DOE/SC-ARM-TR-202

ARM Data-Oriented Metrics and Diagnostics Package (ARM-Diags) for Climate Model Evaluation

Cheng Tao
Chengzhu Zhang
Shaocheng Xie
Minghua Zhang
Xiaojian Zheng

September 2024

DISCLAIMER

This report was prepared as an account of work sponsored by the U.S. Government. Neither the United States nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

DOE/SC-ARM-TR-202

ARM Data-Oriented Metrics and Diagnostics Package (ARM-Diags) for Climate Model Evaluation

Cheng Tao, Lawrence Livermore National Laboratory (LLNL)
Chengzhu Zhang, LLNL
Shaocheng Xie, LLNL
Minghua Zhang, Stony Brook University
Xiaojian Zheng, Argonne National Laboratory

September 2024

Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

ACSM	Aerosol Chemical Speciation Monitor
AOD	Aerosol Optical Depth
ARM	Atmospheric Radiation Measurement
ARMBE	ARM Best Estimate
CCN	Cloud Condensation Nuclei
CDAT	Project Critical Decision Assessment Tool
CF	Central Facility
CMIP	Coupled Model Intercomparison Project
CPC	Condensation Particle Counter
DOE	U.S. Department of Energy
EF	evaporative fraction
ENA	Eastern North Atlantic
GCM	Global Climate Model
L-A coupling	Land-Atmosphere Coupling
LCL	Lifting Condensation Level
LLNL	Lawrence Livermore National Laboratory
MAO	GOAmazon Manacapuru Site
MFRSR	multifilter rotating shadowband radiometer
NSA	North Slope of Alaska
PBL	Planetary Boundary Layer
PDF	Probability Density Function
SGP	Southern Great Plains
SMOS	surface meteorological observation system
SWATS	soil water and temperature system
TWP	Tropical Western Pacific
VAP	value-added product
VARANAL	large-scale continuous forcing data derived using a constrained variational analysis

Contents

Figures

Tables

1.0 Introduction

A Python-based metrics and diagnostics package is developed by the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility Infrastructure Team at Lawrence Livermore National Laboratory (LLNL) to facilitate the use of long-term, high-frequency measurements from the ARM program on model evaluation. This metrics and diagnostics package, ARM-Diags, computes climatological means of targeted climate model simulation and generates tables and plots using a fully automated framework (Zhang et al., 2020). Users can then compare their model simulations directly with the ARM observations. The Coupled Model Intercomparison Project (CMIP) model data sets are also included in the package to enable model intercomparison (Zhang et al., 2018; Zheng et al., 2023). The ensemble means of CMIP models can be served as a reference for individual models as well.

Basic performance metrics are computed to measure the accuracy of mean state and variability of climate models. The evaluated physical quantities include cloud fraction, temperature, relative humidity, cloud liquid water path, total column water vapor, precipitation, sensible and latent heat fluxes, radiative fluxes, aerosol properties, soil moistures, planetary boundary layer, etc. ARM-Diags also includes other variables that describe the coupling of the atmosphere with processes associated with land, aerosols, clouds, and precipitation, process-oriented diagnostics.

The ARM-Diags is currently built upon standard Python libraries and additional Python packages developed by DOE (Project Critical Decision Assessment Tool [CDAT]). It is available to the public and can serve as an easy entry point for climate modelers to quickly compare their models with the ARM observations and the supplemented CMIP datasets.

In this report, we first provide an overview of the metrics included in the ARM-Diags in section 2. The input datasets, which constitute the core content of the metrics and diagnostics package, are summarized in section 3. Section 4 documents the current workflow of the ARM-Diags and provides step-by-step instructions for users' reference.

2.0 Overview of metrics in the ARM-Diags

The standard metrics and diagnostics included in the ARM-Diags version 2.0 (v2) are summarized in Zhang et al. (2020), which covers the basic diagnostics on various climate variabilities (e.g., annual, seasonal and diurnal cycles) as well as metrics that enable process-level studies. Particularly, the convection onset metrics quantifying robust relationships between precipitation, column water vapor, and temperature (Schiro et al., 2016) were added to the ARM-Diags as the first set of process-oriented diagnostics. This convection onset metrics help evaluate the model performance on deep convection with the ARM observations.

The development of the ARM-Diags v3 focuses on the metrics and diagnostics for the aerosol-cloud interactions. Statistical metrics including the annual cycle of aerosol optical depth (AOD), aerosol and cloud condensation nuclei (CCN) number concentration, and aerosol chemicals (organic, sulfate, nitrate, etc.) were added. Moreover, another process-oriented diagnostics, the aerosol-CCN activation metrics were developed, which quantifies the statistical relationship between the aerosol and CCN number concentration at certain supersaturation levels (Zheng et al., 2020). With this metrics, users can quickly assess the aerosol activation parameterization in their models, which serves as a solid entry point for the further assessment on the simulated aerosol indirect effects.

The ARM-Diags v4 has been extended to include the metrics and diagnostics on the land-atmosphere (L-A) coupling. Specifically, basic statistical metrics on the diurnal cycles of surface sensible and latent heat fluxes, planetary boundary layer (PBL) and lifting condensation level (LCL) currently available at the ARM Southern Great Plains (SGP) site have been added. The two-legged metrics which can be used to estimate the coupling strength between the land and the atmosphere based on a land leg and an atmospheric leg (Dirmeyer et al., 2014; Santanello et al., 2018) are also added. The inclusion of metrics on the L-A coupling enables quick evaluation of model simulated L-A coupling processes against the ARM ground-based observations.

A full list of the metrics and diagnostics are as follows, with detailed information summarized in Table 1:

- a set of basic metrics tables: mean, mean bias, correlation and root mean square error based on the annual cycle of each variable.
- line plots and Taylor diagrams (Taylor 2001) for the annual cycle of each variable.
- contour and vertical profiles of the annual cycle and the diurnal cycle of cloud fraction.
- line and harmonic dial plots (Covey et al. 2016) of the diurnal cycle of precipitation.
- probability density function (PDF) plots of precipitation (Pendergrass and Hartmann 2014).
- line plots of the diurnal cycle for quantities relevant to the L-A coupling (e.g., surface sensible and latent heat fluxes, PBL, LCL, etc.).
- convection onset metrics showing the statistical relationship between precipitation rate and column water vapor (Schiro et al. 2016).
- aerosol-CCN activation metrics describing the percentage distribution of how many aerosols can be activated as CCN under different supersaturation levels (Zheng et al. 2020).
- two-legged metrics evaluating the strength of L-A coupling by partitioning the impact of the land states on surface fluxes (the land leg) and from the impact of surface fluxes on the atmospheric states (the atmospheric leg) (Dirmeyer et al. 2014; Santanello et al. 2018).

Table 1. A list of metrics and diagnostics available in the ARM-Diags version 4.0.

Basic diagnostics sets	Input variables	Available sites
Statistical summary of mean state (annual cycle, Taylor diagram)	*Aerosol properties:* CCN number concentration at 0.2% and 0.5% supersaturations*, aerosol number concentration*, aerosol chemical component mass concentrations*. *Column properties:* cloud fraction, cloud optical depth*, column precipitable water vapor, AOD. *Surface properties:* sensible and latent heat fluxes, relative humidity, temperature, precipitation, downwelling shortwave and longwave fluxes, upwelling shortwave & longwave fluxes, soil moisture**.	SGP C1; NSA C1; ENA C1; MAO M1; TWP C1, C2, C3
Vertical variabilities	Cloud fraction	SGP C1; NSA C1; ENA C1; MAO M1; TWP C1, C2, C3
Diurnal and seasonal variabilities	Precipitation	SGP C1; ENA C1; MAO M1; TWP C1, C2, C3

	Sensible and latent heat fluxes, relative humidity, temperature, PBL, LCL	SGP C1
Process-oriented diagnostics sets	**Input variables**	**Available sites**
Convection onset	Column precipitable water vapor and surface precipitation (hourly)	SGP C1; ENA C1; TWP C1, C2, C3; MAO M1
Aerosol-CCN activation	Aerosol and CCN number concentrations (5-min)	SGP C1; ENA C1
Two-legged metrics	Sensible and latent heat fluxes, LCL and soil moisture** (daily)	SGP C1

*Variables available at SGP C1 & ENA C1 only.
** Variables available at SGP C1 only.

3.0 Description of data in the ARM-Diags

3.1 Observational datasets

The observational datasets used to assess model performance are primarily from the ARM Best Estimate (ARMBE) data products (Xie et al. 2010) as well as other ARM value-added products (VAPs) which are available for all the ARM observatories and some ARM mobile facilities. These data often rely on measurements at the ARM Central Facility (CF) locations (i.e., single-point measurements). At the ARM SGP site, particularly, the long-term continuous forcing data derived based on a constrained variational analysis (VARANAL) (Zhang and Lin, 1997; Zhang et al., 2001; Xie et al., 2004; Tang et al., 2019) is applied to improve model-observation comparison. Different from the single-point observations at the ARM CF, the VARANAL dataset represents an average over a domain with size comparable to a grid box in Global Climate Model (GCM). Aerosol properties are collected from the condensation particle counter (CPC), cloud condensation nuclei particle counter (CCN), aerosol chemical speciation monitor (ACSM), and multifilter rotating shadowband radiometer (MFRSR) at the SGP and ENA sites, which are carefully processed by applying several quality control procedures. The diurnal variability of PBL height for the L-A coupling metrics is from Su and Li (2023), which developed a new lidar-based algorithm for retrieving PBL height under cloudy conditions and provided quality-controlled, long-term, continuous retrievals of the PBL height at SGP during the daytime (Su et al., 2020; Su et al., 2022). Detailed information of the ARM data applied in the ARM-Diags v4 is listed in Tables 2 and 3.

Table 2. Observed quantities included in the evaluation package for SGP.

Quantities	Data sources	Time range	Time reso.	Spatial info.
Surface temperature/humidity	VARANAL	2004 - 2015	mon, day, hr	domain averaged
Temperature/humidity profile/wind speed/large-scale tendencies				
Surface precipitation				
Precipitable water				
Surface all-sky radiative fluxes				
Surface latent/sensible heat fluxes				
Aerosol optical depth 550 nm	MFRSRAOD1MICH	2004 - 2015	mon	SGP C1& E13 average
Soil moisture content (10 cm)	SWATS	2004 - 2015	mon, day	domain averaged
Cloud fraction	ARMBE	2004 - 2015	mon, day, hr	SGP C1
Cloud optical depth	MFRSRCLDOD1MIN	2004 - 2015	mon	SGP C1
Cloud condensation nuclei	CCN1COL	2011 - 2016	mon, 5-min	SGP C1
Aerosol number concentration	CPC	2011 - 2016	mon, 5-min	SGP C1
Aerosol chemical component	ACSM	2011 - 2016	mon, 5-min	SGP C1

Planetary boundary layer	PBLH over SGP from 1998 to 2023	2004 - 2015	hr (daytime only)	SGP C1

Table 3. Observed quantities included in the evaluation package for other ARM sites.

Quantities	Data sources	Spatial info. (Time range)	Time reso.
Cloud fraction Surface temperature/humidity Surface precipitation Precipitable water Surface all-sky radiative fluxes Surface latent/sensible heat fluxes	ARMBE	NSA C1 (2001-2016); ENA C1 (2016-2019); TWP C1 (1998-2009); TWP C2 (1999-2010); TWP C3 (2003-2010); MAO M1 (2014-2015);	mon, day, hr
Aerosol optical depth 550 nm	MFRSRAOD1MICH	Same as above	mon
Cloud optical depth	MFRSRCLDOD1MIN	Same as above	mon
Cloud condensation nuclei	CCN1COL	ENA C1 (2016-2019)	mon, 5-min
Aerosol number concentration	CPC	ENA C1 (2016-2019)	mon, 5-min
Aerosol chemical component	ACSM	ENA C1 (2016-2019)	mon, 5-min

3.2 CMIP simulations

Simulations of 23 models contributing to the Phase 6 of the Coupled Model Intercomparison Project (CMIP6, Eyring et al., 2016) are added in the ARM-Diags v4 (Table 4), which allows the modelers to compare a new, candidate version of their model to existing CMIP models. Here, we used the CMIP6 atmospheric only (AMIP) experiments from year 1979 to 2008. Results from CMIP5 (Taylor et al., 2012) AMIP experiments are included as well for users' reference. The nearest model grid points to the ARM sites are selected.

Table 4. CMIP5 and CMIP6 models included in the evaluation package.

Modeling groups	CMIP5 model name	CMIP6 model name
Commonwealth Scientific and Industrial Research Organization; Bureau of Meteorology (BOM), Australia	ACCESS-1-0 ACCESS-3-0	ACCESS-ESM1-5
Beijing Climate Center, China Meteorological Administration, China	BCC-CSM-1-1 BCC-CSM-1-1(m)	BCC-CSM2-MR
College of Global Change and Earth System Science, Beijing Normal University, China	BNU-ESM	
Chinese Academy of Meteorological Sciences, China		CAMS-CSM1-0
Canadian Centre for Climate Modelling and Analysis, Canada	CanAM4	CanESM5
National Center for Atmospheric Research, USA	CCSM4	
Community Earth System Model Contributors	CESM1-CAM5	CESM2 CESM2-WACCM
Centro Euro-Mediterranean Centre on Climate Change, Italy	CMCC-CM	CMCC-CM2-SR5
Centre National de Recherches Météorologiques, France	CNRM-CM5	CNRM-CM6-1-HR
Commonwealth Scientific and Industrial Research Organization; Queensland Climate Change Centre of Excellence, Australia	CSIRO-Mk3-6-0	
Energy Exascale Earth System Model Contributors		E3SM-1-0

European Centre for Medium-Range Weather Forecasts	EC-Earth	EC-Earth3-AerChem
Institute of Atmospheric Physics, Chinese Academy of Sciences; Center for Earth System Science, Tsinghua University, China	FGOALS-g2 FGOALS-s2	FGOALS-f3-L
NOAA Geophysical Fluid Dynamics Laboratory, USA	GFDL-HIRAM-C360 GFDL-HIRAM-C180	GFDL-CM4
NASA Goddard Institute for Space Studies, USA	GISS-E2-R	GISS-E2-1-G
Met Office Hadley Centre, UK	HadGEM2-A	HadGEM3-GC31-LL
Institute Pierre-Simon Laplace, France	IPSL-CM5A-LR IPSL-CM5B-LR IPSL-CM5A-MR	IPSL-CM6A-LR
Centre for Climate Change Research, Indian Institute of Tropical Meteorology, India		IITM-ESM
Institute for Numerical Mathematics, Russia	INM-CM4	INM-CM5-0
National Institute of Meteorological Sciences; Korea Meteorological Administration, Korea		KACE-1-0-G
Atmosphere and Ocean Research Institute; National Institute for Environmental Studies; and Japan Agency for Marine-Earth Science and Technology, Japan	MIROC5	MIROC6
Max Planck Institute for Meteorology, Germany	MPI-ESM-LR MPI-ESM-MR	MPI-ESM1-2-HAM MPI-ESM1-2-HR
Meteorological Research Institute, Japan	MRI-AGCM-3-2 MRI-CGCM-3	MRI-ESM-2-0
Earth System Modeling Center, Nanjing University of Information Science and Technology, China		NESM3
Norwegian Climate Centre, Norway	NorESM1-M	NorESM2-LM
Research Center for Environmental Changes, Academia Sinica, Taiwan		TaiESM1

*Note that a subset of models are used for quantities required in daily or sub-daily temporal resolutions.

3.3 Data limitation and uncertainty

The ARM data used in the package have been through stringent data quality control and represent the "best" estimate of the selected quantities. Fully addressing the data uncertainty is a challenging task and the ARM program is making efforts to address this issue. We recommend users to read the references on the observational data products and contact principal investigators of each data product for additional data quality information.

4.0 User's Guide

4.1 Package workflow

Figure 1 shows the flowchart of creating the diagnostic results by applying the diagnostics tool. Section 4.2 provides the instructions on how to obtain the package. The step-by-step procedure on setting up a working prototype is presented in section 4.3.

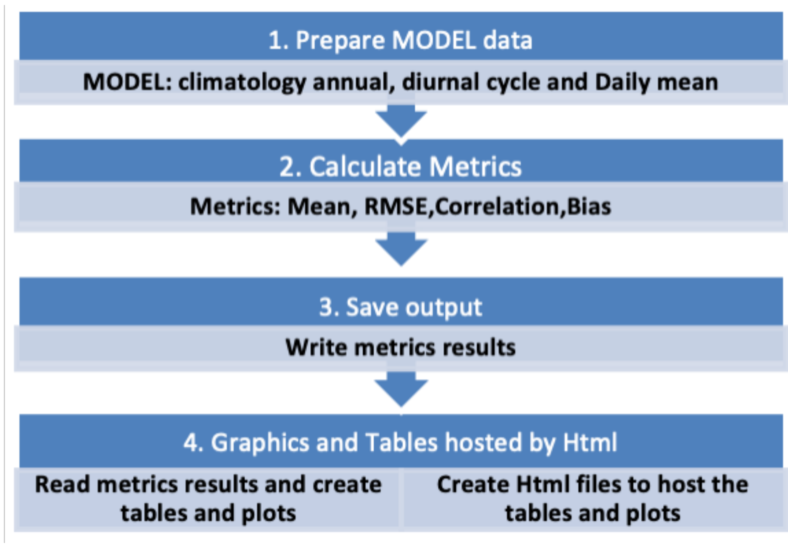

Figure 1. Workflow of the diagnostics package.

The project has the following structure:

```
|____arm_diags
| |____.DS_Store
| |______init__.py
| |____arm_driver.py
| |____arm_parameter.py
| |____arm_parser.py
| |____basicparameter.py
| |____diags_all_multisites_for_cmip5.json
| |____diags_all_multisites_for_cmip6.json
| |____examples
| | |____diags_set1.json
| | |____diags_set2.json
| | |____diags_set3.json
| |____misc
| | |____ARM_DIAGS_logo.png
| | |____ARM_logo.png
| |____src
| | |______init__.py
| | |____aerosol_activation.py
| | |____annual_cycle.py
```

```
| | |____annual_cycle_aci.py
| | |____annual_cycle_zt.py
| | |____convection_onset_driver.py
| | |____convection_onset_statistics.py
| | |____create_htmls.py
| | |____diurnal_cycle.py
| | |____diurnal_cycle_LAcoupling.py
| | |____pdf_daily.py
| | |____seasonal_mean.py
| | |____taylor_diagram.py
| | |____twolegged_metric.py
| | |____utils.py
| | |____varid_dict.py
|____ARM_DIAGS_TechReport_v4.docx
```

4.2 Obtain the ARM-Diags

The ARM-Diags v4 with both basic statistical and process-oriented diagnostics sets is now available to the public. The main html page hosting the results is shown in Figure 2. The data files, including observation, and CMIP5 and CMIP6 model data, can be downloaded through the ARM Data Center. The analytical codes to calculate and visualize the diagnostics results are placed via repository (arm-gcm-diagnostics) at https://github.com/ARM-DOE/arm-gcm-diagnostics.

For downloading data:

- Click www.arm.gov/data/data-sources/adcme-123
- Follow the **Browse Data** link on that page, it will lead to the area where the data files are placed. A short registration is required if you do not have an ARM account.
- The DOI for the citation of the data is 10.5439/1646838

For obtaining codes:

```
$ git clone https://github.com/ARM-DOE/arm-gcm-diagnostics/
```

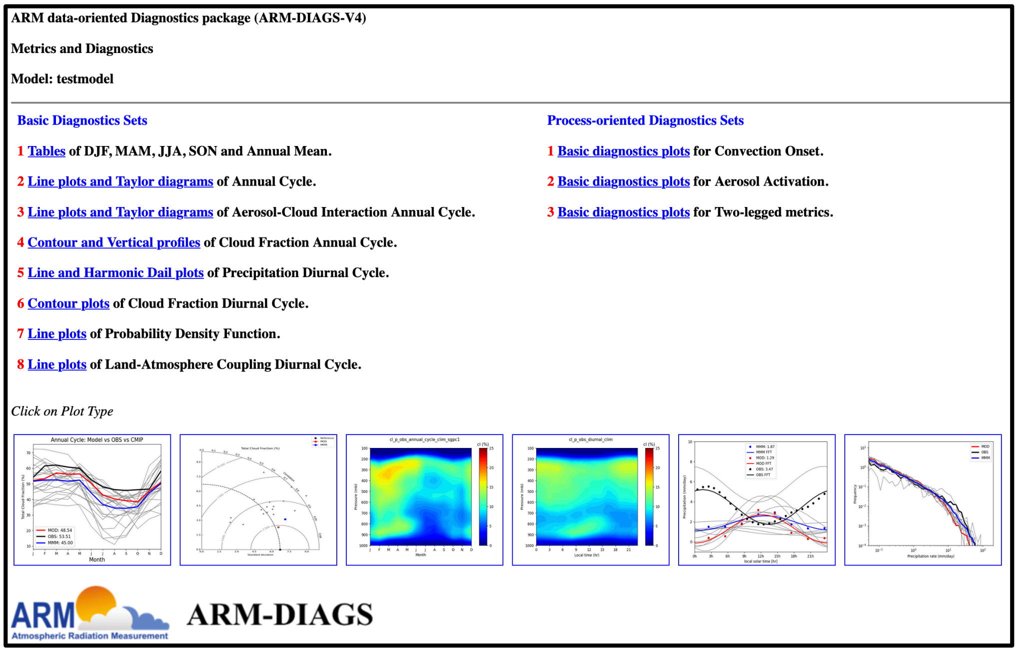

Figure 2. Main html page generated to host the diagnostic results.

4.3 Set up a test case

The software environment is managed through conda. Either Anaconda or Miniconda needs to be installed for setting up the environment of the package.

1. To create a conda environment and then activate it:

```
$conda create -n arm_diags_env_py3 cdp cdutil cdms2 libcdms matplotlib scipy python=3 -c conda-forge

$source activate arm_diags_env_py3
```

2. To install the package, cd <Your directory>/, type following:

```
$python setup.py install
```

3. A working test case has been set up for the users to run the package out-of-the-box. In this case, all the observation, CMIP and test data should be downloaded and placed under directories:
<Your directory>/arm_diags/observation
<Your directory>/arm_diags/cmip6
<Your directory>/arm_diags/testmodel, respectively.

4. To configure basic parameter file: basicparameter.py and edit parameters such as input and output paths, model name (used to search the file), and case name (to create a new folder for the case).

5. To run the package, simply type in the terminal the following:

```
$ python arm_driver.py -p basicparameter.py
```

6. To view the diagnostics results:

   For Mac OS:

```
$ open <User defined output directory>/html/ARM_diag.html
```

For Linux:

```
$ xdg-open <User defined output directory>/html/ARM_diag.html
```

For setting up customized runs and creating new cases, please refer to details at: https://github.com/ARM-DOE/arm-gcm-diagnostics/

4.4 Diagnostics Examples

Diurnal cycle of precipitation. Multiple aspects of the precipitation (total amount, frequency, intensity, and duration, etc.) can be effectively diagnosed through the diurnal cycle of precipitation, which is therefore considered a benchmark for climate models (Covey et al. 2016). With this metrics, users can quickly evaluate the convection parameterizations in their models. Figure 3 shows an example of the metrics on the diurnal cycle of precipitation at the ARM SGP site during the summertime. The observed nocturnal peak, associated with the eastward propagation of mesoscale convective systems, is missed by the model simulations and CMIP6 AMIP runs.

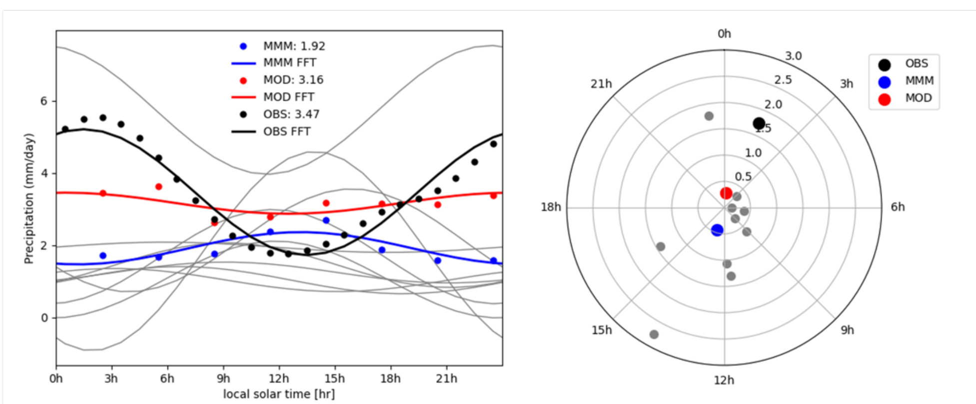

Figure 3. (left) Summertime (June-July-August) mean diurnal cycle of precipitation (dot) and the first Fourier component (line) from the ARM observations (black), test model (red), and CMIP6 AMIP runs (gray lines for individual CMIP6 models and blue line for multimodel mean). (right) Harmonic dial plots of summertime precipitation amplitude (mm/day) and phase of the first Fourier component at the ARM SGP site.

Aerosol-CCN activation metrics. Aerosol-CCN activation metrics allow users to quantify the statistical relationship between the aerosol and CCN number concentration (Zheng et al., 2023). An example of the aerosol-CCN activation metrics at ENA is shown in Figure 4. Compared to the ARM observations, the model tends to predict too many aerosols that cannot be activated to CCN at 0.2% supersaturation levels. This suggests that the model may overproduce the aerosol over such pristine oceanic regions.

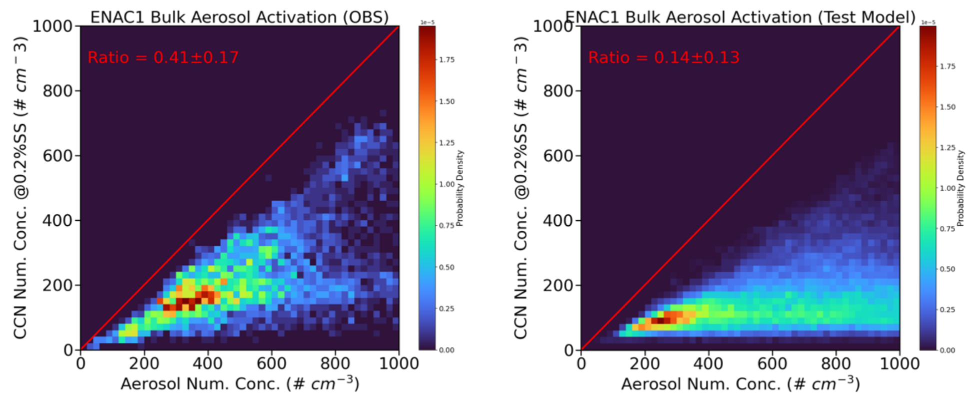

Figure 4. Probability density plots for aerosol number concentration (x-axis) versus CCN number concentration (y-axis) at 0.2% supersaturation level for (a) ARM observations and (b) test model at the ARM ENA site.

Two-legged metrics. Two-legged metrics evaluate the L-A coupling as a two-segment process: a terrestrial leg linking land states to surface fluxes and an atmospheric leg linking surface fluxes to atmosphere states (e.g., Dirmeyer et al., 2014; Santanello et al. 2018). For the terrestrial leg, we focus on the covariance relationships between soil moisture and surface turbulent fluxes. For the atmospheric leg, we emphasize on the covariance relationships between surface turbulent fluxes and LCL, which is a good indicator for the potential of rain. Figure 5 shows an example of the atmospheric component for the two-legged metrics at the ARM SGP site during the summertime. Generally, there is a strong coupling between the evaporative fraction (EF) and LCL in both observations and model simulations, where the LCL tends to be lower with a larger EF. But the coupling strength is stronger in the model than that in the ARM observations.

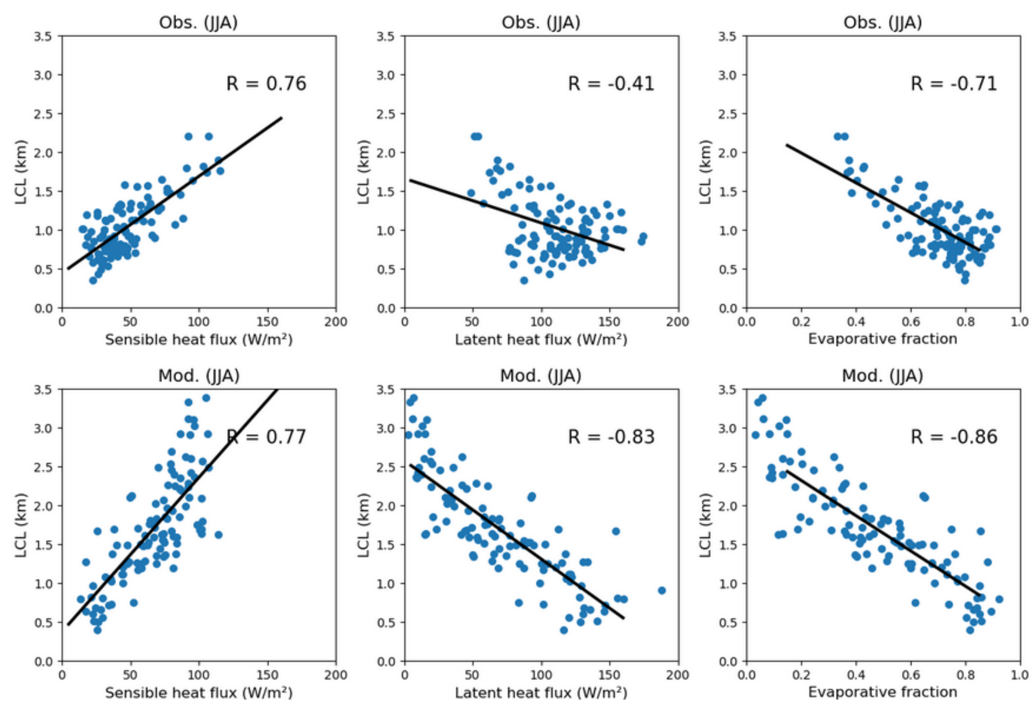

Figure 5. Top: Scatter plots of (left) surface sensible heat flux, (middle) surface latent heat flux, and (right) evaporative fraction (EF) versus LCL at the ARM SGP site during the summertime (June-July-August). Bottom: Same as the top but from the model simulations.

5.0 References

Covey, C, PJ Gleckler, CM Doutriaux, DN Williams, A Dai, JT Fasullo, K Trenberth, and A Berg. 2016. "Metrics for the diurnal cycle of precipitation: Toward routine benchmarks for climate models." *Journal of Climate* 29(12): 4461−4471, https://doi.org/10.1175/JCLI-D-15-0664.1

Dirmeyer, P. A., Wang, Z., Mbuh, M. J., and Norton, H. E. 2014. "Intensified land surface control on boundary layer growth in a changing climate." *Geophys. Res. Let.,* 41, 1290–1294, https://doi.org/10.1002/2013GL058826.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. 2016. "Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization." *Geosci. Model Dev.* 9, 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016.

Santanello, J A., Dirmeyer, P. A., Ferguson, C. R., Findell, K. L., Tawfik, A. B., Berg, A., Ek, M., Gentine, P., Guillod, B. P., van Heerwaarden, C., Roundy, J., and Wulfmeyer, V. 2018. "Land-Atmosphere Interactions: The LoCo Perspective". *B. Am. Meteor. Soc.,* 99, 1253–1272, https://doi.org/10.1175/BAMS-D-17-0001.1.

Schiro, KA, JD Neelin, DK Adams, and BR Lintner. 2016. "Deep convection and column water vapor over tropical land versus tropical ocean: A comparison between the Amazon and the tropical western Pacific." *Journal of the Atmospheric Sciences* 73(10): 4043−4063, https://doi.org/10.1175/JAS-D-16-0119.1

Su, T, and Z Li. 2023."Planetary Boundary Layer Height (PBLH) over SGP from 1998 to 2023". United States: N. p., Web. https://doi.org/10.5439/2007149.

Su, T., Zheng, Y., and Li, Z. 2022. "Methodology to determine the coupling of continental clouds with surface and boundary layer height under cloudy conditions from lidar and meteorological data" *Atmos. Chem. Phys.*, 22, 1453–1466, https://doi.org/10.5194/acp-22-1453-2022

Su, T., Li, Z., and Kahn, R. 2020. "A new method to retrieve the diurnal variability of planetary boundary layer height from lidar under different thermodynamic stability conditions", *Remote Sens. Environ*., 237, 111519, https://doi.org/10.1016/j.rse.2019.111519.

Taylor, K. E. 2001. "Summarizing multiple aspects of model performance in a single diagram". *J. Geophys. Res.,* 106(D7), 7183– 7192, https://doi.org/10.1029/2000JD900719.

Taylor, KE, RJ Stouer, and GA Meehl. 2012. "An overview of CMIP5 and the experiment design." *Bulletin of the American Meteorological Society* 93(4): 485−498, https://doi.org/10.1175/BAMS-D-11-00094.1

Tang, S, C. Tao, S. Xie, M. Zhang. 2019. "Description of the ARM large-scale forcing data from the constrained variational analysis (VARANAL) – version 2, DOE/SC-ARM-TR-222". DOE ARM Climate Research Facility, doi:10.5439/1273323.

Xie, SC, RT Cederwall, and MH Zhang. 2004. "Developing long-term single-column model/cloud system-resolving model forcing data using numerical weather prediction products constrained by surface and top of the atmosphere observations." *Journal of Geophysical Research – Atmospheres* 109(D1): D01104, https://doi.org/10.1029/2003jd004045

Xie, S, RB McCoy, SA Klein, RT Cederwall, WJ Wiscombe, EE Clothiaux, KL Gaustad, JC Golaz, SD Hall, MP Jensen, KL Johnson, Y Lin, CN Long, JH Mather, RA McCord, SA McFarlane, G Palanisamy, Y Shi, and DD Turner. 2010. "ARM Climate Modeling Best Estimate Data: A New Data Product for Climate Studies." *Bulletin of the American Meteorological Society* 91(1): 13−20, https://doi.org/10.1175/2009bams2891.1

Zhang, C, S Xie, SA Klein, H-y Ma, S Tang, K Van Weverberg, CJ Morcrette, and J Petch. 2018. "CAUSES: Diagnosis of the summertime warm bias in CMIP5 climate models at the ARM Southern Great Plains site." *Journal of Geophysical Research − Atmospheres* 123(6): 2968−2992, https://doi.org/10.1002/2017JD027200

Zhang, C., S Xie, C Tao, S Tang, T Emmenegger, JD Neelin, KA Schiro, W Lin, and Z Shaheen. 2020. "The ARM Data-Oriented Metrics and Diagnostics Package for Climate Models − A New Tool for Evaluating Climate Models with Field Data." *Bulletin of the American Meteorological Society* 101(10): E1619–E1627, https://doi.org/10.1175/BAMS-D-19-0282.1

Zhang, M, and J Lin. 1997. "Constrained variational analysis of sounding data based on column-integrated budgets of mass, heat, moisture, and momentum: Approach and application to ARM measurements." *Journal of the Atmospheric Sciences* 54(11): 1503–1524, https://doi.org/10.1175/1520-0469(1997)054<1503:CVAOSD>2.0.CO;2

Zhang, MH, JL Lin, RT Cederwall, JJ Yio, and SC Xie. 2001. "Objective analysis of ARM IOP data: Method and sensitivity." *Monthly Weather Review* 129(2): 295−311, https://doi.org/10.1175/1520-0493(2001)129<0295:oaoaid>2.0.co;2

Zheng, X., B Xi, X Dong, T Logan, Y Wang, & P Wu. 2020. "Investigation of aerosol–cloud interactions under different absorptive aerosol regimes using Atmospheric Radiation Measurement (ARM) southern Great Plains (SGP) ground-based measurements." *Atmos. Chem. Phys.*, 20(6), 3483-3501. https://doi.org/10.5194/acp-20-3483-2020

Zheng, X., C. Tao, C. Zhang, S. Xie, Y. Zhang, B. Xi, and X. Dong. 2023. "Assessment of CMIP5 and CMIP6 AMIP Simulated Clouds and Surface Shortwave Radiation Using ARM Observations over Different Climate Regions." *J. Climate*, 36, 8475–8495, https://doi.org/10.1175/JCLI-D-23-0247.1.

www.arm.gov

U.S. DEPARTMENT OF ENERGY

Office of Science