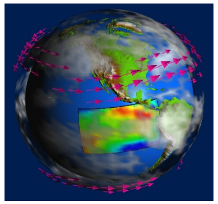
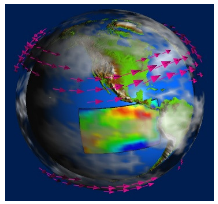
Dynamical Downscaling of Weather & Climate Model Outputs

Mohamed Rasmy



River and Environmental Eng. Lab.

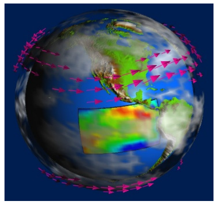


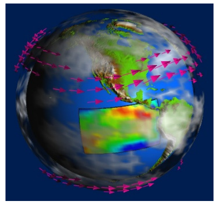
The University of Tokyo

Outline

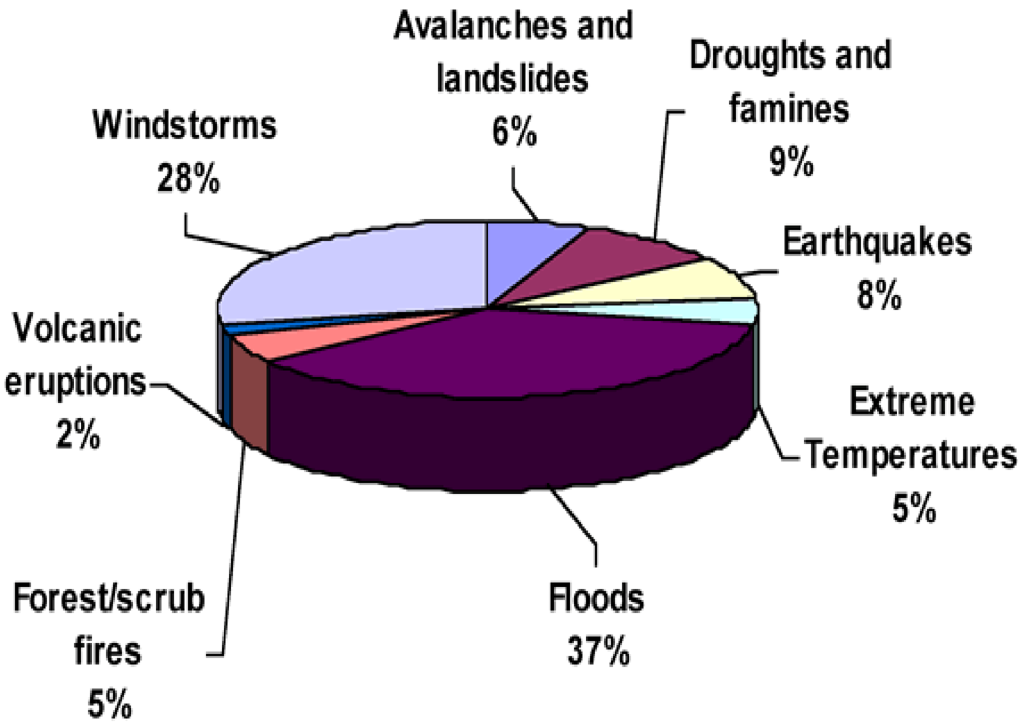
- ✓ Introduction
- ✓ Weather Forecast
  - ✓ Model calibration
  - ✓ Downscaling/nesting
  - ✓ Initial conditions/Boundary conditions
  - ✓ Improvement of IC/BC and Data Assimilation
- ✓ Climate Projections
  - ✓ Psuedo Global Warming Downscaling (PGW-DS) experiments

Introduction





Weather affects everyone, every day



Close to 90 % of all natural disasters are the result of hazards such as floods, droughts, tropical cyclones, severe storms...

Numerical Weather Prediction (NWP)

- The technique used to obtain an objective forecast of the future weather (up to possibly two weeks) by solving a set of governing equations that describe the evolution of variables that define the present state of the atmosphere.

A Brief History

- Recognition by V. Bjerknes in 1904 that forecasting is fundamentally an initial-value problem .
- L. F. Richardson's (1922) attempt at practical NWP
- Radiosonde invention in 1930s made upper-air data available
- Late 1940s: First successful dynamical-numerical forecast made by Charney, Fjortoft, and von Neumann
- 1960s: Edward Lorenz showed the atmosphere is chaotic and its predictability limit is about two weeks

Basic or Governing Equation of Earth's Atmosphere

$$\frac{Du}{Dt} - \frac{uv\tan\phi}{a} + \frac{uw}{a} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + 2\Omega v\sin\phi - 2\Omega w\cos\phi + F_{rx}$$

$$\frac{Dv}{Dt} + \frac{u^2\tan\phi}{a} + \frac{vw}{a} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - 2\Omega u\sin\phi + F_{ry}$$

$$\frac{Dw}{Dt} - \frac{u^2 + v^2}{a} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + 2\Omega u\cos\phi + F_{rz}$$

Conservation of momentum

Newton's 2nd law → Navier-Stokes equations (u,v,w)

$$\frac{D\rho}{Dt} = -\rho\nabla\bullet\mathbf{U}$$

Conservation of Mass (ρ)

$p = \rho RT$ and $\alpha = 1/\rho$

Ideal gas law (P)

$$c_v\frac{DT}{Dt} + p\frac{D\alpha}{Dt} = J$$

Thermodynamic energy equation (T)

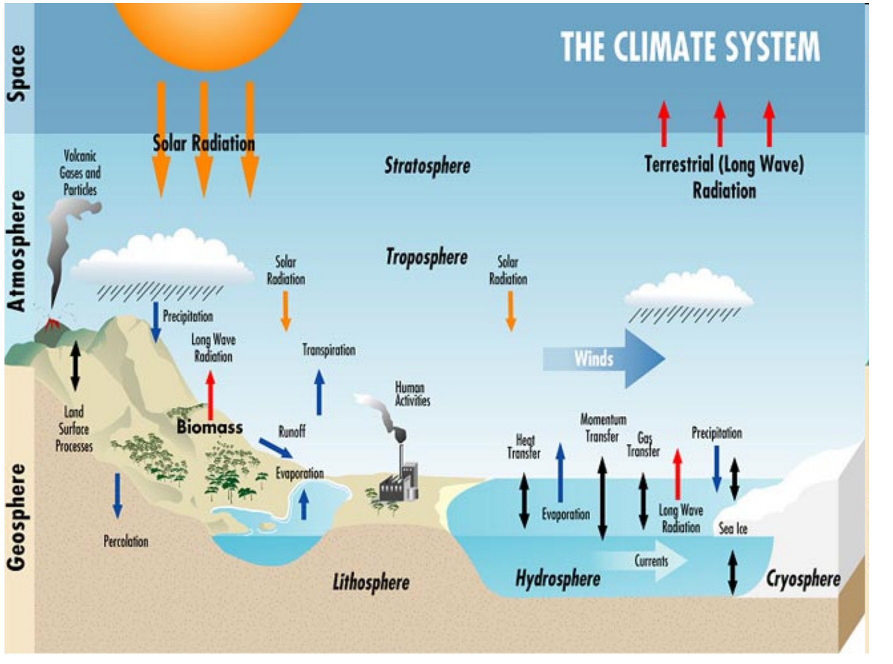
Currently, we have **6 independent variables** u, v, w, ρ, p, T & **6 equations**.

Also: moisture, salinity etc. conservation, radiation, cloud physics, turbulance, vegetation, snow, ice, ocean → too complecated

Weather and Climate System

The weather/climate system is an <u>interacting system</u> consisting of five major components:

1. Atmo-sphere
2. Geo-sphere (land surface)
3. Hydro-sphere
4. Bio-sphere
5. Cryo-sphere.
6. Anthropo-sphere (Human)



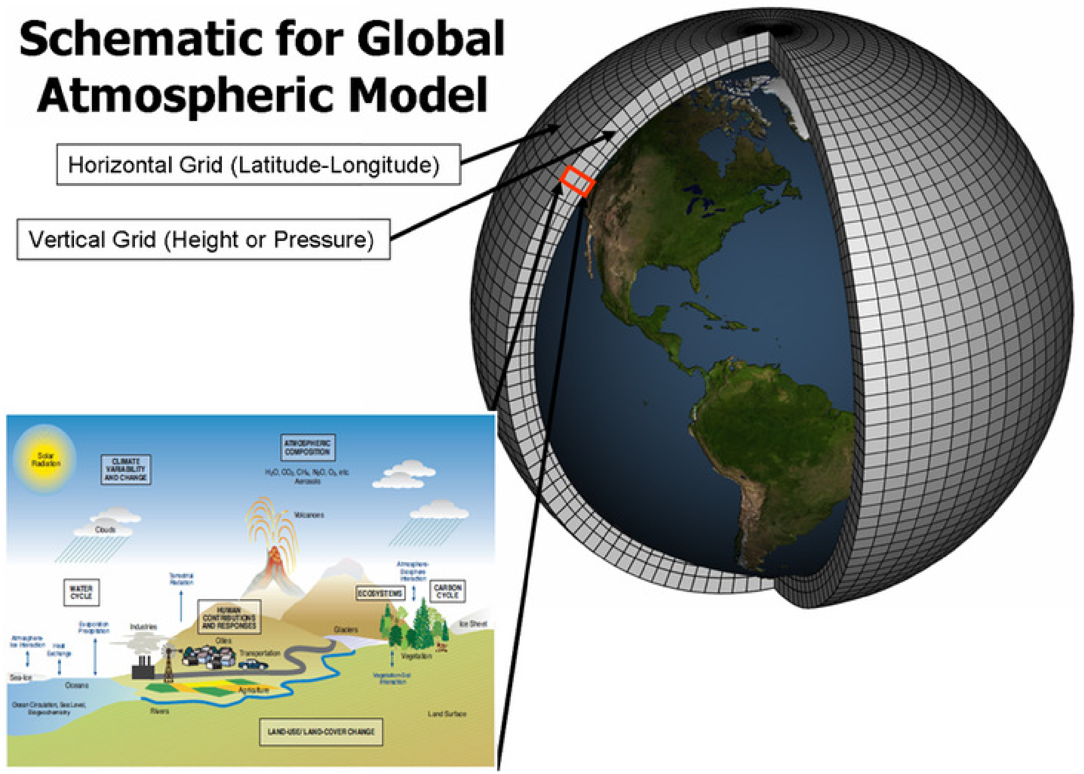
It is influenced by various external forcing mechanisms *(the Sun, changes in orbit and chemical compositions and volcanic dust).*

GCMs – Fundamental tool for weather & climate

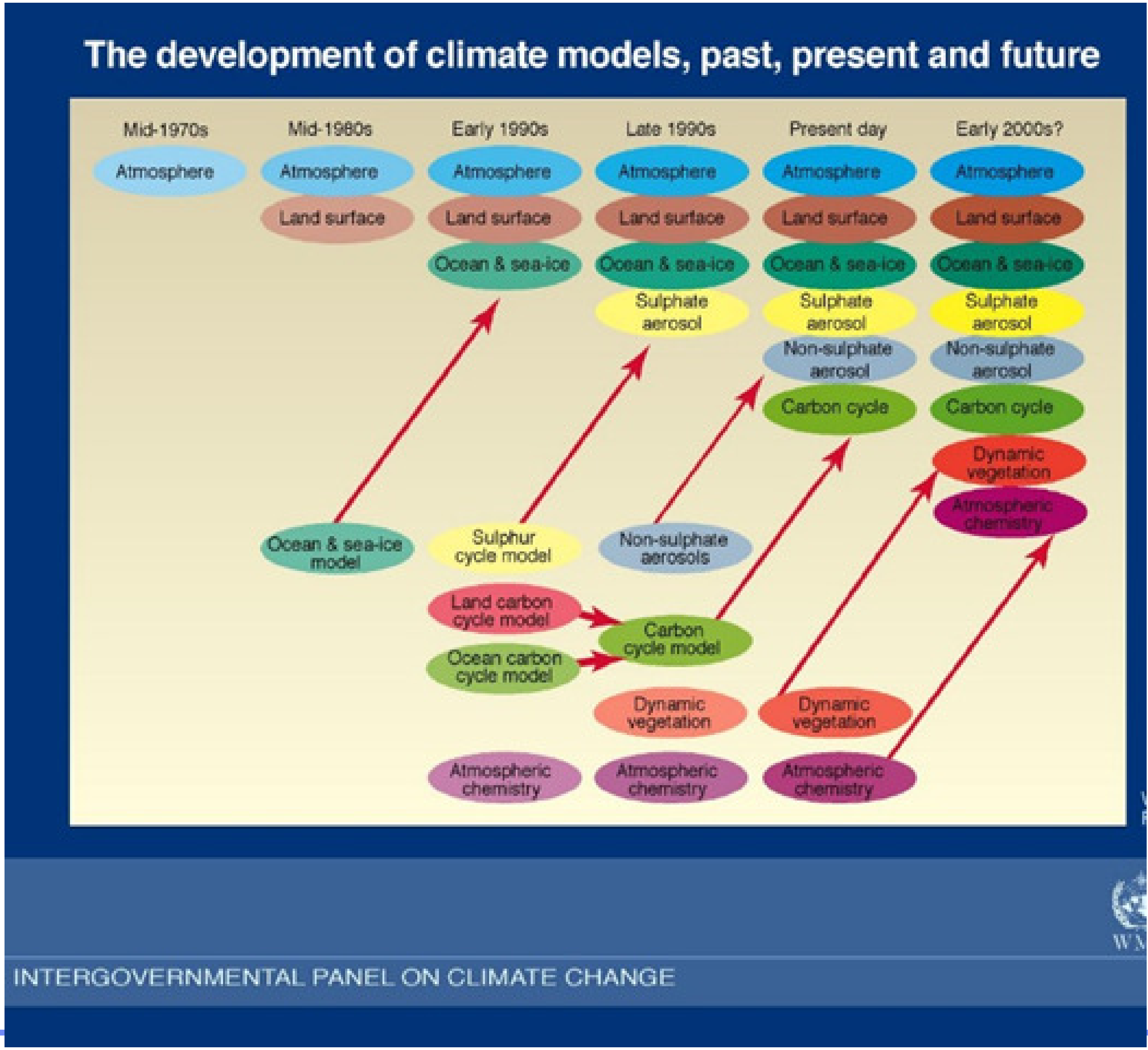
A General Circulation Model (GCM) is a mathematical model of the general circulation of the planet's atmosphere (and oceans) based on mathematic equations that represent physical processes.

The primary earth system components in GCM include the atmosphere, oceans, land surface – including vegetation, and the cryosphere (ice and snow)

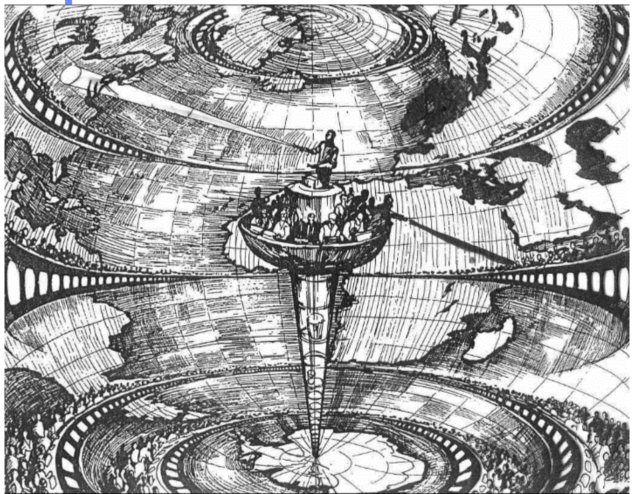
→ more complicated but major hope for reliable results



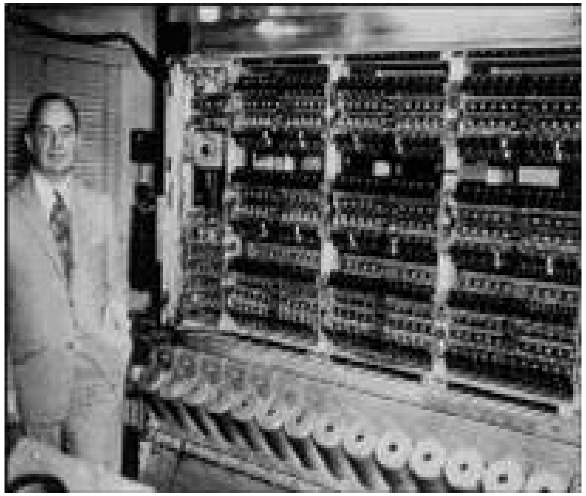
Evolution of GCMs



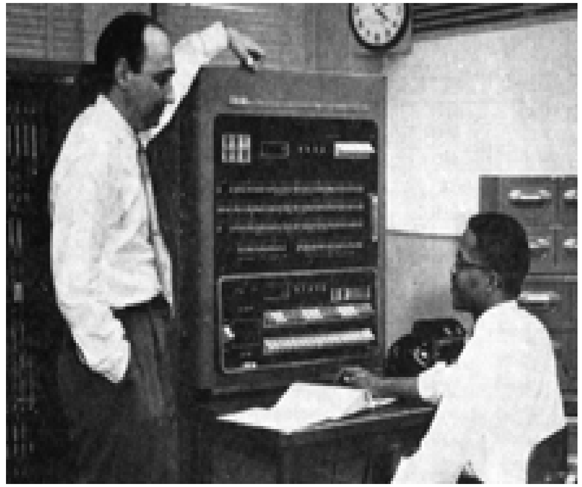
Advancement of computer power used in NWP



Richardson’s forecast factory with 64,000 human “computers”-1922



Neumann and the ENIAC computer.- 1948



IBM 701 was the first computer used by the JNWPU operational NWP-1954

Computers in JMA

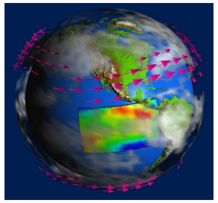
サーバ
- CPU80コア
- メモリ2048GB

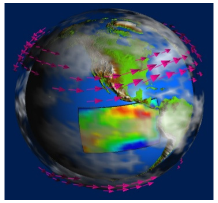
サーバ(クラスタ)
- 60ノード
- CPU20コア/ノード
- メモリ64GB/ノード
- 演算コプロセッサ搭載

ディスクアレイ
- ~11.6PB

DIAS/ Data archiving, analysis, and simulation Unit

Downscaling of Weather Forecast





Numerical Weather Forecast

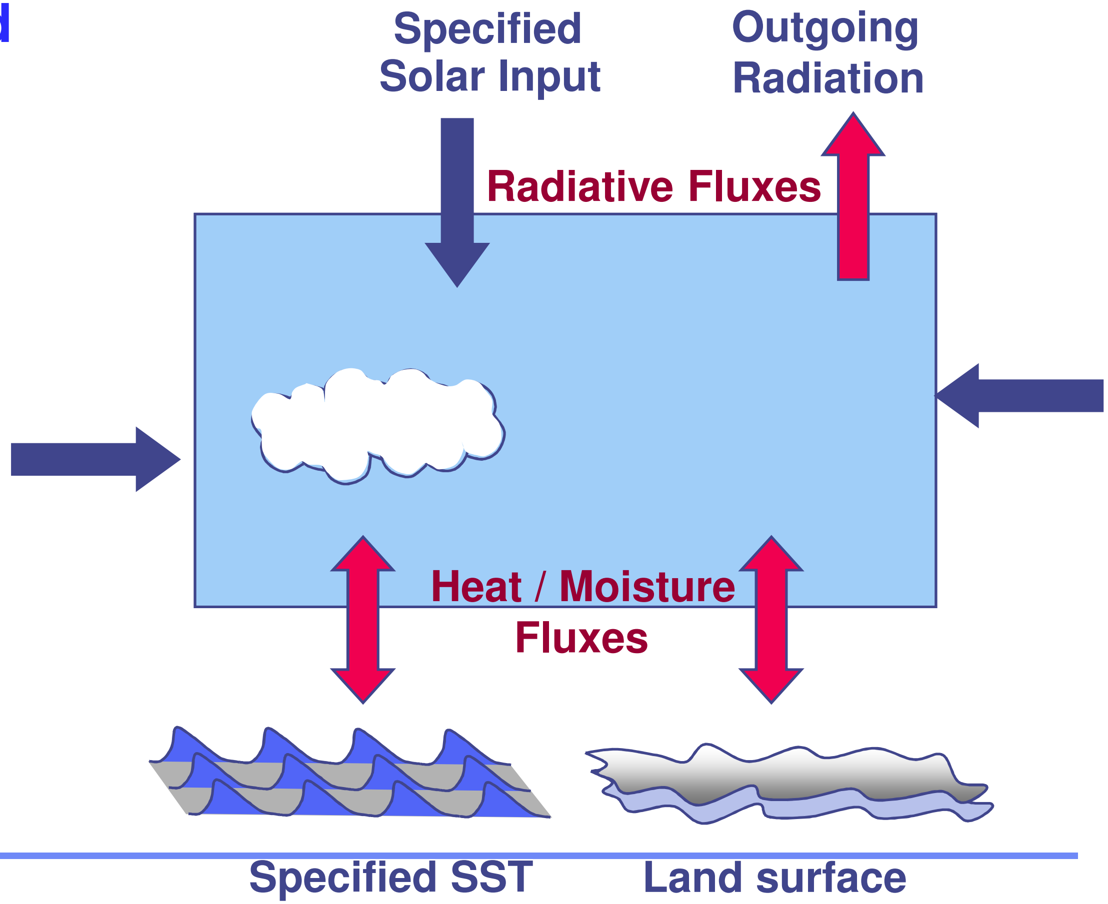
- Initial state is CRITICAL
- Non-conservation of mass/energy to match observed state

State of atmosphere & Land Surface:

P, T, q, u, v, w
Soil moisture, vegetation
SST
…

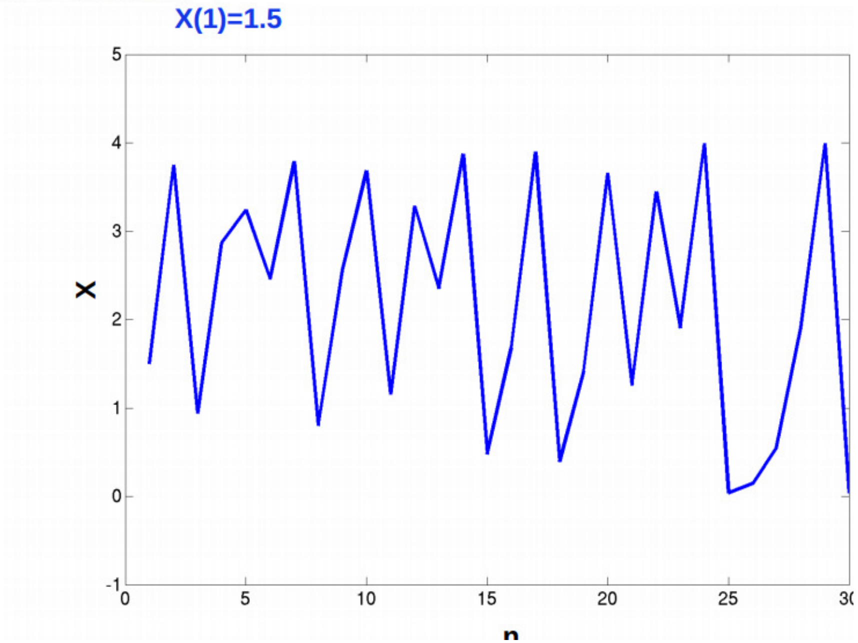
Primary Configuration

Clouds microphysics
Moist Convection
Land Surface Physics
Radiative Transfer
Boundary layer



Important of Initial State (Observations) in NWP

A typical climate model non-linear equation: $X(n+1) = A\,X(n) - X(n)^2$
Assume constant A=4



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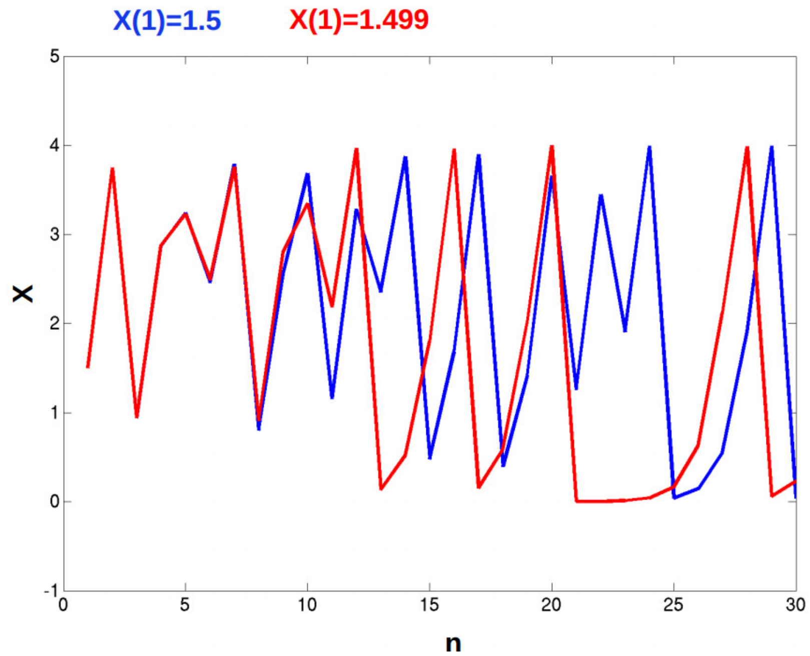
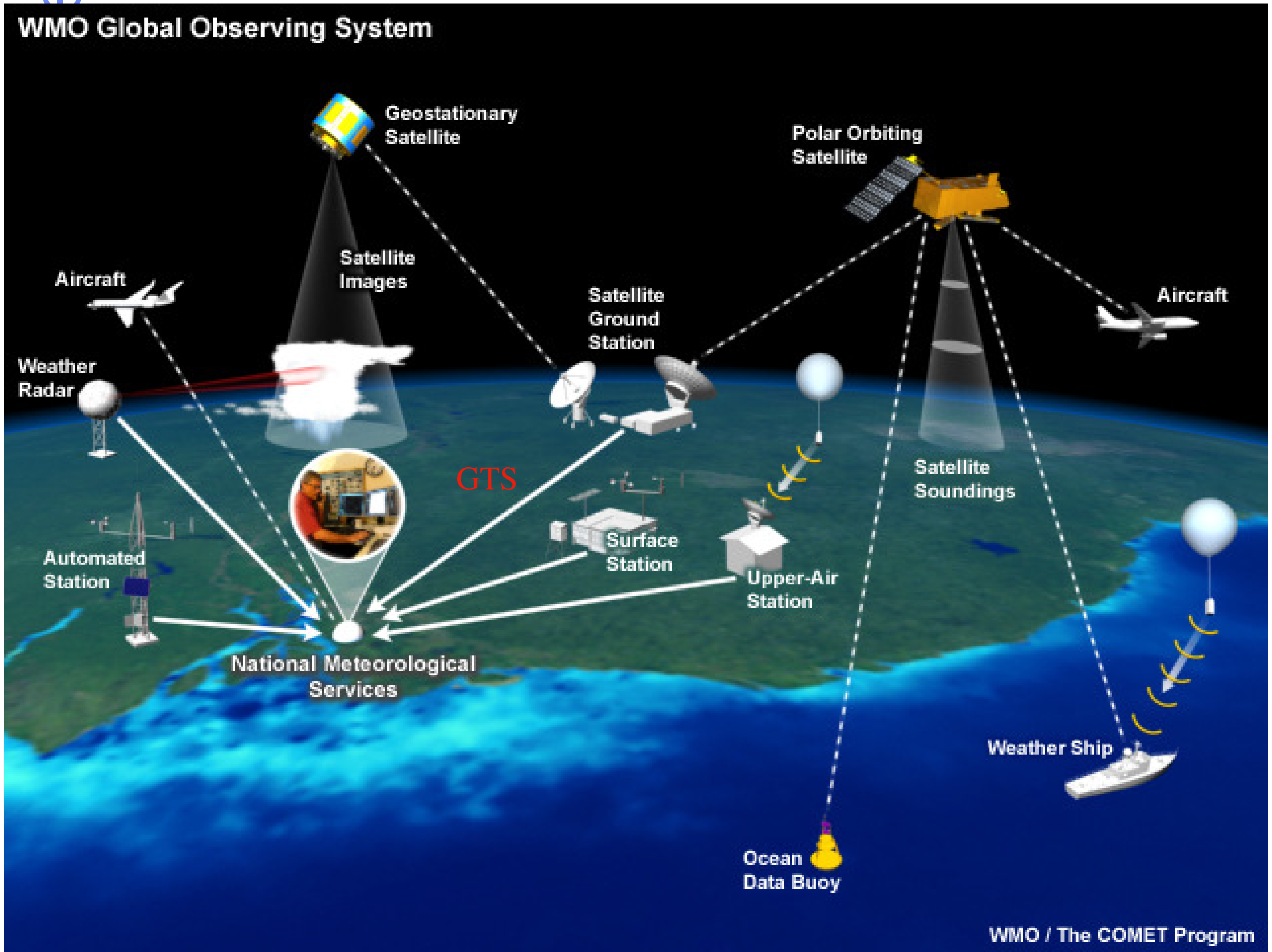
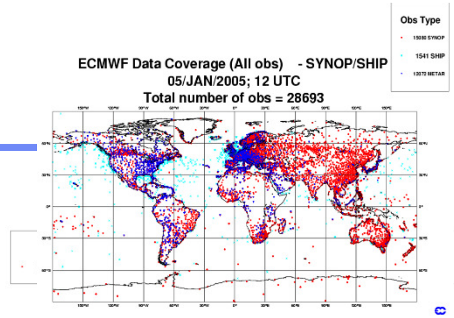
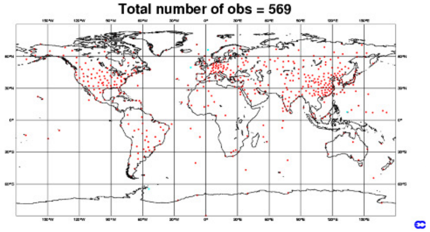
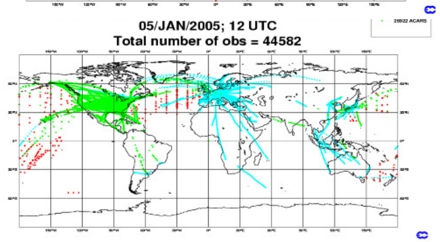


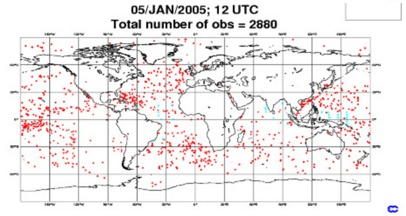
WMO Global Observing System



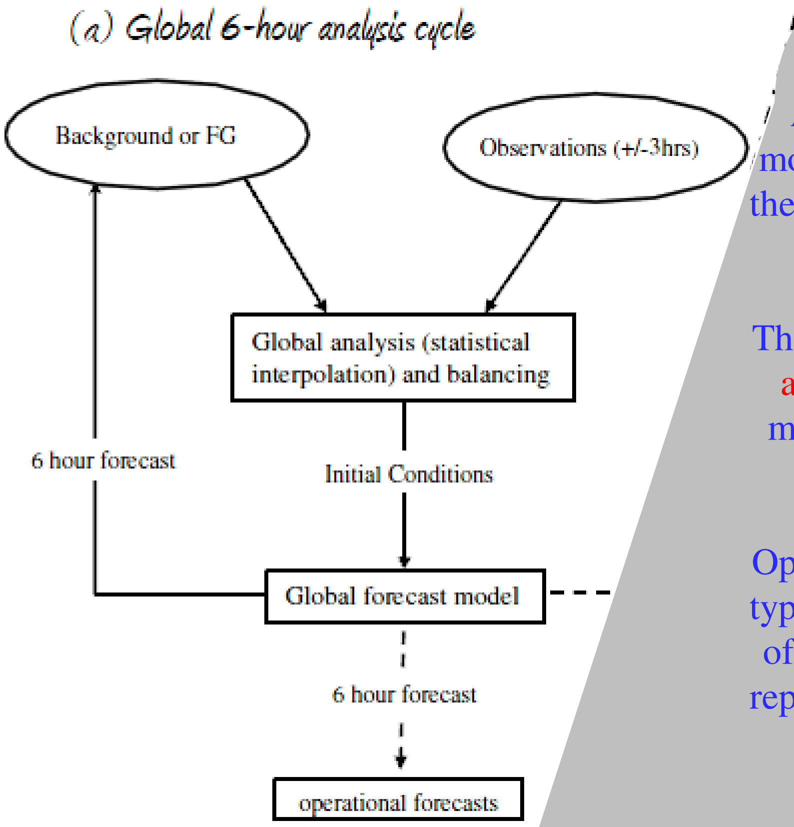








Operational Forecasting: Improvement of Initial conditions



Available observational data usually do not include all of the model's prognostic fields, have different spatial distribution from the forecast model grid, are valid over a range of times rather than a single time, and are also subject to observational error.

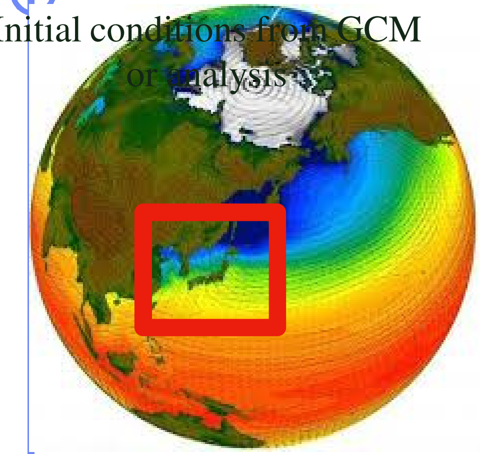
The technique of data assimilation is therefore used to produce an analysis of the initial state, which is a best fit of the numerical model to the available data, taking into account the errors in the model and the data.

Operational analysis dataset (used for the real-time forecasts) will typically suffer from inconsistency if it spans any extended period of time. Reanalysis projects (JMA, ECMWRF, NCEP) involves reprocessing (additional) observational data spanning an extended historical period using a consistent modern analysis system.

FIGURE 3.1: Schematic representation of operational analysis cycles (a) global 6-h analysis cycles performed at 00, 06, 12, at UTC (b) regional 1-hr analysis cycles.

Nesting of RCM with GCM

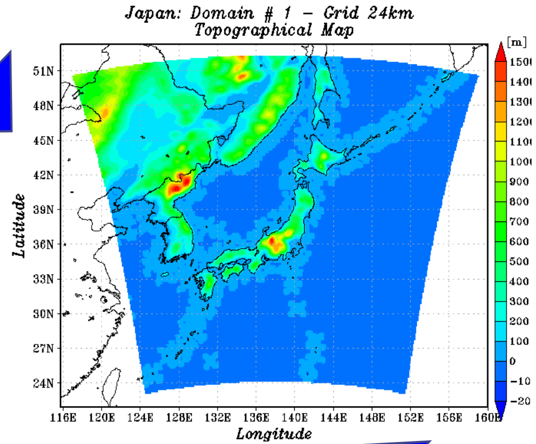
Initial conditions from GCM or analysis



GCM simulate the response of the global circulation to large-scale forcings but at course resolutions (computational constrains) → to bridge the gap between global and local scale, nesting was implemented to obtain more information on local weather.

GCM → Initial and time-varying lateral and surface boundary conditions to capture the important synoptic- and mesoscale features.

One-way Nesting- information in one direction

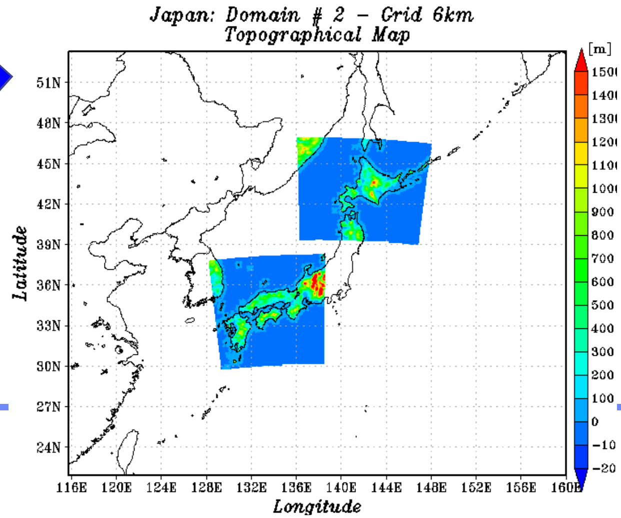


Goal of nesting:

•Provide good environment reasonable boundary condition of large-scale environment to the innermost grid.

•Enables running at finer resolution at low computational cost with mismatched time and spatial lateral boundary conditions

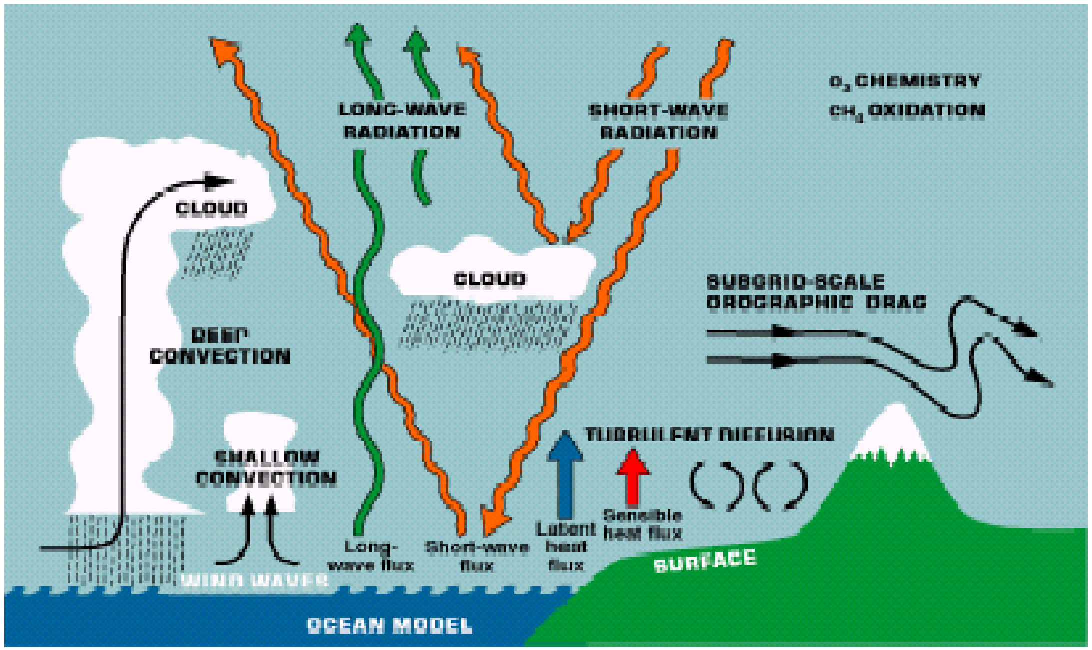
Two-way Nesting- information in both direction



➢ The RCM account for sub-GCM grid scale forcings (e.g., complex topographical features and land cover inhomogeneity) in a physically-based way to enhance the simulation of atmospheric circulations and climatic variables at fine spatial scales.

Concept of Parameterizations

- Trade-off between computational costs and resolutions
- The complexity is often reduced in GCM by parameterizations, which describe their larger-scale effect from known quantities.
  - Computers are not powerful enough to directly treat the concerned physical process, because the phenomena are too small or too complex to be resolved numerically
  - Processes are not understood well to be represented by an equation
  - Processes strongly affect model fields and can't be neglected in creating realistic outputs.



Some sub-grid scale processes that are parameterized in ECMWF model.

Weather Research and Forecasting (**WRF**) **Model**

What is WRF?

- State-of-the-art mesoscale atmospheric modeling system

  designed to serve both atmospheric research & NWP communities

  (flexible, modular, ...)

- Solves fully compressible non-hydrostatic Euler equations

  (conservation of mass, momentum, energy)

  designed for use at scales ranging from meters to 1000s of kilometers

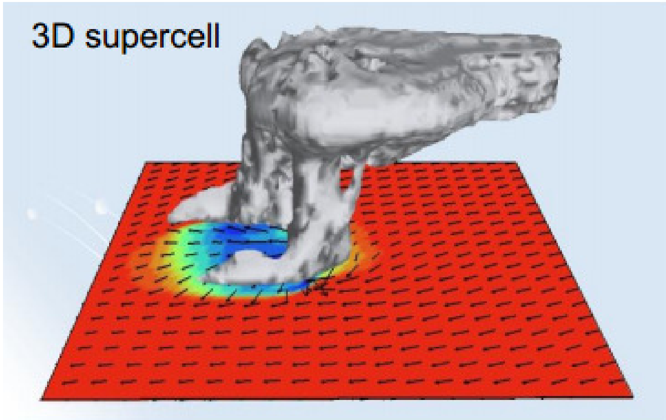
- Community model

  distributed development, centralized support

- Primary developers

  NCAR, NOAA-ESRL, NOAA-NCEP

  + universities & govt agencies in U.S. and oversees



WRF Physics and Parameterization

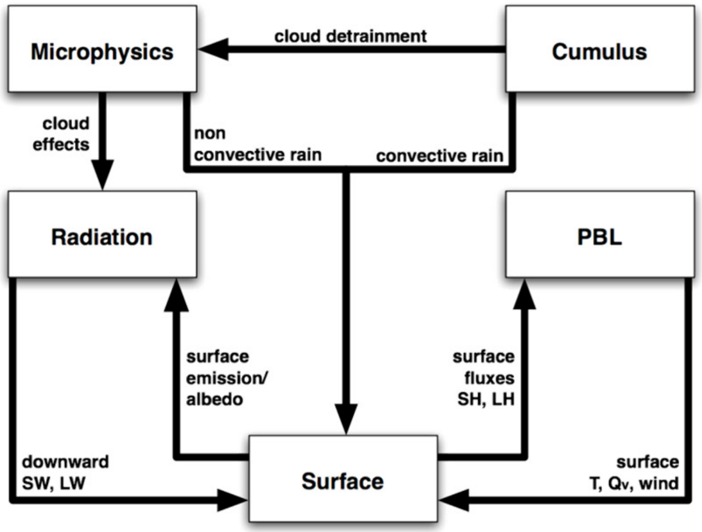
WRF Physics Modules & Coupling

Dynamics Solver – *integrates the compressible non-hydrostatic Euler equations (ARW, NMM)*

- Shortwave Radiation
  - *Dudhia, Goddard, CAM, RRTMG, FLG, GFDL*
- Longwave Radiation
  - *RRTM, CAM, RRTMG, Goddard, FLG, Held-Suarez, GFDL*
- Cloud Microphysics
  - *Kessler; Lin; NCEP; WSM 3,5,6 class; Eta; Goddard; Thompson; Milbrandt; Morrison; SBU-Ylin; WDM 5,6 class, NSSL 2-moment*
- Cumulus Cloud Parameterization
  - *Kain-Fritsch, Betts-Miller-Janjic, Grell-Devenvi, Arakawa-Schubert, Grell-3, Tiedtke, Zhang-McFarlane, new SAS*
- Planetary Boundary Layer
  - *YSU, MYJ, GFS, QNSE, MYNNx, ACM2, BouLac, UW, TEMF, MRF*
- Land Surface Model
  - *Noah LSM, RUC LSM, Pleim-Xiu LSM, NoahMP, SSiB, (CLM)*

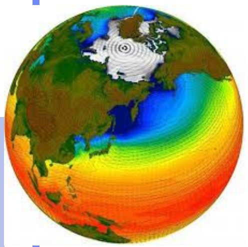
Community model
- Parameterization schemes shared by community giving rise to a collection of different schemes developed for diverse purposes and applications

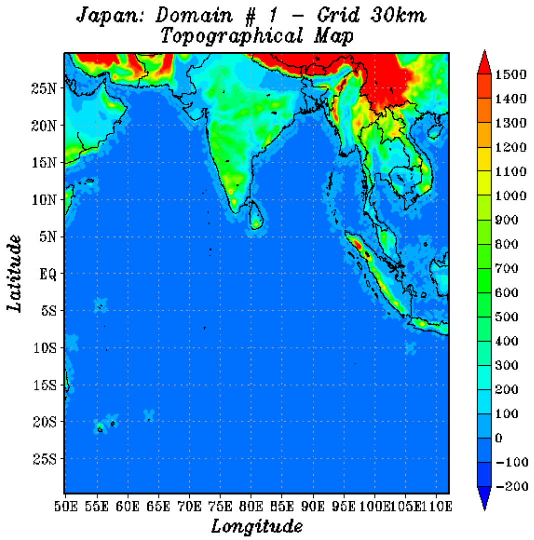
Subgrid processes



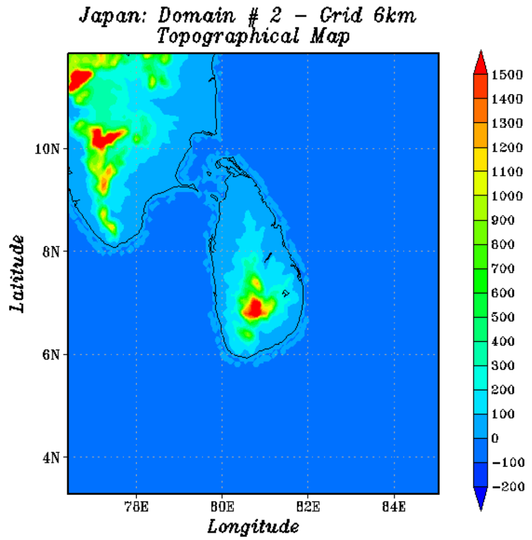
– Selection of physics and parameterizations depends on geographical region, seasons, types of events or phenomena, spatial resolutions, and etc.

WRF Simulations – Pakistan & Sri Lanka

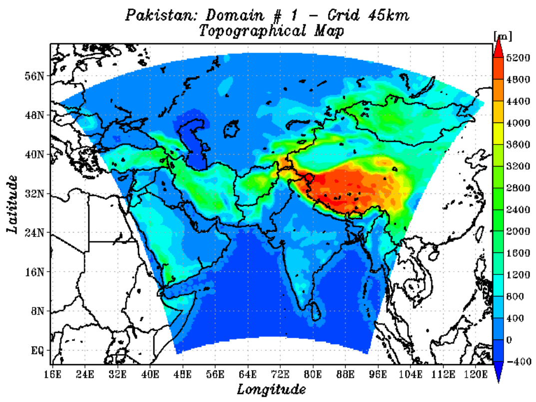




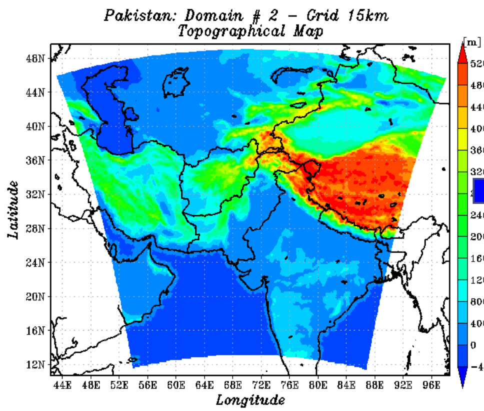
30 km



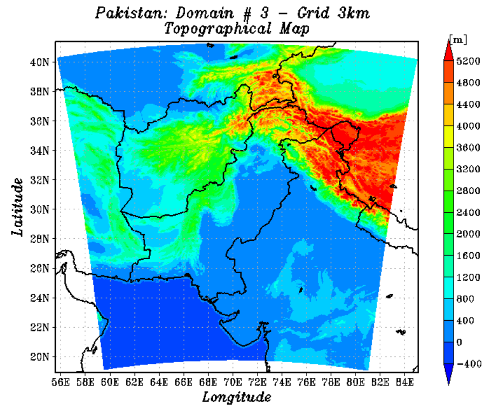
6 km



45 km



15 km

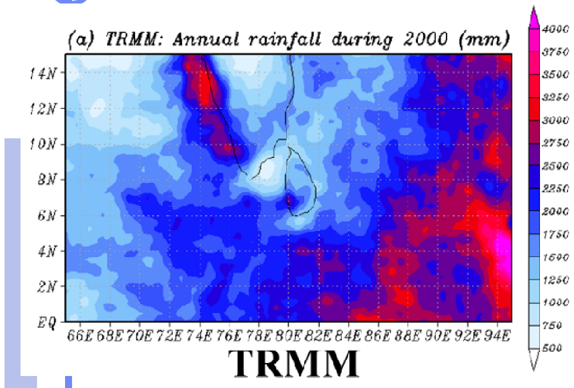


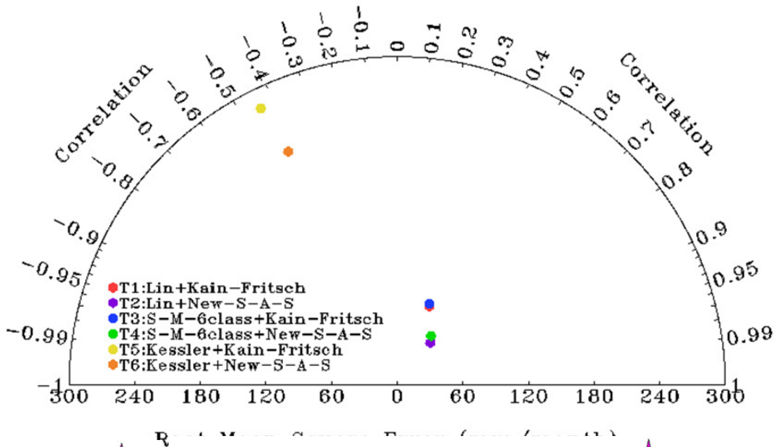
3 km

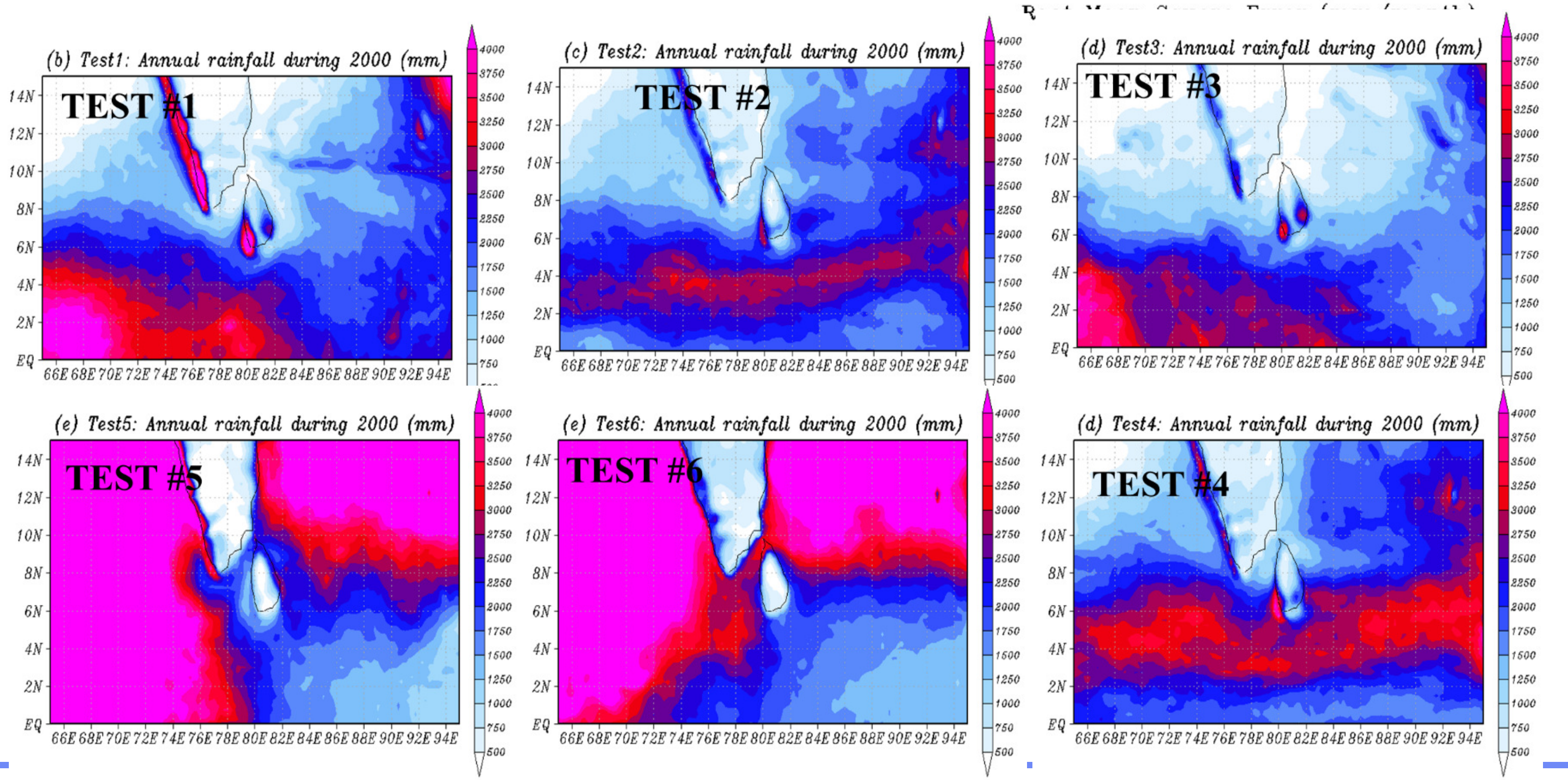
✓NECP-FNL DATA

✓Period → 28th July-29th July 2010 (2days)

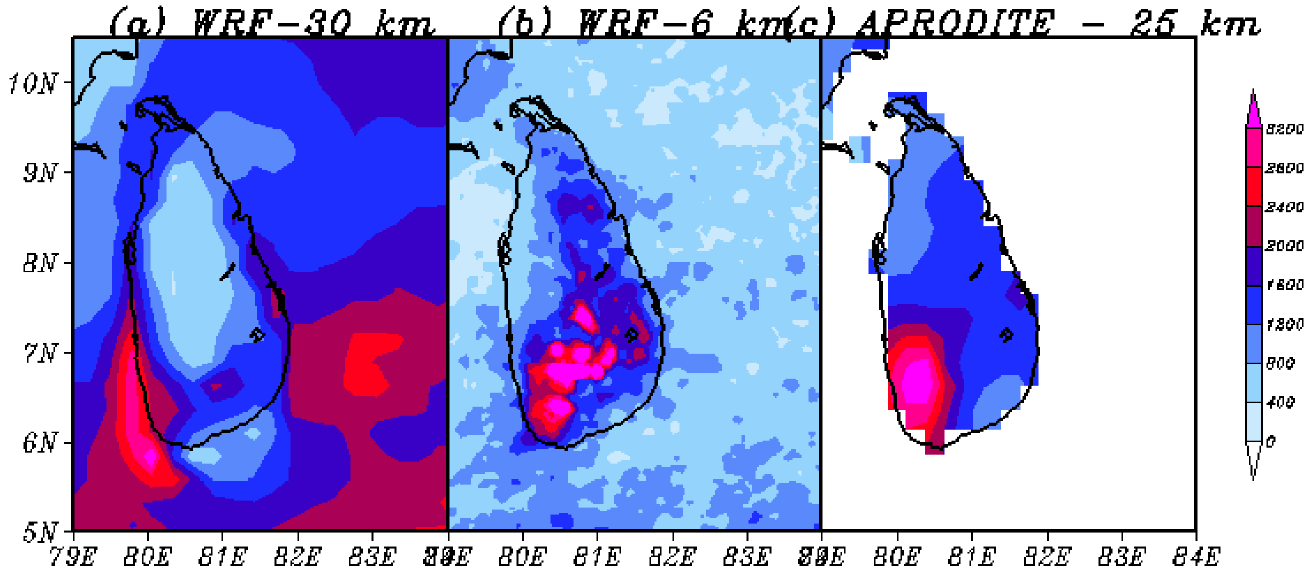
Model Calibration – Microphysics & Cumulus Parameterizations

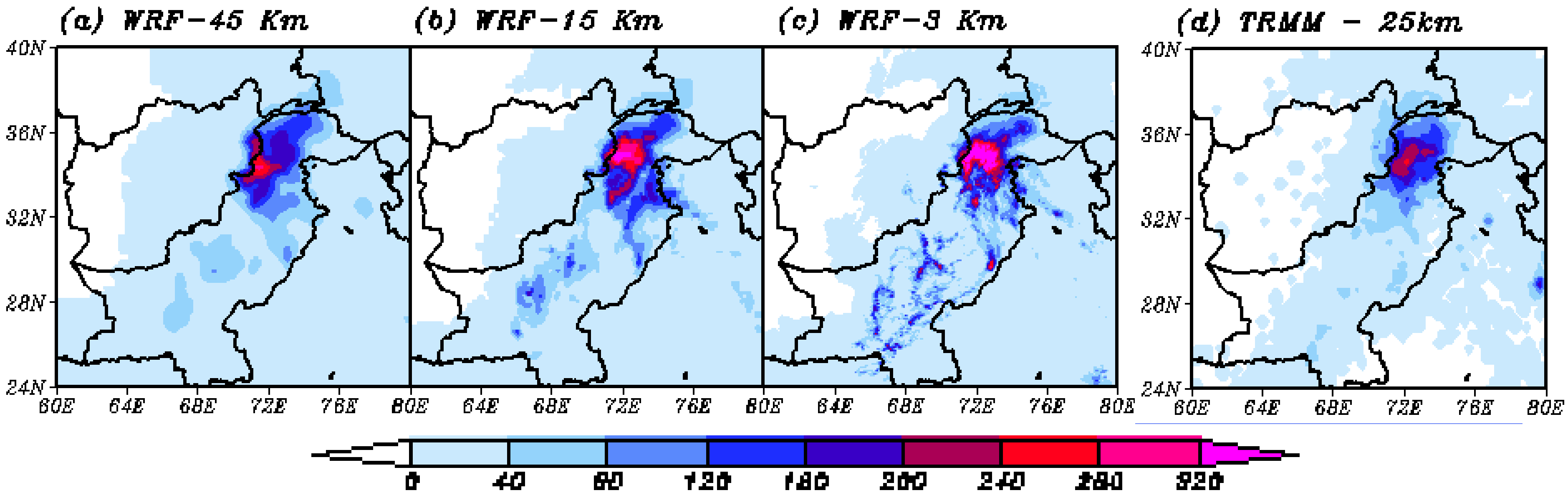




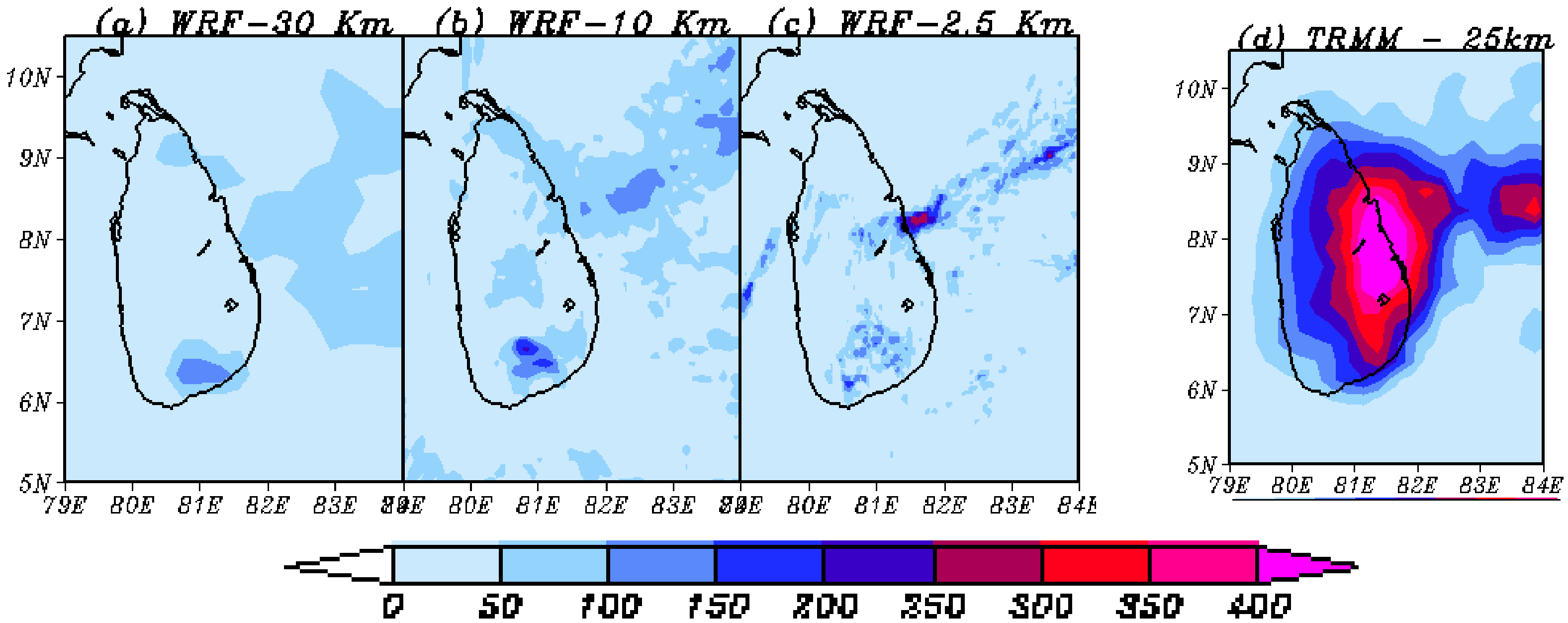


Rainfall Estimation & Validation @ different spatial resolutions





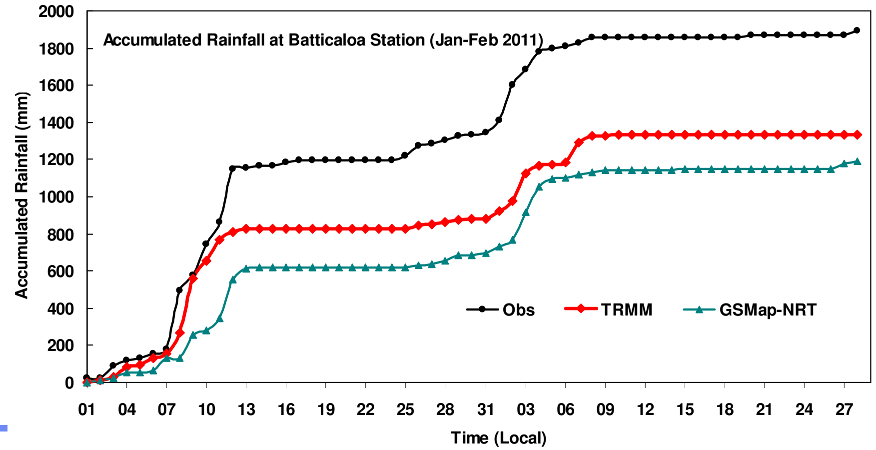
When a Weather Forecast goes Wrong !!!



✓NECP-FNL DATA

✓Period → 7th Jan.-9th Jan. 2010 (3days)

Rainfall over Sri Lanka during January 2011. The rainfall ranges up to a total of 800 mm with the heaviest rainfall over the East.



Why forecasts go wrong most of the time

- Model limitations
  - Models represent a "simplified" atmosphere - not every real process in atmosphere can be resolved in the models
  - The model equations compute quantities at grid points (50-200 km), phenomena smaller in size that grid spacing will not be resolved in models (e.g., cloud, radiations)
  - Local impact not represented in model – topography features and orography effects

- Boundary condition errors
  - Observation are not global in coverage.
  - Bias from GCM

- Initial condition errors
  - Lack of data network→ Ini. atmospheric state is not well-known
  - The data may also have errors in it.
  - chaotic nature of atmosphere → error in IC can
  - produce radically different results later in time

- Each Model can produce different forecast
  - Different physics and parameterization
  - Different data processing techniques

Data Assimilation: Improvement of IC/BC

Regional Downscaling with Data Assimilation

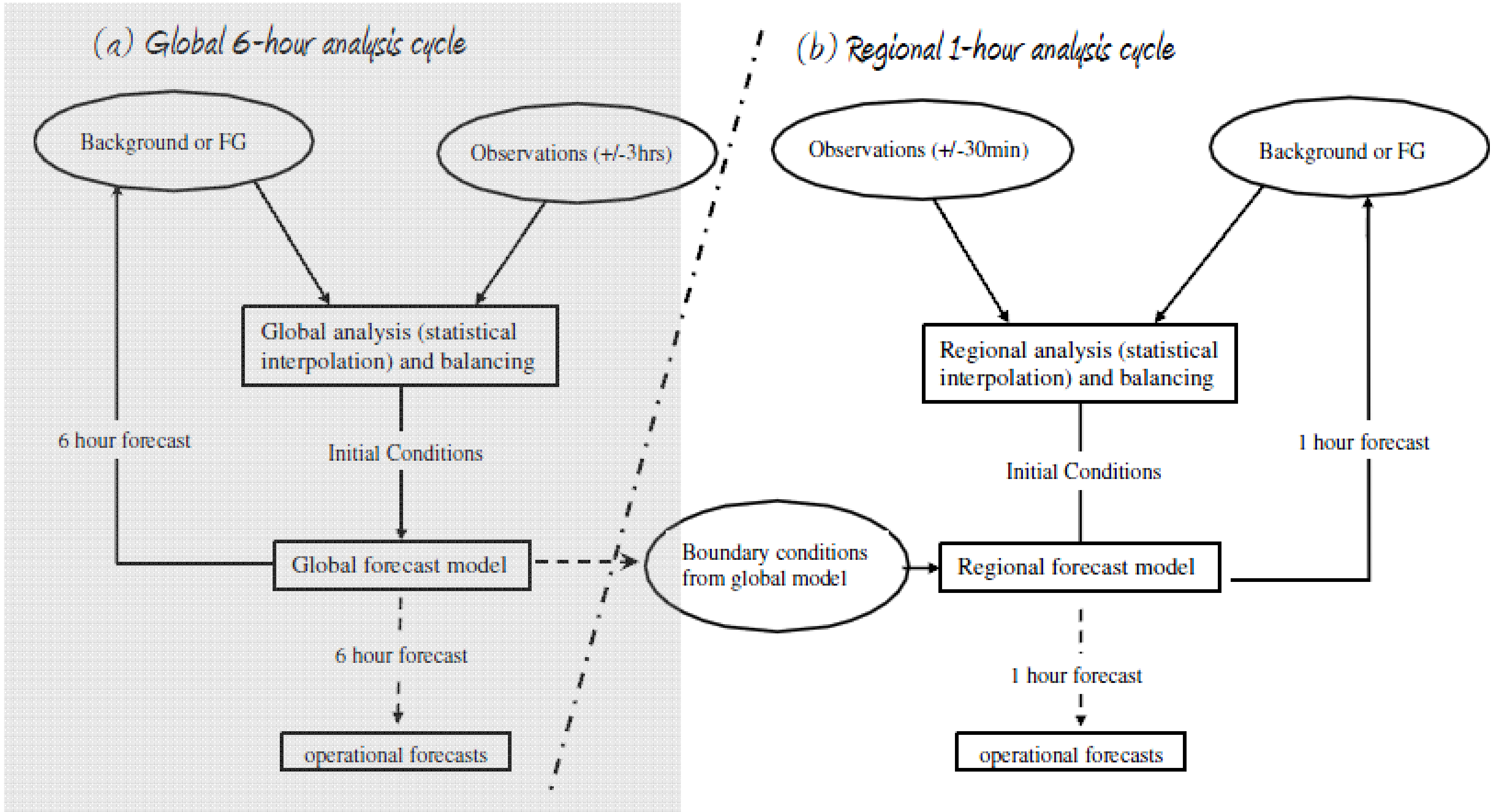
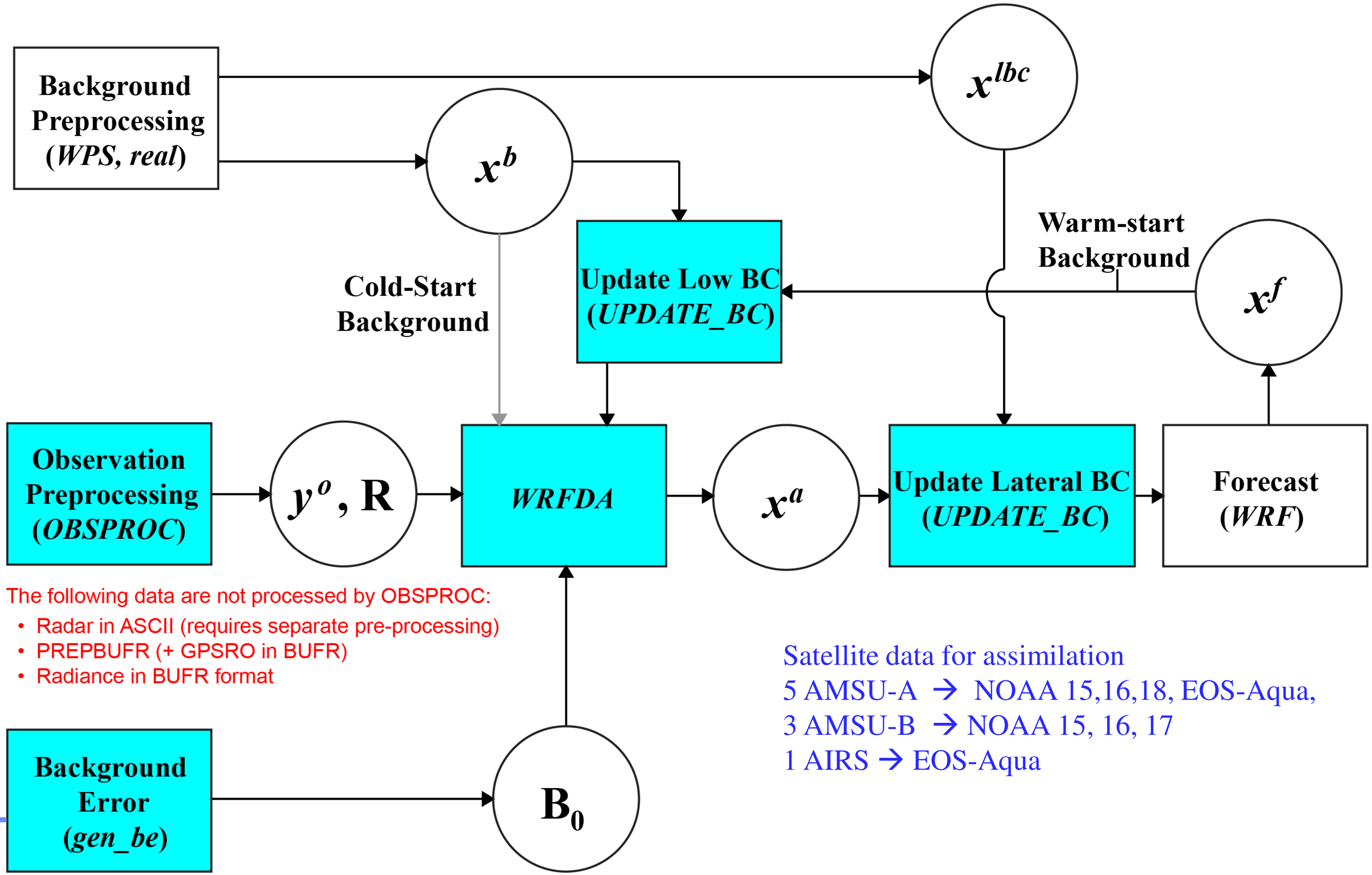


FIGURE 3.1: Schematic representation of operational analysis cycles (a) global 6-h analysis cycles performed at 00, 06, 12, at UTC (b) regional 1-hr analysis cycles.

Data Assimilation of Satellite Data in WRF

WRFDA in the WRF Modeling System

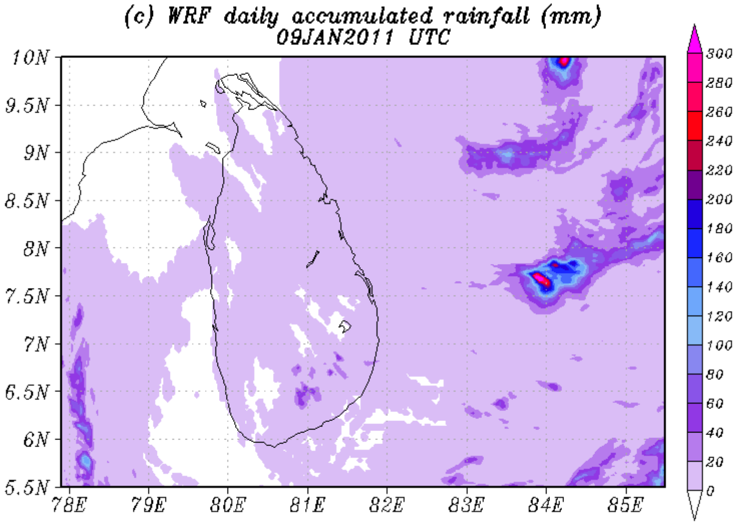


The following data are not processed by OBSPROC:

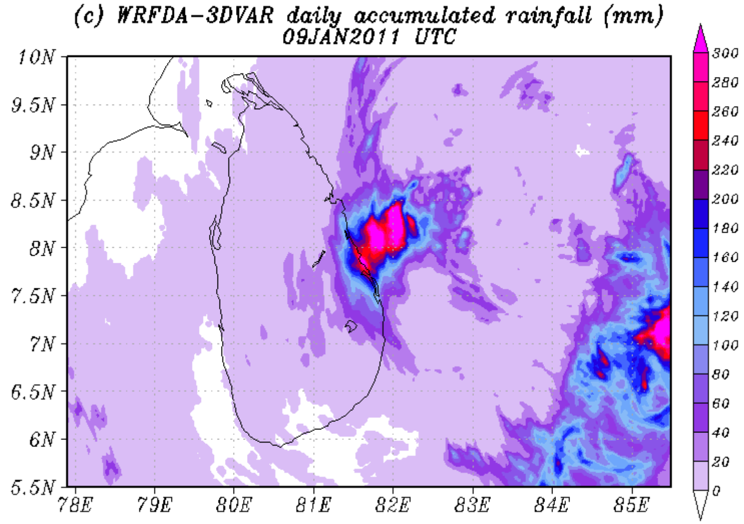
- Radar in ASCII (requires separate pre-processing)
- PREPBUFR (+ GPSRO in BUFR)
- Radiance in BUFR format

Satellite data for assimilation
5 AMSU-A → NOAA 15,16,18, EOS-Aqua,
3 AMSU-B → NOAA 15, 16, 17
1 AIRS → EOS-Aqua

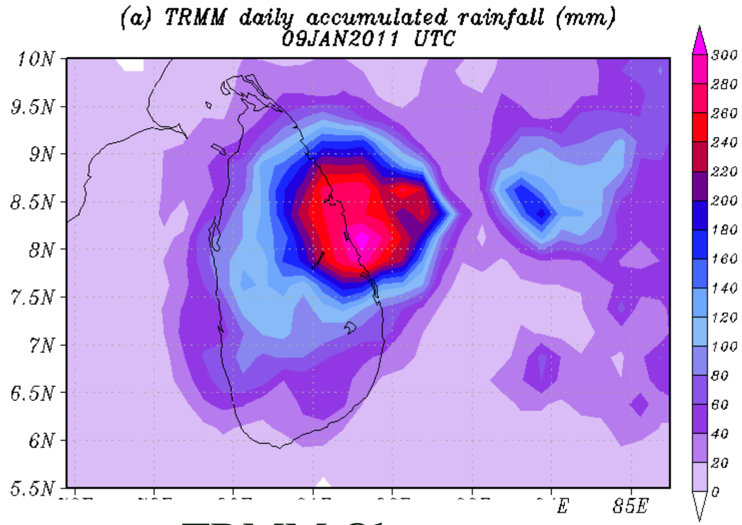
Improvement of IC/BC → Better Forecast



Downscaling



3D-Var Data Assimilation + Downscaling



TRMM Obs.

Some Common Challenges in NWP prediction

Problem I: Different components of the earth system (atmosphere, land, ocean, ice, clouds, etc) are strongly interacting with each other

("Feedback Problem")

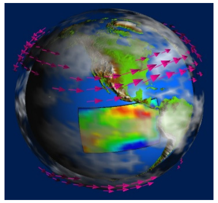
Problem II: The earth system composes of both very big objects (such as the whole Pacific Ocean) and very small objects (such as the cloud droplets), making it very difficult to draw them on the same page

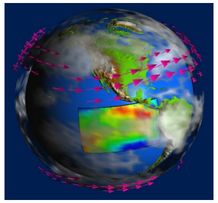
("Subgrid-Scale Problem")

Problem III: Different parts of the world are strongly connected to each other Eg. Remote impacts of Amazon deforestation

("Teleconnection Problem")

Downscaling of Climate Projections





Climate Prediction

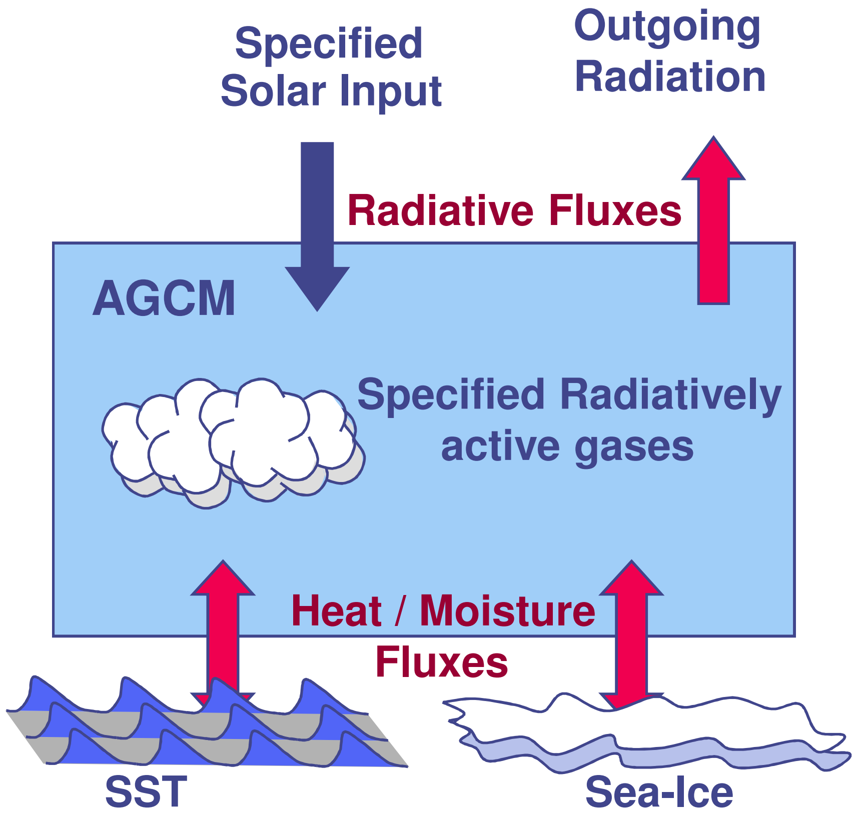
- Boundary state is CRITICAL
- Conservation of mass & energy critical

Boundary conditions:

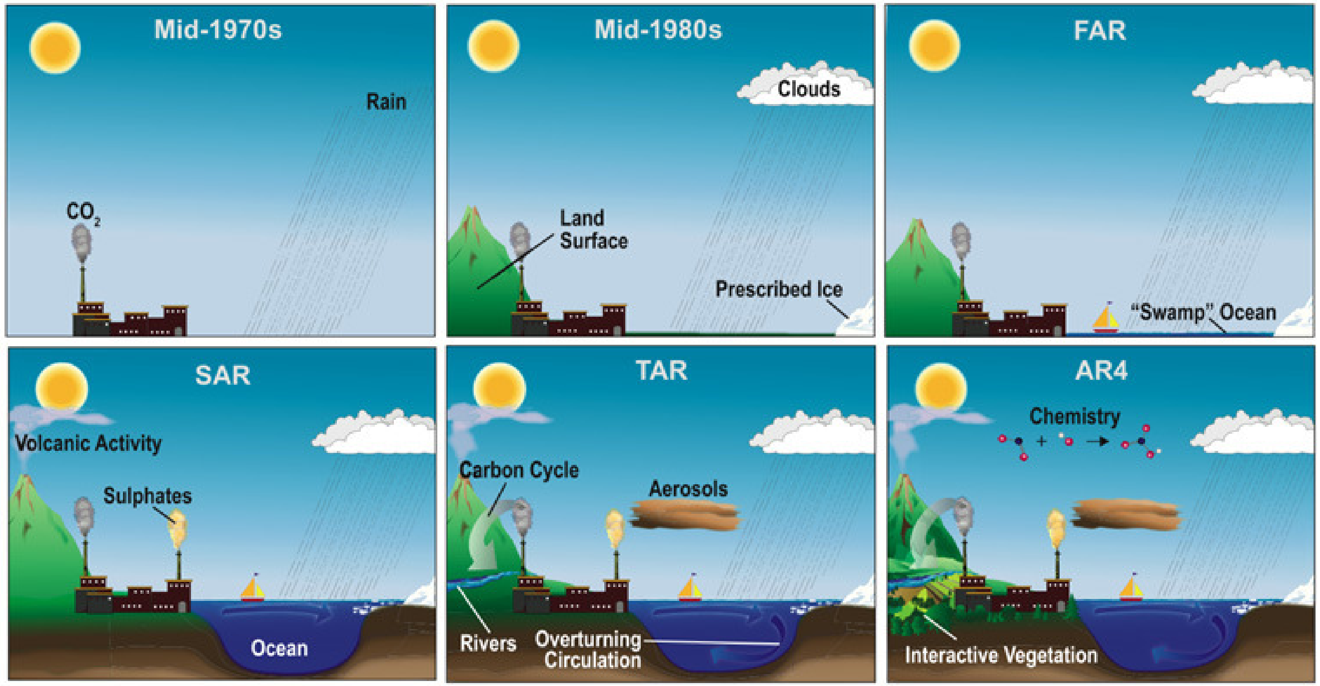
SST
Sea ice
Solar input
Radiatively active gasses (e.g. O3, CO2, NH4, N2O)
Vegetation
Valconic, anthropogenic & natural aerosols

Primary Configuration

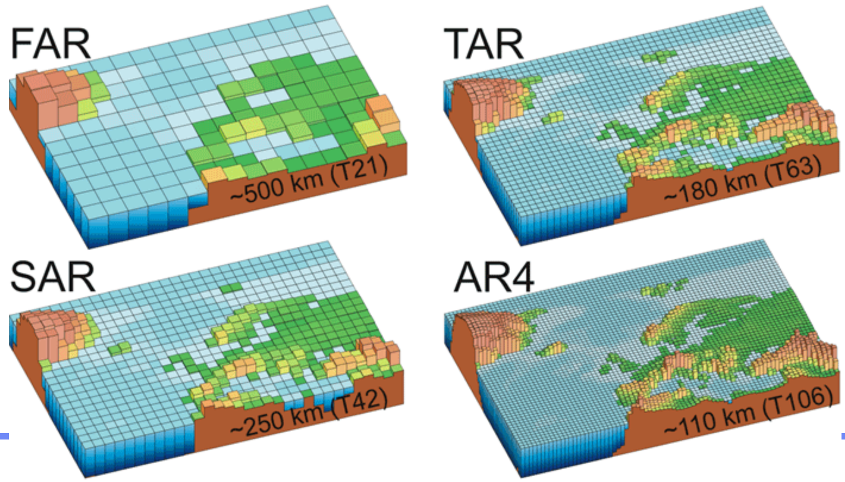
Land Surface Physics
Radiative Transfer
Clouds microphysics
Moist Convection
Boundary layer



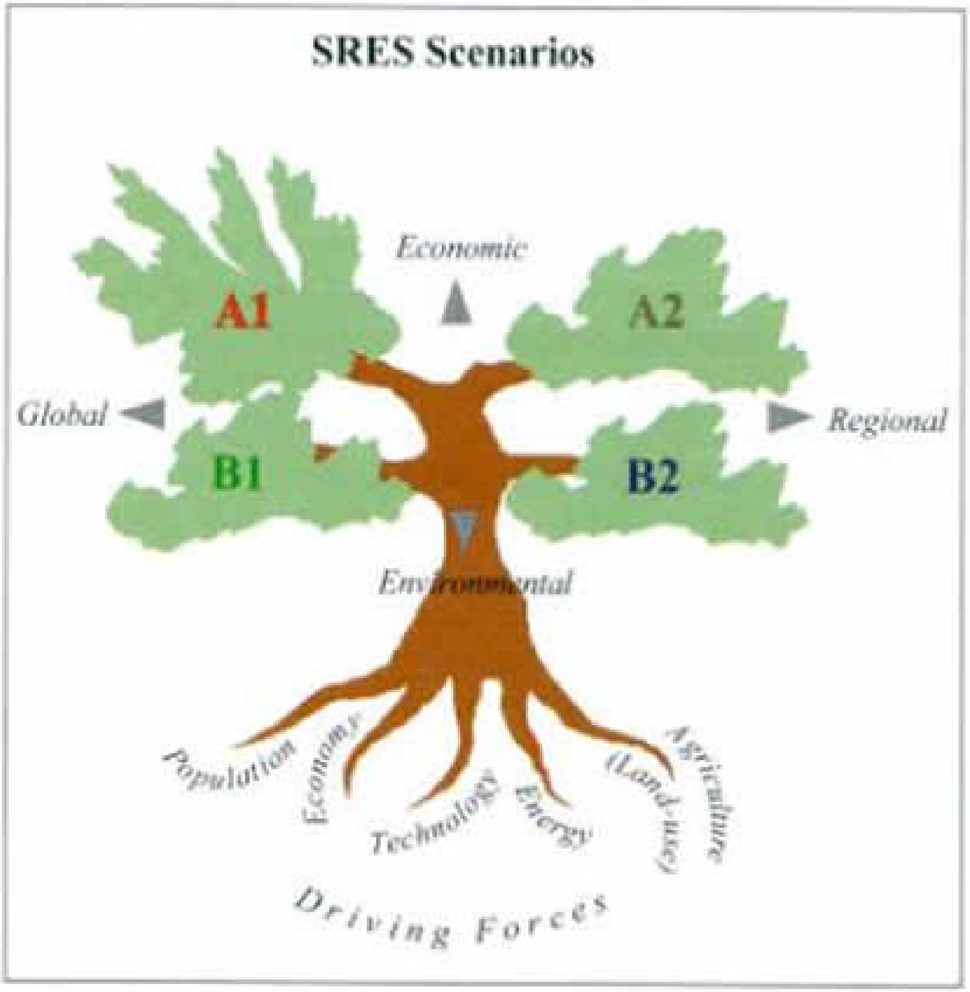
Evolution of Climate GCMs - IPCC



[AR4 WG 1 Chapter 1]



IPCC: Special Report on Emission Scenarios (SRES)



A1: a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies.

A2: a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines.

B1: a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.

B2: a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

CMIP5 Experiments

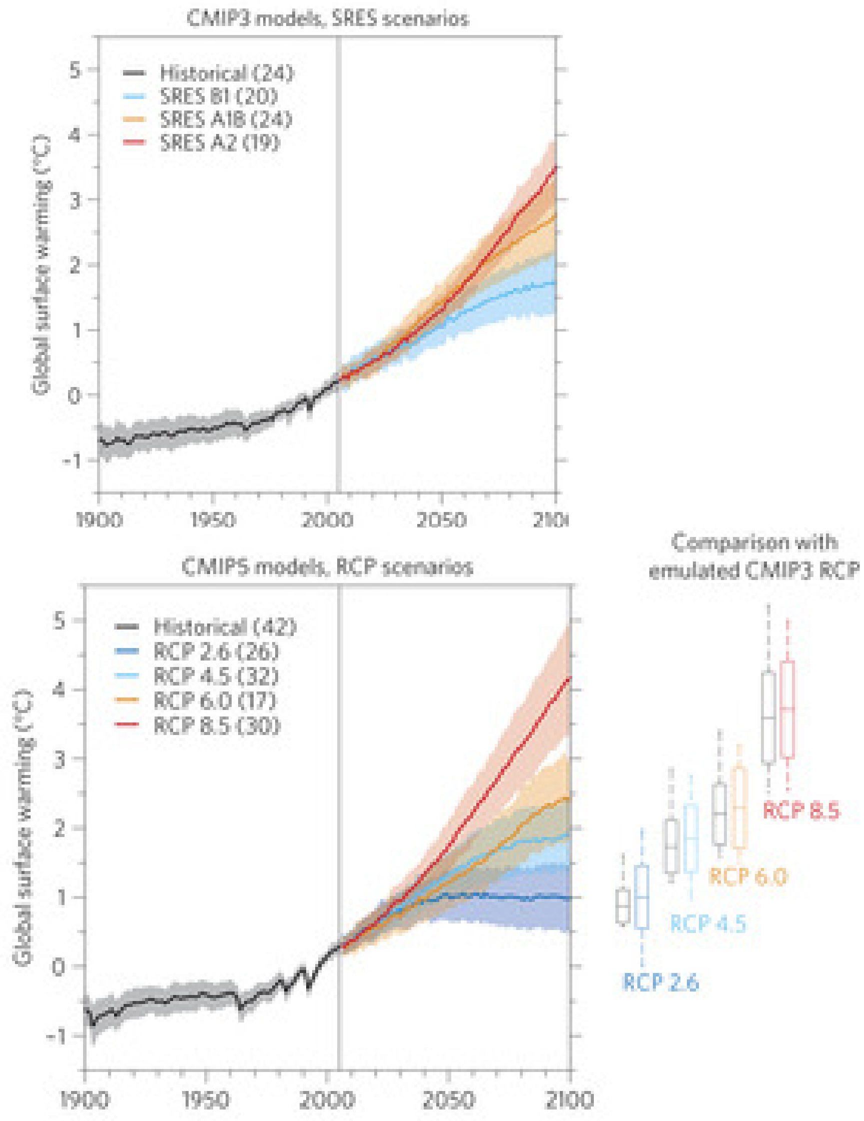
b. Future climate projections.

A collaborative process involving the WGCM, AIMES, and the Integrated Assessment Modeling Consortium has produced four emission scenarios for future climate, one non-mitigated and three taking into account various levels of mitigation. These are called “representative concentration pathways” (RCPs)[11] that will begin in year 2006 and continue through the end of year 2300. The RCPs are labeled according to the approximate target radiative forcing at year ~2100 (e.g., RCP4.5 identifies a concentration pathway that approximately results in a radiative forcing of 4.5 W m^{-2} at year 2100, relative to pre-industrial conditions). There is apparently some interest in considering separately the highly uncertain projected changes in land use, but these are not included in the CMIP5 experiments.

Table 4. Future climate projections with models forced by RCP concentrations.

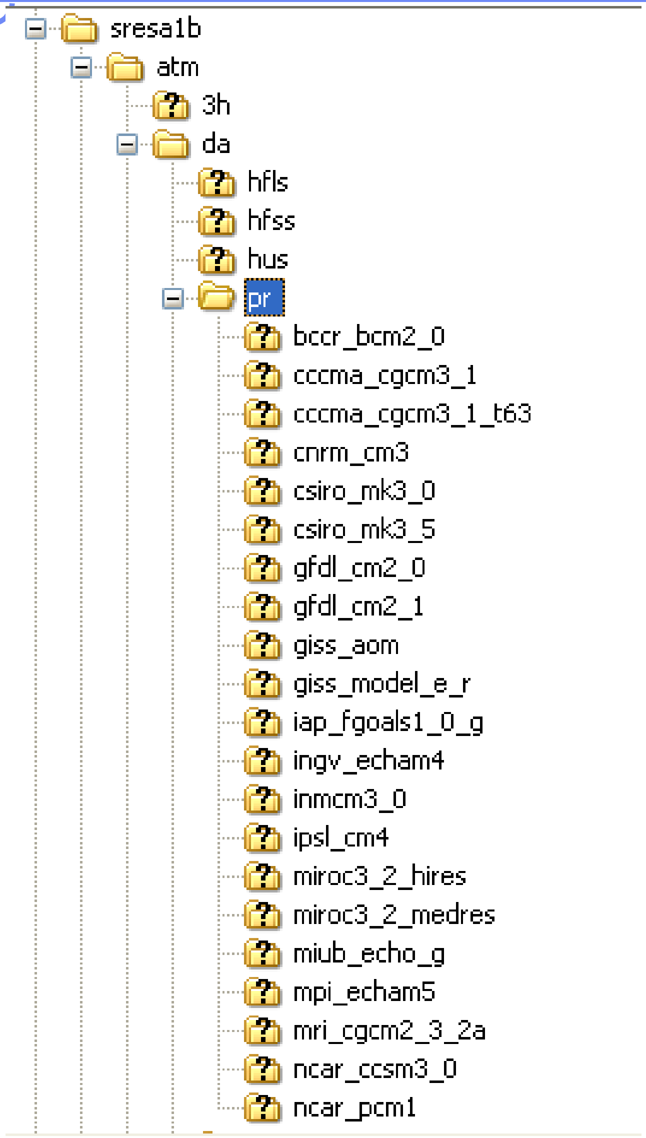
	#	Experiment	Notes	# of years
CORE	4.1	RCP4.5 (2006-2100)	Radiative forcing stabilizes at ~4.5W m^{-2} after 2100. (if ESM, save CO_2 fluxes from the surface to calculate allowable emissions)	95
CORE	4.2	RCP8.5 (2006-2100)	Radiative forcing reaches ~8.5 W m^{-2} near ~2100. (if ESM, save CO_2 fluxes from the surface to calculate allowable emissions)	95
TIER 1	4.3	RCP2.6 (2006-2100)	Radiative forcing peaks at ~2.6 Wm^{-2} near 2100.	95
TIER 1	4.4	RCP6 (2006-2100)	Radiative forcing stabilizes at ~6 W m^{-2} after ~2100.	95
TIER 1	4.1-L	RCP4.5 extended through year 2300	Extension of expt. 4.1 through the end of the 23rd century.	200
TIER 2	4.2-L & 4.3-L	Extend RCP8.5 & RCP2.6 through year 2300	Extension of expts. 4.2 and 4.3 through the end of the 23rd century.	2x200

[11] For a description of the RCPs, see Moss et al., 2008, report from the IPCC Expert Meeting Towards New Scenarios, held in Noordwijkerhout, The Netherlands, in September, 2007 (see http://www.mnp.nl/ipcc/, “IPCC New Scenarios”)



Reto Knutti & Jan Sedláček, Nature Climate Change 3, 369–373 (2013) doi:10.1038/nclimate1716

Which GCMs from IPCC GCMs ?

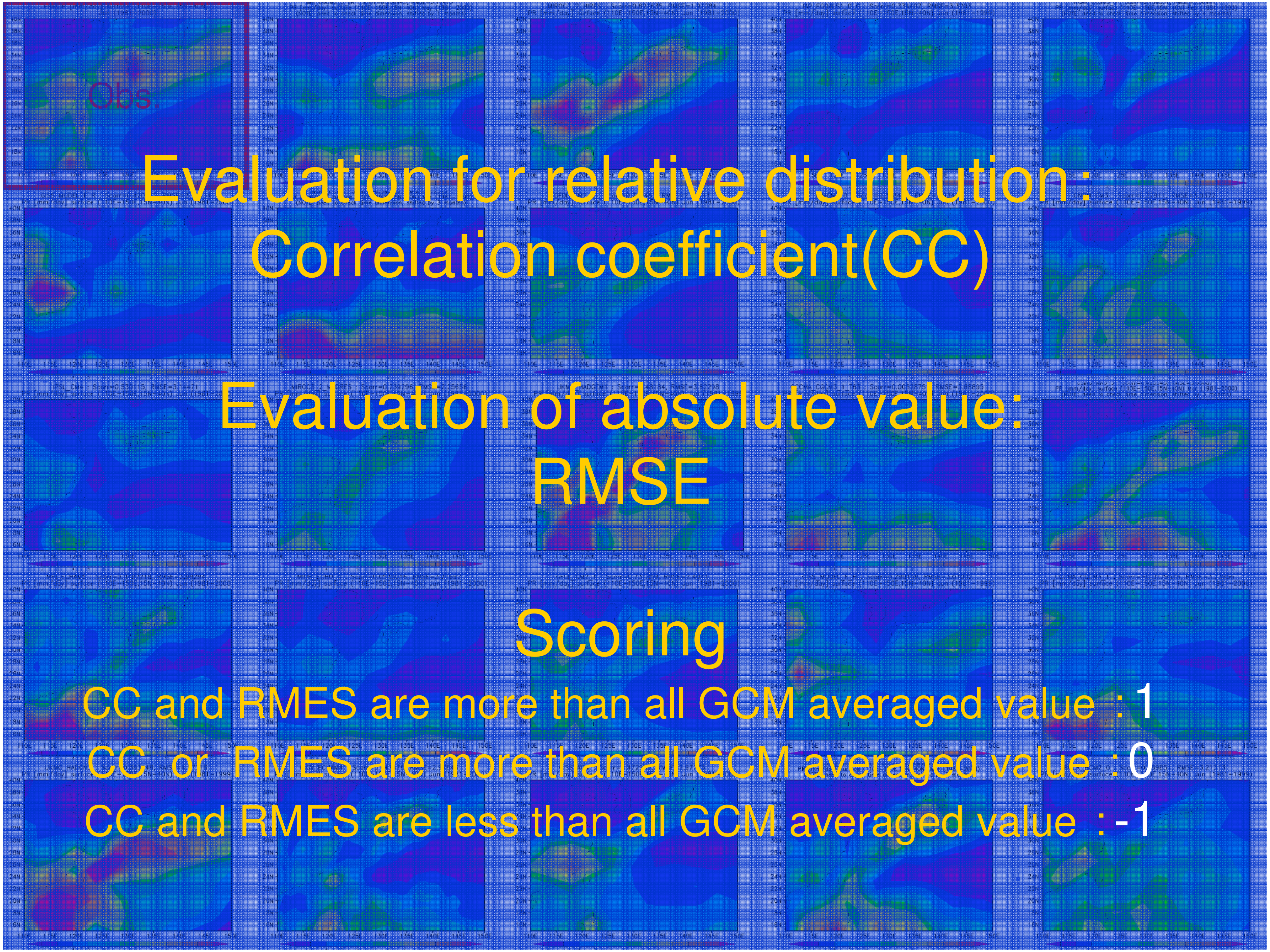


GCMs which simulate present-day climate most faithfully are considered to be more reliable.

By comparing GCM performance with observed data an indication is obtained of those models which are more successful than others.

However, this success will depend on the region size and also on the climate variable.

It is probably better to think in terms of excluding experiments where the performance of the model is unacceptably poor - especially at estimating the features of climate that are of critical importance for the impacts application.



Evaluation for relative distribution :
Correlation coefficient(CC)

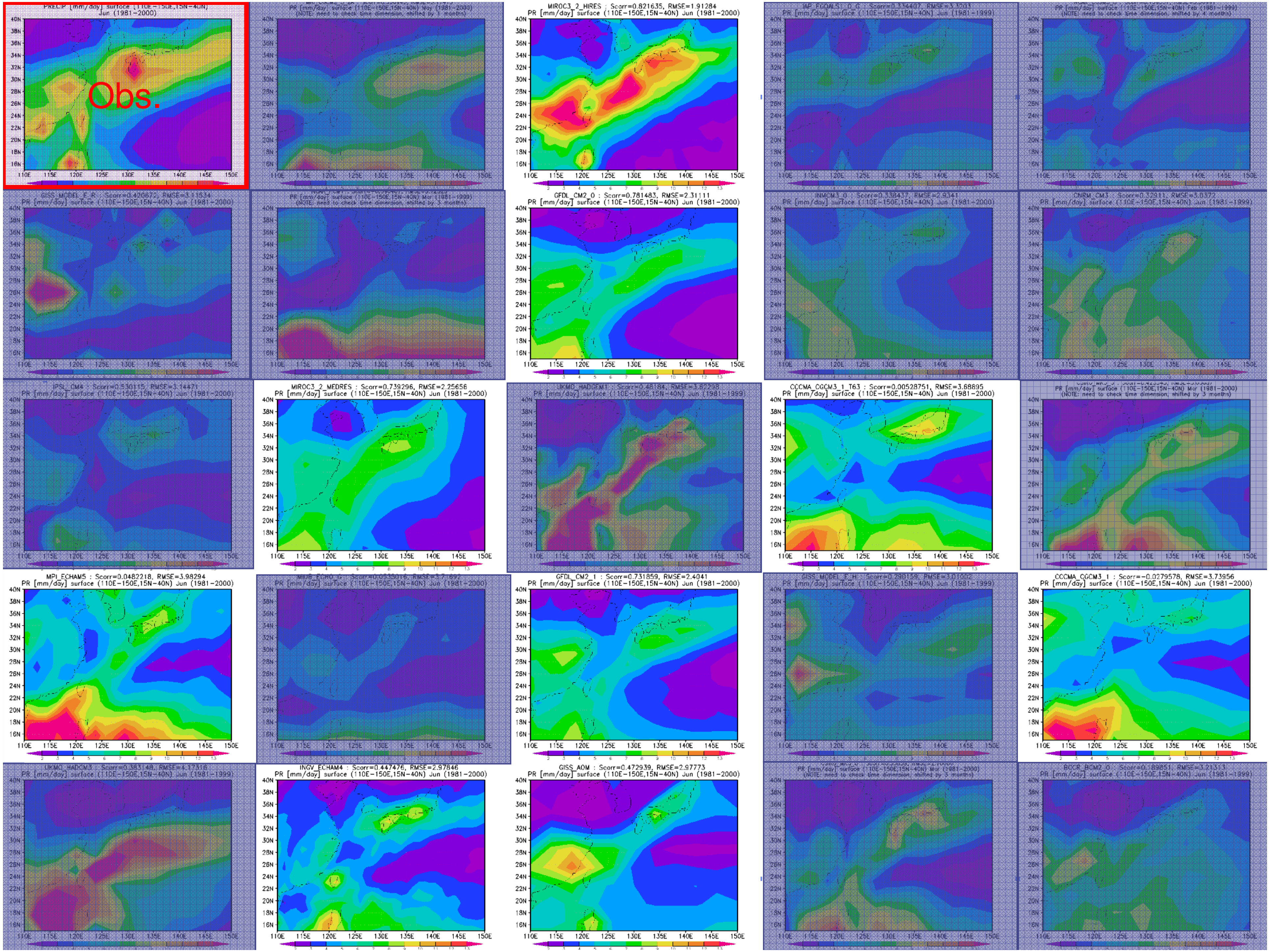
Evaluation of absolute value:
RMSE

Scoring

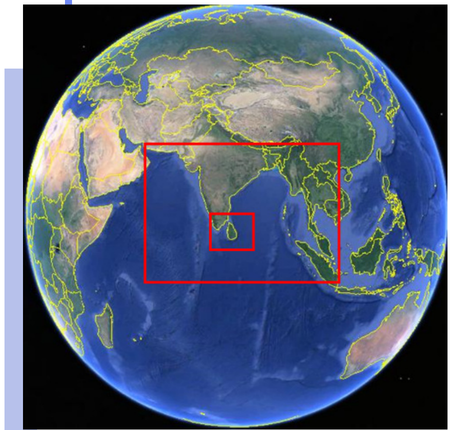
CC and RMES are more than all GCM averaged value : 1

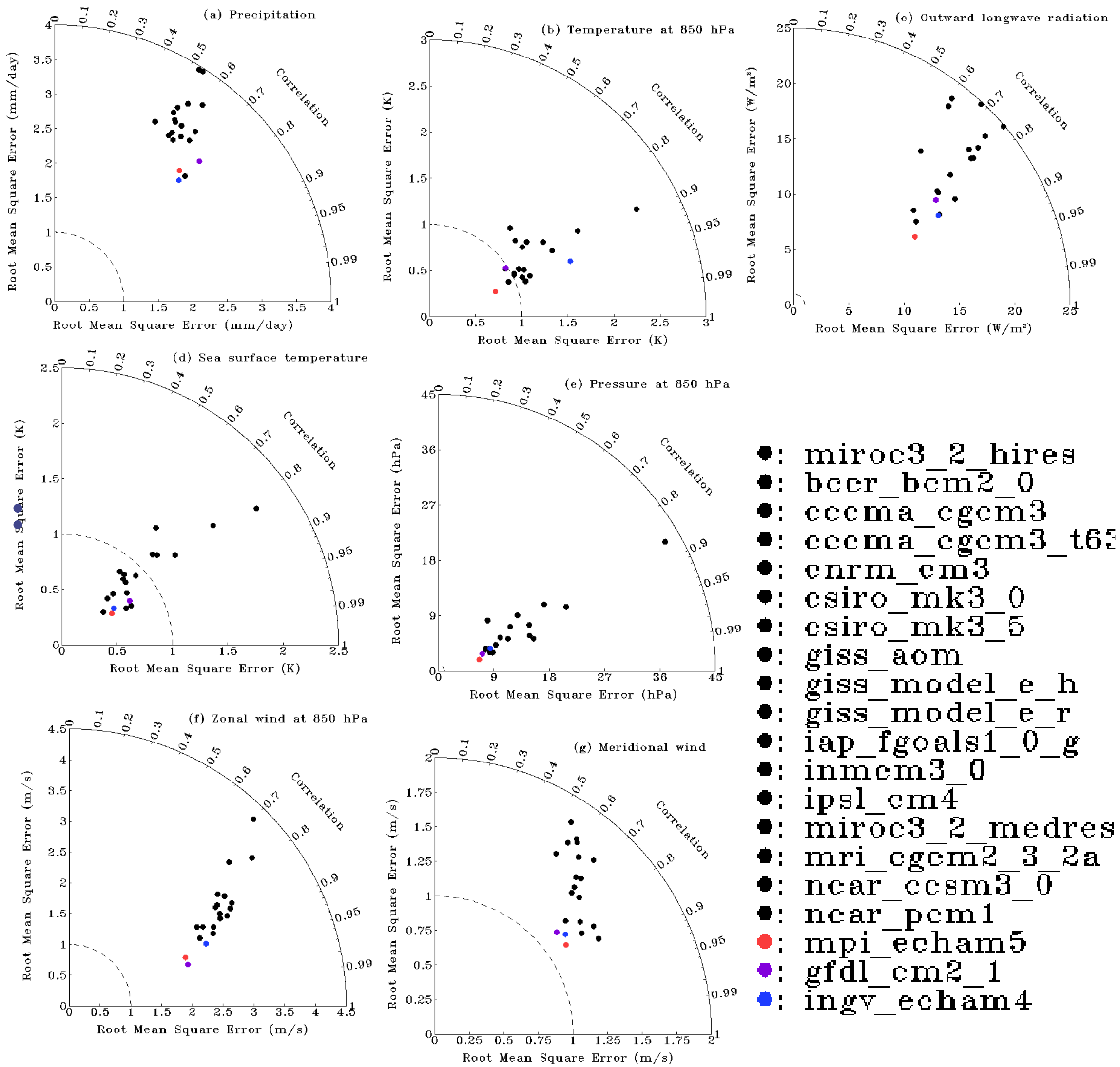
CC or RMES are more than all GCM averaged value : 0

CC and RMES are less than all GCM averaged value : -1


Obs.
MIROC3_2_HIRES : Scorr=0.821635, RMSE=1.91284
PR [mm/day] surface (110E-150E,15N-40N) Jun (1981-2000)
GFDL_CM2_0 : Scorr=0.781483, RMSE=2.31111
PR [mm/day] surface (110E-150E,15N-40N) Jun (1981-2000)
MIROC3_2_MEDRES : Scorr=0.739296, RMSE=2.25656
PR [mm/day] surface (110E-150E,15N-40N) Jun (1981-2000)
CCCMA_CGCM3_1_T63 : Scorr=0.00528751, RMSE=3.68895
PR [mm/day] surface (110E-150E,15N-40N) Jun (1981-2000)
MPI_ECHAM5 : Scorr=0.0482218, RMSE=3.98294
PR [mm/day] surface (110E-150E,15N-40N) Jun (1981-2000)
GFDL_CM2_1 : Scorr=0.731859, RMSE=2.4041
PR [mm/day] surface (110E-150E,15N-40N) Jun (1981-2000)
CCCMA_CGCM3_1 : Scorr=-0.0279578, RMSE=3.73956
PR [mm/day] surface (110E-150E,15N-40N) Jun (1981-2000)
INGV_ECHAM4 : Scorr=0.447476, RMSE=2.97846
PR [mm/day] surface (110E-150E,15N-40N) Jun (1981-2000)
GISS_AOM : Scorr=0.472939, RMSE=2.97773
PR [mm/day] surface (110E-150E,15N-40N) Jun (1981-2000)

GCM Selection





- **Parameters & Reference data**
  - Precipitation (GPCP)
  - OLR (NOAA)
  - SST(HEADLY)
  - Sea level pressure (JRA25)
  - Air temperature (JRA25),
  - Meridional Wind (JRA25)
  - Zonal Wind (JRA-25)

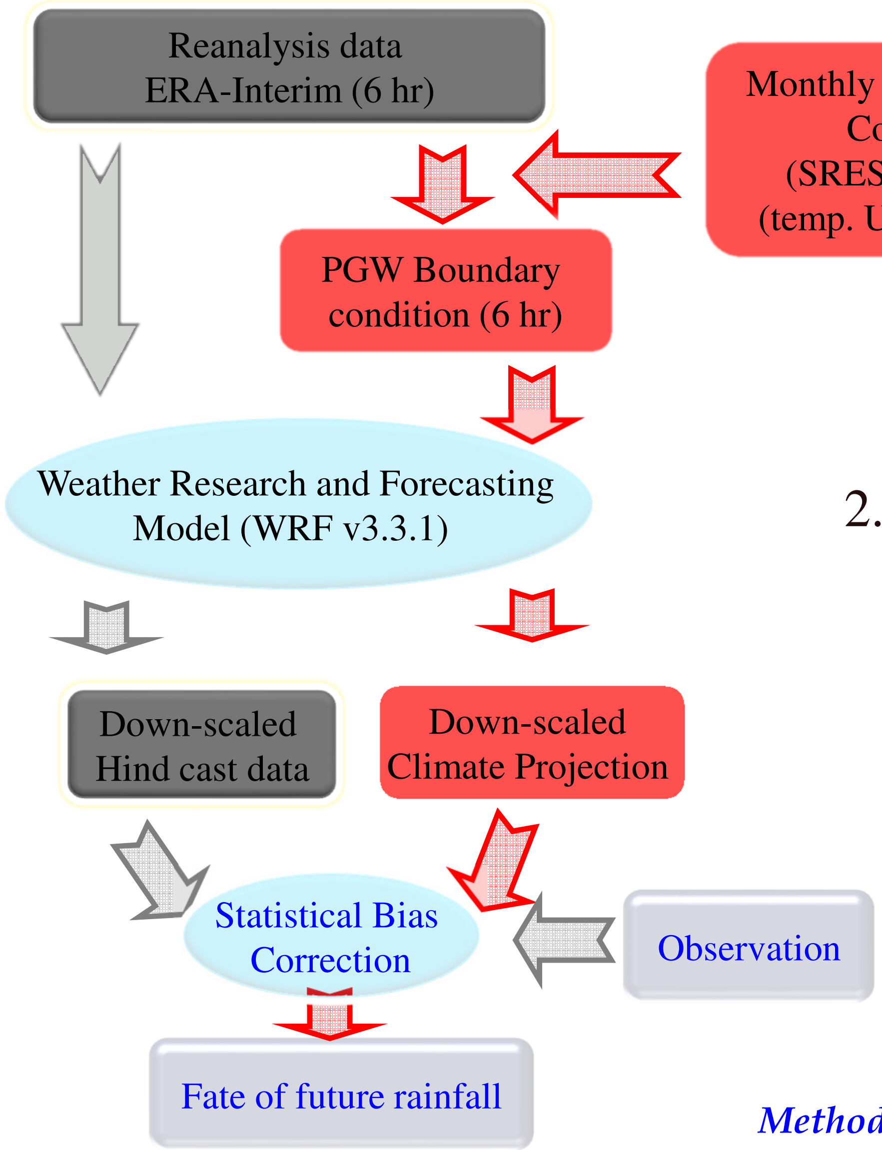
- **Target year:** 1981-2000

Issues in dynamical downscaling of climate projections

- Computationally and financially very expensive
  - Need enormous resources to downscale several GCMs
- Bias of GCMs & RCMs
  - Model physics and parameterization of sub-grid scale processes.
    - e.g. shift of a regional scale climate system may gives serious error in the nested model (Wang et al, 2004)
- PGW-DS (Kimura & kitoh, 2007, Kawase et al, 2009)
  - Same as conventional method but boundary conditions are assumed to be a linear coupling of the reanalysis data and the difference component of the global warming estimated by ensemble of GCMs.
  - Advantages
    - Reduction of model bias contained in GCMs
    - Circumvention of the uncertainty caused by inter-annual variability
    - Ensemble GCMs → computationally feasible
  - Disadvantages
    - Difficult to evaluate the changes in the inter-annual variability and the frequency of disturbances in future climate because those have unchanged variability.
    - Bias from parent GCM and RCM still exists

A COMBINED DYNAMICAL/STATISTICAL DOWNSCALING APPROACH FOR ASSESSING FUTURE OF WATER RESOURCES IN THE TONE RIVER BASIN, JAPAN

A Combined Method --(PGW-DS) & SBC



PGW: S8 Scenario (A1B)

(1) GFDLCM2.1

(2) Miroc3_2_hires

(3) Csiro_mk3_0

(4) MRI-CGCM2.3.2

Assumptions:

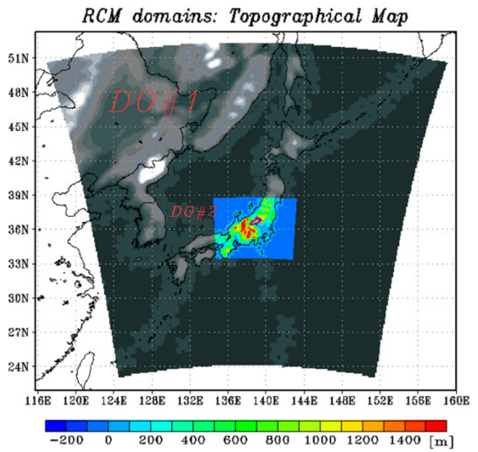
1. Linear coupling
2. Unchanged inter-annual variability

→ improves the biases utilizing long-term observations, while maintaining the effect of finer scale features and continuity.

Methodology : Best Poster Award- WCRP-CORDEX-2013

PGW-DS: Psuedo Global warming downscaling

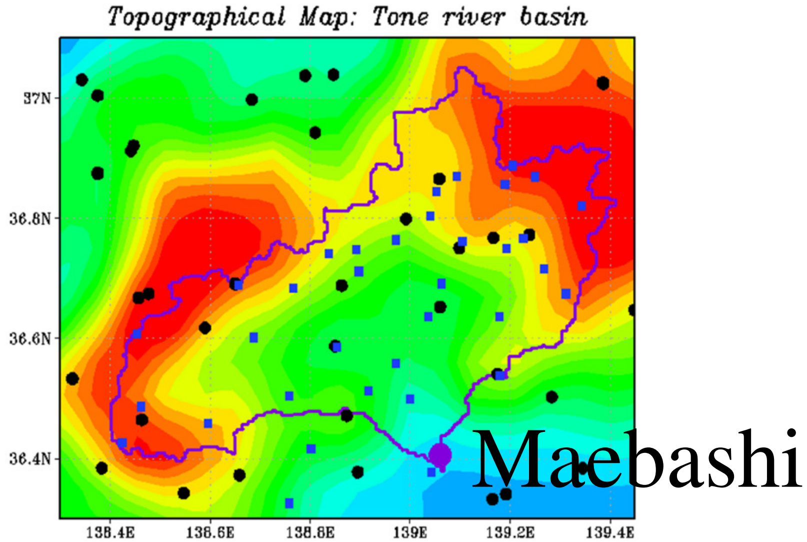
Data & Model Configurations



Parameters	Domain 1	Domain 2
Number of grids	121X131	149X149
Spatial resolution (km)	24	6
Time resolution (s)	120	30
Microphysics scheme	WRF Single-Moment 6-class scheme (WSM6)	same as Domain 1
Cumulus scheme	Kain-Fritsch	None
Shortwave radiation	RRTMG shortwave	same as Domain 1
Longwave radiation	RRTMG longwave	same as Domain 1
Surface physics	Noah Land Surface Model	same as Domain 1
Planetary Boundary layer	Mellor-Yamada Nakanishi and Niino Level 2.5	same as Domain 1

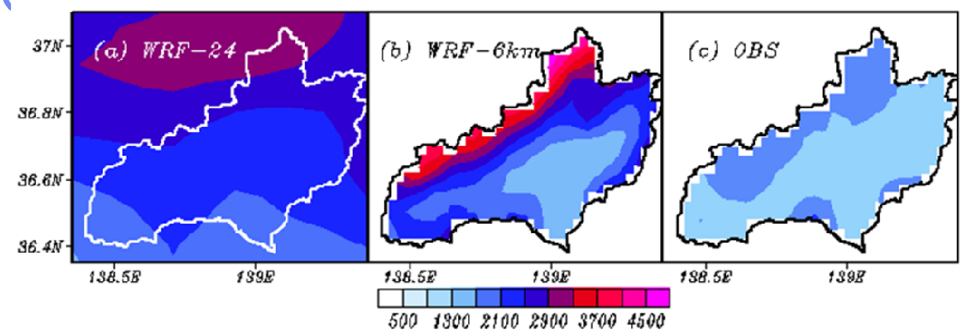
- ✓**ERA-Interim**
- ✓**Baseline → 1981-2010 (30 yrs)**
- ✓**Global Warming → 2081-2100 (20 yrs)**
- ✓ **Year by year Simulations to reduce the bias propagation**

Water and Energy Budget-based Distributed Hydrological Model (WEB-DHM) was used. [Wang et. al, J. Hydrology, 2009]

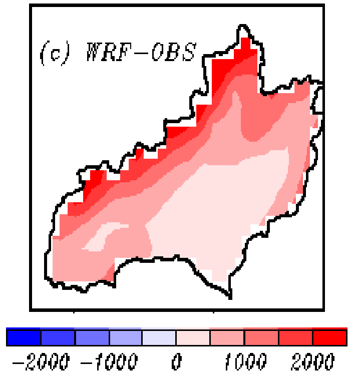


AMeDAS & MLIT rain gauges

WRF-ERA rainfall Characteristics

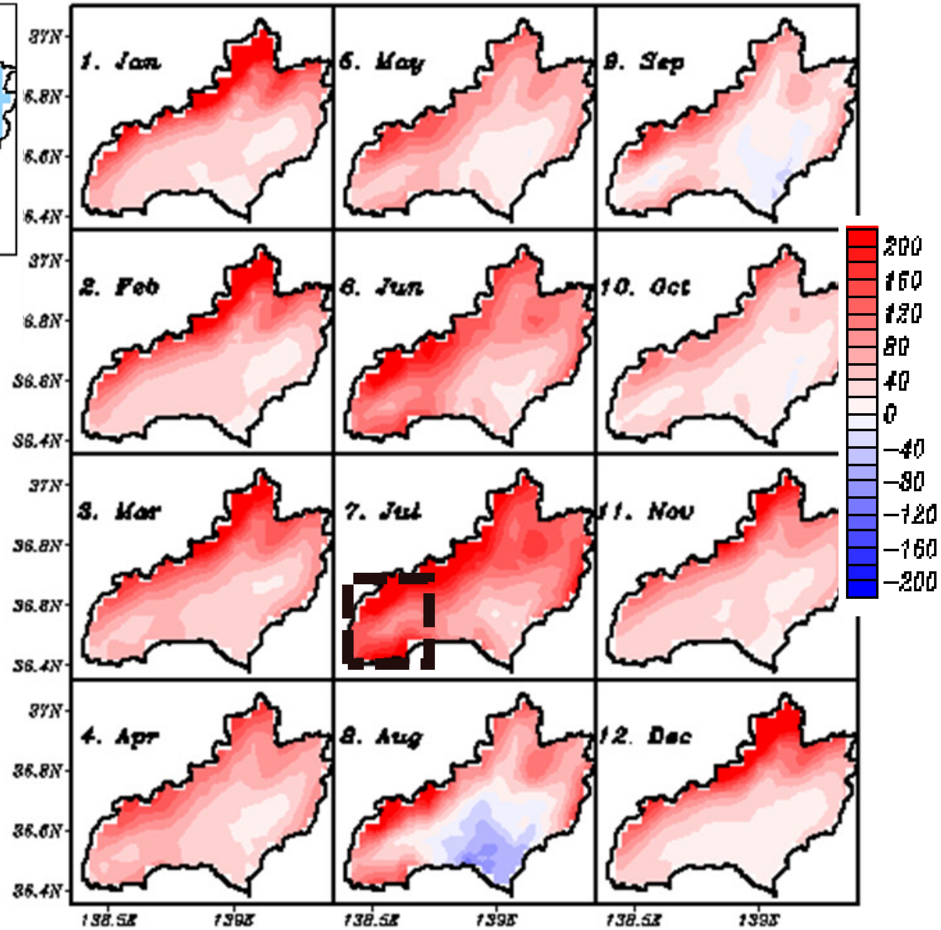


Annual Climatology



Difference (WRF-OBS)

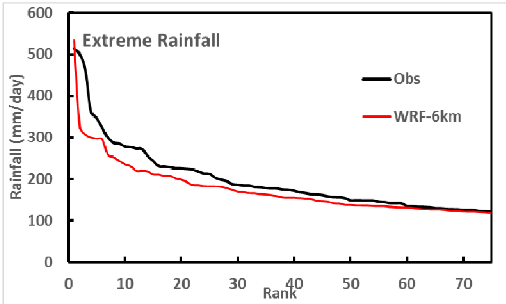
SCORR = 0.75
MBE = 882 mm/yr
RMSE = 1080 mm/yr



Monthly difference (WRF-OBS)

- Strong bias especially over mountainous regions due to resolution enhancement that must be taken into account to achieve reliable assessments of future climate change.

Statistical Bias correction

<table>
<tr><th>Rain Type</th><th>Threshold</th><th>Correction</th></tr>
<tr><td>Extreme
</td><td>> 99% of daily precipitation during analysis period
- same frequencies of extreme as insitu station as in GCM
</td><td>Generalized Pareto Distribution
-Non every year statistics
-Extreme (long or short tailed) fitting
-Peak over threshold method

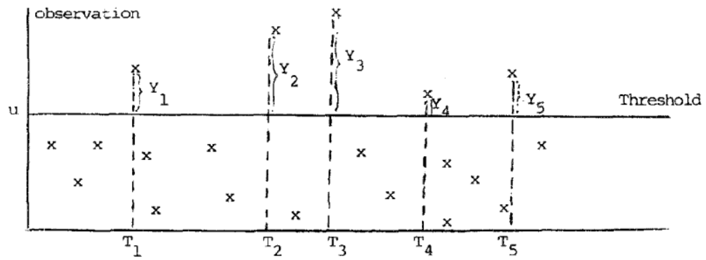
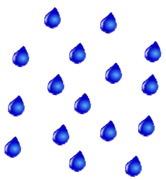
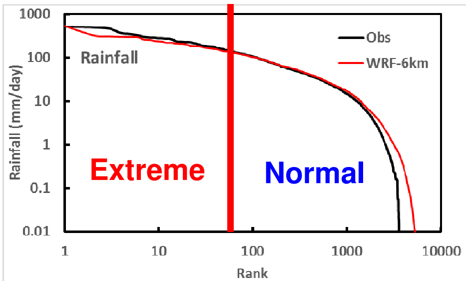



Fig. 2. Illustration of threshold model.</td></tr>
<tr><td>Normal
</td><td></td><td>Two parameters Gamma Distribution
- monthly CDF of RCM mapping to monthly CDF of gridded rainfall
- inverse of Gamma CDF in each month is used to correct future rainfall.</td></tr>
</table>

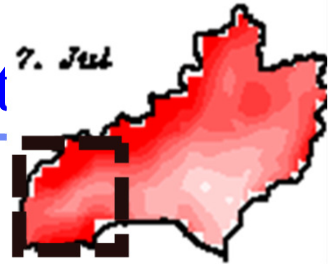
WRF

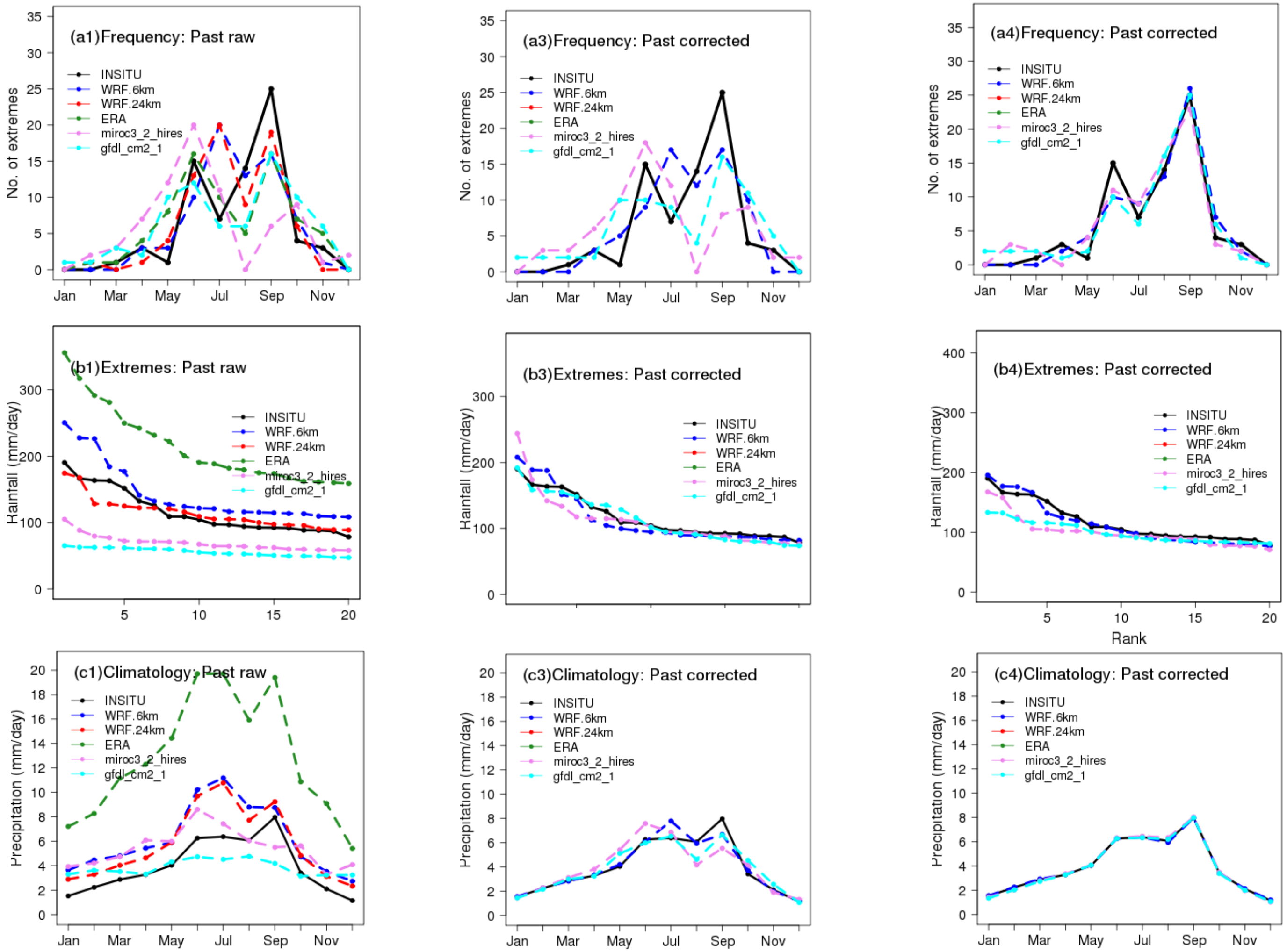
1. Extreme (GPD) and normal rainfall (monthly CDF mapping)
2. Monthly CDF mapping of entire data

CGCMs

+ correction for drizzling days

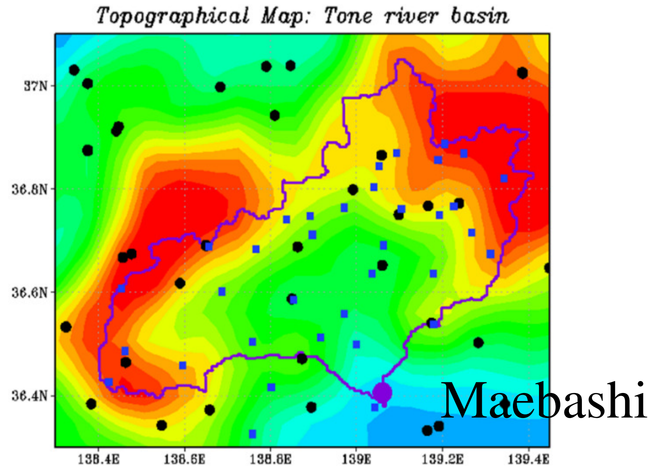
Statistics of raw and bias corrected rainfall at





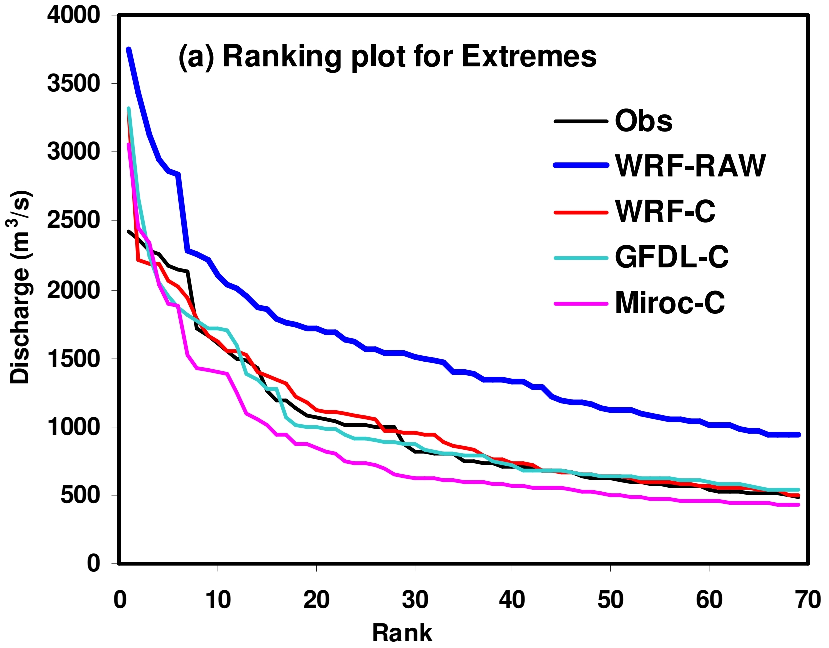
RAW DATA **EXTEME + GAMMA BC** **GAMMA BC**

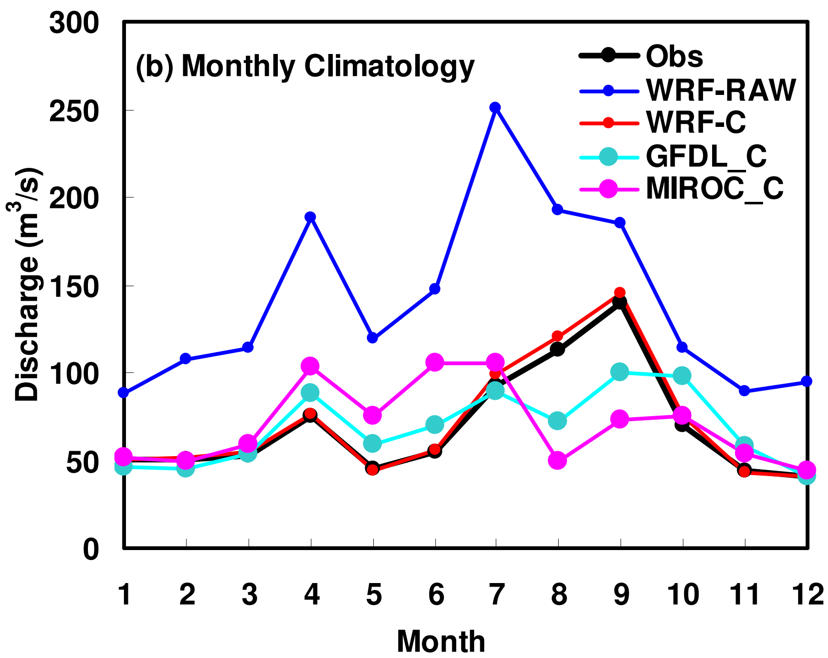
Hypothetical Discharge Analysis @ Maebashi



DHM experiments for natural flow conditions

Integrated validation for all the grids





DHM: Distributed Hydrological Modeling

Summary

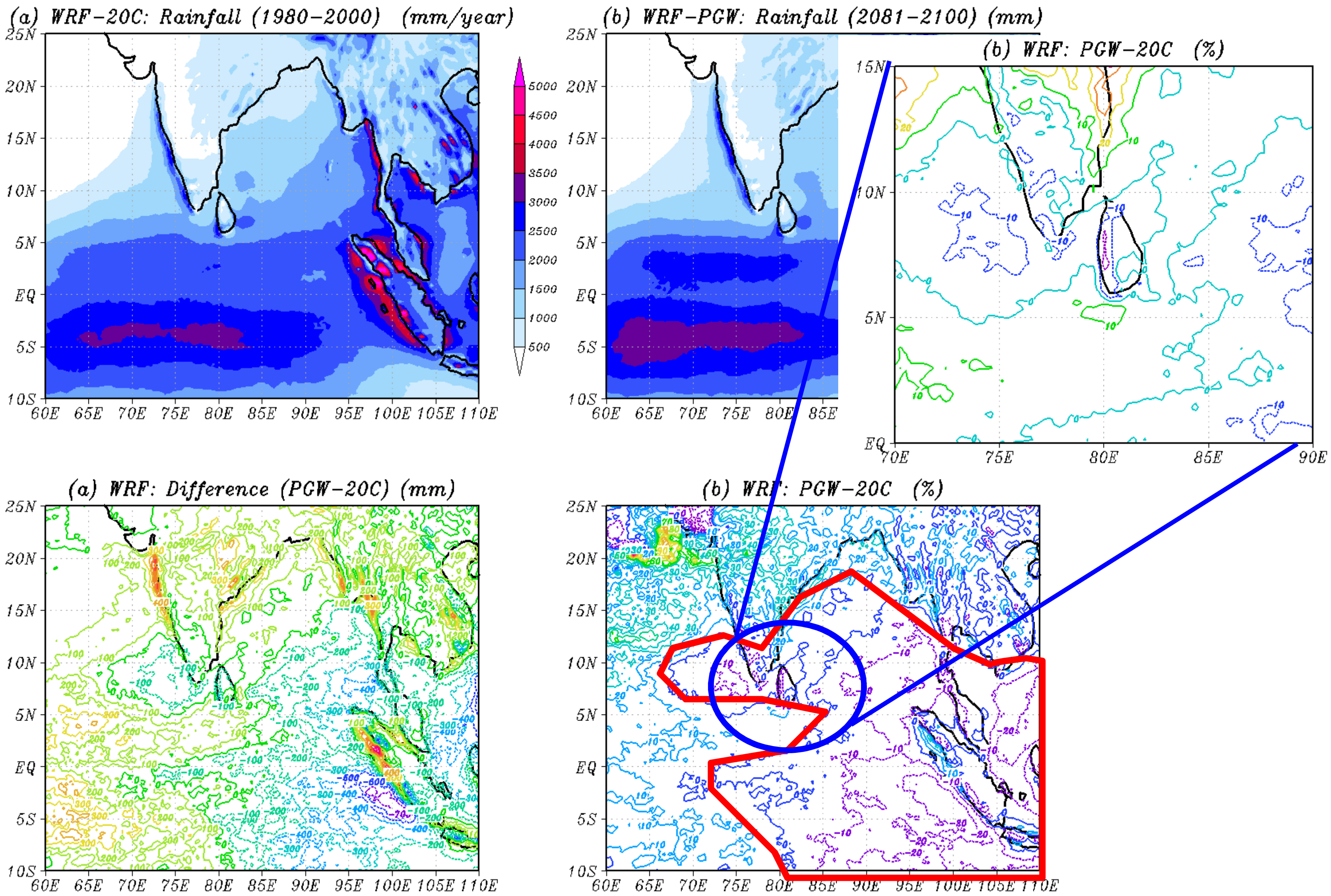
- WRF performed statistically better results with observation, however, there are biases in monthly climatology and extremes.

- The identified biases are complemented using simple monthly CDF matching for past and future climate.

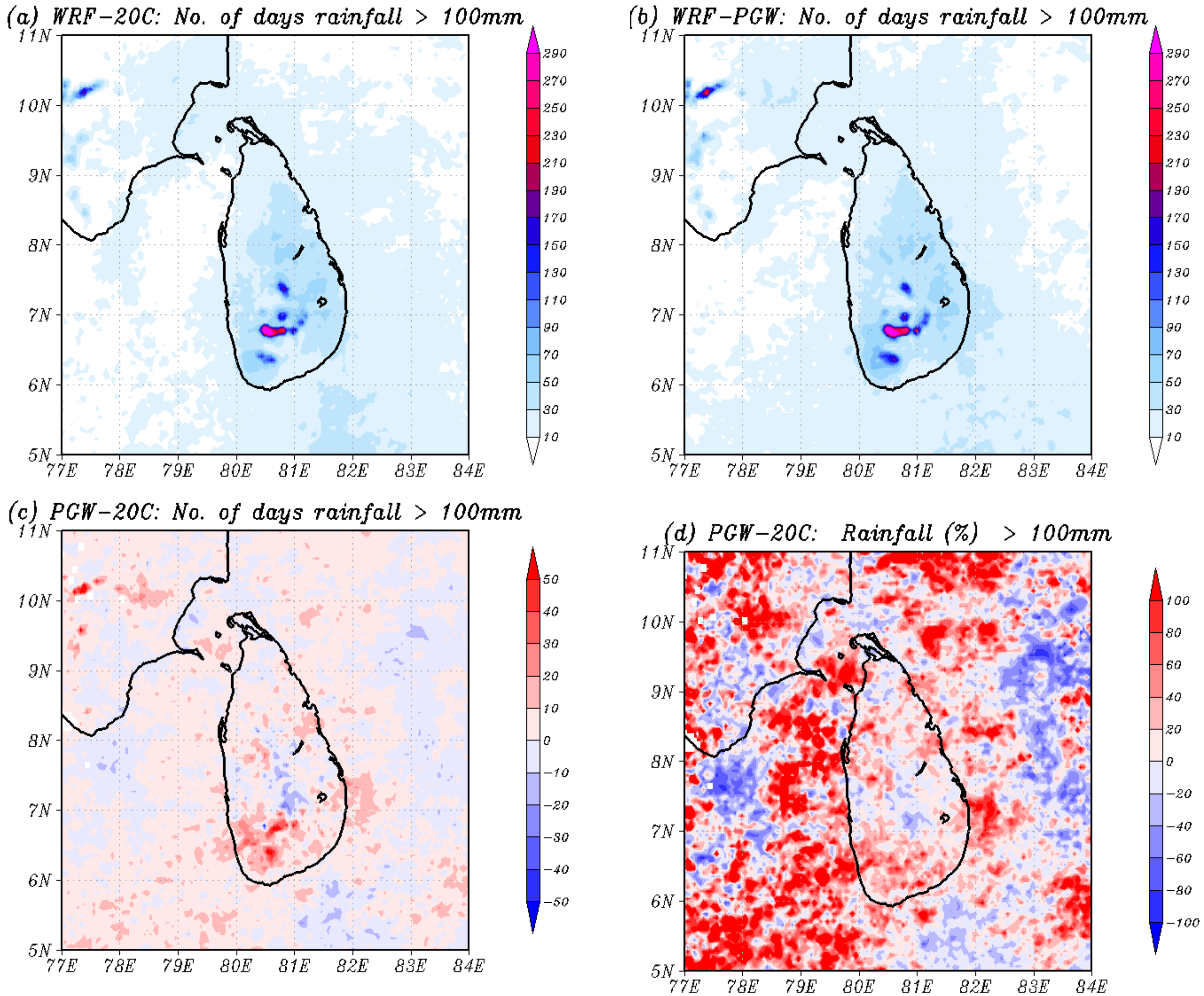
- *Value added climate dataset* prepared in this research will be used to asses the impacts of climate change.

PGW for Sri Lanka

Changes in Annual Climatology: Regional

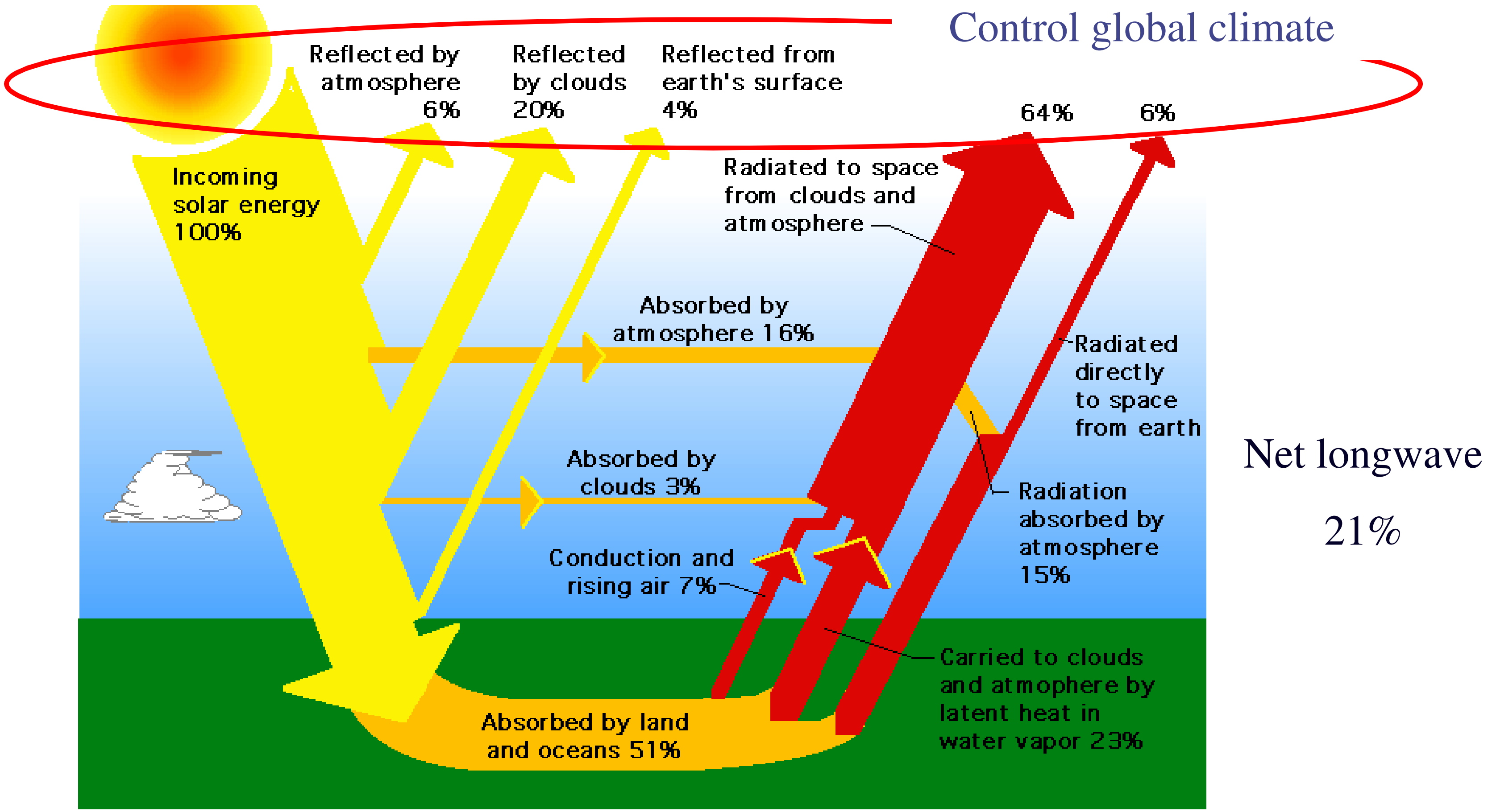


Changes in Extreme Climate



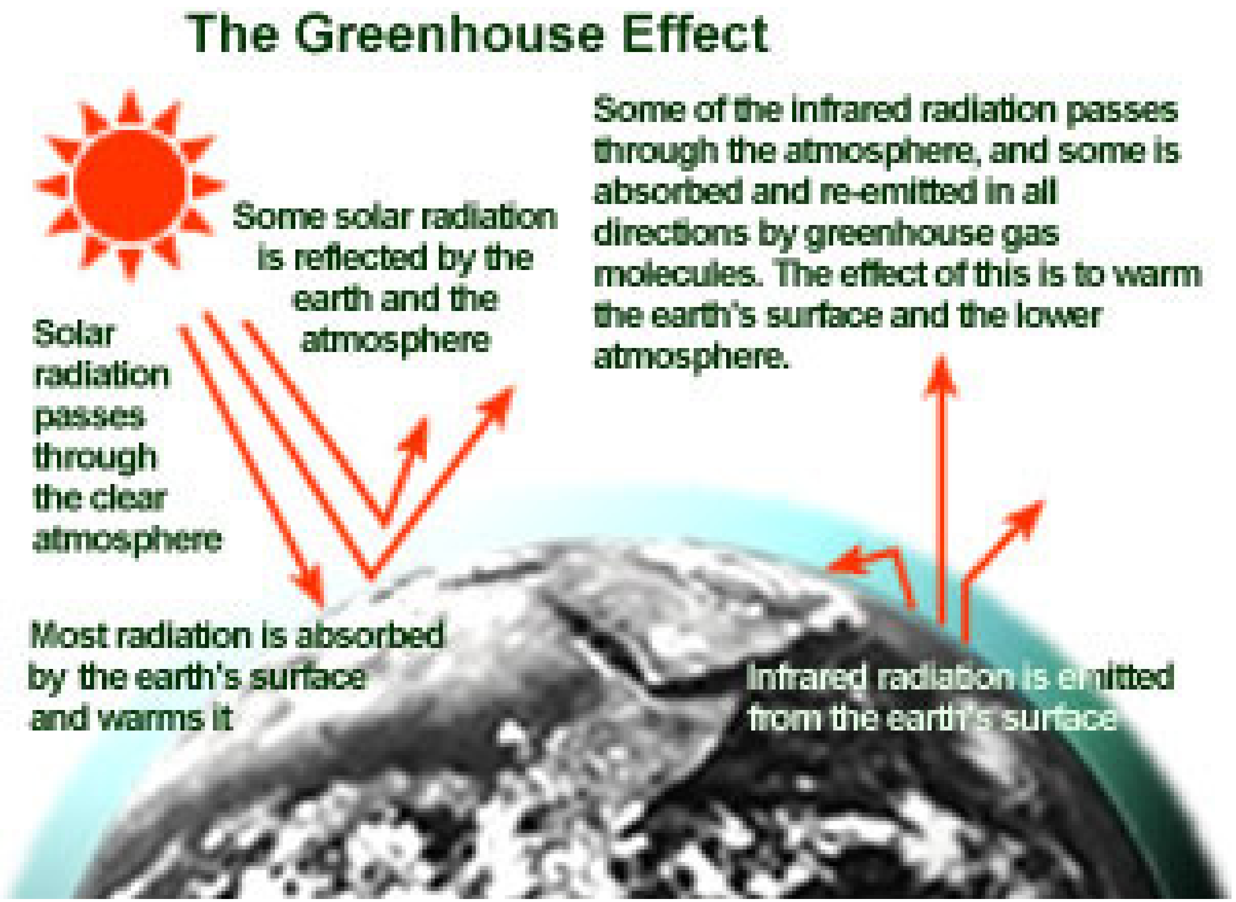
- END -

Radiation and Energy Budget



- At the top of the atmosphere: Incoming shortwave = Reflected shortwave + Emitted longwave
- At the surface: Incoming shortwave + Incoming longwave = Reflected shortwave + Emitted longwave + **SH** + LH

The Greenhouse Effect

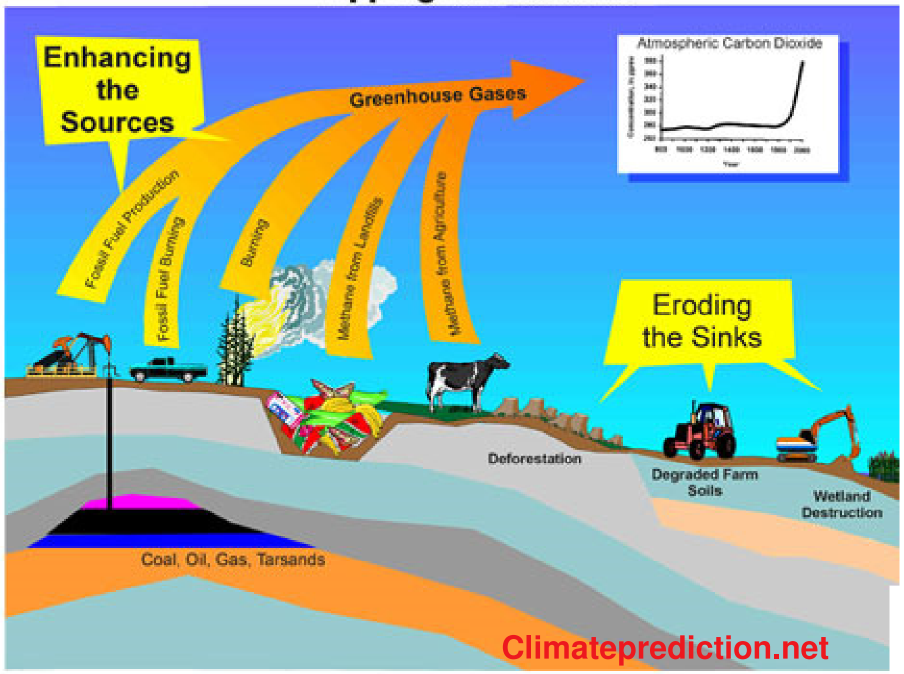


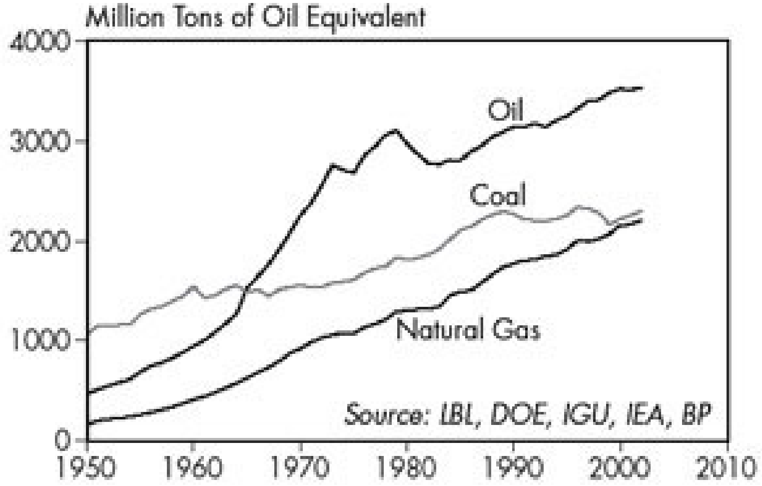
Greenhouse gases are those that can absorb and emit infrared radiation:

- Water vapor (H_2O)
- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Ozone (O_3)
- CFCs

Tipping the Balance & What will happen next?

Tipping the Balance





World Fossil Fuel Consumption by Source, 1950–2002

Global carbon dioxide emissions from human activities, 1750-2004

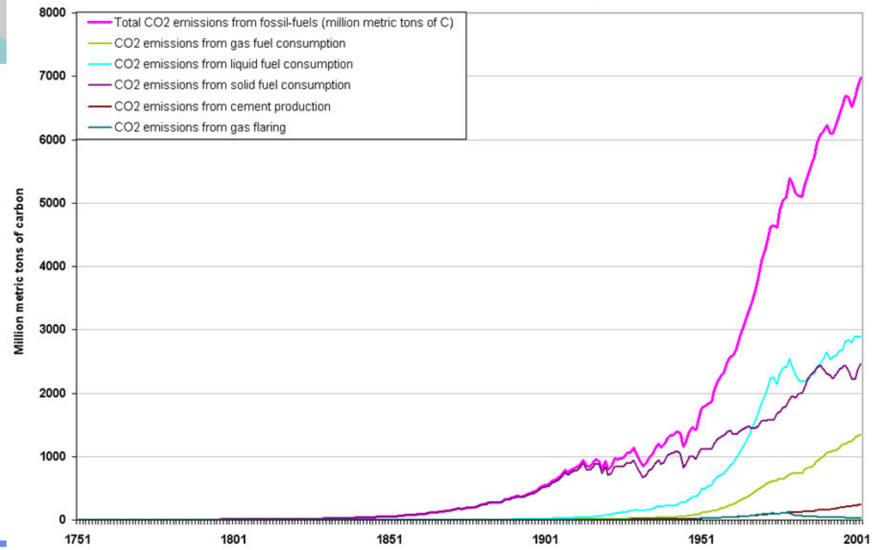
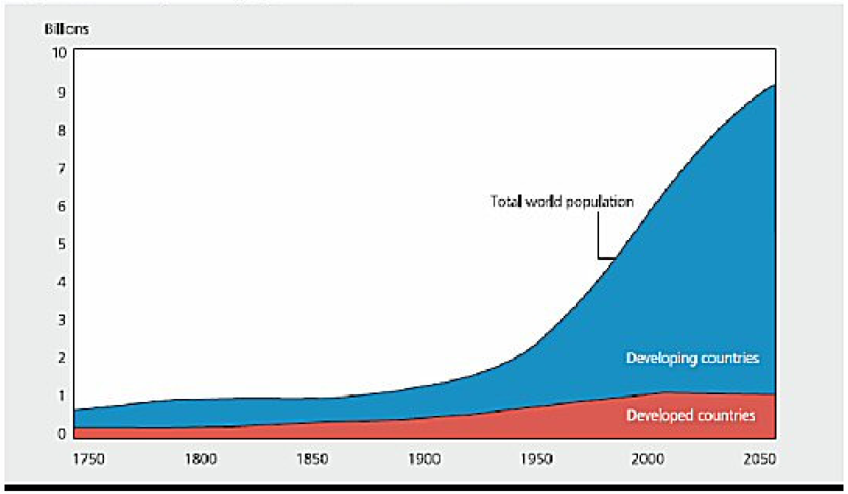
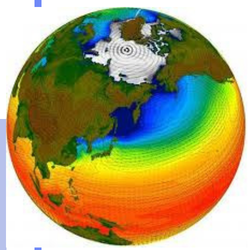
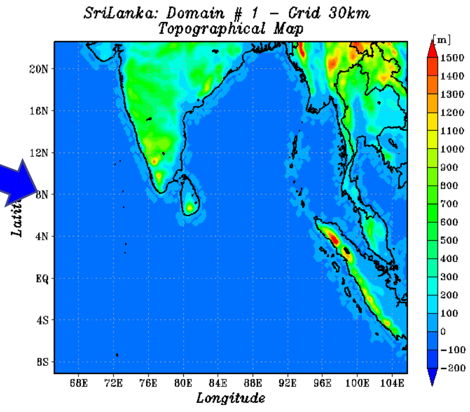


Figure 3.1 World population, 1750–2050

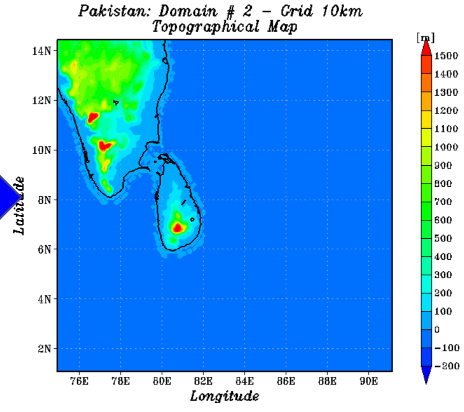


WRF Simulations – Pakistan & Sri Lanka

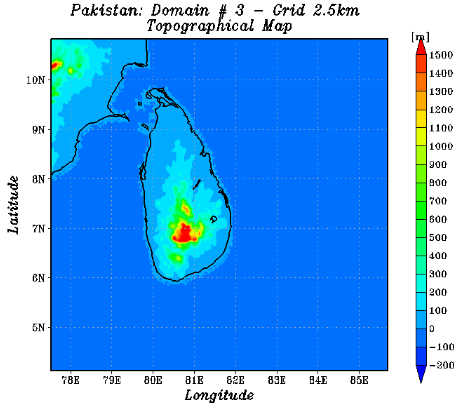




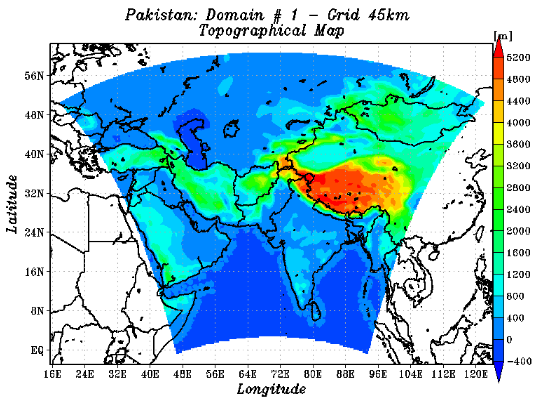
30 km



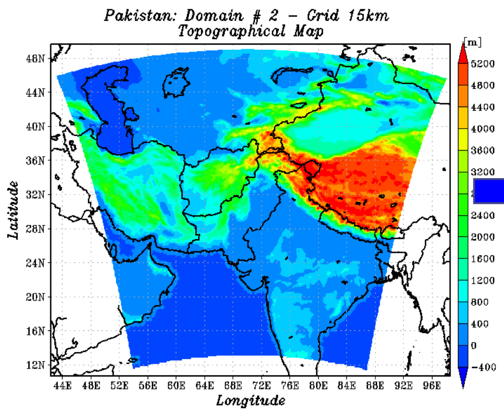
10 km



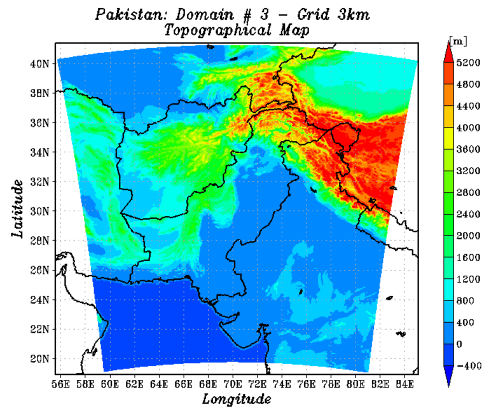
2.5 km



45 km



15 km

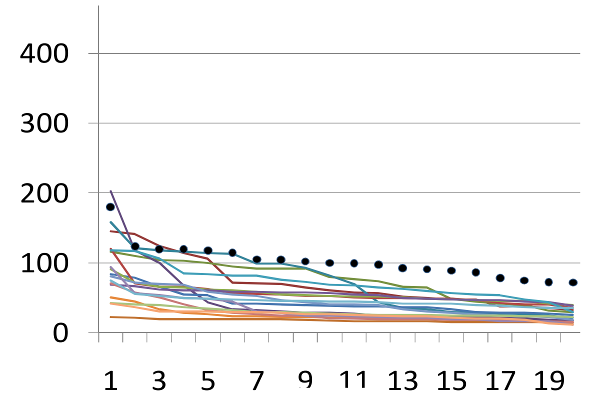


3 km

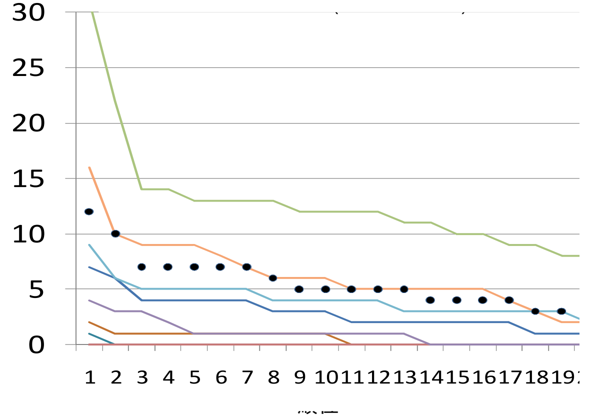
✓NECP-FNL DATA Period → 28th July-29th July 2010 (2days)

Problems with the GCM Outputs

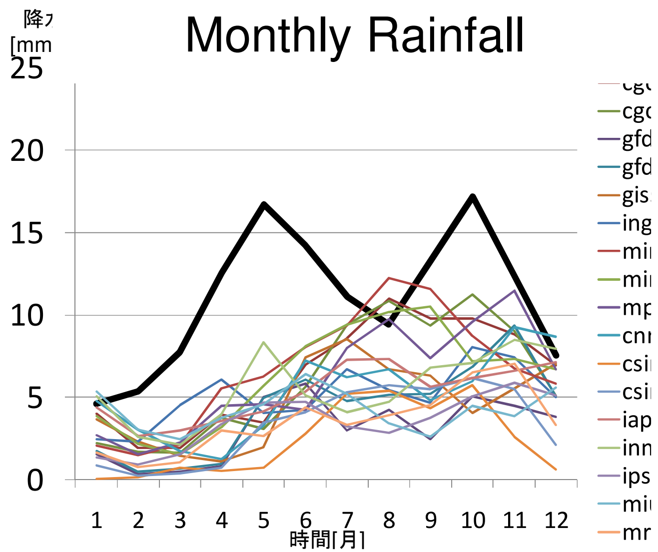
Annual Maximum Daily Rainfall



Maximum number of
the continuous no-rain days



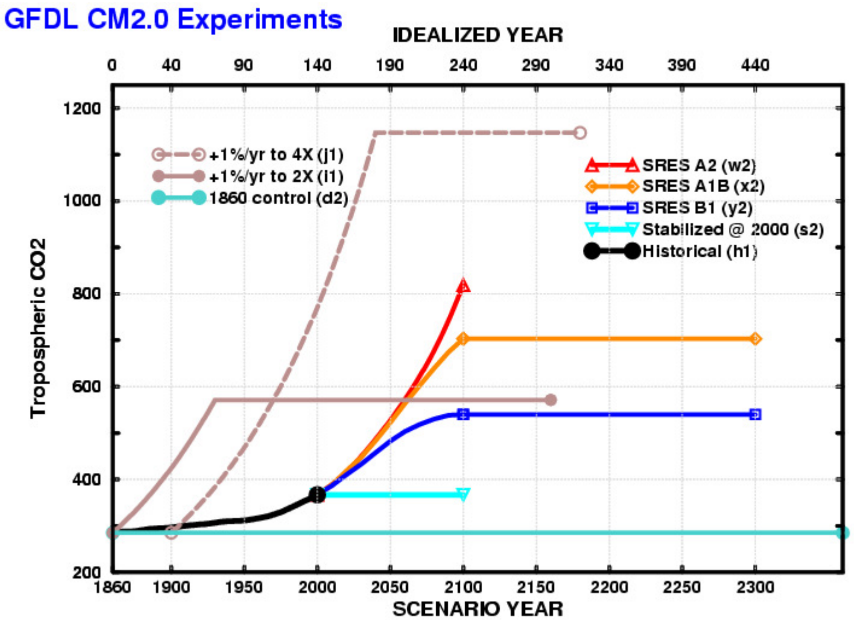
Monthly Rainfall

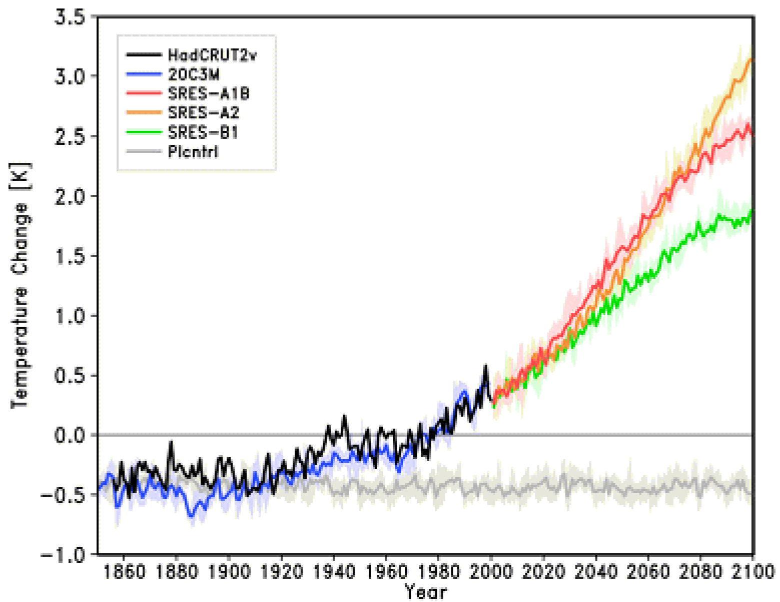


Main Problems with the GCM Outputs:

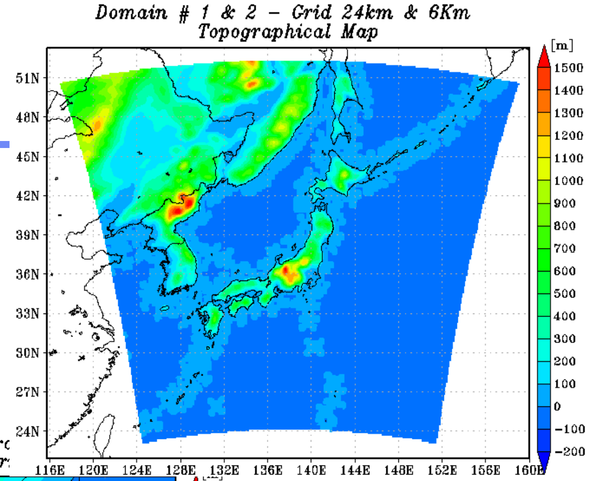
- •Large Diversity
- •Low Extreme Heavy Rainfall Rate
- •Small Number of No Rainfall Day but Long Drizzle
- •Low Seasonal Representation
- •Low Spatial Distribution

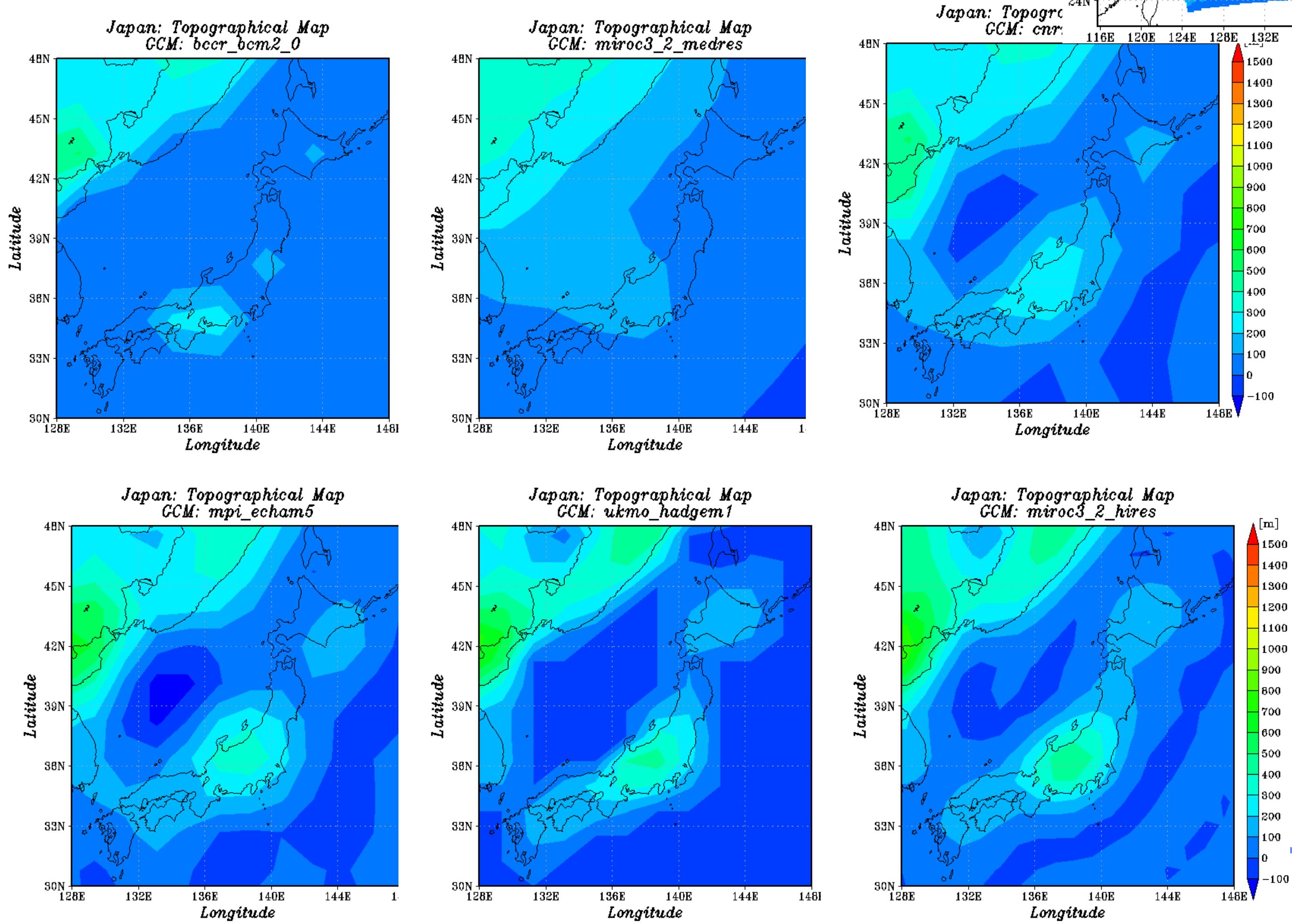
GCM Climate Change Experiments



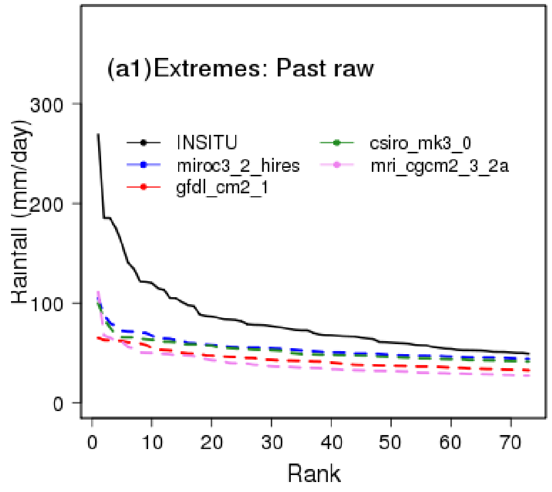


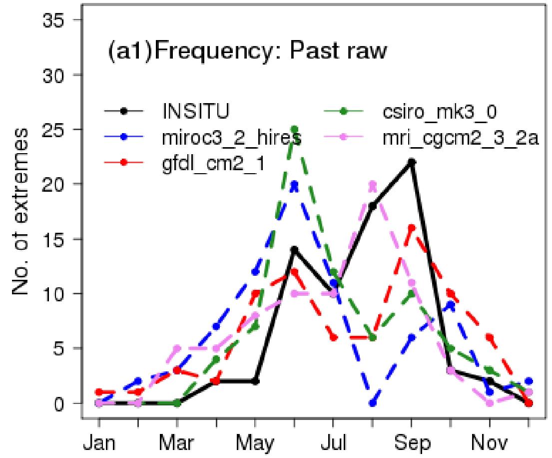
Topographical representation in GCMs

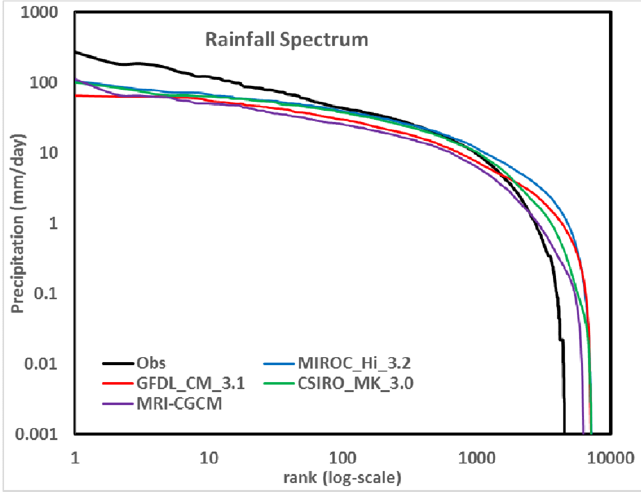


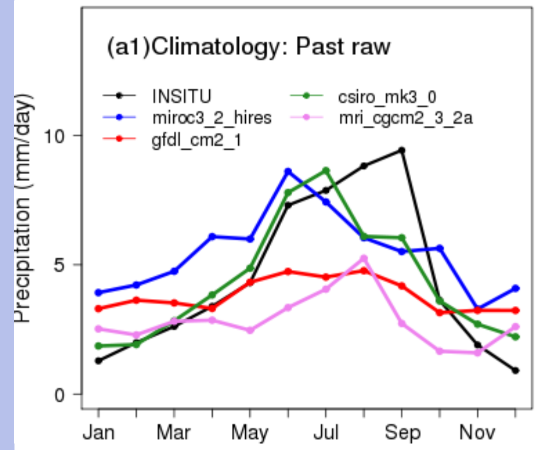


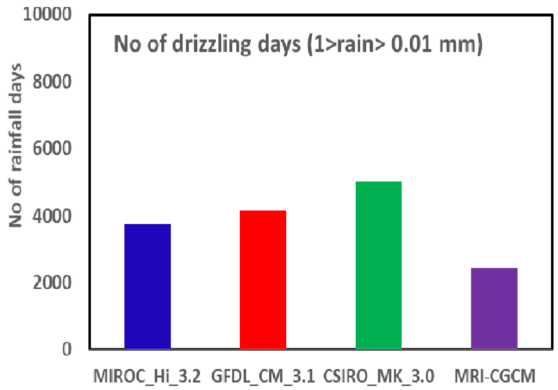
CGCMs rainfall characteristics – Tone River Basin











- Rainfall Biases in the selected CGCMs
  - Extreme
  - Climatology
  - Number of rainfall days
- Impact models cannot be forced with the native form of CGCM