Seventh WMO International Workshop on Monsoons (IWM-7)
22-26 March 2022, New Delhi, India

Implications of volcanic aerosols for seasonal forecasting of the Indian monsoon in a changing climate

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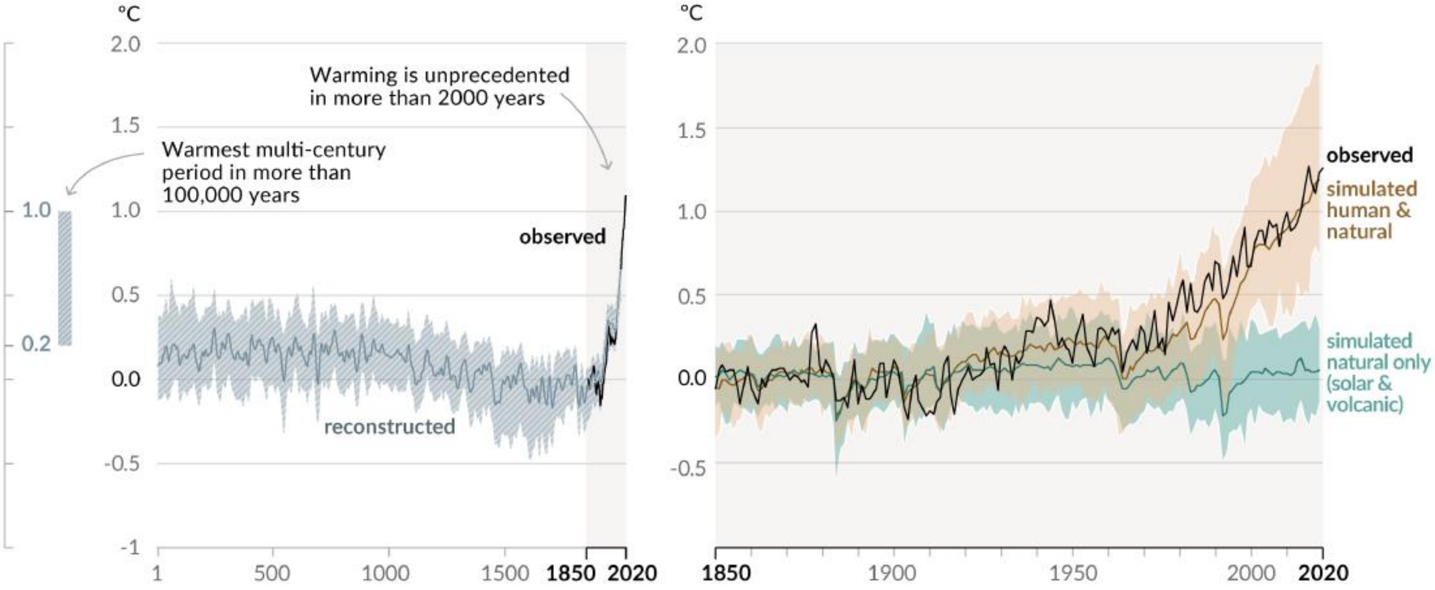
Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years

Figure SPM.1

Changes in global surface temperature relative to 1850-1900

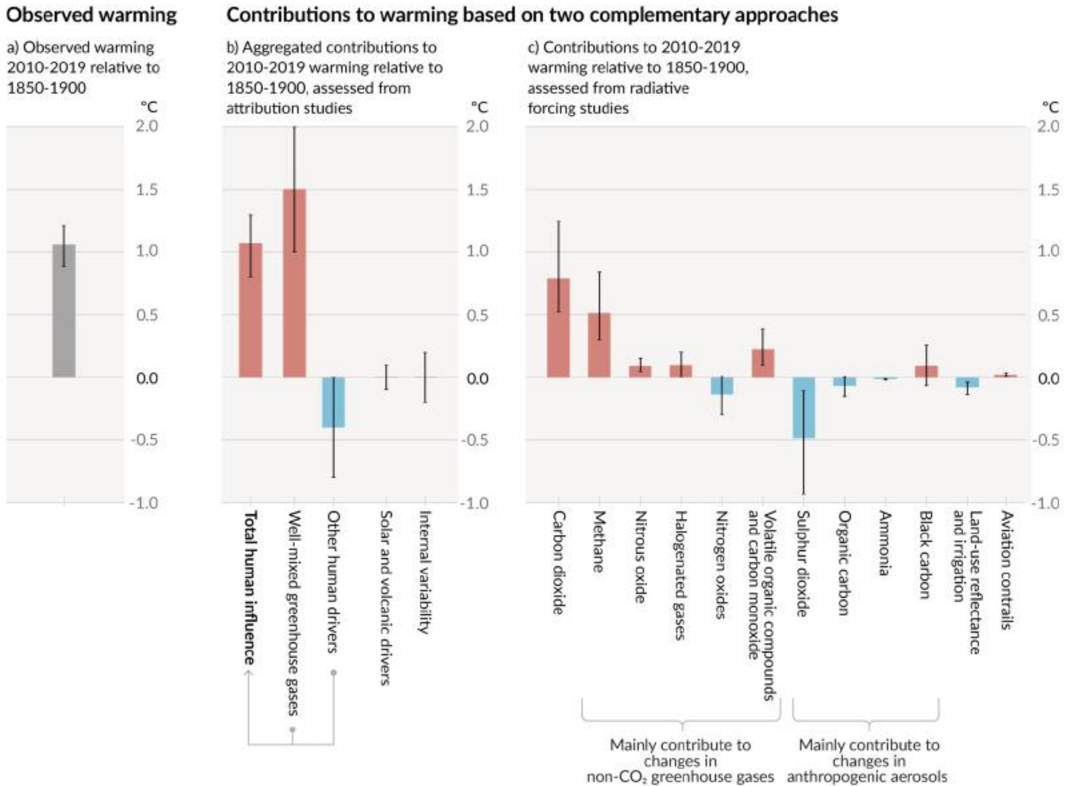
a) Change in global surface temperature (decadal average) as reconstructed (1-2000) and **observed** (1850-2020)

b) Change in global surface temperature (annual average) as **observed** and simulated using **human & natural** and **only natural** factors (both 1850-2020)



Observed warming is driven by emissions from human activities, with greenhouse gas warming partly masked by aerosol cooling

Figure SPM.2



Observed warming

a) Observed warming 2010-2019 relative to 1850-1900

Contributions to warming based on two complementary approaches

b) Aggregated contributions to 2010-2019 warming relative to 1850-1900, assessed from attribution studies

c) Contributions to 2010-2019 warming relative to 1850-1900, assessed from radiative forcing studies

Global and regional monsoon domains

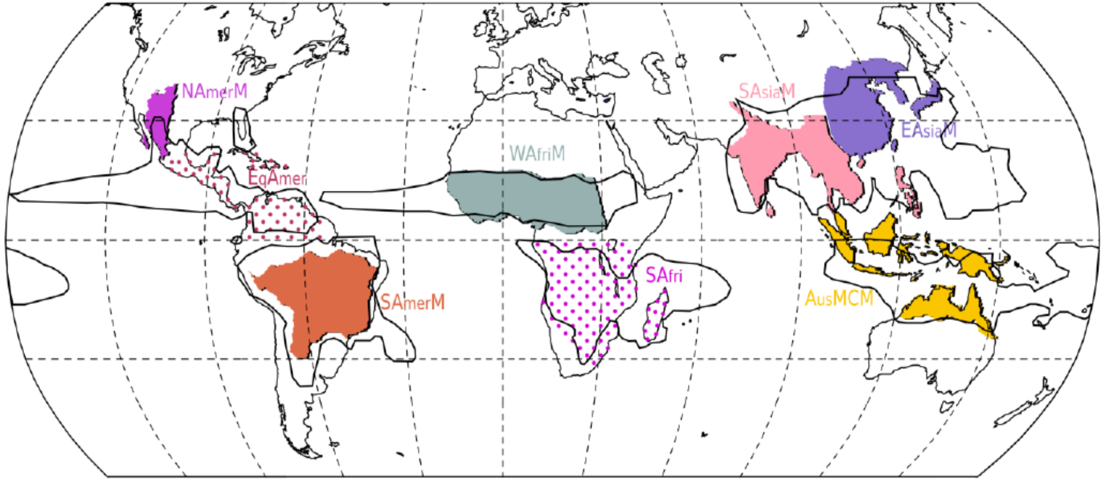


Figure AV.1 - **Annex V: Monsoons**

Global (black contour) and regional monsoons (color shaded) domains. The global monsoon (*GM*) is defined as the area with local summer-minus-winter precipitation rate exceeding 2.5 mm day^{-1}. The regional monsoon domains are defined based on published literature and expert judgement and also accounting for the fact that the climatological summer monsoon rainy season varies across the individual regions.

Box TS.13: Monsoons

- Global land monsoon precipitation decreased from the 1950s to the 1980s, partly due to anthropogenic aerosols, but has increased since then in response to GHG forcing and large-scale multi-decadal variability (*medium confidence*).
- During the 21st century, global land monsoon precipitation is projected to increase in response to GHG warming in all time horizons and scenarios (*high confidence*).
- In the long term, global monsoon rainfall change will feature a robust north-south asymmetry characterized by a greater increase in the Northern Hemisphere than in the Southern Hemisphere and an east-west asymmetry characterized by enhanced Asian-African monsoons and a weakened North American monsoon (*medium confidence*).

Trend and change in monsoon precipitation (1951-2014) for South & Southeast Asia (SAsiaM) and East Asia (EAsiaM)

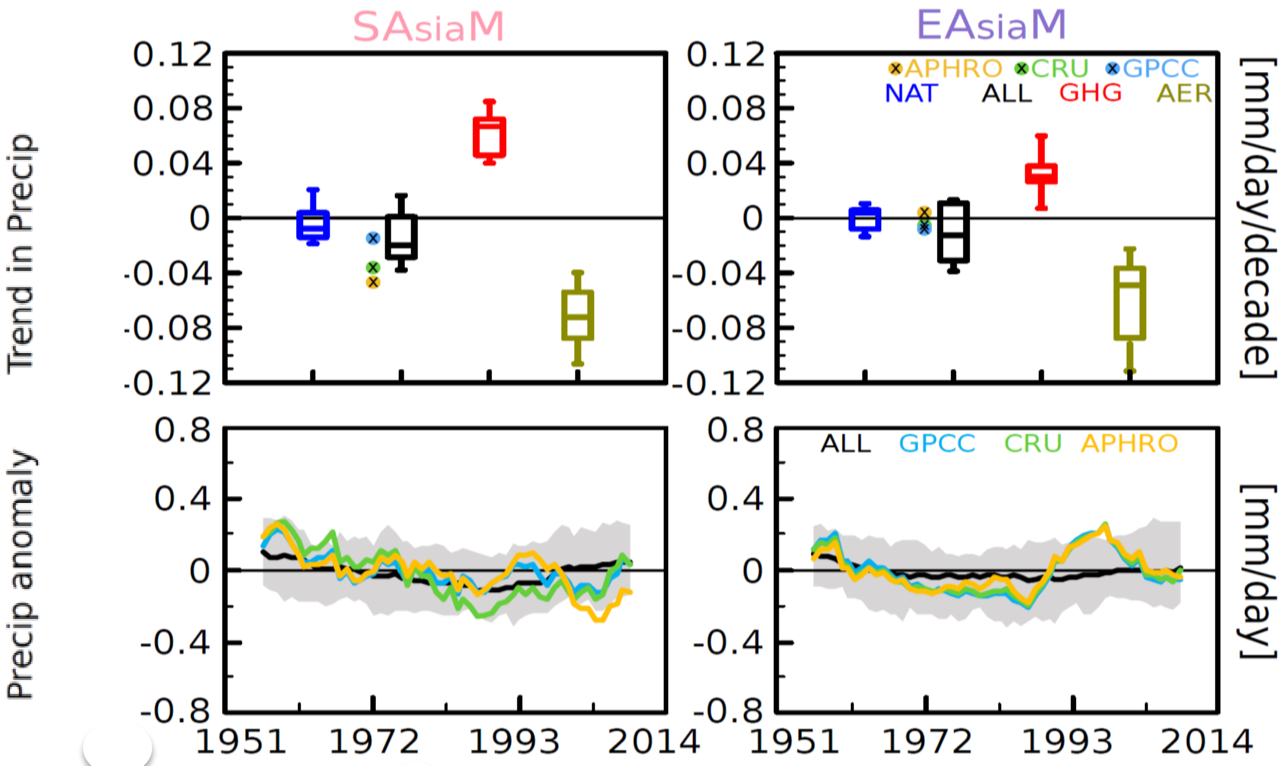
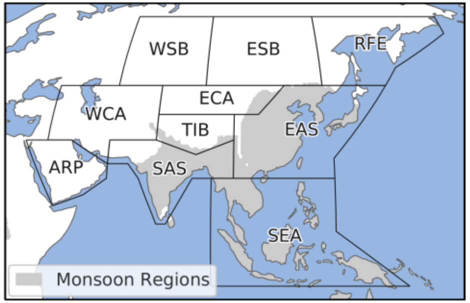
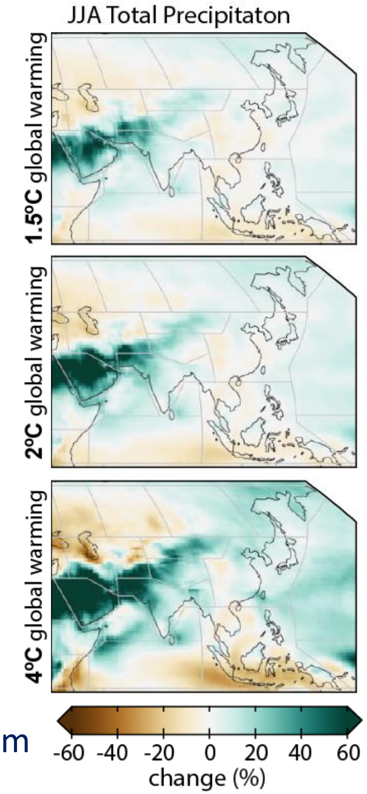


Figure 8.11

Asian Monsoons

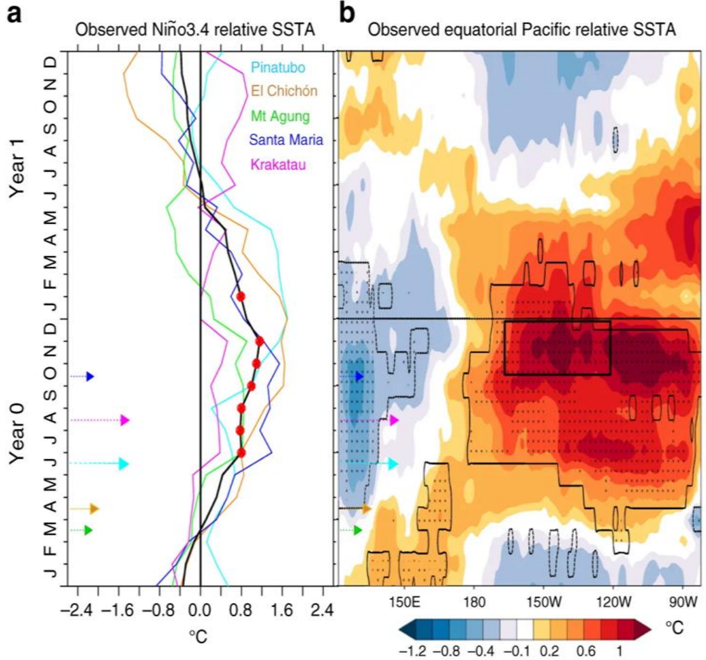


- The South and Southeast Asian monsoon precipitation decreased since the mid-20th century (*high confidence*), the dominant cause being anthropogenic aerosol forcing.
- The dry-north and wet-south pattern of East Asian summer monsoon precipitation change results from the combined effects of greenhouse gases and aerosols (*high confidence*).
- In the near-term (2021-2040), South and Southeast Asian monsoon and East Asian summer monsoon precipitation will be dominated by the effects of internal variability (*medium confidence*), but will increase in the long-term (2081-2100) (*medium confidence*).



Unpredictable natural forcings (e.g., volcanic eruptions) - Source of uncertainty for near-term projections of regional monsoon changes.

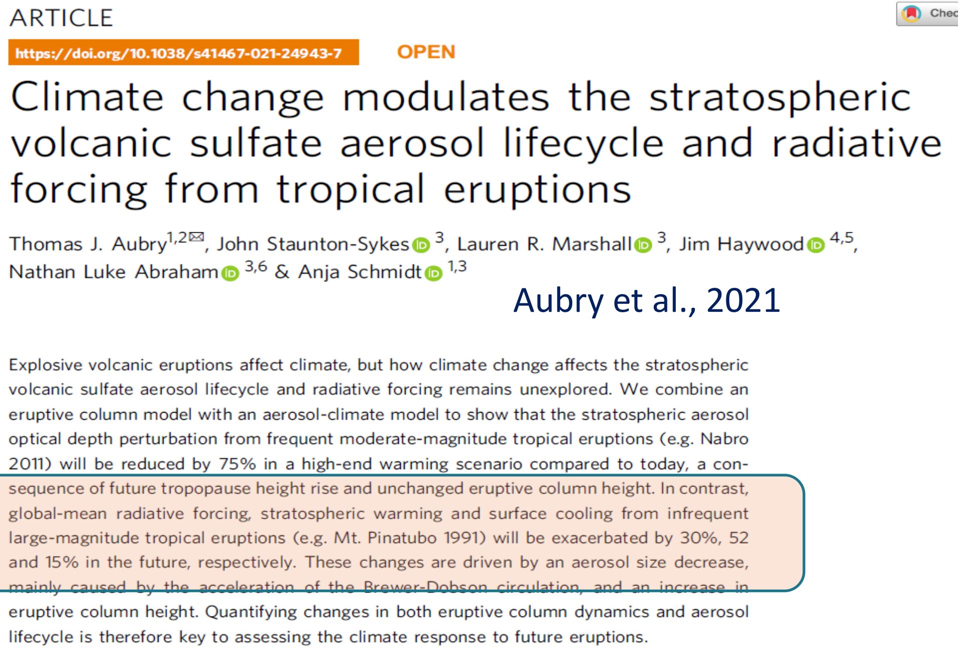
Large volcanic eruptions can trigger El Ninos



Khodri, M., Izumo, T., Vialard, J., Janicot, S., Cassou, C., Lengaigne, M., Mignot, J., Gastineau, G., Guilyardi, E., Lebas, N. and Robock, A., 2017. Tropical explosive volcanic eruptions can trigger El Niño by cooling tropical Africa. *Nature communications*, *8*(1), pp.1-13.

Stratospheric aerosols from large tropical explosive volcanic eruptions backscatter shortwave radiation and reduce the global mean surface temperature. Observations suggest that they also favour an El Niño within 2 years following the eruption. Modelling studies have, however, so far reached no consensus on either the sign or physical mechanism of El Niño response to volcanism. Here we show that an El Niño tends to peak during the year following large eruptions in simulations of the Fifth Coupled Model Intercomparison Project (CMIP5). Targeted climate model simulations further emphasize that Pinatubo-like eruptions tend to shorten La Niñas, lengthen El Niños and induce anomalous warming when occurring during neutral states. Volcanically induced cooling in tropical Africa weakens the West African monsoon, and the resulting atmospheric Kelvin wave drives equatorial westerly wind anomalies over the western Pacific. This wind anomaly is further amplified by air–sea interactions in the Pacific, favouring an El Niño-like response.

Agung eruption 1963-64, Bali, Indonesia. Photograph, 16 May 1963



ARTICLE

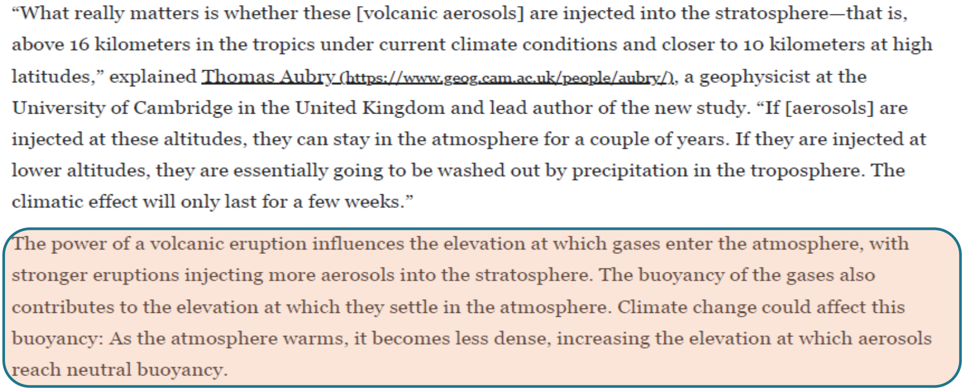
https://doi.org/10.1038/s41467-021-24943-7 OPEN

Climate change modulates the stratospheric volcanic sulfate aerosol lifecycle and radiative forcing from tropical eruptions

Thomas J. Aubry[1,2]✉, John Staunton-Sykes[3], Lauren R. Marshall[3], Jim Haywood[4,5], Nathan Luke Abraham[3,6] & Anja Schmidt[1,3]

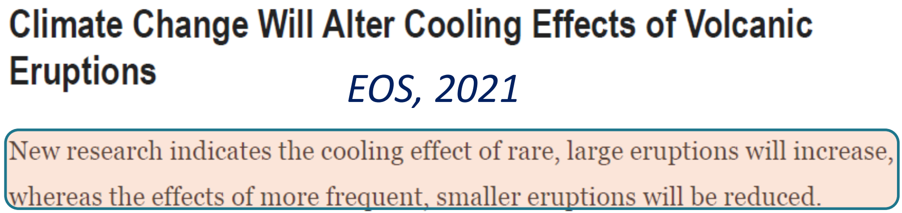
Aubry et al., 2021

Explosive volcanic eruptions affect climate, but how climate change affects the stratospheric volcanic sulfate aerosol lifecycle and radiative forcing remains unexplored. We combine an eruptive column model with an aerosol-climate model to show that the stratospheric aerosol optical depth perturbation from frequent moderate-magnitude tropical eruptions (e.g. Nabro 2011) will be reduced by 75% in a high-end warming scenario compared to today, a consequence of future tropopause height rise and unchanged eruptive column height. In contrast, global-mean radiative forcing, stratospheric warming and surface cooling from infrequent large-magnitude tropical eruptions (e.g. Mt. Pinatubo 1991) will be exacerbated by 30%, 52 and 15% in the future, respectively. These changes are driven by an aerosol size decrease, mainly caused by the acceleration of the Brewer-Dobson circulation, and an increase in eruptive column height. Quantifying changes in both eruptive column dynamics and aerosol lifecycle is therefore key to assessing the climate response to future eruptions.



“What really matters is whether these [volcanic aerosols] are injected into the stratosphere—that is, above 16 kilometers in the tropics under current climate conditions and closer to 10 kilometers at high latitudes,” explained Thomas Aubry (https://www.geog.cam.ac.uk/people/aubry/), a geophysicist at the University of Cambridge in the United Kingdom and lead author of the new study. “If [aerosols] are injected at these altitudes, they can stay in the atmosphere for a couple of years. If they are injected at lower altitudes, they are essentially going to be washed out by precipitation in the troposphere. The climatic effect will only last for a few weeks.”

The power of a volcanic eruption influences the elevation at which gases enter the atmosphere, with stronger eruptions injecting more aerosols into the stratosphere. The buoyancy of the gases also contributes to the elevation at which they settle in the atmosphere. Climate change could affect this buoyancy: As the atmosphere warms, it becomes less dense, increasing the elevation at which aerosols reach neutral buoyancy.



Climate Change Will Alter Cooling Effects of Volcanic Eruptions

EOS, 2021

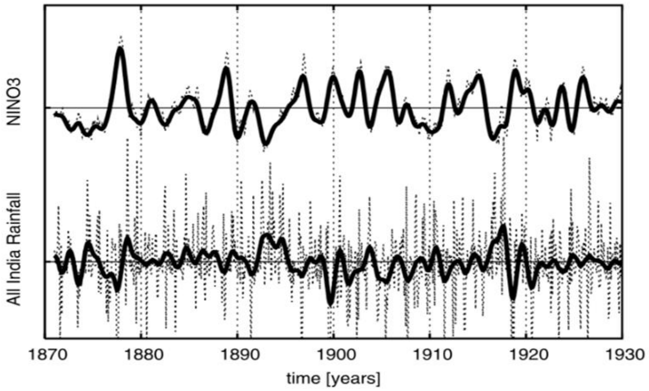
New research indicates the cooling effect of rare, large eruptions will increase, whereas the effects of more frequent, smaller eruptions will be reduced.

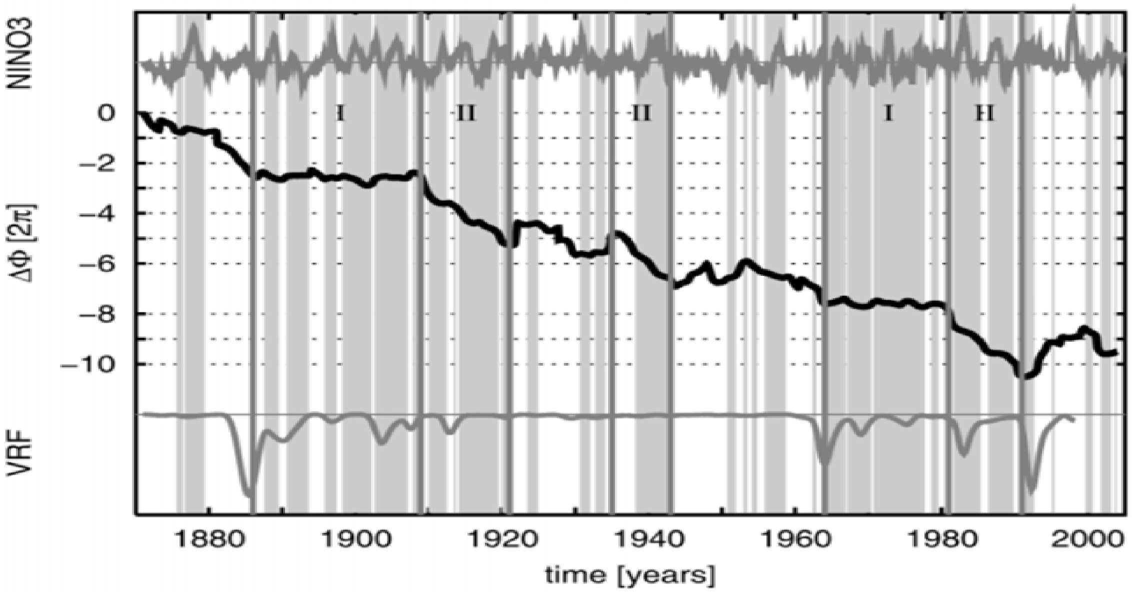
The eruption of Mount Pinatubo, Philippines, in June 1991 was one of the most powerful of the most powerful of the 20th century.

Phase coherence analysis (PCA) observed ENSO-IM time series (Maraun and Kurths 2005)

ENSO and IM phase difference and Volcanic Radiative Forcing (VRF)

Filtered ENSO and AIR





Maraun, D. and Kurths, J., 2005. Epochs of phase coherence between El Nino/Southern Oscillation and Indian monsoon. Geophysical Research Letters, 32(15).

SCIENCE ADVANCES | RESEARCH ARTICLE

GEOLOGY

Fingerprint of volcanic forcing on the ENSO–Indian monsoon coupling

M. Singh[1,2], R. Krishnan[1]*, B. Goswami[3,4], A. D. Choudhury[1], P. Swapna[1], R. Vellore[1], A. G. Prajeesh[1], N. Sandeep[1], C. Venkataraman[2], R. V. Donner[3,5], N. Marwan[3], J. Kurths[3,6]

Coupling of the El Niño–Southern Oscillation (ENSO) and Indian monsoon (IM) is central to seasonal summer monsoon rainfall predictions over the Indian subcontinent, although a nonstationary relationship between the two nonlinear phenomena can limit seasonal predictability. Radiative effects of volcanic aerosols injected into the stratosphere during large volcanic eruptions (LVEs) tend to alter ENSO evolution; however, their impact on ENSO-IM coupling remains unclear. Here, we investigate how LVEs influence the nonlinear behavior of the ENSO and IM dynamical systems using historical data, 25 paleoclimate reconstructions, last-millennium climate simulations, large-ensemble targeted climate sensitivity experiments, and advanced analysis techniques. Our findings show that LVEs promote a significantly enhanced phase-synchronization of the ENSO and IM oscillations, due to an increase in the angular frequency of ENSO. The results also shed innovative insights into the physical mechanism underlying the LVE-induced enhancement of ENSO-IM coupling and strengthen the prospects for improved seasonal monsoon predictions.

Phase Coherence Analysis (PCA)

Understand the phase relationships between ENSO and IM following LVEs

Hilbert Transform

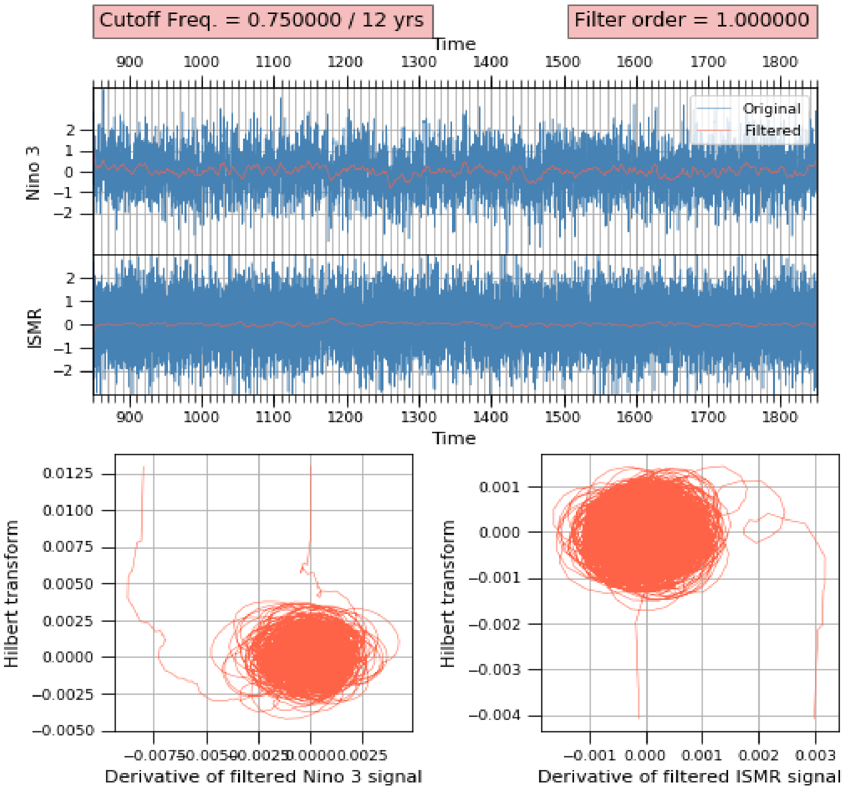
$$H(u)(t) = \frac{1}{\pi} \, \mathrm{p.\,v.} \int_{-\infty}^{+\infty} \frac{u(\tau)}{t-\tau} \, d\tau,$$

- Time series of ENSO and IM are filtered to remove intra-annual oscillations (cutoff = 0.75 cycles per year)
- Second order time differencing followed by Hilbert Transform
- Phase ϕ computed from transformed series (Anal)
- $\phi = \tan^{-1}$ (Real (Anal) / Imag(Anal))

PCA of Last Millennium using PMIP3

- NINO3 SST (5°N-5°S, 150°W-90°W) and IM rainfall (74.5°E-86.5°E, 16.5°N-26.5°N) from IPSL model (850 - 1850 AD) used

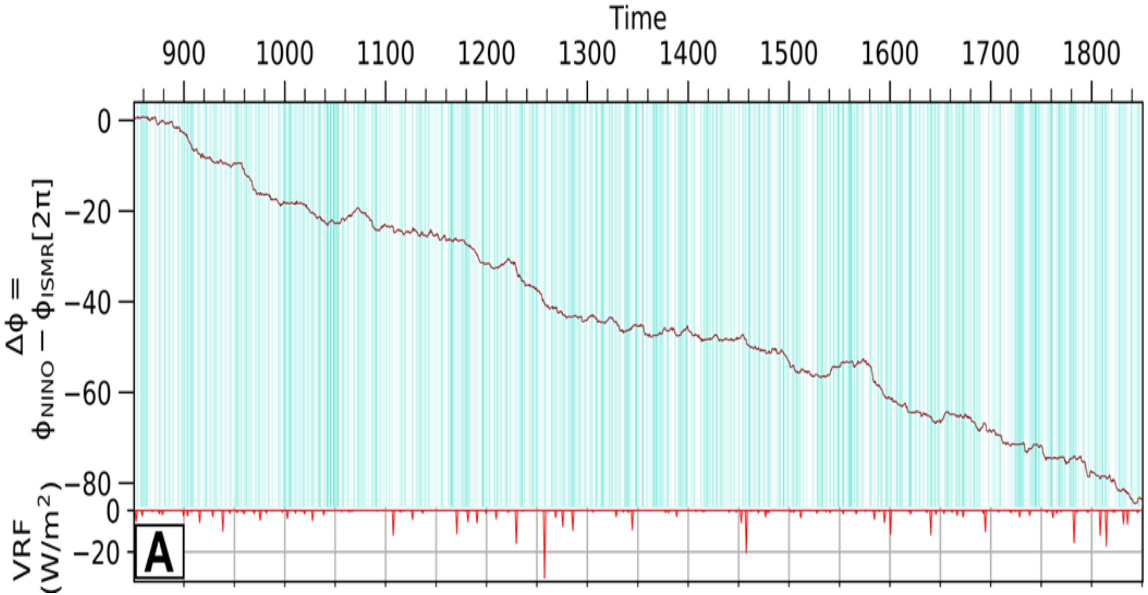
- Phase space plot oscillating around a common attractor -> ENSO and IM self sustained oscillators -> all theories of phase synchronization applicable on filtered time series

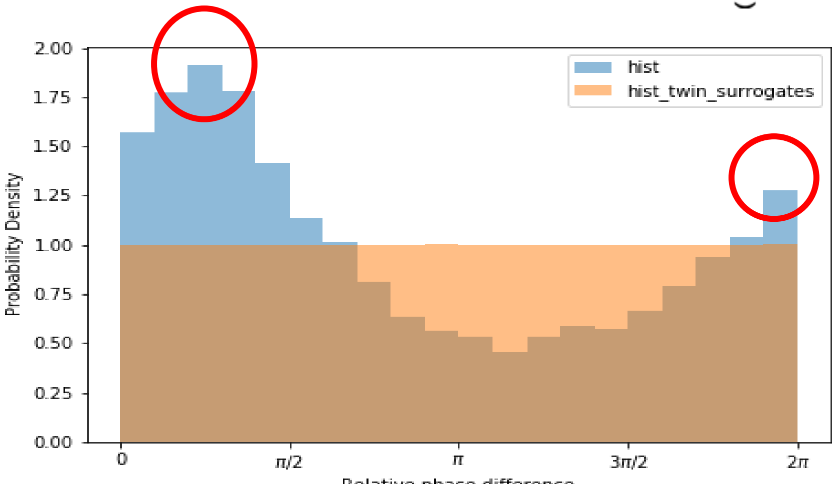


Source: Manmeet Singh et al., 2020

PCA of Last Millennium
PMIP3 – IPSL Model

Last Millennium (850-1850)





Statistical significance using 5000 twin surrogates

Peaks in relative phase difference between 0 and pi/2. Significant phase coherence relative to null distribution (twin surrogates)

Manmeet Singh et al. 2020

Bayesian Analysis

Paleoclimate proxies
of ENSO (14) and IM (11)

$$P(ENSO - IM\ co - occurrence|ENSO) = \frac{X+Y}{Z+W}$$

where,

X = Total count of drought events co-occurring with El Niño

Y = Total count of monsoon-excess events co-occurring with La Niña

Z = Total count of El Niños

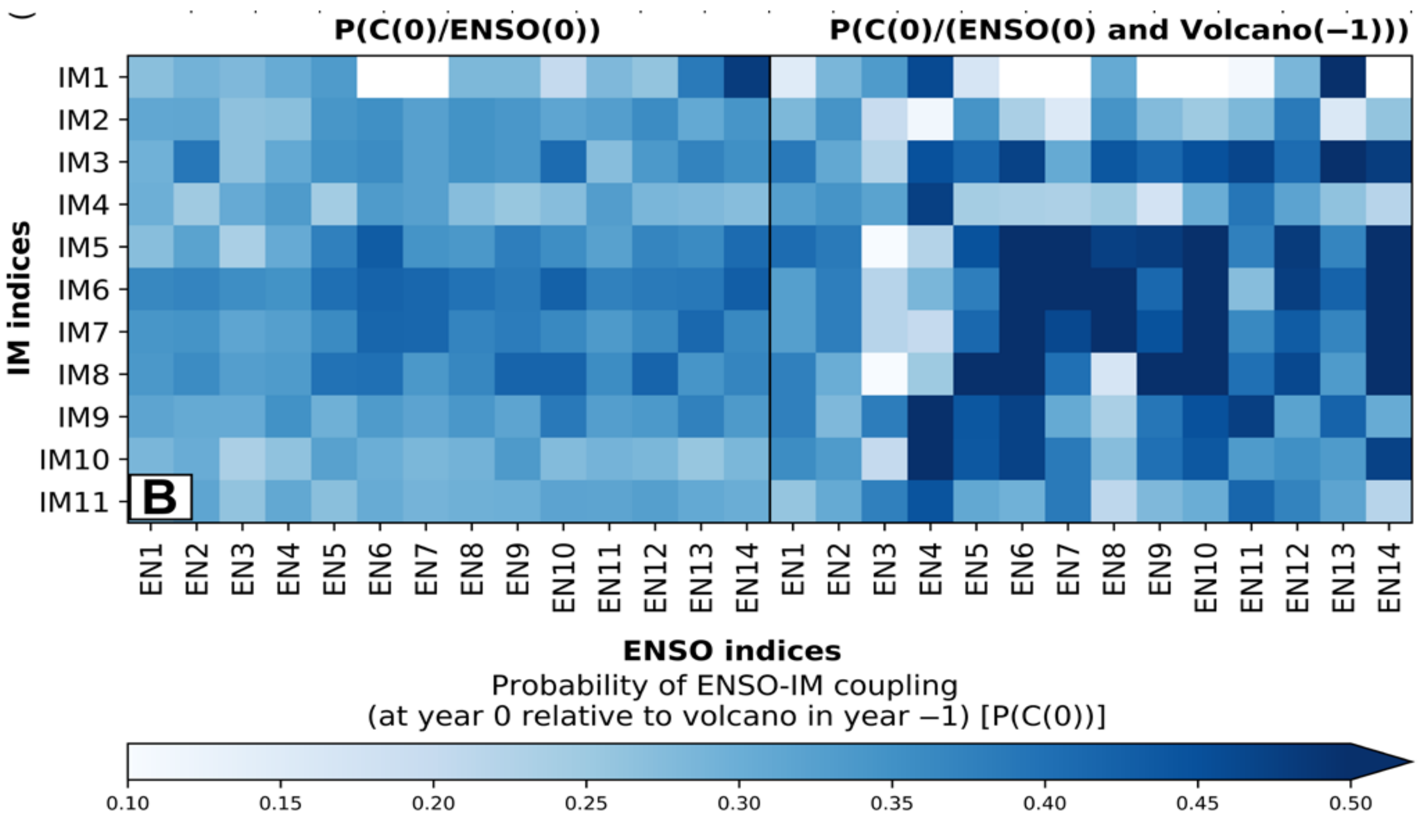
W = Total count of La Niñas

Probability of ENSO - IM co-occurrence conditional to

- ENSO
- ENSO and LVE
- ENSO and PDO
- ENSO and PDO and LVE

Wilks, D.S., 2011. Statistical methods in the atmospheric sciences (Vol. 100). Academic press.

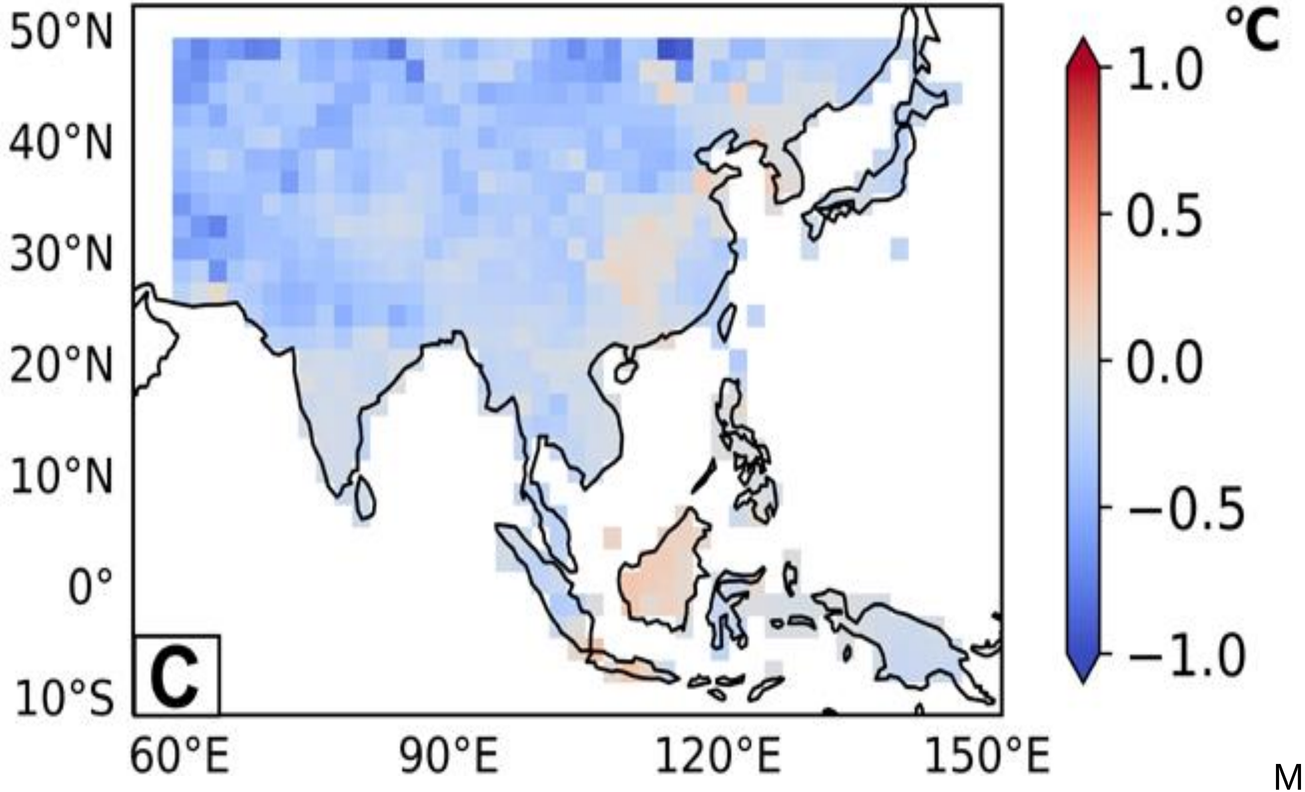
Bayesian analysis in the year following LVE



Probability of ENSO-IM coupling enhances in 93 (out of 149), more than doubling in a number of cases for last millenium

Manmeet Singh et al. 2020

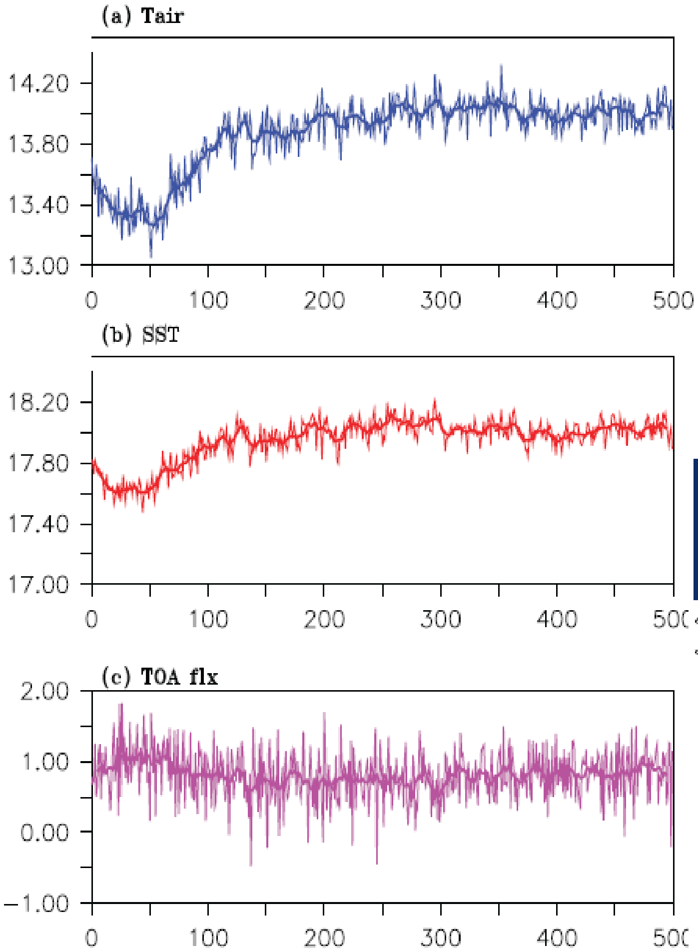
Northern Hemispheric land cooling following LVEs

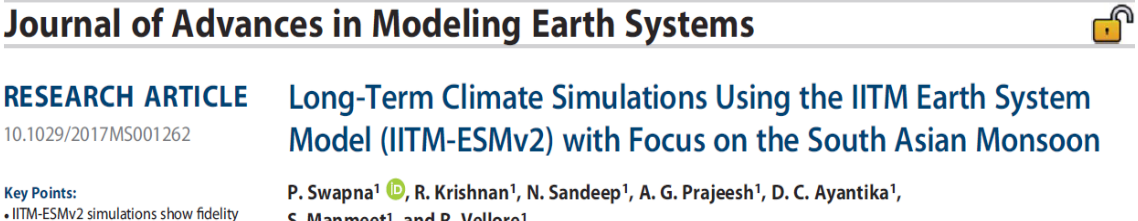


Last millennium gridded surface air temperature anomalies from the Cook et al. 2013 dataset shows cooling of Eurasian landmass following LVEs

Manmeet Singh et al. 2020

IITM Earth System Model for long term climate studies – the first from India





Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE

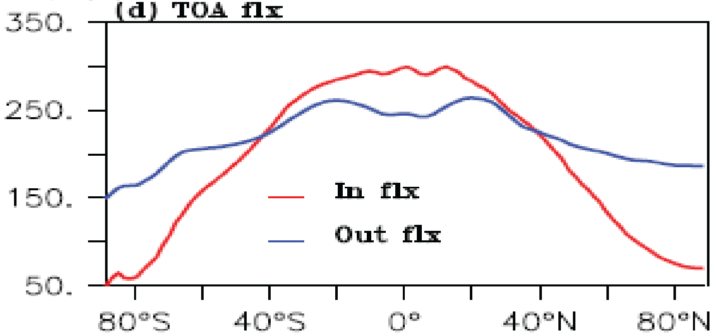
10.1029/2017MS001262

Long-Term Climate Simulations Using the IITM Earth System Model (IITM-ESMv2) with Focus on the South Asian Monsoon

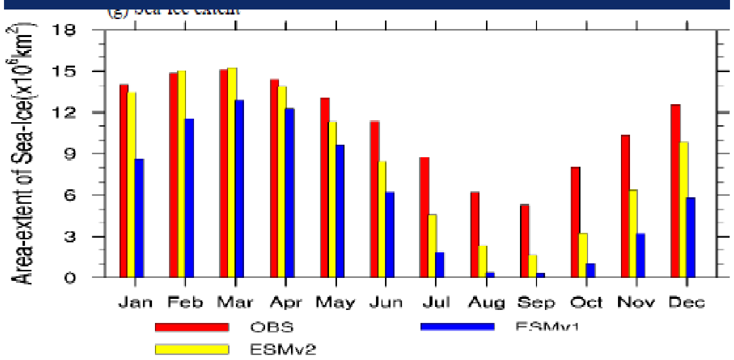
P. Swapna[1], R. Krishnan[1], N. Sandeep[1], A. G. Prajeesh[1], D. C. Ayantika[1], S. Manmeet[1], and R. Vellore[1]

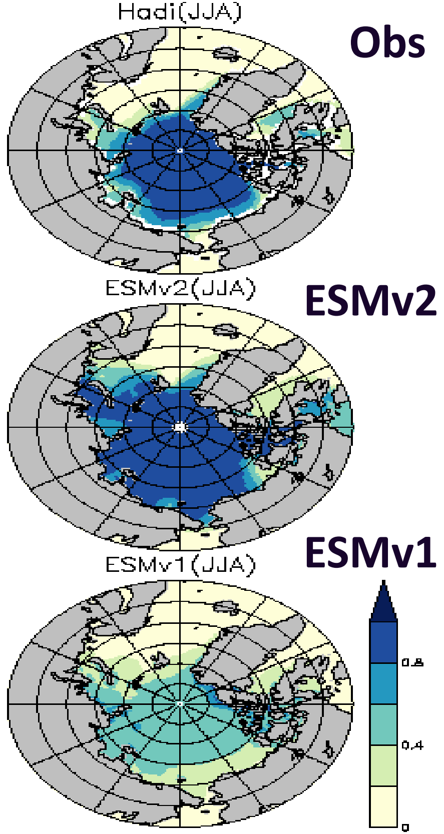
Key Points:

- IITM-ESMv2 simulations show fidelity in capturing large-scale circulation

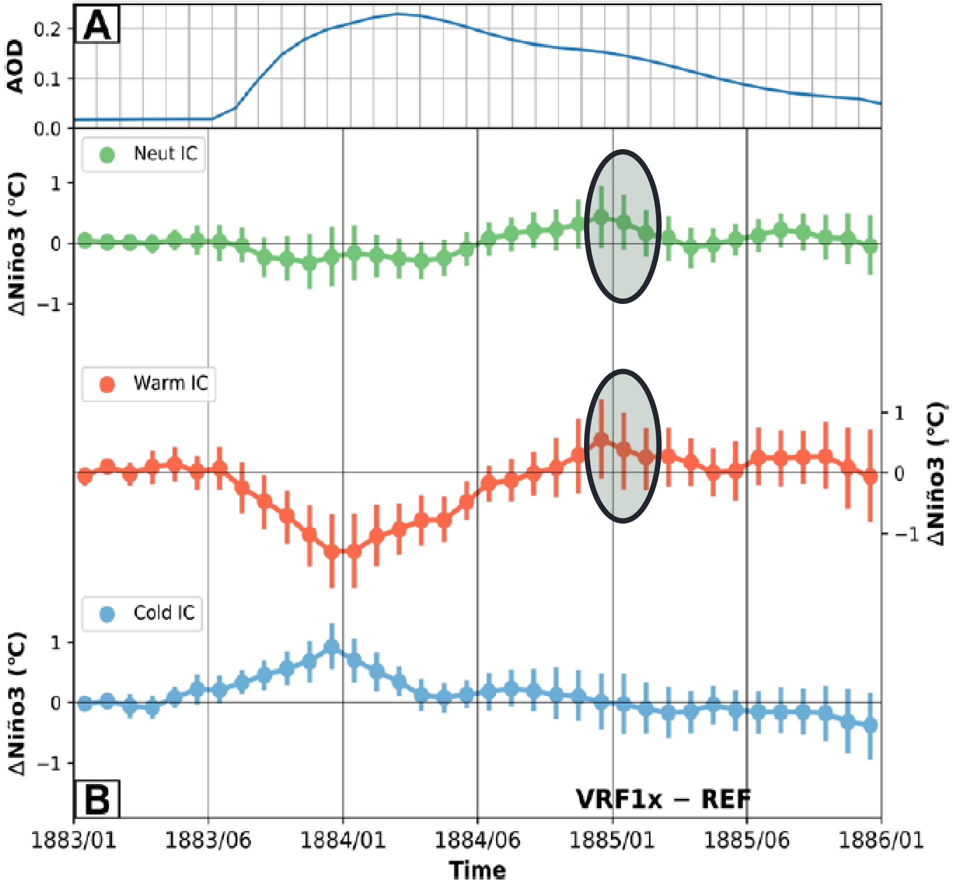


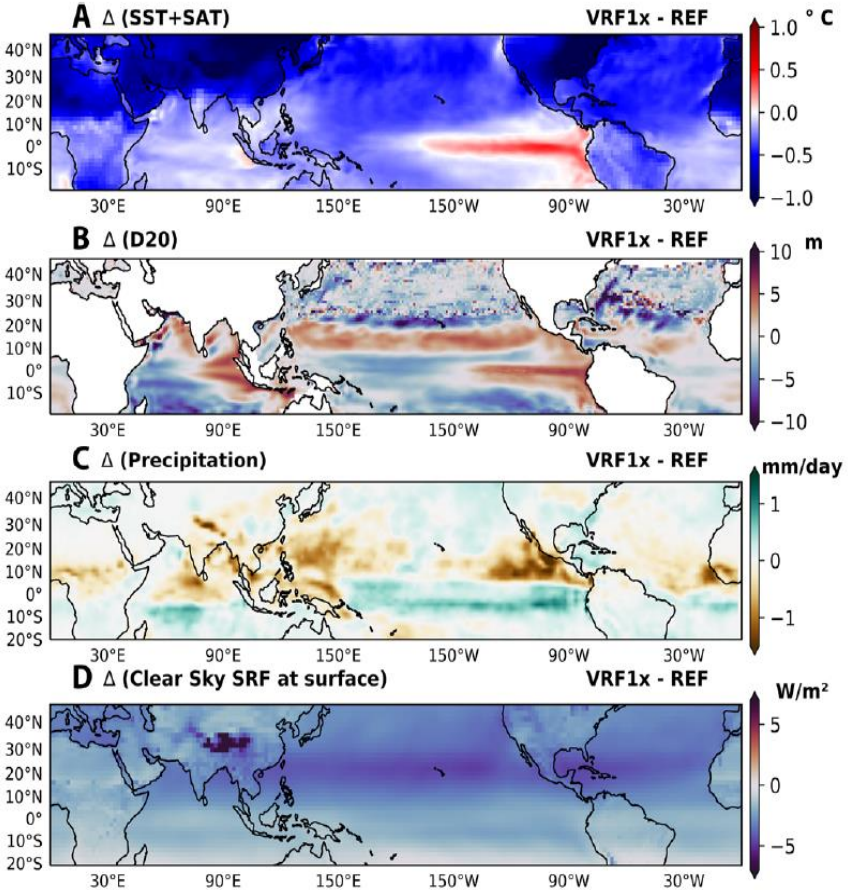
Improved simulation of sea-ice





IITM-ESM Large Ensemble Experiments: Volcanic forcing & ENSO-Indian monsoon coupling

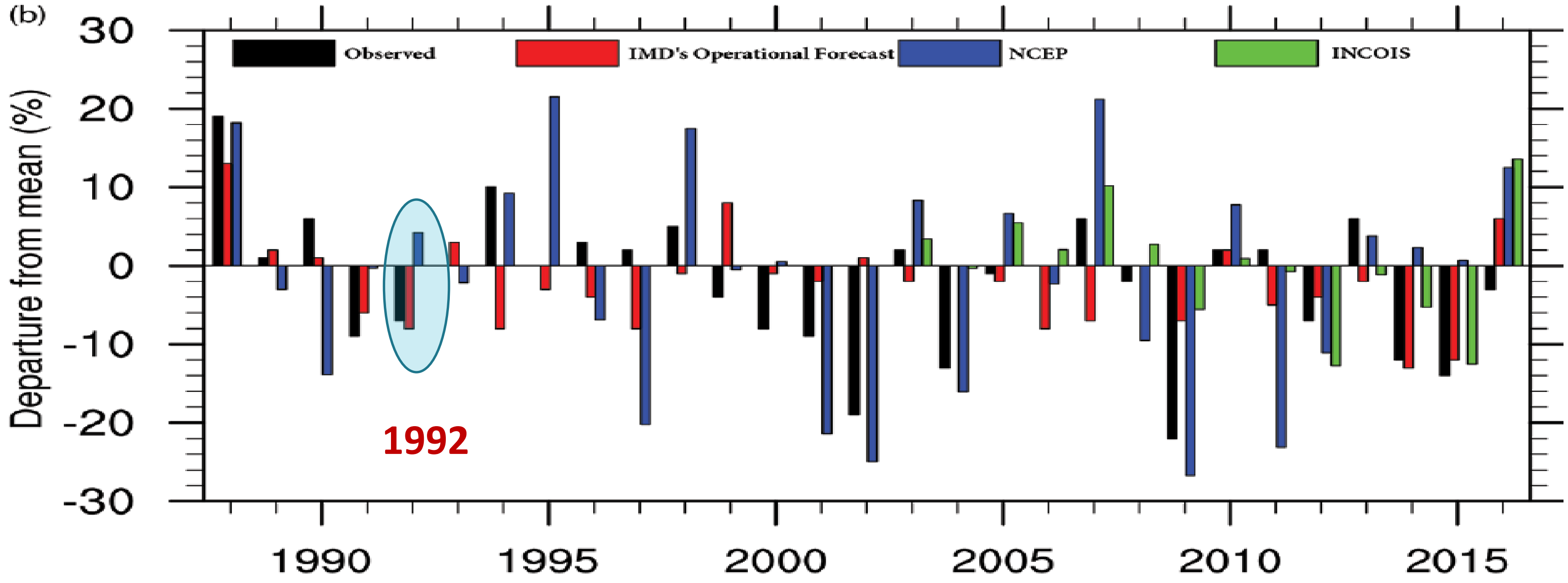




Manmeet Singh et al. 2020

MONSOON MISSION

A Targeted Activity to Improve
Monsoon Prediction across Scales



Comparison of observed ISMR, operational ISMR forecast based on IMD's statistical model , and MM CFSv2-T382-predicted (hindcast) based on NCEP & INCOIS initial conditions from 1988 to 2017. ISMR is calculated as the rainfall averaged over Indian land points only.

Rao et al., 2019, BAMS

Ensemble seasonal experiments using IITM-ESM

Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune

Atmosphere : GFS (Global Forecast System)

T62 ; vertical: 64 sigma – pressure hybrid levels

Resolution ~200 km

Model top 0.2 mb

Prescribed MAC-v2 aerosols

Land surface : Noah LSM

Ocean: Modular Ocean Model v4p1 (MOM4p1)

Tripolar; 360x200 ; 1 deg poleward ; 0.33 deg near equator

50 levels ; Top grid cell 5m

Ocean Biogeochemistry : TOPAZ

Ice Model : Sea Ice Simulator

30 members seasonal hindcast experiments during 1992

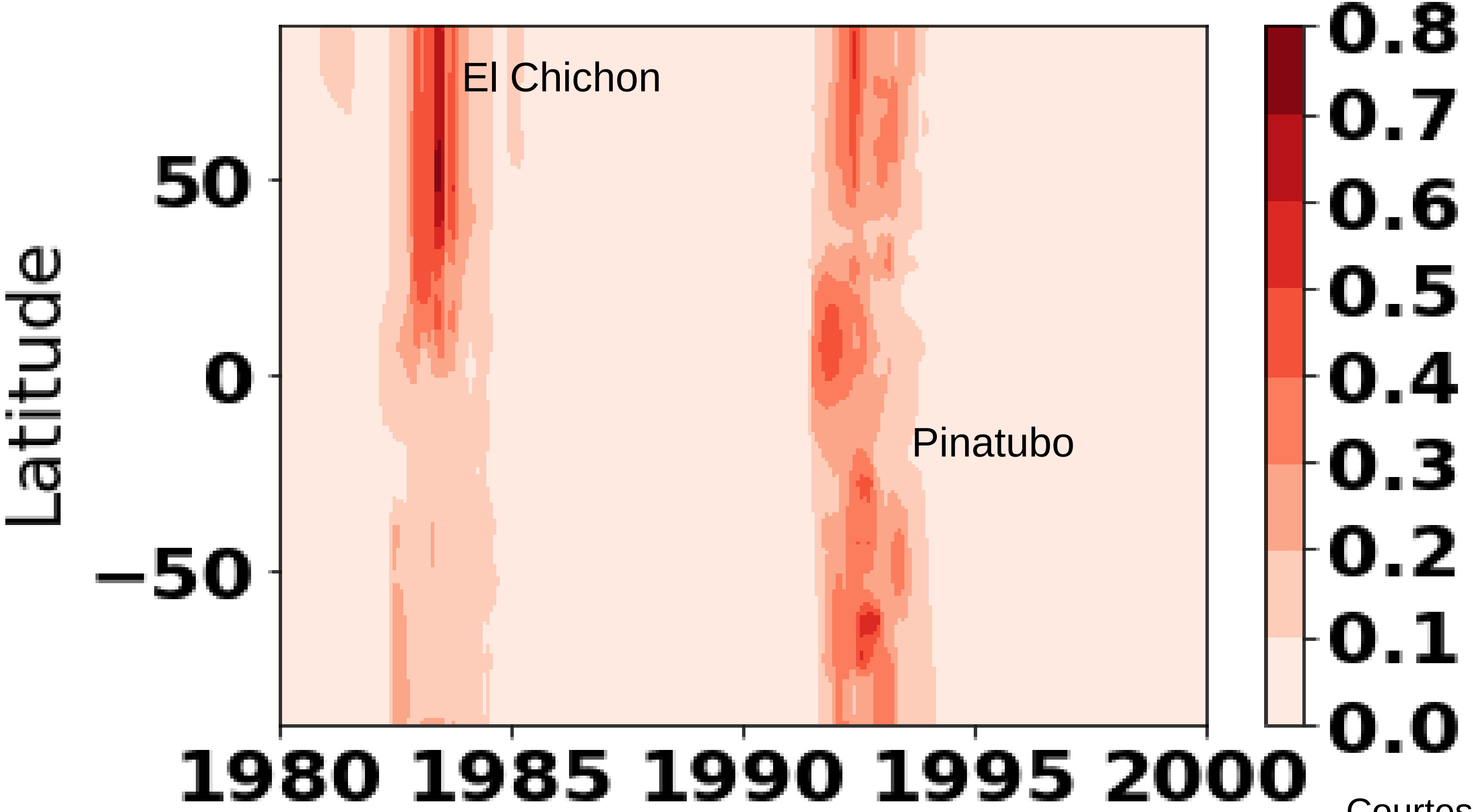
30 initial conditions (00Z)-
21 April – 20 May, 1992

Atmos IC: ERA-Interim
Ocean IC: GODAS
Land IC: CFS-Reanal

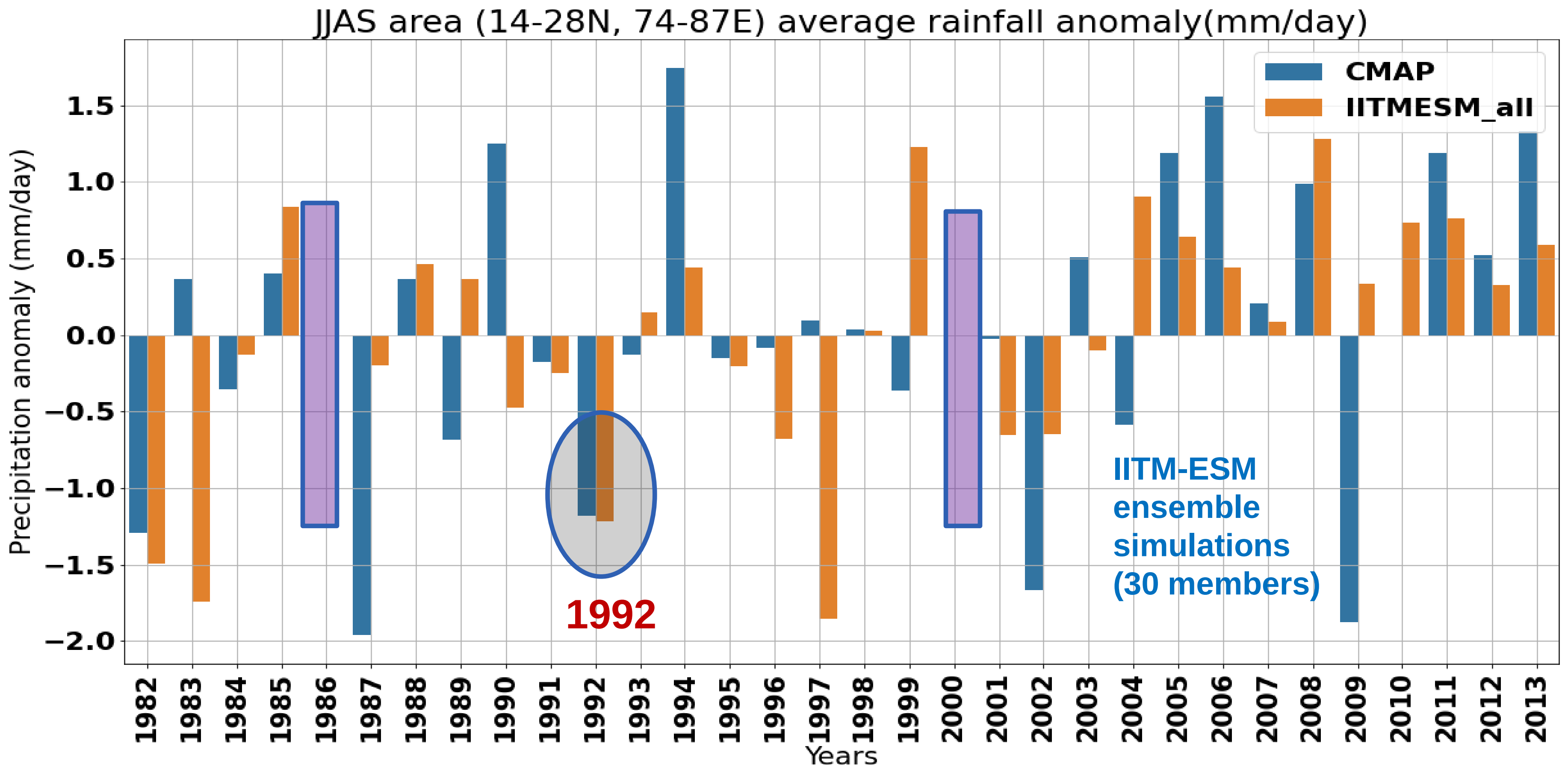
All forcing: GHG, Aerosols (Natural – Dust, Volcanic ..) Plus Anthropogenic (CMIP6)

Courtesy: Manmeet Singh

Stratospheric aerosol optical depth at 550 nm

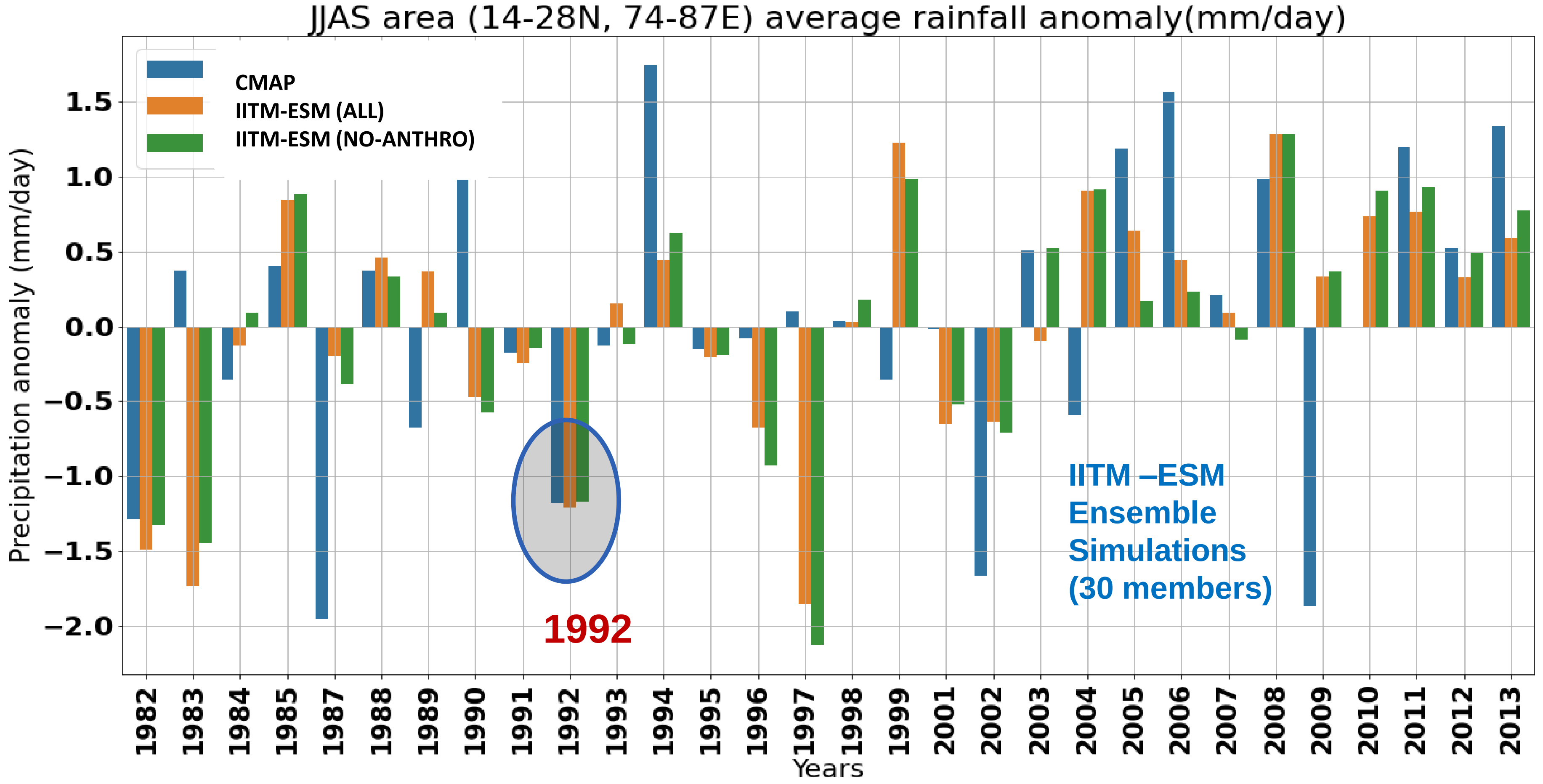


Courtesy: Manmeet Singh



1986 and 2000 hindcasts to be done (TBD)

Courtesy: Manmeet Singh

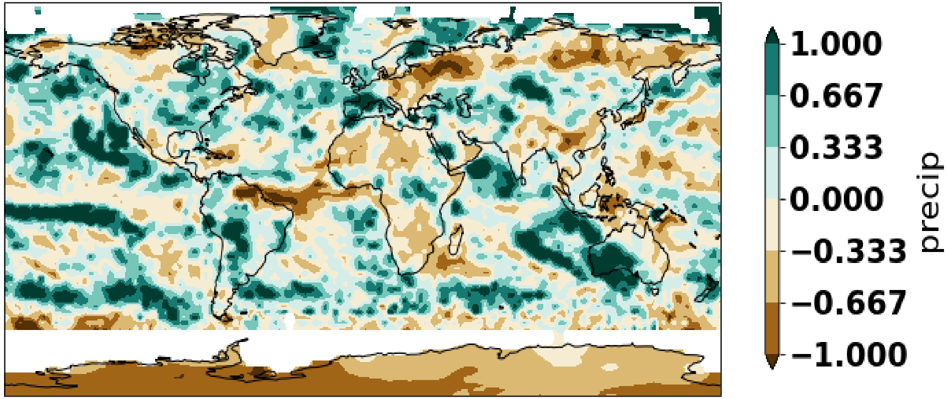


1986 and 2000 hindcasts to be done (TBD)

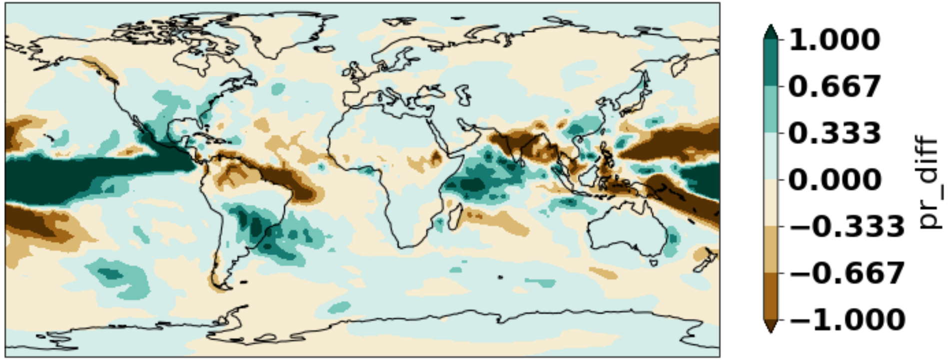
Courtesy: Manmeet Singh

JJAS 1992 precipitation anomaly

CMAP observations



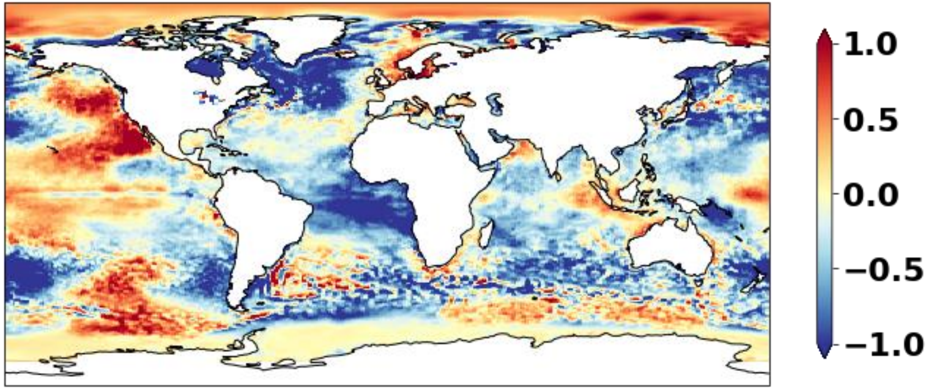
IITM-ESM anomaly



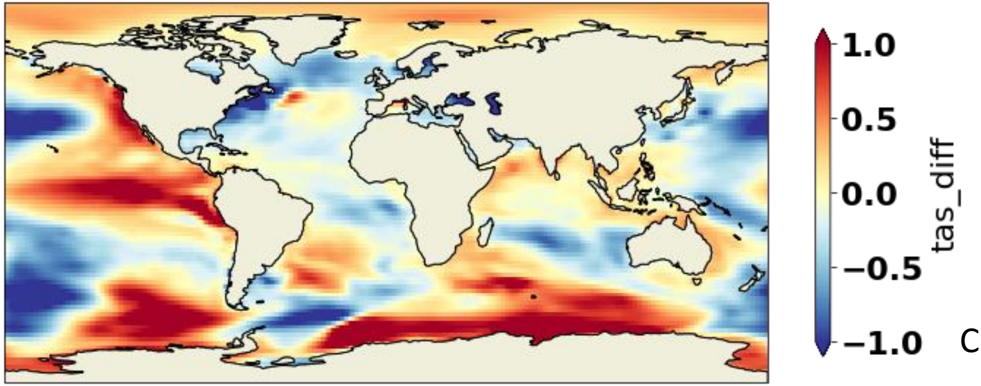
Courtesy: Manmeet Singh

JJAS 1992 SST anomaly

HadiSST anomaly



IITM-ESM anomaly



Courtesy: Manmeet Singh

Summary

- Human-induced climate change, in particular GHG emissions, has been the main driver of observed intensification of heavy precipitation over the land regions across the globe (IPCC AR6, 2021).

- The expected enhancement of South Asian monsoon precipitation by GHG forcing since 1950s has been offset by precipitation reduction caused by Northern Hemispheric anthropogenic aerosols.

- Internal variability and unpredictable natural forcings (e.g., volcanic eruptions) can lower the degree of confidence in projecting regional monsoonal changes, especially in the near-term (2021-2040).

- Volcanic ash and gaseous matter from large volcanic eruptions (LVE) injected into the stratosphere alter the global mean surface temperature through backscatter and absorption of shortwave radiation, leading to changes in the atmospheric and ocean circulation and the global hydrological cycle.

- Large volcanic eruptions (LVEs) can trigger El Nino-like SST anomalies within 2-yrs following the eruption.

- LVEs promote a significantly enhanced phase synchronization of ENSO and Indian monsoon oscillations due to an increase in the angular frequency of ENSO (Singh et al., 2020).

- Ensemble hindcast experiments using the IITM-ESM indicate that the Pinatubo volcanic eruption in 1991 had a significant role in the decrease of Indian summer monsoon precipitation during 1992.

- Question: Whether LVEs are an important source of predictability of the Indian monsoon ?

Thanks for your kind attention!