Earth and Regional Water Resources Systems - Climate Change Impacts

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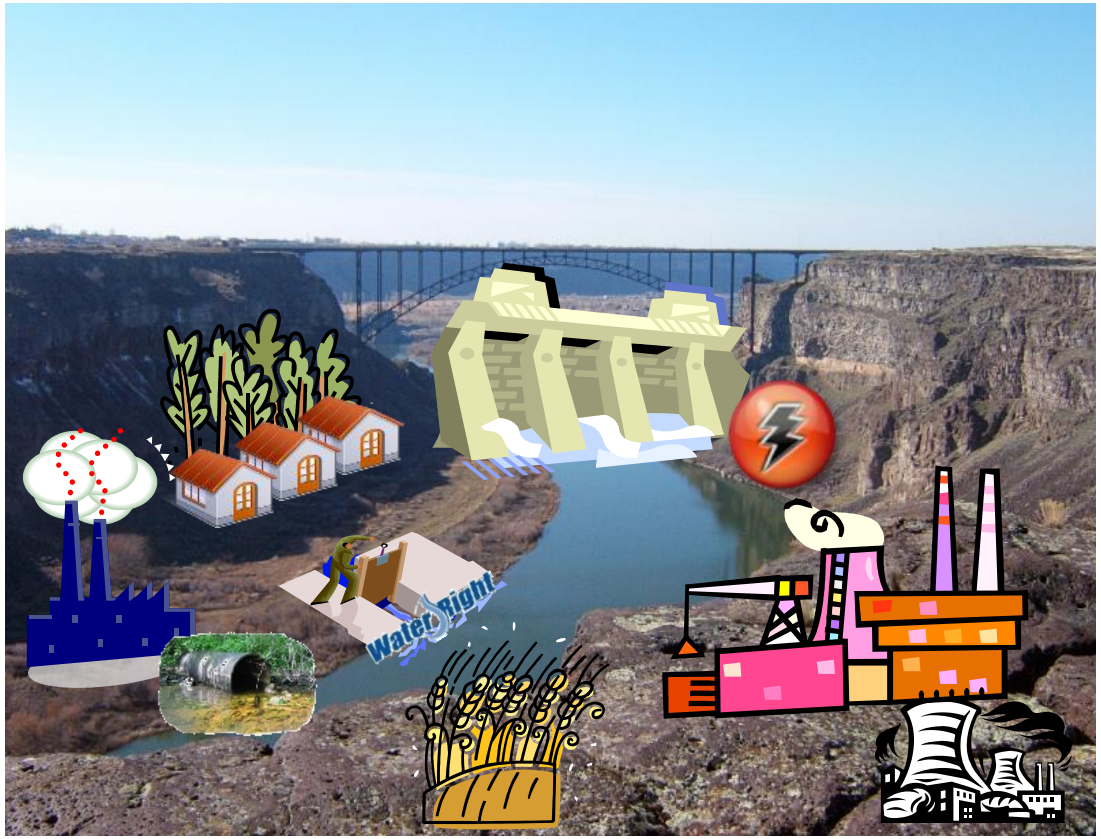
Regional Water Resources System

Systems Involved

- Climate System
- Hydrological Modeling
- Water Inflow/Availability to Reservoir/Dam
- Downstream River Water Quality – Effluents
- Irrigation Water Management
- Hydropower Water Management
- Reservoir Operation, Optimum Releases, Water Demand



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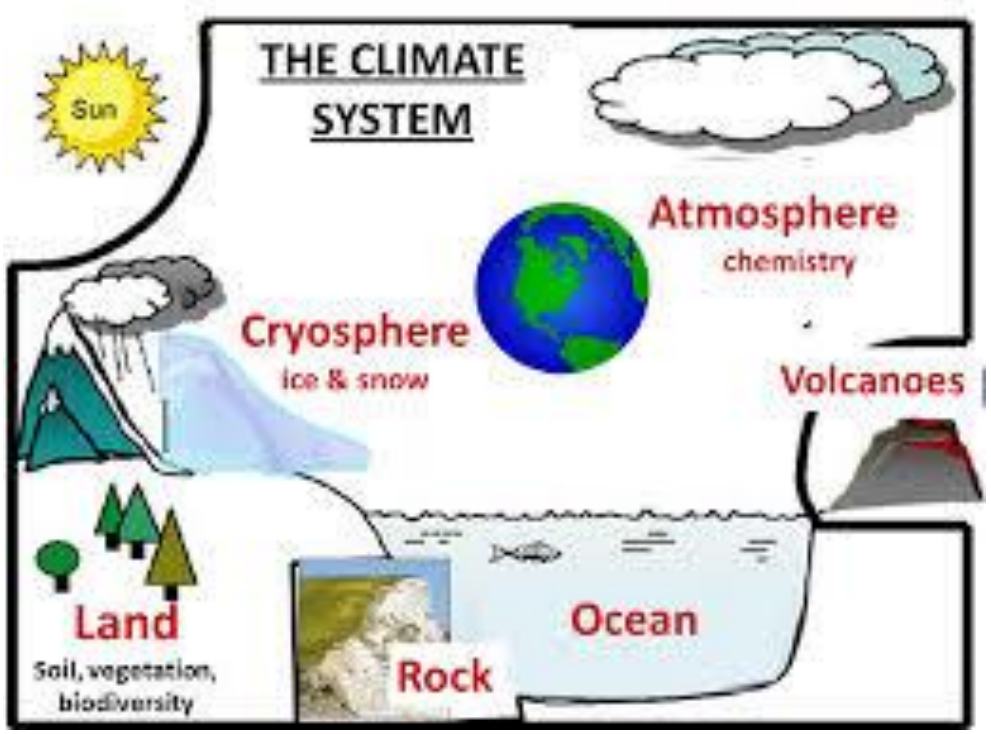
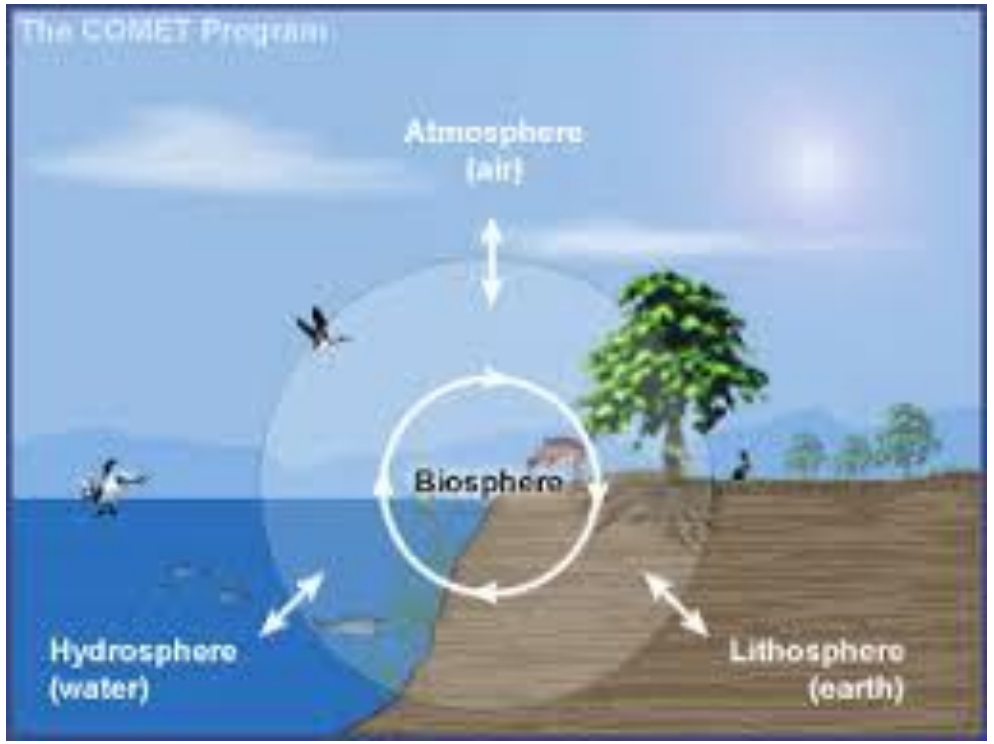
What is ‘Climate’?

- **Weather:** Characteristics of the atmosphere over a short period of time, in terms of few days.
    - Ex: ***Current*** Temperature, Rainfall, Humidity, Solar radiation

- **Climate:** The statistics of weather over a long period of time.
    - Ex: ***Average*** Temperature, Rainfall, Humidity, Solar radiation

Climate System





- ‘Atmosphere, hydrosphere, biosphere and geosphere and their interactions’ - UNFCCC

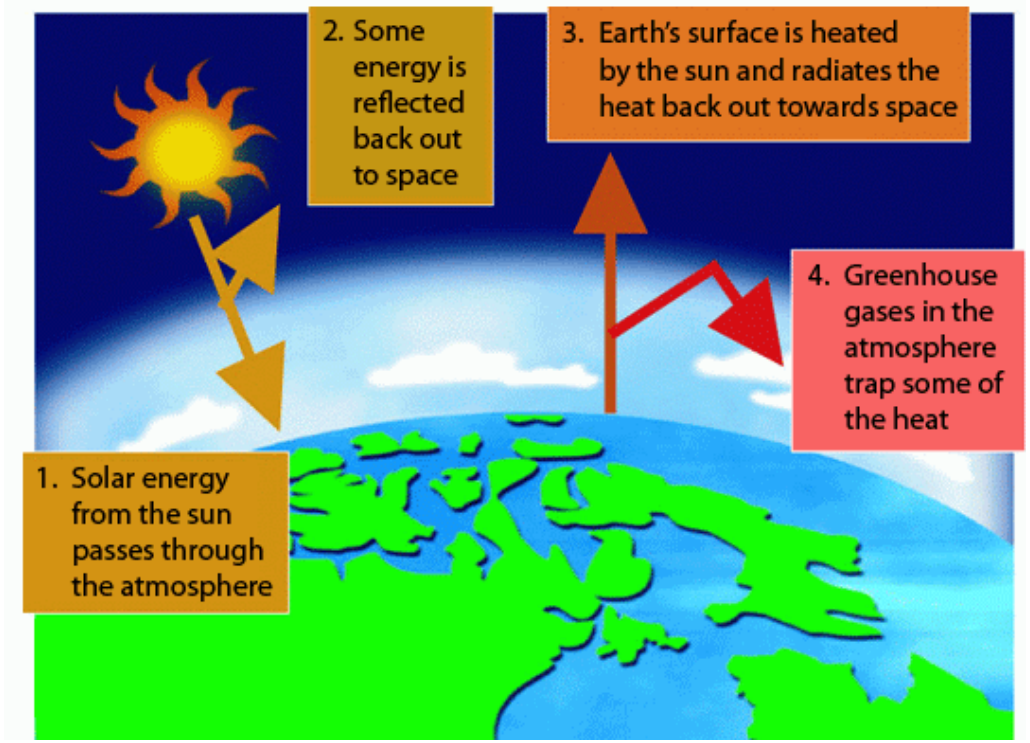
What is ‘Climate Change’?

- Variations in the "average weather patterns" that occur over time.
- Climate is the average weather at a given point and time of year, over a long period (typically 30 years).
- Weather is expected to change a lot from day to day, but climate is expected to remain relatively constant.
- If the climate doesn’t remain constant, we call it climate change.

What Causes Earth's Climate to Change?

- Changes in the atmosphere
- Natural processes
  - Volcanic eruption
  - Solar radiation fluctuations
  - Ocean circulation changes
- Human activities – any activity that releases "greenhouse gases" into the atmosphere, Deforestation

Climate Change

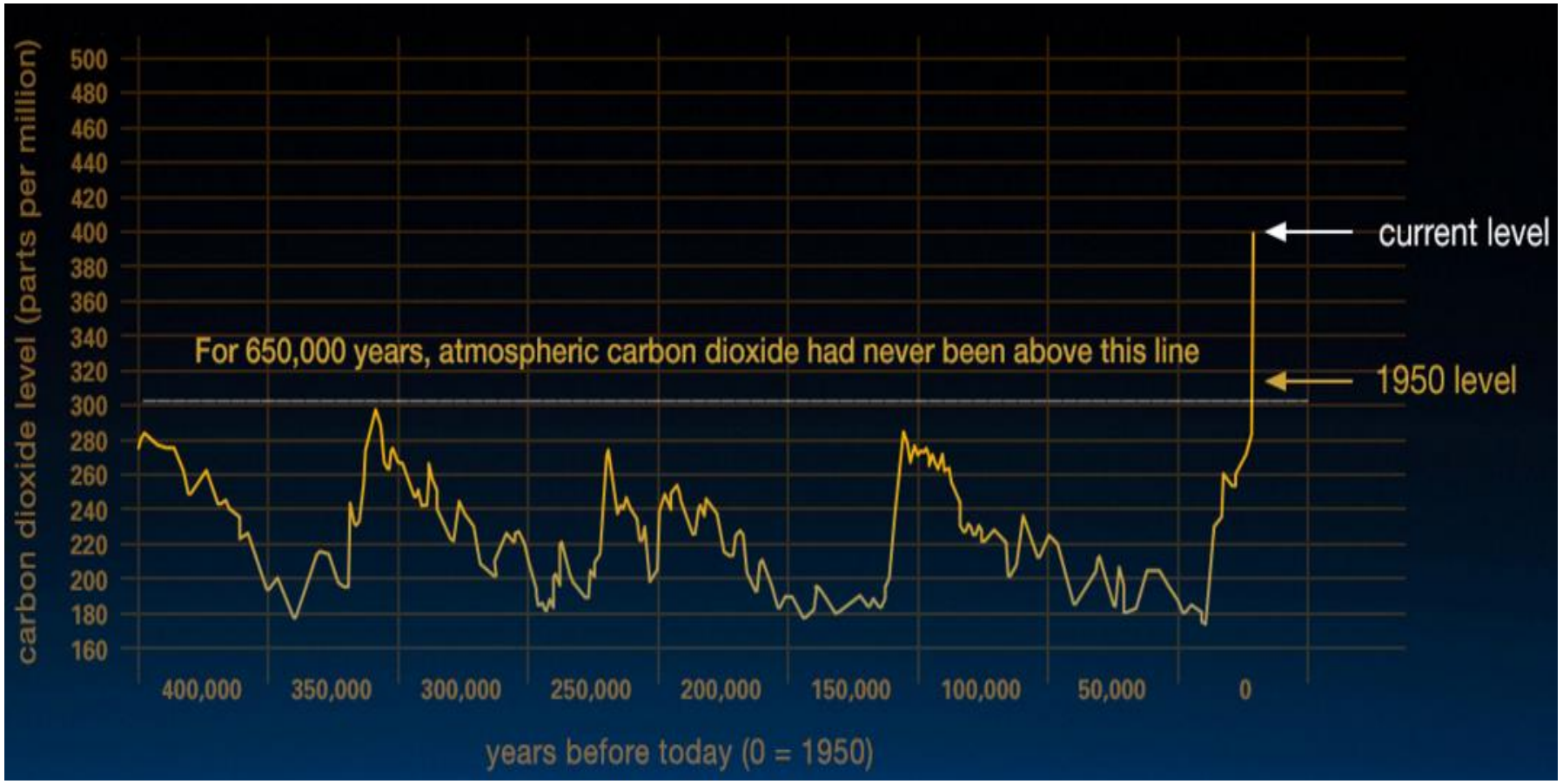


A number of greenhouse gases occur naturally in the Earth's atmosphere

- Water vapor
- Carbon dioxide
- Methane
- Nitrous oxide

- **Climate Change:** Difference between climatic states. Statistical description over a period of time
- **Climatic Anomaly:** Difference between climatic state and mean state

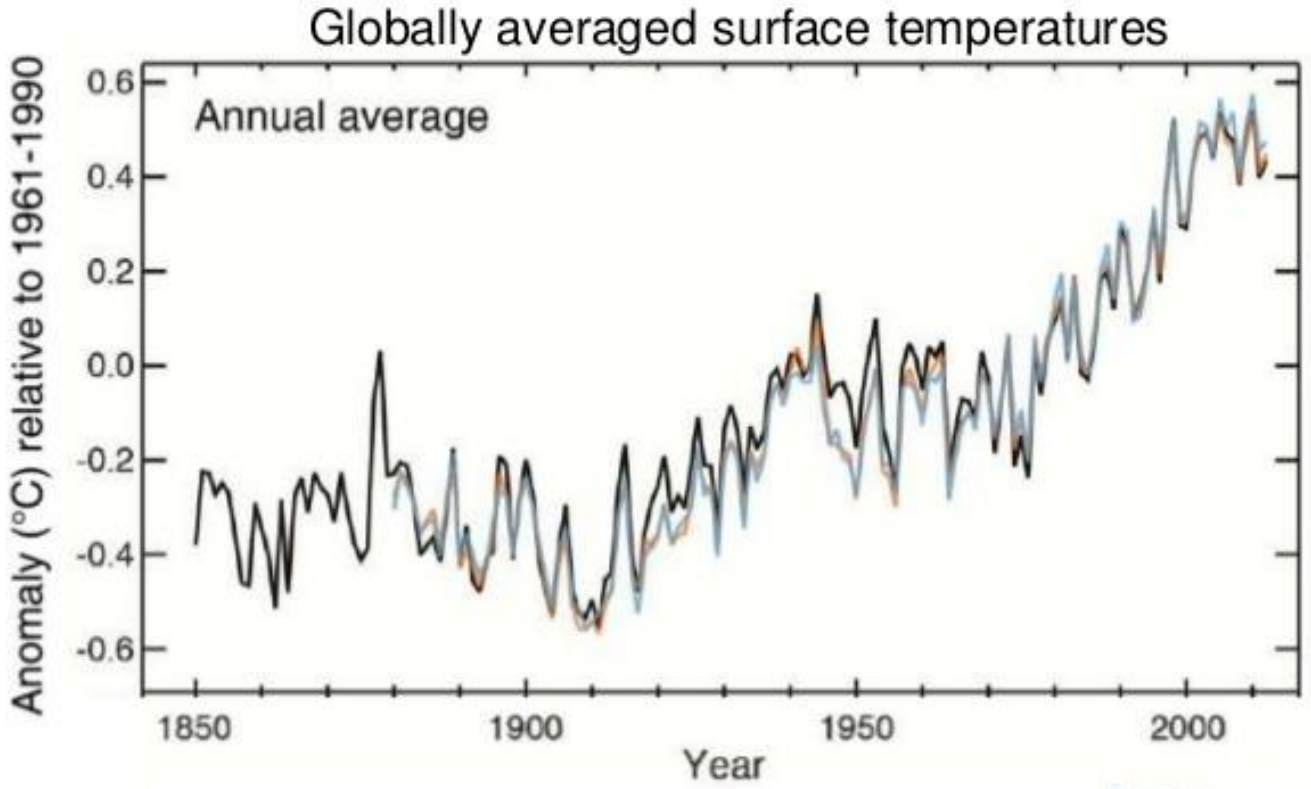
How do we know the climate is changing? – CO2



The graph is based on the comparison of atmospheric samples contained in ice cores and adapted from the NASA website for Climate Change as viewed on 14th February 2016

How do we know the climate is changing? – Surface temperature

Global mean surface temperatures increased by 0.89ºC between 1901 and 2012

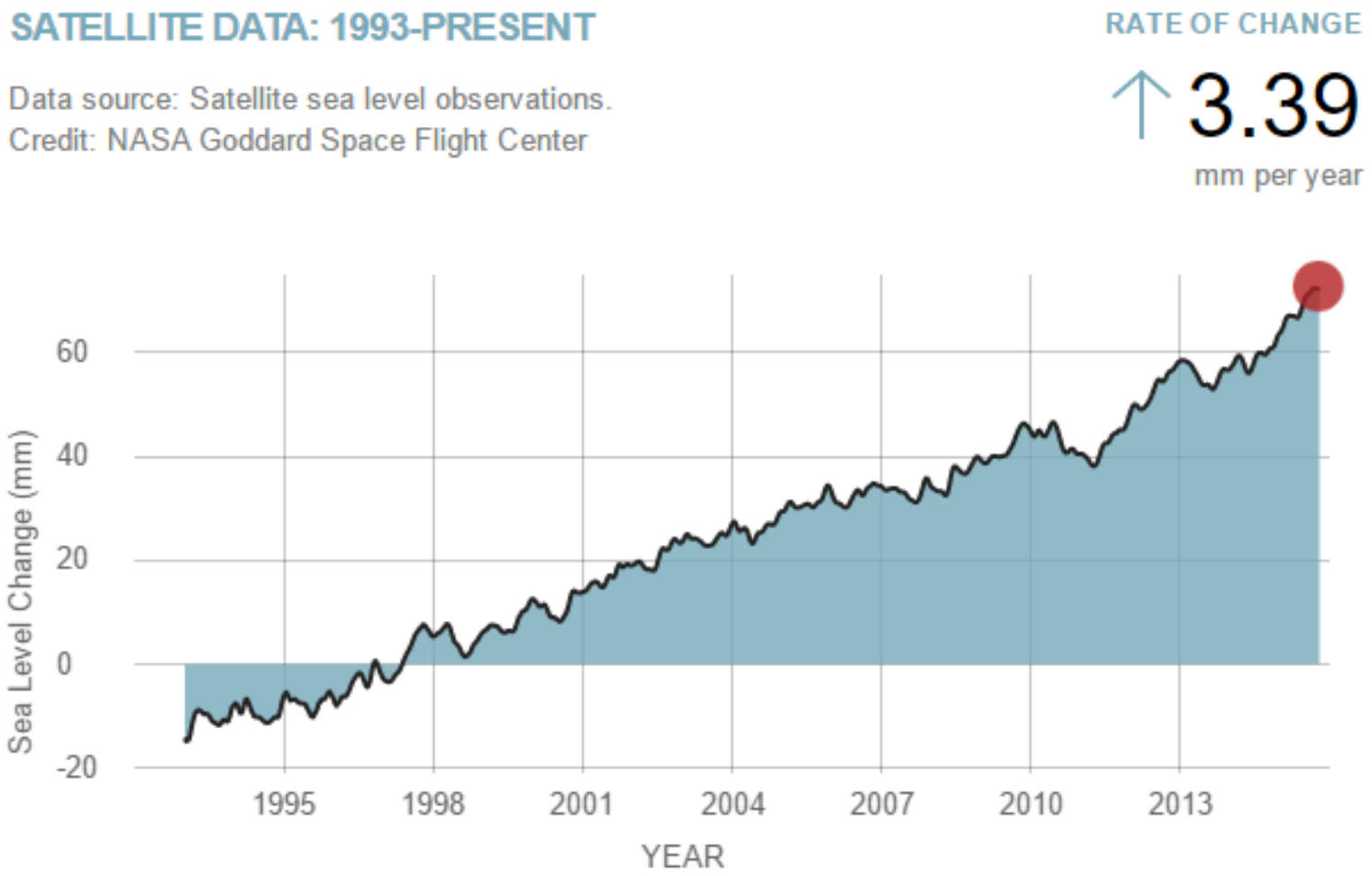


IPCC AR5 Working Group I
Climate Change 2013: The Physical Science Basi...

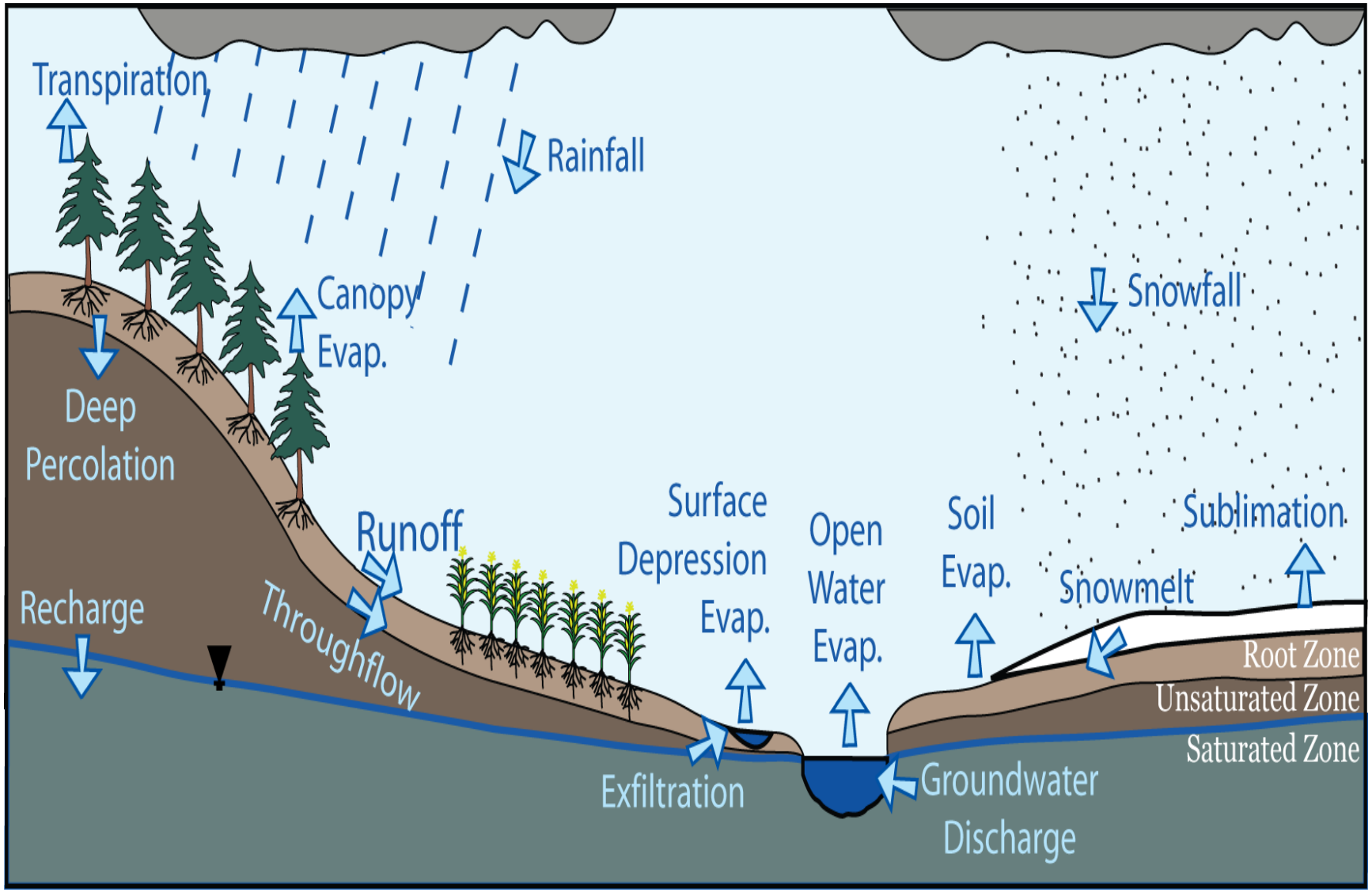
IPCC (2013) Figure SPM.1

ipcc
INTERGOVERNMENTAL PANEL ON climate change

How do we know the climate is changing? – Sea Level Rise



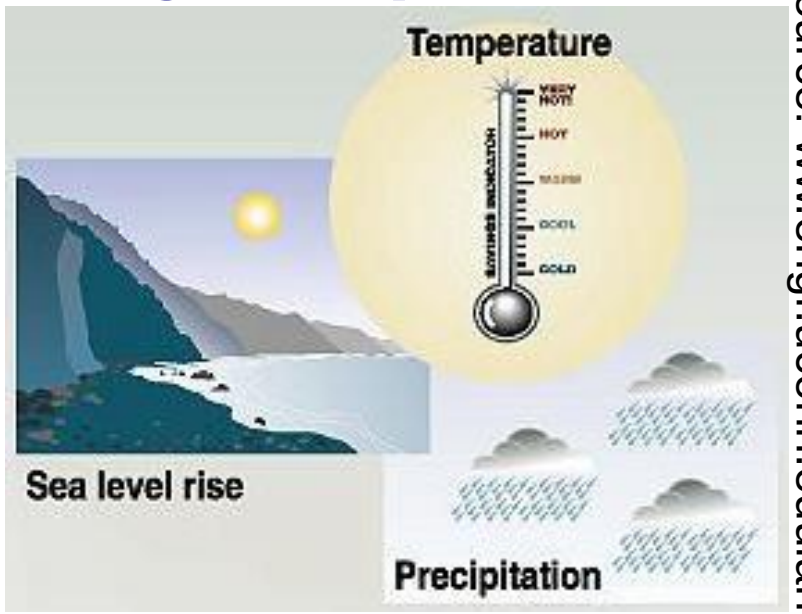
Hydrologic System



Source: http://hydrogeology.glg.msu.edu/research/active/modeling-and-monitoring-hydrologic-processes-in-large-watersheds

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



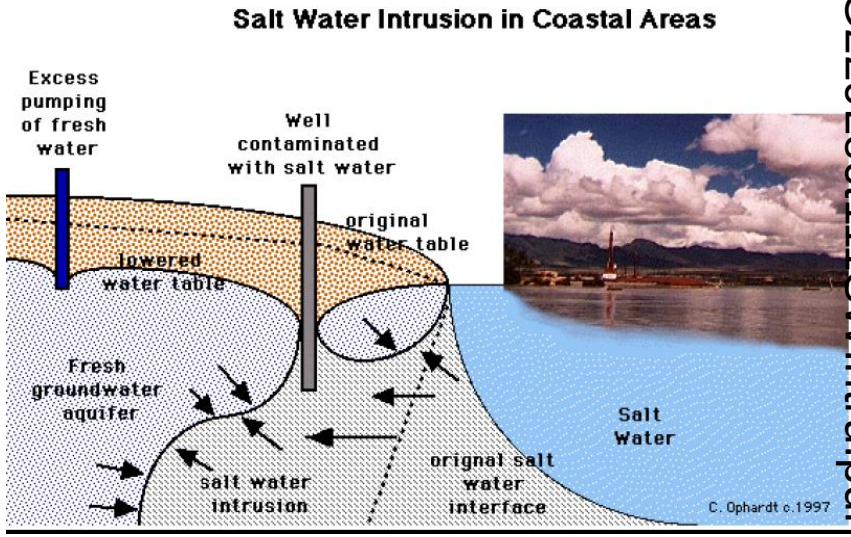
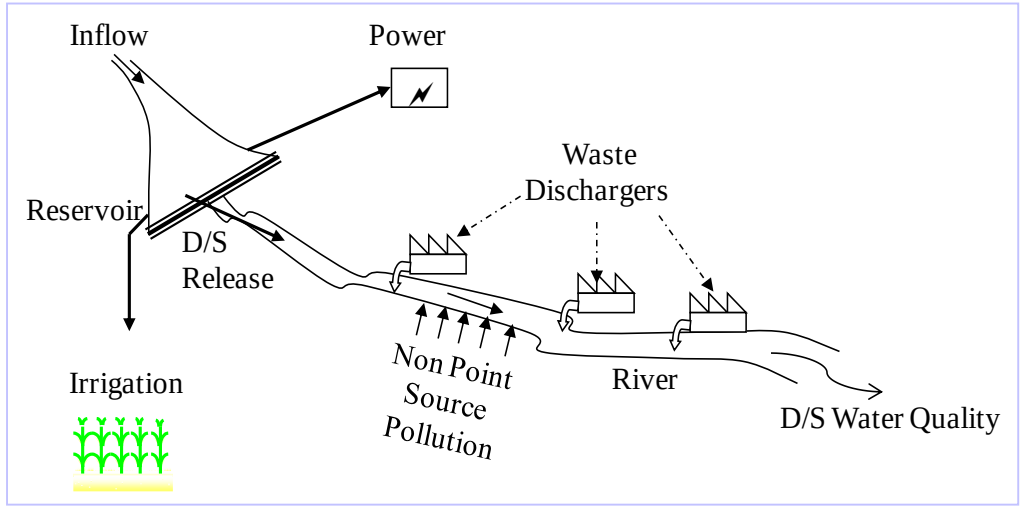


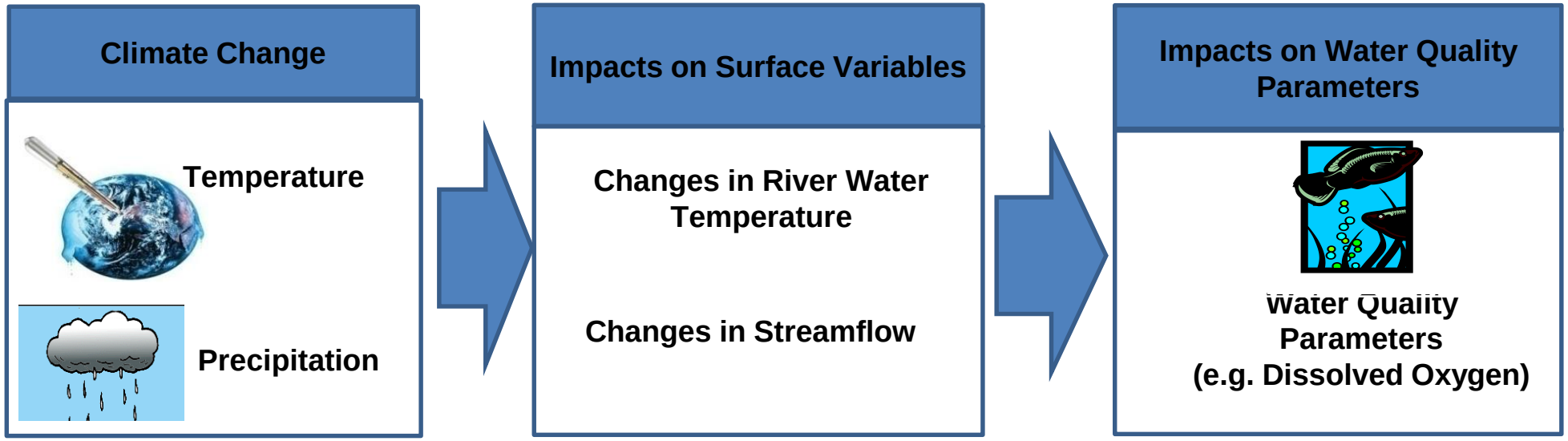
Fig. Source: ww.engr.uconn.edulanboG229Lect11SWIntru.pdf

Climate Change Impact Assessment of a Water Resources System



- Impacts on River Water Quality
- Impacts on Irrigation Water Demands
- Impacts on Water Availability/ Supply and Demand
- Impacts on Reservoir Operation
- Impacts on Long Term Operating Policies

Climate Change Impacts on River Water Quality



- Climate change could lead to changes in streamflow that might affect pollutant transport.

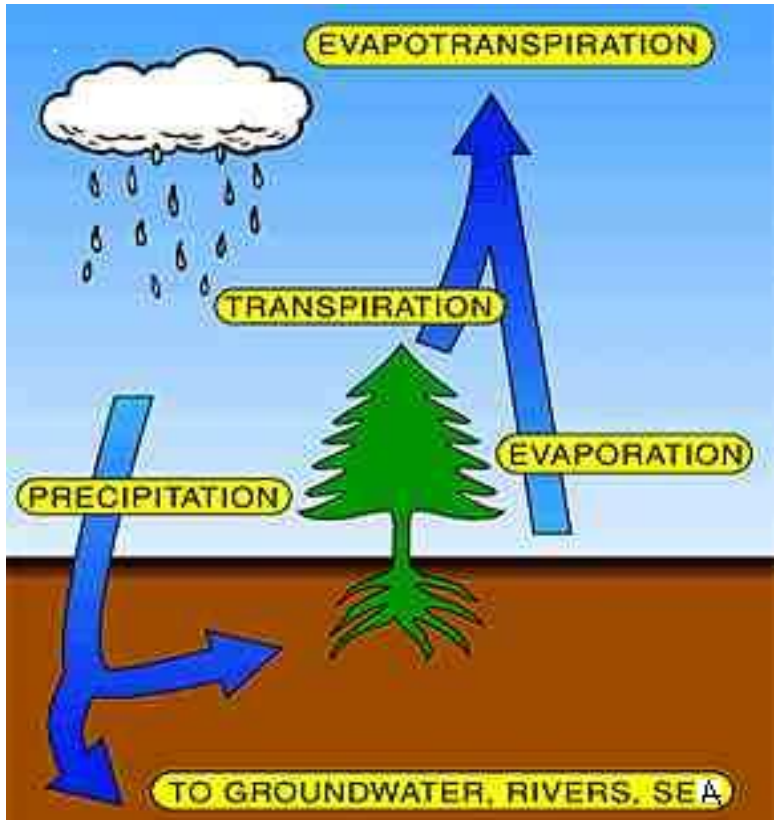
- Climate seriously affect fresh water systems.

Impacts of Climate Change on Irrigation Water Demands

- The irrigation water requirement are affected by
  - **Crop factors:** type of crop, cropping pattern, crop season, growth stage of the crops, soil type and topography.
  - **Climatic factors:** rainfall and evapotranspiration
  - Irrigation water demand model

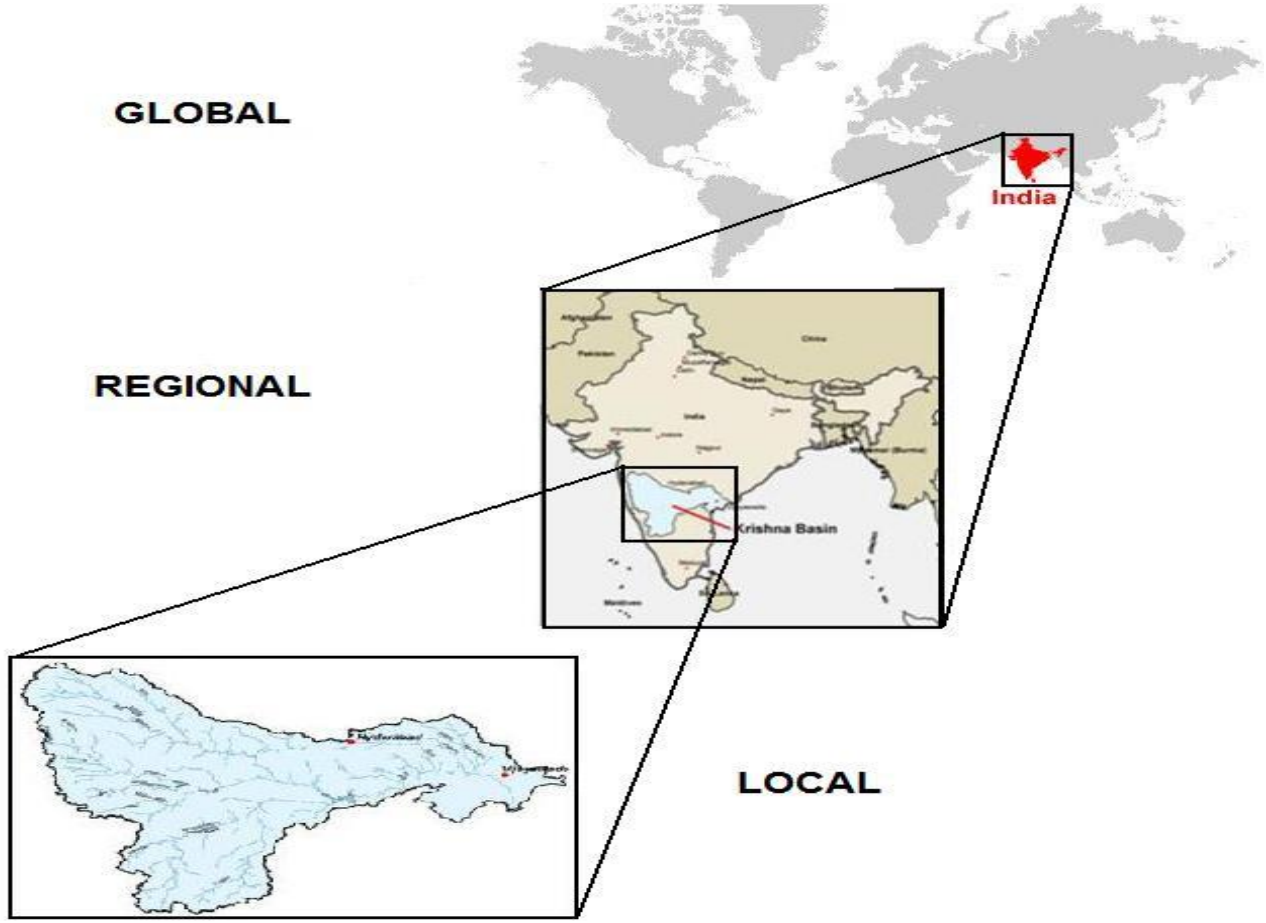
Factors affecting Evapotranspiration

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



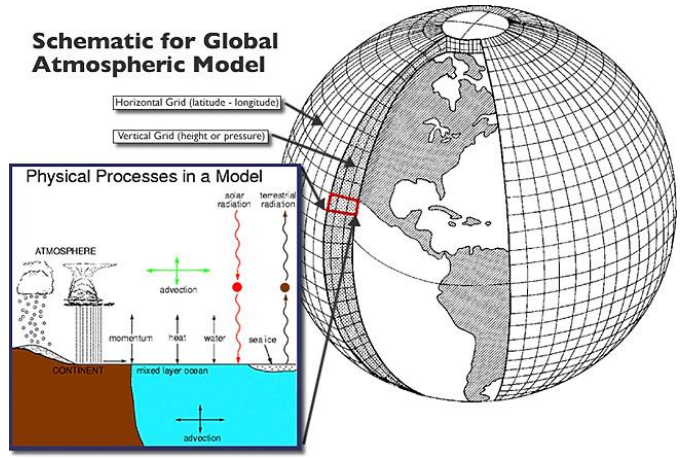
Source for figure : http://eoedu.belspo.be/en/applications/evap-contexte.asp?section=4.1

Regional or local climate is generally much more variable than climate on a hemispheric or global scale because regional or local variations in one region are compensated for by opposite variations elsewhere.



Climate Change Impact Assessment using Climate Models

- They represent the physical, ocean, cryosphere and land surface processes in the atmosphere
- Used to explore past climate events and to project future warming events
- Many climate models have been developed to perform climate projections, i.e. to simulate and understand climate changes in response to the emission of greenhouse gases and aerosols.



Climate Models or Global Circulation Models (GCMs)

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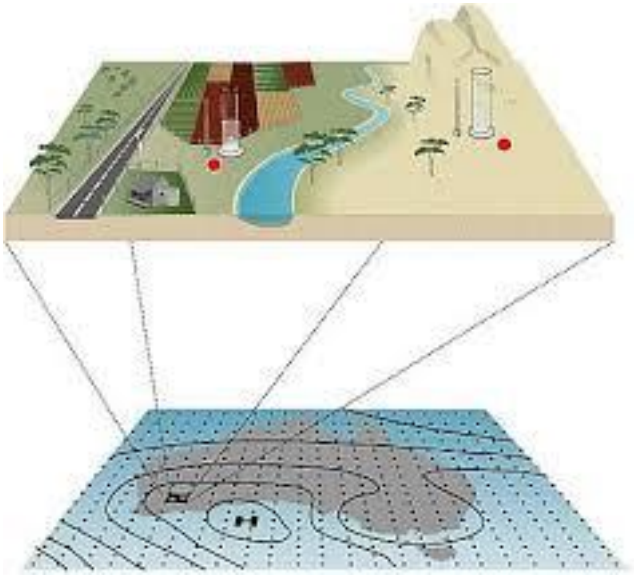
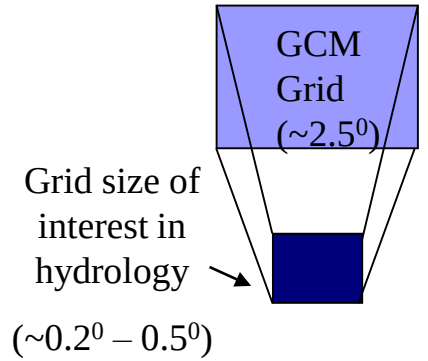
Climate Models (Contd..)

- GCMs perform reasonably well in simulating climatic variables at larger spatial scales, 2.0^0 latitude x 2.0^0 longitude, but poorly at the smaller space and time scales relevant to regional impact analyses.
- Accuracy of GCMs decreases from climate related variables, such as wind, temperature, humidity and air pressure to hydrologic variables such as precipitation, evapotranspiration, runoff and soil moisture, which are also simulated by GCMs.
- Poor performances of GCMs at local and regional scales have led to the development of downscaling models



Downscaling



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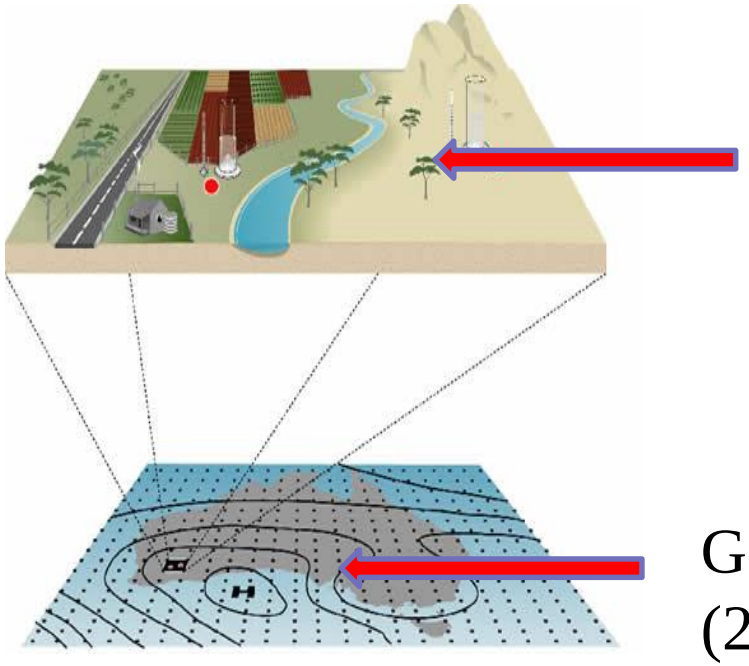
Limitations of GCM

- The spatial resolution of GCMs will be at 2.5 X 2.5 deg. (nearly 250 to 600 km)
- The region of interest will be at 50 to 100 km
- The major limitation of GCM is the mismatch between the spatial resolution of GCM outputs and region of interest

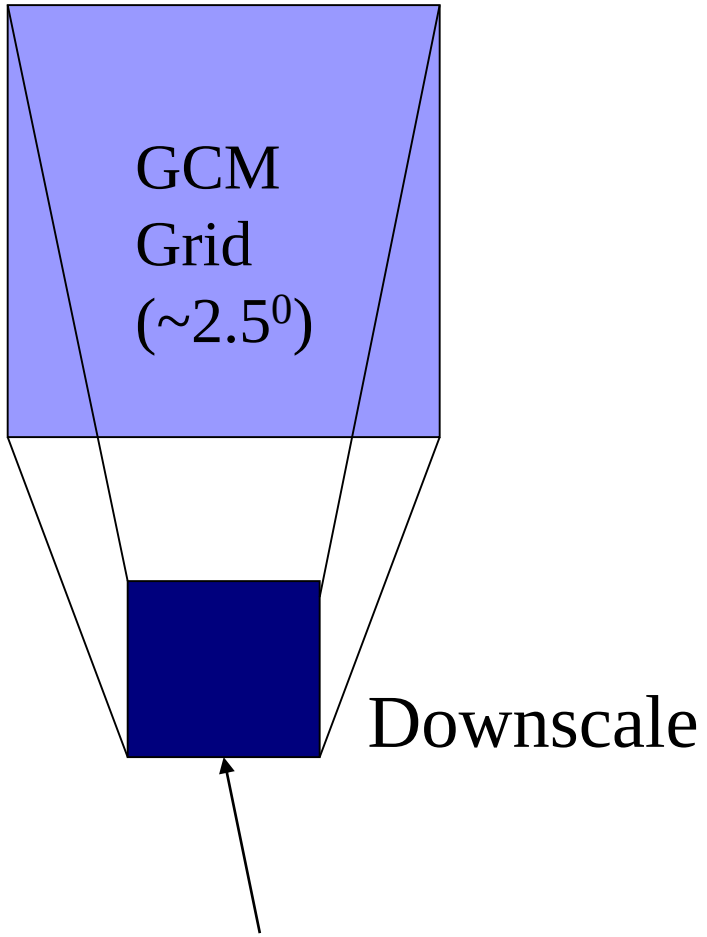


Region of Interest
(0.2 to 0.5 deg)

GCM Resolution
(2.5 X 2.5 deg)

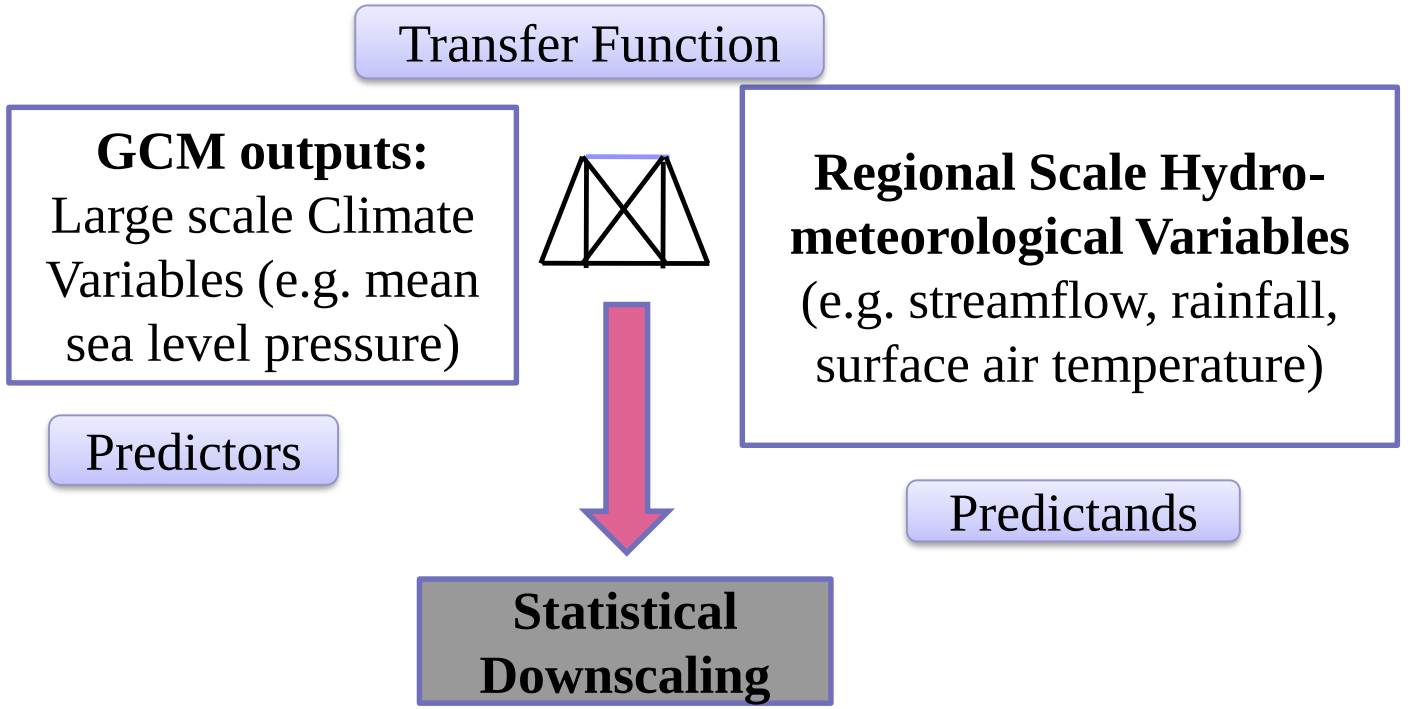
Solution: Downscaling

- Downscale: to reduce the size, scale or extent
- It is the procedure to take information known at large scales to make predictions at local scales
- Deriving climate information at finer spatial resolution from coarser spatial resolution GCM output.
- To model the hydrologic variables (e.g., precipitation) at a smaller scale based on large scale GCM outputs.



Climate Change Impact Assessment

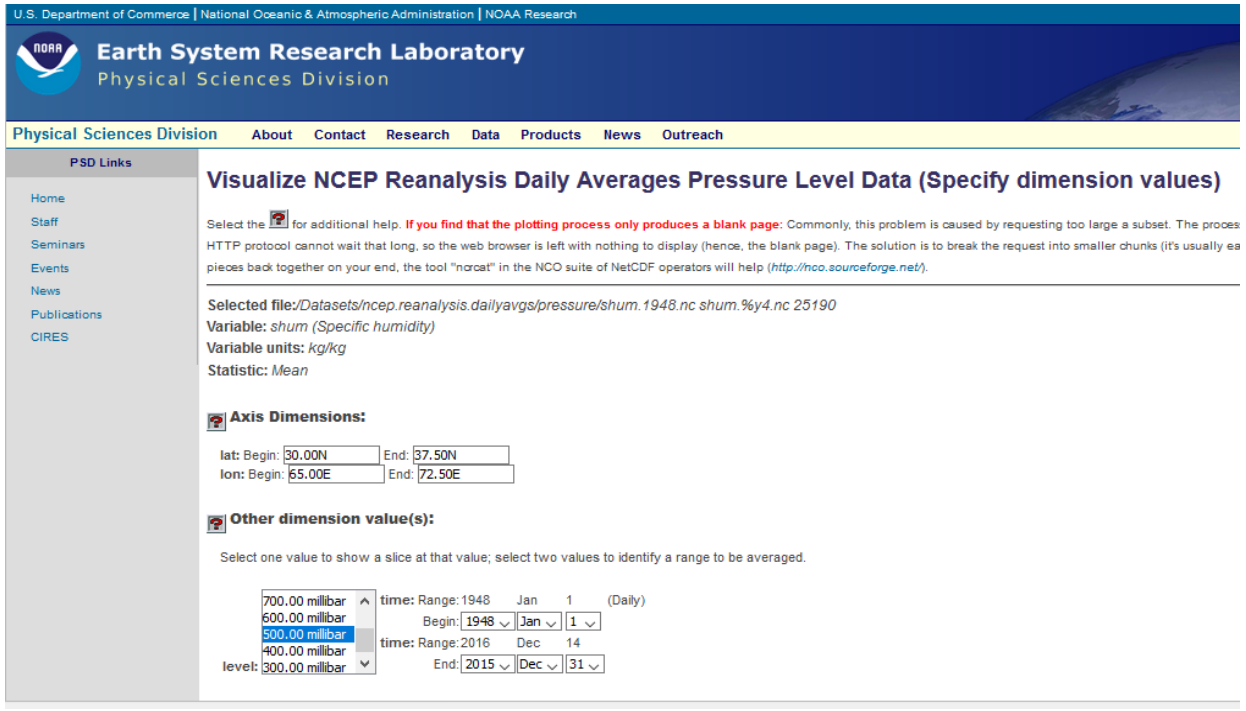
- To bridge the spatial and temporal resolution gaps between what GCMs are currently able to provide and what impact assessment studies require.
- Involves deriving empirical relationships between large-scale features of the GCM climate variables and regional-scale variables.



Climate Change Impact Assessment (Contd..)

- Observed/Predictand Data
  - Source: IMD, CWC etc.
- Observed Climate Data/Predictors Data
  - Source: Reanalysis data
- GCM Current and Future Predictors Climate Data
  - Source: Different GCMs – About 23 Climate Modeling Centres
    - ✓ EX: Beijing Climate Center, Canadian Centre for Climate Modelling and Analysis, Meteorological Research Institute, NASA/GISS (Goddard Institute for Space Studies) USA

Predictors from NCEP/NCAR DATA



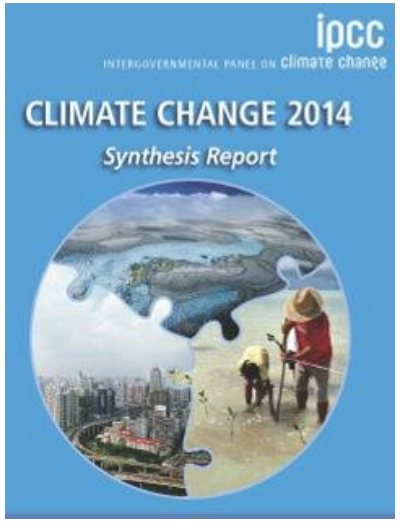
The large scale climatological variables will be extracted from the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) reanalysis data (available at http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html) for Afghanistan central zone – 30-37.5 N and 65 – 72.5 E

GCM Model Outputs from IPCC Data Distribution Centre

IPCC

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

- Reviews current scientific and technical literature relevant to global climate change
- Provides reports on their findings at regular intervals
- Reports are designed to be politically neutral and of high scientific and technical standards
- Provides Long term emission **scenarios**



IPCC Assessment Reports

- Review current scientific and technical literature relevant to global climate change
- Provide reports on their findings at regular intervals
  - First (1990)
  - 1992 sup.
  - Second (1995)
  - Third (2001)
  - Fourth (2007) AR4
  - Fifth (2014) AR5

- Reports are designed to be politically neutral and of high scientific and technical standards

IPCC Assessment Reports

- Review current scientific and technical literature relevant to global climate change
- Provide reports on their findings at regular intervals
- Reports are designed to be politically neutral and of high scientific and technical standards
- Long term emission scenarios (SRES scenarios)

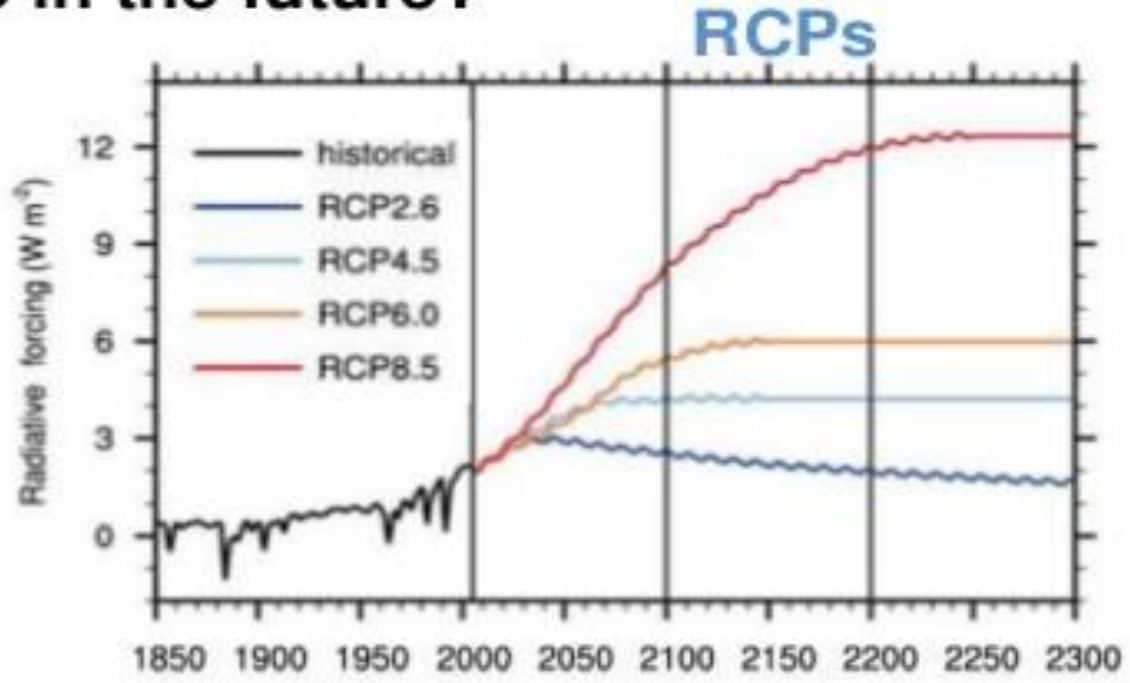
What is Scenario?

- Scenario: Description of what could possibly happen
- We are not sure exactly how climate will change
- Climate change scenarios are plausible combinations of variables consistent with what we know about human-induced climate change
- The human-induced climate change related to green house gas emission, population, economic, technology growths

How will the climate change in the future?

Future climate depends on:
– inherent variability
– social & economic choices
– response of the Earth system

⇒ use a scenario approach where a variety of potential pathways are examined



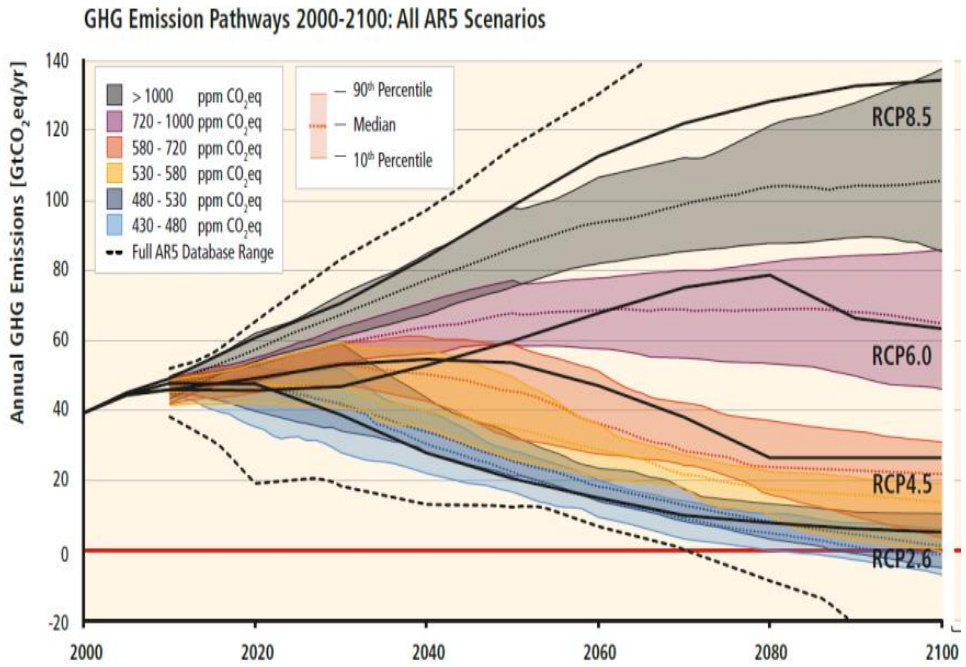
IPCC (2013) Figure TS.15

⇒ Representative Concentration Pathways (RCPs) encompass a range of plausible futures

⇒ use comprehensive climate models as they are the best tools available for projections

IPCC Climate Change Scenarios

- IPCC (Intergovernmental Panel on Climate Change) AR5 (Assessment Report 5) models implemented a set of scenarios called Representative Concentration Pathways (RCPs) in which radiative forcing due to anthropogenic factors reaches 2.6 (RCP 2.6), 4.5 (RCP 4.5) and 8.5 (RCP 8.5) W m−2 by 2100.
  - 421 ppm (RCP2.6)
  - 538 ppm (RCP4.5)
  - 670 ppm (RCP6.0)
  - 936 ppm (RCP 8.5)

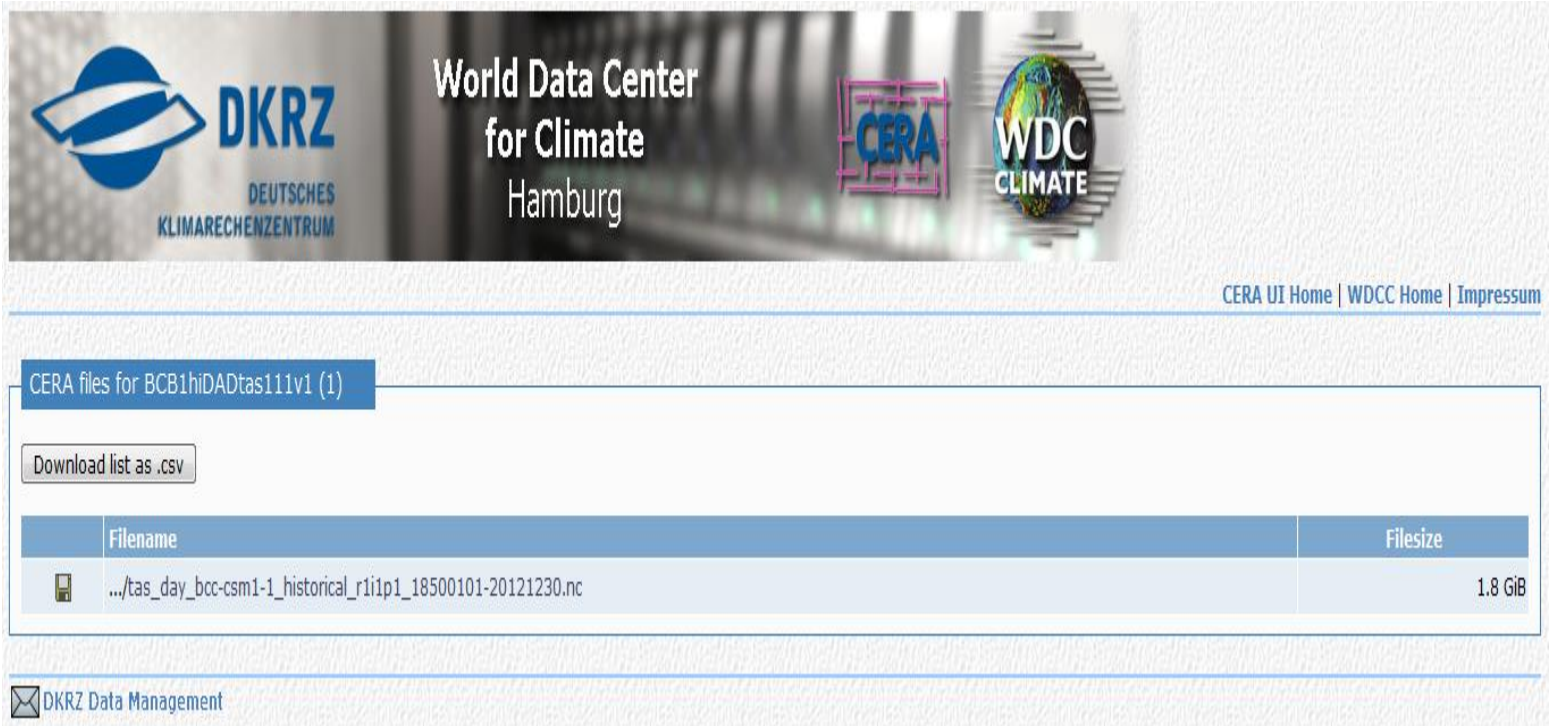


Various GCMs

Various RCPs: Climate Change Scenarios

Centre(s)	Centre Acronym(s)	Model	piControl	amip	historical	rcp	other	esm	sst	palaeo	aqua	add. data	known issues
Beijing Climate Center **China**	BCC	BCC-CSM1.1	piControl	amip amip4K amip4xCO2 amipFuture	historical historicalGHG historicalNat	rcp26 rcp45 rcp60 rcp85	abrupt4xCO2 1pctCO2	esmControl esmFdbk1 esmFdbk2 esmFixClim1 esmFixClim2 esmHistorical esmrcp85	sstClim sstClim4xCO2 sstClimAersosol sstClimSulfate	midHolocene past1000	-		
		BCC-CSM1.1(m)	piControl	amip	historical	rcp26 rcp45 rcp60 rcp85	abrupt4xCO2 1pctCO2	esmControl esmHistorical esmrcp85	-	-	-		
Beijing Normal University **China**	BNU	BNU-ESM	piControl	amip	historical historicalGHG historicalMisc historicalNat	rcp26 rcp45 rcp85	abrupt4xCO2 1pctCO2	esmControl esmHistorical esmrcp85	sstClim sstClim4xCO2	-	-	-	CMIP5 page
Canadian Centre for Climate Modelling and Analysis **Canada**	CCCma	CanAM4	-	amip amip4K amip4xCO2 amipFuture	-	-	-	-	-	-	-	-	CMIP5 page
		CanCM4	-	-	historical	rcp45	-	-	-	-	-		
		CanESM2	piControl	-	historical historicalExt historicalGHG historicalMisc historicalNat	rcp26 rcp45 rcp85	abrupt4xCO2 1pctCO2	esmControl esmFdbk1 esmFdbk2 esmFixClim1 esmFixClim2 esmHistorical esmrcp85	sstClim sstClim4xCo2 sstClimAerosol sstClimSulfate	-	-		
Centro Euro-Mediterraneo sui Cambiamenti Climatici **Italy**	CMCC	CMCC-CESM	piControl	-	historical	rcp85	-	-	-	-	-	-	CMIP5 page
		CMCC-CM	piControl	amip	historical	rcp45 rcp85	1pctCO2	-	-	-	-		
		CMCC-CMS	piControl	-	historical	rcp45 rcp85	-	-	-	-	-		

Typical GCM Outputs for Historical Period



The output from GCM BCC-CSM1.1 of Beijing Climate Center, China for historical period of 1850 to 2012

Typical GCM Outputs for Future Periods and Scenarios

	Filename	Filesize
	.../ta_day_bcc-csm1-1_rcp26_r1i1p1_20060101-20251231.nc	1.8 GiB
	.../ta_day_bcc-csm1-1_rcp26_r1i1p1_20260101-20451231.nc	1.8 GiB
	.../ta_day_bcc-csm1-1_rcp26_r1i1p1_20460101-20651231.nc	1.8 GiB
	.../ta_day_bcc-csm1-1_rcp26_r1i1p1_20660101-20851231.nc	1.8 GiB
	.../ta_day_bcc-csm1-1_rcp26_r1i1p1_20860101-20991231.nc	1.2 GiB
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	.../ta_day_bcc-csm1-1_rcp26_r1i1p1_22810101-23001231.nc	1.8 GiB

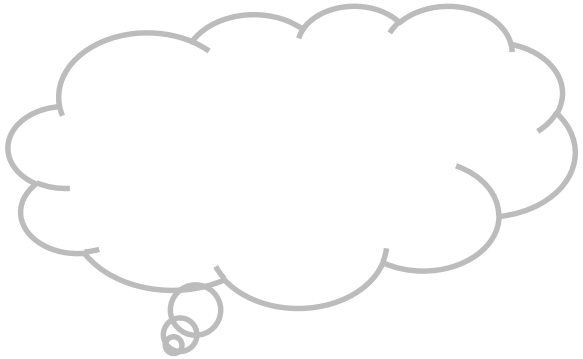
The output from GCM BCC-CSM1.1 of Beijing Climate Center, China for Representative Concentration Pathway (RCP) 26 for different time slices, starting from 2006 to 2300

Typical GCM Outputs for Future Periods and Scenarios

	Filename	Filesize
	.../ta_day_bcc-csm1-1_rcp60_r1i1p1_20060101-20251231.nc	1.8 GiB
	.../ta_day_bcc-csm1-1_rcp60_r1i1p1_20260101-20451231.nc	1.8 GiB
	.../ta_day_bcc-csm1-1_rcp60_r1i1p1_20460101-20651231.nc	1.8 GiB
	.../ta_day_bcc-csm1-1_rcp60_r1i1p1_20660101-20851231.nc	1.8 GiB
	.../ta_day_bcc-csm1-1_rcp60_r1i1p1_20860101-20991231.nc	1.2 GiB
	.../ta_day_bcc-csm1-1_rcp60_r1i1p1_21000101-21001230.nc	91.0 MiB

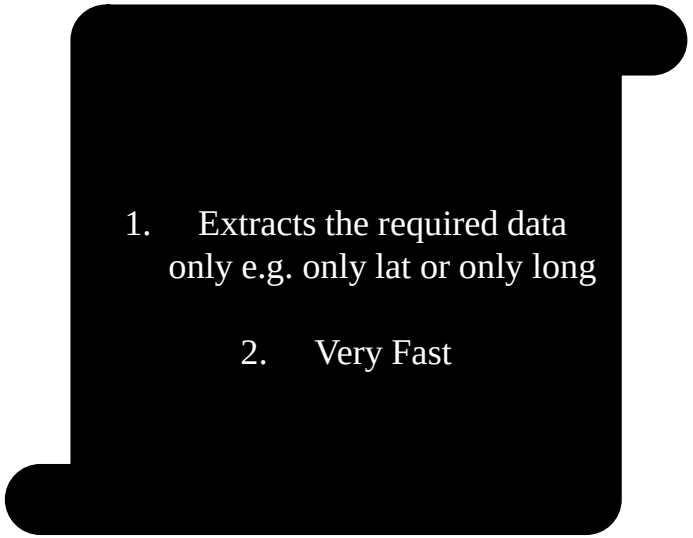
The output from GCM BCC-CSM1.1 of Beijing Climate Center, China for Representative Concentration Pathway (RCP) 60 for different time slices, starting from 2006 to 2100

Converting ".nc" files to ".mat"

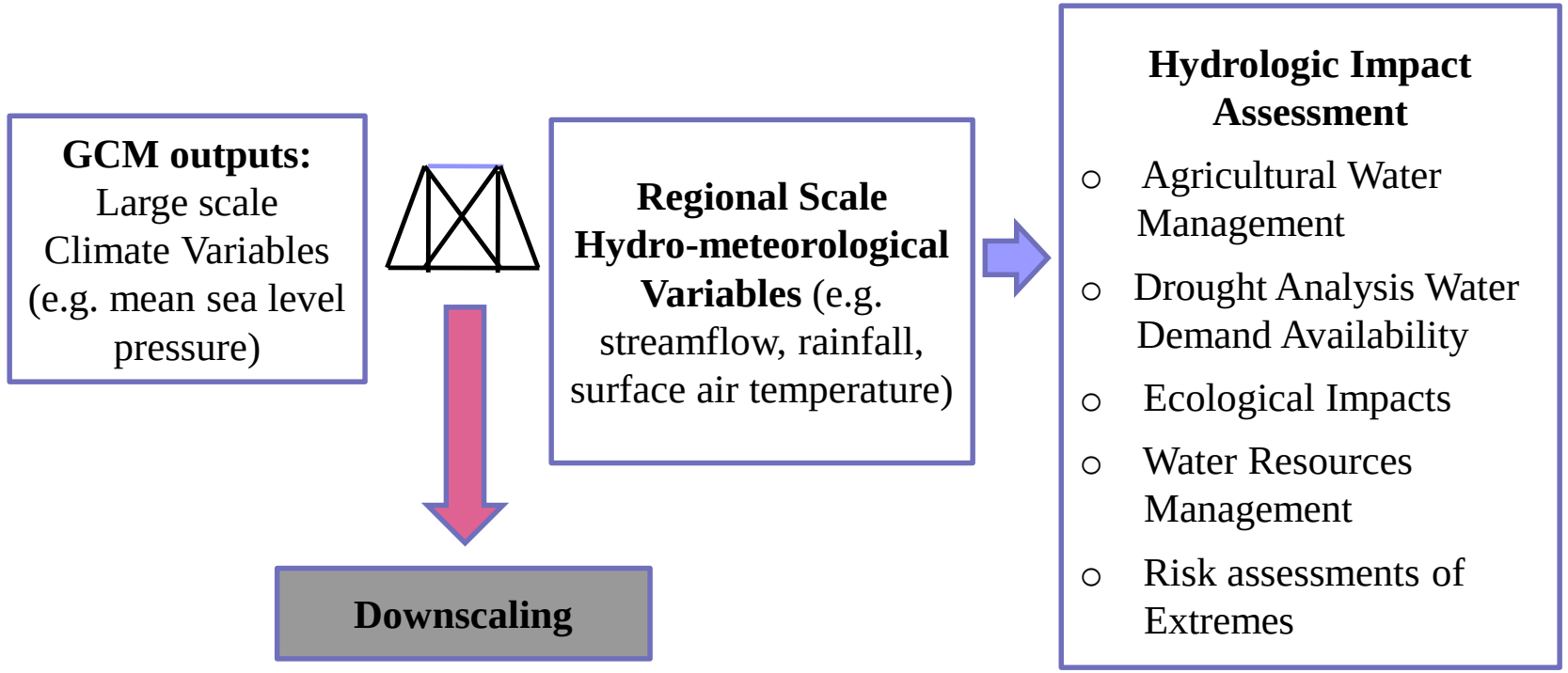


Var_x = netcdf ('file.nc');

Var_x = nc_varget ('file.nc', 'data');



Statistical Downscaling



To bridge the spatial and temporal resolution gaps between what GCMs are currently able to provide and what impact assessment studies require.

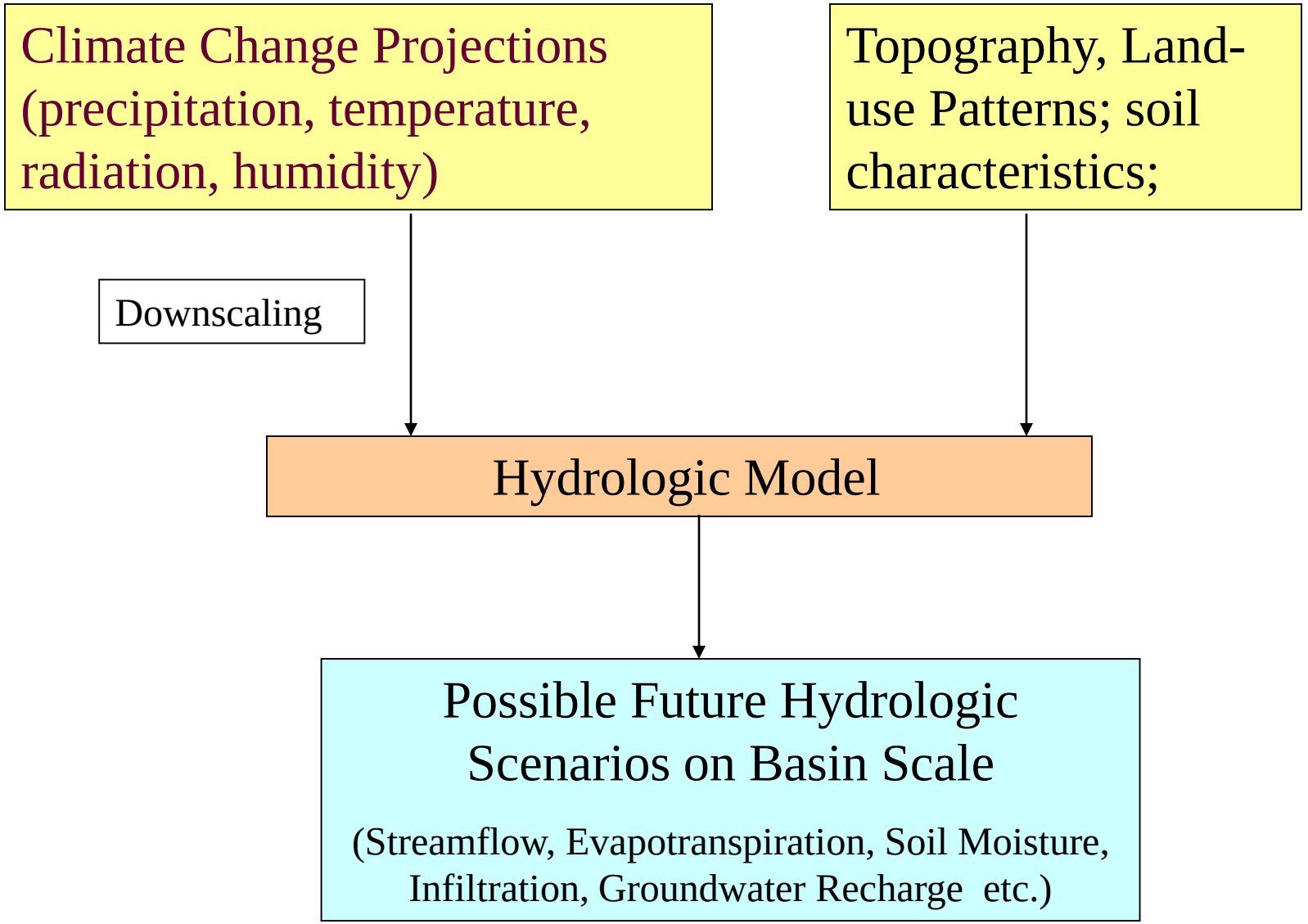
Terminology

- Predictors
- Predictands
- Transfer Function

GENERAL CIRCULATION MODEL

- Mathematical models developed by considering physics involved in land, ocean and atmospheric processes in form of a set of linear and non linear partial differential equations.
- Available at coarse grid size of 300Kms.
- Project climatic variables globally at coarse resolution.

Projecting Climate Change Impacts on Hydrology



Selection of Predictors and Assumptions in Downscaling Methods

Selection of Predictors

- Reliably simulated by GCMs
- Readily available from archives of GCM outputs
- Strongly correlated with the surface variables of interest

Assumptions

- Predictors are variables of relevance and are realistically modeled by the host GCM
- Empirical relationship is valid also under altered climatic conditions
- Predictors employed fully represent the climate change signal

Transfer Function and Future Scenario Predictions

$$Y_{Current} = f_{Current}(X_{Current})$$

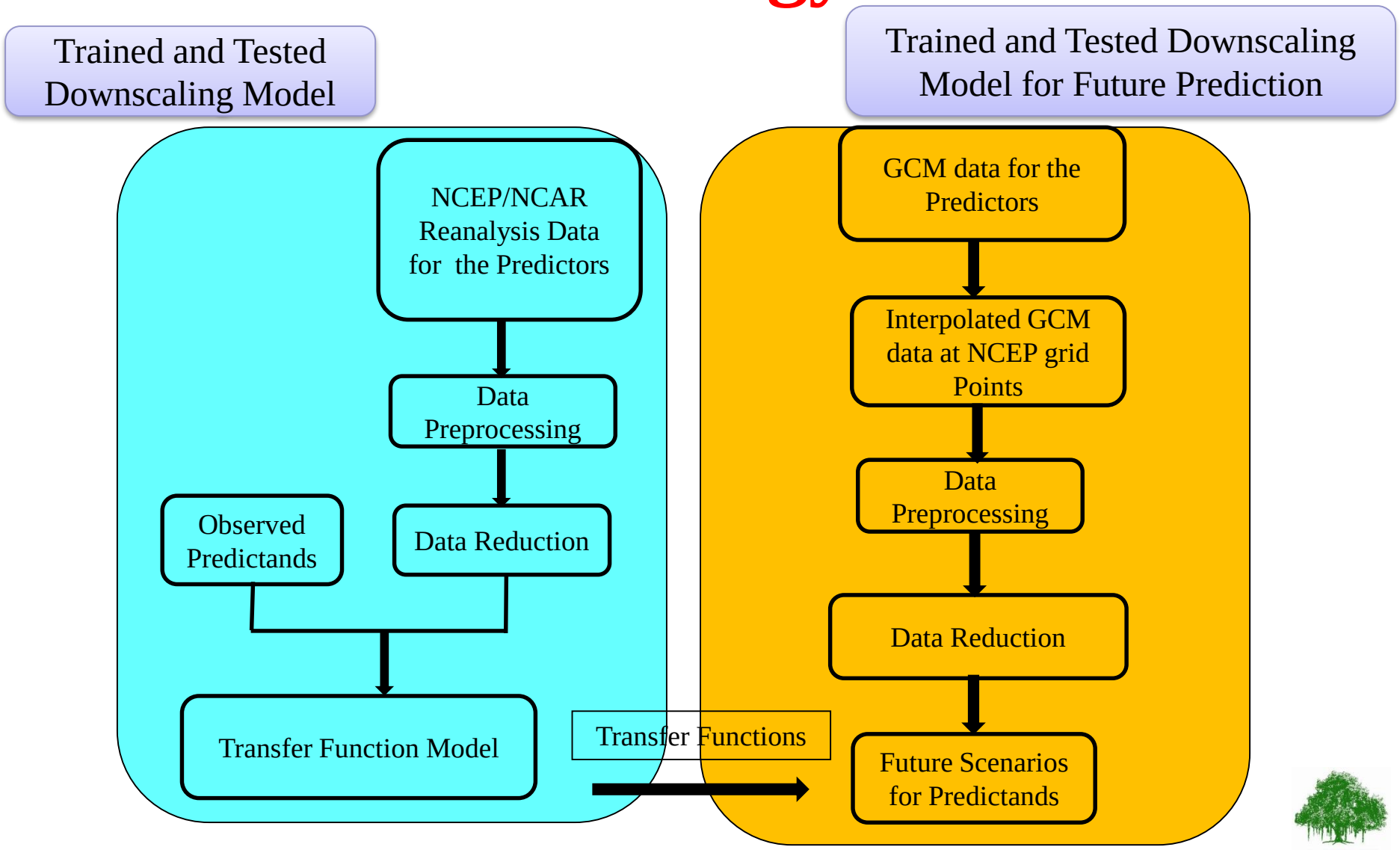
Trained and Tested Downscaling Model

Where $f_{Current}$ is the transfer Function, Statistical Relationship Developed between predictors (X) and Predictands (Y) in Training

$$Y_{Future} = f_{Current}(X_{Future})$$

Trained and Tested Downscaling Model for Future Prediction

Statistical Downscaling Methodology



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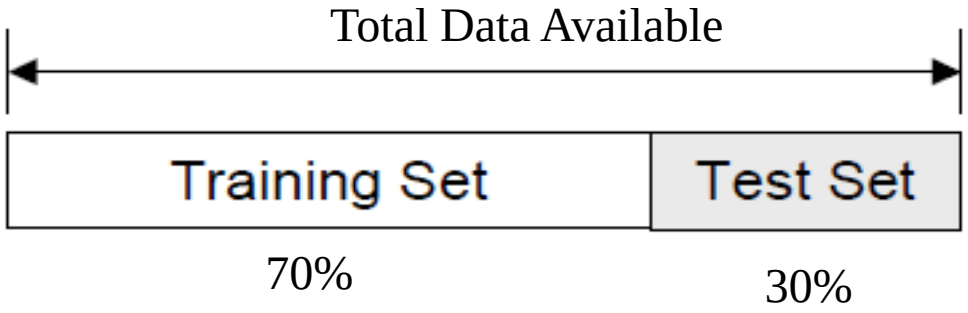
Statistical Downscaling Model Development

Procedure:

- Identifying Large-scale predictors (NCEP) (X) that could control the surface/local variables (Y): strong correlation between X and Y
- Finding a statistical relationship between X and Y - Training
- Validating the relationship with independent data - Testing
- Generate Y using values of X from GCM Data - Future Projections



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Data Reduction Method

- Several Predictors and grid points
  - Ex: 10 predictors at 25 grid points – Dimension of the data: 250
- Working out the model with this large number would be computationally very expensive
- To reduce the dimensionality and to effectively summarize the spatial information
- The most common method is Principal Component Analysis (PCA)

Various Statistical Downscaling Models in Literature

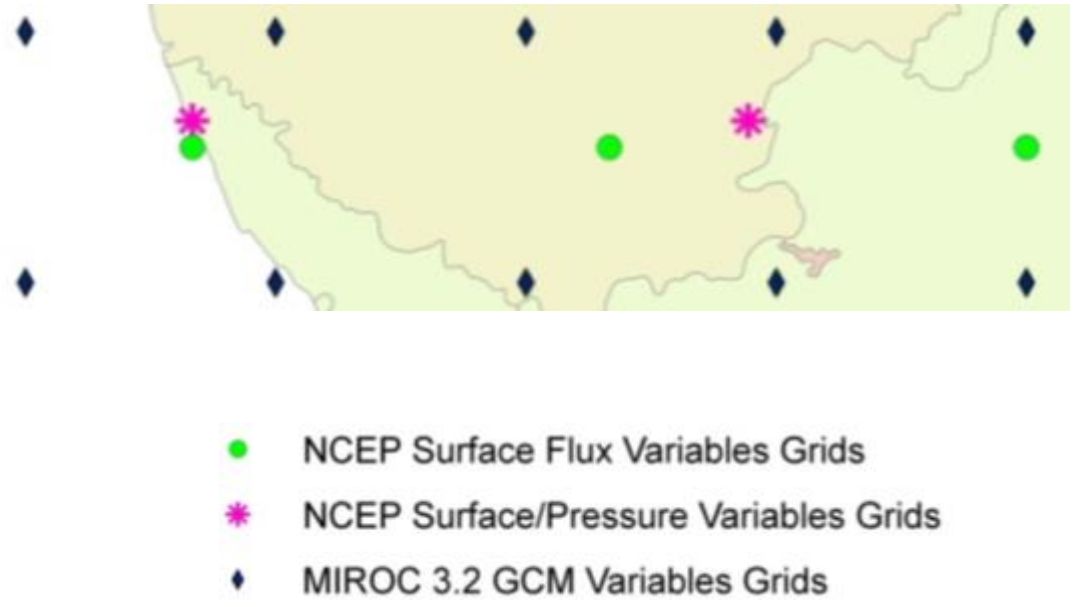
- Linear regression (Karl et al., 1990)
- Generalized Linear Model (Dobson, 2001)
- Artificial Neural Network (Hewitson and Crane, 1992)
- Support Vector Machine (SVM) approach (Anandhi et al., 2008)
- Canonical Correlation Analysis (CCA) approach (Rehana and Mujumdar, 2014)
- Kernel Regression (KR) based downscaling model (Salvi et al., 2013)

Transfer Function: Linear and Non-Linear

- Linear, Multiple Linear and Logistic Regression
- Kernel Regression
- Support Vector Machine
- Relevance Vector Machine
- Artificial Neural Networks
- Canonical Correlation Analysis
- Various Machine Learning Methods

Data Preprocessing GCM Data Interpolation

Interpolation has to be performed before standardization to obtain the GCM output at NCEP grid points as NCEP/NCAR grid points and GCM grid points do not match.



NCEP Data Resolution: 2.5^{o} X 2.5^{o}
GCM Data Resolution: 1.125^{0} X 1.125^{0}

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Transfer Function and Future Scenario Predictions

$$Y_{Current} = f_{Current}(X_{Current})$$

Trained and Tested Downscaling Model

Where $f_{Current}$ is the transfer Function, Statistical Relationship Developed between predictors (X) and Predictands (Y) in Training

$$Y_{Future} = f_{Current}(X_{Future})$$

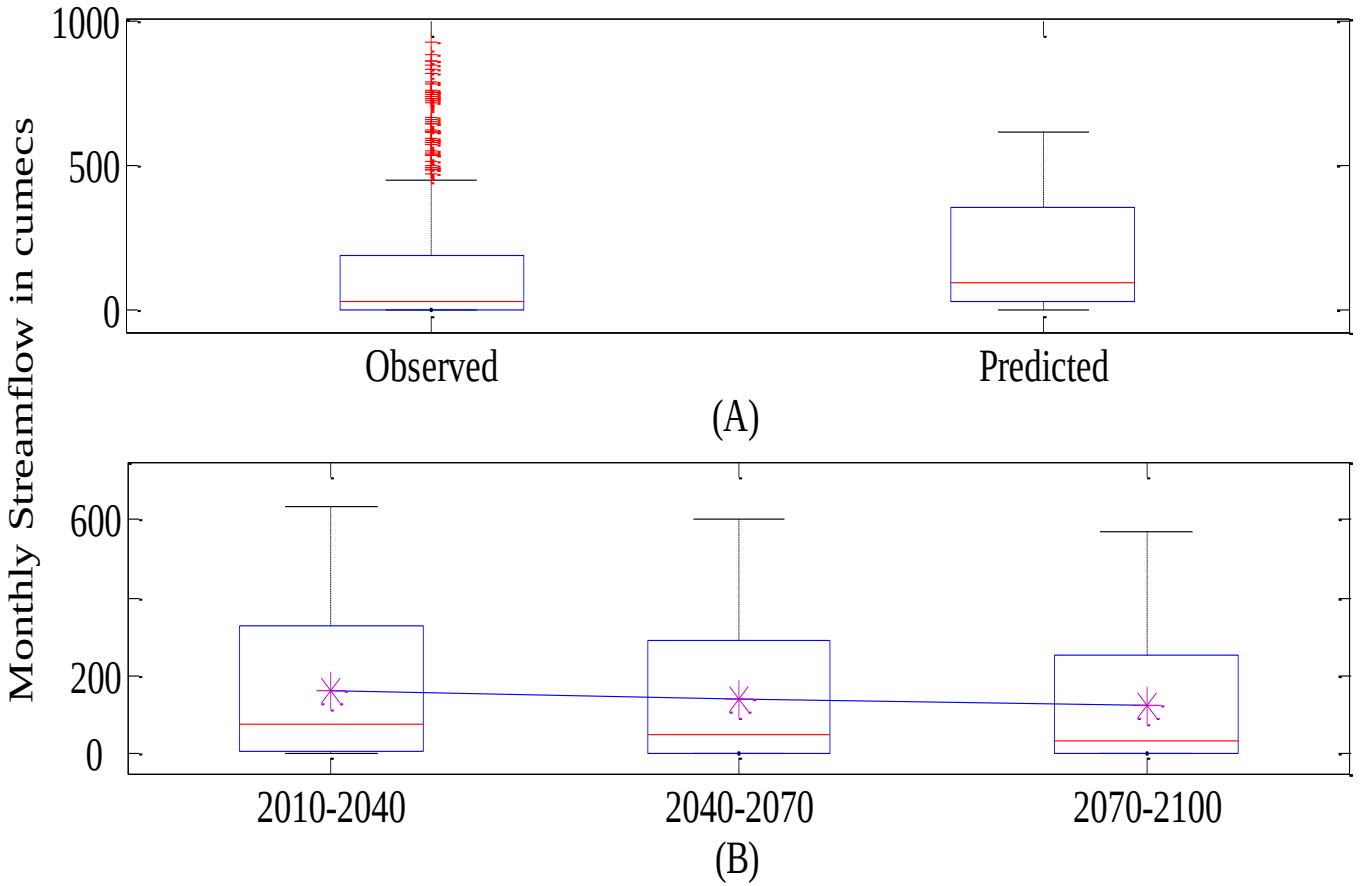
Trained and Tested Downscaling Model for Future Prediction

Statistical Downscaling Methods

The selection of a downscaling model depends on the type of impact assessment study under consideration.

- Single Variable Downscaling: $X_{N\times t} = f(Y_t)$
- Multivariable Downscaling: $X_{N\times t} = f(Y_{M\times t})$
- Multisite Downscaling: $X_{N\times S\times t} = f(Y_{S\times t})$
- Multivariable and Multisite Downscaling: $X_{N\times S\times t} = f(Y_{M\times S\times t})$

Typical Downscaling Results



Results of observed and predicted Streamflow from GCM. The horizontal line in the middle of the box represents the median. The star denotes the mean value of the period under consideration while the line connecting the stars depicts the mean trend of Streamflow projected by GCM. In these figures, (A) gives the validation of the GCM predicted data with the observed data and (B) gives the future projections with the GCM.

Downscaling Methods Practical Applicability

- Planning, design, and management of various hydraulic structures such as flood protection works, urban sewers, etc.
- River Water Quality Management
- Agricultural Water Management
- Reservoir Water Management
- Drought Impact Management
- Water Resources Management

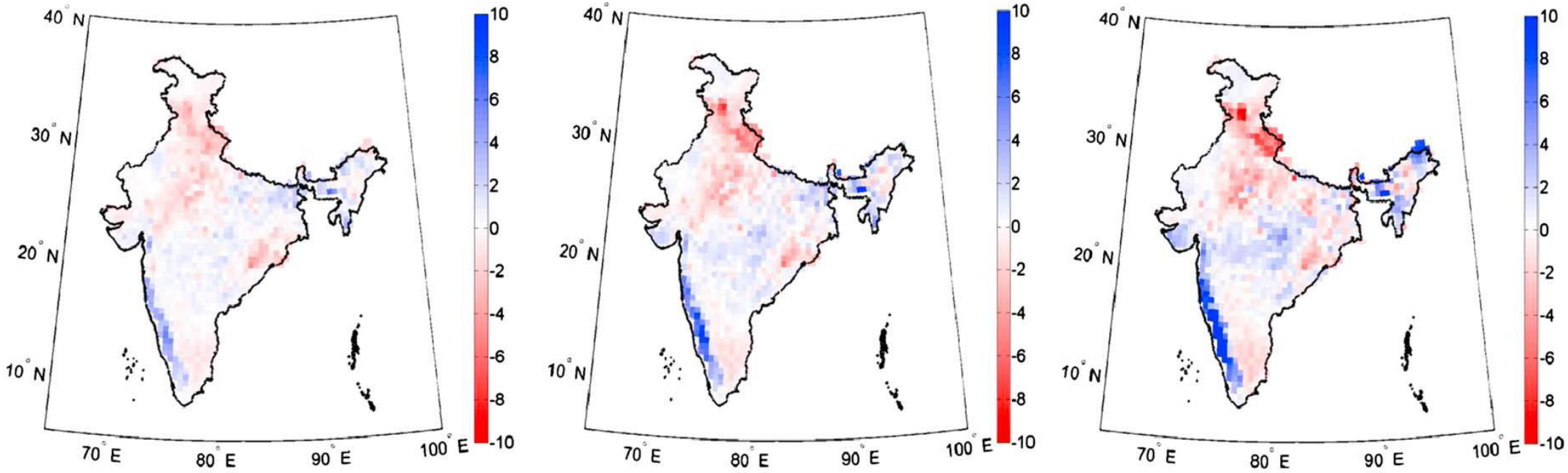
Case Studies

Major Climate Change Challenges in India

- Water availability
  - How do water fluxes vary on catchment scale in response to global climate events?
  - Impacts on Water Quality
- Change in Frequency and Magnitude of extreme events
- Design storm intensities - Urban Flooding
- Delays in onset of monsoon
  - Impact on agriculture
  - Over-year storage policies
  - Real-time adaptive decisions
- Water Demands
  - Evapotranspiration
  - Municipal and Industrial Demands
- Salinity Intrusions & Coastal flooding
- Robust & Resilient water management policies to offset adverse impact due to climate change

Source for the map:
www.mapsofIndia.com

Indian Rainfall Projections for Future Scenarios

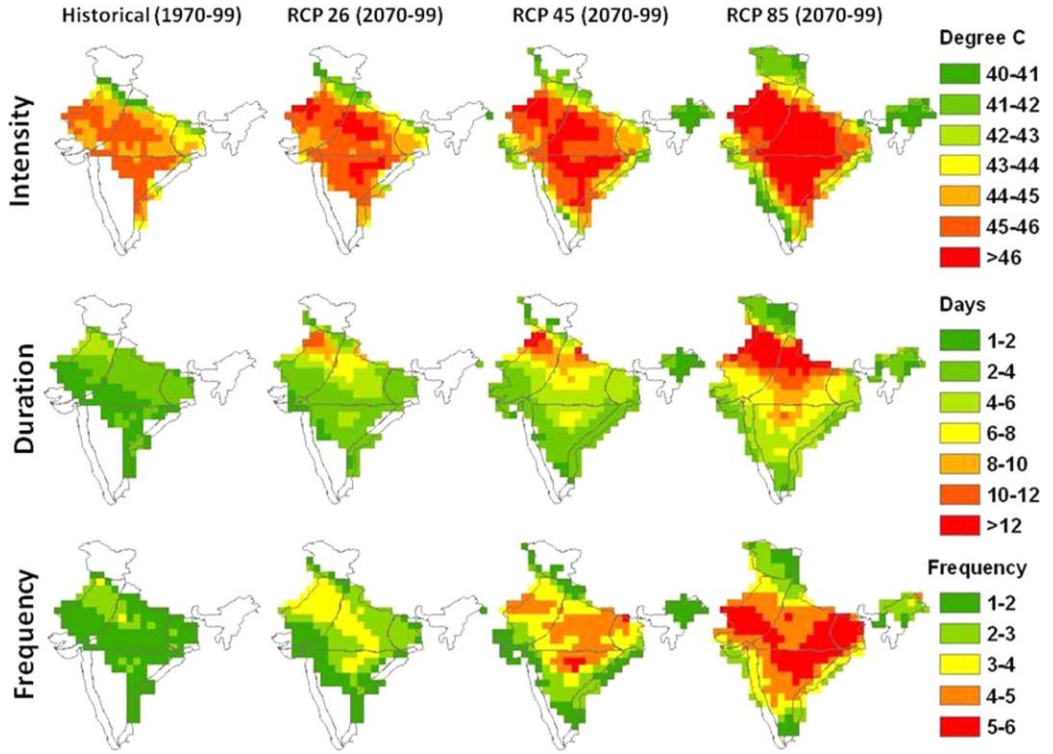


The west coast, central India, and northeast India show increase in the mean rainfall, whereas east coast (southern part) and north India show decrease in the mean rainfall.

Source: High-resolution multisite daily rainfall projections in India with statistical downscaling for climate change impacts assessment, K Salvi, S Ghosh, Journal of Geophysical Research: Atmospheres 118 (9), 3557-3578

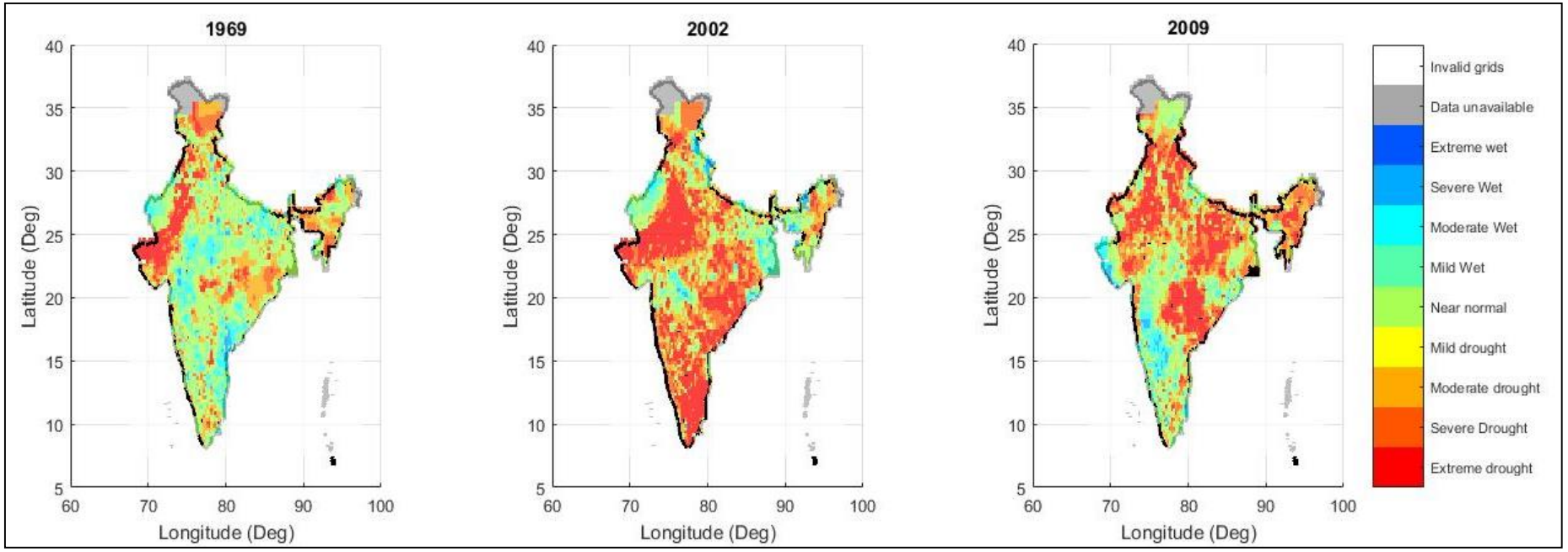
Intensification of Future Severe Heat Waves in India

- In India, a warming trend in the range of 0.8 to 1 ^{o}C per century has been observed
- Northern India shows high occurrence of heat waves



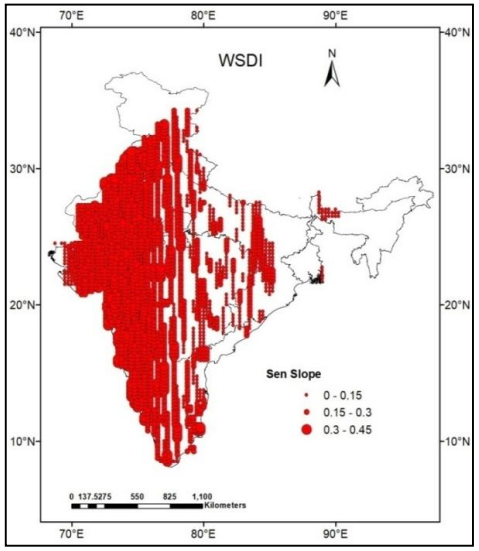
Source: KK Murari, S Ghosh, A Patwardhan, E Daly, K Salvi, Intensification of future severe heat waves in India and their effect on heat stress and mortality Regional Environmental Change 15 (4), 569-579

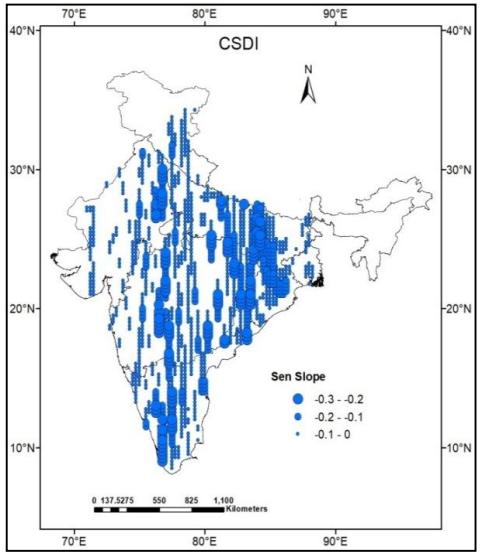
Drought – Climate Change

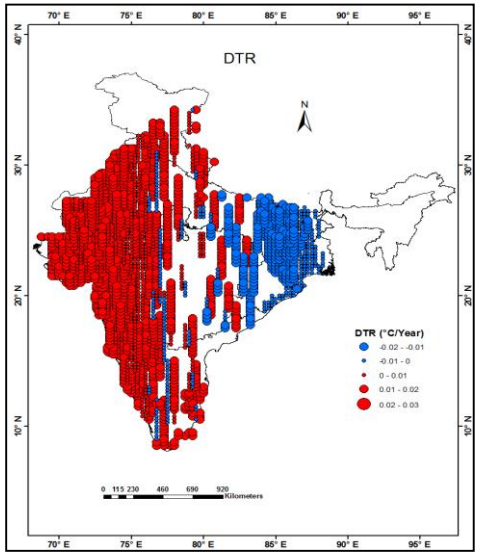


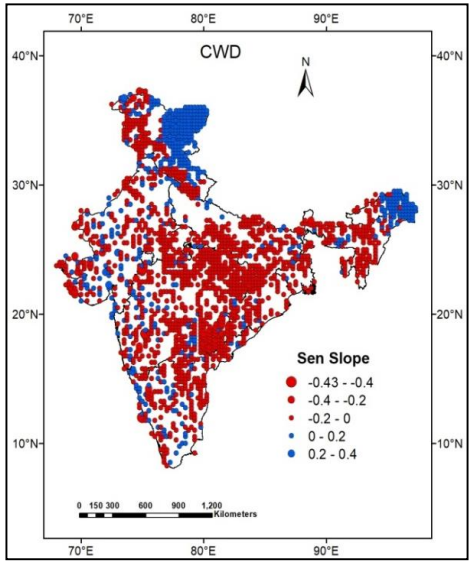
Contributors: Dr. Shaik Rehana, IIITH; N.T. Monish, IIITH

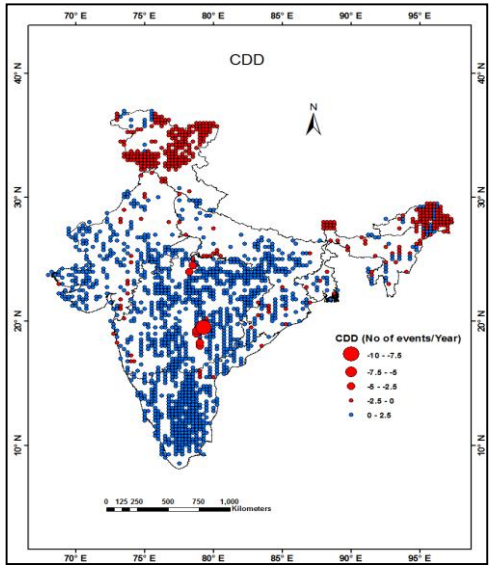
Spatial pattern of trends of temperature and precipitation extreme indices in India: warm spell duration indicator (WSDI), cold spell duration indicator (CSDI) consecutive dry days (CDD), consecutive wet days (CWD), daily temperature range (DTR), very wet days (R95p).

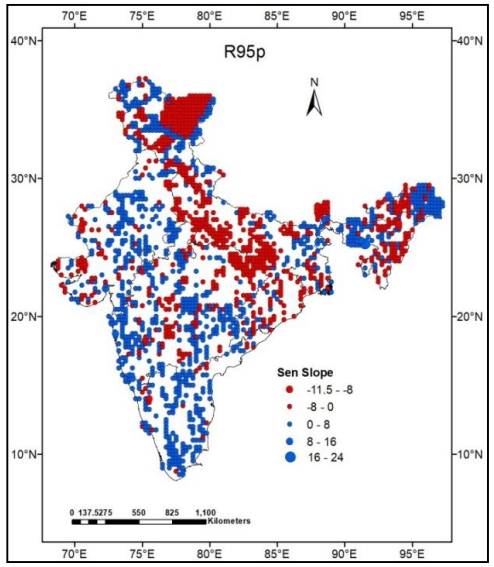




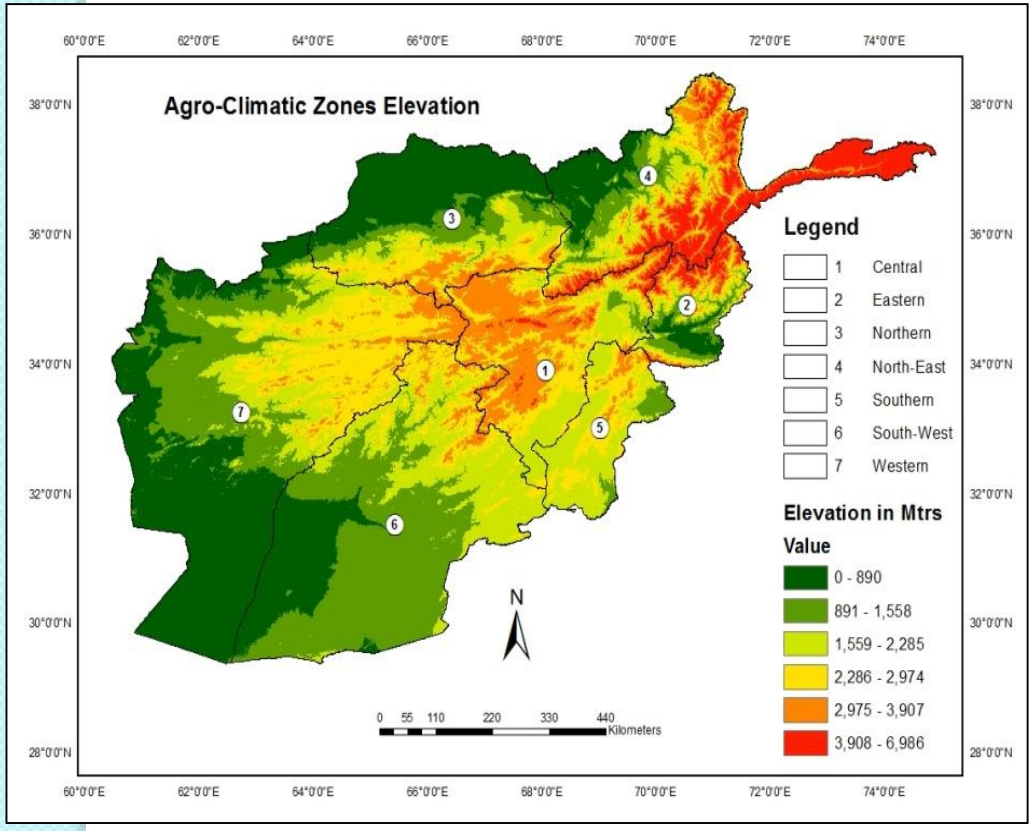


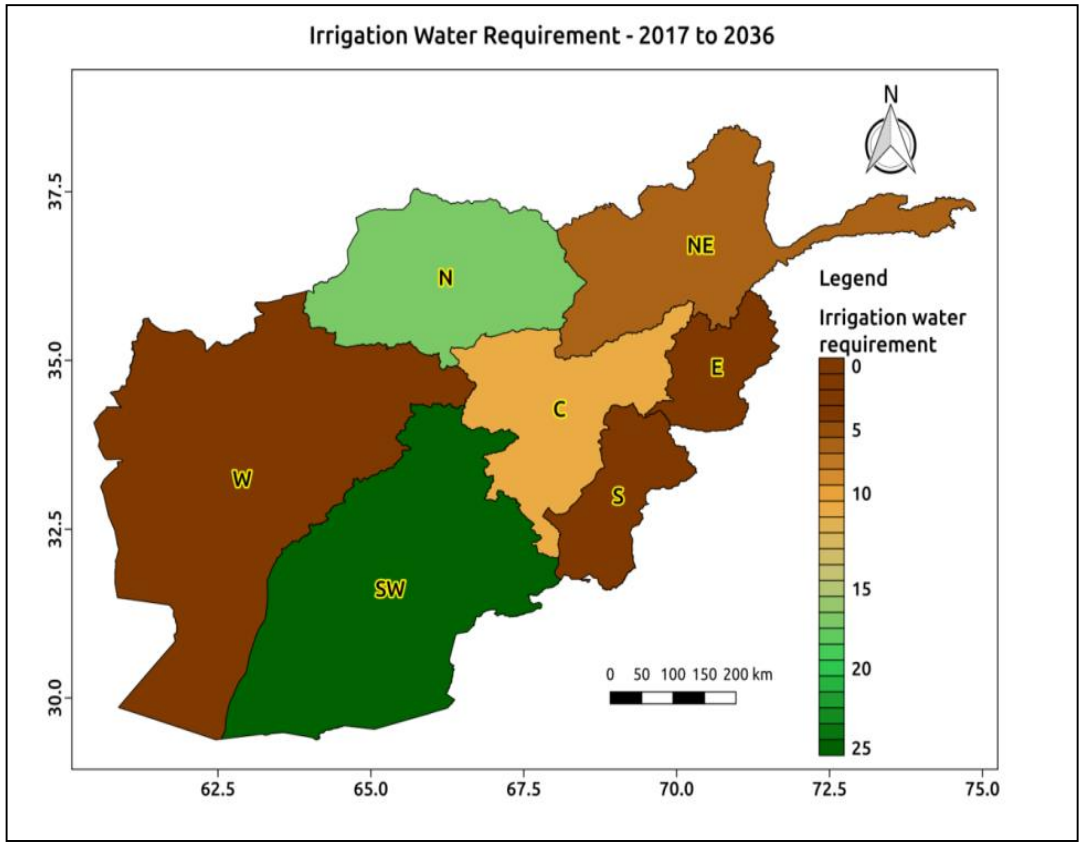




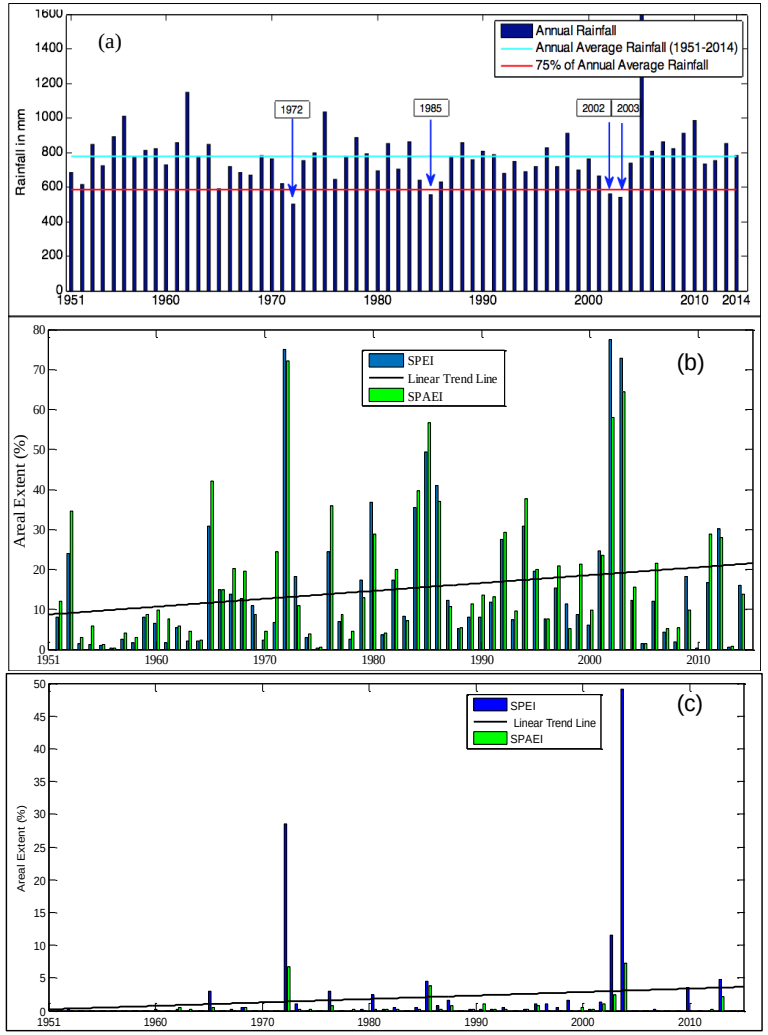


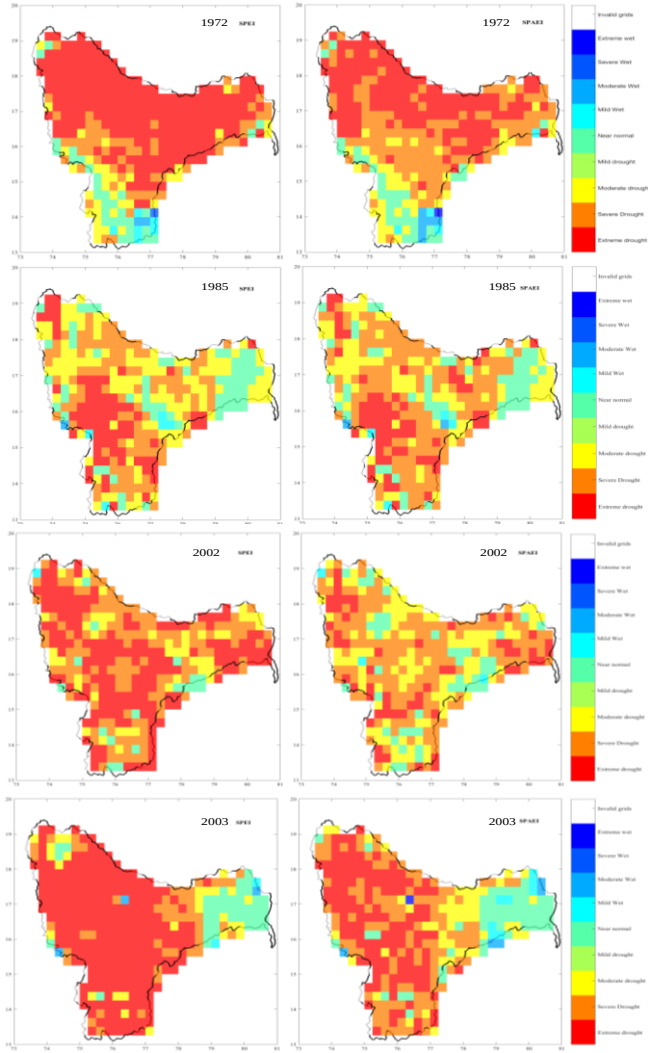
Climate Change Impacts on Agriculture over Afghanistan





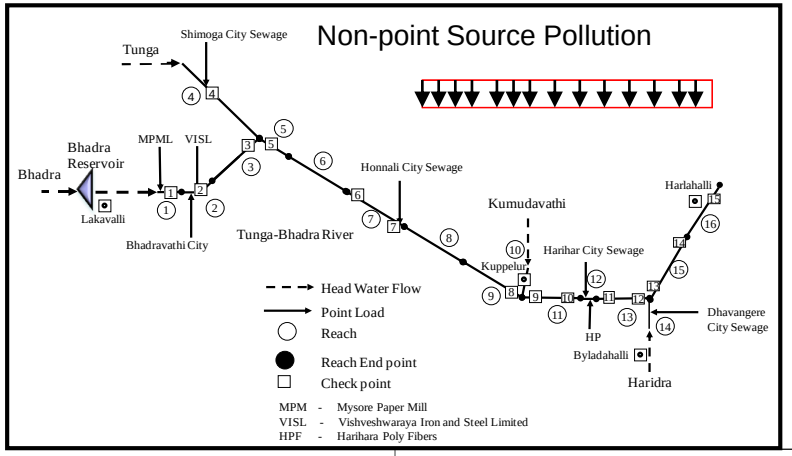
Drought – Climate Change

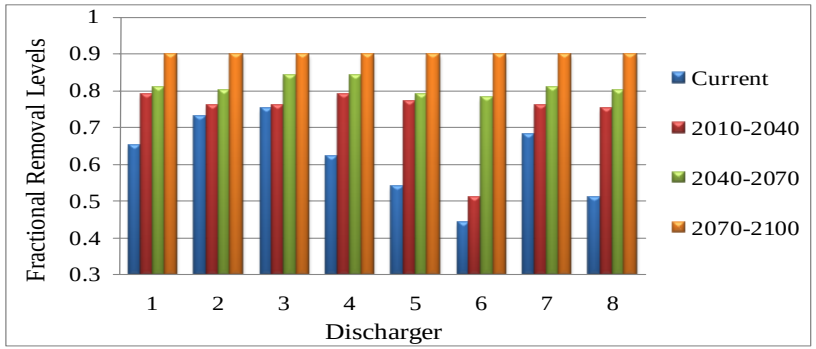




Shaik Rehana, Sireesha, G. Monish, N.T. (2017), Study of Observed Precipitation and Temperature Extreme Indices over India, 30th Conference on Climate Variability and Change, 24th Conference on Probability and Statistics, and 16th Conference on Artificial Intelligence, 28–29 July 2017, Baltimore, Maryland, U.S.A.

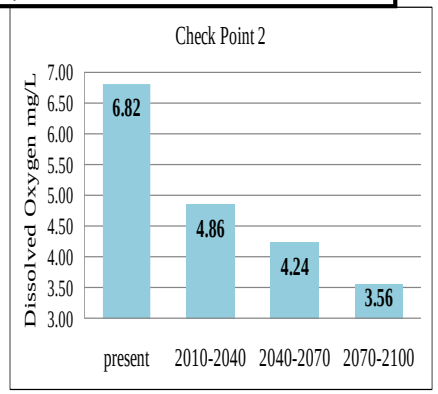
River Water Quality Responses under Climate Change along Tunga-Bhadra River

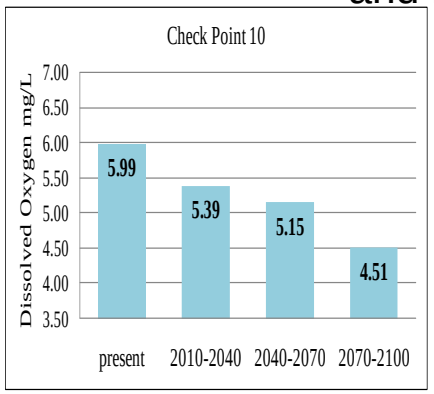


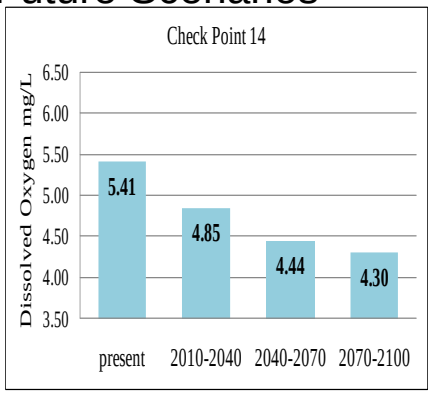


Fractional Removal Levels for Various Dischargers for Current and Future Scenarios

- Tunga River = 147 km; Bhadra River = 178 km;
- Tunga-Bhadra River through Karnataka = 382 km;
- Tunga-Bhadra River Stretch under Study = 200 km;
- Total Catchment Area = 69552 km^2 ;







The steady state DO levels are simulated for the present and for the future time slices of 2010-2040, 2040-2070 and 2070-2100(Rehana and Mujumdar 2012)

Source: Rehana, S. and Mujumdar, P. P. (2012), Climate change induced risk in water quality control problems, **Journal of Hydrology**, 444 - 445, 63-77. (Pub: Elsevier, Netherlands).

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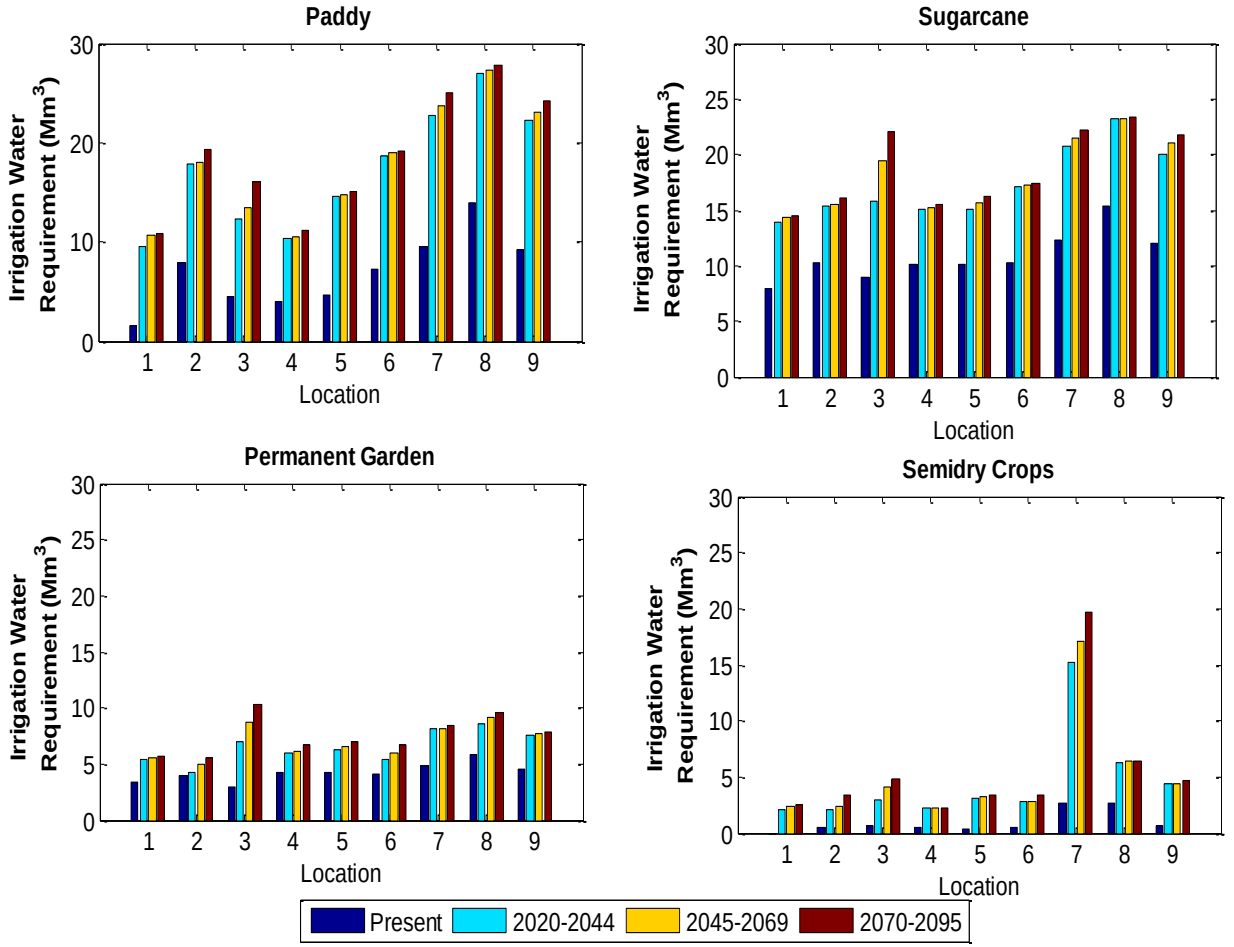
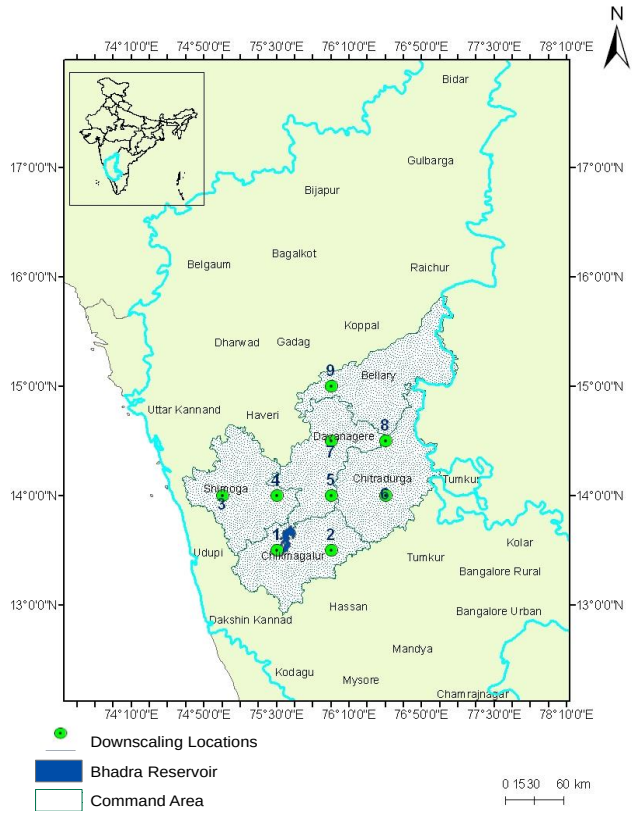
Projected Annual Irrigation Water Requirements





Projected Annual Irrigation Water Requirements at each location for each crop for Bhadra Command Area

Case Study: Bhadra Command Area

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Urban Flooding – Climate Change

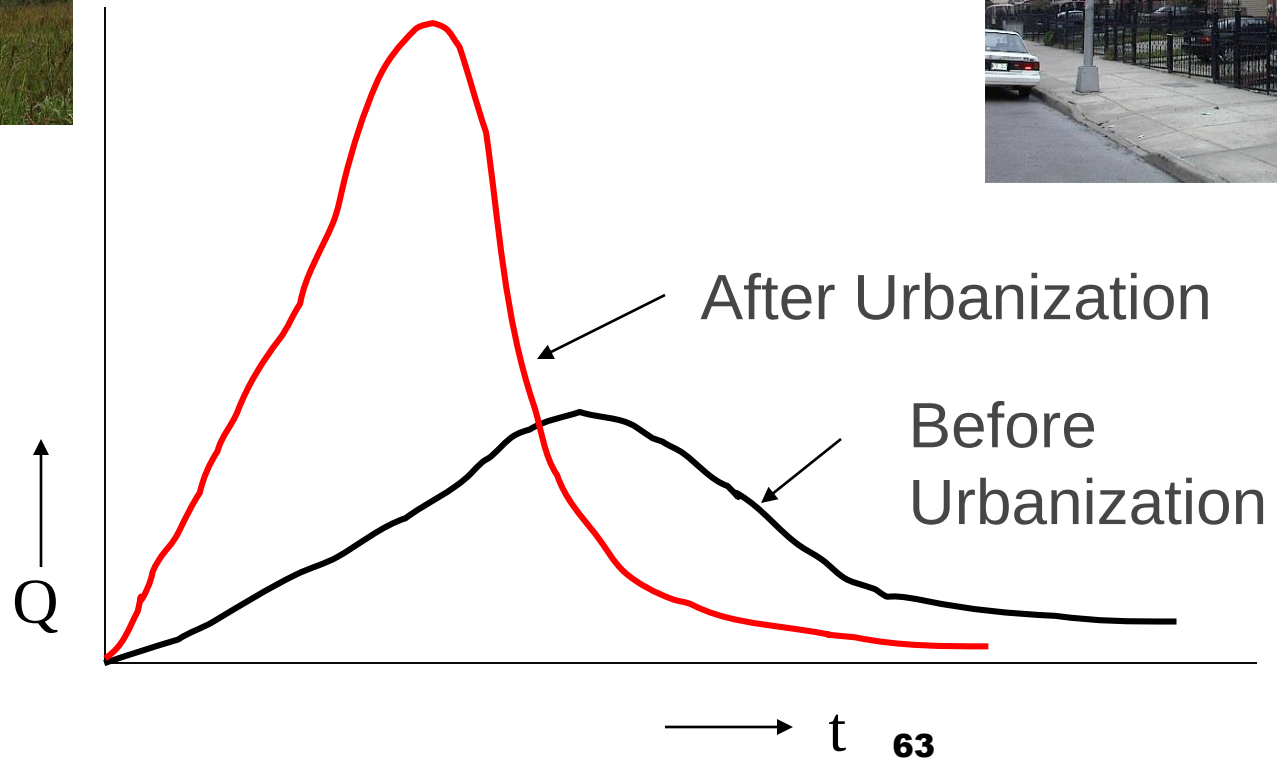
Hyderabad Floods

Bangalore Floods

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

Urban Flooding – Climate Change

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



Adaptive Policies

- Even though the dischargers maintain the safe permissible limits for the effluents, due to the impacts of climate change on temperature and flows, a significant reduction in water quality can be observed.

- The current water quality standards will not be adequate if a rise of even 1^0C in air temperature.

- Need to improve the adaptation policies of PCB considering the future deterioration of water quality to account for the climate change conditions.

Adaptive Policy

- More than 70% of India's population lives in rural areas with main occupation as agriculture. Around 93% of farmers cultivate nearly 55% of the arable land (FAO).
- It is estimated that every 10 ^{o}C increase in temperature is likely to lead to a 5-10% reduction in yields of some crops (Pachauri 2009)
- Therefore, significant impact on food security as changes in patterns of extreme weather events will affect the stability of food supplies
- Need to modify the irrigation strategies accounting for the shifts in the monsoon

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Adaptive Policy

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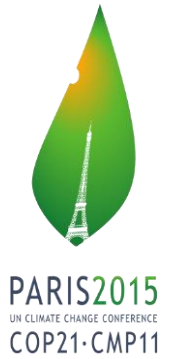
Dealing with Global Climate Change- Relationship Between Mitigation and Adaptation

Less Mitigation → **More** Greenhouse Gases Production → **Greater** Impacts on Natural and Human Environment → **More** Adaptation Policies

More Mitigation → **Less** Greenhouse Gases Production → **Lesser** Impacts on Natural and Human Environment → **Less** Adaptation Policies

2015 United Nations Climate Change Conference - Paris Agreement



- An agreement is set a goal of limiting global warming to less than 2 °C compared to pre-industrial levels.
- The agreement calls for zero net anthropogenic greenhouse gas emissions to be reached during the second half of the 21st century.
- Efforts to limit the temperature increase to 1.5 °C
- According to scientists, the 1.5 °C goal will require zero emissions sometime between 2030 and 2050

Summary

- Climate change is likely to impact most hydrologic systems
- Impacts need to be assessed at regional/river basin and smaller scales
- Results from the studies are useful in developing adaptive responses (e.g., long term reservoir operating policies; modifications in hydrologic designs; change in cropping patterns; water use adjustments etc.)
- Climate Change as Driving Force in Water Resources Systems