Climate Change Projections

&

Monsoon Variability

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WMO

WCRP World Climate Research Programme

WWRP

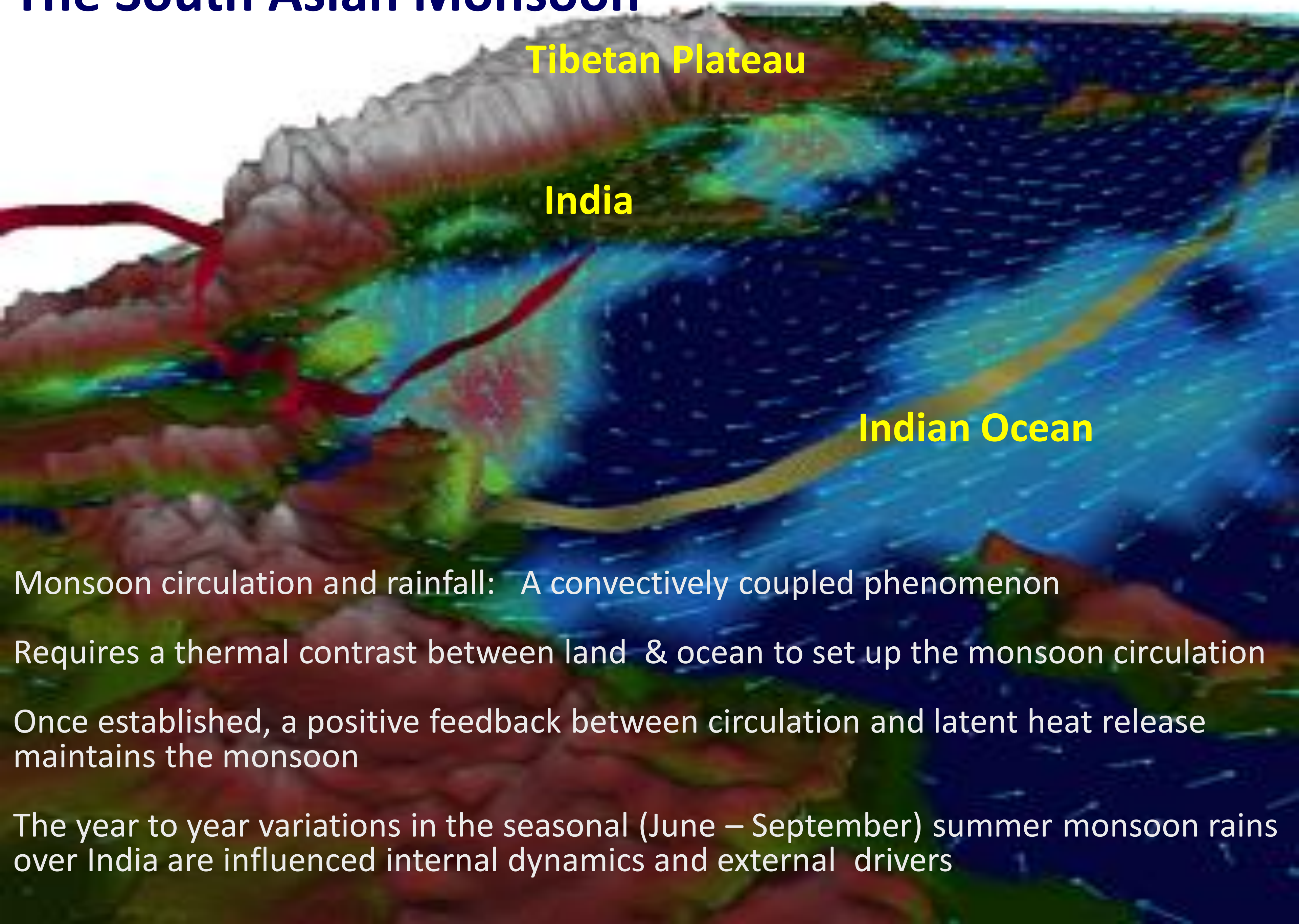
Subseasonal-to-Seasonal S2S Prediction Project

Virtual InternationalConference on the
"Future directions of Subseasonal to Seasonal Prediction over South Asia",

29-31March 2021, IITM, Pune, India

In the Spirit of Azadi ka #AmritMahotsav

The South Asian Monsoon



Monsoon circulation and rainfall: A convectively coupled phenomenon

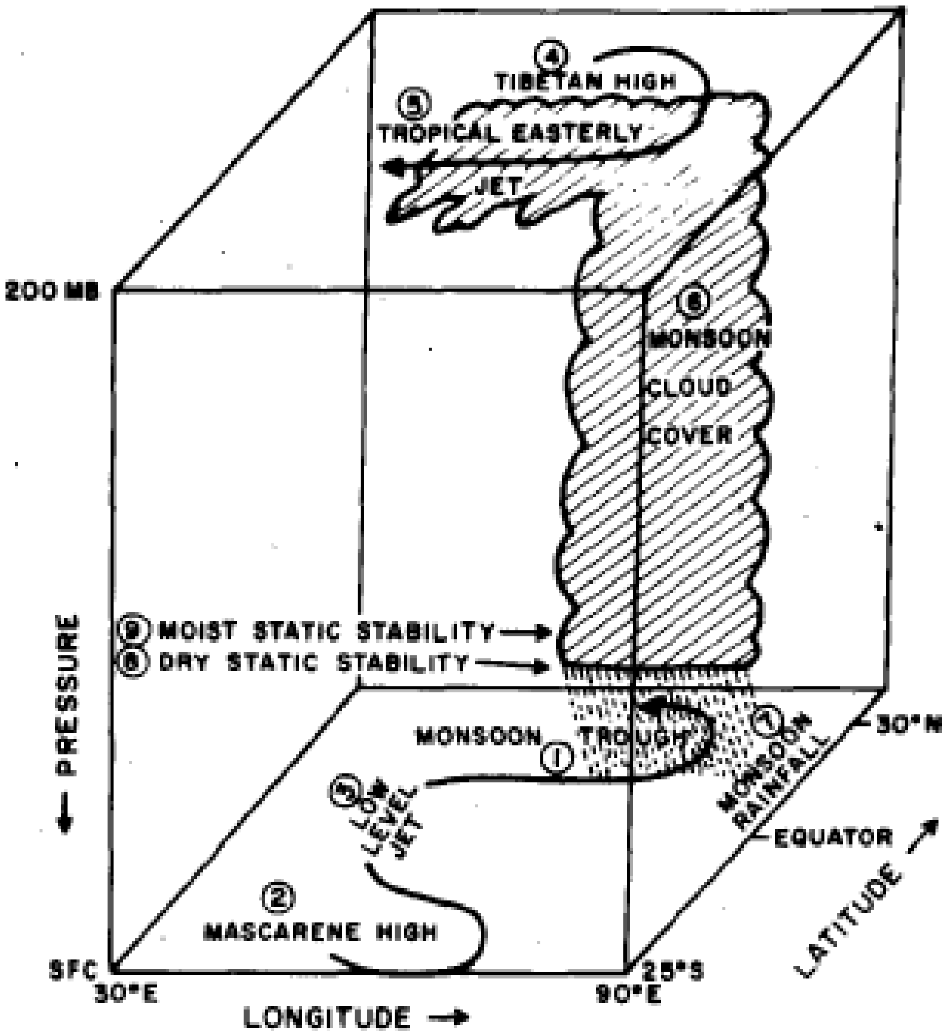
Requires a thermal contrast between land & ocean to set up the monsoon circulation

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

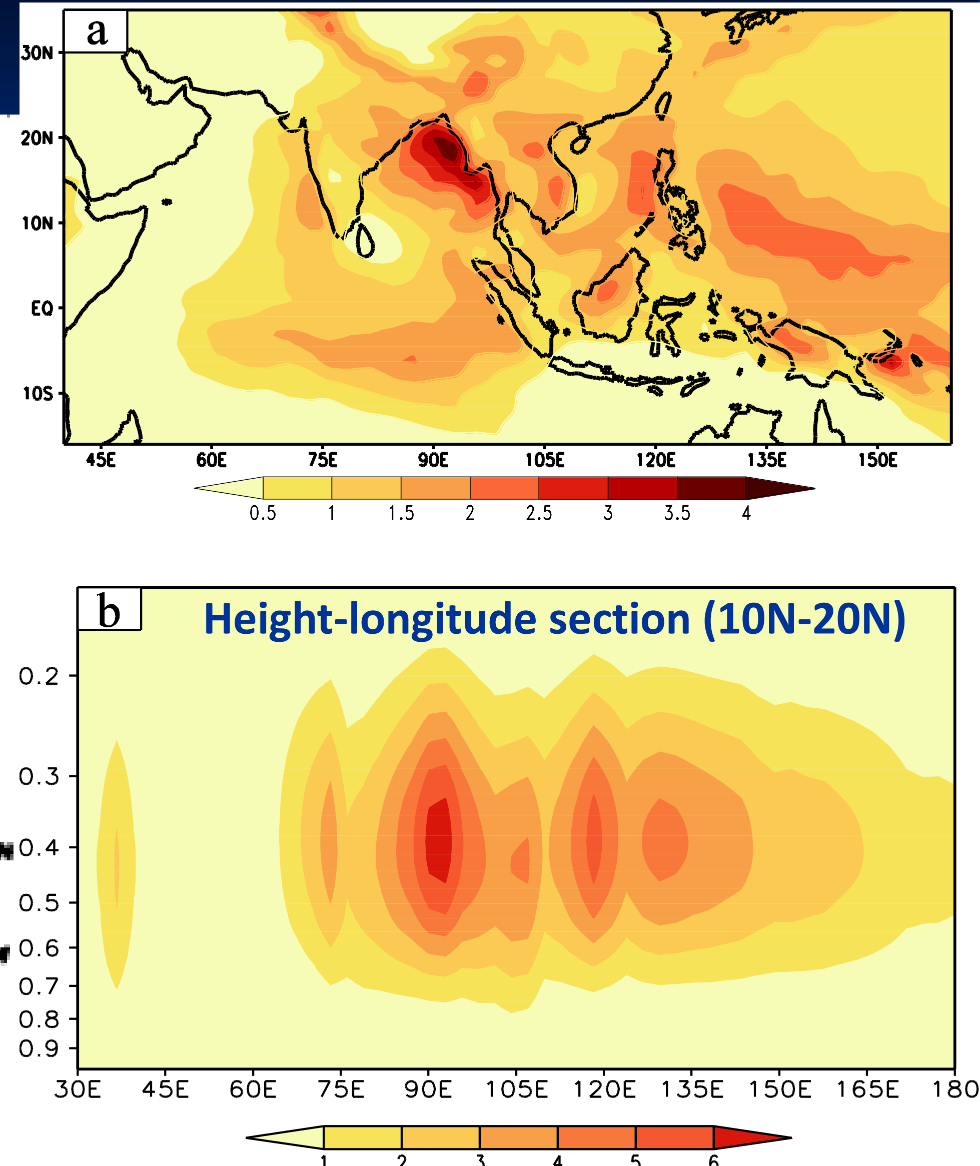
A 3-D schematic of the South Asian Monsoon

Large-scale monsoon overturning circulation is coupled to organized convection

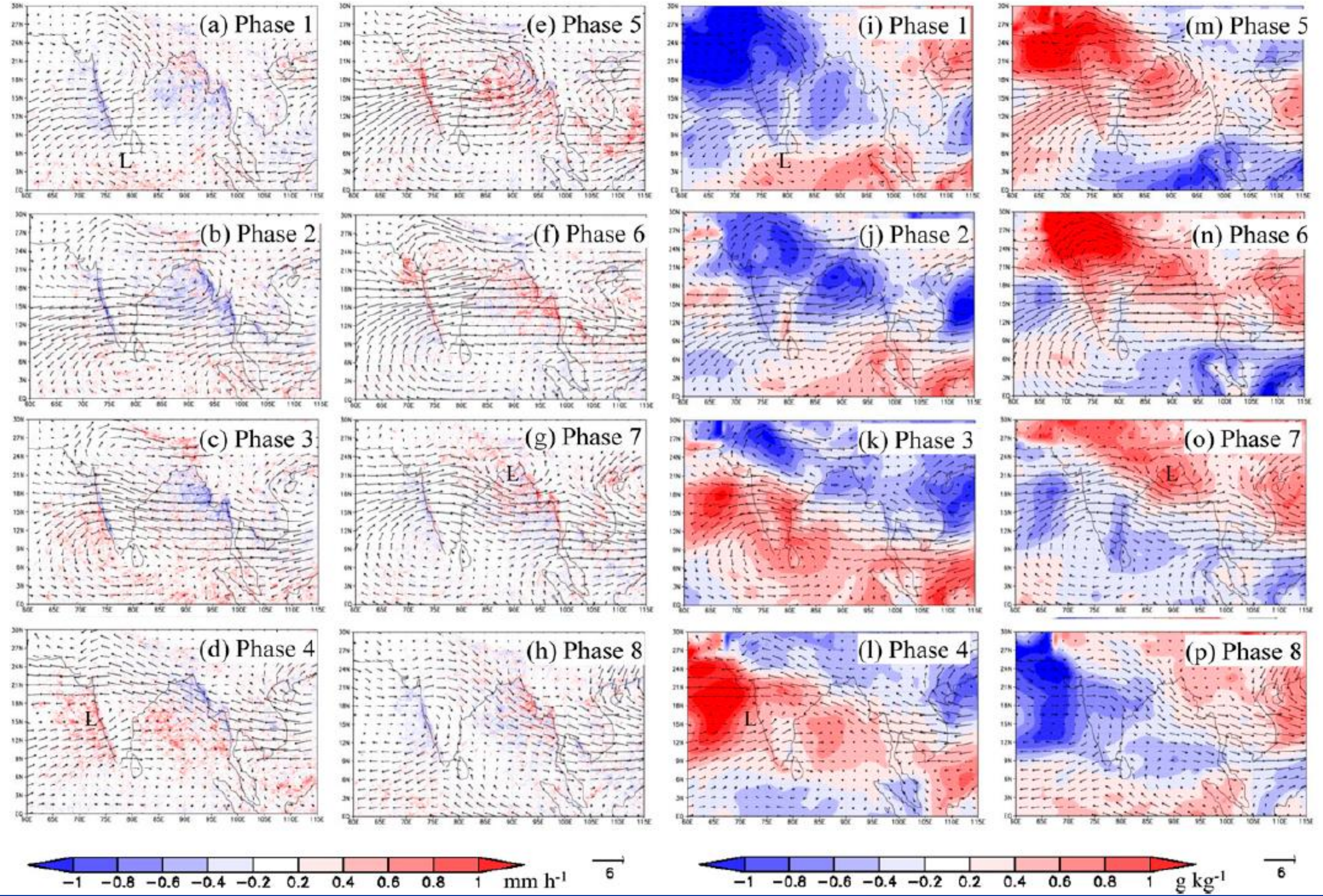


Schematic diagram of salient elements of the monsoon system: Krishnamurti and Bhalme, 1976

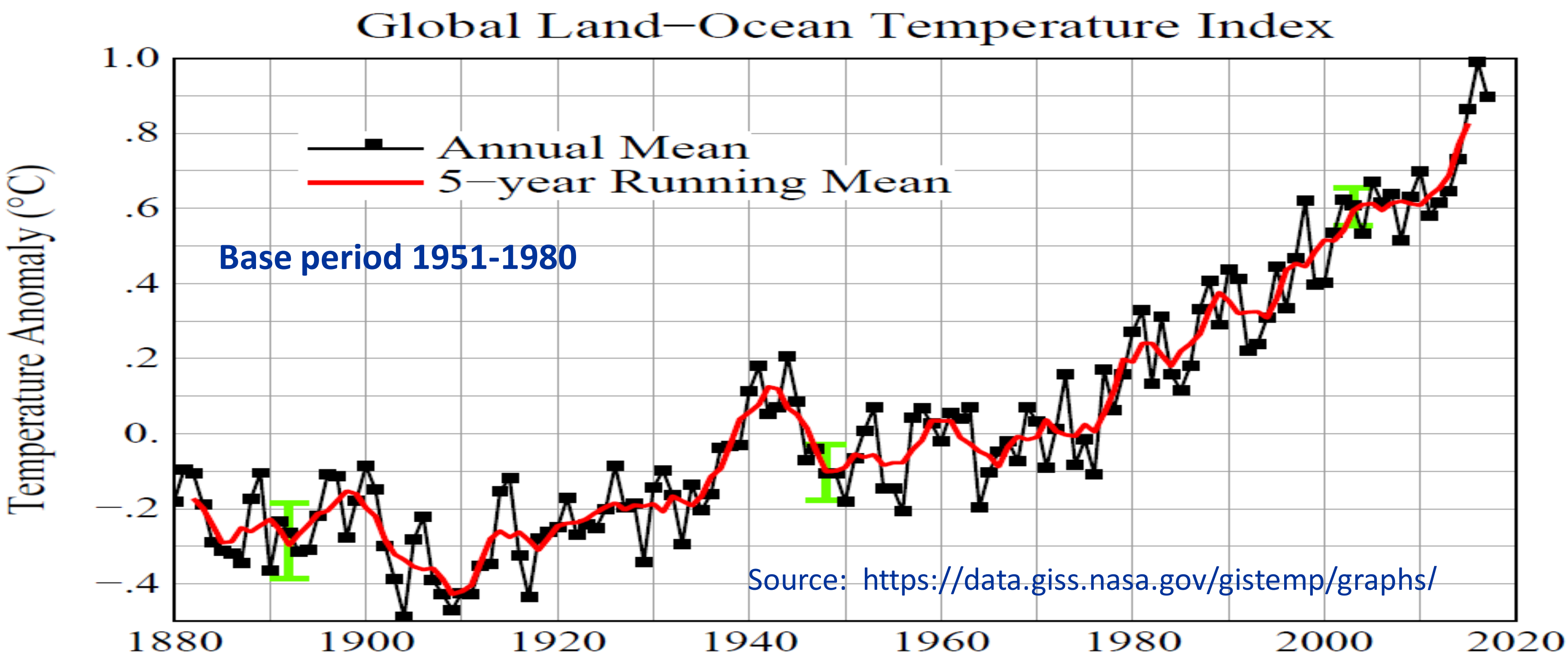
Mean latent heating derived from TRMM (vertically averaged)

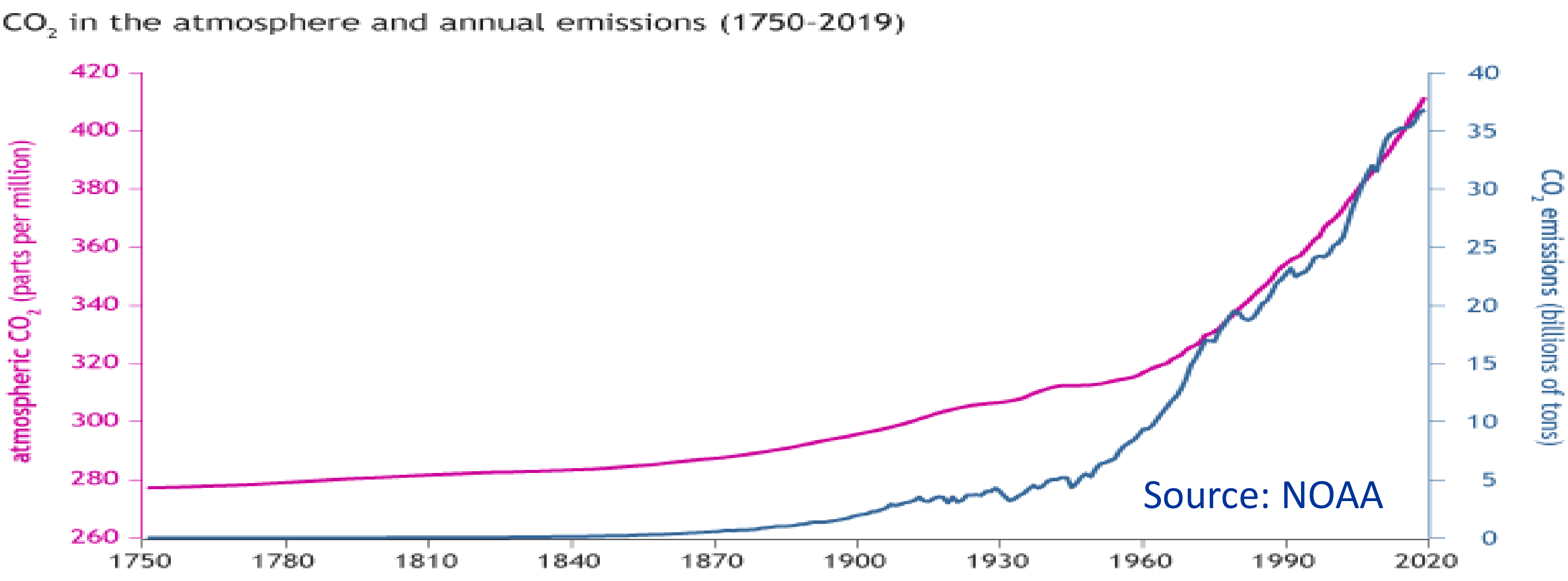


Choudhury and Krishnan, 2011

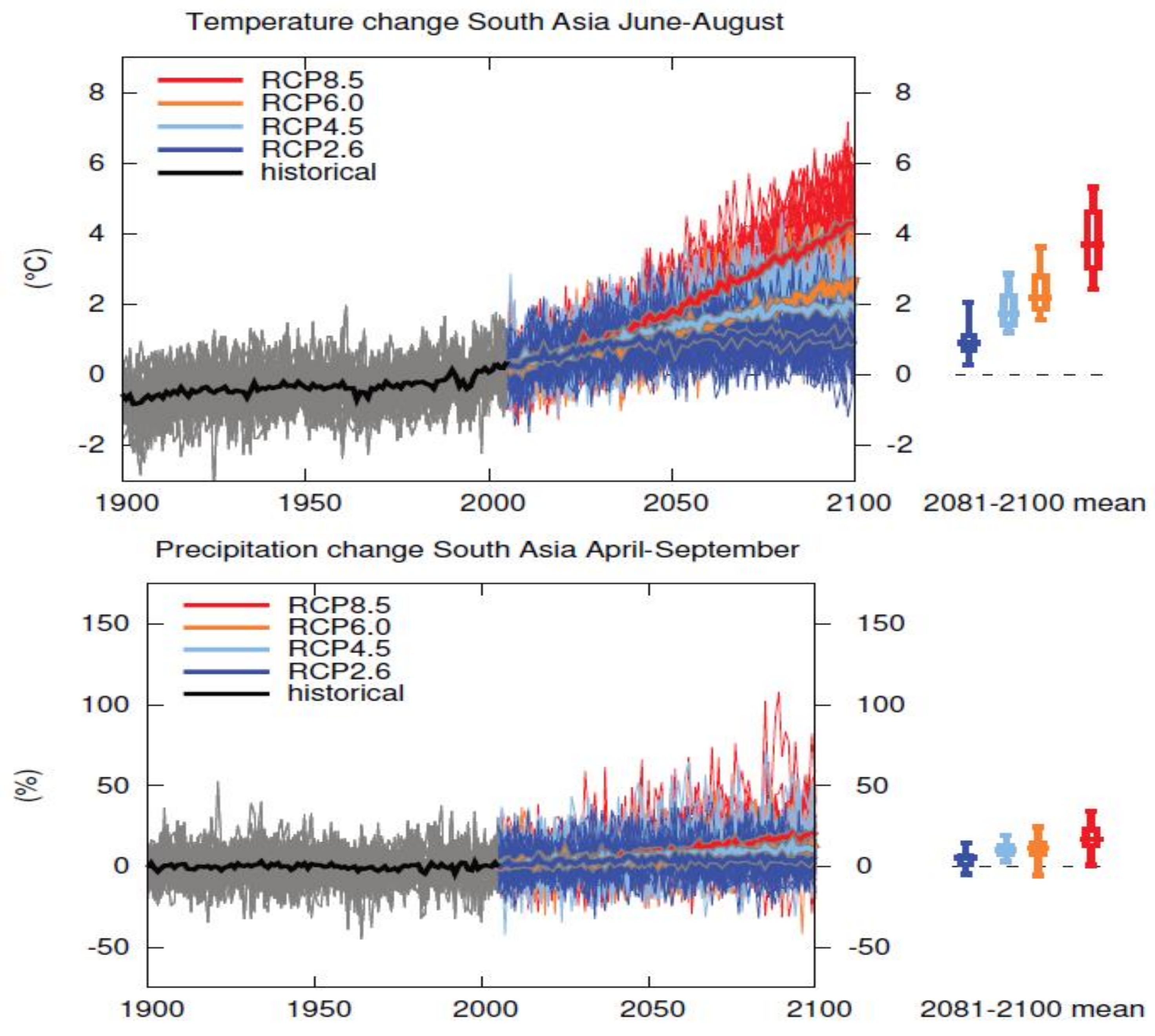


TRMM PR rainfall anomaly and ERA-Interim specific humidity anomaly with ERA-Interim 850 hPa winds during the eight BSISO phases (Shige et al. 2017)

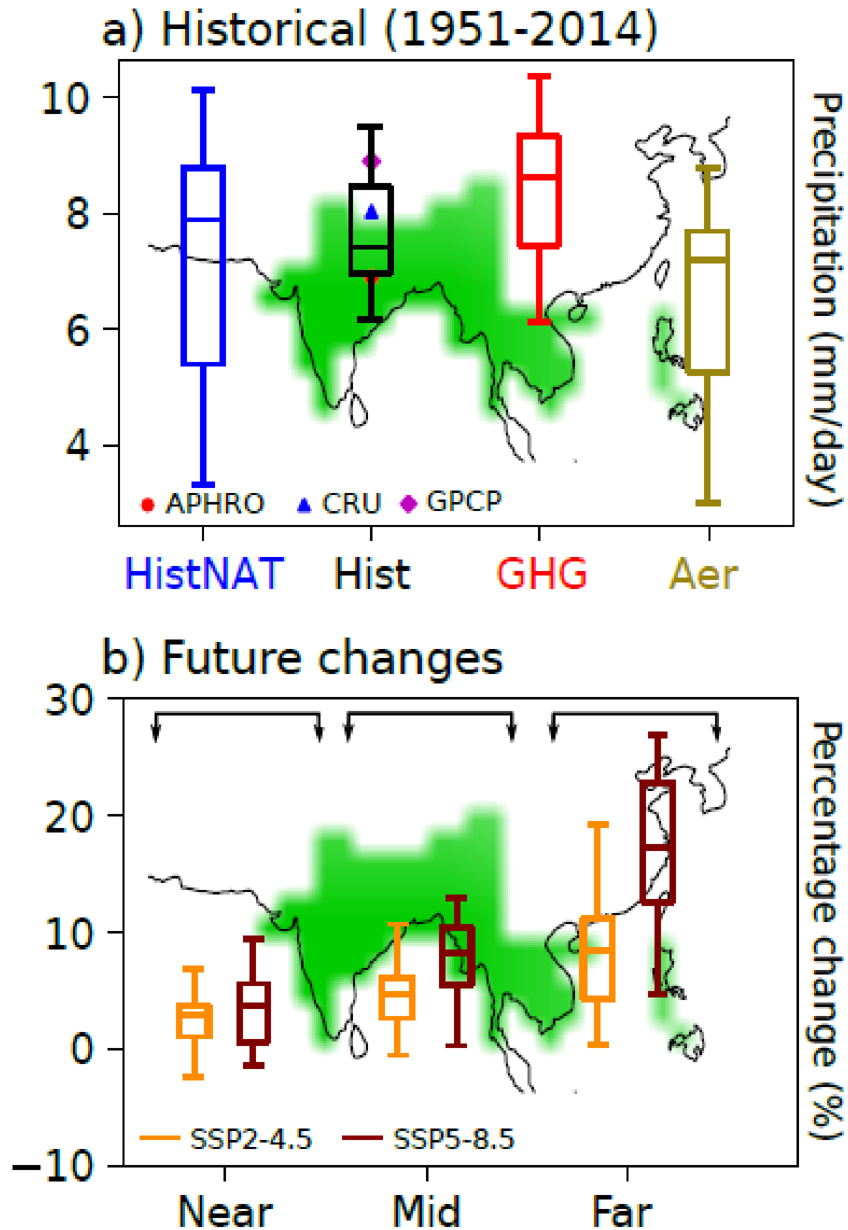

Global Land–Ocean Temperature Index
Annual Mean
5–year Running Mean
Base period 1951-1980
Temperature Anomaly (°C)
1.0
.8
.6
.4
.2
0.
–.2
–.4
1880
1900
1920
1940
1960
1980
2000
2020
Source: https://data.giss.nasa.gov/gistemp/graphs/


CO2 in the atmosphere and annual emissions (1750-2019)
atmospheric CO2 (parts per million)
CO2 emissions (billions of tons)
420
400
380
360
340
320
300
280
260
40
35
30
25
20
15
10
5
0
1750
1780
1810
1840
1870
1900
1930
1960
1990
2020
Source: NOAA

South Asian Climate Change – Source: IPCC, 2013 (Annex 1)



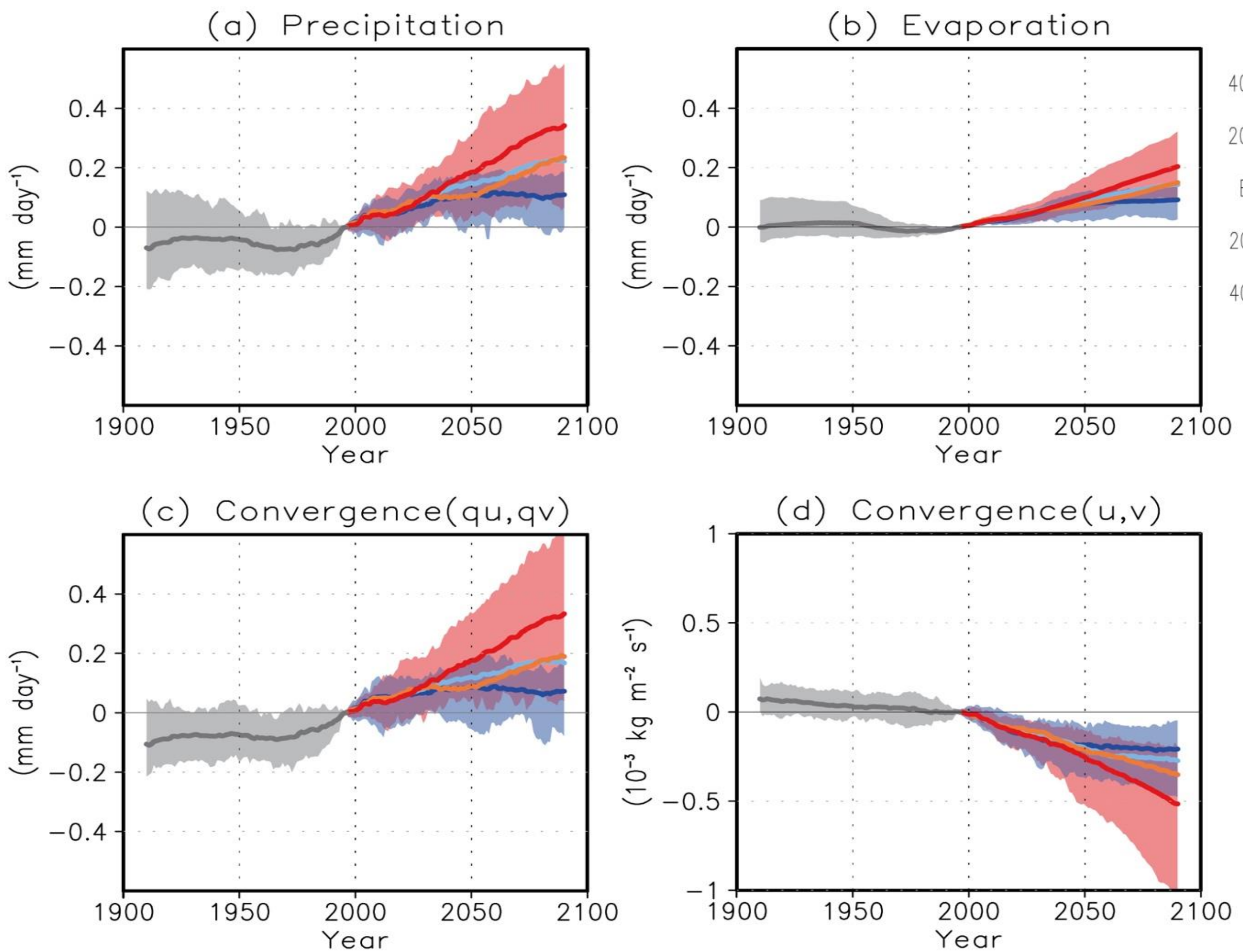
For the high emission scenario, ensemble mean warming is about 4 K & precipitation change is about 15%



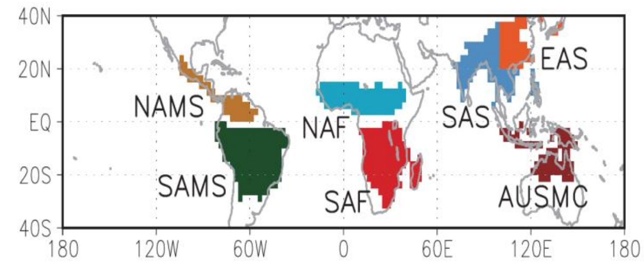
CMIP6 Multi-model projections

Krishnan, R., T.P. Sabin, Aswin Sagar, P. Swapna and A.D. Choudhury (2020) – CLIVAR Exchanges

CMIP5: Time series of simulated anomalies over the global land monsoon domain



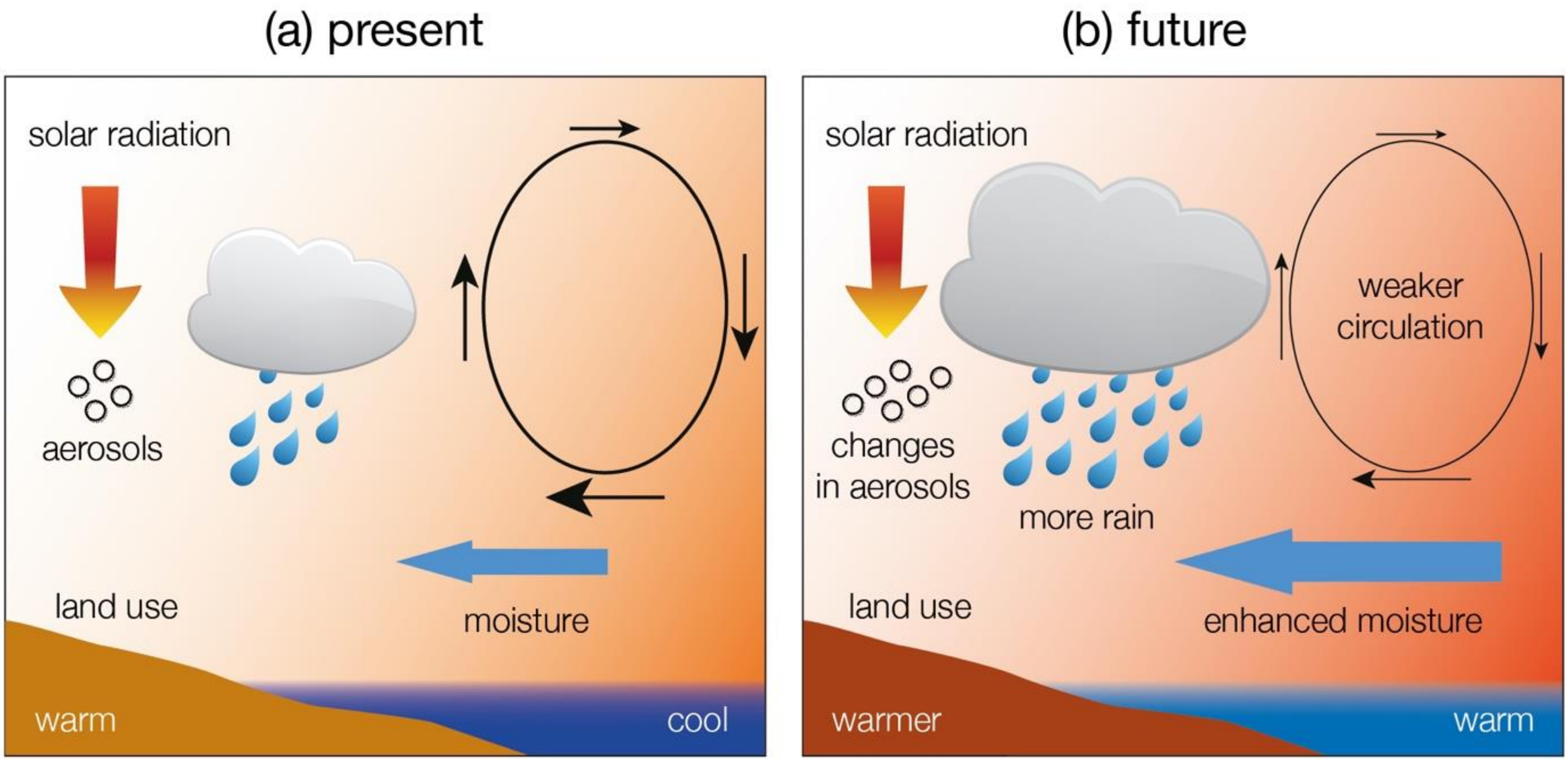
IPCC AR5, 2013



Regional land monsoon domain based on 26 CMIP5 multi-model mean precipitation with a common 2.5° × 2.5° grid in the present-day (1986–2005). For regionalndivisions, the equator separates the northern monsoon domains (North America Monsoon System (NAMS), North Africa (NAF), Southern Asia (SAS) and East Asian summer (EAS))from the southern monsoon domains (South America Monsoon System (SAMS), South Africa (SAF), and Australian-Maritime Continent (AUSMC)), 60°E separates NAF from SAS,and 20°N and 100°E separates SAS from EAS. All the regional domains are within 40°S to 40°N.

Caption: Time series of simulated anomalies, smoothed with a 20-year running mean over the global land monsoon domain for (a) precipitation (mm day^{-1}), (b) evaporation (mm day^{-1}), (c) water vapour flux convergence in the lower (below 500 hPa) troposphere (mm day^{-1}), and (d) wind convergence in the lower troposphere (10^{-3} kg m^{-2} s^{-1}), relative to the present-day (1986–2005), based on CMIP5 multi-model monthly outputs. Historical (grey; 29 models), RCP2.6 (dark blue; 20 models), RCP4.5 (light blue; 24 models), RCP6.0 (orange; 16 models), and RCP8.5 (red; 24 models) simulations are shown in the 10th and 90th percentile (shading), and in all model averages (thick lines).

Simplified illustration of the effect of climate change on monsoon rainfall

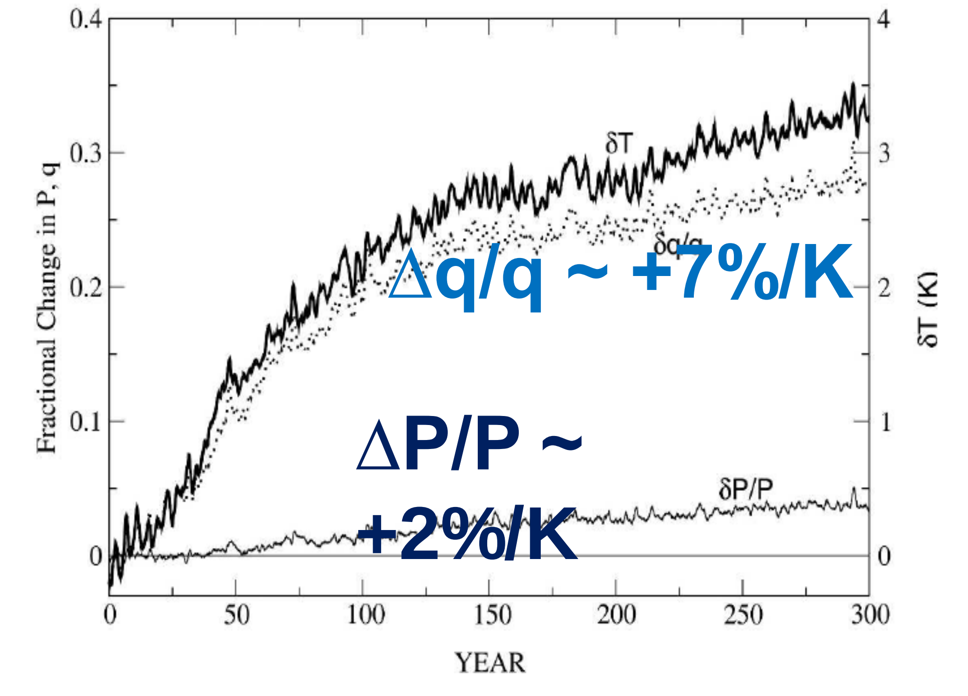


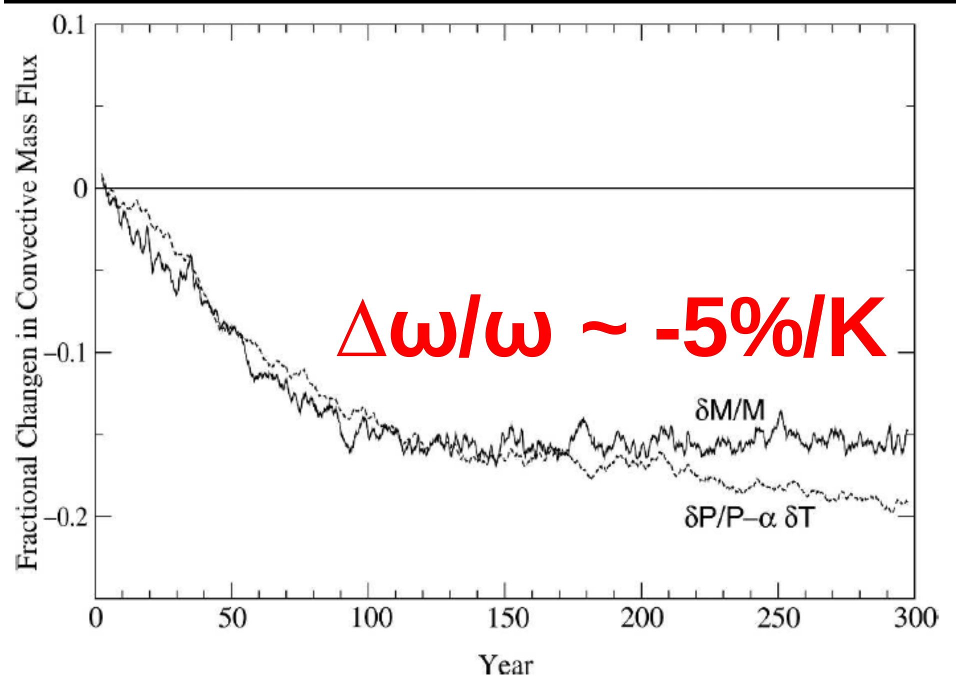
Caption: Schematic diagram illustrating the main ways that human activity influences monsoon rainfall. As the climate warms, increasing water vapour transport from the ocean into land increases because warmer air contains more water vapour. This also **increases the potential for heavy rainfalls.** Warming-related changes in large-scale circulation influence the strength and extent of the overall monsoon circulation. Land use change and atmospheric aerosol loading can also affect the amount of solar radiation that is absorbed in the atmosphere and land, potentially moderating the land–sea temperature difference.

Physics behind weakening circulation but more precipitation

$$P = \omega q; \frac{\Delta P}{P} = \frac{\Delta q}{q} + \frac{\Delta \omega}{\omega}$$

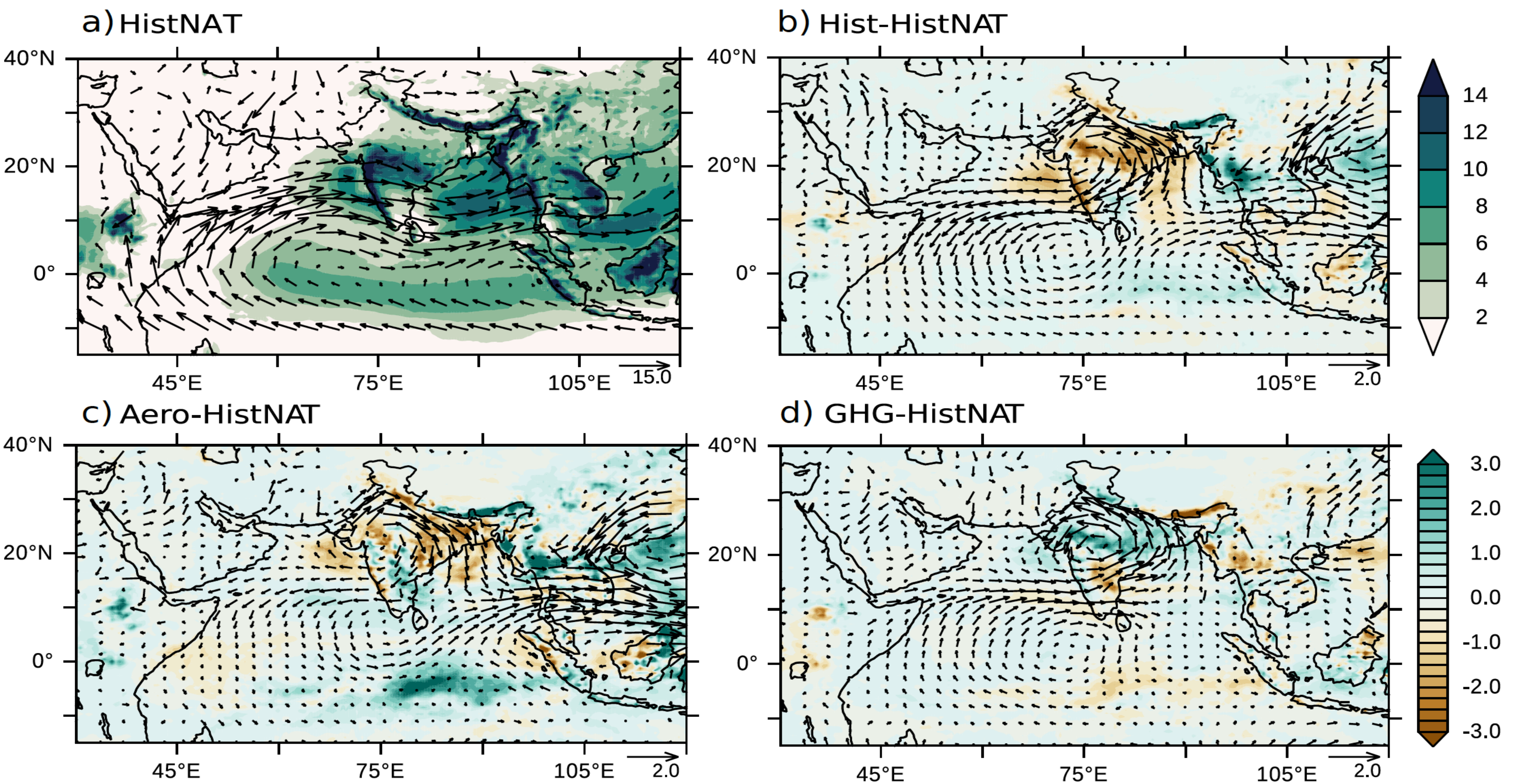
Valid for closed domains





Held and Soden, 2006

Will the southwest monsoon circulation weaken under global warming ?

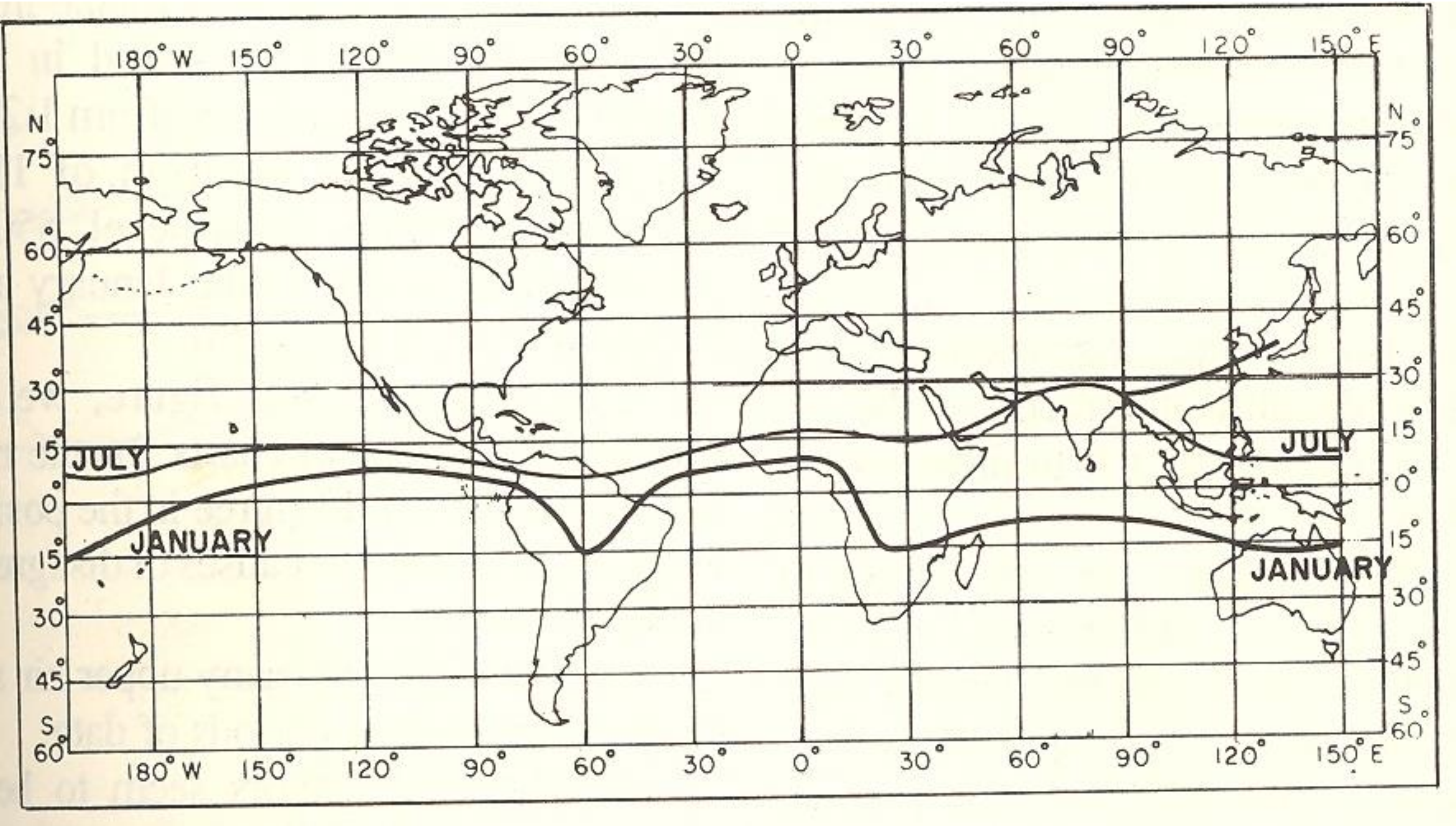


Anthropogenic influence on the South Asian monsoon: GHG and Aerosol forcing: ***(a)*** Spatial map of JJAS mean rainfall (mm day^{-1}) and 850 hPa winds (ms^{-1}) from the HistNAT simulation for the period (1951-2005) based on a global climate model with high-resolution (grid size < 35 km) telescopic zooming over South Asia (see Krishnan et al. 2016). Also shown are the difference maps of the JJAS mean rainfall and winds for the Historical all-forcing (Hist), Aerosol-only (AER) and GHG-only (GHG) experiments relative to HistNAT ***(b)*** [Hist – HistNAT] ***(c)*** [AER-HistNAT] ***(c)*** [GHG-HistNAT]. It is important to highlight the strengthening of the large-scale monsoon circulation in the GHG experiment, together with enhancement of precipitation over India. Both the Hist and AER experiments show distinct weakening of monsoon precipitation and circulation, relative to HistNAT. Note that the AER experiment is a new addition to the high-resolution simulations, since the earlier study by Krishnan et al. (2016).

Krishnan, R., T.P. Sabin, Aswin Sagar, P. Swapna and A.D. Choudhury (2020) – CLIVAR Exchanges

Reducing uncertainties in future projections of regional monsoons ?

Intertropical Convergence Zone (ITCZ)

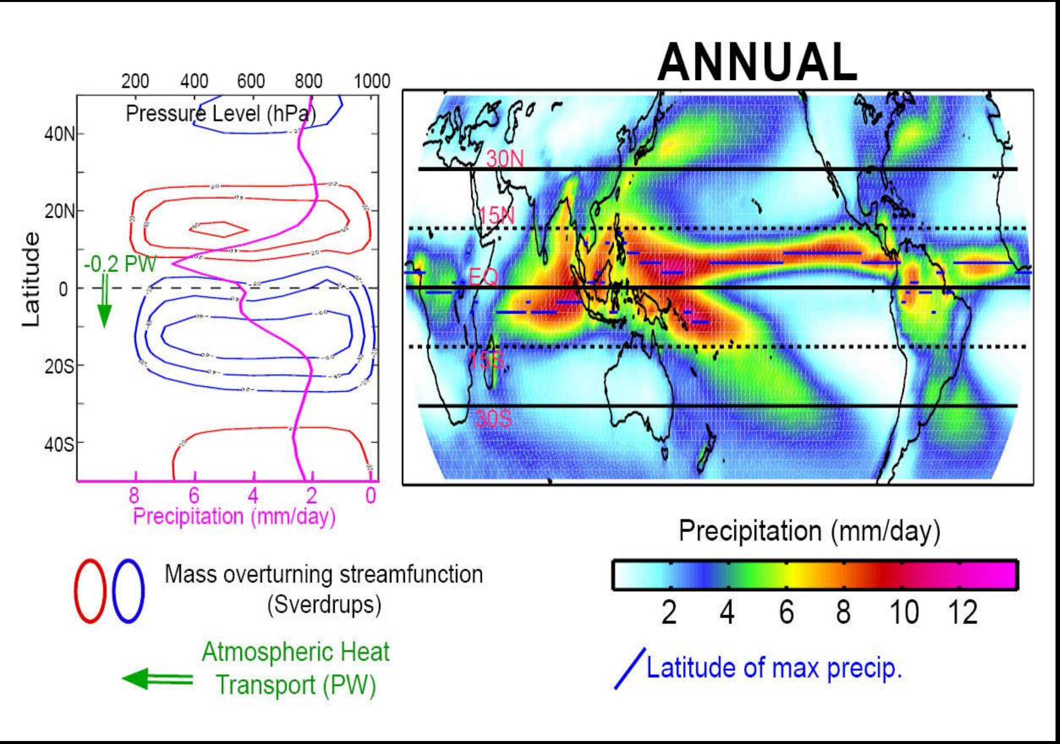


Surface position of ITCZ during January and July

Source: Prof. G.C. Asnani, Tropical Meteorology

Dynamics perspective on ITCZ

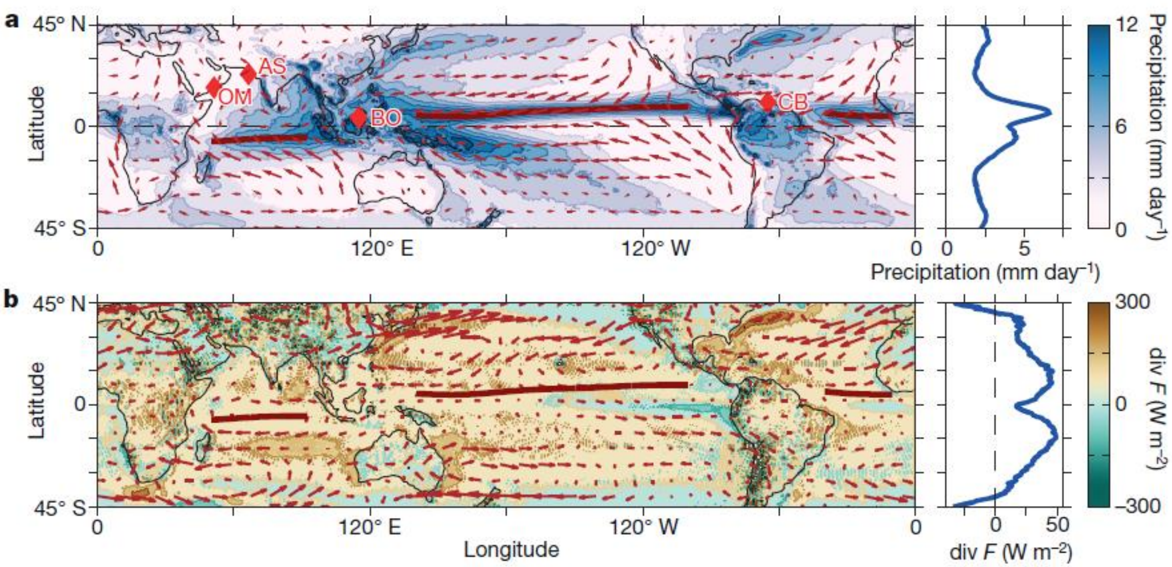
- Zonal mean ITCZ is located north of equator (Annual Mean)
- ITCZ co-located with ascending branch of Hadley cell
- Atmosphere exports energy in the upper branch of Hadley cell
- Atmosphere fluxes energy (AHT_{EQ}) out of the hemisphere with the ITCZ
- ITCZ stays in the warmer hemisphere where atmosphere is heated more strongly (by radiation or ocean heat transport).

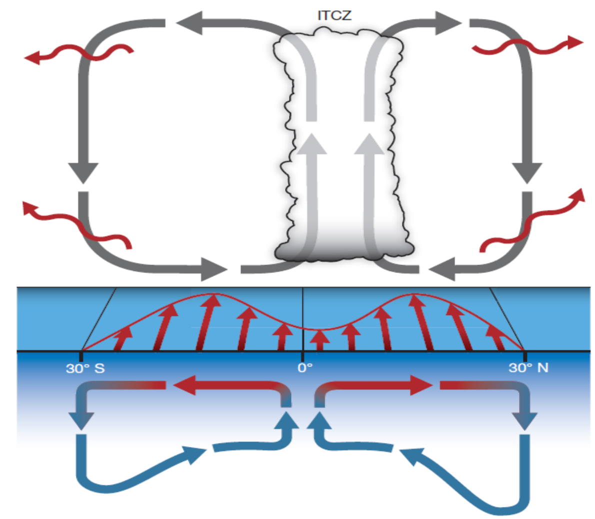


Source: Donohoe et al.

Migrations and Dynamics of the ITCZ – Schneider et al. 2014, Nature

Rainfall on Earth is most intense in the intertropical convergence zone (ITCZ), a narrow belt of clouds centred on average around six degrees north of the Equator. The mean position of the ITCZ north of the Equator arises primarily because the Atlantic Ocean transports energy northward across the Equator, rendering the Northern Hemisphere warmer than the Southern Hemisphere. On seasonal and longer timescales, the ITCZ migrates, typically towards a warming hemisphere but with exceptions, such as during El Niño events. An emerging framework links the ITCZ to the atmospheric energy balance and may account for ITCZ variations on timescales from years to geological epochs.





Processes controlling zonal-mean ITCZ position: The lower branches of the Hadley circulation (grey arrows) bring warm and moist air masses towards the ITCZ, where they converge, rise and diverge as cooler and drier air masses aloft. Because the **moist static energy** aloft is greater than near the surface, **the Hadley circulation transports energy away from the ITCZ**. Eddies transport that energy farther into the extratropics (red wavy arrows). Hemispheric asymmetries in the energy export out of the tropics generally lead to an energy flux that crosses the Equator. Currently, the energy export into the extratropics in the south exceeds that in the north, leading to a southward cross-equatorial energy flux. This implies an ITCZ in the Northern Hemisphere. Coupled to the Hadley circulation are mean zonal winds (red arrows at the sea surface), which are easterly where the near-surface mass flux is equatorward, and westerly where it is poleward. **In the oceans, these zonal winds drive subtropical cells,** with near-surface mass flux to the right of zonal winds in the Northern Hemisphere, and to the left in the Southern Hemisphere. Water masses cool and sink along their way towards the Hadley circulation termini and return below the sea surface (red and blue arrows). With mean easterlies in the tropics, the returning cool water masses upwell at the Equator, and **the subtropical cells transport energy away from the Equator**. But the upwelling location can migrate with the ITCZ away from the Equator and can dampen the ITCZ migration

Global energetics and local physics as drivers of past, present and future monsoons – Biasutti et al. 2018 Nature Geoscience

Global constraints on momentum and energy govern the variability of the rainfall belt in the ITCZ and the structure of the zonal mean tropical circulation. The **continental-scale monsoon systems** are also facets of a momentum and energy-constrained global circulation, but their modern and palaeo variability **deviates substantially** from that of the **ITCZ.** The mechanisms underlying deviations from expectations based on the longitudinal mean budgets are neither fully understood nor simulated accurately. We argue that a framework grounded in global constraints on energy and momentum yet encompassing the complexities of monsoon dynamics is needed to identify the causes of the mismatch between theory, models and observations, and ultimately to improve regional climate projections. In a first step towards this goal, disparate regional processes must be distilled into gross measures of energy flow in and out of continents and between the surface and the tropopause, so that monsoon dynamics may be coherently diagnosed across modern and palaeo observations and across idealized and comprehensive simulations. Accounting for zonal asymmetries in the circulation, land/ocean differences in surface fluxes, and the character of convective systems, such a monsoon framework would integrate our understanding at all relevant scales: from the fine details of how moisture and energy are lifted in the updrafts of thunderclouds, up to the global circulations.

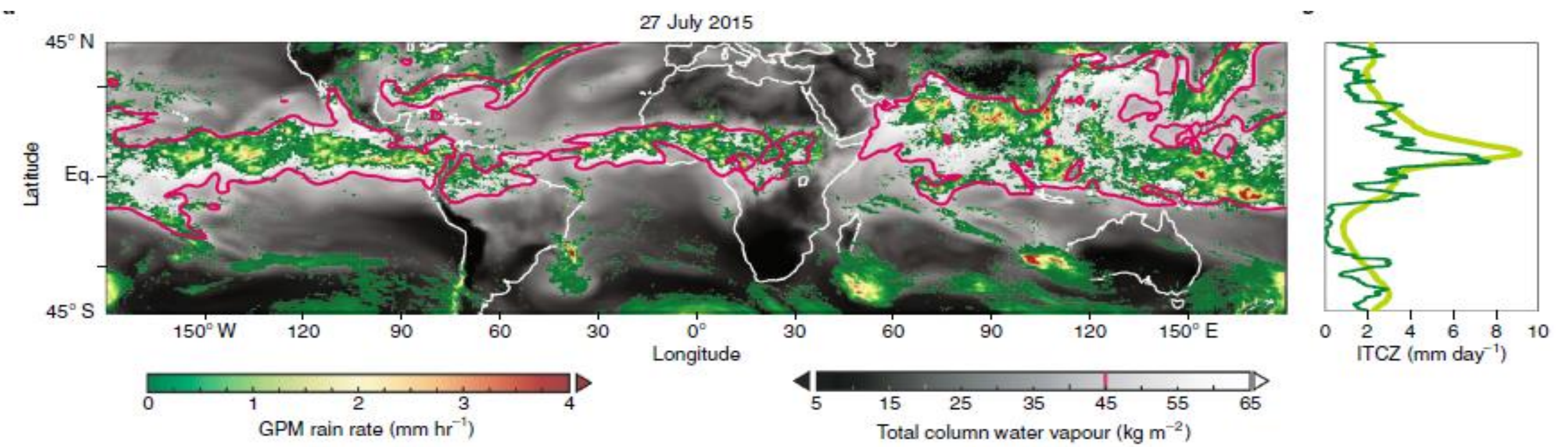
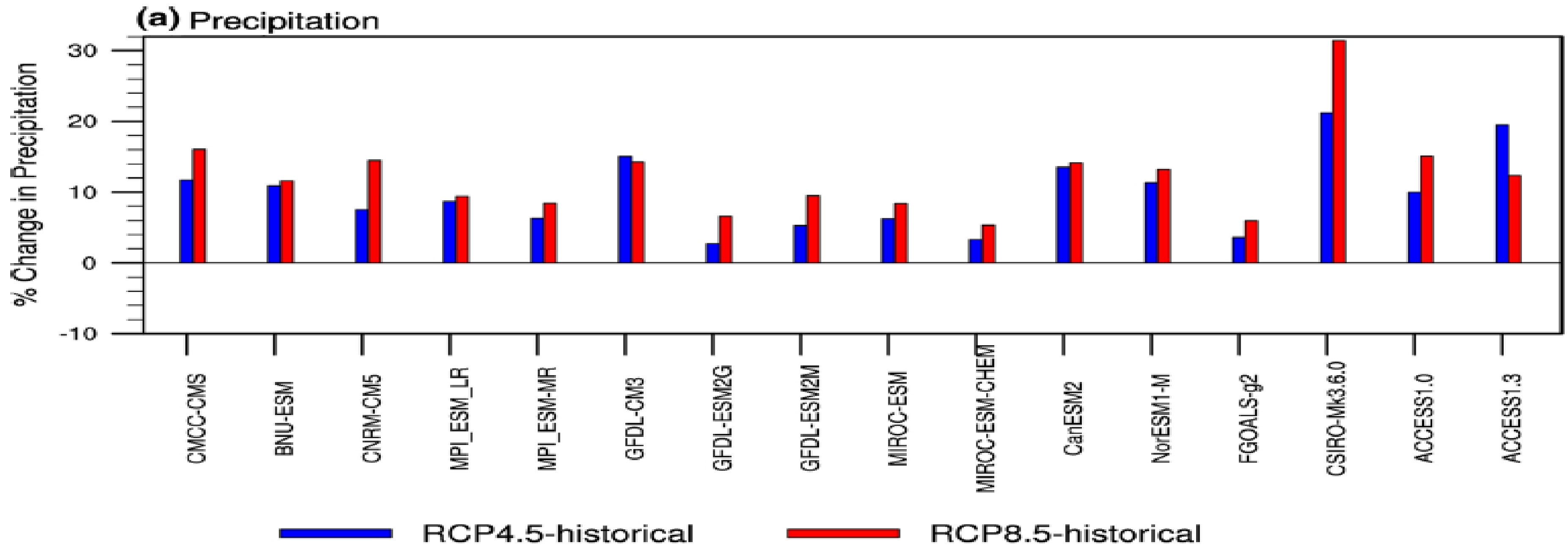


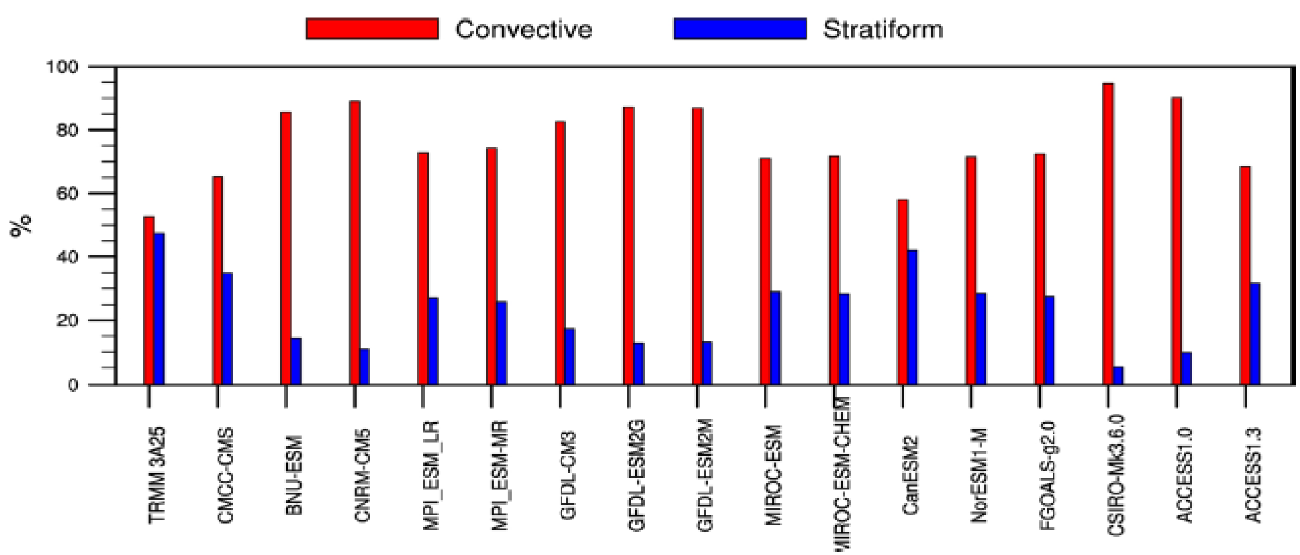
Fig. 1 | Distinct tropical convection systems are organized in a planetary-scale rain belt. a, Rainfall (coloured) on 27 July 2015, and the high atmospheric moisture enveloping it (indicated by the 45 mm contour of column-integrated water vapour, the full field is in grey). GPM, global precipitation measurement. **b**, Zonal mean rainfall for the same day (dark green) and climatological values for the same period (light green).



CMIP5 models

Sabeerali et al. 2015

Percentage of precipitation over **South Asian Monsoon region** explained by convective (red) and stratiform (blue) types in historical simulations of 16 CMIP5 models along with TRMM observations

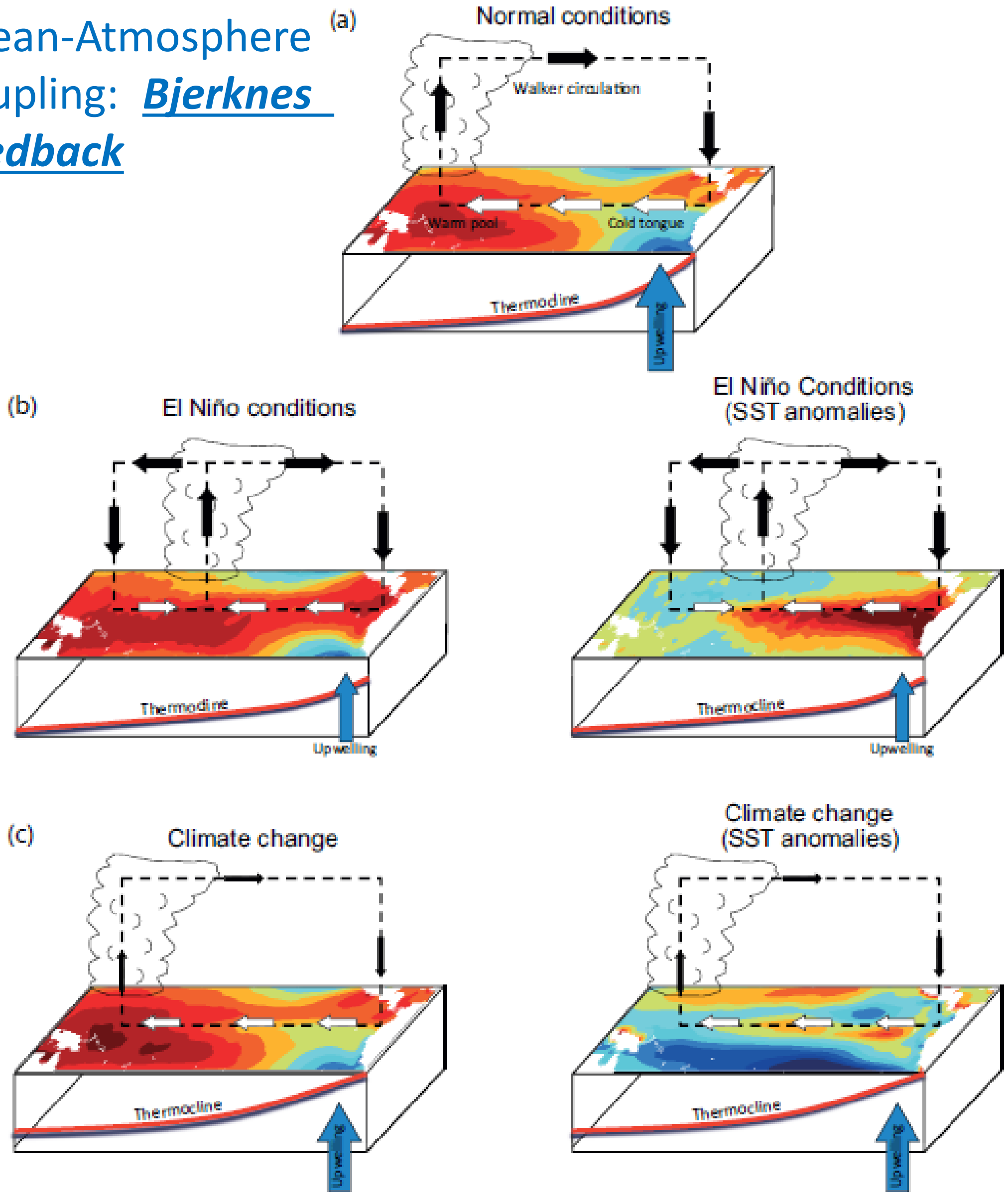


Monsoon Interannual & Decadal variability

(Links with ENSO, IOD and PDO)

IPCC AR5 2015: Likely changes in Walker Circulation under Climate Change

Ocean-Atmosphere Coupling: ***Bjerknes Feedback***

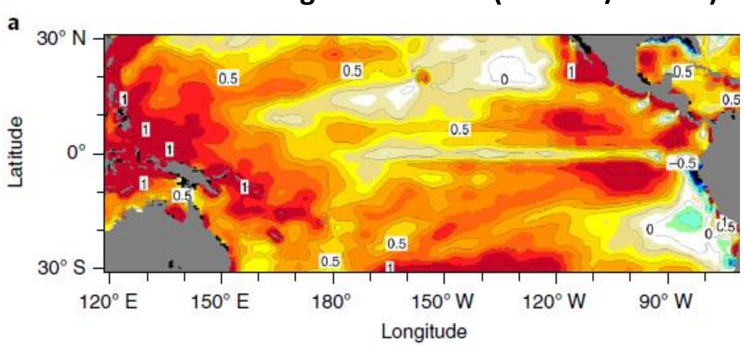


Idealized schematic showing atmospheric and oceanic conditions of the tropical Pacific region and their interactions during normal conditions, El Niño conditions, and in a warmer world. (a) Mean climate conditions in the tropical Pacific, indicating sea surface temperatures (SSTs), surface wind stress and associated Walker Circulation, the mean position of convection and the mean upwelling and position of the thermocline. (b) Typical conditions during an El Niño event. SSTs are anomalously warm in the east; convection moves into the central Pacific; the trade winds weaken in the east and the Walker Circulation is disrupted; the thermocline flattens and the upwelling is reduced. (c) The likely mean conditions under climate change derived from observations, theory and coupled General Circulation Models (GCMs). The trade winds weaken; the thermocline flattens and shoals; the upwelling is reduced although the mean vertical temperature gradient is increased; and SSTs (shown as anomalies with respect to the mean tropical-wide warming) increase more on the equator than off. Diagrams with absolute SST fields are shown on the left, diagrams with SST anomalies are shown on the right. For the climate change fields, anomalies are expressed with respect to the basin average temperature change so that blue colours indicate a warming smaller than the basin mean, not a cooling **(Collins et al., 2010).**

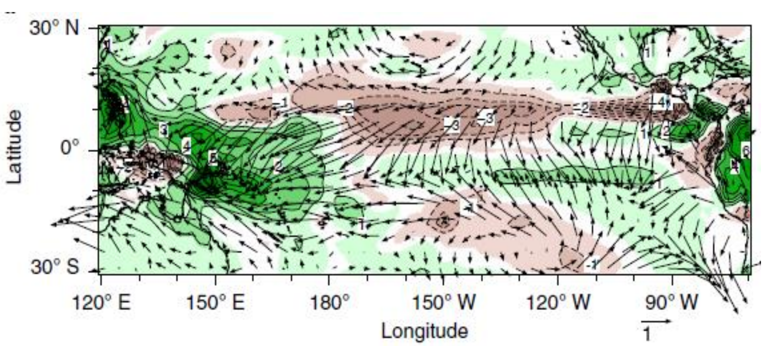
Strengthening tropical Pacific zonal sea surface temperature gradient consistent with rising greenhouse gases - Richard Seager, Mark Cane et al. 2020 Nature Climate Change

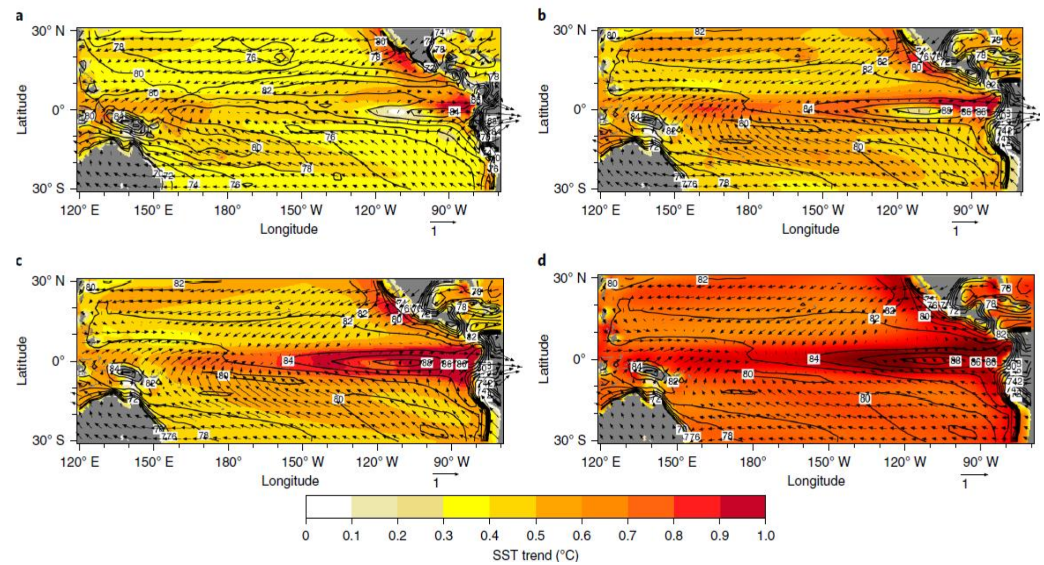
As exemplified by El Niño, the tropical Pacific Ocean strongly influences regional climates and their variability worldwide. It also regulates the rate of global temperature rise in response to rising GHGs. The tropical Pacific Ocean response to rising GHGs impacts all of the world's population. State-of-the-art climate models predict that rising GHGs reduce the west-to-east warm-to-cool sea surface temperature gradient across the equatorial Pacific. In nature, however, the gradient has strengthened-in recent decades as GHG concentrations have risen sharply. This stark discrepancy between models and observations has troubled the climate research community for two decades. Here, by returning to the fundamental dynamics and thermodynamics of the tropical ocean–atmosphere system, and avoiding sources of model bias, we show that a parsimonious formulation of tropical Pacific dynamics yields a response that is consistent with observations and attributable to rising GHGs. We use the same dynamics to show that the erroneous warming in state-of-the-art models is a consequence of the cold bias of their equatorial cold tongues. The failure of state-of-the-art models to capture the correct response introduces critical error into their projections of climate change in the many regions sensitive to tropical Pacific sea surface temperatures.

Observed SST change 1958–2017 (ECMWF/ORAS4)



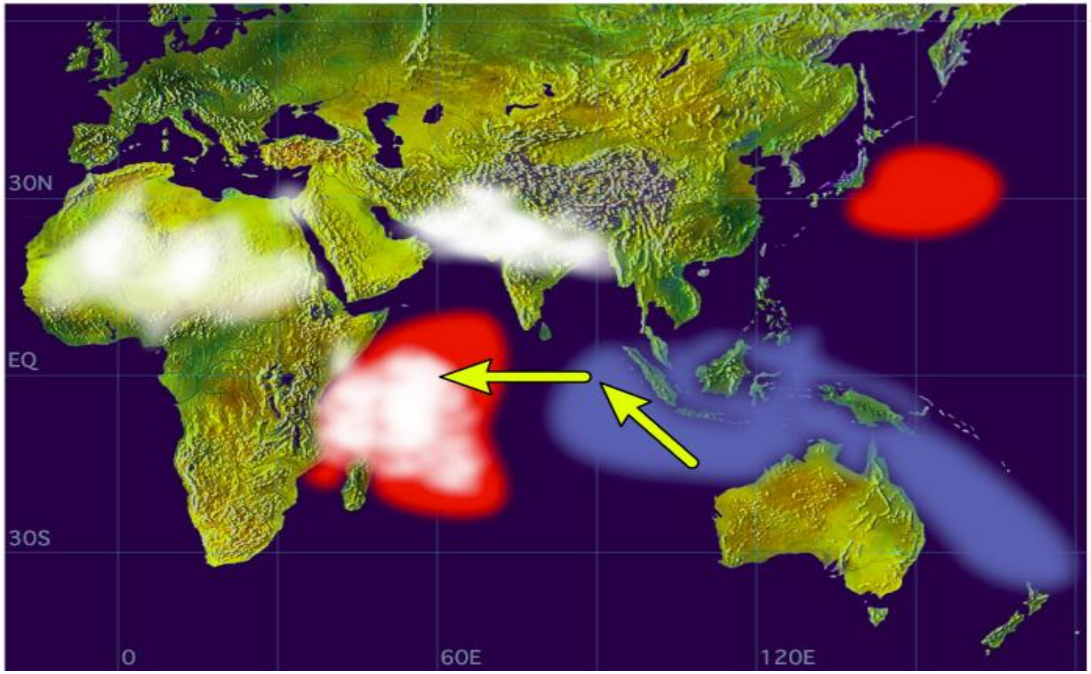
Trends in surface winds and precipitation based on ECMWF reanalysis over 1958–2017





Coupled model trends over 1958–2017, and attribution of erroneous trends in CMIP5 models to model bias. a–**d**, Trends in winds (vectors; scale bar in m s^{-1}) and SST (colours; see scale bar) over 1958–2017 within the coupled model (CM), moving from the observed world to the CMIP5 world. In **a**, the observed spatially varying relative humidity (%, contours) from ECMWF is imposed in the model instead of a uniform value ('CM-ECMWF world' in **e**). In **b**, the CMIP5 multimodel mean spatially varying relative humidity (%, contours in **b**–**d**) is imposed ('CM-ECMWF C-RH' in **e**). In **c**, the CMIP5 wind speed is also imposed ('CM-ECMWF C-RH W' in **e**). Finally, in **d**, the ocean model is additionally 'q-fluxed' towards the CMIP5 multimodel mean SST climatology ('CM-CMIP5 world' in **e**)

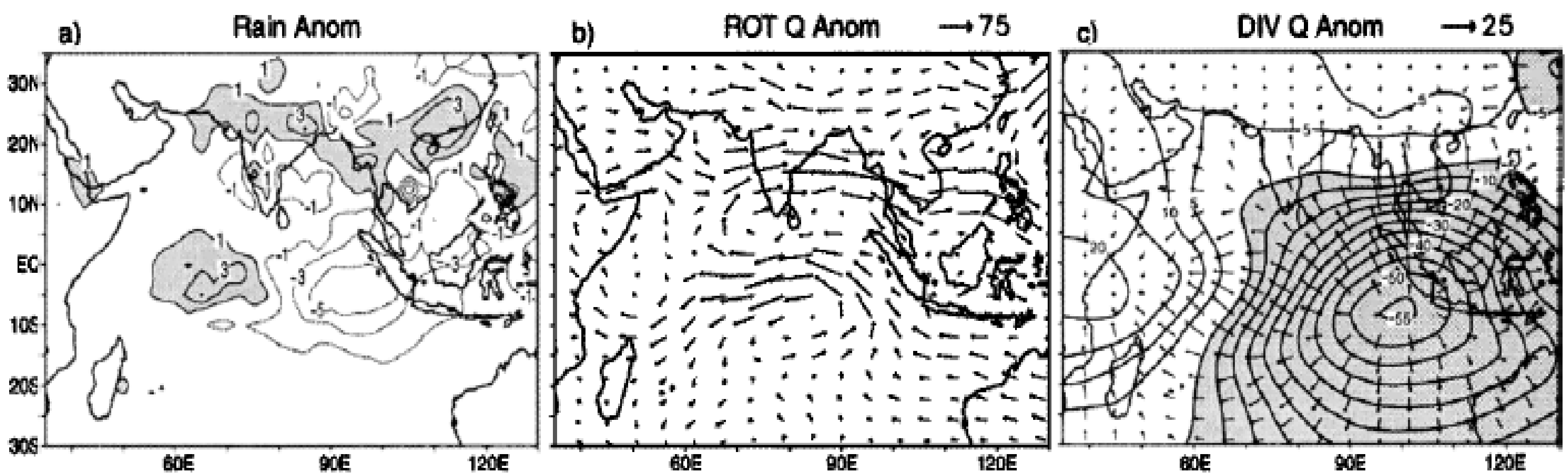
Positive Dipole Mode



Indian Ocean Dipole - Saji et al., 1999

Schematic: SST anomalies (red - warming; blue - cooling) during positive IOD. White patches - increased convective activity.

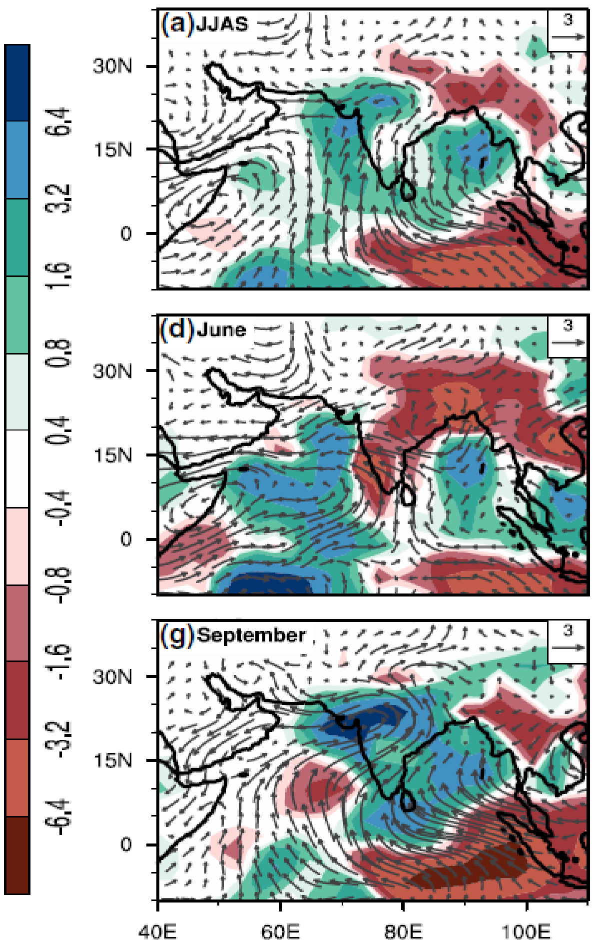
- Enhanced monsoon precipitation over India during positive IOD events - **e.g., 1994, 1961, 2019**
- Intensified **cross-equatorial transport of moisture** from the Southeastern equatorial Indian Ocean (SETIO)

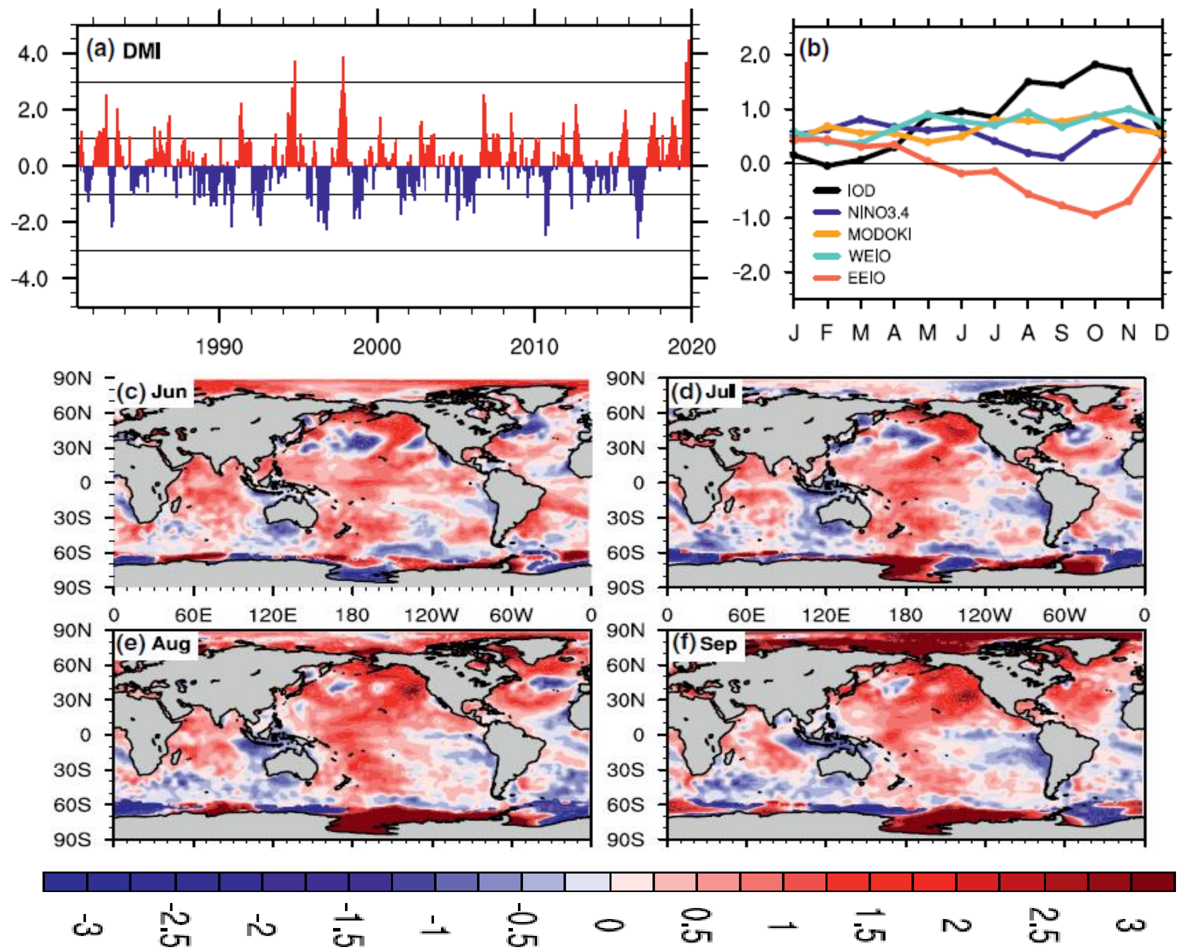


Behera, Krishnan and Yamagata, 1999 GRL

The extreme positive IOD of 2019 and associated Indian summer monsoon rainfall response - Satyaban Ratna et al. (2020)

The positive Indian Ocean Dipole (IOD) event in 2019 was among the strongest on record, while the Indian Summer monsoon (ISM) was anomalously dry in June then very wet by September. We investigated the relationships between the IOD, Pacific sea surface temperature (SST), and ISM rainfall during 2019 with an atmospheric general circulation model forced by observed SST anomalies. The results show that the extremely positive IOD was conducive to a wetter-than-normal ISM, especially late in the season when the IOD strengthened and was associated with anomalous low-level divergence over the eastern equatorial Indian Ocean and convergence over India. However, a warm SST anomaly in the central equatorial Pacific contributed to low-level divergence and decreased rainfall over India in June. These results help to better understand the influence of the tropical SST anomalies on the seasonal evolution of ISM rainfall during extreme IOD events.





Summary

•Monsoon sub-seasonal variability: Multi-scale interactive phenomena

•Prospects for improving S2S monsoon predictive capabilities in a changing climate

- Reducing uncertainties in monsoon projections
- Develop a framework based on global energy constraints and regional monsoon complexities
- Improve the representation of large-scale organized convection, latent heating, warm rain processes, orographic precipitation, mid-level circulation, aerosol-cloud interactions
- Large-scale tropical SST gradients are fundamental in regulating tropical and regional monsoon precipitation *(mean, variability and extremes)* – by altering heat and moisture fluxes, convective activity and large-scale circulations
- *Process and Predictive Understanding:* Combining observations and models for advancing predictive understanding of ocean-atmosphere coupled interactions on different scales (Ocean observing system – Moorings: Pacific, Indian (RAMA), Atlantic; ARGO floats, Satellite observations, Data assimilation, Climate model experiments)

Thanks for your kind attention!