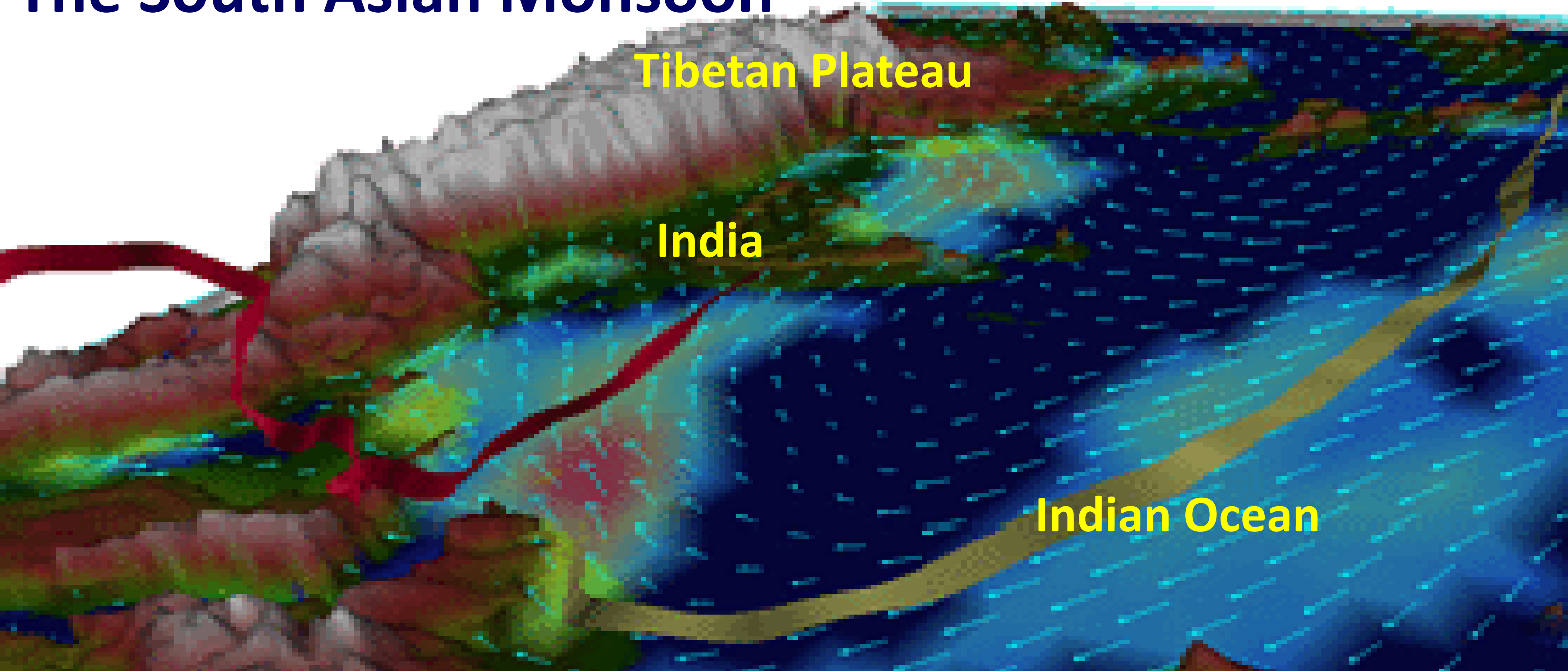
Understanding the South Asian monsoon response to greenhouse gas (GHG) and aerosol forcing

R. Krishnan
Centre for Climate Change Research (CCCR)
Indian Institute of Tropical Meteorology, Pune
Speaker: Ramesh Vellore

Training workshop in Seasonal Climate forecasting for South Asia, 6-8 December 2017

SAARC Disaster Management Centre, Gandhinagar

The South Asian Monsoon

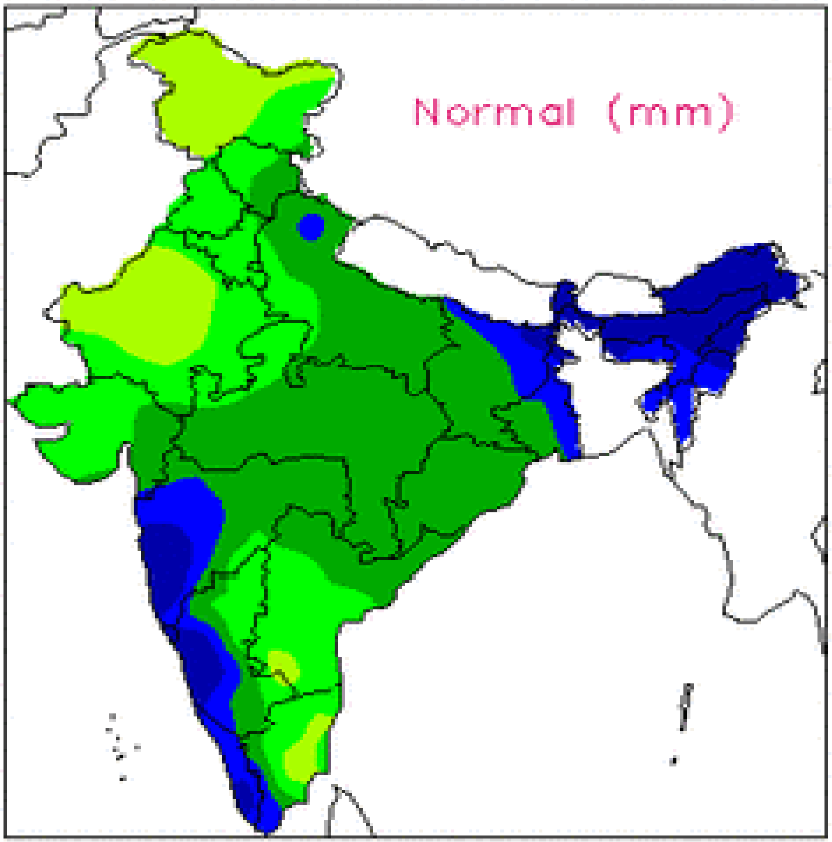


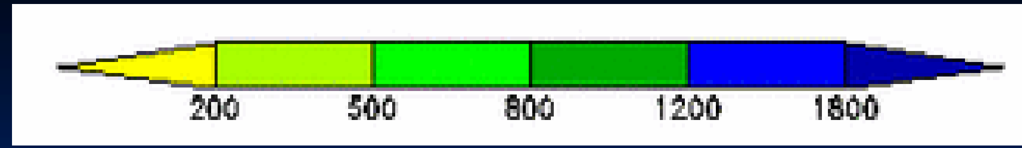
Monsoon circulation and rainfall: A convectively coupled phenomenon

Requires a thermal contrast between land & ocean to set up the monsoon circulation

Once established, a positive feedback between circulation and latent heat release maintains the monsoon

The year to year variations in the seasonal (June – September) summer monsoon rains over India are influenced internal dynamics and external drivers



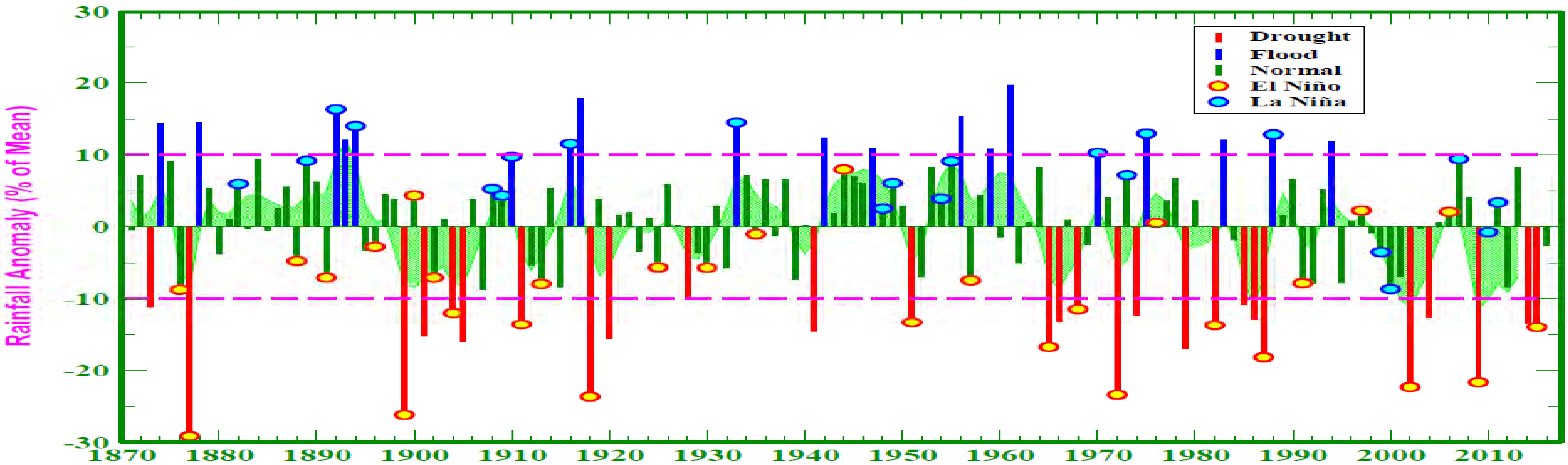


Long-term climatology of total rainfall over India during (1 Jun - 30 Sep) summer monsoon season (http://www.tropmet.res.in)

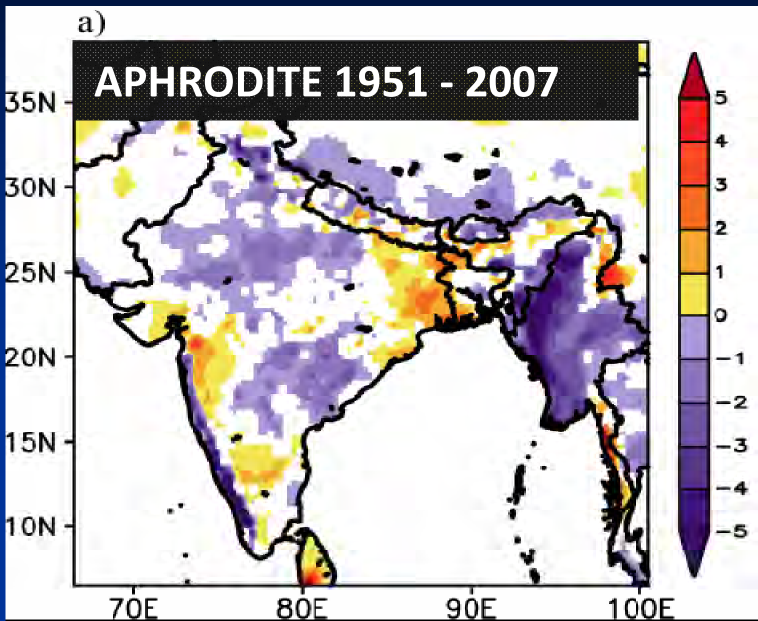
Interannual variability of the Indian Summer Monsoon Rainfall

All-India Summer Monsoon Rainfall, 1871-2016

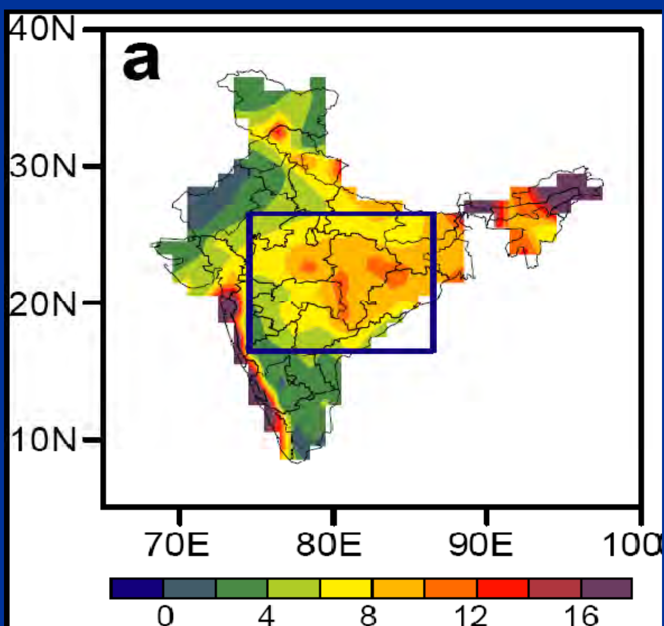
(Based on IITM Homogeneous Indian Monthly Rainfall Data Set)



Spatial map of linear trend of JJAS rainfall (1951 – 2007)

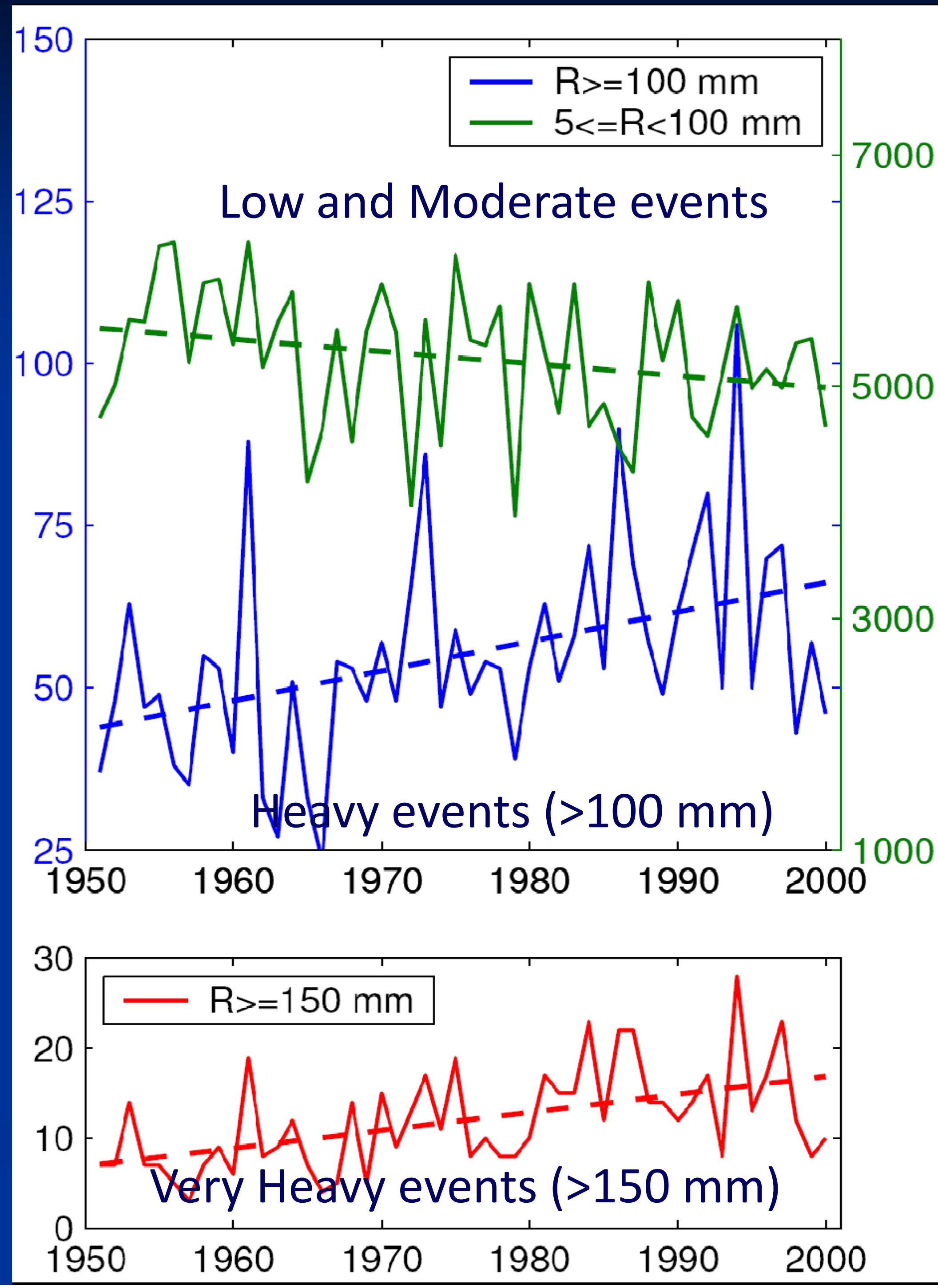


Increasing Trend of Extreme Rain Events over India in a Warming Environment

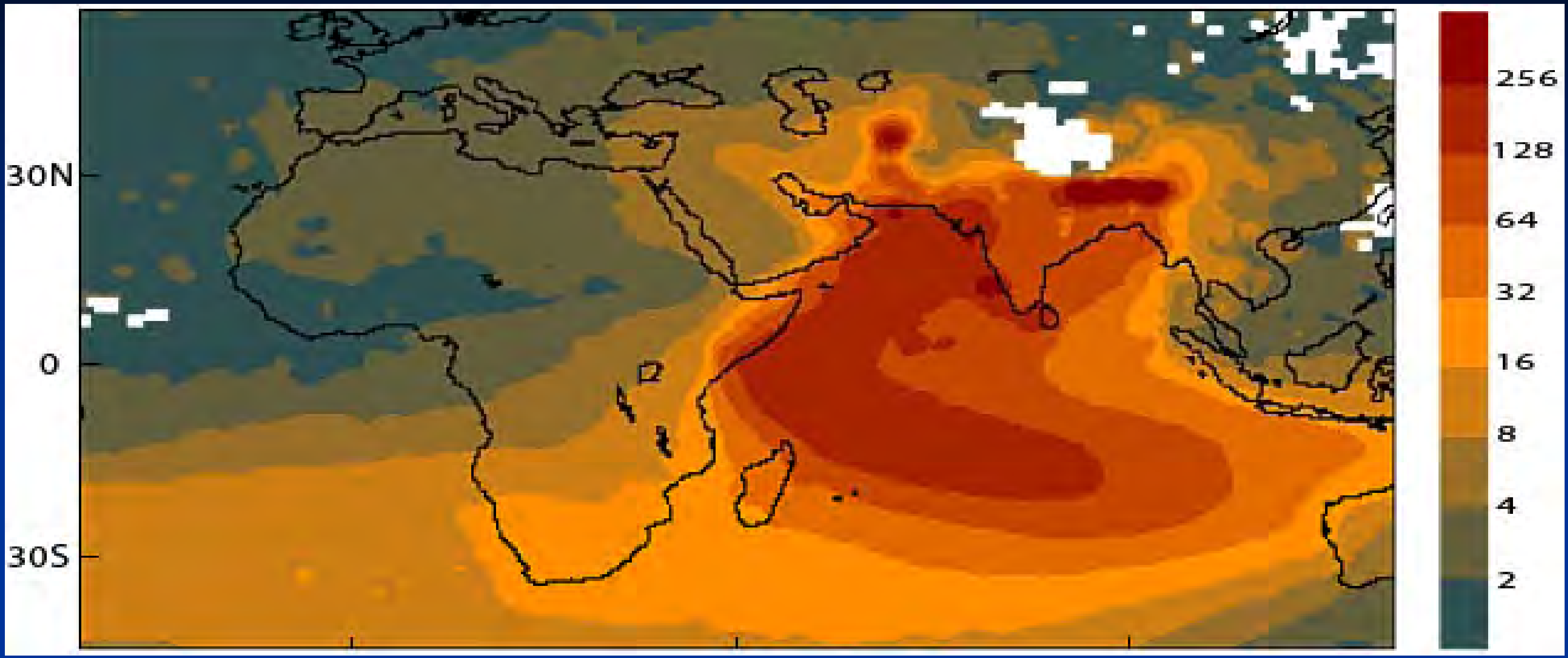


Goswami et al. 2006, Science

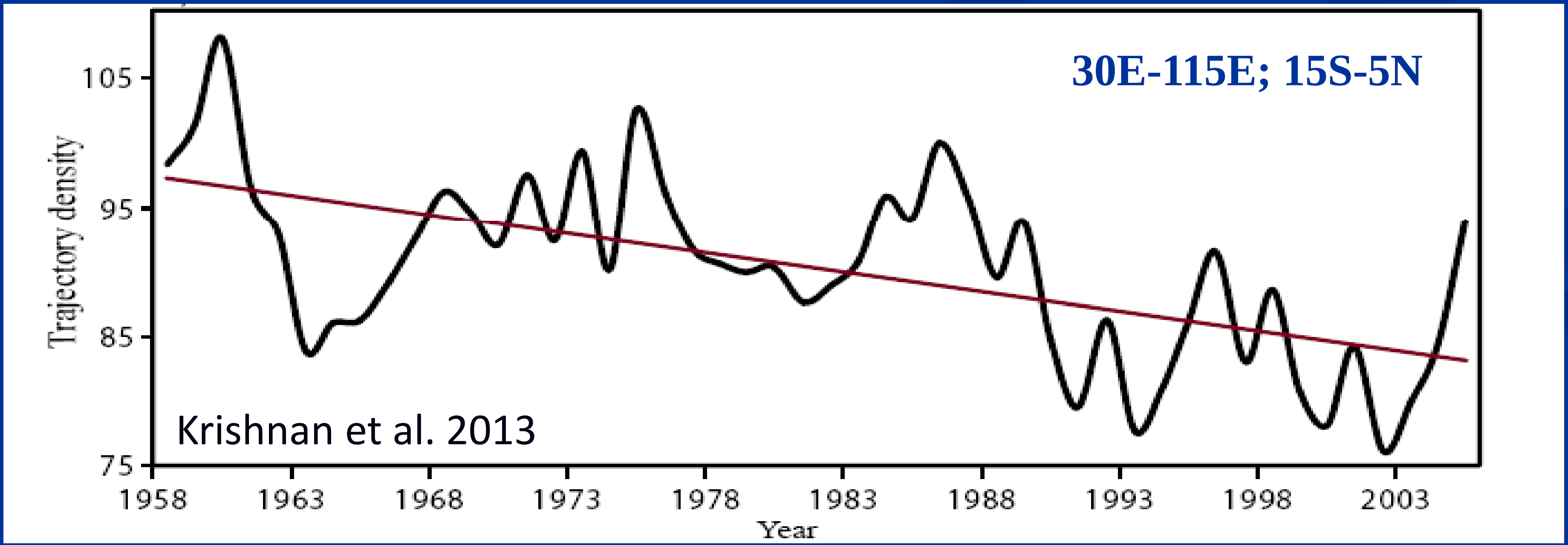
Time series of count over Central India



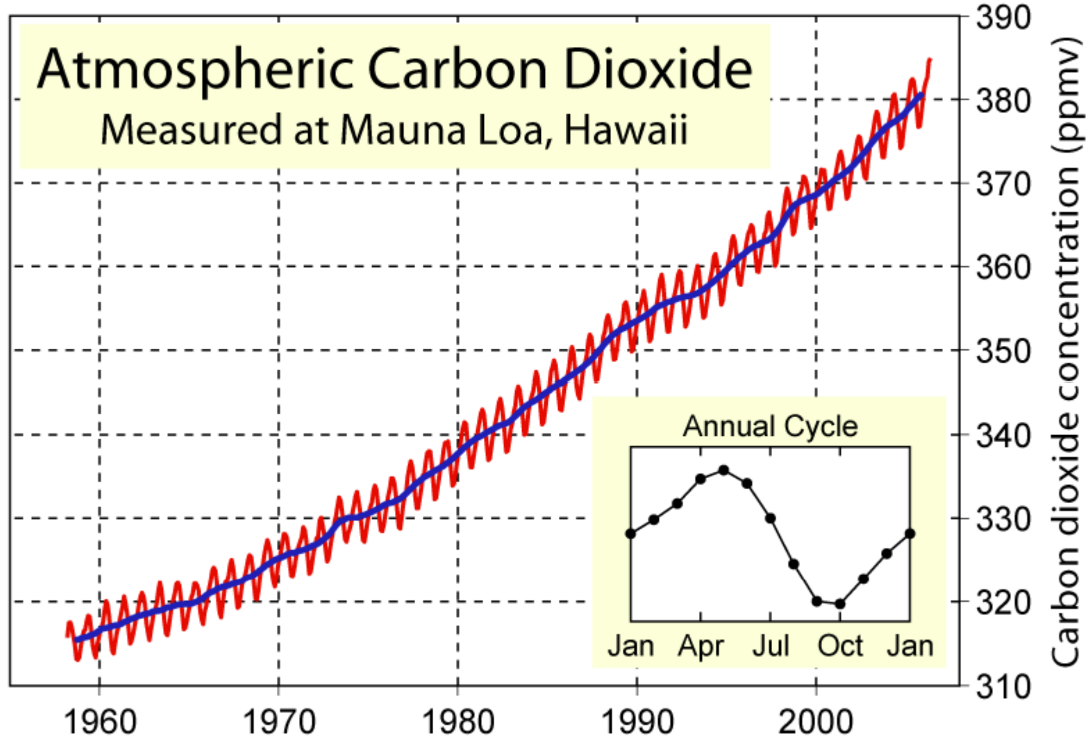
Climatological mean density of back-trajectories of monsoon flows reaching Indian region



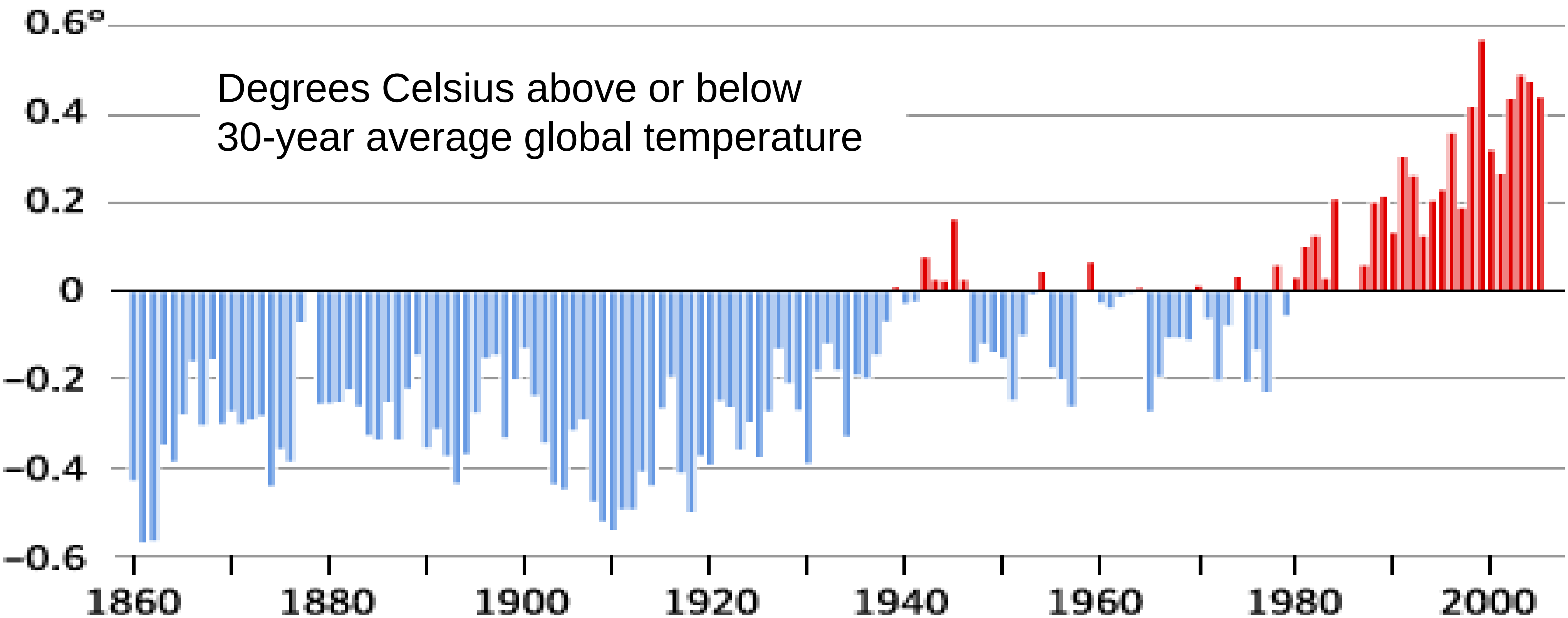
Interannual variability of JJAS seasonal mean trajectory density (1958 – 2006)



CO_2 problem

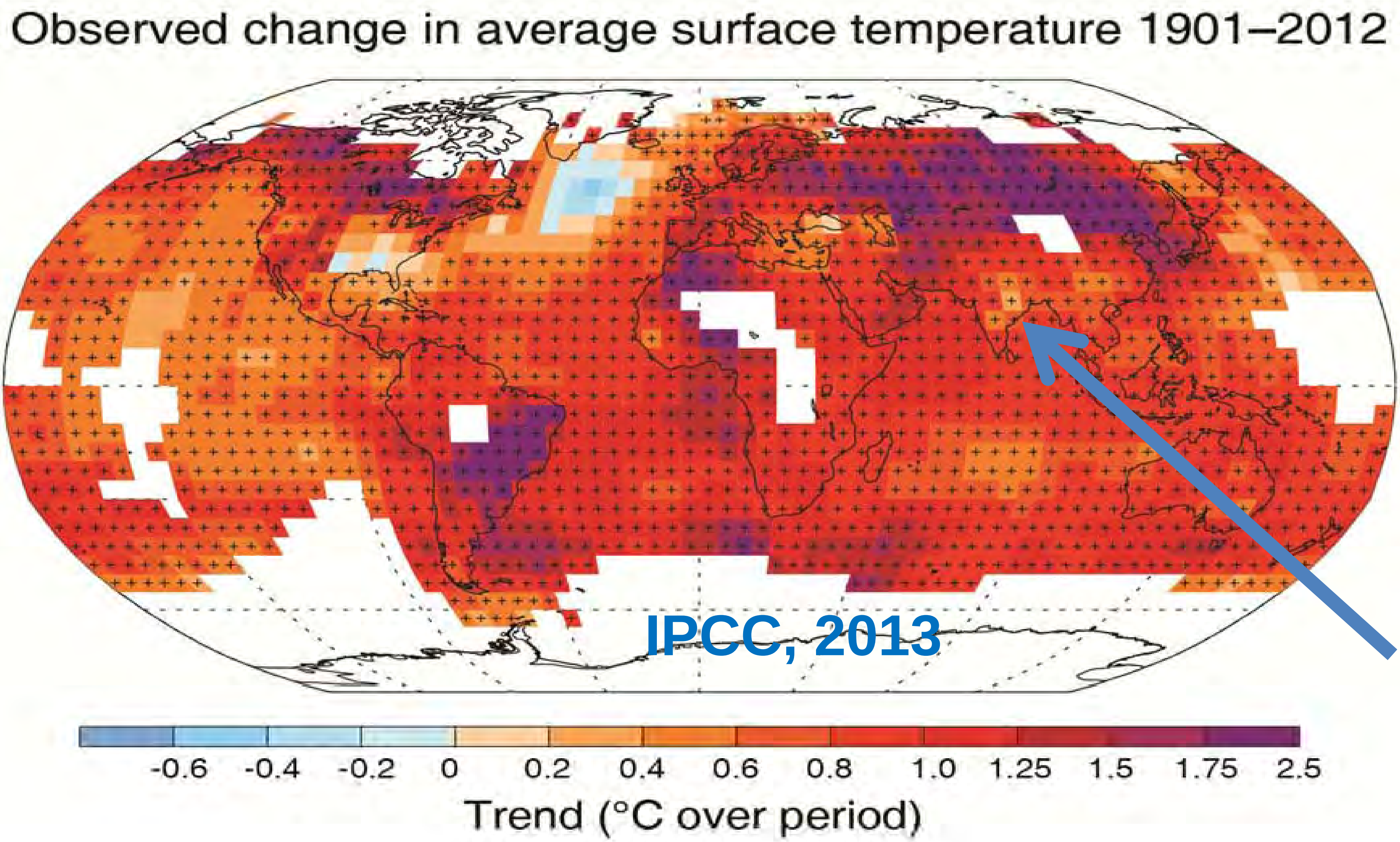


Atmospheric Carbon Dioxide
Measured at Mauna Loa, Hawaii
Annual Cycle
Jan Apr Jul Oct Jan
Carbon dioxide concentration (ppmv)
390 380 370 360 350 340 330 320 310
1960 1970 1980 1990 2000



Degrees Celsius above or below
30-year average global temperature
0.6° 0.4 0.2 0 −0.2 −0.4 −0.6
1860 1880 1900 1920 1940 1960 1980 2000

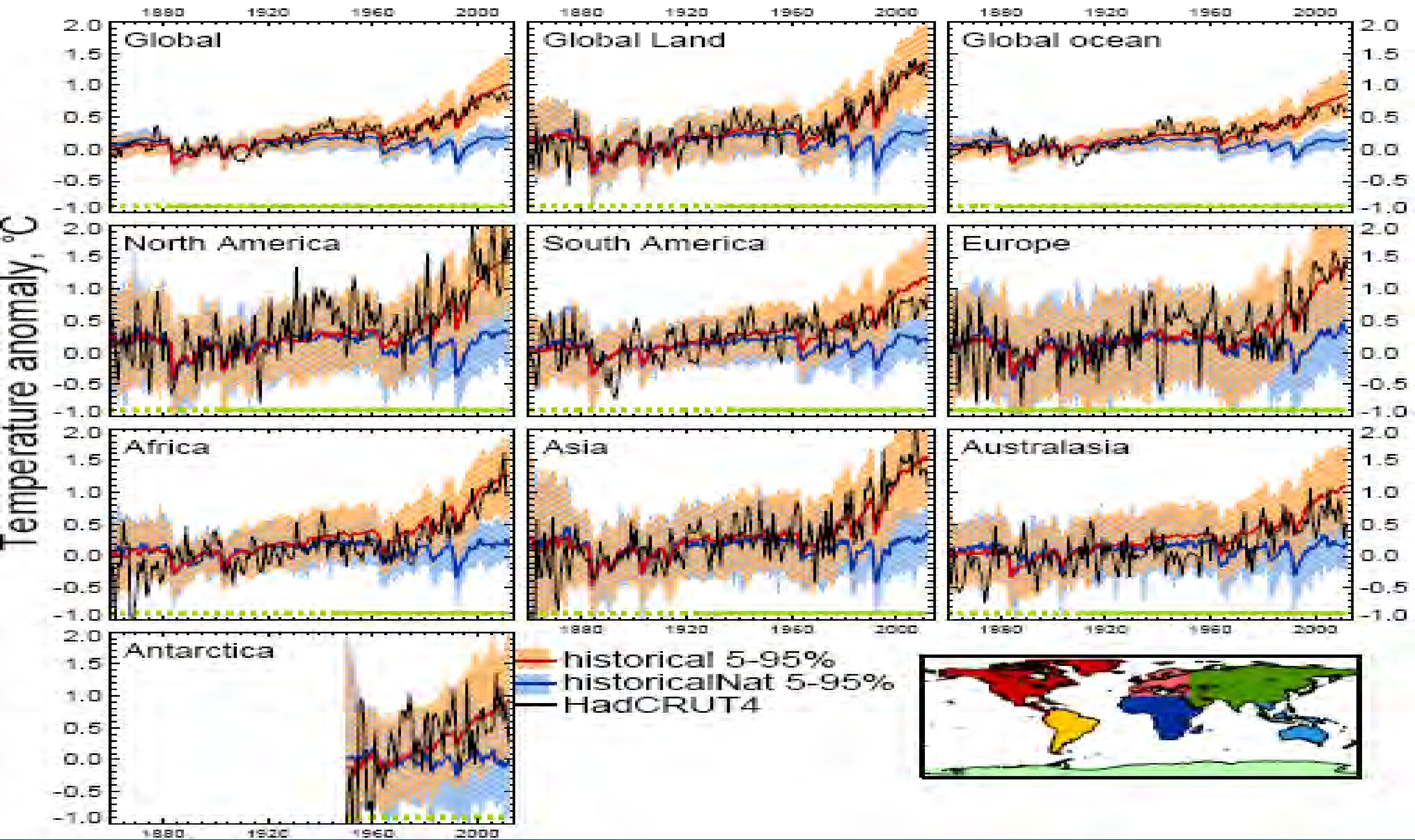
Recent climate change report



Planet has warmed by 0.85 K over 1880-2012

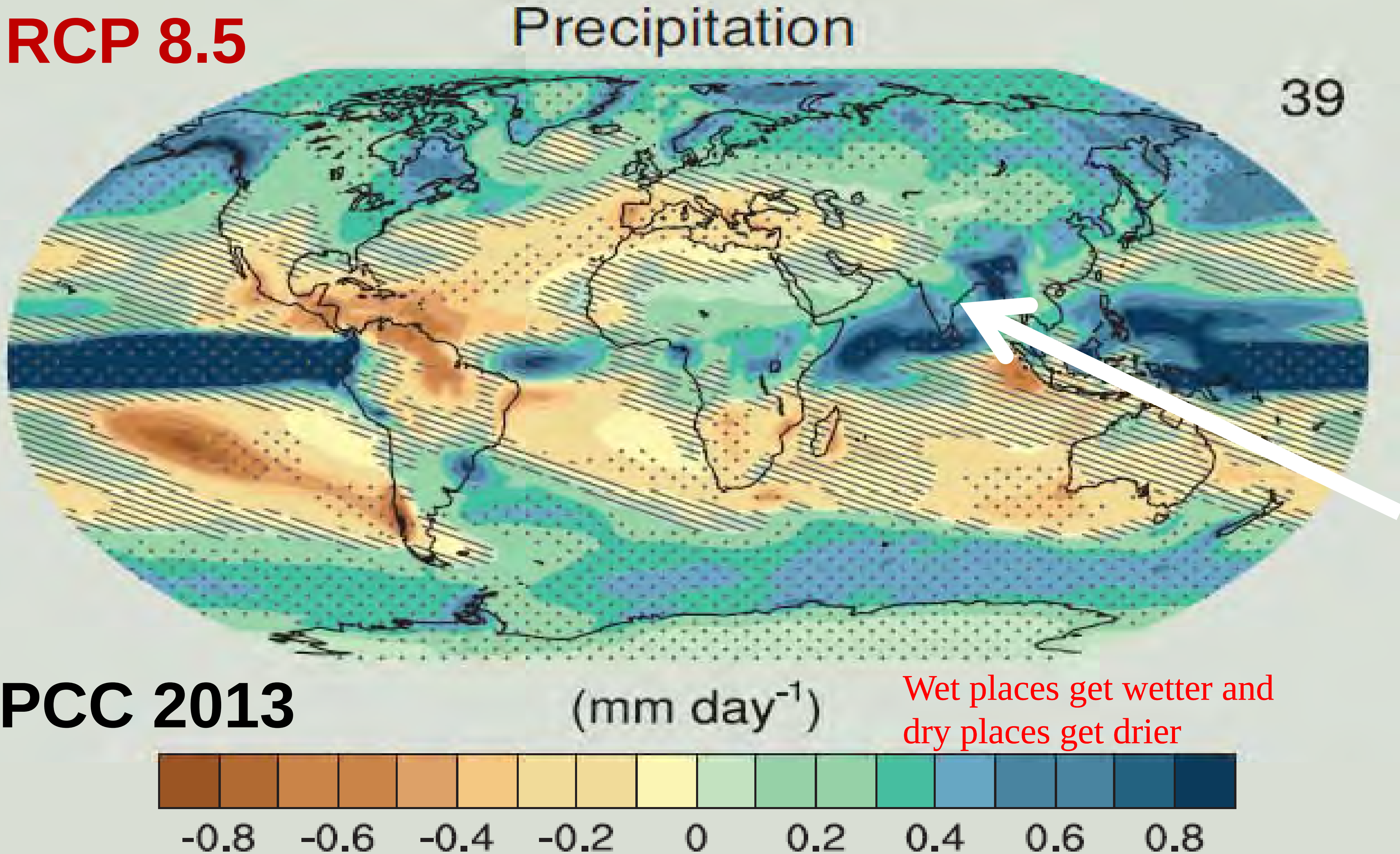
Climate Change 2013: WG1 contribution to IPCC Fifth Assessment Report

Warming of the Climate System is unequivocal



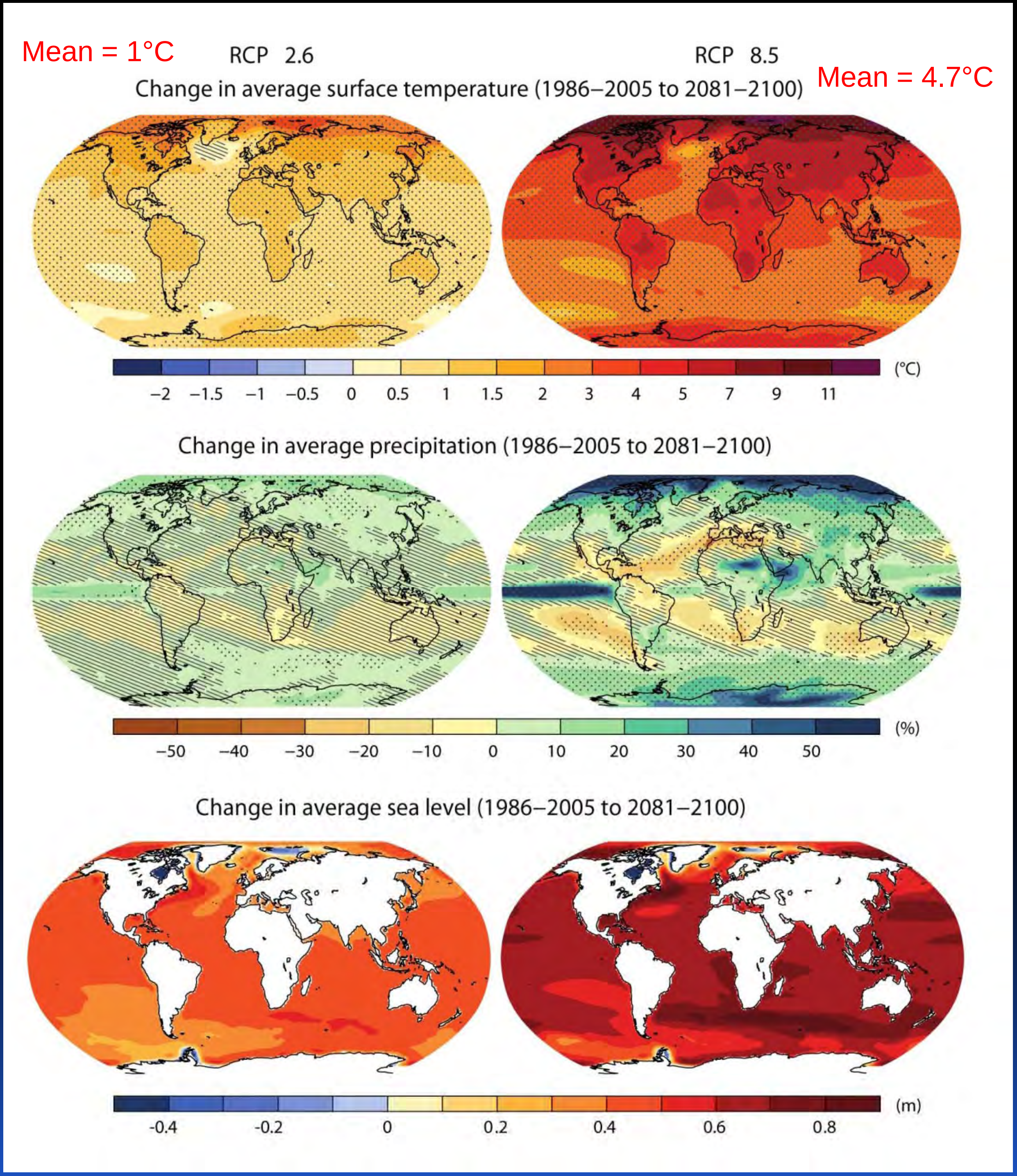
Projected rainfall Change (2081-2100)

RCP 8.5



IPCC 2013

Wet places get wetter and dry places get drier



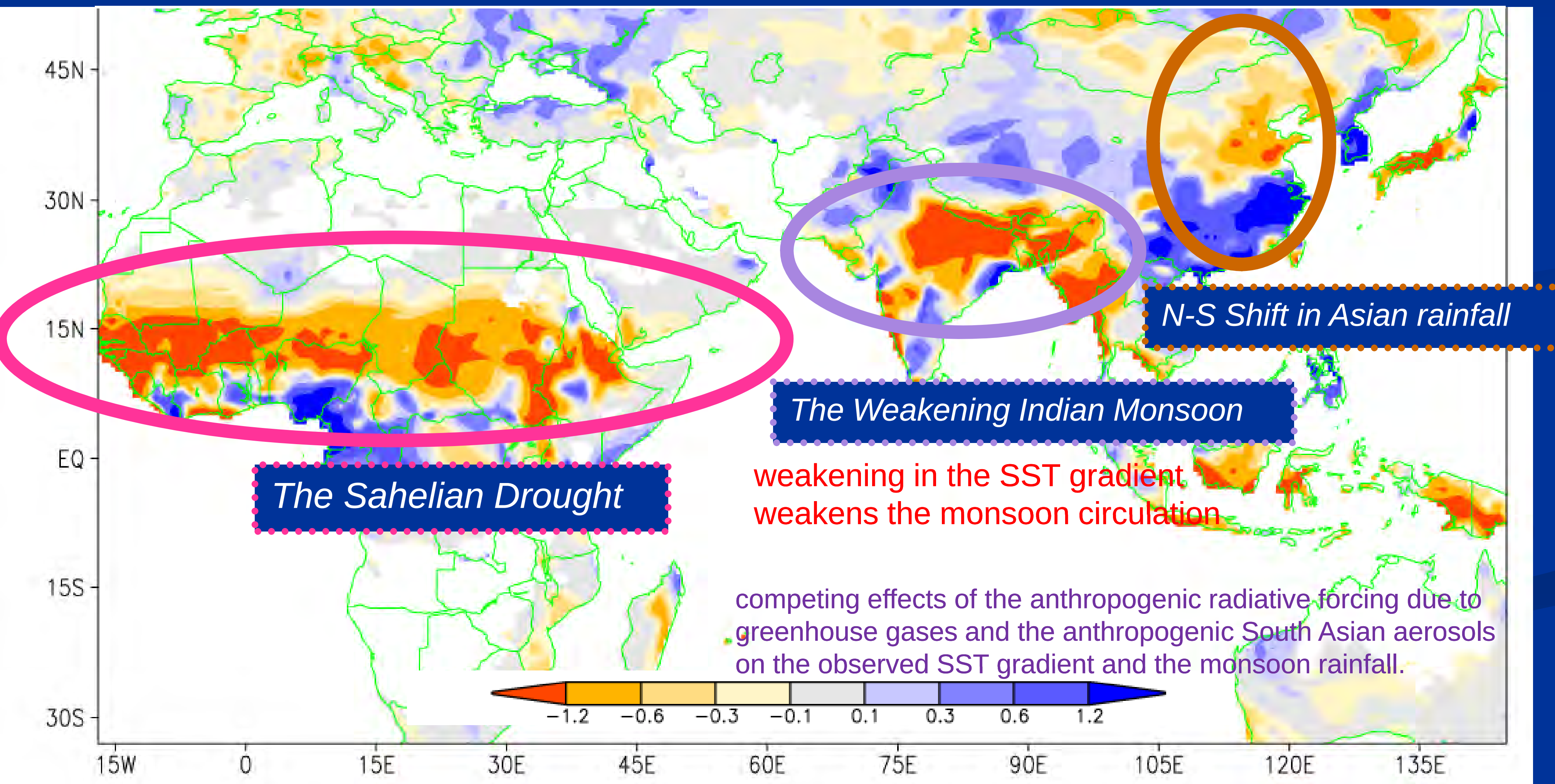
Mean = 1°C
RCP 2.6
RCP 8.5
Mean = 4.7°C
Change in average surface temperature (1986–2005 to 2081–2100)
(°C)
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2 3 4 5 7 9 11
Change in average precipitation (1986–2005 to 2081–2100)
(%)
−50 −40 −30 −20 −10 0 10 20 30 40 50
Change in average sea level (1986–2005 to 2081–2100)
(m)
-0.4 -0.2 0 0.2 0.4 0.6 0.8

J. Climate 2006

Weakening of North Indian SST Gradients and the Monsoon Rainfall in India and the Sahel

CHUL EDDY CHUNG AND V. RAMANATHAN

Observed Trends in Summer Rainfall: 1950 to 2002



Emerging consensus on likely role of anthropogenic aerosols on the decreasing trend of the South Asian monsoon precipitation

Physical mechanisms for the aerosol-monsoon connection include:

•Reduction of solar insolation ('solar dimming') at surface through scattering & absorption by aerosols, decrease of meridional SST gradient between equator & 25^{o}N, resulting in decreased moisture convergence and suppressed convective activity over the Bay of Bengal (Ramanathan et al. 2005, Meehl et al. 2008).

•Scattering-type aerosols over the Asian continent can induce large-scale cooling over the Northern Hemisphere causing inter-hemispheric energy imbalance and weaken the boreal summer monsoon circulation (Bollasina et al. 2011)

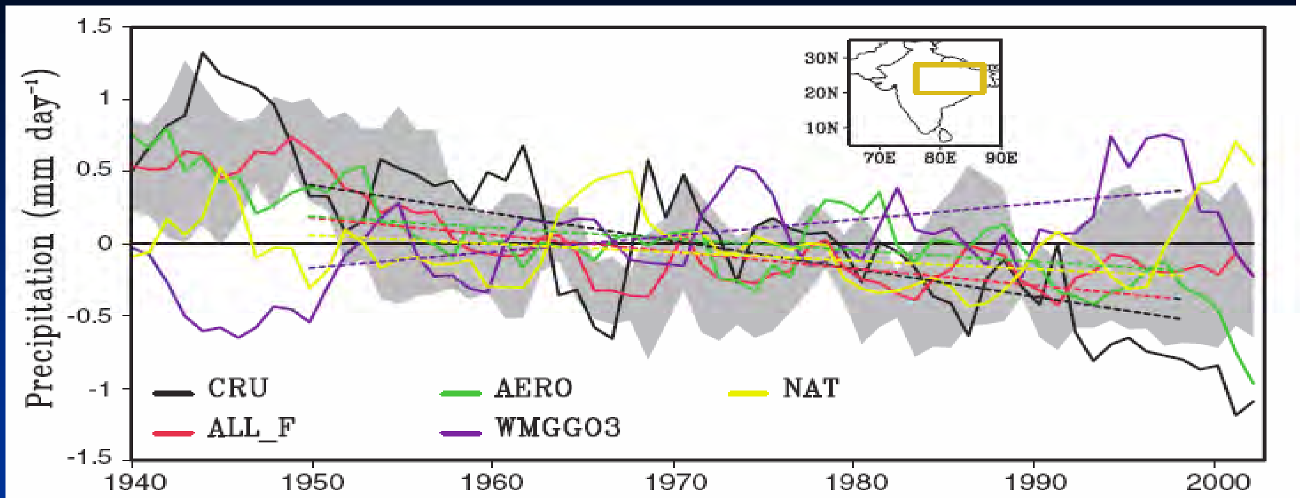
•Decrease of meridional gradient of tropospheric temperature & vertical wind-shear (Ganguly et al. 2012)

•Increase of atmospheric static stability due to solar absorption by the aerosol layer (0-3 km) in the lower levels (Ramanathan et al. 2005)

•Role of enhanced CCN counts in disrupting organized convection of the monsoon depression . Impacts of air pollution over Asia **(Krishnamurti et al. 2012)**

•Surface cooling over the Indian subcontinent (Sanap et al. 2015)

•Decrease of water vapor availability (Salzmann et al. 2014)



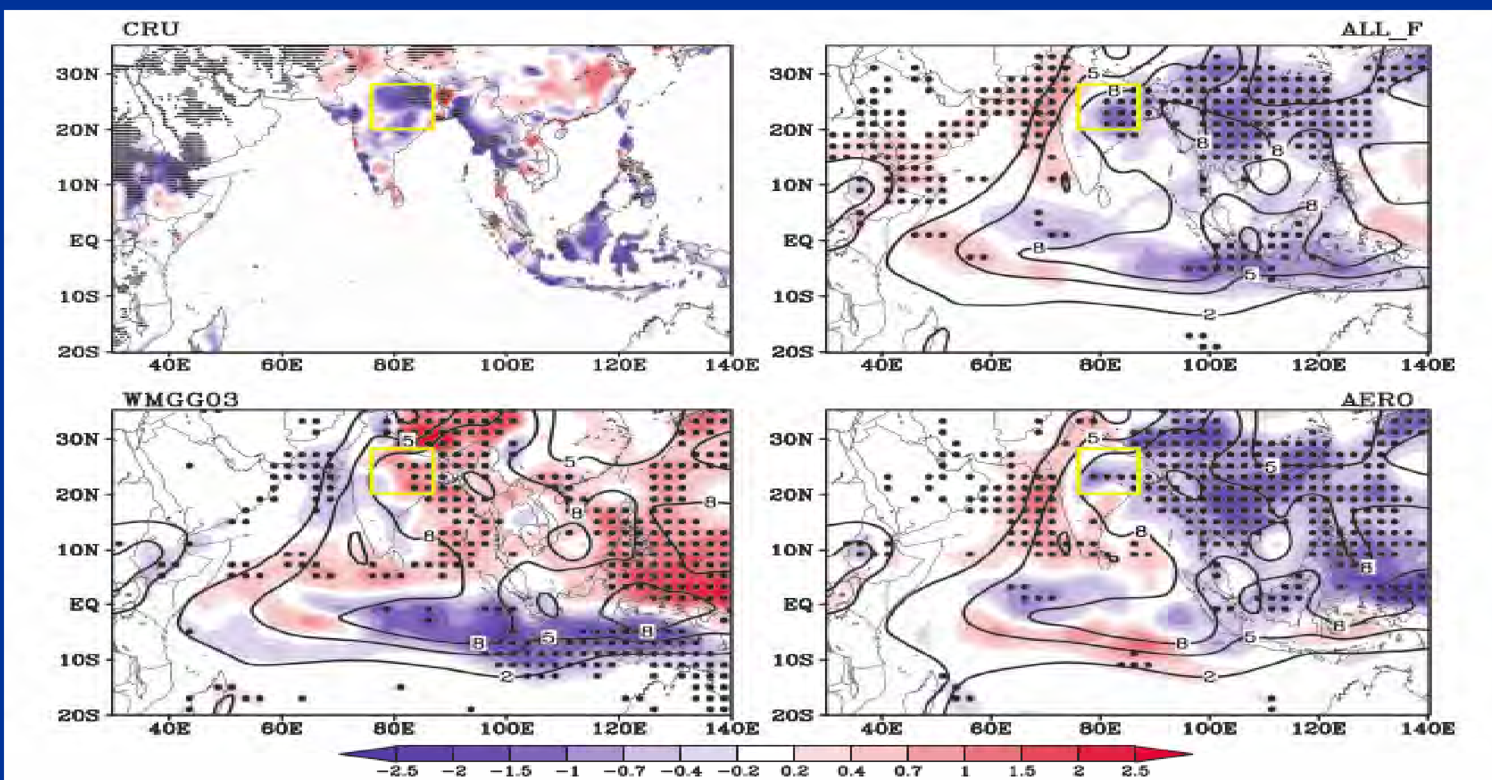
Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon

Massimo A. Bollasina *et al.*

Science **334**, 502 (2011);

DOI: 10.1126/science.1204994

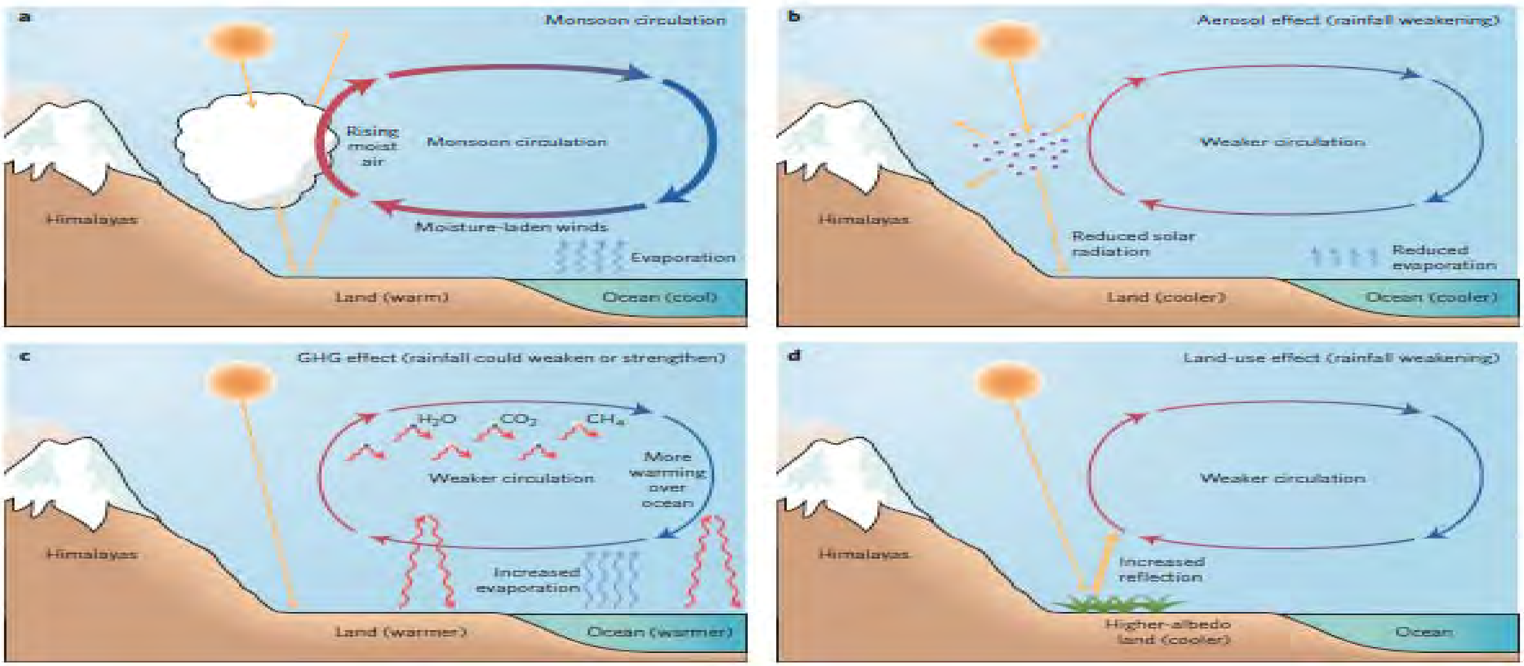
Bollasina, Ming and Ramaswamy Science, 2011



Scattering-type aerosols over the Asian continent can induce large-scale cooling over the Northern Hemisphere causing inter-hemispheric energy imbalance and weaken the boreal summer monsoon circulation (Bollasina et al. 2011)

Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world

R. Krishnan[1] · T. P. Sabin[1] · R. Vellore[1] · M. Mujumdar[1] · J. Sanjay[1] · B. N. Goswami[1,2] · F. Hourdin[3] · J.-L. Dufresne[3] · P. Terray[4,5]



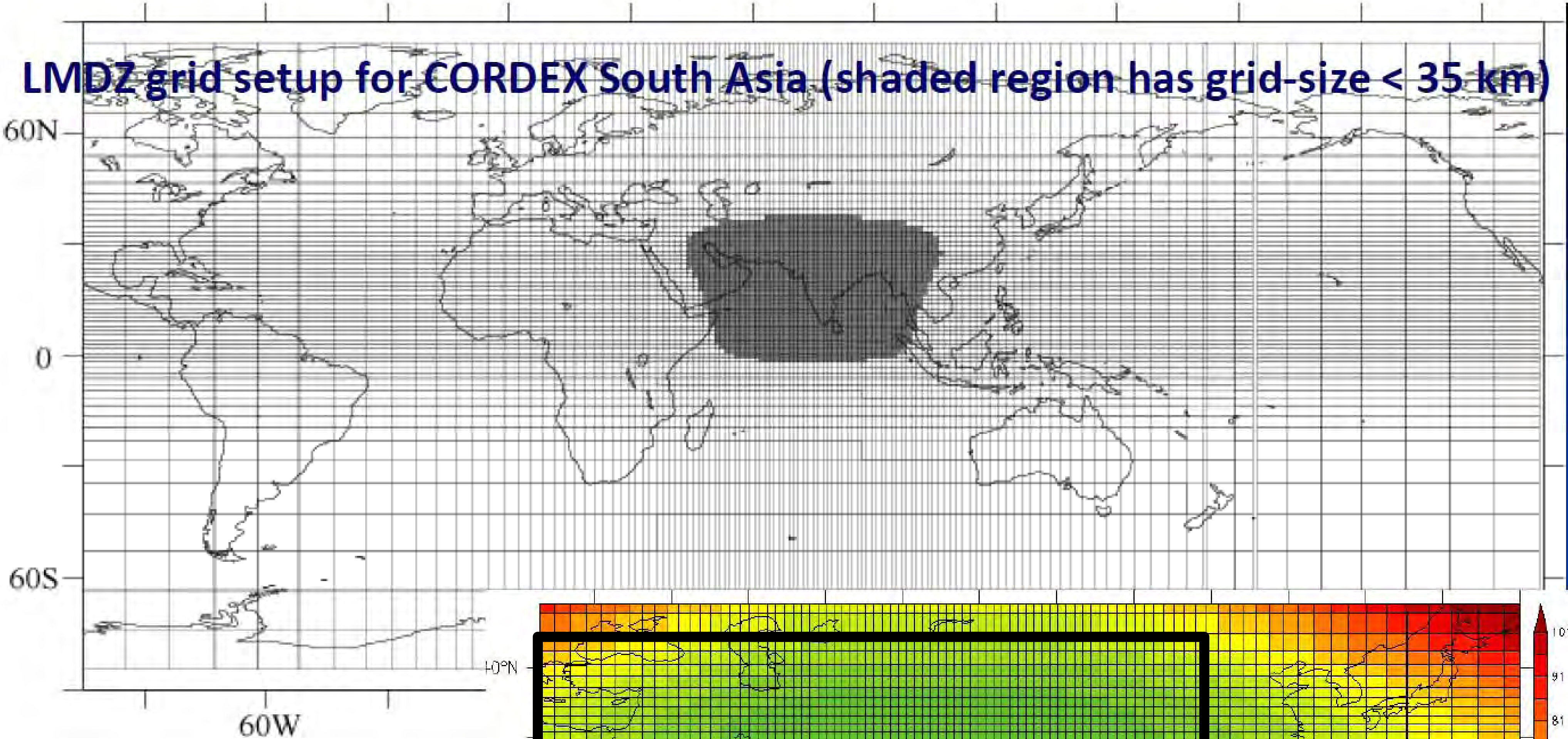
The onset of the monsoon in early June brings with it a burst of life across the region — children playing on the streets, blossoming flora, flowing rivers, and sowing of agricultural lands. The monsoon supplies ~80% of South Asia's annual rainfall, supporting the region's primarily rain-fed agriculture and recharging rivers, aquifers and reservoirs that provide water to over one-fifth of the global population. Since the 1950s, the monsoon has weakened[1] and become more erratic, with increased occurrence of extreme rainfall events[2]. This has led to crop failures and water shortages with severe socio-economic and humanitarian impacts across South Asia. Writing in *Climate Dynamics*, R. Krishnan and colleagues[3] suggest that anthropogenic greenhouse gas (GHG) emissions, aerosol emissions and agricultural land-cover changes are responsible for the observed changes in rainfall patterns. They predict that the monsoon weakening will continue through the twenty-first century, threatening the livelihoods and resources of over 1.6 billion people in the region.

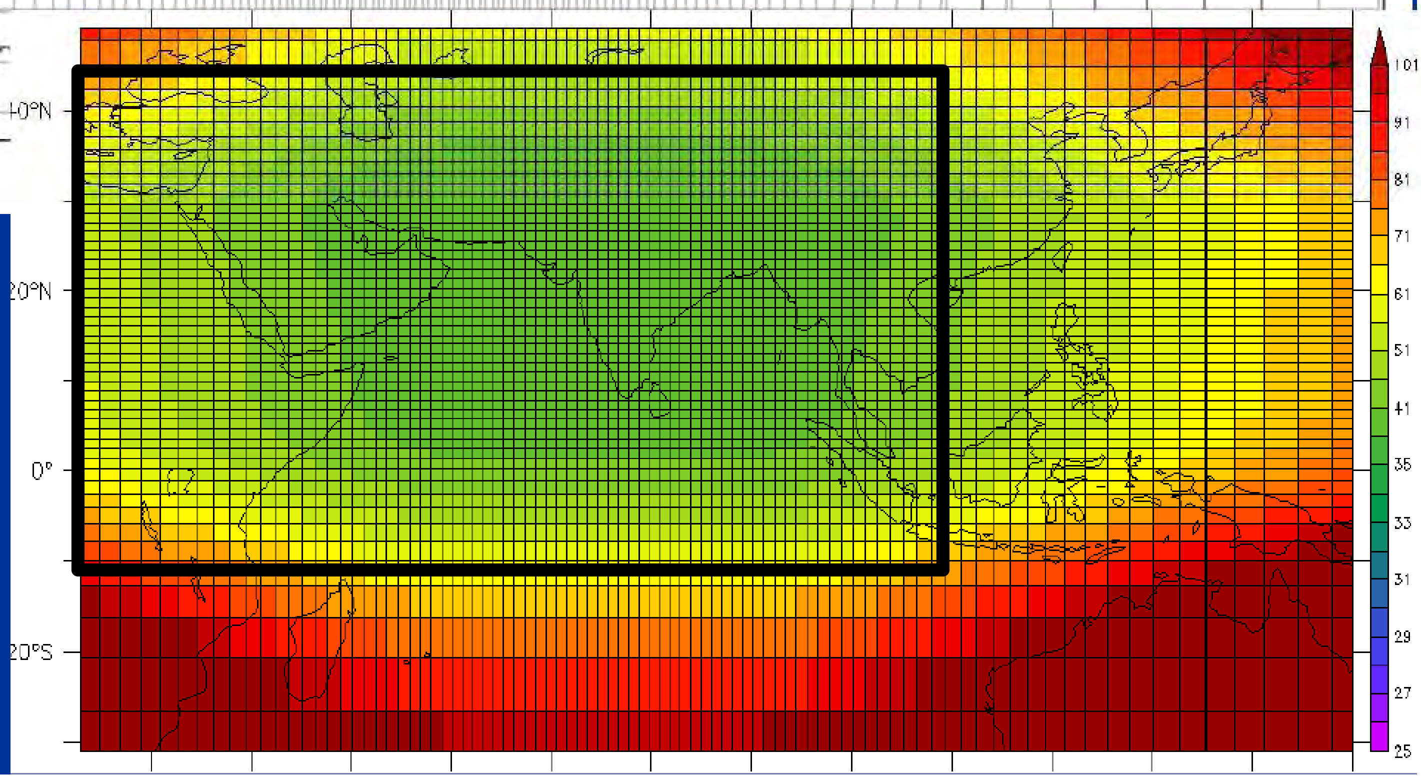
SOUTH ASIAN MONSOON

Tug of war on rainfall changes

Rainfall associated with the South Asian summer monsoon has decreased by approximately 7% since 1950, but the reasons for this are unclear. Now research suggests that changes in land-cover patterns and increased emissions from human activities have contributed to this weakening, which is expected to continue in the coming decades.

LMDZ grid setup for CORDEX South Asia (shaded region has grid-size < 35 km)





LMDZ global atmospheric model: Variable resolution with zooming capability

Source: Sabin, CCCR, IITM

High-resolution (~ 35 km) modeling of **climate change over S.Asia**

Historical (1886-2005):

Includes natural and anthropogenic (GHG, aerosols, land cover etc) climate forcing during the historical period (1886 – 2005) ~ 120 yrs

Historical Natural (1886 – 2005):

Includes only natural climate forcing during the historical period (1886– 2005) ~ 120 yrs

RCP 4.5 scenario (2006-2100) ~ 95 yrs:

Future projection run which includes both natural and anthropogenic forcing based on the IPCC AR5 RCP4.5 climate scenario. The evolution of GHG and anthropogenic aerosols in RCP4.5 produces a global radiative forcing of + 4.5 W m^{-2} by 2100

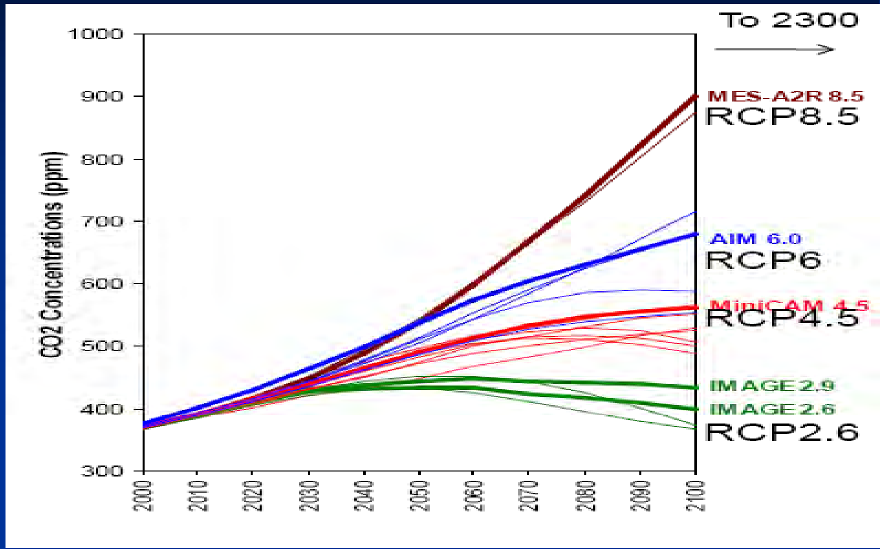
GHG-Only (1951-2005):

Includes GHG only forcing. Other forcing set to pre-industrial values

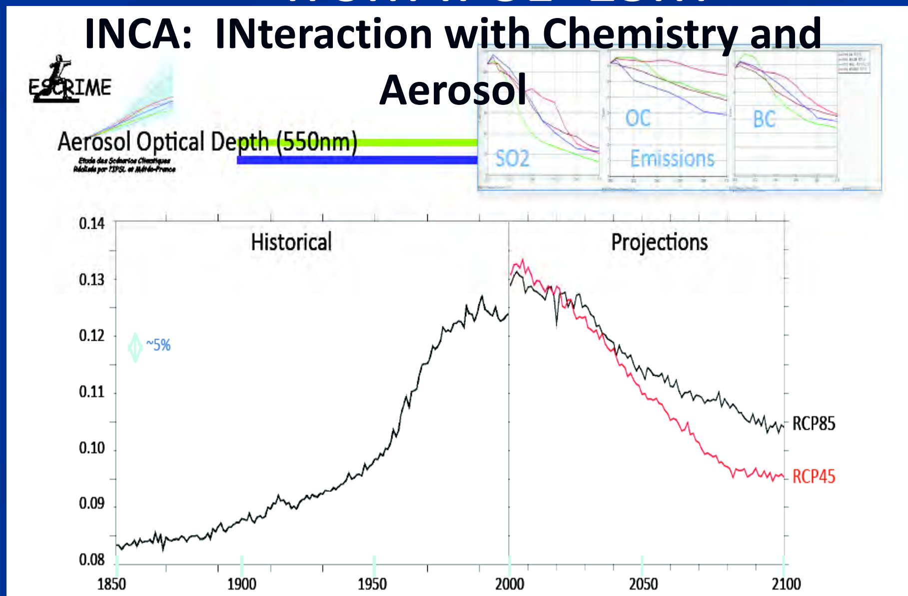
Aerosol-Only (1951– 2005):

Includes Aerosol only forcing. Other forcing set to pre-industrial values

CO2 concentration in future IPCC AR5 scenarios

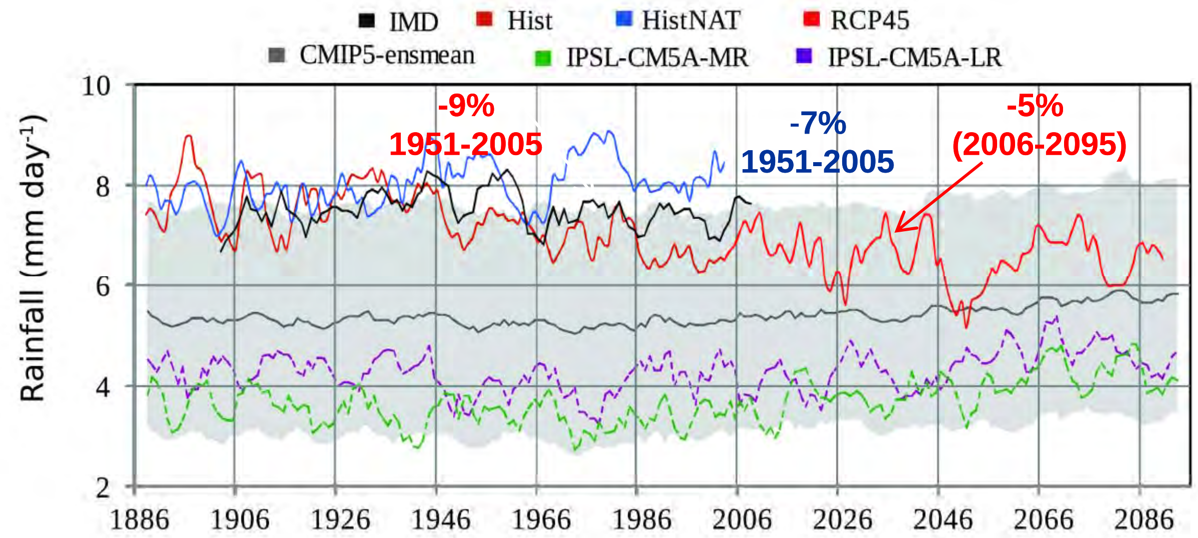


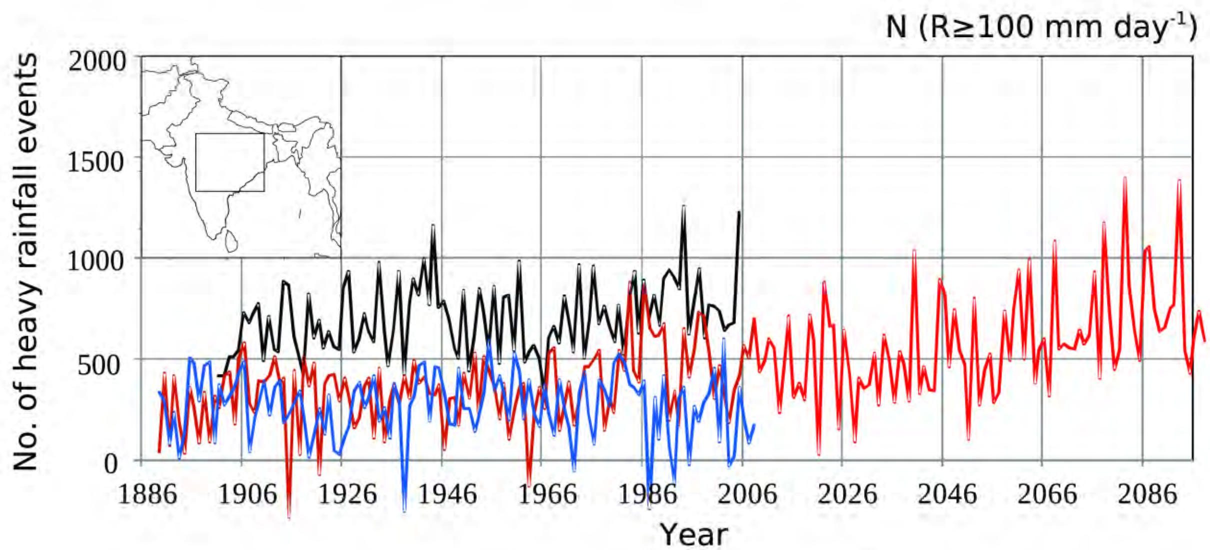
Aerosol distribution from IPSL ESM

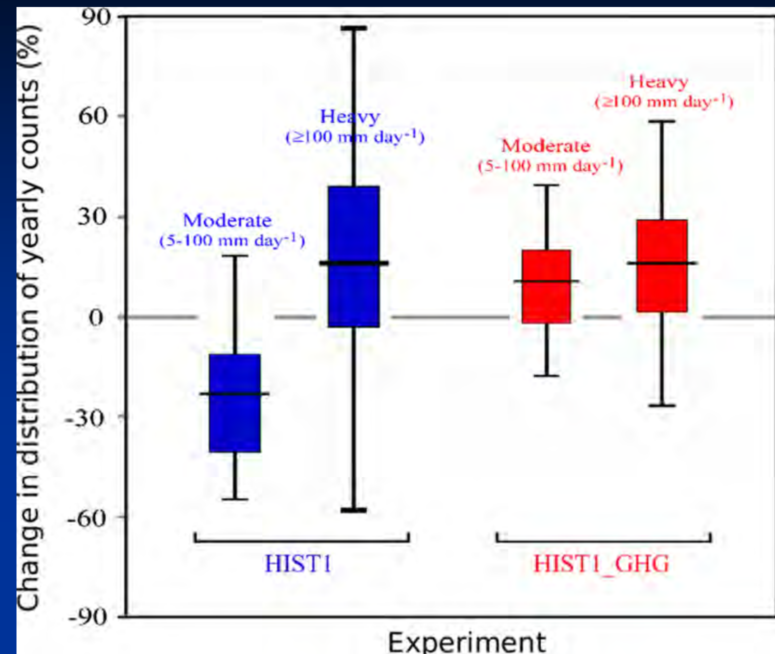


Runs performed on PRITHVI, CCCR-IITM

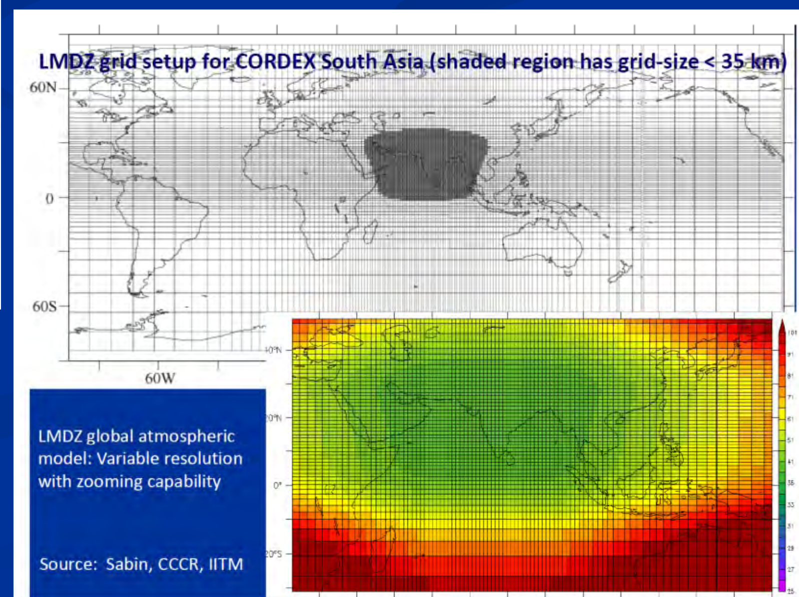
Indian summer monsoon precipitation – Observed and Simulated







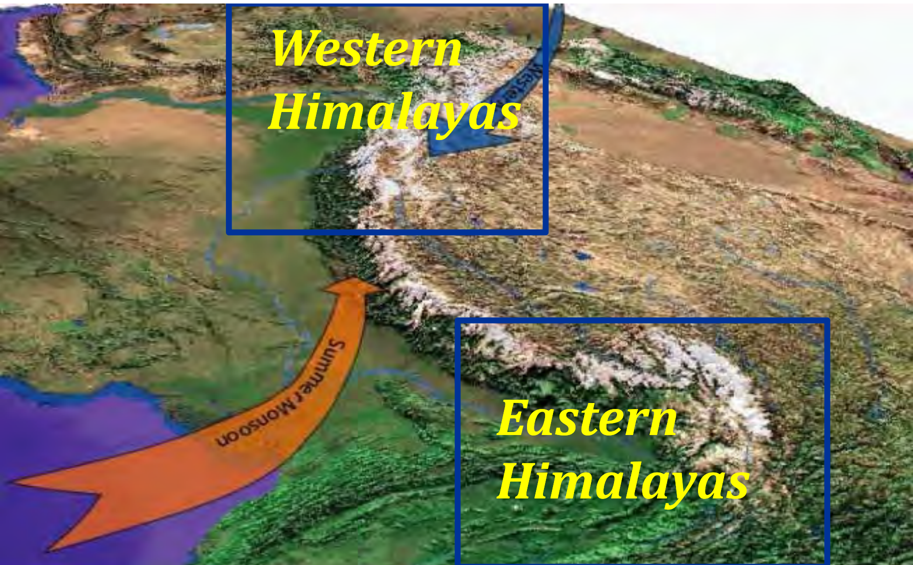
Changes with respect to Natural forcing
Blue (all forcing)
Red (Greenhouse forcing)

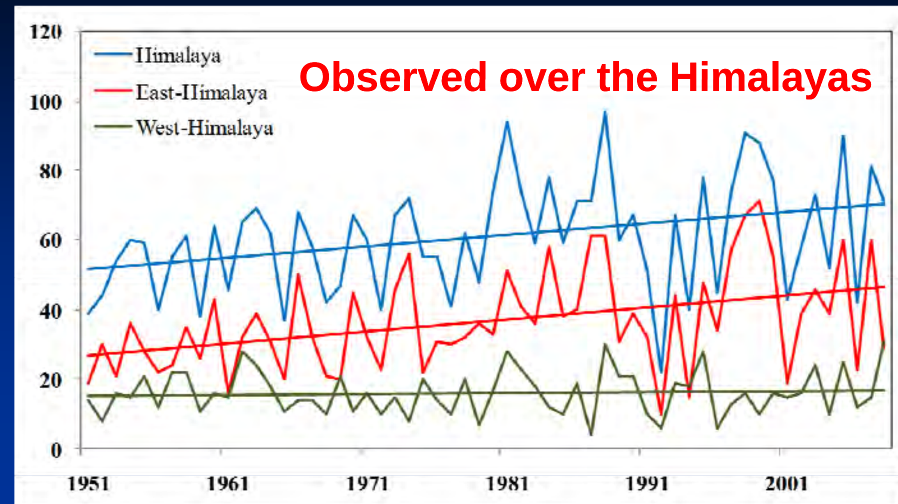


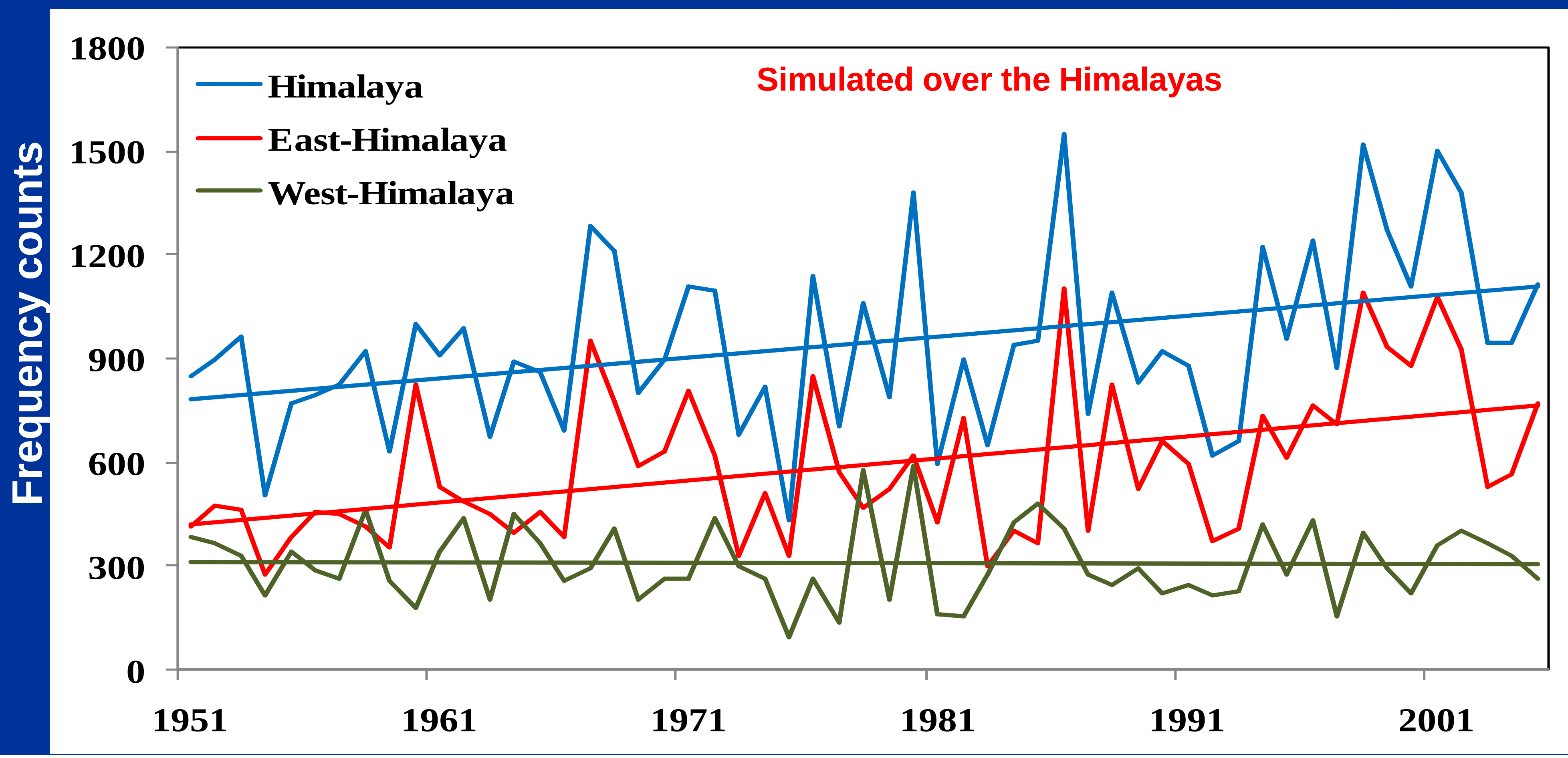
Clim Dyn
DOI 10.1007/s00382-015-2886-5

Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world

R. Krishnan [1] · T. P. Sabin [1] · R. Vellore [1] · M. Mujumdar [1] · J. Sanjay [1] ·
B. N. Goswami [1,2] · F. Hourdin [3] · J.-L. Dufresne [3] · P. Terray [4,5]

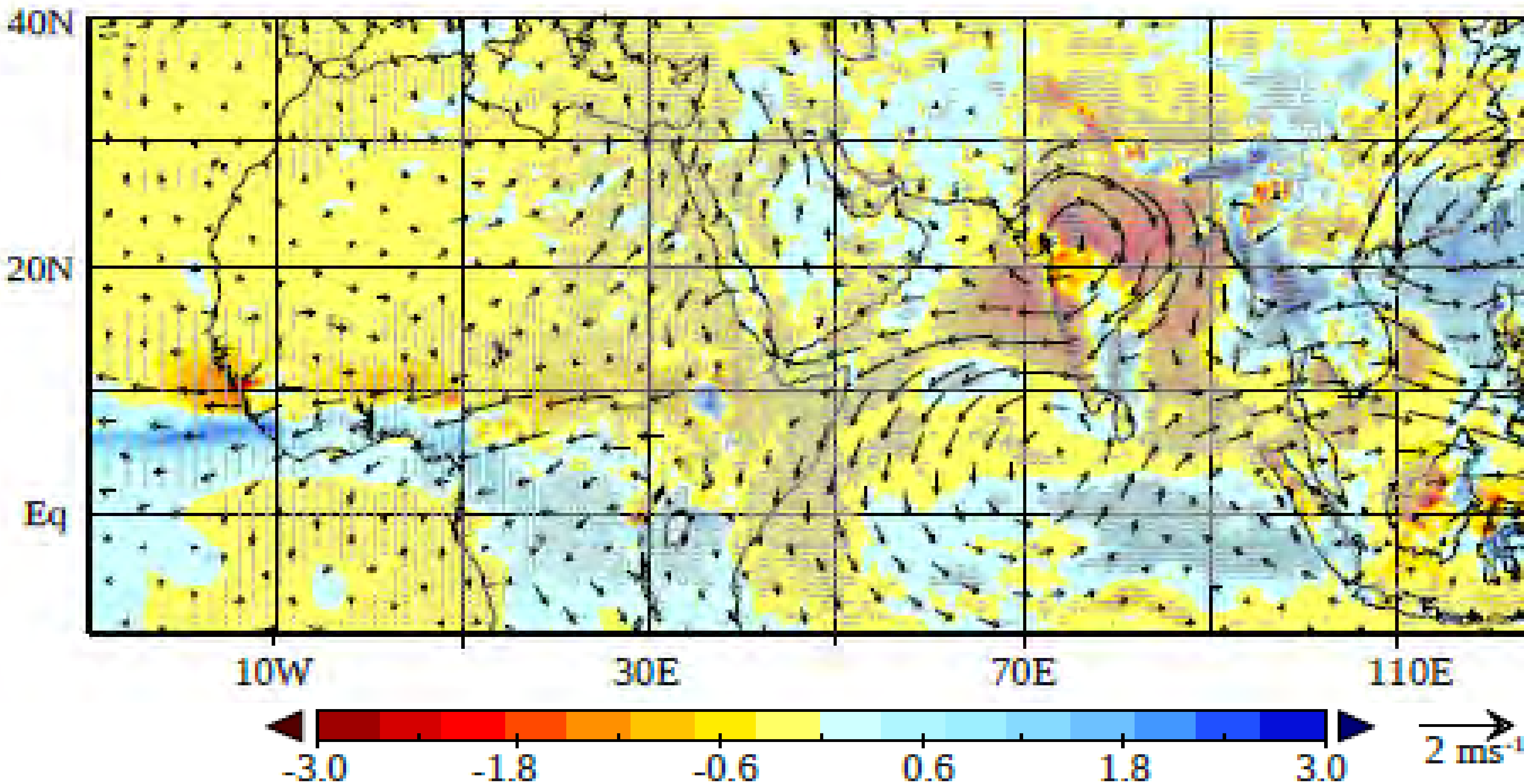

Western Himalayas
Eastern Himalayas
Summer Monsoon


Observed over the Himalayas
Himalaya
East-Himalaya
West-Himalaya
0
20
40
60
80
100
120
1951
1961
1971
1981
1991
2001

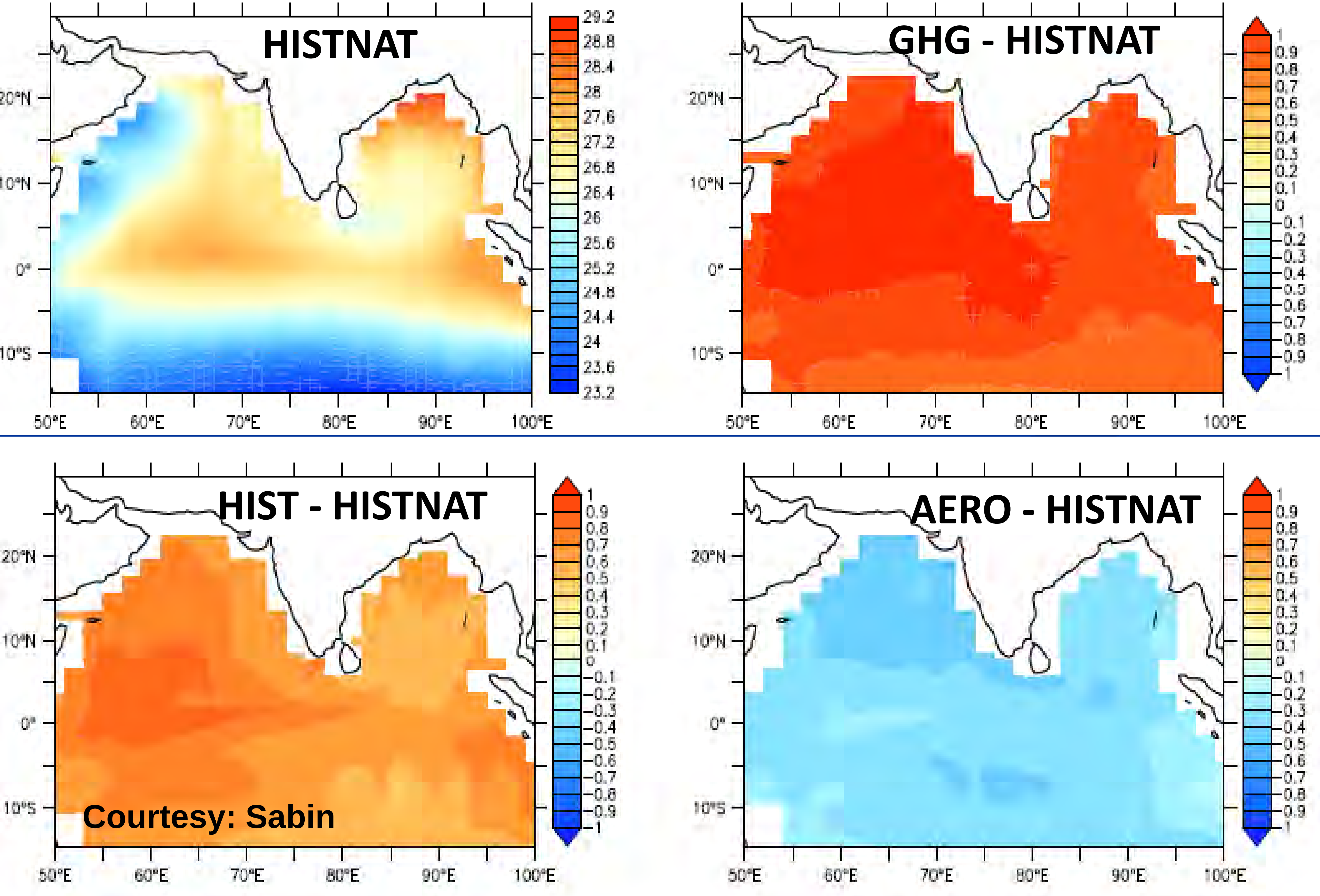

Simulated over the Himalayas
Frequency counts
Himalaya
East-Himalaya
West-Himalaya
0
300
600
900
1200
1500
1800
1951
1961
1971
1981
1991
2001

Mean difference maps (HIST minus HISTNAT) during 1951-2005

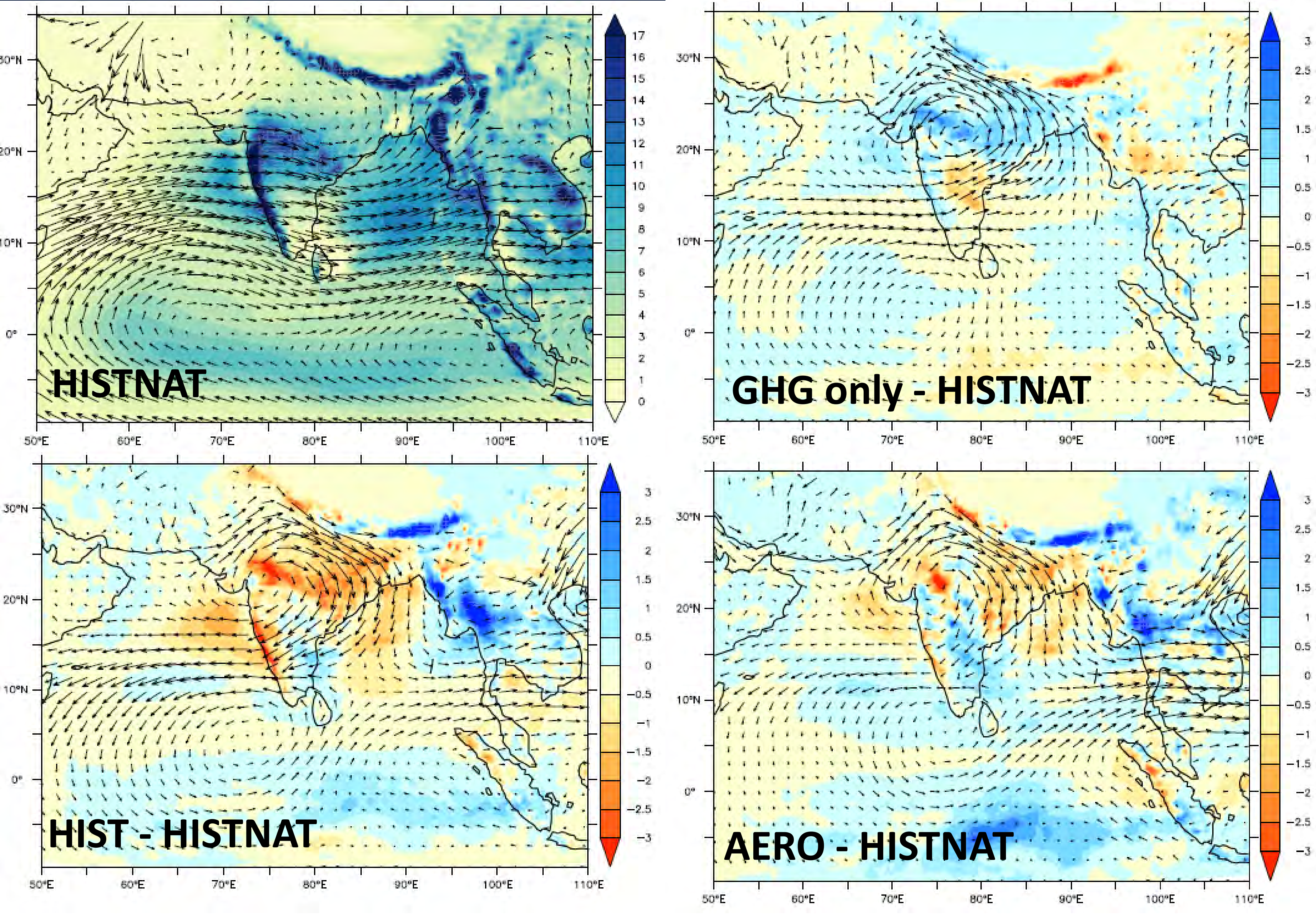
JJAS rainfall and 850 hPa winds



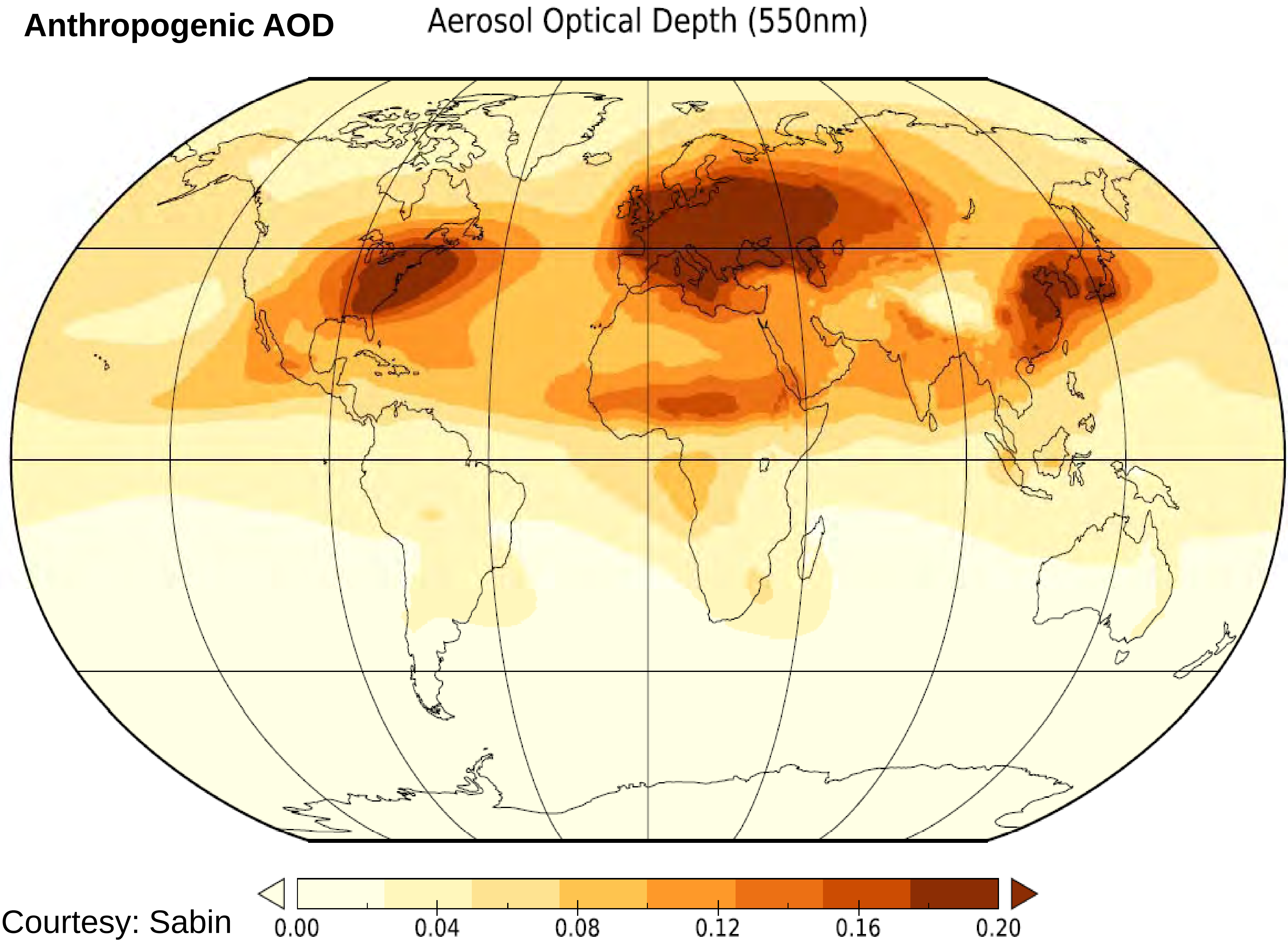
SST boundary forcing and SST change



Simulation of summer monsoon precipitation & 850 hPa circulation

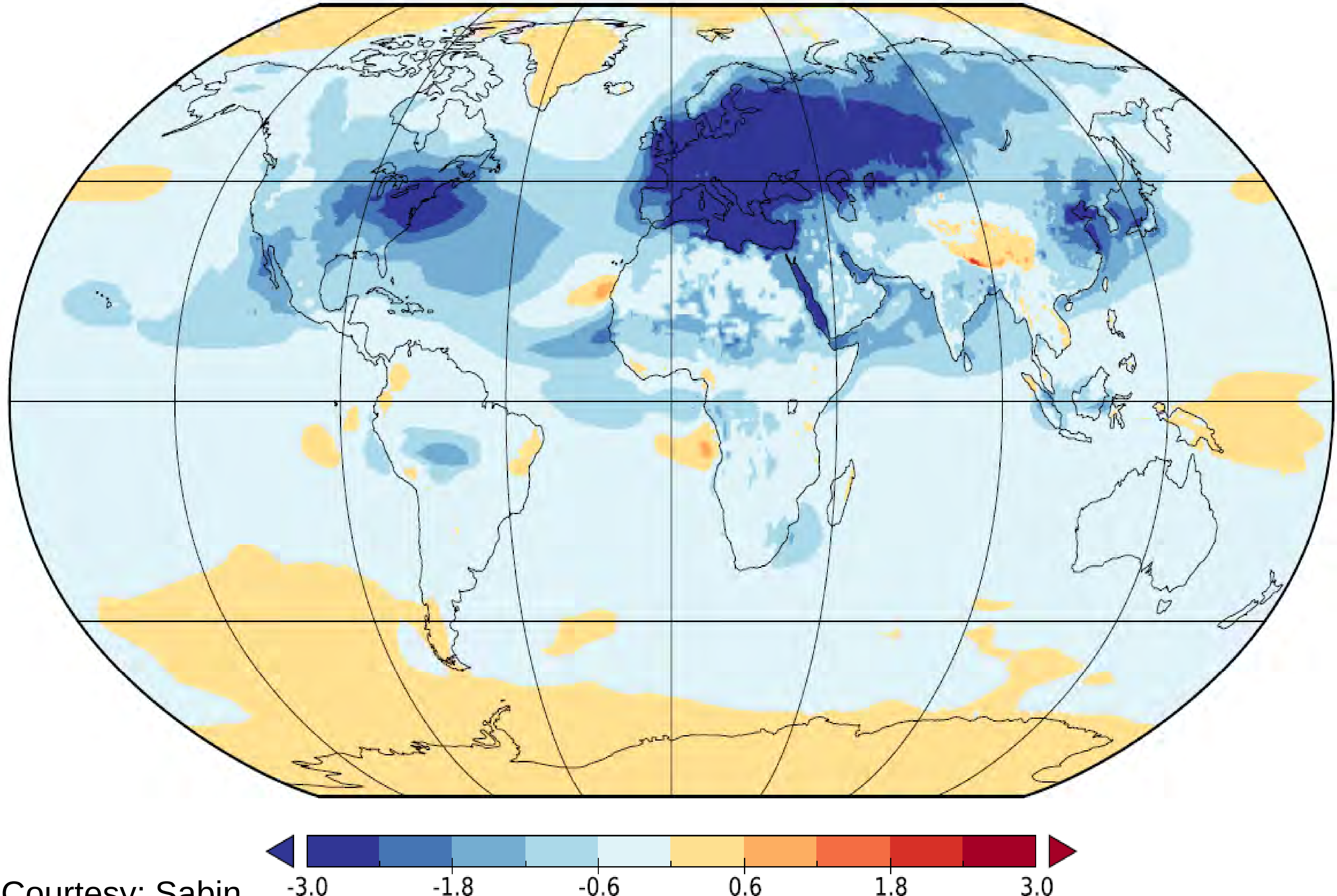


Anthropogenic AOD



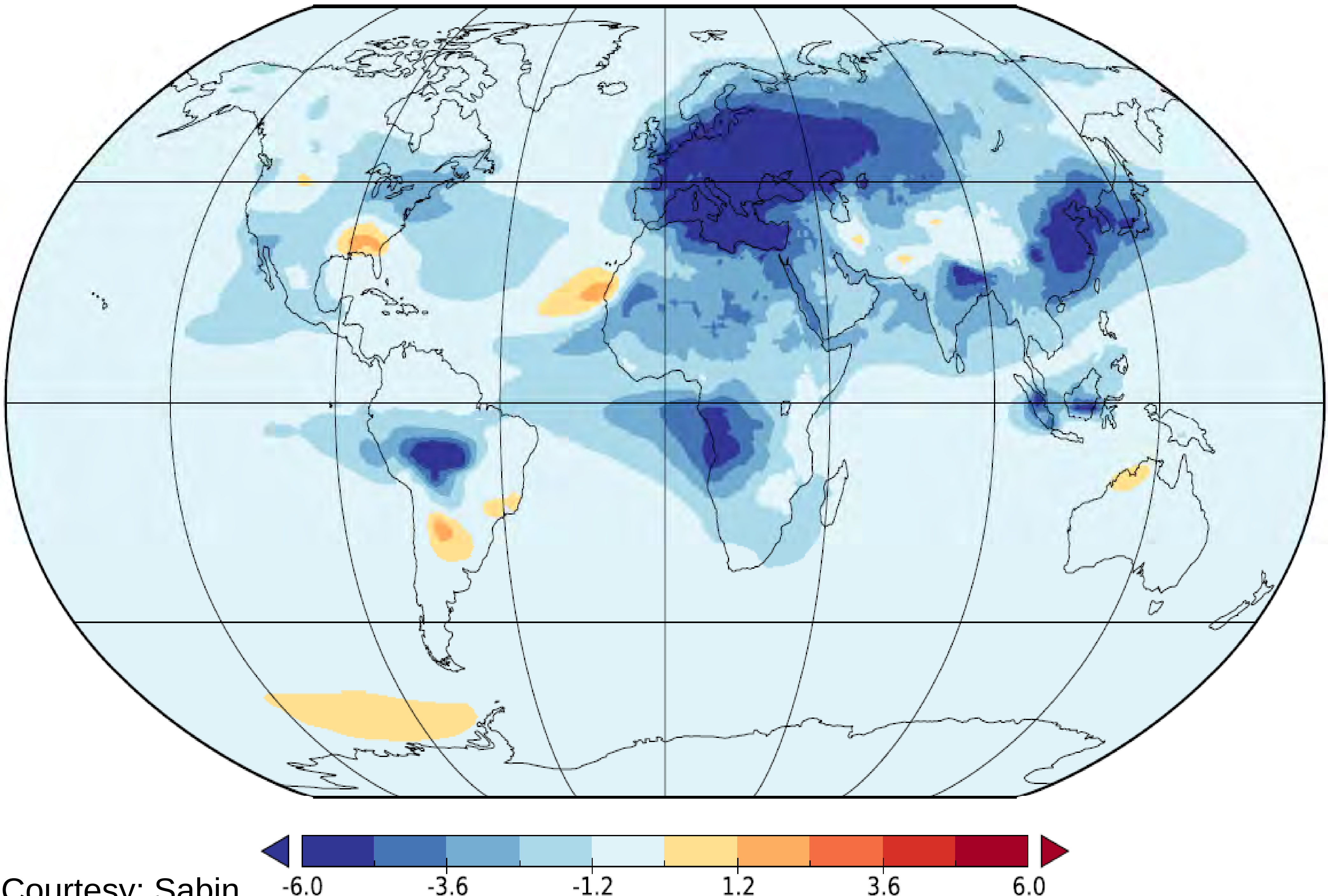
Courtesy: Sabin

Anthropogenic Aerosol RF at TOA



Courtesy: Sabin

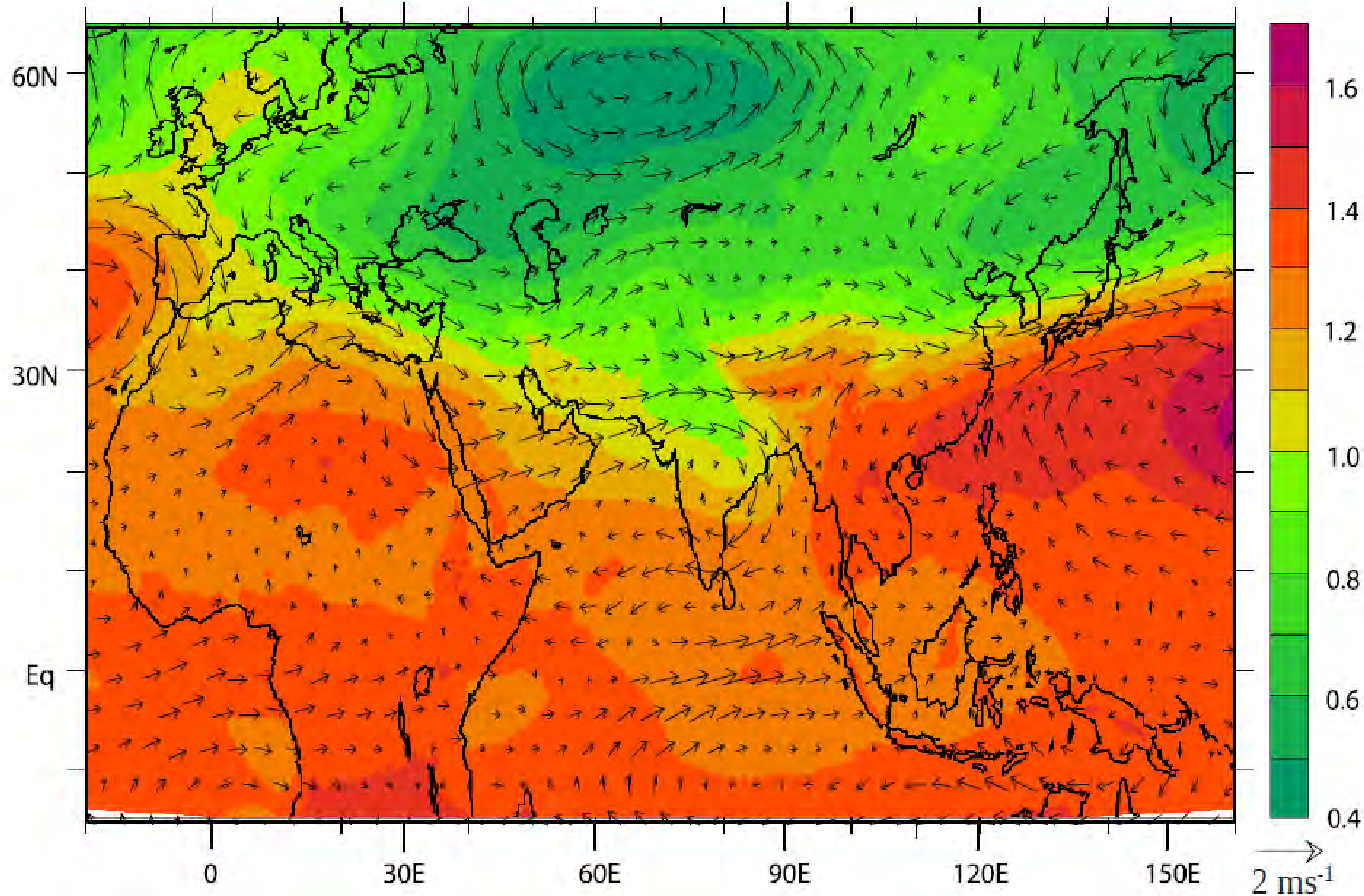
Anthropogenic Aerosol RF at SRF



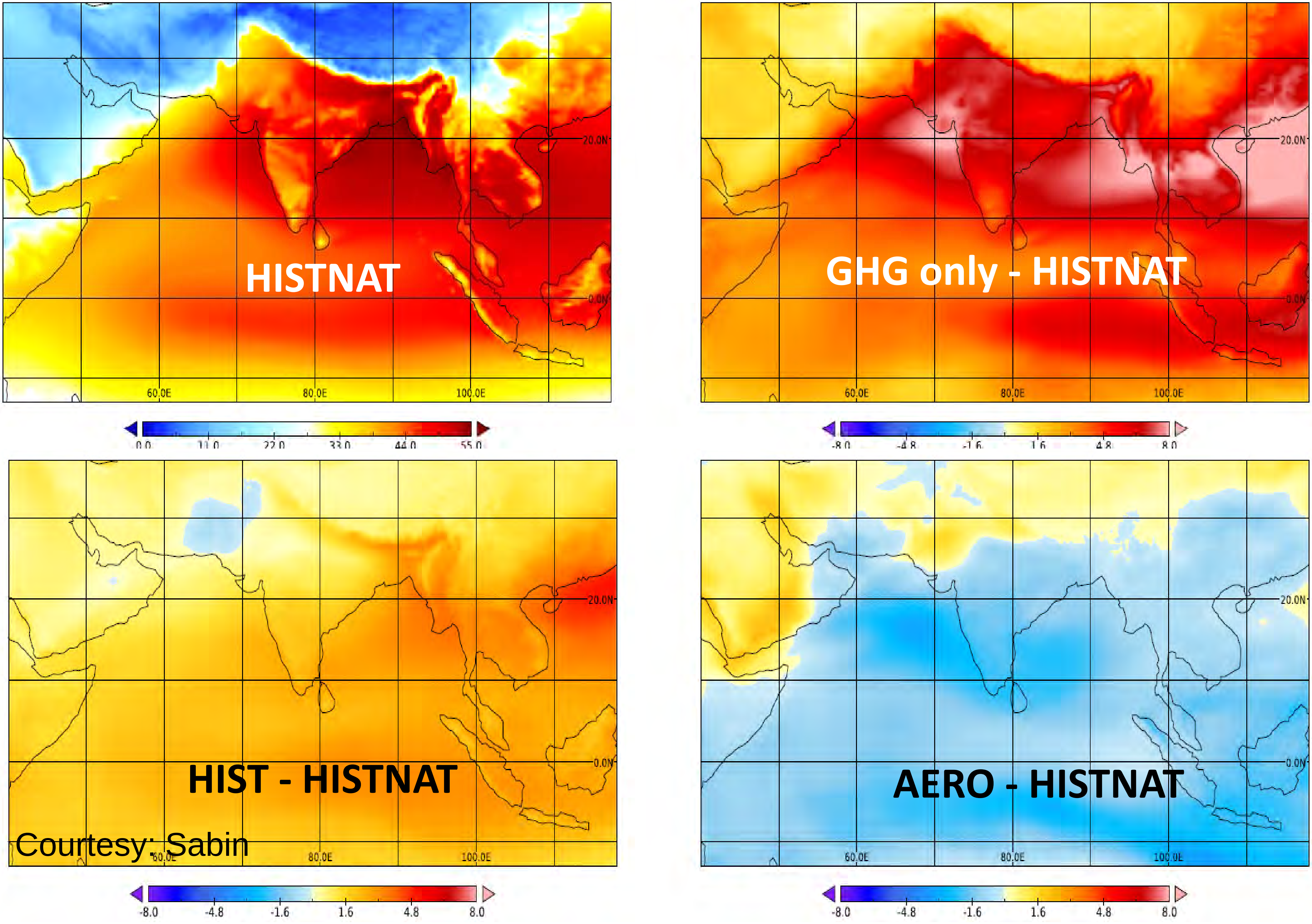
Courtesy: Sabin

Response of tropospheric temperature & large-scale circulation to Anthropogenic forcing

HIST minus HISTNAT (1951 – 2005): Winds & temperature vertically averaged 600-200 hPa



Simulation of summer monsoon precipitable water response



To summarize

•Long-term climate change experiments conducted at CCCR-IITM using a global variable grid climate model with high-resolution zooming (grid < 35 km) over S.Asia

•The high-resolution simulation with anthropogenic forcing captures the decreasing trend of Indian monsoon precipitation in the post-1950s.

•Recent monsoon decline likely influenced significantly by **Anthropogenic Aerosols** with contributions from land use land cover change, equatorial Indian Ocean warming.

•Anthropogenic aerosols induce large-scale cooling over NH and continental Eurasia. Dynamical response to energy imbalance weakens South Asian monsoon via mid-latitude circulation anomalies reminiscent of break-monsoon conditions.

•Robust increase in frequency of heavy precipitation (R > 100 mm/day) occurrences over Central India is noted in the high-resolution climate change simulation.

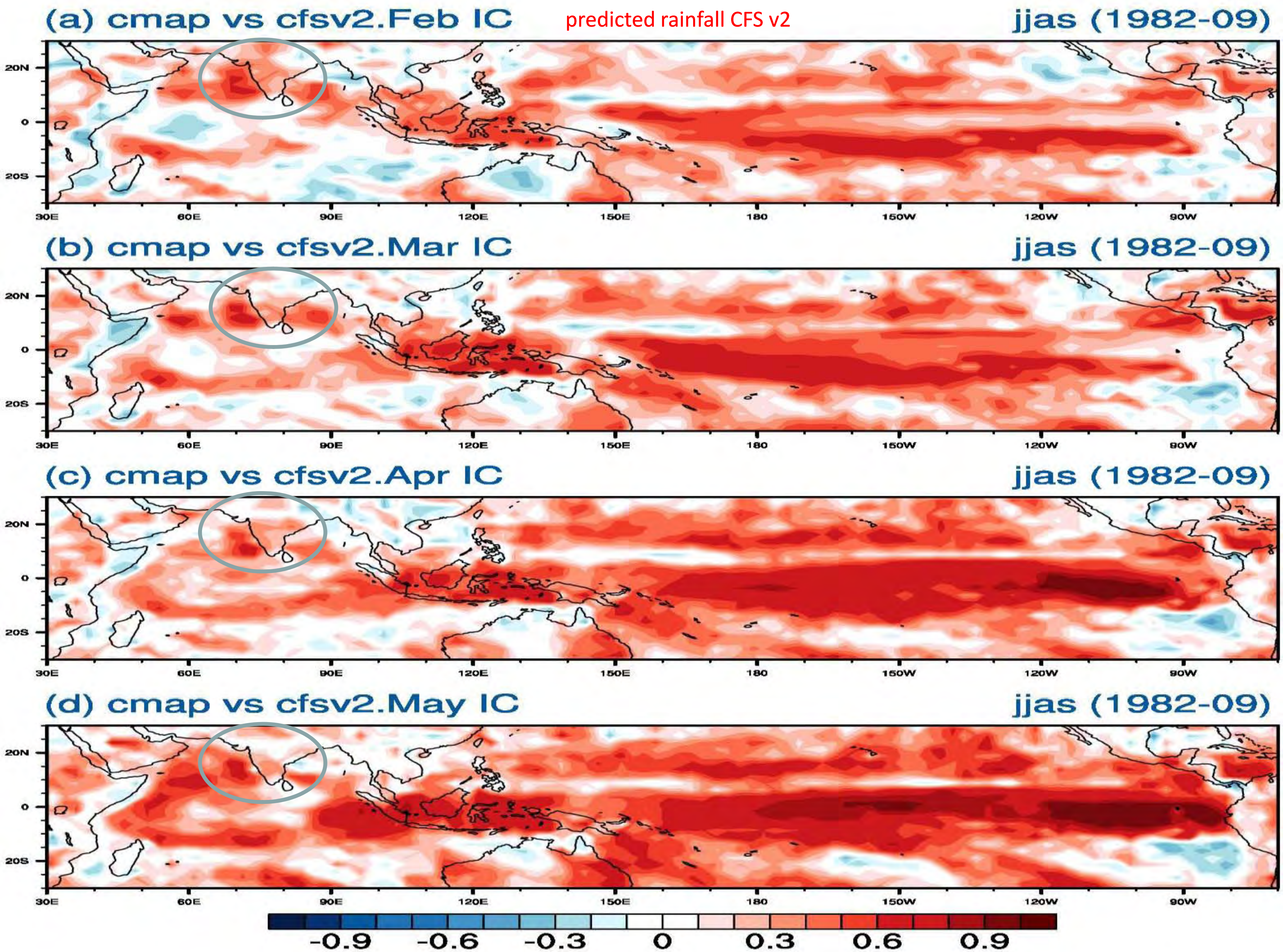
•Strong internal variability of the South Asian monsoon system makes it necessary to have multiple realizations to better quantify aerosol impact on monsoon precipitation.

•Indian Ocean Warming Signal (decadal variability and long-term trend): Not well understood.

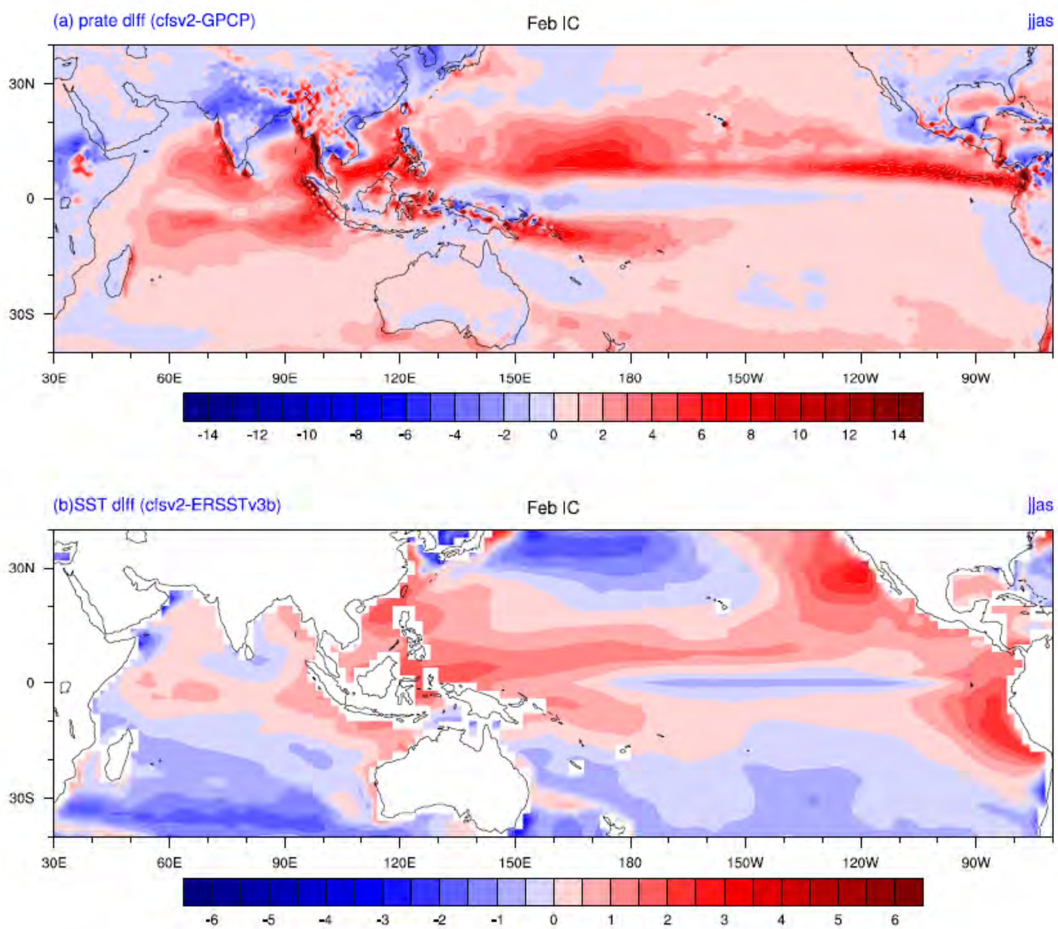
•Requirement of high-resolution atmosphere-ocean coupled model to better quantify the role of aerosol forcing on the South Asian monsoon.

In seasonal forecasts, most important predictable signal is SST forced variability.

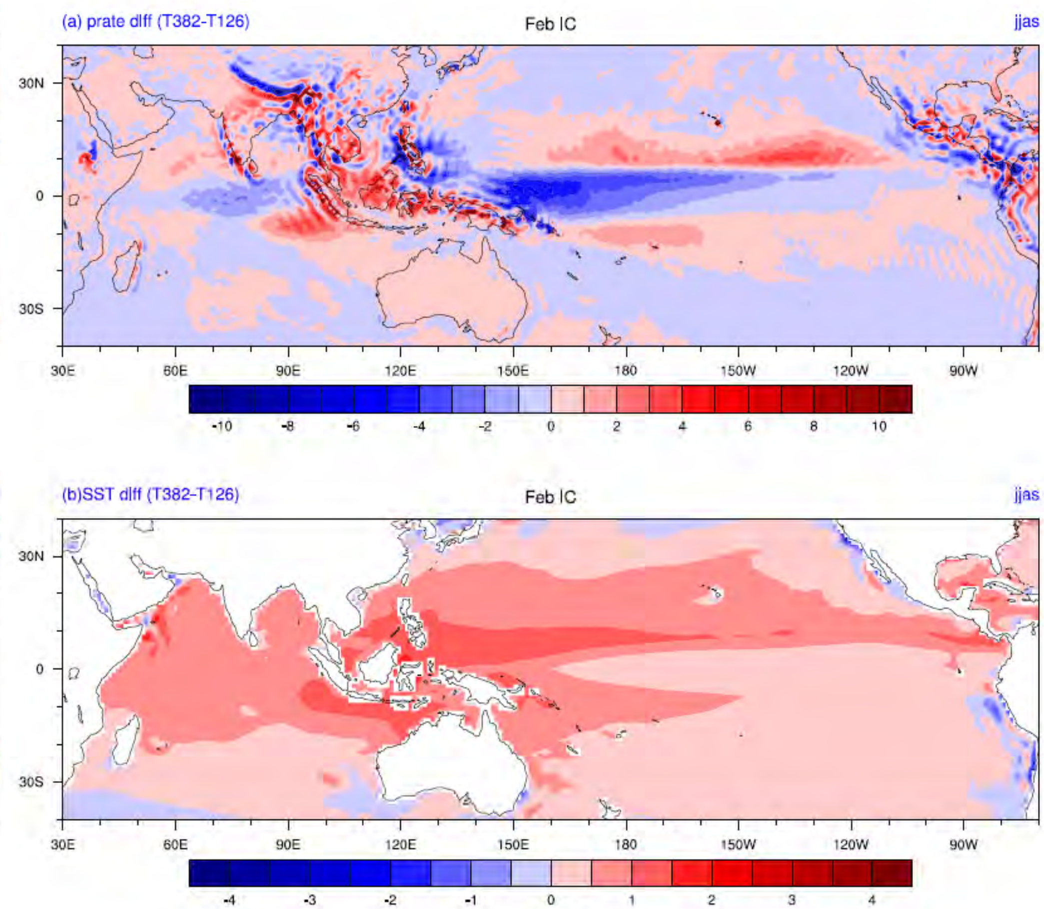
Correlation between observed and predicted rainfall CFS v2



High resolution (in atmosphere model) has resulted in reducing the dry bias over land and also resulted in improvement of skill



T382 model bias



T382 vs. T126

whether seasonal predictability will change in a future climate?

response to global warming is sensitive to the model

Changes in Seasonal Predictability due to Global Warming

TIMOTHY DELSOLE, XIAOQIN YAN, AND PAUL A. DIRMEYER
George Mason University, Fairfax, Virginia, and Center for Ocean–Land–Atmosphere Studies, Calverton, Maryland

MIKE FENNESSY AND ERIC ALTSHULER
Center for Ocean–Land–Atmosphere Studies, Calverton, Maryland

2014

CCSM4

The dominant source of predictability on seasonal time scales is the ENSO phenomenon.

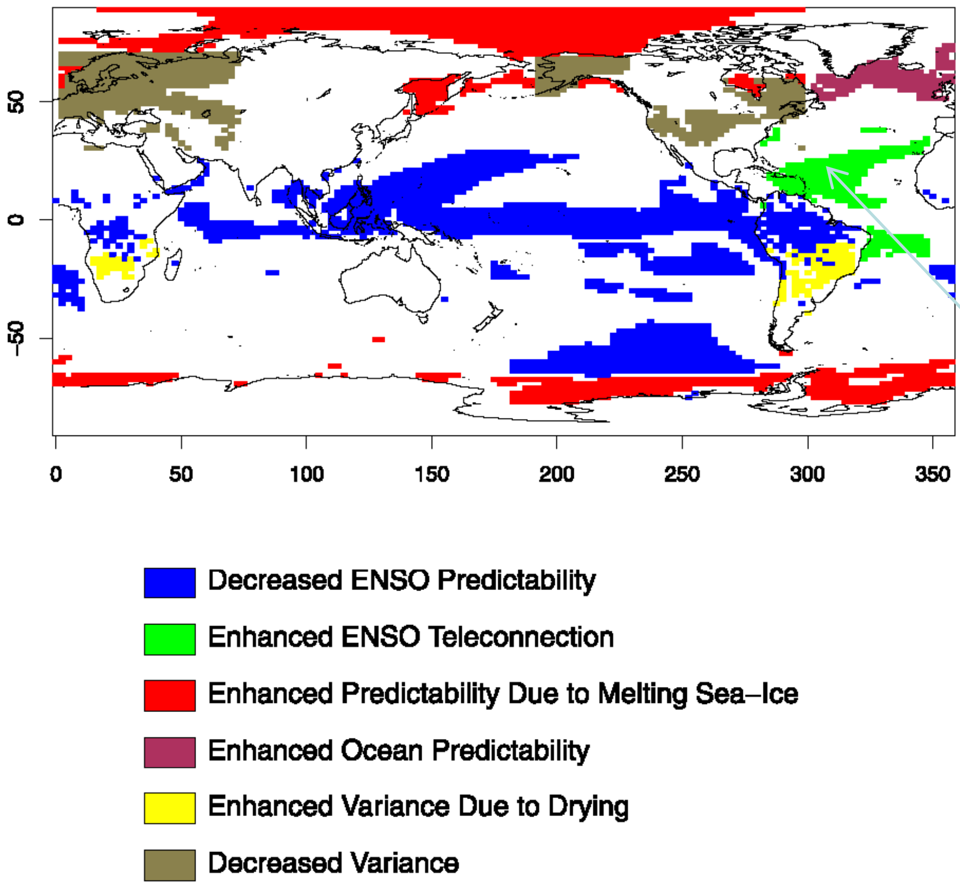


FIG. 8. Schematic showing statistically significant changes in predictability of February-mean surface air temperature inferred from CCSM4.

Based on model ENSO variance, the North Atlantic overtakes the El Nino–Southern Oscillation (ENSO) as the dominant area of seasonal predictability by 2095. This change arises partly because ENSO becomes less variable and partly because the ENSO teleconnection pattern expands into the Atlantic.

Over land, the largest change in temperature predictability occurs in the tropics and is predominantly due to a decrease in ENSO variability.

Forecasting day-to-day weather is primarily an atmospheric initial condition problem, although there can be an influence from ocean and land conditions. Forecasting at the seasonal to inter-annual range, in contrast, depends strongly on slowly-evolving components of the Earth system, especially the sea-surface temperatures (SST). In between these two time scales is sub-seasonal variability, which is defined here as the time range between two weeks and two months.

Sub-seasonal to seasonal forecasting is at a relatively early stage of development.

Assessment of extreme weather episodes

- *Major issues from a climate perspective include the occurrence of extreme events, from heat waves to hurricanes, how seasonal-to-interannual variability affects their probability of occurrence, and whether such climatic variations are usefully predictable.*

- *Assessing how sub-seasonal to seasonal variations may alter the frequencies, intensity and locations of high impact events will be a high priority area of research from the societal decision-making perspective.*

Sources of sub-seasonal to seasonal predictability come from various processes in the atmosphere, ocean and land. A few of such processes are:

The Madden-Julian Oscillation: as the dominant mode of intra-seasonal variability in the tropics that modulates organized convective activity, the Madden-Julian Oscillation has a considerable impact not only in the tropics, but also in the middle and high latitudes, and is considered as a major source of global predictability on the sub-seasonal time scale (e.g. Waliser 2011).

Soil moisture: inertial memory in soil moisture can last several weeks, which can influence the atmosphere through changes in evaporation and surface energy budget and can affect the forecast of air temperature and precipitation in certain areas during certain times of the year on intra-seasonal time scales (e.g. Koster et al. 2010).

Snow cover: The radiative and thermal properties of widespread snow cover anomalies have the potential to modulate local and remote climate variability over monthly to seasonal time scales (e.g. Sobolowski et al. 2010).

Stratosphere-troposphere interaction: signals of changes in the polar vortex and the Northern Annular Mode/Arctic Oscillation (NAM/AO) are often seen to come from the stratosphere, with the anomalous tropospheric flow lasting up to about two months (Baldwin et al. 2003).

Ocean conditions: anomalies in upper-ocean thermal structure, in particular sea-surface temperature, lead to changes in air-sea heat flux and convection, which affect atmospheric circulation. The tropical intraseasonal variability forecast skill is improved when a coupled model is used (e.g. Woolnough et al. 2007), while coupled modes of ocean-atmosphere interaction, including the El Niño–Southern Oscillation in particular, can yield substantial forecast skill even within the first month.

Modeling issues that need improvement

The majority of the current sub-seasonal to seasonal operational forecasting systems are based on ensembles of coupled ocean-atmosphere integrations because realistic representation of ocean-atmosphere coupling is likely to be important on the sub-seasonal to seasonal time range.

However, several important modelling issues still need to be addressed:

- *What is the optimal way to initialize a coupled ocean-atmosphere system for successful sub-seasonal to seasonal prediction?*
- *What is the best forecast system configuration for representing uncertainty to achieve successful sub-seasonal to seasonal forecasts?*
- *What is the impact of increasing horizontal or vertical atmospheric and oceanic resolution?*
- *What are the main sources of systematic errors at this time range?*
- *What is the impact of coupling the atmosphere to an ocean, land surface and cryosphere model?*
- *What is the benefit of multi-model combinations?*

Some references mentioned

Waliser, D.E., 2011: Predictability and Forecasting. Intraseasonal Variability of the Atmosphere-Ocean Climate System, W.K.M. Lau and D.E. Waliser, Eds., Springer, Heidelberg, Germany 2nd Edition. ISBN 978-3-642-13913-0, DOI 10.1007/978-3-642-13914-7.

Koster, R.D., and Coauthors 2010: Contribution of land surface initialization to subseasonal forecast skill: First results from a multi-model experiment. Geophysical Research Letters, 37, L02402, 10.1029/2009GL041677.

Sobolowski, Stefan, Gavin Gong, Mingfang Ting, 2010: Modeled Climate State and Dynamic Responses to Anomalous North American Snow Cover. J. Climate, 23, 785–799.

Baldwin, M.P., D.B. Stephenson, D.W.J. Thompson, T.J. Dunkerton, A.J. Charlton, A. O'Neill, 2003: Stratospheric memory and extended-range weather forecasts, Science, 301, 636-640.

Woolnough, S.J., F. Vitart, and M.A. Balmaseda, 2007: The role of the ocean in the Madden-Julian Oscillation: Implications for the MJO prediction. Quart. J. Meteor. Soc., 133, 117-128.

Thank you