# Training session on Regional Climate Model Evaluation System (RCMES)

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**December 24, 2018**

http://rcmes.jpl.nasa.gov

http://climate.apache.org

# Acknowledgement


- My special thanks of gratitude to Dr. Sanjay, Dr. Krishnan, Dr. Neena, and Dr. Suhas.
- Regional Climate Model Evaluation System (RCMES) team

Duane Waliser (PI), Huikyo Lee (co-I), **Alexander Goodman**, Peter Gibson, Elias Massoud, Brian Wilson, Paul Loikith[2], and Antonio Monge[3]

[1]JPL/Caltech, [2]California State U. LA, [3]Portland State U.

- **Virtual Information-Fabric Infrastructure (VIFI)** team led by Prof. William Tolone at U. of North Carolina, Charlotte
- Parallelized BCSD codes from Dr. TJ Vandal and NASA Earth eXchange (NEX) team at NASA Ames center

# RCMES Training Outline (10:00-12:30)

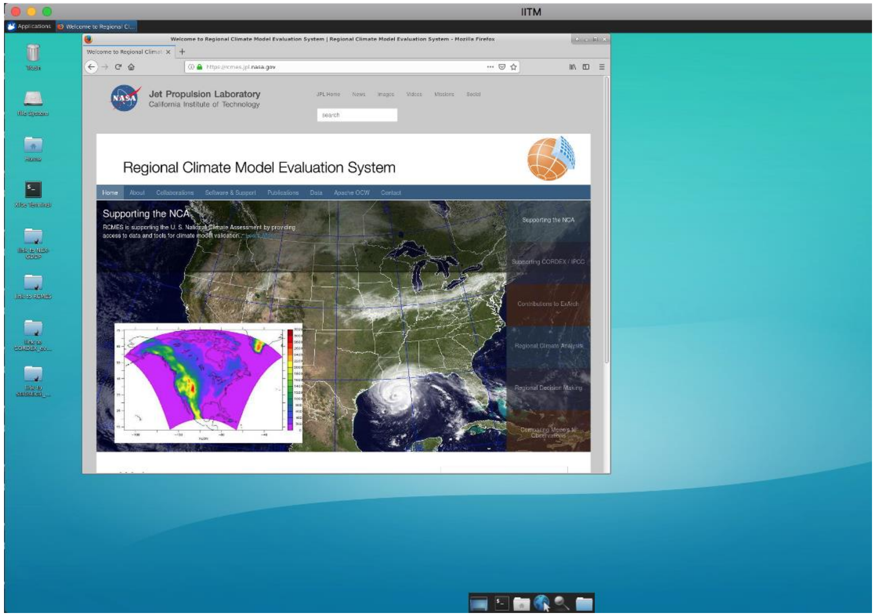
| Time | Agenda Item | Process/presentations/materials |
|---|---|---|
| 10:00-10:15 | Welcome and connect to Amazon Elastic Compute Cloud (EC2) | • Check the IP address of the assigned server<br>• Connect to the server using Microsoft Remote Desktop (or terminal software) |
| 10:15-10:30 | Activity #1<br>: Correct biases in CORDEX RCM simulations | • Quantile-based bias correction of the CORDEX WAS simulations using satellite-based precipitation observation data |
| 10:30-10:50 | Activity #2<br>: Evaluate CORDEX RCM simulations | • Systematic evaluation of CORDEX RCMs against obs4mips using RCMES |
| | Break (10:50-11:00) | |
| 11:00-11:30 | Activity #3<br>: Pointwise Statistical downscaling using RCMES | • CMIP5 temperature and precipitation datasets for present and future climate<br>• Compare the IPCC climate change scenarios<br>• (RCP 4.5 vs. RCP 8.5) |
| 11:30-11:45 | Activity #4<br>: Download and visualize the NEX-GDDP data | • NASA Earth Exchange Globally Daily Downscaled Projections (NEX-GDDP) in Amazon Simple Storage Service (S3) |
| 11:45- | Activity #5 | • Analyze the bias corrected RCM output and check the evaluation result |

# Two different ways to connect to the virtual Linux machine on Amazon Web Service

- SSH connection using your terminal application
- Prerequisite software
  - terminal: putty, xshell, xterm
  - X Server: Xming, XQuartz
  - NetCDF/HDF viewer: Panoply
  - (Optional) sftp client: xftp, FileZilla

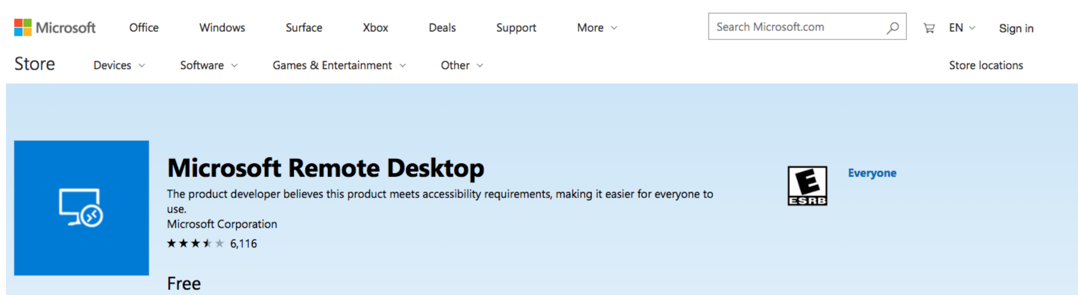
- ssh -Y user1@xx.xxx.xx.xxx
- password: cordex

- Remote desktop



# Prerequisite software to run remote desktop

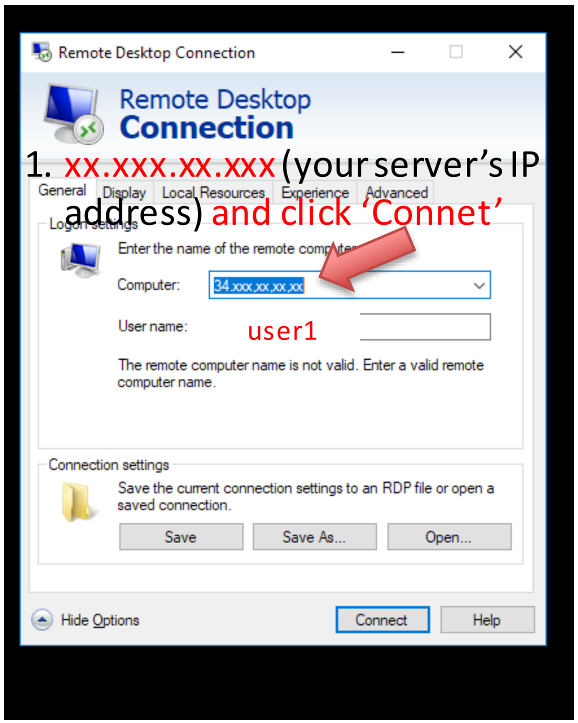
- ~~Linux based system~~
- Windows laptops: Microsoft Remote Desktop




- Macbooks: Microsoft Remote Desktop **10**

**(do not use version 8)**

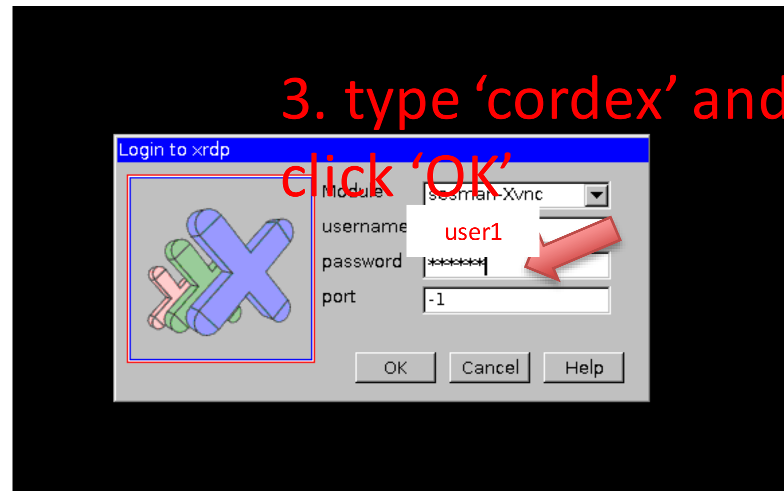
# Set up your remote desktop (Windows)




1. xx.xxx.xx.xxx (your server's IP address) and click 'Connet'

user1


2. Click 'OK'

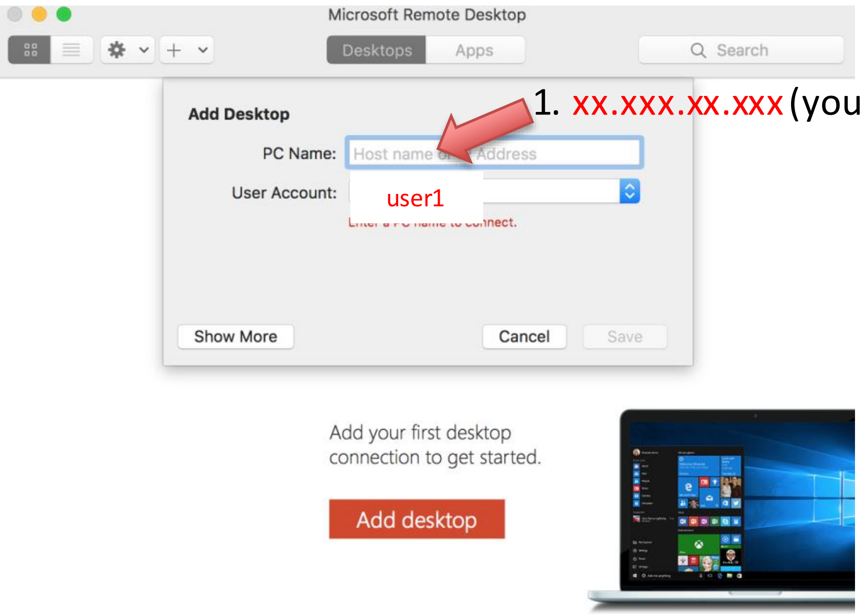


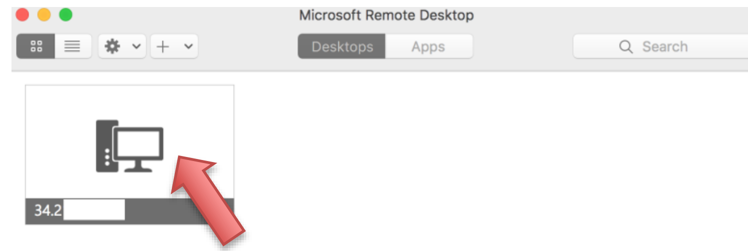

3. type 'cordex' and click 'OK'

user1

# Set up your remote desktop (Mac)

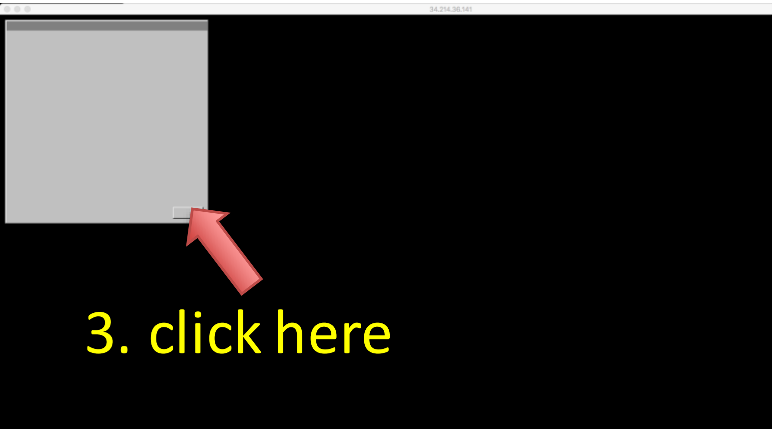
1. xx.xxx.xx.xxx (your server’s IP address)

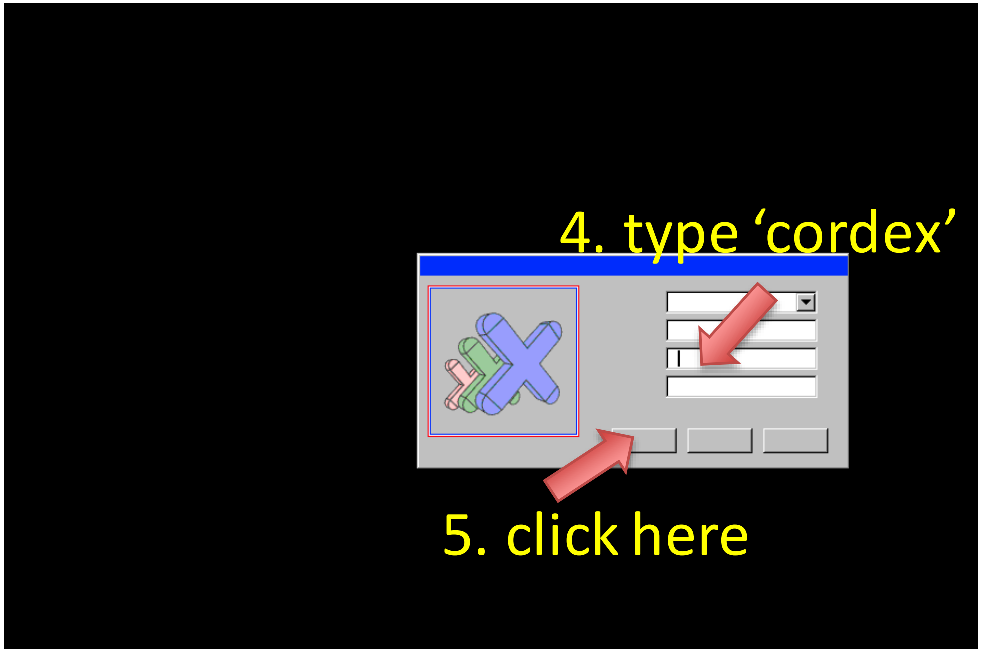



2. Double click!!!

# Bugs in the Mac version



- **Activity #1**

**: Correct biases in CORDEX RCM simulations**

- Activity #2

: Evaluate CORDEX RCM simulations

- Activity #3

: Pointwise Statistical downscaling using RCMES

- Activity #4

: Download and visualize the NEX-GDDP data

**Running the bias correction script**

(courtesy of Dr. TJ Vandal at NASA Ames, https://github.com/tjvandal/bcsd-python)

1. Open Terminal and type `cd RCMES`

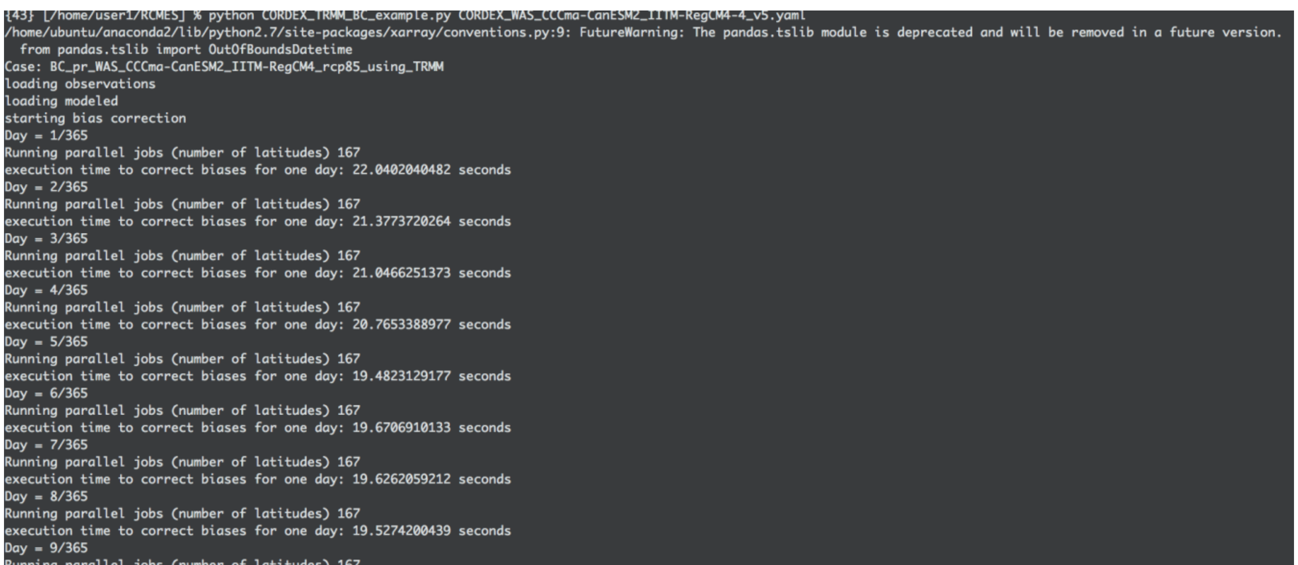
(Five options: please choose one of yaml files)

ex) To correct biases in the CSIRO-MK3-6-0_IITM-RegCM4-4_v5 for the CORDEX South Asia domain,

Python script — One of the five configuration files

```
python CORDEX_TRMM_BC_example.py CORDEX_WAS_CSIRO-QCCCE-CSIRO-Mk3-6-0_IITM-RegCM4-4_v5.yaml
```

(Running this parallelized script takes more than an hour.)



# Bias Correction of CORDEX simulations

- The IITM-RegCM simulations have high spatial resolution (~44 km) relative to CMIP GCMs.

- ~~BCSD~~ => BC : spatial disaggregation (SD) may not be necessary thanks to the resolution of CORDEX simulations.

# Quantile mapping to correct simulated precipitation using TRMM observations (1)

- Inside the configuration file (CORDEX_WAS_CCCma-CanESM2_IITM-RegCM4-4_v5.yaml)

**fobserved:** TRMM_regridded_RegCM4-4_v5_day_19980101-20131201_WAS-44.nc

**observed_varname:** TRMM_daily_pr

**fmodeled_present:** pr_WAS-44_CCCma-CanESM2_historical_r1i1p1_IITM-RegCM4-4_v5_day_19900101-20051231.nc

**fmodeled_future:** pr_WAS-44_CCCma-CanESM2_rcp85_r1i1p1_IITM-RegCM4-4_v5_day_20840101-20991231.nc

**modeled_varname:** pr

**(Observation)**
Read TRMM_daily_pr from TRMM_regridded_RegCM4-4_v5_day_19980101-20131201_WAS-44.nc

**(Simulation for the present climate)**
Read pr from pr_WAS-44_***_19900101-20051231.nc

**(Simulation for the future climate)**
Read pr from pr_WAS-44_***_20840101-20991231.nc

# Quantile mapping to correct simulated precipitation using TRMM observations (2)

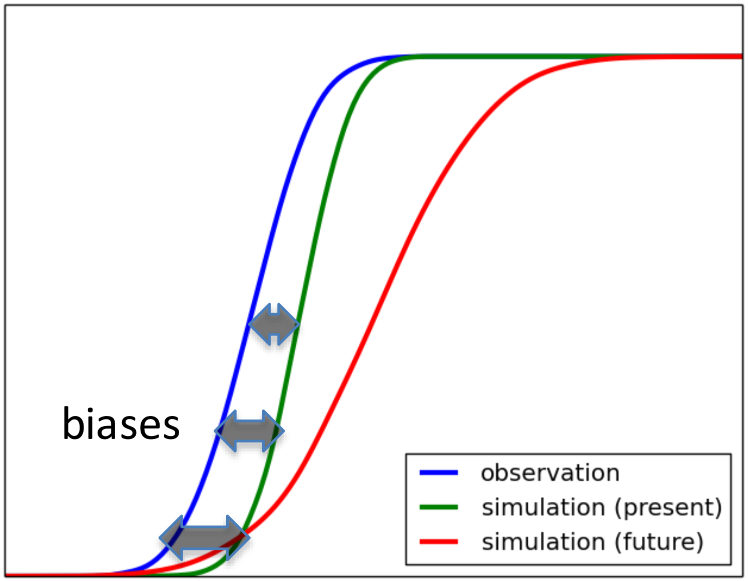
- At each RCM grid point, biases in simulated precipitation are is corrected for each quantile (0.5-99.5%) by comparing two cumulative distributions from TRMM and the RCM (±15 days).

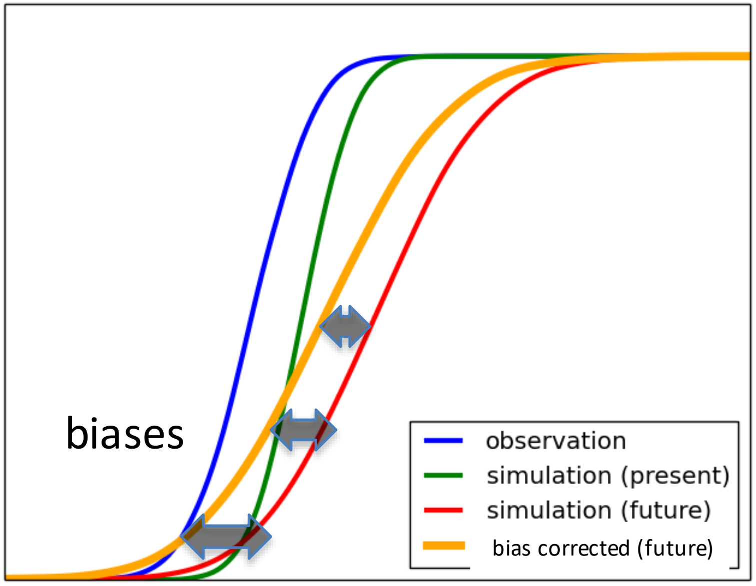
**(Observation)**
TRMM_daily_pr for 19980101-20131231

**(Simulation for the present climate)**
pr_WAS-44_***_19900101-20051231.nc

**(Simulation for the future climate)**
pr_WAS-44_***_20840101-20991231.nc

**(Bias corrected future simulation)**
BC_pr_WAS-44_***_20840101-20991231.nc



- Activity #1

: Correct biases in CORDEX RCM simulations

- **Activity #2**

**: Evaluate CORDEX RCM simulations**

- Activity #3

: Pointwise Statistical downscaling using RCMES

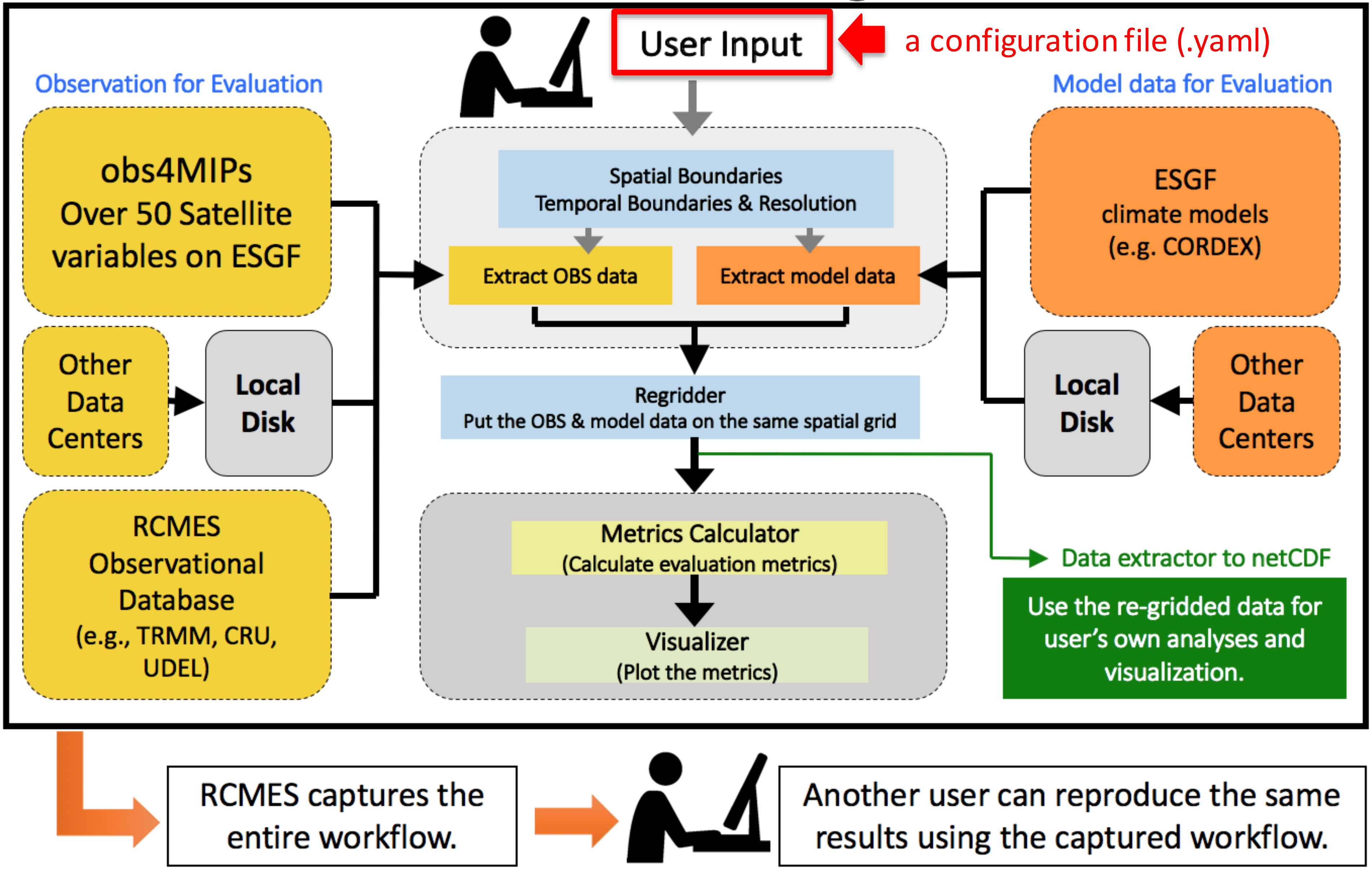
- Activity #4

: Download and visualize the NEX-GDDP data

# The Regional Climate Model Evaluation System (RCMES, https://rcmes.jpl.nasa.gov)

- Lee et al. (2018), Regional Climate Model Evaluation System powered by Apache Open Climate Workbench v1.3.0: an enabling tool for facilitating regional climate studies, Geoscientific Model Development.
- Python-based open source software powered by the Apache Open Climate Workbench (OCW)
- Main components
  1) Database of observations
  2) Toolkit for facilitating systematic evaluation of CORDEX RCMs using satellite observations (Activity #2)
  3) Statistical downscaling of coarse-resolution GCM output or bias correction of high-resolution RCM output (Activity #1 & 3)
  4) Stand-alone scripts for data processing and visualization based on OCW

# Model evaluation using RCMES



# Apache Open Climate Workbench (OCW)

https://climate.apache.org/

Apache Open Climate Workbench | Downloads | Development | Documentation | Community | ASF

APACHE OPEN CLIMATE WORKBENCH

## Apache Open Climate Workbench

Apache Open Climate Workbench is an effort to develop software that performs climate model evaluation using model outputs from a variety of different sources the Earth System Grid Federation, the Coordinated Regional Climate Downscaling Experiment, the U.S. National Climate Assessment and the North American Regional Climate Change Assessment Program and temporal/spatial scales with remote sensing data from NASA, NOAA and other agencies. The toolkit includes capabilities for rebinning, metrics computation and visualization.

### Apache Open Climate Workbench 1.0.0 Released

September 24, 2015

The Apache Open Climate Workbench team is pleased to announce the 1.0.0 release! This release addresses no less than 52 issues, bugs, and improvements. For a full breakdown of the work packaged into this release please see the release report.

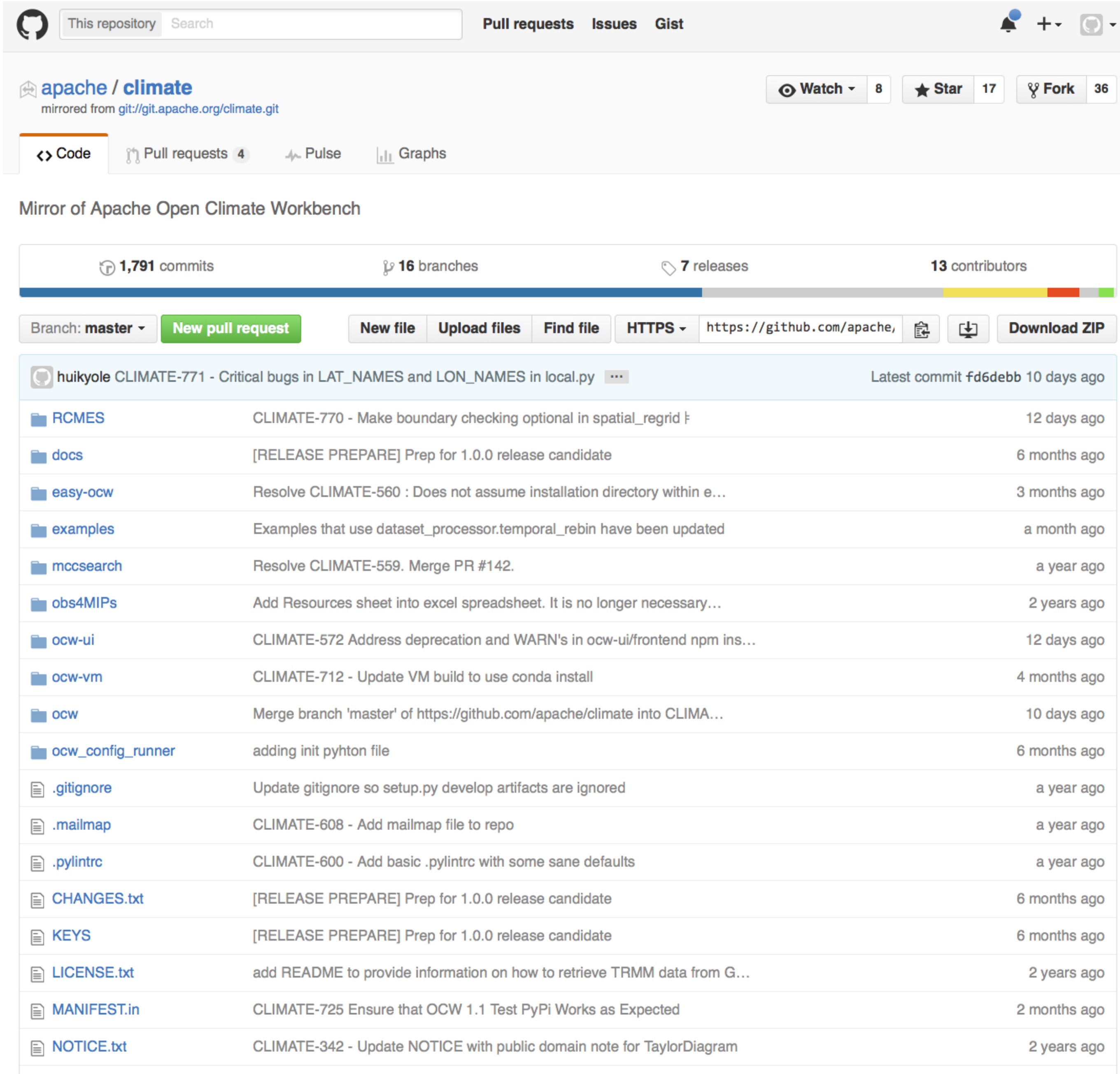
Some important features this release packs include statistical downscaling capabilities such as Delta Method, Quantile Mapping and Quantile Regression, configuration driven evaluation improvements, better plot support to config based evaluations and a brand new module to calculate area mean and standard deviation with given subregion information.

Download

We urge all users to upgrade to this version immediately. Please let us know how you are using OCW over on the community mailing lists.

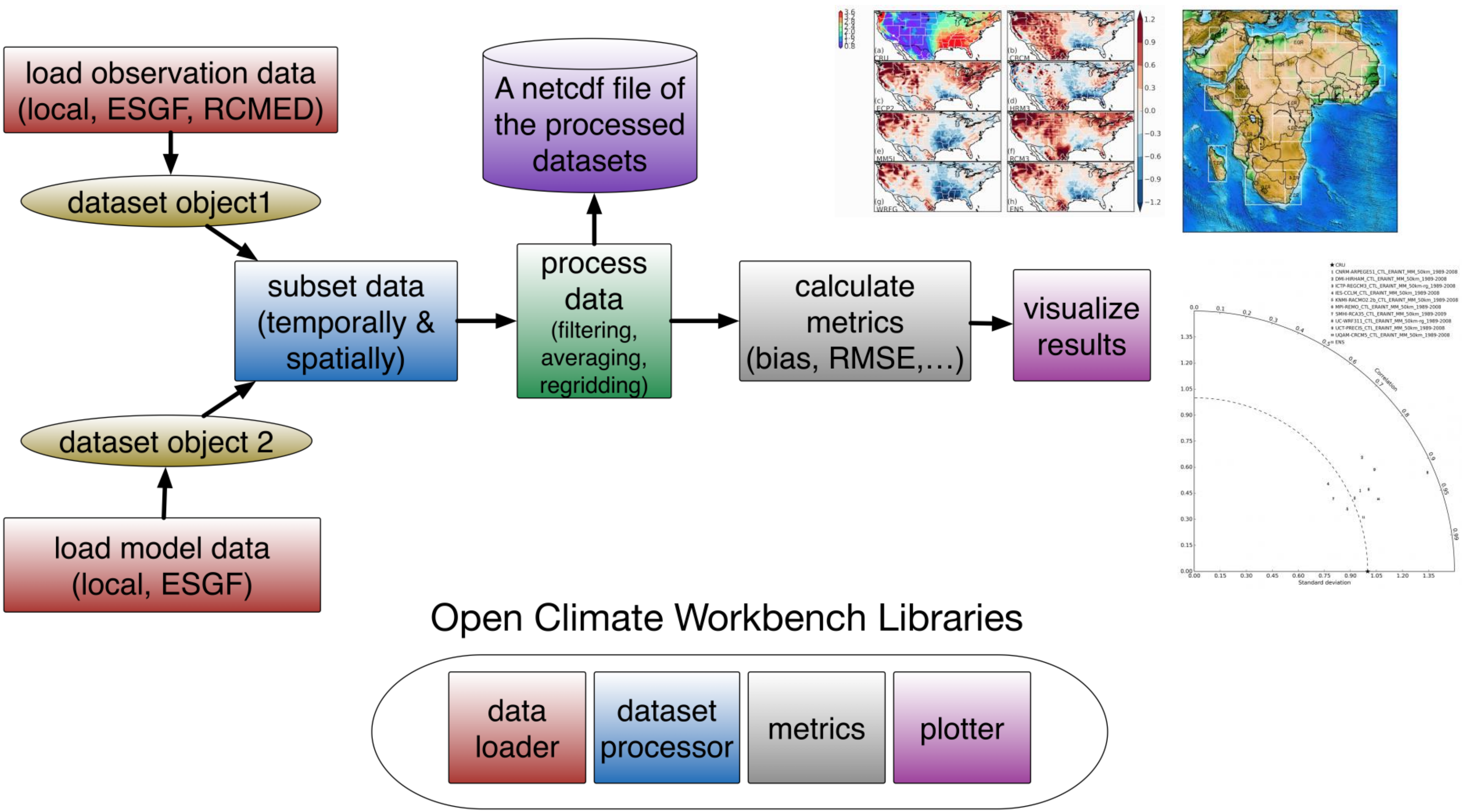
Finally, please see our 1.1 Roadmap for an idea of the next line of development.

# Source at github.com/apache/climate



# Running RCMES using configuration files:

## a complete start-to-finish workflow to evaluate multi-scale climate models using observational data



# Running the systematic evaluation of CORDEX WAS simulations

1. Open Terminal and type

```
cd RCMES
```

```
cd CORDEX_evaluation
```

2. Type

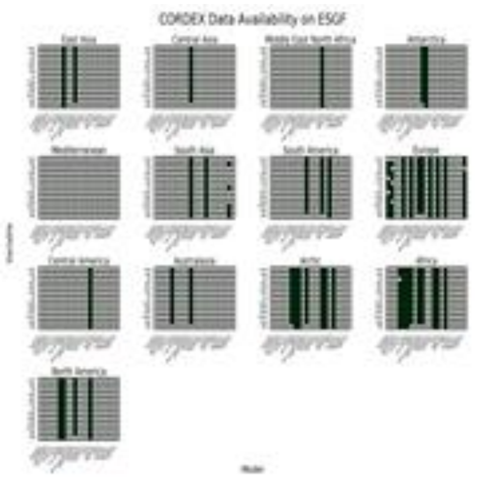
```
./evaluate_WAS-44
```

Terminal

File Edit View Terminal Tabs Help

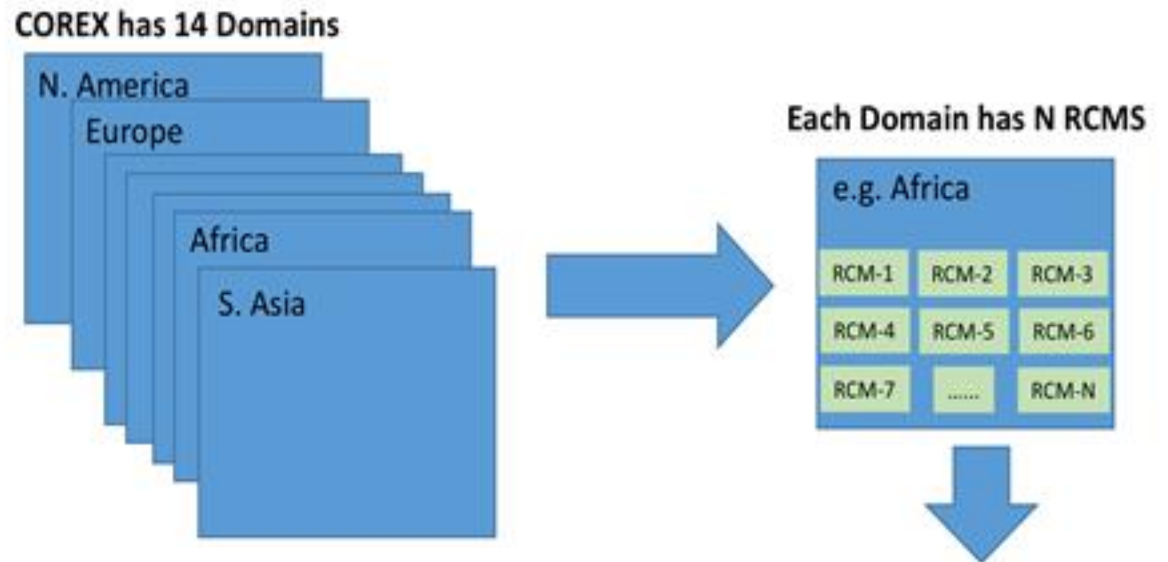
```
metrics 1/2: Map_plot_bias_of_multiyear_climatology
metrics 2/2: Taylor_diagram_spatial_pattern_of_multiyear_climatology
Reading the configuration file evaluation_result/WAS-44/MODIS/clt/summer/WAS-44_
MODIS_clt_summer.yaml
Loading datasets:
[{'file_path': '/mnt/CORDEX-efs/obs4mips/clt_MODIS_L3_C5_*.nc', 'name': 'MODIS',
 'loader_name': 'local_split', 'variable_name': 'clt'}, {'lat_name': 'lat', 'nam
e': 'SMHI-RCA4', 'loader_name': 'local_split', 'variable_name': 'clt', 'file_pat
h': '/mnt/CORDEX-efs/CORDEX/WAS-44/clt/clt_WAS-44_ECMWF-ERAINT_evaluation_r1i1p1
_SMHI-RCA4_v2_mon_*.nc', 'lon_name': 'lon'}, {'lat_name': 'lat', 'name': 'MOHC-H
adRM3P', 'loader_name': 'local_split', 'variable_name': 'clt', 'file_path': '/mn
t/CORDEX-efs/CORDEX/WAS-44/clt/clt_WAS-44_ECMWF-ERAINT_evaluation_r1i1p1_MOHC-Ha
dRM3P_v1_mon_*.nc', 'lon_name': 'lon'}]
Maximum overlap period
start_time: 2001-01-01 00:00:00
end_time: 2010-12-01 00:00:00
Dataset loading completed
Reference data: MODIS
Number of target datasets: 2
SMHI-RCA4
MOHC-HadRM3P
Regridding datasets: {'regrid_on_reference': True}
SMHI-RCA4 has been regridded
```

ERA-Interim Reanalysis Forced RCM simulations Available on ESGF

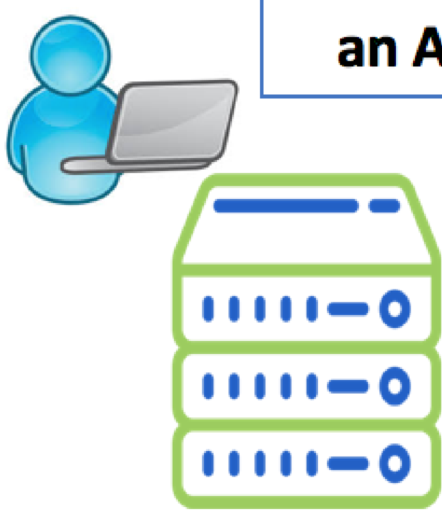



Schematic of Multi-Domain, Multi-Model and Multi-Variate CORDEX Model Evaluation with Obs4MIPs

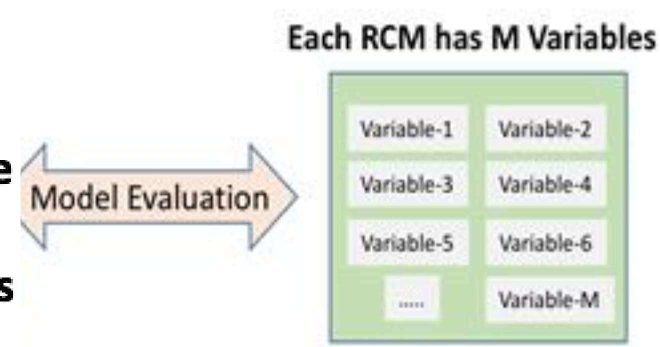
Schematic of Multi-Domain, Multi-Model and Multi-Variate CORDEX Model Evaluation with Obs4MIPs

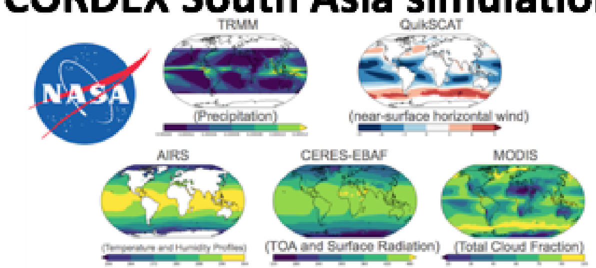



**Mount an EFS storage to an AWS EC2 instance**



**Elastic File System (EFS) storage containing obs4MIPs and CORDEX South Asia simulations**



```yaml
workdir: /home/goodman/data_processing/CORDEX/analysis/NAM-44/CERES-EBAF/rlus/annual
output_netcdf_filename: rlus_CERES-EBAF_NAM-44_annual.nc

# (RCMES will temporally subset data between month_start and month_end.
# If average_each_year is True (False), seasonal mean in each year is (not) calculated and used for metrics calcula
time:
    maximum_overlap_period: True
    temporal_resolution: monthly
    month_start: 1
    month_end: 12
    average_each_year: True

space:
    boundary_type: CORDEX NAM

regrid:
    regrid_on_reference: True

datasets:
  - loader_name: local_split
    name: CERES-EBAF
    file_path: /proj3/data/obs4mips/rlus_CERES-EBAF_L3B_Ed2-8_*.nc
    variable_name: rlus
  - loader_name: local_split
    name: UQAM-CRCM5
    file_path: /proj3/data/CORDEX/NAM-44/rlus/rlus_NAM-44_ECMWF-ERAINT_evaluation_r1i1p1_UQAM-CRCM5_v1_mon_*.nc
    variable_name: rlus
    lat_name: lat
    lon_name: lon
  - loader_name: local_split
    name: SMHI-RCA4
    file_path: /proj3/data/CORDEX/NAM-44/rlus/rlus_NAM-44_ECMWF-ERAINT_evaluation_r1i1p1_SMHI-RCA4_v1_mon_*.nc
    variable_name: rlus
    lat_name: lat
    lon_name: lon
  - loader_name: local_split
    name: DMI-HIRHAM5
    file_path: /proj3/data/CORDEX/NAM-44/rlus/rlus_NAM-44_ECMWF-ERAINT_evaluation_r1i1p1_DMI-HIRHAM5_v1_mon_*.nc
    variable_name: rlus
    lat_name: lat
    lon_name: lon
  - loader_name: local_split
    name: MOHC-HadRM3P
    file_path: /proj3/data/CORDEX/NAM-44/rlus/rlus_NAM-44_ECMWF-ERAINT_evaluation_r1i1p1_MOHC-HadRM3P_v1_mon_*.nc
    variable_name: rlus
    lat_name: lat
    lon_name: lon
```


Season

Domain

Observations

Models

# Why we need "Systematic Evaluation"

- This Config file (namelist file) is necessary to run each evaluation combination (CORDEX Domain, Season and Variable), forming a large "evaluation matrix".
- 14 variables x 13 domains x 3 seasons x ~10 models > 5000 evaluations
- Writing that many Config files manually would be cumbersome/prohibitive.

# Solution: Extract metadata from input filenames

rlus_NAM-44_ECMWF-ERAINT_evaluation_r1i1p1_UQAM-CRCM5_v1_mon_*.nc

Variable Domain

Model

**User Input: Dataset Locations (obs4mips, CORDEX)** → **Evaluation Groups (Season, Domain, Variable)** → **Config File** → **RCMES**

We can group all models and obs datasets together by common attributes (domain and variable) to form a unique evaluation, and therefore **automatically generate Config Files using only the dataset locations as user input**.

```
./evaluate_WAS-44
```

↓

output folder name

```
python cordex.py WAS-44 evaluation_result /mnt/CORDEX-efs/obs4mips
/mnt/CORDEX-efs/CORDEX/WAS-44
```

- Activity #1

: Correct biases in CORDEX RCM simulations

- Activity #2

: Evaluate CORDEX RCM simulations

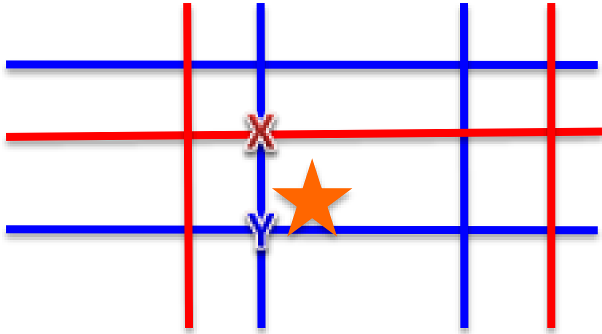
- Activity #3

: Pointwise Statistical downscaling using RCMES

- Activity #4

: Download and visualize the NEX-GDDP data

# Statistical downscaling using RCMES




- To statistically downscale CMIP5 variables at a specific location (star marker), RCMES uses statistical relationship between the nearest model grid point data (X) and observation grid point data (Y)

  : **simultaneous correction of both bias and collocation**

$$Y = f(X)$$

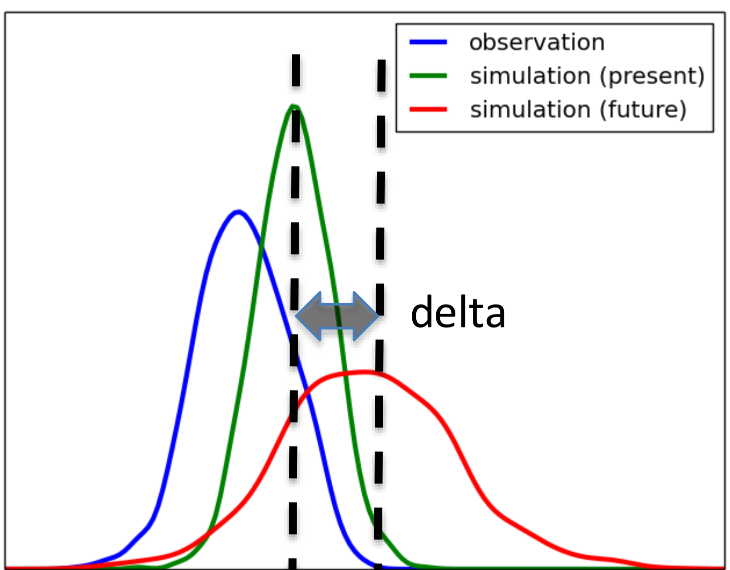
- Four different methods for model calibration (Stoner et al., 2013)
  - Delta method (addition)
  - Delta method (bias correction)
  - Quantile mapping
  - Asynchronous linear regression
- The observational datasets in RCMES database can be used to determine the observation-model relationship.

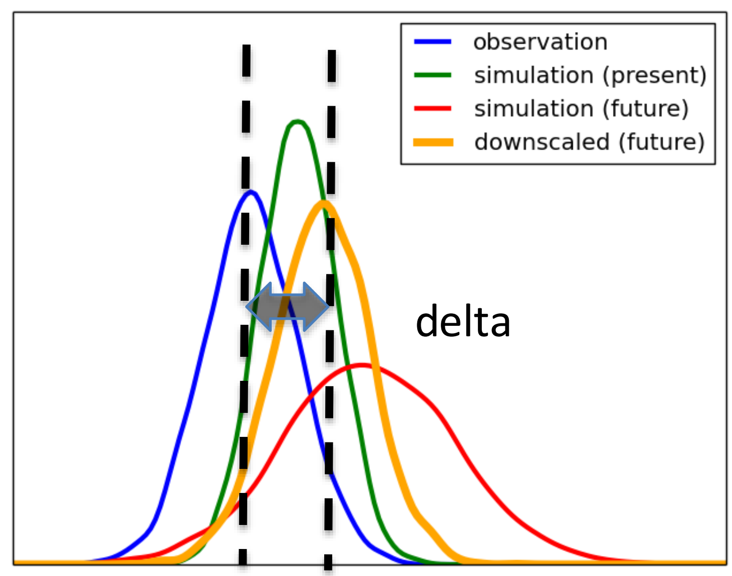
# Delta method (Delta addition)

$Y_0$: present observation, $X_0$: present simulation, $X_1$: future simulation

$$Y_1 = Y_0 + \bar{X}_1 - \bar{X}_0$$

- (future climate) = (present observation) + (mean difference between $X_0$ and $X_1$)



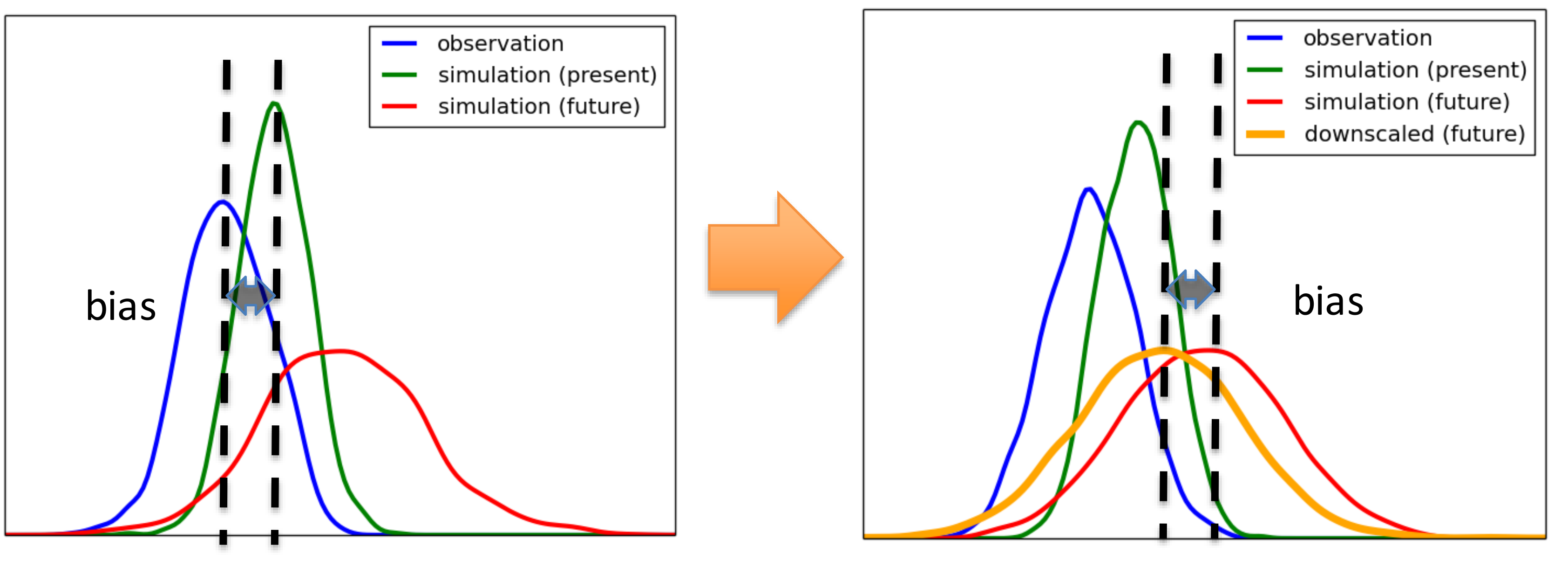



# Delta method
# (Bias correction)

$Y_0$: present observation, $X_0$: present simulation, $X_1$: future simulation

$$Y_1 = X_1 + \bar{Y_0} - \bar{X_0}$$

- (future climate) = (future simulation) + (mean bias)

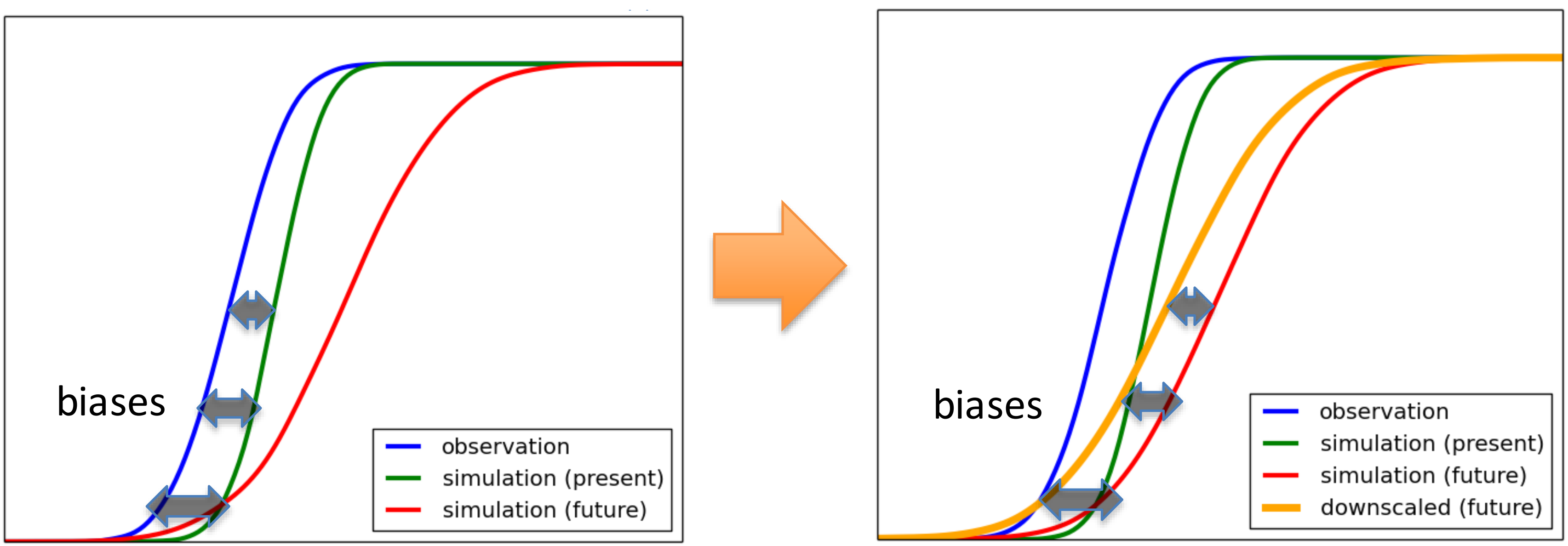


# Quantile mapping

$Y_0$: present observation, $X_0$: present simulation, $X_1$: future simulation

$Y_1 = f(X_1)$ where $f$ is bias correction function for each quantile ($Y_0 = f(X_0)$).

- (future climate) = (bias corrected future simulation)
- Bias is corrected for each quantile.

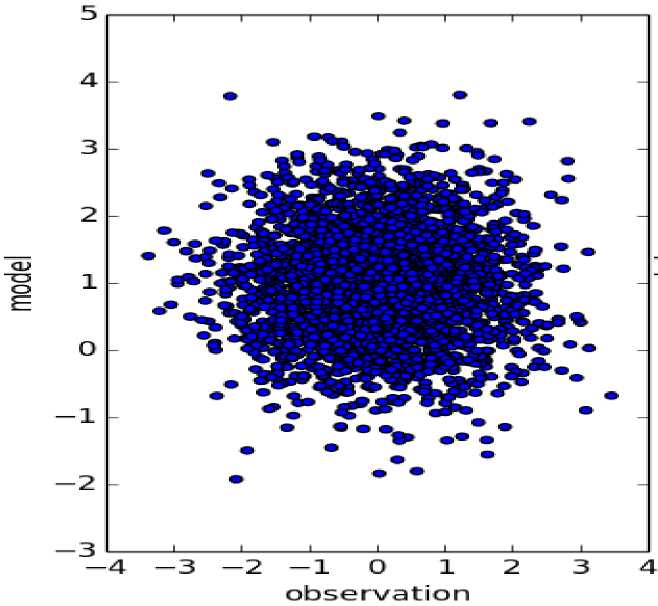


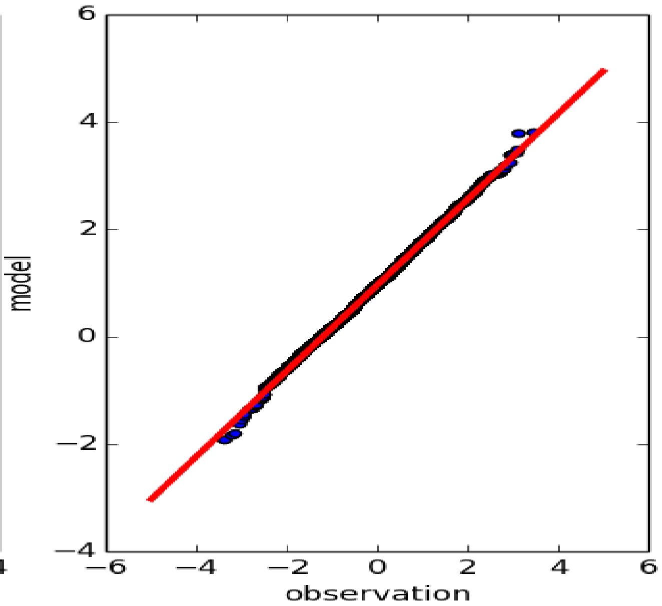
# Asynchronous linear regression

$Y_0$: present observation, $X_0$: present simulation, $X_1$: future simulation
$Y_0'$, $X_0'$, $X_1'$: sorted in ascending order

$Y_1' = a\dot{X}_1' + b$ where $Y_0' = a\dot{X}_0' + b$. a and b are the slope and intercept for the least square regression line.

- The linear relationship between observation and present simulation is determined after sorting them in ascending order.



# Statistical Downscaling using RCMES

1. Open Terminal and `cd RCMES/statistical_downscaling/`
2. To run the statistical downscaling script, type

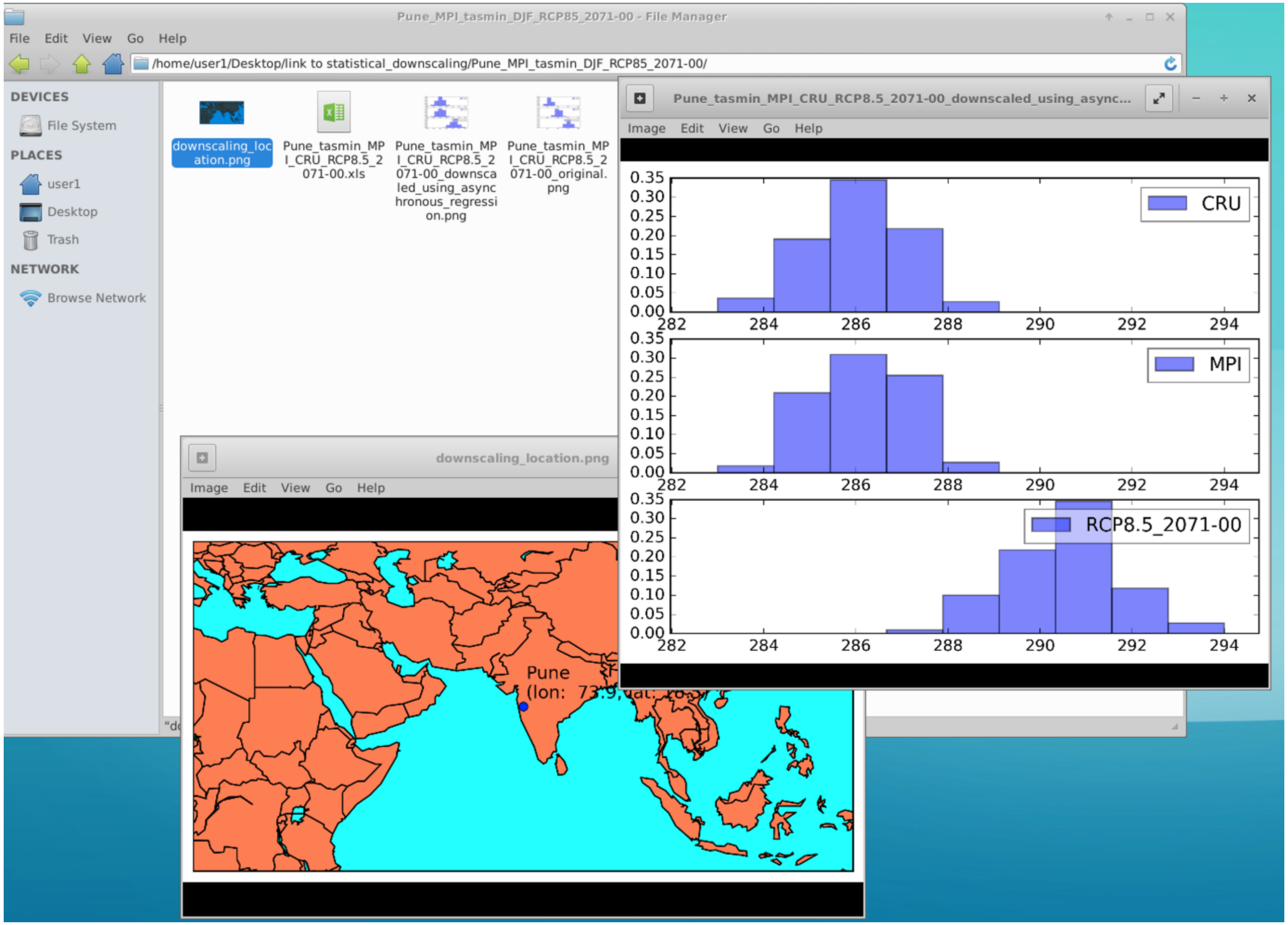
`python run_statistical_downscaling.py MPI_tasmin_DJF.yaml`

Python script — Configuration file

```
{13} [/home/ubuntu] % cd RCMES/statistical_downscaling/
data/  LaPaz_MPI_tas_JJA_RCP85_2071-00/  MIROC5_tasmax_JJA.yaml  MPI_tas_JJA.yaml  run_statistical_downscaling.py
{14} [/home/ubuntu/RCMES/statistical_downscaling] % python run_statistical_downscaling.py MPI_tas_JJA.yaml
Reading the configuration file  MPI_tas_JJA.yaml
Processing CRU  data
Loading ./data/tas_cru_monthly_1981-2010.nc into an OCW Dataset Object
CRU values shape: (times, lats, lons) - (360, 360, 720)

Loading ./data/tas_Amon_MPI_decadal1980_198101-201012.nc into an OCW Dataset Object
MPI values shape: (times, lats, lons) - (360, 96, 192)

RCP8.5_2071-00:MPI values shape: (times, lats, lons) - (360, 96, 192)

Temporal subsetting for the selected month(s)
Spatial aggregation of observational data near latitude 10.75 and longitude 106.67
Creating a statistical downscaling object
asynchronous_regression: Downscaling model output
Plotting results
Generating spreadsheet
{15} [/home/ubuntu/RCMES/statistical_downscaling] %
```

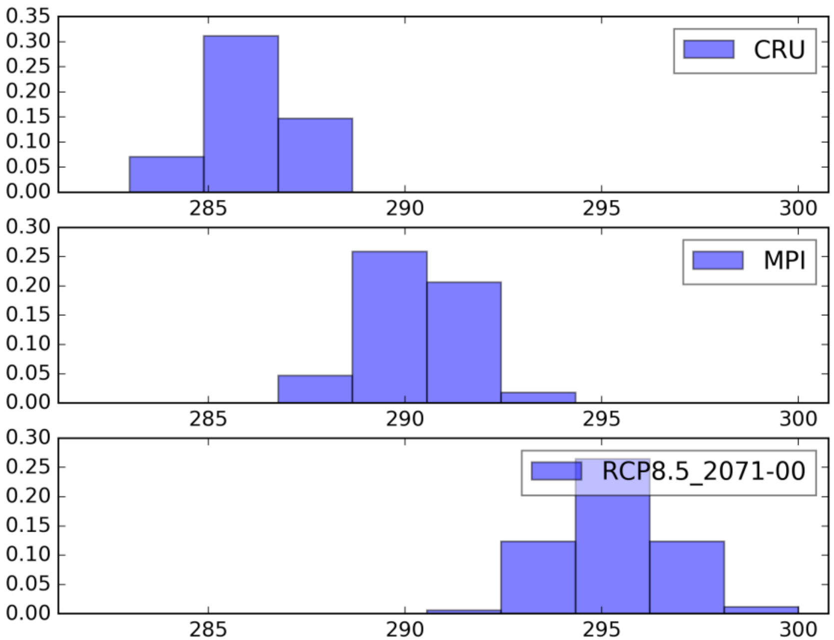
# View the statistically downscaled tasmin results

- The results can be found in statistical_downscaling/Pune_tasmin_MPI_CRU_RCP8.5_2071-00 folder

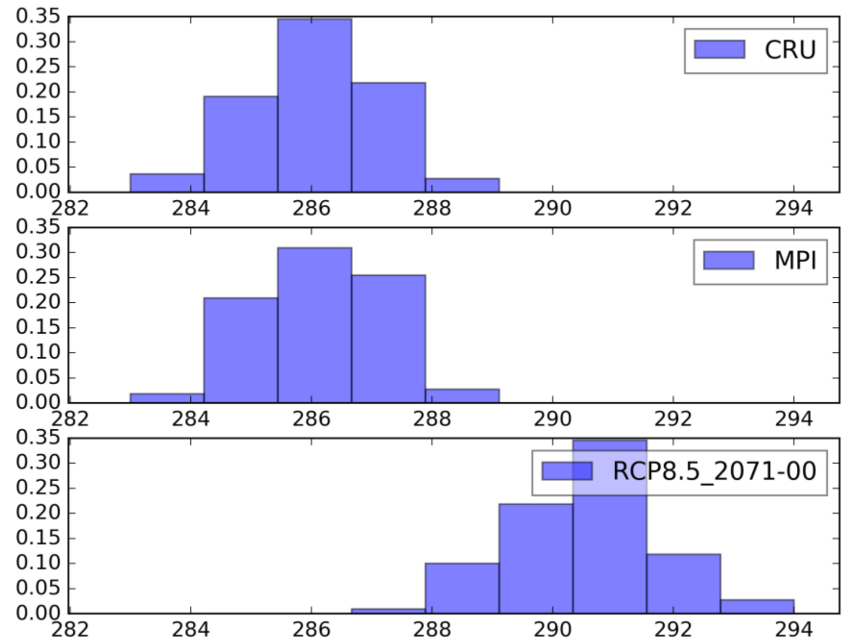


# Quantile mapping of the daily minimum temperature for Pune in DJF

**Original model output**




**Statistically downscaled model output**



# Run another example: taxmax in Pune

```
python run_statistical_downscaling.py MIROC5_taxmax_DEC.yaml
```

Python script (run_statistical_downscaling.py) — Configuration file (MIROC5_taxmax_DEC.yaml)

# Make your own example by editing the yaml file

```yaml
case_name: Pune_MIROC5_tasmax_DEC_RCP85_2071-00
downscaling_option: 3
location:
   name: Pune
   grid_lat: 18.5204
   grid_lon: 73.8567
 month_index: !!python/tuple [12]
reference:
   data_source: local
   data_name: CRUs
   path: ./data/tasmax_cru_monthly_1981-2010.nc
   variable: tasmax
model:
   data_name: MIROC5
   variable: tasmax
   present:
      path: ./data/tasmax_Amon_MIROC5_decadal1980_198
   future:
      scenario_name: RCP8.5_2071-00
      path: ./data/tasmax_Amon_MIROC5_rcp85_207101-210012.nc
```

Output folder name

Search Google with the keyword ‘latitude and longitude of XXX’

Season: December only in this case

(Options)
1. **IPSL**, **MPI**, and **MIROC5**
2. **tas**, **tasmin**, and **tasmax**
3. **RCP 4.5** and **8.5**
4. (**2041-2070**) and (**2071-2100**)

- Activity #1

: Correct biases in CORDEX RCM simulations

- Activity #2

: Pointwise Statistical downscaling using RCMES

- **Activity #3**

**: Download and visualize the NEX-GDDP data**

- Activity #4

: Analyze the bias corrected RCM output

# NASA's Earth Exchange (NEX, https://nex.nasa.gov)


- NEX is a platform for scientific collaboration, knowledge sharing and research for the Earth science community.
- The new project, Open NEX, is aimed at making a number of important datasets more accessible.

NASA Earth Exchange
Global Daily Downscaled Projections (NEX-GDDP)

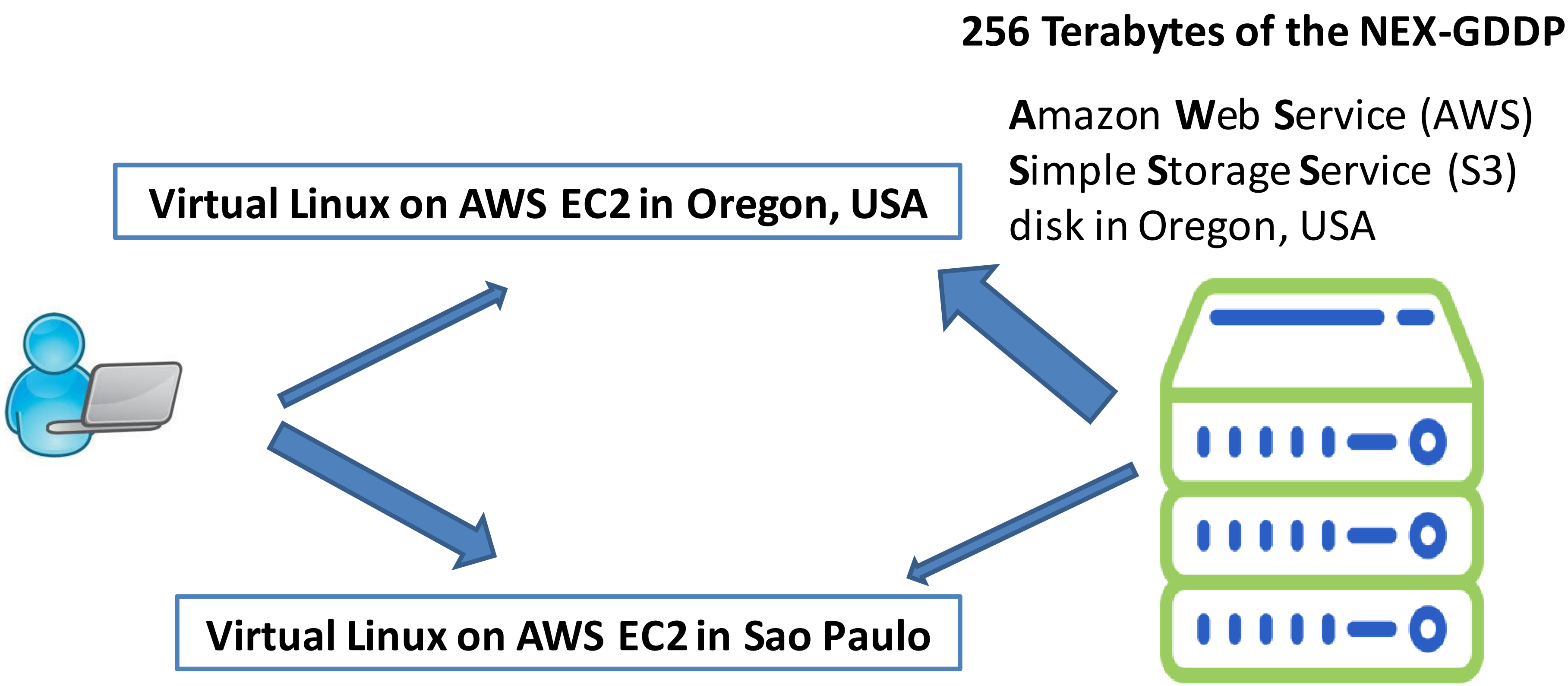
CMIP5 historical and RCP 4.5/8.5 simulations (from 21 models, 1950-2100)

Global Meteorological Forcing Dataset (observation, 1950-2005)

Bias-Correction Spatial Disaggregation (BCSD)

NEX-GDDP
: tasmax, tasmin, precipitation

# Access to the statistically downscaled NEX-GDDP




- The NEX S3 is mounted in your linux EC2.
- Open terminal and type `df -h`

# What are inside s3://nasanex?

**[/home/ubuntu] %** aws s3 ls s3://nasanex

PRE AVHRR/

PRE CMIP5/

PRE LOCA/

PRE Landsat/

PRE MAIAC/

PRE MODIS/

PRE NAIP/

PRE NEX-DCP30/

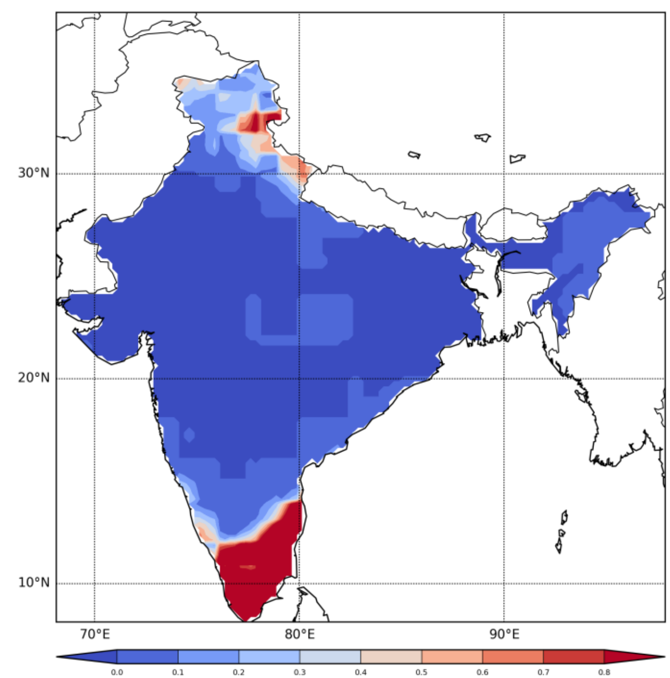
PRE NEX-GDDP/

# List, download and visualize NEX-GDDP

1. Open terminal and `cd NEX-GDDP`
2. `./list`
3. `./download` How fast!
4. `python plot_NEX-GDDP_example.py`

This script is an example of Open Climate Workbench, an open-source Python library that comprise RCMES.

Statistically downscaled precipitation from NorESM1-M model for December 2100



- Activity #1

: Correct biases in CORDEX RCM simulations

- Activity #2

: Pointwise Statistical downscaling using RCMES

- Activity #3

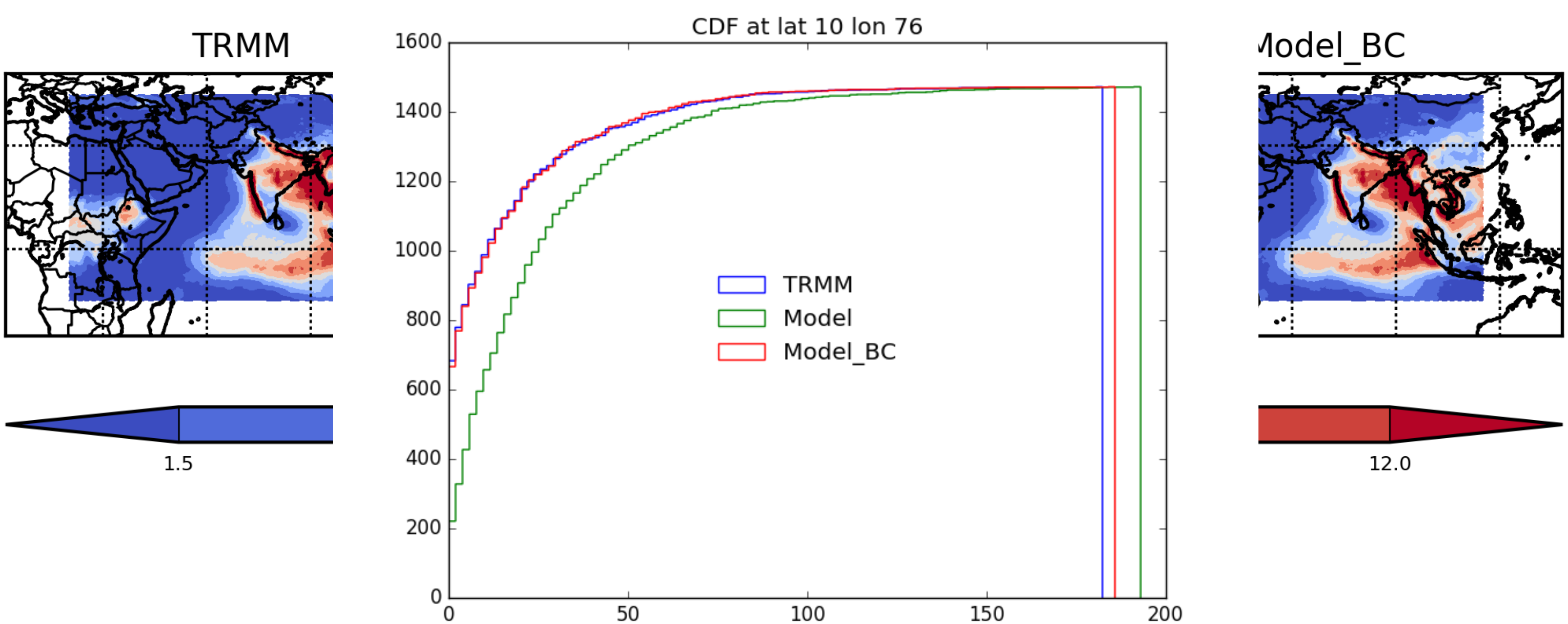
: Download and visualize the NEX-GDDP data

- **Activity #4**

**: Analyze the bias corrected RCM output**

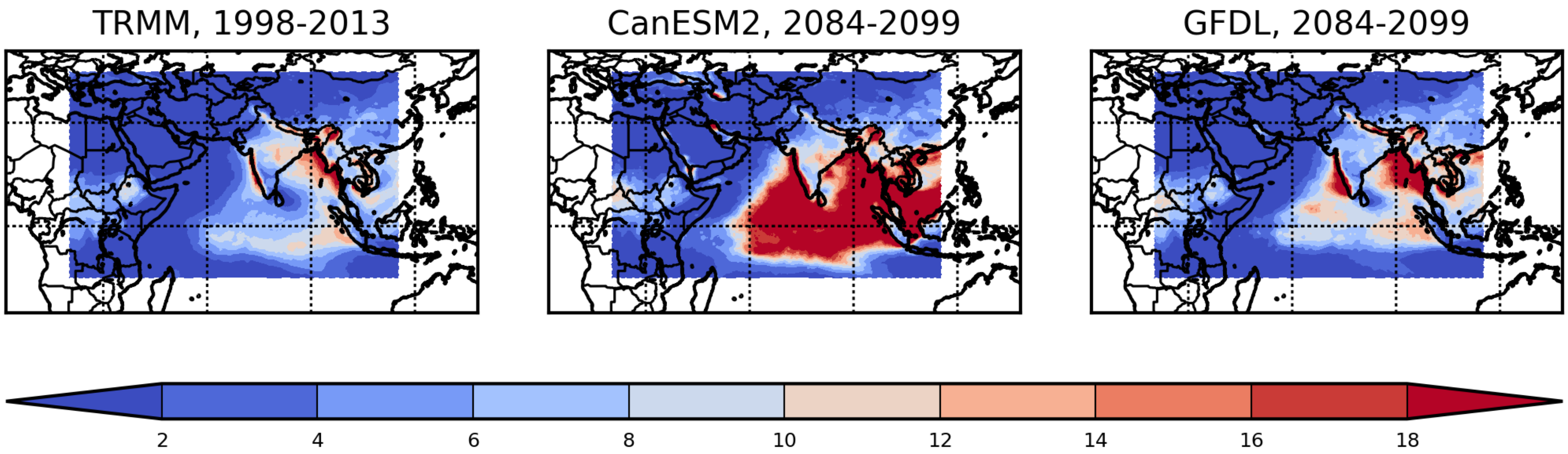
# Compare TRMM, original simulation, and bias corrected simulation

1. Open terminal and `cd RCMES/analysis_examples`
2. `python check_bias_correction.py` ← OCW-based script



# How does the bias-corrected precipitation look like in the future (in July-August, TRMM (1998-2013) vs. two bias-corrected simulations (2084-2099))?

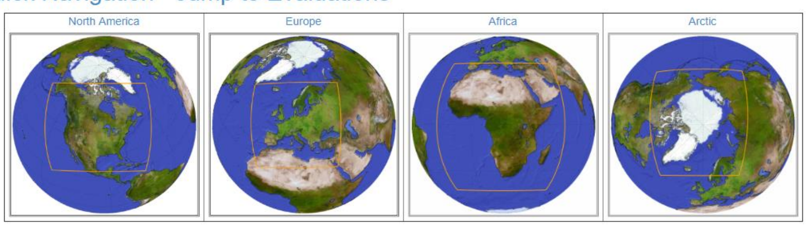
```
python compare_present_and_future.py
```



# Future Direction

- Development is ongoing…
  - Adding more metrics to assure traceability and reproducibility of model evaluation results.
  - Growing user and developer base by utilizing AWS and OpenNEX datasets.
- Develop a comprehensive model evaluation system for the United States National Climate Assessment and CORDEX.

Quick Navigation - Jump to Evaluations




Results

North America Evaluations

| Reference Dataset | Variables | Results Page by Seasons | | |
|---|---|---|---|---|
| CERES-EBAF | Downwelling Longwave Radiation (Surface) | Annual | Summer | Winter |
| | Upwelling Longwave Radiation (Surface) | Annual | Summer | Winter |
| | Upwelling Longwave Radiation (TOA) | Annual | Summer | Winter |
| | Downwelling Shortwave Radiation (Surface) | Annual | Summer | Winter |
| | Downwelling Shortwave Radiation (TOA) | Annual | Summer | Winter |
| | Upwelling Shortwave Radiation (Surface) | Annual | Summer | Winter |
| | Upwelling Shortwave Radiation (TOA) | Annual | Summer | Winter |

https://rcmes.jpl.nasa.gov/content/cordex-evaluation

# Where to find more information:

- http://rcmes.jpl.nasa.gov
- http://climate.apache.org/
- Email team members or dev@climate.apache.org
- https://nex.nasa.gov

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Geosci. Model Dev., 11, 4435–4449, 2018
https://doi.org/10.5194/gmd-11-4435-2018


Geoscientific Model Development

**Regional Climate Model Evaluation System powered by Apache Open Climate Workbench v1.3.0: an enabling tool for facilitating regional climate studies**

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Received: 24 April 2018 – Discussion started: 18 June 2018
Revised: 5 October 2018 – Accepted: 11 October 2018 – Published: 5 November 2018

**Abstract.** The Regional Climate Model Evaluation System (RCMES) is an enabling tool of the National Aeronautics and Space Administration to support the United States National Climate Assessment. As a comprehensive system for evaluating climate models on regional and continental scales using observational datasets from a variety of sources, RCMES is designed to yield information on the performance of climate models and guide their improvement. Here, we present a user-oriented document describing the latest version of RCMES, its development process, and future plans for improvements. The main objective of RCMES is to facilitate the climate model evaluation process at regional scales. RCMES provides a framework for performing systematic evaluations of climate simulations, such as those from the Coordinated Regional Climate Downscaling Experiment (CORDEX), using in situ observations, as well as satellite and reanalysis data products. The main components of RCMES are (1) a database of observations widely used for climate model evaluation, (2) various data loaders to import climate models and observations on local file systems and Earth System Grid Federation (ESGF) nodes, (3) a versatile processor to subset and regrid the loaded datasets, (4) performance metrics designed to assess and quantify model skill, (5) plotting routines to visualize the performance metrics, (6) a toolkit for statistically downscaling climate model simulations, and (7) two installation packages to maximize convenience of users without Python skills. RCMES website is maintained up to date with a brief explanation of these components. Although there are other open-source software (OSS) toolkits that facilitate analysis and evaluation of climate models, there is a need for climate scientists to participate in the development and customization of OSS to study regional climate change. To establish infrastructure and to ensure software sustainability, development of RCMES is an open, publicly accessible process enabled by leveraging the Apache Software Foundation's OSS library, Apache Open Climate Workbench (OCW). The OCW software that powers RCMES includes a Python OSS library for common climate model evaluation tasks as well as a set of user-friendly interfaces for quickly configuring a model evaluation task. OCW also allows users to build their own climate data analysis tools, such as the statistical downscaling toolkit provided as a part of RCMES.



**1 Introduction**

The anthropogenic climate change signal in the Earth system is not globally uniform. Instead, the magnitude and character of climate change, including long-term trends, year-to-year variability, and characteristics of extremes of key meteoro-

**Published by Copernicus Publications on behalf of the European Geosciences Union.**