Mechanisms limiting the poleward extent of summer monsoon convective zones

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• Seasonal movement of deep convection zones over continents
• Dynamical mechanisms mediating land-ocean contrast?
• Given the large insolation extending poleward over continents, why do deep convection zones not extend farther poleward?
• Do mechanisms affecting convection zones differ from continent to continent?
• Intermediate atmospheric model coupled to a mixed-layer ocean and simple land model
• Focus on dynamical aspects, less on surface type
• No-topography case emphasizes ocean-land contrast
Dynamics of summer monsoon convective zones

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Wind-based definitions of monsoons

Khromov (1957); from Ramage (1971)
Latitude-height cross section at 90E from Bay of Bengal across Tibetan Plateau (shaded regions are rising motion)

From Yanai et al. (1992)
Seasonal precipitation minus Annual Average

JJA ave. – Annual ave.

DJF ave. – Annual ave.

mm/day
Seasonal percentage of annual precipitation

JJA % of annual precipitation

Masked < 5 mm/day

DJF % of annual precipitation
**Quasi-equilibrium Tropical circulation model:**

- Primitive equations projected onto vertical basis functions from convective quasi-equilibrium analytical solutions
- for Betts-Miller (1986) convective scheme, accurate vertical structure in deep convective regions for low vertical resolution
- baroclinic instability crudely resolved
- less than 5min/yr on a Sun 2 at 5.6x3.75 degree resolution
- GCM-like parameters but easier to analyze

**Radiation/cloud parameterization:**

- Longwave and shortwave schemes simplified from GCM schemes (Harshvardhan et al. 1987, Fu and Liou 1993)
- deep convective cloud, CsCc fraction param. on precip

**Simple land model:**

- 1 soil moisture layer; evapotranspiration with stomatal/root resistance dep. on surface type (e.g., forest, desert, grassland)
- low heat capacity; Darnell et al 1992 albedo
* Primitive equations projected onto vertical basis functions from quasi-equilibrium based analytical solutions
* for Betts-Miller (1986) convective scheme, accurate vertical structure in deep convective regions for low vertical resolution

Neelin & Zeng; Zeng et al 2000
QTCM1 Precipitation climatology 1982-1997
clradi1 cloud-radiation package

Zeng, Neelin and Chou 2000  QTCM1 V2.0  clradi1
QTCM1 Precipitation (daily)

January 13

Zeng, Neelin and Chou 2000  QTCM1 V2.0  clrad1
ENSO Composite (JJA)

Warm - Cold DJF: QTGM Precipitation (mm/day)
(87 92 95) - (82 89 96)

Warm - Cold DJF: Xie - Arkin Precipitation (mm/day)
(87 92 95) - (82 89 96)

Zeng, Neelin and Chou 2000  QTGM1 V2.0  clrad1
**Observed climatology January**

**Precipitation**

Xie - Arkin

**Net flux into atmosphere**

COADS, ERBE and Darnell et al.

**Low-level wind**

Wind at 850mb: NCEP

**Upper-level wind**

Wind at 200mb: NCEP
Observed net flux into atmosphere and net surface flux

July Climatology: Observed net flux into atm. $F_{\text{net}}$

July Climatology: Observed net surface flux $F_s$
QTCM climatology July
(coupled to a mixed-layer ocean)

Precipitation

Net flux into atmosphere

Low-level wind

Upper-level wind

wind at 850mb

wind at 200mb

QTCM1V2.2
Observed climatology January

Precipitation

Net Flux into the atmosphere
Observed climatology  July

Precipitation

Net Flux into the atmosphere
Temperature $T$ and Moisture $q$ equations

dry static energy $s = T + \phi$

$$(\partial_t + \mathbf{v} \cdot \nabla)T + \omega \partial_p s - \partial_p R + \partial_p S - \partial_p F_{SH} = Q_c$$

convective heating

vertical velocity

Fluxes: longwave radiation($R$), solar($S$) sensible($SH$), latent heat($L$)

$$(\partial_t + \mathbf{v} \cdot \nabla)q + \omega \partial_p q - \partial_p F_L = Q_q$$

moisture source/sink

Energy constraint in vertical integral $\langle \rangle$

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

Moist static energy equation

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

Transport of moist static energy by divergent flow

$\approx$ (measure of divergence) $\times$ gross moist stability

Net energy flux into column

Moist static energy

$h = s + q$
Moist convection interacting with large-scale dynamics

• Convective Quasi-Equilibrium:
  Fast convective motions reduce Convective Available Potential Energy (CAPE)
  - Constrains temperature through deep column
  - Baroclinic pressure gradients

• Gross moist stability at large scales

$Q_c$ constrains temperature through deep column baroclinic pressure gradients

- REGION 1
  - warm sounding
  - $h_{sat}$
  - $h_{cloud}$
  - cloud scale instability
  - gross moist stability

- REGION 2
  - cooler sounding

$h$ moist static energy ($10^4$ J Kg$^{-1}$)
QTTCM coupled to mixed-layer ocean, Idealized continent case

- Perpetual equinox
- Zero ocean heat transport
- Saturated soil moisture
- Constant albedo (0.3 land/ocean)
- Only deep convective cloud and Cs/Cc interactive
Zero ocean heat transport - Idealized continent case

- Perpetual equinox
- Interactive soil moisture

- Divergence of ocean heat transport included as idealized Q flux
  \[ Q = Q_{\text{max}} \cos(3.5 \times \text{latitude}), \]
  \[ Q_{\text{max}} = 20 \ \text{W/m} \] (similar to observed zonal average)
Zero ocean heat transport - Seasonal cycle case
\[ Q_{\text{max}} = 20 \text{ W/m}^2 \]

- Interactive soil moisture
- Divergence of ocean heat transport

\[ Q = Q_{\text{max}} \cos(3.5 \times \text{latitude}) \]
\( Q_{\text{max}} = 50 \text{ W/m}^2 \)

- Interactive soil moisture
- Divergence of ocean heat transport

\[ Q = Q_{\text{max}} \cos(3.5 \times \text{latitude}) \]
QTCM + mixed-layer ocean - Idealized continent case

- Zero ocean heat transport

- Idealized divergence of ocean heat transport
  \[ Q = Q_{\text{max}} \cos(3.5 \times \text{latitude}) \]
  \[ Q_{\text{max}} = 20 \text{ W/m}^2 \]
• Divergence of ocean heat transport

\[ Q = Q_{\text{max}} \cos(3.5 \times \text{latitude}), \]
\[ Q_{\text{max}} = 20 \text{ W/m}^2 \]

• Saturated soil moisture case
The “interactive Rodwell-Hoskins mechanism”

• Rodwell and Hoskins (1996): imposed convective heating in Asia gives Rossby wave descent pattern to west, enhancing deserts.

• when convection is interactive: associated flow feeds back on heating, creating characteristic convection/dry region pattern

  » we emphasize feedback
    (convection ⇔ baroclinic Rossby wave dynamics), hence:

  » “interactive Rodwell-Hoskins” (IRH) mechanism
The “ventilation mechanism”

• import of low moist static energy air from ocean where heat storage opposes summer warming
• Ocean mixed-layer stores heat from large summer insolation, so atm. is not strongly heated over oceans, limits deep convection zone movement over oceans
• temperature is cooler over ocean, and moisture is lower than convection threshold over warm continent
• import to continents by wind (including upper level jets) via advection terms in temperature and moisture equations
Experiments with ventilation mechanism suppressed

- $\nu \cdot \nabla T$ and $\nu \cdot \nabla q$ set to zero in temperature and moisture equations
- Divergence of ocean heat transport $Q = Q_{\text{max}} \cos(3.5 \times \text{latitude})$, $Q_{\text{max}} = 20$ W/m$^2$
Ventilation suppressed and no β-effect

- Coriolis parameter $f$ set to constant $f(13N)$ in northern hem. (north of 2N)
- Divergence of ocean heat transport $Q = Q_{\text{max}} \cos(3.5 \times \text{latitude})$, $Q_{\text{max}} = 20 \ \text{W/m}^2$
South American region case (observed albedo) Jan

Precipitation

Control

Saturated soil moisture over South American region

No ventilation: \( \mathbf{v} \cdot \nabla q, \mathbf{v} \cdot \nabla T \) set to zero over South American region

No ventilation and no \( \beta \)-effect: \( f = \) constant in South American region (9S-56S - 70W-20W)
North American region case (observed albedo) July

Precipitation

Control

No ventilation: $\mathbf{v} \cdot \nabla q$, $\mathbf{v} \cdot \nabla T$ set to zero over North American region

Saturated soil moisture over North American region

No ventilation and no $\beta$-effect: $f = \text{constant}$ in North American region
African region case (observed albedo) July

Precipitation
Control

Saturated soil moisture over African region

No ventilation: $\nu \cdot \nabla q$, $\nu \cdot \nabla T$ set to zero over African region

No ventilation and no $\beta$-effect: $f = \text{constant in African region (0 - 50N)}$
African region case (albedo set to 0.2 over land) July

Precipitation
Control

Saturated soil moisture over African region

No ventilation: $\nu \cdot \nabla q$, $\nu \cdot \nabla T$ set to zero over African region

No ventilation and no $\beta$-effect: $f$ = constant in African region (0 - 50N)
Refinement of experimental design

1. Consistent treatment of $v_\chi$:
   - Irrotational (purely divergent) wind component $v_\chi$
   - Non-divergent wind component $v_\psi$
   - “No ventilation” = suppress $v_\psi \cdot \nabla T$, $v_\psi \cdot \nabla q$
   - Retains conservation property: $\int_{\text{Domain}} (v_\chi \cdot \nabla q + q \nabla \cdot v) \, dA = 0$ since $\nabla \cdot v_\psi = 0$

2. “Partial-$\beta$” experiment:
   - Retain $\beta$ - effect on zonal mean wind (across region)
North American region case

July Precipitation

Control

Saturated soil moisture

No ventilation: \( \mathbf{v} \cdot \nabla q, \mathbf{v} \cdot \nabla T \) set to zero

No \( \beta \)-effect: \( f = \) constant in region

Chou and Neelin 2003
North American region case
July Precipitation

No ventilation and no $\beta$-effect:

No ventilation and partial $\beta$-effect

Chou and Neelin 2003
North American region case

July Precipitation

Control

No ventilation: $v \cdot \nabla q$, $v \cdot \nabla T$ set to zero

No $T$ ventilation

No $q$ ventilation

Chou and Neelin 2003
North America with and without ventilation

Ventilation suppressed through May, turned on in June
Asian region case – July

Precipitation

Control

Saturated soil moisture

No ventilation: $\mathbf{v} \cdot \nabla q$, $\mathbf{v} \cdot \nabla T$ set to zero

No $\beta$-effect: $f = \text{constant}$

Chou and Neelin 2003
Asian region case – July

Precipitation

No ventilation and no \( \beta \)-effect: No ventilation and partial \( \beta \)-effect

Chou and Neelin 2003
Asian region case – July

Precipitation

Control

No ventilation: $\nu \cdot \nabla q$, $\nu \cdot \nabla T$ set to zero

No $T$ ventilation

No $q$ ventilation

Chou and Neelin 2003
African region case (observed albedo) July

Precipitation

Control

Saturated soil moisture

No ventilation: $v \cdot \nabla q$, $v \cdot \nabla T$ set to zero

No ventilation and no $\beta$-effect:

Chou and Neelin 2003
African region constant albedo case (0.26 over Africa) July

Precipitation

Control

Saturated soil moisture

No ventilation: $\nu \cdot \nabla q$, $\nu \cdot \nabla T$ set to zero

No ventilation and no $\beta$-effect:

Chou and Neelin 2003
## Summary: (General/Idealized Continent)

### Ventilation
- **import of low moist static energy air from ocean where heat storage keeps cool**
  - balances heating of midlatitude continent
  - limits poleward extension of summer monsoon convection
  - produces east-west asymmetry

### Interactive Rodwell-Hoskins mechanism
- Rossby wave div/convergence pattern interacts with convection
  - eastern continent convection favored
  - western continent convection disfavored (eastern favored)

### Soil moisture
- drying tendency in subtropical descent region
  - contributes to limiting poleward extent of convection
  - tropical continent convection disfavored

### Ocean heat transport
- tropical ocean cooled by transport
  - tropical continent convection favored
Mechanisms affecting continental convective zones

Soil moisture feedbacks

Ocean heat transport out of the tropics

Ventilation and the interactive Rodwell-Hoskins mechanism
Ventilation and the interactive Rodwell-Hoskins mechanism

- Ocean heat storage
- Ventilation disfavors convection limits poleward extent
- Low moist static energy air
- Rossby wave descent
- Enhanced convection

EQ

Ocean

Land

Ocean
• **Observed estimate of net energy flux** $F_{\text{net}}$ **into atmospheric column**: positive $F_{\text{net}}$ extends much further poleward than convective zone

• **Dynamical factors limit poleward extension of summer convective zone**

<table>
<thead>
<tr>
<th>South America</th>
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<tbody>
<tr>
<td>• Ventilation and interactive Rodwell-Hoskins (IRH) mechanism important</td>
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<td>• Both affect NW-SE tilt of convergence zone</td>
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<td>• Soil moisture feedback secondary</td>
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<table>
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<th>North America</th>
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<tr>
<td>• Ventilation strongly affects poleward extent of convergence zone</td>
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<tr>
<td>• IRH mechanism a major dynamical influence favoring dryer southwestern continent</td>
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<tr>
<td>• Ventilation by either of $\nu_{\psi} \cdot \nabla T$, $\nu_{\psi} \cdot \nabla q$ can prevent poleward extension of convergence zone</td>
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Regional summary (cont’d)

- Moisture supply not limiting if drying/cooling advection by nondivergent flow does not overcome supply by divergent flow responding to heating

Asia
- Ventilation stops poleward extension (esp. \( \nabla \cdot \nu \psi \) term)
- Interactive Rodwell-Hoskins (IRH) mechanism important to interior deserts
- [tests of IRH that retain regional zonal mean show little difference so “local Hadley cell” irrelevant]

Africa
- Albedo effects dominate in deserts
- If albedo set to constant, dynamical effects (esp. ventilation) control poleward extent
Mechanisms affecting convective zones (S. American case)

Ocean heat transport out of the tropics

Ventilation and the interactive Rodwell-Hoskins mechanism
Summary: N. & S. America (1)

- Observed estimate of net energy flux $F_{\text{net}}$ into atmospheric column, positive $F_{\text{net}}$ extends much further poleward than convective zone
- QTCM mixed-layer ocean with Q-flux “heat transport”
- Caveats: No topography, North American precipitation imperfect
Factors limiting poleward extension of summer convective zone:

**South America**
- 2 leading effects important:
- Ventilation
- Interactive Rodwell-Hoskins mechanism
- Both affect NW-SE tilt of convergence zone
- Soil moisture feedback secondary

**North America**
- Interactive Rodwell-Hoskins mechanism a major dynamical influence favoring dryer southwestern continent
- Soil moisture feedback and ventilation effects also substantial

**[Africa:]**
- All of the above plus albedo
Monsoon talk title page

Tropical average temperature response

NSIPP moist static energy budget

End show

EQ 20S 20N

convect

ocean

low moist static energy air

enhanced convect

ocean heat storage

ventilation disfavors convect

limits poleward extent

Rossby wave descent