Climate Change Causes and Hydrologic Predictive Capabilities

V.V. Srinivas
Associate Professor
Department of Civil Engineering
Indian Institute of Science, Bangalore
vvs@civil.iisc.ernet.in

Overview of Presentation

- **Climate Change Causes**
- **Effects of Climate Change**
- **Hydrologic Predictive Capabilities to Assess Impacts of Climate Change on Future Water Resources**
  - **GCMs and Downscaling Methods**
  - **Typical case studies**
- **Gaps where more research needs to be focused**

Weather & Climate

Weather

- **Definition**: Condition of the atmosphere at a particular place and time
- **Time scale**: Hours-to-days
- **Spatial scale**: Local to regional

Climate

- **Definition**: Average pattern of weather over a period of time
- **Time scale**: Decadal-to-centuries and beyond
- **Spatial scale**: Regional to global

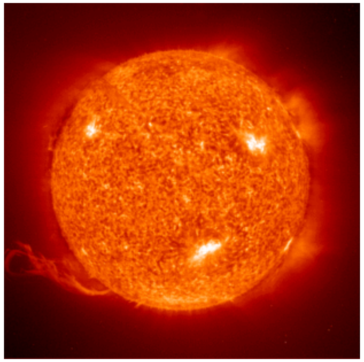
Climate Change

Variation in global and regional climates

Climate Change – Causes

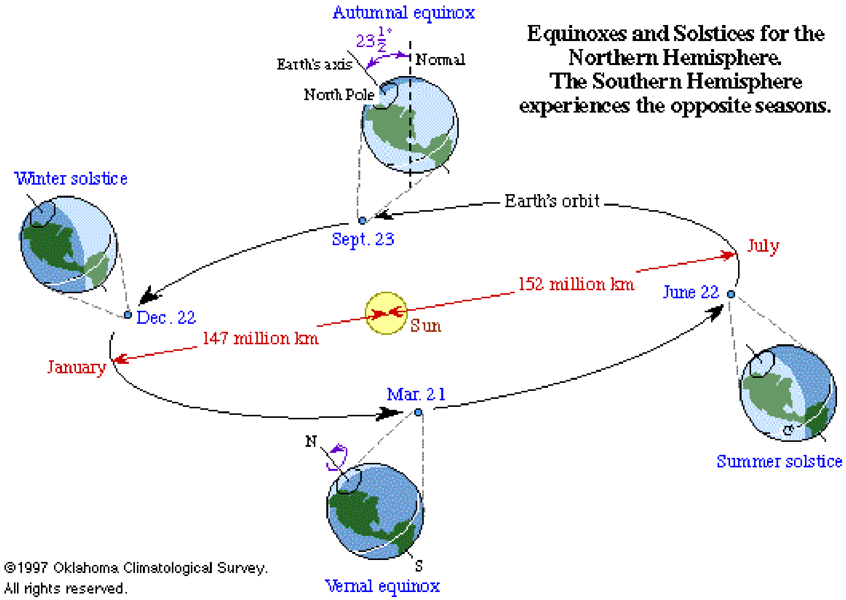
- **Variation in the solar output/radiation**

  Sun-spots (dark patches) (11-years cycle)



(Source: PhysicalGeography.net)

- **Cyclic variation in Earth's orbital characteristics and tilt - three Milankovitch cycles**
  - **Change in the orbit shape (circular↔elliptical) (100,000 years cycle)**
  - **Changes in orbital timing of perihelion and aphelion – (26,000 years cycle)**
  - **Changes in the tilt (obliquity) of the Earth's axis of rotation (41,000 year cycle; oscillates between 22.1 and 24.5 degrees)**



Climate Change - Causes

- **Volcanic eruptions**
- **Ejected SO_2 gas reacts with water vapor in stratosphere to form a dense optically bright haze layer that reduces the atmospheric transmission of incoming solar radiation**

Figure : Ash column generated by the eruption of Mount Pinatubo. (Source: U.S. Geological Survey).

Climate Change - Causes

Variation in Atmospheric GHG concentration

- Global warming due to absorption of longwave radiation emitted from the Earth's surface
- Sources of GHGs
  - Burning of fossil fuels
  - Agriculture: livestock, agricultural soils, and rice production
  - Land use and Forestry - act as a source/sink
  - Oceans: release/absorb CO_2 depending on temperature

Table |: *The past and present concentrations of three main greenhouse gases.*

Greenhouse gas	Pre-industrial concentration	Concentration in 2005	Global warming potential#	Main human-derived sources
CO_2	280 ppm*	379 ppm	1	Energy use; deforestation
CH_4	0. 72 ppm	1.77 ppm	25	Agriculture; energy use
N_2O	0.27 ppm	0.32 ppm	298	Agriculture

source: IPCC, 2007

* ppm = parts per million by volume. For example, 280 ppm means that 1 million liters of air holds 280 liters of CO_2.

Global warming potential is the relative warming effect of the gas, compared to CO_2, when considered over a 100-year period. Thus, one kg of CH_4 has 25 times the warming effect of 1 kg CO_2.

Others: Hydrofluorocarbons, Perfluorocarbons and Sulfur hexafluoride

Climate Change - Causes

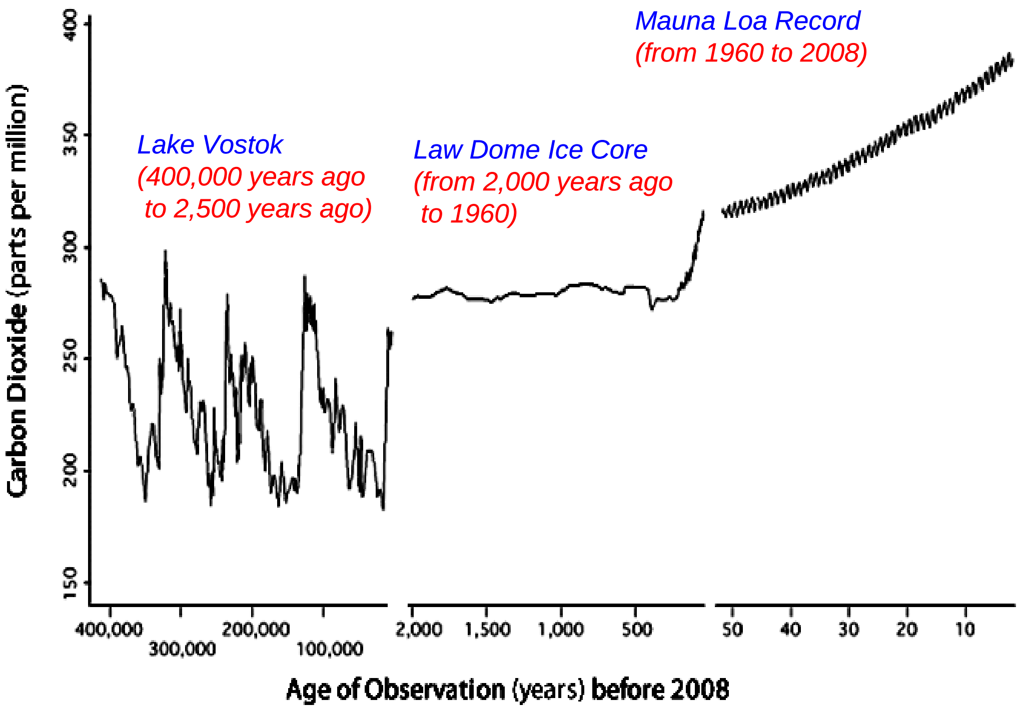
- **Most of the pre-anthropogenic (pre-1850) decadal-scale temperature variations was due to changes in solar radiation and volcanism – [*Crowley* 2000, Science]**

- **Most of the warming in 20th-century is due to increase in GHG resulting from anthropogenic causes – [*Crowley* 2000, Science]**

Basis:

- **Reconstructed Northern Hemisphere temperatures and climate forcing over the past 1000 years**
- **Indices of volcanism, Solar variability, Changes in GHGs and Tropospheric aerosols**

Effects of Climate Change



Ref: http://www.climate.gov

Figure: Reconstructed and observed CO_2 records for the past 400,000 years

Lake Vostok : The largest of Antarctica's almost 400 known subglacial lakes
Law Dome, East Antarctica
Mauna Loa: One of five volcanoes that form the Island of Hawaii in the U.S.
Station ALOHA: Deep water (~4,800 m) location approximately 100 km north of the Hawaiian Island of Oahu

Effects of Climate Change

Melting of ice sheets (Greenland, Alaskan, West Antarctic) → Sea level rise

WAIS (2.2 million km^3): 3.3 metres (10 ft) **[*Ref: Lythe et al., 2001 (JGR); Bamber et al., 2009 (Science)*]**

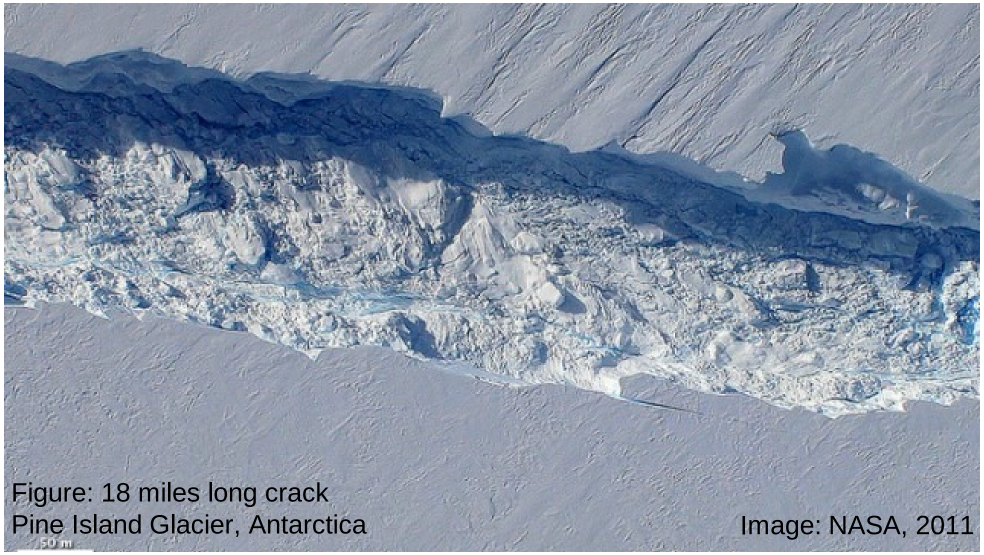


Figure: 18 miles long crack
Pine Island Glacier, Antarctica

Image: NASA, 2011

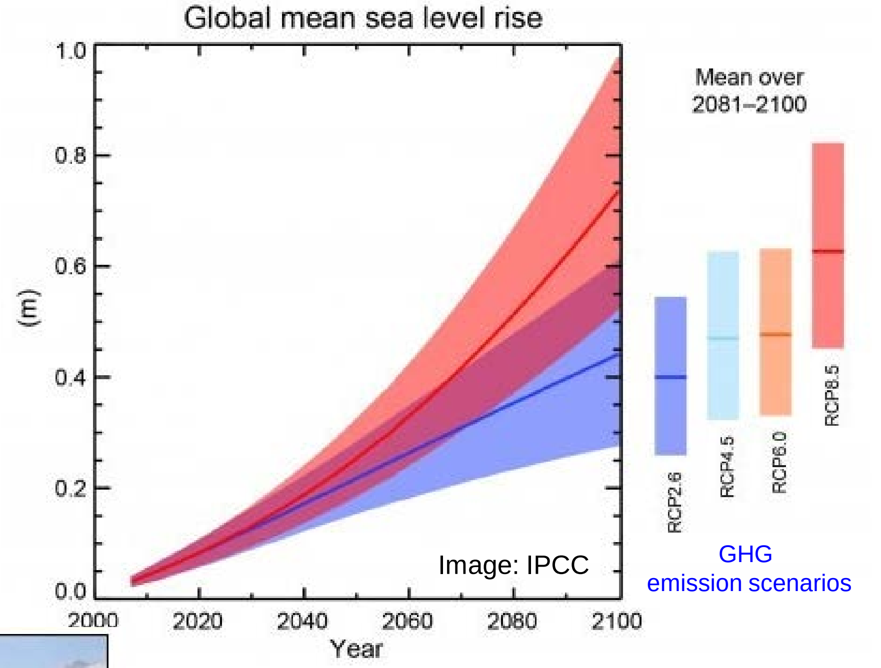


Image: IPCC

GHG emission scenarios

Muir Glacier in Alaska, as seen in 1941 and 2004

Credit: Photo courtesy of William Field (1941) and Bruce Molnia (2004) and the National Snow and Ice Data Center, University of Colorado, Boulder.

Effects of Climate Change

- **Changes to duration of seasons**

- **Dieback of the Amazon rainforest (southern portion) due to increase in dry season length (by about a week per decade since 1979).**

  (*Area: 1.4 billion acres, containing 90-140 billion metric tons of carbon*)

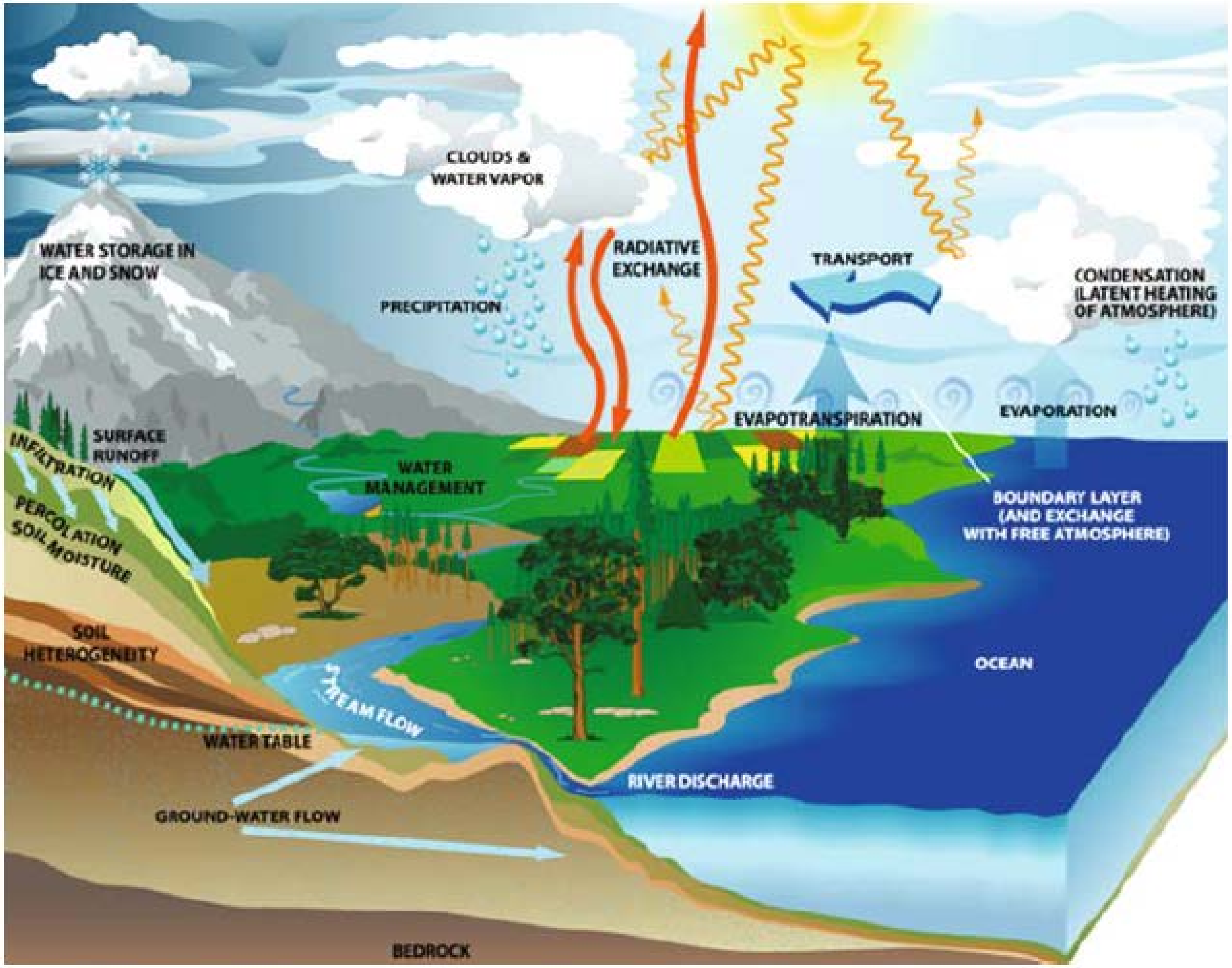
  (could cause the release of large volumes of the CO_2 into atmosphere)

- **Changes to frequency and severity of hydrologic extremes such as floods and droughts**

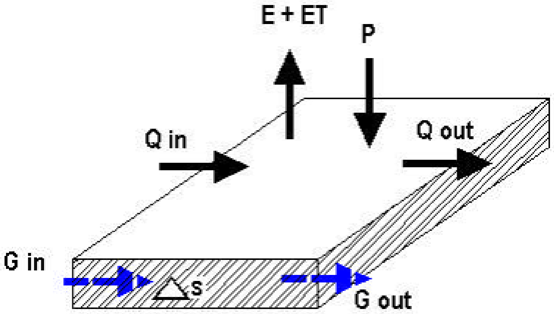
- **Changes in the thermohaline circulation in the north Atlantic that affects global ocean heat transport**

- **Intensification of desertification (through spatio-temporal variation in patterns of temperature, rainfall, solar radiation and winds) - West African Sahel, China**

Hydrologic Predictive Capabilities
to
Assess Impacts of Climate Change on Future Water Resources

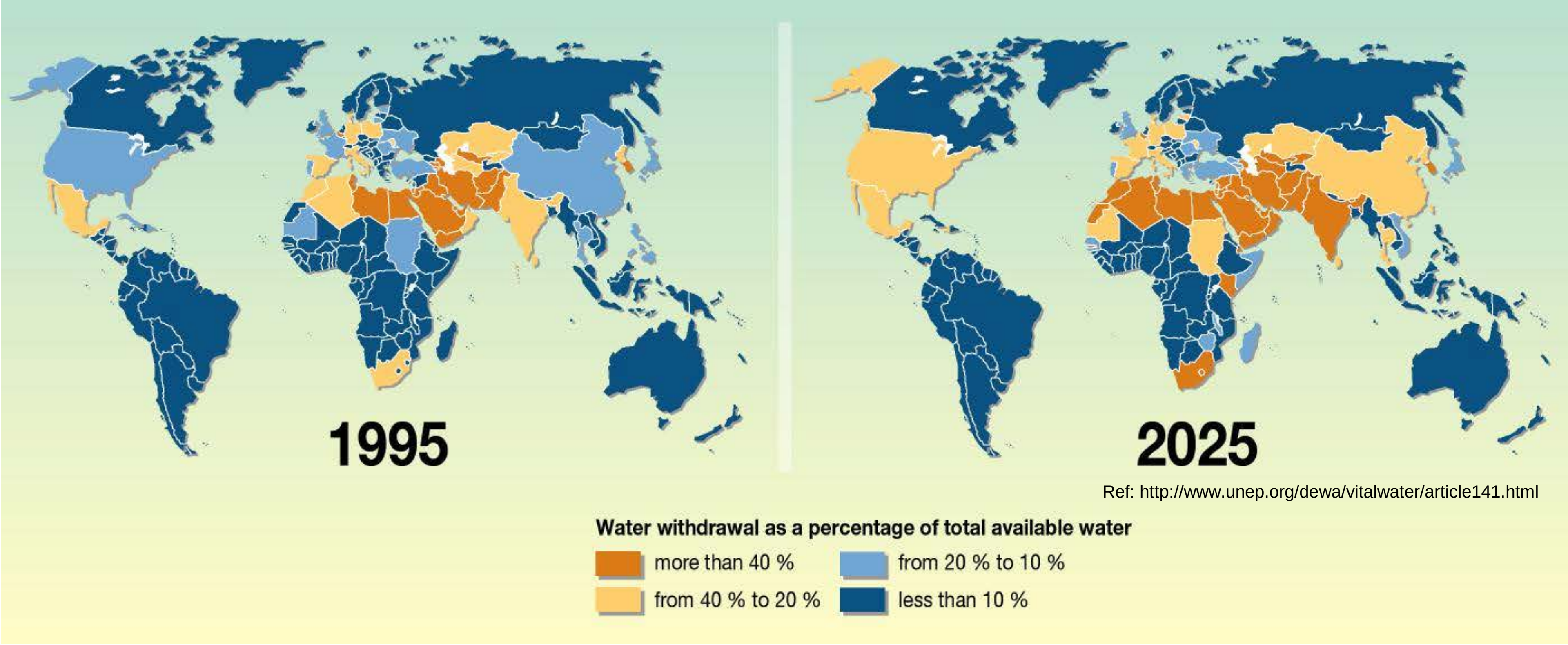


The hydrologic cycle.
Source: US Global Change Research Program, http://www.usgcrp.gov/usgcrp/ProgramElements/water.htm



Water Balance

Hydrologic Predictive Capabilities



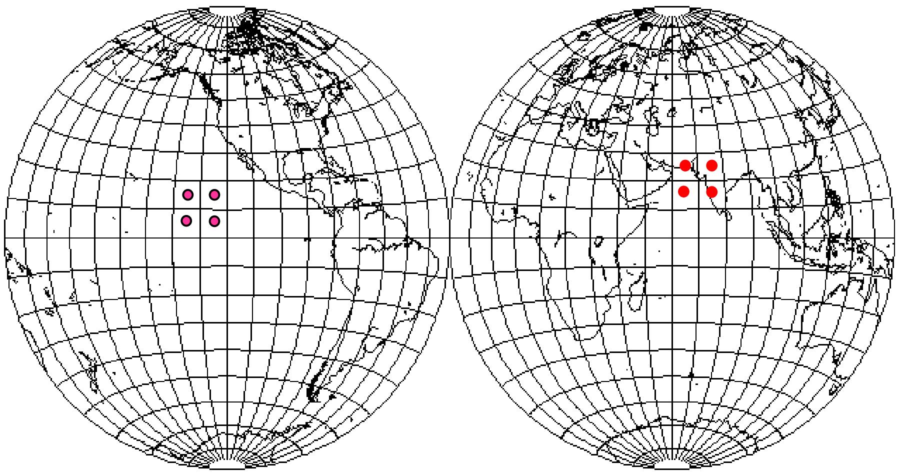
Ref: http://www.unep.org/dewa/vitalwater/article141.html

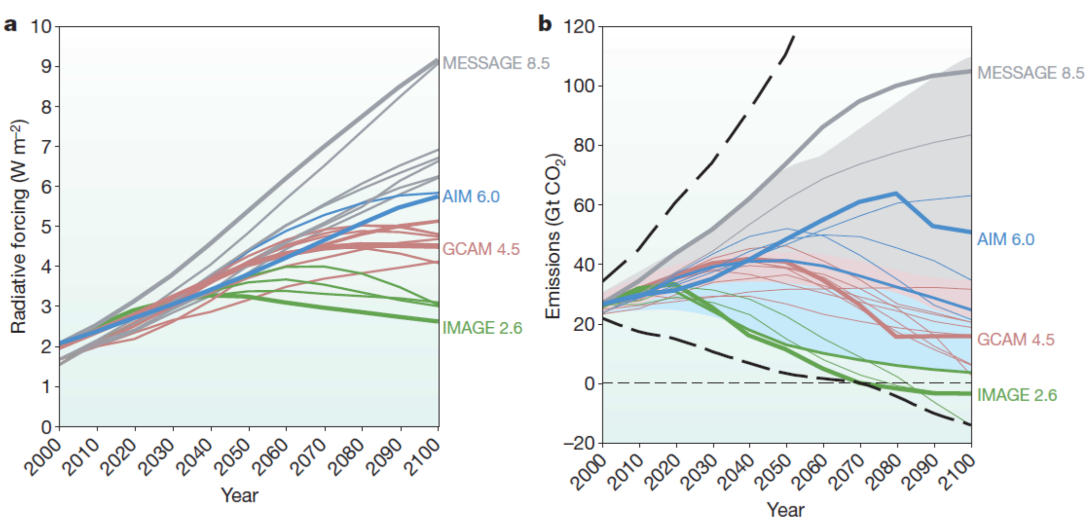
Future projections of water demand – Based on population growth

Future projections of water balance components – What can be the basis?

General Circulation Models (GCMs) – Numerical Models

- **Simulate the response of the global climate system to future projections of GHG emissions & Radiative forcing**





New Scenarios approved by IPCC in 2013

Economic emphasis

Global integration | Regional emphasis

A1 storyline World: market-oriented Economy: fastest per capita growth Population: 2050 peak, then decline Governance: strong regional interactions; income convergence Technology: three scenario groups: • **A1FI**: fossil-intensive • **A1T**: non-fossil energy sources • **A1B**: balanced across all sources	**A2 storyline** World: differentiated Economy: regionally oriented; lowest per capita growth Population: continuously increasing Governance: self-reliance with preservation of local identities Technology: slowest and most fragmented development
B1 storyline World: convergent Economy: service and information-based; lower growth than A1 Population: same as A1 Governance: global solutions to economic, social and environmental sustainability Technology: clean and resource-efficient	**B2 storyline** World: local solutions Economy: intermediate growth Population: continuously increasing at lower rate than A2 Governance: local and regional solutions to environmental protection and social equity Technology: more rapid than A2; less rapid, more diverse than A1/B1

Environmental emphasis

General Circulation Models (GCMs)

- **GCMs depict the climate using a three dimensional grid over the globe**
- **Several vertical layers in the atmosphere and oceans**

General Circulation Models (GCMs) – Typical Examples

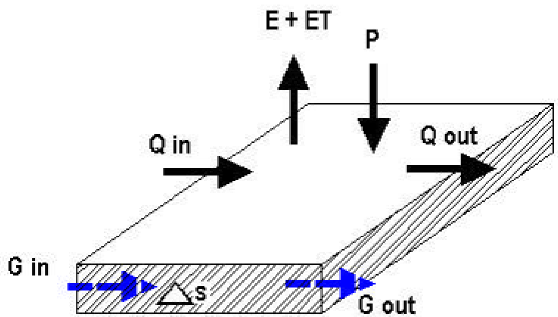
Climate model name	Agency/Source	Atmospheric resolution	Oceanic resolution
BCC-CM1	Beijing Climate Center, China	T63L16	1.875° x 1.875°, L30
BCCR: BCM2.0	Bjerknes Centre for Climate Research, Norway	T63L31	1.5° x (0.5°-1.5°), L35*
CCCma: CGCM3	Canadian Center for Climate Modelling and Analysis, Canada	T47, L31	1.8° x 1.8°, L29
		T63, L31	1.4° Lon x 0.9° Lat, L29
CNRM-CM3	Centre National de Recherches Meteorologiques, France	T63, L45	182 x 152 grid†
CSIRO: MK3	Australia's Commonwealth Scientific and Industrial Research Organisation, Australia	T63, L18	1.875° Lon x approx. 0.84° Lat, L31
MPIM: ECHAM5-OM	Max-Planck-Institut for Meteorology, Germany	T63 L31	1.5°x1.5°, L40

T refers to horizontal resolution (number of waves with triangle truncation in horizontal direction)
L refers to the number of vertical levels or layers.

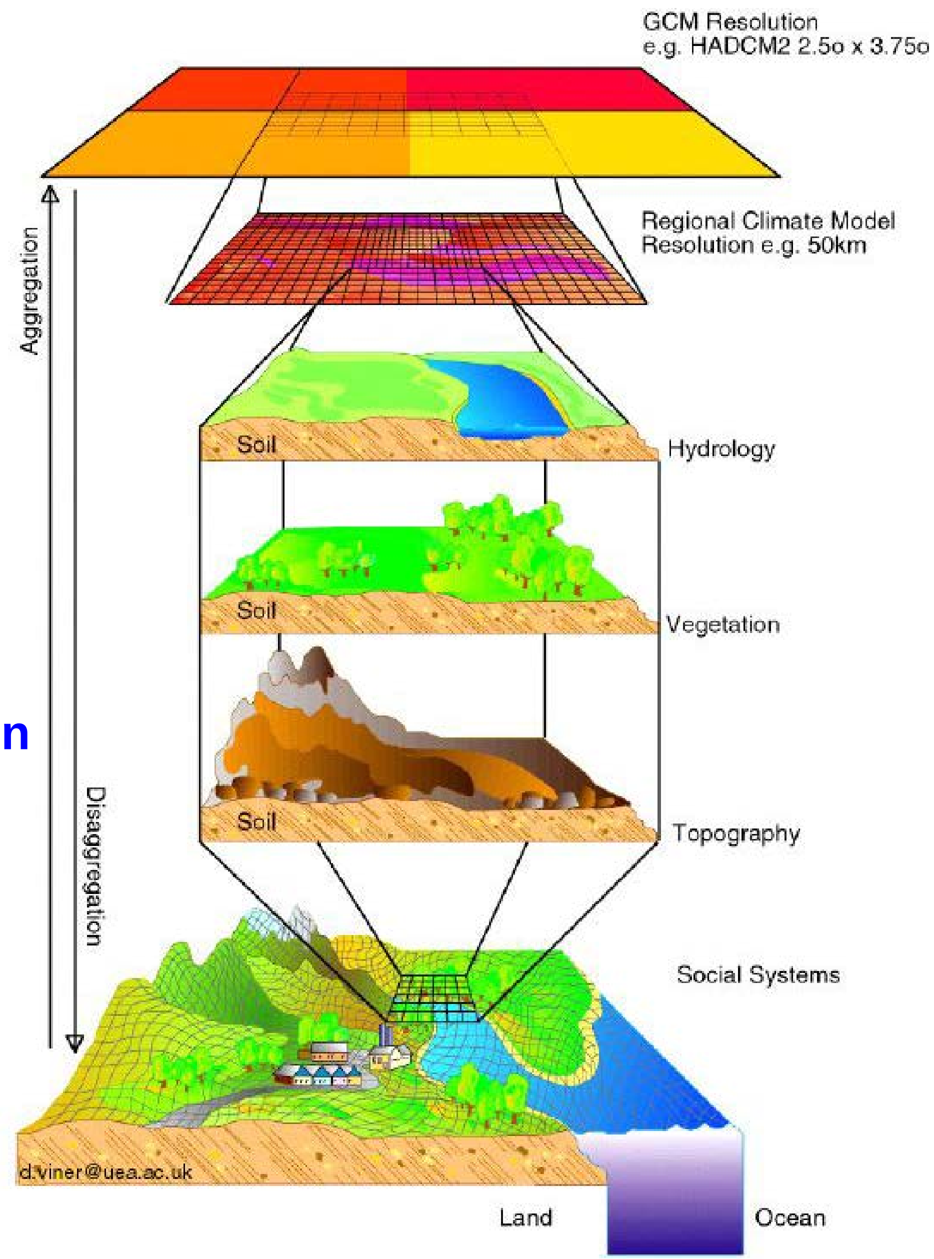
General Circulation Models (GCMs) – Issues

- Simulate coarse-scale atmospheric dynamics reasonably well
- Fail to simulate climate variables at finer watershed scale, as many of the physical processes which control local climate, e.g. topography, vegetation and hydrology, are not considered

- **Spatial Downscaling**
  - Dynamical downscaling
  - Statistical downscaling
- **Temporal downscaling/disaggregation**



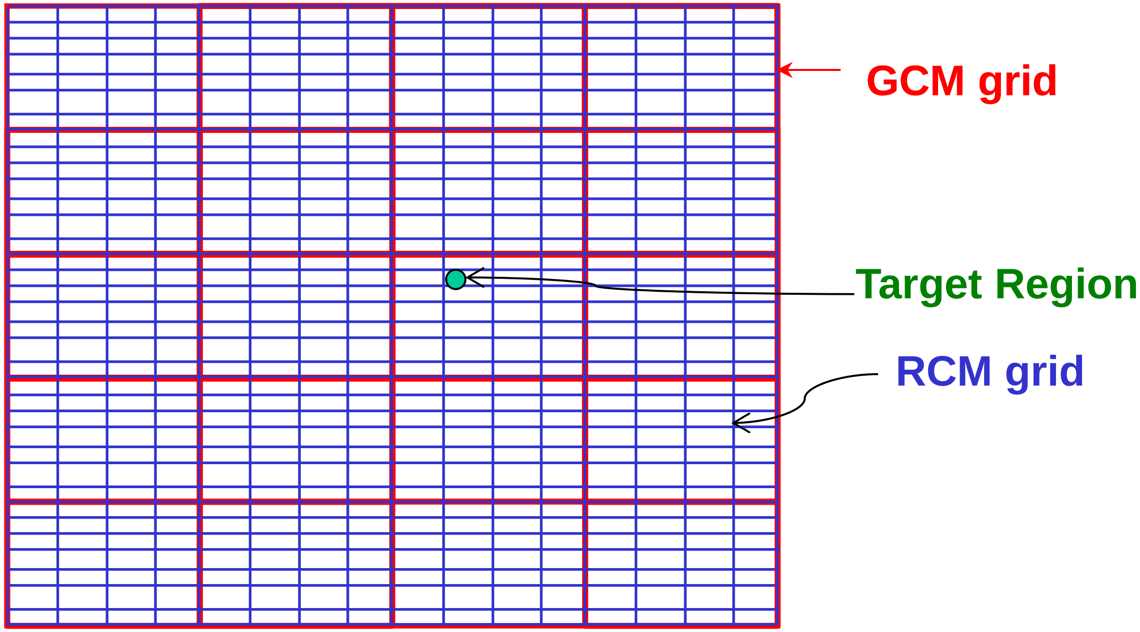
Water Balance



Spatial Downscaling Methods – An Overview

Dynamic downscaling

- Involves nesting of Regional Climate Model (RCM) in GCM
- Grid spacing of RCM: 20–50 km



RCM

- Accounts for finer-scale atmospheric dynamics (e.g., orographic precipitation)
- time-dependent lateral meteorological conditions defined by GCM

Spatial Downscaling Methods – An Overview

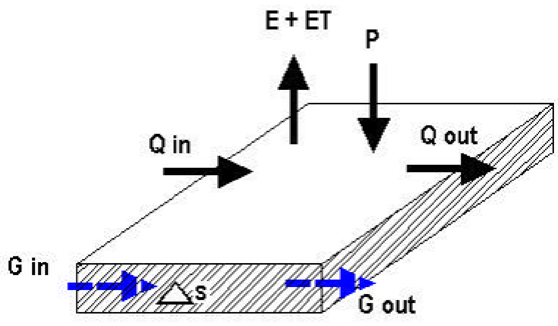
Statistical downscaling methods

Transfer Function based Methods

Empirical relationship is developed between the local scale variable (predictand) and large scale atmospheric variables (predictors)

RSV = *g* (LSAV)

***g*(.) is a downscaling function [e.g., linear/nonlinear regression; ANN; Vector machine**



Water Balance

Strength: Ease in application
Limitations: sensitive to the choice of LSAV and *g*(.)

Reanalysis Data

- **Considered as a surrogate for unavailable/sparse data on LSAV**
- **Produced by integration of historical observations and model simulations using data assimilation techniques**

Examples: NCEP/NCAR; ECMWF; JRA-55

National Centers for Environmental Prediction (NCEP)
National Center for Atmospheric Research (NCAR)
Department of Energy (DoE)
European Centre for Medium-Range Weather Forecasts (ECMWF)

Spatial Downscaling Models – An Overview

Weather Typing Methods

- Local meteorological (predictand) data are partitioned into groups/clusters based on past patterns of atmospheric circulation
- Future local climate scenarios are constructed by resampling predictand data from clusters by conditioning on the future circulation patterns produced by a GCM

Limitation

- Assume validity of the model parameters under future climate conditions

Stochastic Weather Generators

Climate change scenarios are generated stochastically using conventional weather generators by modifying their parameters conditional on outputs from a GCM

Examples: WGEN, LARS–WG or EARWIG

Limitation

- Low skill at reproducing inter-annual to decadal climate variability
- Unanticipated effects that changes to precipitation occurrence may have on secondary variables such as temperature

Spatial Downscaling Models – An Overview

S N	Predictors (coarser scale variables)	Predictand (local scale variable)
1	Temperature, geo-potential height, specific humidity, zonal and meridional wind velocities, precipitable water, surface pressure	Precipitation
2	Temperature at higher elevations zonal and meridional wind velocities at higher elevations Latent heat, sensible heat, shortwave radiation and longwave radiation fluxes	Max. & Min. temperature
3	zonal and meridional wind velocities at higher elevations	Wind speed
4	Temperature at higher elevation Specific humidity at higher elevation Surface temperature, Latent heat flux	Relative humidity
5	Precipitable water	Cloud cover
6	Mostly predictors selected for precipitation Some times wind speed, relative humidity, cloud cover	Streamflow

Predictor set depends on governing physical processes

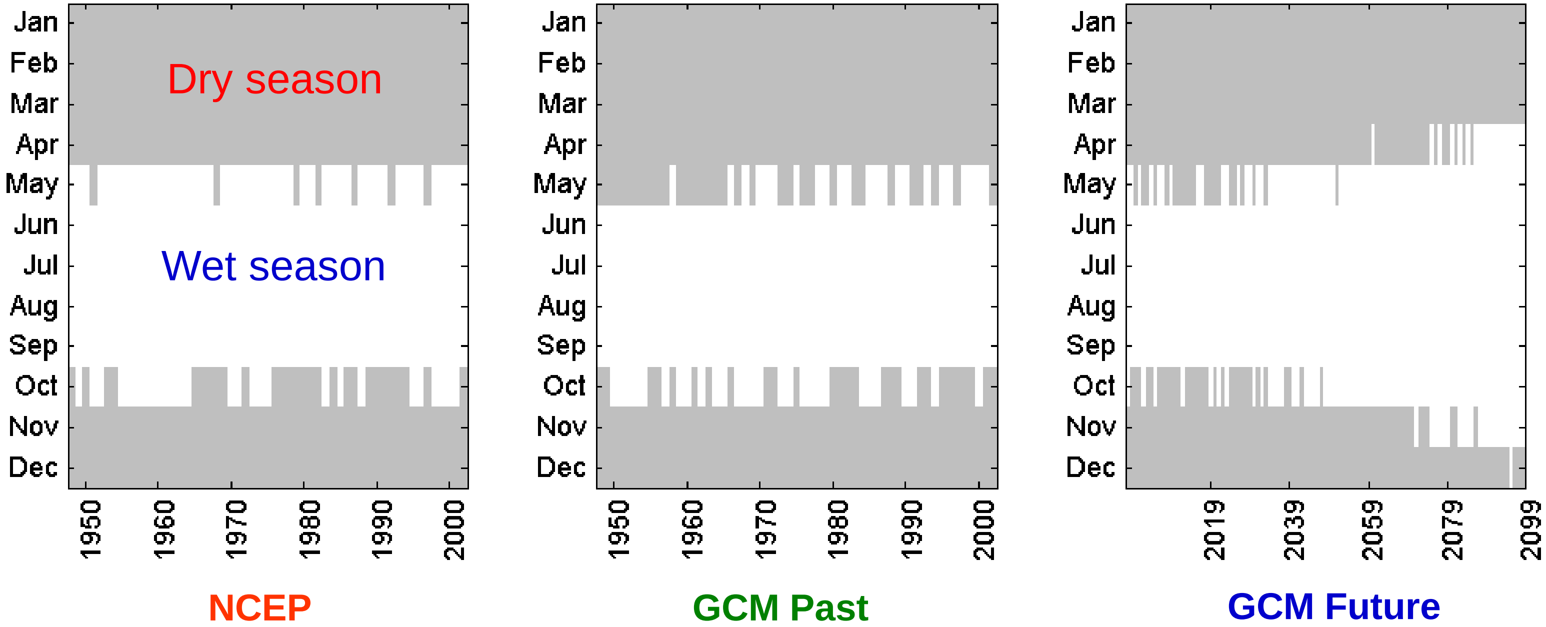
Spatial Downscaling – Case study in India

➢ Downscaling precipitation to meteorological subdivisions - SVM approach

Procedure

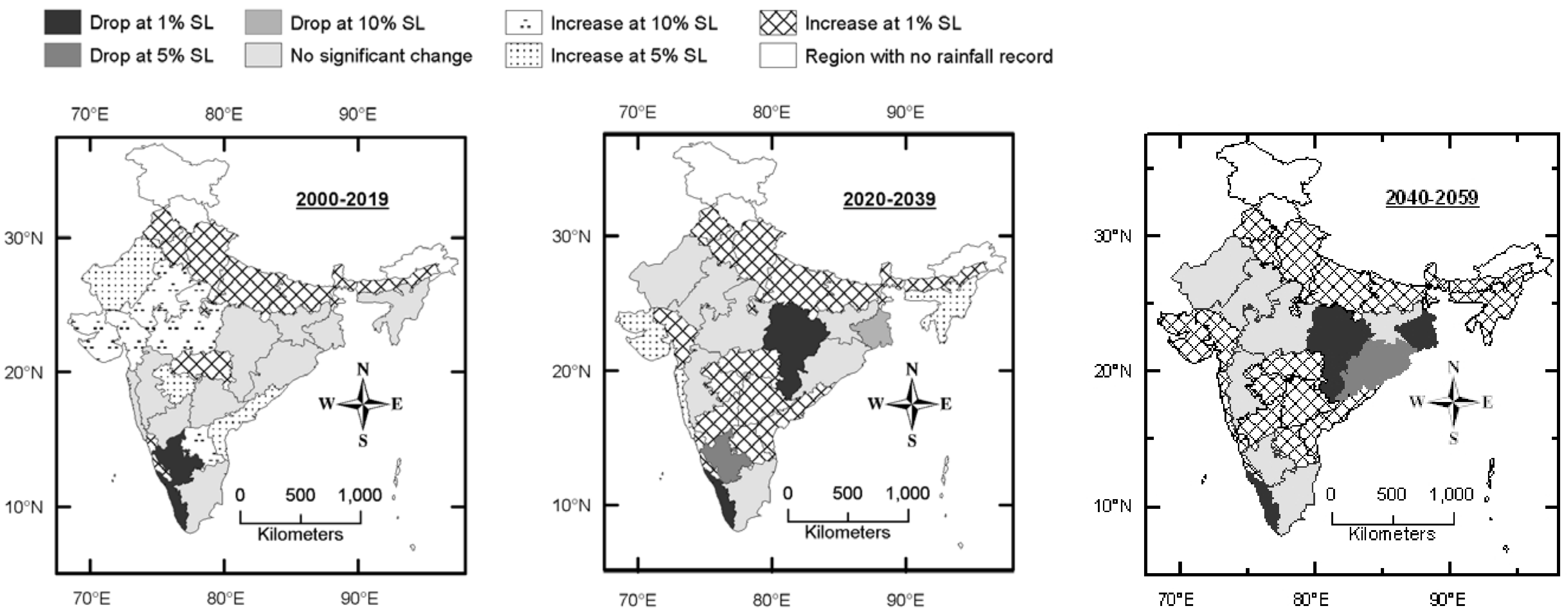
- NCEP reanalysis data (2.5°x2.5°) (Climate Diagnostics Center, Co, USA)
- Output from CGCM2, CCCma (3.75°)
- Area weighted rainfall (1948-2002)
- Seasonal stratification
- SVM for downscaling

➢ Seasonal stratification using cluster analysis



Study area: North Interior Karnataka, India

Spatial Downscaling – Case Study in India



Results

Significant increase in precipitation is projected for Konkan and Goa, Coastal Karnataka, Gujarat, Saurashtra and Kutch along west coast of India, Coastal Andhra Pradesh along east coast, Telangana and Rayalaseema in peninsula India, Punjab and Haryana in the north-west, east Uttar Pradesh, west Uttar Pradesh plains and Bihar plains in the north, and north Assam and south Assam in the north-east India. Drop in precipitation is projected for Kerala and East Madhya Pradesh, while mixed trend in precipitation is projected for the remaining parts of the country by the LS-SVM downscaling model for the simulations of CGCM2 model under IS92a scenario.

Published in J. of Hydrology

Ref: Tripathi et al. (2006)

Future Streamflow projection in Climate Change Scenario

Methods

- GCM simulated future streamflows are accepted

- GCM simulated meteorological variables are used to drive a hydrological model
  (unrealistic streamflows owing to inadequate and simplistic representation of the hydrologic cycle within GCMs)

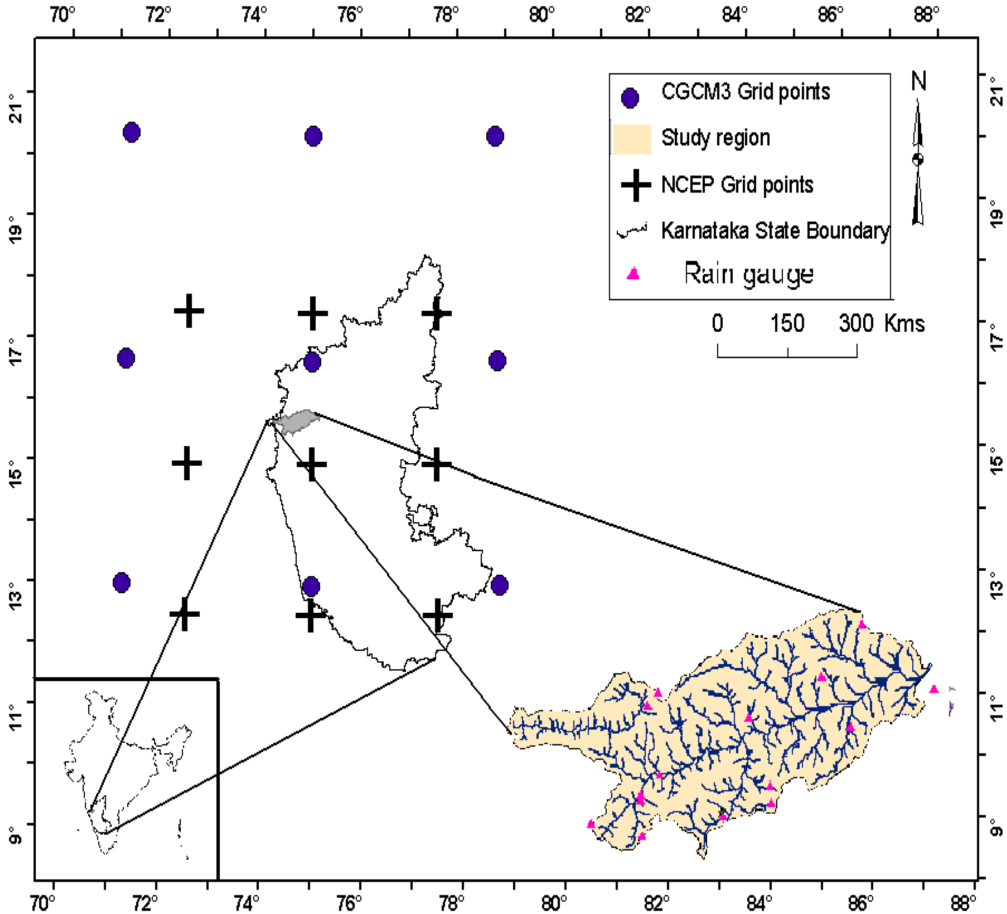
- GCM simulated meteorological variables are downscaled to local scale meteorological variables that are used to drive a hydrological model

- GCM simulated LSAVs are downscaled to streamflow
  (Do not take into account dynamics of regional hydrological processes and the mechanisms governing streamflow generation in a watershed)

- Hydrological models are driven by hypothetical/synthetic or analogue scenarios of meteorological variables

Spatial Downscaling – Case study in India

- Impact Assessment of Climate Change on Streamflows in Malaprabha Catchment

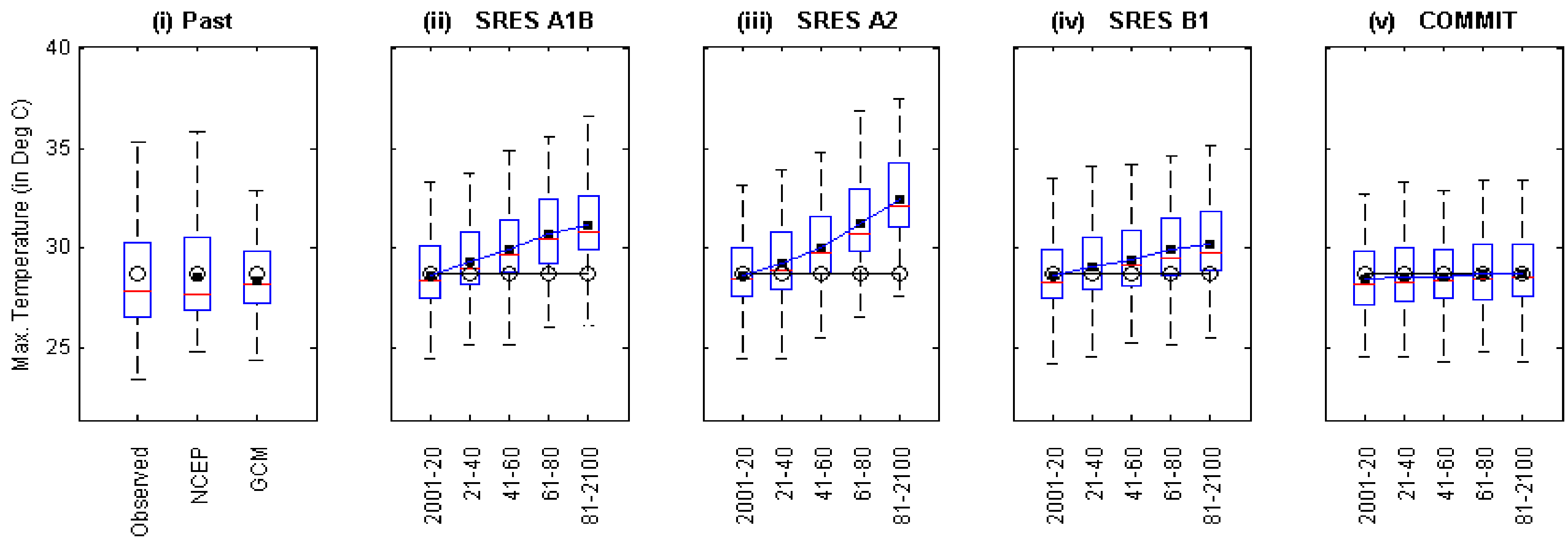


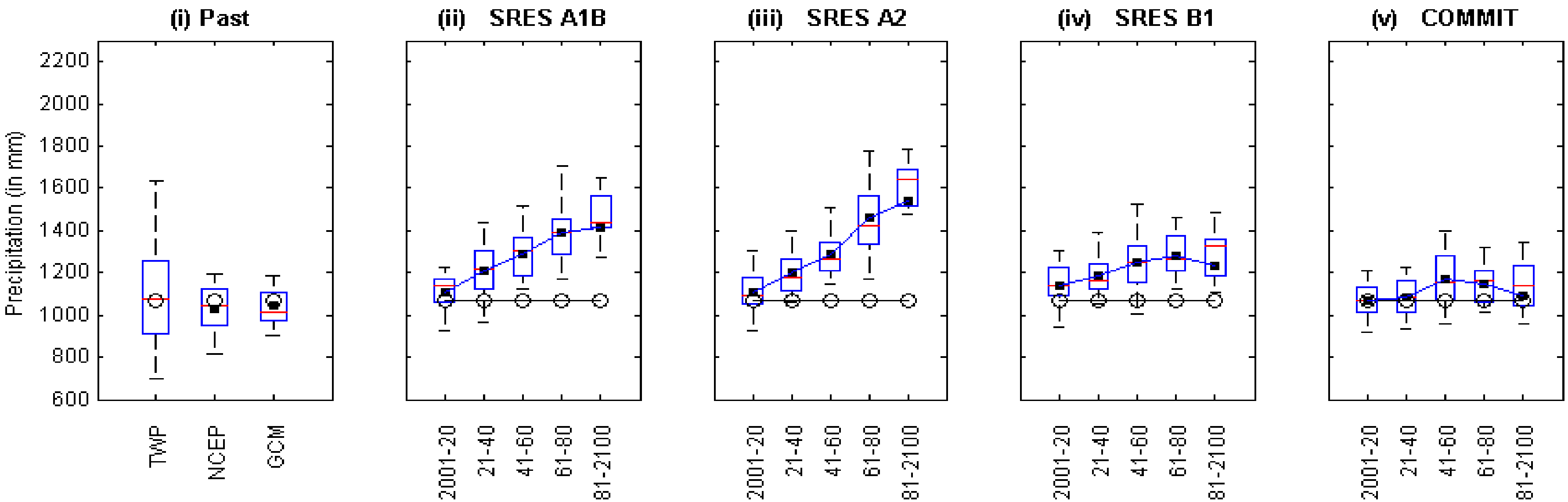
- Annual rainfall - 1051 mm
- Catchment area: 2564 km^2
- Gross storage capacity of dam: 1056 Mm^3 (37.73 tmc)

Figure: NCEP & GCM grid points and rain gauge locations in Malaprabha reservoir catchment

Ref: http://waterresources.kar.nic.in/salient_features_malaprabha.htm

Spatial Downscaling – Case study in India

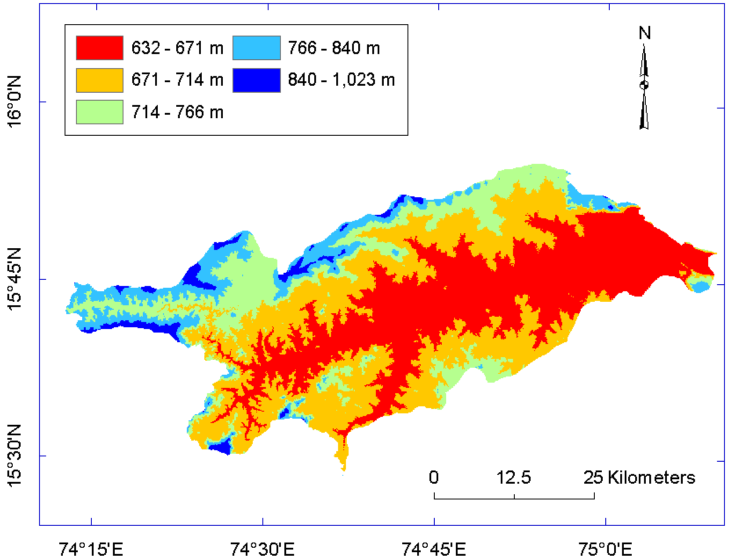


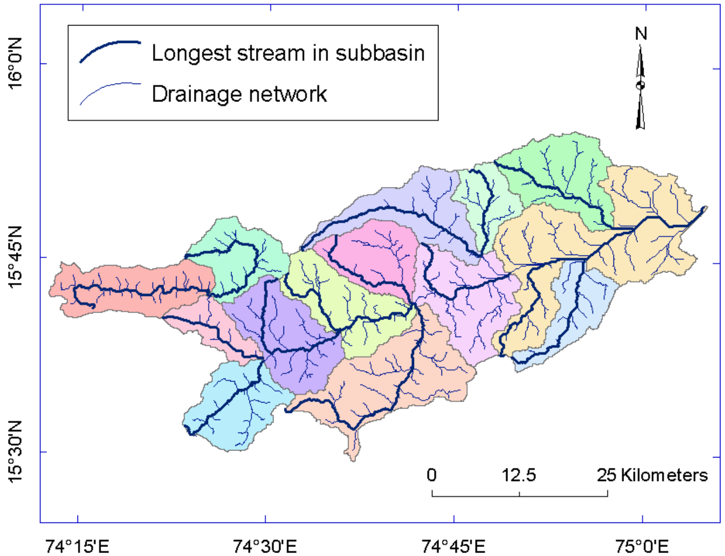


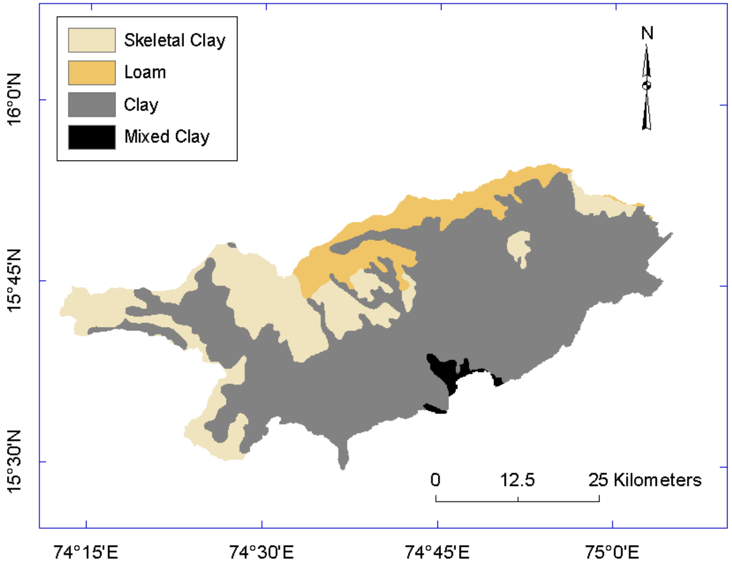
Published in Int. J. of Climatology

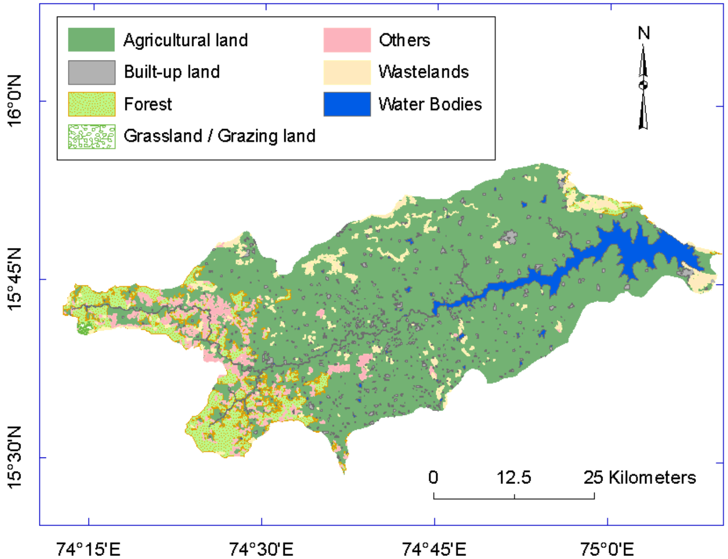
Ref: Anandhi et al. (2008,2009)

Spatial Downscaling – Case study in India



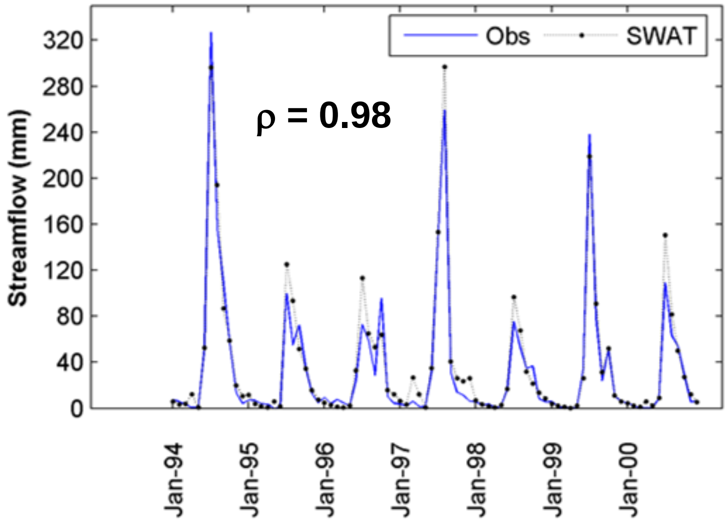


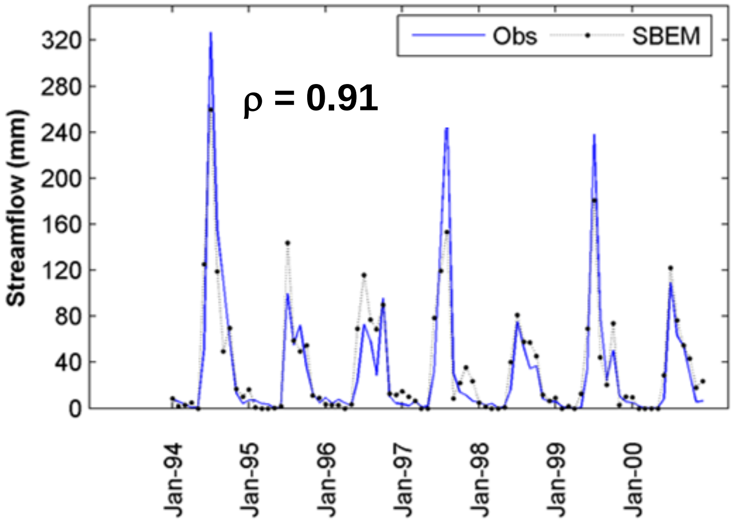


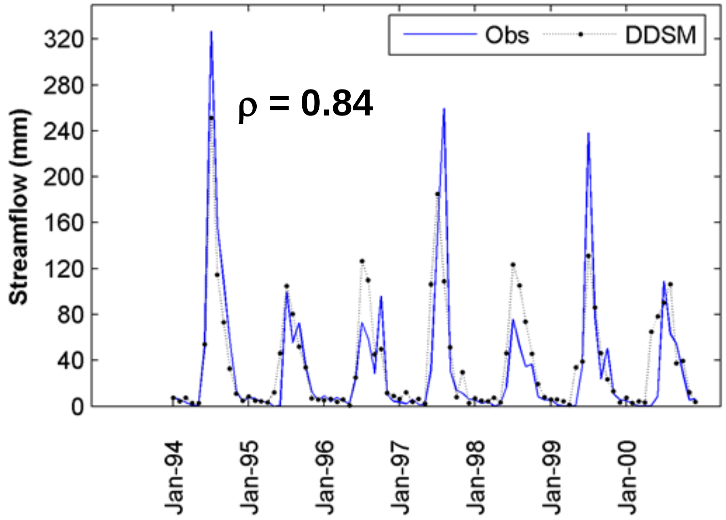


Input for SWAT Model

Spatial Downscaling – Case study in India







Study area: Catchment of Malaprabha reservoir
Calibration period: 1978-1993
Validation period: 1994 –2000

SWAT : Soil and Water Assessment Tool
SBEM : Support vector machine based empirical model
DDSM : Direct downscaling model

1mm: 2.564 Mm^3

- Bias in predicting peak flows is less for SWAT
- SBEM and DDSM under predicted high peaks and over predicted low peaks

Spatial Downscaling – Case Study in India

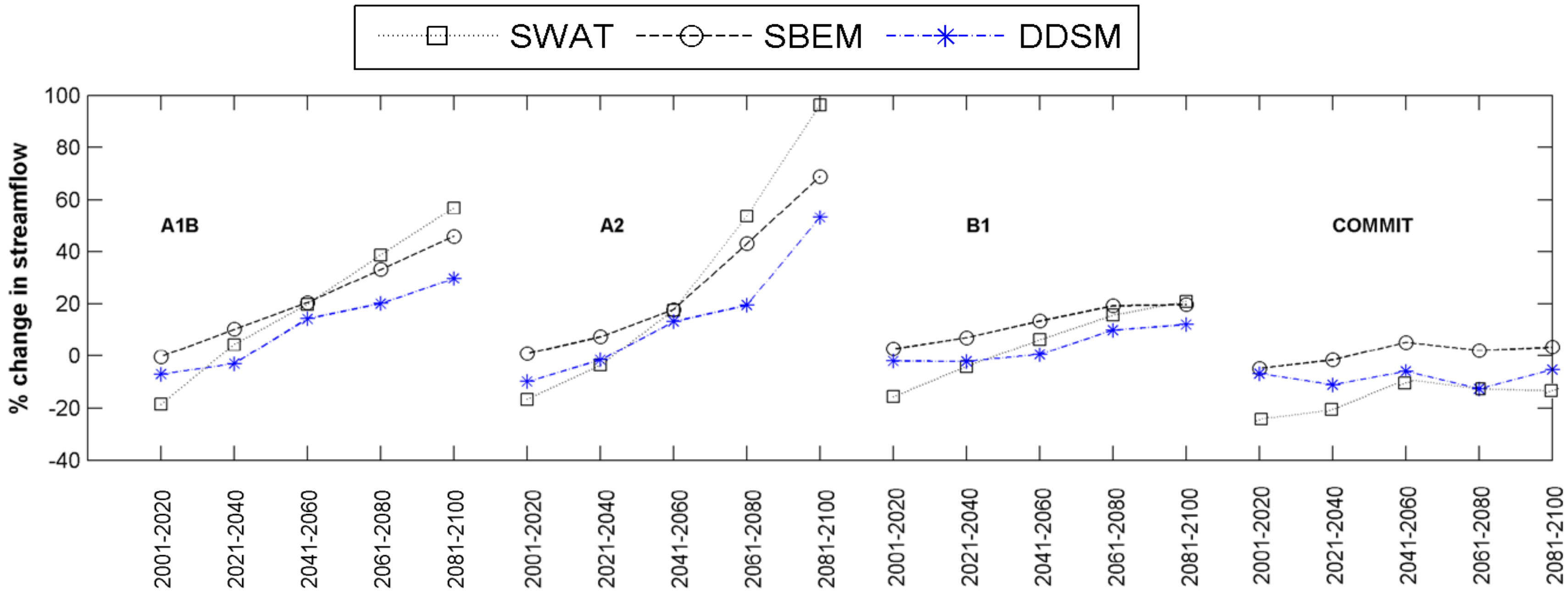


Figure: Projections for Monsoon Period (June-September)

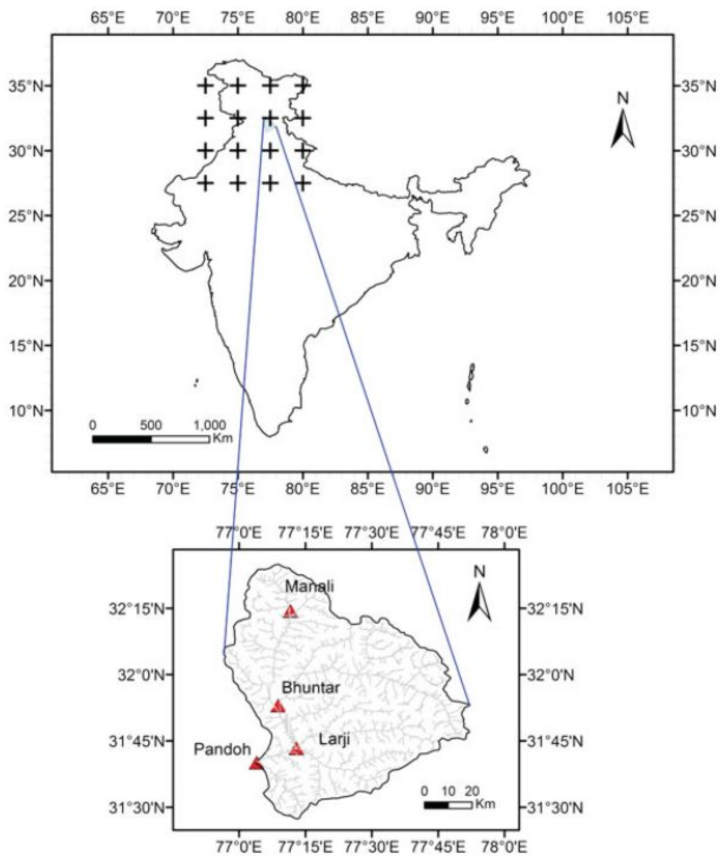
Monsoon streamflow~ 950 Mm^3 (Annual streamflow ~ 1200 Mm^3)

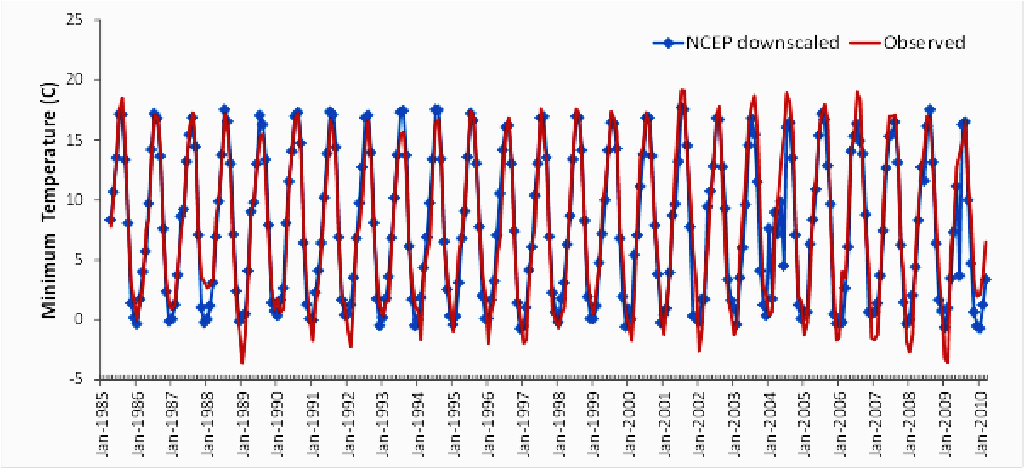
What would be the implications of this uncertainty in river basin planning and management of water resources?

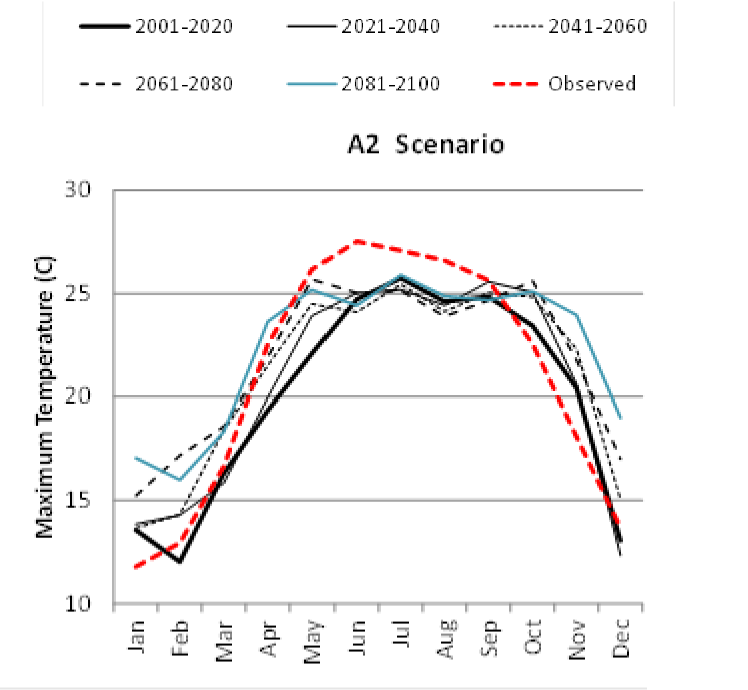
The scenario A2 has the highest concentration of equivalent carbon dioxide (CO_2) equal to 850 ppm, while the same for A1B, B1 and COMMIT scenarios are 720 ppm, 550 ppm and ≈ 370 ppm respectively.

Spatial Downscaling – Case Study in India

- **Multi-site downscaling of maximum and minimum daily temperature using support vector machine**







Published in Int. J. of Climatology: 2014

Bias correction / Change factor methodologies

- Biases /change factors of the mean monthly climatology are computed

Strategy-1

- Estimation of change between GCM past and station observations
- Application of bias corrections to GCM/RCM future simulations

Strategy-2

- Estimation of change between GCM past and GCM future
- Application of bias correction to station observations

Issue: The methods apply the correction to the mean and do not take account of model deficiencies in reproducing observed variability

Strategy-3

- Estimation of the percent changes in the climate variables per degree of global warming for each season
- Scaling the values by three levels of global warming projected by IPCC to obtain "seasonal scaling" factors

Quantile-based strategies (Matching probability distributions of predictor variables in the GCM/RCM control simulations (1850-2000) to match probability distributions of observed predictor data

Gaps where focused research is needed

- Identification of appropriate predictors for downscaling in various parts of the world

  Challenges:

  - Understanding governing physical processes

- Developing effective multi-site multivariate downscaling models

  Challenges in modelling:

  - Cross-correlations between time series of a predictand for all possible pairs of sites.
  - Cross-correlations between time series of different predictands at each site and for all possible pairs of sites

- Developing methods to address uncertainty in choice of

  - Reanalysis data and spatial domain of predictors
  - GCM and Climate change scenarios
  - Method for re-gridding (GCM-to-Reanalysis) - *Inverse square distance; bilinear ; Bessel*
  - Downscaling method
  - Hydrological model: SWAT, HEC HMS, MIKE SHE, VIC, MODFLOW
  - Relaxing assumption of stationarity in predictors -predictand relationship

- Developing method to arrive at realistic future projections of extreme hydrologic events (floods and droughts)

  Challenges:

  - No proper strategy even in stationary scenario

Gaps where focused research is needed

Water Resources Research
AN AGU JOURNAL

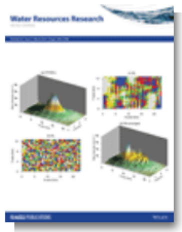
Research Article

Regional flood frequency analysis using kernel-based fuzzy clustering approach

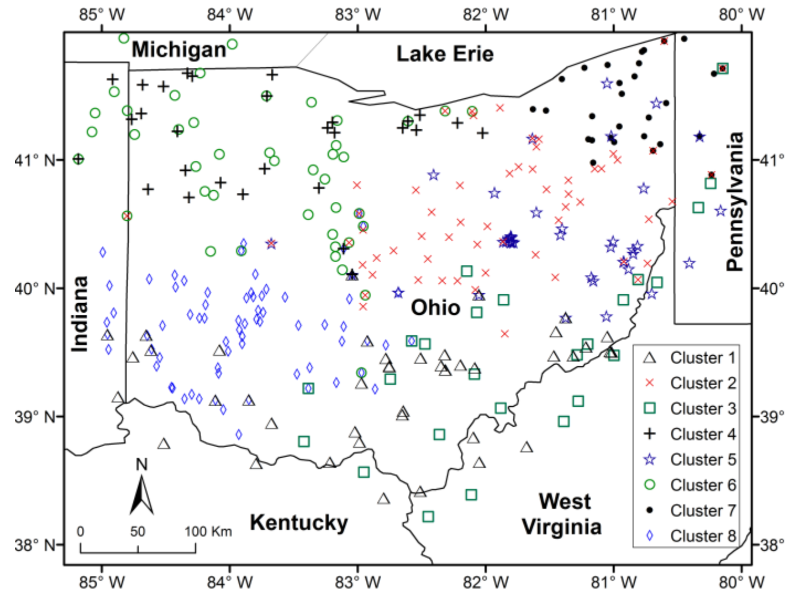
Bidroha Basu and V. V. Srinivas*

Article first published online: 16 APR 2014
DOI: 10.1002/2012WR012828

Issue



Water Resources Research
Early View (Online Version of Record published before inclusion in an issue)



ROI [Burn, 1990] & Regression Analysis [GLS, Stedinger & Tasker, 1985, USGS]

Water Resources Research
AN AGU JOURNAL

Regular Article

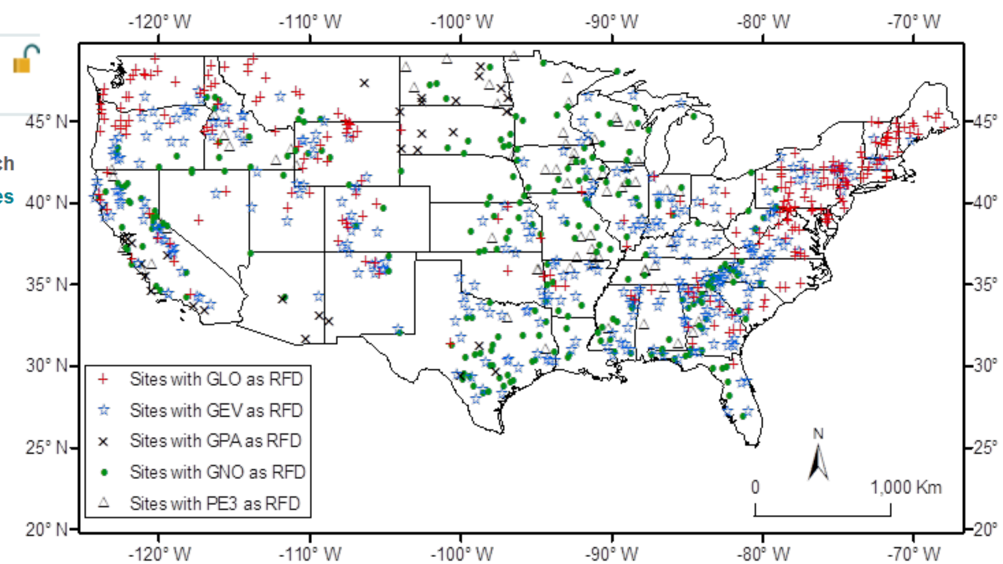
Formulation of a mathematical approach to regional frequency analysis

Bidroha Basu and V. V. Srinivas*

Article first published online: 21 OCT 2013
DOI: 10.1002/wrcr.20540

Issue

Water Resources Research
Volume 49, Issue 10, pages 6810–6833, October 2013



Index flood procedure [Dalrymple, USGS, 1960]

THANK YOU