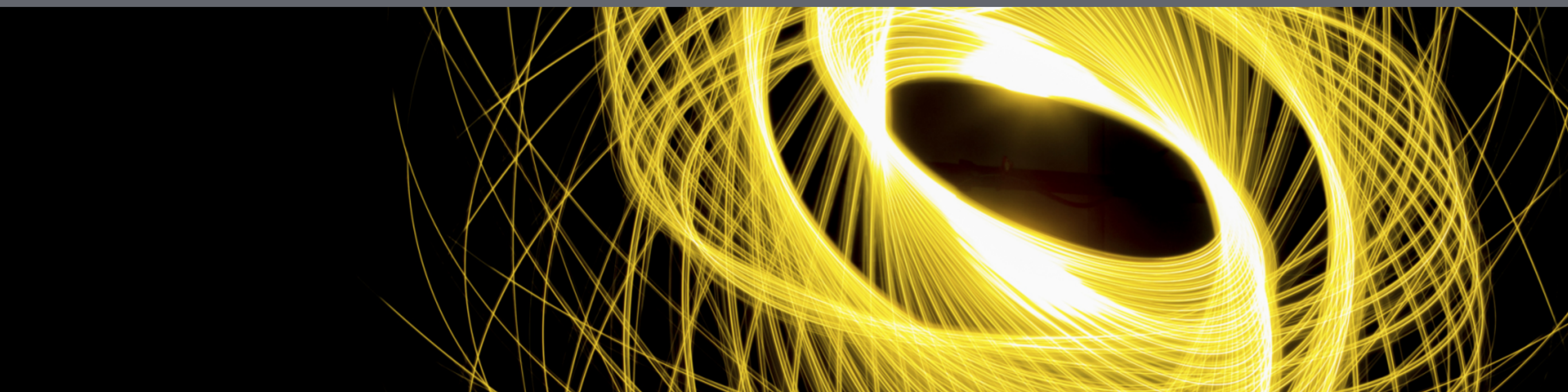
Dr Andy Turner, NCAS-Climate &
Department of Meteorology

University of Reading

CLIMATE PROJECTIONS OF THE SOUTH ASIAN MONSOON



ICTP Targeted Training Activity: Monsoons in a changing climate

31 July-4 August 2017

Seasonal monsoon precipitation

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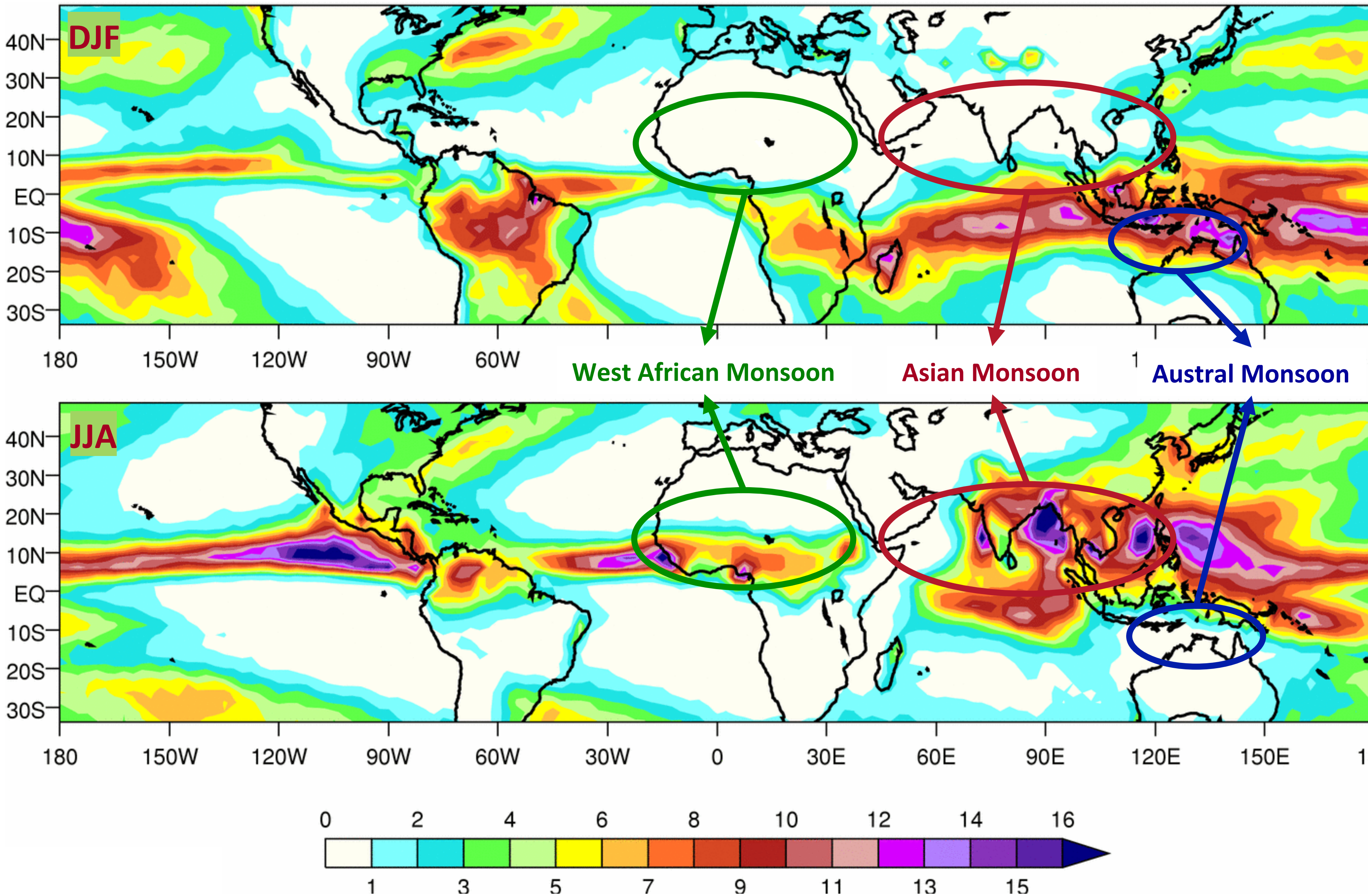
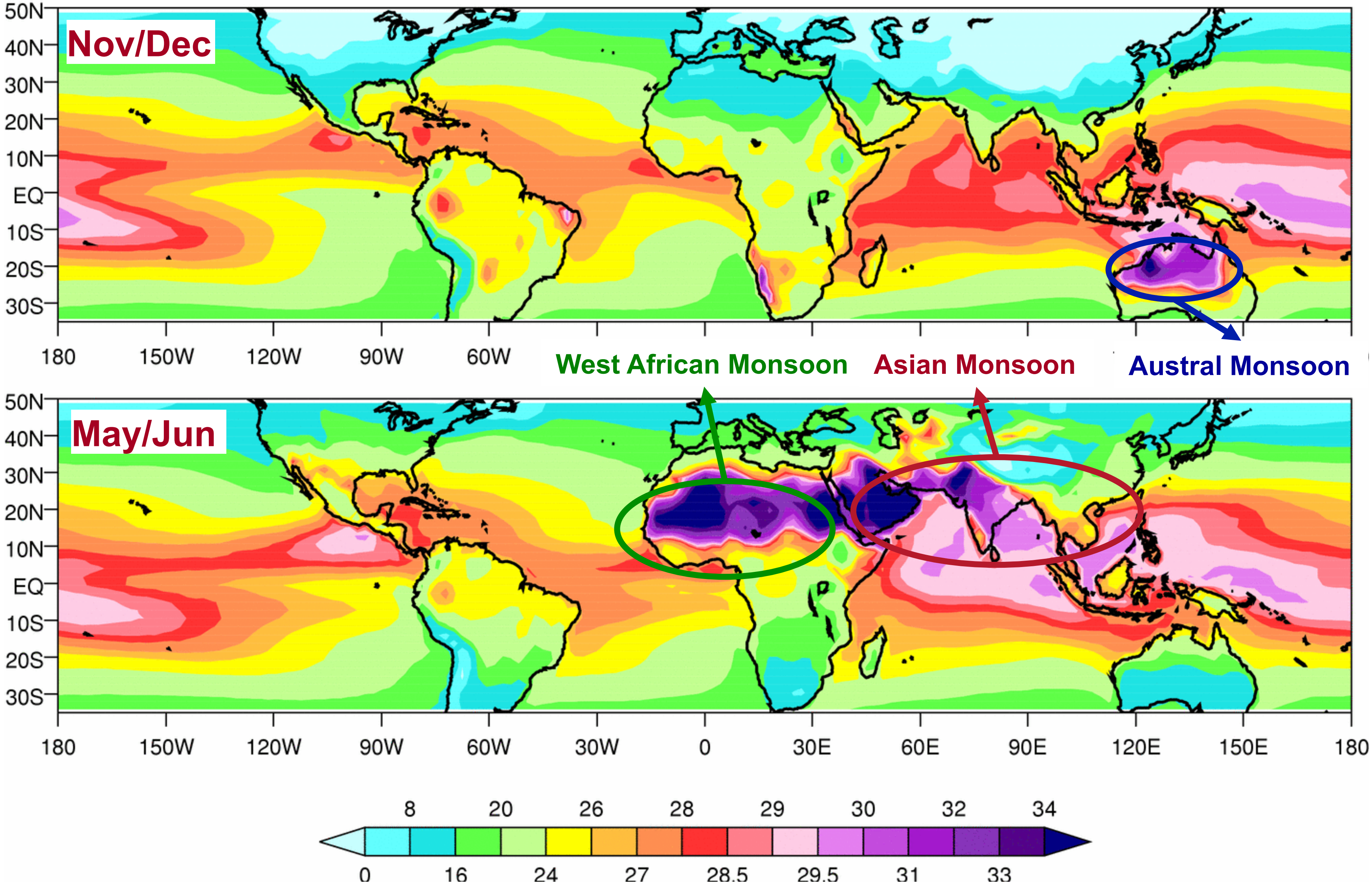
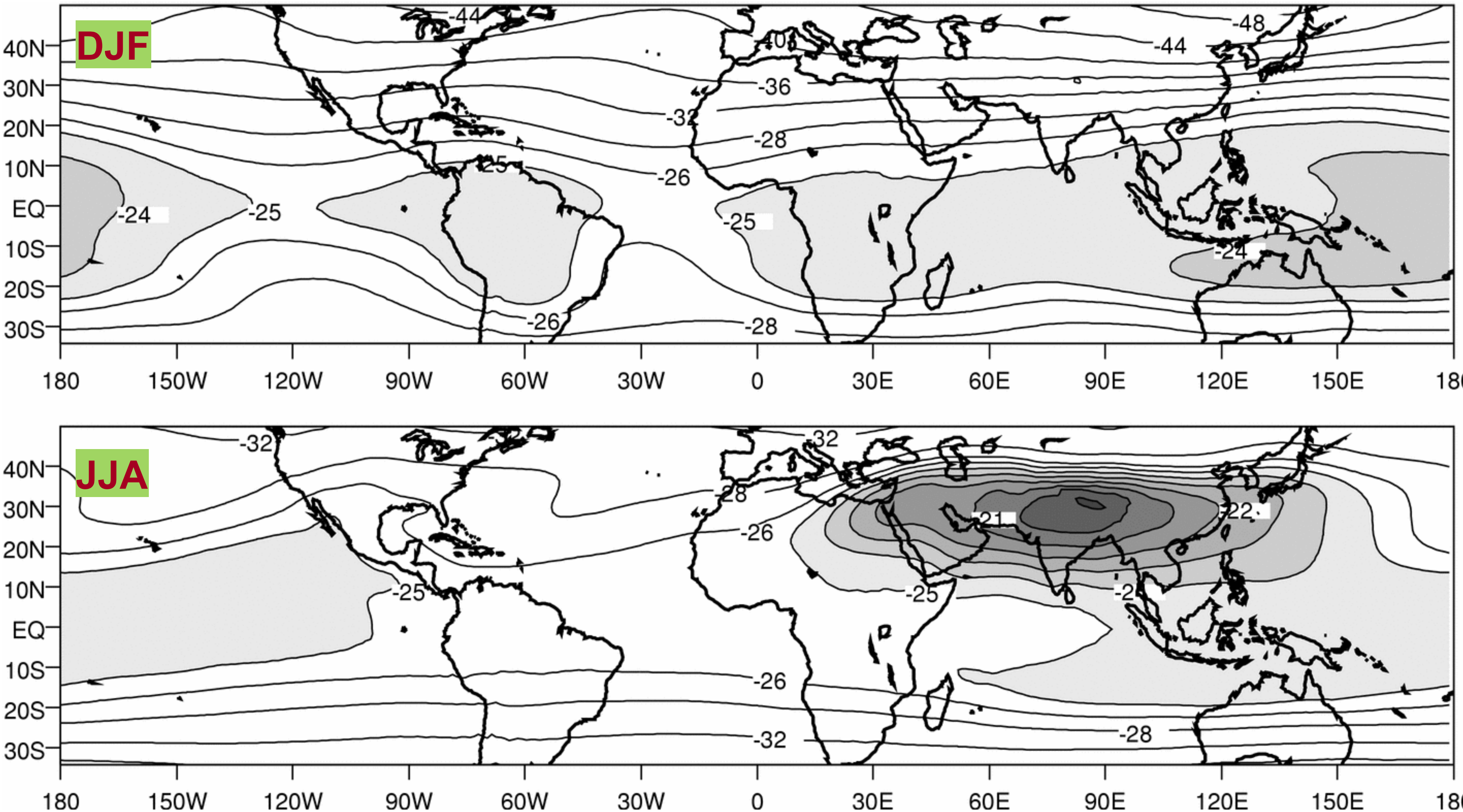


Meridional surface temperature contrasts



Tropospheric temperature gradient (200-500hPa)



Seasonal monsoon winds (850hPa)

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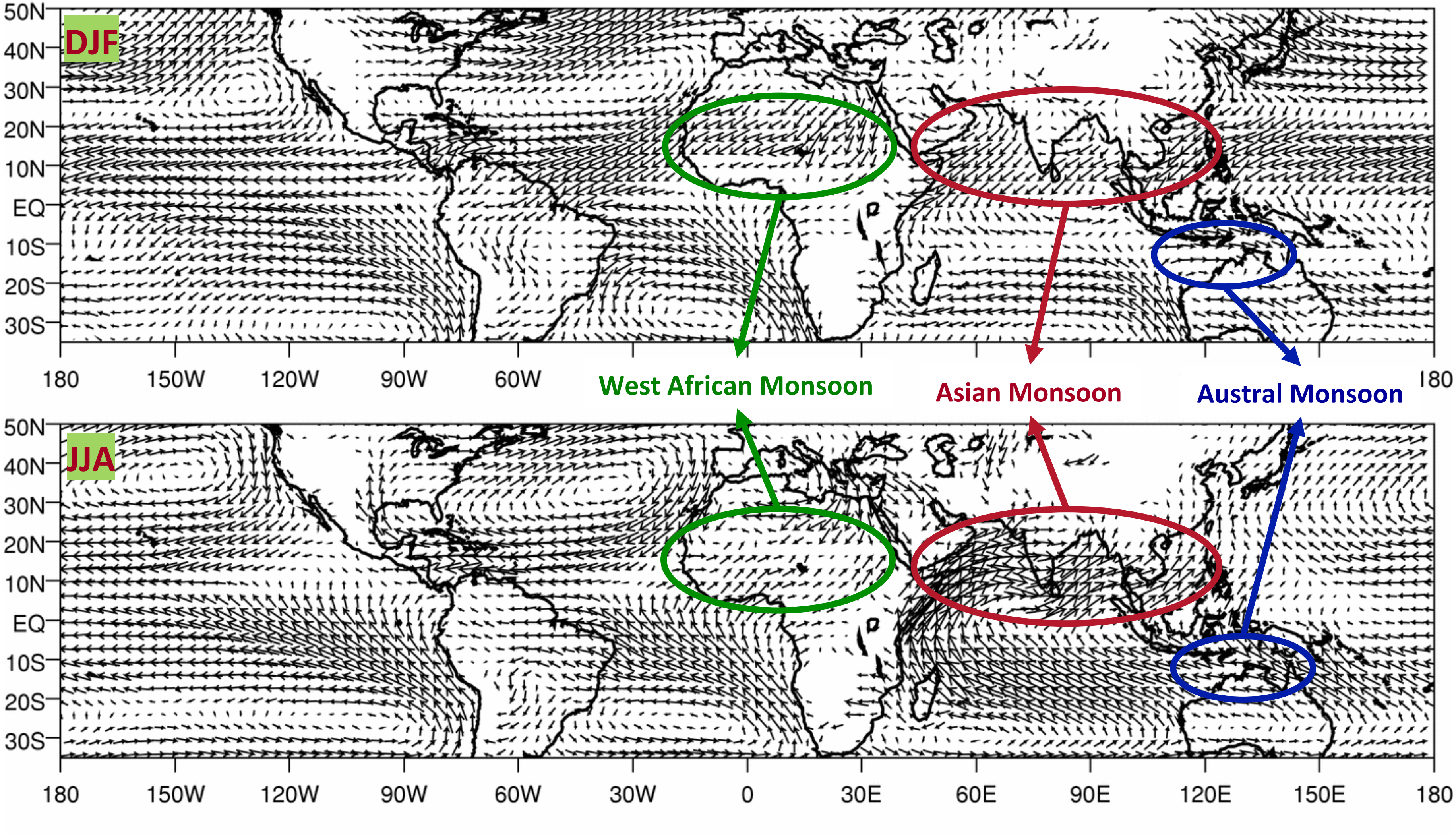

POTENTIAL DRIVERS OF CHANGE IN THE MONSOON

- Changing land-sea contrast
  - More accurately, change in meridional tropospheric temperature contrast
  - What if the troposphere warms differently to the surface?
- Changing circulation
- Changing availability of moisture

OUTLINE

- The global context
- Impacts of greenhouse gases on the Indian monsoon
- Observed trends
- 20th-century impacts of anthropogenic aerosols
- Idealized impact of anthropogenic aerosol

GLOBAL MEAN PRECIPITATION CHANGE

- Linear changes in GMP with GMT, c.f. energy budget arguments (Allen & Ingram, 2002)
- Equivalent to approx. 2%/°C for land & ocean, although in a range up to around 4%/°C

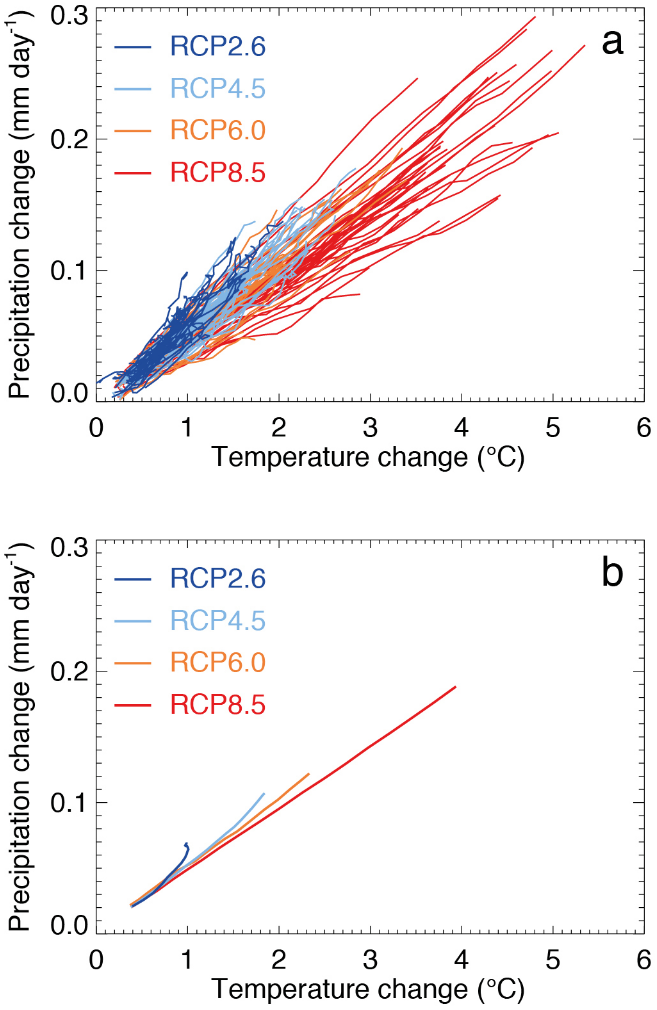

Figure 12.6 | Global mean precipitation (mm day^{-1}) versus temperature (°C) changes relative to 1986–2005 for the four RCPs for (a) means over decadal periods starting in 2006 and overlapped by 5 years (2006–2015, 2011–2020, up to 2091–2100), each line representing a different model (one ensemble member per model) and (b) corresponding multi-model means for each RCP

PROJECTED T&P PATTERNS & DEPENDENCE ON MEAN ΔT

- Greater warming over land than ocean regions
- Stronger warming in NH
- Evidence of Arctic amplification (sea-ice albedo feedbacks etc.)
- Intensification of ITCZ & monsoon regions, drier subtropics
- (Pattern-scaling approach)

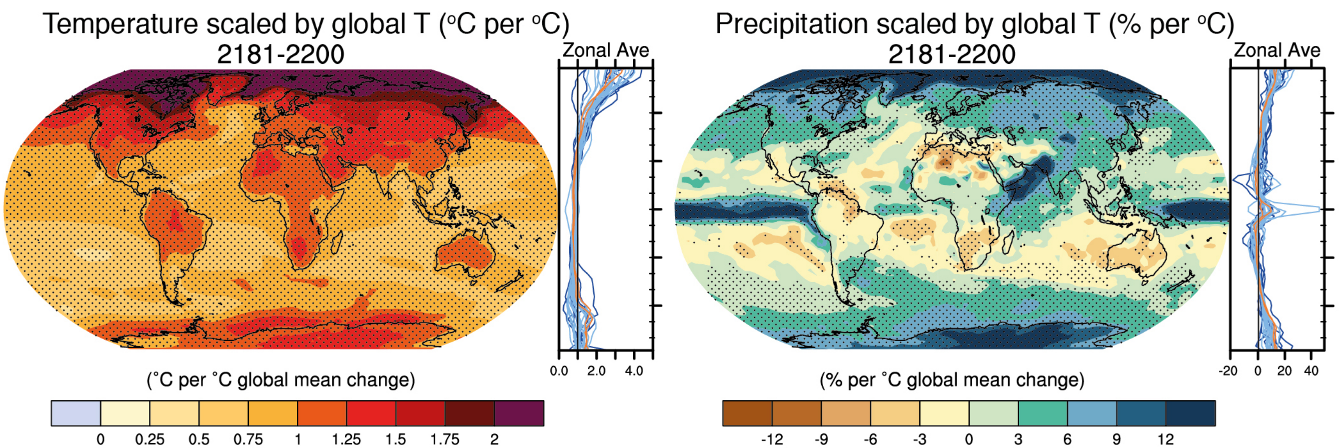

Figure 12.10 | Temperature and precipitation change patterns, scaled to 1°C of global mean surface temperature change since1986–2005

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IMPACTS OF GHG ON INDIAN MONSOON

SOME STUDIES OF FUTURE CHANGE

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- Increased monsoon due to the land-sea temperature gradient (Hu et al., 2000); northward shift of the flow structure (Kitoh et al., 1997)
- Increases in monsoon rainfall due to increased moisture from a warmer Indian Ocean: Meehl & Arblaster (2003), Turner et al. (2007). Increased moisture transport overriding decreases in monsoon circulation: May (2002; 2010)

➢ Cherchi *et al*. (2010): single model, various levels of CO_2; thermodynamic component increasing moisture overcomes effects of weakened circulation. Evidence for increased low-level flow

Cherchi, A, A Alessandri, S Masina & A Navarra (2010) *Clim. Dyn.*

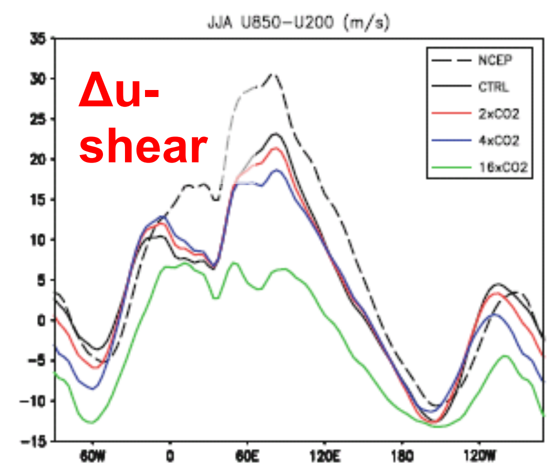
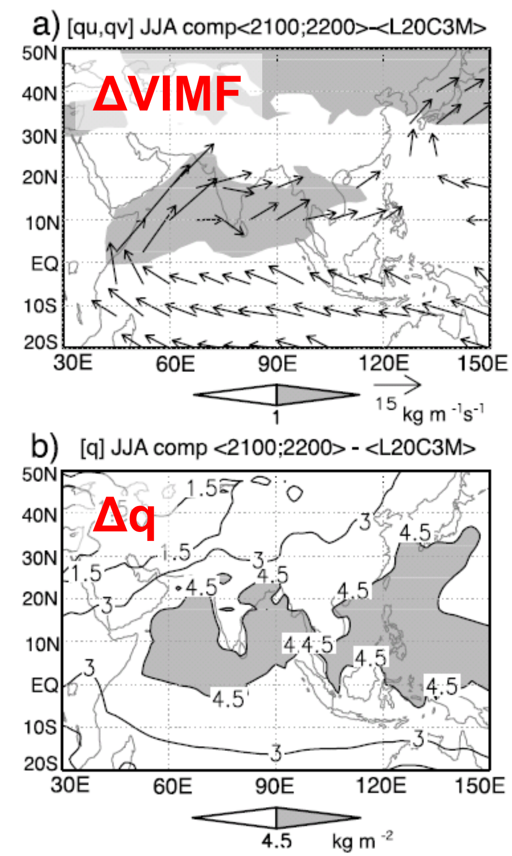


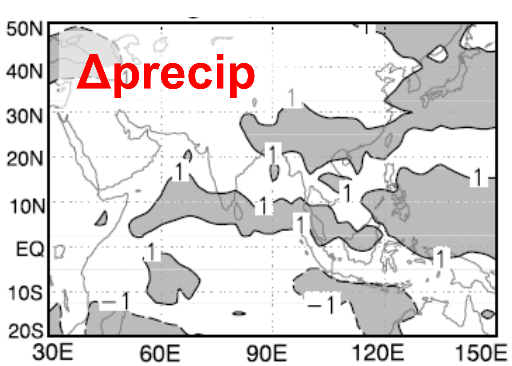
Fig. 2 Mean JJA U850-U200 (m s^{-1}) averaged between 5°S–15°N for NCEP winds (*dashed black line*), CTRL (*solid black line*), 2×CO_2 (*red line*), 4×CO_2 (*blue line*) and 16×CO_2 (*green line*) experiments

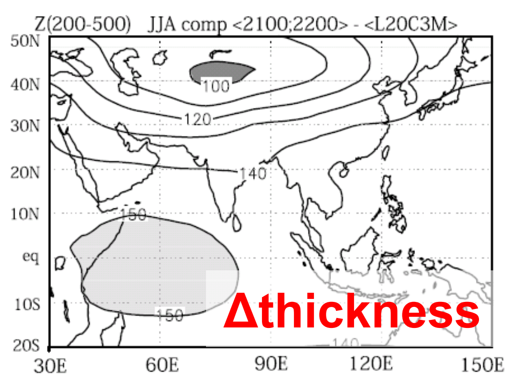
WIND-PRECIPITATION PARADOX

8 CGCM comparison at A1B yields the wind-precipitation paradox:

- enhanced monsoon precipitation due to enhanced moisture transport from warmer Indian Ocean
- decreased monsoon circulation relating to warming in the upper tropical troposphere





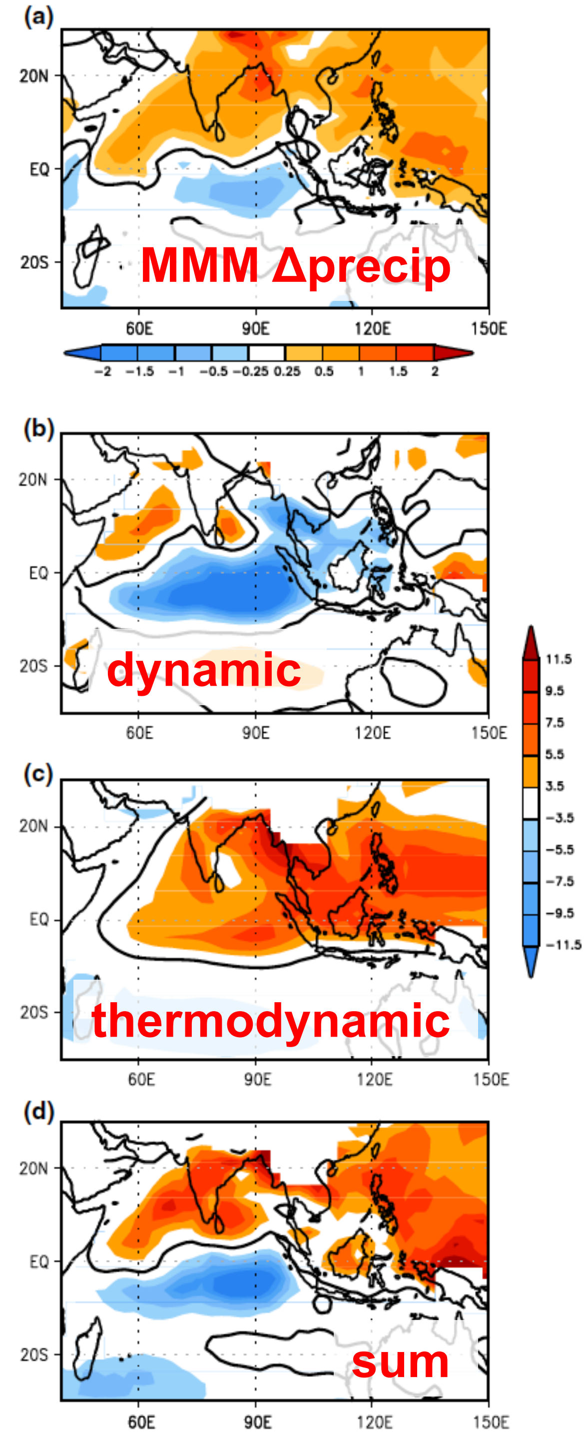


Ueda, H, A Iwai, K Kuwako & ME Hori (2006) *GRL* 33, L06703

THERMODYNAMICS VS. DYNAMICS

- Multiple studies for the South Asian monsoon show the dominance of thermodynamics, rather than dynamics
  - Changes in moisture win over changes in circulation, even if circulation weakens

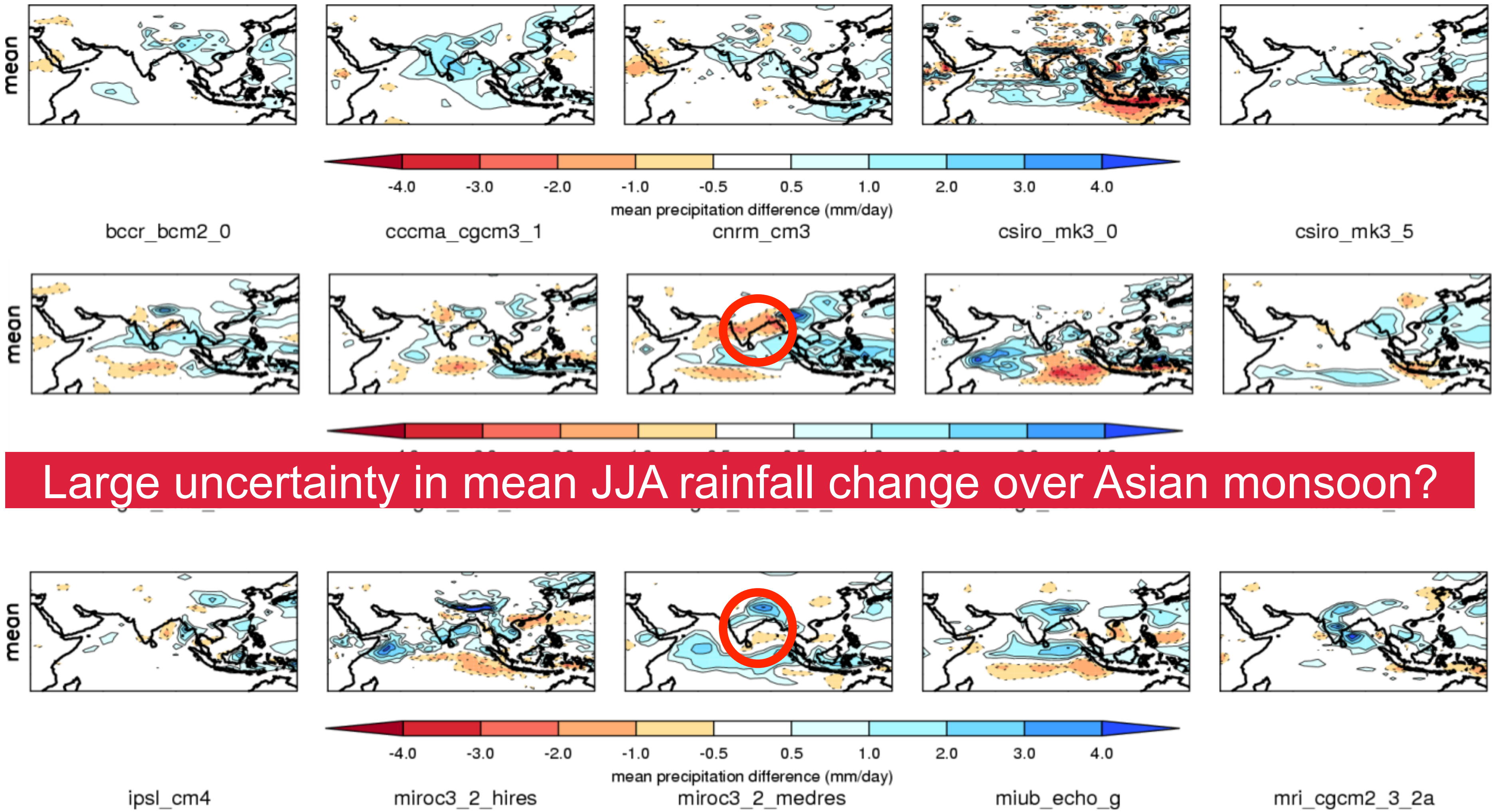
$$\Delta P \sim (\Delta\omega \cdot \bar{q} + \bar{\omega} \cdot \Delta q)$$



Sooraj *et al.* (2015) *Climate Dynamics*

Fig. 9 Decomposition of future rainfall change in the ENS average as determined from the water vapour budget Eq. (1), see text for more details. **a** Rainfall (in mm day^{-1}) change, **b** dynamic component ($\Delta\omega \cdot \bar{q}$) and **c** thermodynamic component ($\bar{\omega} \cdot \Delta q$). **d b** + **c**. Unit for (**b**)–(**d**) is in 10^{-5} Pa s^{-1}. In all the panels, zero contours are highlighted in *black colour*. Note here that Eq. (1) implicitly assumes that the upward velocity is positive

PATTERN UNCERTAINTIES AT DOUBLED CO_2



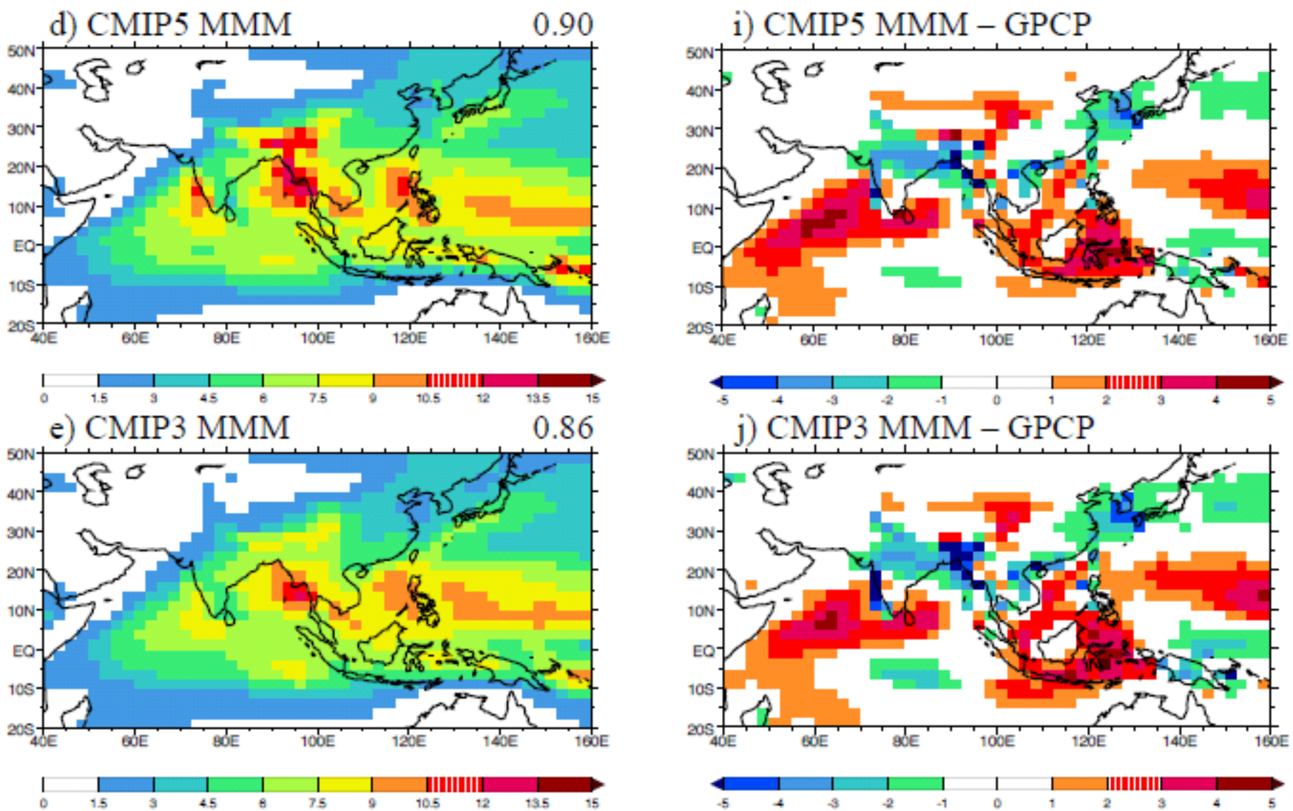
Large uncertainty in mean JJA rainfall change over Asian monsoon?

from Turner & Slingo (2009b) *Atmos. Sci. Lett.* **10**

RECAP: CMIP PERFORMANCE

Mean JJAS precipitation (left) & bias versus GPCP obs (right)

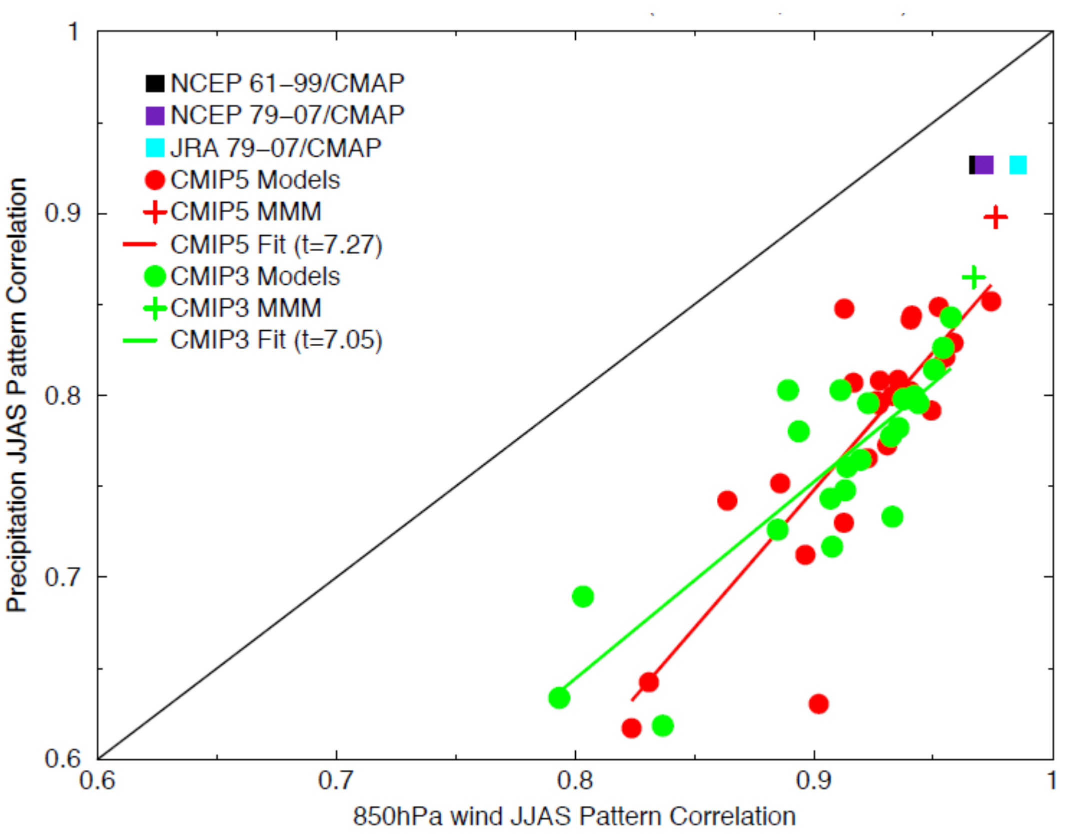
Sperber *et al.* (2013, *Clim. Dyn.*)



- Incremental improvements only since CMIP3

RECAP: CMIP PERFORMANCE

- Intimate link between monsoon circulation and precipitation biases
- Considerable effort still needed to improve coupled model performance



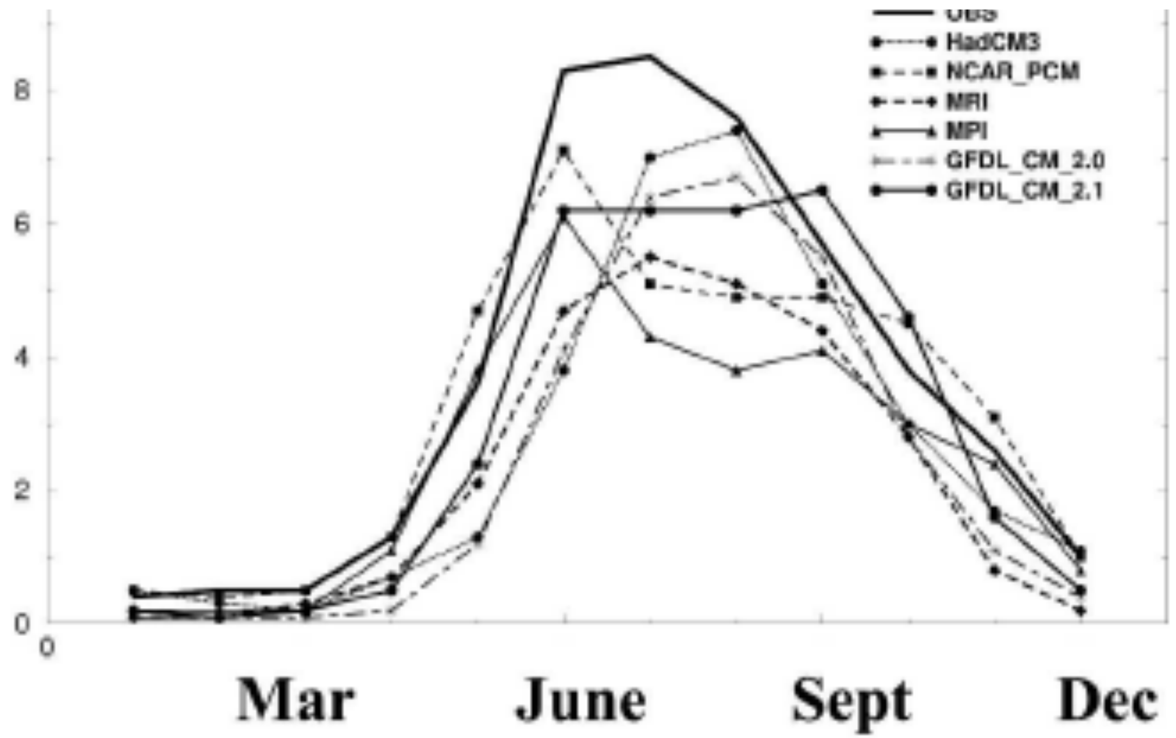
Sperber *et al*. (2013, Clim. Dyn.): Scatter diagrams of model pattern correlation skill for historical simulation of precip (y) and winds (x)

CMIP3 vs. CMIP5

SEASONAL CYCLE AS PERFORMANCE INDICATOR

- Only 6 CMIP3 models can reasonably simulate both the spatial distribution and seasonal cycle of rainfall over South Asia!
- These “best” models simulate changes in mean monsoon rainfall of 5-25% & IAV of 5-10%

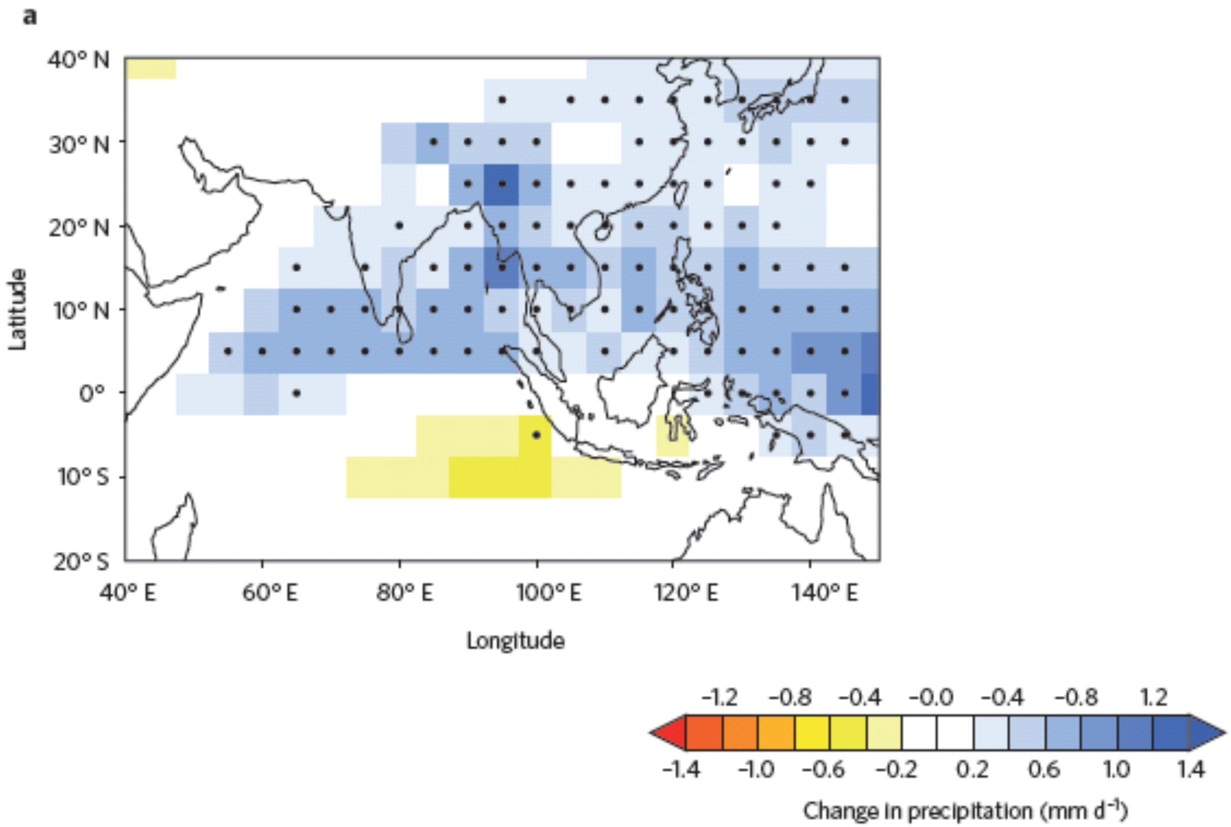
Seasonal cycle of precipitation over South Asia in CMIP3 models



from Annamalai *et al*. (2007) *J. Climate*

MMM FUTURE PROJECTIONS

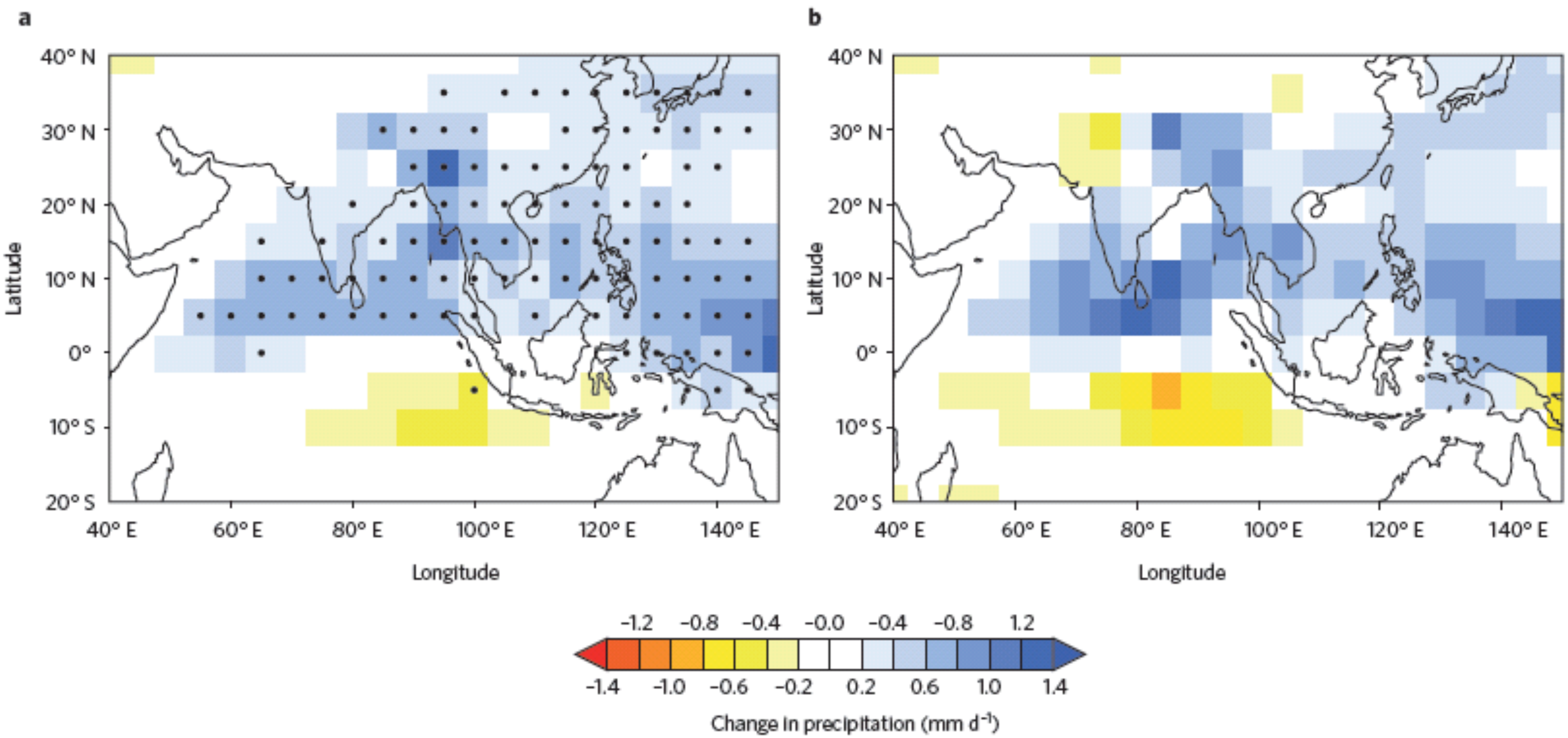
JJAS precipitation change for CMIP3 models: 1pctto2x-picntrl



- Mean JJAS precipitation is shown to increase for much of South, Southeast and East Asia with increasing CO2 concentrations
- From Turner & Annamalai (2012) *Nature Climate Change*

"GOOD" MODEL PROJECTIONS

JJAS precipitation change for CMIP3 models: 1pctto2x-picntrl



- Selecting only four models according to their skill at the mean monsoon, interannual variability & monsoon-ENSO teleconnection yields similar results for mean projection

CMIP5 VS. CMIP3

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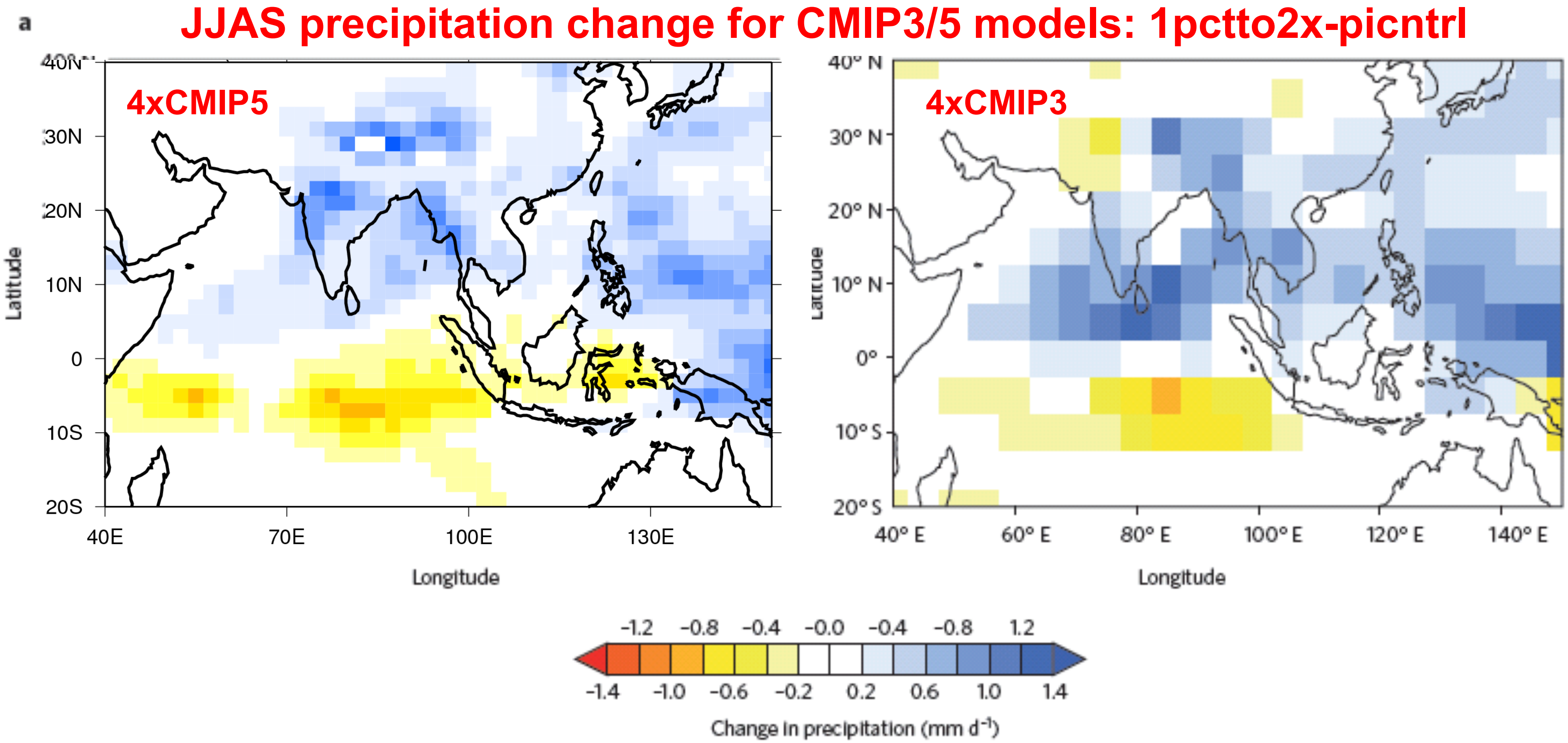
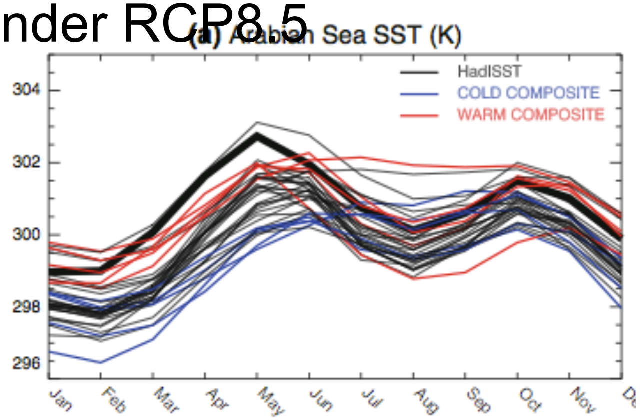
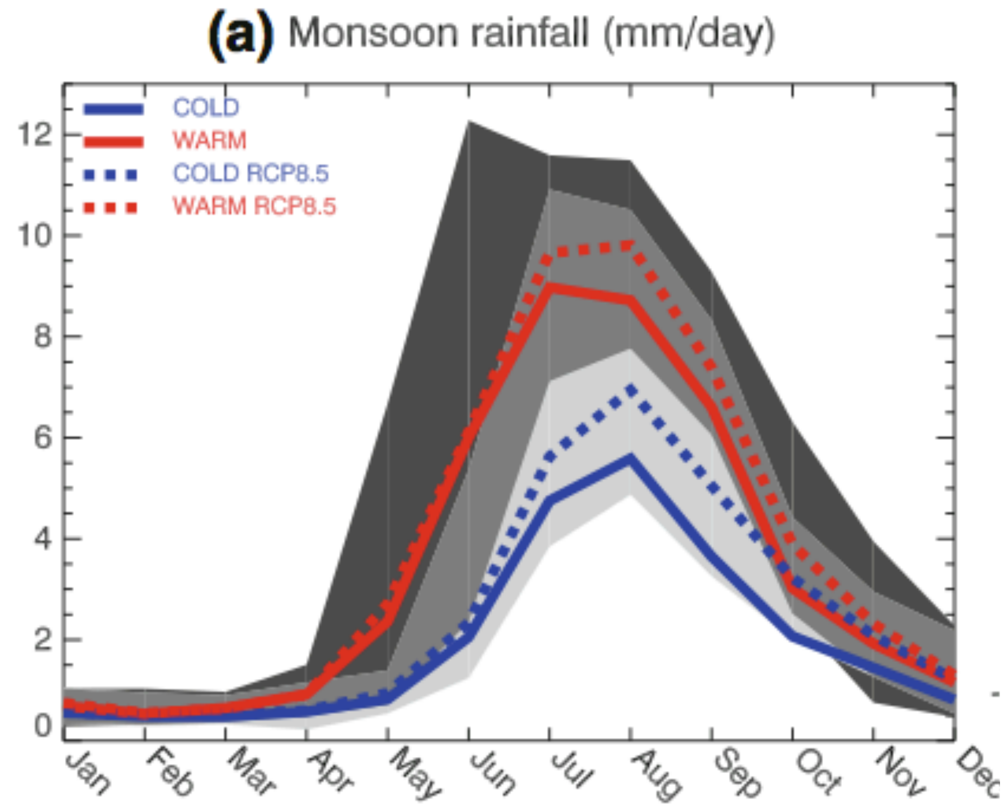


- Now selecting four CMIP5 models according to their pattern correlation for monsoon precipitation over South, Southeast and East Asia monsoon domain (CCSM4, CNRM-CM5, GFDL-CM3, NorESM1-M)

SST BIAS IMPACT ON FUTURE

- CMIP5 models with cold winter/spring Arabian Sea have a weakened seasonal cycle of rainfall, later onset and lower absolute rainfall levels under RCP8.5





Levine, Turner, Marathayil & Martin (2013, *Clim. Dyn.*)

HISTORICAL & FUTURE

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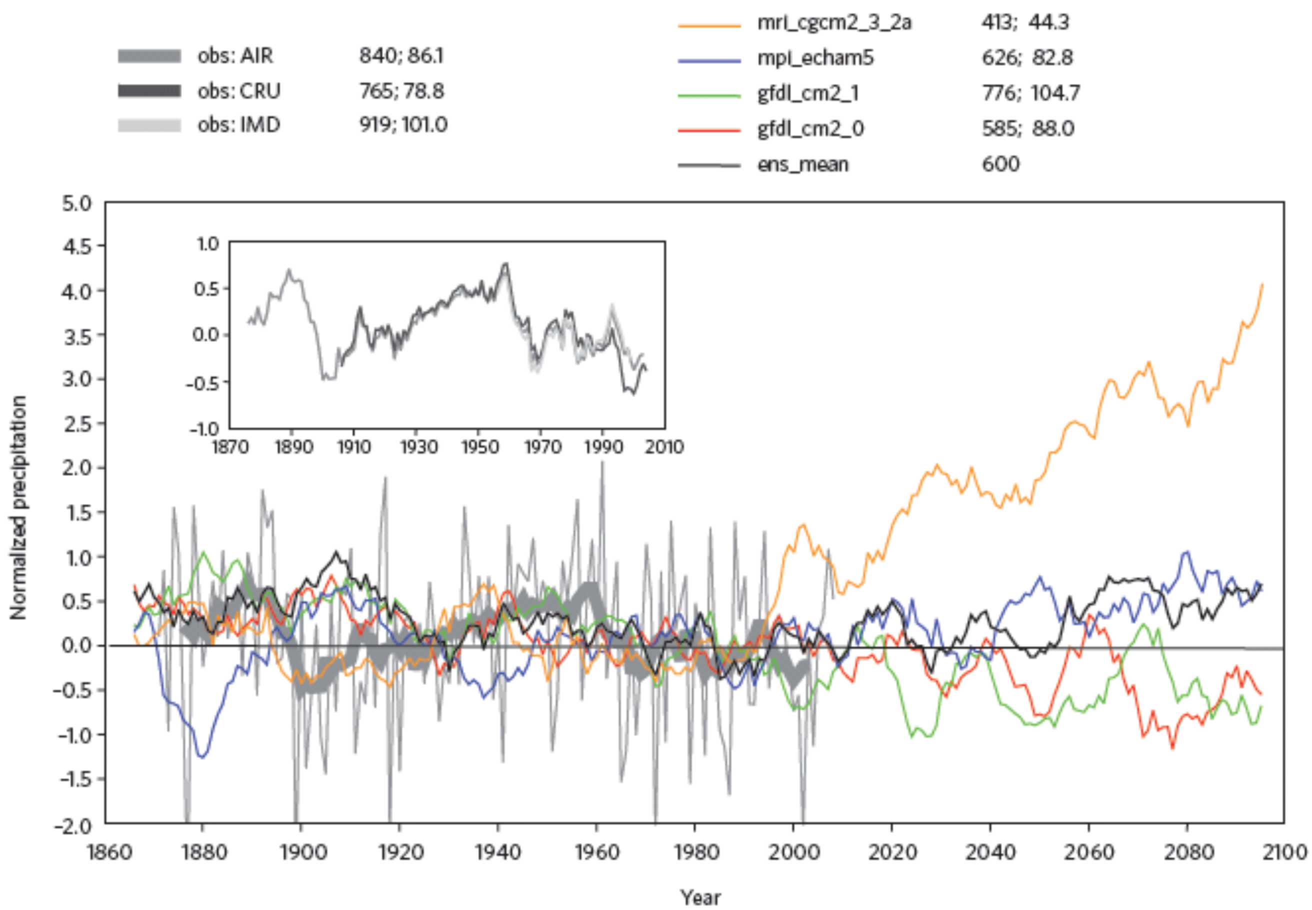
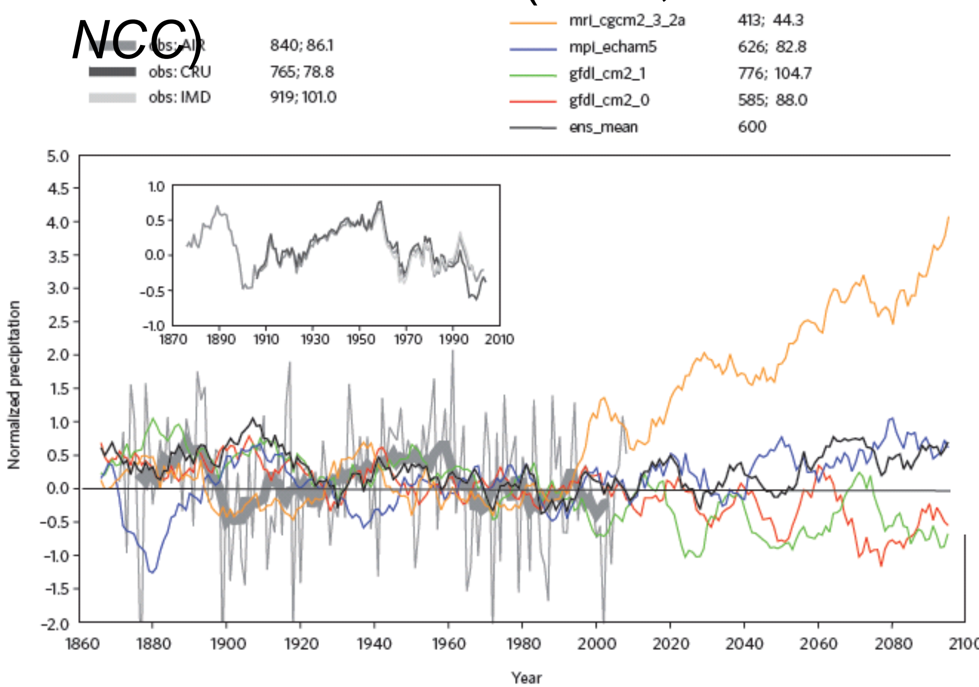
JJAS precipitation time series in 20c3m and SRES-A1B scenario

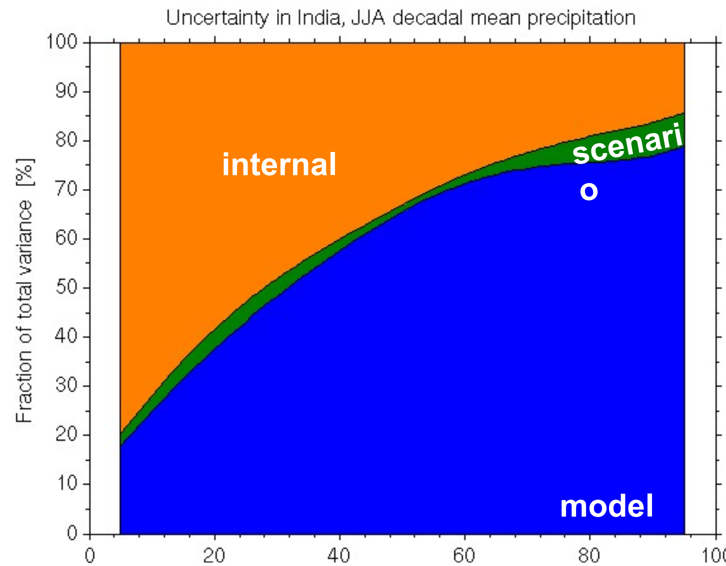


Turner & Annamalai (2012)
Nature Climate Change

ASIAN MONSOON: CLIMATE CHANGE

Turner & Annamalai (2012, *NCC*)





Hawkins & Sutton (2011, *Clim. Dyn.*): India JJA-mean precip projections (10-yr mean)

- Even among limited selection of well-performing models, 21st century precipitation projections have huge spread
- In some cases, decadal variability swamps climate trends
- Need to better constrain future based on current climates

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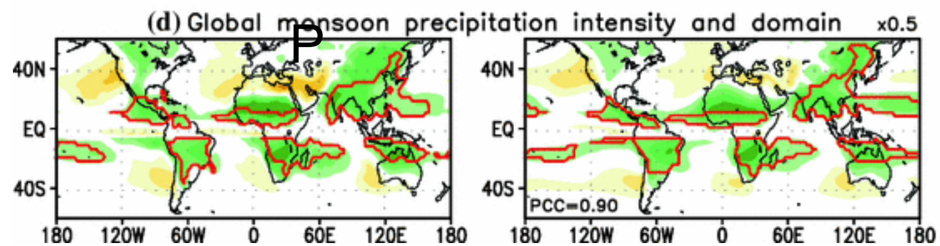
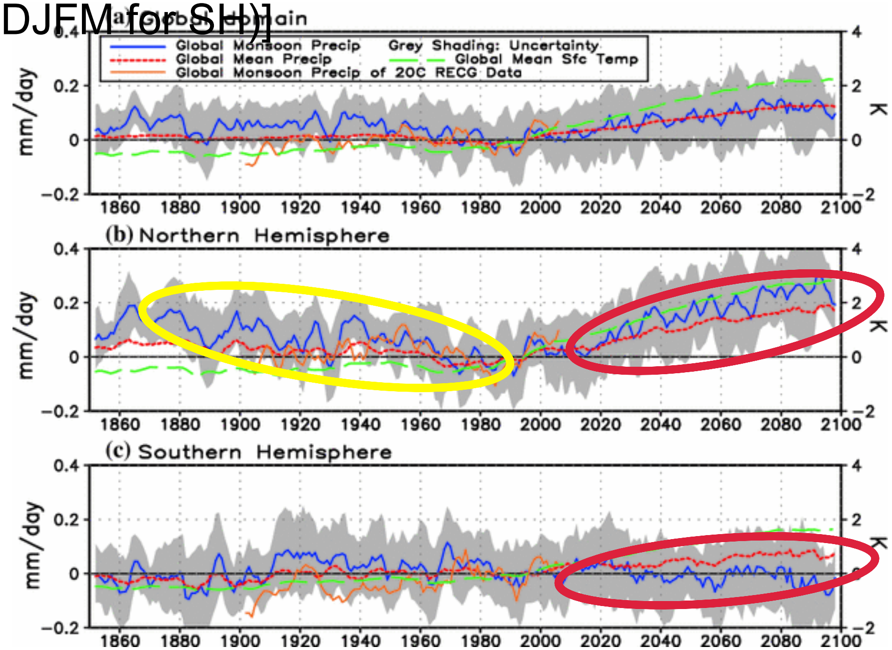
GLOBAL MONSOON PROJECTIONS

- "Global monsoon" domain precip tracks global-mean precip
- Hemispheric breakdown reveals more complex picture
- Note also negative trends in NH 20th century…

GPCP MMM



Global monsoon precipitation domain (outlined *red*): summer-minus-winter precipitation exceeds 2.5mm/day and summer precipitation exceeds 55% of annual total [summer=MJJAS (NDJFM for SH)]



Lee & Wang (2014, *Clim. Dyn.*): Transient response of the global monsoon precipitation (*blue*) versus global mean precipitation (*red*) for **a** global domain, **b** NH, and **c** SH obtained from the best four models' MME for the historical run period (1850–2005) and the RCP45 run period (2006–2100). 5-year moving averaging was applied

INTERIM SUMMARY

- CMIP5 (and CMIP3) multi-model projections of South Asian monsoon suggest small increases in rainfall in the future (5-10%)
- Considerable model diversity on size of change
- Pattern of change in a "poor-man's" mini-ensemble of good models gives similar result
- Some better way of constraining future projections would be valuable

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OBSERVED TRENDS

TRENDS IN RECENT OBS

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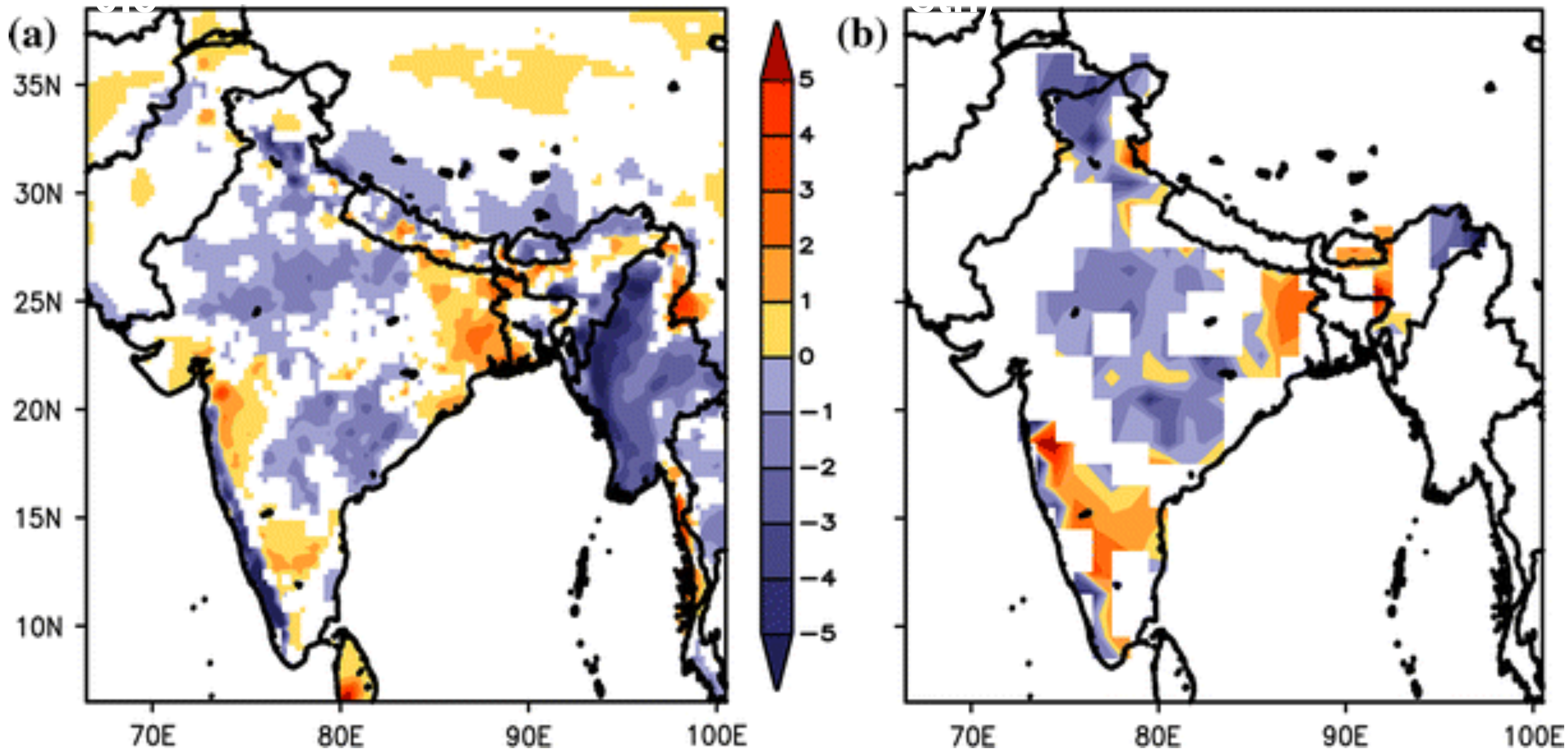
- Trends 1951-2007 (mm/d per 57yr)
- Dynamical reasoning: can we interpret decline on Western Ghats due to decreasing wind?

APRHODITE Monsoon Asia

IMD 1°-gridded (from 2140



Krishnan *et al*. (2013, *Climate Dynamics)*

TRENDS & HISTORICAL SIMULATIONS

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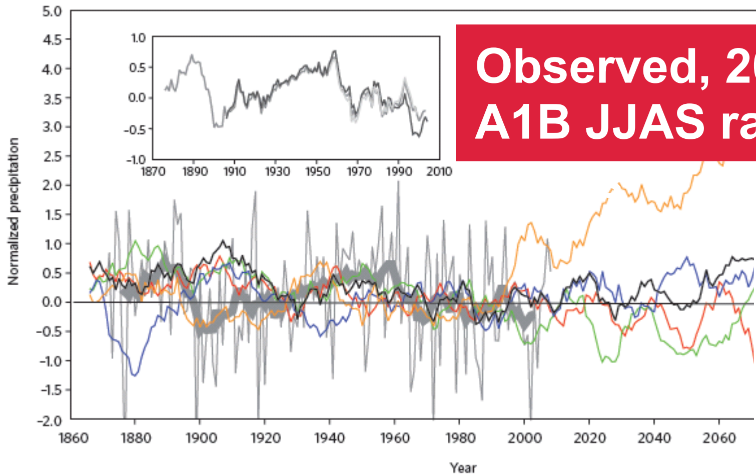
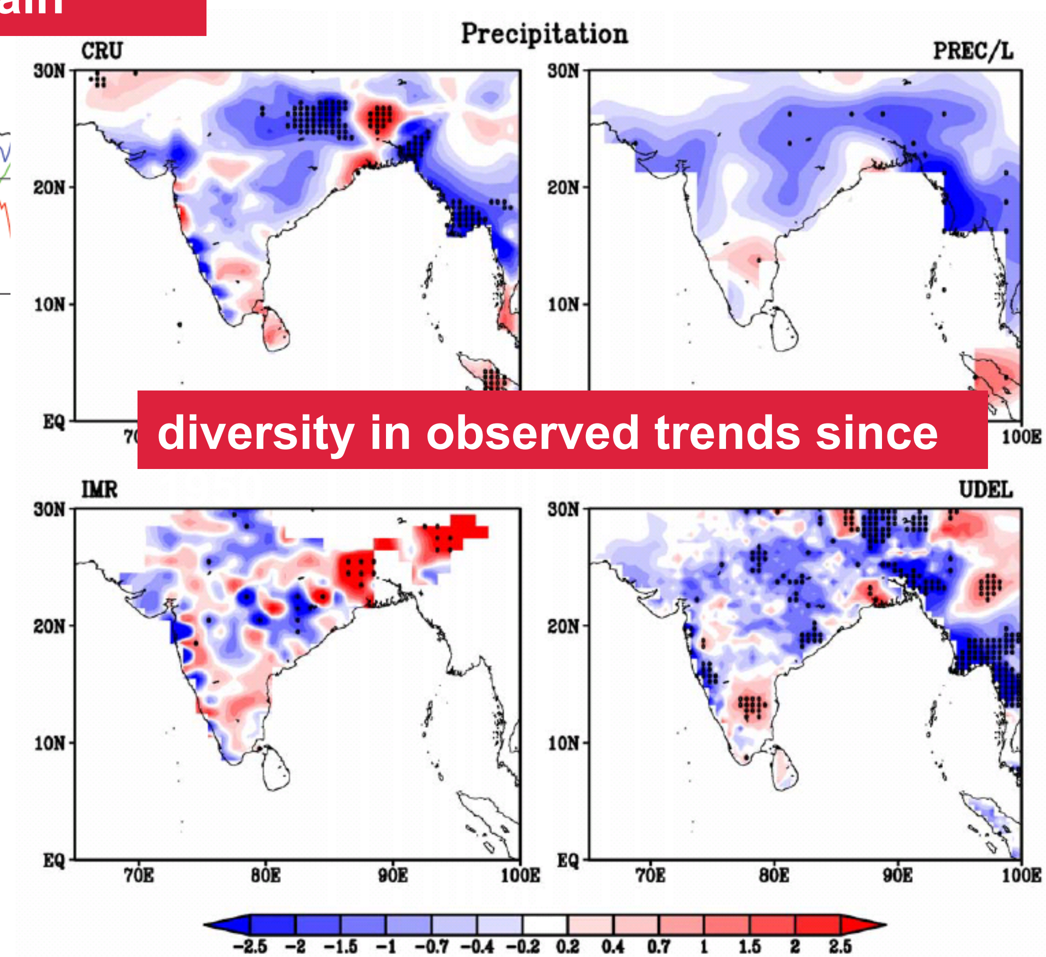


Observed, 20c3m & A1B JJAS rain

Bollasina *et al*. (2011, *Science*); mm/d per 50yr



diversity in observed trends since

Turner & Annamalai (2012, *Nature Climate Change*)

- South Asian rainfall is decreasing since the 1950s
- Spatial uncertainty

OBSERVED TRENDS

- Negative trends in rainfall in variety of datasets over parts of India since 1950s, chiefly west coast and NE peninsula
- See also earlier discussions on Indian Ocean warming
- What about anthropogenic aerosol as a cause?

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20TH CENTURY IMPACTS OF ANTHROPOGENIC AEROSOL

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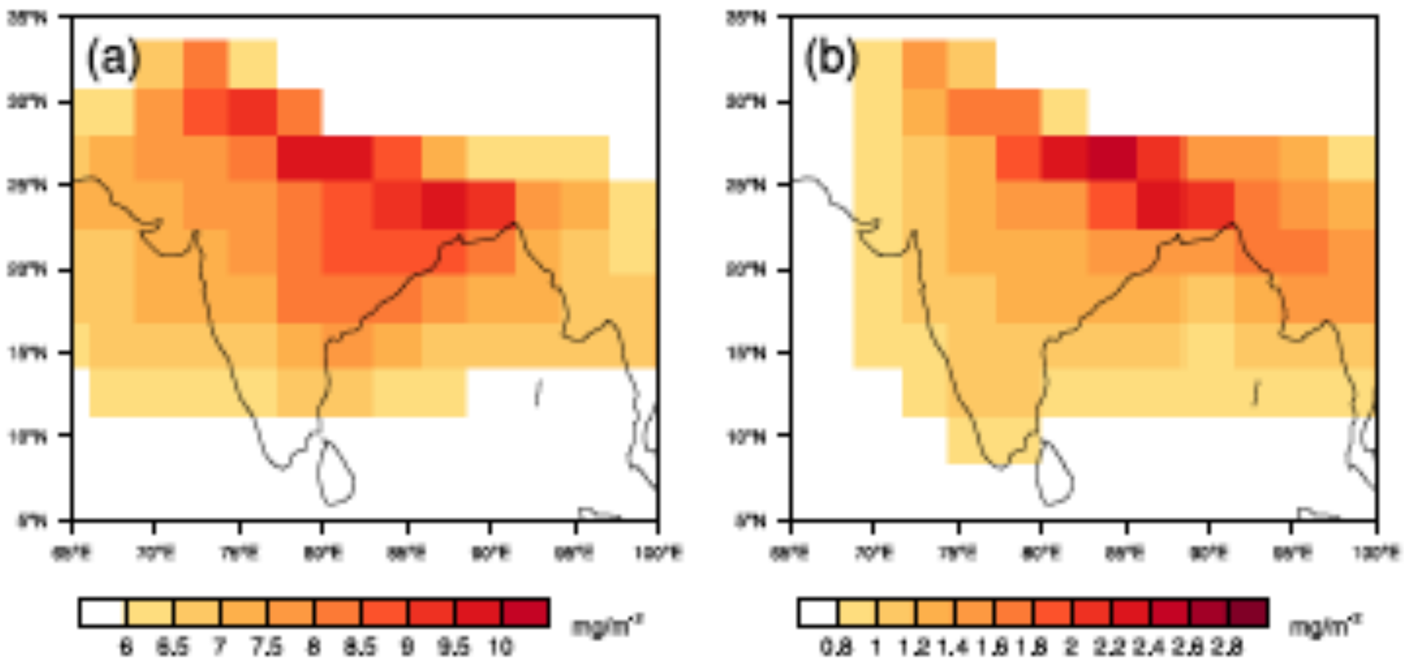
AEROSOL LOADINGS OVER INDIA

- Sulphate (L) and black carbon loadings (R) (mg/m3) over 1986-2005 in CMIP5
- Most aerosol over India is local to emissions source
- Strong loading up against Himalayas/Ganges basin
- Large increa

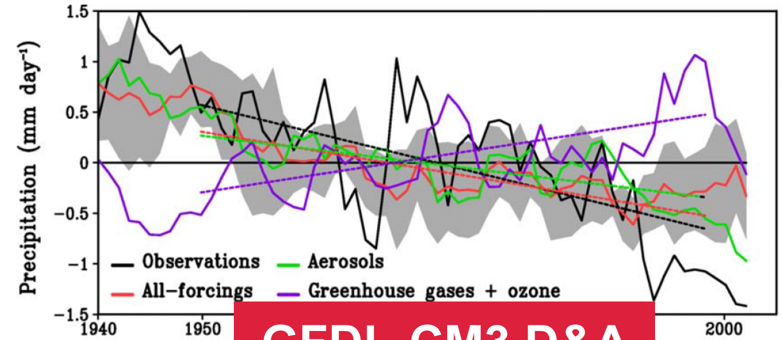


Guo, Turner, Highwood (2015, *ACPD*)

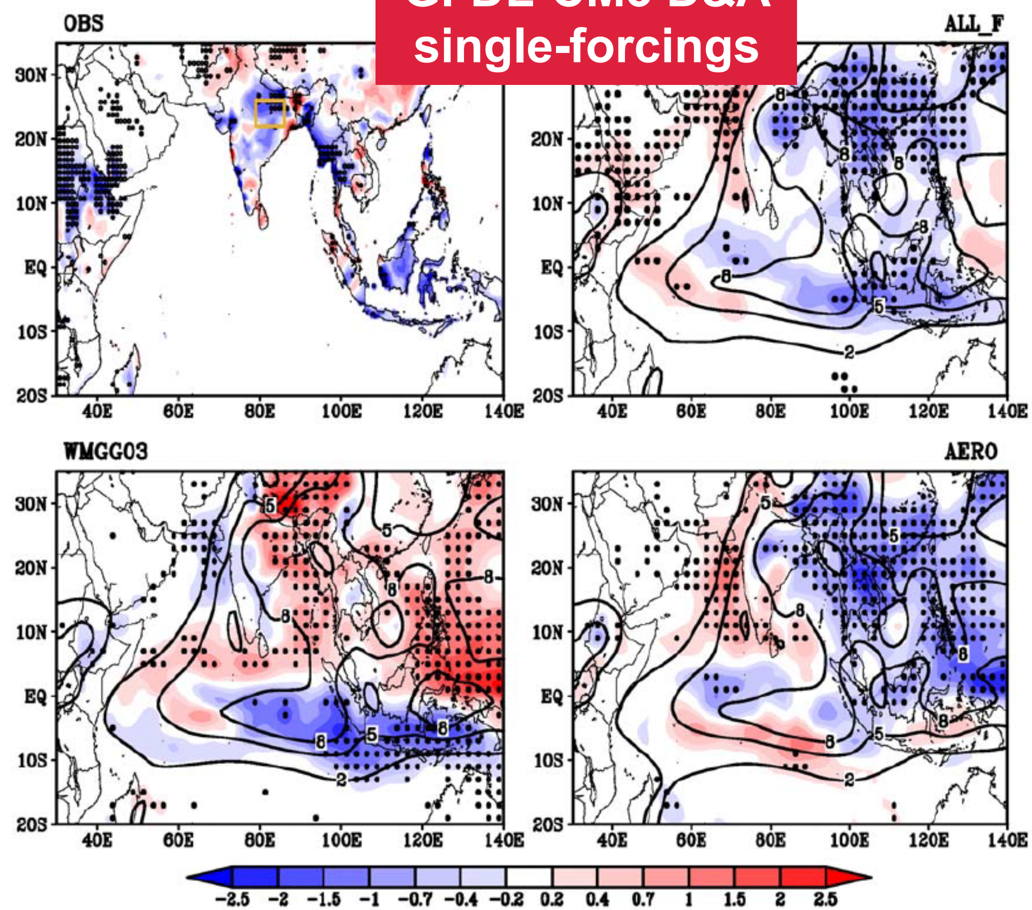
ATTRIBUTION TO RISING AEROSOL EMIS.

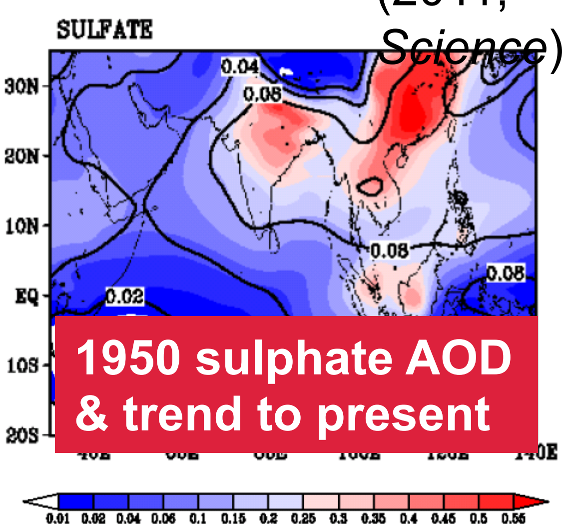
- Considerable work by Lau, Ramantaham, Ramaswamy & others on role of aerosol in monsoon
- Bollasina's GFDL study attributes Indian rainfall trend to increasing aerosol emissions over region

Bollasina *et al*. (2011, *Science*)



GFDL-CM3 D&A single-forcings





1950 sulphate AOD & trend to present

THE HEMISPHERIC VIEWPOINT

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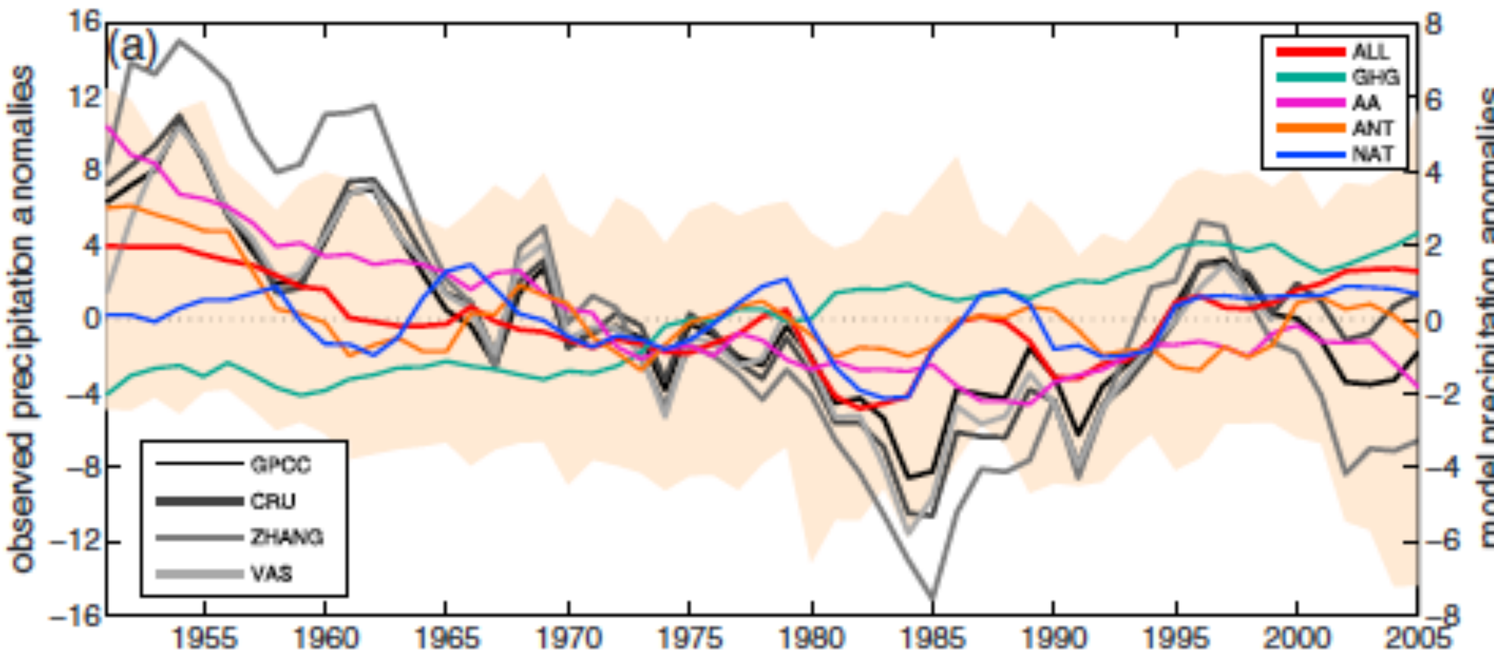
- Opposing signals can be seen at the hemisphere-wide scale due to GHG (upwards) and anthropogenic aerosol (downwards, generally)
- Com
  (obs

1950-to-present NH monsoon precip



Polson *et al*. (2014, *GRL*)

INDIA: GHGS VERSUS ANTHROPOGENIC AEROSOL

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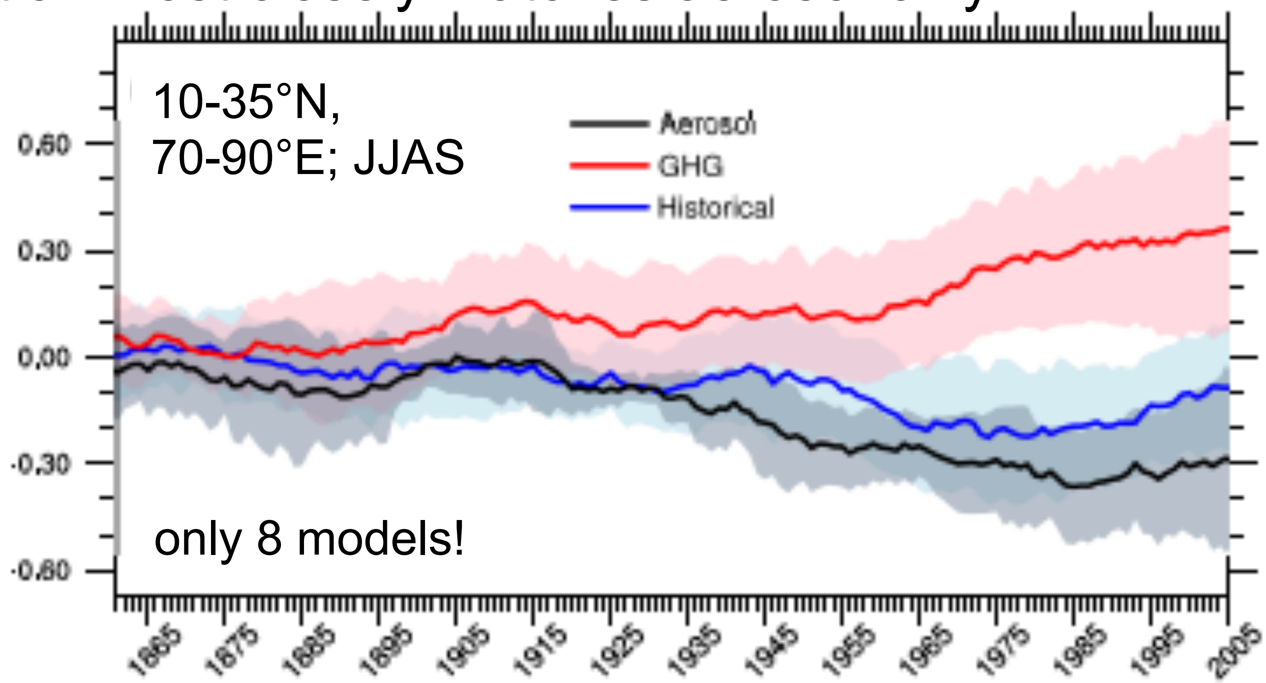
- Comparison of effects of GHG versus anthropogenic aerosol on South Asian monsoon rainfall in historical integrations
- GHG-only integration shows rising trend towards the present day, consistent with future projections using increased CO_2
- All-forcings integration most closely matches aerosol-only

Changing water cycle



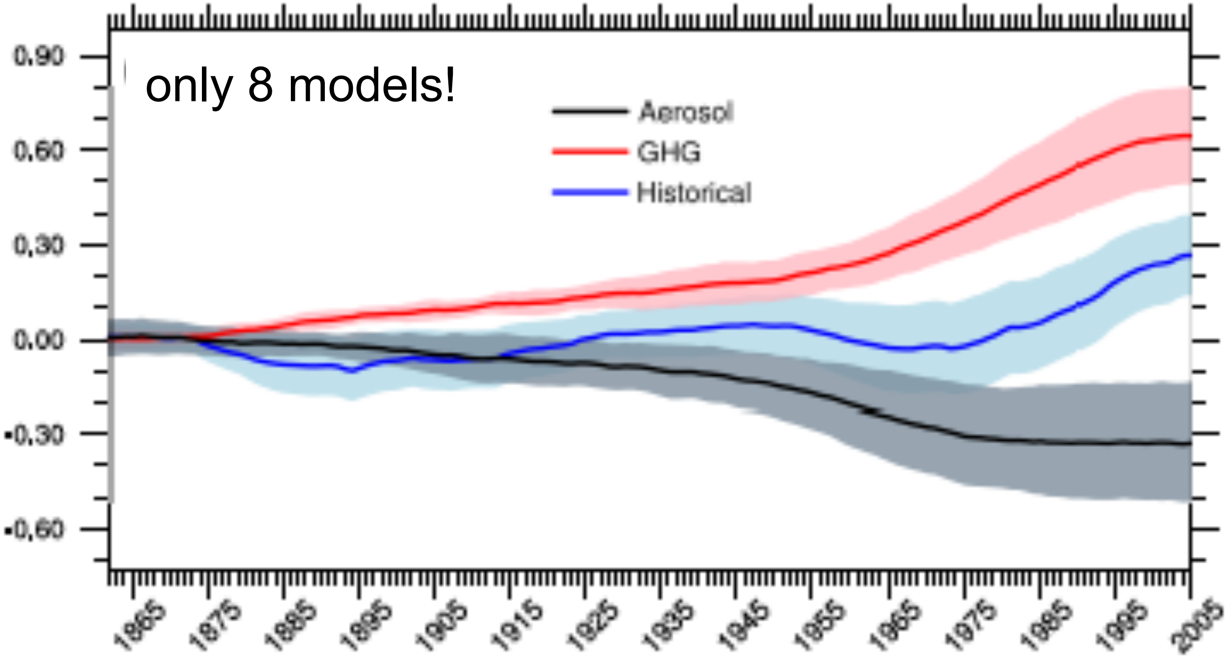
Guo, Turner, Highwood (2015, *ACPD*)

GHGS VERSUS ANTH. AEROSOL: GLOBAL LAND-SEA CONTRAST

- Comparison of effects of GHG versus anthropogenic aerosol on global "land-sea contrast" in historical integrations
- We might expect this to relate to the hemispheric distribution of aerosol
- Aerosol emissions particularly on NH land

Changing water cycle

Guo, Turner, Highwood (2015, *ACPD*)

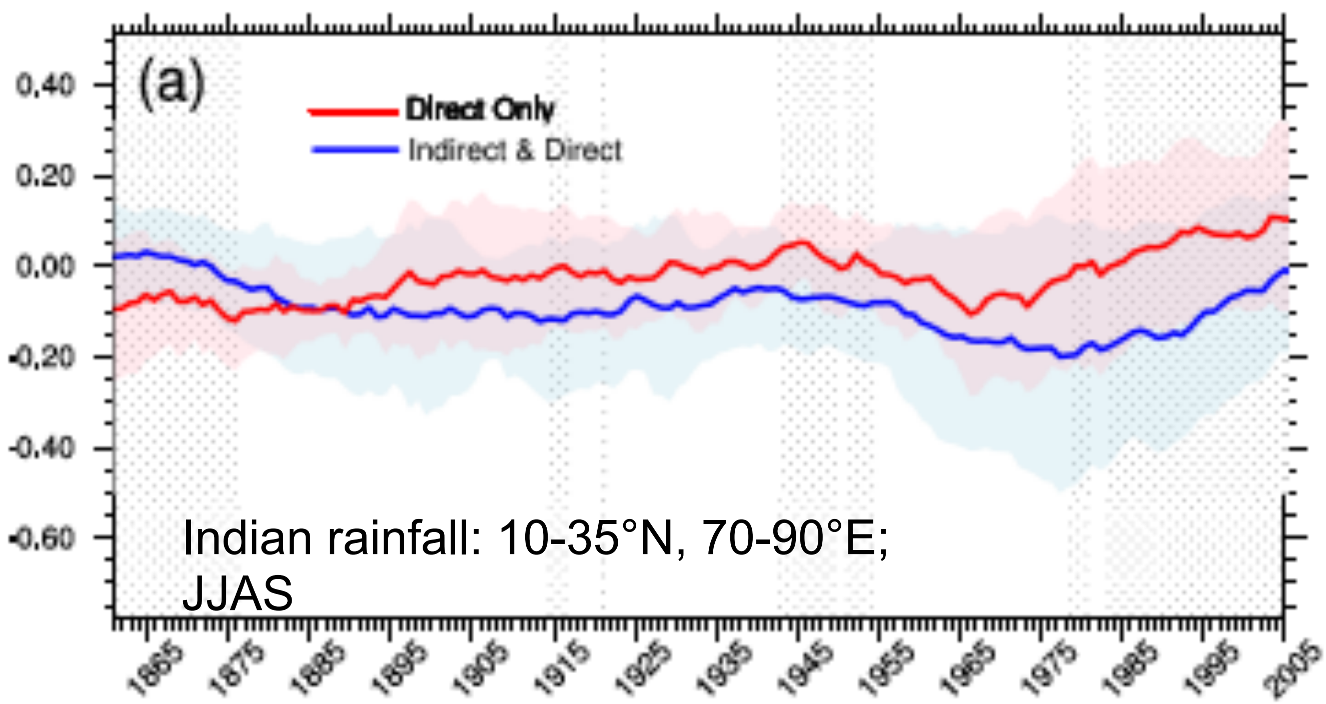


COMPARISON OF INDIRECT & DIRECT EFFECTS

- All-forcings historical experiments
- Models including the direct effect only show a clear increasing trend since the pre-industrial period
- Suggestion of clear impact of indirect effects on South Asian monsoon rainfall

Guo, Turner, Highwood (2015, *ACPD*)

Differences during stippled periods pass permutation significance test at 90% level



COMPARISON OF INDIRECT & DIRECT EFFECTS

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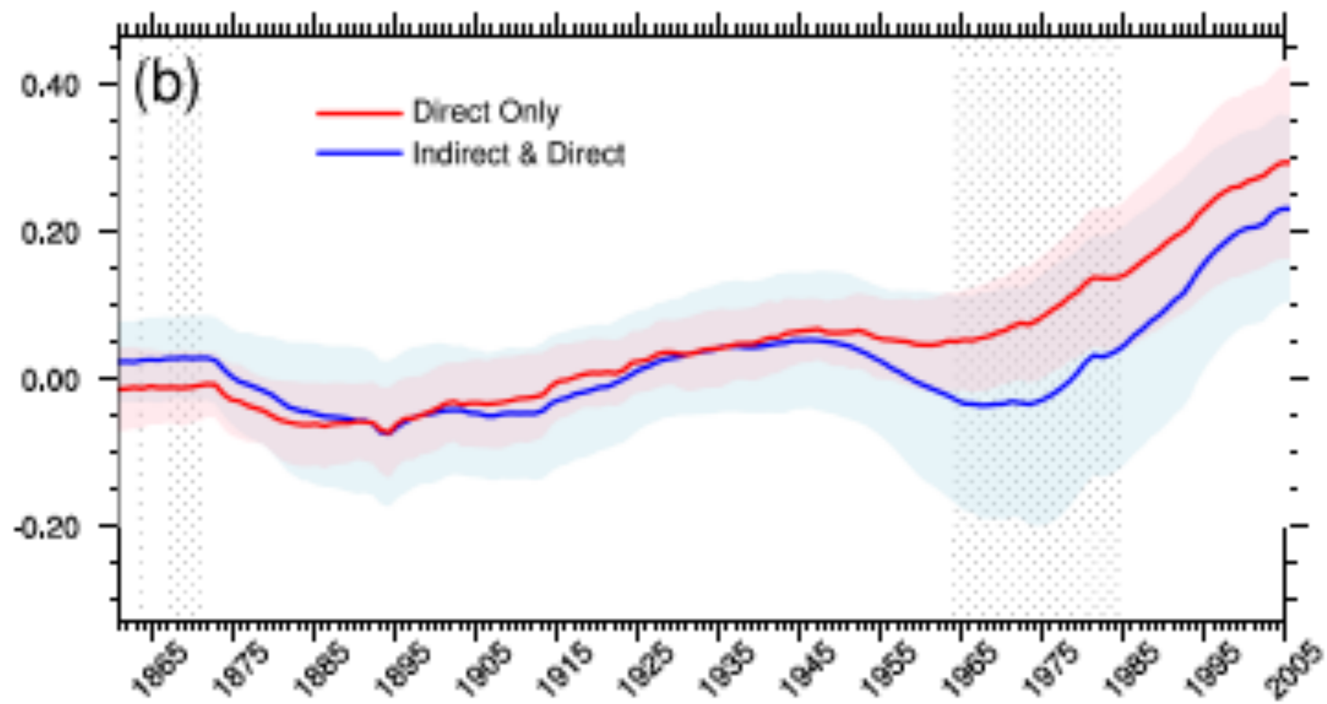
- Direct-only models feature a stronger “land-sea contrast” in the late 20th century
- Indirect models feature more negative radiative forcing in the northern hemisphere
- Weakens the NH monsoons (see Polson et al., 2014)

Guo, Turner, Highwood (2015, *ACPD*)

Differences during stippled periods pass permutation significance test at 90% level

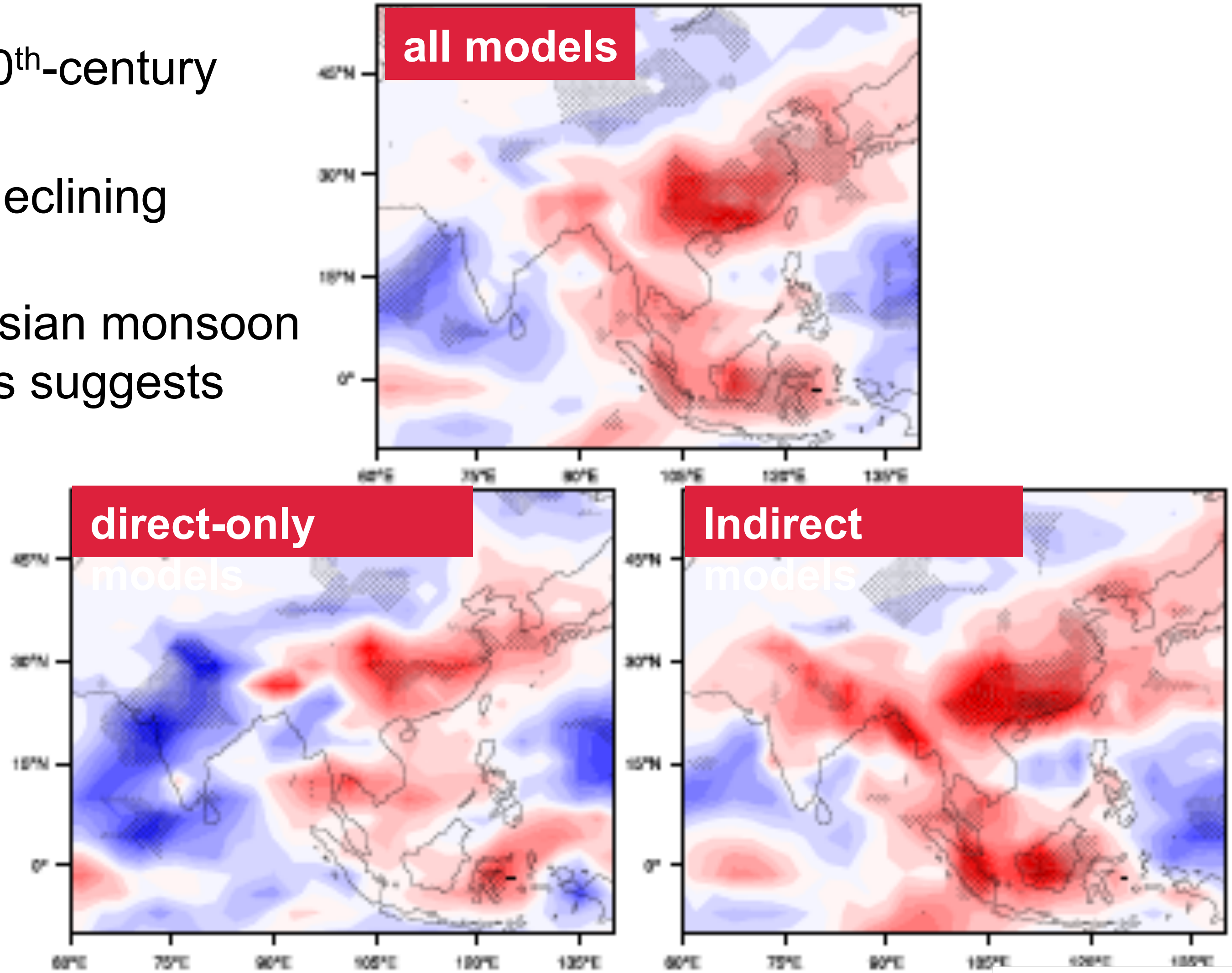


COMPARISON OF INDIRECT & DIRECT EFFECTS

Comparison of late-20th-century minus PI:

- Common signal of declining rainfall in E/SE Asia
- Increase of South Asian monsoon in direct-only models suggests GHG dominance

➢ Reinforces importance of indirect effects on South Asian monsoon



Guo, Turner, Highwood (2015,

MOISTURE FLUX CHANGE

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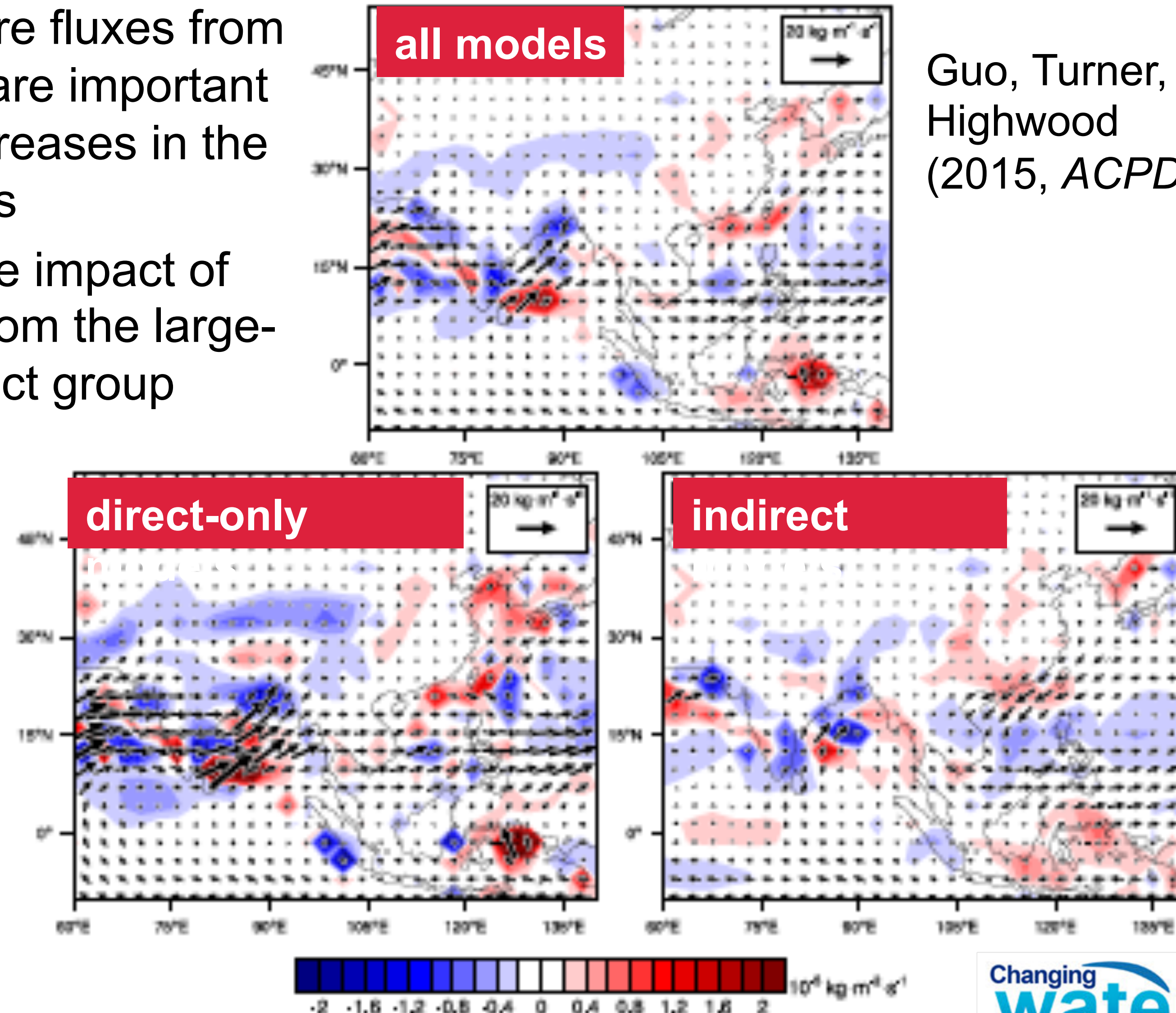
- Increased moisture fluxes from the Arabian Sea are important for the rainfall increases in the direct-only models
- Suggestion of little impact of moisture fluxes from the large-scale in the indirect group



Guo, Turner, Highwood (2015, *ACPD*)

Changing water cycle

20^{TH} CENTURY ANTH. AEROSOLS

- Declining northern hemisphere monsoon rainfall since 1950s consistent with anthropogenic aerosol forcing (and consistent with biased aerosol emissions to NH)
- Declining Indian rainfall since the 1950s also consistent with anthropogenic aerosol forcing (whereas rainfall increased in 20^{th}-century GHG-only scenarios)
- Models including indirect aerosol effects show greater impact (see also T. Zhou talk yesterday)

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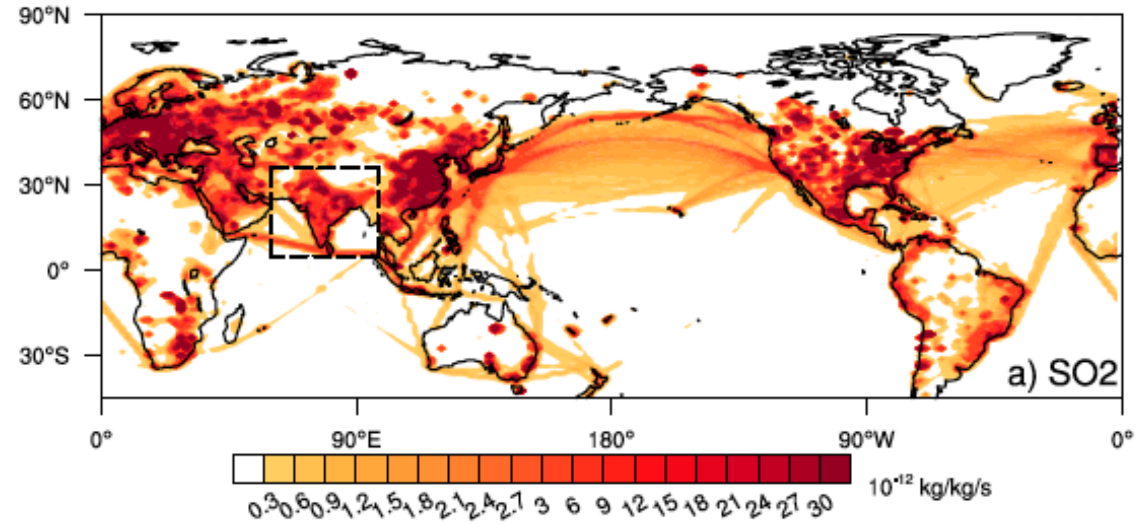
IDEALIZED IMPACTS OF ANTHROPOGENIC AEROSOL

TRENDS IN SO2 & BC EMISSIONS TO PRESENT DAY

- Strong emissions growth in northern hemisphere and over India, China
- India signal mainly in Ganges basin

Guo et al. (2016, *J. Clim.*)



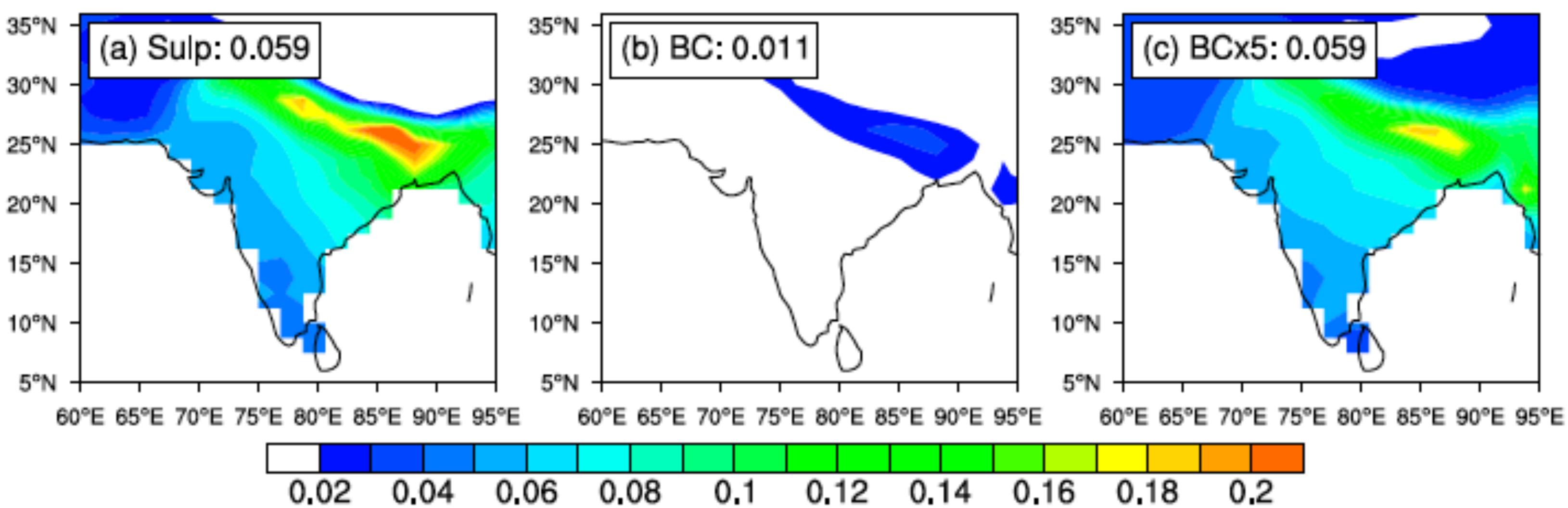
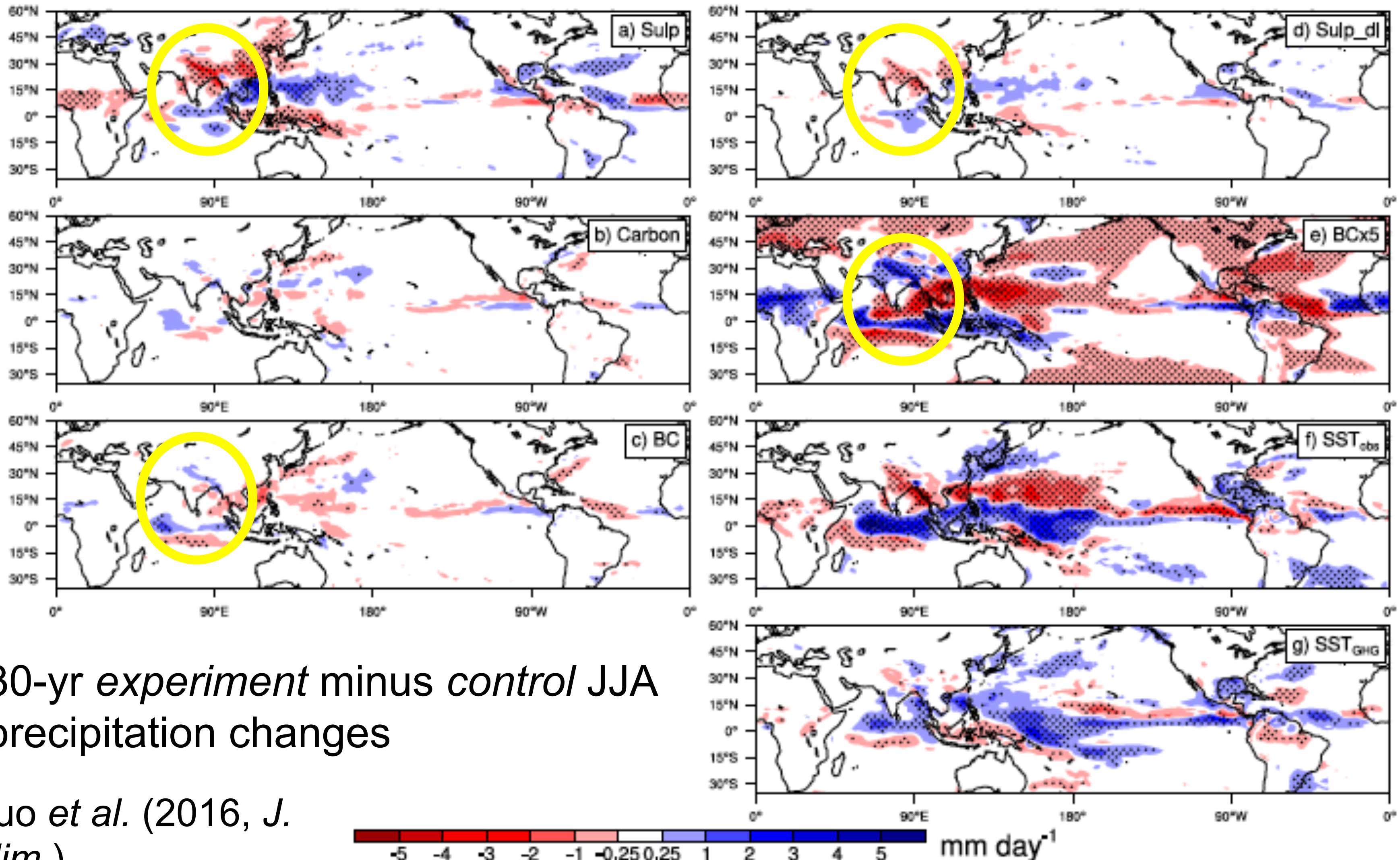


FIG. 1. Change of emissions (10^{-12} kg kg^{-1} s^{-1}) from the preindustrial (1860) to present-day (1976–2005) periods: (a) SO_2 and (b) BC. Data are from the RCPs database (Smith et al. 2001; Bond et al. 2007).

AEROSOL SENSITIVITY EXPERIMENTS

- Experiments performed with HadGEM2-A model (atmosphere only model, N96 resolution, L38)
- 30-year means taken
- Aerosol emissions imposed according to pre-industrial or present day (1970-2000) values
  - Globally
  - Regionally
- Results from Guo *et al.* (2016, *Journal of Climate*)

AEROSOL FORCING → MONSOON PRECIPITATION CHANGE



30-yr *experiment* minus *control* JJA precipitation changes

Guo *et al.* (2016, *J. Clim.*)

BLACK CARBON & EHP

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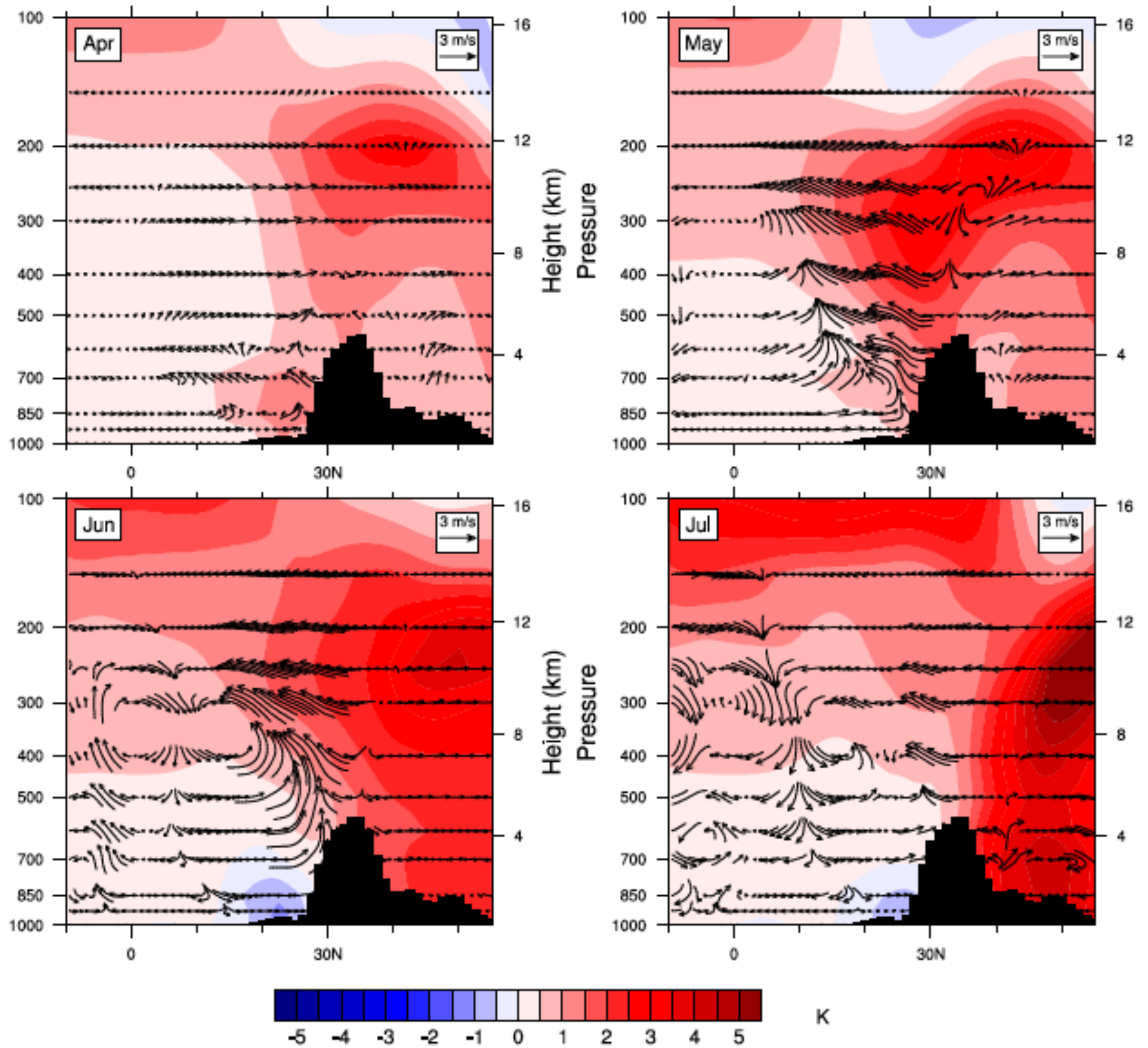
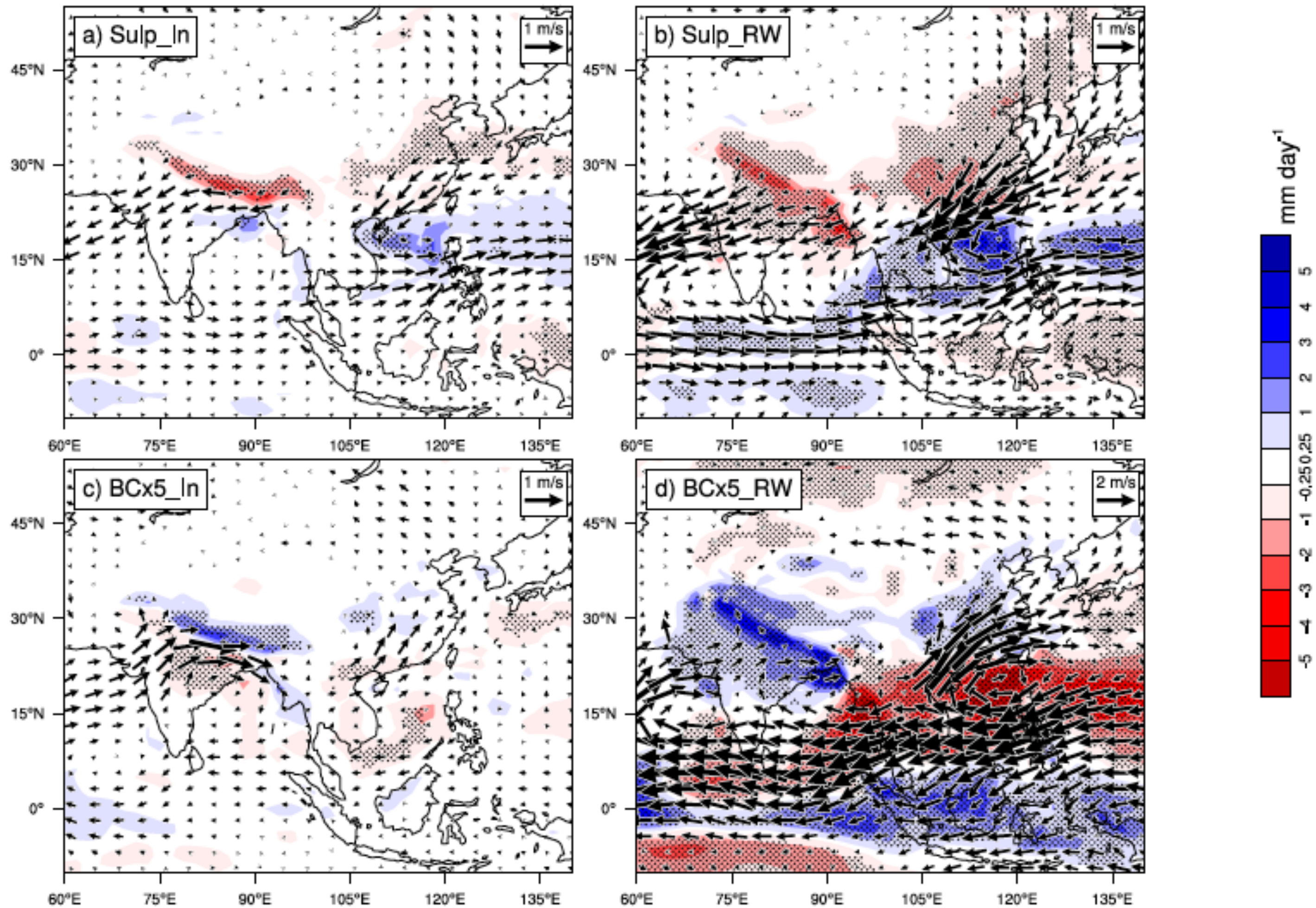
- 50-70°E meridional sections
- *BCx5* experiment minus *control*
- EHP leads to enhanced heating and ascent up against Himalayas during early monsoon period
- Only active in *BCx5* experiment



Guo *et al*. (2016, *J. Clim.*)

LOCAL & REMOTE AEROSOL



- Aerosol trends are imposed either over India-only or in RoW
- RoW forcing dominates (asymmetric hemispheric distribution)

Guo *et al*. (2016, *J.*

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AEROSOL SUMMARY

- Idealised experiments show that SO2 forcing yields negative impact on Indian monsoon rainfall (see also results of Bollasina etc.)
  - Contributions from local emissions
  - Contributions from rest-of-world emissions
- BC and the EHP mechanism appear to enhance monsoon during onset
  - But in this model non-realistic BC emissions need to be prescribed to achieve this

SUMMARY & OUTLOOK

- Future projections dominated by GHG forcing suggest increases in mean monsoon rainfall (albeit with large model uncertainty!)
- Observational trends are more complex: suggestion of weakening rainfall since the 1950s
- Weakening can be attributed to (scattering) aerosol emissions on the large and local scales
- Coupled model (SST) biases can also explain some uncertainties in future projections of monsoon rainfall
- What about:
  - Land-use change (including impacts of irrigation)?
  - Dominant warming of equatorial SST (e.g. Roxy et al.)?
  - Decadal modes
- Open question: can we use emergent constraints of 20th century tropical behaviour to narrow uncertainty in future projections of monsoon?

OTHER CLIMATE CHALLENGES

- In addition to monsoon rainfall, pre-monsoon heatwaves will become increasingly deadly
- Im et al. (2017) Deadly heat waves projected in the densely populated
- agricultural regions of South Asia, *Science Advances*

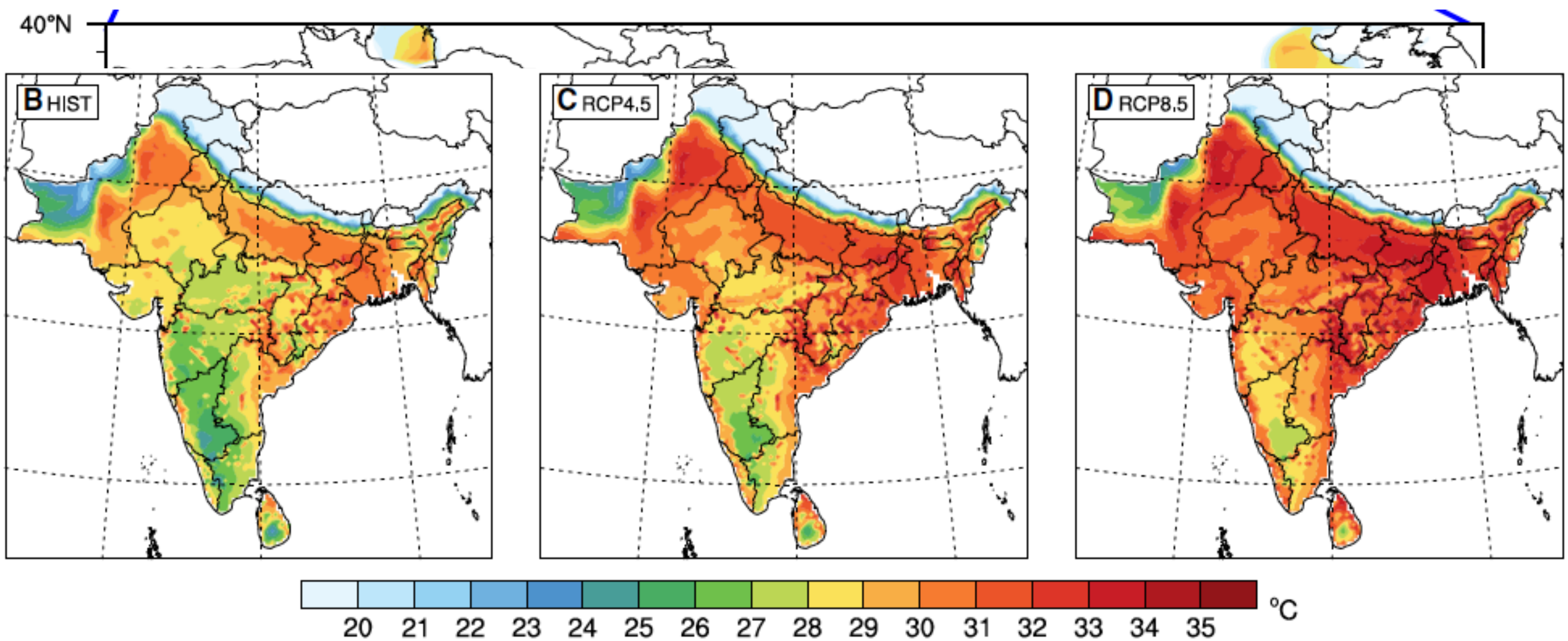

Fig. 2. Histograms of daily maximum wet-bulb temperature, TW_{max} (°C), and maps of the ensemble averaged 30-year TW_{max}. (**A**) The histograms are generated for the most populous cities in the selected regions for each scenario: HIST (blue), RCP4.5 (green), and RCP8.5 (red). Values within each panel correspond to the 2- and 25-year return period of the bias-corrected annual maxima of TW_{max}, and the *x* and *y* axes indicate TW_{max} (°C) and the number of occurrences on a logarithmic scale, respectively. The background image was obtained from NASA Visible Earth. (**B** to **D**) The spatial distributions of bias-corrected ensemble averaged 30-year TW_{max} for each GHG scenario: HIST (1976–2005) (B), RCP4.5 (2071–2100) (C), and RCP8.5 (2071–2100) (D).

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THANK YOU!

See:

- Turner & Annamalai (2012) *Nature Climate Change* **2**: 587-595 or http://dx.doi.org/doi:10.1038/nclimate1495
- Krishnan *et al*. (2013) Climate Dynamics
- Levine *et al*. (2013) Climate Dynamics
- Guo, Turner & Highwood (2015) *Atmos. Chem. Phys.*
- Guo, Turner & Highwood (2016) *J. Climate*

COHERENT DRIVERS OF THE GLOBAL MONSOON

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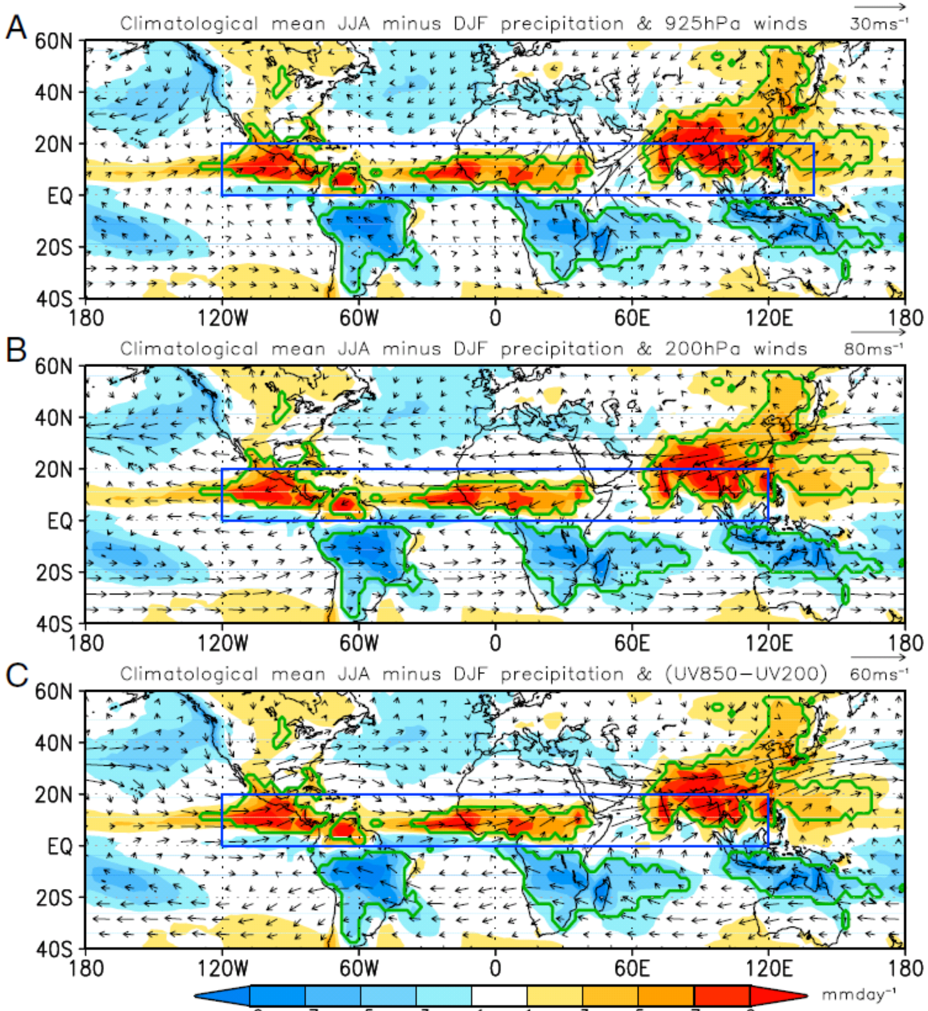
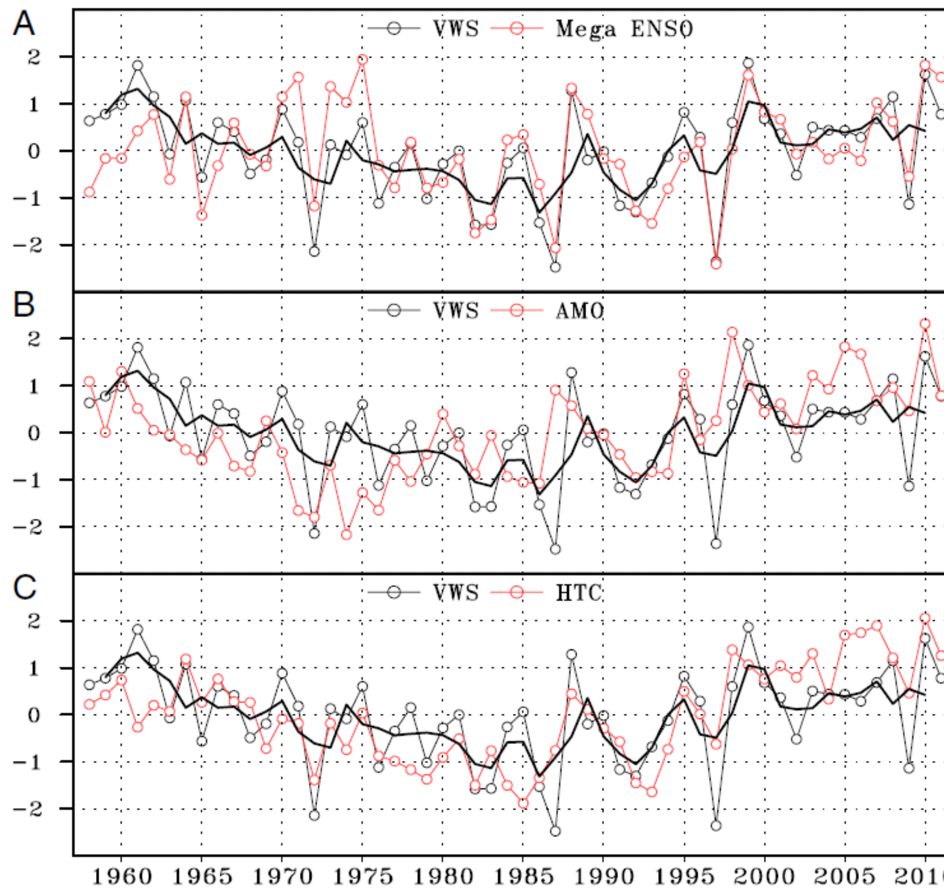
- Northern tropics wind shear as an index for NHSM
- Varies on decadal time scales with IPO/AMO/HTC





Wang *et al.* (2013) PNAS