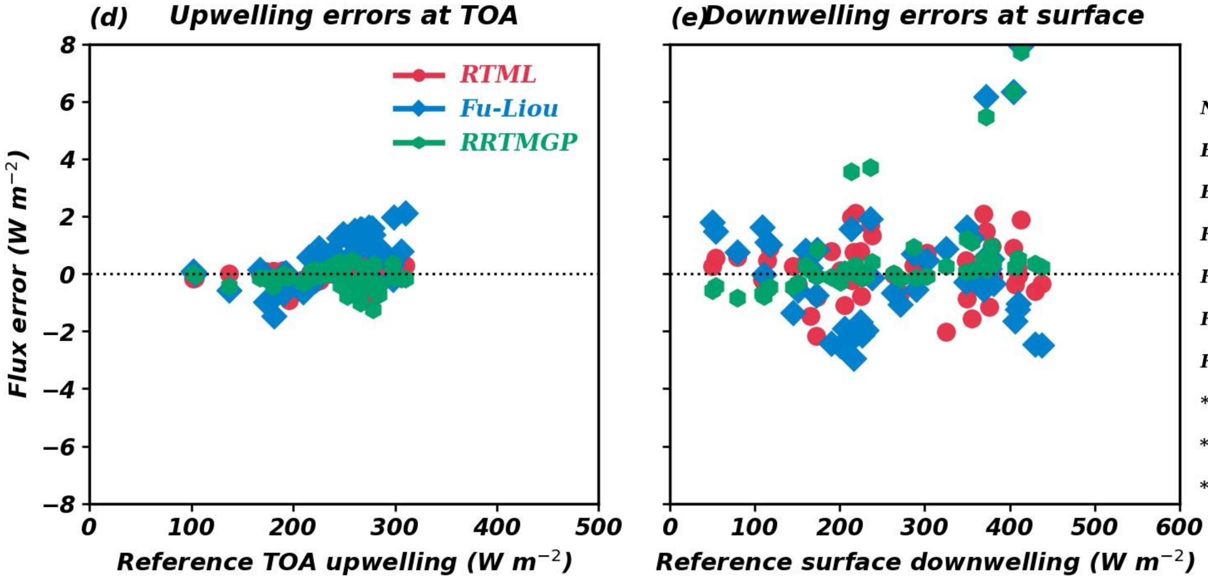


Radiative Transfer Model for LIBERA (RTML) – continued

❑ *RTML Performance*

- *Purpose: examine the gas optical model (**LW**)*
- *Input consists of 50 atmospheric columns (each: 55 levels), covering **polar regions, the tropics (land and ocean), and mid-latitudes (land and ocean)** (Hogan & Matricardi, 2020)*
- *Subplots and statistical metrics demonstrate the high accuracy of the RTML*





	RTML	Fu-Liou	RRTMGP
Number of g-points	112	79	128
Bias surface downward	0.136	0.059	0.632
Bias TOA upward	0.015	0.555	-0.133
RMSE surface downward	0.993	2.183	1.831
RMSE TOA upward	0.253	0.982	0.369
RMSE HR (4-1100 hPa)	0.122	0.199	0.121
RMSE HR (0.02-4 hPa)	0.260	1.666	0.314

* Heating Rate (HR) unit: K day^{-1}; Flux unit: W m^{-2}.

* Fu-Liou: NASA LaRC Fu-Liou

* Scenario: present-day (2020); CO_2 level: 415 ppm

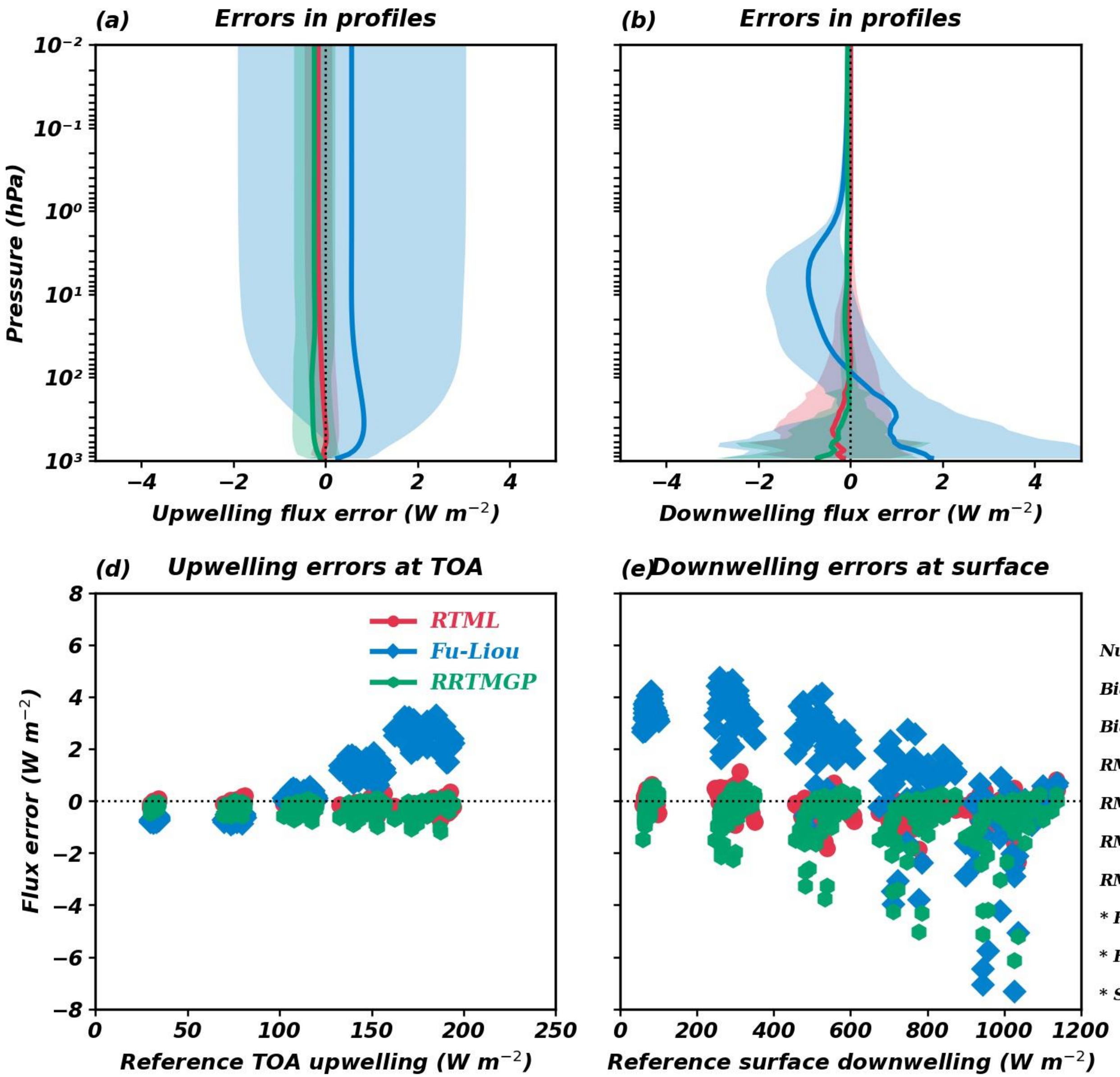
Comparisons of calculated **LW fluxes and heating rates** against LBLRTM (clear sky; no aerosols)

Radiative Transfer Model for LIBERA (RTML) – continued

❑ *RTML Performance*

- *Purpose: examine the gas optical model (**SW**)*
- *Subplots and statistical metrics demonstrate the high accuracy of the RTML*
- *RTML efficiency (LW+SW): Total runtime in **seconds** per 50 columns (repeat 100 runs and average)*

Solve	2-strs	4-strs
Fu-Liou	~ 0.70	~ 0.80
RTML Uses 8 cores	~ 0.085	~0.092
RTML Uses 14 cores	~ 0.064	~0.073



	RTML	Fu-Liou	RRTMGP
Number of g-points	96	70	128
Bias surface downward	-0.154	1.758	-0.722
Bias TOA upward	-0.161	0.568	-0.244
RMSE surface downward	0.512	2.896	1.303
RMSE TOA upward	0.222	1.384	0.334
RMSE HR (4-1100 hPa)	0.060	0.116	0.052
RMSE HR (0.02-4 hPa)	0.133	3.204	0.218

* Heating Rate (HR) unit: K day^{-1}; Flux unit: W m^{-2}.

* Fu-Liou: NASA LaRC Fu-Liou

* Scenario: present-day (2020); CO2 level: 415 ppm

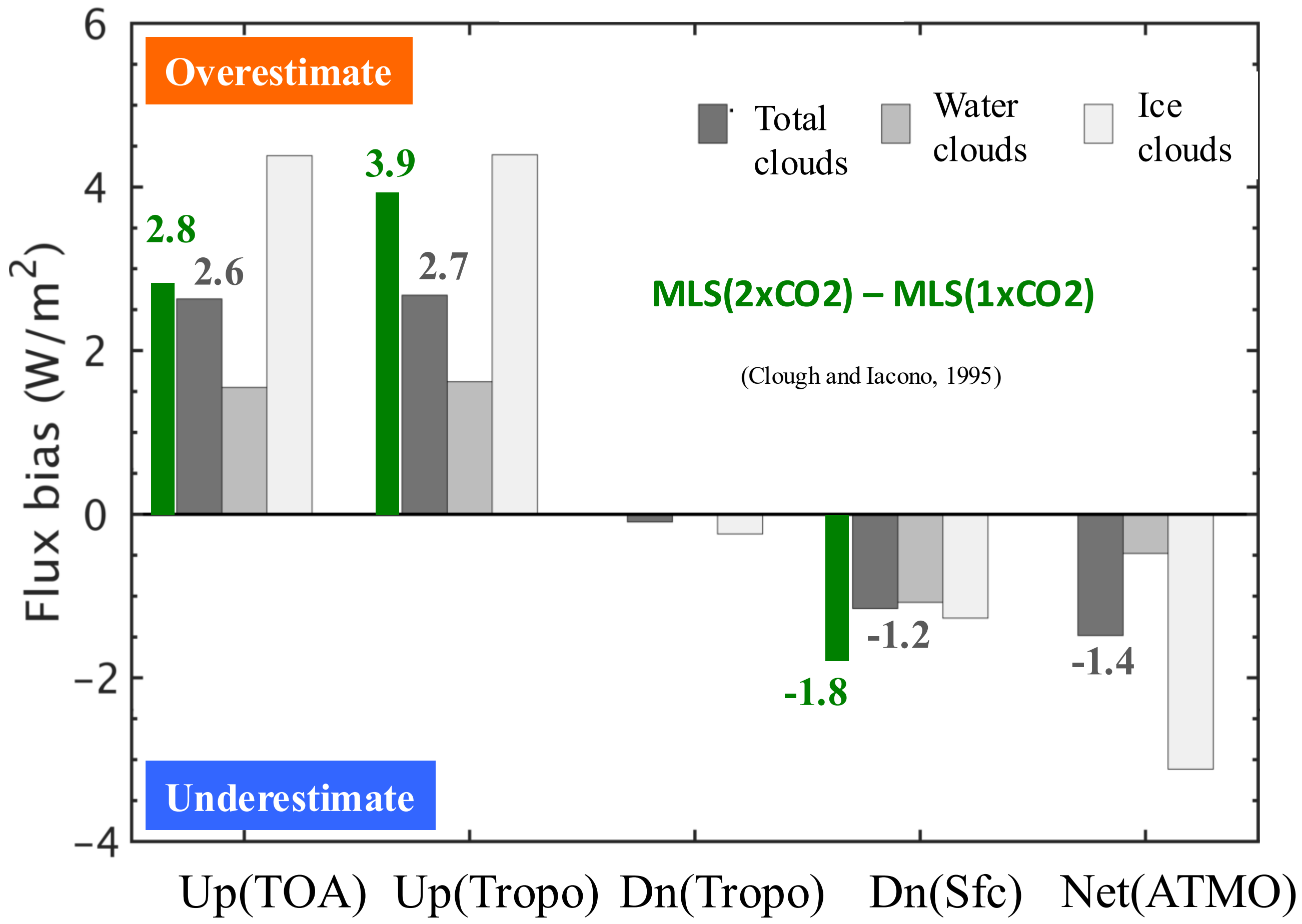
Cosine SZA: 0.1, 0.3, 0.5, 0.7, 0.9

*Figure. Comparisons of calculated **SW fluxes and heating rates** against LBLRTM (clear sky; no aerosols)*

Importance of the scattering effect of LW radiation

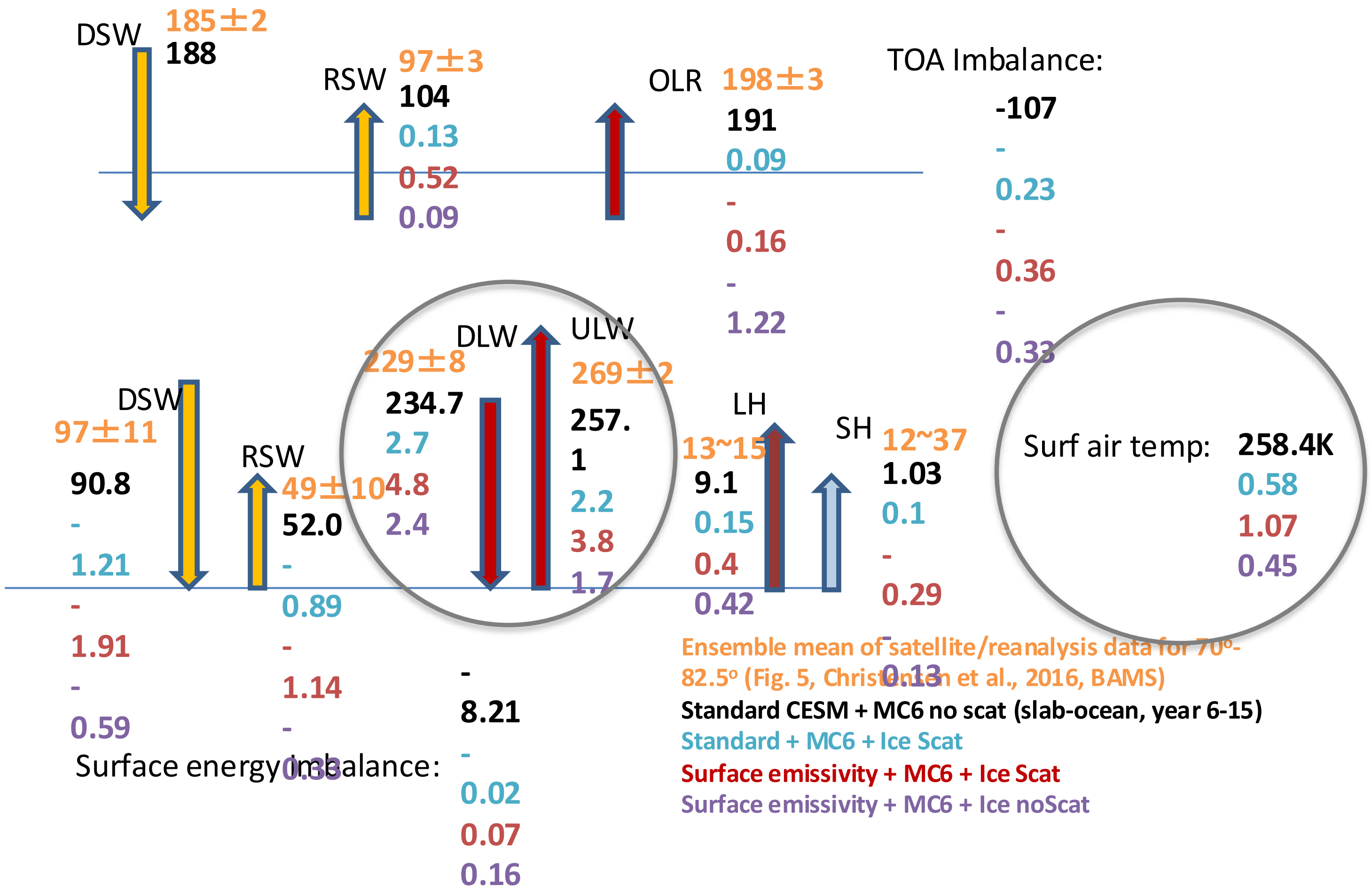
PI: Ping Yang, Co-I: Eli Mlawer
Source: NSF
Project Title: "Collaborative Research: Systematic Evaluation and Further Improvement of present broadband radiative transfer modeling capabilities"
Project duration: 09/01/2016-08/31/2019 (no-cost extension to 08/31/2020)

Flux Biases



Kuo, C.-P., P. Yang, X. Huang, D. Feldman, M. Flanner, C. Kuo, and E. J. Mlawer, 2017: *Journal of Advances in Modeling Earth Systems*.

NCAR CESM Annual-mean energy budget over the Arctic (66.5°-90°N)



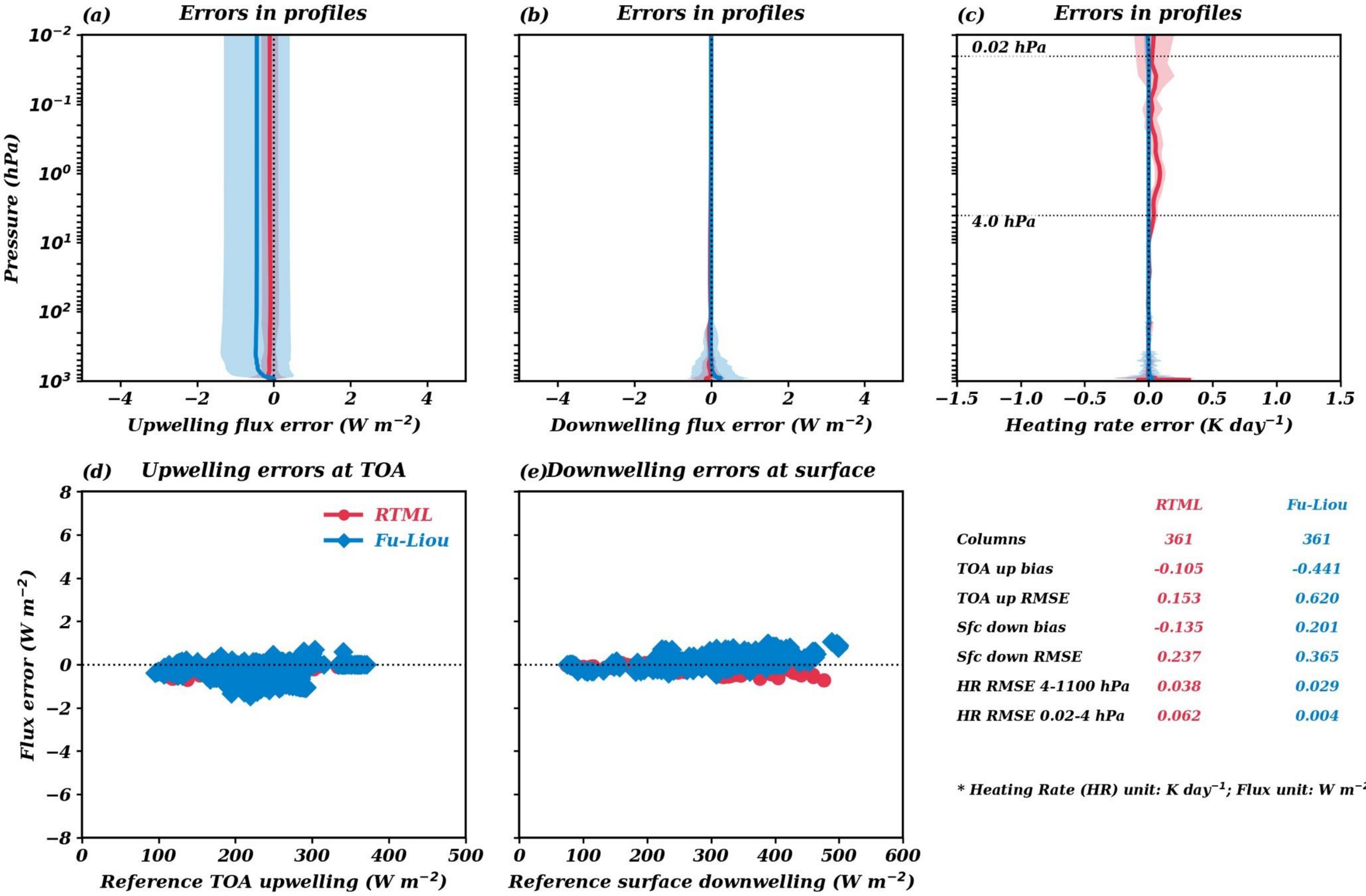
As expected, including both surface emissivity and cloud LW scattering warms up the surface more.
DoE E3SM v2 showed similar results. Fan, C., Chen, Y.-H., Chen, X., Lin, W., Yang, P., & Huang, X. (2023). A refined understanding of the ice cloud longwave scattering effects in climate model. Journal of Advances in Modeling Earth Systems, 15, e2023MS003810. https://doi.org/10.1029/2023MS003810

Courtesy of Xianglei Huang

Radiative Transfer Model for LIBERA (RTML) – continued

❑ RTML Performance

- Purpose: examine the capability in handling **multiple scattering** in the opaque atmosphere (**LW**)
- Input: One ERA5/MERRA2 slice
  - latitude: 90S ~ 90N
  - time: 2019-07-11 00:00
  - 361 columns, 137 layers
  - ice/liquid clouds
  - no aerosols
- Subplots and statistical metrics demonstrate the high accuracy of the RTML



	RTML	Fu-Liou
Columns	361	361
TOA up bias	-0.105	-0.441
TOA up RMSE	0.153	0.620
Sfc down bias	-0.135	0.201
Sfc down RMSE	0.237	0.365
HR RMSE 4-1100 hPa	0.038	0.029
HR RMSE 0.02-4 hPa	0.062	0.004

* Heating Rate (HR) unit: K day^{-1}; Flux unit: W m^{-2}.

*Figure. Comparisons of calculated **LW fluxes and heating rates** against **64 streams DISORT** (all sky)*

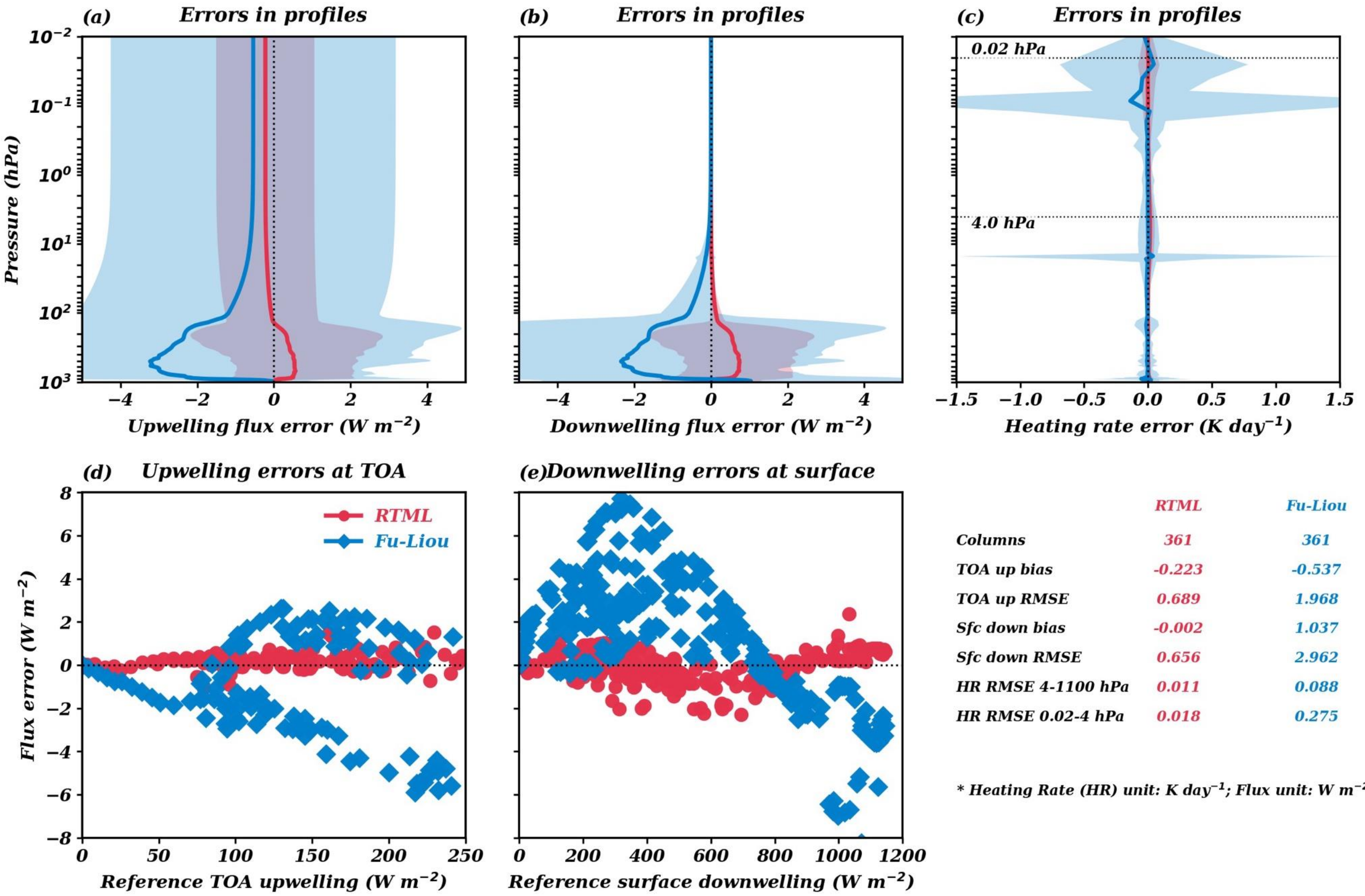
Radiative Transfer Model for LIBERA (RTML) – continued

❑ *RTML Performance*

- *Purpose: examine the capability in handling **multiple scattering** in the opaque atmosphere (**SW**)*

- *Input: One ERA5/MERRA2 slice*
  latitude: 90S ~ 90N
  time: 2019-07-11 00:00
  361 columns, 137 layers
  ice/liquid clouds
  no aerosols

- *Subplots and statistical metrics demonstrate the high accuracy of the RTML*



	RTML	Fu-Liou
Columns	361	361
TOA up bias	-0.223	-0.537
TOA up RMSE	0.689	1.968
Sfc down bias	-0.002	1.037
Sfc down RMSE	0.656	2.962
HR RMSE 4-1100 hPa	0.011	0.088
HR RMSE 0.02-4 hPa	0.018	0.275

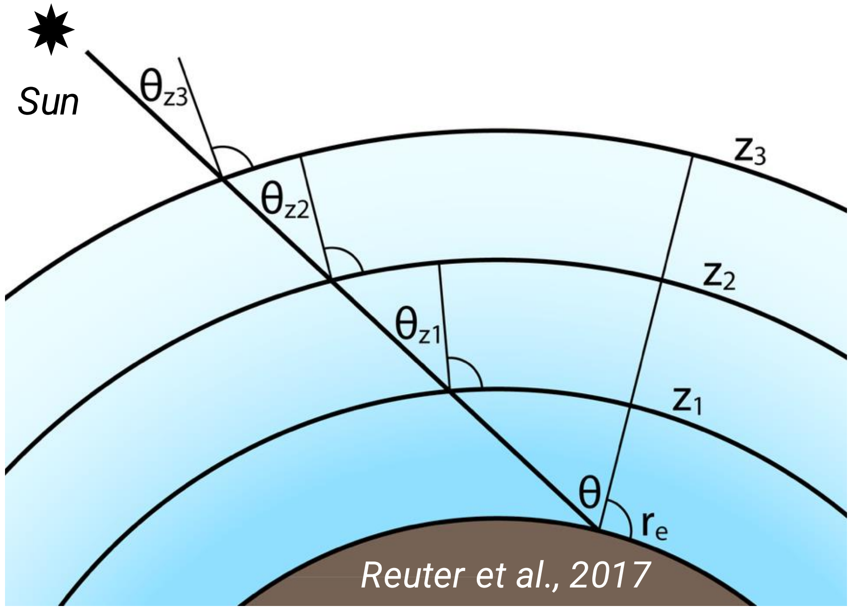
* Heating Rate (HR) unit: K day^{-1}; Flux unit: W m^{-2}.

*Figure. Comparisons of calculated **SW fluxes and heating rates** against **64 streams DISORT** (cloudy sky)*

Radiative Transfer Model for LIBERA (RTML) – continued

❑ *RTML new features (an example)*

- *RTML—PP: plane parallel atmosphere*
- *RTML—ps: pseudo-spherical atmosphere (see the diagram: height-dependent SZA)*



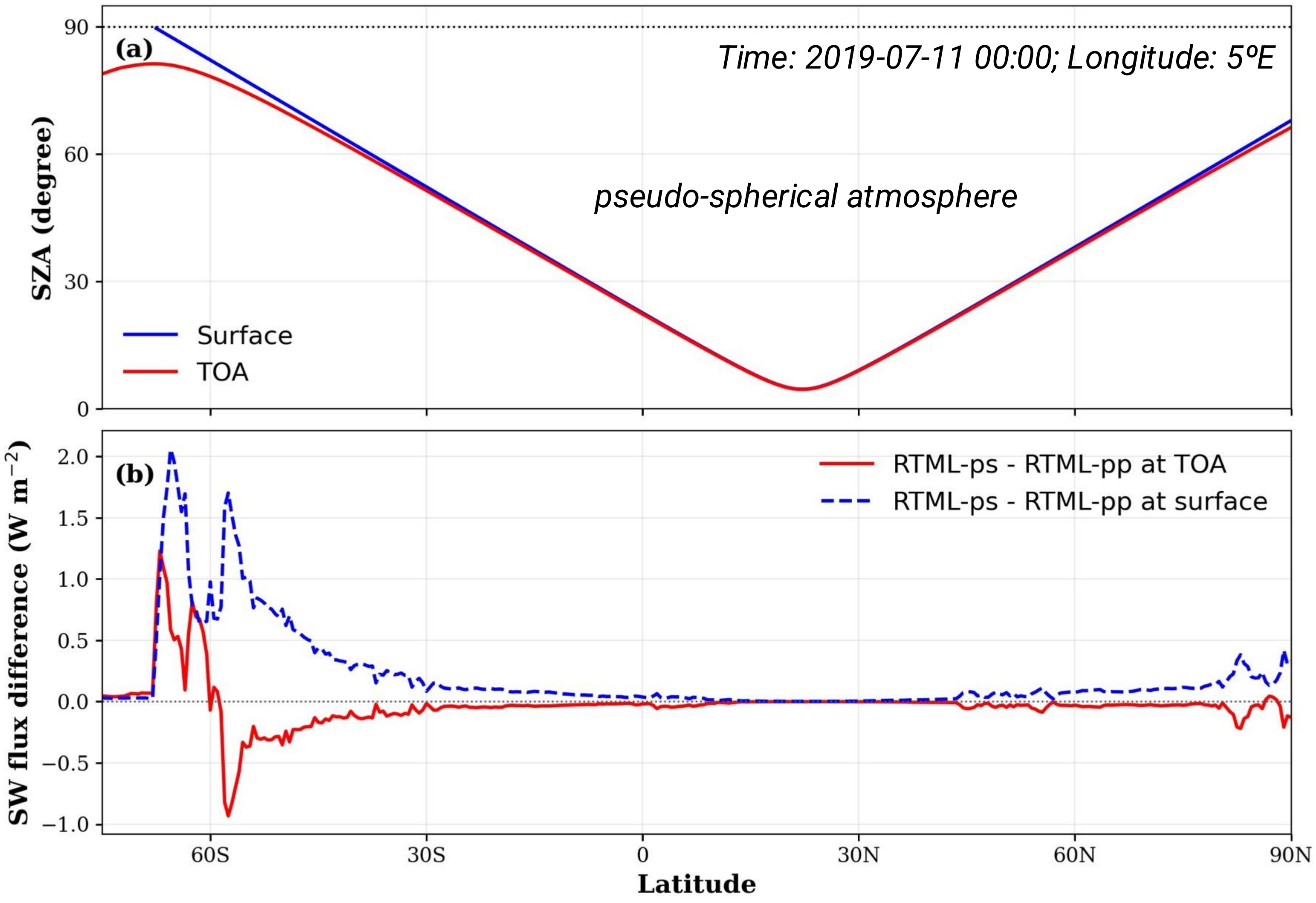
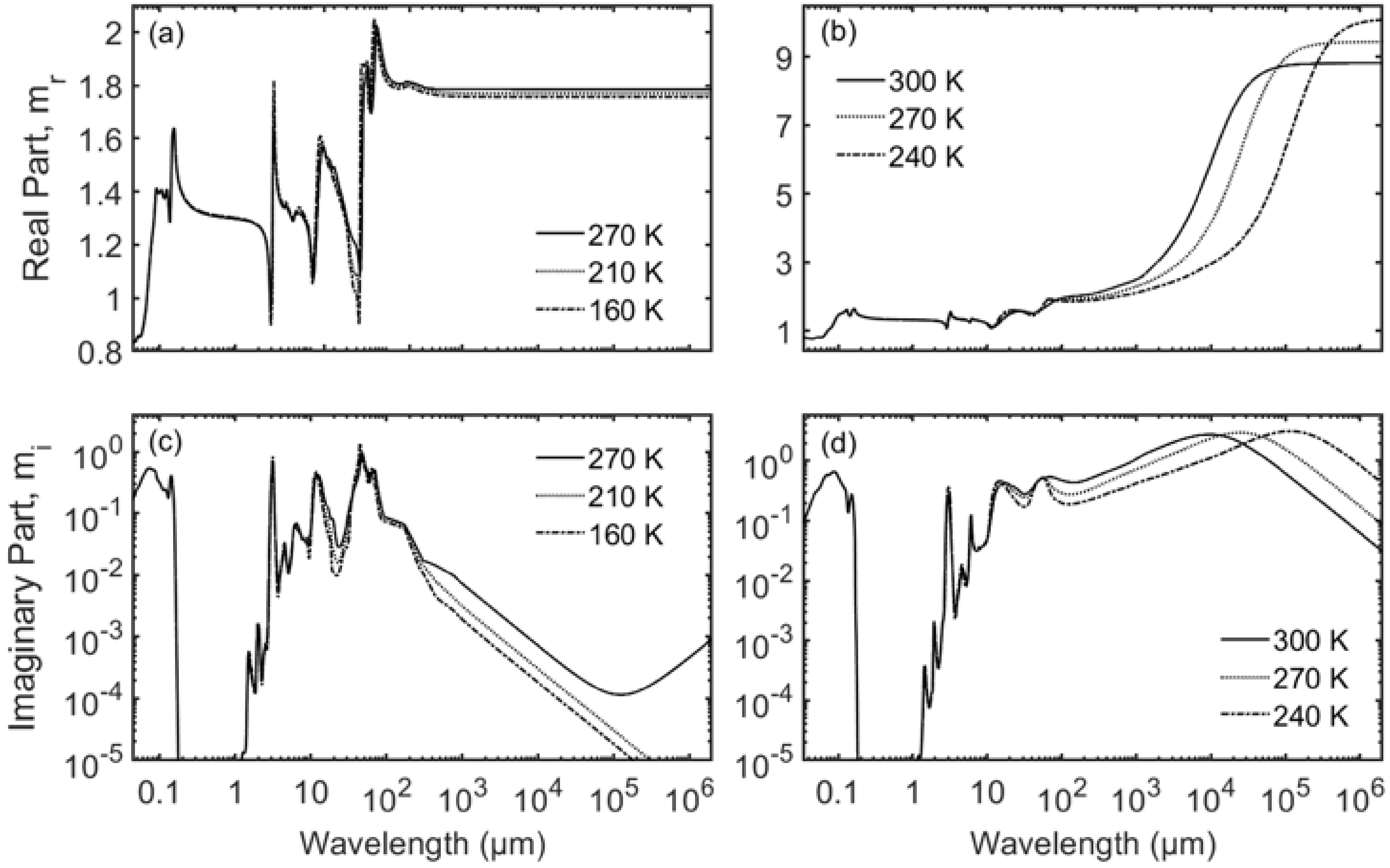


Figure. Comparisons of calculated ***SW*** ***upward flux differences at TOA*** **and** ***downward flux differences at the surface***

Optical properties of ice and water clouds



The refractive indices of ice (left panels) at temperatures 160, 210, and 270K, and the refractive indices of liquid water (right panels) at temperatures 240, 270, and 300K at wavelengths from ultraviolet to microwave.

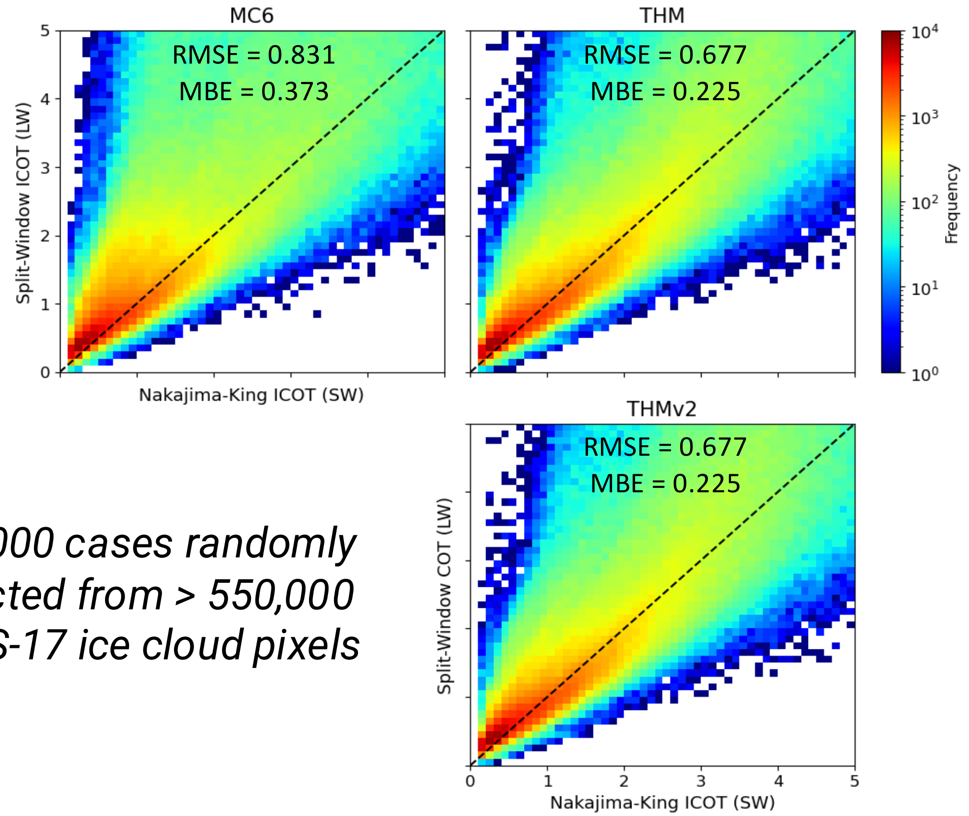
S. Wang, T. Ren, P. Yang, M. Saito, and H. E. Brindley, "Improved Temperature-Dependent Ice Refractive Index Compilation in the Far-Infrared Spectrum," *Geophys. Res. Lett.*, vol. 51, no. 14, Jul. 2024, doi: 10.1029/2024GL110176.

S. Wang, P. Yang, H. E. Brindley, X. Huang, and T. S. L'Ecuyer "Enhanced Full Spectral Temperature-Dependent Refractive Index of Liquid Water from Supercooled to Ambient Conditions," *Geophys. Res. Lett.*, 2026 doi.org/10.1029/2025GL119385

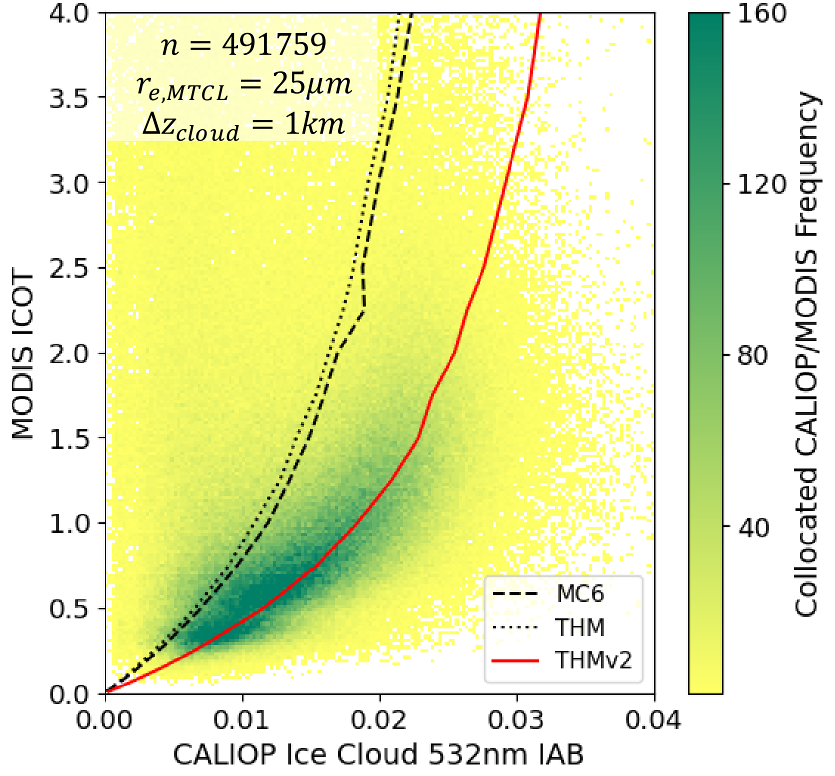
New updates to the ice cloud optical model

❑ *Spectral consistency; Passive-active consistency*

- *The recently developed Two Habit Model version 2 (THMv2) achieves passive sensor spectral consistency of ice cloud optical thickness (ICOT) retrievals as well as significantly improved integrated attenuated backscatter (IAB) consistency with respect to ICOT for active sensors.*
- *Based on these results, THMv2 achieves passive and active consistency of ice cloud radiative property retrievals.*



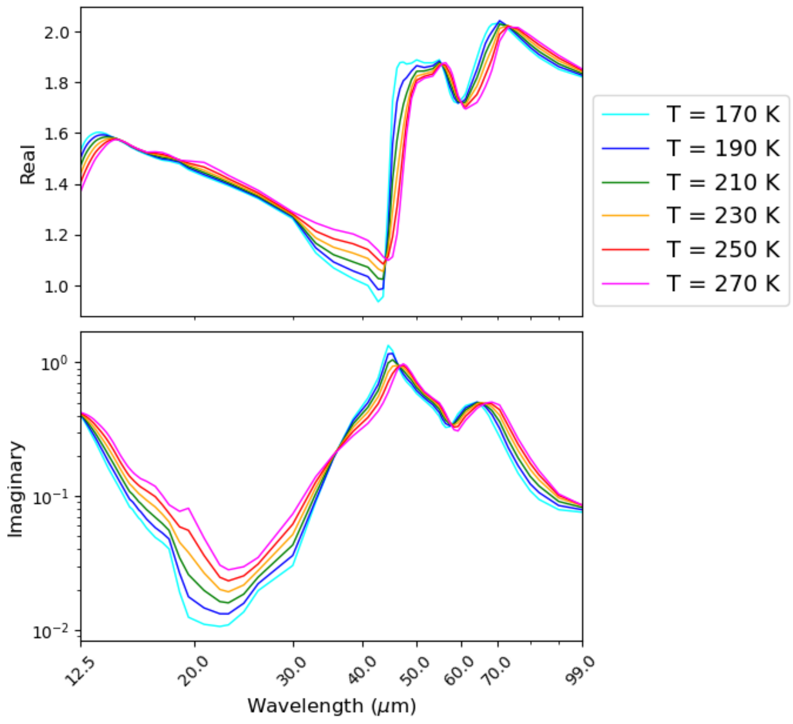
400,000 cases randomly selected from > 550,000 GOES-17 ice cloud pixels

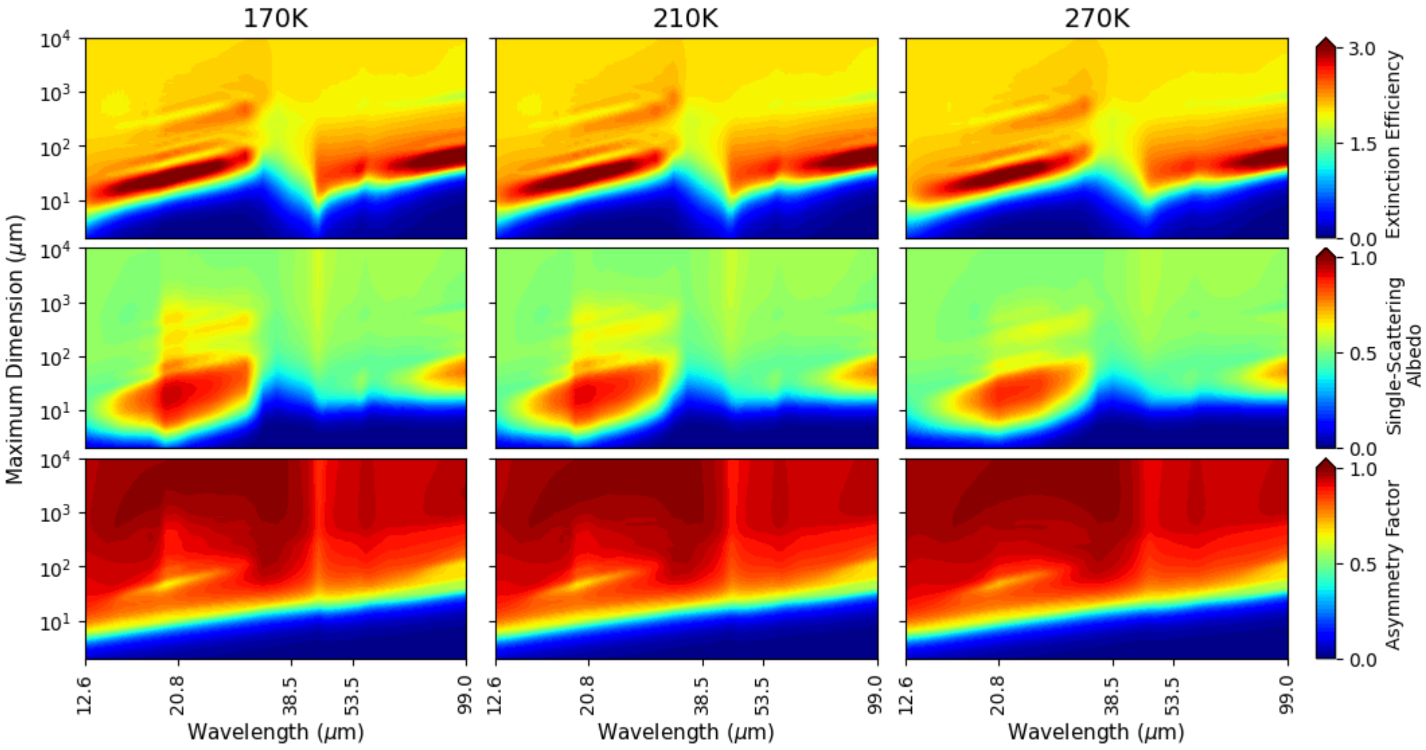


New updates to the ice cloud optical model-continued

❑ *Temperature-dependence*

- *For the far-infrared spectral regime covered by the THMv2-TEMP Model (12.6 – 99μm), the corresponding complex refractive index becomes noticeably sensitive to temperature.*
- *The changes in complex refractive indices result in noticeable changes in the corresponding single-scattering properties which can affect ice cloud optical property retrievals.*
  - ***Most significant changes in refractive indices are concentrated in the "dirty" far-infrared window between 400–600 cm^{-1} (16 – 25μm).***
  - *These changes have significant impacts in the corresponding extinction efficiencies and single-scattering albedos.*

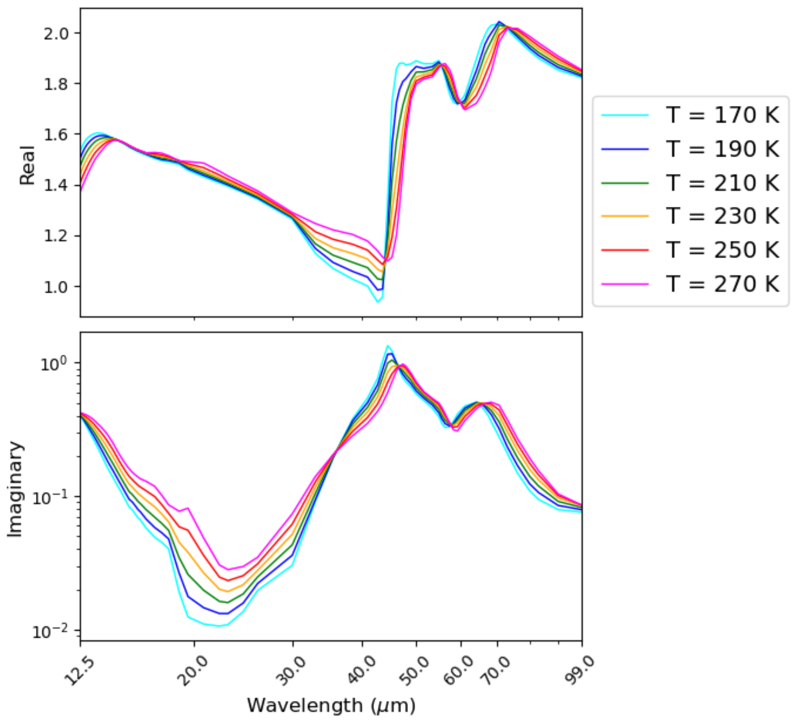


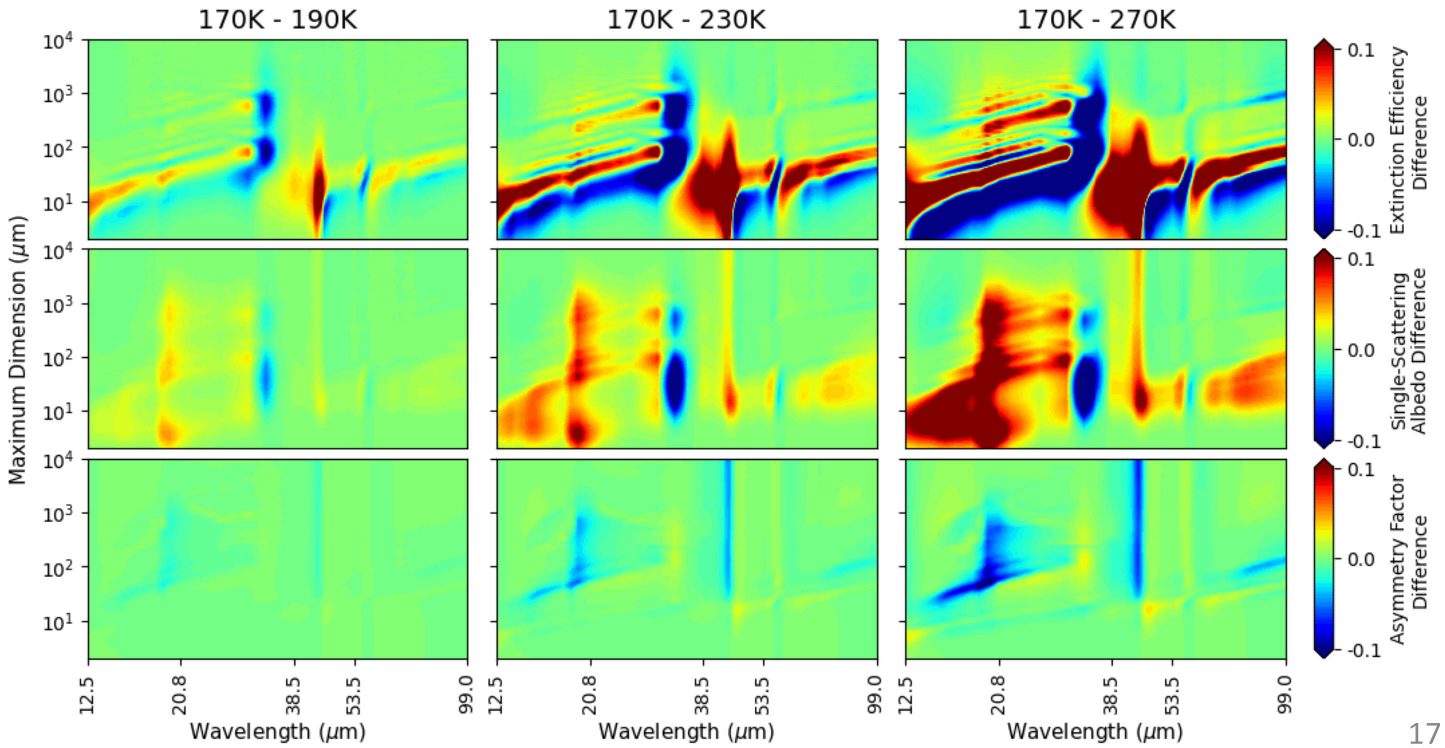


New updates to the ice cloud optical model-continued

❑ *Temperature-dependence*

- *Plotting the differences in single-scattering properties of THMv2-TEMP highlights their sensitivity to temperature.*
- *As stated before, the largest differences in single-scattering properties are concentrated in the "dirty" far-infrared window region (16 – 26μm).*
- *Another area of large differences in single-scattering properties is the absorption peak (peak imaginary refractive index magnitude) between 40 - 50μm.*

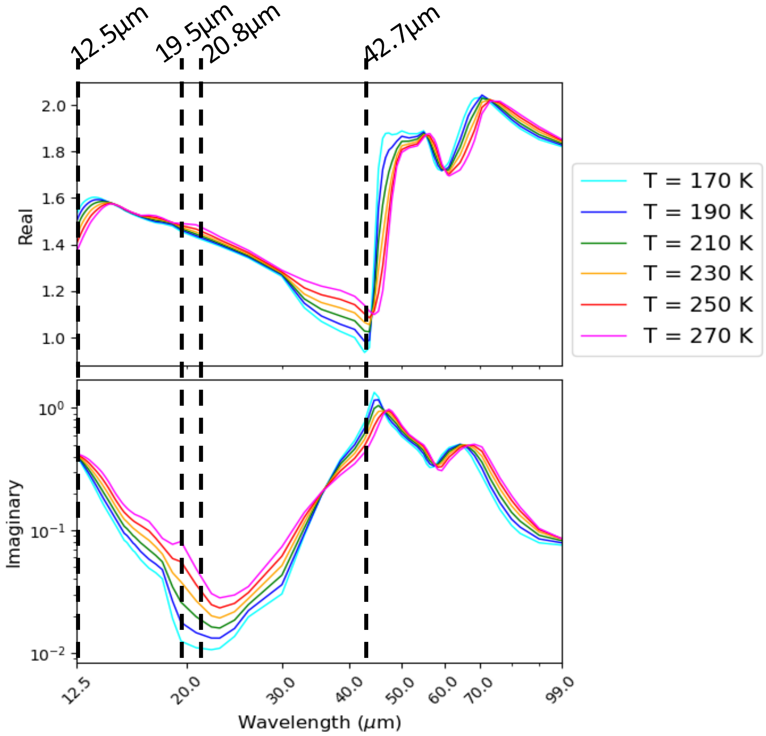


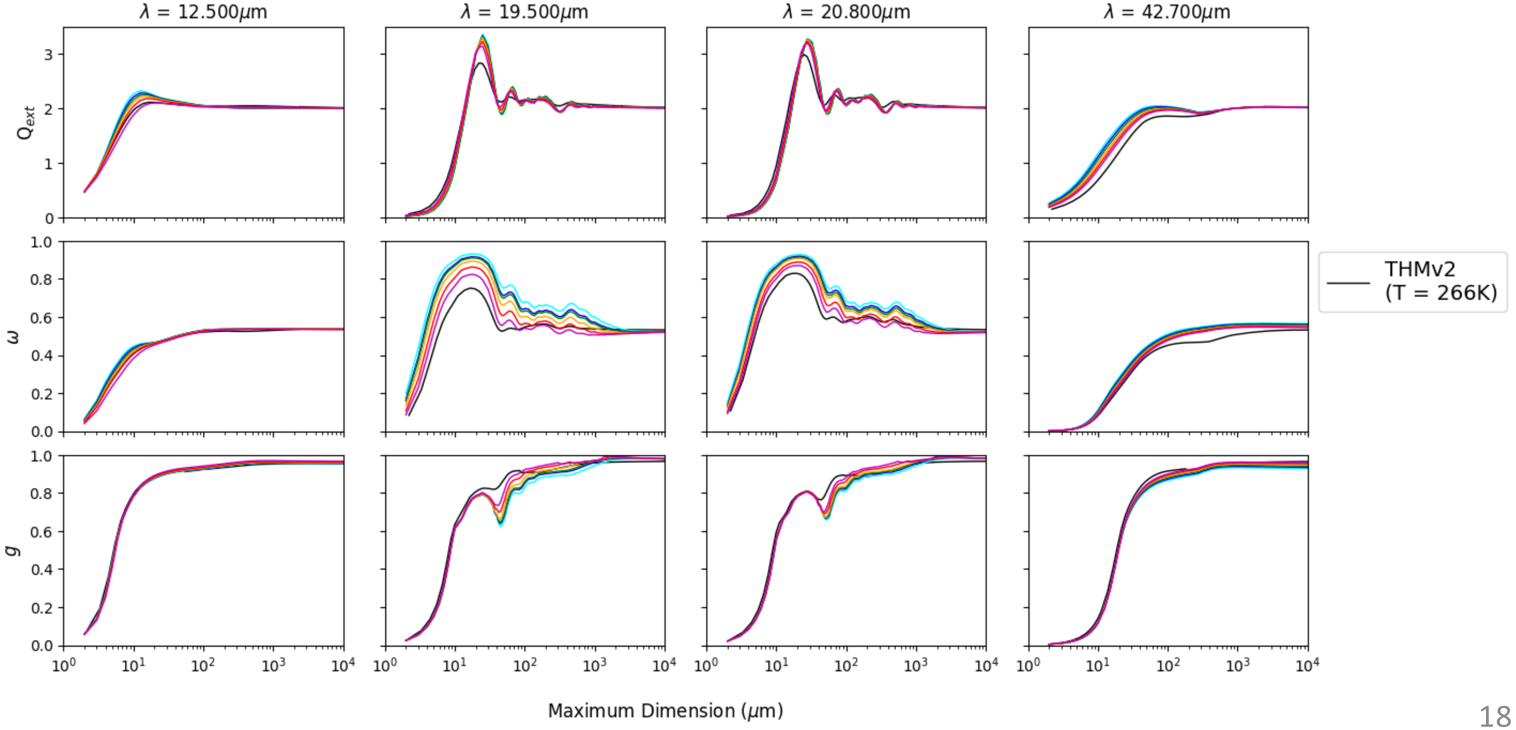


New updates to the ice cloud optical model-continued

❑ *Temperature-dependence*

- *Single-scattering property comparisons between the THMv2-TEMP and THMv2 ice cloud models are plotted to ensure consistency is achieved despite roughened hexagonal column and 20-column aggregate particles being considered for THMv2-TEMP instead of their distorted ensemble variants.*
- *THMv2 was developed using the complex refractive index database from Warren and Brandt (2008), which corresponds to a temperature of 266K.*
- *Overall, THMv2-TEMP is moderately consistent with THMv2 with the differences being due to different particle geometries being used which would slightly change their corresponding single-scattering properties.*





An example application of temperature-dependent THMv2

❑ ***Implemented in RTML***

- *Purpose: examine the simulated longwave flux difference*
- *Input: One ERA5/MERRA2 slice*
  latitude: 90S ~ 90N
  time: 2019-07-11 00:00
  361 columns, 137 layers
  ice/liquid clouds
  no aerosols
- *Ice cloud models at 170K, 230K, 270K*
- *Downward flux biases can be slightly larger than **1.0 W m-2;** upward flux biases can be ~ **0.5 W m-2***

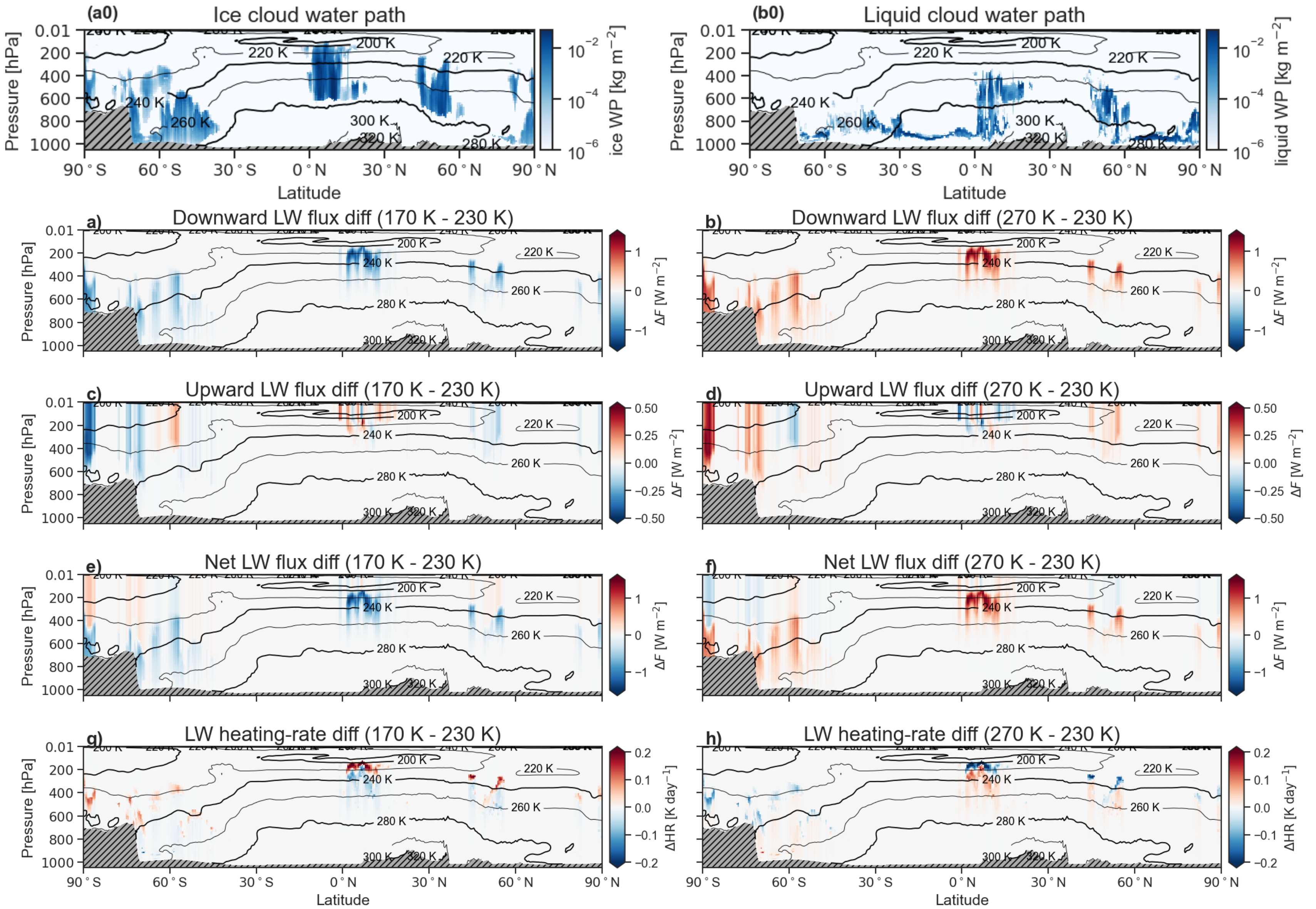


Figure. Comparisons of calculated ***LW flux biases and heating rates*** *using temperature-dependent ice cloud model*

Summary

- *RTML was developed in **alignment with the LIBERA mission's science goals**, to support monitoring of Earth's radiation budget;*
- *RTML is highly configurable and flexible, offering multiple options for specifying optical properties, solvers, and a streamlined **user interface** based on simple configuration files with NetCDF input/output;*
- *RTML was designed for **high-efficiency** computing with **parallelization and optimization**, while supporting multiple platforms and compilers;*
- *RTML performance has been evaluated against reference benchmarks, **demonstrating research-grade accuracy** for the LIBERA satellite mission applications;*
- *The **updated THMv2 achieves passive and active consistency** of ice cloud radiative property retrievals, and has been extended to far-IR with the inclusion of the **temperature dependence** of the cloud optical properties;*
- ***RTML may be a candidate for current and future satellite mission applications.***