Tropical precipitation change under global warming

J. Meyerson*, C. Holloway*, U. Lohmann***, J. Feichter****

*Dept. of Atmospheric Sciences &
Inst. of Geophysics and Planetary Physics, U.C.L.A.,
**Inst. of Earth Sciences, Academia Sinica, Taiwan
***ETH, Institute of Atmospheric and Climate Science, Zurich;
****Max-Planck-Institut fuer Meteorologie, Hamburg

- **Background:** Global warming basics; rainfall issues
- **[Precipitation regional response to El Nino teleconnections (Su & Neelin 2002; Neelin, Chou & Su 2003, GRL; Neelin & Su 2005, J Clim.)]**
- **[Aerosol case (Chou, Neelin, Lohmann & Feichter 2005, J Clim.)]**
- **Tropical precip. change in multi-model ensemble assoc. with Inter-governmental Panel on Climate Change (IPCC) 4th Assessment Report (Neelin, Munnich, Su, Meyerson and Holloway 2006 PNAS)**
Increase greenhouse gases ⇒ Incr. atm. IR absorption ⇒ Warming ⇒ Climate feedbacks: H2O, ice, clouds...
Global warming as simulated in 10 climate models

- Global avg. sfc. air temp. change (ann. means rel. to 1901-1960 base period)

- Est. observed greenhouse gas + aerosol forcing, followed by SRES A2* scenario (inset) in 21st century

*SRES: Special Report on Emissions Scenarios
A2: uneven regional economic growth, high income toward non-fossil, population 15 billion in 2100; similar to an earlier “business-as-usual” scenario “IS92a”
Surface air temperature change (relative to 1961-90)

NCAR CCSM3

annual avg.

Response to the SRES A2 scenario

2010-2039

2040-2069

2070-2099

*Unexplained acronyms denote climate model names
Surface air temperature change for three models* 2040-2069 annual avg. (rel. to 1961-90)

*Unexplained acronyms denote climate model names
Precipitation: climatology

January

Note intense tropical moist convection zones (intertropical convergence zones)

July

Later: 4 mm/day contour as indicator of precip. climatology
Precipitation change under global warming


Three ocean-atmos. climate models (Greenhouse gas + aerosol forcing scenarios)

See also eg. Wetherald & Manabe 2002, JGR; …

Neelin et al 2003, GRL
Detour: Tropical remote precip. relation to El Nino

- Observed Precip rank correlation to equatorial Pacific sea surface temperature index

- Clim. precip. as 4 mm/day contour (green) for reference

(CMAP Precip; Reynolds OIv2 Nino3.4 SST; 1982-2003; CMAP=Climate prediction center Merged Analysis of Precipitation)

El Nino/Southern Oscillation (ENSO) precip. anoms

• Warm-cold composite for Xie-Arkin obs, ECMWF-AMIP2, NCEP-AMIP2, QTCM

Observed vs. 3 models forced by observed sea surface temperature (AMIP2=Atm. Model intercomparison project)

Other models, see Sperber and Palmer 1996, Giannini et al 2001; Saravanan & Chang, 2000

(El Niño avg 1982-83, 87-88, 92-93, 95-96 – La Niña avg 1984-85, 89-90, 96-97)
ENSO precip anoms: obs vs atm models

• Warm-cold composite for Xie-Arkin obs, NCEP-AMIP2, NCAR-AMIP2, QTCM
ENSO tropospheric temperature anomalies

- Warm-cold composite
- NCEP reanalysis vs. atm models driven by obs SST (AMIP2): NCEP-AMIP2, NCAR-AMIP2, QTCM

(El Niño avg 1982-83, 87-88, 92-93, 95-96 – La Niña avg 1984-85, 89-90, 96-97)
ENSO teleconnections to regional precip. anomalies

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

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

Su & Neelin, 2002
Precipitation change under global warming

Reprise...

Three ocean-atmos. climate models (Greenhouse gas + aerosol forcing scenarios)

Neelin et al 2003, GRL
Simpler case: doubled CO\textsubscript{2} experiments
QTCM+mixed-layer ocean

Dec - Feb
Precip change
2xCO\textsubscript{2} rel. to base

Dec - Feb
QTCM Precip climatology

Neelin et al 2003; Chou & Neelin 2004
The “upped-ante” mechanism

Neelin, Chou & Su, 2003 GRL
Temperature $T$ and Moisture $q$ equations

$$\begin{align*}
\text{dry static energy } s &= T + \phi \\
(\partial_t + v \cdot \nabla)T + \omega \partial_p s - \partial_p R + \partial_p S - \partial_p F_{SH} &= Q_c \\
\text{vertical velocity} \\
\text{Fluxes: longwave radiation}(R), \text{ solar}(S) \text{ sensible}(SH), \text{ latent heat}(L) \\
(\partial_t + v \cdot \nabla)q + \omega \partial_p q - \partial_p F_L &= Q_q \text{ moisture source/sink}
\end{align*}$$

Energy constraint in vertical integral $\langle \rangle$

$$\langle Q_c \rangle = -\langle Q_q \rangle$$

$$\langle \text{Moist static energy equation} \rangle$$

$$\langle (\partial_t + v \cdot \nabla)(T + q) \rangle + \langle \omega \partial_p h \rangle - F_{\text{net}} = 0$$

Transport of moist static energy by divergent flow

$\approx$ (measure of divergence)

$\times$ gross moist stability

$\text{Net energy flux into column}$

$\text{Moist static energy}$

$h = s + q$
MSE diagnostics for mechanisms

- Moist Static Energy transport by divergent flow $\approx MV \cdot \nabla$
- Gross Moist Stability $M = M_s - M_q$, ($M_q$ inc. with moisture)

MSE budget for perturbations $T' +$ ocean mixed layer / land

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

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

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

- Upped-ante Rich-get-richer
- GMS multiplier effect
- Rad cooling, $(\mathbf{v} \cdot \nabla T)'$
- SST disequilibrium
QTGM doubled CO₂ experiments
Moisture budget contributions

\[ M_q' \nabla \cdot \vec{v} \]
Anomalous moisture convergence due to moisture anom. \( q' \)

\[ (\vec{v} \cdot \nabla q)' \]
Anomalous moisture advection
The "upped-ante" mechanism

Neelin, Chou & Su, 2003 GRL
The Rich-get-richer mechanism
Formerly M' (anomalous Gross Moist Stability) mechanism

Center of convergence zone:
increased moisture \Rightarrow lower gross moist stability \Rightarrow increased convergence, precip

Descent region:
increased descent \Rightarrow less precip.

Chou & Neelin, 2004
QTGM $2xCO_2$ Expt. suppressing change in moisture advection

Testing the upped-ante mechanism

Suppression experiment

$2xCO_2$ Precip. change (mm/day)

Control

$2xCO_2$ Precip. change

Neelin, Chou & Su, 2003 GRL
Suppression experiment

2xCO₂ Precip. change (mm/day)

Control

2xCO₂ Precip. change

Testing the rich-get-richer ($M'$) mechanism

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)

Precip. anom. rel. to control

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

Moisture anom.
(1000-900 hPa)

Moisture anom.
(900-700 hPa)

Chou, Neelin, Tu & Chen (2006, J. Clim., in pr.)
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)
ECHAM4 DJF
Contributions to the moisture/MSE budget

Assoc. with upped ante

Assoc. with M’ mechanism

Assoc. with GMS multiplier

Chou, Neelin, Tu and Chen 2006, *J. Clim.*, in press
Aerosol case: remote and local response

0. Bump into Ulrike Lohmann in Toronto…
2. Specify in QTCM
3. Simulation adequately reproduces tropical precip and temperature change
4. Analyse mechanisms
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
Prec. & Temp. anomalies Dec-Feb QTCM

Present Day – Pre-Industrial

Precipitation
(shaded ±10 W/m²)

Clim. Precip.
(150 W/m² contour)

Tropospheric Temperature
(850-200hPa)

shading below -0.6°C
Aerosol case: remote and local response


0. Bump into Ulrike Lohmann in Toronto…
1. Shortwave radiative forcing anomaly from ECHAM4…
2. Specify in QTCM
3. Simulation adequately reproduces tropical precip and temperature change
4. Analyse mechanisms

- Remote effects on precipitation operate by same mechanisms as GHG warming but with opposite sign:
  - cooler tropospheric temperature
  - Upped-ante wet convective margins; weakened precip in centers of convection zones
- In transient scenario runs with both aerosol and greenhouse gas, the warming effects eventually dominate
Fourth Assessment report models

- Data archive at Lawrence Livermore National Labs, Program on Model Diagnostics and Intercomparison
- SRES A2 scenario (heterogeneous world, growing population, ...) for greenhouse gases, aerosol forcing

Neelin, Munnich, Su, Meyerson and Holloway, 2006, *PNAS*

CNRM_CM3

DJF Prec. Anom.

4AR cnrm SRES A2 DJF Pa(2070–99) (61–90)
UKMO_HadCM3

DJF Prec. Anom.
MIROC_3.2

DJF Prec. Anom.

4AR miroc3.2 SRESA2 DJF Pa(2070–99) (61–90)
NCAR_PCM1

DJF Prec. Anom.

4AR pcm1 SRESA2 DJF Pa(2070–99) (61–90)
MPI_ECHAM5

DJF Prec. Anom.

4AR echem5 SRESA2 DJF Pp(2070–99) (61–90)
NCAR_CCSM3
JJA Prec. Anom.

ccsm3 SRESA2 JJA Pa(2070–99) (61–90)
CCCMA

JJA Prec. Anom.

cccma SRESA2 JJA Pa(2070–99) (61–90)
CNRM_CM3

JJA Prec. Anom.

cnrm SRESA2 JJA Pa(2070–99) (61–90)
CSIRO_MK3

JJA Prec. Anom.

csiro SRESA2 JJA Pa(2070–99) (61–90)
GFDL_CM2.0

JJA Prec. Anom.

gfdl_2.0 SRESA2 JJA Pa(2070–99) (61–90)
GFDL_CM2.1

JJA Prec. Anom.

gfdl_2.1 SRESA2 JJA Pa(2070−99) (61−90)
UKMO_HadCM3

JJA Prec. Anom.

HadCM3 SRESA2 JJA Pa(2070–99) (61–90)
MRI_CGCM2

JJA Prec. Anom.

cgcm2 SRESA2 JJA Pa(2070–99) (61–90)
NCAR_PCM1

JJA Prec. Anom.

pcm1 SRESA2 JJA Pa(2070–99) (61–90)
MPI_ECHAM5

JJA Prec. Anom.
Tropical surface warming (10 models+obs)

• Tropical avg. (23S-23N) surface air temperature (Annual avg)

• SRES A2 scenario forcings

• Note large interannual variability (El Nino, etc.)
Tropical surface warming (10 models)

- Tropical avg. (23S-23N) surface air temperature
  For June-Aug. (30 yr avgs.)

- SRES A2 scenario forcings
Observed (CMAP) and 5 coupled models 4 mm/day precip. contour
Coupled simulation climatology (20th century run, 1979-2000)

December-February precipitation climatology

June - August precipitation climatology
Climatological precip: Observed vs. 10 coupled models (4 mm/day contour)

June - August precipitation climatology

Coupled simulation clim.  
(20th century run, 1979-2000); 5 models per panel; observed from CMAP
Global warming (SRES-A2) dry regions: negative precip change (2070-2099 minus 1951-1980) overlaid for 6 models (0.5, 2 mm/day contours)
Hypothesis for analysis method:

- models have similar processes for precip increases and decreases but the geographic location is sensitive

Check agreement on amplitude measure:

Spatial projection of precip change for each model on that model’s own characteristic pattern of change
Hypothesis for analysis method:

- models have similar processes for precip increases and decreases but the geographic location is sensitive to differences in model clim. of wind, precip; to variations in the moistening process (shallow convection, moisture closure, …)

- Check agreement on amplitude measure:
  - Spatial projection of precip change for each model on that model’s own characteristic pattern of change
Hypothesis for analysis method:

• models have similar processes for precip increases and decreases but the geographic location is sensitive

• Check agreement on amplitude measure:
  • Spatial projection of precip change for each model on that model’s own characteristic pattern of change
Projection of JJA (30yr running mean) precip pattern onto normalized positive & negative late-century pattern for each model

Precipitation Anomaly Projection

Neelin, Munnich, Su, Meyerson and Holloway, 2006, PNAS
Regional precip. anomaly relation to temperature

Dry region precip. anomaly projection (on late-21\textsuperscript{st} century pattern) $\Delta$\textsubscript{Precip\textsubscript{dry}} versus tropical average surface air temperature

Neelin, Munnich, Su, Meyerson and Holloway, 2006, *PNAS*
Model agreement on amplitudes of tropical changes
(June-Aug. 2070-2099 minus 1901-60)

Surface air temperature $\Delta T_{as}$

$\Delta$Precip$_{dry}$ (dry region projection)

Sensitivity (ratio to $T_{as}$):
$\Delta$Precip$_{dry}/\Delta T_{as}$

$\Delta$Precip$_{wet}/\Delta T_{as}$

Vert avg. troposph. temp. $\Delta T_{trop}/\Delta T_{as}$

Moisture difference (inside/outside $P=4$mm/day) $/\Delta T_{as}$

Neelin, Munnich, Su, Meyerson and Holloway, 2006, PNAS

(each variable scaled to multi-model mean)
Precipitation change: measures at the local level

Trend of the 10-model ensemble median

> 99% significance (1979-2099)

Neelin, Munnich, Su, Meyerson and Holloway, 2006, *PNAS*
Inter-model precipitation agreement

Number of models (out of 10) with > 99% significant* dry/wet trend (1979-2099) and exceeding 20% of the median clim./century

[Spearman-rho test]  Neelin, Munnich, Su, Meyerson and Holloway, 2006, PNAS
Observed precipitation trend in region of high intermodel agreement

CMAP satellite data set 1979-2003

Land station data:
CPC (2.5 degrees, 1950-2002)
VASCLIMO (1 deg, 1951-2000)
Shaded over 95% significance

Neelin, Munnich, Su, Meyerson and Holloway, 2006, PNAS
50-year trend: obs. drying vs. model control runs

Histogram of occurrences of 50-yr. trends (multi-model)

Caribbean/ C. American region avg. precip.

Cumulative dist. for 50-yr trends

Estimate of natural variability of 50 year trends in model control runs without anthropogenic forcing
Model median June-August precipitation trend as percent of median climatology per century
Inter-model Dry/Wet trend agreement

Number of models (out of 10) with > 99% significant trend (1979-2099), exceeding 20% of the median clim./century
Model names

cccma_cgcm3.1, Canadian Community Climate Model

cnrm_cm3, Meteo-France, Centre National de Recherches Meteorologiques, CM3 Model

csiro_mk3.0, CSIRO Atmospheric Research, Australia, Mk3.0 Model

gfdl_cm2.0, NOAA Geophysical Fluid Dynamics Laboratory, CM2.0 Model

gfdl_cm2.1, NOAA Geophysical Fluid Dynamics Laboratory, CM2.1 Model

giss_model_er, NASA Goddard Institute for Space Studies, ModelE20/Russell

miroc3.2_medres, CCSR/NIES/FRCGC, MIROC Model V3.2, medium resolution

mpi_echam5, Max Planck Institute for Meteorology, Germany, ECHAM5 / MPI OM

mri_cgcm2.3.2a, Meteorological Research Institute, Japan, CGCM2.3.2a

ncar_eccsm3.0, NCAR Community Climate System Model, CCSM 3.0

ncar_pcm1, Parallel Climate Model (Version 1)

ukmo_hadcm3, Hadley Centre for Climate Prediction, Met Office, UK, HadCM3 Model
Summary: mechanisms

• tropospheric warming increases moisture gradient between convective and non-convective regions

• the "upped-ante mechanism":
  ▪ negative precipitation anomaly regions along margins of convection zones with wind inflow from dry zones

• the “rich-get-richer mechanism" (a.k.a. M’ mechanism):
  ▪ Positive/negative precipitation changes in regions of with high/low climatological precipitation

• [+ocean heat transport anomaly in equatorial Pacific]
Summary: multi-model tropical precipitation change

- agreement on amplitude of wet/dry precip anom, despite differing spatial patterns
  - growth with warming for projected precip. patterns; consistency of spatial pattern with time in each model
  - ⇒ take qualitative aspects of these changes seriously

- agreement on Caribbean/Central America summer drying trend
- observed trend in this region; but caution on attribution (poor observational constraints on interdecadal variatiability)