EVALUATING BIASES & VARIABILITY IN CLOUDS, PRECIPITATION AND EARTH'S ENERGY BALANCE

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INTRODUCTION

• Greenhouse gas emissions have driven a warming of around 1°C since pre-industrial times; the hydrological cycle is beginning to intensify but global precipitation has barely begun to increase
• Satellite data is vital in assessing recent climate change globally, monitoring ongoing change but also evaluating and helping to improve model processes crucial for future projections (your work is vital!)
• There are simple physical processes determining global and regional responses that can be evaluated with observations
• Different diagnostics are important for the detection of climate change, physical understanding of processes and predicted impacts from regional changes in the water cycle but all are linked
RECENT GLOBAL CLIMATE VARIABILITY

NEAR SURFACE HUMIDITY TRENDS

- HadISD specific and relative humidity trends (Dunn et al. 2017 ESD)
- Declining RH over land since ~2000.
- Not captured by CMIP5 simulations but is when models forced with SST
- Explained by land/sea warming contrast: O’Gorman & Byrne (2018) PNAS
MOISTURE TRANSPORT AND INTENSIFICATION OF WET/DRY SEASONS

- Increased moisture with warming implies amplified P-E (e.g. Held & Soden 2006) & more moisture transport: dry→wet regimes

- Multi-annual P-E > 0 over land implies increased P-E (e.g. Greve et al. 2014)

- Changes in T/RH gradients also important (Byrne & O’Gorman 2015)

- P-E < 0 in dry season over land: more intense dry and wet seasons? (Chou et al. 2013; Liu & Allan 2013; Kumar et al. 2014)

- Aridity metrics more relevant (Scheff & Frierson 2015; Greve & Seneviratne 2015; Roderick et al. 2014; Milly & Dunne 2016)

- Changes in circulation dominate locally (e.g. Scheff & Frierson 2012; Chadwick et al. 2013; Muller & O’Gorman 2011; Allan 2014)
GLOBAL PRECIPITATION DETERMINED BY ENERGY BUDGET

- Atmospheric latent heating from precipitation (LP) balanced by radiative cooling (Q) (…minus sensible heating, SH)
- A warmer atmosphere radiates energy away more effectively, increasing precipitation (kΔT
- Atmospheric heating by greenhouse gases & absorbing aerosol reduce precipitation (fFΔF
- These effects compensate explaining why global precipitation has only just started to increase (e.g. Allan et al. (2014) Surv. Geophys) and SH is temporarily a significant term (Myhre et al. (2018) Nature Comms)


ΔP ~ ΔQ/L ~ (kΔT − fFΔF)/L

CMIP5 historical/RCP8.5
PRECIP & ENERGY BUDGET CHANGES

Update from Allan et al. (2014) Surv. Geophys.; Allan et al. (2014) GRL
CURRENT ENERGY BUDGET CHANGES

• Preliminary comparison with AMIP6 and ERA5
• Large uncertainty in pre-CERES EEI remains
• ERA5 does not capture observed ASR increase after warming slowdown (e.g. Loeb et al. 2018)
• AMIP vs reconstruction:
  • NET: $r = 0.46$
  • OLR: $r = 0.57$
  • ASR: $r = 0.70$
NEW GLOBAL SURFACE FLUX ESTIMATES

top of atmosphere surface

Surface energy flux dataset combines top of atmosphere satellite reconstruction with reanalysis energy transports: Liu et al. (2015) JGR

Liu et al. (2017) JGR Data: http://dx.doi.org/10.17864/1947.111

LIMITLESS POTENTIAL | LIMITLESS OPPORTUNITIES | LIMITLESS IMPACT
HEMISPHERIC ASYMMETRY IN EARTH’S ENERGY BUDGET

- Mean position of the tropical rainy belt in northern hemisphere determined by northward energy transport by ocean e.g. Frierson et al. (2013) Nature Geosci

![Diagram showing hemispheric energy budget]

Important to quantify hemispheric energy budget:

**EARTH’S ENERGY BUDGET & REGIONAL CHANGES IN THE WATER CYCLE**


- Sulphate aerosol also affects Asian monsoon e.g. [Bollasina et al. 2011 Science](https://www.sciencemag.org/content/332/6029/210) & may link to drought in Horn of Africa [Park et al. (2011) Clim Dyn](https://link.springer.com/article/10.1007/s00382-011-1141-z) though internal variability dominates [Chung et al. (2019) NatureClim](https://www.nature.com/articles/s41467-019-08325-8)
CROSS-EQUATORIAL HEAT TRANSPORT & PRECIPITATION BIAS LINKED

Many climate models simulate incorrect sign of cross equatorial energy flow and northern minus southern hemispheric precipitation difference

Also: Haywood et al. (2016) GRL

• Many processes contribute to hemispheric asymmetry…

Estimated cross equatorial atmospheric heat transport in peta Watts ($AHT_{\text{EQ}}$) against an index of tropical precipitation asymmetry (TPA) between hemispheres in simulations and observations.
CLIMATE MODEL BIASES IN SOUTHERN OCEAN INFLUENCE ASYMMETRY

- Use surface flux product to trace causes of coupled SST biases to atmospheric model processes
- Biases in AMIP5 simulations of cloud linked to SST & zonal wind maximum latitude (ZWML) bias

Hyder et al. (2018) *Nature Comms*
CLOUD-AEROSOL EFFECTS

- Indirect aerosol effects on cloud may have dominated inter-hemispheric climate shifts including Sahel drought in 1980s Chung & Soden (2017) Nature Geosci.

- Volcanic aerosol effect on cloud droplet size observable and consistent with simulations
- Further indirect effects in cloud water not detectable
- More complex sub-sampling may show effects for mid-latitude cyclones and marine stratocumulus

Malavelle et al. (2017) Nature
McCoy et al. (2018) ACPD
Rosenfeld et al. (2019) Science
SAHEL RAINFALL SENSITIVE TO REGIONAL ITCZ VARIABILITY

- Reduced Sahel rainfall 1950-1980s due to aerosol cooling (e.g. Hwang et al. (2013) GRL) may now be dominated by increases due to greenhouse gas heating (Dong & Sutton 2015 NatureCC)

Maidment et al. 2015 GRL
STRENGTHENING SAHARA HEAT LOW DELAYS WET SEASON

- Seasonal timing of wet season linked to impacts across Africa.
- New method to define wet season in satellite products/models (Dunning et al. 2016 JGR)
- Intensification of Sahara Heat Low drives later wet seasons in projections: Dunning et al. 2018 J. Clim
BIASES IN SEASONAL RAINFALL SIMULATION HINDER PROJECTIONS

Atmosphere-only simulations capture seasonal cycle, **coupled simulations** don’t:
- Due to systematic biases in Gulf of Guinea sea surface temperature (SST) & deficient representation of SST/rainfall relationship (Wainwright et al. in prep)
- Are there links to Southern Ocean biases? (Hyder et al. in prep).
SYSTEMATIC BIASES IN CLOUD, RAINFALL & ENERGY BUDGET OVER WEST AFRICA

- Systematic biases in cloud/rainfall/radiation evident in CMIP5 simulations → Hill et al. 2016 JGR

- Cloud contributions to radiation budget
  Hill et al. 2018 J Clim:
CONCLUSIONS

• Water vapour increasing with warming climate as expected from thermodynamics
  • Abatement of near surface moistening over land since ~2000 remains
• Global precipitation barely increasing, expected from energy constraints
  • Direct atmospheric heating from radiative forcings offsetting much of increase due to atmospheric warming that enhanced radiative cooling rate
• Imbalance in Earth’s energy budget driving climate change
  • Heating currently dominated by southern hemisphere
  • Imbalance in heating between hemispheres affecting precipitation patterns
• Systematic model biases related to hemispheric imbalance:
  • Aerosol indirect effects on cloud
  • Biases in cloud and SST in Southern Ocean & Africa/Atlantic region
  • Warming of climate and strengthening Sahara heat low expected to drive increases in rainfall and its intensity and later wet season over north Africa