Climate Modelling:

Basics

Lecture at

APN-TERI Student Seminar

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Focus

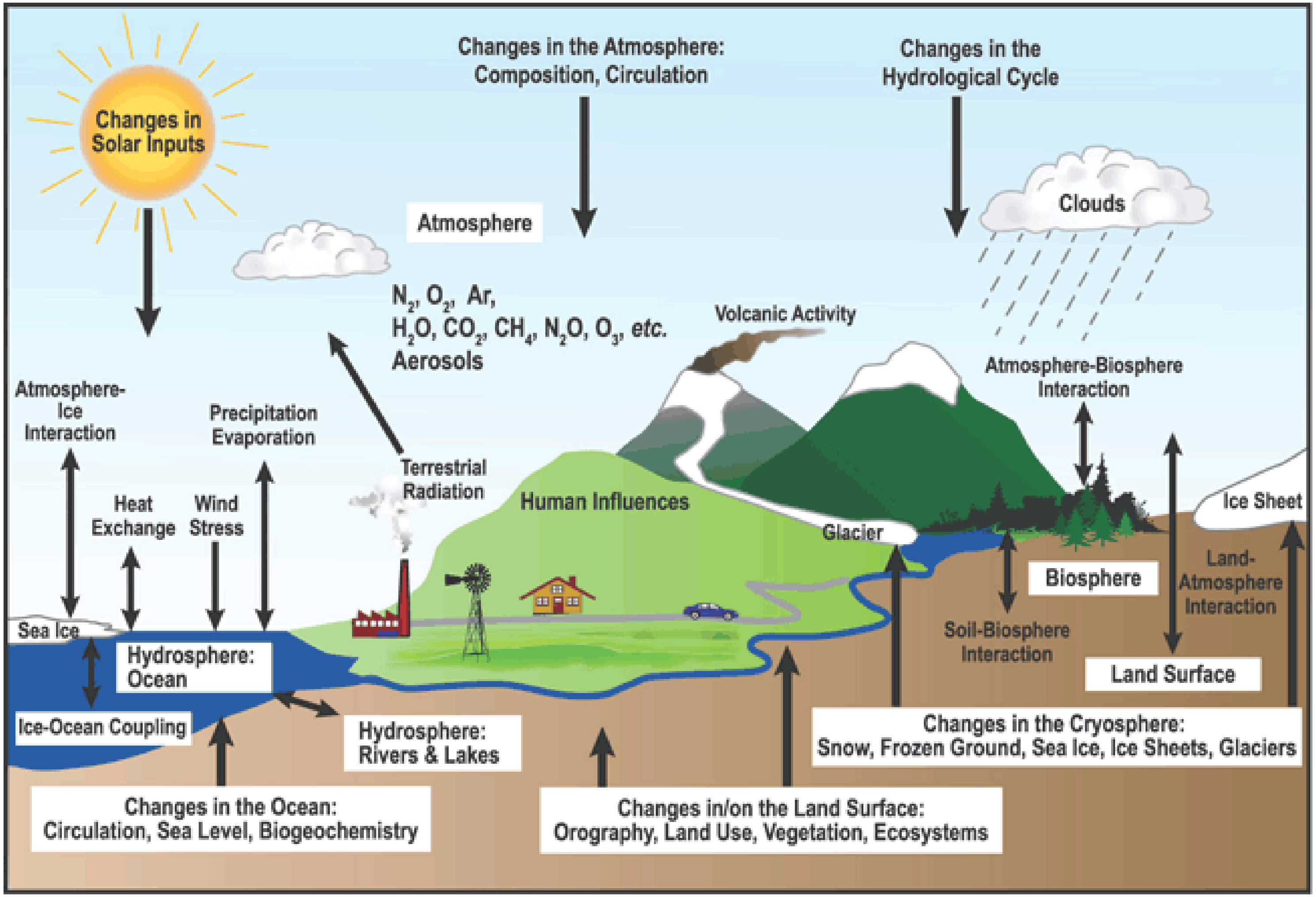
- Modelling
  - Basics, Theory
  - Types
  - Components
  - Improvements
- Downscaling
- Uncertainties
- Evidences
  - Global and national
- Projections
  - Global and national

Pic. Charley Harper, OSU

Factors influencing climate

- Incident solar radiation - variation with latitude
- Closeness to large water bodies - distribution of land & water
- Mountain barriers
- Altitude
- Ocean temperature and currents
- Land cover
- Atmospheric composition

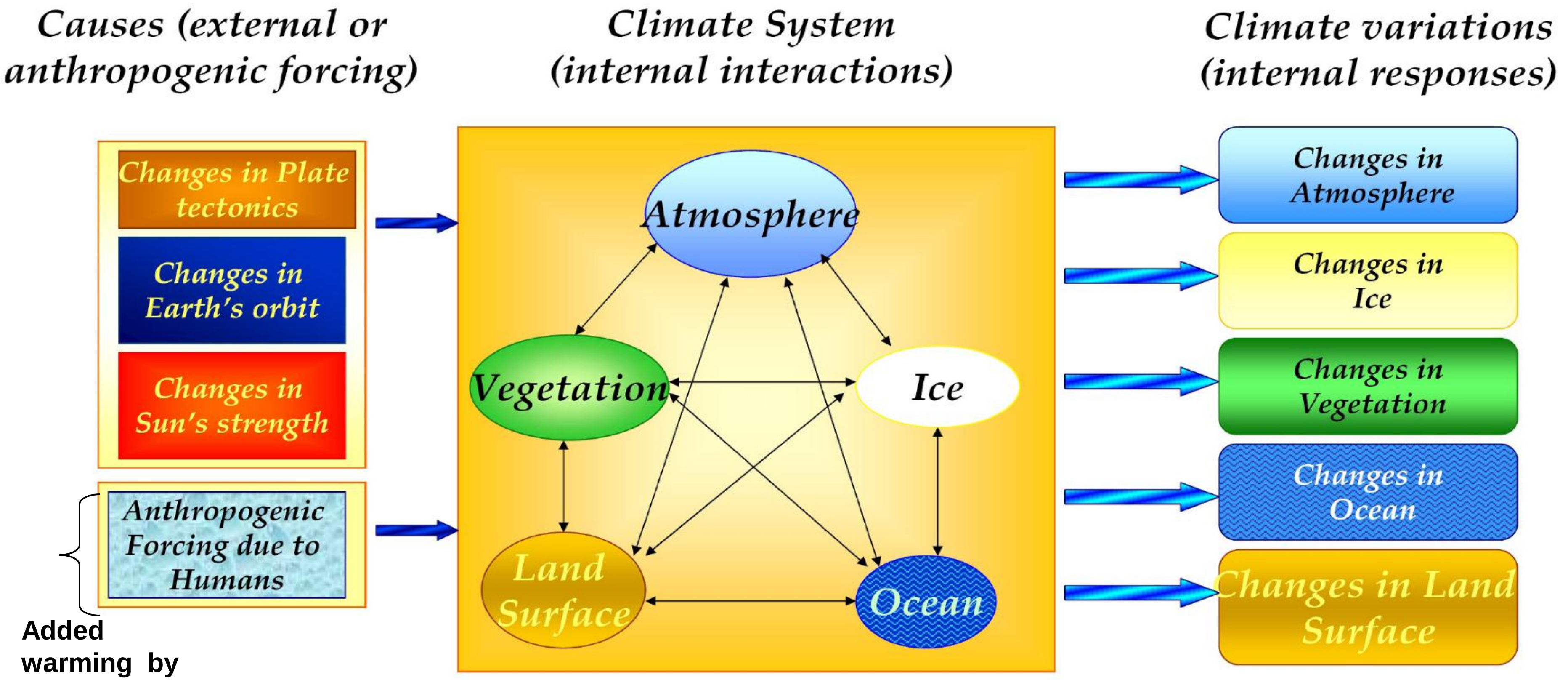
Interactions



The non-linear interaction among the components leads to climate variability at a range of spatial and temporal scales

Pic . NOAA

Review of Basics: Climate System



Added warming by human intervention

The non-linear interaction among the components leads to climate variability at a range of spatial and temporal scales

How do we quantify the response of the climate?

- The response of the climate system to this forcing agents is complicated by:
  - feedbacks
  - the non-linearity of many processes
  - different response times of the different components to a given perturbation
- The only means available to calculate the response is by using numerical models of the climate system.

What is a Model ?

"a simplified description, esp. a mathematical one, of a system or process, to assist calculations and predictions"

- dictionary

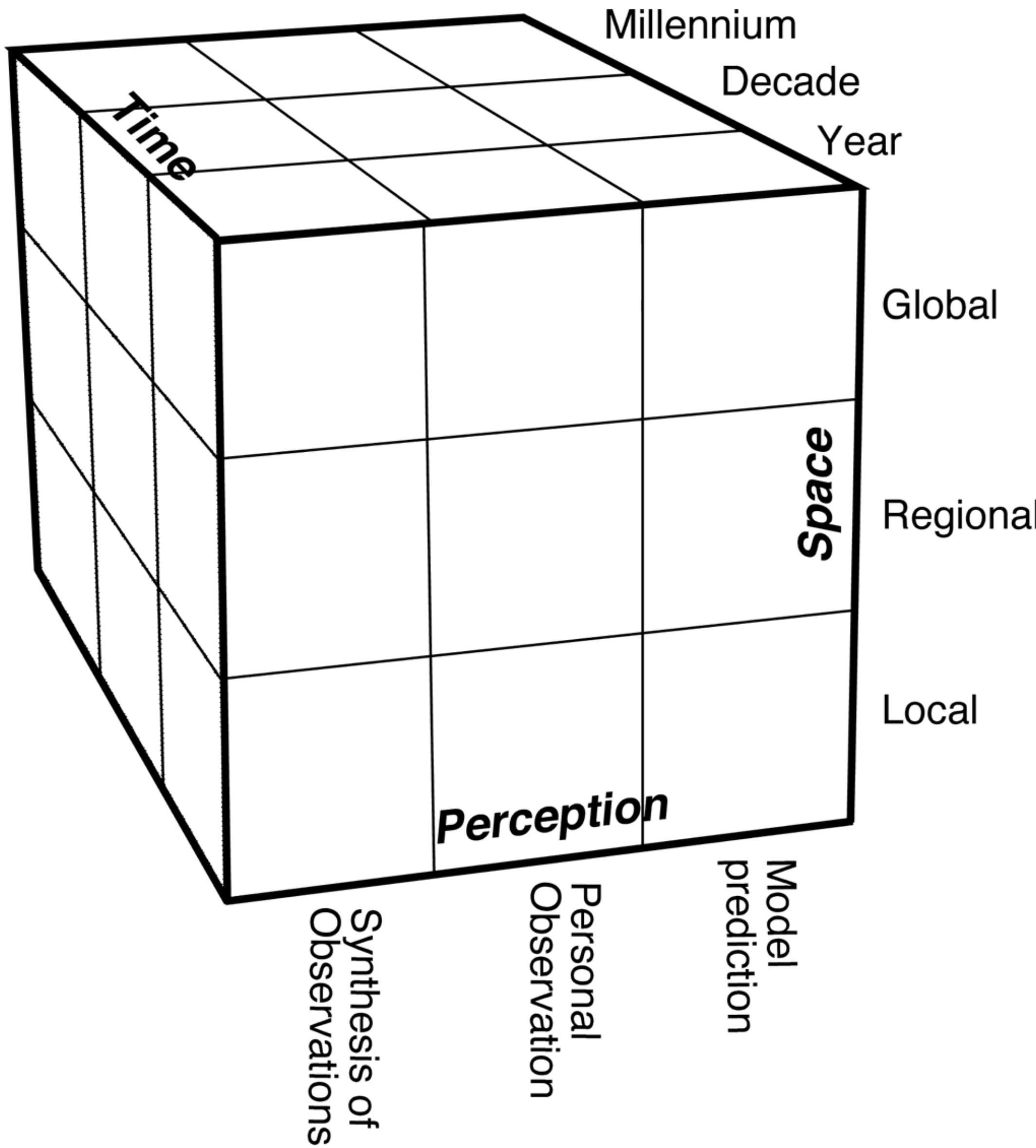
How do we define a Climate Model ?

"A climate model is a mathematical representation of the physical processes that determine climate"

Why do we need Climate Models ?

- **To create an understanding of the climate processes.**
- **To create plausible-scenarios, reflecting the current state of scientific understanding.**
- **To plan for the future.**

The Climate Cube



McGuffie, K. and Henderson-Sellers, A. (2005) A Climate Modelling Primer. 3rd ed., Wiley.

Climate model - an attempt to simulate many processes that produce climate

The simulation is accomplished by describing the climate system of basic physical laws.

Model is comprised of series of equations expressing these laws.

Climate models can be slow and costly to use, even on the faster computer, and the results can only be approximations.

The objective is to understand the processes and to predict the effects of changes and interactions.

The processes of climate system interact with each other, producing feedbacks, which in turn involves great deal of computation to simulate.

The solutions start from some "initialized" state and investigate the effects of changes in different components of climate system.

Boundary conditions – solar radiation or SST – set from obs. data, but since data itself aren't that complete, hence inherent uncertainty exists.

2 sets of simplifications

- **Involving process**
- **Involving resolution of model in time and space**

Process simplification –

- Treating some processes in detail and approximating others due to their inadequate understanding or lack of computer resources.

- E.g.- treating radiation process in detail, but approximating the horizontal energy flows associated with regional – scale winds.

- These approximations may be approached either by using available obs. data, some empirical approaches, or through simplifications of physical laws.

Time and space simplifications –

- Resolution of a model should be used appropriately.

- If process involved is larger than model resolution, finer resolutions for that model may be avoided.

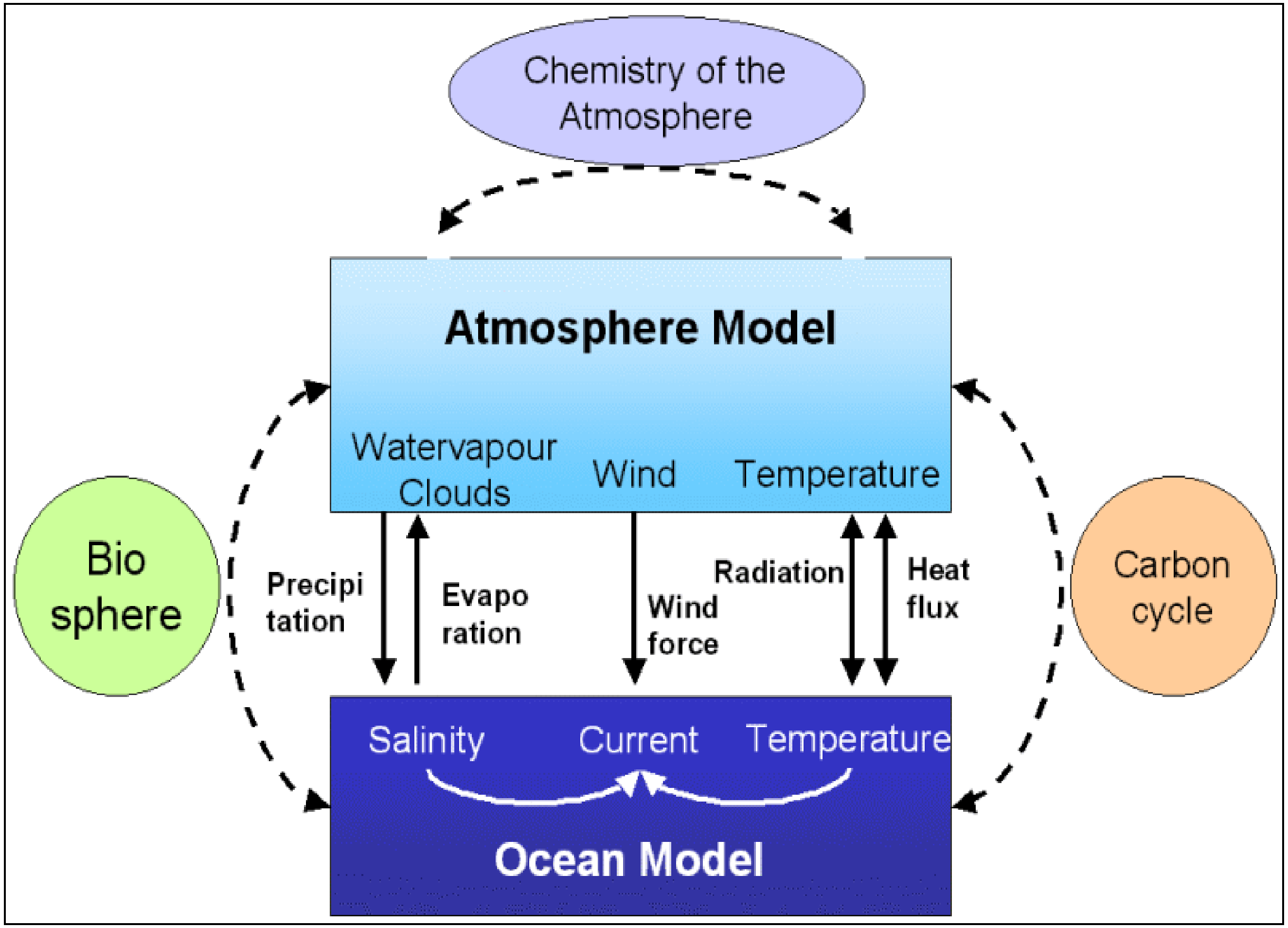
- Temporal resolution or "timestep' approach may have constraints imposed by data, computational ability and model design

- Process allowed to simulate for a certain time → new conditions calculated → process repeated with new values → continues till conditions at the required time have been established.

Components of Climate models

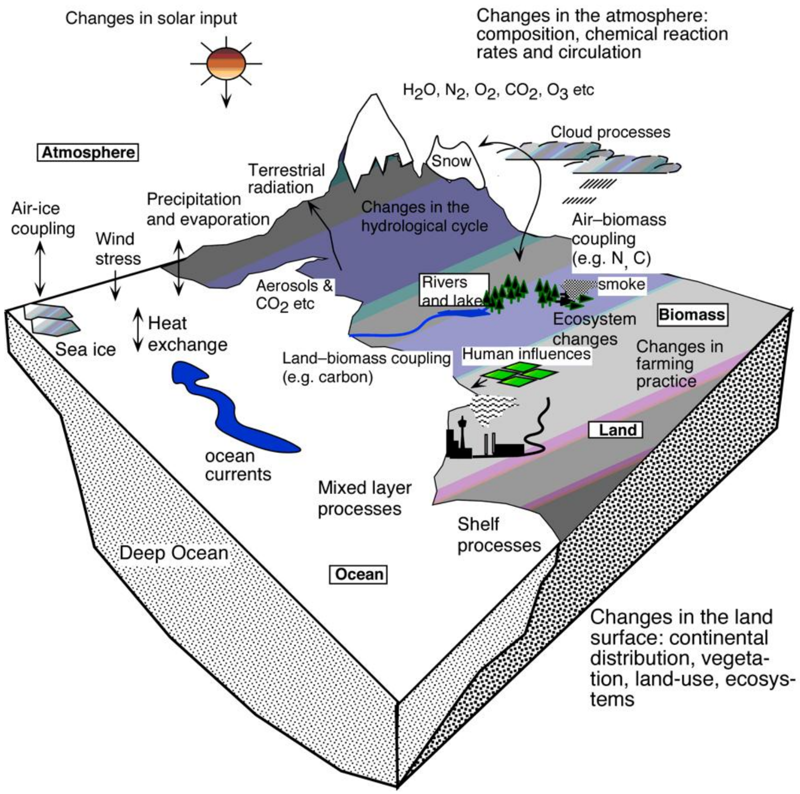
- ***Radiation*** **– input and absorption of solar radiation and emission of infrared radiation handled.**
- ***Dynamics*** **– horizontal movements of energy around the globe (low to high lat.) and vertical movements (convection etc.)**
- ***Surface processes*** **– inclusion of land/ocean/ice and the resultant change in albedo, emissivity and surface-atmosphere energy interactions.**
- ***Resolution in both time and space*** **– the time step of the model and the horizontal and vertical scales resolved.**

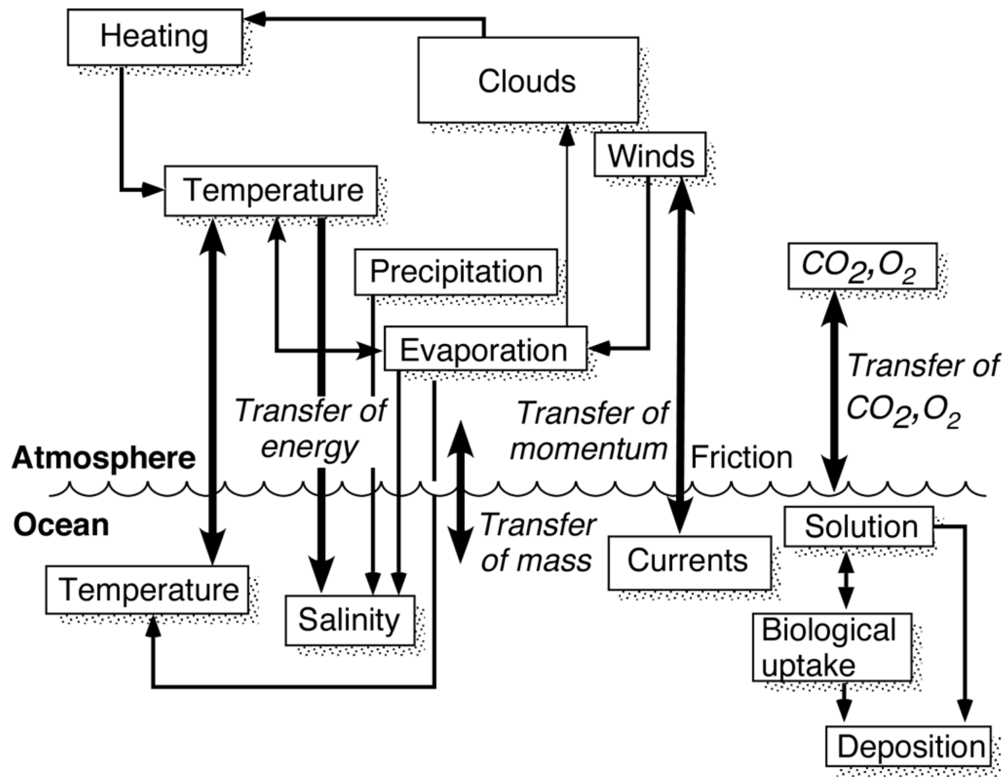
Framework for a Model



Source: MPI, Germany

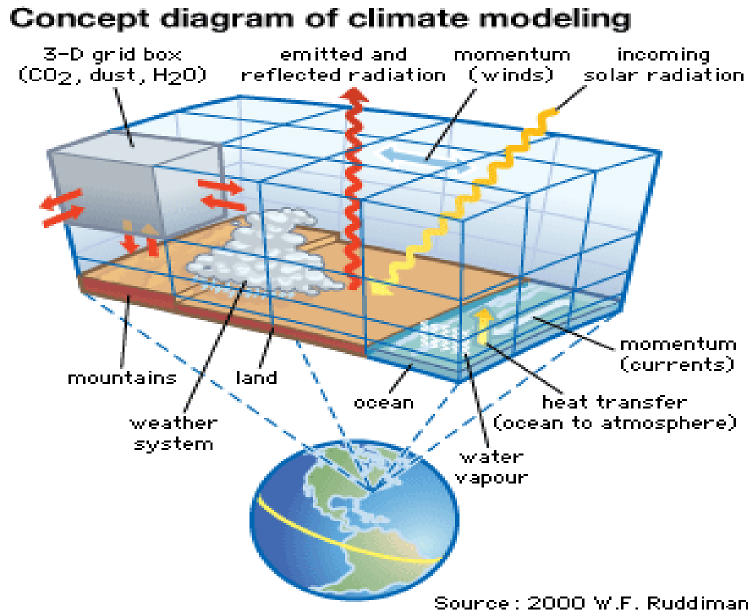
Components of a weather/climate model

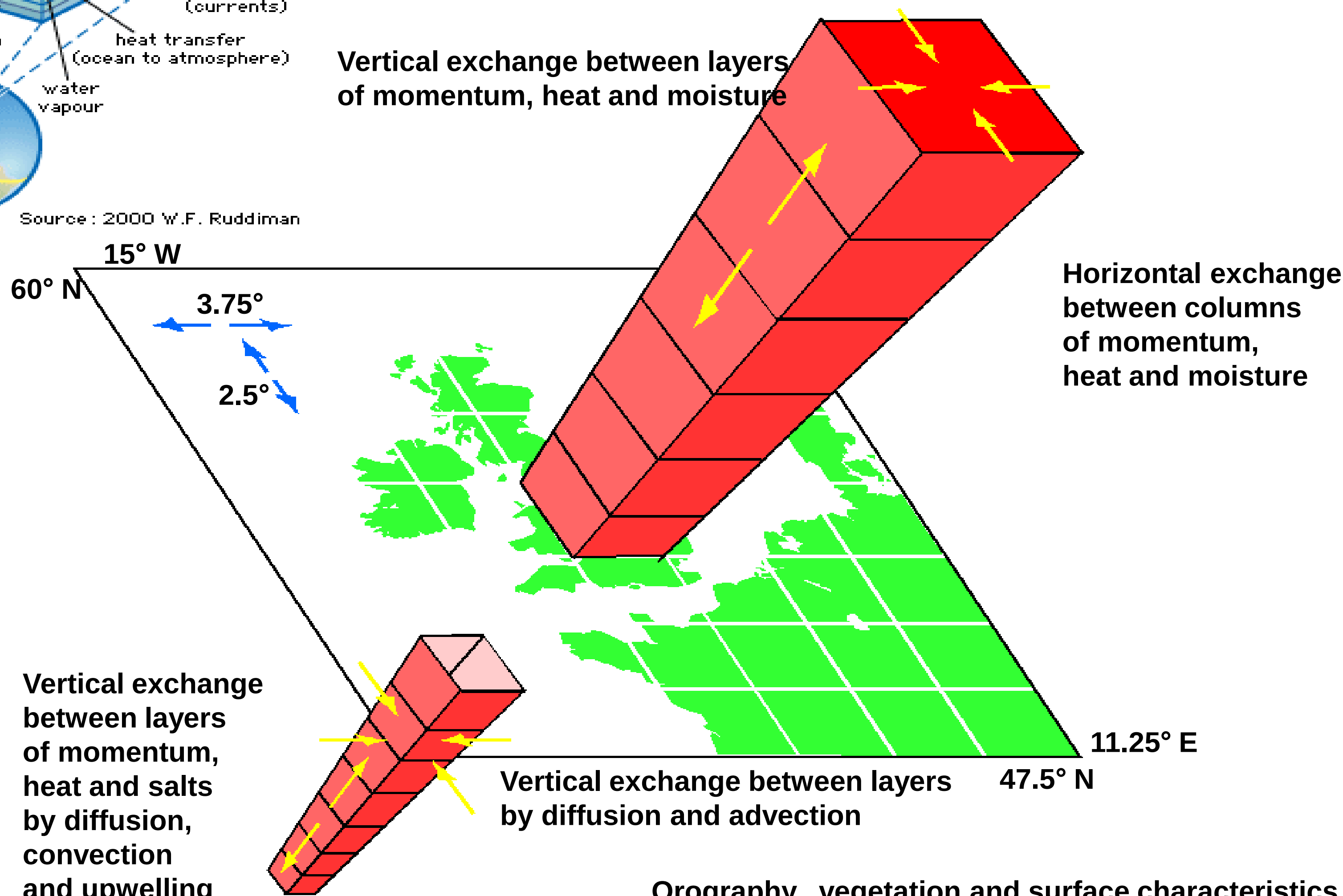




McGuffie, K. and Henderson-Sellers, A. (2005) A Climate Modelling Primer. 3rd ed., Wiley.

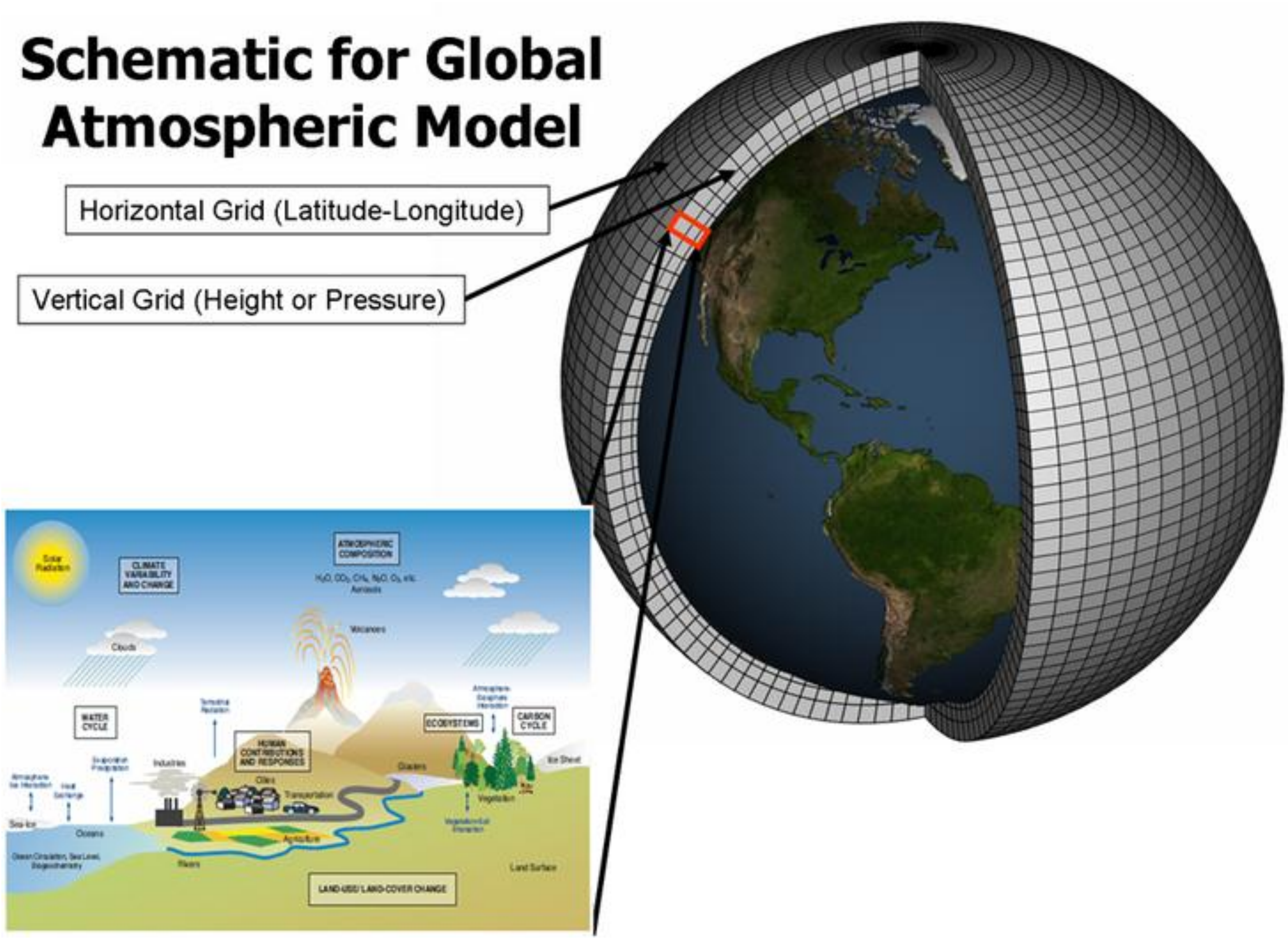
Modelling Climate





Orography, vegetation and surface characteristics included at surface on each grid box

Numerical Solution: Time steps and Grid boxes



All the physical processes occurring in the climate system are resolved at individual grid and the coupling occurs at these grids.

Source: NASA

Basic equations

General Circulation Model:

$$d\overline{\mathbf{V}}/dt + fk \times \overline{\mathbf{V}} + \nabla\overline{\phi} = \mathbf{F}, \qquad \textit{(horizontal momentum)}$$

$$d\overline{T}/dt - \kappa\overline{T}\omega/p = Q/c_p, \qquad \textit{(thermodynamic energy)}$$

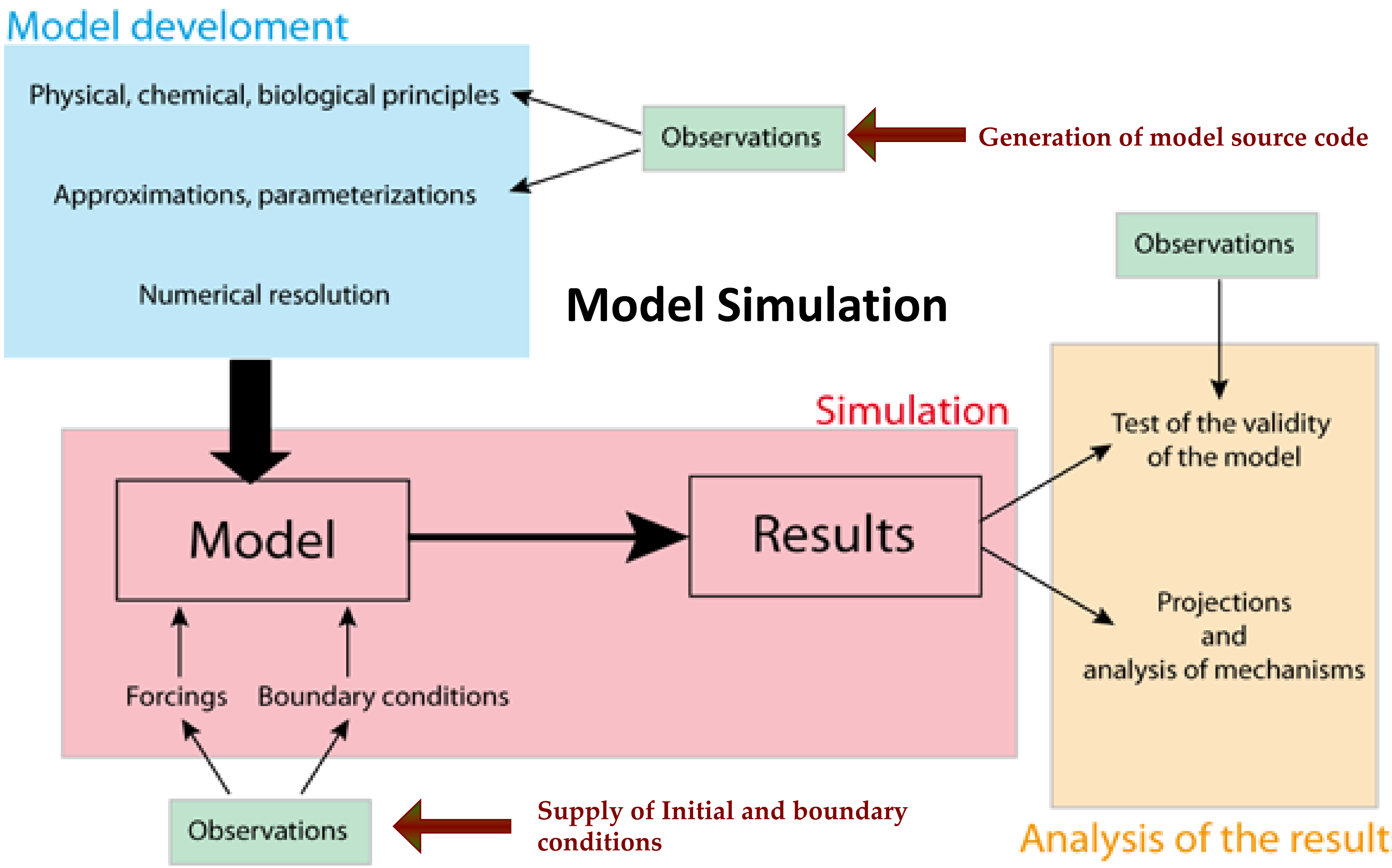
$$\nabla \cdot \overline{\mathbf{V}} + \partial\overline{\omega}/\partial p = 0, \qquad \textit{(mass continuity)}$$

$$\partial\overline{\phi}/\partial p + R\overline{T}/p = 0, \qquad \textit{(hydrostatic equilibrium)}$$

$$d\overline{q}/dt = S_q. \qquad \textit{(water vapor mass continuity)}$$

Harmless looking terms F, Q, and $S_q \Longrightarrow$ "physics"

Process of Model Simulation



Source: Goosse et al 2010

Types of climate Models

1. **Energy Balance Models (EBMs)**

   zero or one dimensional

2. **Radiative Convective (RC) Models**

   one dimensional

3. **Statistical Dynamical (SD) Models**

   two dimensional

4. **Global Circulation Models (GCMs)**

   Three dimensional

Energy Balance Models (EBMs)

Zero or one-dimensional models predicting the variation of the surface (strictly sea level) temperature as a function of the energy balance of the earth with latitude.

Used to investigate sensitivity of climate systems to external changes and interpret results from complex models.

Radiative-Convective climate Models

Are 1-D with respect to altitude and compute the vertical (usually globally averaged) temperature profile by explicit modelling of radiative processes and 'convective adjustment' which re-establishes a predetermined lapse rate.

RC models study the effects of changing atmospheric composition and investigate likely relative influences of different external and internal forcings.

Statistical Dynamical (SD) Models

Are 2-D models that deal explicitly with surface processes and dynamics in a zonally averaged framework and have vertically resolved atmosphere.

SD models used to make simulations of the chemistry of stratosphere and mesosphere.

Global Circulation Models (GCMs)

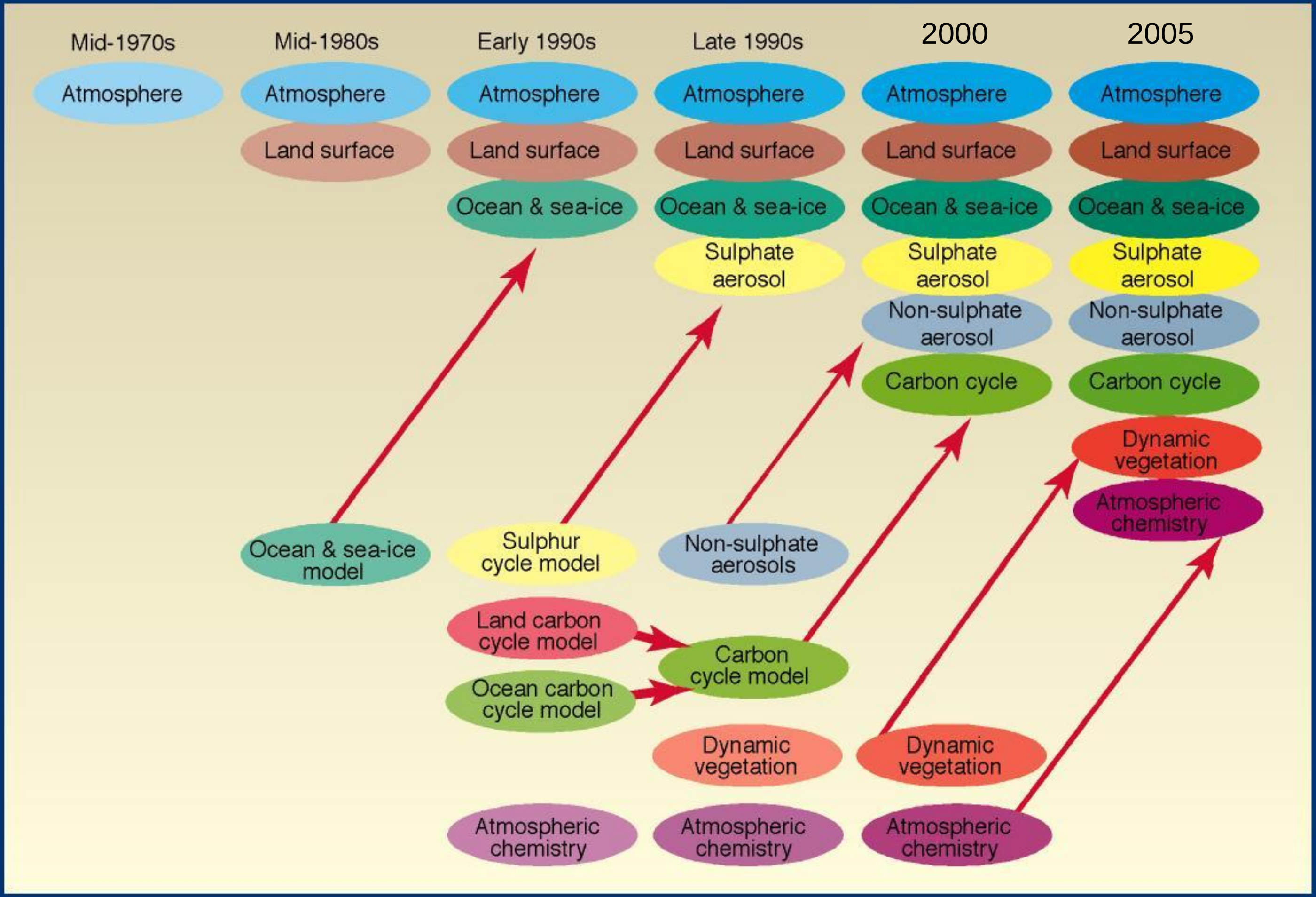
Where the 3-dimensional nature of the atmosphere and/or ocean is incorporated. Vertical resolution is generally finer than horizontal resolution. Includes AGCM, OGCM and the coupled AOGCM.

The resulting set of coupled non-linear equations are solved at each grid point using numerical techniques that use time step approach.

Atmospheric grid points ~ 2^o-5^o with time steps ~ 20-30 min. Vertical resolution ~ 6-50 levels (20 being typical).

Development of climate models

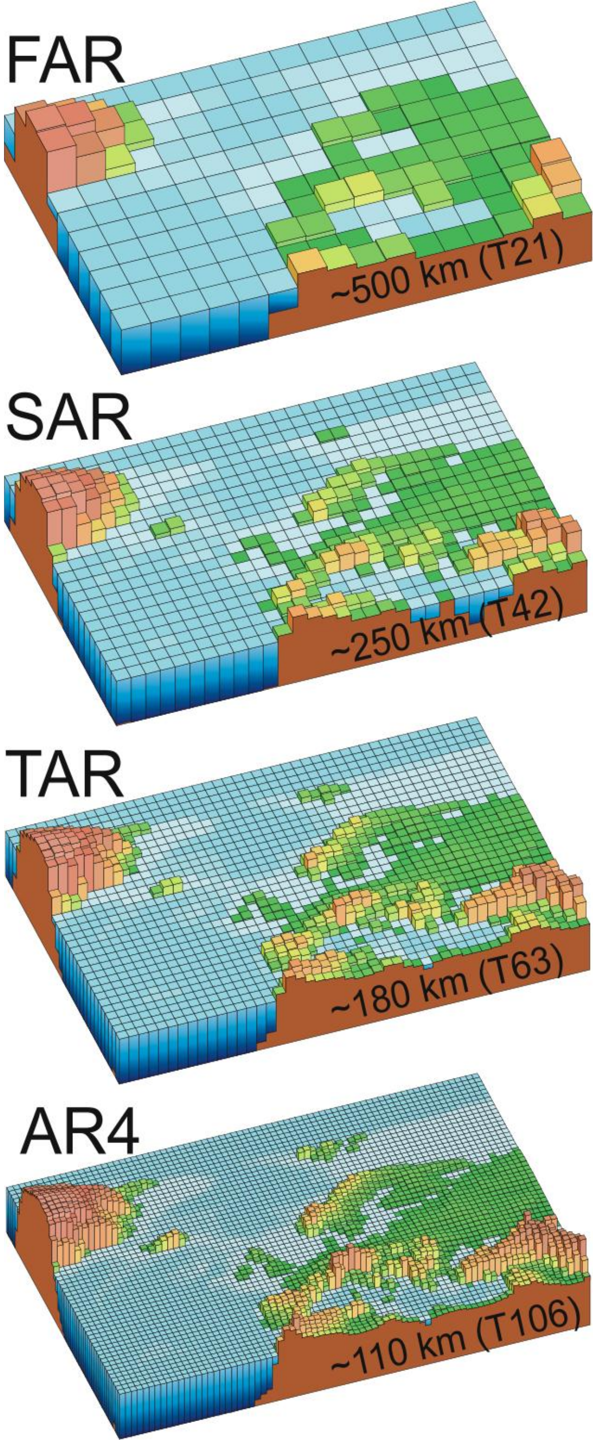
The development of climate models, past, present and future



WG1 - TS BOX 3
FIGURE 1

Improvements in Grid resolution

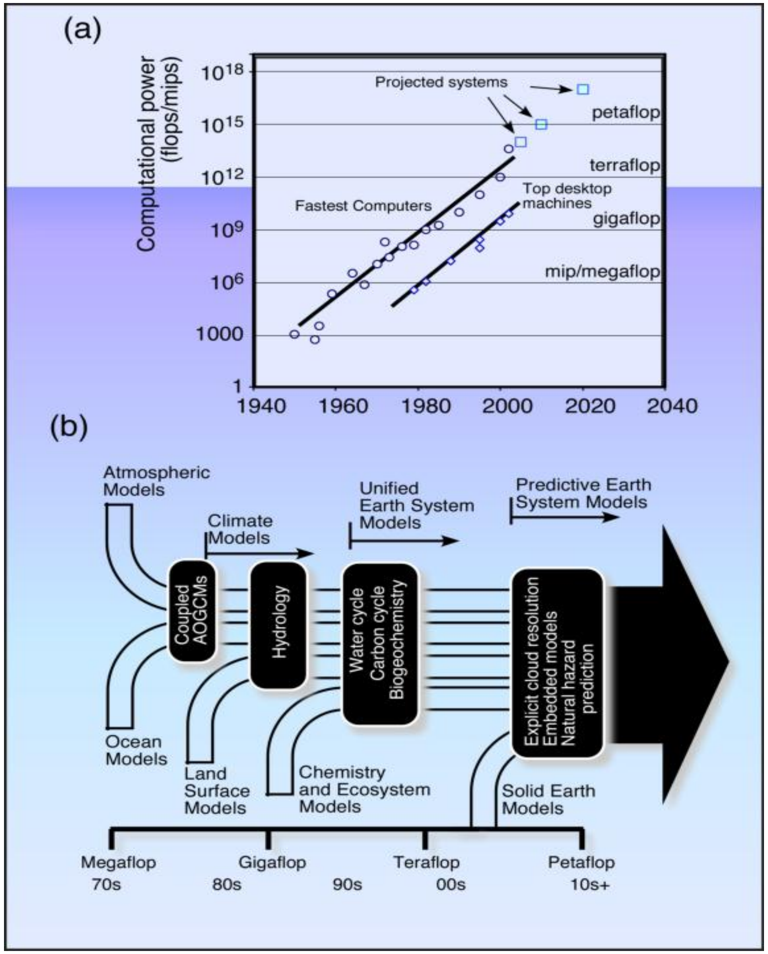
- The evaluation of the Climate models has become an essential pre-requisite to understand the Earth's climate system
- A Model Inter-comparison Project is an approach to model verification and they are part of community analysis and verification/activity.
- Intergovernmental Panel for Climate Change has started its MIP programs with Atmospheric Models in 1995 till today with CMIP (Coupled Ocean Atmospheric Models).



Computational Capabilities and Needs

Improvements in computational capabilities have paved the developments of atmospheric simulation capabilities

Source: NCAR



Source: McGuffe, Henderson and sellers

As an example, a 10-year global atmospheric simulation using a state-of-art GCM can require several tens of hours of supercomputer time approx 10^9 floating operations per second (1 Giga Flops)

What can we expect to simulate?

1. Basic features of the general circulation of the atmosphere (e.g. Hadley cell, mid-latitude jets)
2. Climatology (based on at least 5-10 years) e.g. seasonal and monthly means.
3. Climate variability, e.g. behaviour of dominant modes of inter-annual variability such as ENSO, NAO.
4. Statistics of sub-seasonal variability e.g. monsoon active/break cycles, storm-track characteristics

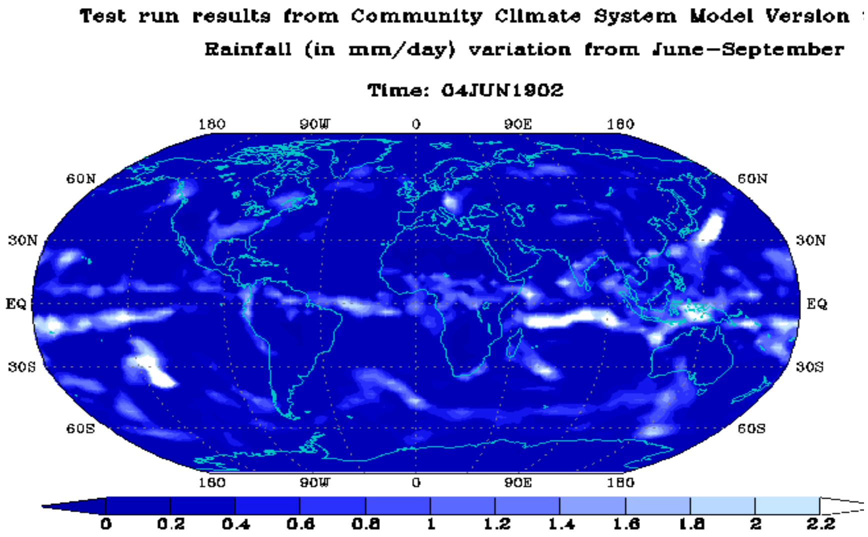
What can we not expect to simulate?

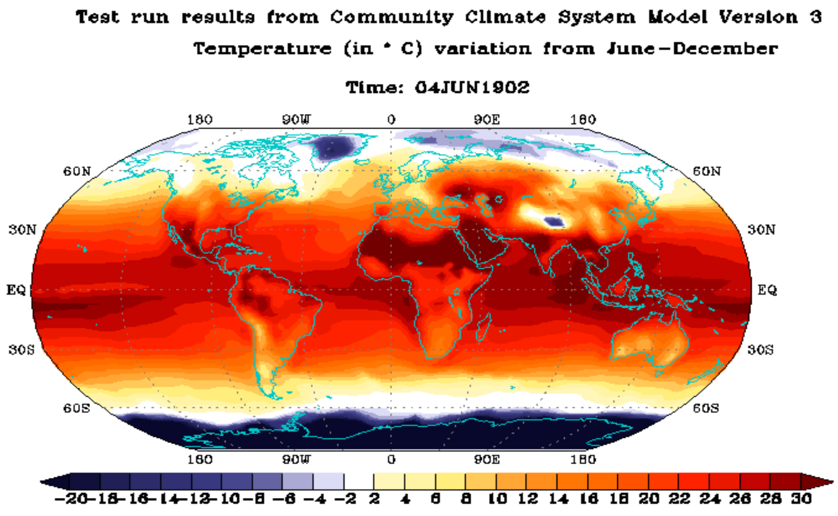
1. The actual weather observed at individual locations, at specific times.

2. A 100 % correlation with observations due to inherent climate uncertainty. Hence, ensemble approach is utilized.

3. Individual weather events. But climatological statistics able to provide future frequency and magnitude of such events.

Simulations using a Global Coupled Model:

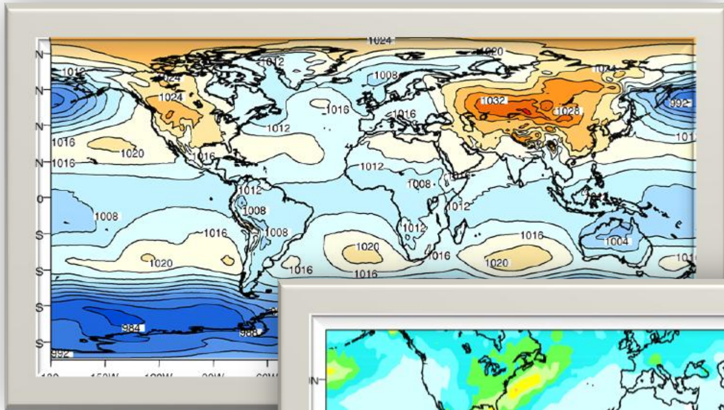




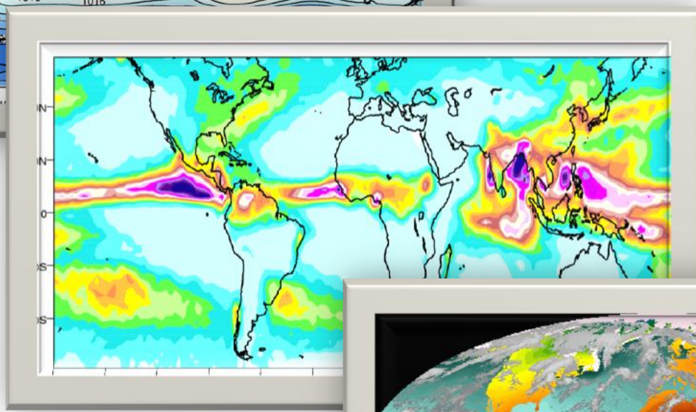
The simulations of a model should be comparable to the observations, this step is called as Validation of the model outputs

Source: TERI (2011)

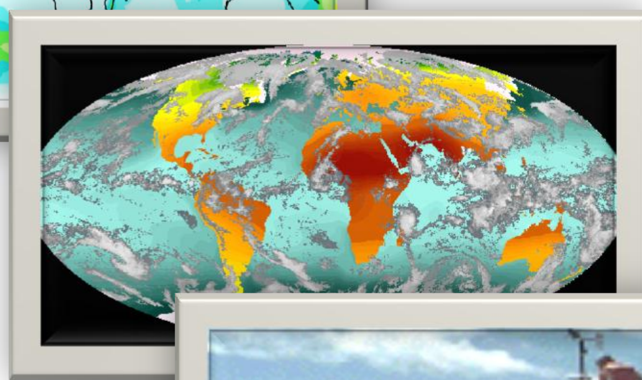
Typical data used to evaluate climate models



Re-analyses of the global circulation (ERA40, NCEP)



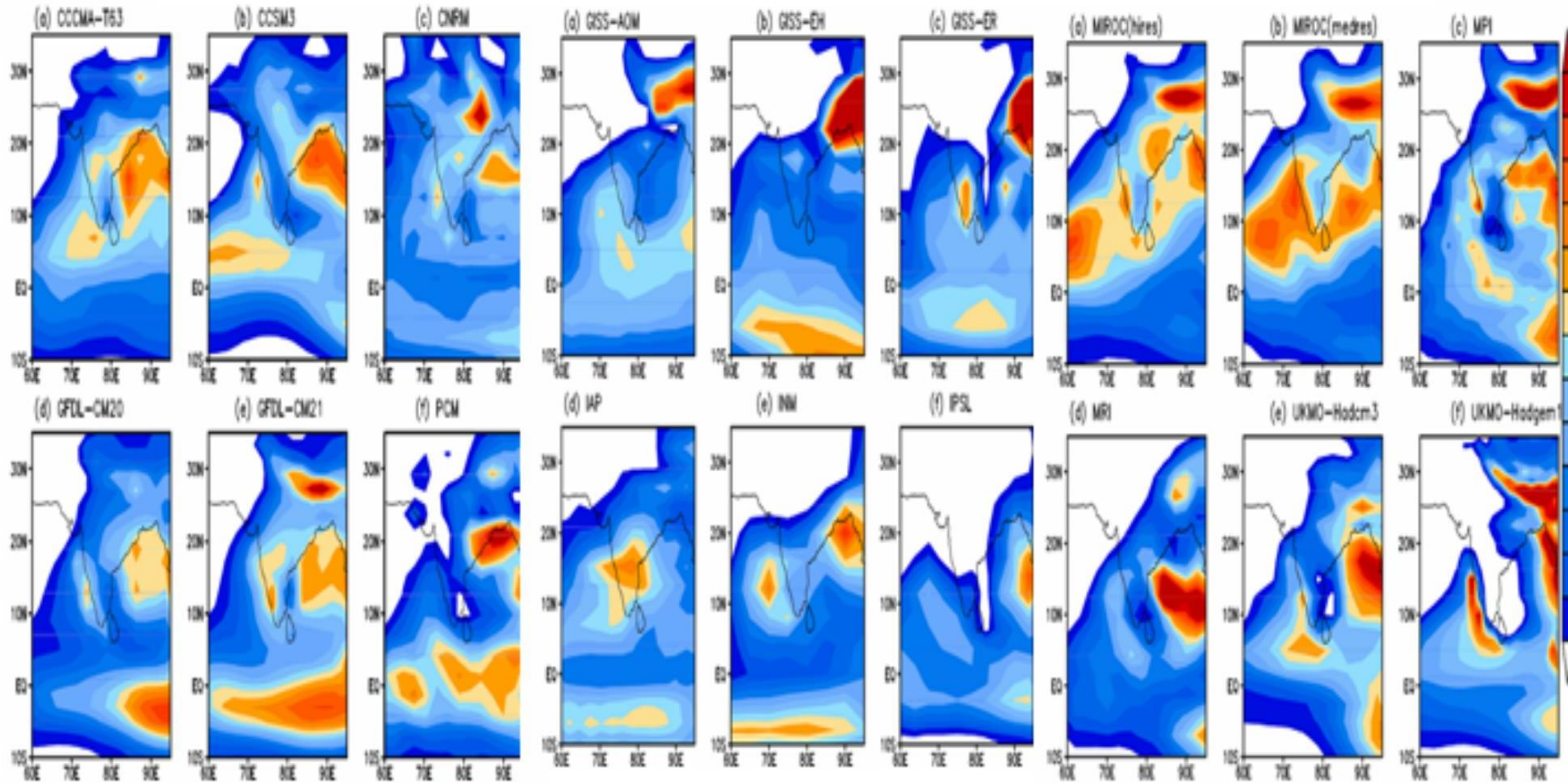
Synthesised climatologies e.g. precipitation



Satellite observations

In situ measurements

Need for Regional Climate Modeling Tool

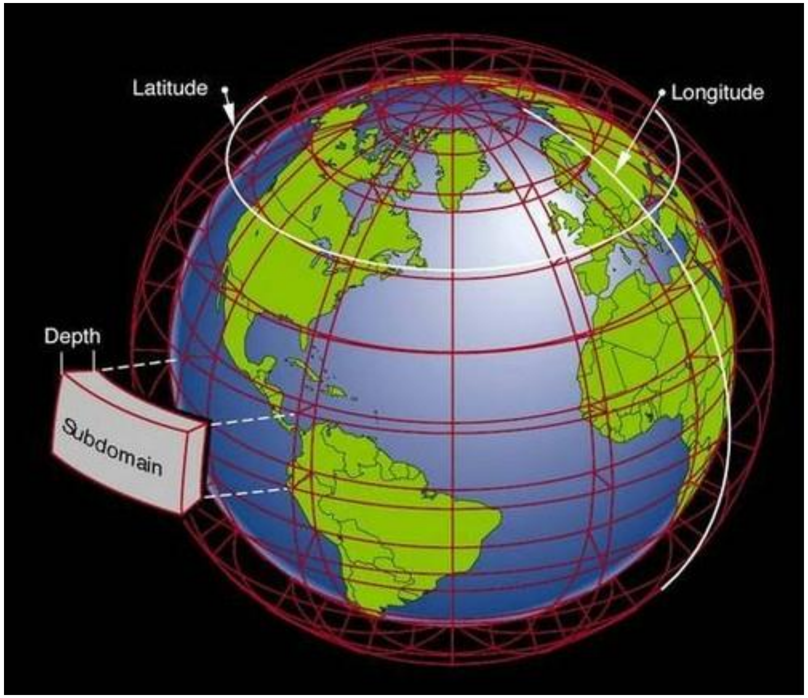


Most of AR4 coupled models even with high spatial resolution of 110km x 110km were unable to represent the mean monsoon pattern similar to observations.

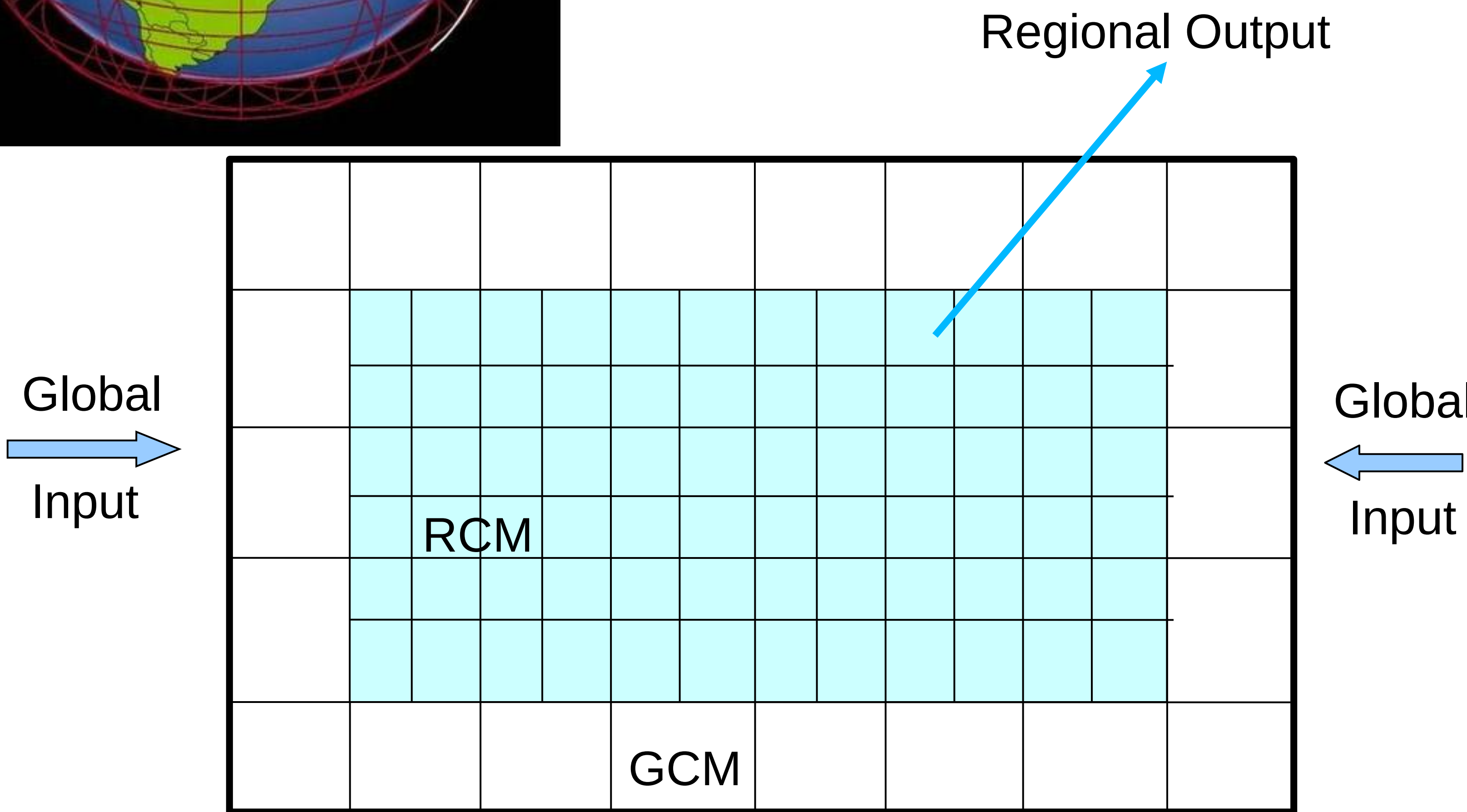
Downscaling from GCMs

- **Downscaling is a way to obtain higher spatial resolution output based on GCMs.**
- **Options include:**
  - **Combine low-resolution monthly GCM output with high-resolution observations**
  - **Use statistical downscaling**
    - **Easier to apply**
    - **Assumes fixed relationships across spatial scales**
  - **Use regional climate models (RCMs)**
    - **High resolution**
    - **Capture more complexity**
    - **Limited applications**
    - **Computationally very demanding**

Downscaling



Dynamical Downscaling

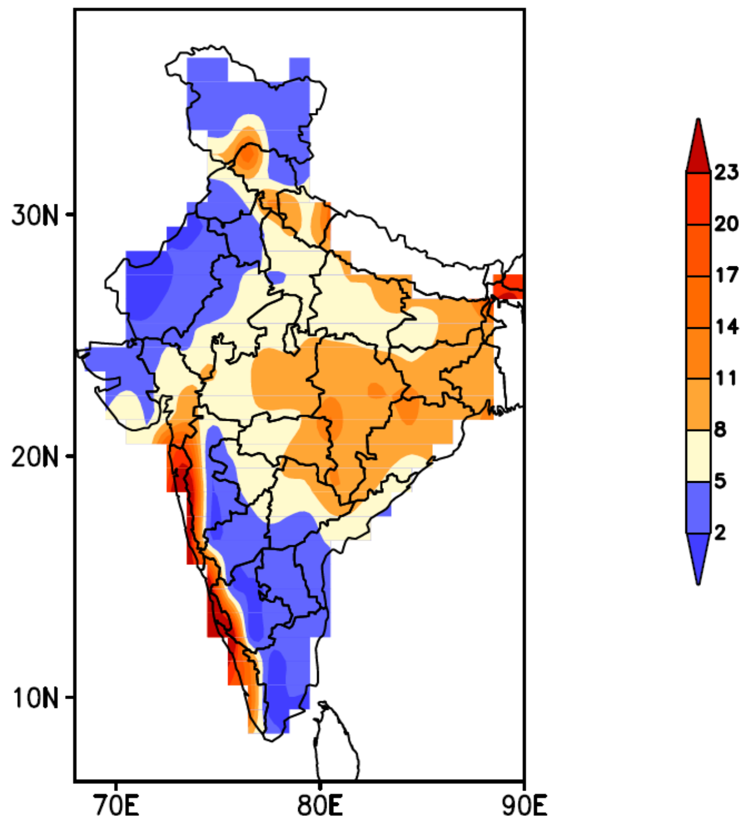


Regional Climate Models (RCMs)

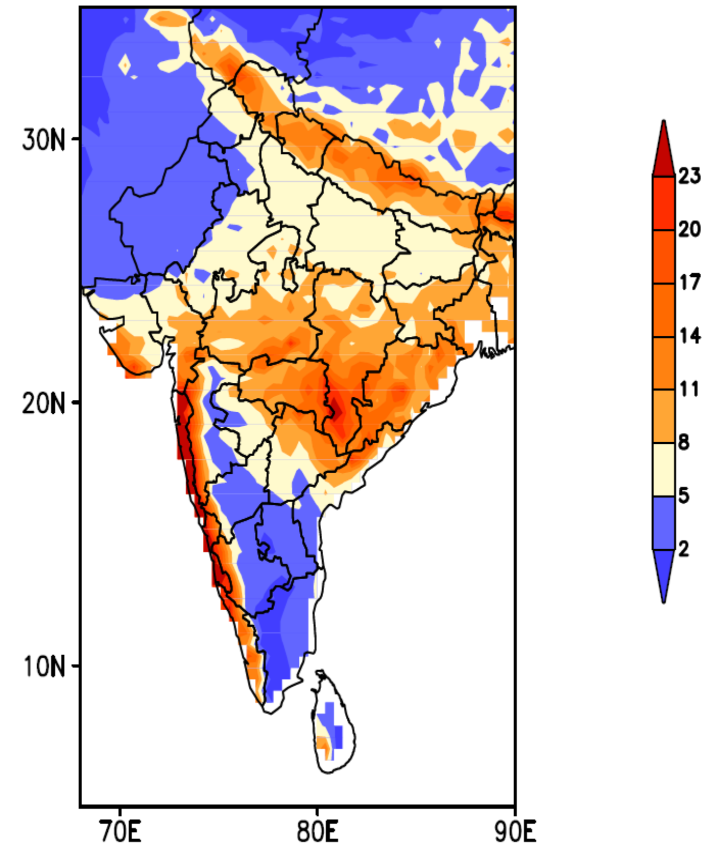
- **These are high resolution models that are “nested” within GCMs**
- **A common grid resolution is 50 km or lesser.**
- **RCMs are run with boundary conditions from GCMs**
- **They give much higher resolution output than GCMs**
- **Hence, much greater sensitivity to smaller scale factors such as mountains, lakes**

Regional Modelling Product

IMD JJA rainfall mean of 50 years (1961–2007)



PRECIS JJA rainfall mean of 30 years (1960–1990)

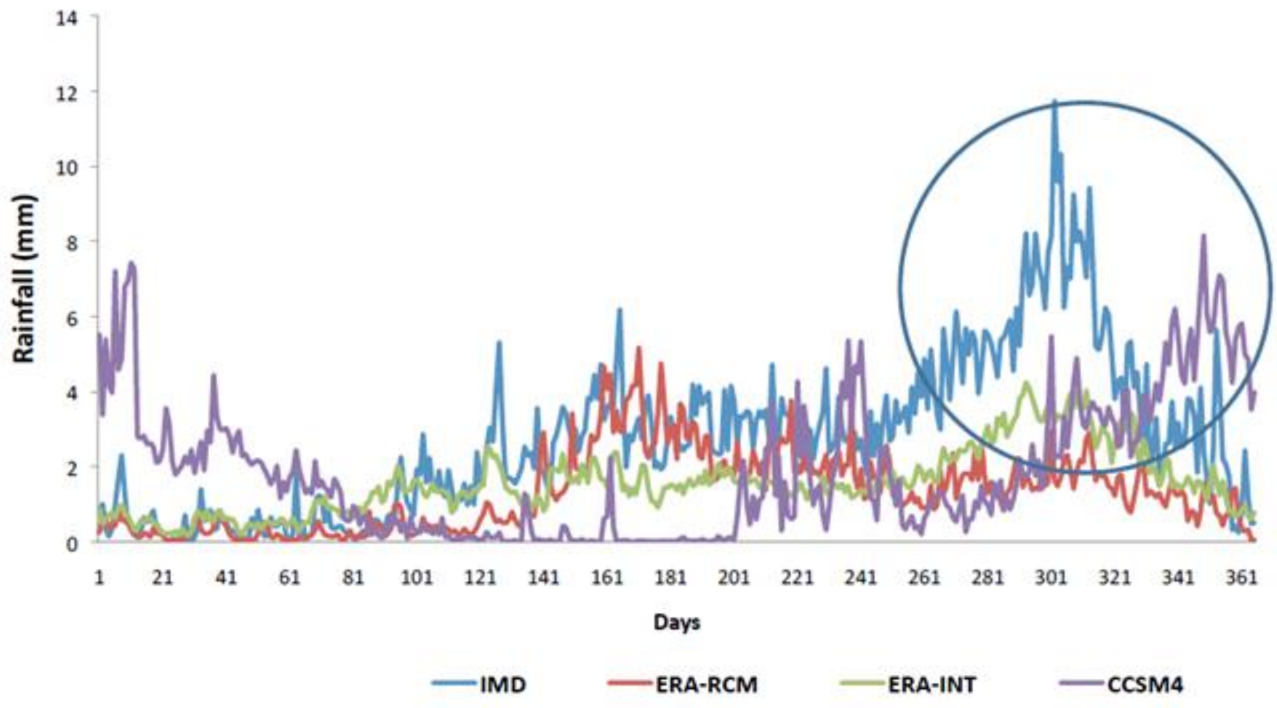


Source: TERI (2011)

RCM is able to capture the major features but overestimates the rainfall in few regions.

Lack of observations: poor model result

Observed rainfall climatology compared with IPRC_RegCM over peninsular India

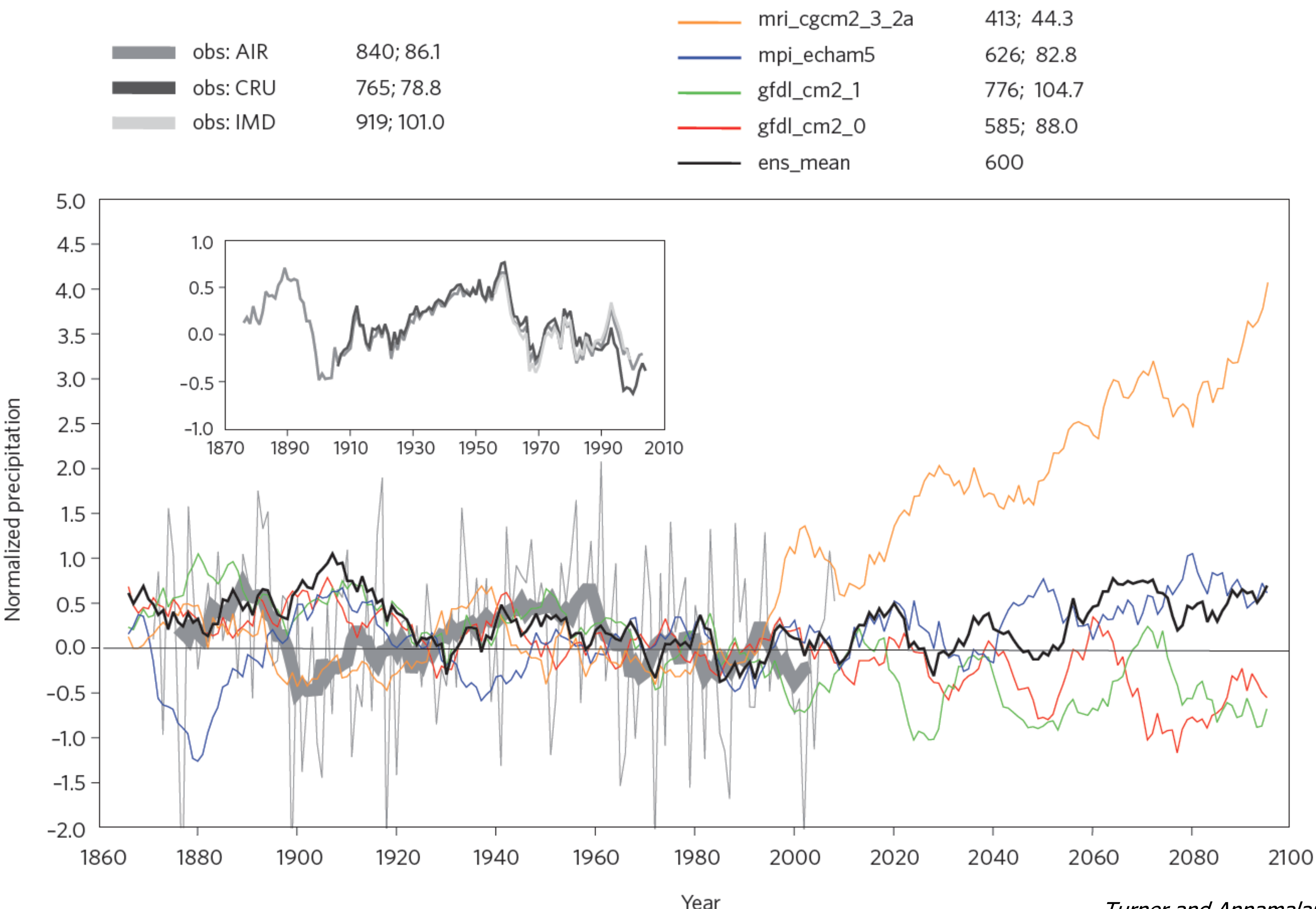


Reanalysis – temporal variability of atmospheric states and internal variability preserved – yet, results are not encouraging

Monsoon region – lack of 3-D moisture observations – severe constraint

Annamalai, 2012

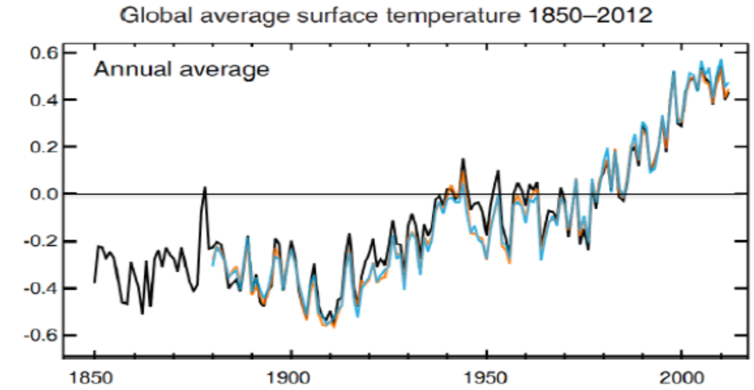
Uncertainties in Observation and Models



Turner and Annamalai, 2012

OBSERVATIONAL EVIDENCES

Annual Global Combined Land and Sea Temperature

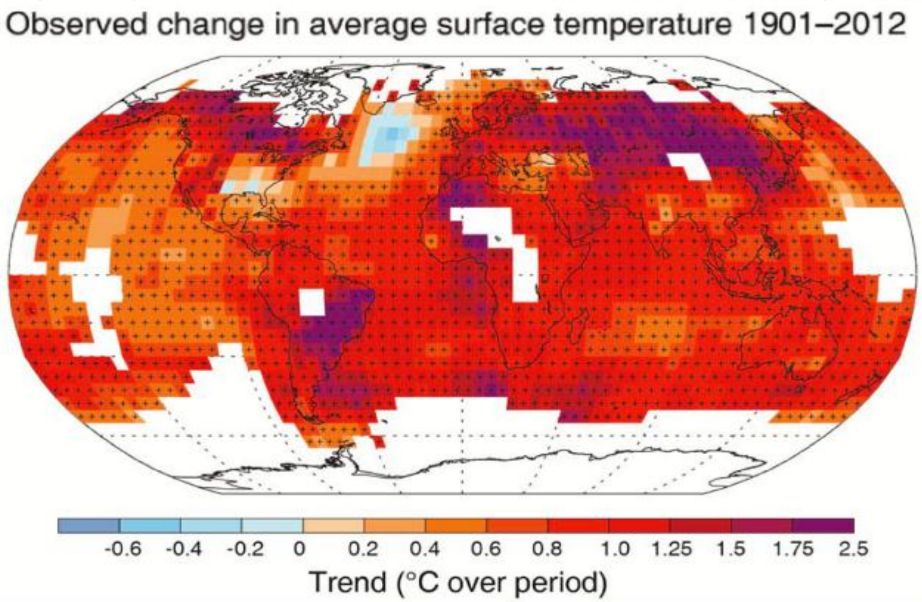


HadCRUT4 (black), MLOST(orange) and GISS (blue) are shown.

The globally averaged combined land and ocean surface temperature data, show a warming of 0.85 [0.65 to 1.06] °C , over the period 1880–2012. The total increase between the average of the 1850–1900 period and the 2003–2012 period is 0.78 [0.72 to 0.85].

IPCC AR5 Working Group I
Climate Change 2013: The Physical Science Basis

ipcc INTERGOVERNMENTAL PANEL ON climate change



(IPCC 2013, Fig. SPM.1b)

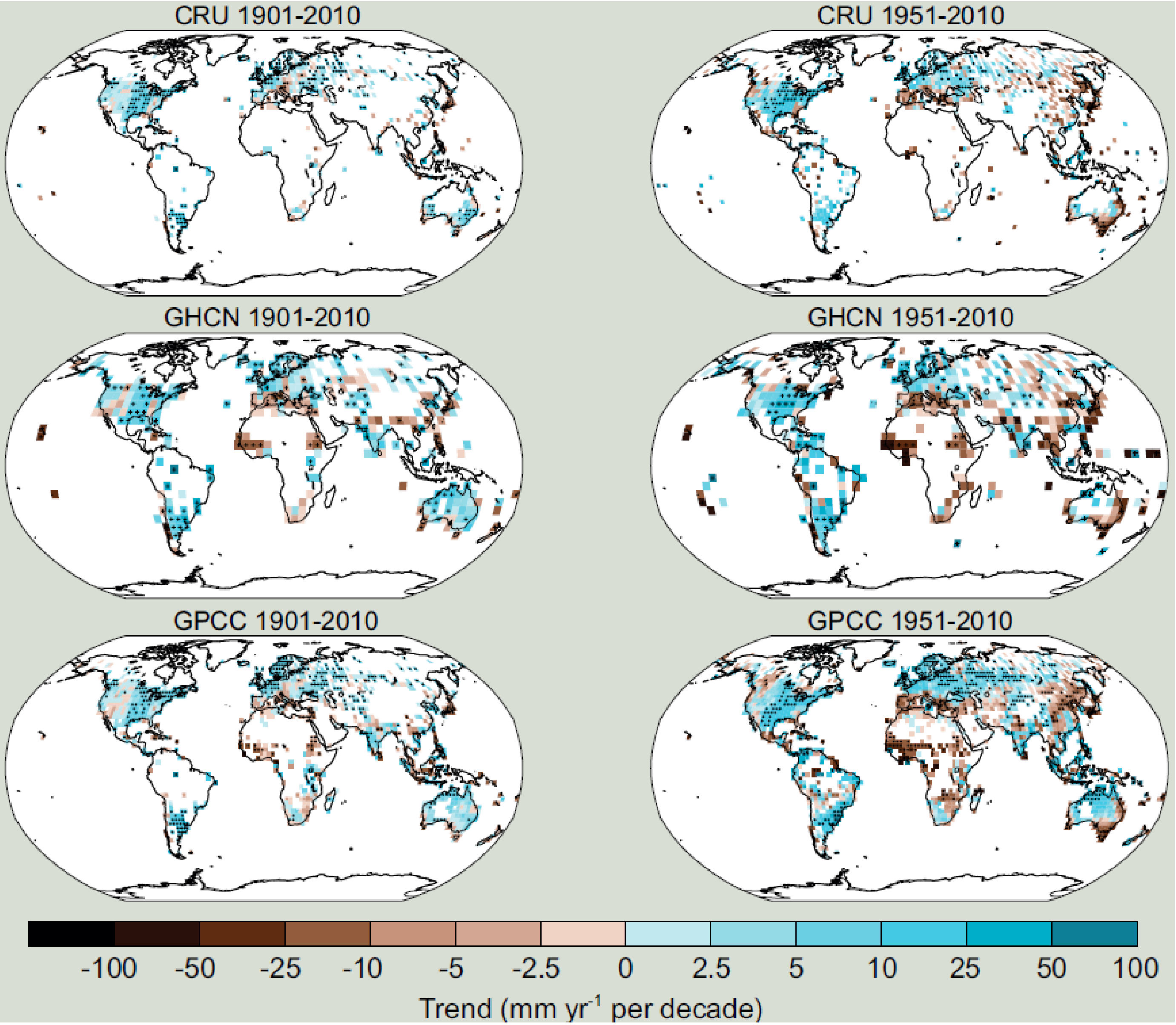
Warming in the climate system is unequivocal

Temperature has risen

Warming is Unequivocal

IPCC, 2013, AR5 WG1

OBSERVATIONAL EVIDENCES

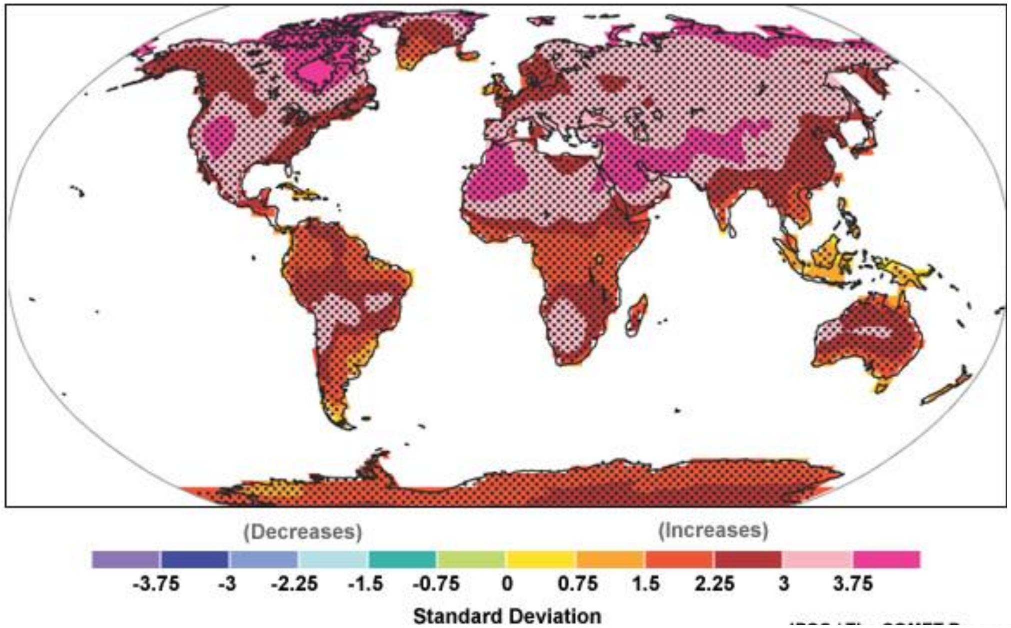


Precipitation show varied trends

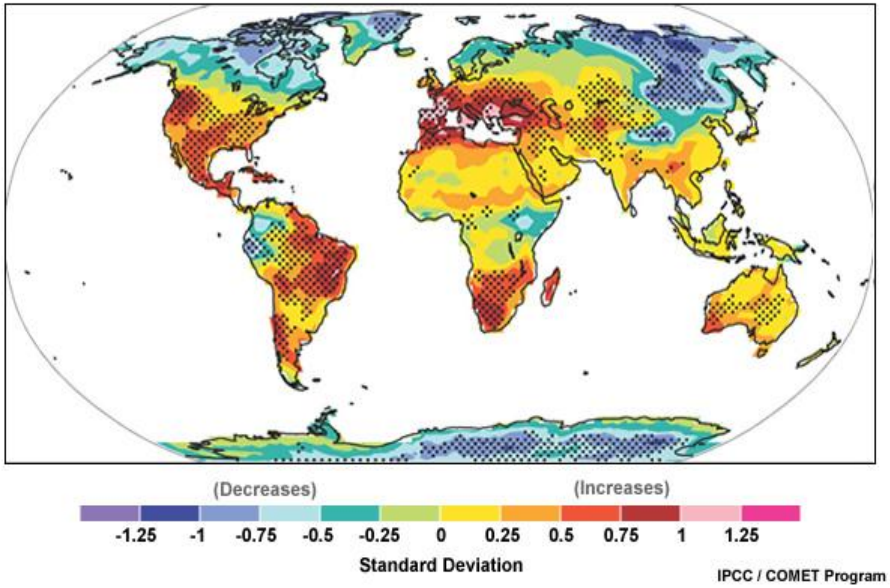
Different observations data show the variability

IPCC, 2013, AR5 WG1

Multi-model Simulation of Heat Wave Changes,
Years 2080-2099 Minus Years 1980-1999 (middle emissions scenario)

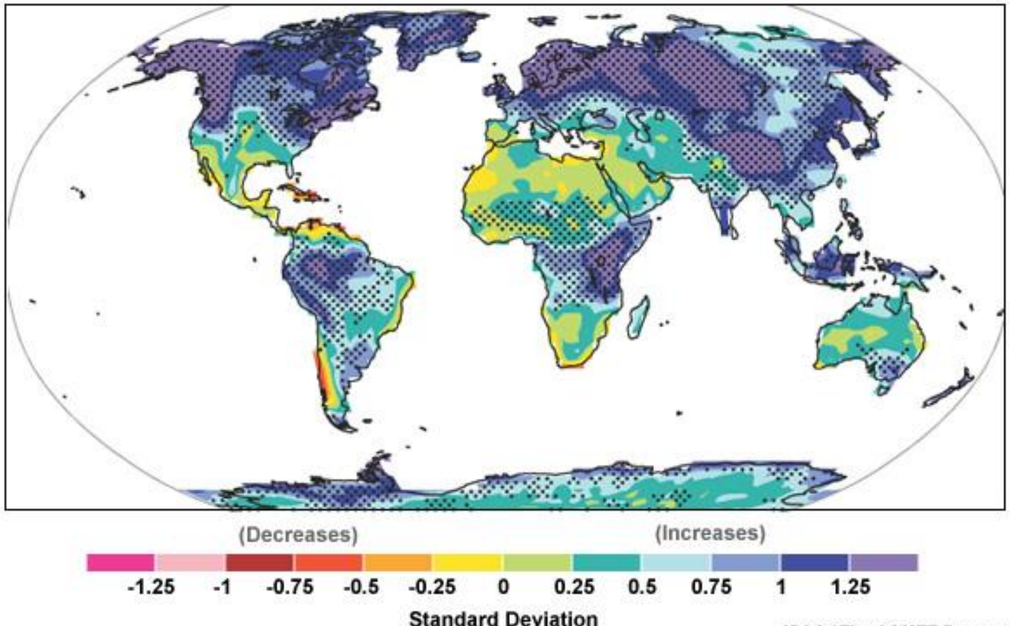


Multi-model Simulation of Changes in Dry Days
Years 2080-2099 Minus Years 1980-1999 (middle emissions scenario)



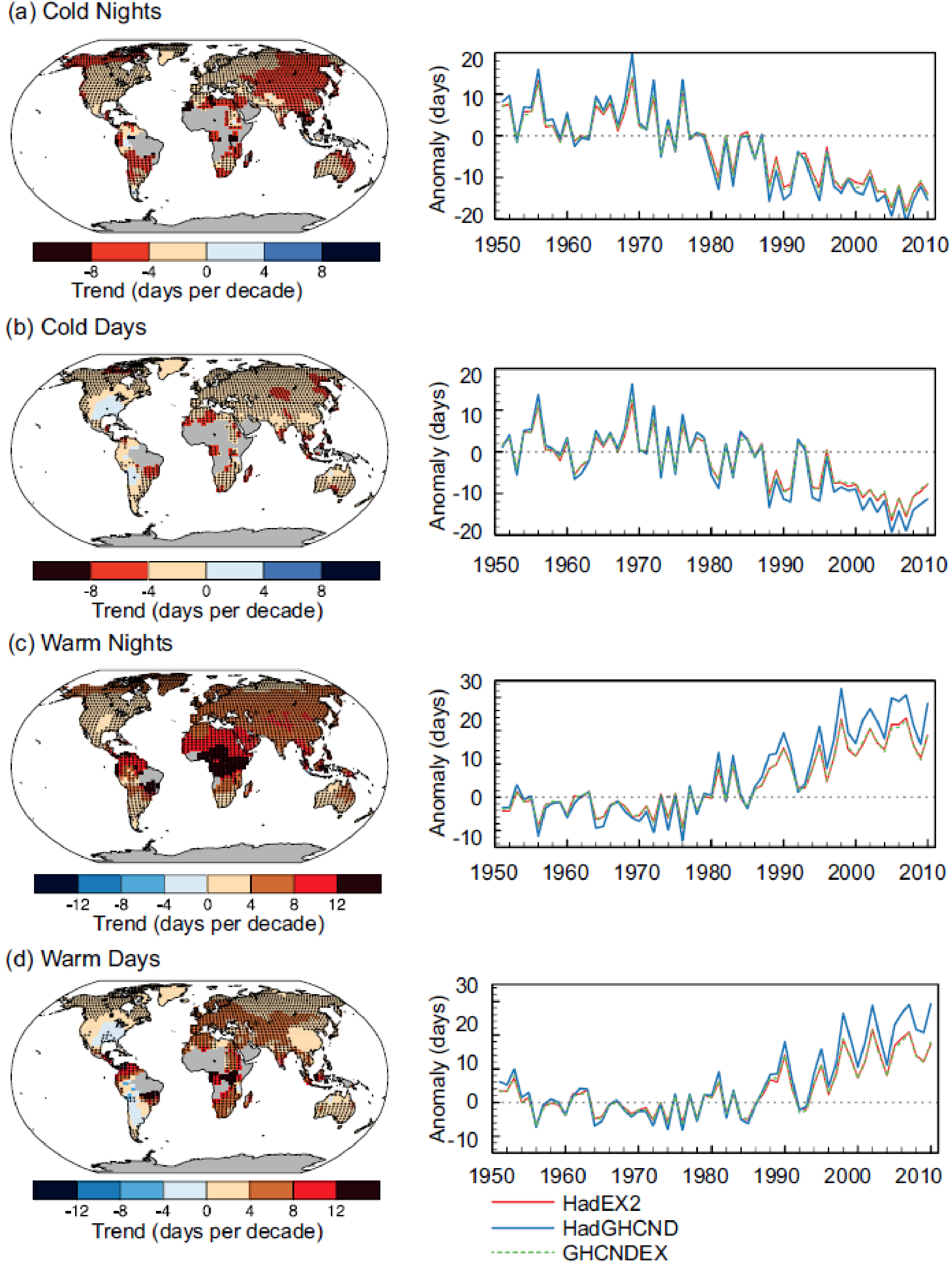
IPCC / COMET Program

Multi-model Simulation of Precipitation Intensity Changes
Years 2080-2099 Minus Years 1980-1999 (middle emissions scenario)



IPCC / The COMET Program

S. Asia showing increasing climate extremes

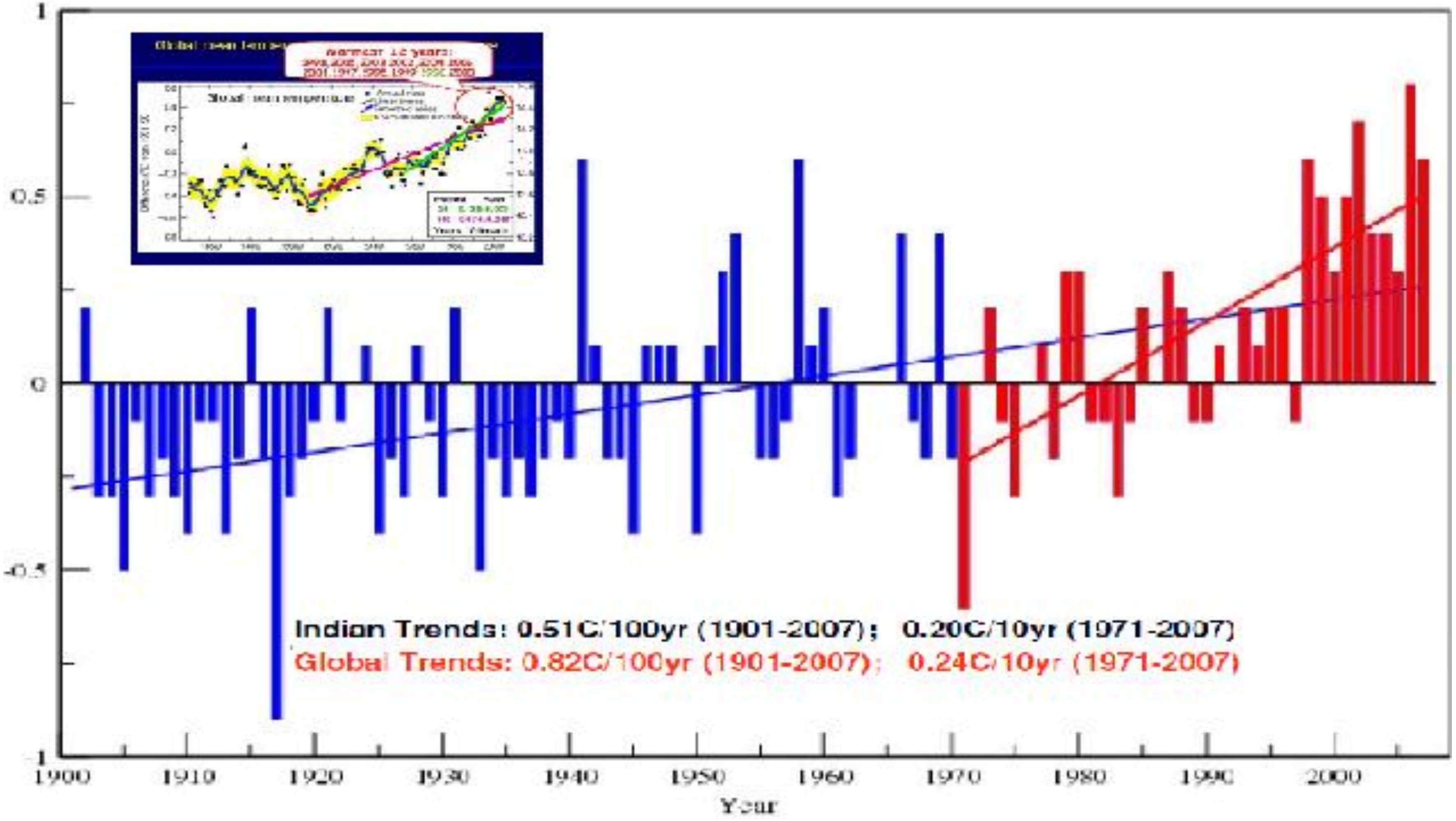


Decreasing cold nights and days

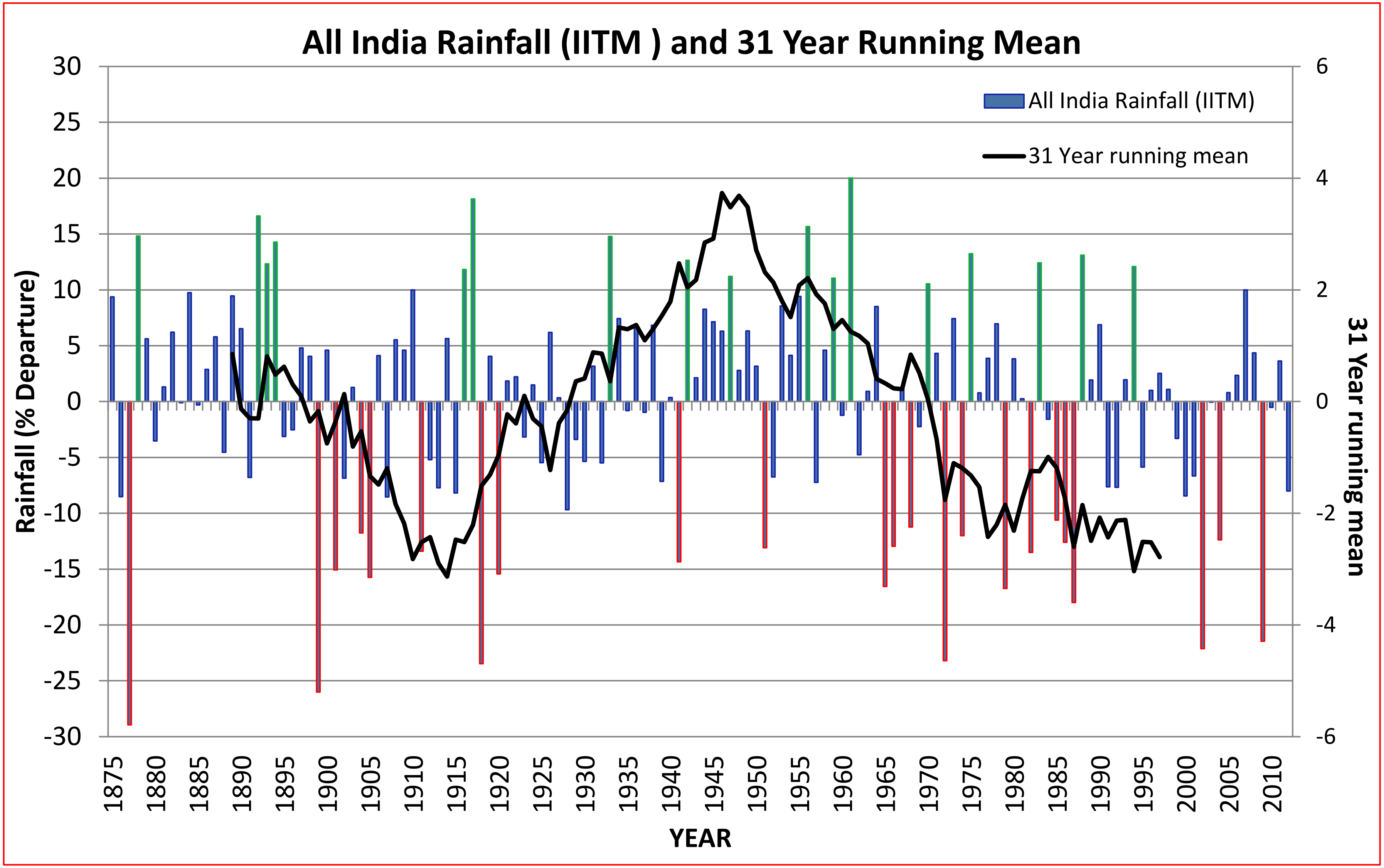
Increasing warm nights and days

IPCC, 2013, AR5 WG1

All India Mean Annual Temperature Anomalies (1901-2007) (Base: 1961-1990)



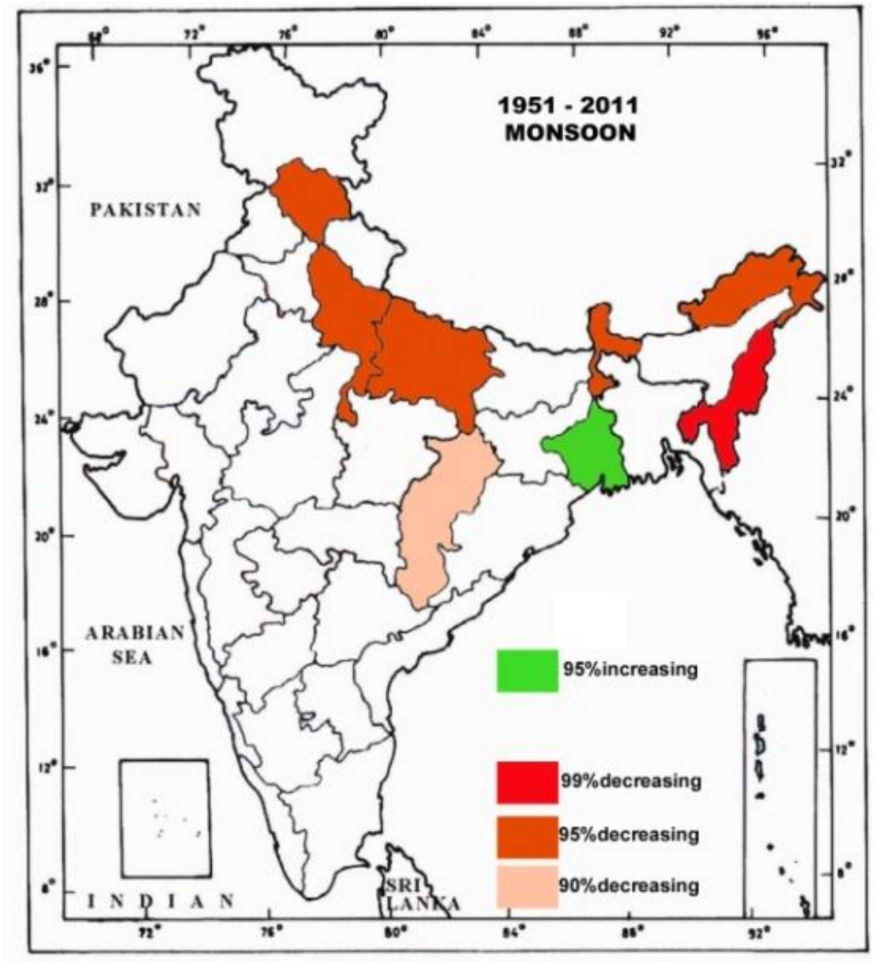
Krishna Kumar, 2009

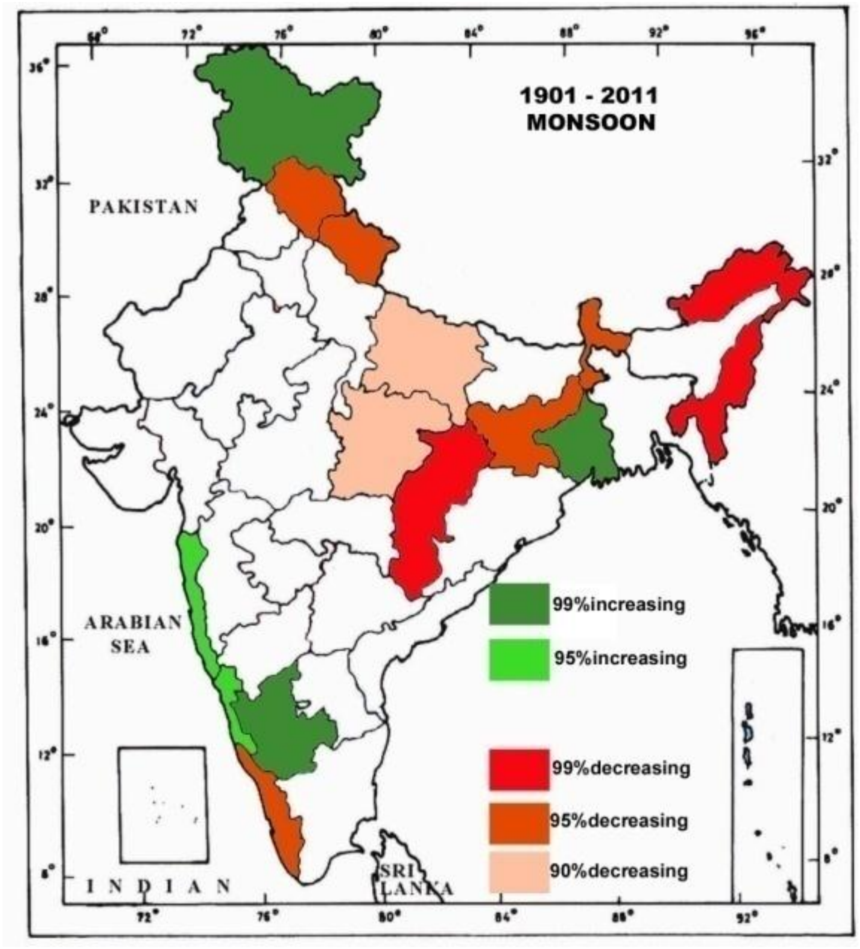


All-India monsoon season rainfall time series shows NO long term trends. It is marked by large year to year variations. There is a tendency of occurrence of more droughts in some epochs (for example, 1901-1930, 1961-1990).

Rajeevan, 2013

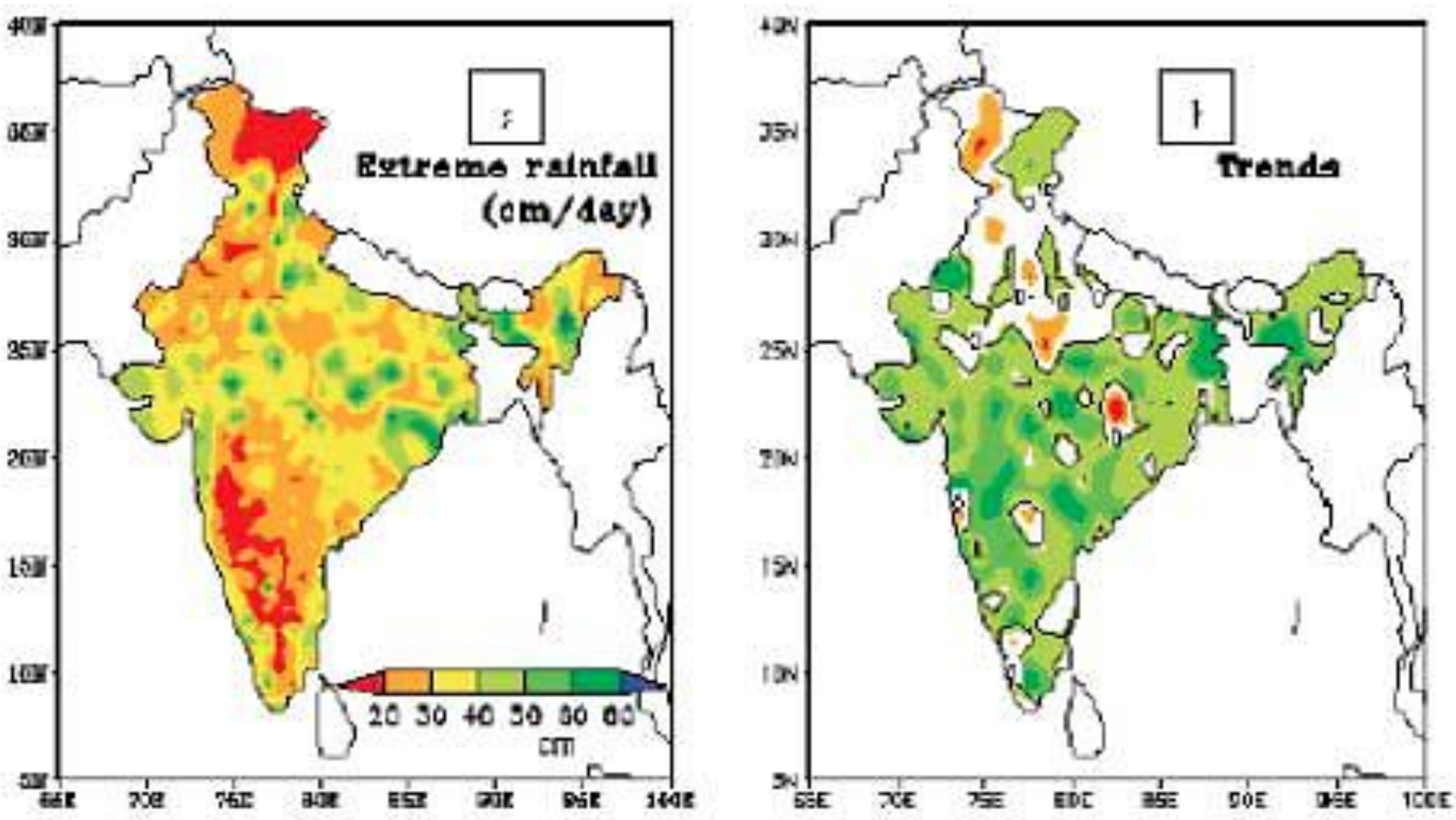
Regional Rainfall Trends





Guhathakurta et al. 2014, Int J. Climatology

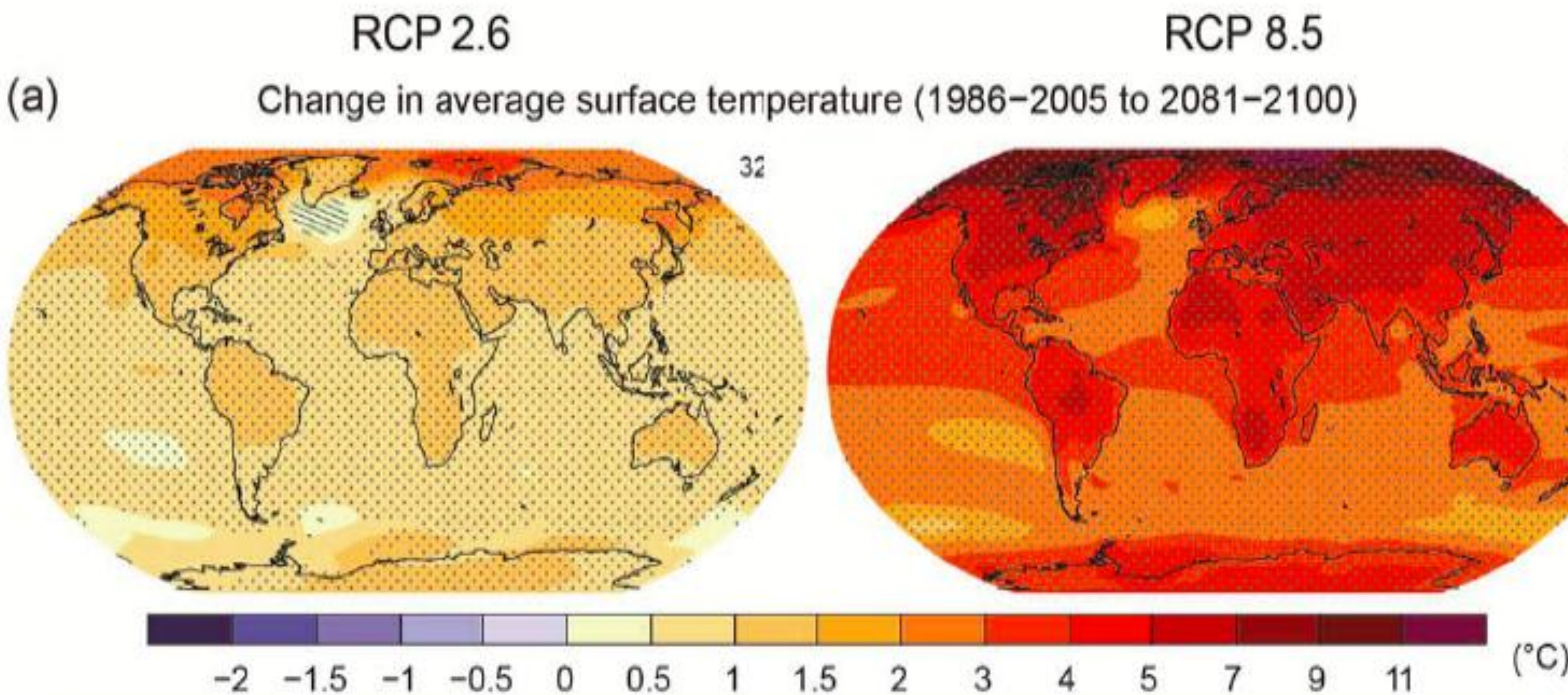
Rainfall Extremes and Trends for 1951-2004



MoEF, 2010

PROJECTIONS

(IPCC 2013, Fig. SPM.8)



Increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to likely be in the ranges derived from the concentration driven CMIP5 model simulations, that is, 0.3°C to 1.7°C (RCP2.6), 1.1°C to 2.6°C (RCP4.5), 1.4°C to 3.1°C (RCP6.0), 2.6°C to 4.8°C (RCP8.5).

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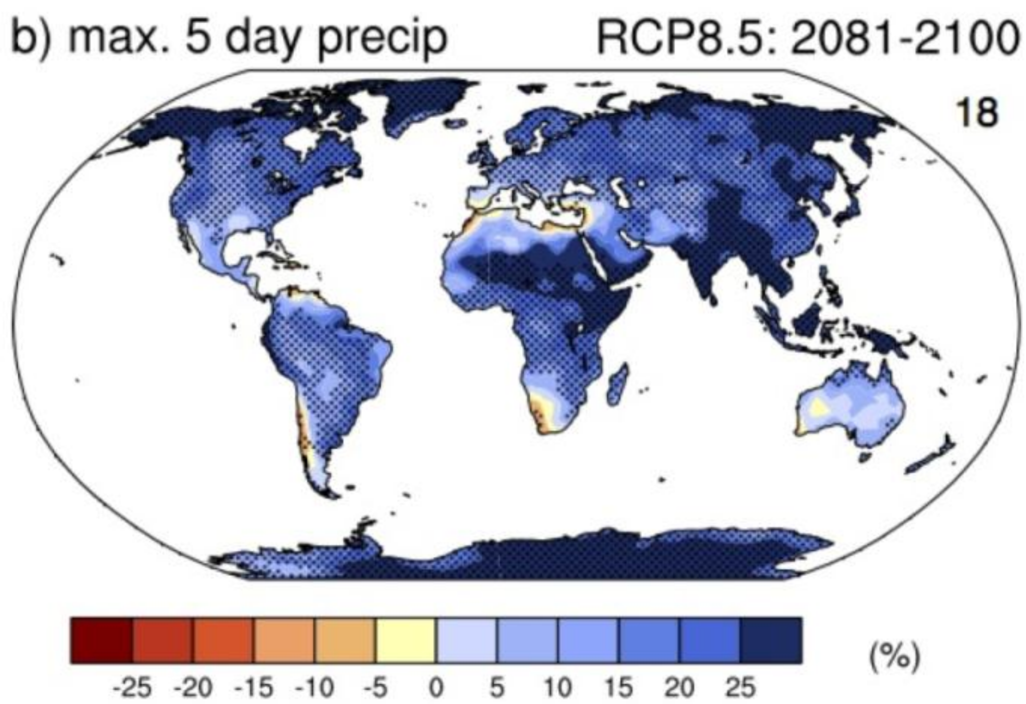
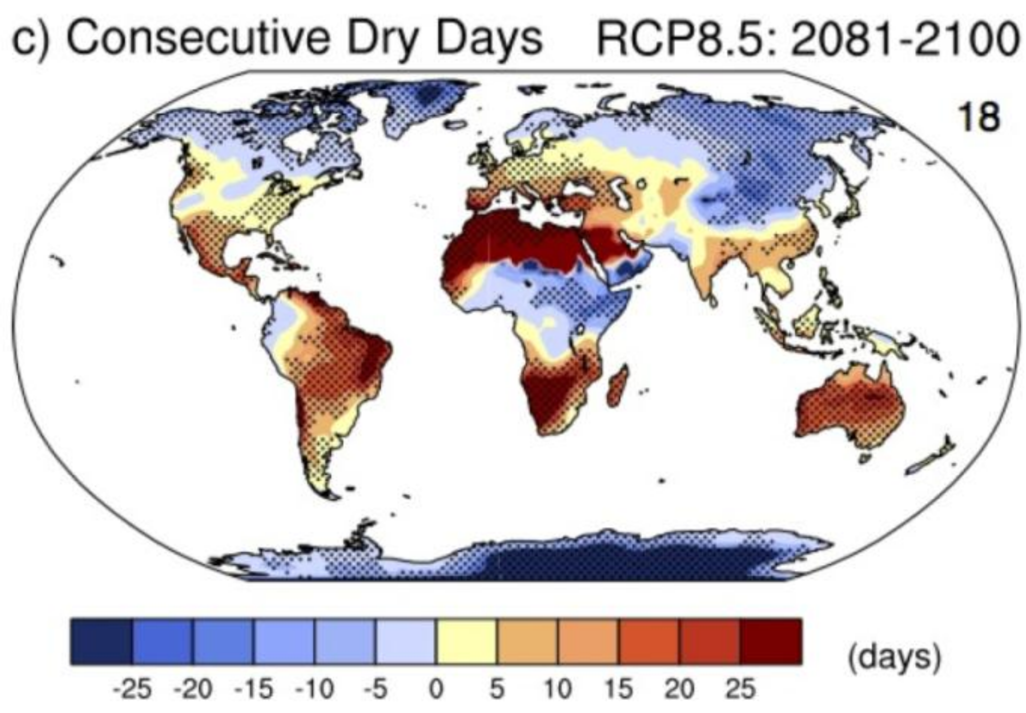
S. Asia projects increasing trend for end of 21st century



Rainfall

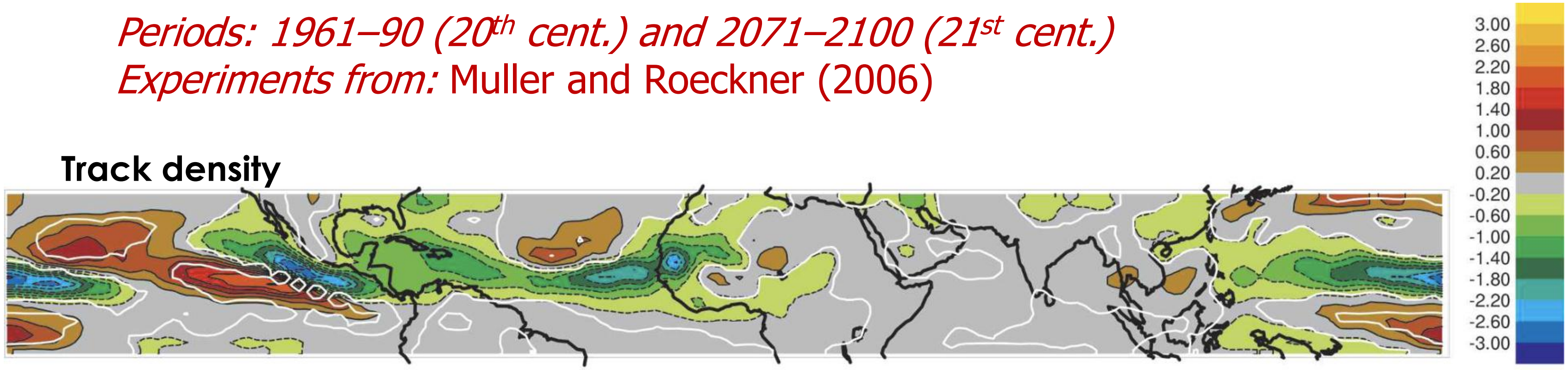


Consecutive Dry days

Projections for Tropical cyclones

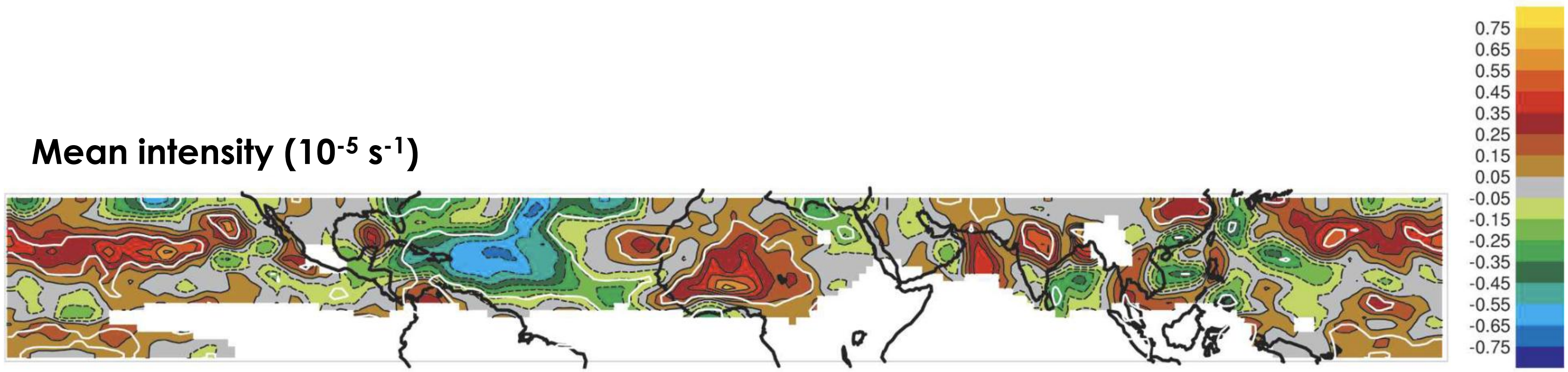
SRES scenario A1B.
Periods: 1961–90 (20th cent.) and 2071–2100 (21st cent.)
Experiments from: Muller and Roeckner (2006)

Track density



(a)

Mean intensity (10^{-5} s^{-1})



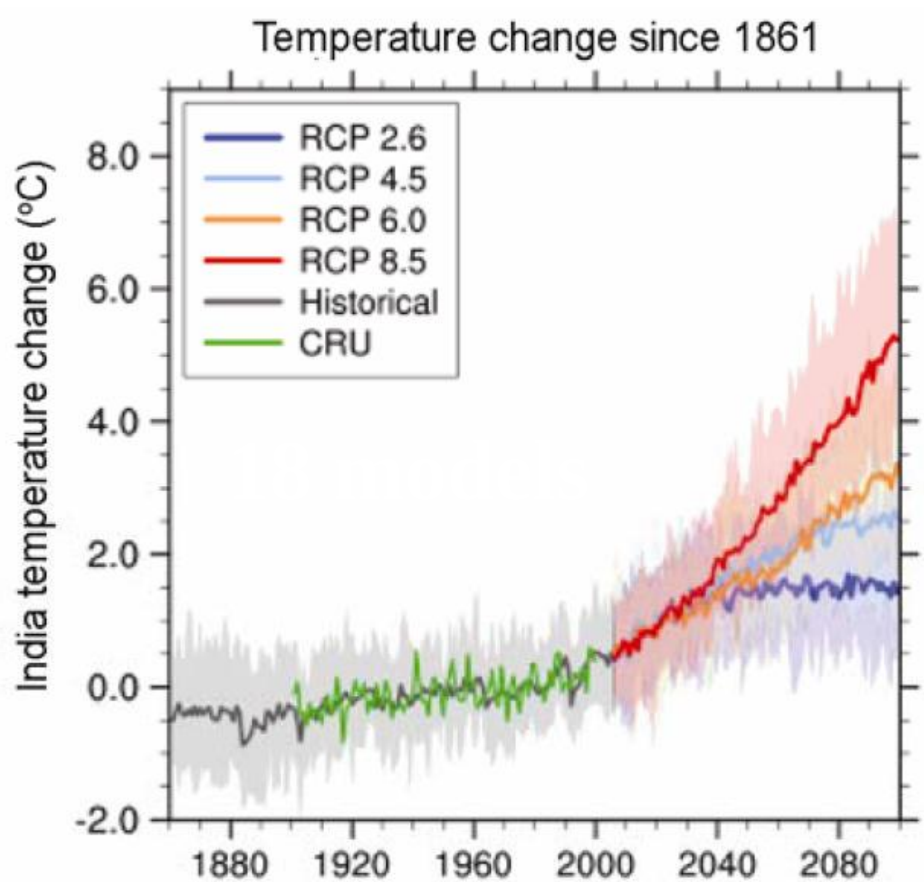
(b)

Difference in tropical easterly wave and cyclone statistics for 850 RV, between the 21C and 20C periods (21C – 20C), averaged over the three ensemble members before differencing. Mean intensity differences are only plotted where the track density is greater than 0.5 per month per unit area.

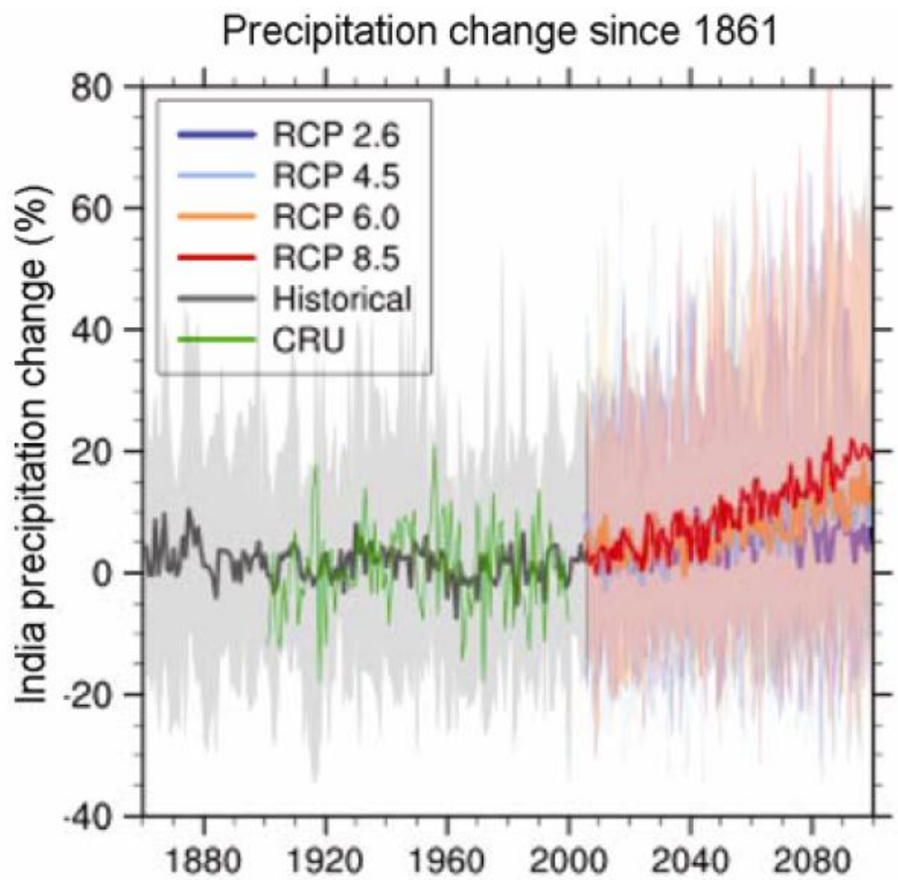
Source: Bengtsson et al. (2006) using TRACK

CMIP5 projections for India

Temperature Change

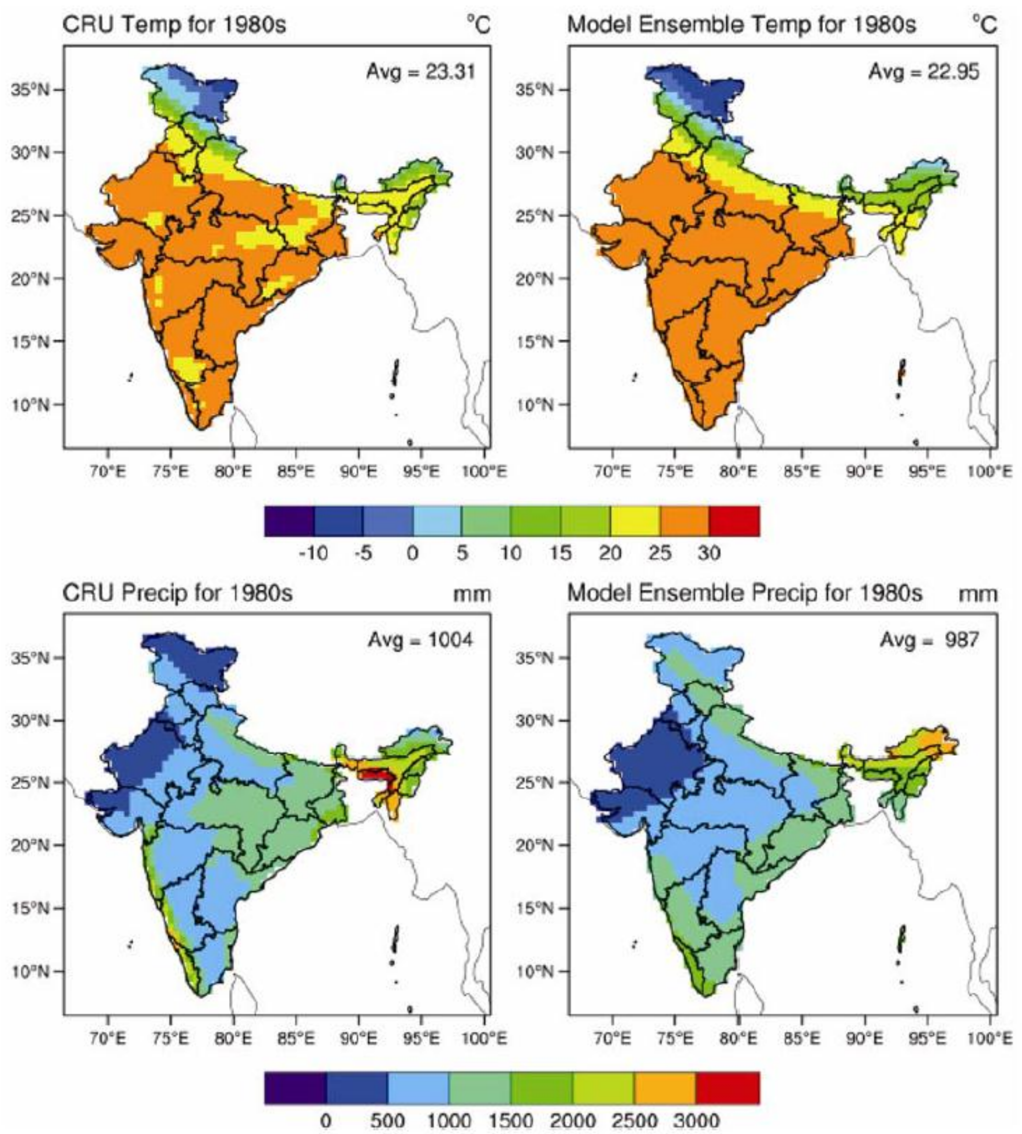


Rainfall Change



Chaturvedi etal. 2012, Current Science

But how good are the models?



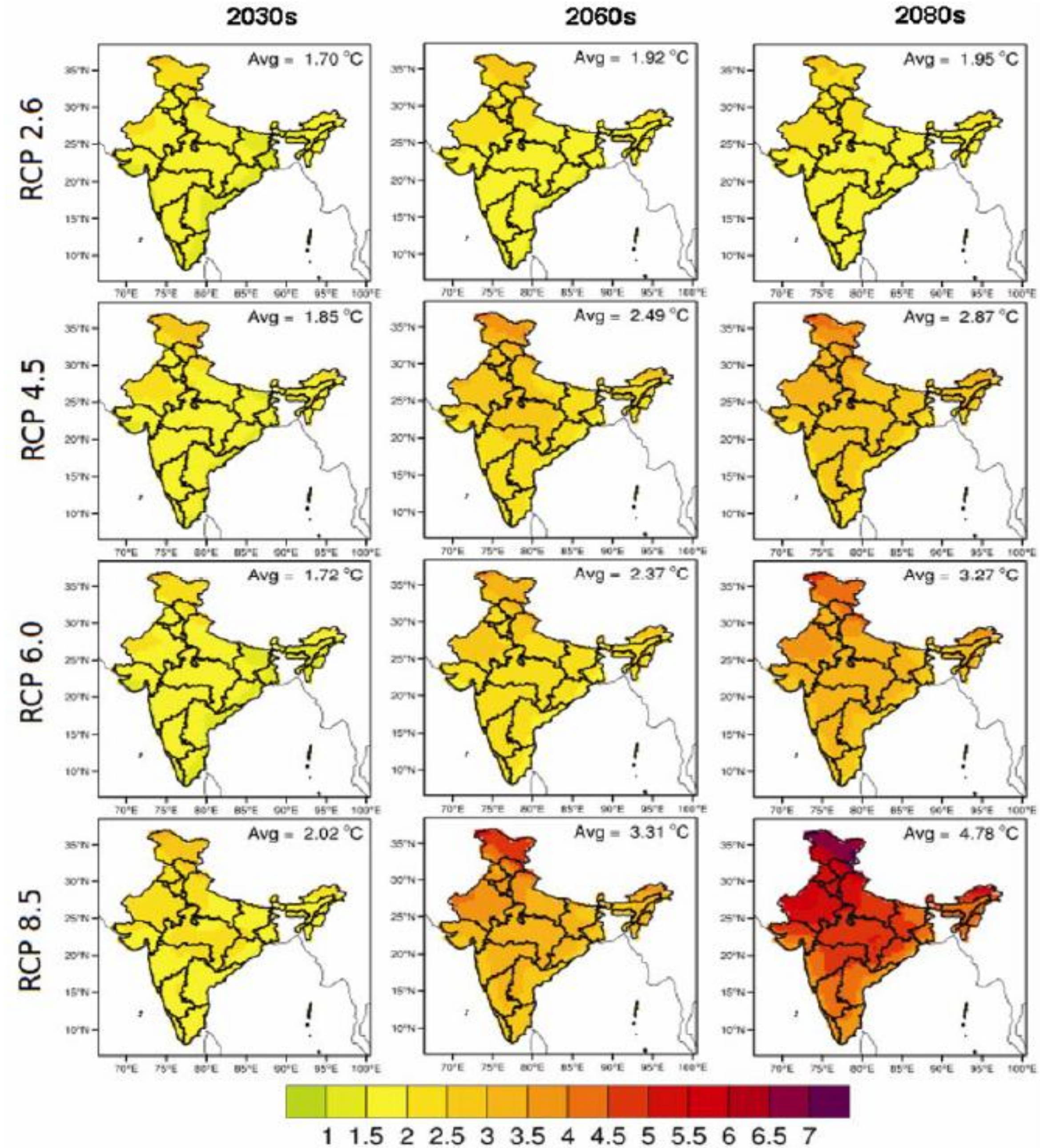
Observations Versus Ensemble mean for 1971-1990

Temperature

Rainfall

Chaturvedi etal. 2012, Current Science

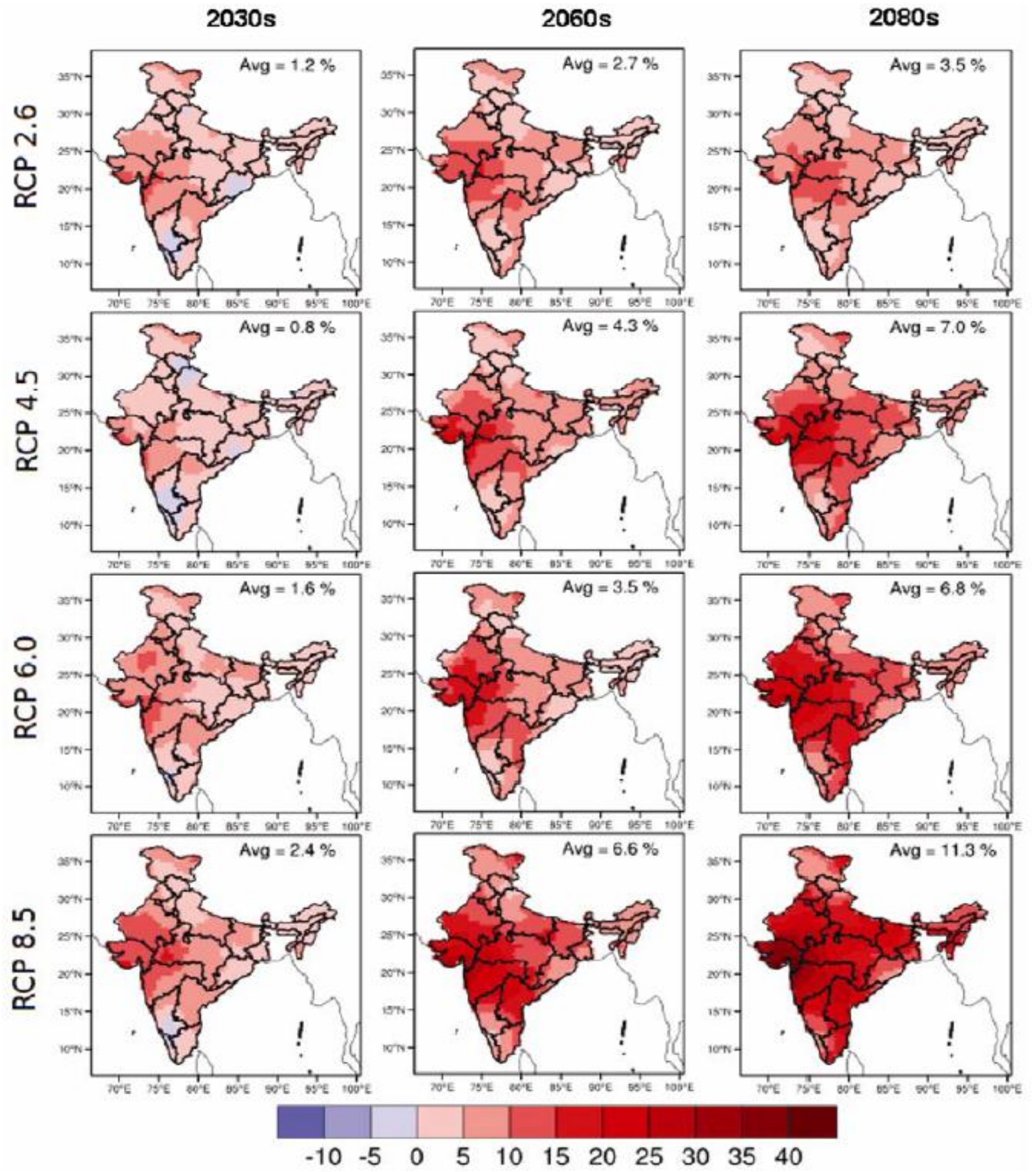
Clear indication of Warming



Ensemble mean from 18 models

Chaturvedi etal. 2012, Current Science

% change in rainfall



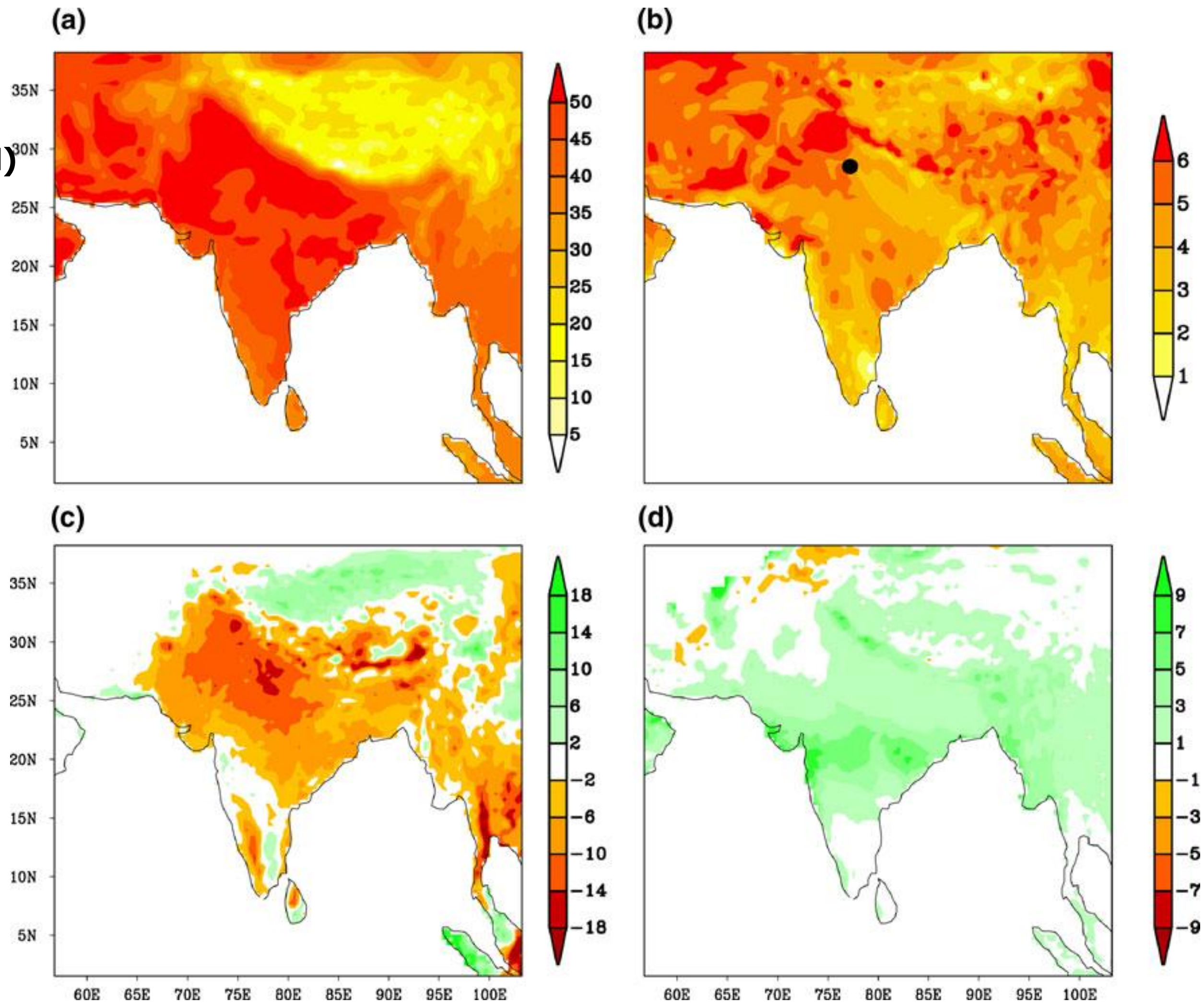
Ensemble mean from 18 models

Chaturvedi etal. 2012, Current Science

Projected changes in daily maximum temperature and daily rainfall

Pre-monsoon (MAM) Tmax for the baseline period (1961–1990).

projected future (2071–2100 minus 1961–1990 mean) change.



Projected future change in number of rainy days (rainfall >2.5 mm) during monsoon season (JJAS).

Projected change in the intensity (mm/day) of rainfall on a rainy day.

Krishna Kumar et al., 2009

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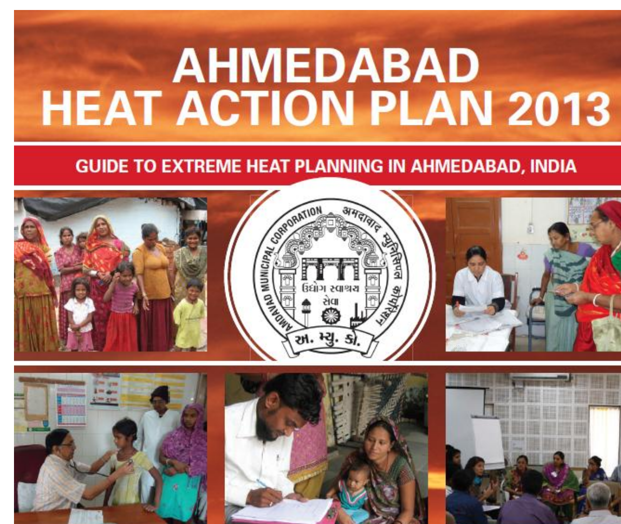
Forecast on Cyclone Phailin was "more or less" accurate: IMD

PTI Oct 13, 2013, 02.10PM IST

PM's address at 101st Indian Science Congress in Jammu

"Our advances in meteorology were evident during the recent cyclone in Odisha, when we received accurate forecasts of the landfall point that were more accurate than the forecasts of well known international bodies. Our decision to set up a new Ministry of Earth Sciences following the Indian Ocean Tsunami in 2004 and to invest in world-class tsunami forewarning systems in 2007 has been amply rewarded. We now have the ability to issue alerts within 13 minutes of a tsunami-genic event. This has established India's scientific leadership in the Indian Ocean region.

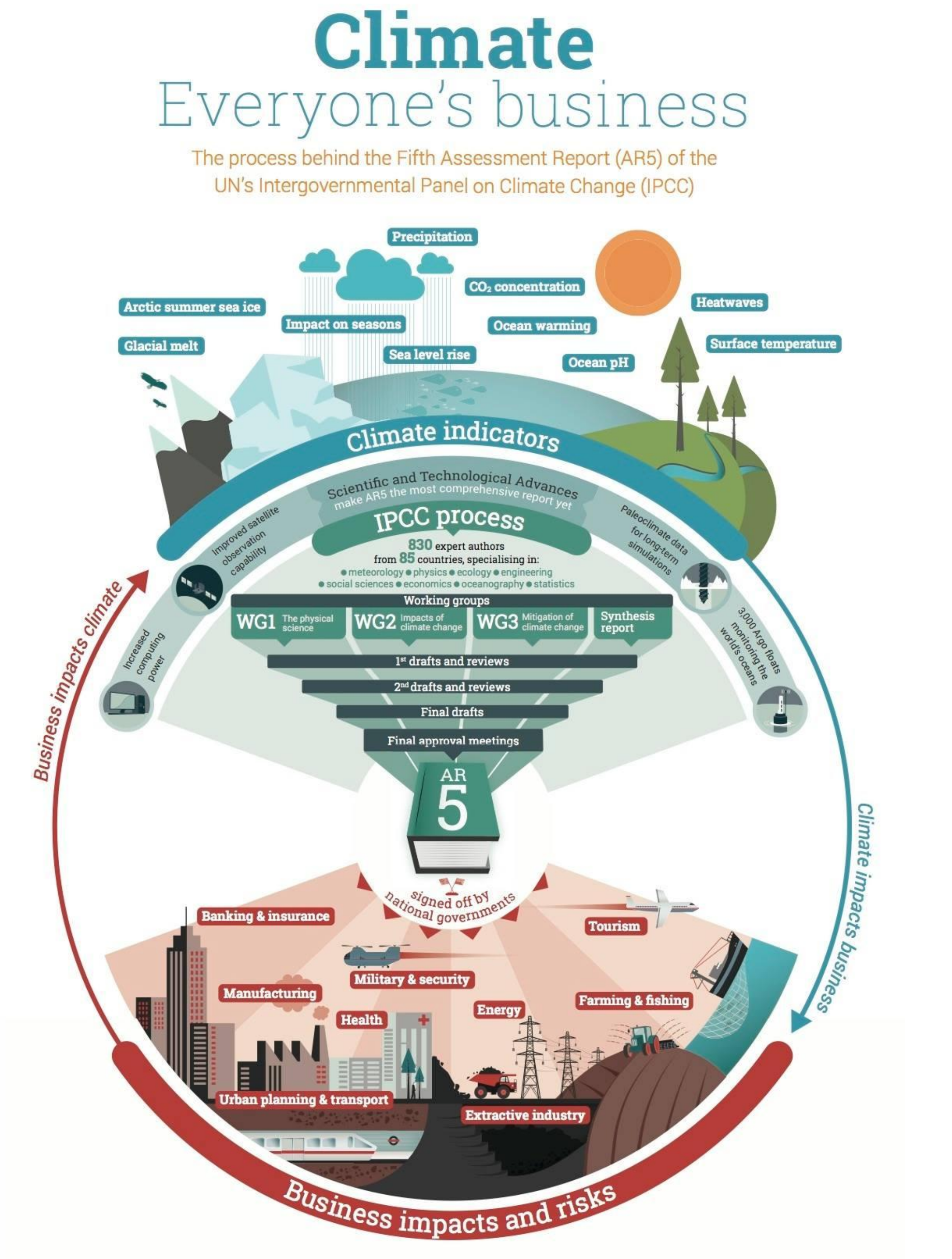
I would also like to see continuous improvement in our monsoon prediction capability through the recently launched Monsoon Mission so that we avert the kind of calamities that we saw in Uttarakhand last year. "



Source-IMD

Thank you

saurabh.bhardwaj@teri.res.in



This material can be freely used to advance discussion on the implications of the IPCC's Fifth Assessment

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