Hydroclimate of Gangetic ecosystem

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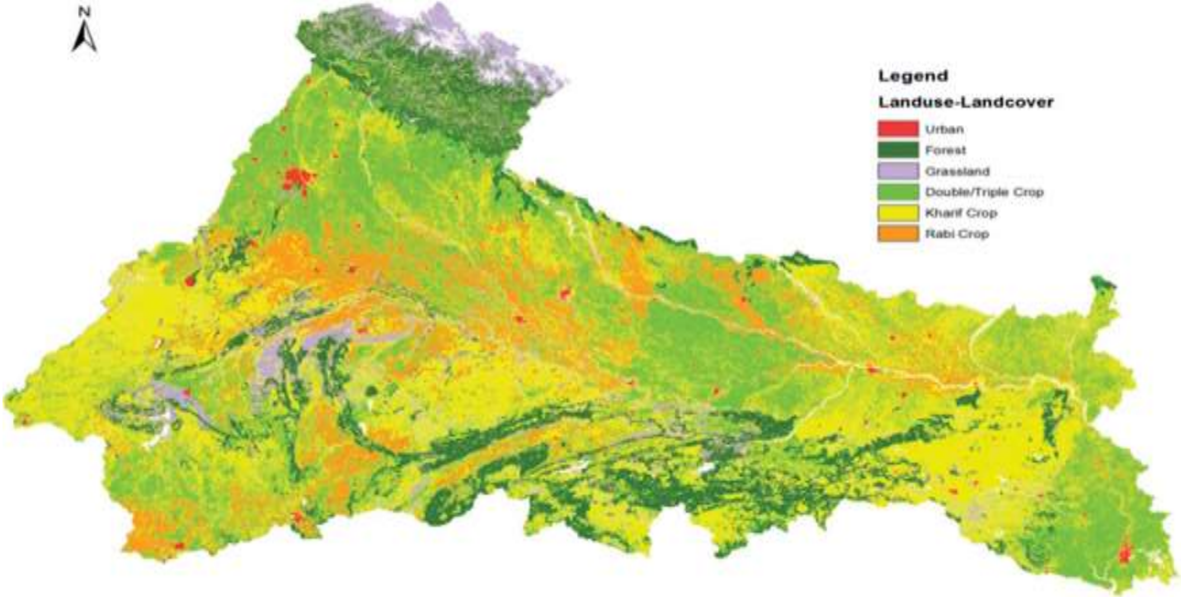
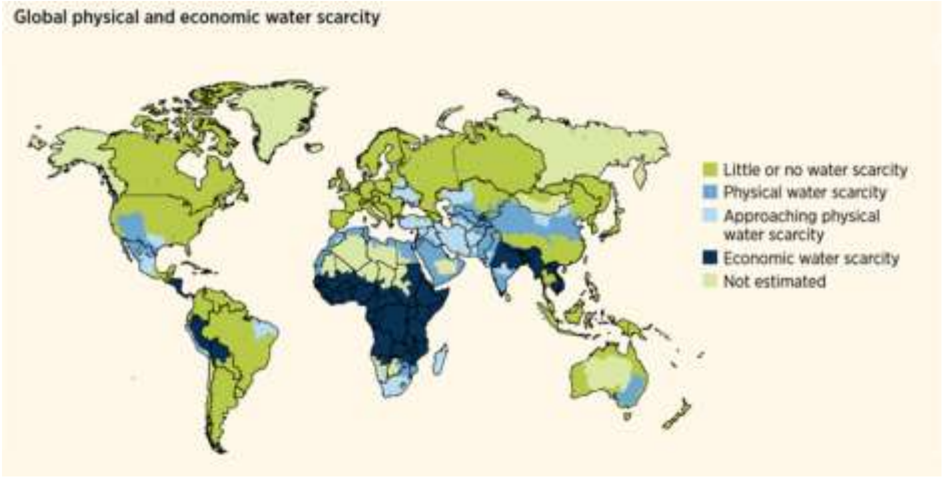
The River Ganga…

- Gangetic basin is Lifeblood of 600 million people and commonly known as the food basket of India
- Not only source of water, but also for Spiritual Inspiration.
- Ganga basin system drains through eight states of India
- 37 percent of India's population live on the Gangetic Basin
- Contains about 47 percent of the total irrigated area in India

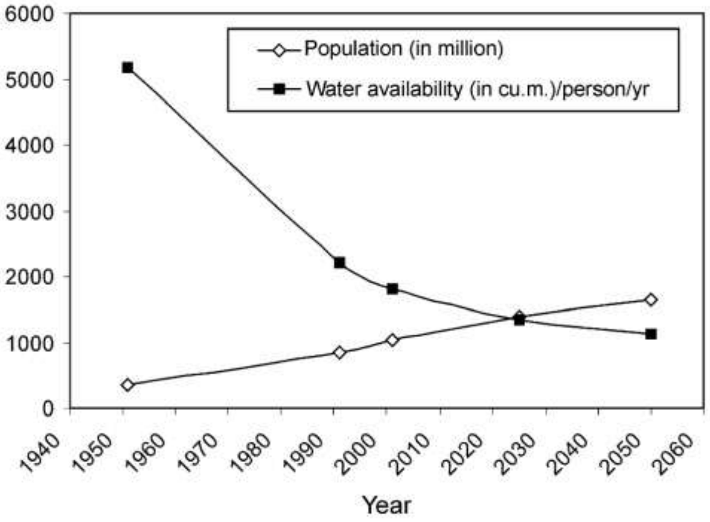


Whitehead, et al, 2015, Environmental Science Processes & Impacts

Water stress: present and future…

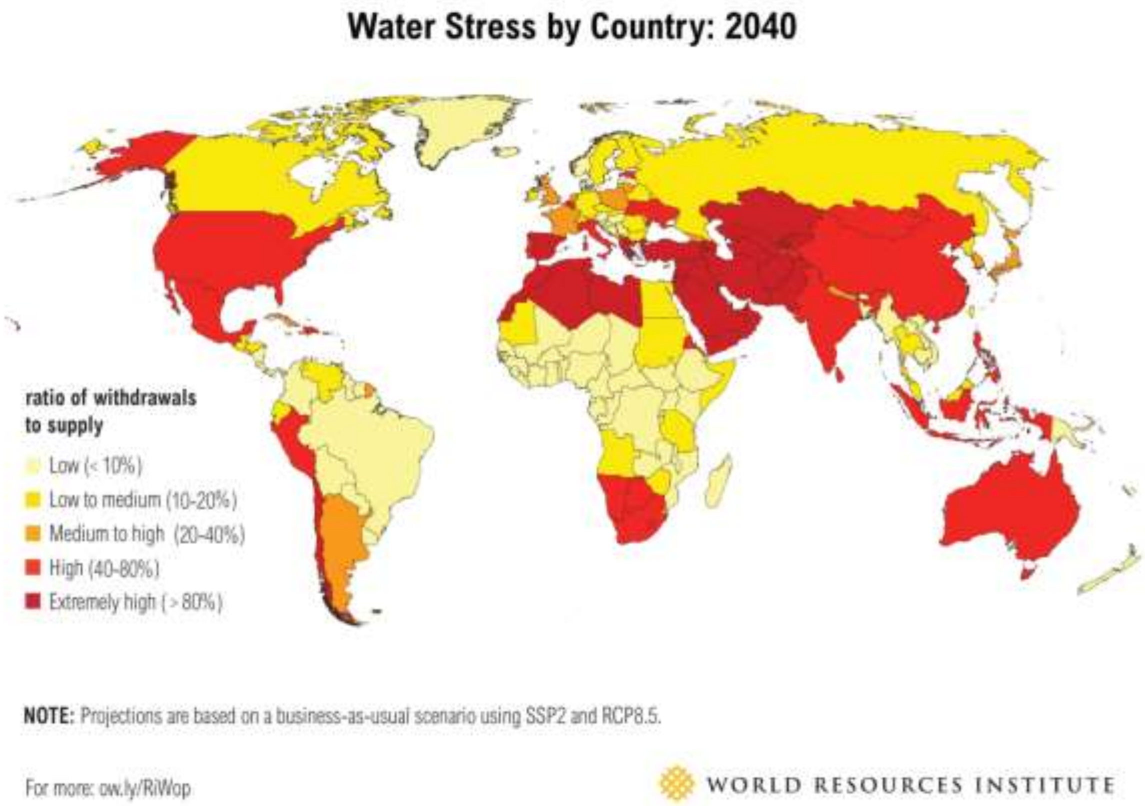


United Nations World Water Assessment Programme, 2012

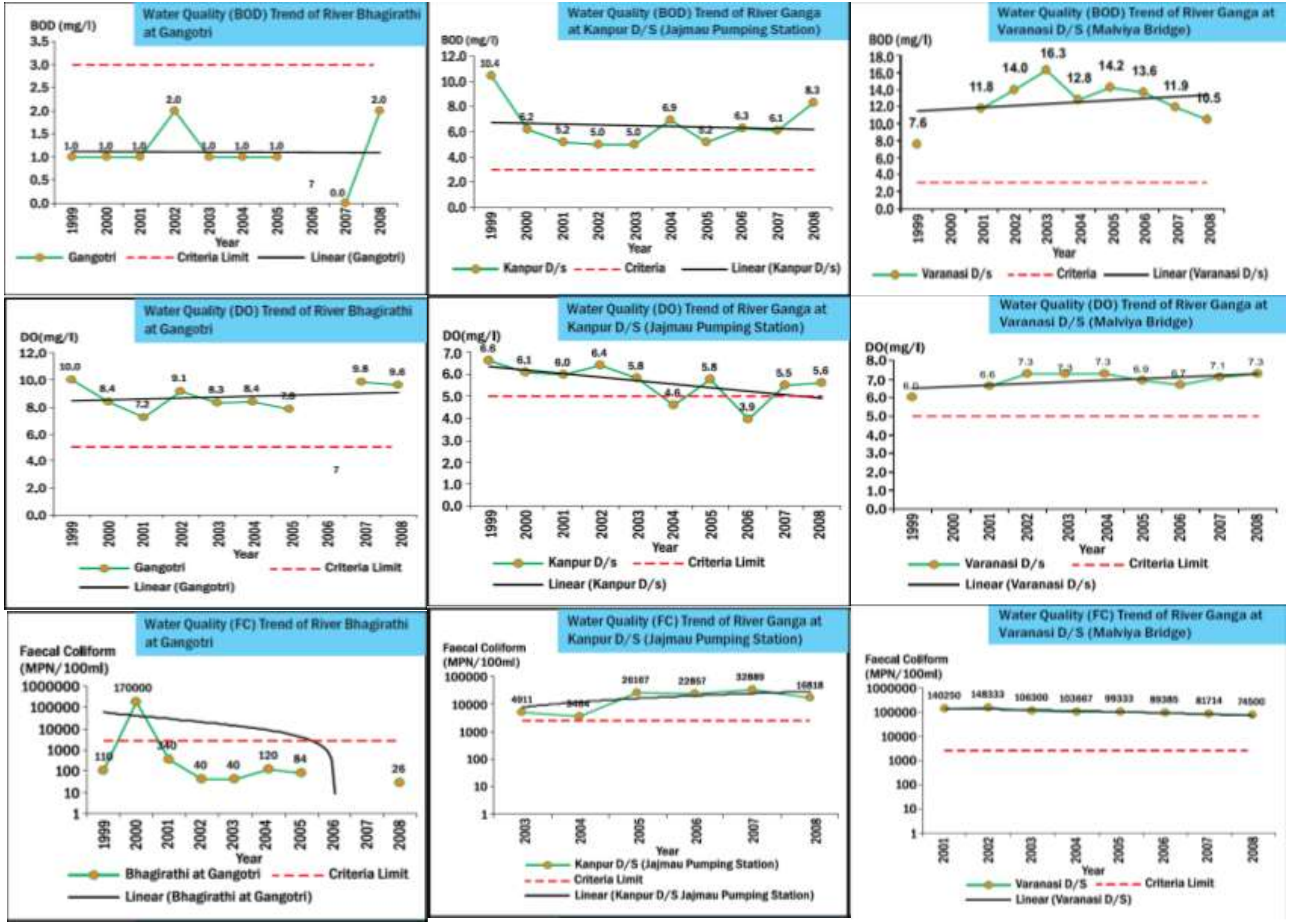


Ministry of water resources, 2003

❖ **The per capita water availability has been going down and will reach critical levels by 2050**

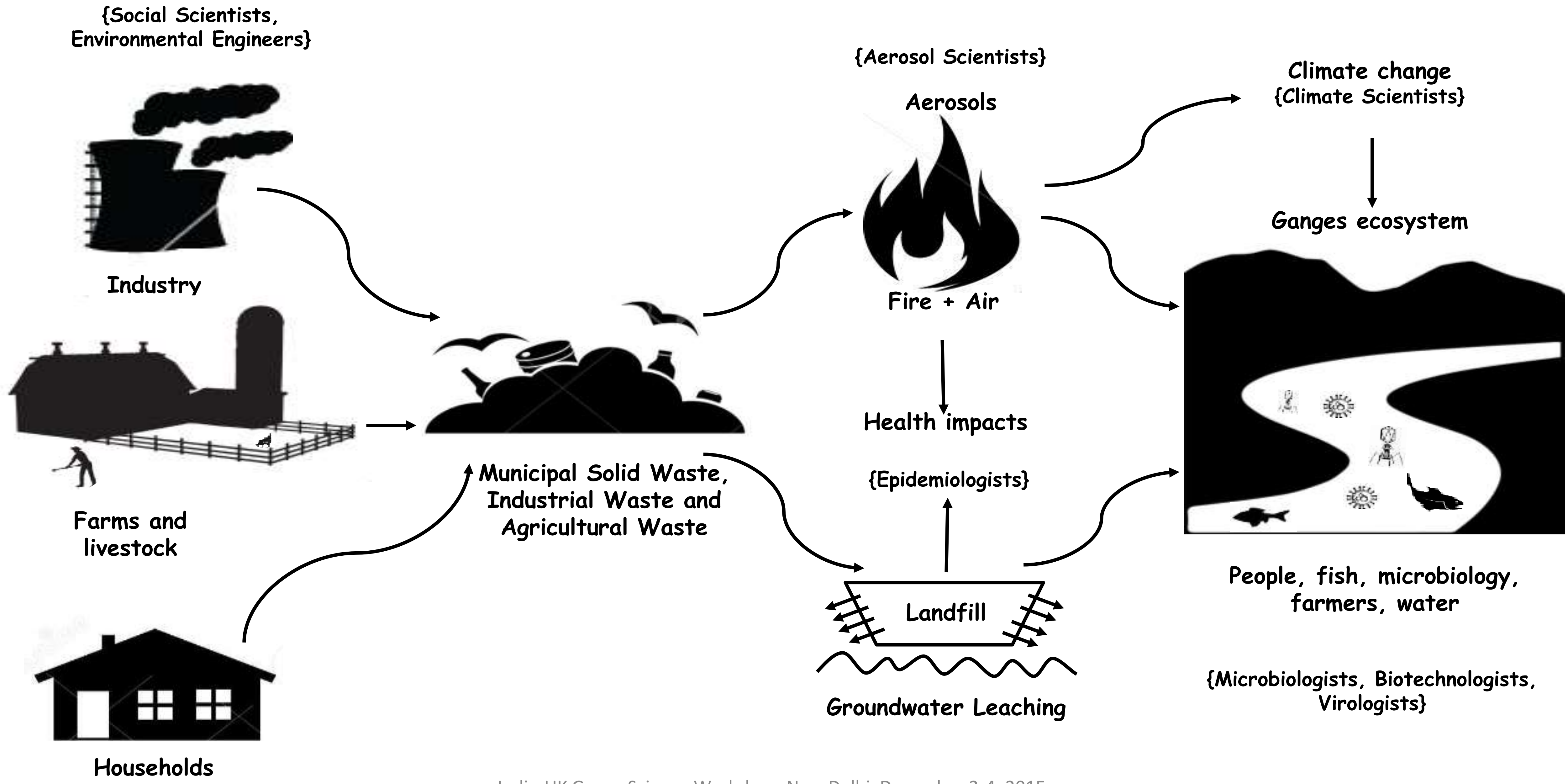


The deteriorating water quality of the Ganges…



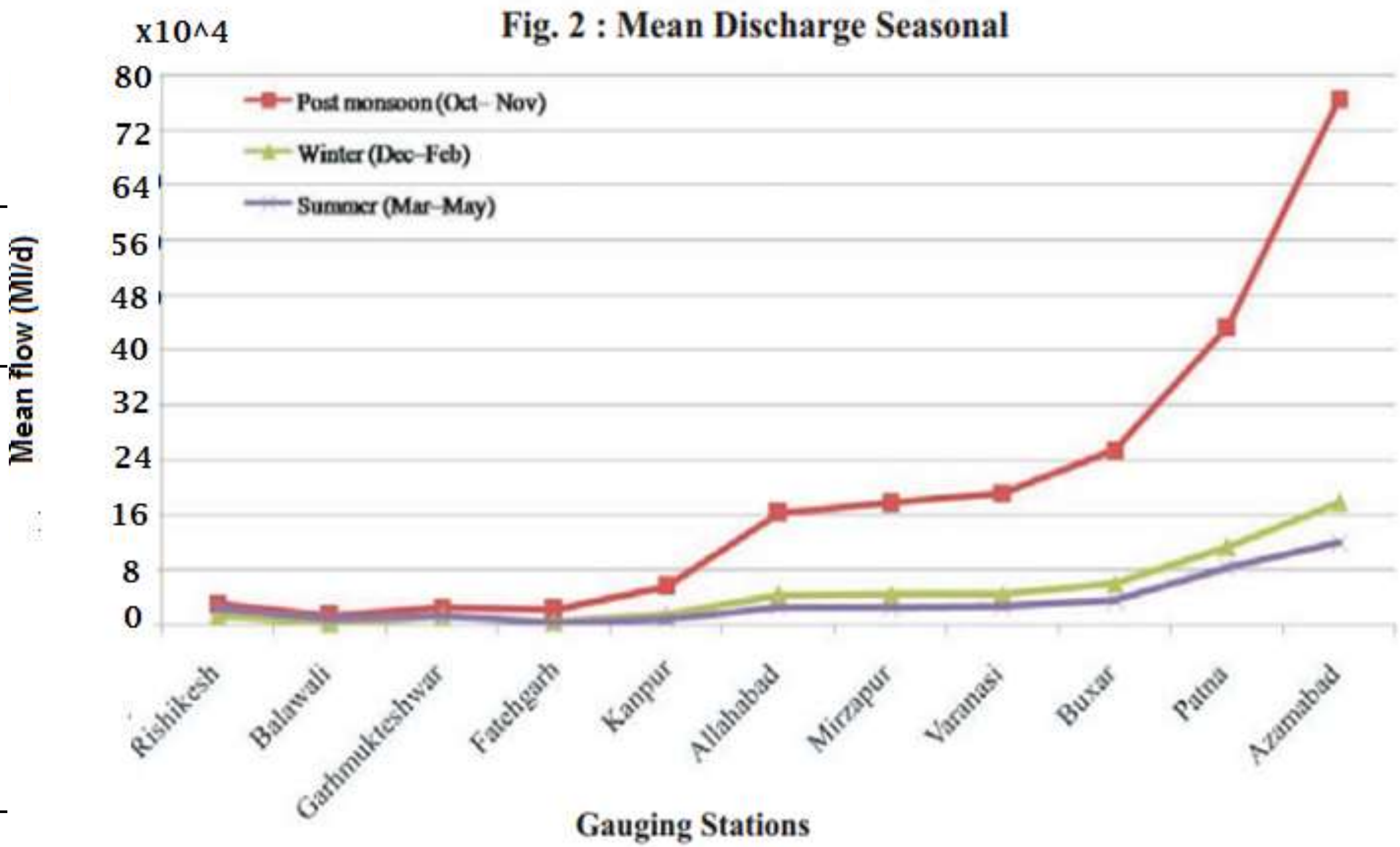
CPCB, 2009

What affects the quality of Ganga water?



Discharge data…

City/Town	Population	State	Total Sewage (Mld)	Capacity of STP (Mld)	Capacity gap (Mld)	Percent treatment capacity (%)
Kanpur	2532138	Uttar Pradesh	339.3	171.1	168.2	50.4
Varanasi	1100748	Uttar Pradesh	187.1	141	46.1	75.4
Allahabad	990298	Uttar Pradesh	208	89	119	42.8
Patna	1376950	Bihar	249.2	109	140.2	43.7
Kolkata	4580544	West Bengal	618.4	172	446.4	27.8
Howrah	1008704	West Bengal	136.2	63.9	72.3	46.9



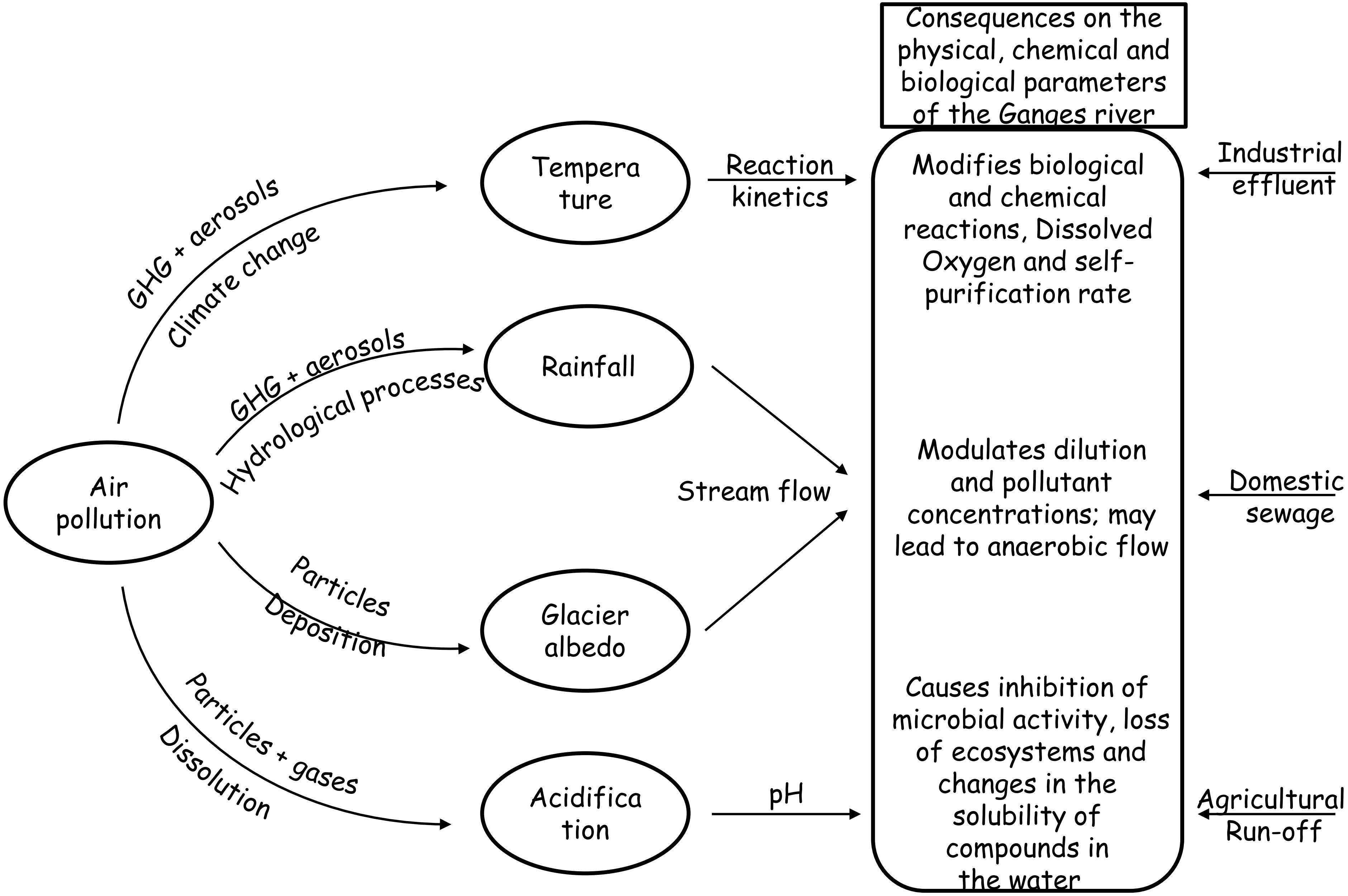
State	Industrial Effluent (Mld)	Municipal Sewage (Mld)
Uttarakhand	3.5	61.3
Uttar Pradesh	152.3	897.8
Bihar	56.2	407.2
West Bengal	79.0	1317.3
Total	285.9	2683.6

Data taken from CPCB

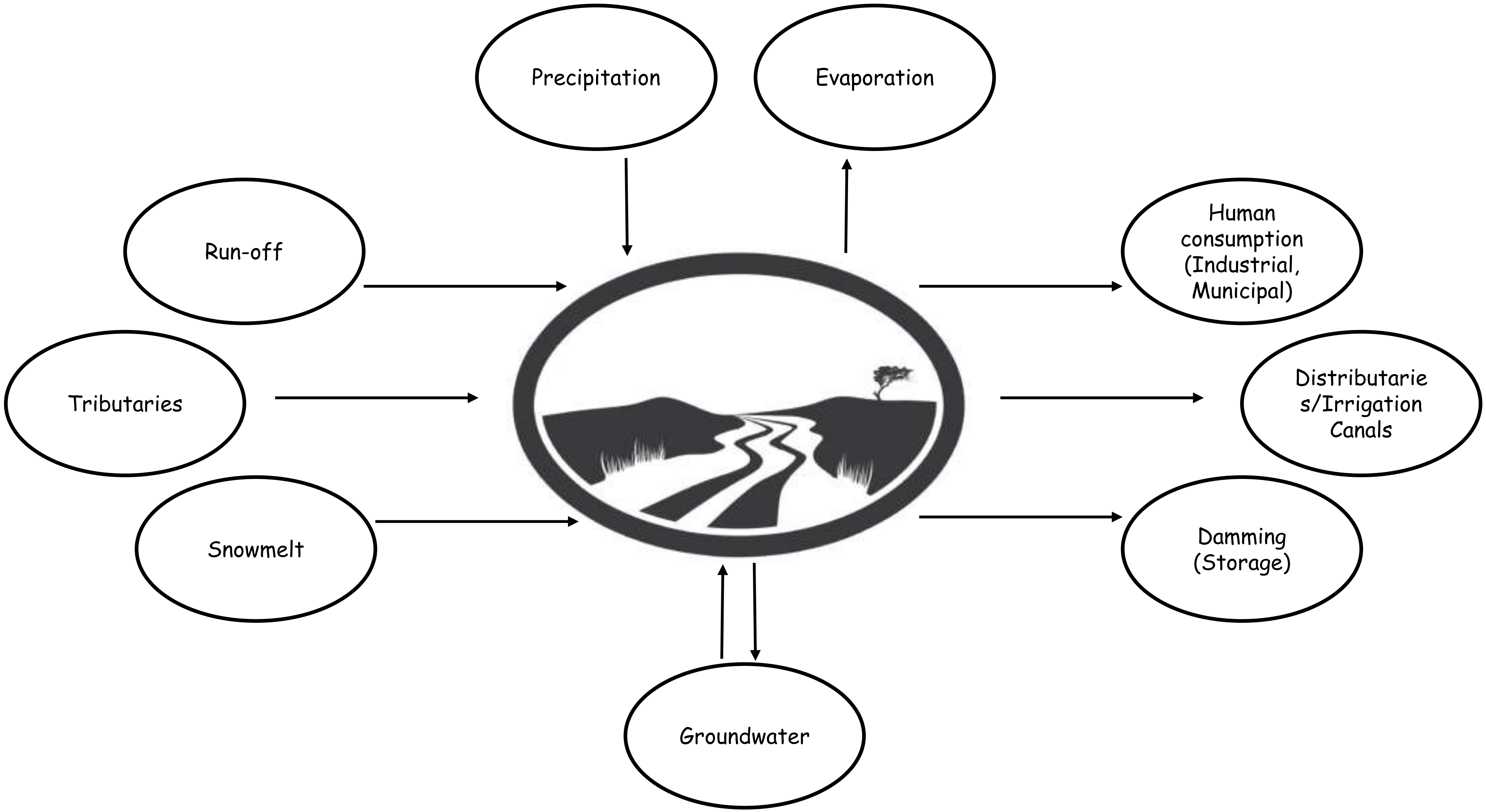
Direct Link to Air Pollution…

- Air pollution deteriorates the water quality through acidification, eutrophication, and bio-accumulation and affects the microbial dynamics, and relations between aquatic organisms and food web.
- Dry and wet deposition of aerosols may add contaminants, especially heavy metals, to river water, thus degrading its quality. For Varanasi, concentrations of six metals [Cd, Cr, Cu, Ni, Pb and Zn] were found to increase consistently corresponding to atmospheric deposition [Pandey et al, 2010, Tropical Ecology]
- Deposition of aerosols on glaciers may contribute to deteriorating water quality through contaminated snowmelt. For Gangetic Plain, for the dry season, contribution of these sources to PCBs (polychlorinated biphenyls) and high molecular weight PAHs (polycyclic aromatic hydrocarbons) can exceed that from diffuse sources within the catchment. [Sharma et al, 2015, Environmental Pollution]

Pathways impacting microbiome and human health…

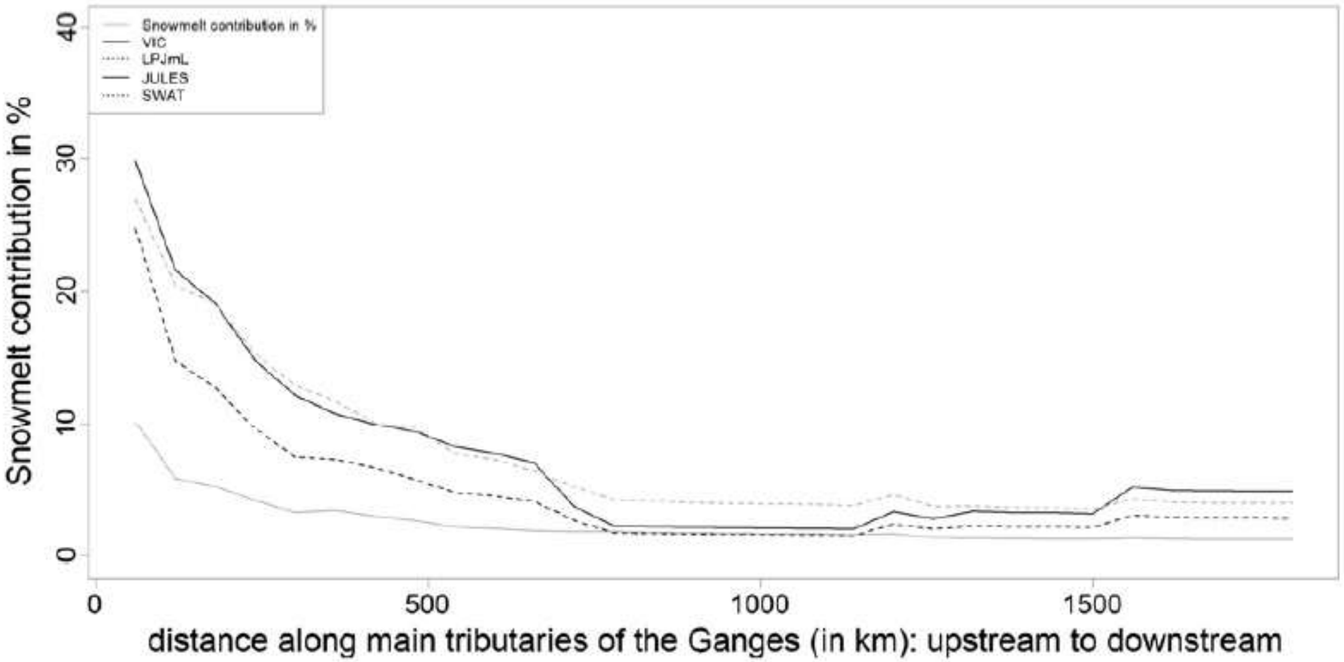


Sources/sinks of River Discharge…

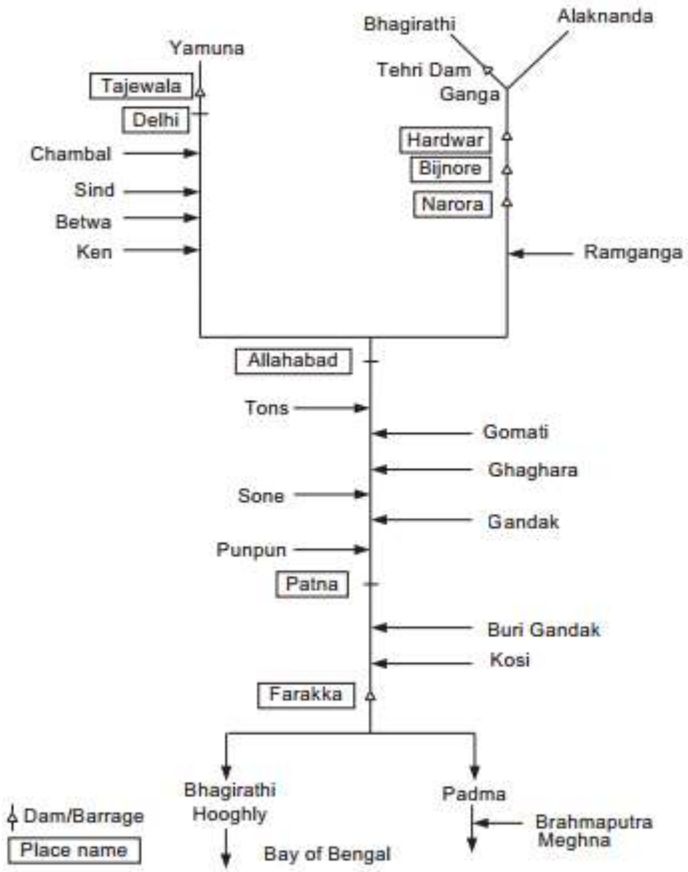


Major sources of water…

- Rainfall is the major source annually, especially the monsoon rains
- During dry season (March-April-May), contribution ranges from 39% to 77% in headwater basins, 16% and 51% 850 km downstream and 12% to 38% at Farakka



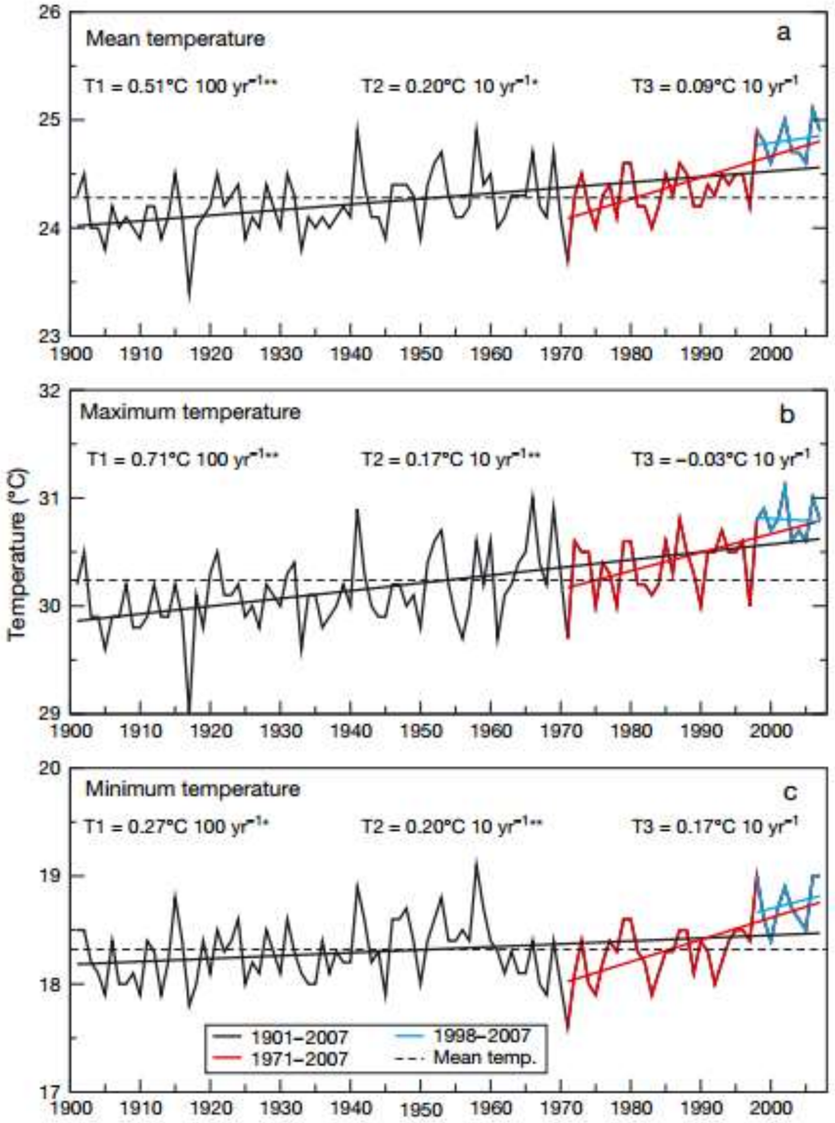
Siderius et al, 2013, Science of Total Env.



Ministry of Environment and Forests, 2009

Observations; climate variables…

Long-term temperature changes over India…

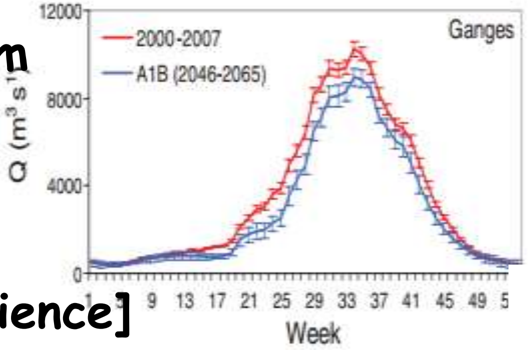


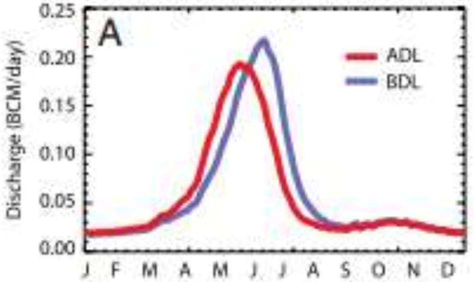
Kothawale et al, 2010, Climate Research

- Temperature data for 121 stations with full time series and 388 stations with climatological normal of temperature all over India analyzed
- Indian mean, maximum and minimum annual temperatures have significantly increased by 0.51, 0.71 and 0.27°C 100 yr–1, respectively, during 1901–2007. However, an accelerated warming was observed during 1971–2007, mainly due to the last decade 1998–2007.
- Like the global case, Indian mean annual and seasonal temperatures also showed a significant warming trend in all seasons. The magnitude of the warming trend of winter and post-monsoon seasons was almost the same for these 2 areas, while pre-monsoon and monsoon temperature trends for India were half that of the global trend.

Climate change and snowmelt…

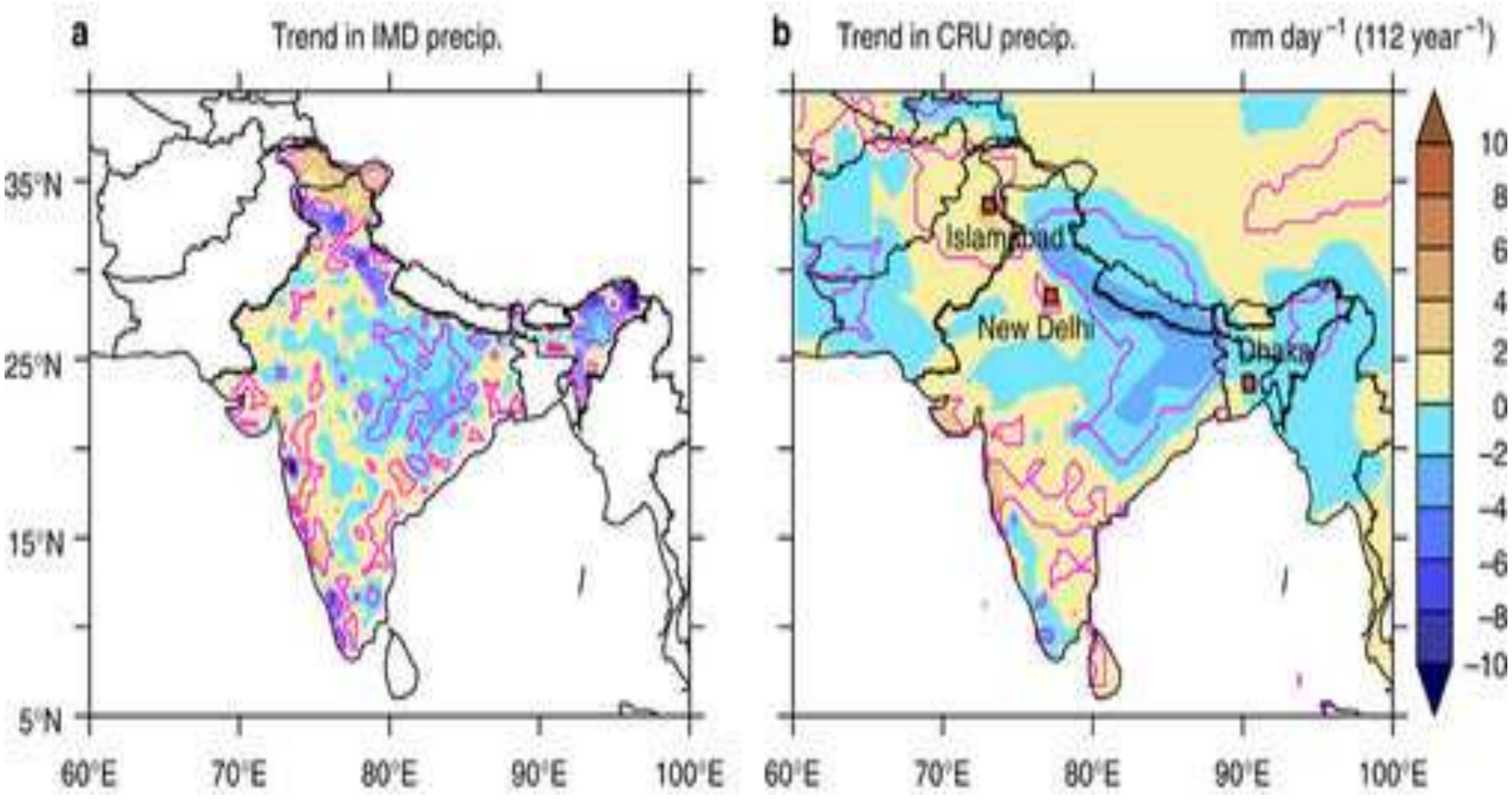
- Gangotri glacier, the major snowmelt source for the Ganges, has been retreating since 1780 and the rate quickened after 1971 [Nasa, 2001]
- 36% of the total recession of the Himalayan glaciers due to deposition of black carbon aerosols [Menon et al, 2010, Atmospheric Chemistry and Physics]
- Study shows a decrease in mean upstream water supply from the Ganges (−17.6%) in the future in spite of increasing precipitation [Immerzeel et al, 2010, Science]
- Increase in radiative forcing due to dust has also been shown to shift the hydrograph for the Colorado river basin. [Painter, et al, 2010, PNAS]





Variable	D	D+I	D+I+SA
NR-TOA (Wm^{-2})	−0.60	0.14	−0.75
NR-Sfc (Wm^{-2})	−1.58	−1.11	−1.22
Atmos. forcing (Wm^{-2})	0.98	1.25	1.97
Snow/ice cover (%)	0.09	−0.46	−0.86
Low cloud cover (%)	−0.02	−0.28	−0.31

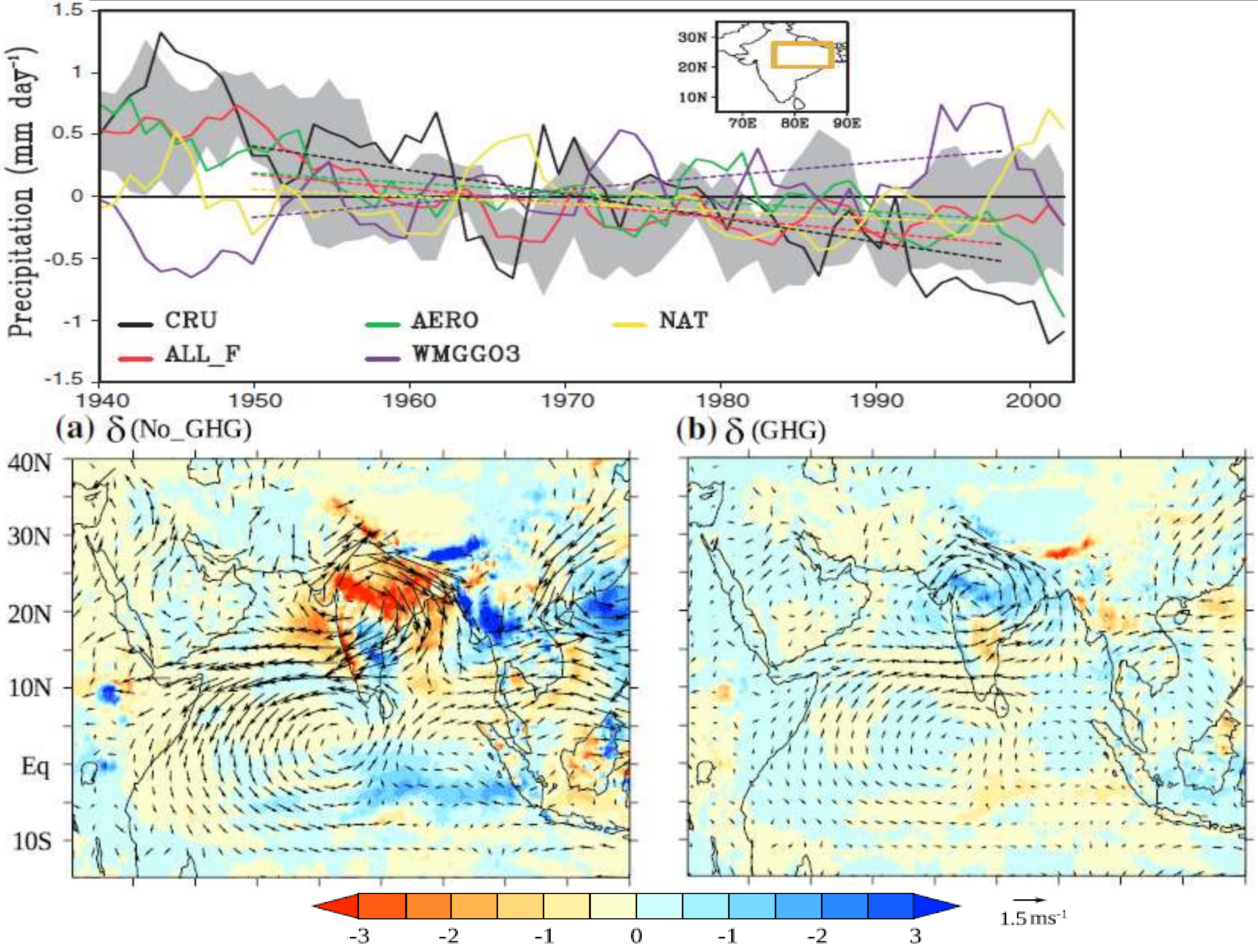
Decrease in South Asian precipitation



Roxy et al., Nature communications, 2015

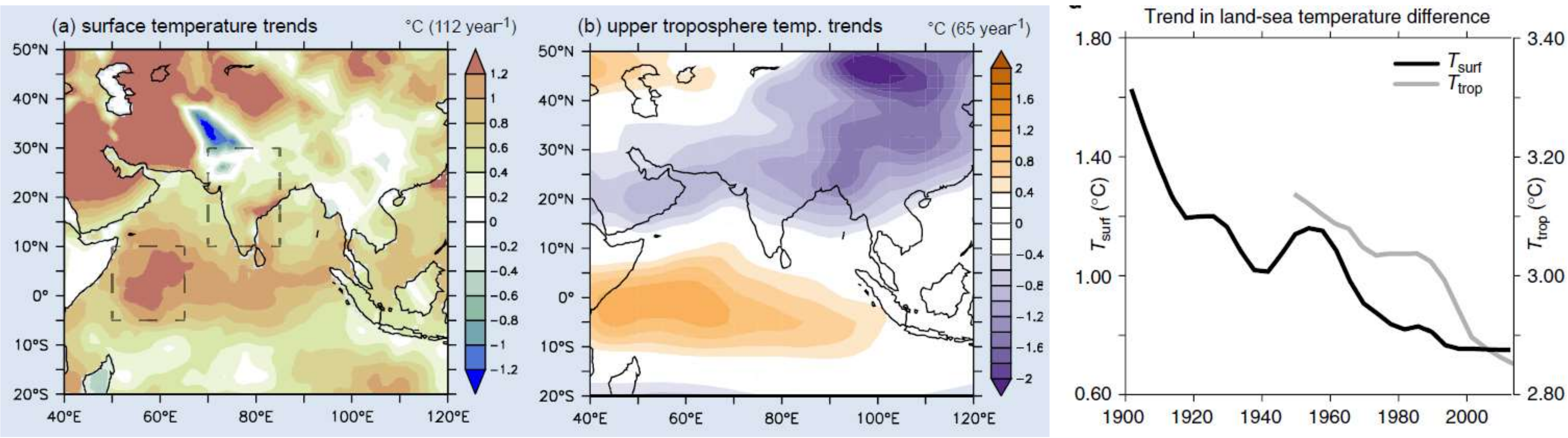
- ❖ Ideally, increase in surface temperature should lead to increase in moisture availability and enhanced precipitation as found at a global scale (Ref)
- ❖ But over India precipitation is decreasing in last half of the century.
- ❖ This can add to the water stress in 2050

Long-term precipitation changes over India…



- Using GFDL coupled atmosphere-ocean GCM, the response of the South-Asian monsoon to the ensemble-mean all-forcing (ALL_F), aerosol-only (AERO), greenhouse gases and ozone-only (WMGGO3), and natural forcing-only (NAT) was tested
- Decrease in precipitation was attributed mainly to human-influenced aerosol emissions [Bollasina, Ming, Ramaswamy, 2011, Science]
- CRU is the measured change in precipitation from 1940-2000
- According to Krishnan [2015, Climate Dynamics], considering all forcing elements other than GHG shows a prominent weakening of the monsoon circulation and a decrease in the June-September rainfall compared to considering all forcing elements including GHG.
- This indicates the aerosol-influence on the decreasing trend of the South-Asian monsoon

Synoptic forcing: Decrease in land-sea thermal gradient

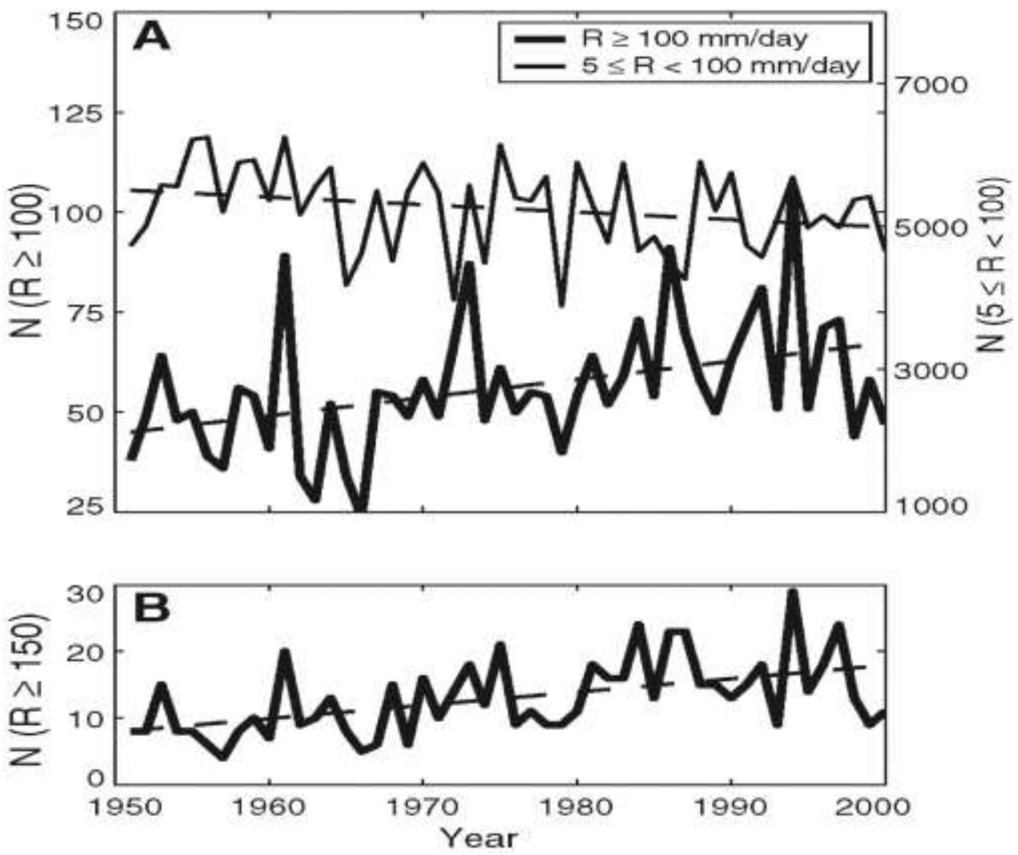


- ❖ **Long-term observational and coupled model simulation indicate that the western Indian ocean is warming at a higher rate than the Indian landmass and hence the land-sea thermal gradient at surface and upper troposphere both show a decreasing trend**

- ❖ **This can be a contributing factor for decrease in south Asian monsoon**

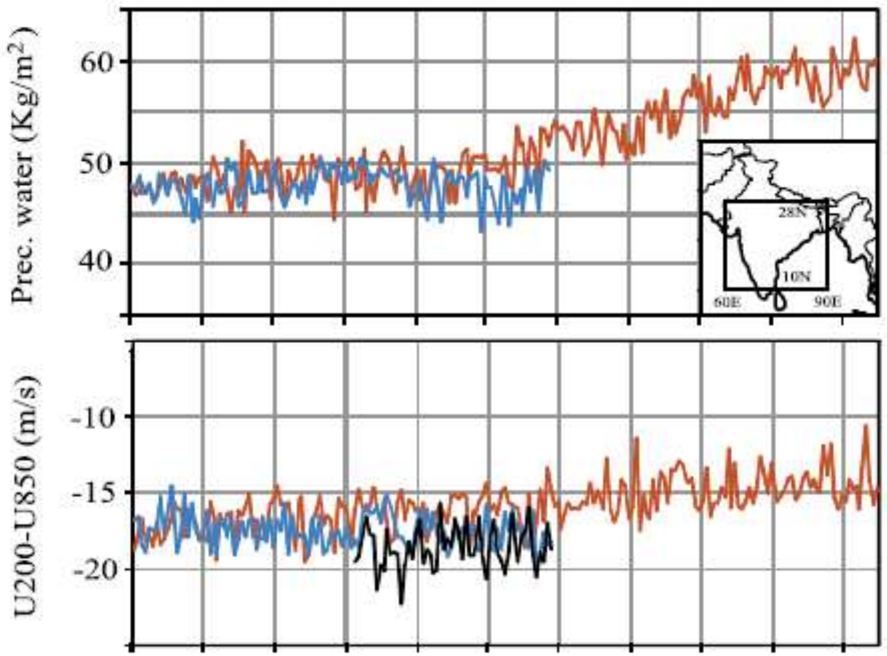
Roxy et al., Nature communications, 2015

Daily rainfall events over Indian landmass



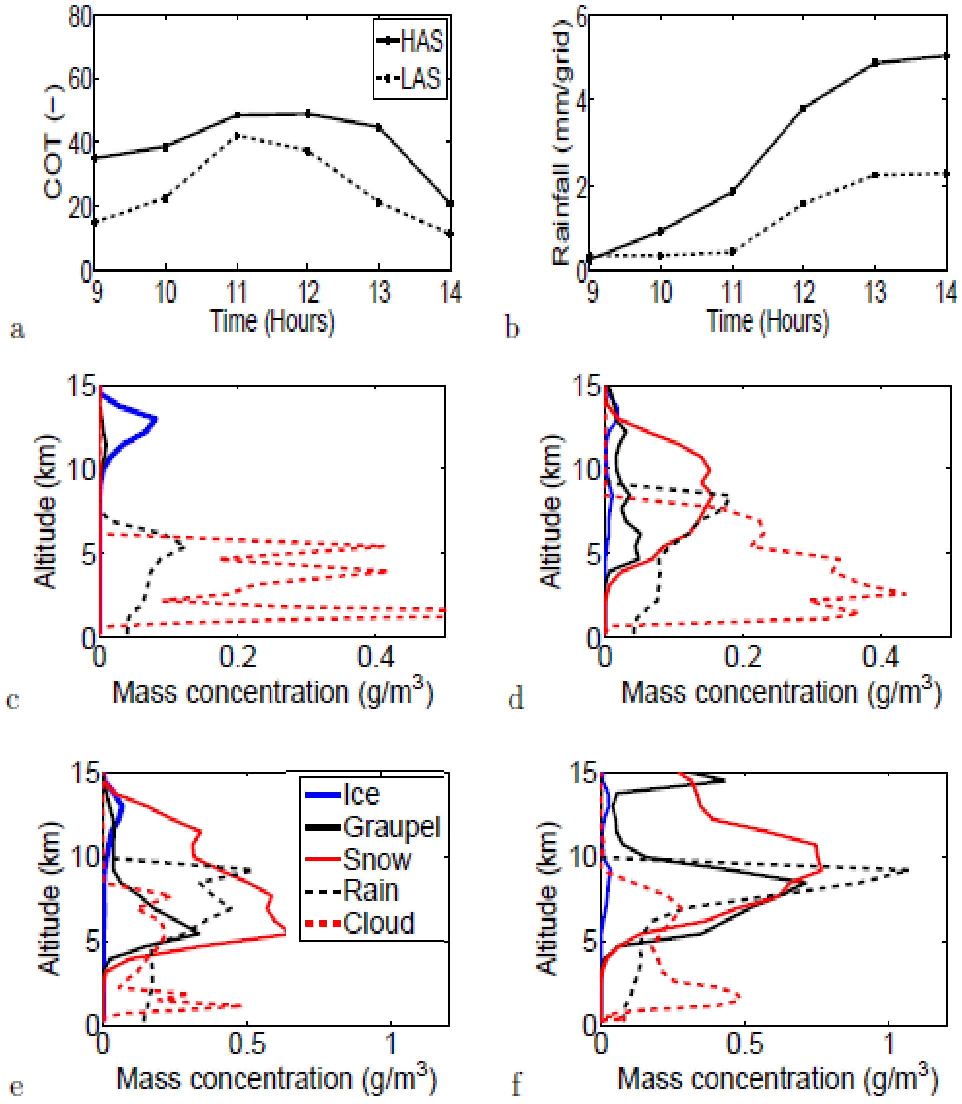
Analysis of IMD gridded dataset shows that frequency of extreme rainfall events are increasing in last century between 15-28 N and 70-90 E

Goswami et al., 2006, Science



- ❖ Recent study [Krishnan, 2015, Climate Dynamics] finds that the increase of atmospheric moisture and decrease of easterly vertical shear of the South-Asian Monsoon circulation provide conditions favorable for localized heavy precipitation occurrences at the expense of moderate monsoonal rains.
- ❖ Blue line = natural forcing; brown line = anthropogenic+natural forcing; black line= NCEP reanalysis data

Aerosol-induced cloud deepening: Cloud resolving WRF-Chem simulation…



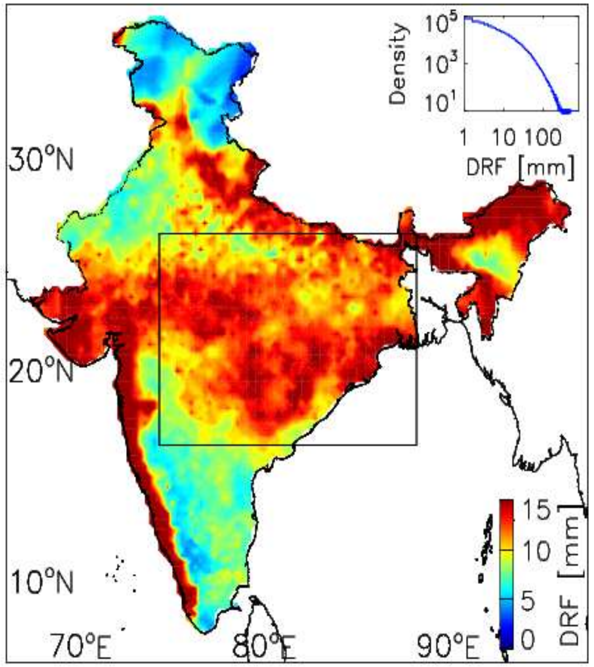
Time series of (a) area averaged COT and (b) accumulated rainfall/grid in domain 3. Vertical distribution of simulated cloud microphysical species at 0900 UTC (c, d) and 1100 hours (e, f). The left column represent low aerosol scenario and the right column represent High aerosol scenario.

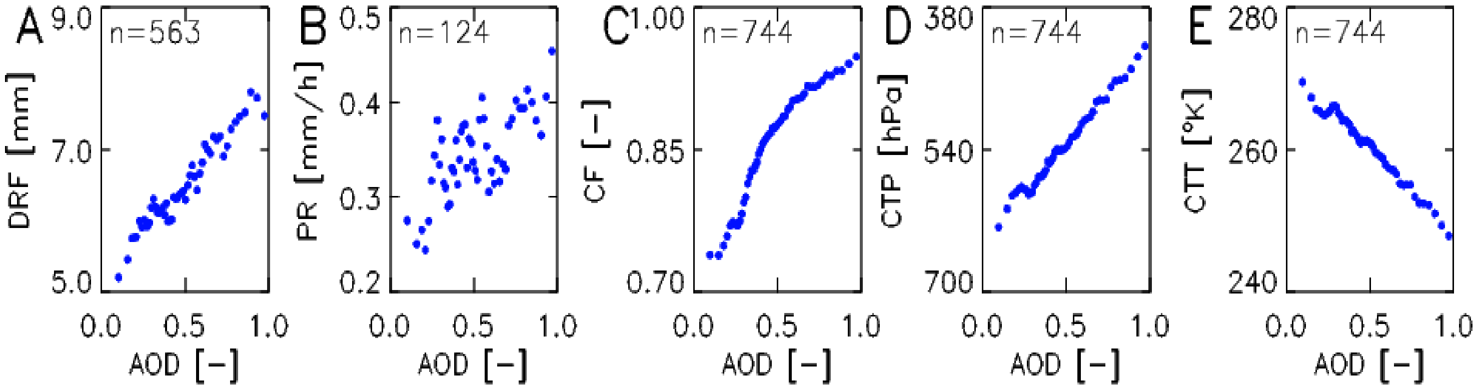
With increase in aerosol:

1. More Cloud droplets and Rain drops were lifted upward
2. Cloud top height increased
3. Mass density of Graupel and snow increased
4. Cloud Optical thickness and accumulated rainfall increased

Sarangi and Tripathi et al., 2015, JGR

Aerosol-cloud macrophysics – daily rainfall associations…

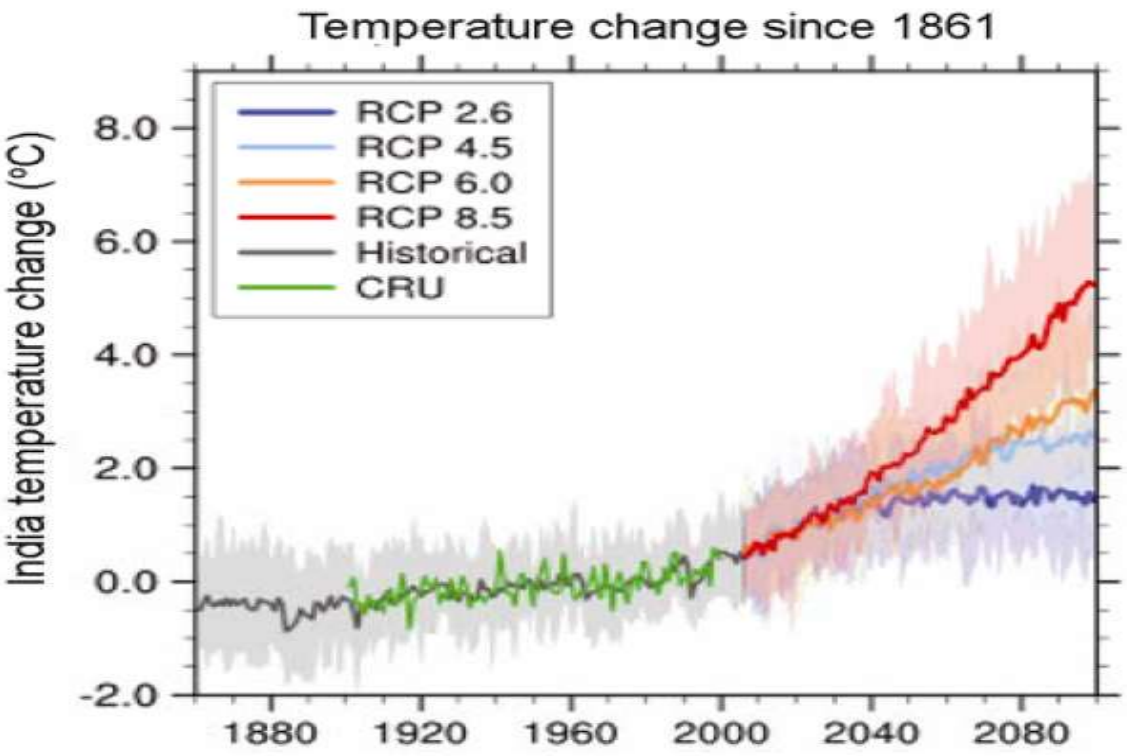


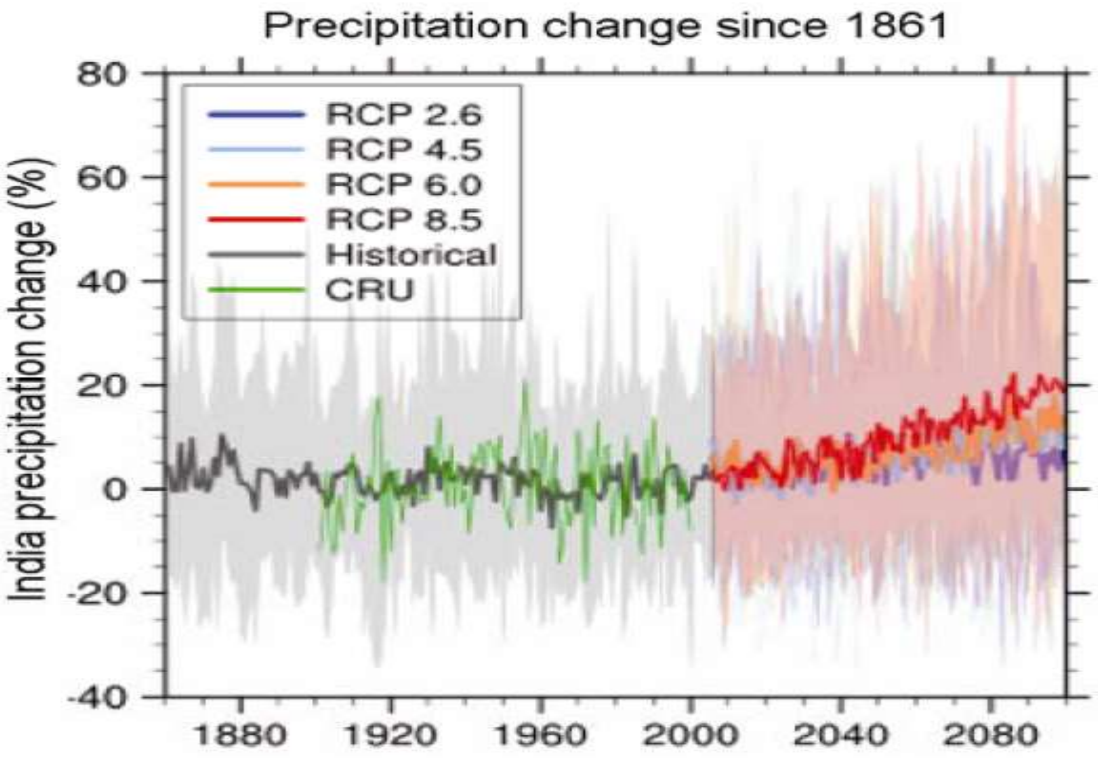


- Gridded datasets (1 deg x1 deg) of Daily rainfall (DRF), Precipitation rate (PR), cloud fraction (CF), cloud top pressure (CTP) and cloud top temperature (CTT) were sorted as a function of aerosol optical depth (AOD), and averaged to create 50 scatter points for correlation analysis
- Only those data samples of DRF, PR and cloud properties were used where collocated AOD measurements were available.
- The analysis shows that with increase in aerosol loading clouds grow deeper and wider, indicating dominance of cloud invigoration phenomena over Gangetic Basin. The invigorating clouds results in intensification of PR and thereby in enhancement of daily accumulated rainfall.
- Meteorology can play an important role, hence additional checks were performed.

GCM simulations; present and future…

CIMP5 models projections…





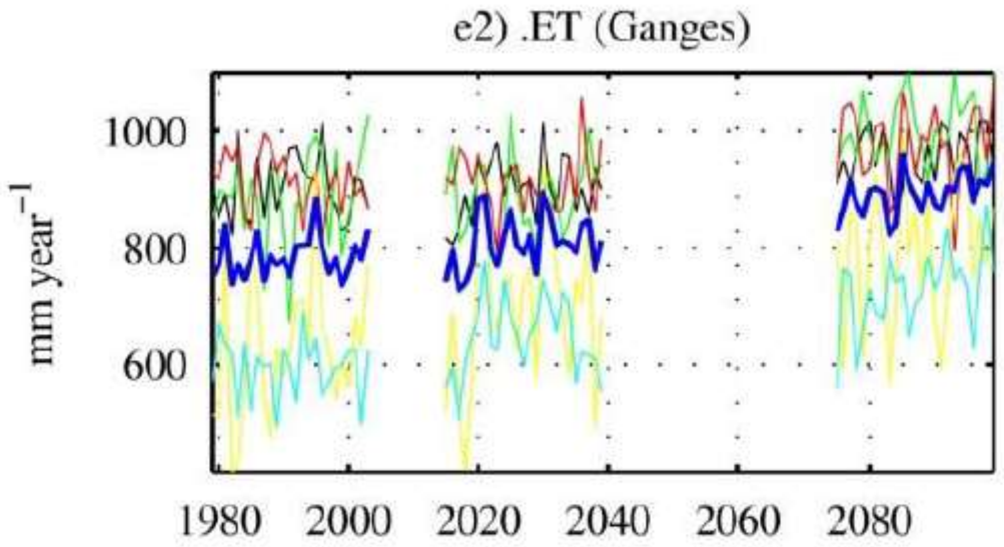
- **CMIP5 model-based time series of simulated temperature and precipitation from 1861 to 2009 relative to the 1961-1990 baseline for the RCP scenario over India using 18 models**

- **CMIP5 models show an increase in Indian rainfall in last century and there is very high variability**

Chaturvedi et al., 2012, Current Science, CORDEX report

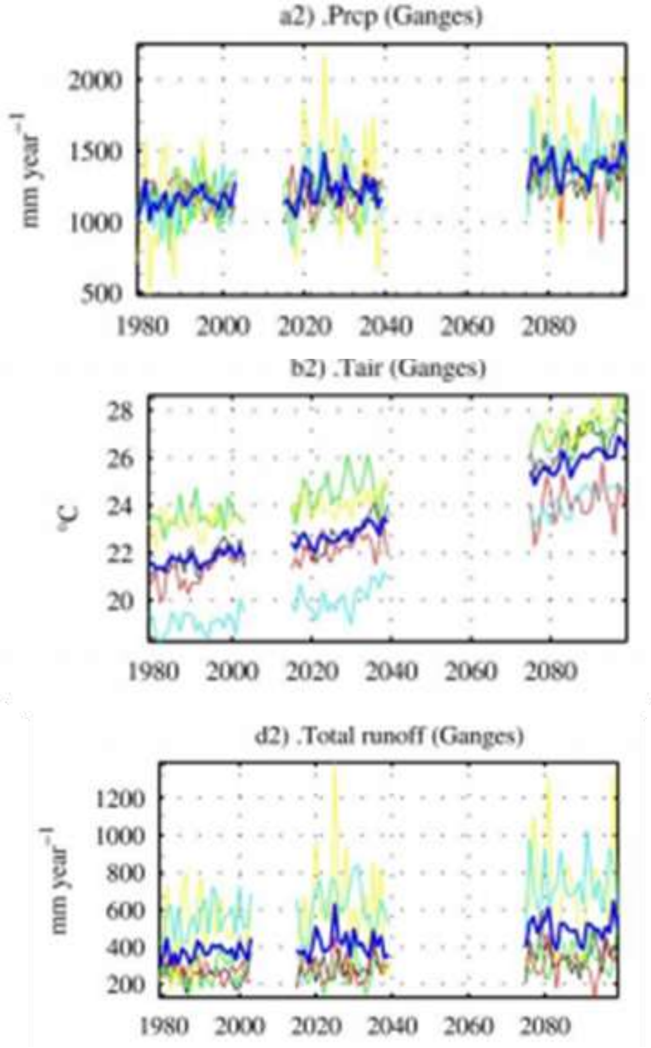
Climate change and evaporation…

- Rising aerosol concentrations in the atmosphere around 1980 led to an increase in river runoff by up to 25% in the most heavily polluted regions in Europe [Gedney et al, 2014, Nature Geosciences]
- The change of ET in the near-future period is relatively low but increases to be quite large by the end of the century [Masood, 2015, Hydrology and Earth System Science]



- Though simulated precipitation minus evaporation (P −E), total runoff (R) and precipitation (P) quantities are neither consistent with the observations nor among the models themselves, most of the models foresee an increase in the inter-annual variability of P-E for the Ganges basin, thus suggesting an increase in large low-frequency dry/wet events [Hasson, 2013, Earth System Dynamics].

Projected implications of climate change in the Gangetic basin



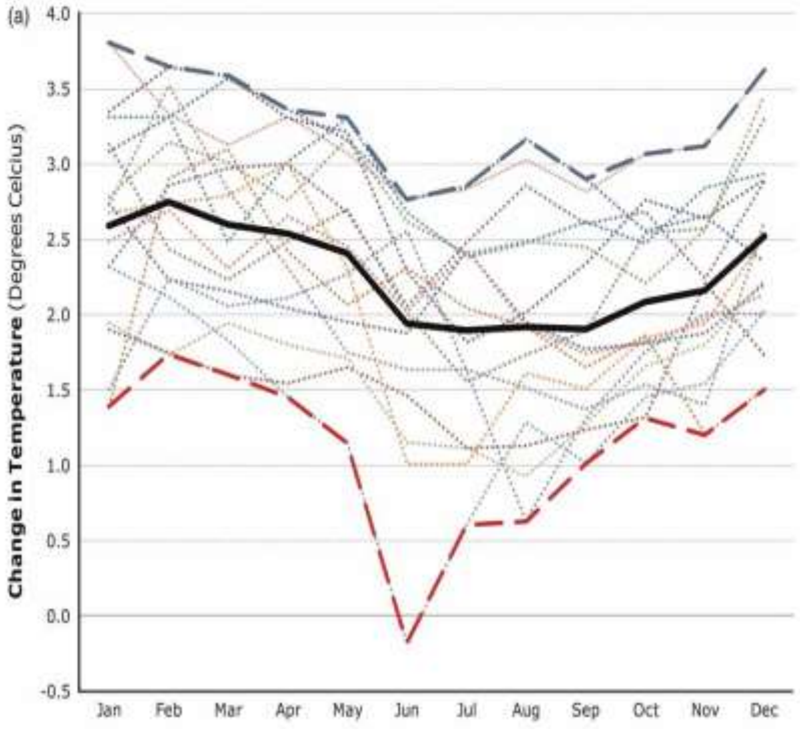
Various river basin scale hydrological model studies using statistical downscaled climate projection from GCMs to predict increase in runoff. Most of these predict increase in river runoff due to increase in precipitation

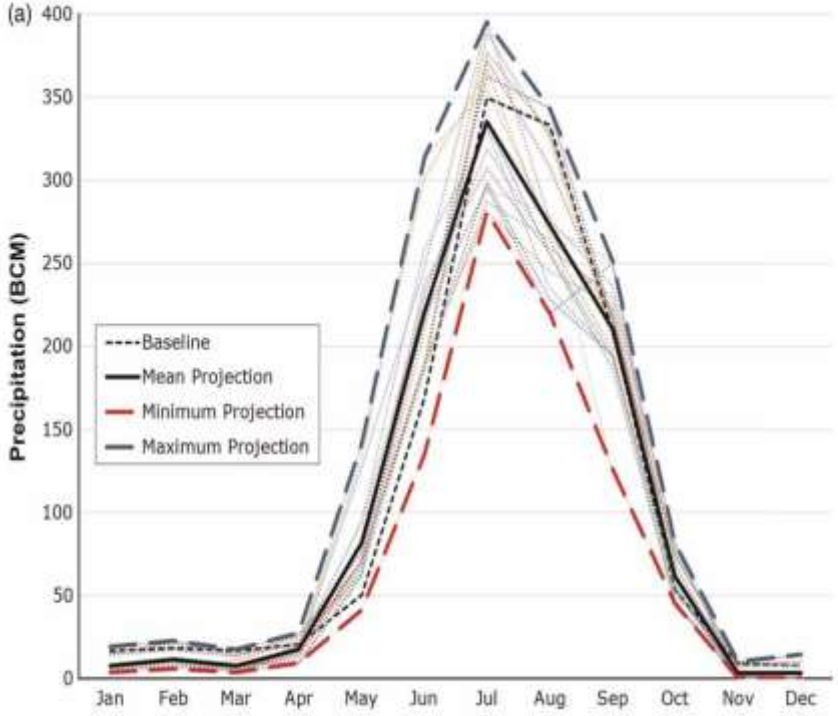
Ganges*	Increase in peak flow	Mirza et al. (2003)
Ganges***	Upstream water supply might decrease by up to 17%	Immerzeel et al. (2010)
Ganges***	Runoff is likely to increase	Lutz et al. (2014)
Tamor **	Decrease in annual runoff	Sharma et al. (2000)
Langtang **	Continuous decrease in glacier area; runoff will increase to mid-century and then decrease, but reduction will be compensated by increase in precipitation	Immerzeel et al. (2013)
Koshi***	Runoff is likely to increase; hydrograph remains constant	Lutz et al. (2014)
Dudh Kosi**	Snow melt contribution will decrease substantially under 2 °C or 4 °C rise in temperature	Nepal et al. (2014b)
Eastern Himalaya***	Reduced glacier volume resulting from decreased snowfall and increased ablation	Wiltshire (2014)

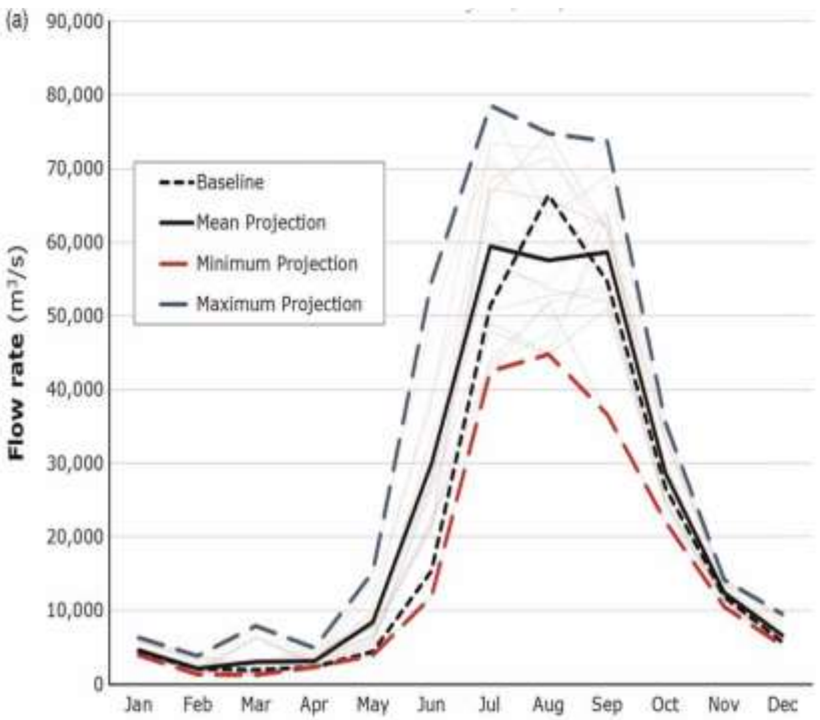
Nepal and Sreshtha, 2015, International Journal of Water Resources Development

In this recent study, CMIP5 climate projections from 6 GCMs was used to force the hydrological model. Increase in T, precipitation and runoff/flow was seen simulated between 1980-2099. Masood, 2015, Hydrology and Earth system sciences

Projected climate change in the Gangetic basin…







- ❖A recent study near Farakka illustrate a more regional overview of Ganges.

- ❖Range of projected temperature change, precipitation and basin flow rate at Farakka in in 2040-2069 relative to 1961-1990 (baseline) based on 16 GCM results for A2 emission scenario [Jeuland et al., 2013, Water Policy]

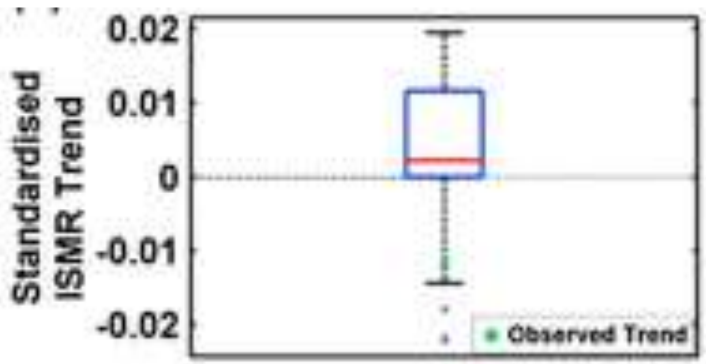
- ❖A large variability can be seen till a factor of 2.

Failure of GCM studies…

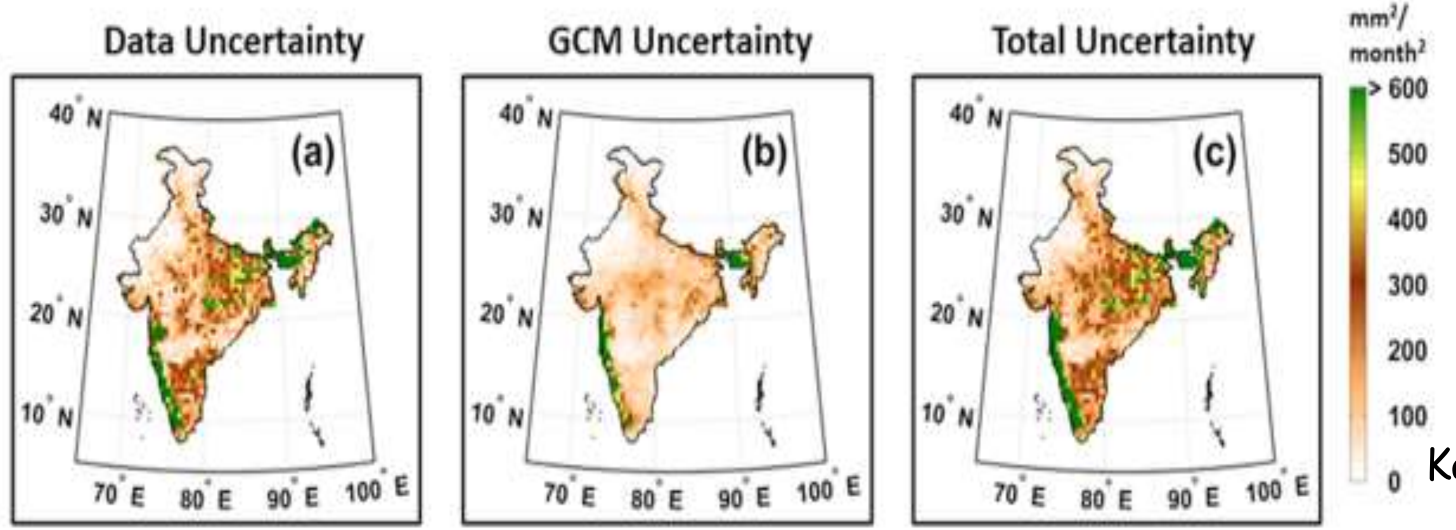
- **Future emission scenarios:** Large uncertainties are there in possible future scenarios. According to IPCC Special Report on Emissions Scenarios, these differences will only have major consequences for projections beyond 2050
- **Model uncertainties:**

1. Uncertainity involved in physical parameterizations.
2. Due to incorrect representation of intial conditions.
3. Due to limitations in computing power and coarse resolutions used in GCM studies

- **Data uncertainty:** Use of multiple observed and reanalysis data products in model calibration can also lead to uncertainty



- The green dot is the linear trend of
  ISMR for the period 1950-2005
- The linear trend of ISMR, as simulated by 42 GCMs, is presented in terms of box plot
- Only 9 out of 42 models show statistically significant negative trends, and the observed trend is very close to the negative outliers [Saha et al, 2014, GRL]



Kannan, 2014, GRL

Synopsis of Hydrological modelling in the Gangetic basin…

Model	Application	Area	Source	Ganges application
SWAT	Process-based continuous hydrological model	Ganges basin 414 sub-basins Daily	Gosain et al. (2011) World Bank (2012)	Water availability and basin water balance under climate change GSBA - water balance, irrigation use, water quality, and climate change implications on hydrology in a more detailed spatial perspective; water quality implications of scenarios
MIKE-BASIN MIKE 11 hydrodynamic; MIKE 21 salinity	Hydrological and hydrodynamic models	Ganges Basin Daily ~100 sub-basins	World Bank (2012) IWM Bangladesh	GSBA – system linkages, hydrological impact of development and climate scenarios. Linked to economic optimisation
GSBA economic optimisation model	Node and link network	Ganges Basin (77 inflow nodes; 29+23 dams, 34 irrigation nodes) Annual	World Bank (2012)	Economic value of hydropower, irrigation, reduced flood damage; increased low flows
SWAT	Process-based continuous hydrological model	Upper Ganges Basin 2000 – (2005) 21 sub-basins Daily – calibrated monthly	Bharati et al. (2011)	Impacts of CC and infrastructure on hydrology
SWAT		Simulated daily, accumulate to monthly 21 sub-basins	WWF (2011)	Environmental flow requirements
CPWF water account (Ganges)	Top-down lumped model	Ganges basin monthly 14 sub-catchments	Eastham et al. (2010a, b)	Simple basin scale water account
HEPEX	Lumped catchment model (CLM) and a sub-catchment distributed model (SDM) – coupled nonlinear two-layer model	Ganges and Bramaputra SDM uses 0.5o grid Daily	Hopson and Webster (2010)	Operational real-time forecasts of river discharge into Bangladesh at daily to seasonal timestep – flood forecasting
"Super-Model" Run since 1998	MIKE11 HD linked to MIKE 11 RR	Bangladesh including Ganges Daily 16 stations	http://www.ffwc.gov.bd/	Bangladesh Flood Forecasting and Warning Centre (FFWC) - Flood forecasting – operational, daily 1D hydrodynamic model (MIKE 11 HD) incorporating all major rivers and floodplains. linked to a lumped conceptual rainfall-runoff model (MIKE 11 RR) which generates inflows from catchments within the country.
WEAP	Water allocation	Ganges basin 53 sub-basins upstream Farakka; 65 in all monthly	de Condappa et al. (2009)	Assessment and planning of water resources, contribution of glacier melt, impact of climate change
Snowmelt Runoff Model			Seidel et al. (2000) Bharati et al. (2011)	Runoff regime of the Ganges and Brahmaputra basins
Satellite altimetry Topex/ Poseidon		Bangladesh	Biancamaria et al. (2011)	Flood forecasting Biancamaria et al. (2011)
PAR	periodic autoregressive model		Mondal and Wasimi (2006)	Monthly flow forecasting and generation
LPJmL model	Global dynamic vegetation and hydrology model,	Ganges basin 0.5° resolution	High Noon Project (no date, http://www.eu-highnoon.org/datatools/applied-methods)	High Noon project - impacts of climate change on mountain regions Also uses SWAT. Includes crop growth and reservoir operation modules
HECS-HMS		Indian part of Ganges basin 1965–68.17 sub-basins, 37 reaches Simulated daily based on monthly data	Gosardji et al. (2008)	National River Linking Project No snowmelt method; no diversions, dams, or irrigation
Water quality model	Discharge as function of tributary watershed area using ANCOVA; combined with multiple linear regression of pollutant loadings	Ganges basin	Lacy (2006)	Pollutant loads and water quality to assess Ganges Action Plan
ANN (Artifical Neural Networks)	Data driven model using travel time and flowlength.	Ganges basin 1 km2 DEM 0.25 TRMM Daily	Akhtar et al. (2009)	Flow forecasting using satellite rainfall data Alternative to forecasting with hydrological models
Stochastic flow prediction	Stochastic Thomas - Fiering model	Monthly Ganges Basin inflows to Bangladesh	Tarekul and Yoshihita (2009)	Planning of water resources projects in Ganges dependent area in Bangladesh

- ❖ **Lack of publicly available discharge data due to transboundary flow of river limits calibration of hydrological models [Condappa et al, 2009, Water International]**
- ❖ **No examples of basin scale groundwater models were found in the literature [Johnston et al, 2014, Water resource Management]**
- ❖ **Rainfall-runoff modeling studies in Bangladesh found limits of forecasting lead time of 2–3 days, which could be considerably improved if more timely upstream data were available [Hossain and Katiyar, 2006, Earth and Space Science News]**

The problem of scale: Downscaling

- The modelling scale is much larger or much smaller than the observation scale. To bridge that gap, 'scaling' is needed
- *To scale*, literally means 'to zoom'; *upscaling* refers to transferring information from a given scale to a larger scale
- *Downscaling* refers to transferring information to a smaller scale.
- *Regionalization* involves the transfer of information from one catchment (location) to another.
- One of the factors that make scaling so difficult is the heterogeneity of catchments and the variability of hydrological processes.

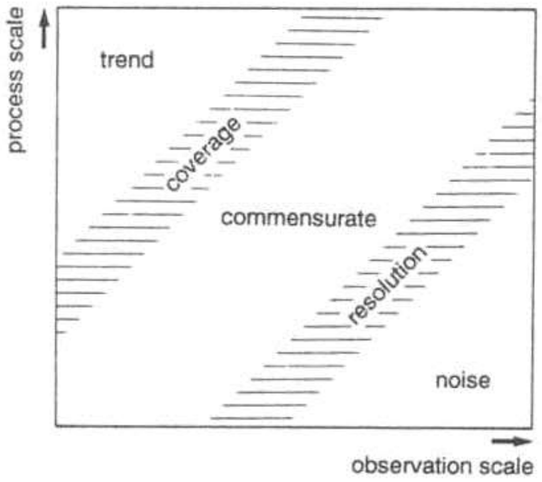
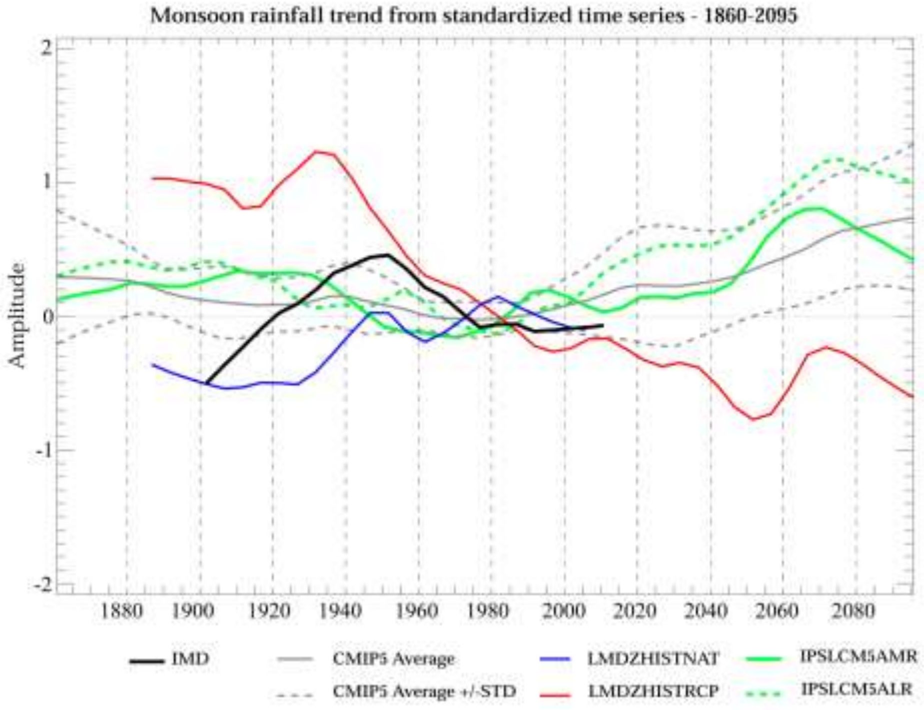


Figure 5. Process scale versus observation scale

Blöschl, 1995, Hydrological Processes

- The problem of scale may explain the increasing trend of South-Asian Monsoon predicted by the CMIP5, which is not seen in the IMD observations since 1940

- The high resolution LMDZ4 model with RCP4.5 emission scanerio (red line) replicate the decline in the South-Asian Monsoon and lie outside the average+/-std of the CMIP5 model predictions [Krishnan, 2015, Climate Dynamics]



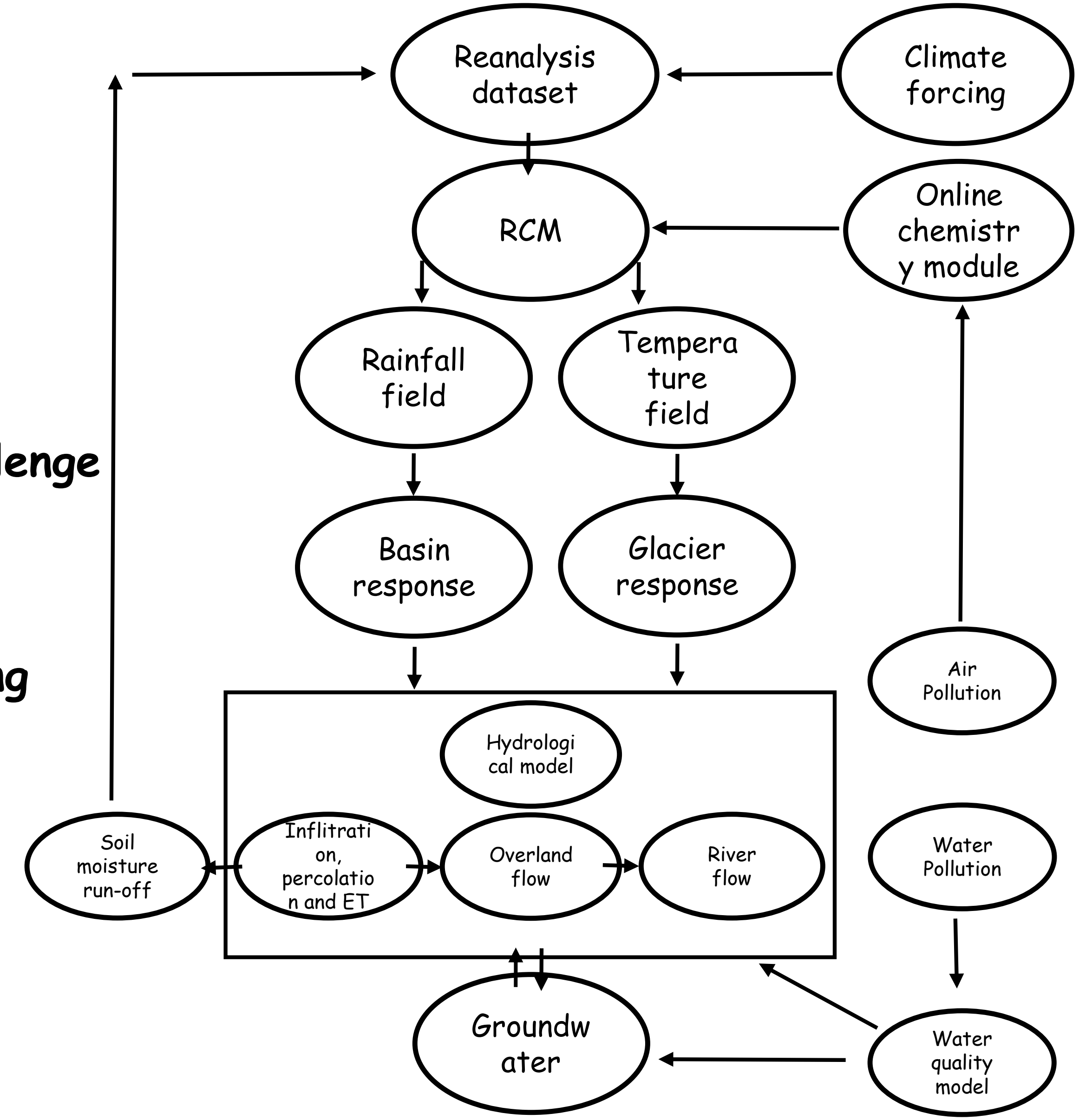
Chemistry aware coupled atmospheric-hydrological models

- ❖ **Atmospheric models provide boundary conditions (precipitation, energy and fluxes) to hydrological model whereas hydrological model returns moisture and energy fluxes as feedback to atmospheric model to produce full water budget.**

- ❖ **Reconciling incompatible time scales between atmospheric and hydrologic processes is a great challenge when coupling atmospheric and hydrologic models**

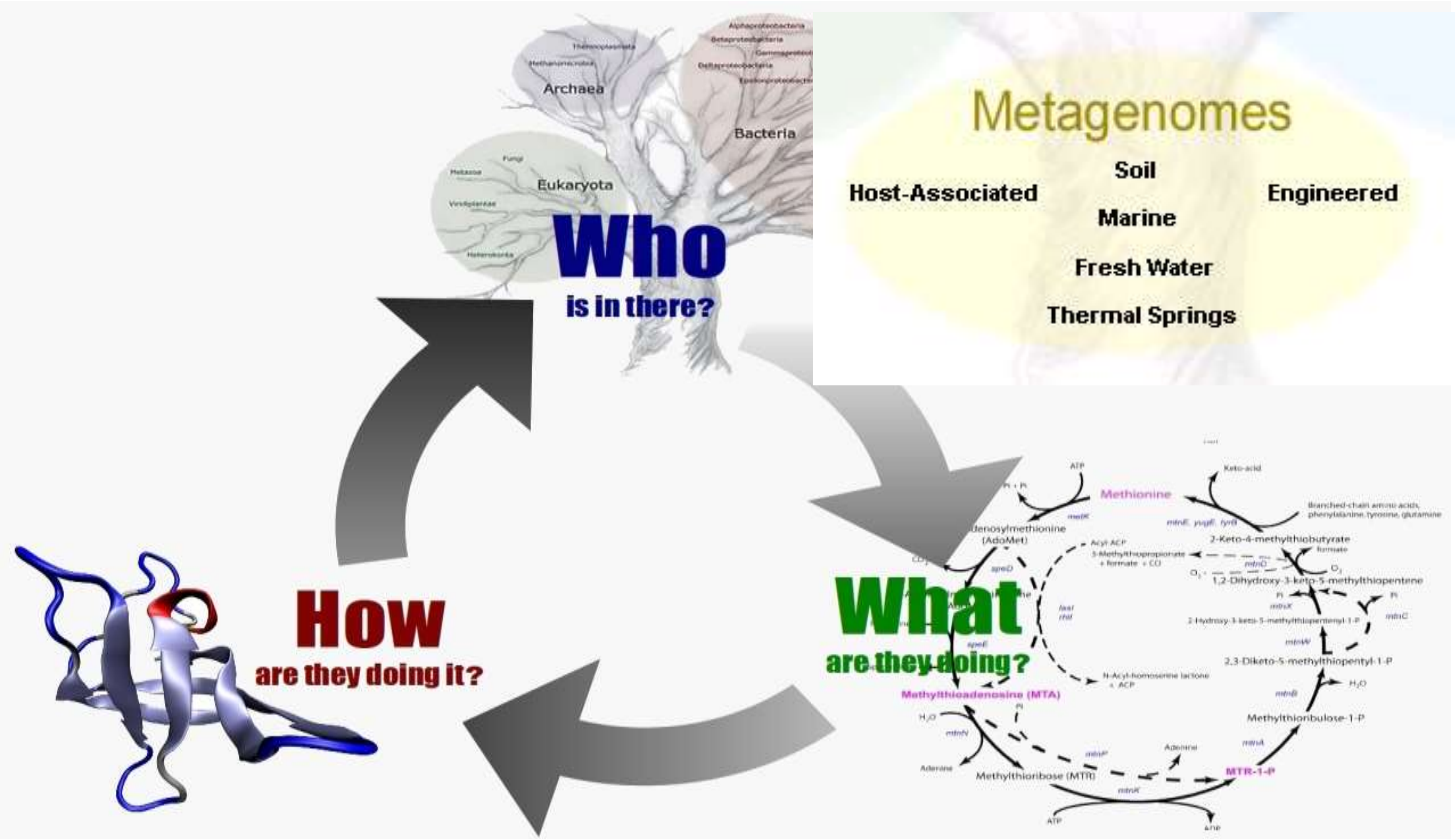
- ❖ **An improvement in the annual mean runoff simulation was seen for the Upper Danube catchment by coupling the RCM MM5 and the hydrological model PROMET [Zabel, et al, 2013, Hydrological and Earth System Sciences]**

Model configuration	Runoff
NOAH	1712 $m^2\,s^{-1}$
PROMET, 1-way coupled	1583 $m^2\,s^{-1}$
PROMET, 2-way coupled	1474 $m^2\,s^{-1}$
Measurements	1412 $m^2\,s^{-1}$



Adapted from Goswami and Himesh, 2002

Unraveling the Science behind non-putrefying properties of Ganga



http://www.cbs.dtu.dk/researchgroups/metagenomics/metagenomics.php

Sampling and Profiling of the microbial system

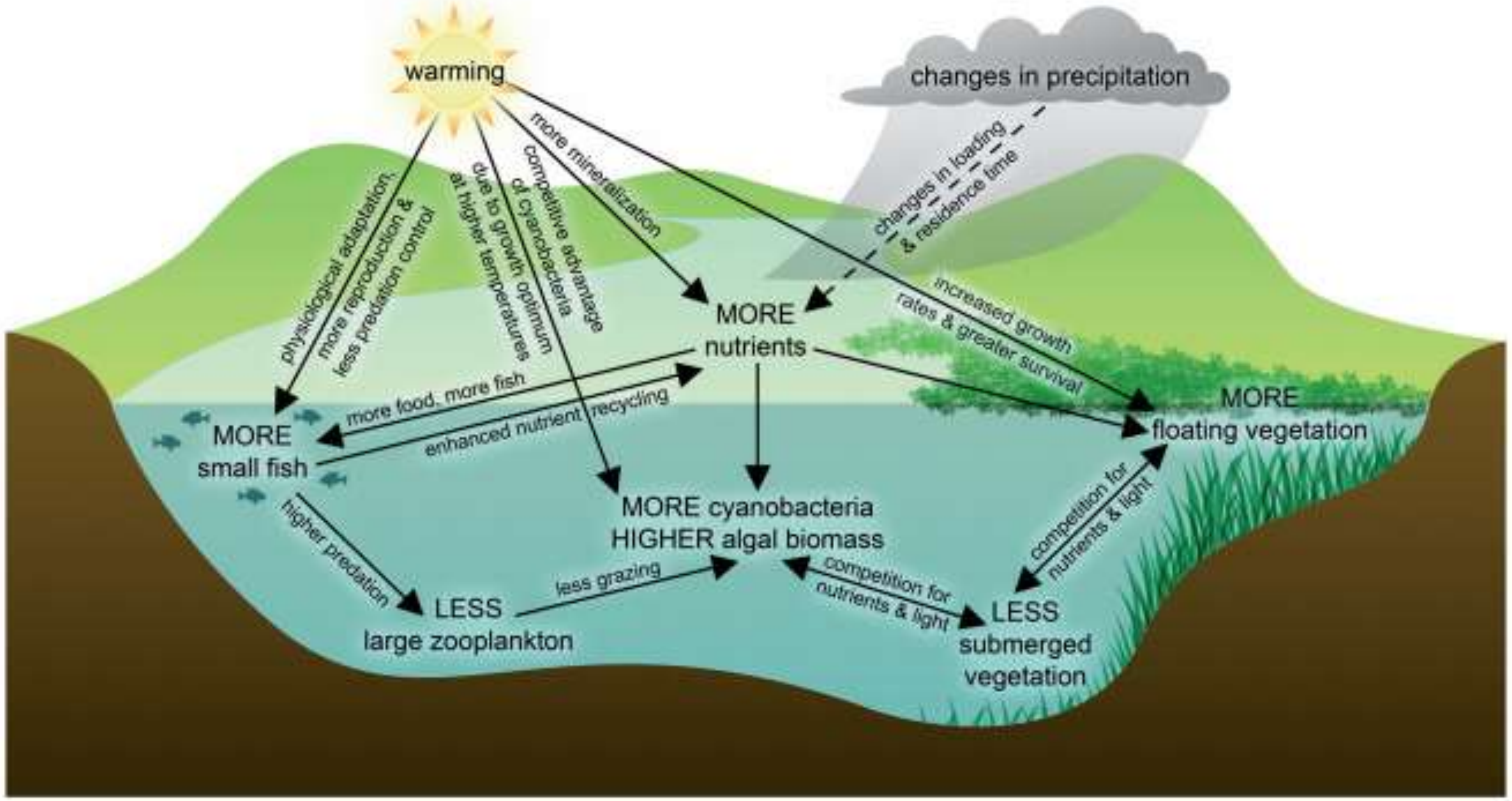
❖ **Profiling of Bacteriophages/pathogenic bacteria across the Ganges basin and novel techniques to identify and characterize the microbial diversity of Ganga water and its tributaries, and environmental sustainability.**

Location	**Detected Waterborne Pathogen (multiple hits)**
Ganges - Haridwar	None*
Ganges - Kanpur	Rotavirus A; Campylobacter; ETEC LT; Giardia
Yamuna - Agra	Campylobacter; Shigella; Salmonella; Giardia

*Individual hits on Giardia, Camplyobacter, and ETEC LT

Improving our understanding of the effect of anthropogenic climate change on the Ganga river system

- There is substantial evidence that anthropogenic climate change through warming and aerosols are affecting precipitation rates in the Gangetic Basin and snow coverage in the Himalayas
- The consequences of these changes on the future of Gangetic Basin is still uncertain
- Some studies show an increase in discharge, while others show a decrease



- In additional, climate change and eutrophication symptoms are connected [Moss, et al, 2011, Inland Waters]
- It is important to have reasonable future projections to plan and implement catchment management policies

Major needs

<u>The questions:</u>

- ❖ How much can climate change affect snowmelt in the future and how will the decreasing glacier coverage affect low flows in the Ganges during the dry season?
- ❖ How do anthropogenic perturbations affect rainfall amount and patterns and what are its consequences on catchment run-off?
- ❖ What are the reasons behind the higher self-purification rate of the Ganges and how is our misuse of the river water affecting it?

<u>The road ahead:</u>

- ❖ Incorporation of atmospheric chemistry in coupled model runs to delineate its effect on hydrological processes
- ❖ Better multi-lateral collaborations between hydrologists, meteorologists and glaciologists to develop coupled atmospheric-hydrological-glaciological models
- ❖ High quality data collection and preparation of high-resolution inventory of air and water pollution sources to reduce data and model uncertainties

Our goals and observational facilities…

❖Quantifying radiative forcing of aerosols, particularly black carbon, over Northern India

❖Understanding the effect of aerosols and changes in LU/LC on precipitation over the Ganges Basin

Our goals and observational facilities…

❖Determining exchange of heat and water between the land and the atmosphere, which plays a major role in evaporation losses and convective precipitation

Eddy Covariance Flux Tower - IIT Kanpur

A Mobotix S15 camera to take panoramic photographs of the terrain 5 times a day (a)

A 2D windsonic anemometer for standard measurements of wind speed and direction at a height of 10 m (not shown in picture).

Four Acclima Soil Sensors for measuring soil temperature and moisture at 5 cm and 15 cm depths; provide highly accurate soil moisture readings at all temperature and soil chemistry (b).

Two HFP01SC self-calibrating heat flux plates to measure the soil heat flux; together with the 3D anemometer and net radiometer, provides measurements of all components of the surface energy balance (c).

A tipping bucket type aerodynamic precipitation sensor to collect rainfall data at .2 mm per tip; designed to minimise out-splash and evaporation losses (d).

An HMP155 temperature/RH probe to monitor temperature and RH; provided with aspirated radiation shield to maintain continuous flow of ambient air and reduce build-up of heat (e).

A 3D sonic anemometer to measure the three orthogonal wind components twenty times a second, which can be used to calculate the turbulent fluxes (f).

A LI-COR Biosciences Li7500 Infrared gas analyser, which, in conjunction with the 3D anemometer, measures the Carbon Dioxide and latent heat fluxes (g).

A four component net radiometer to measure the incoming and outgoing shortwave and longwave radiation (h).

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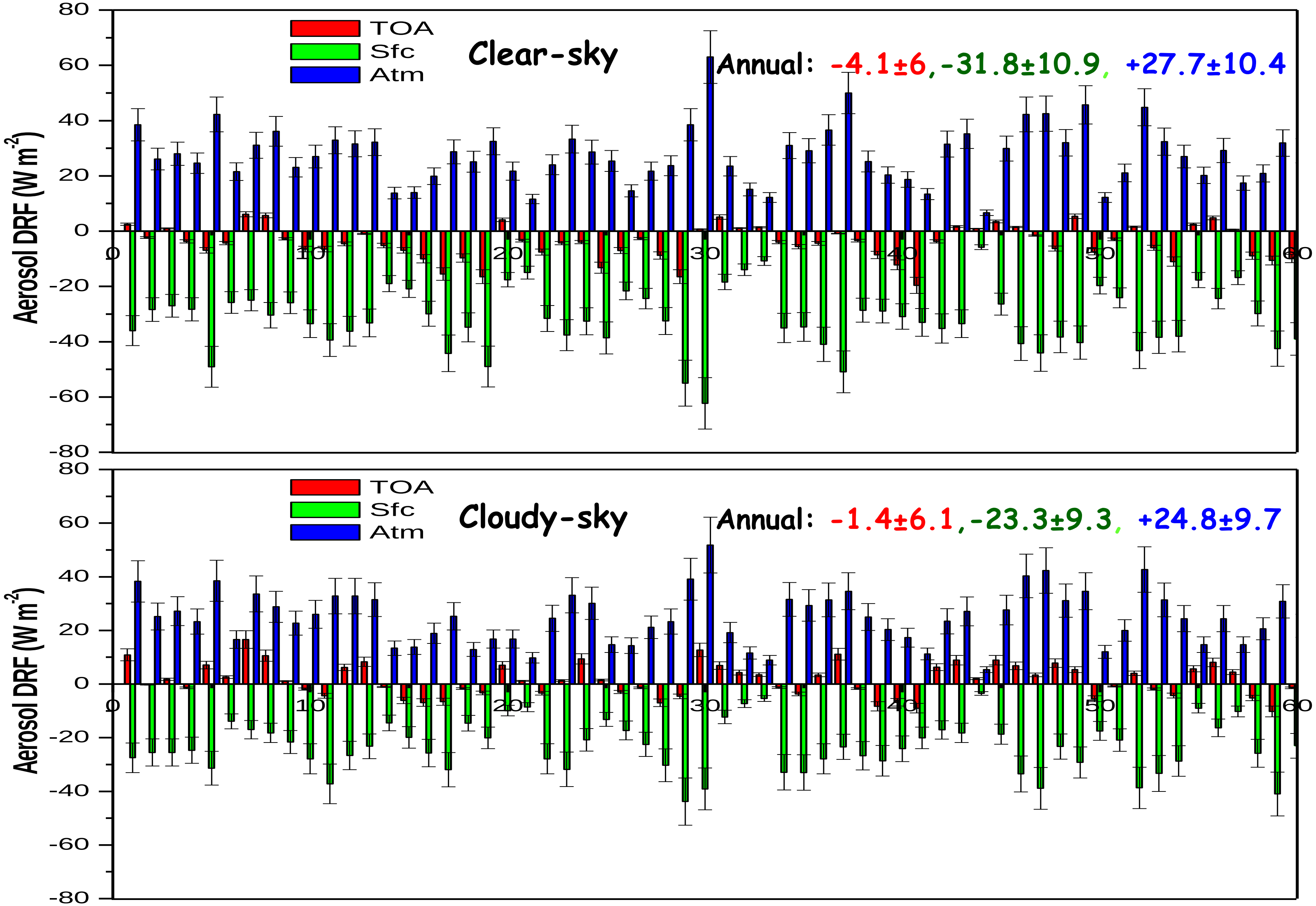
Thank You !!

SW Aerosol Radiative Forcing (2001-2005)…

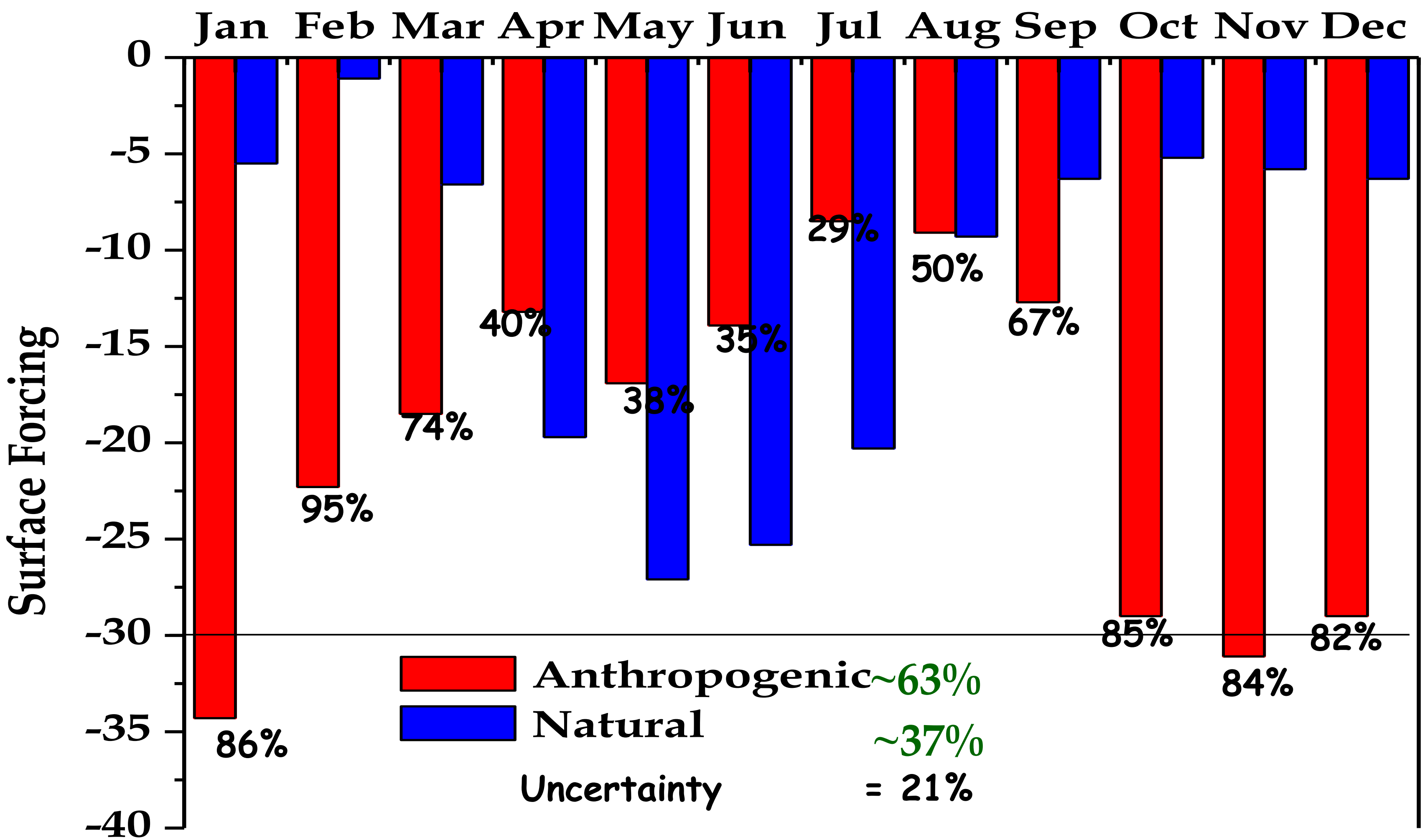


Columnar Cloud Parameters

Dey and Tripathi, JGR, 2007, 2008

Anthropogenic Aerosol Radiative Forcing (Case study: Over Kanpur)…

5 year (2001-2005) monthly mean estimates



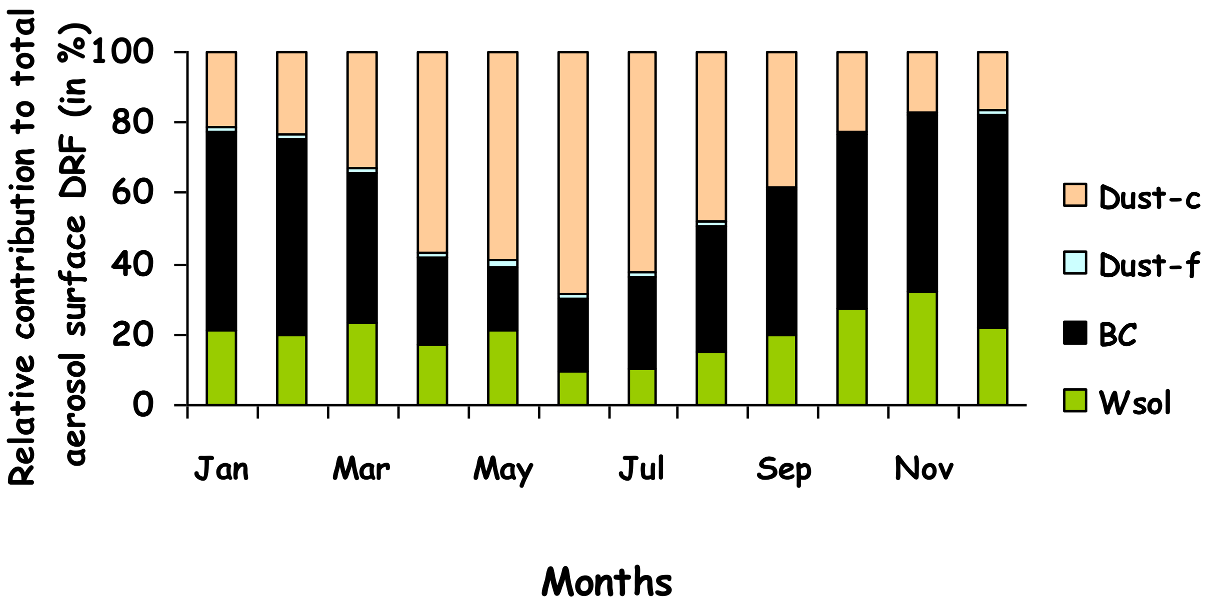
Annual Anthropogenic: +0.3±2.5, -19.9±9.0, +20.2±9.9 (Clear)

+2.4±4.3, -16.7±8.1, +19.1±9.7 (Cloudy)

Tripathi et al. 2005, 2007
Dey et al. 2006
Dey and Tripathi, 2008

Implications of the Aerosol Radiative Forcing…

- Excess atmospheric forcing transformed into heat energy.
- Mean annual heating rate : 0.84±0.3 K day^{-1}
- Solar Dimming



	F_m	RC_{AOD}	RC_{sfc}
Wsol	71.3	55.1	19.9
BC	5.5	8.4	40
$Dust_f$	0.2	2.5	1.1
$Dust_c$	23.1	34	39

At surface, warming due to GHG is partially balanced by cooling due to aerosols

Limitations: Columnar, so not very useful
No/limited vertical information on HR
No information during monsoon

Dey and Tripathi, 2008