RCEMIP Data Guide

Allison A. Wing

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Contents

1 Overview of RCEMIP

The Radiative-Convective Equilibrium Model Intercomparison Project, RCEMIP, is a coordinated intercomparison of models configured in radiative-convective equilibrium (RCE; Wing et al., 2018, 2020). RCE is an idealization of the tropical atmosphere in which the large-scale atmospheric circulation (larger than the domain size) is neglected and there is thus no energy import into or export out of the domain. Convection is allowed to come into a statistical equilibrium with the net radiative cooling of the atmosphere.

RCE has long been used to study basic questions in climate science, from the vertical temperature structure of the tropics and the first estimates of climate sensitivity, to the scaling of the hydrological cycle with warming, interactions between convection and radiation, and the organization of convection. The overarching scientific questions for RCEMIP are changes in clouds and convective activity with warming, cloud feedbacks and climate sensitivity, and the aggregation of convection and its role in climate. These topics are related to some of the biggest open questions in climate dynamics, as detailed by the WCRP Grand Challenge on Clouds, Circulation, and Climate Sensitivity (Bony et al., 2015). In addition to addressing these important questions, RCEMIP serves as a common baseline, enabling assessment of the formulaic sensitivity of simulations of RCE and providing a fixed point for past and future studies. RCEMIP is unique due to the unparalleled accessibility of the RCE framework to a variety of models, including cloud-resolving models (CRMs), general circulation models (GCMs), global cloud-resolving models (GCRMs), single column models (SCMs), and large-eddy simulation models (LES).

RCE is simulated in a modeling setting by imposing a homogeneous lower boundary representing the thermodynamic state of a sea surface with a fixed (i.e., spatially and temporally uniform) temperature and spatially uniform insolation as a forcing. The model is initialized with the same temperature and moisture sounding at every grid point and zero wind, and convection is generated by prescribing some symmetry-breaking random noise. The model is then run to stationarity, at which time irradiances, precipitation, and other variables have stopped trending up or down and exhibit variability about an approximately constant value. Here, we consider RCE in a non-rotating setting; i.e., the Coriolis parameter, f, or Earth's angular velocity, Ω, is zero.

1.1 Experiments

RCEMIP consists of, for each model, two sets of simulations:

1. `RCE_small`: RCE simulation on small, square domain (for CRMs and GCRMs) or single column (for GCMs)
   (a) `RCE_small295`: uniform, fixed SST of 295 K.
   (b) `RCE_small300`: uniform, fixed SST of 300 K.
   (c) `RCE_small305`: uniform, fixed SST of 305 K.
2. `RCE_large`: RCE simulation on large, rectangular domain (for CRMs) or global (for GCMs and GCRMs)
   (a) `RCE_large295`: uniform, fixed SST of 295 K.
   (b) `RCE_large300`: uniform, fixed SST of 300 K.
   (c) `RCE_large305`: uniform, fixed SST of 305 K.

Note that there are several GCMs and GCRMs for which there is no `RCE_small` output available; for those GCMs that do have it, `RCE_small` is a single column simulation. Several models also completed simulations with additional vertical levels (`RCE_small_vert`) or finer horizontal grid spacing (`RCE_small_les`). Table 1 summarizes the set-up of each simulation type.

Table 1: Simulation Configuration

Simulation Type	Model Type	Convection	Domain Size	Grid Spacing	Vertical Levels
`RCE_small`	CRM	Explicit	$\sim$100 x $\sim$100 km^2	1 km	$\sim$74
`RCE_small`	SCM	Parameterized	Single Column	N/A	as in CMIP6
`RCE_large`	CRM	Explicit	$\sim$6000 x $\sim$400 km^2	3 km	$\sim$74
`RCE_large`	GCRM	Explicit	Reduced Sphere Global	$\sim$3-4 km	$\sim$74
`RCE_large`	GCM	Parameterized	Global	$\sim$1°	as in CMIP6
`RCE_large`	WRF-GCM	Parameterized	$\sim$6000 x $\sim$400 km^2	50 km	48
`RCE_small_vert`	CRM	Explicit	$\sim$100 x $\sim$100 km^2	1 km	$\sim$146
`RCE_small_les`	LES	Explicit	$\sim$100 x $\sim$100 km^2	200 m	$\sim$146

The `RCE_large` simulations are initialized from the time- and horizontal-mean profiles from the corresponding `RCE_small` simulations simulations. The `RCE_small` simulations are in turn initialized from an analytic sounding that is representative of typical tropical conditions consistent with the corresponding SST. CRM simulations are run for 100 days while GCM simulations are typically run for 1000 days. More details on the simulation design and experimental configuration are provided in Wing et al. (2018).

As described in the RCEMIP overview paper Wing et al. (2020), the `RCE_small` simulations typically do *not* exhibit convective self-aggregation whereas the `RCE_large` simulations *do* allow for self-aggregation, in which the convection spontaneously self-organizes into one or several moist, intensely precipitating cloudy bands or clusters surrounded by dry, subsiding, mostly clear air.

1.2 Models

There participating models are indicated in Table 2. More information and documentation is available at `http://myweb.fsu.edu/awing/rcemip.html` and in Wing et al. (2020).

Table 2: Participating Models

Model Abbreviation	Model Name/Version	Model Type
CM1	Cloud Model 1, cm1r19.6	CRM/LES
DALES	Dutch Atmospheric Large-Eddy Simulation model v4.2	CRM/LES
DALES-damping	Dutch Atmospheric Large-Eddy Simulation model v4.2	CRM
DAM	Das Atmosphaerische Modell	CRM
FV3	GFDL-FV3CRM	CRM
ICON-LEM	ICOsahedral Nonhydrostatic-2.3.00, LEM config.	CRM/LES
ICON-NWP	ICOsahedral Nonhydrostatic-2.3.00, NPW config.	CRM
MESONH	Meso-NH v5.4.1	CRM/LES
MicroHH	MicroHH v2.0	CRM/LES
SAM-CRM	System for Atmospheric Modeling 6.11.2	CRM/LES
SCALE	SCALE v5.2.5	CRM
UCLA-CRM	UCLA Large-Eddy Simulation model	CRM
UKMO-CASIM	UK Met Office Idealized Model v11.0 - CASIM	CRM
UKMO-RA1-T	UK Met Office Idealized Model v11.0 - RA1-T	CRM
UKMO-RA1-T-hrad	UK Met Office Idealized Model v11.0 - RA1-T	CRM
UKMO-RA1-T-nocloud	UK Met Office Idealized Model v11.0 - RA1-T	CRM
WRF-COL-CRM	Weather Research and Forecasting model v3.5.1	CRM
WRF-CRM	Weather Research and Forecasting model v3.9.1	CRM
MPAS	Model for Prediction Across Scales v6.1	GCRM
NICAM	Non-hydrostatic Icosahedral Atmospheric Model v16.3	GCRM
SAM-GCRM	System for Atmospheric Modeling v7.3	GCRM
CAM5-GCM	Community Atmosphere Model v5	GCM/SCM
CAM6-GCM	Community Atmosphere Model v6	GCM/SCM
CNRM-CM6-1	Atmospheric component of the CNRM Climate Model 6.1	GCM/SCM
ECHAM6-GCM	MPI-M Earth System Model-Atmosphere component v6.3.04p1	GCM
GEOS-GCM	Goddard Earth Observing System model v5.21	GCM/SCM
ICON-GCM	ICOsahedral Nonhydrostatic Earth System Model-Atmos. component	GCM
IPSL-CM6	IPSL-CM6A-LR	GCM
SAM0-UNICON	Seoul National University Atmosphere Model v0	GCM
SP-CAM	Super-parameterized Community Atmosphere Model	GCM
SPX-CAM	Multi-instance super-parameterized CAM	GCM
UKMO-GA7.1	UK Met Office Unified Model Global Atmosphere v7.1	GCM/SCM
WRF-GCM-cps0	Weather Research and Forecasting model v3.5.1 - no conv. param.	GCM
WRF-GCM-cps1	Weather Research and Forecasting model v3.5.1 - KF	GCM
WRF-GCM-cps2	Weather Research and Forecasting model v3.5.1 - BMJ	GCM
WRF-GCM-cps3	Weather Research and Forecasting model v3.5.1 - GF	GCM
WRF-GCM-cps4	Weather Research and Forecasting model v3.5.1 - SAS	GCM
WRF-GCM-cps6	Weather Research and Forecasting model v3.5.1 - Tiedtke	GCM

1.3 Output

Available output variables are listed in Table 3 to Table 7. Table 3 indicates the list of zero-dimensional domain-averaged profiles (functions of t only), Table 4 indicates the list of one-dimensional domain-averaged profiles (functions of z and t), Tables 5 and 6 indicates the list of two-dimensional variables (functions of x, y, and t) and Table 7 indicates the list of three-dimensional variables (functions of x, y, z and t). In all tables, the italicized variables are non-standard outputs, all others are standard CMIP6 output. The starred variables are outputs available for CRMs only. The variables with a (-)$^!$ symbol are outputs available for GCMs only. Variables with a

(ˆ) are available for models in height coordinates, variables with a (˜) are available for models in pressure-based coordinates.

The output files are NetCDF. The directory structure and file naming convention is `/RCEMIP/$MDL/$EXP/$OUT/$MDL_$EXP_$OUT_(variablename,timestep,etc...).nc` where `$MDL` is the model abbreviation given in the first column of Table 2, `$EXP` is the experiment name (`RCE_small295`, for example) and `$OUT` is the output type (`0D`,`1D`,`2D`, or `3D`).

In addition to this raw data, several post-processed domain- and time-average statistics are available in the A-Statistics folder as .csv files. The A-Statistics folder contains calculations of convective organization metrics from Wing et al. (2020). `Metrics_large.csv` is a comma-separated value file that includes time-average (neglecting the first 75 days of simulation) organization metrics for each `RCE_large` simulation. The three organization metrics included are v%SST (spatial variance of column relative humidity), S%SST (subsidence fraction), and I%SST (I_{org}).

In addition, the A-Statistics folder contains time-mean 0D data and 1D profiles of commonly used variables. Domain and time averages (neglecting the first 75 days of simulation, except for `RCE_small_les` for which an average over days 25-50 is used) are provided for each model. The 0D data includes comma-separated value files of domain-average statistics for both `RCE_small` and `RCE_large` simulations (A1 and A2, respectively), and, for models who performed both simulations, the difference between the two (A3, taken as large-small). Standard deviation, interquartile range, and mean across all models are also included. Table 8 lists the available variables.

The 1D A-Statistics data provides NetCDF files of domain- and time-averaged profiles for each models in the `RCE_small` and `RCE_large` simulations at each SST. The file structure is as follows:

- 0-model-list.txt provides a list of models included and their identifier
- `$MODEL_RCE_large$SST_cfv$X-profiles.nc` are the files for the `RCE_large` simulations
- `$MODEL-VER/LES_RCE_small$SST_cfv$X-profiles.nc` are the files for the `RCE_small` simulations.

Tables 9 and 10 provide the list of available variables. If examining cloud fraction, we recommend using the cfv2_avg variable, which was calculated by Stauffer and Wing (2022). See the README for more details:
`https://swift.dkrz.de/v1/dkrz_70a517a8-039d-4a1b-a30d-841923f8bc7a/RCEMIP/A-Statistics/1D/README_v6.pdf`.

More details on the output specification are provided in Wing et al. (2018) and at `http://myweb.fsu.edu/awing/rcemipsims.html`. Known output bugs are noted at `https://tinyurl.com/RCEMIPbugs`. The standardized RCEMIP output is hosted by the German Climate Computing Center (DKRZ) and is publicly available at `http://hdl.handle.net/21.14101/d4beee8e-6996-453e-bbd1-ff53b6874c0e`.

References

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Table 3: 0D hourly-averaged variables (t)

Variable Name	Description	Units
pr_avg	domain avg. suface precipitation rate	kg m^{-2} s^{-1}
hfls_avg	domain avg. surface upward latent heat flux	W m^{-2}
hfss_avg	domain avg. surface upward sensible heat flux	W m^{-2}
prw_avg	domain avg. water vapor path	kg m^{-2}
clwvi_avg	domain avg. condensed water path	kg m^{-2}
clivi_avg	domain avg. ice water path	kg m^{-2}
sprw_avg	domain avg. saturated water vapor path	kg m^{-2}
rlds_avg	domain avg. surface downwelling longwave flux	W m^{-2}
rlus_avg	domain avg. surface upwelling longwave flux	W m^{-2}
rsds_avg	domain avg. surface downwelling shortwave flux	W m^{-2}
rsus_avg	domain avg. surface upwelling shortwave flux	W m^{-2}
rsdscs_avg	domain avg. surface downwelling shortwave flux - clear sky	W m^{-2}
rsuscs_avg	domain avg. surface upwelling shortwave flux - clear sky	W m^{-2}
rldscs_avg	domain avg. surface downwelling longwave flux - clear sky	W m^{-2}
rluscs_avg	domain avg. surface upwelling longwave flux - clear sky	W m^{-2}
rsdt_avg	domain avg. TOA incoming shortwave flux	W m^{-2}
rsut_avg	domain avg. TOA outgoing shortwave flux	W m^{-2}
rlut_avg	domain avg. TOA outgoing longwave flux	W m^{-2}
rsutcs_avg	domain avg. TOA outgoing shortwave flux - clear sky	W m^{-2}
rlutcs_avg	domain avg. TOA outgoing longwave flux - clear sky	W m^{-2}

Table 4: 1D hourly-averaged variables (z,t)

Variable Name	Description	Units
ta_avg	domain avg. air temperature profile	K
ua_avg	domain avg. eastward wind profile	m s^{-1}
va_avg	domain avg. northward wind profile	m s^{-1}
hus_avg	domain avg. specific humidity profile	kg/kg
hur_avg	domain avg. relative humidity profile	%
clw_avg	domain avg. mass fraction of cloud liquid water profile	kg/kg
cli_avg	domain avg. mass fraction of cloud ice profile	kg/kg
plw_avg	domain avg. mass fraction of precipitating liquid water profile	kg/kg
pli_avg	domain avg. mass fraction of precipitating ice profile	kg/kg
theta_avg	domain avg. potential temperature profile	K
thetae_avg	domain avg. equivalent potential temperature profile	K
tntrs_avg	domain avg. shortwave radiative heating rate profile	K s^{-1}
tntrl_avg	domain avg. longwave radiative heating rate profile	K s^{-1}
tntrscs_avg	domain avg. shortwave radiative heating rate profile - clear sky	K s^{-1}
tntrlcs_avg	domain avg. longwave radiative heating rate profile - clear sky	K s^{-1}
cldfrac_avg	global cloud fraction profile	

Table 5: 2D hourly averaged variables (x,y,t)

Variable Name	Description	Units
pr	surface precipitation rate	kg m^{-2} s^{-1}
pr_conv[!]	surface convective precipitation rate	kg m^{-2} s^{-1}
evspsbl	evaporation flux	kg m^{-2} s^{-1}
hfls	surface upward latent heat flux	W m^{-2}
hfss	surface upward sensible heat flux	W m^{-2}
rlds	surface downwelling longwave flux	W m^{-2}
rlus	surface upwelling longwave flux	W m^{-2}
rsds	surface downwelling shortwave flux	W m^{-2}
rsus	surface upwelling shortwave flux	W m^{-2}
rsdscs	surface downwelling shortwave flux - clear sky	W m^{-2}
rsuscs	surface upwelling shortwave flux - clear sky	W m^{-2}
rldscs	surface downwelling longwave flux - clear sky	W m^{-2}
rluscs	surface upwelling longwave flux - clear sky	W m^{-2}
rsdt	TOA incoming shortwave flux	W m^{-2}
rsut	TOA outgoing shortwave flux	W m^{-2}
rlut	TOA outgoing longwave flux	W m^{-2}
rsutcs	TOA outgoing shortwave flux - clear sky	W m^{-2}
rlutcs	TOA outgoing longwave flux - clear sky	W m^{-2}
prw	water vapor path	kg m^{-2}
clwvi	condensed water path	kg m^{-2}
clivi	ice water path	kg m^{-2}
psl	sea level pressure	Pa
tas	2m air temperature	K
tabot	air temperature at lowest model level	K
uas	10m eastward wind	m s^{-1}
vas	10m northward wind	m s^{-1}
uabot	eastward wind at lowest model level	m s^{-1}
vabot	northward wind at lowest model level	m s^{-1}
wa500[^]	vertical velocity at 500 hPa	m s^{-1}
wap500[~]	omega at 500 hPa	Pa s^{-1}
sprw	saturated water vapor path	kg m^{-2}
cl[!]	total cloud fraction of grid column	

Table 6: 2D hourly averaged frozen moist static energy budget variables (x,y,t)

Variable Name	Description	Units
fmse	mass-weighted vertical integral of frozen moist static energy (FMSE)	J m^{-2}
hadvfmse	mass-weighted vertical integral of horizontal advective tendency of FMSE	J m^{-2} s^{-1}
vadvfmse	mass-weighted vertical integral of vertical advective tendency of FMSE	J m^{-2} s^{-1}
tnfmse	total tendency of mass-weighted vertical integral of FMSE	J m^{-2} s^{-1}
tnfmsevar	total tendency of spatial variance of mass-weighted vertical integral of FMSE	J^2 m^{-4} s^{-1}

Table 7: 3D instantaneous 6-hourly variables (x,y,z,t)

Variable Name	Description	Units
clw	mass fraction of cloud liquid water	g/g
cli	mass fraction of cloud ice	g/g
plw	mass fraction of precipitating liquid water	g/g
pli	mass fraction of precipitating ice	g/g
mc$^{!}$	convective mass flux	kg m^{-2} s^{-1}
ta	air temperature	K
ua	eastward wind	m s^{-1}
va	northward wind	m s^{-1}
hus	specific humidity	g/g
hur	relative humidity	%
wap$^{\sim}$	omega	Pa s^{-1}
wa$^{\wedge}$	vertical velocity	m s^{-1}
zg$^{\sim}$	geopotential height	m
pa$^{\wedge}$	pressure	Pa
tntr	tendency of air temperature due to radiative heating	K s^{-1}
tntc$^{!}$	tendency of air temperature due to moist convection	K s^{-1}
tntrs	tendency of air temperature due to shortwave radiative heating	K s^{-1}
tntrl	tendency of air temperature due to longwave radiative heating	K s^{-1}

Table 8: 0D time-averaged statistics

Variable Name	Description	Units
F_{NET}	Atmospheric energy imbalance (magnitude of difference between energy imbalance at surface and top of atmosphere)	W m^{-2}
R_{TOA}	Net radiation at top of atmosphere (ASR - OLR, where positive values indicate net radiation into the atmosphere)	W m^{-2}
Q_{OCN}	Implied ocean heat update at the surface (R_{SFC} - LHF - SHF, where positive values indicate a flux into the ocean)	W m^{-2}
R_{NET}	Column net radiative flux convergence (R_{TOA} - R_{SFC}, where negative values indicate net atmospheric radiative cooling)	W m^{-2}
OLR	outgoing longwave radiation	W m^{-2}
ASR	Top of atmosphere absorbed solar radiation	W m^{-2}
LHF	Surface latent heat flux	W m^{-2}
SHF	Surface sensible heat flux	W m^{-2}
PW	Precipitable water	mm
Precip.	Surface precipitation rate	mm day^{-1}
LWP	Liquid water path (cloud liquid water)	mm
IWP	Ice water path (cloud ice)	mm
Lapse rate	Tropospheric lapse rate	K km^{-1}

Table 9: 1D time-averaged statistics, %cfv0-profiles.nc files

Variable Name	Description	Units
cfv0_avg	Cloud fraction cfv0	-
ta_avg	Temperature	K
pa_avg	Pressure	hPa
tw_avg	Total cloud water (cloud ice + cloud liquid)	g/g
hur_avg	Relative humidity	%
hus_avg	Specific humidity	g/kg
zg_avg	Height	km
Total_precip	Total precipitating water (precipitating ice + liquid, `RCE_small` only)	g/kg
Cr	RGBA Red color for Wing et al. (2020) color scheme	-
Cg	RGBA Green color for Wing et al. (2020) color scheme	-
Cb	RGBA Blue color for Wing et al. (2020) color scheme	-
Ca	RGBA Alpha color for Wing et al. (2020) color scheme	-

Table 10: 1D time-averaged statistics (z), %cfv1-cfv2-profiles.nc files

Variable Name	Description	Units
cfv1_avg	Cloud fraction cfv1	-
cfv2_avg	Cloud fraction cfv2	-
ta_avg	Temperature	K
pa_avg	Pressure	hPa
tw_avg	Total cloud water (cloud ice + cloud liquid)	g/g
zg_avg	Height	km
Cr	RGBA Red color for Wing et al. (2020) color scheme	-
Cg	RGBA Green color for Wing et al. (2020) color scheme	-
Cb	RGBA Blue color for Wing et al. (2020) color scheme	-
Ca	RGBA Alpha color for Wing et al. (2020) color scheme	-