CLIMATE PROJECTIONS OF THE SOUTH ASIAN MONSOON

ICTP Targeted Training Activity: Monsoons in a changing climate
31 July-4 August 2017
Seasonal monsoon precipitation

DJF

JJA

Asian Monsoon

Austral Monsoon

West African Monsoon
Meridional surface temperature contrasts

Nov/Dec

May/Jun

West African Monsoon  Asian Monsoon  Austral Monsoon
Tropospheric temperature gradient (200-500hPa)
Seasonal monsoon winds (850hPa)
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 since 1986–2005
IMPACTS OF GHG ON INDIAN MONSOON
SOME STUDIES OF FUTURE CHANGE

- Increased monsoon due to the land-sea temperature gradient (Hu et al., 2000); northward shift of the flow structure (Kitoh et al., 1997)

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

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*
Large uncertainty in mean JJA rainfall change over Asian monsoon?
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)
SEASONAL CYCLE AS PERFORMANCE INDICATOR

Seasonal cycle of precipitation over South Asia in CMIP3 models

- 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%

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

JJAS precipitation change for CMIP3/5 models: 1pctto2x-picntrl

- 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

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

Turner & Annamalai (2012)

Nature Climate Change
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.

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

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.

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)].
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
OBSERVED TRENDS

ITCP TTA: Monsoons in a changing climate, August 2017
TRENDS IN RECENT OBS

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

Krishnan et al. (2013, Climate Dynamics)
TRENDS & HISTORICAL SIMULATIONS

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

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?
20TH CENTURY IMPACTS OF ANTHROPOGENIC AEROSOL
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 increase

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)

1950 sulphate AOD & trend to present

GFDL-CM3 D&A single-forcings
THE HEMISPHERIC VIEWPOINT

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

- Corr (obs)

Polson et al. (2014, GRL)
INDIA: GHGS VERSUS ANTHROPOGENIC AEROSOL

- 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

Guo, Turner, Highwood (2015, ACPD)
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

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

Indian rainfall: 10-35°N, 70-90°E; JJAS
COMPARISON OF INDIRECT & DIRECT EFFECTS

- 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-20\textsuperscript{th}-century minus PI:

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

\begin{itemize}
\item Reinforces importance of indirect effects on South Asian monsoon
\end{itemize}

Guo, Turner, Highwood (2015, ACPD)
MOISTURE FLUX CHANGE

- 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)
20\textsuperscript{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\textsuperscript{th}-century GHG-only scenarios)
- Models including indirect aerosol effects show greater impact (see also T. Zhou talk yesterday)
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.)
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 $\rightarrow$ MONSOON PRECIPITATION CHANGE

30-yr experiment minus control JJA precipitation changes

Guo et al. (2016, J. Clim.)
BLACK CARBON & EHP

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

Guo et al. (2016, J.)
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?
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, $T_{W_{\text{max}}}$ ($^\circ\text{C}$), and maps of the ensemble averaged 30-year $T_{W_{\text{max}}}$. (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 $T_{W_{\text{max}}}$, and the x and y axes indicate $T_{W_{\text{max}}}$ ($^\circ\text{C}$) 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 $T_{W_{\text{max}}}$ for each GHG scenario: HIST (1976–2005) (B), RCP4.5 (2071–2100) (C), and RCP8.5 (2071–2100) (D).
THANK YOU!

See:

- Turner & Annamalai (2012) *Nature Climate Change* **2**: 587-595 or [http://dx.doi.org/doi:10.1038/nclimate1495](http://dx.doi.org/doi:10.1038/nclimate1495)
- Krishnan *et al.* (2013) *Climate Dynamics*
- Levine *et al.* (2013) *Climate Dynamics*
- Guo, Turner & Highwood (2016) *J. Climate*
COHERENT DRIVERS OF THE GLOBAL MONSOON

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

Wang et al. (2013) PNAS