Modeling Climate Change Impacts on Regional Water Resources

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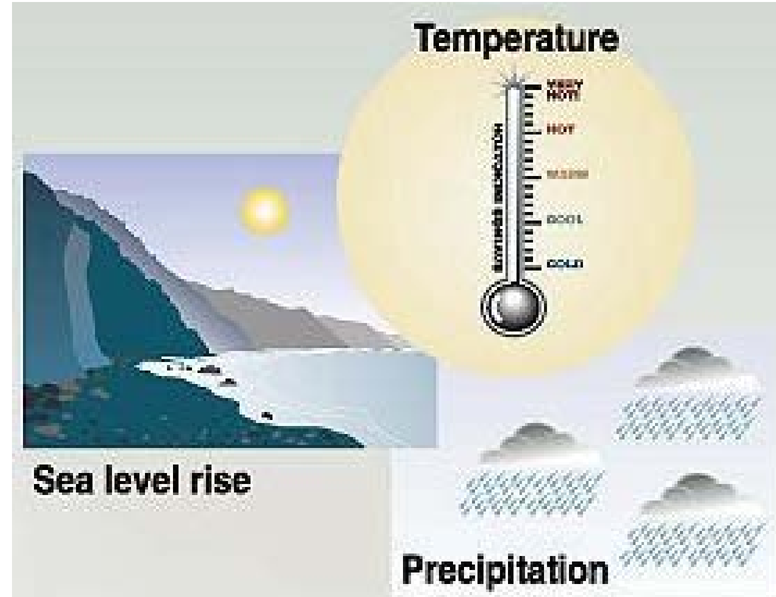
Organisation of the Talk

- Introduction
  - Climate Change Impacts on Water Resources
- Scale Issues & Uncertainties
  - Brief summary of earlier work
- Impacts on Water Availability
- Urban Flooding
- River Water Quality
- Irrigation Water Demands
- Detection and Attribution Studies
- Science Questions
- Summary

Climate Change – Hydrologic Implications

- Increasing Temperatures
  - Evapotranspiration
  - Water Quality
- Change in Precipitation Patterns
  - Streamflow; Water availability
  - Intensity, Frequency and Magnitude of Floods and Droughts
  - Groundwater Recharge
- Rise in Sea Levels
  - Inundation of coastal areas
  - Salinity Intrusion



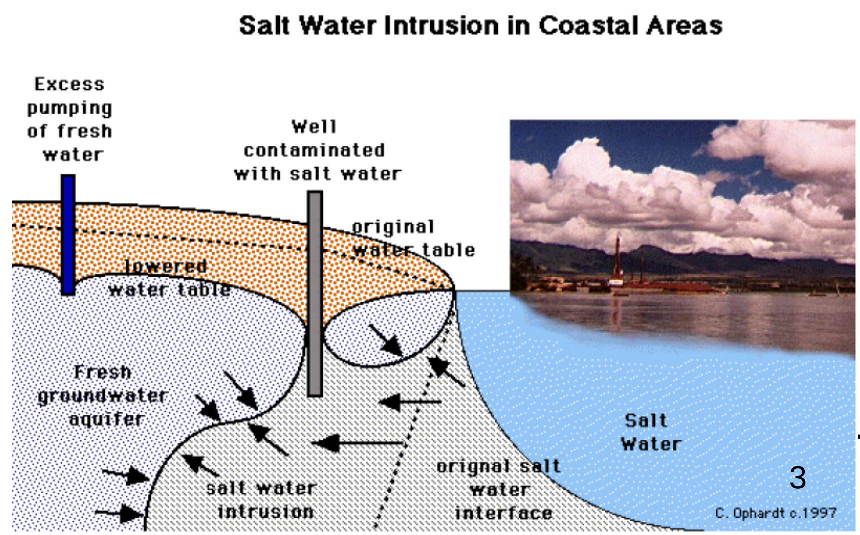


Fig. Source: ww.engr.uconn.edu/anboG229Lect11SWIntru.pdf

Water Resources : Issues of Climate Change

- **Water availability**
  - **How do water fluxes vary on catchment scale in response to global climate events?**
  - **Groundwater Recharge**

- **Water Demands**
  - **Evapotranspiration - Irrigation Demands**
  - **Municipal and Industrial Demands**
  - **Ecological and Environmental Demands**

- **Impacts on Water Quality**

- **Change in frequency and magnitude of extreme events (floods and droughts)**

- **Delays in onset of monsoon:**
  - **Impact on Agriculture**

- **Salinity Intrusions & Coastal flooding**

Source for the map:
www.mapsofIndia.com

➢General Circulation Models (GCMs):

Tools for simulating time series of *climate variables globally*, accounting for effects of *greenhouse gases* in the *atmosphere.*

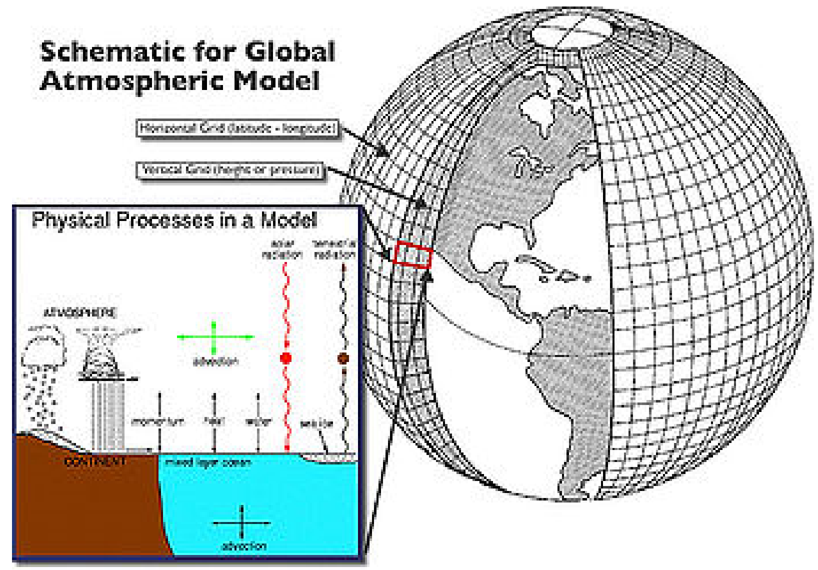
➢can simulate *largescale circulation patterns (e.g., pressure* and *geo potential heights) well*

➢do not reproduce well nonsmooth fields such as *precipitation.*

➢Scale Mismatch:

spatial scale of a GCM: > 2^0, (e.g. For Coupled Global Climate Model (CGCM2) 3.75^0 in both latitude and longitude(>150Km.))

Scale for modeling hydrologic process (precipitation) :order of 50 Km



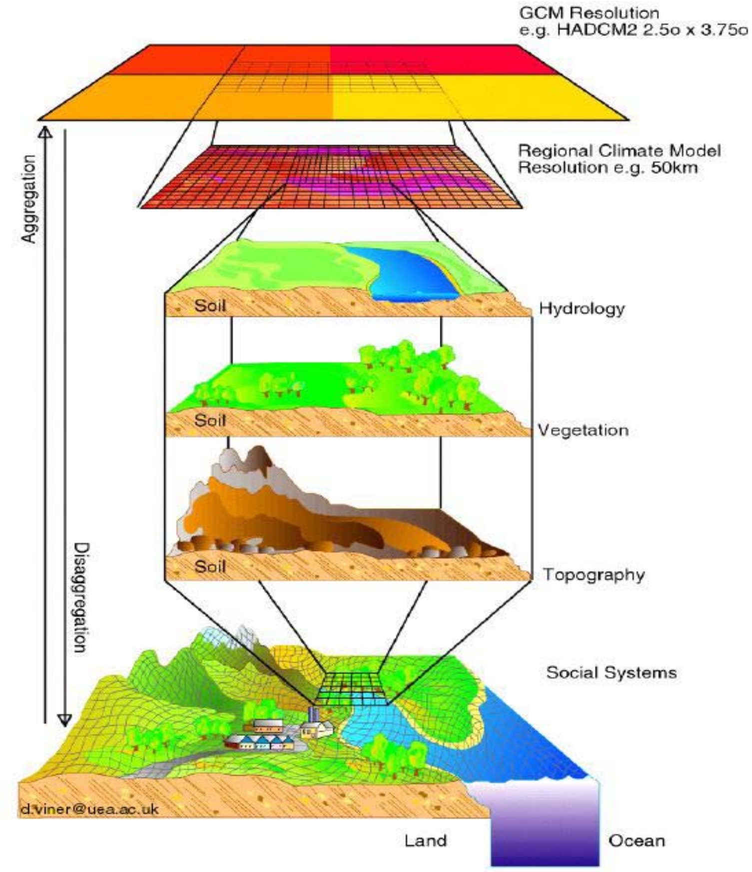
Climate models are systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. To “run” a model, scientists divide the planet into a 3-dimensional grid, apply the basic equations, and evaluate the results. Atmospheric models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid and evaluate interactions with neighboring points.

Source : Wikipedia

Need for Downscaling

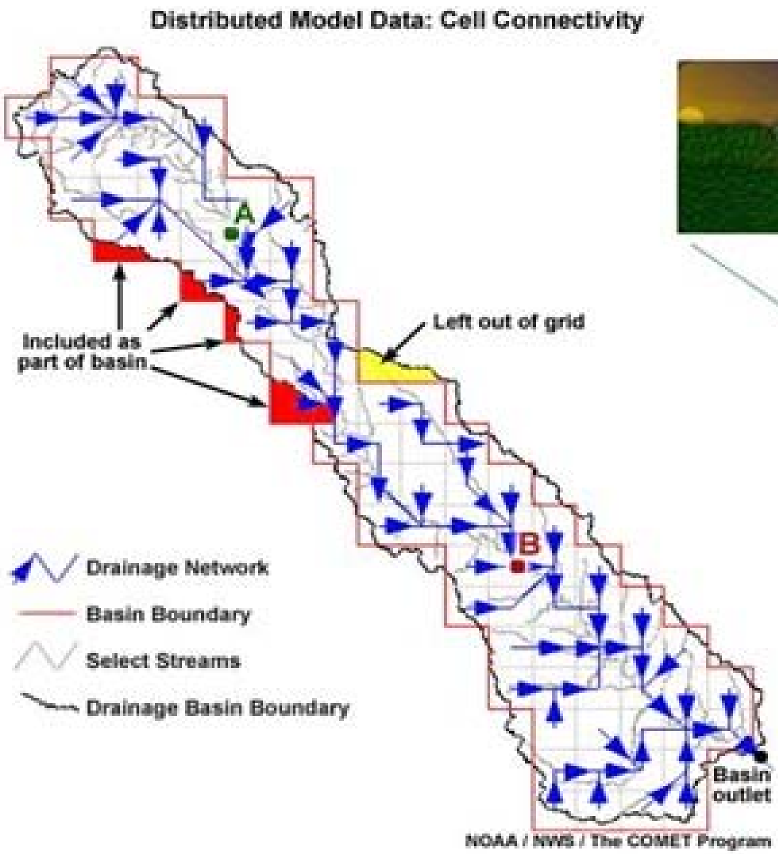
Some existing gaps between GCMs' ability and hydrology need

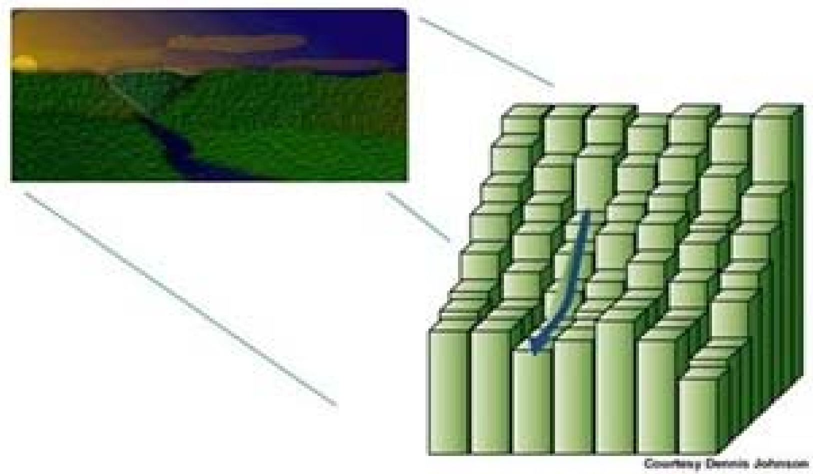
	Better simulated	Less-well simulated	Not well simulated
Spatial scales Mismatch	Global 500×500 km	Regional 50×50 km	Local 0–50 km
Temporal scales Mismatch	Mean annual and seasonal	Mean monthly	Mean daily
Vertical scale Mismatch	500 hPa	800 hPa	Earth surface
Working variables Mismatch	Wind Temperature Air pressure	Cloudiness Precipitation Humidity	Evapotranspiration Runoff Soil moisture
GCMs' ability declines			
Hydrological importance increases			



Source: Xu Chong-Yu, Water Resources Management 13: 369–382, 1999.

Distributed hydrologic models

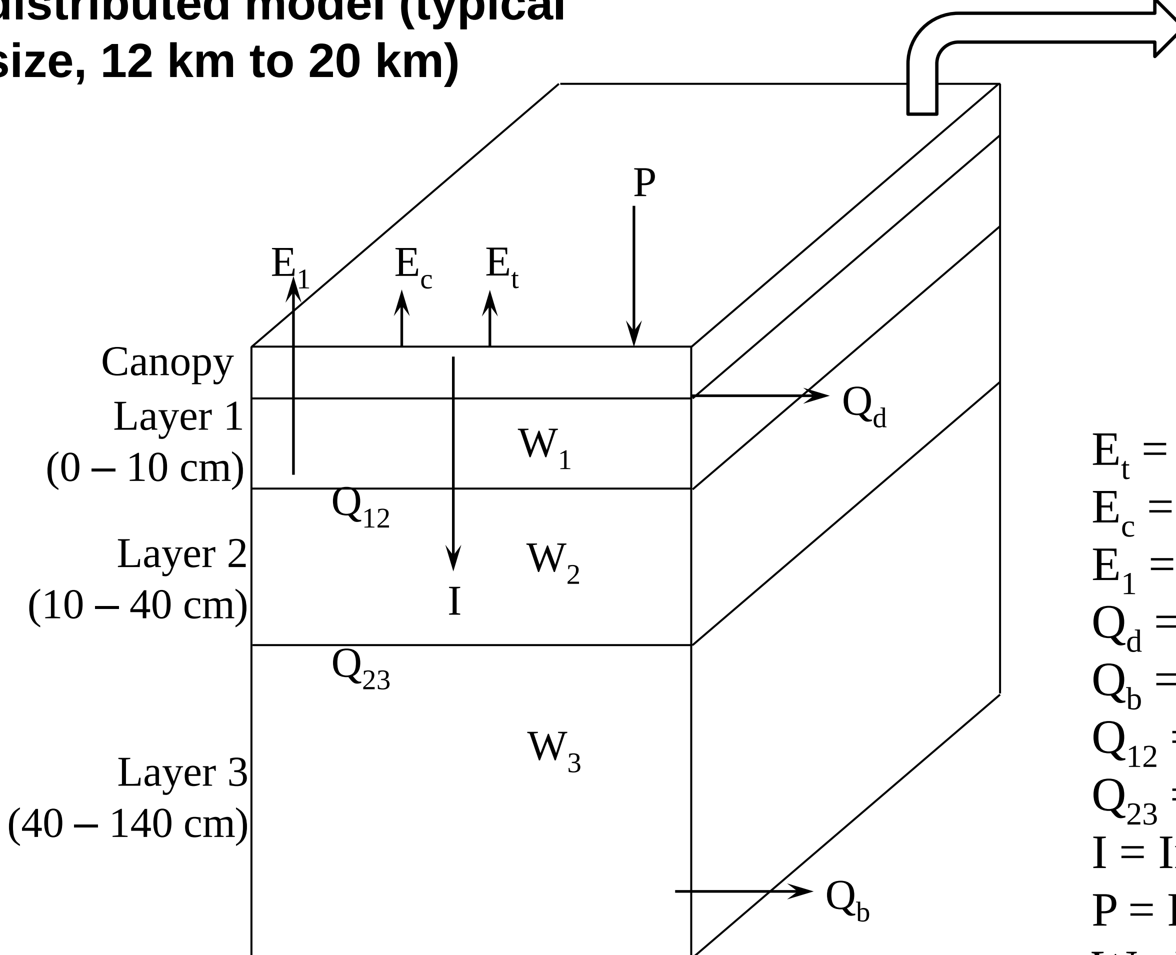


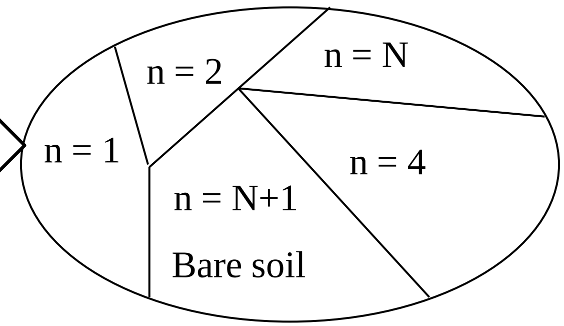


Simulate Streamflow, Evapotranspiration, Soil Moisture, Deep percolation, Detention Storage and other surface water processes

Source: University Corporation for Atmospheric Research (UCAR)

A computational grid in a distributed model (typical size, 12 km to 20 km)





Land-cover (vegetation) classes

E_t = Evapotranspiration
E_c = Canopy Evaporation
E_1 = Baresoil Evaporation
Q_d = Direct Runoff
Q_b = Subsurface Flow
Q_{12} = Gravity flows layer 1 to 2
Q_{23} = Gravity flows layer 2 to 3
I = Infiltration
P = Precipitation
W_1, W_2, W_3 = Water content in respective layers

Projecting Climate Change Impacts on Water Resources

Climate Change Projections (precipitation, temperature, radiation, humidity)

Topography, Land-use/Land Cover ; Soil characteristics; Other catchment data

Downscaling

Hydrologic Model

Possible Future Water Resources Scenarios at Basin Scale (Streamflow – flow duration curves, Rainfall, Evapotranspiration – crop water demands, Soil Moisture, Infiltration, Groundwater Recharge etc.)

Downscaling Models Developed

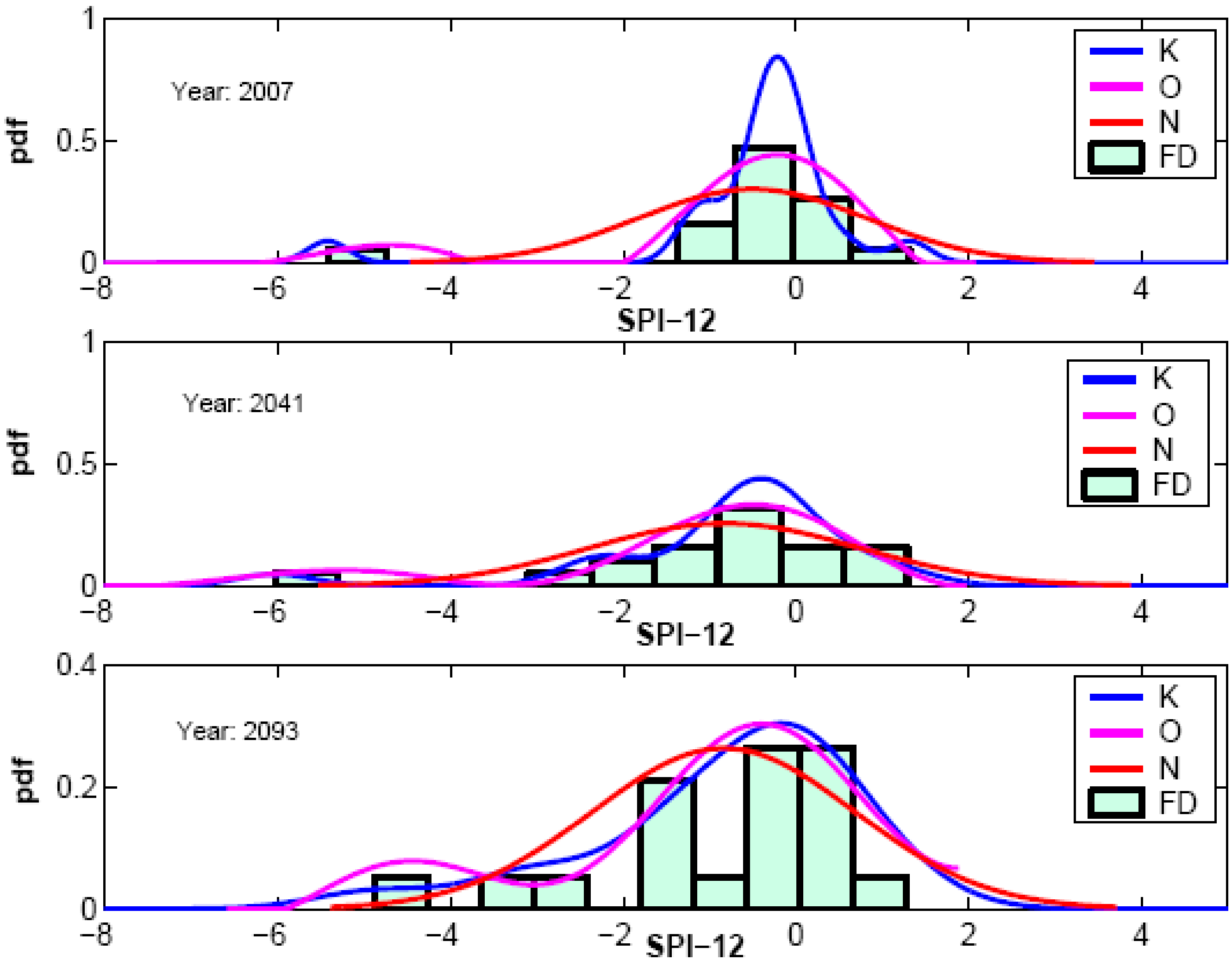
- **Principal Component Analysis-Fuzzy Clustering-Linear Regression**
- **Artificial Neural Networks (ANNs)**
- **Support Vector Machines (SVMs)**
- **Relevance Vector Machines (RVMs)**
- **Conditional Random Fields (CRFs)**
- **Canonical Correlations**

Three levels of uncertainties addressed

- All model outputs and all scenarios are equally likely
- Models and scenarios weighted with respect to their performance in the recent past (1990-2005) when climate change signals are visible
- Models and scenarios are weighted with respect to their agreements on future projections.

pdfs of Drought Indicator

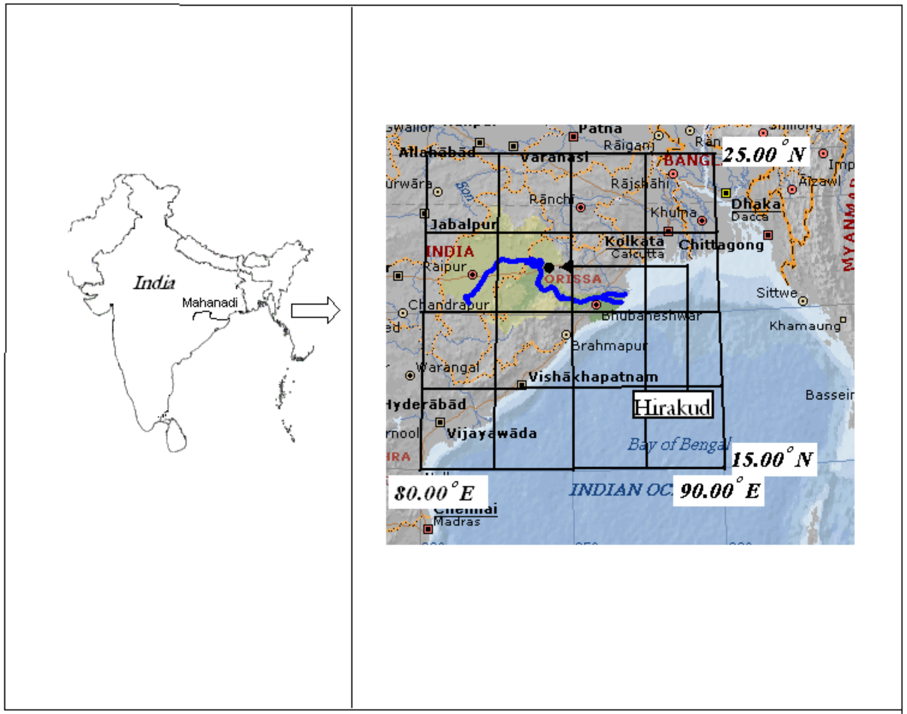
- All **scenarios** are **equally possible**
- Projections from all **GCMs** are **equally likely to be realized.**
- Time series generated by a **downscaled GCM simulation** with one scenario is considered as one **realization**.

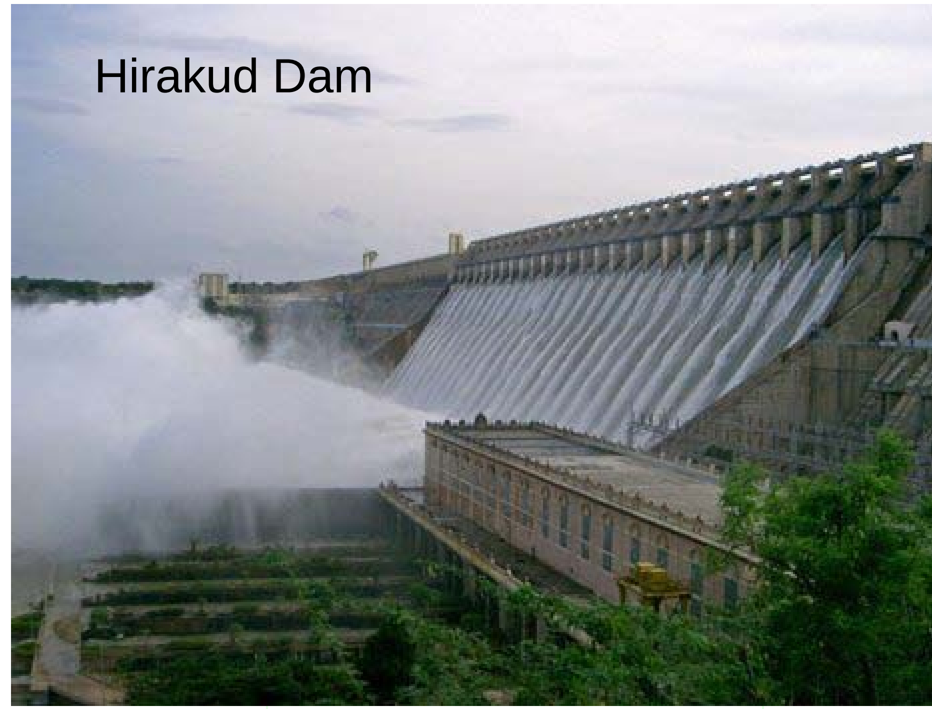


K − Kernel Density, O − Density by Orthonormal Series, N − Density assuming Normal Distribution, FD − Frequency Distribution of SPI−12

Water Resources Research, No. 43 (2007)

Mahanadi River Basin - Streamflow





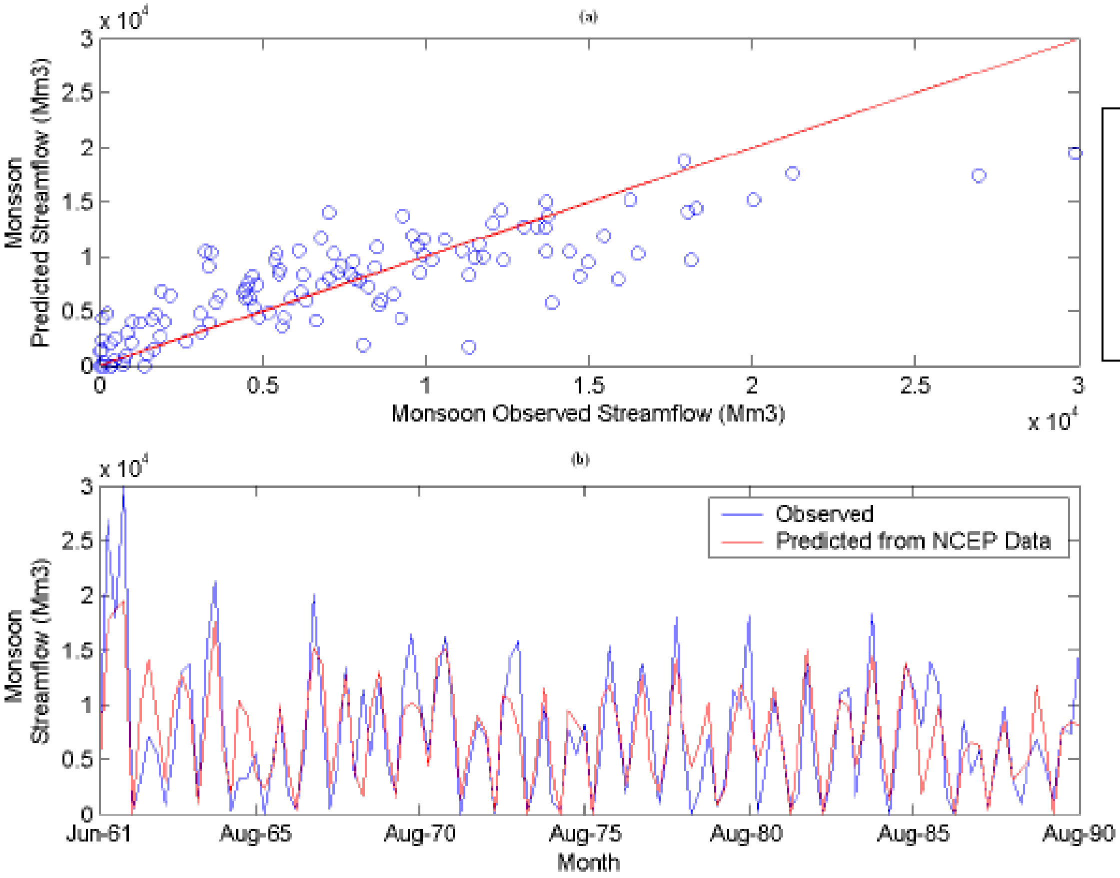
Climate Predictors

2m Surface Temperature
Geopotential Height at 500 hPa
Specific Humidity
Mean Sea Level Pressure

Predictand:

Monsoon Streamflow of Mahanadi River at Hirakud Dam

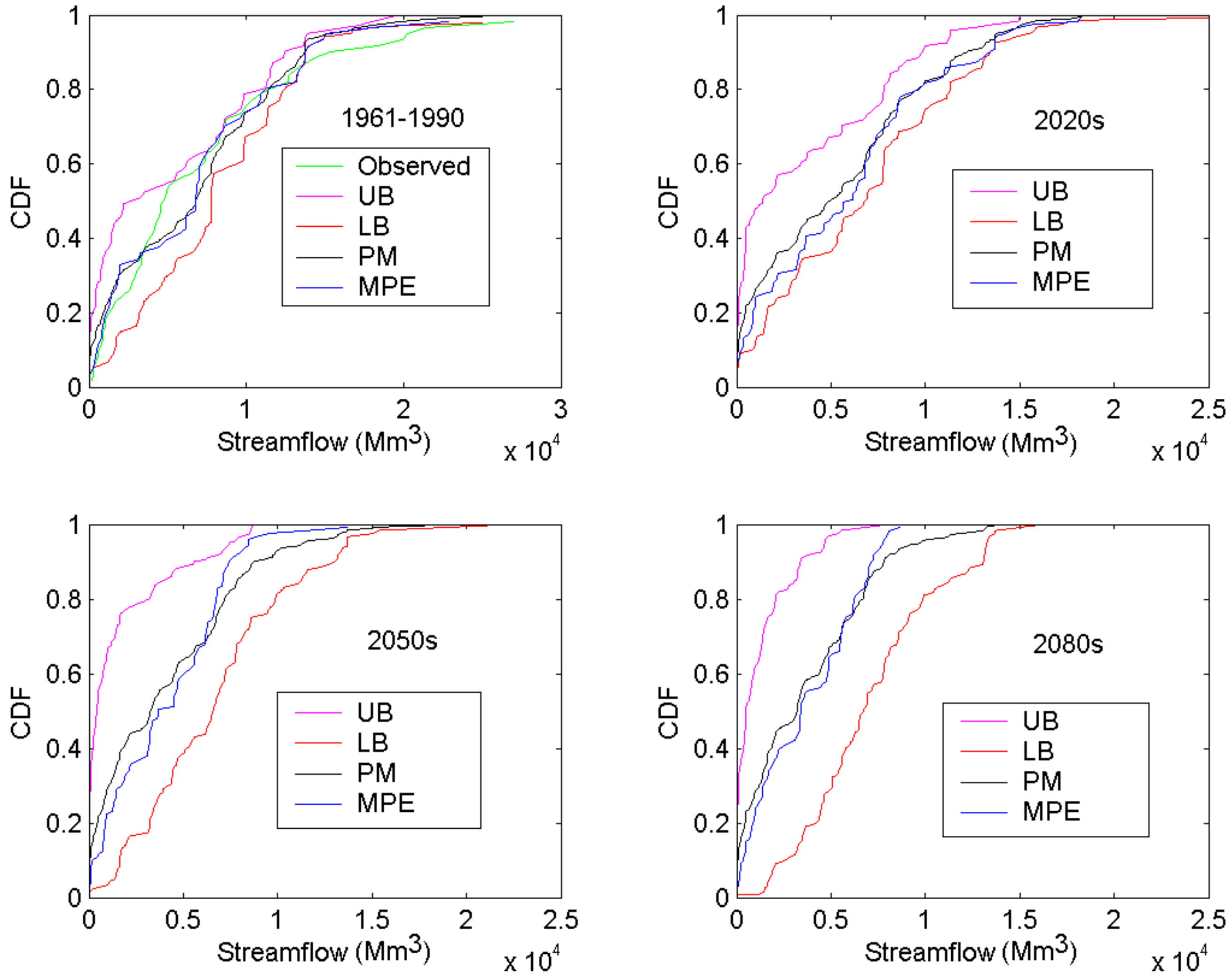
Observed and Predicted Streamflow (from NCEP/NCAR reanalysis data)



	Observed	Predicted
Mean	7332 Mm^3	7384 Mm^3
Std. Dev	5996 Mm^3	4607 Mm^3

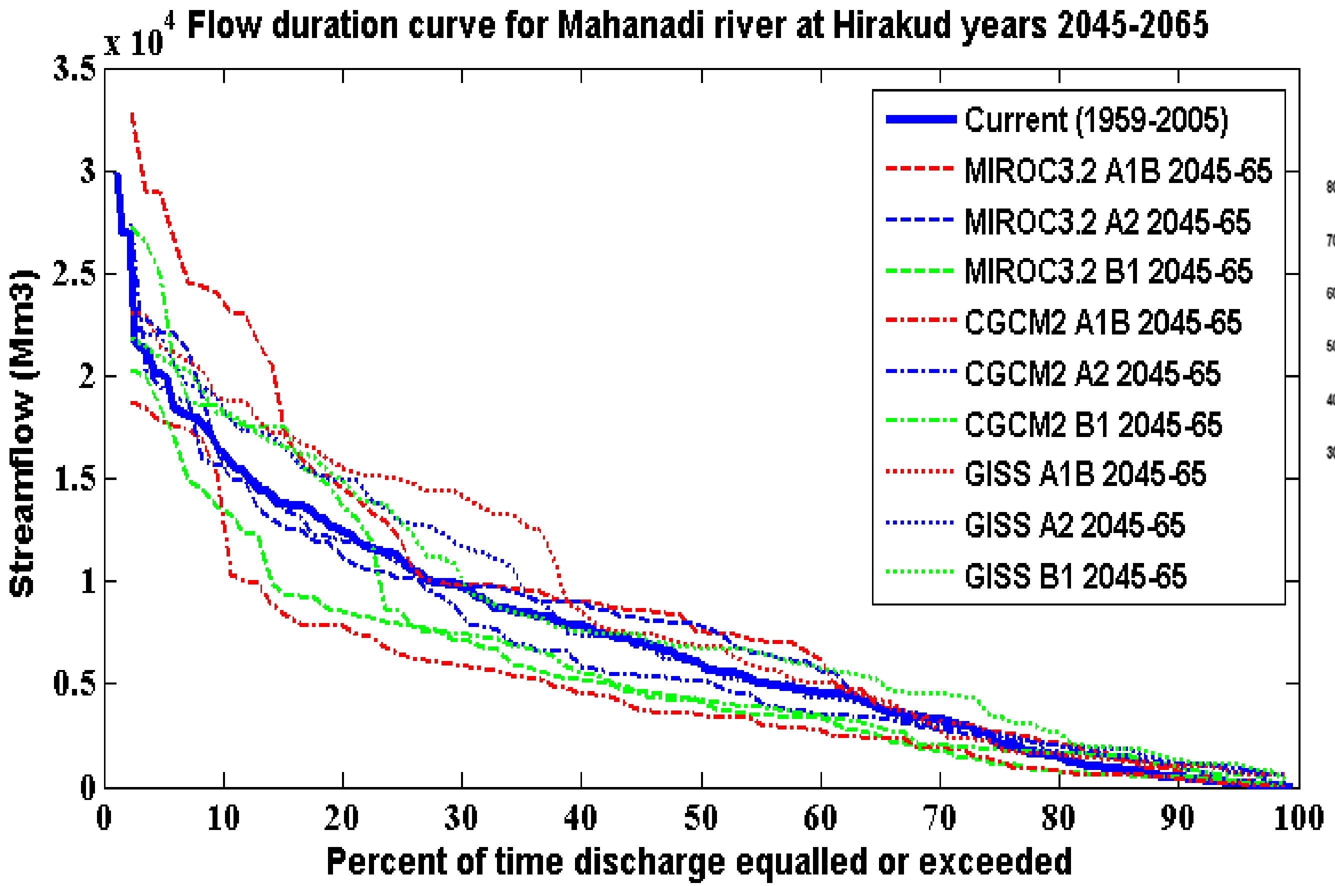
Nash-Sutcliffe coefficient, E = 0.67

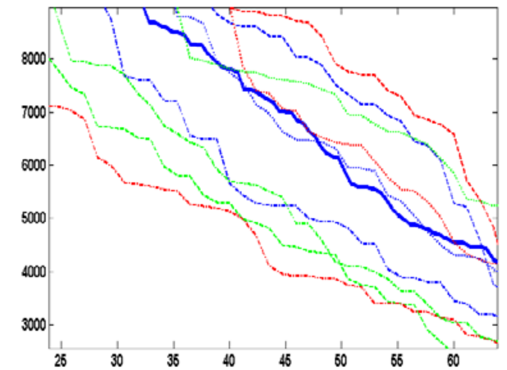
Projected Streamflow CDF



UB - Upper Bound, LB - Lower Bound, PM - Possibilistic Mean, MPE - Most Possible Experiment

Projections for future monsoon inflows to Hirakud Reservoir



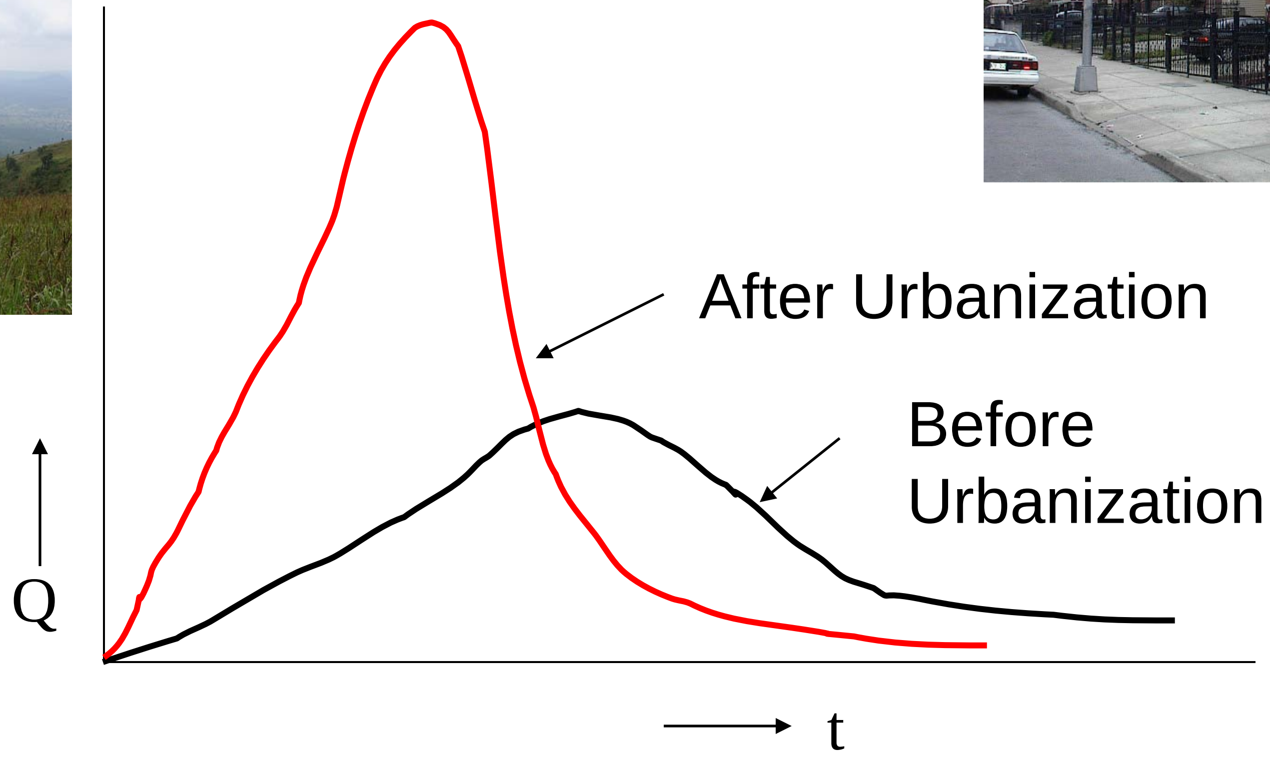


Reduction in 'normal' (middle level) flows

Range of projected future flow duration curves at Hirakud

Urban Flooding

Urbanisation alters the hydrology of a region; rainfall – runoff relationships get affected; quicker and higher peak flows ; more runoff



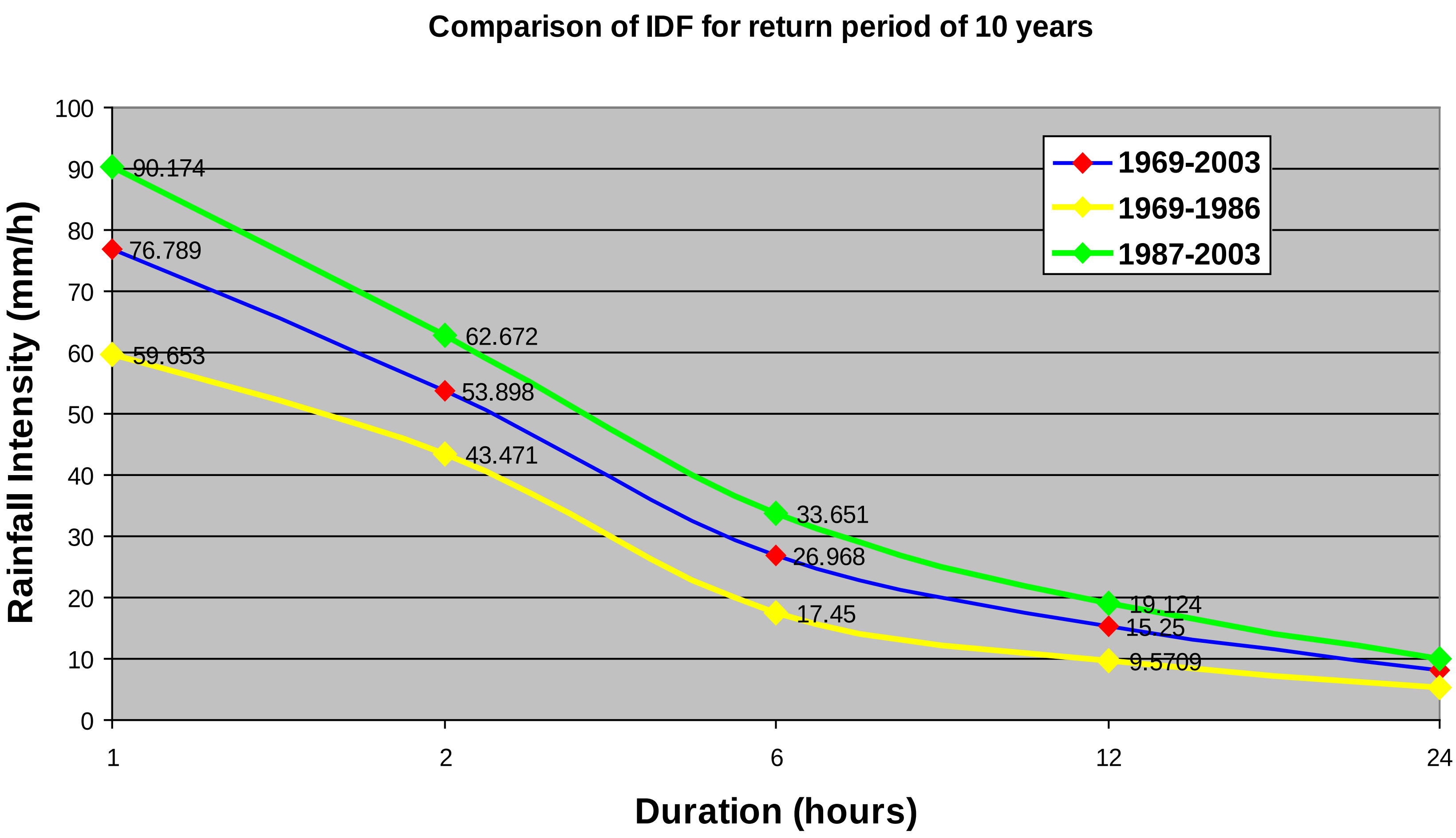
Bangalore Floods

How do the short term intensities of rainfall respond to the climate change?

Urban Flooding

Likely changes in IDF (Intensity-Duration-Frequency) relationships due to climate change

Bangalore City – Change in the IDF Relationships



Bangalore City : Projected change in the IDF Relationship :- CMIP5 models with AR5 scenarios

CMIP 5 Ensemble

↓

Downscaling (Daily Scale) Rainfall

↓

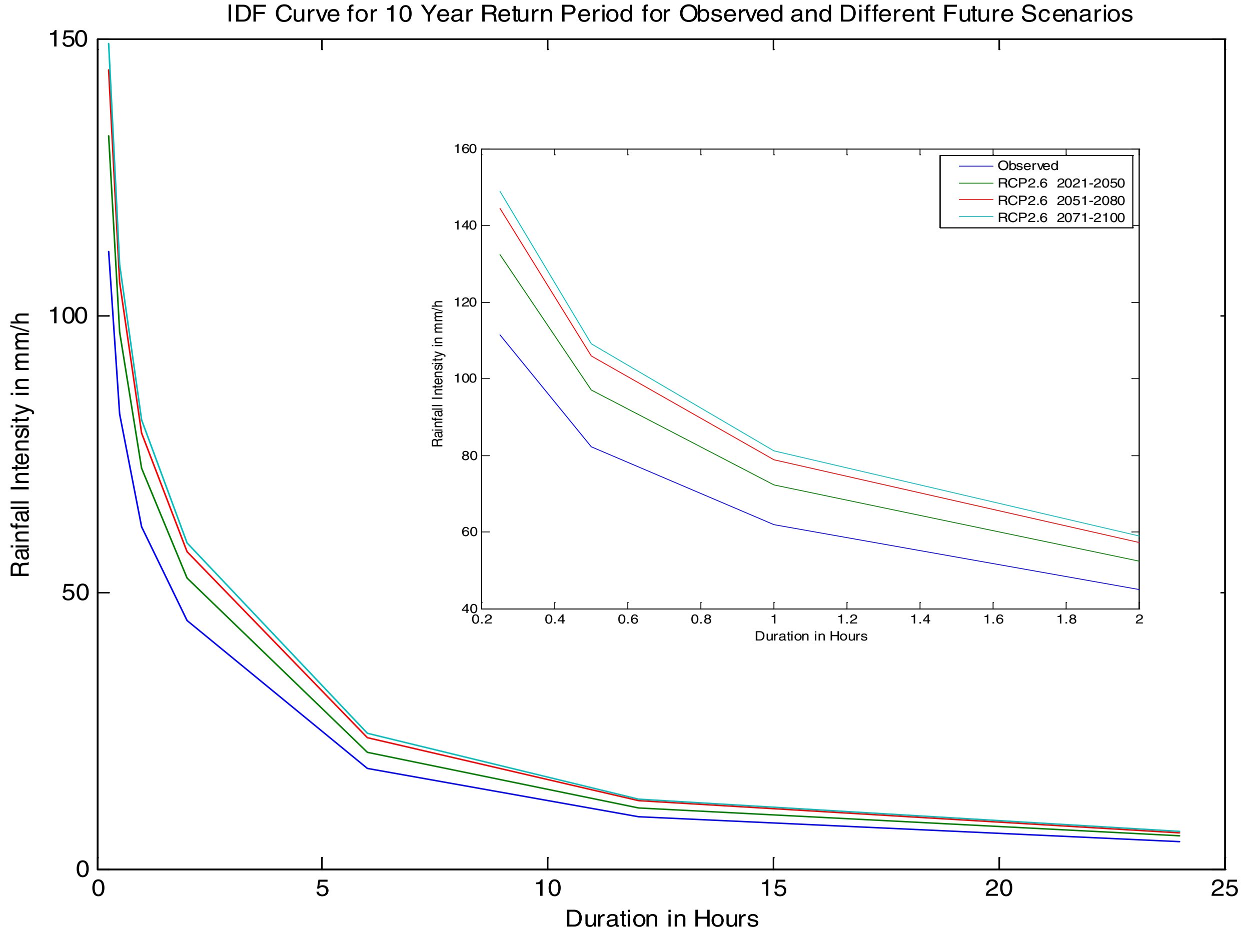
Stochastic Disaggregation

↓

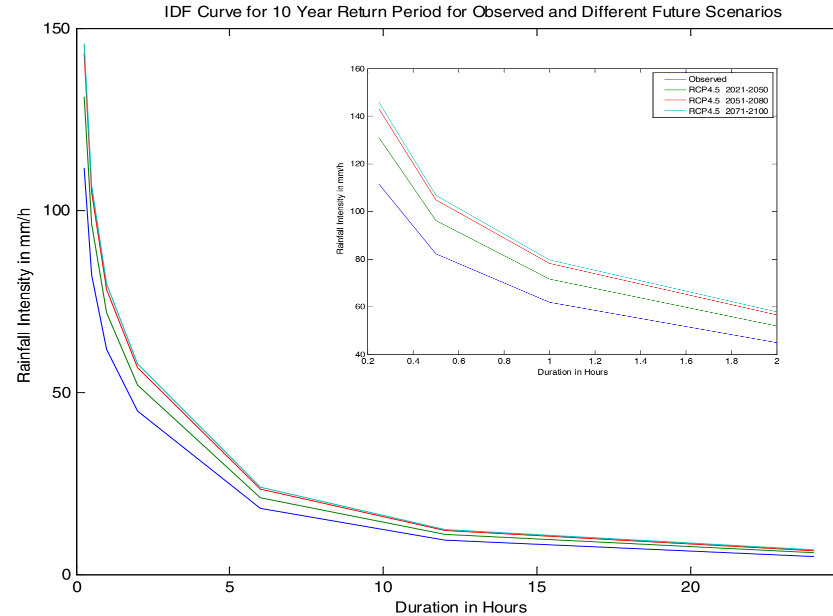
Hourly and Sub-hourly Scale Rainfall Intensity

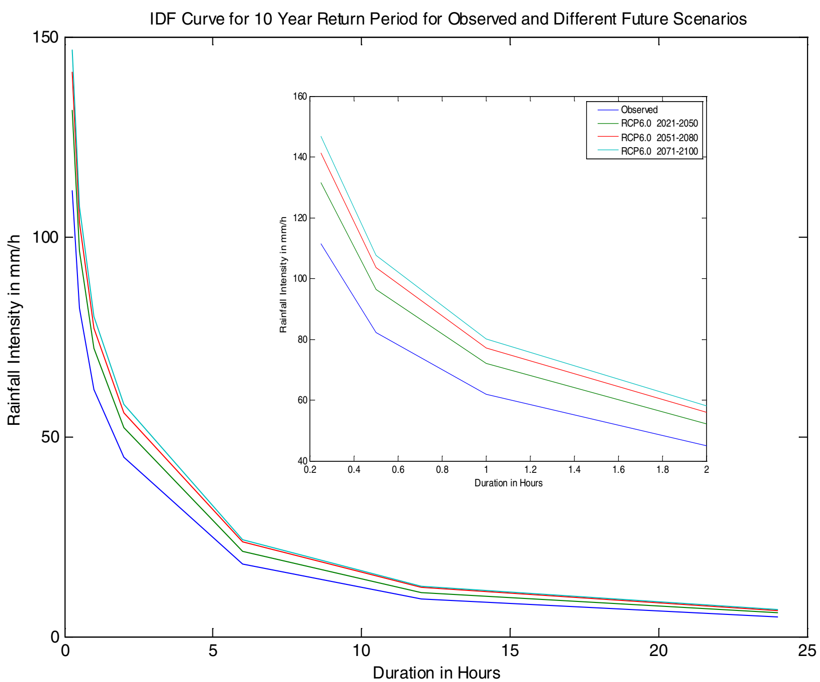
↓

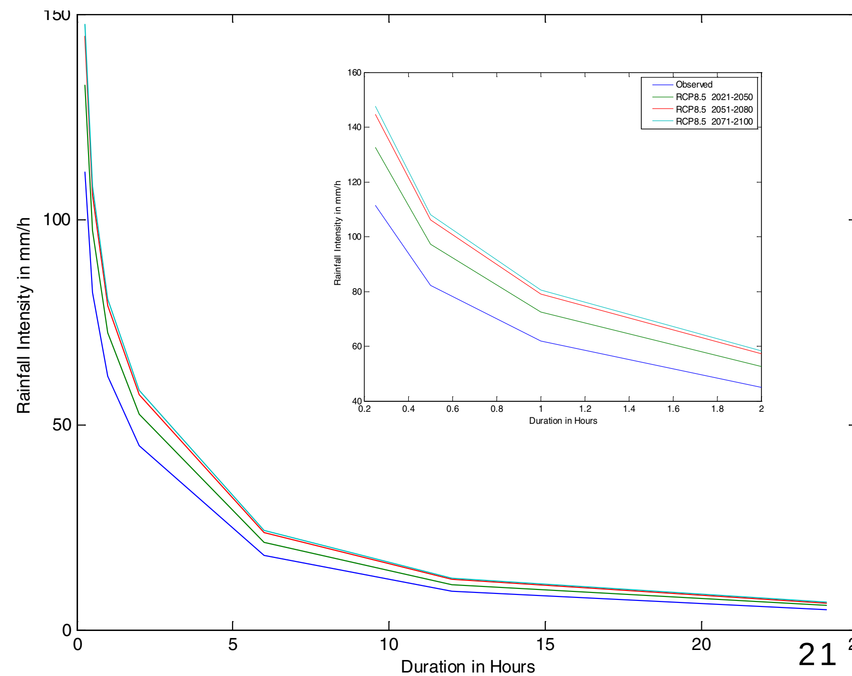
Ensemble Averaged Projections



Bangalore City :
Projected change in the IDF Relationship :
CMIP5 models with AR5 scenarios (contd)

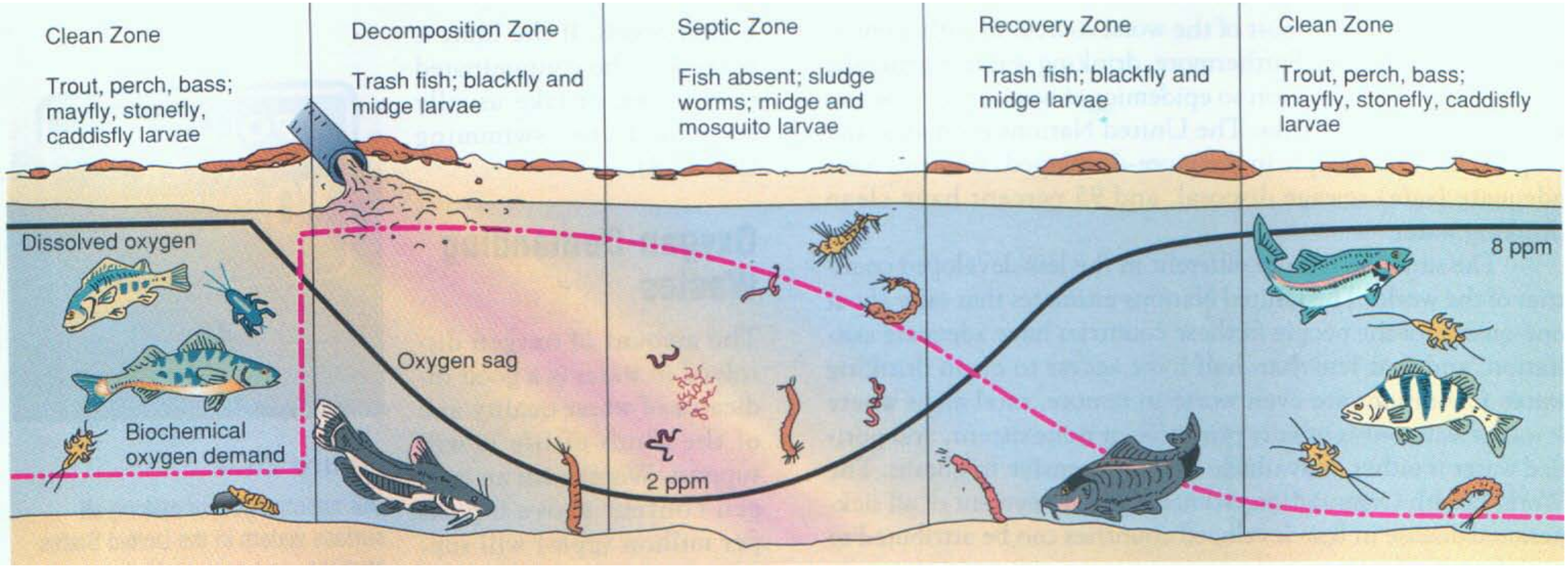






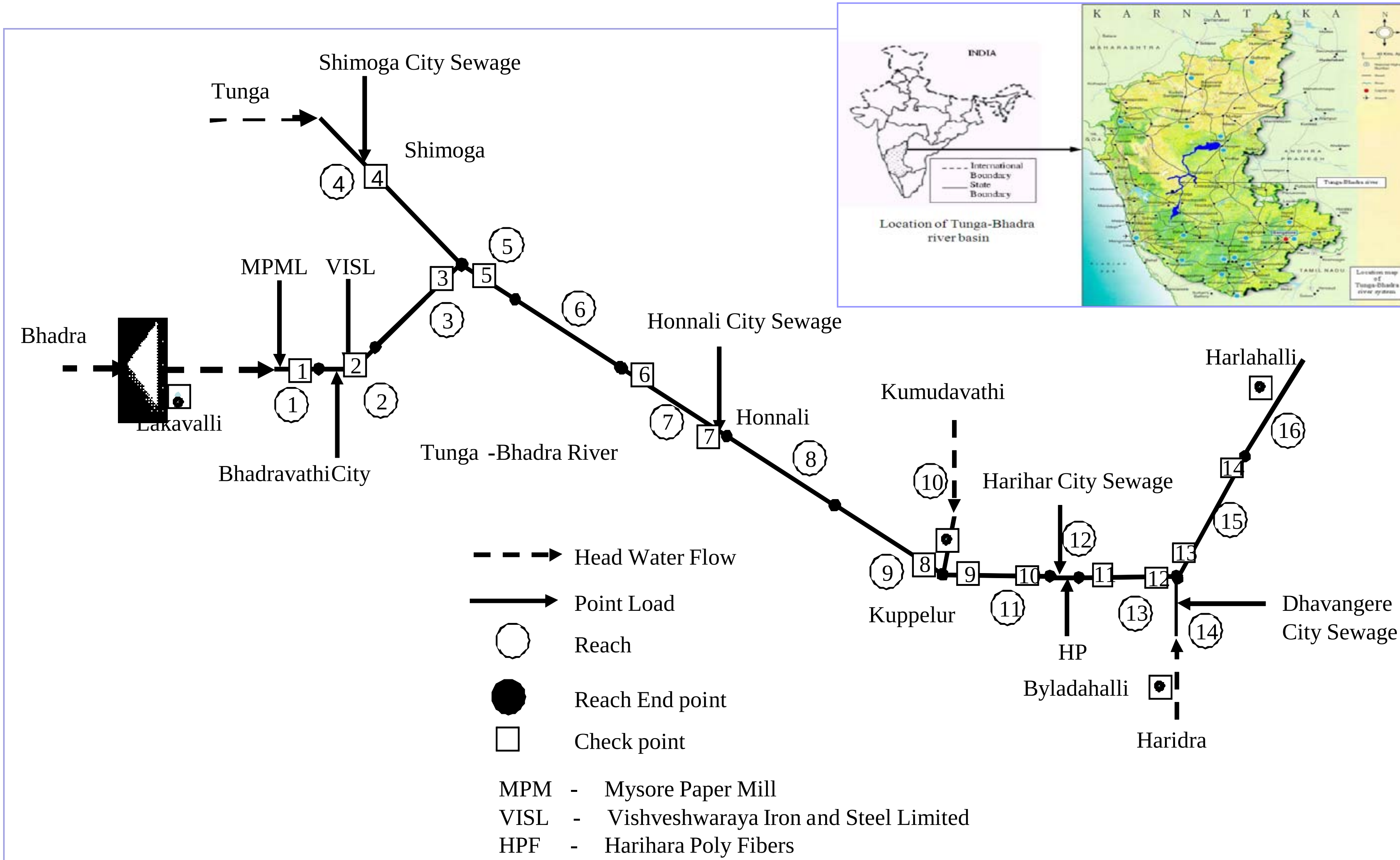
Impacts on River Water Quality

Dissolved Oxygen Depletion



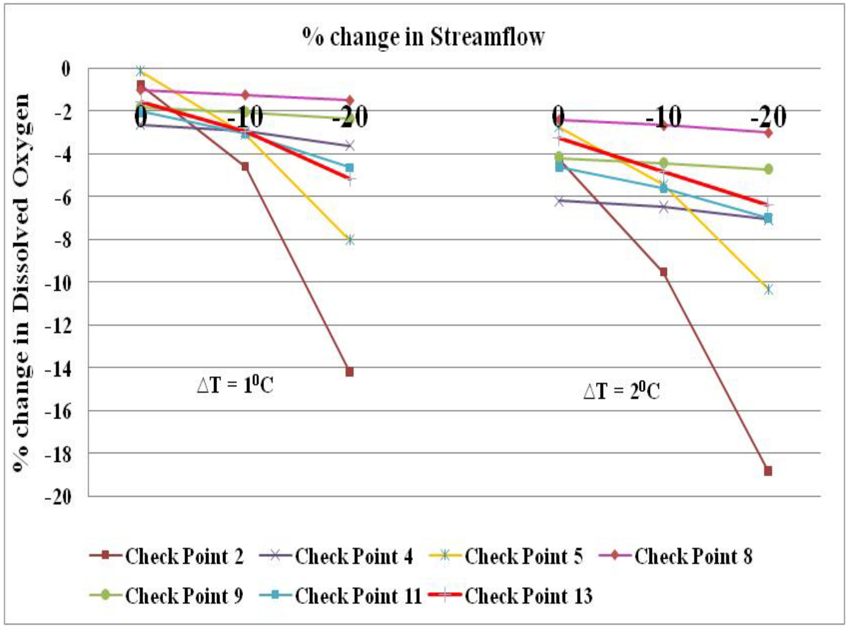
(From: Environmental Science: A Global Concern, 3rd ed. by W.P Cunningham and B.W. Saigo, WC Brown Publishers, © 1995)

Tunga-Bhadra River

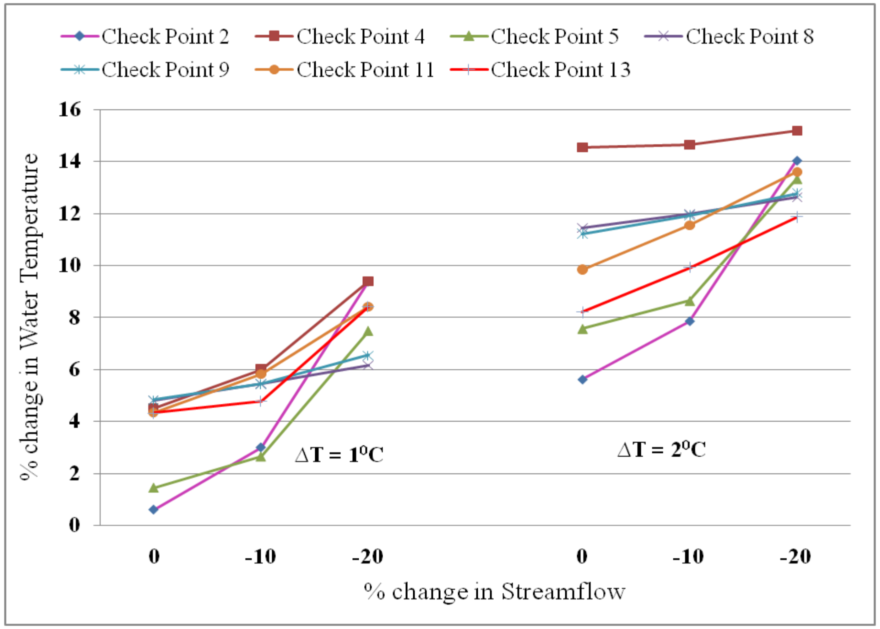


Water Quality Response to Hypothetical Scenarios using QUAL2K

Hydrological Processes (2011)



Change in DO level in response to change in streamflow for a given temperature change



Change in River Water Temperature in response to change in streamflow for a given Air temperature change

Statistical Downscaling : Selection of Predictnad Variables

Input Variables to a water quality model

- Streamflow
- Water Temperature

Variables for a Water Temperature Model

River temperature is mainly controlled by ambient atmospheric conditions **(**e.g. Edinger et al.,1974; Ward,1985; Wu,1992; and Stefan and Preud'homme,1993**)**

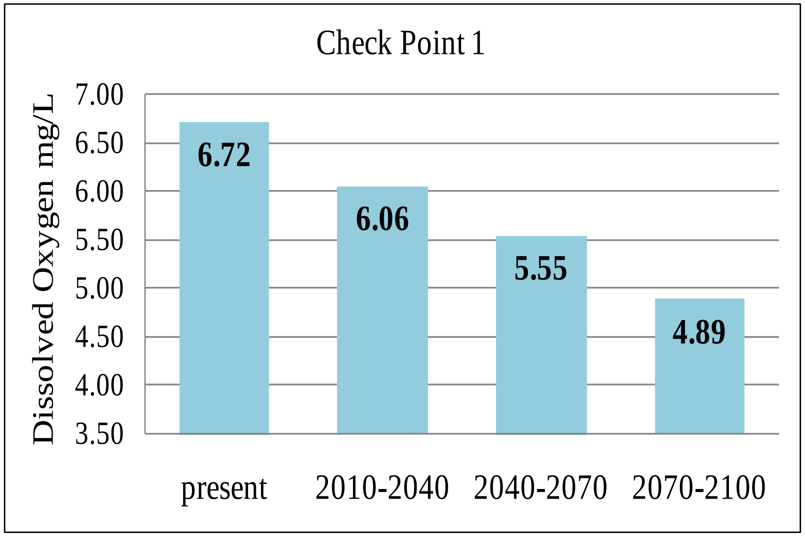
- Average Air Temperature
- Relative Humidity
- Wind Speed
- Dew Point Temperature
- Solar Radiation
  - Maximum Temperature
  - Minimum Temperature

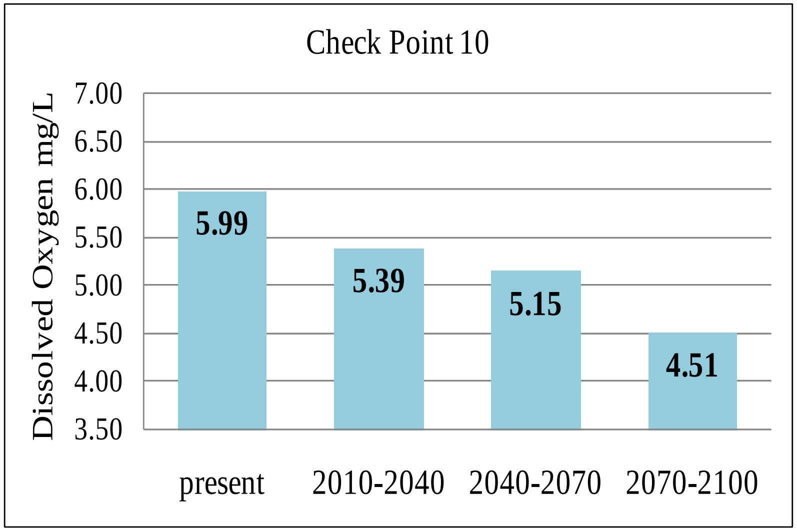
Predictand Variables Selected

1. Streamflow
2. Average Air Temperature
3. Maximum Temperature
4. Minimum Temperature
5. Dew Point Temperature
6. Average Wind Speed
7. Relative Humidity

- Effluent loadings and Diffuse Sources are assumed as unchanged in the future.

DO Levels at various Check Points



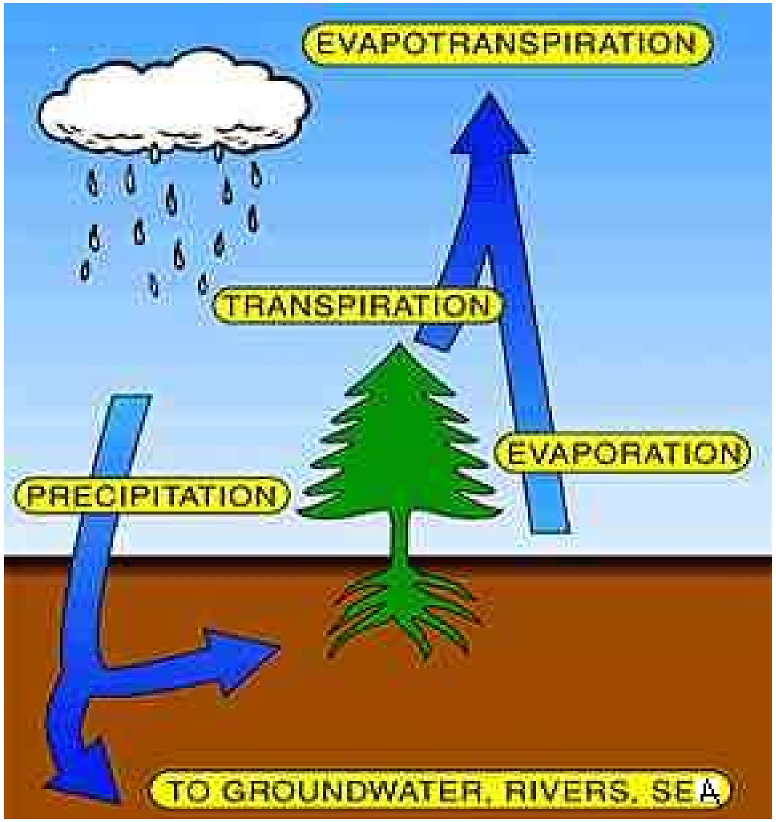


Jl of Hydrology (2012)

Impacts on Irrigation Water Demands

Factors affecting Crop Evapotranspiration

- **Air Temperature**
- **Net Radiation**
- **Wind Speed**
- **Vapour Pressure**
- **Relative Humidity**
- **Soil Moisture**
- **Type of Crop**
- **Season of Crop Growth**

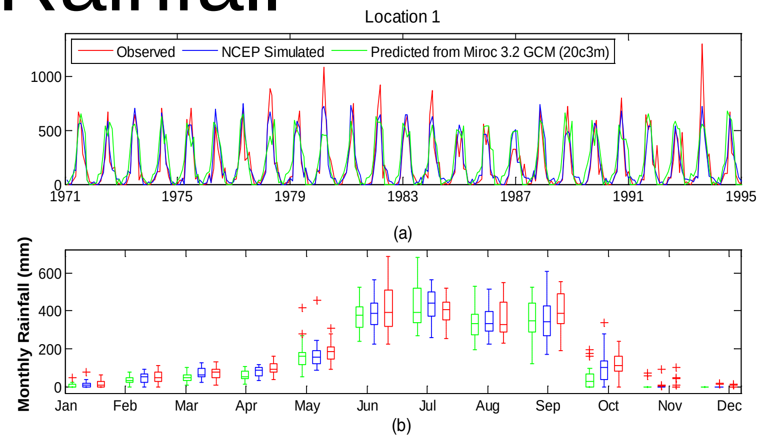


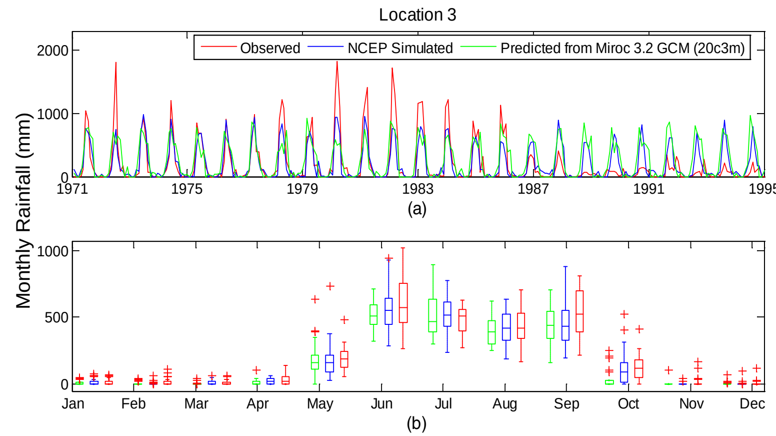
Source for figure : http://eoedu.belspo.be/en/applications/evap-contexte.asp?section=4.1

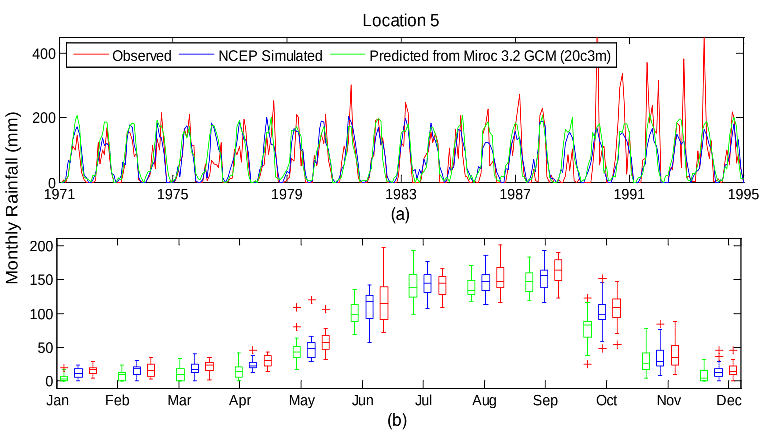
- Irigation water requirements are affected by
  - **Crop/soil characteristics :** type of crop, cropping pattern, crop season, growth stage of the crops, soil type and topography.
  - **Climatic factors:** rainfall and evapotranspiration
    - **Evapotranspiration:** complex function of various climatic variables including air temperature, wind speed, relative humidity, and solar radiation.

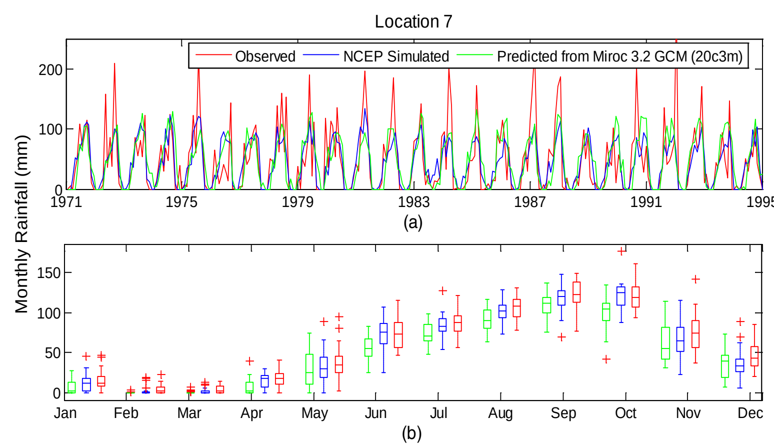
Downscaling Results of Rainfall

Bhadra Command Area



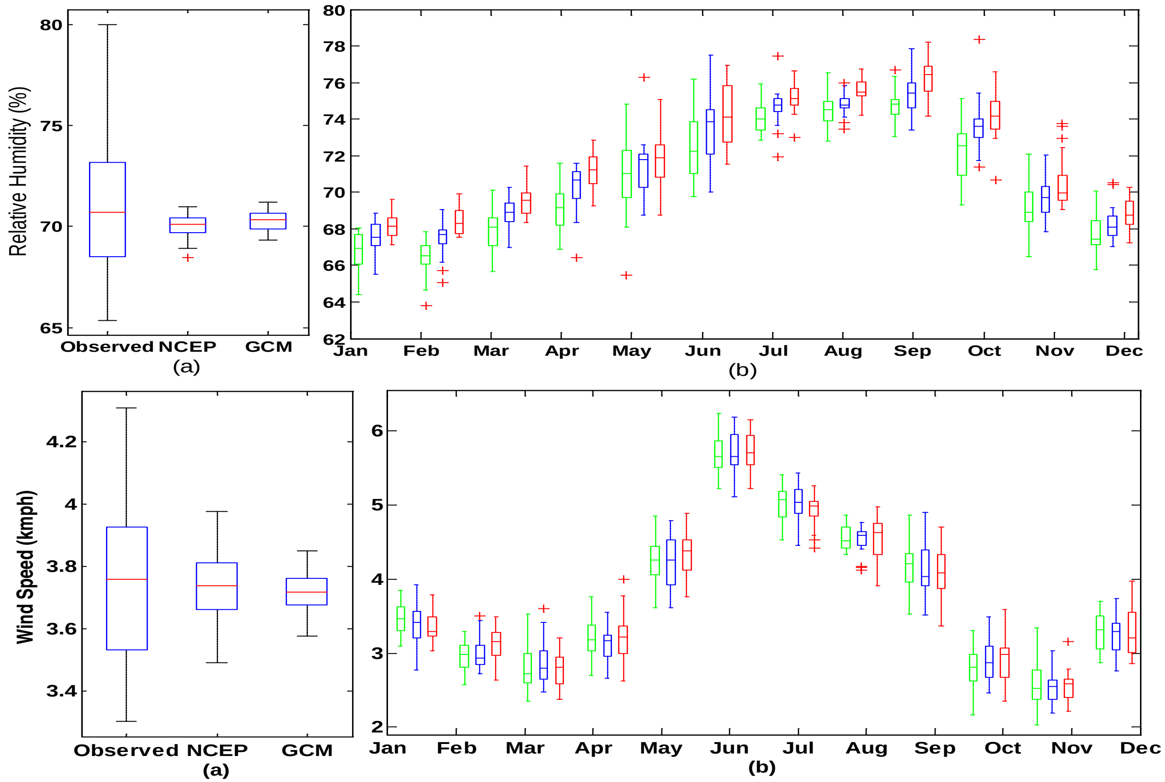






(a)shows the observed, simulated from NCEP data and predicted from MIROC 3.2 GCM with 20c3m experiment for the training period of 1971 to 1995, (b) represents the future projections from MIROC 3.2 GCM with A1B scenario for each month ; green box plots for period 2020-2044, blue box plots are for period 2045-2069 and the red box plots are for period 2070 to 2095.

Downscaling Results of Relative Humidity and Wind Speed

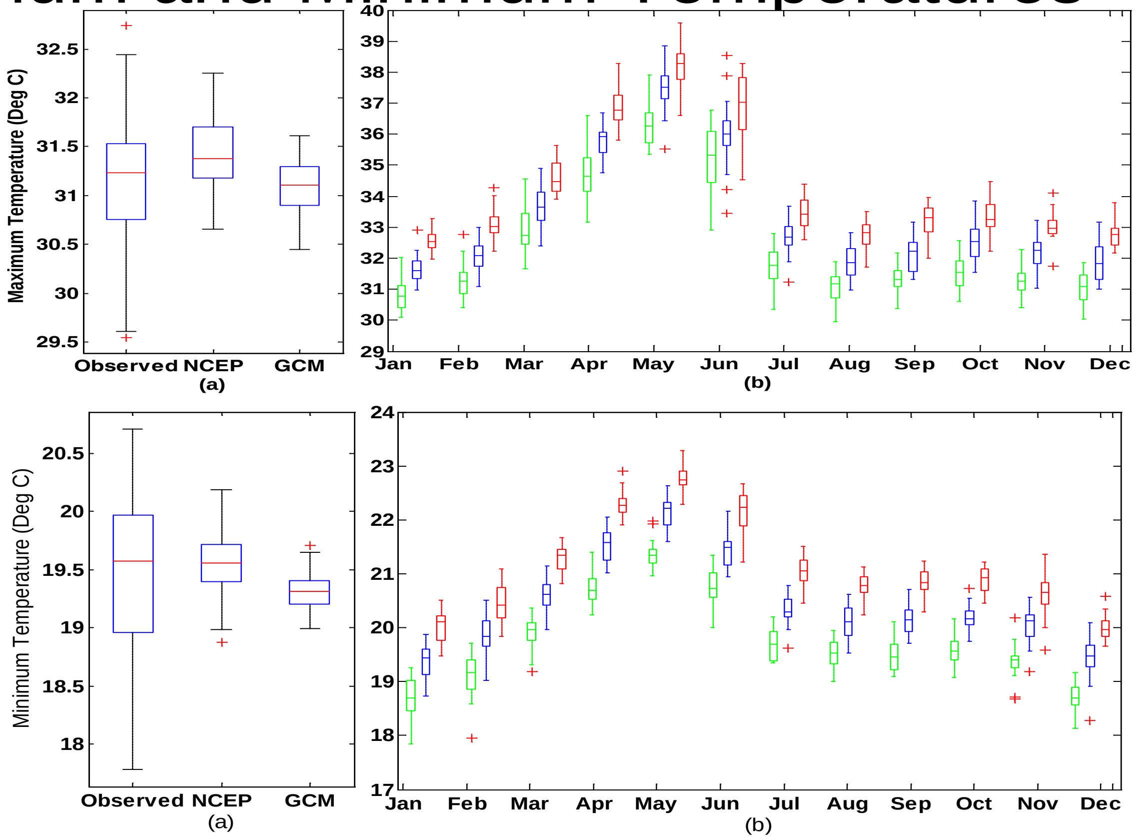


(a) Denotes annual scale observed, simulated from NCEP and simulated from MIROC 3.2 GCM with 20c3m experiment for the training period of 1971 to 1995.

(b) Denotes monthly scale projections; green box plots are for 2020-2044; blue box plots are for 2045-2065 and red box plots are for 2070-2095.

Downscaling Results of Maximum and Minimum Temperatures

Bhadra Command Area

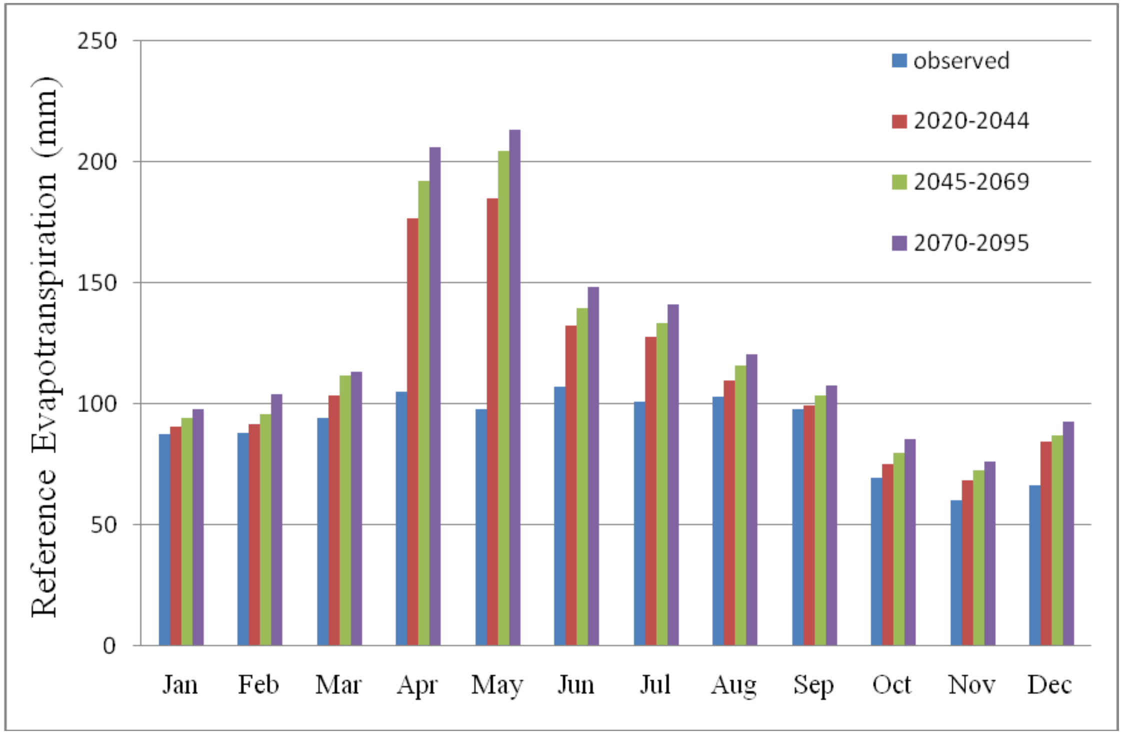


(a) Denotes annual scale observed, simulated from NCEP and simulated from MIROC 3.2 GCM with 20c3m experiment for the training period of 1971 to 1995.

(b) Denotes monthly scale projections ; the green box plots are for 2020-2044, blue box plots are for 2045-2065 and red box plots are for 2070-2095.

Monthly Reference Evapotranspiration for Bhadra Command Area Estimated from MIROC 3.2 GCM Output with A1B Scenario

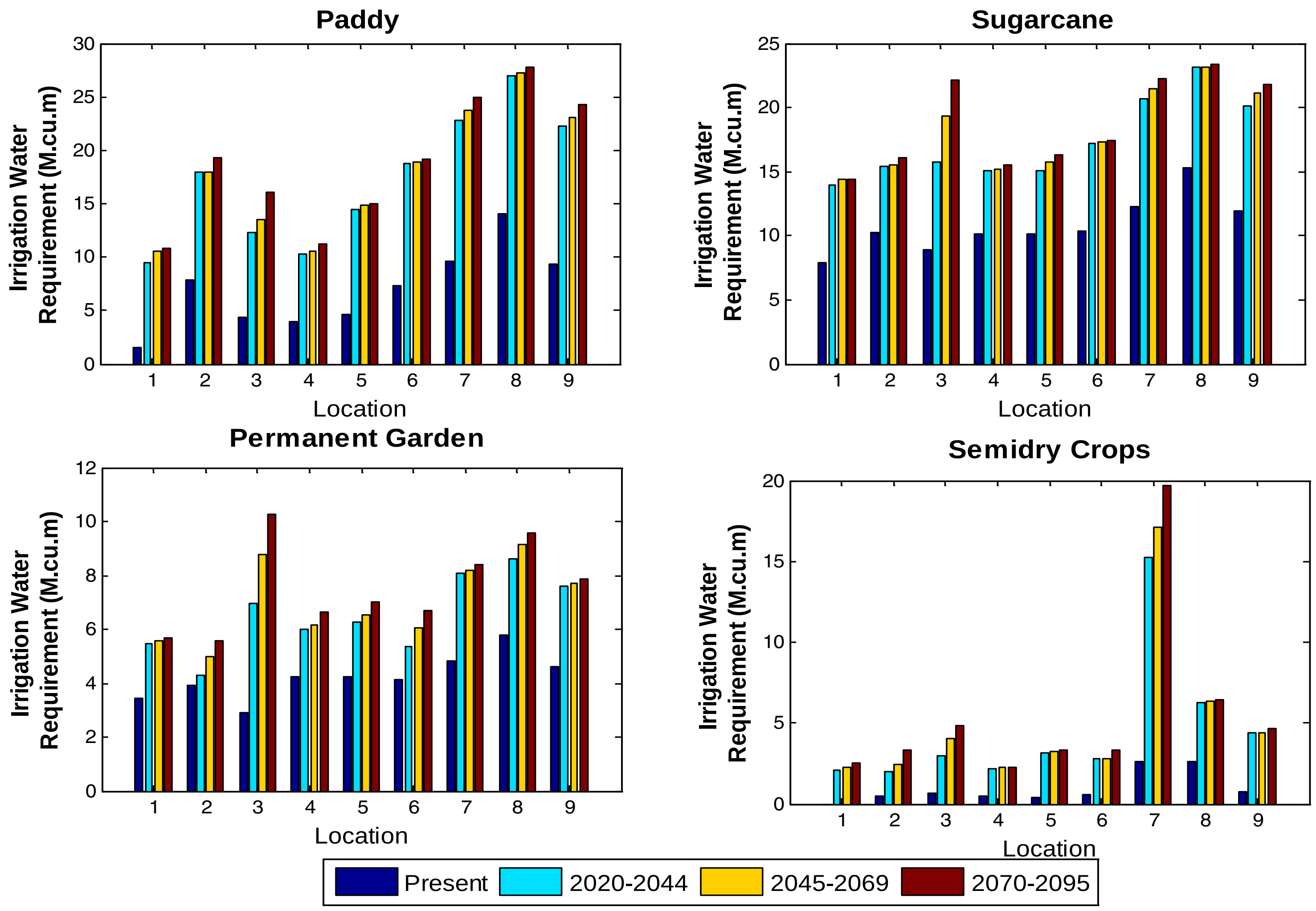
Hydrological Processes (2012)



Penman-Monteith evapotranspiration Model

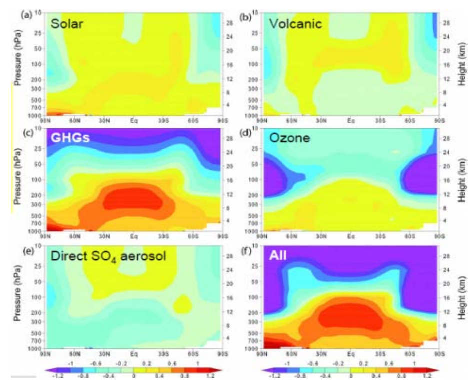
$$ET_{t,R} = \frac{0.408\Delta(R_n - G) + \gamma(900/(T+273))U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

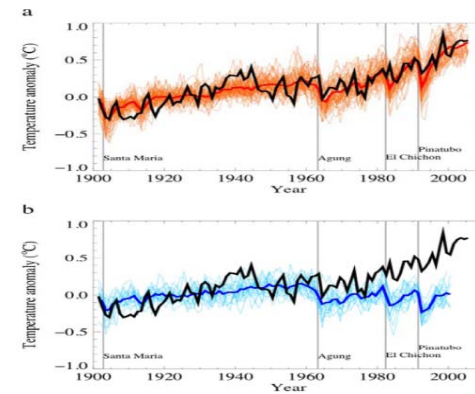
Projected Annual Water Requirements



Detection and attribution of human-induced climate change in basin-scale hydrology

Detection and Attribution (D&A) of human-induced climate change





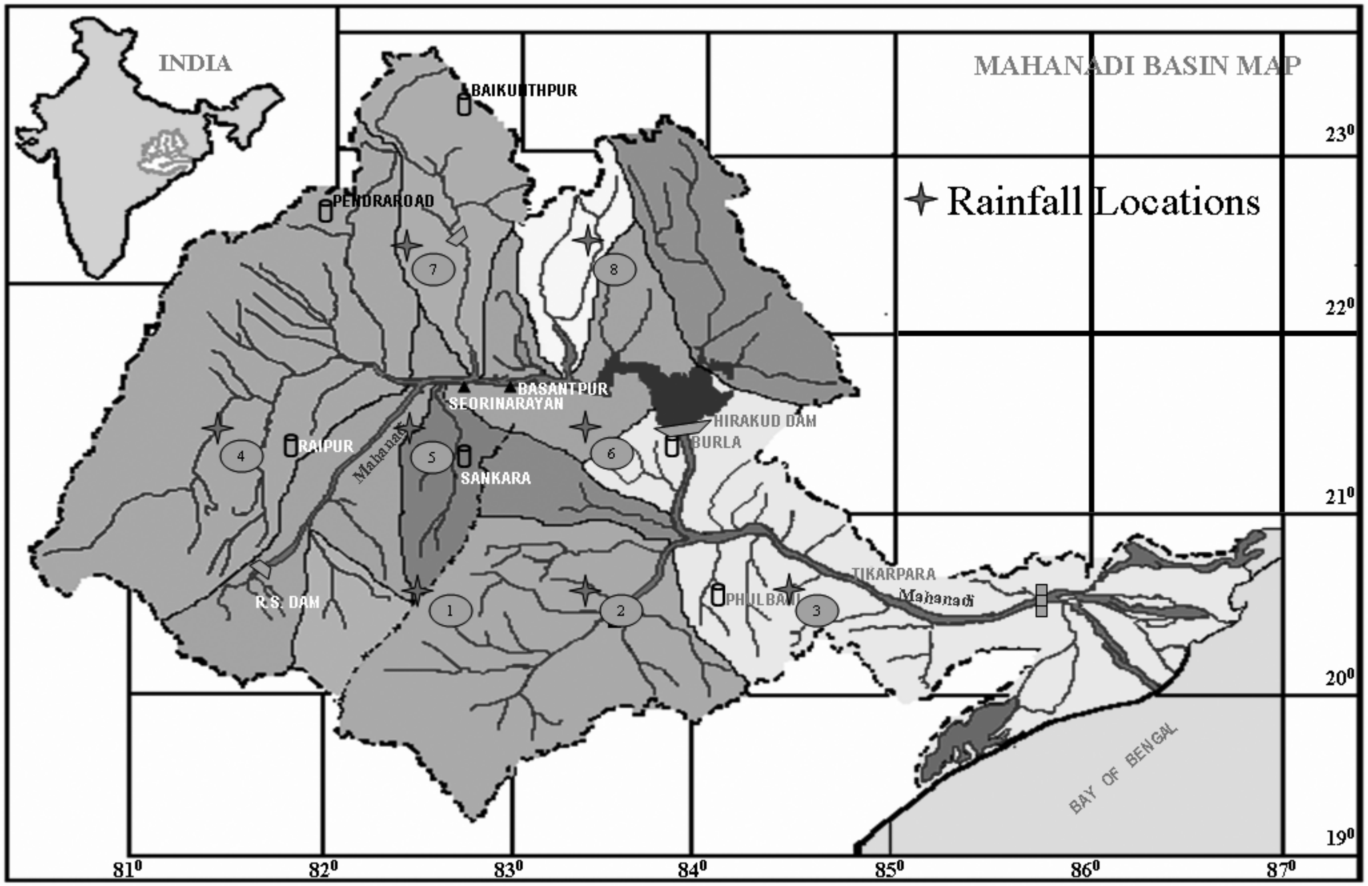
- Fingerprint of human-induced climate change searched for, in observations
- ‘Detection’ of climate change is ‘the process of demonstrating that climate or a system affected by climate has changed in some defined sense, without providing a reason for that change’.
- ‘Attribution’ is ‘the process of evaluating the relative contribution of multiple causal factors to a change or event with an assignment of statistical confidence’.

Source : IPCC, (2007)

Why is D&A Analysis Necessary?

- IPCC AR4 infers:
  - Observed warming *extremely unlikely* due to unforced variability alone
  - Human emission induced greenhouse gases (GHGs) *very likely* caused most of the observed warming since mid-century
- It becomes necessary to assess whether a signal of human-induced climate change is indeed discernible in hydrological observations in the past, considering scale issues and variability across climate models
- It helps in quantifying such changes, and thus can be used to increase reliability in future projections

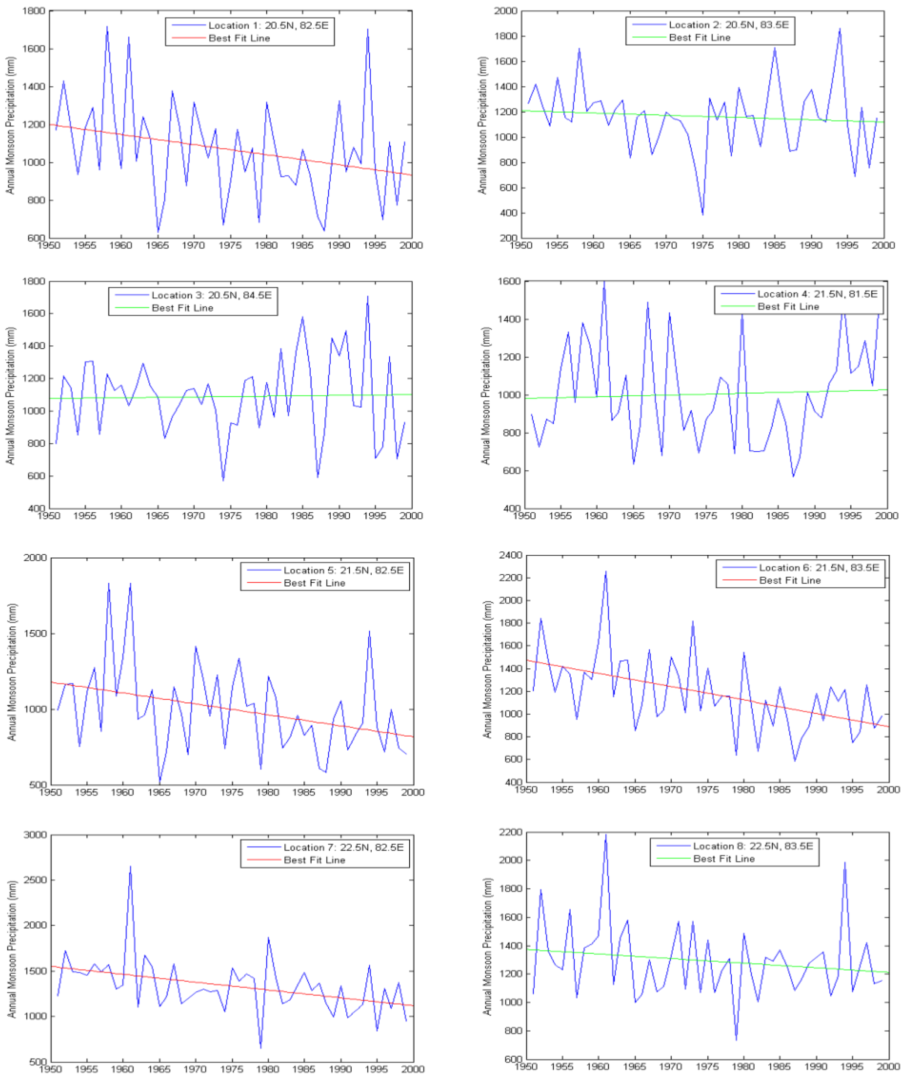
Mahanadi river basin

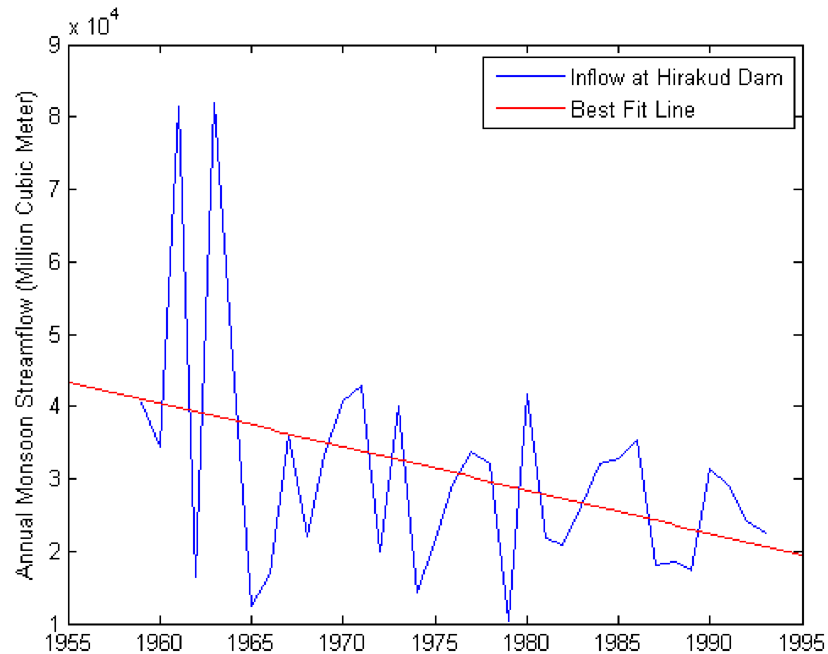


- Monsoon (JJAS) precipitation at 8 IMD locations, and accumulated monsoon streamflow at Hirakud dam considered

Trends in observed monsoon (JJAS)

precipitation and streamflow



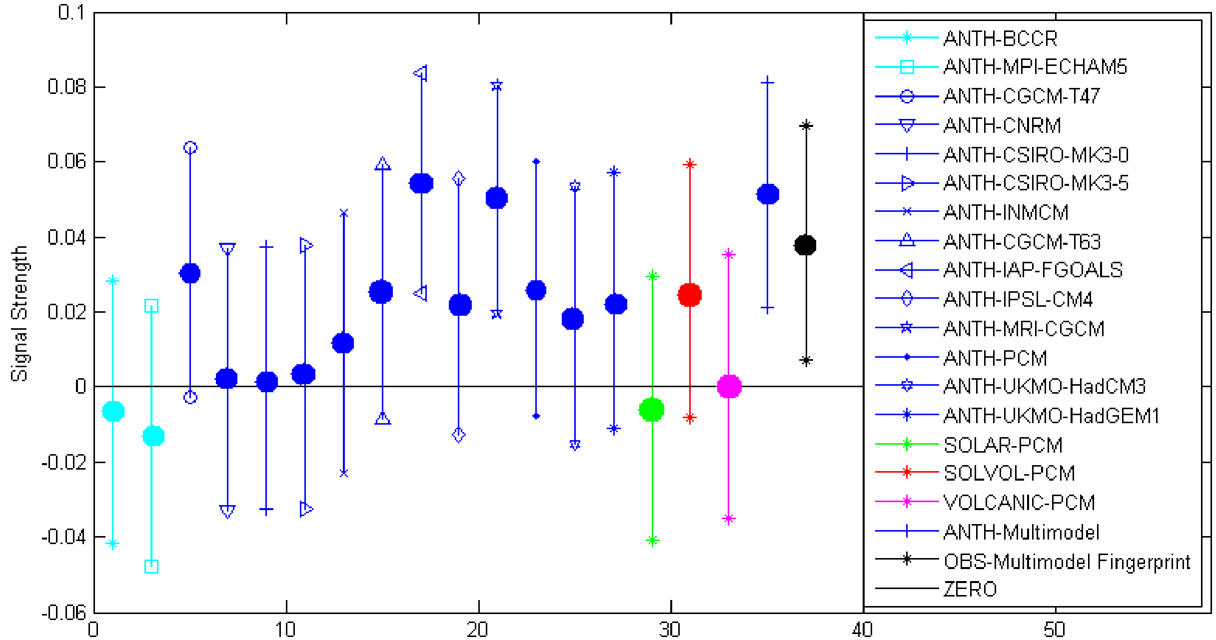


Are these decreases a part of natural internal climate variability alone, in absence of any external forcings?

D&A results: Signal-strengths for

Water Resources Research, 2012

- Monsoon streamflow



The ensemble-averaged signal strengths (S values) from each model run (dots) and their 95% confidence intervals (bars) are shown. The observed signal strength (S_{obs}) with its 95% confidence interval, considering the multi-model ensemble-averaged ANTH fingerprint is shown in black. The GCMs for which the ANTH signal strength is inconsistent in sign with the observed signal strength are marked in cyan and those for which the ANTH signal strength is consistent with the observed signal strength are marked in blue.

Major findings for Mahanadi river basin

- observed trends over the second half of the twentieth century in both monsoon precipitation and streamflow lie outside the range expected from natural internal climate variability alone at 95% statistical confidence level for most of the GCMs
- observed hydrological changes cannot yet be collectively attributed to human-induced climate change across all the climate models
- multi-model ensemble averaged anthropogenic signal strength is found to explain the trends in the observations, for both monsoon precipitation and streamflow – Detection more conspicuous in streamflow!
- there may exist uncertainties in the analysis because of the detection methodology, data and/or models

Science Issues

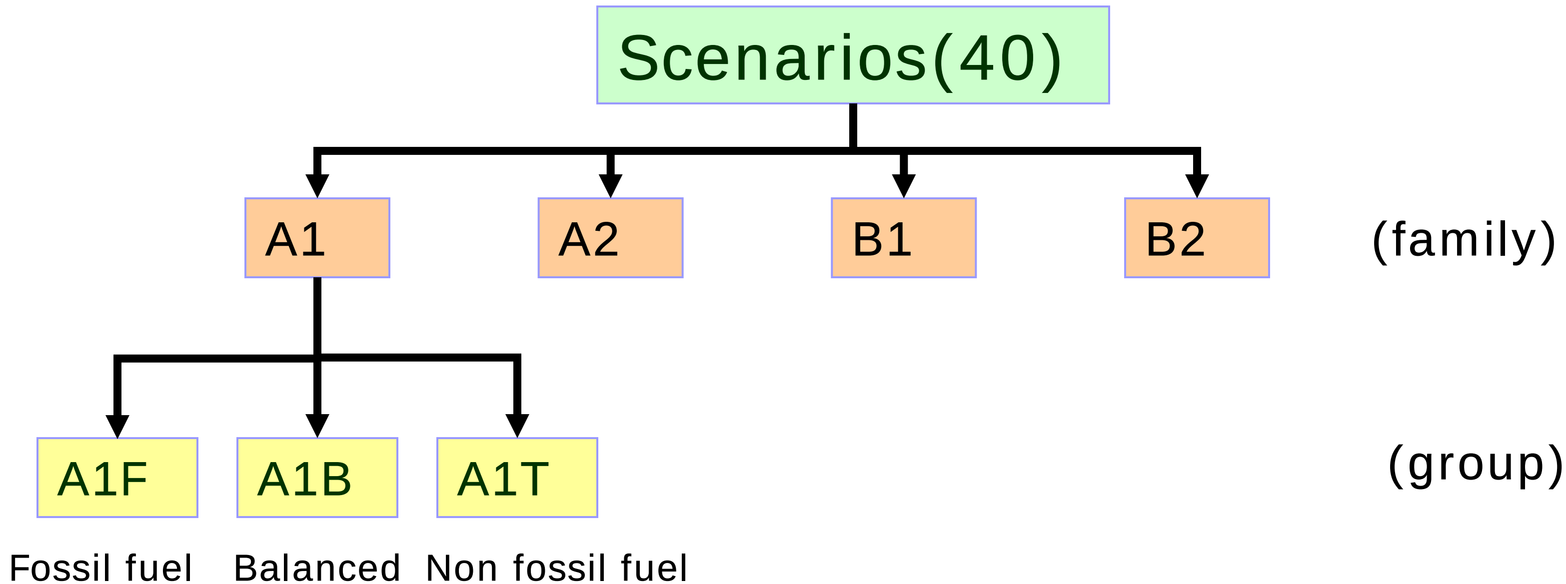
- Detection and Attribution at Riverbasin Scales (Mondal and Mujumdar, *Water Resources Research*, 2012)
- Account for non-stationarity introduced by anthropogenic interventions and climate change
    - Stationarity in hydrology is dead (*Science*, 319, 2008)
- Quantify – and reduce - uncertainties due to a large number of sources, in the hydrologic projections
- Provide high-resolution climate simulations, specifically for hydrologic applications.
- Quantify hydrologic feedbacks to the climate system

Summary

- Climate change is likely to impact most hydrologic processes
- Impacts need to be assessed at regional/riverbasin and smaller scales
- GCMs are the most credible tools available today for impact assessment
- Scale issues and uncertainties are addressed in recent studies
- Impacts on flow distributions, IDF relationship, river water quality and irrigation demands are assessed
- ‘Detection and Attribution’ studies are carried out at river basin scales.

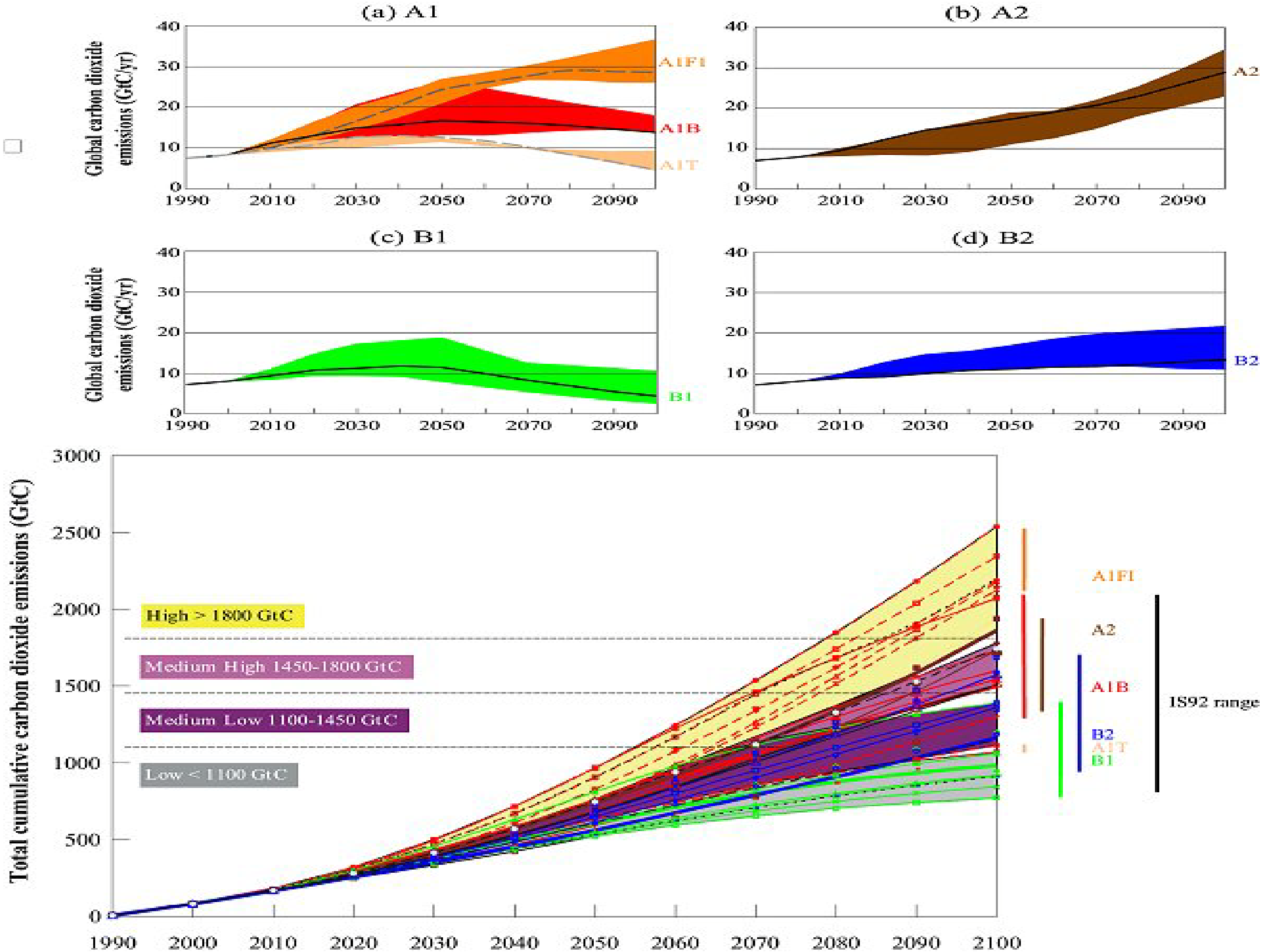
THANK YOU

IPCC SRES (2001)

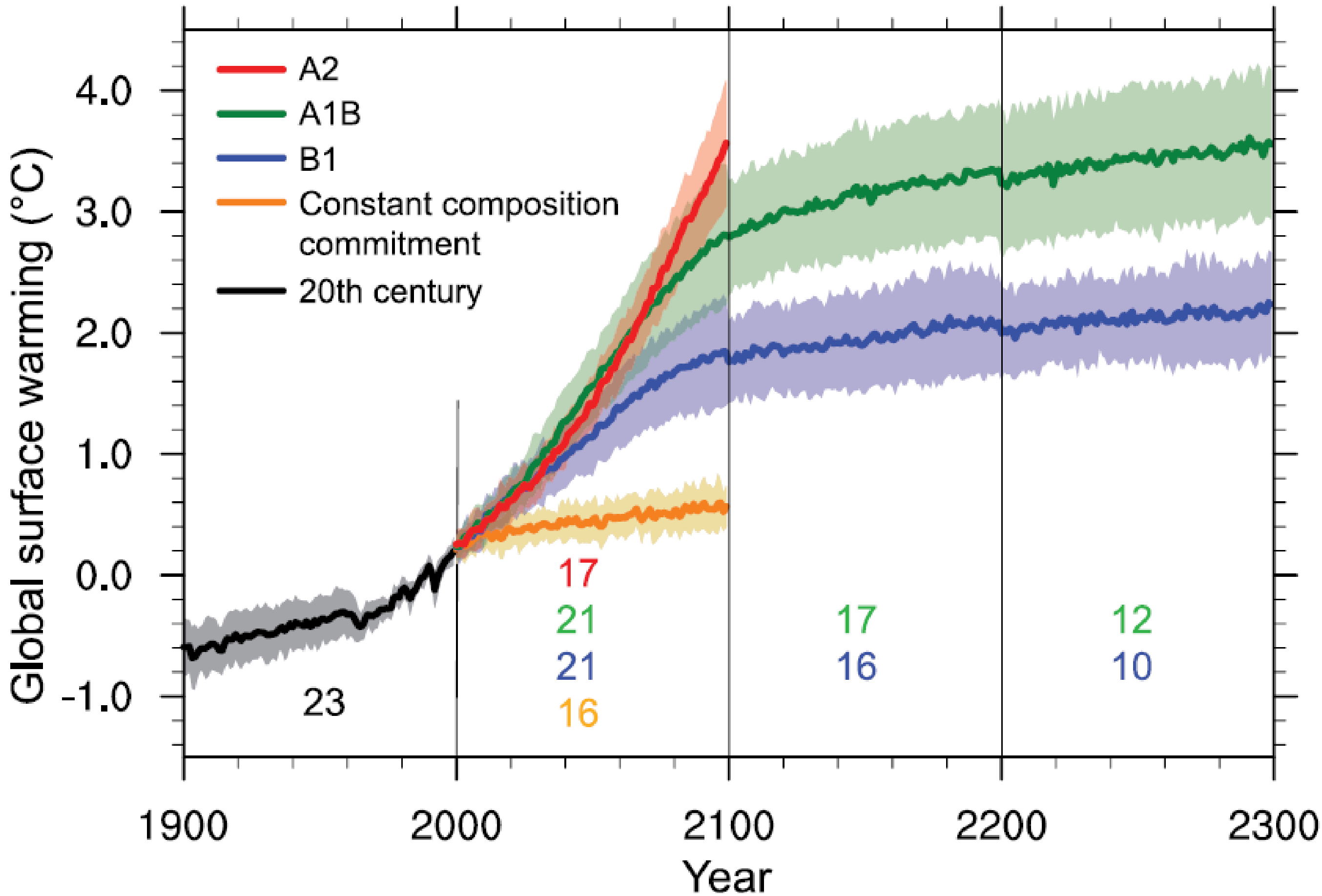


Scenario family	A1	A2	B1	B2
World order	Integrated	Divided	Integrated	Divided
Ecologically friendly	No	No	Yes	Yes
Population	Increases till 2050 and then declines	Continuously increasing	Same as A1	Increasing but lower than A2
Economic growth	Rapid	Regionally oriented	Rapid (service-oriented)	Intermediate
Technology growth	Rapid	Slower fragmented	Rapid	Slower fragmented

IPCC Scenarios



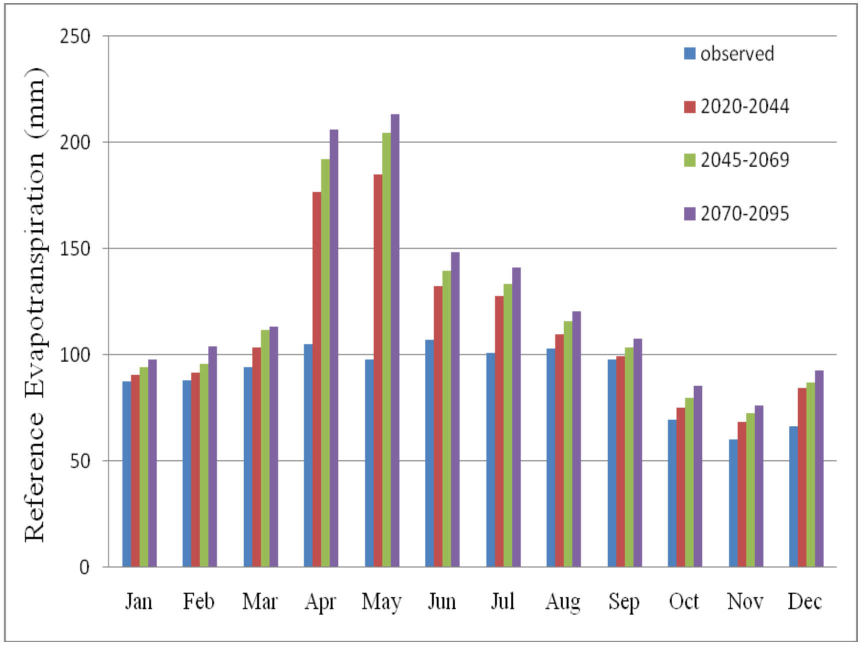
Climate change projections



Source: Meehl et al., Climate Change 2007: The Physical Science Basis, WG I, AR4, IPCC

Evapotranspiration Model

- The evapotranspiration projections are modeled with a Penman-Monteith evapotranspiration model (Allen *et al*., 1998) accounting for the projected changes in temperature, relative humidity, solar radiation and wind speed.



$$ET_{t,R} = \frac{0.408\Delta(R_n - G) + \gamma(900/(T+273))U_2(e_s - e_a)}{\Delta + \gamma(1+0.34U_2)}$$

$$ET^c_{t,p} = ET_{t,R} \text{ X } k_{t,c}$$

where $ET_{t,R}$ is the reference evapotranspiration of each month (mm/month); Δ is slope of the vapor pressure curve, R_n is net radiation at the surface (w/m^2); *G* is the soil heat flux density (w/m^2), γ is psychrometric constant (kPa ^{0}C^{-1}) = 0.665 x 10^{-3} P$_a$, where P$_a$ is atmospheric pressure (kPa), *T* is the average air temperature at 2-m height, U$_2$ is wind speed at 2-m height, is the saturated vapor pressure and is the actual vapor pressure (kpa). $ET^c_{t,p}$ is the potential evapotranspiration for each crop, *c* for each period, *t* ; $k_{t,c}$ crop coefficient for each period, *t* for a crop, *c.*