Tropical regional rainfall impacts under anthropogenic climate change

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- Moist dynamical mechanisms for convection zone regional response to global scale radiative forcing
- Greenhouse gas (Neelin et al 2003, GRL; Chou & N 2004, J Clim)
- Aerosol case (Chou et al 2005, J Clim subm)

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DJF precip. anom.
Three GCM Greenhouse gas scenarios for 2070-2090 rel. to 1961-1990 clim (GHG forcing dominant)

Neelin et al 2003
QTTCM doubled CO₂ experiments Qflux mixed-layer ocean

Dec - Feb Precip change

Dec - Feb QTTCM Precip climatology

Neelin et al 2003; Chou & Neelin 2004
Anomalous moisture
convergence due to
moisture anom. $q'$

Anomalous moisture
advection

$M_q' \nabla \cdot \mathbf{v}$

QTSM doubled CO$_2$ experiments
Moisture budget contributions
QTMC doubled CO$_2$ experiments
Moisture budget contributions

\[ \bar{M}_q \nabla \cdot \mathbf{v}' \]

Anomalous moisture convergence due to anomalous divergence (GMS multiplier effect feedback)
The “upped-ante” mechanism

Neelin, Chou & Su, 2003 GRL
The $M'$ (anomalous Gross Moist Stability) mechanism

Center of convergence zone:
- incr. moisture $\Rightarrow$
- lower gross moist stability $\Rightarrow$
- incr. convergence

Chou & Neelin, 2004
Anomalous Gross Moist Stability ($M'$) mechanism

- **Moist Static Energy** transport by divergent flow $\approx M \nabla \cdot \nu$
- $M = M_s - M_q$

  increases with increasing moisture, tends to reduce $M$

  may partially compensate if cloud top rises

- $M \nabla \cdot \nu' + M' \nabla \cdot \nu = F'_\text{net} - (\nu \cdot \nabla q)' + \ldots$

  reduced

  increases to compensate

- $P' \approx \frac{\tilde{M}_q}{\tilde{M}} \nabla \cdot \tilde{\nu}(-M')$

- Mechanism increases convergence & precip. in strong convergence zones: “rich-get-richer”
Response to imposed T change in CAPE

- $T' = 1.5 \, ^\circ C$ added to temperature only inside convection scheme
- Mimics 2xCO$_2$ moisture and regional precip response
- DJF Precip (W/m$^2$), surface temp, moisture (K), tropospheric mean temp

Chou & Neelin, 2004, J Clim
QTCM 2xCO₂ Expt. suppressing change in moisture advection

(testing the upped-ante mechanism)

Experiment
2xCO₂ Precip. change
(mm/day)

Control
2xCO₂ Precip. change

Neelin, Chou & Su, 2003 GRL
**QTCM 2xCO₂ Expt. suppressing change in gross moist stability, M**  
(testing the M' mechanism)

**Experiment**  
2xCO₂ Precip. change (mm/day)

**Control**  
2xCO₂ Precip. change

Chou & Neelin, 2004, J Clim
ECHAM4 + ocean mixed layer 2xCO2 equilib.

Precip. anom. rel. to control

--- Clim. Precip.
(6 mm/day contour)

Moisture anom.
(1000-900 hPa)

Moisture anom.
(900-700 hPa)

Chou et al, in prep.
Precip. anom. rel. to control
--- Clim. Precip. (6 mm/day contour)

Moisture anom. (1000-900 hPa)

Moisture anom. (900-700 hPa)

Chou et al, in prep.
ECHAM4/OPYC3 2070-2099 IS92a (GHG only)

Precip. anom. rel. to control

--- Clim. Precip.
(6 mm/day contour)

Moisture anom.
(1000-900 hPa)

Moisture anom.
(900-700 hPa)
Aerosol case: remote and local response

- Shortwave radiative forcing anomaly from ECHAM4 runs with present day (PD) minus pre-industrial (PI) aerosol (Feichter et al 2004, J. Clim.)
  - specify in QTCM
  - simulation adequately reproduces tropical precip and temperature
  - analyse mechanisms
- Do remote effects operate by same mechanisms as GHG warming but with opposite sign?
- Estimate of indirect aerosol effects included per Lohmann et al (1999, 2000, JGR)

Aerosol Forcing anomalies Dec-Feb ECHAM4

Present Day – Pre-Industrial

Solar atmos. absorption
(W/m²)

Solar reflection at TOA
(W/m²)

Net sfc. solar absorption
(W/m²)
Prec. & Temp. anomalies Dec-Feb ECHAM4

Present Day – Pre-Industrial aerosol

Precipitation (shaded ±10 W/m²)

--- Clim. Precip. (150 W/m² contour)

Tropospheric Temperature (850-200hPa) shading below -0.8C
Prec. & Temp. anomalies Dec-Feb ECHAM4

Present Day – Pre-Industrial aerosol

Precipitation (shaded ±10 W/m²)

Tropospheric Temperature (850-200hPa) shading below -0.8°C
Aerosol forced anomalies Dec-Feb ECHAM4

Temperature (1000hPa) (W/m²)

Moisture (1000-700hPa) (W/m²)

Net sfc. flux (W/m²)
Prec. & Temp. anomalies Dec-Feb QTCM

Present Day – Pre-Industrial

Precipitation (shaded ±10 W/m$^2$)

--- Clim. Precip. (150 W/m$^2$ contour)

Tropospheric Temperature (850-200hPa) shading below -0.6C
Precipitation anomalies Dec-Feb QTCM

Present Day – Pre-Industrial

Precipitation (shaded ±10 W/m²)

Tropospheric Temperature (850-200hPa) shading below -0.6°C
No absorption case Dec-Feb QTCM

Aerosol TOA reflection anom. only
Precipitation (shaded ±10 W/m²)

Tropospheric Temp. anom.
(850-200hPa) shading below -0.6°C
Absorption only case Dec-Feb QTCM

Precipitation anomalies (shaded $\pm 10 \text{ W/m}^2$ contour $2 \text{ W/m}^2$)

Anoms an order of magnitude smaller
Aerosol Forcing by region Dec-Feb QTCM

Precipitation anom (W/m²) (Forcing within box)

Precipitation anom (W/m²) (Forcing outside box)

Temperature anom (850-200hPa) (Forcing outside box)
Aerosol Forcing by region Dec-Feb QTGM

Aerosol Forcing
20N-50N

Precip. anom.
(Shaded ±10 W/m²)

Tropospheric Temp. anom.
(850-200hPa)
Shading below -0.2°C
Other mechanisms

- Moist Static Energy transport by divergent flow $\approx \mathbf{M} \nabla \cdot \mathbf{v}$
- Gross Moist Stability $\mathbf{M} = \mathbf{M}_s - \mathbf{M}_q$, ($\mathbf{M}_q$ inc. with moisture)

Perturbation MSE budget + ocean mixed layer / land

$$\mathbf{M} \cdot \nabla \cdot \mathbf{v}' = -\mathbf{M}' \cdot \nabla \cdot \mathbf{v} - (\mathbf{v} \cdot \nabla \mathbf{q})' - c \partial_t T_s' + F_{\text{net}}' + (\mathbf{v} \cdot \nabla T)' \ldots$$

Yields precip anoms as $\mathbf{T}' \Rightarrow \mathbf{q}' \Rightarrow \nabla \mathbf{q}', \mathbf{M}'; \mathbf{v}', \mathbf{q}' \Rightarrow \mathbf{E}'$ etc.

$$P' \approx \frac{\mathbf{M}_q}{\mathbf{M}} \left[ -(\mathbf{v} \cdot \nabla \mathbf{q})' + \nabla \cdot \mathbf{v}(-\mathbf{M}') - c \partial_t T_s' + \ldots \right]$$

- Upped-ante Rich-get-richer
- Rad cooling, $(\mathbf{v} \cdot \nabla T)'$
- SST disequilibrium
- GMS multiplier effect
- SST disequilibrium
- Ocean transp, …
Summary: Tropical regional rainfall impacts...

• QTCM analysis & expts., coord. with ECHAM4 analysis
• $2\text{XCO}_2$, mixed-layer (ML) ocean case
  • $\Rightarrow$ upped-ante and $M'$ mechanisms [SST $'$ ~by-product in eqbm]
• transient GHG, coupled oc-atm case: similar + some regions where ocean transport $'$ $\Rightarrow$ sfc heat flux $'$ $\Rightarrow$ precip $'$
• Aerosol SW forcing case (ECHAM4 forcing into QTCM+ML)
  • nonlocal via cool $T'$ $\Rightarrow$ upped-ante and $M'$ mechanisms
  • Local SW aerosol effects, TOA reflection $\Rightarrow$ negative precip $'$
• upped-ante mechanism:
  ▪ precipitation anomaly regions at margins of convection zones
  ▪ negative in GHG warming; nonlocal positive in aerosol cooling
• anomalous gross moist stability ($M'$) mechanism:
  ▪ positive precip' in strong precip regions in GHG warming; nonlocal negative in aerosol cooling
ENSO teleconnections: widespread warming yields regional precip. anomalies by “zoo” of mechanisms

Main descent anomalies occur in subregions with various cooling mechanisms; $V' \cdot \nabla (q + T)$, $E'$ due to $V'$, ...

Atmospheric wave dynamics tends to spread warming, reducing pressure gradients, creating non-local $T'$, $V'$

Energy input from ocean to atmosphere

Su & Neelin, 2002