CHANGES IN EARTH’S ENERGY IMBALANCE & IMPLICATIONS FOR WATER CYCLE

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INTRODUCTION

- Earth's energy budget determines the trajectory and magnitude of climate change
- Powerful constraint and also diagnostic of the water cycle globally and regionally

  Flows of energy and moisture between land/ocean, northern/southern hemispheres and high/low latitudes fundamental for the climate that societies depend upon

- How is Earth’s energy imbalance currently changing and what are the implications for the global water cycle?
HOW WILL WATER CYCLE CHANGE?

- Increased Precipitation
- More Intense Rainfall
- More intense droughts
- Intensification of wet and dry seasons?
- Regional projections??

IPCC (2013)
EARTH’S ENERGY BUDGET AND PRECIPITATION RESPONSE

\[ \Delta P \approx k \Delta T - f_F \Delta F \]

Andrews et al. (2009) J Clim

Using simple model:
\[ L \Delta P = k \Delta T - f_F \Delta F \]

\[
\frac{d\Delta T_m}{dt} = \frac{1}{C_m} (\Delta F - Y \Delta T_m - D)
\]

\[ N = \Delta F - Y \Delta T \]

\[ D = c(\Delta T_m - \Delta T_D)/d \]


Zahra Mousavi (PhD project)
MOISTURE TRANSPORT AND INTENSIFICATION OF WET/DRY SEASON

- Increased moisture with warming implies amplified P-E (e.g. Held & Soden 2006)
- 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 wet/dry 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)
- Changes in circulation dominate locally (e.g. Scheff & Frierson 2012; Chadwick et al. 2013; Muller & O’Gorman 2011)
RECENT TRENDS IN RAINFALL ACROSS AFRICA

• Africa particularly susceptible to changes in water cycle
• West Africa – particularly complex mix of pollution/cloud/dynamics

DACCIWA project - Knippertz et al. 2015 BAMS

Maidment et al. (2015) GRL
EARTH’S ENERGY BUDGET & REGIONAL CHANGES IN THE WATER CYCLE

- Regional precipitation changes sensitive to asymmetries in Earth’s energy budget
- N. Hemisphere cooling: stronger heat transport into hemisphere
- Reduced Sahel rainfall from:
  - Anthropogenic aerosol cooling 1950-1980s: Hwang et al. (2013) GRL
  - Asymmetric volcanic forcing e.g. Haywood et al. (2013) Nature Climate

• Sulphate aerosol effects on Asian monsoon e.g. Bollasina et al. 2011 Science (left)
• Links to drought in Horn of Africa? Park et al. (2011) Clim Dyn
OBSERVED ASYMMETRY IN EARTH’S ENERGY BUDGET

- Observed inter-hemispheric imbalance in Earth’s energy budget
- Not explained by albedo: brighter NH surface but more clouds in SH (Stephens et al. 2015)
- Inter-hemispheric heat transports determine and are influenced by position of ITCZ (e.g. Frierson et al. 2013) – more in next talk!!

CROSS-EQUATORIAL HEAT TRANSPORT LINKED TO MODEL PRECIPITATION BIAS

- Clear link between bias in cross-equatorial heat transport by atmosphere and inter-hemispheric precipitation asymmetry

Estimated cross equatorial atmospheric heat transport in peta Watts (AHT$_{EQ}$) against an index of tropical precipitation asymmetry (TPA) between hemispheres in simulations and observations.

See talk in afternoon!
HOW IS EARTH’S ENERGY BALANCE CHANGING & WHAT ARE IMPLICATIONS?


20°N-20°S
AT WHAT RATE IS EARTH HEATING?

What are implications for climate sensitivity and the global water cycle?

RECONSTRUCTING GLOBAL RADIATIVE FLUXES SINCE 1985

Combine CERES/ARGO accuracy, ERBS WFOV stability and reanalysis circulation patterns to reconstruct radiative fluxes

ERBS/CERES variability

CERES monthly climatology

ERA Interim spatial anomalies
CHANGES IN IMBALANCE IN MODELS/OBS

Imbalance: 0.23 0.00 0.78 0.63 0.63 (Wm\(^{-2}\))

0.34±0.67 Wm\(^{-2}\)

0.62±0.43 Wm\(^{-2}\)

La Niña

El Niño

Allan et al. (2014) GRL
DISCREPANCY BETWEEN RADIATION BUDGET & OCEAN HEATING

- Large ocean heating anomaly in 2002
- Inconsistent with radiation budget observations and simulations
- Changing observing system influence?
- Slight drop in net flux 1999-2005?

Smith et al. (2015) GRL
INDIRECT ESTIMATES OF AIR-SEA ENERGY FLUXES FROM SATELLITE/REANALYSES

\[ F_{SFC} = F_{TOA} - \frac{\partial TE}{\partial t} - \nabla \cdot \frac{1}{g} \int_0^1 V (Lq + C_pT + \phi_s + k) \frac{\partial \rho}{\partial \eta} d\eta \]

Net surface downward energy flux (Wm\(^{-2}\))
Liu et al. (2015) JGR

CERES/Argo Net Flux

Surface Flux

Estimate horizontal energy flux
WHERE IS THE HEAT GOING?

CHANGES IN SURFACE ENERGY FLUX

- Surface energy flux dominated by atmospheric transports
- Contrasting model pattern of change
- Are reanalysis transports reliable?

Liu et al. (2015) JGR
CONCLUSIONS

• Heating of Earth continues at rate of ~0.6 Wm\(^{-2}\)
  • Manifest as positive imbalance in Southern Hemisphere
  • Variability from radiative forcings & ocean changes
• Radiative transfer & Thermodynamics explain increased global precipitation with warming ≈ 2%/K
  • Radiative forcings also directly affect water cycle responses
  • Greenhouse gas & absorbing aerosol forcing suppress global precipitation response to warming ("hydrological sensitivity")
• Inter-hemispheric heating, moisture budget & unforced variability dictate regional responses and determine climate model biases
  • Decadal changes in ITCZ and global atmospheric/ocean circulation
  • Has the “hiatus” affected water cycle?
  • How do changes in cloud/circulation fit in?
  • Where is energy going? NERC DEEP-C project...