Mechanisms limiting the poleward extent of summer monsoon convective zones

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Dept. of Atmospheric Sciences & Inst. of Geophysics and Planetary Physics, U.C.L.A.

- 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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***Now at Academia Sinica, Taiwan**

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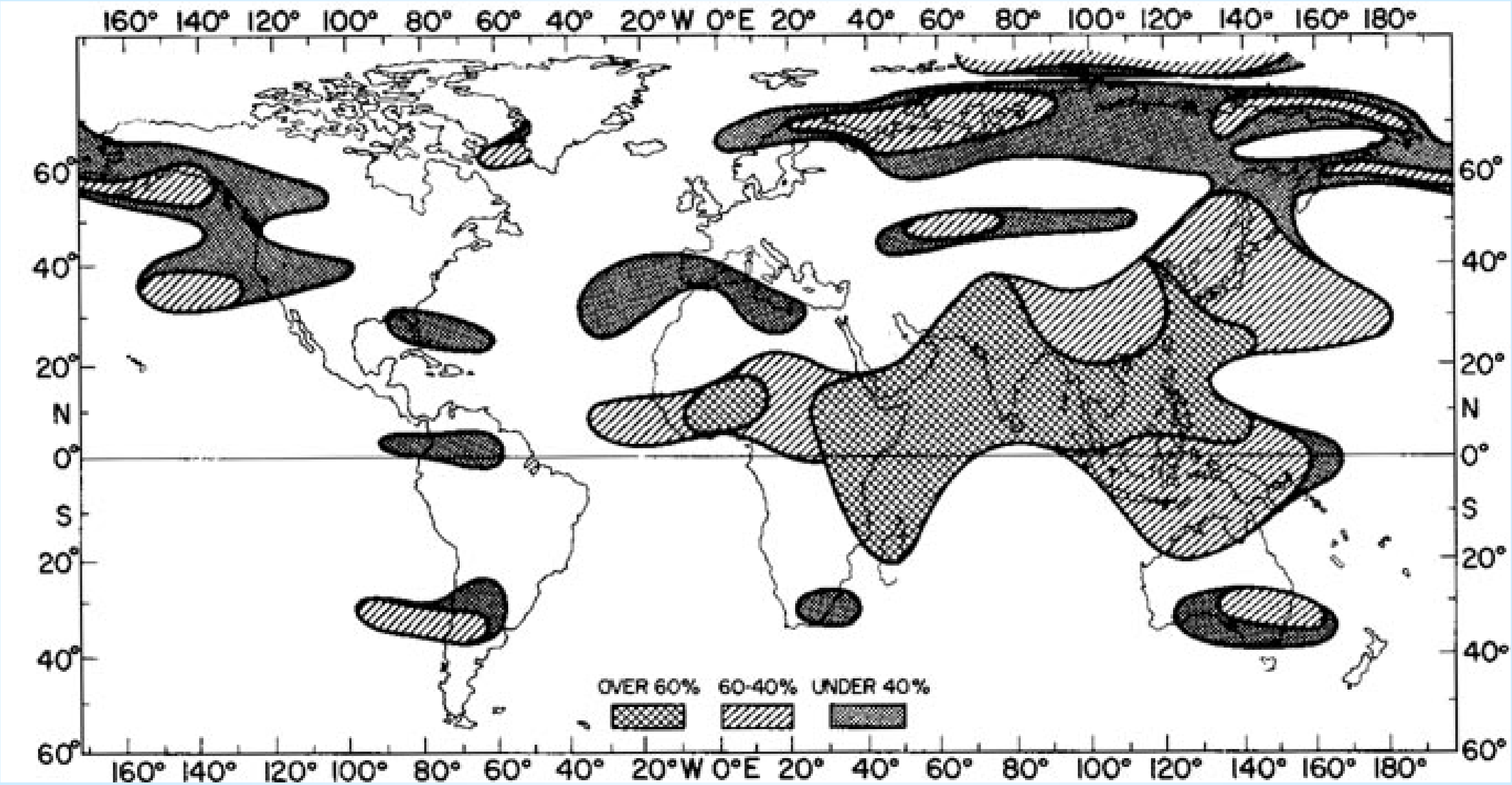
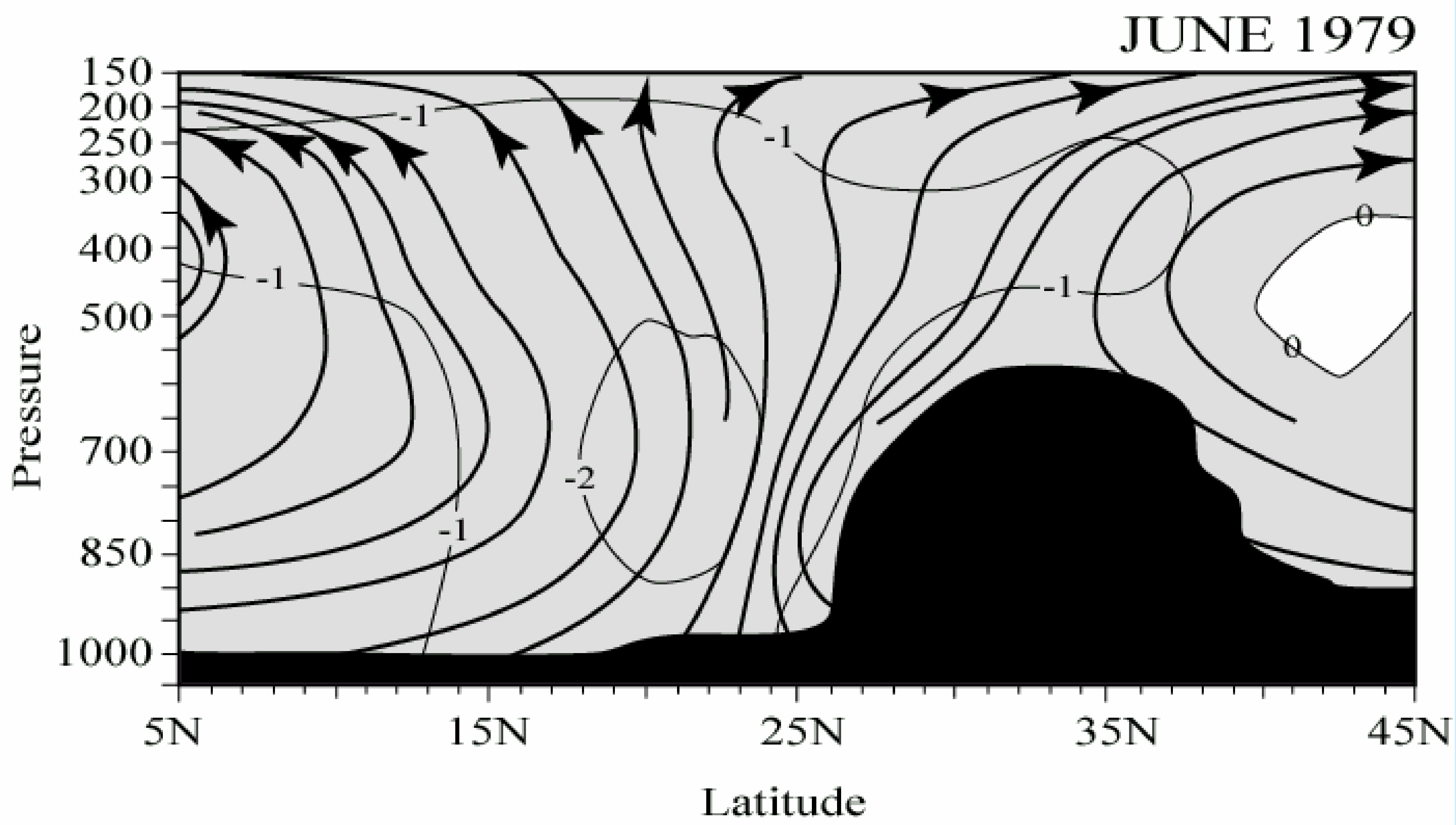
Wind-based definitions of monsoons



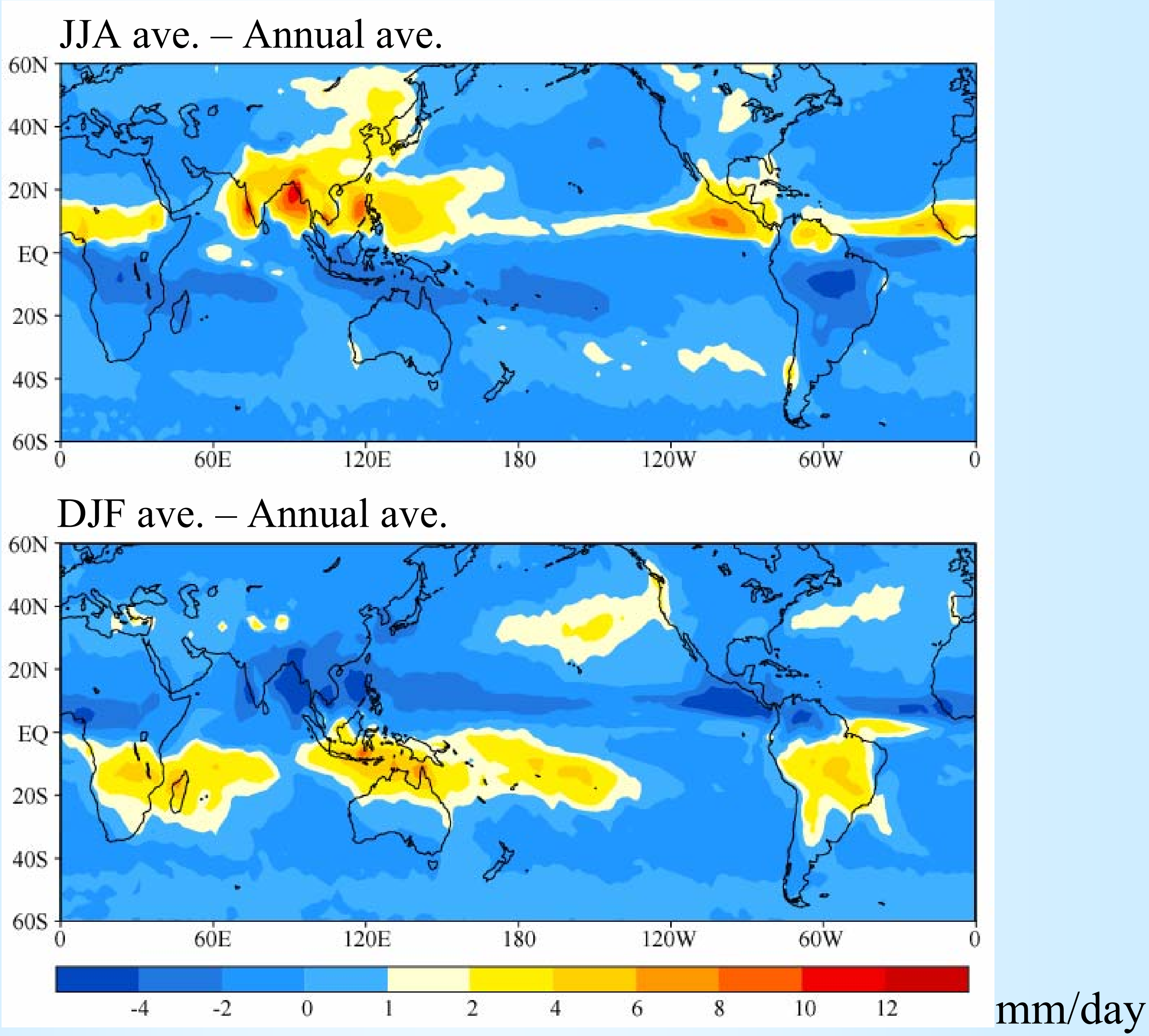
Khromov (1957); from Ramage (1971)

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

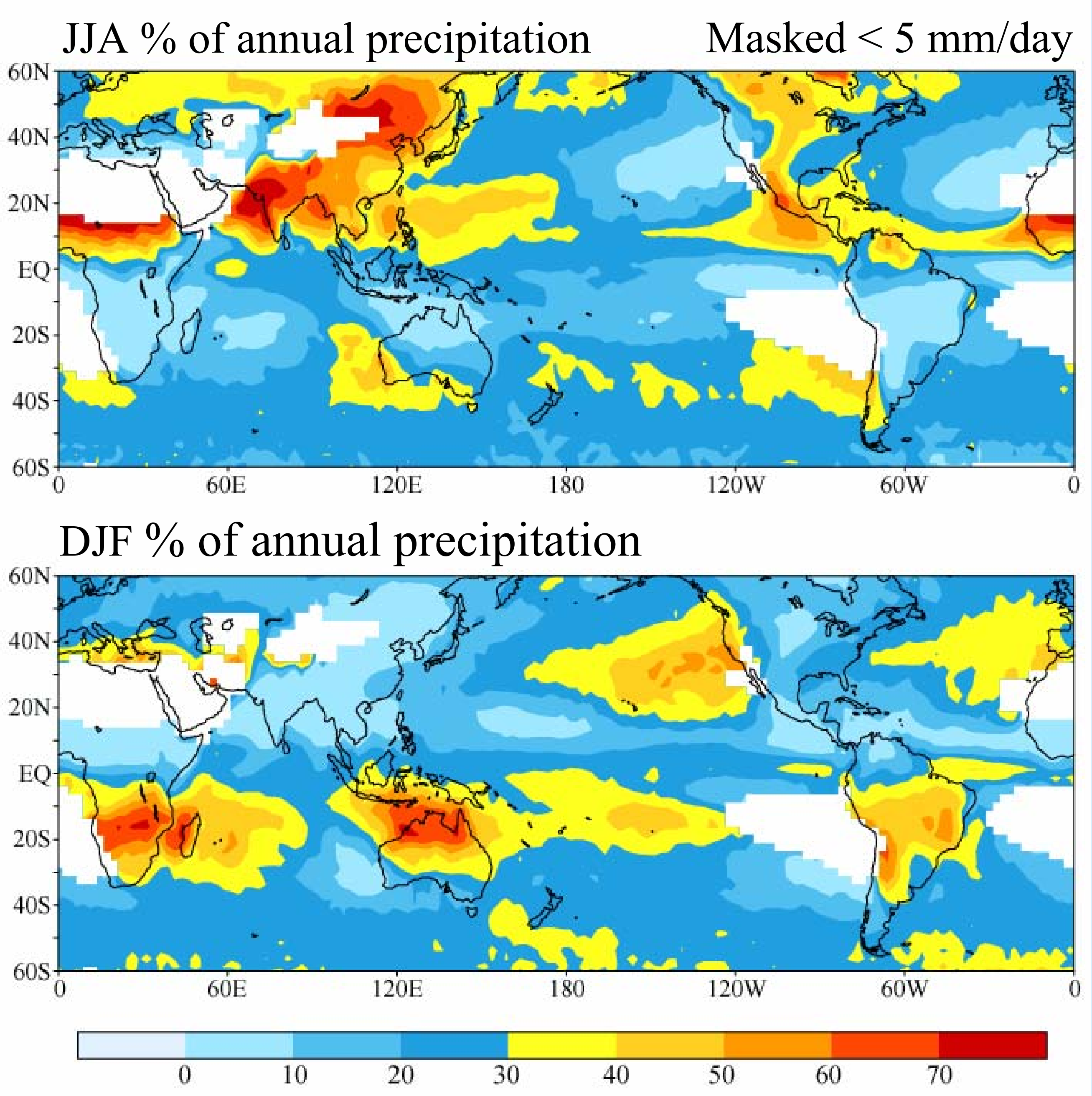


From Yanai et al. (1992)

Seasonal precipitation minus Annual Average



Seasonal percentage 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

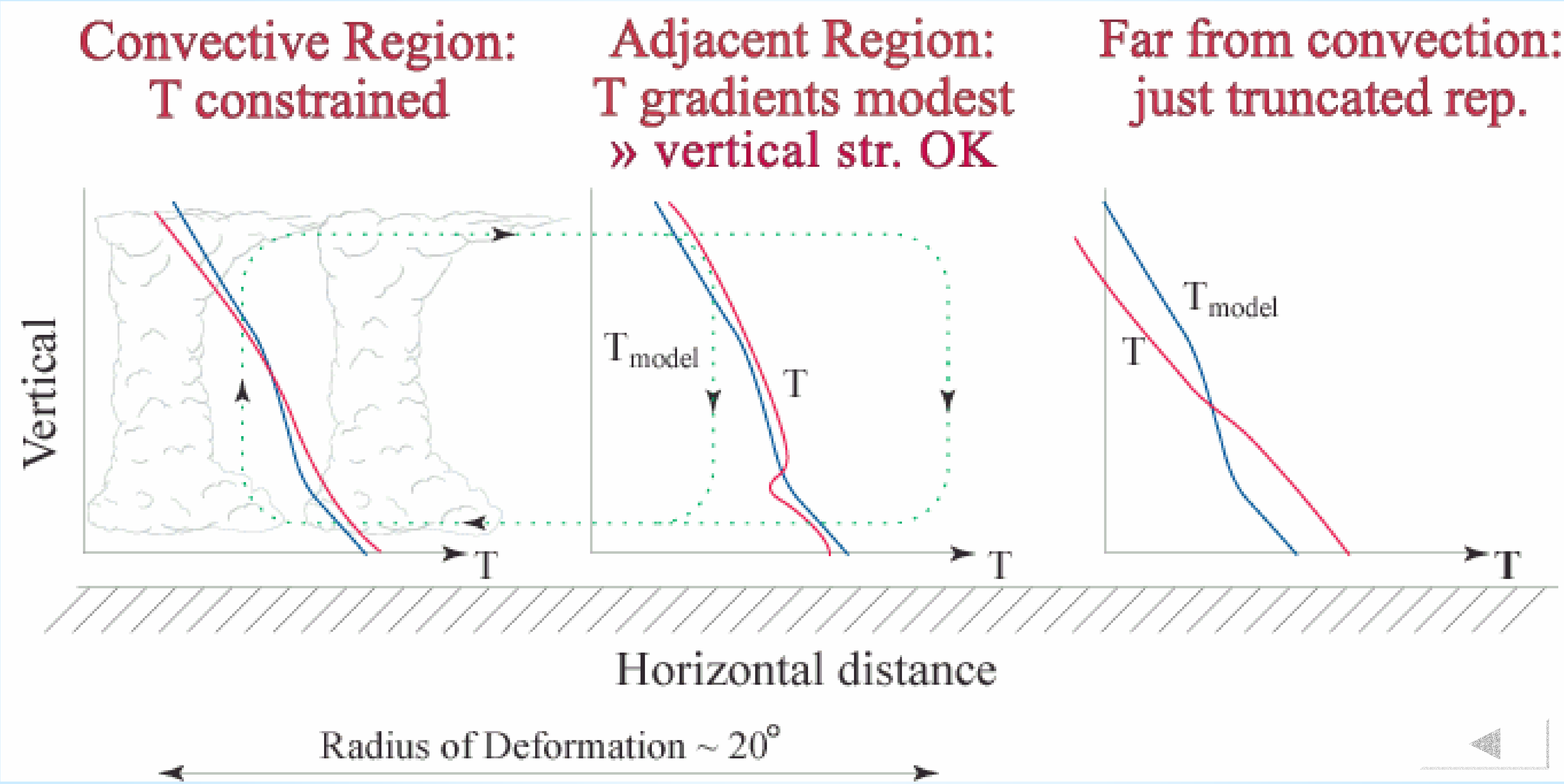
Radiation/cloud parameterization:

- 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:

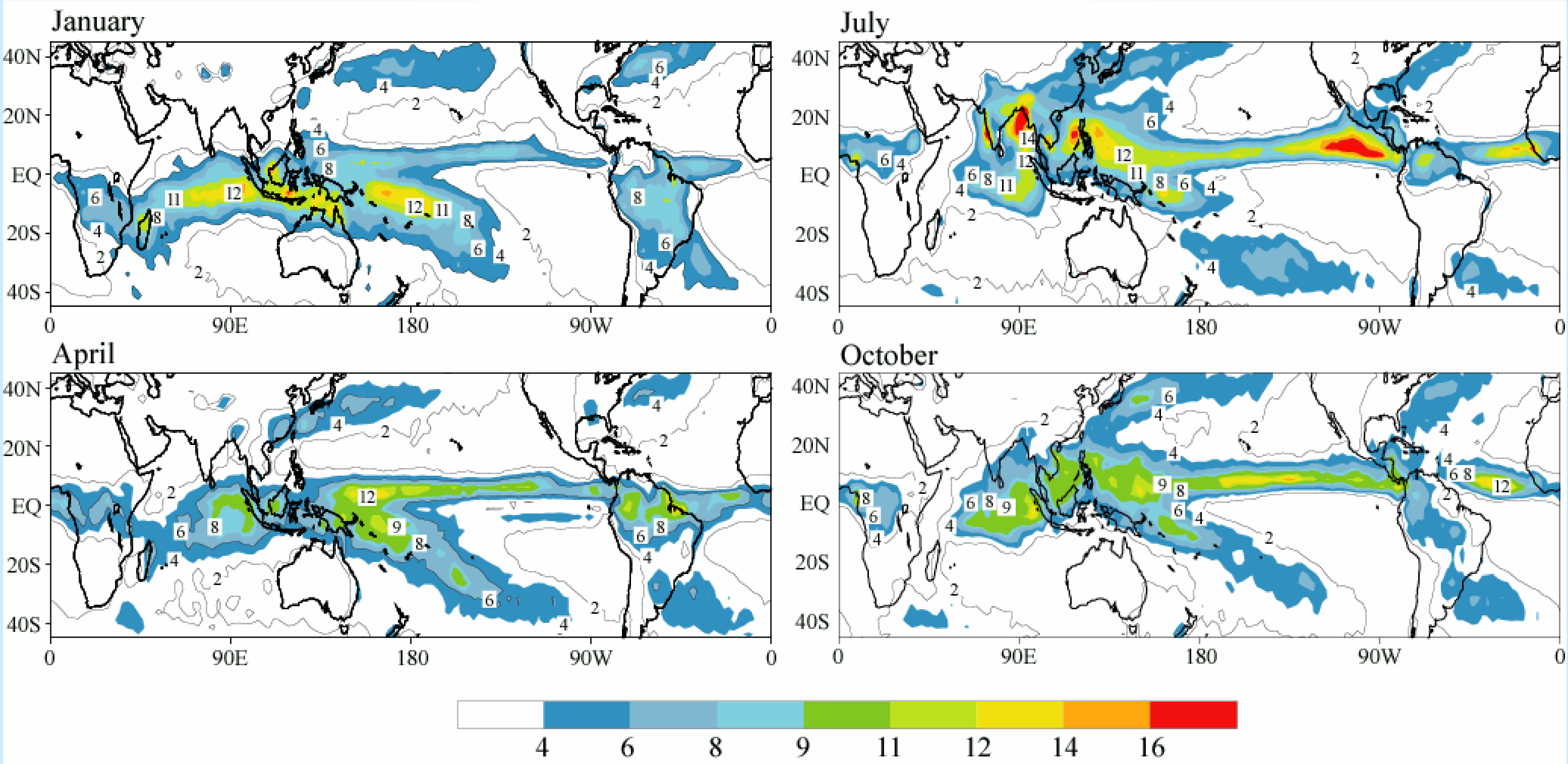
- 1 soil moisture layer; evapotranspiration with stomatal/root resistance dep. on surface type (e.g., forest, desert, grassland)
- low heat capacity; Darnell et al 1992 albedo

* 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

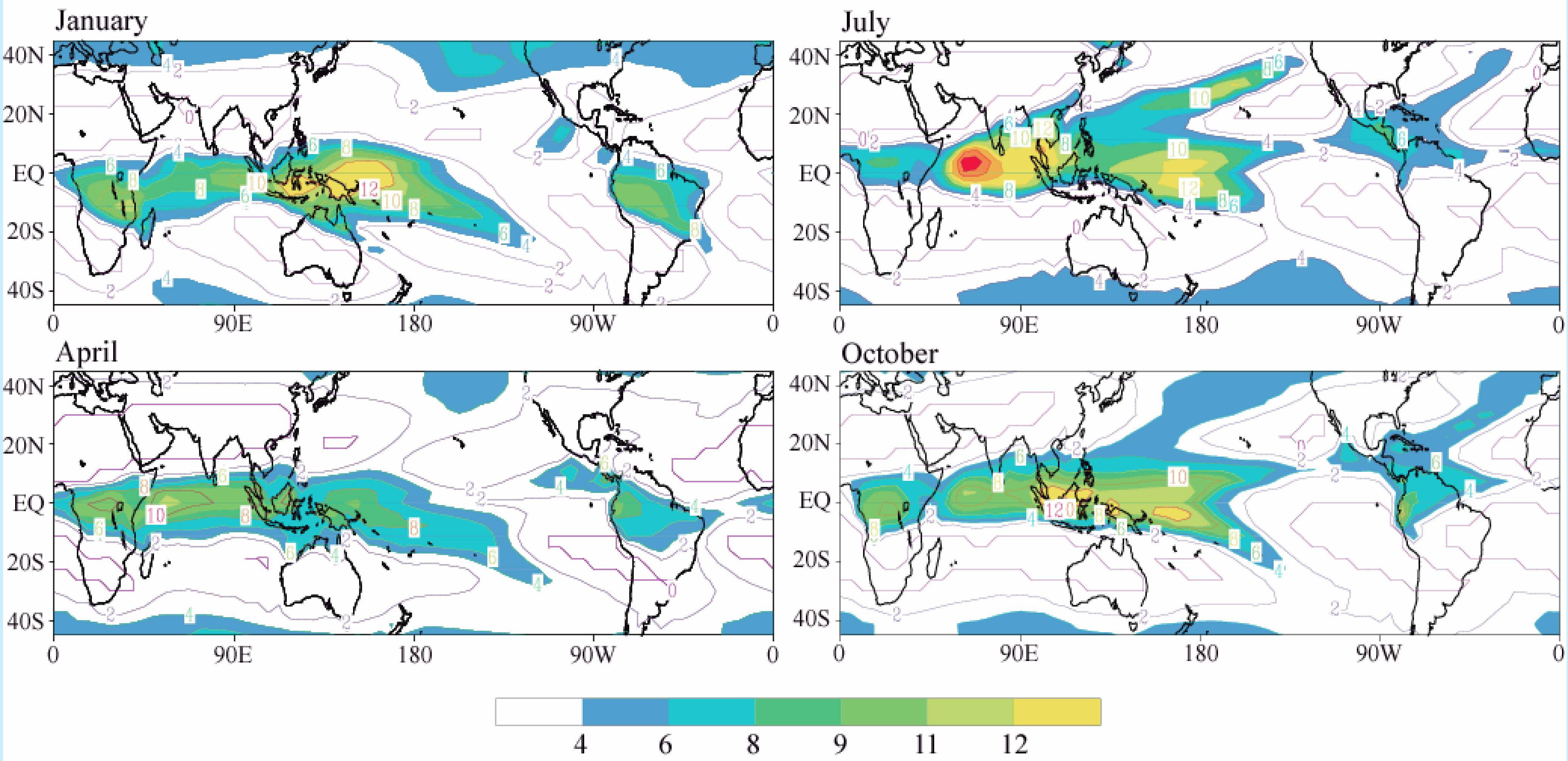


Neelin & Zeng; Zeng et al 2000

Xie - Arkin Precipitation climatology 1982 -1997

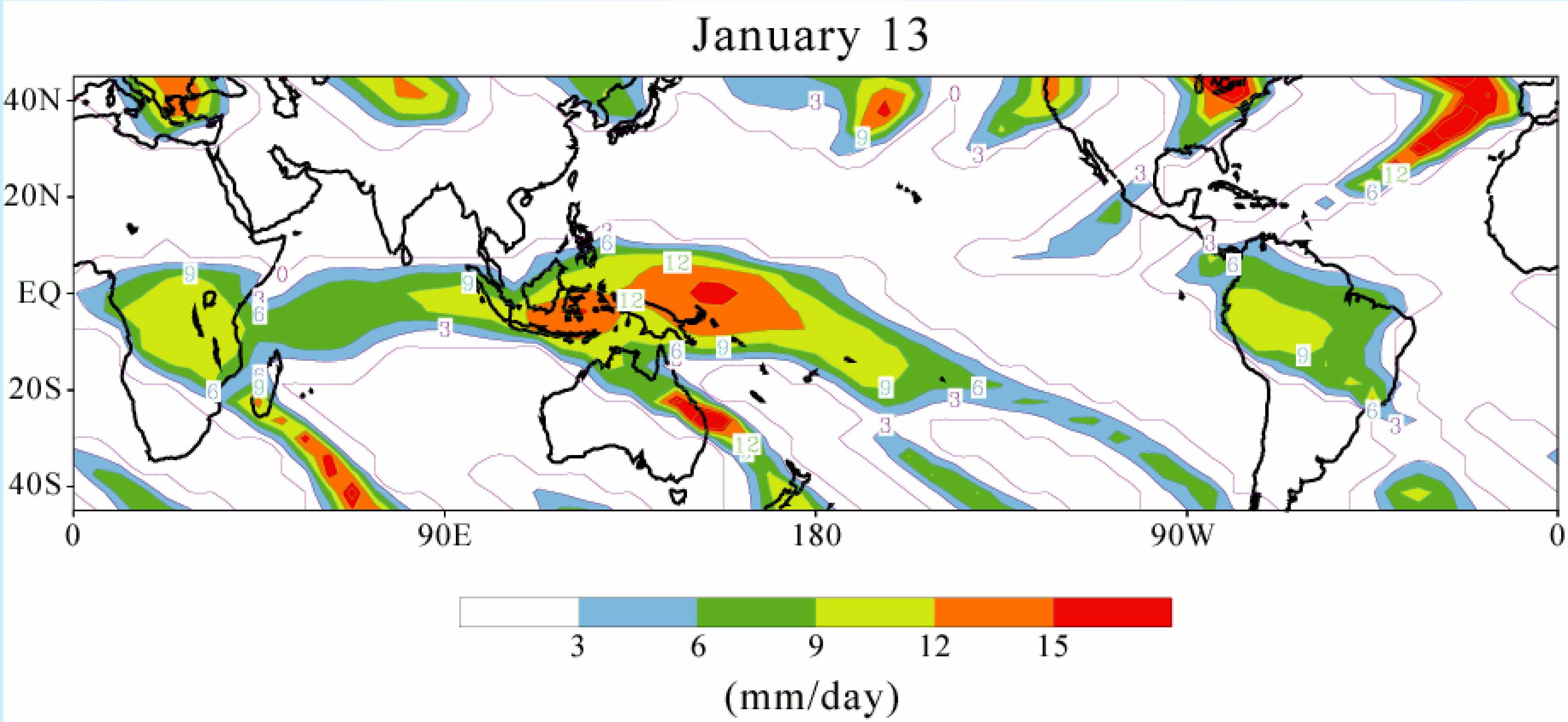


QTCM1 Precipitation climatology 1982-1997
clrad1 cloud-radiation package



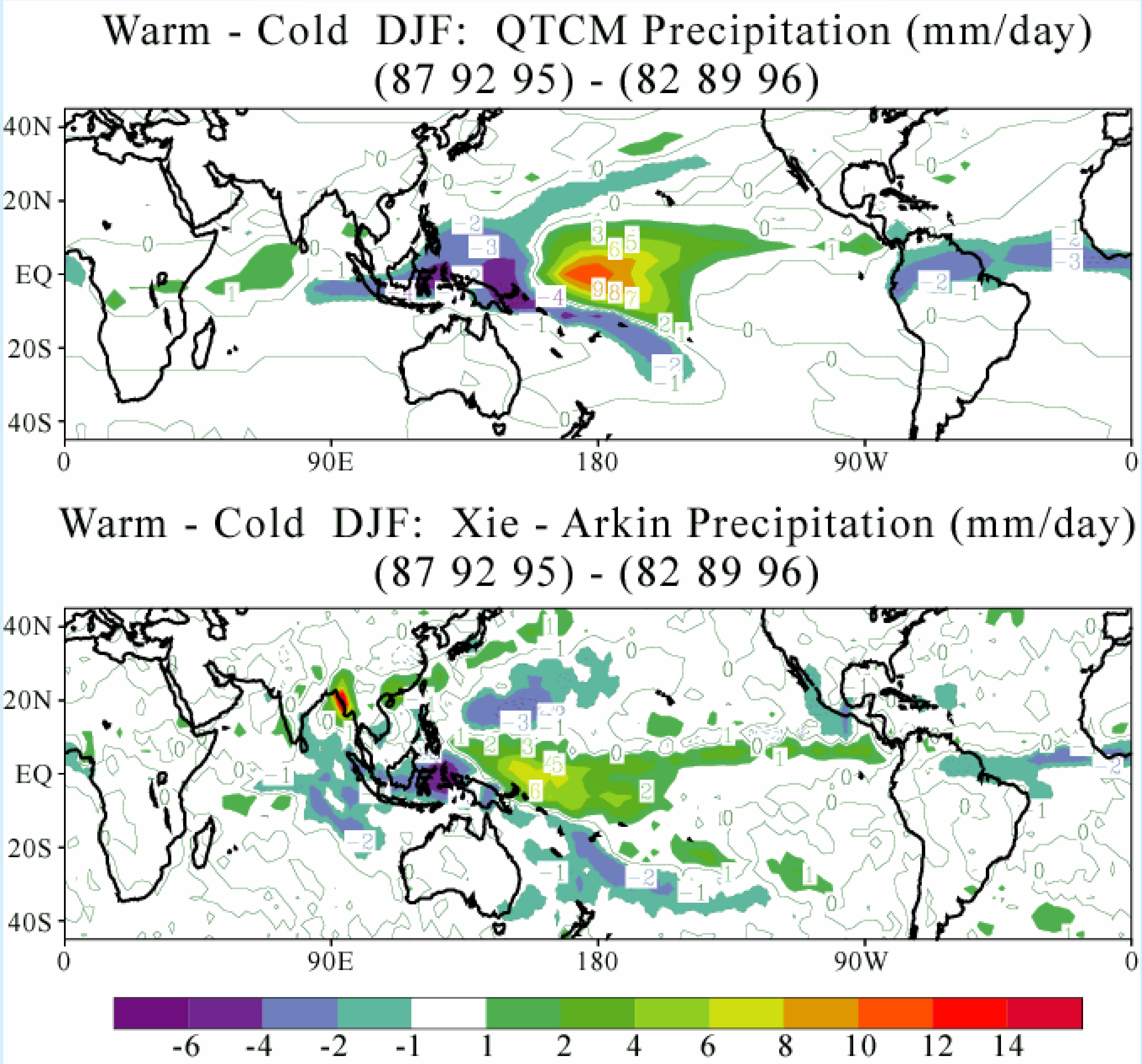
Zeng, Neelin and Chou 2000 QTCM1 V2.0 clrad1

QTCM1 Precipitation (daily)



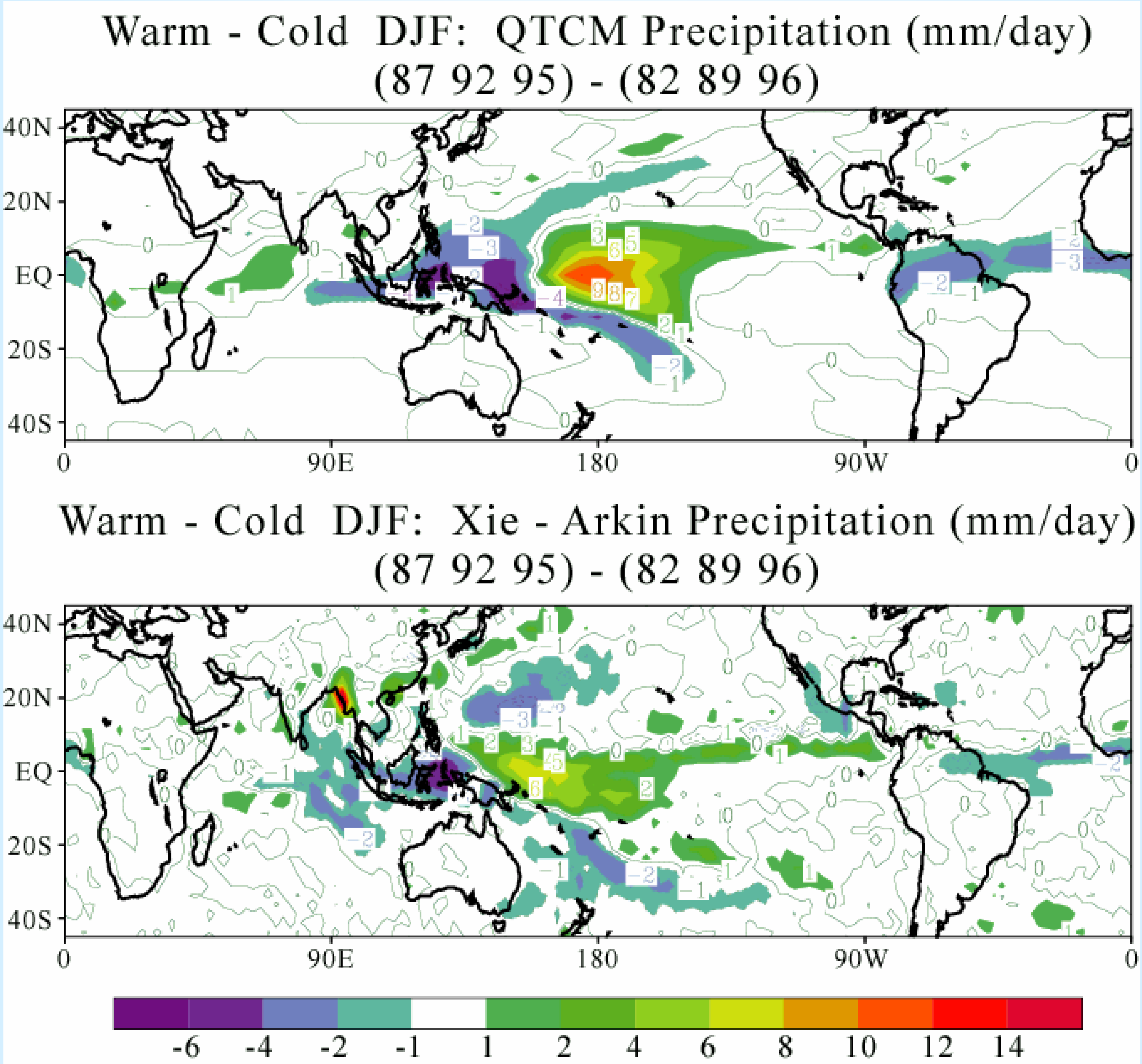
Zeng, Neelin and Chou 2000 QTCM1 V2.0 clrad1

ENSO Composite (DJF)



Zeng, Neelin and Chou 2000 QTCM1 V2.0 clrad1

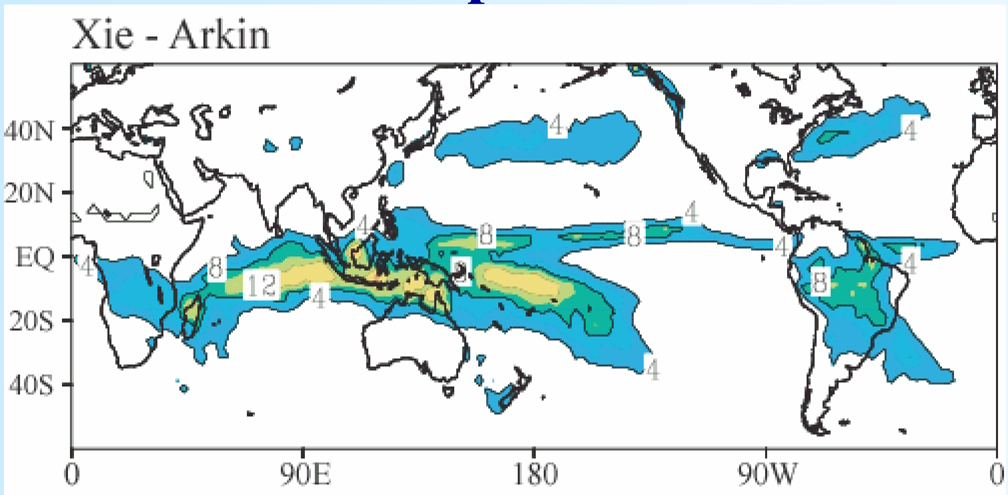
ENSO Composite (JJA)



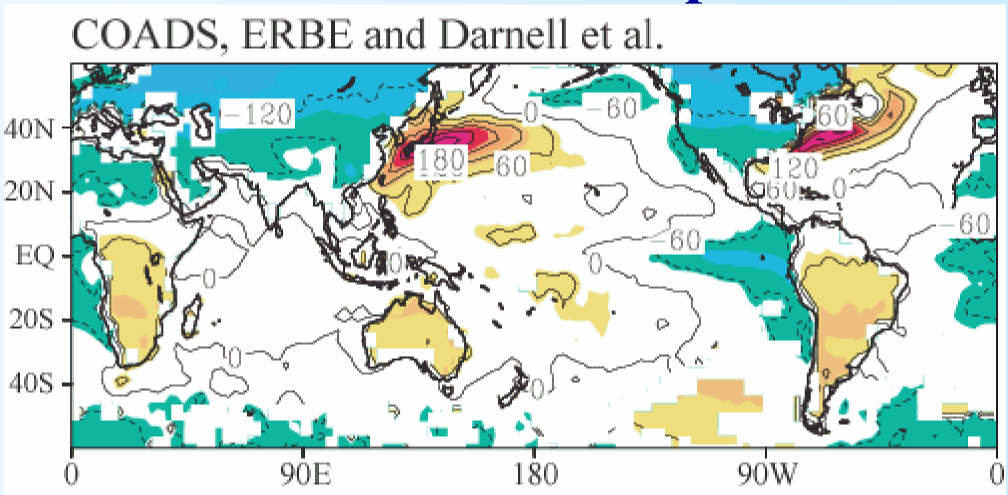
Zeng, Neelin and Chou 2000 QTCM1 V2.0 clrad1

Observed climatology January

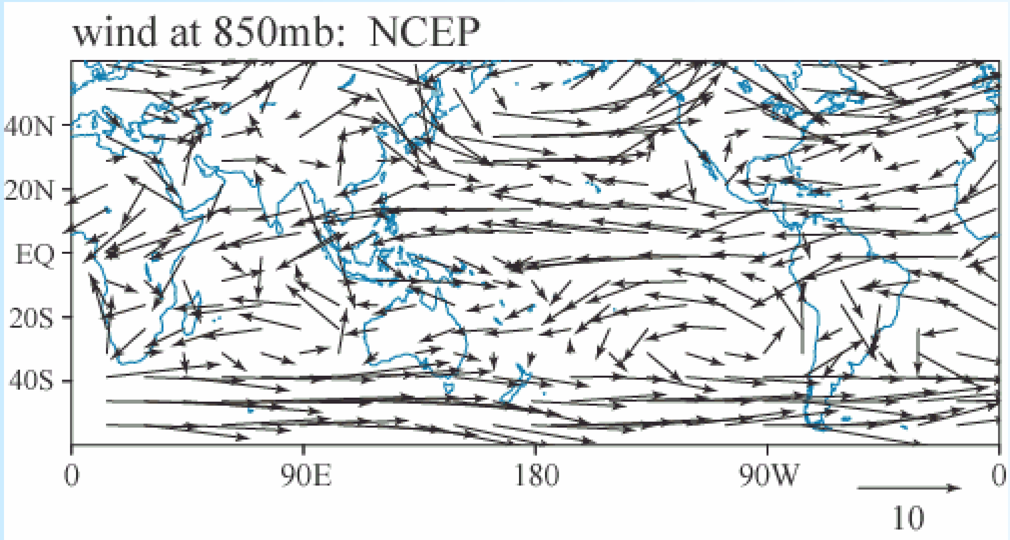
Precipitation



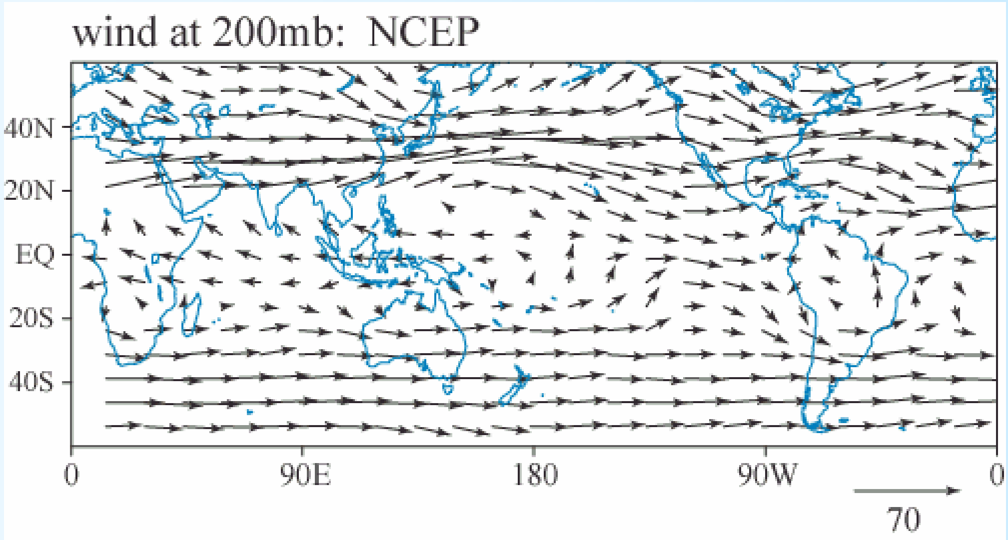
Net flux into atmosphere



Low-level wind

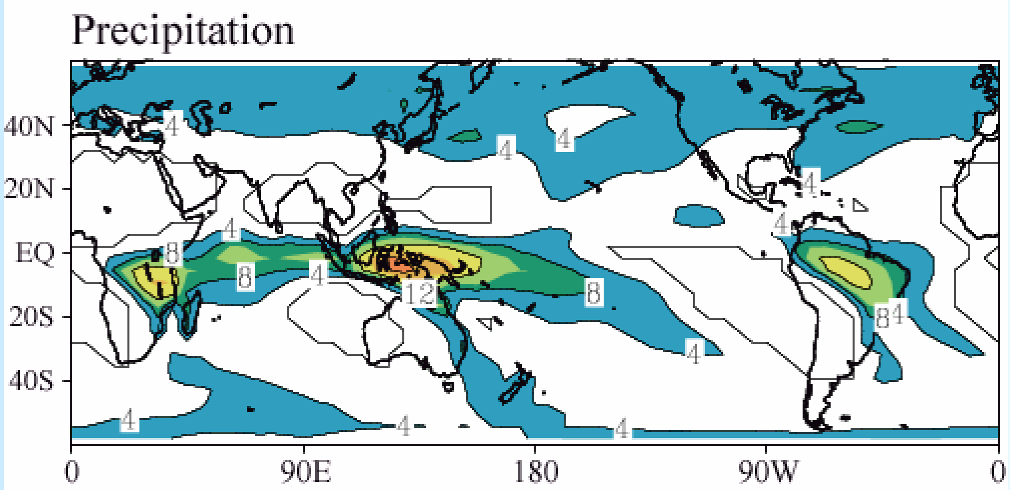


Upper-level wind

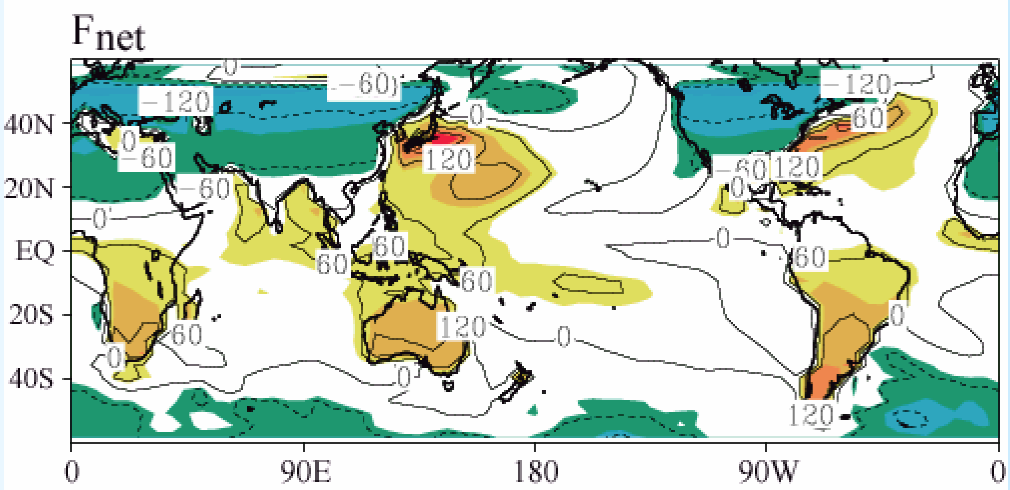


QTCM climatology January
(coupled to a mixed-layer ocean)

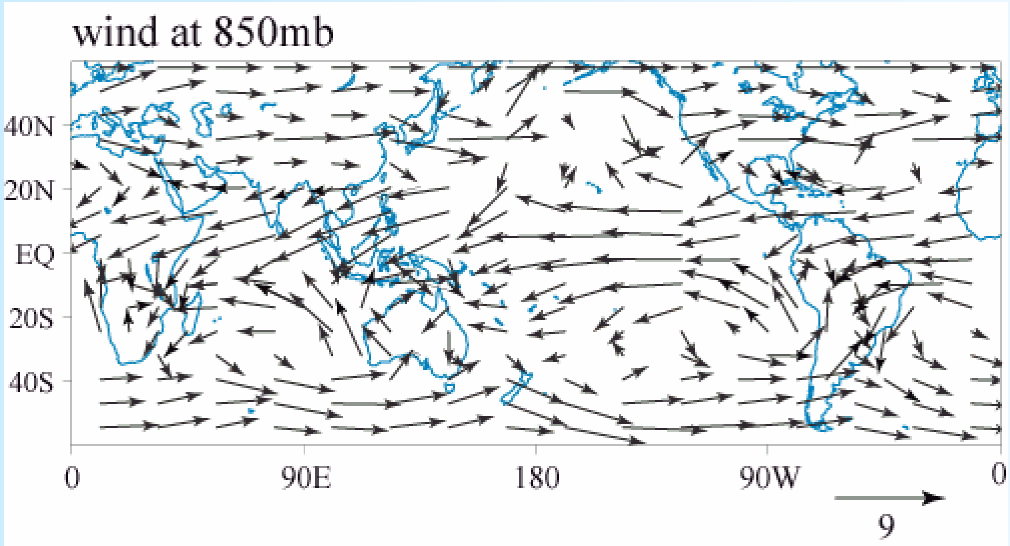
Precipitation



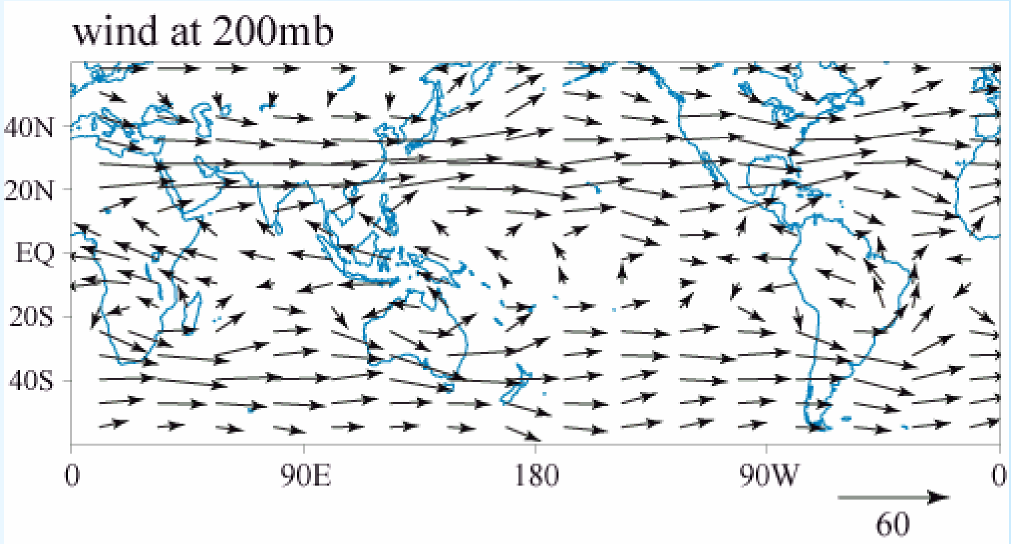
Net flux into atmosphere



Low-level wind



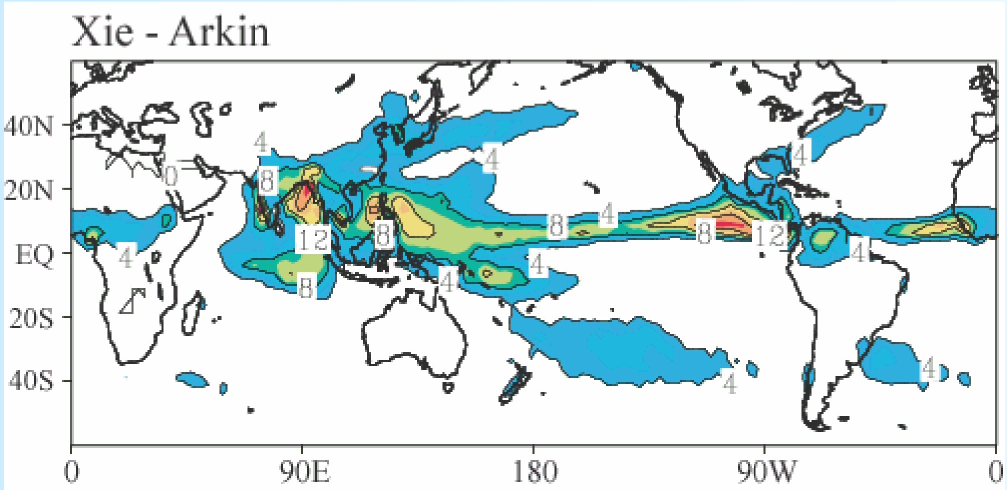
Upper-level wind



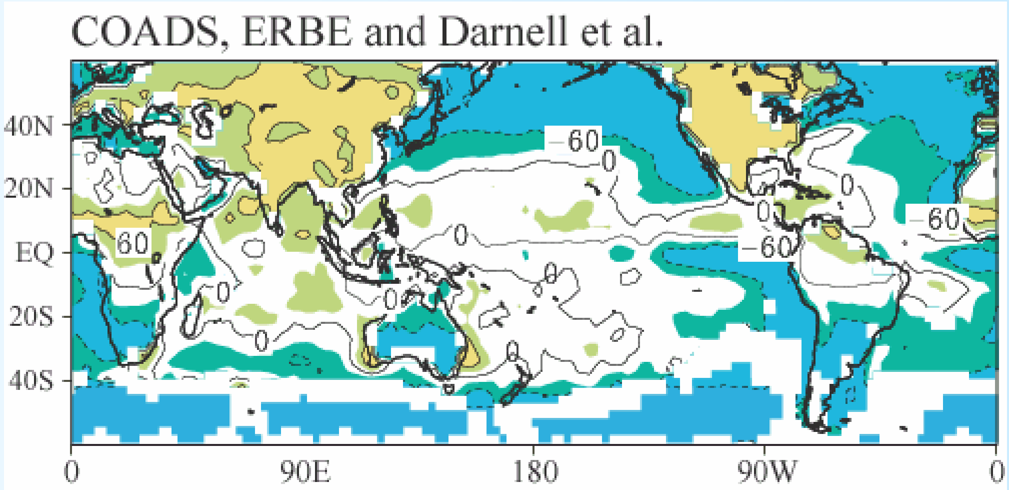
QTCM1V2.2

Observed climatology July

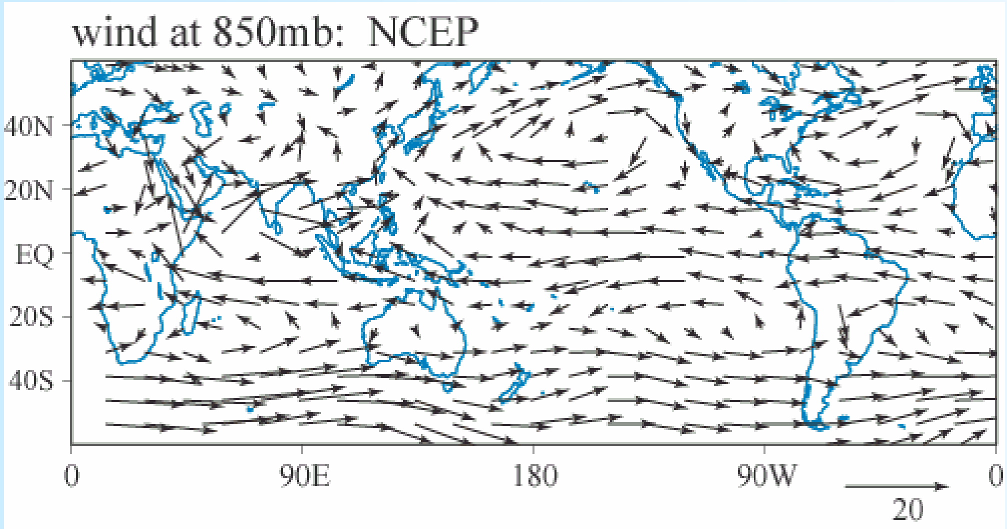
Precipitation



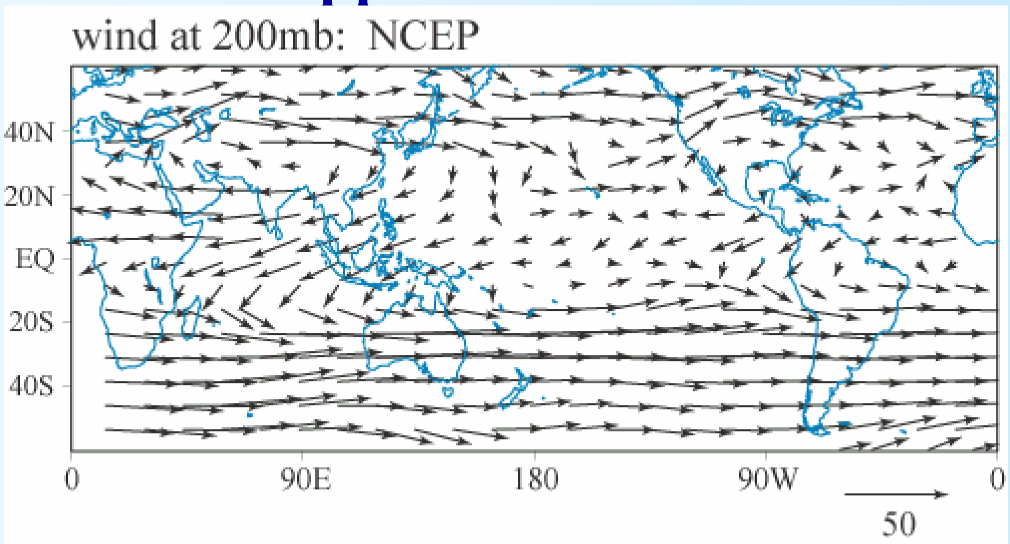
Net flux into atmosphere



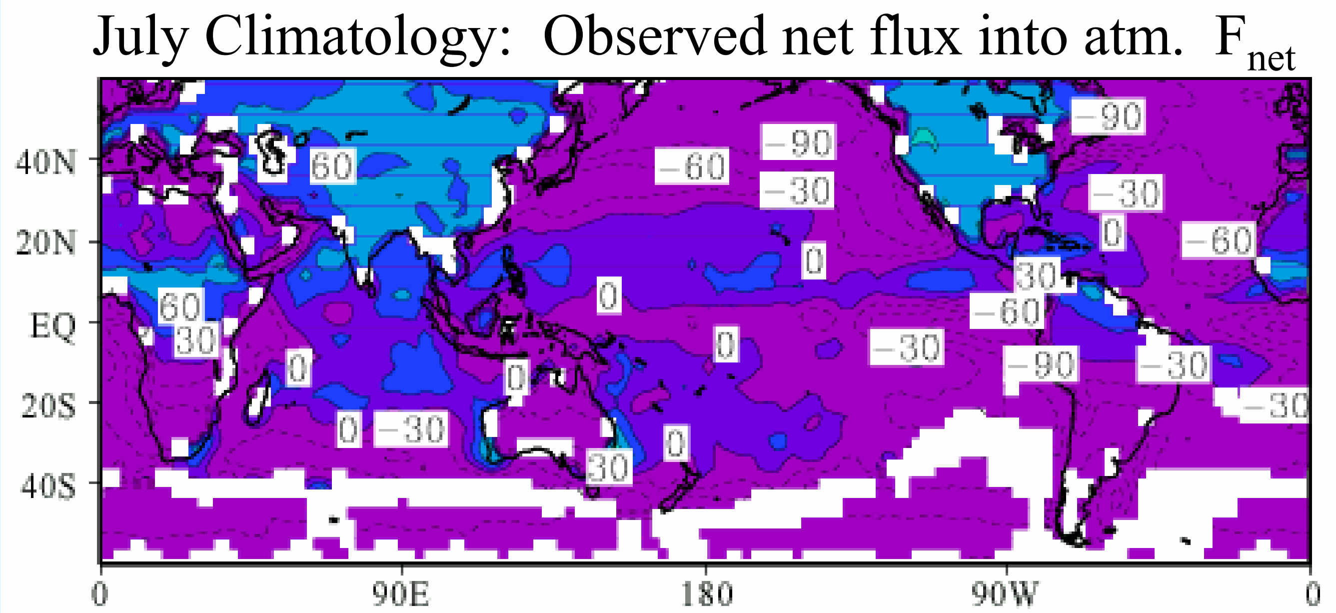
Low-level wind

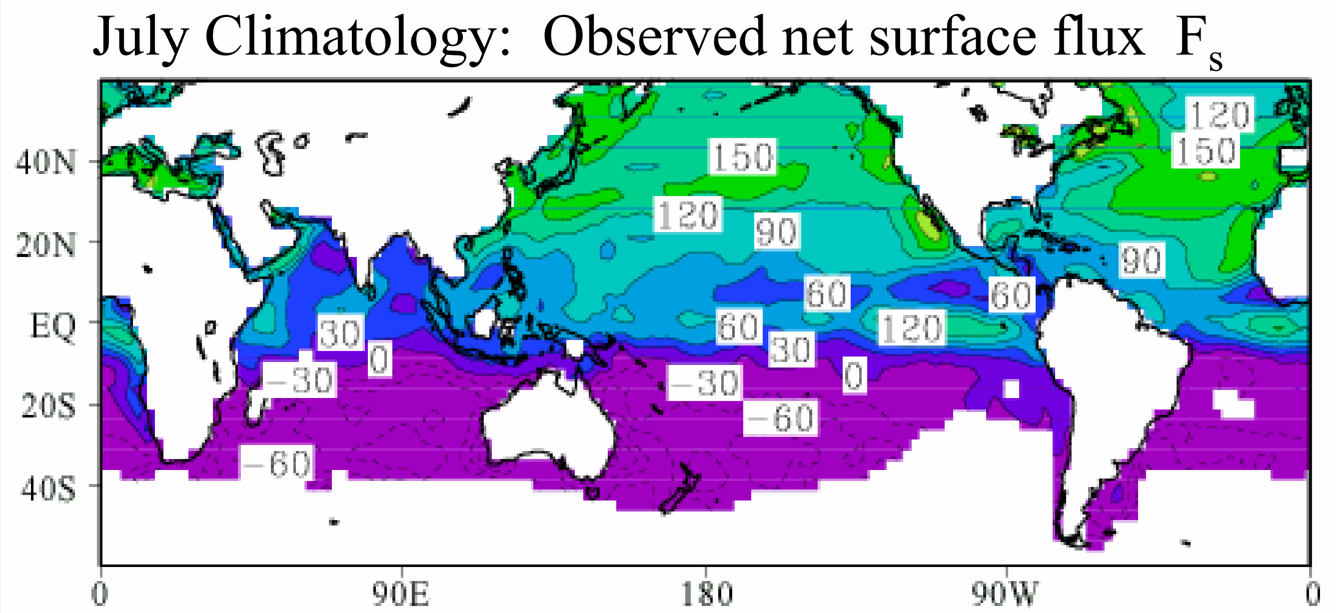


Upper-level wind



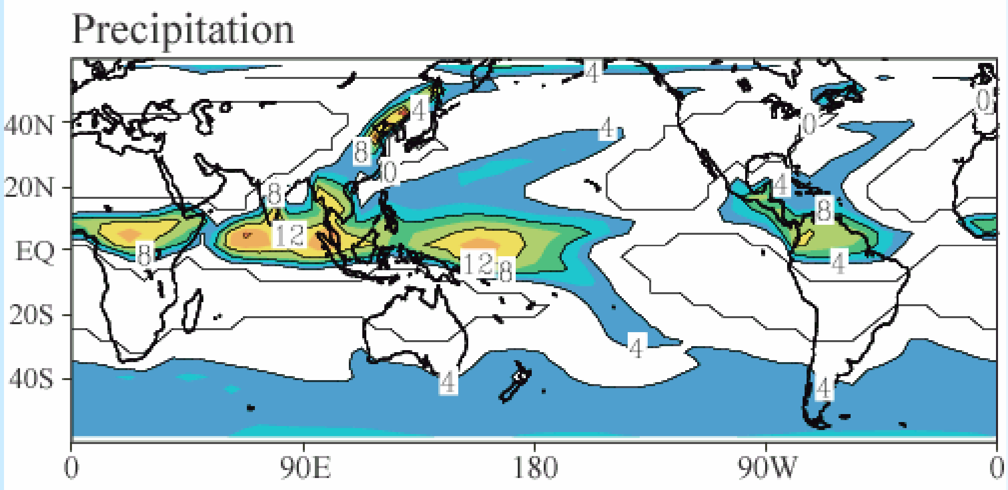
Observed net flux into atmosphere and net surface flux



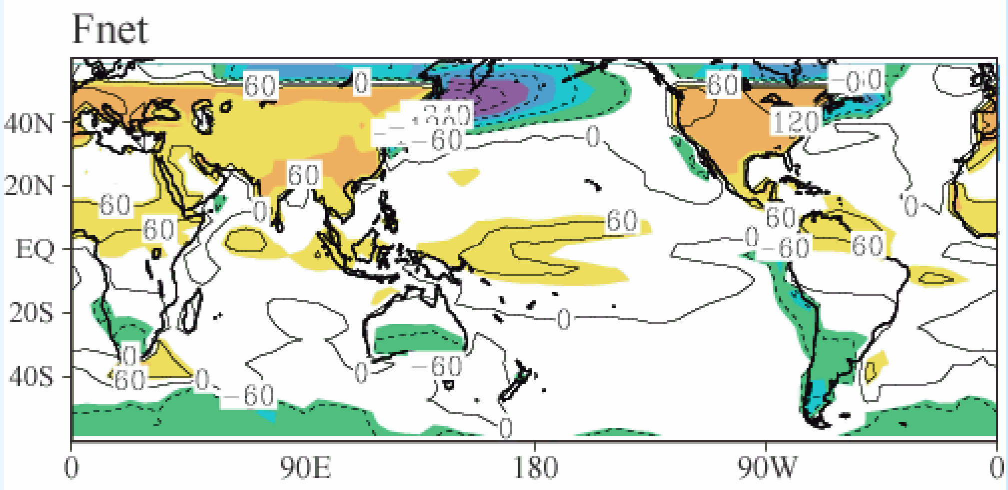


QTCM climatology July
(coupled to a mixed-layer ocean)

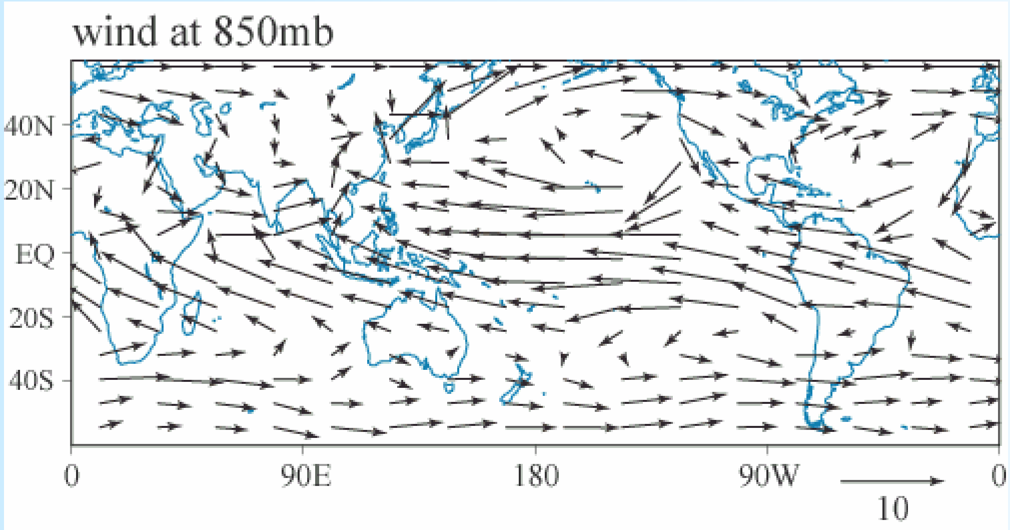
Precipitation



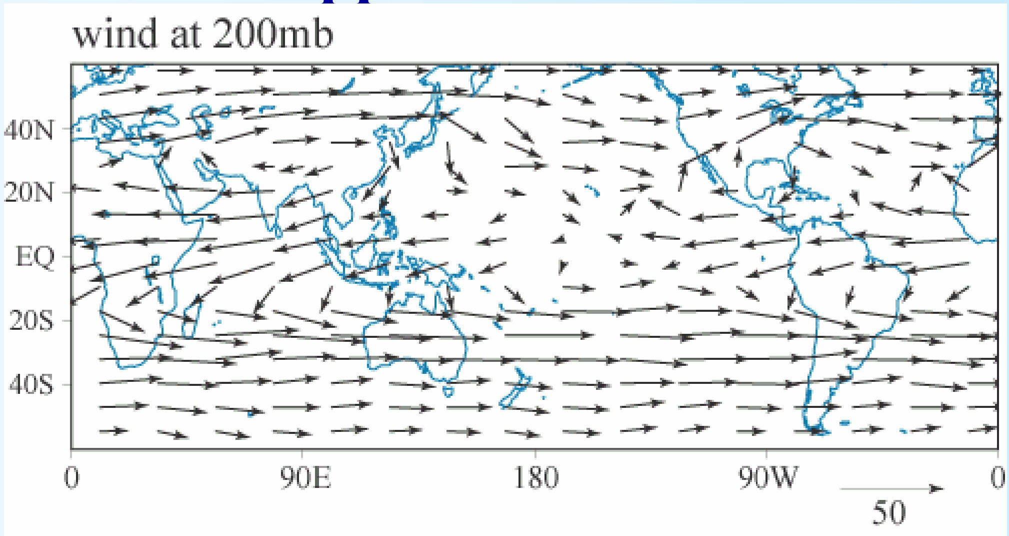
Net flux into atmosphere



Low-level wind



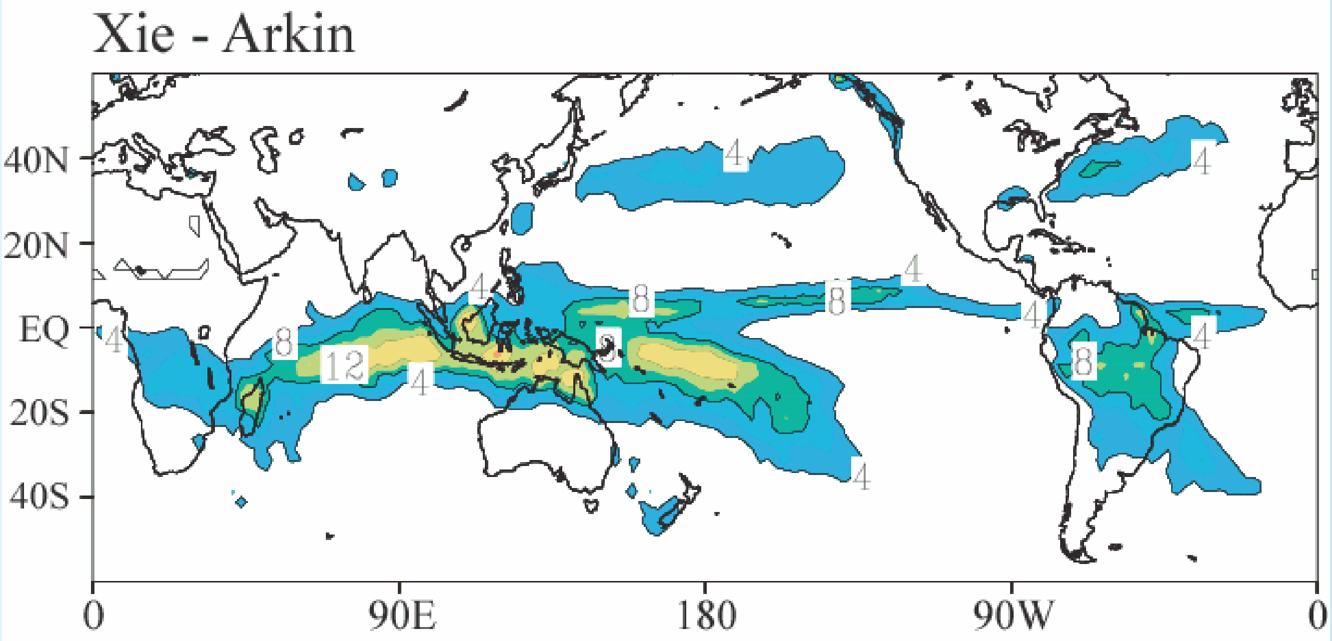
Upper-level wind



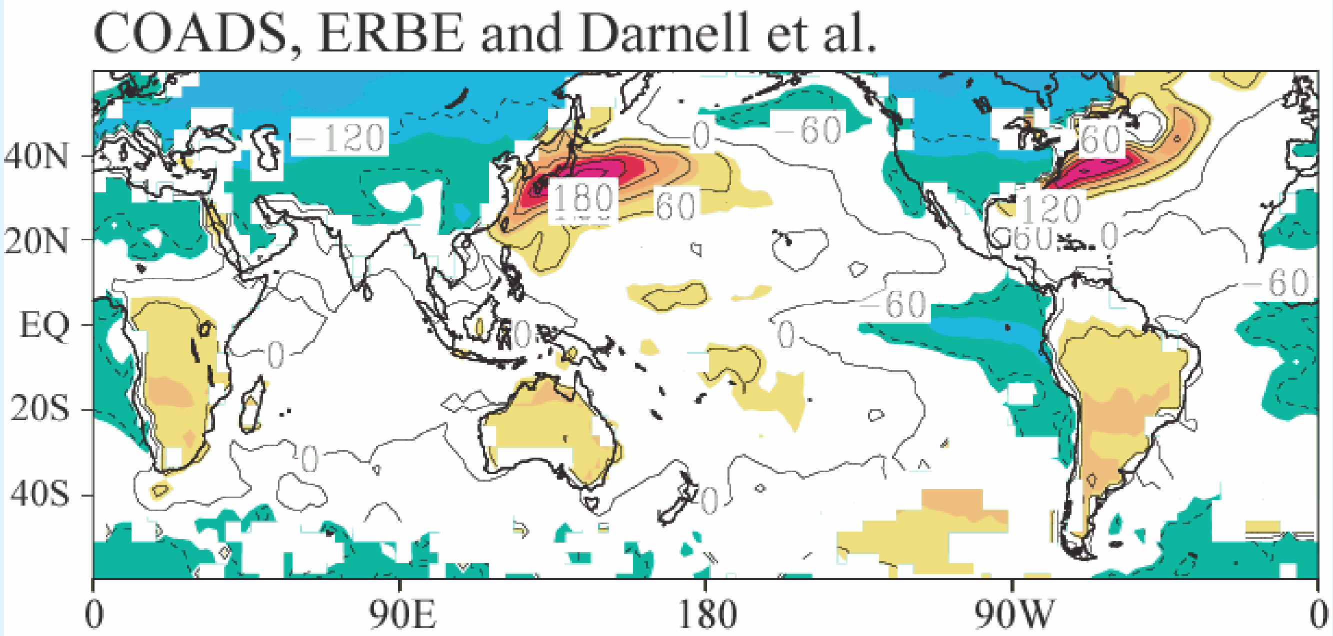
QTCM1V2.2

Observed climatology January

Precipitation

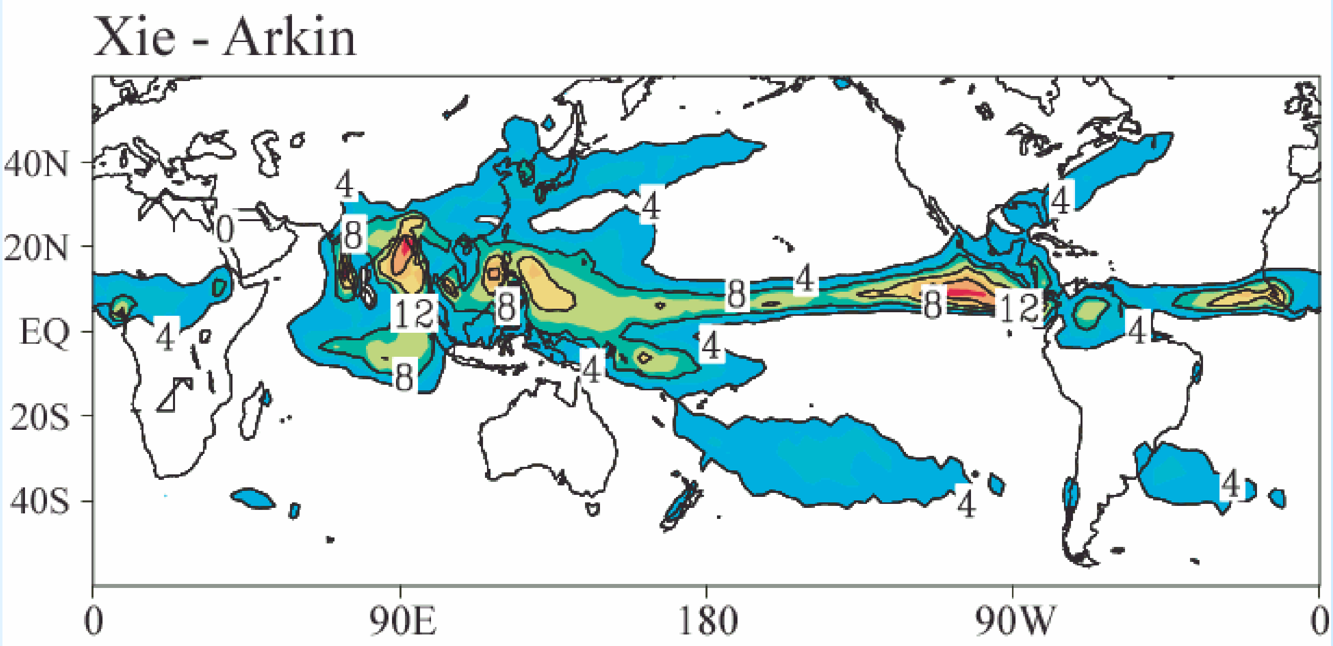


Net Flux into the atmosphere

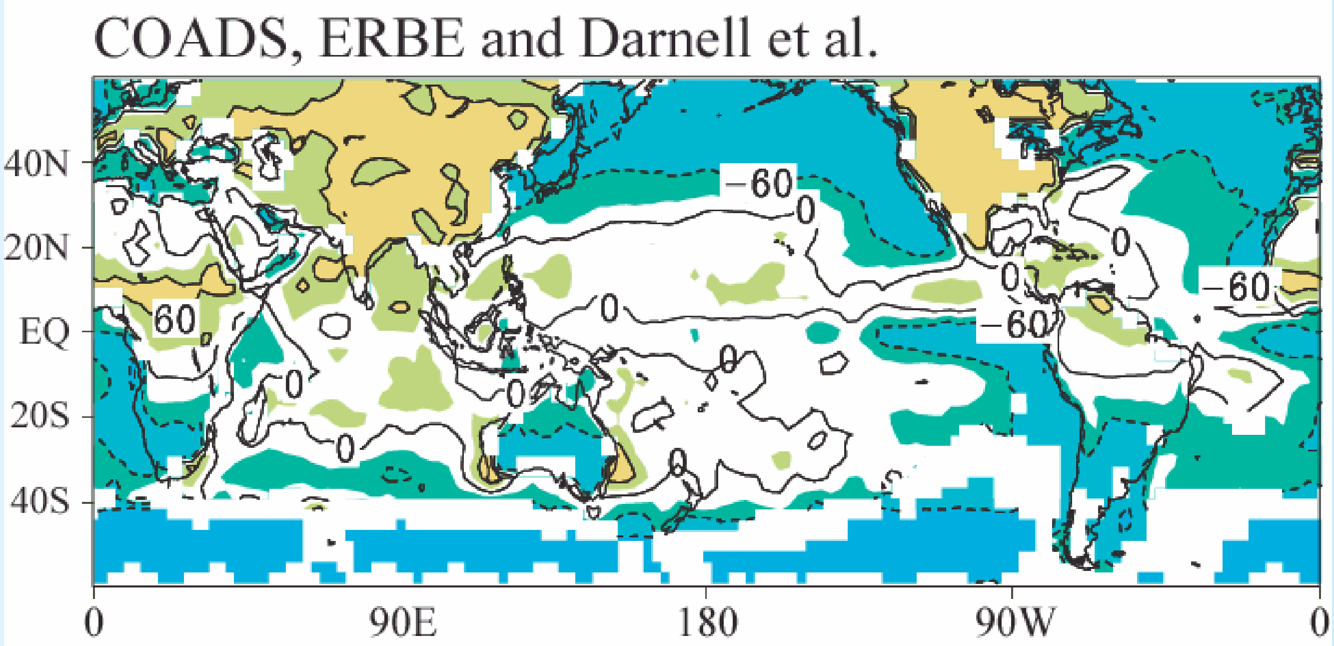


Observed climatology July

Precipitation



Net Flux into the atmosphere



Temperature *T* and Moisture *q* equations

dry static energy $s = T + \phi$

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

convective heating

vertical velocity

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

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

moisture source/sink

Energy constraint in vertical integral ⟨ ⟩

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

⟨Moist static energy equation⟩

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

Transport of moist static energy by divergent flow
≈ (measure of divergence)
x gross moist stability

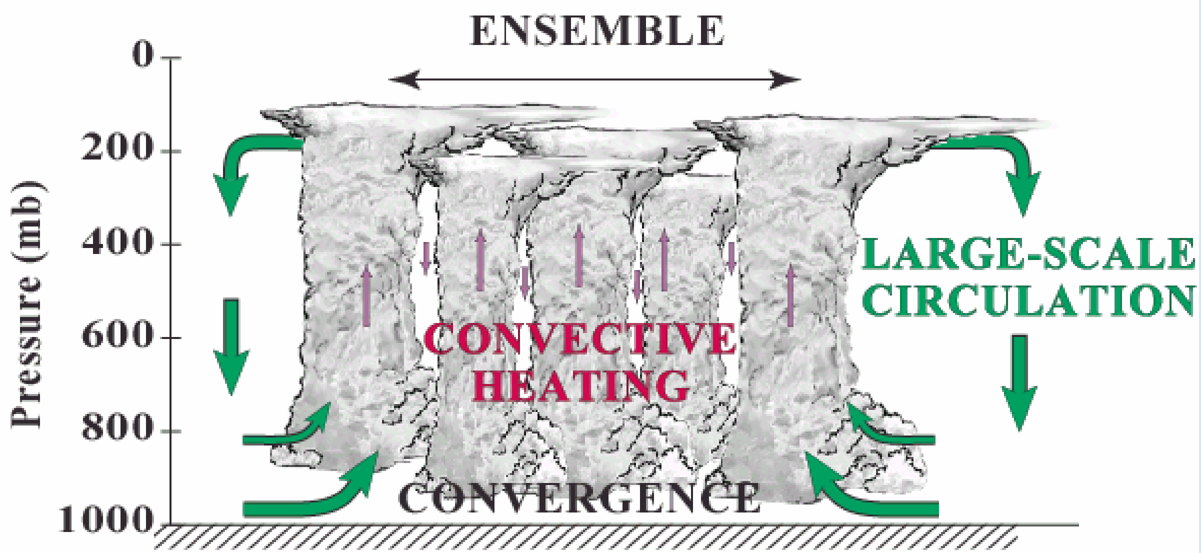
Net energy flux into column

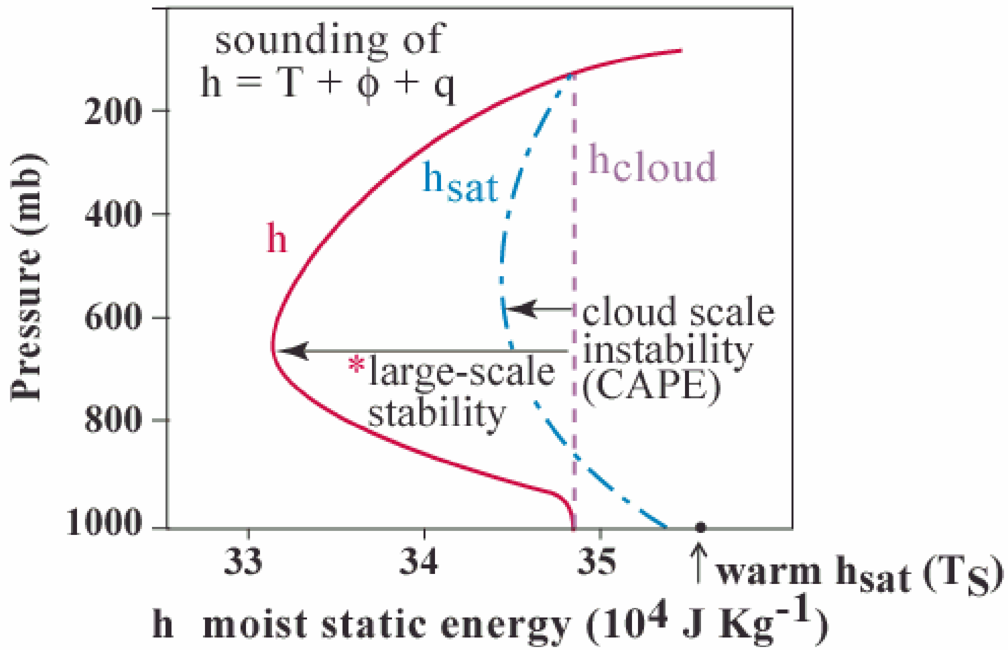
Moist static energy
$h = s + q$

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**

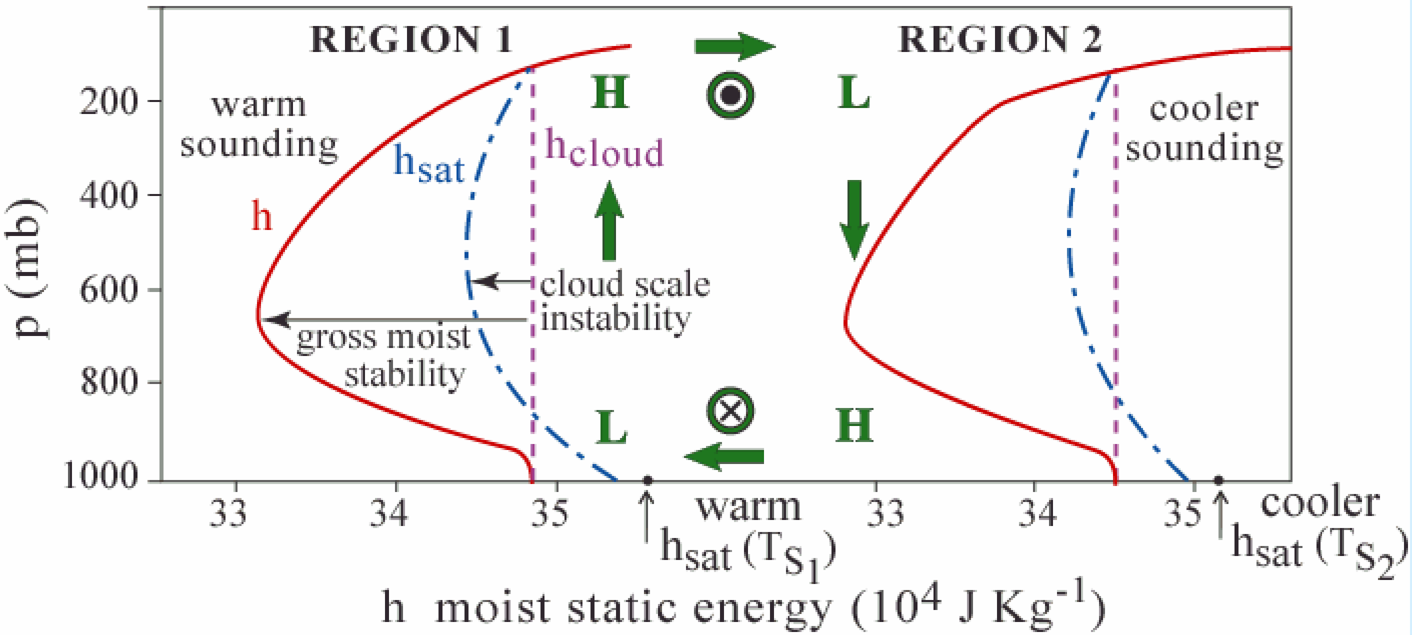




(After Neelin (1997))

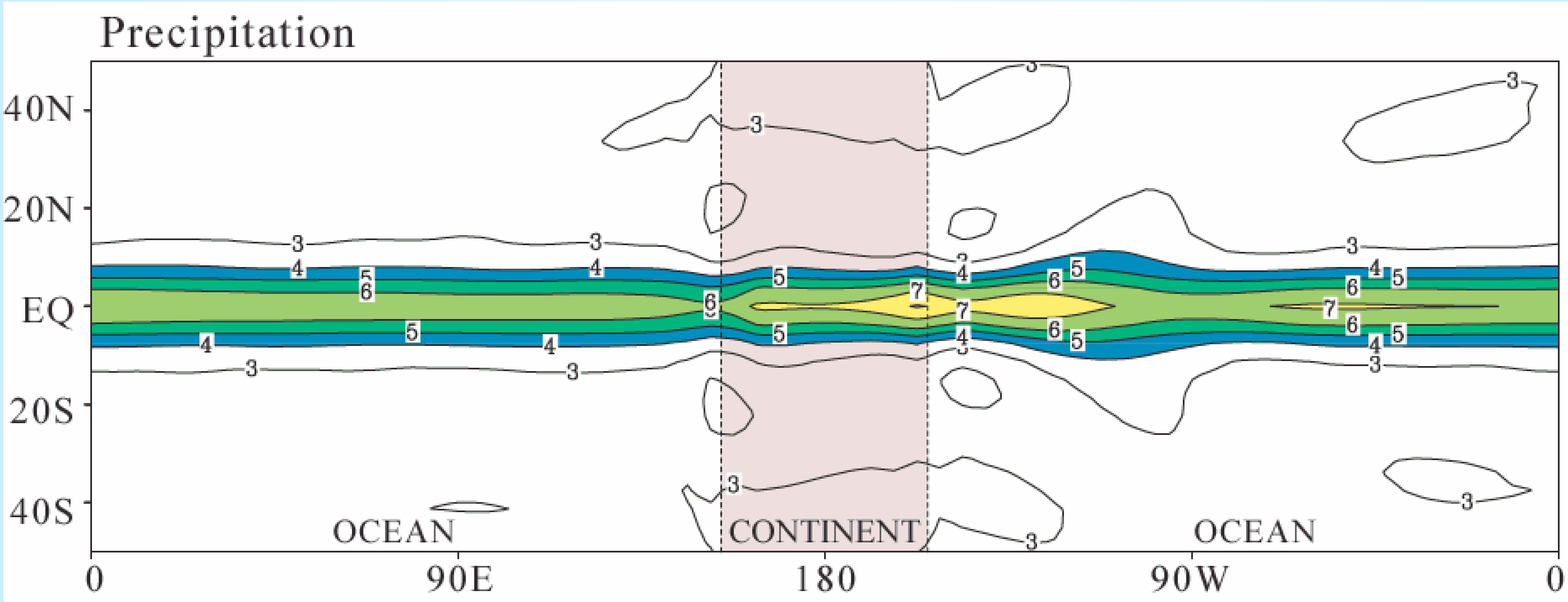
Refs: Arakawa & Schubert 1974; Emanuel et al 1994; Neelin & Yu 1994; Brown & Bretherton 1997; Neelin & Zeng 2000

Q_c constrains temperature through deep column
➔ baroclinic pressure gradients



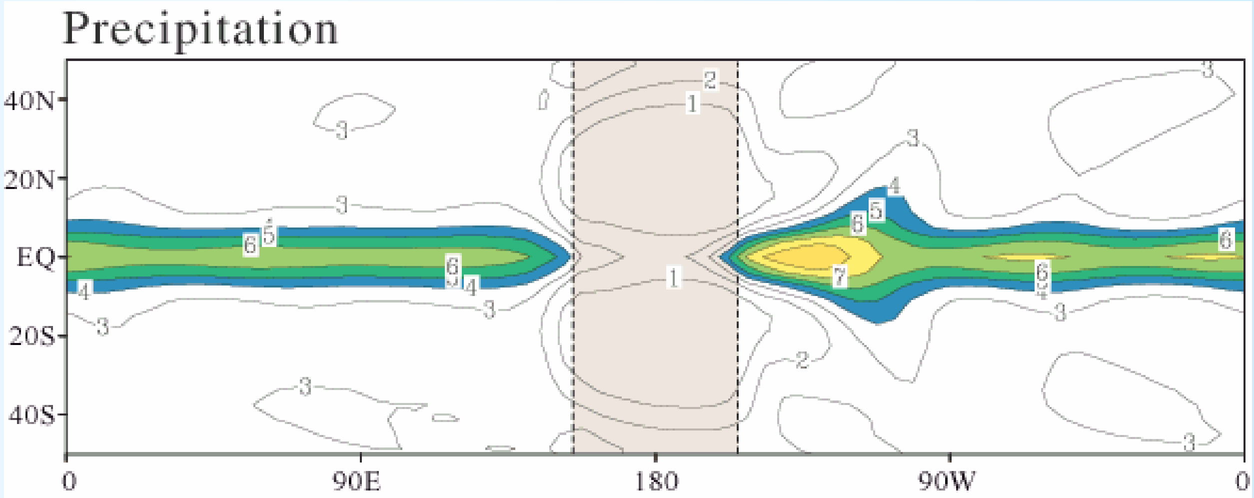
QTCM coupled to mixed-layer ocean, Idealized continent case

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



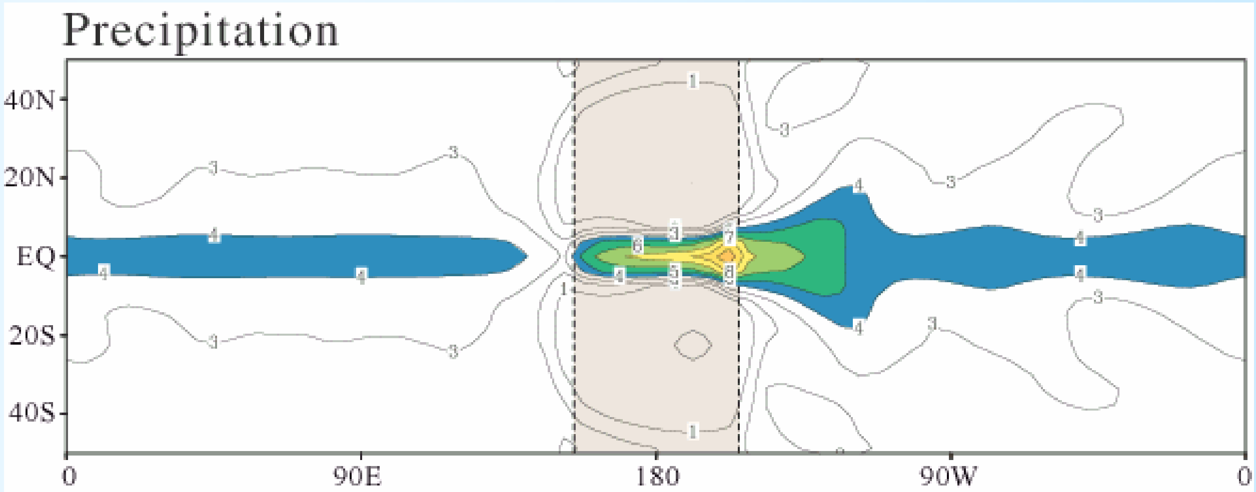
Zero ocean heat transport - Idealized continent case

- **Perpetual equinox**
- **Interactive soil moisture**

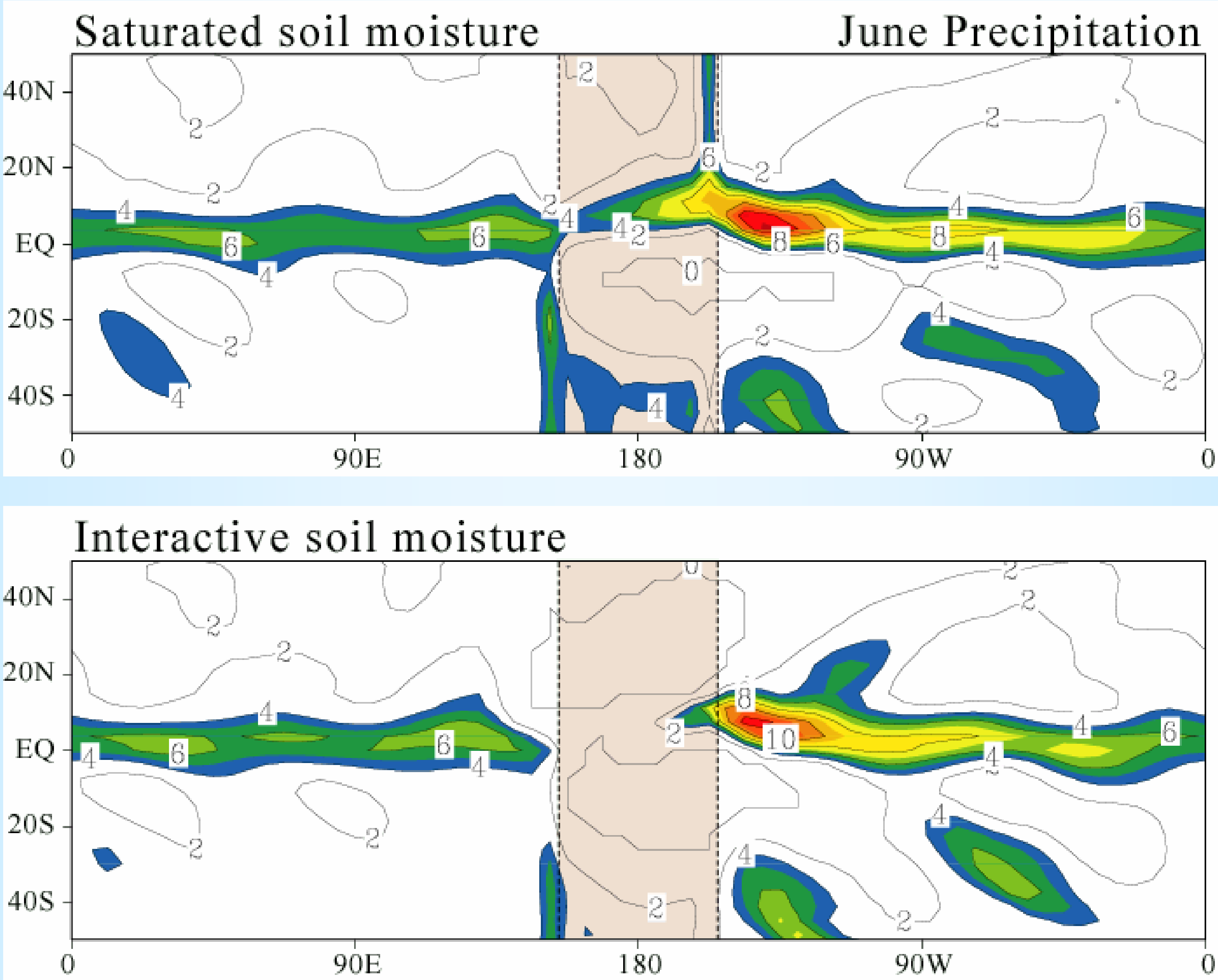


- **Divergence of ocean heat transport included as idealized Q flux**

$Q = Q_{max} \cos(3.5 \times \text{latitude})$, $Q_{max} = 20$ W/m (similar to observed zonal average)



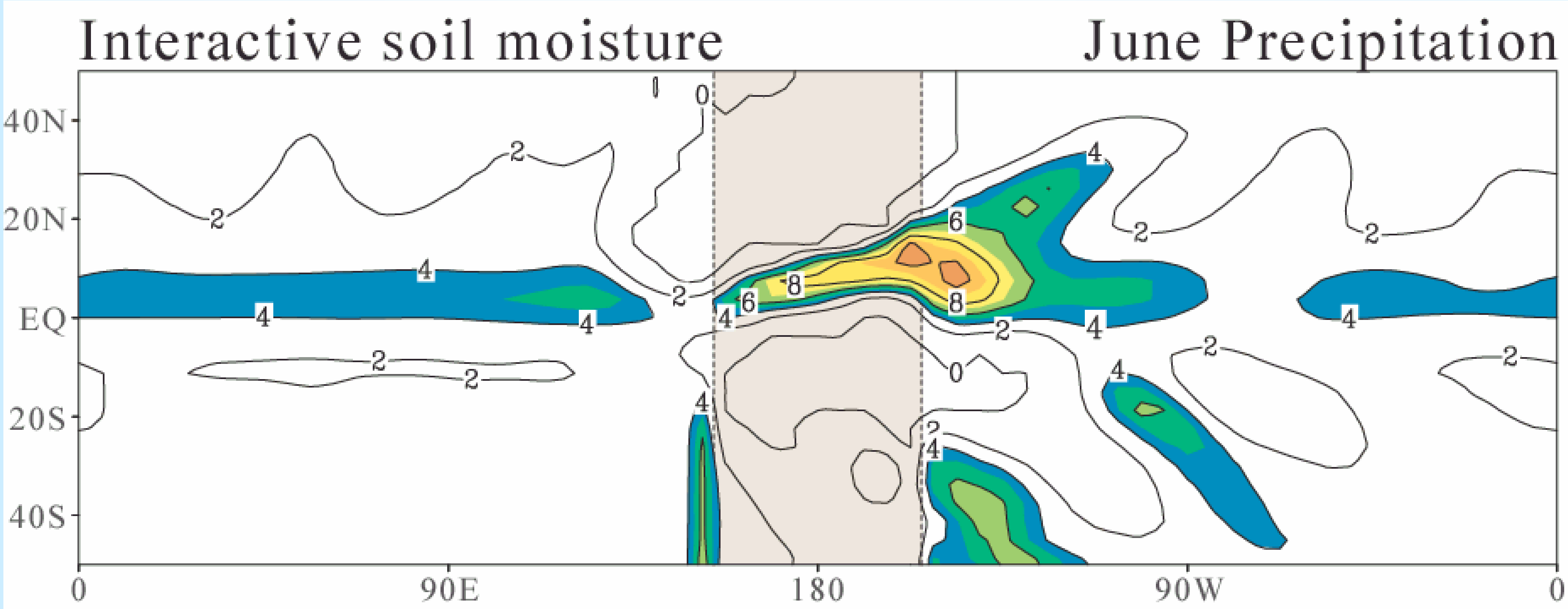
Zero ocean heat transport - Seasonal cycle case



$Q_{max} = 20\ W/m^2$

- **Interactive soil moisture**
- **Divergence of ocean heat transport**

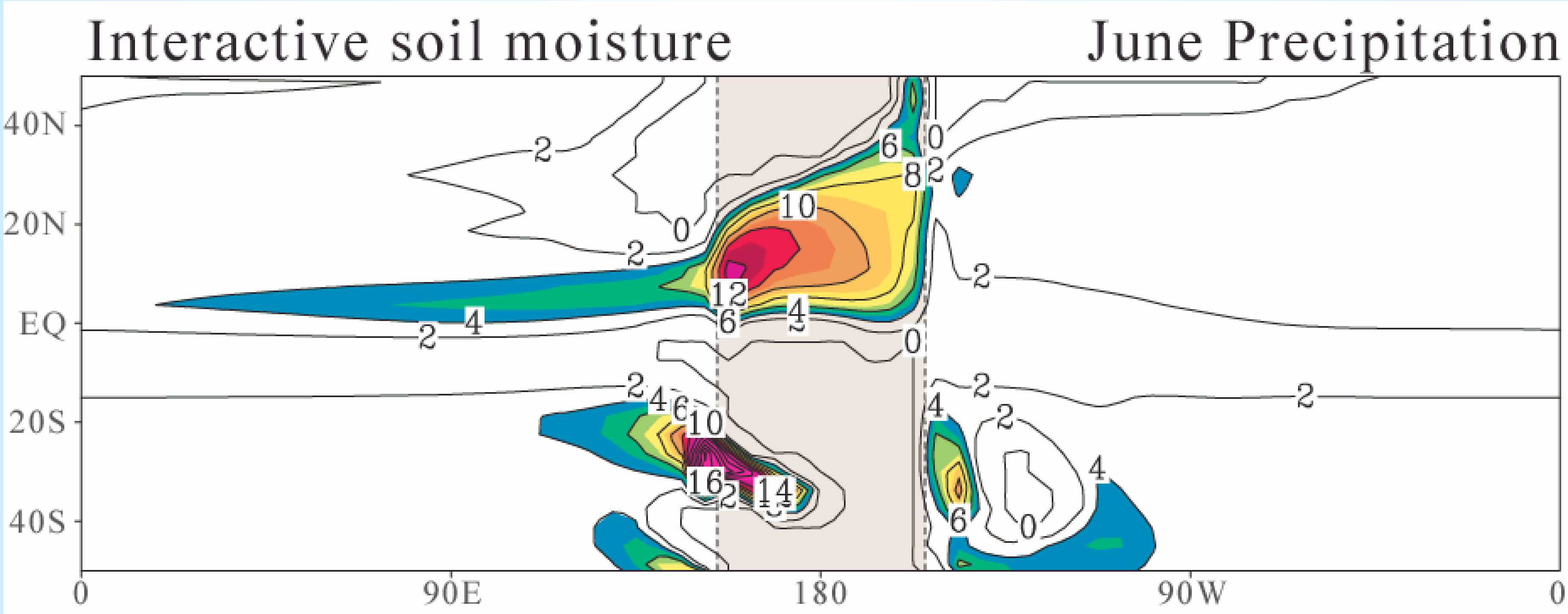
$Q = Q_{max} \cos(3.5 \times \text{latitude})$



Qmax = 50 W/m^2

- Interactive soil moisture
- Divergence of ocean heat transport

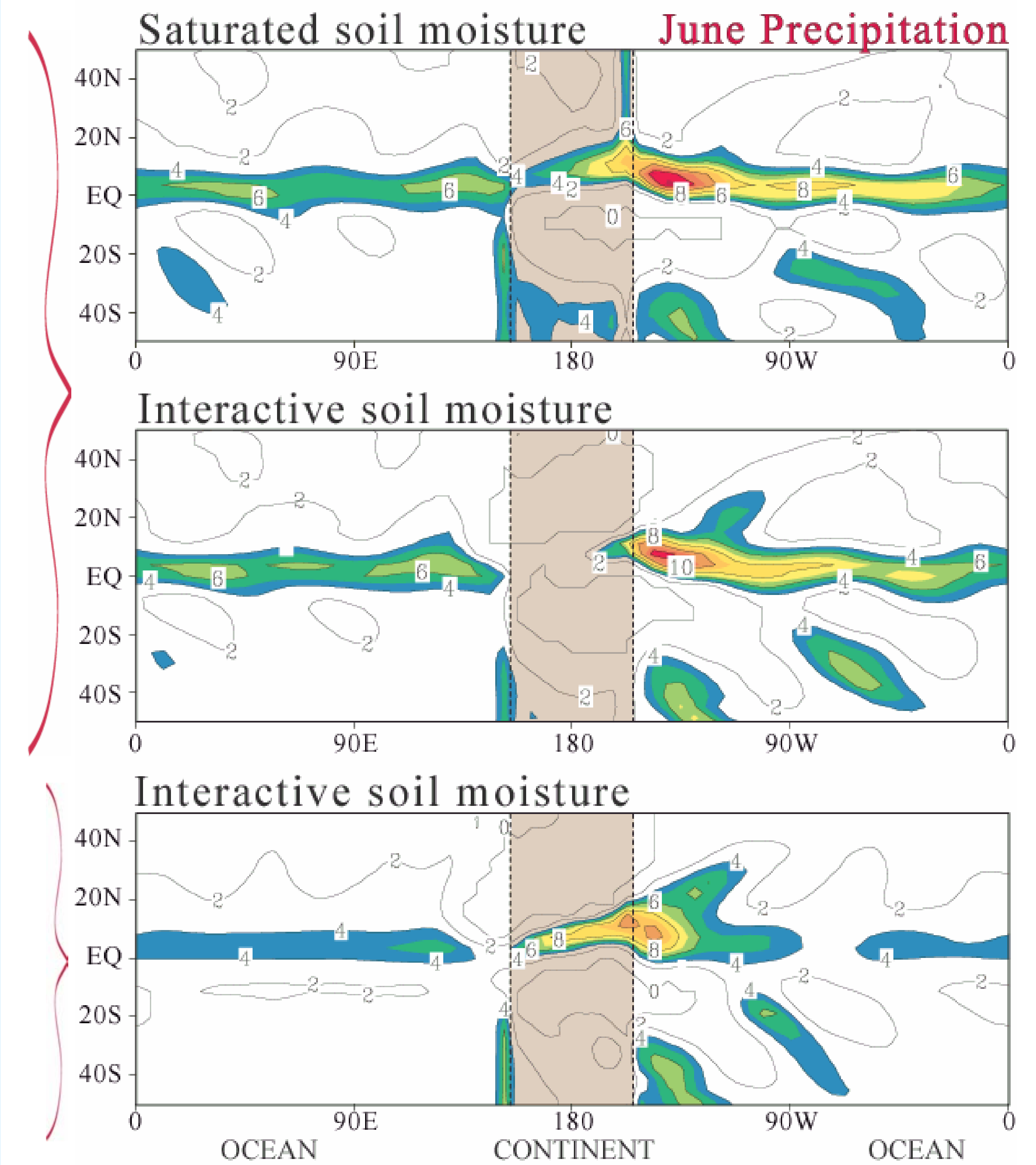
$Q = Qmax \cos(3.5 \times \text{latitude})$



QTCM + mixed-layer ocean - Idealized continent case

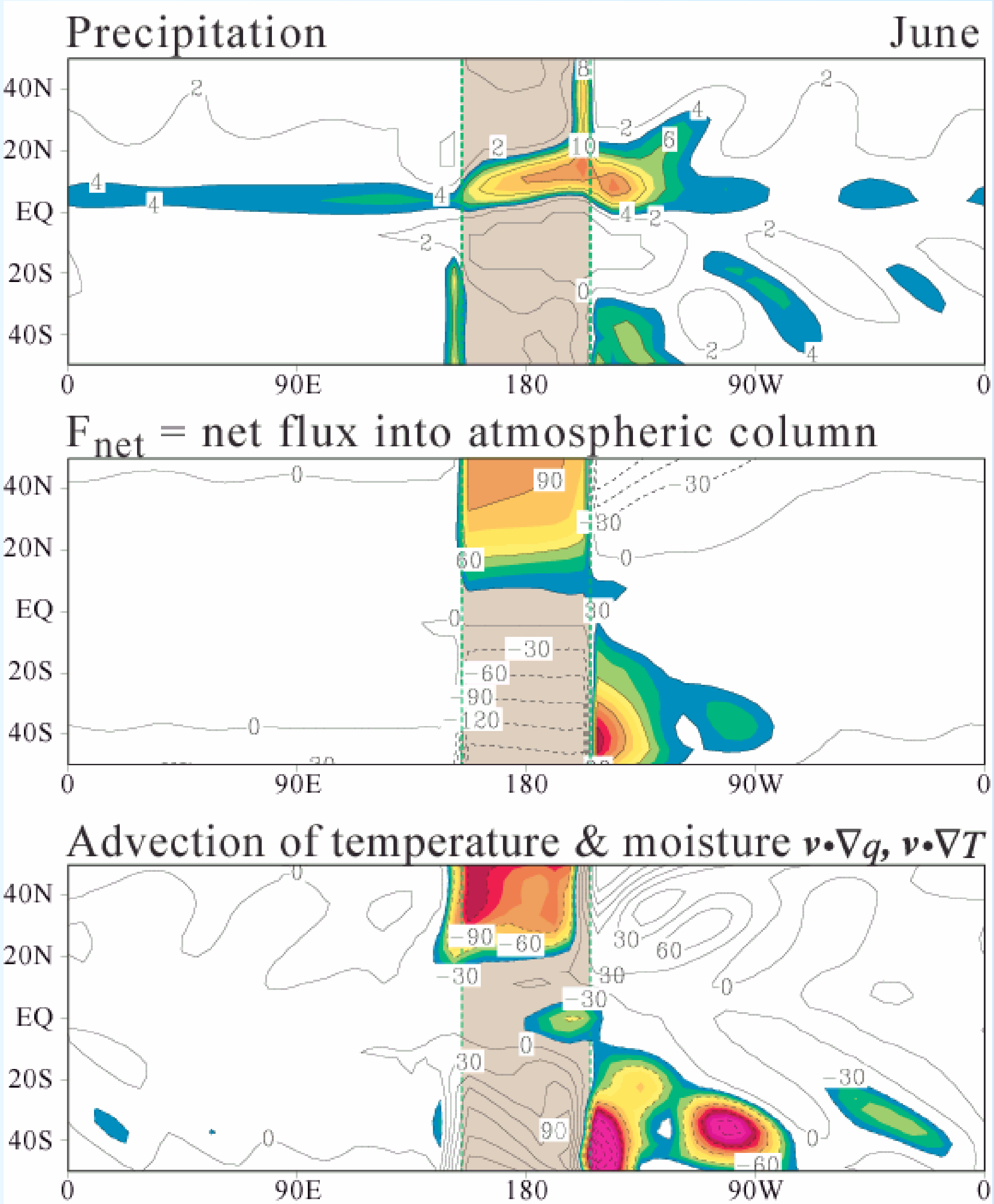
- **Zero ocean heat transport**

- **Idealized divergence of ocean heat transport**
  $Q = Q_{max} \cos(3.5 \times \text{latitude})$,
  $Q_{max} = 20\ W/m^2$



Idealized continent case

- **Divergence of ocean heat transport**
  $Q = Q_{max} \cos(3.5 \times \text{latitude})$,
  $Q_{max} = 20\ W/m^2$
- **Saturated soil moisture case**



The "interactive Rodwell-Hoskins mechanism"

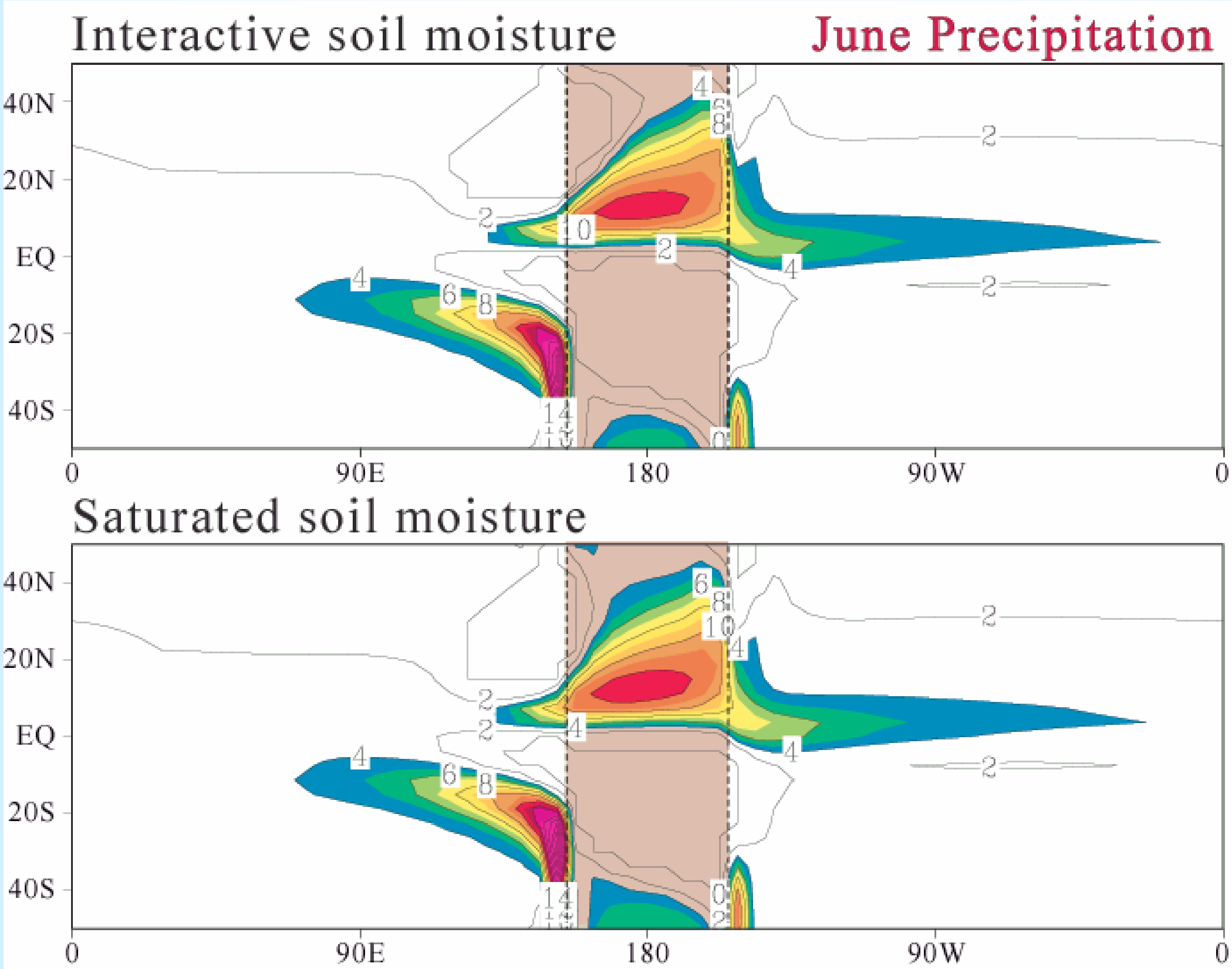
- Rodwell and Hoskins (1996): imposed convective heating in Asia gives Rossby wave descent pattern to west, enhancing deserts.
- when convection is interactive: associated flow feeds back on heating, creating characteristic convection/dry region pattern
  - » we emphasize feedback (convection ⇔ baroclinic 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

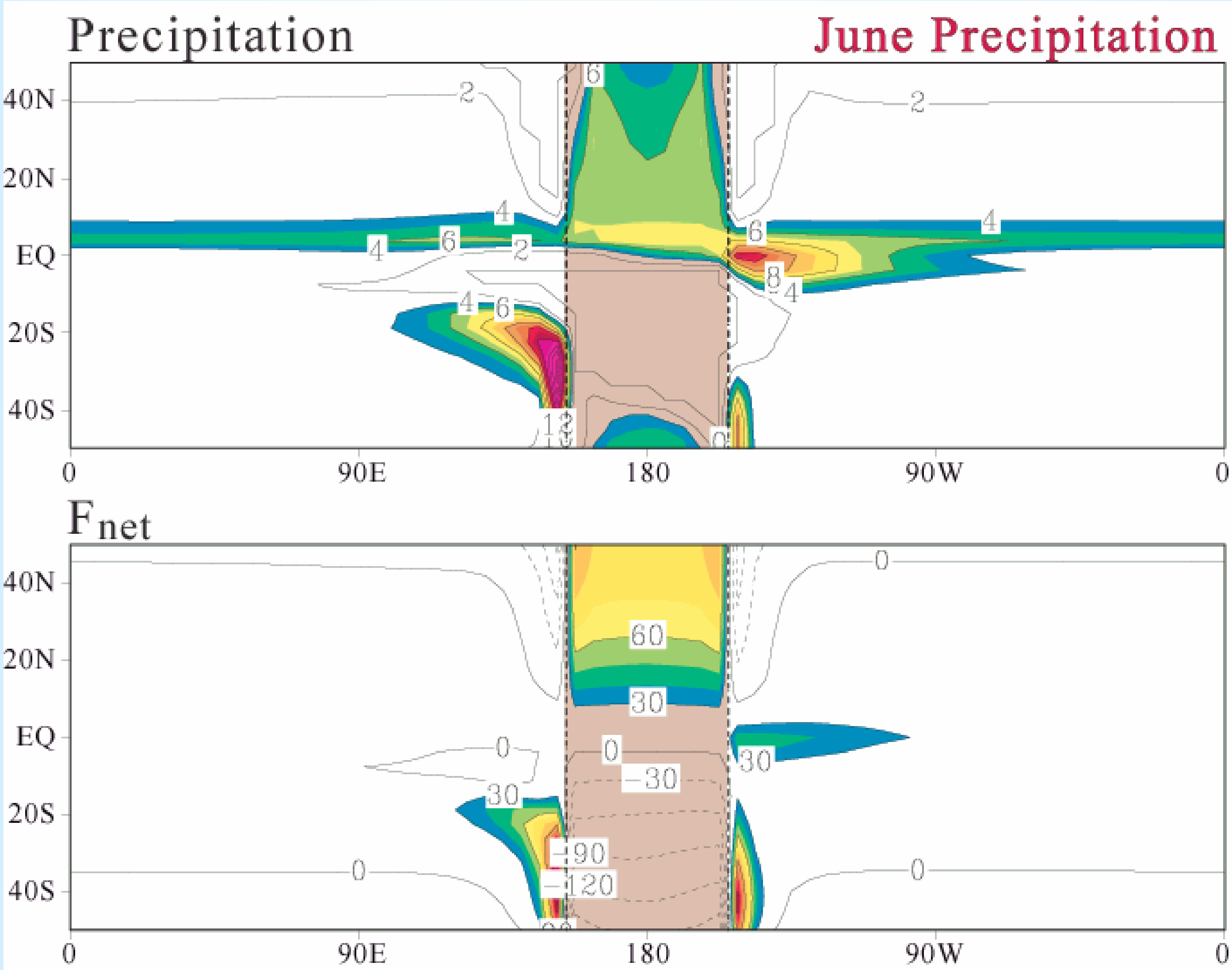
Experiments with ventilation mechanism suppressed

- $v \bullet \nabla T$ and $v \bullet \nabla q$ set to zero in temperature and moisture equations
- Divergence of ocean heat transport $Q = Q_{max} \cos(3.5 \times \text{latitude})$, $Q_{max} = 20\ W/m^2$



Ventilation suppressed and no β-effect

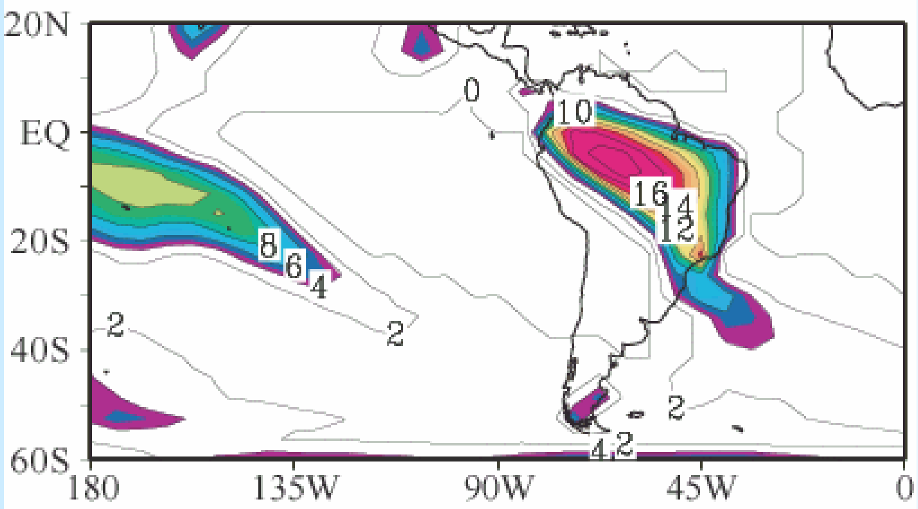
- Coriolis parameter *f* set to constant *f*(13N) in northern hem. (north of 2N)
- Divergence of ocean heat transport $Q = Q_{max} \cos(3.5 \times \text{latitude})$, $Q_{max} = 20\ W/m^2$



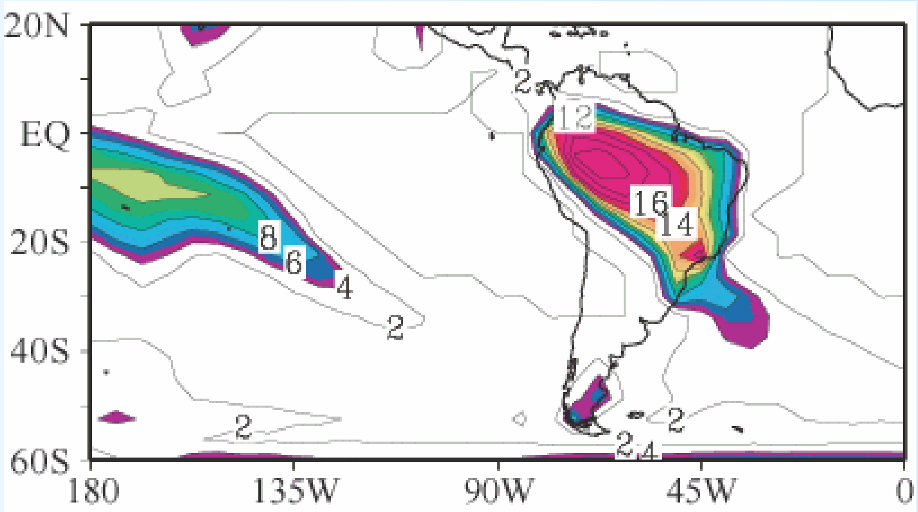
South American region case (observed albedo) Jan

Precipitation

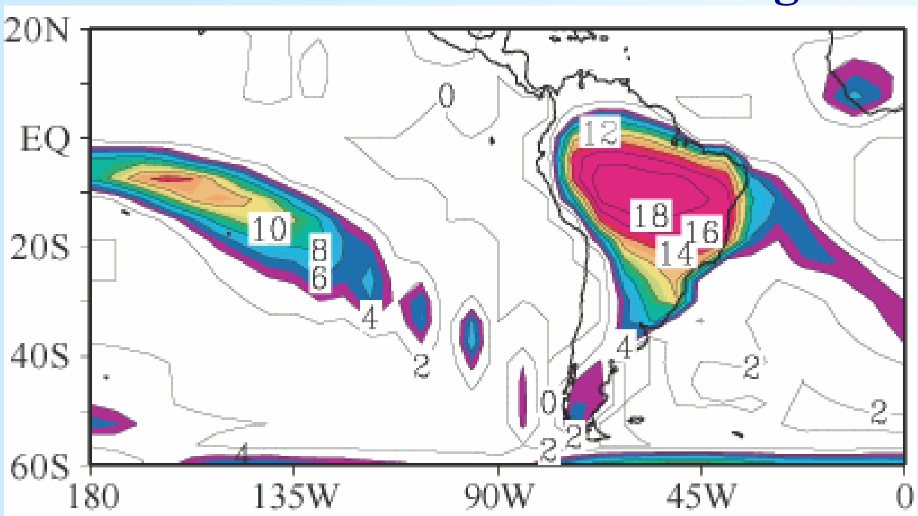
Control



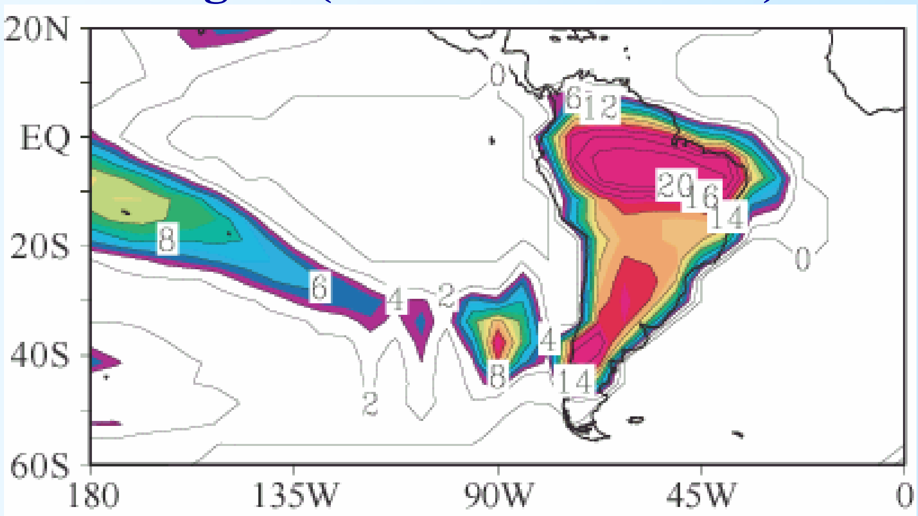
Saturated soil moisture over South American region



No ventilation: *v*•∇*q*, *v*•∇*T* set to zero over South American region



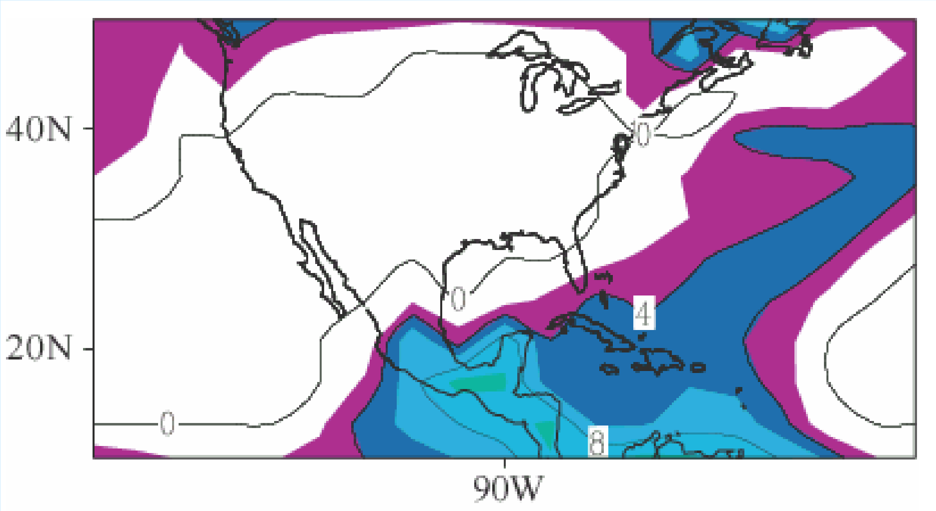
No ventilation and no β-effect: *f* = constant in South American region (9S-56S - 70W-20W)



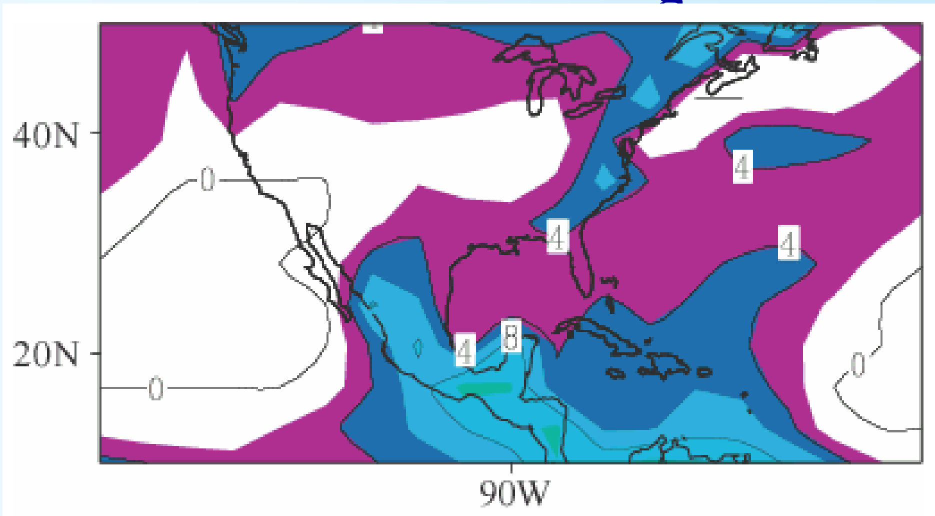
North American region case (observed albedo) July

Precipitation

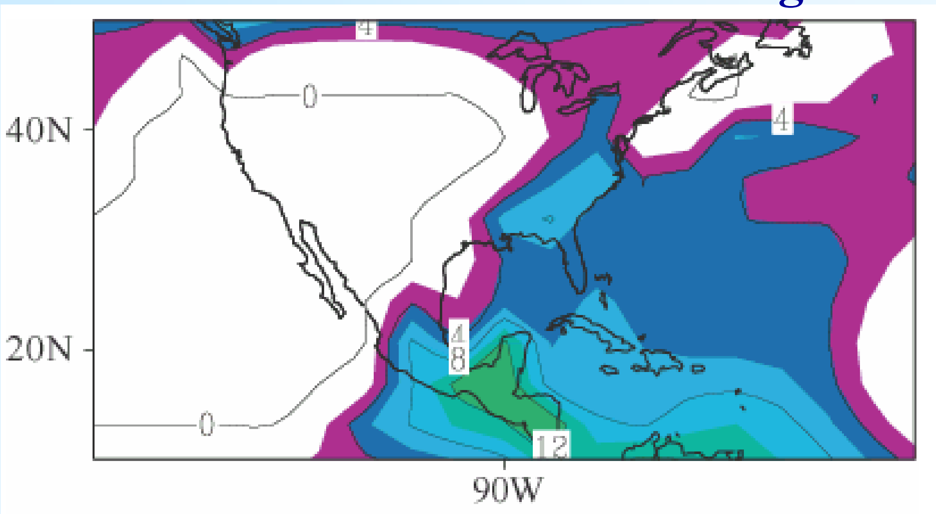
Control



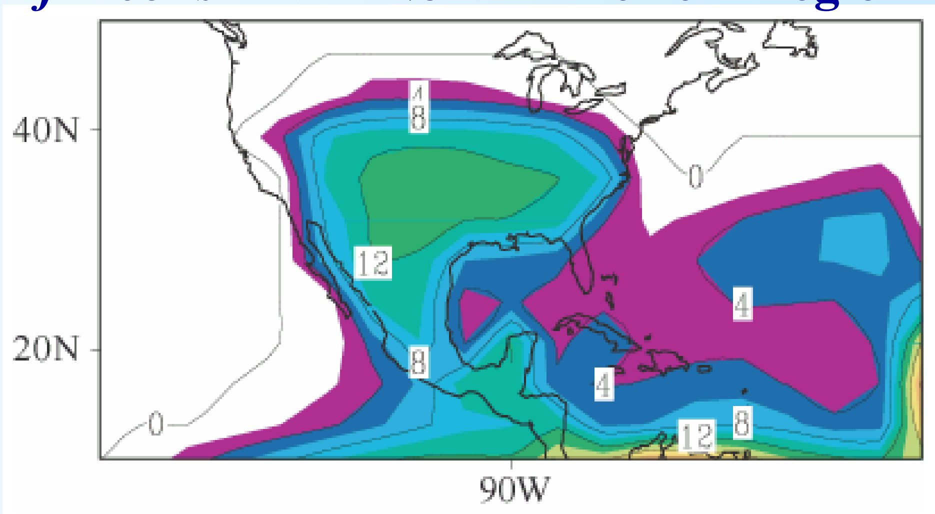
Saturated soil moisture over North American region



No ventilation: *v*•∇*q*, *v*•∇*T* set to zero over North American region



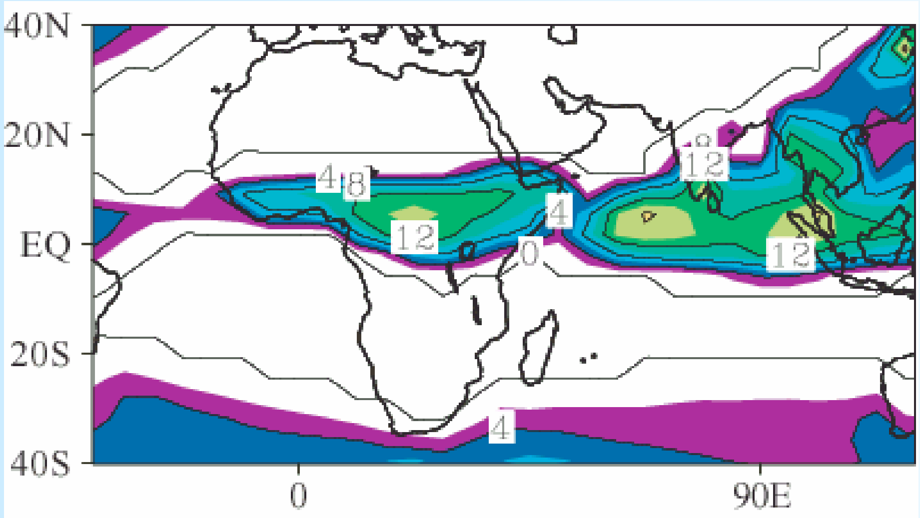
No ventilation and no β-effect: *f* = constant in North American region



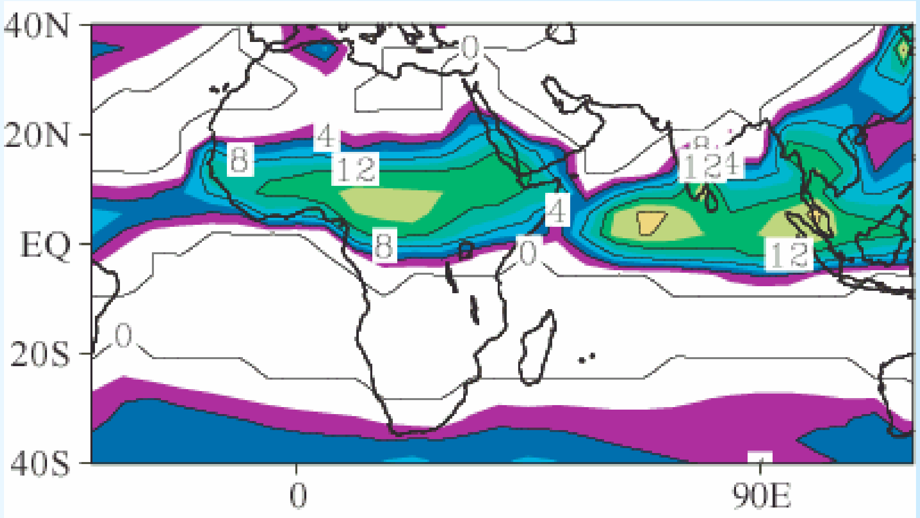
African region case (observed albedo) July

Precipitation

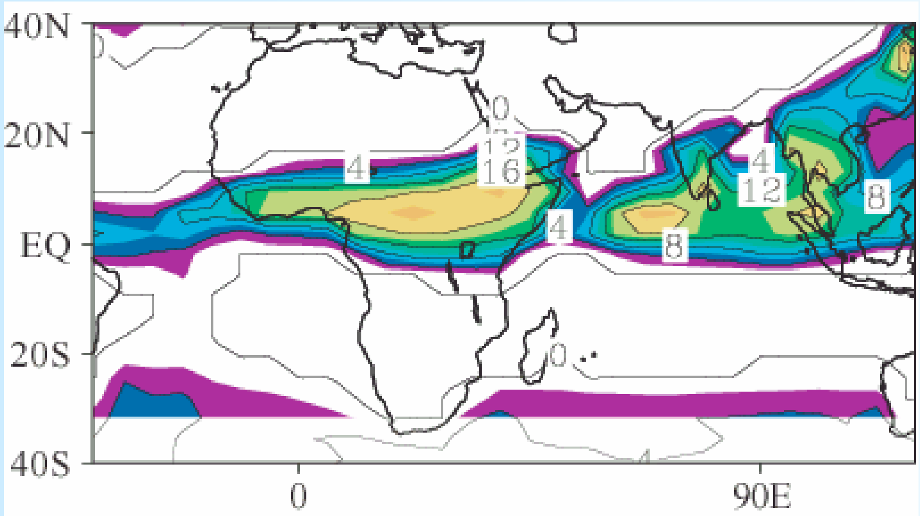
Control



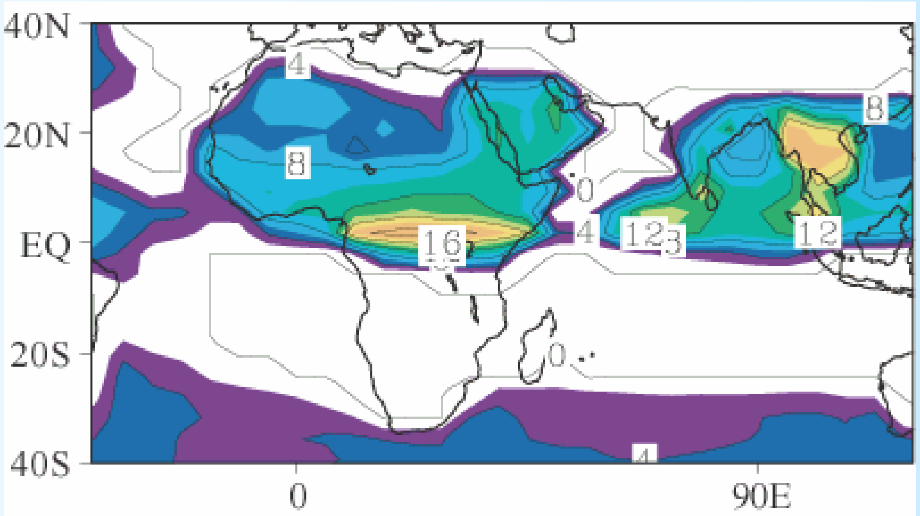
Saturated soil moisture over African region



No ventilation: $\mathbf{v} \bullet \nabla q$, $\mathbf{v} \bullet \nabla T$ set to zero over African region



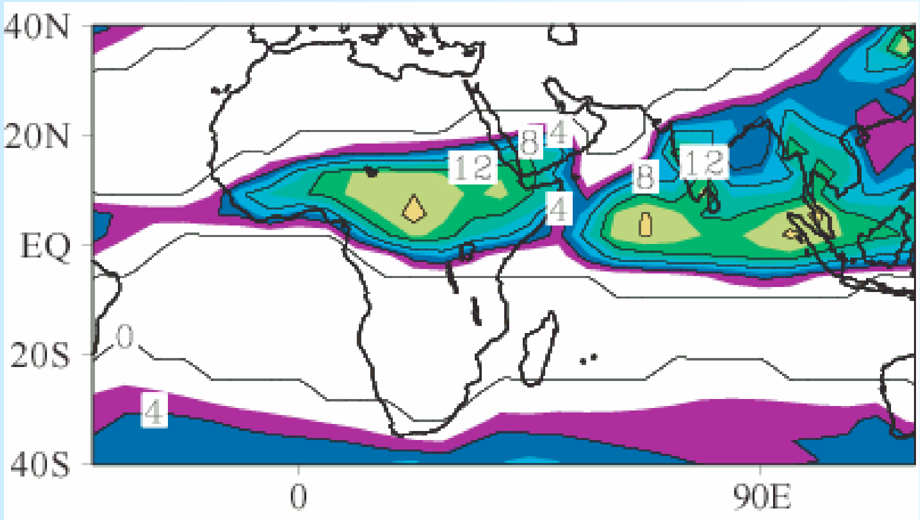
No ventilation and no β-effect: f = constant in African region (0 - 50N)



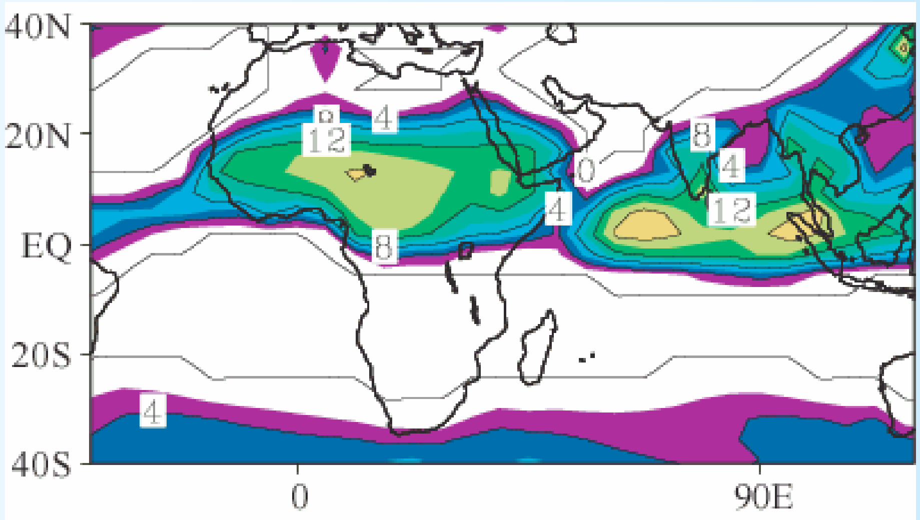
African region case (albedo set to 0.2 over land) July

Precipitation

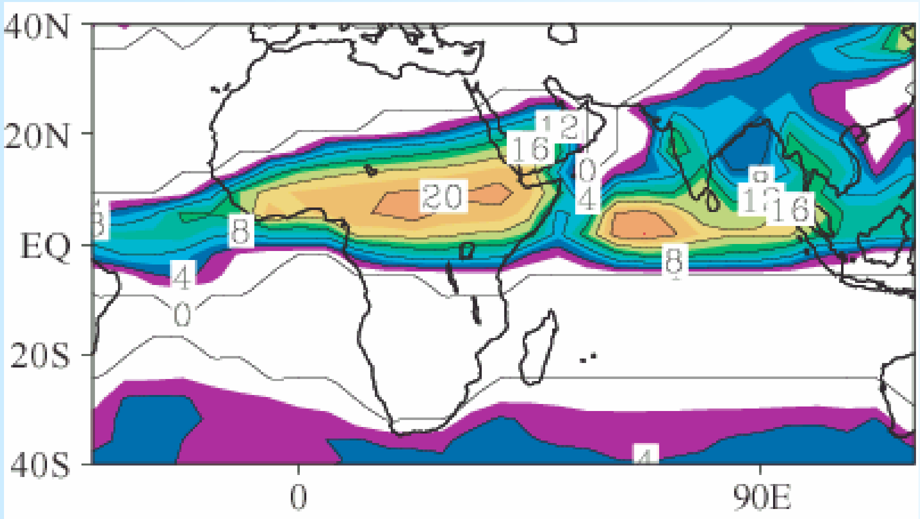
Control



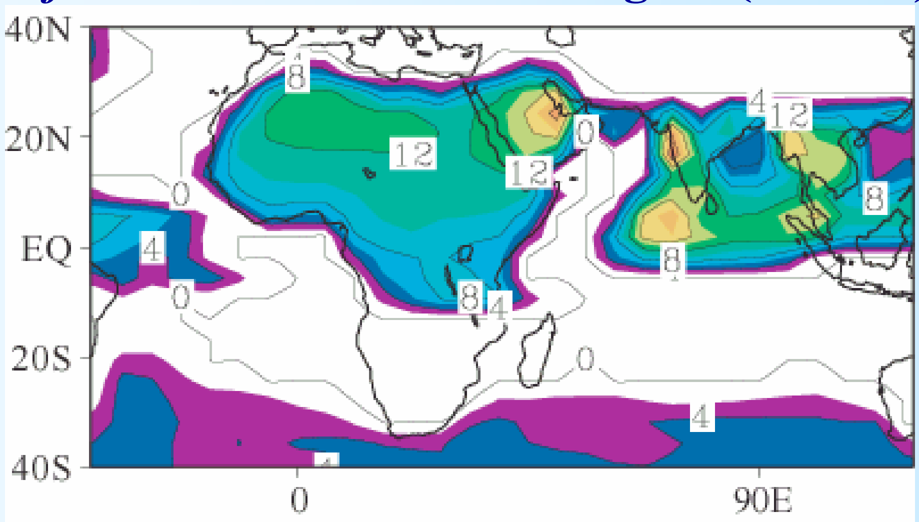
Saturated soil moisture over African region



No ventilation: $v \bullet \nabla q$, $v \bullet \nabla T$ set to zero over African region



No ventilation and no β-effect: f = constant in African region (0 - 50N)



Refinement of experimental design

1. Consistent treatment of $\boldsymbol{v}_\chi$:

- Irrotational (purely divergent) wind component $\boldsymbol{v}_\chi$
- Non-divergent wind component $\boldsymbol{v}_\psi$

➢ "No ventilation" = suppress $\boldsymbol{v}_\psi \cdot \nabla T$, $\boldsymbol{v}_\psi \cdot \nabla q$

➢ Retains conservation property: $\int_{\text{Domain}} (\boldsymbol{v}_\chi \cdot \nabla q + q \nabla \cdot \boldsymbol{v}) \mathrm{d}A = 0$ since $\nabla \cdot \boldsymbol{v}_\psi = 0$

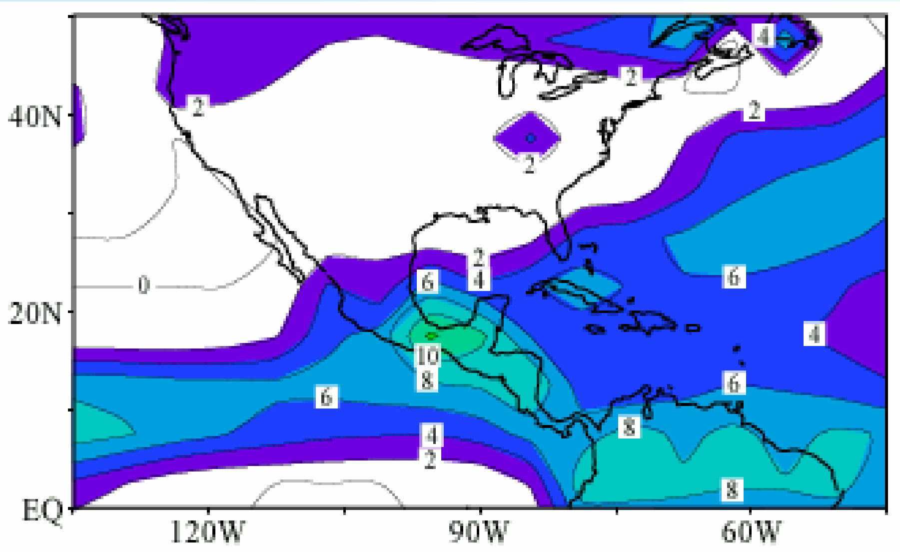
2. "Partial-β" experiment :

- Retain β - effect on zonal mean wind (across region)

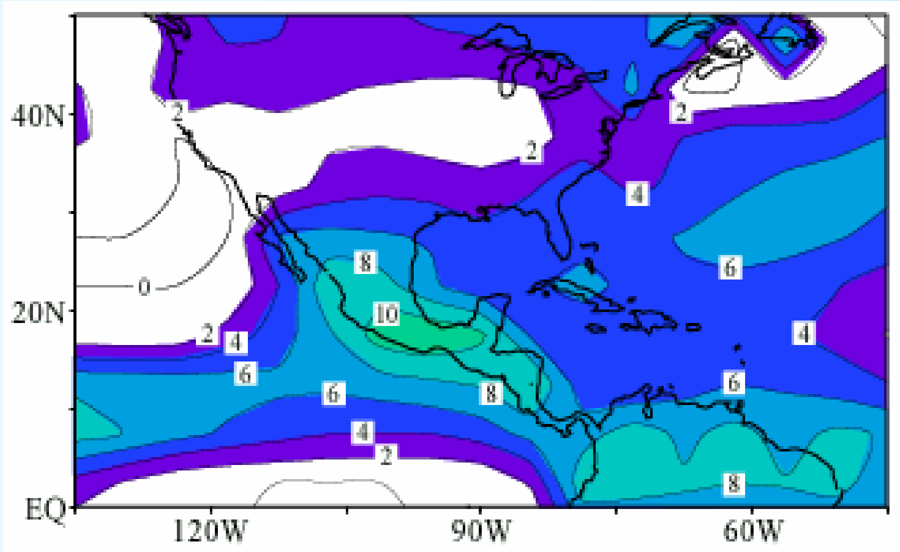
North American region case

July Precipitation

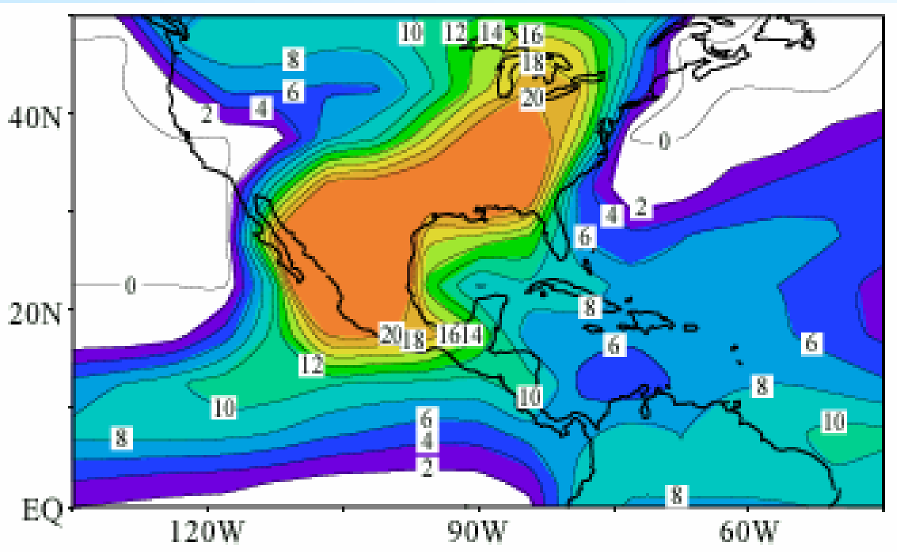
Control



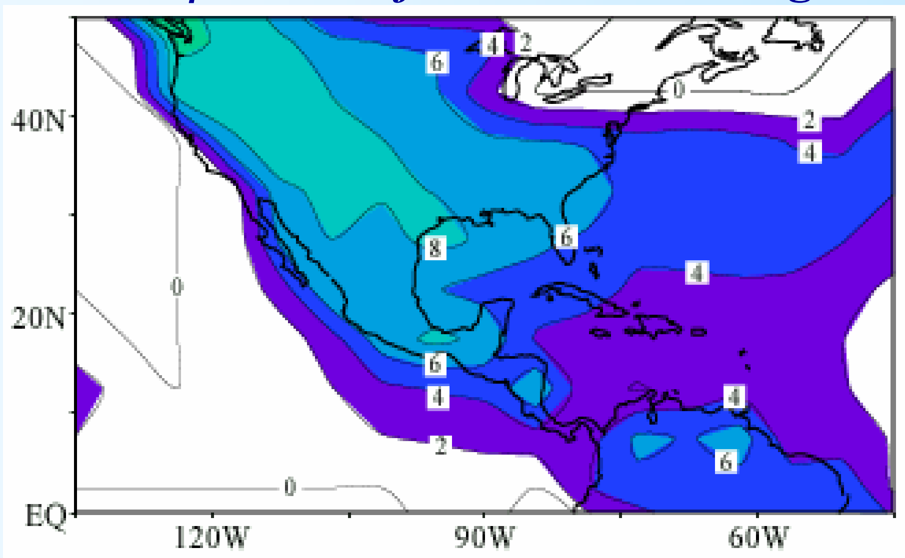
Saturated soil moisture



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



No β-effect: f = constant in region

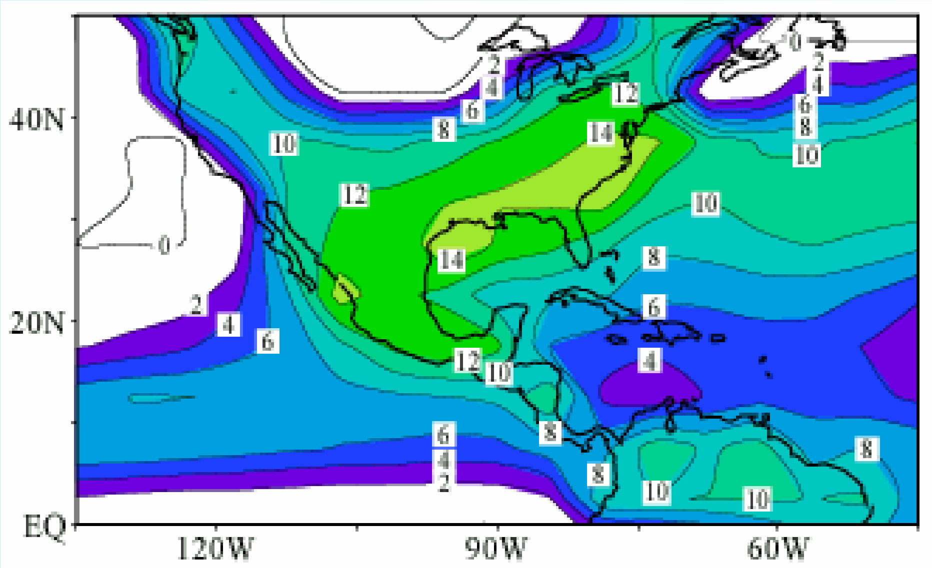


Chou and Neelin 2003

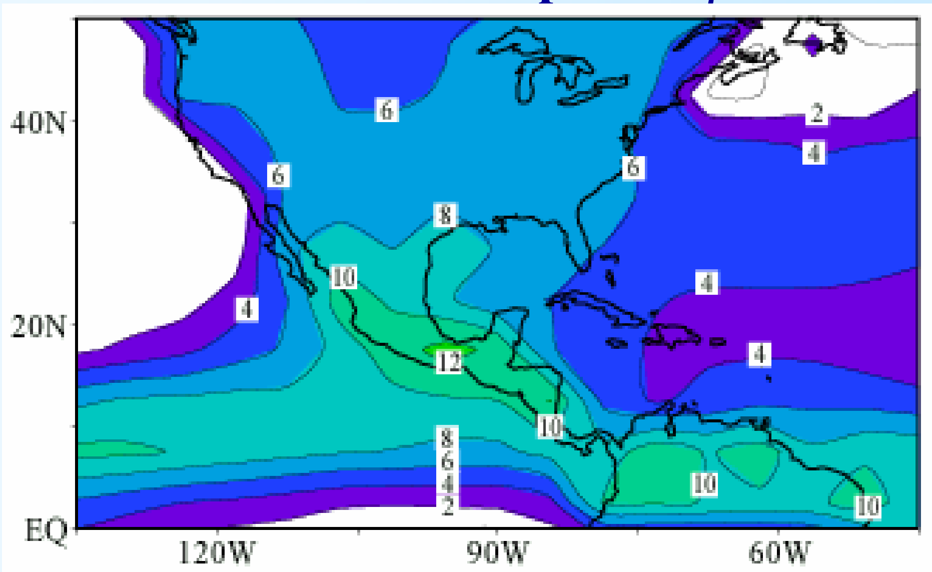
North American region case

July Precipitation

No ventilation and no β-effect:



No ventilation and partial β-effect

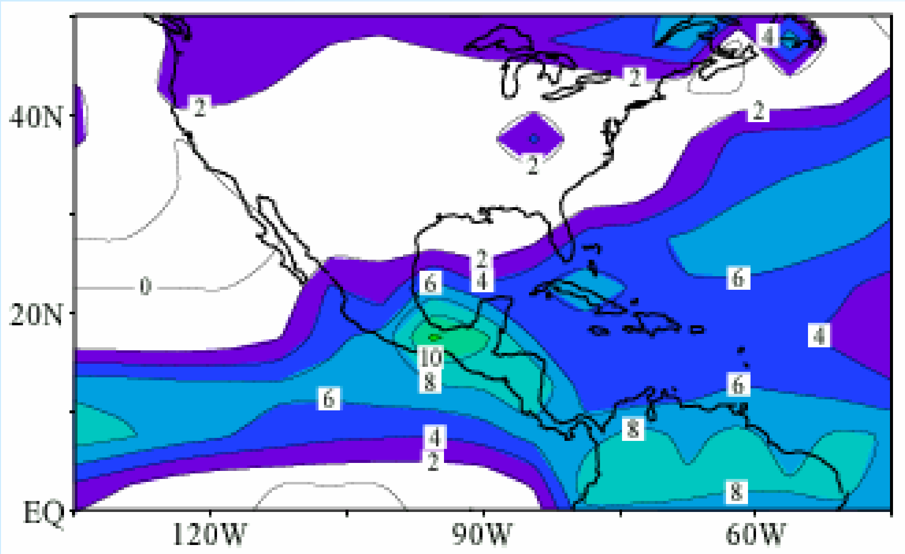


Chou and Neelin 2003

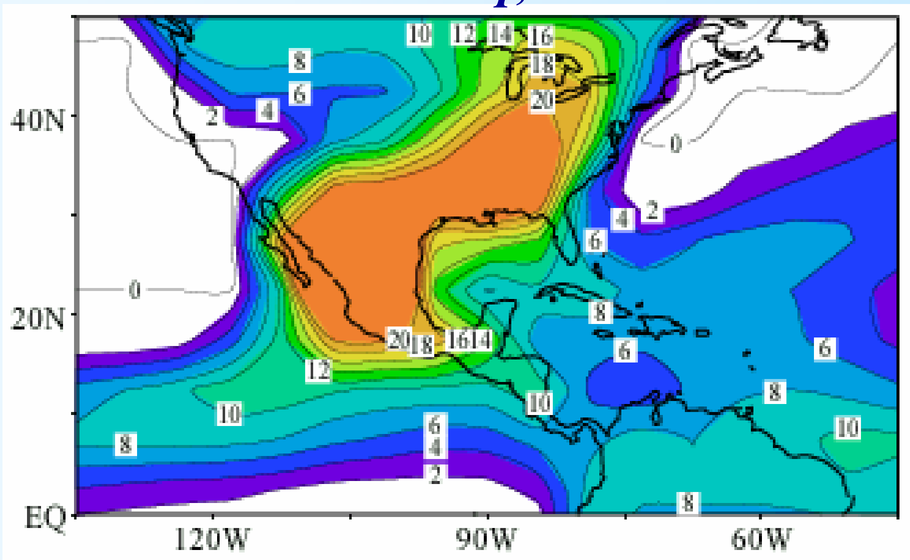
North American region case

July Precipitation

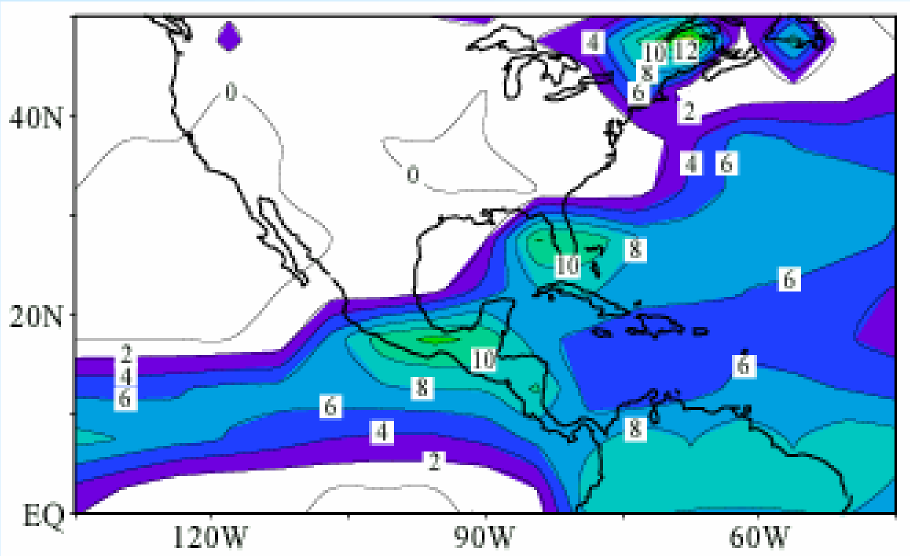
Control



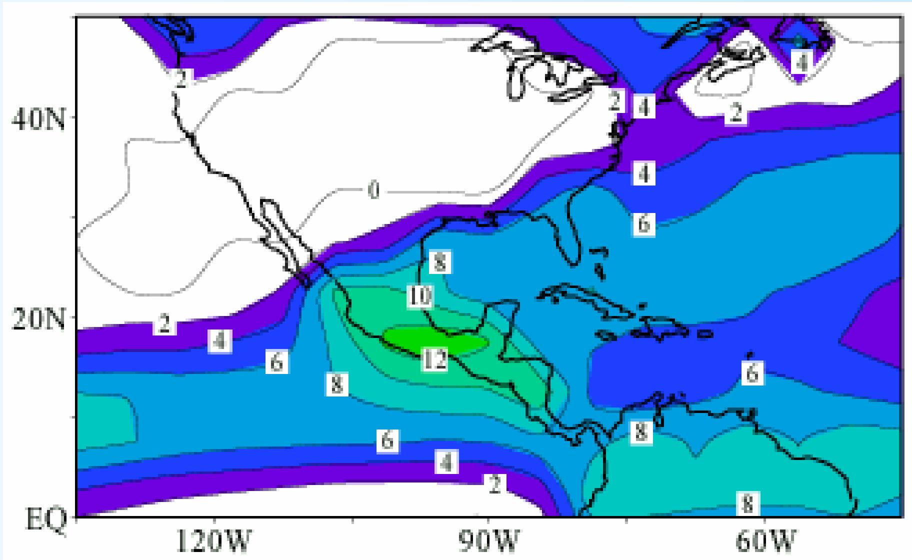
No ventilation: $v \bullet \nabla q$, $v \bullet \nabla T$ set to zero



No *T* ventilation



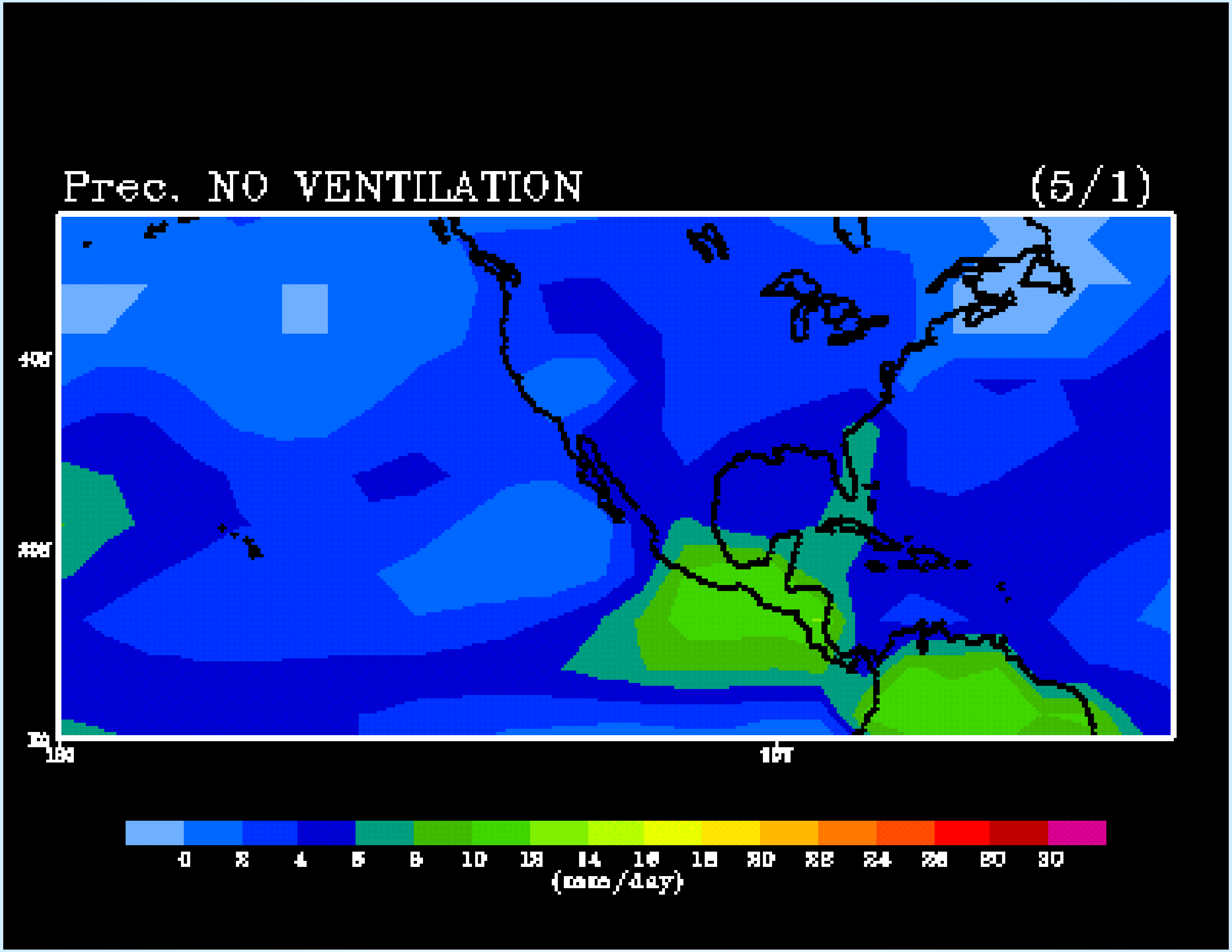
No *q* ventilation



Chou and Neelin 2003

North America with and without ventilation

Ventilation suppressed through May, turned on in June

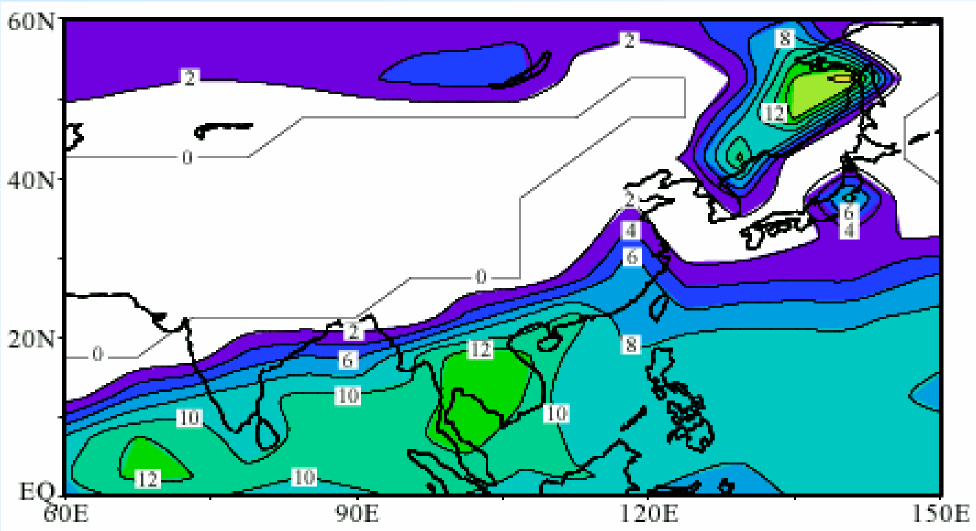


Start

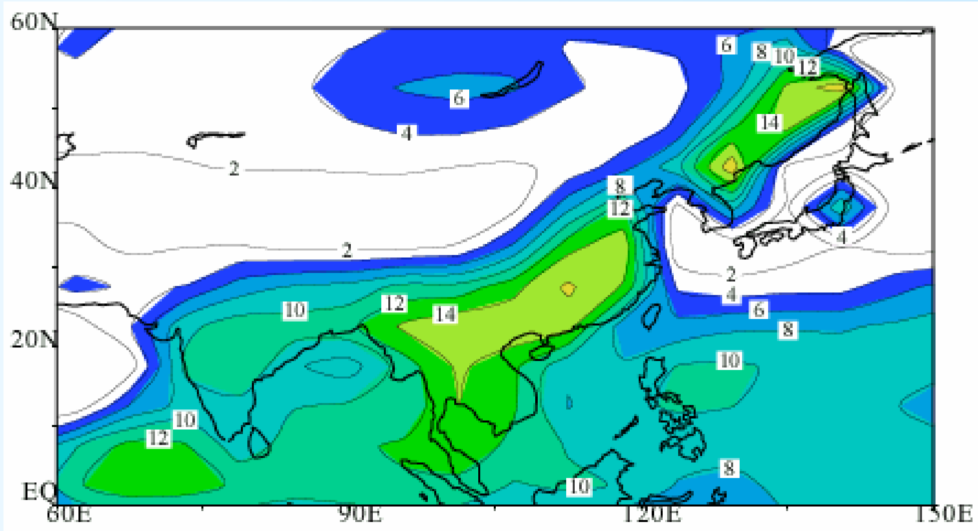
Asian region case – July

Precipitation

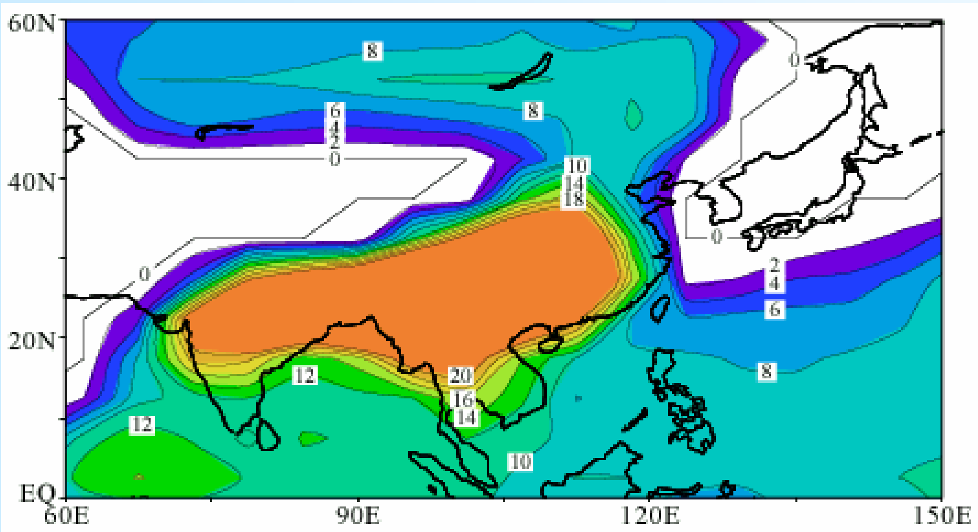
Control



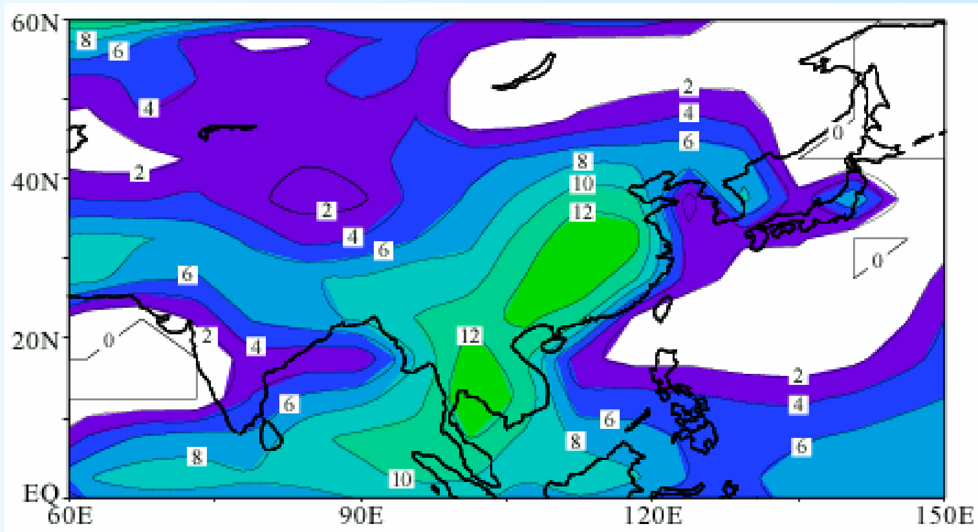
Saturated soil moisture



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



No β-effect: f = constant

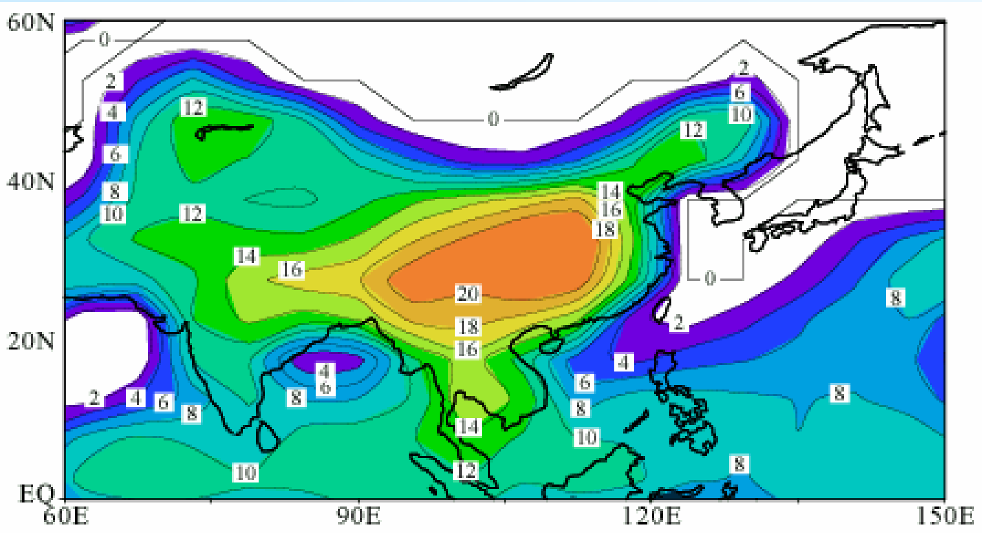


Chou and Neelin 2003

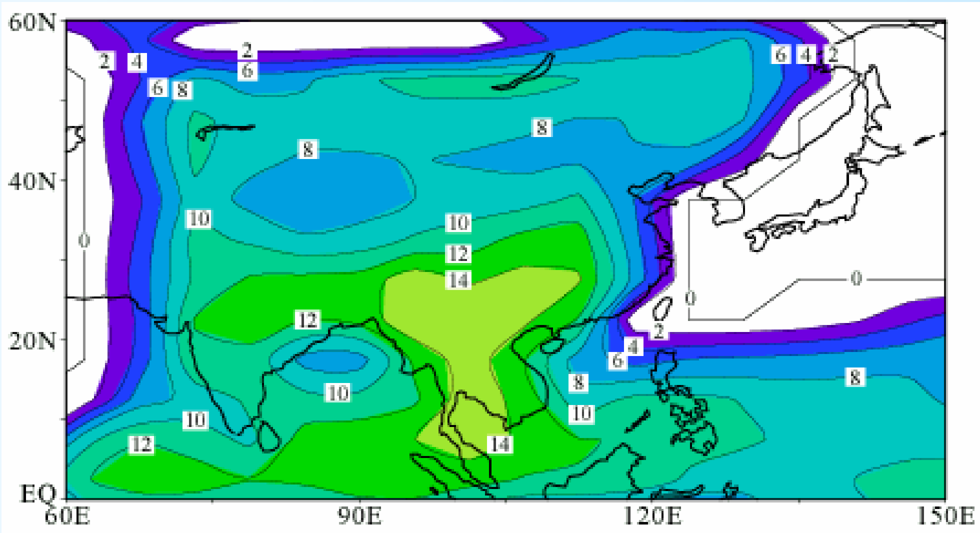
Asian region case – July

Precipitation

No ventilation and no β-effect:



No ventilation and partial β-effect

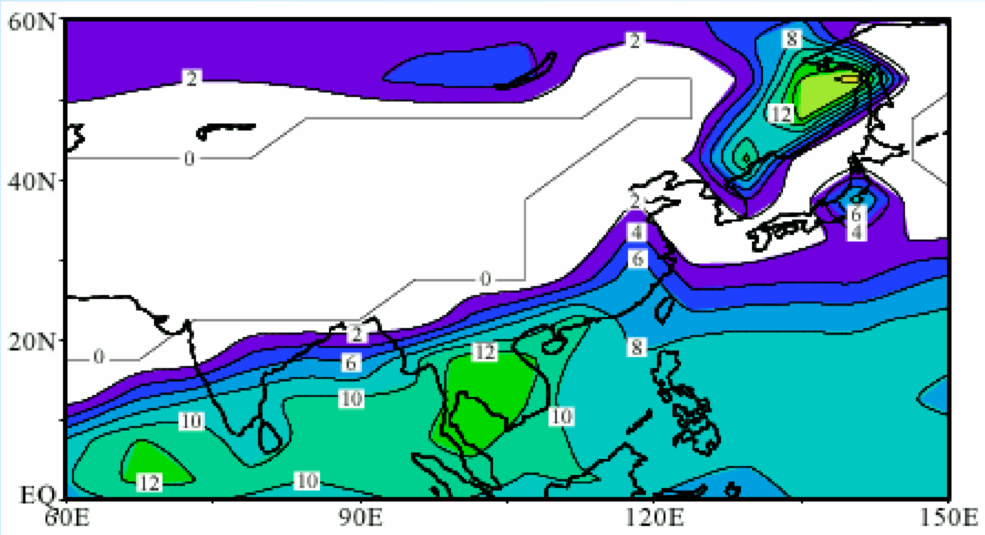


Chou and Neelin 2003

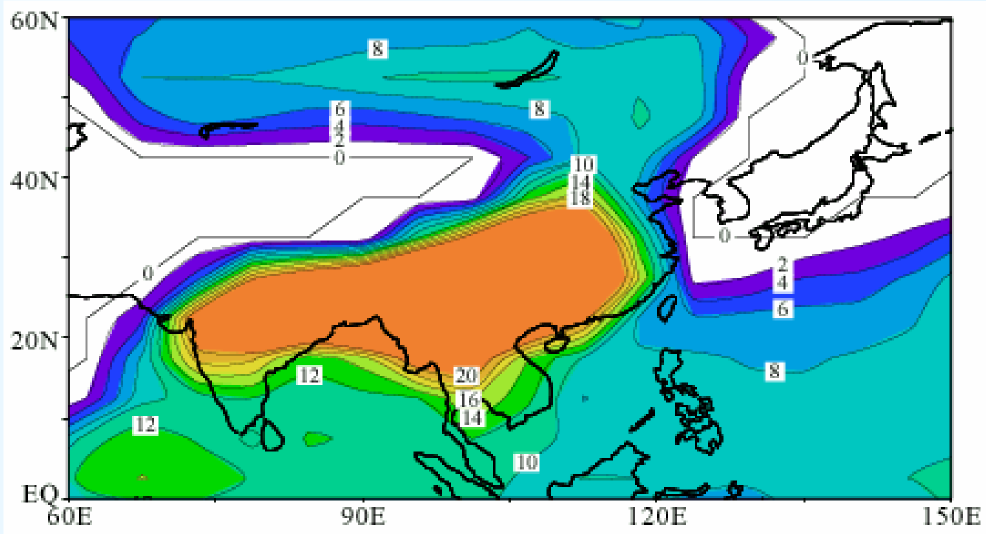
Asian region case – July

Precipitation

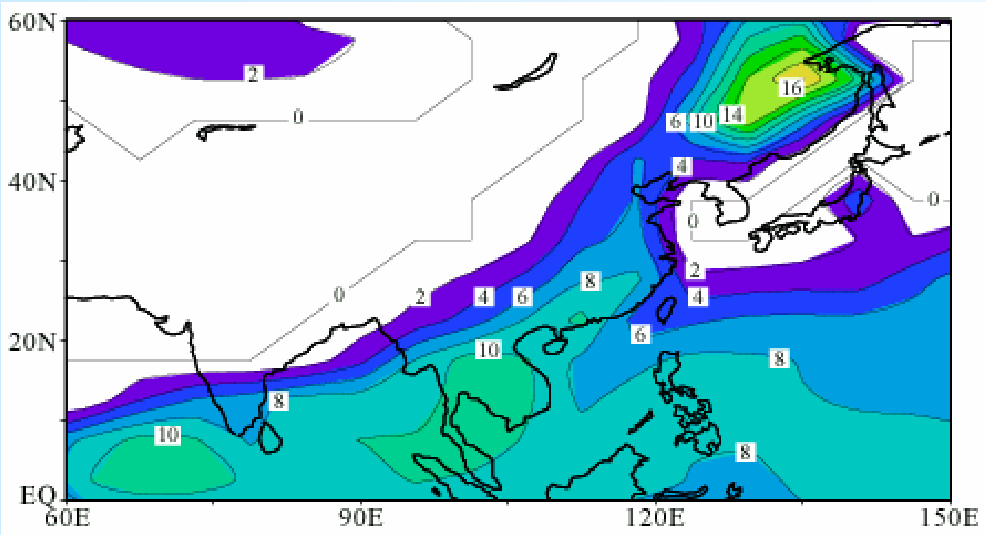
Control



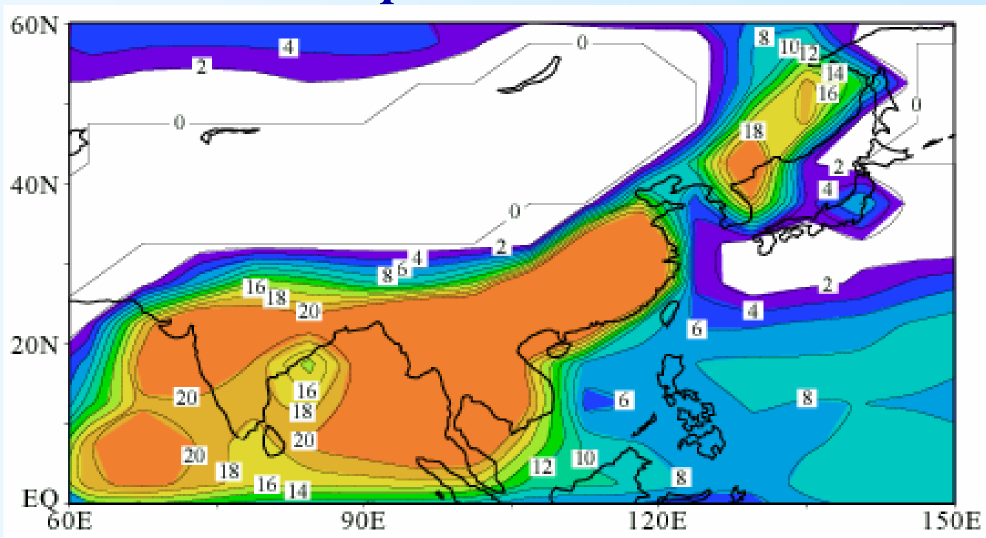
No ventilation: $v \bullet \nabla q$, $v \bullet \nabla T$ set to zero



No *T* ventilation



No *q* ventilation

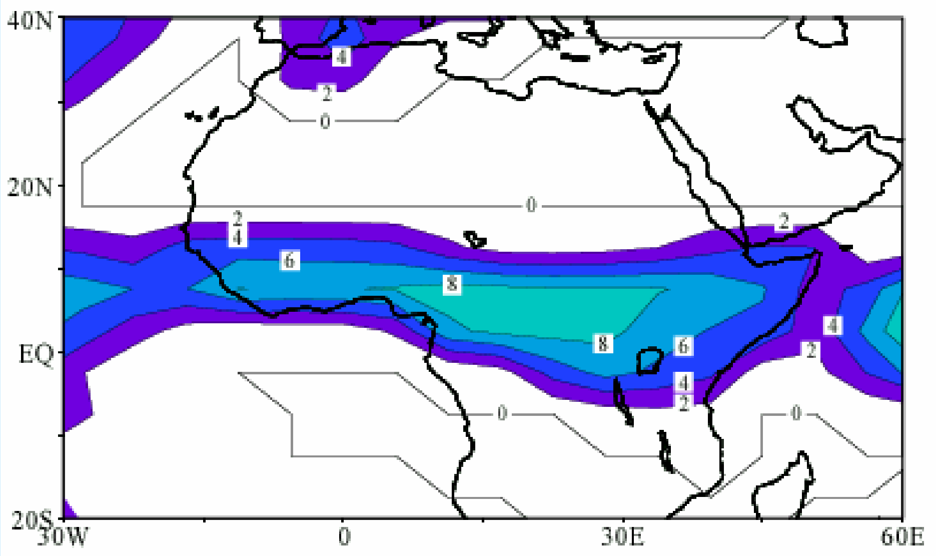


Chou and Neelin 2003

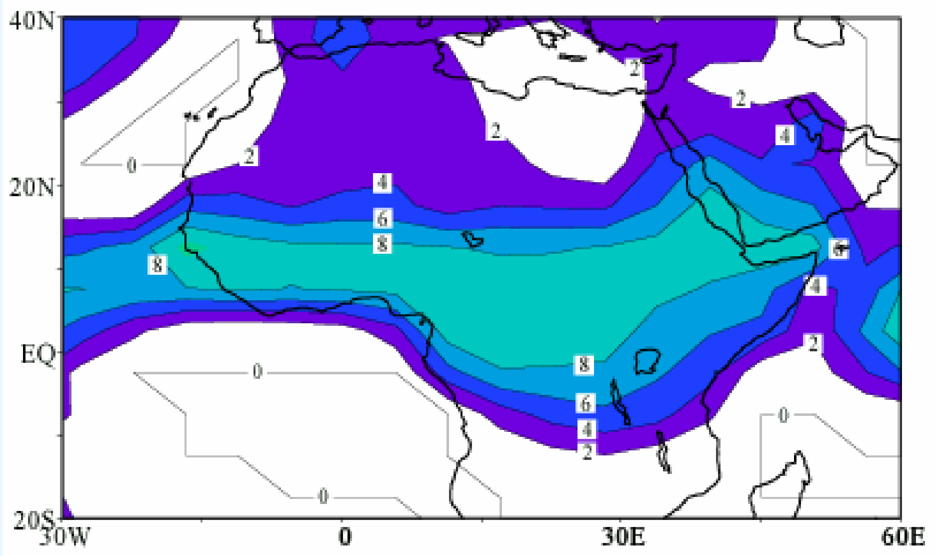
African region case (observed albedo) July

Precipitation

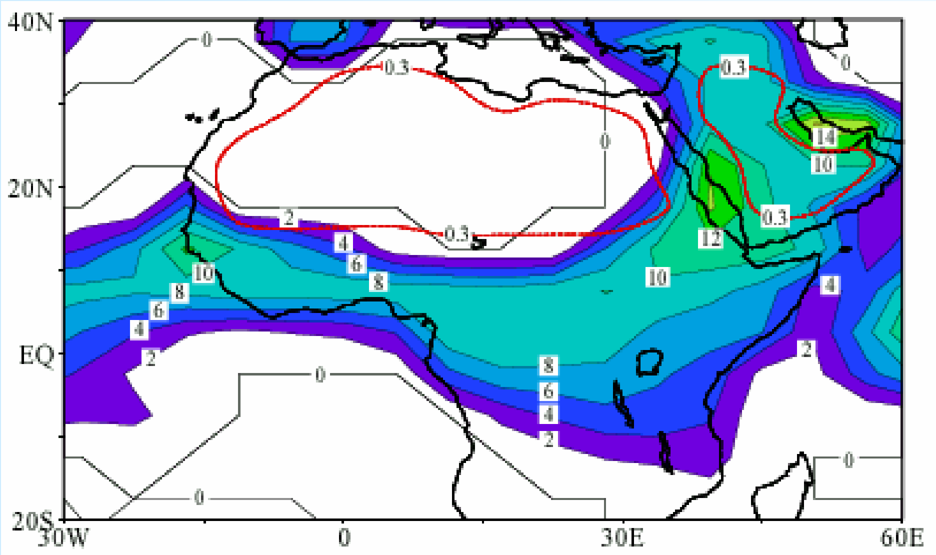
Control



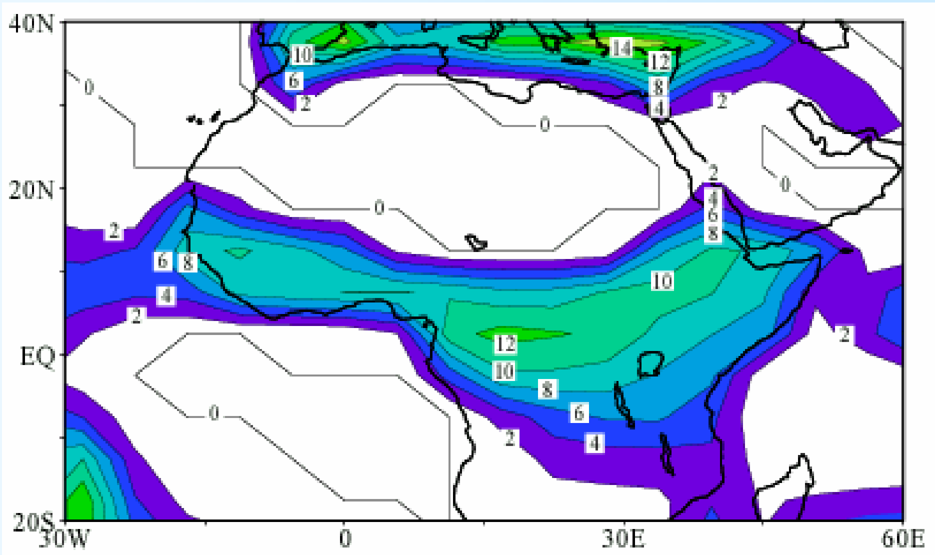
Saturated soil moisture



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



No ventilation and no β-effect:

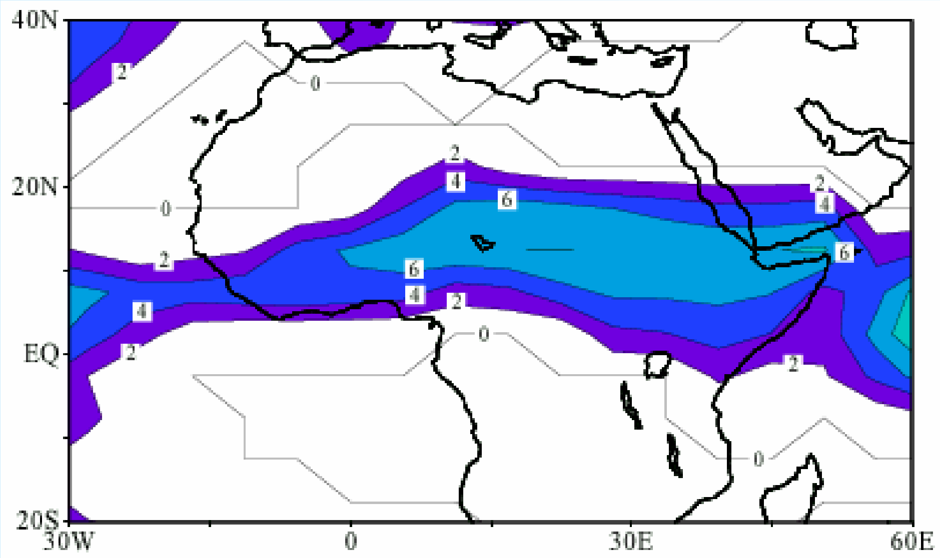


Chou and Neelin 2003

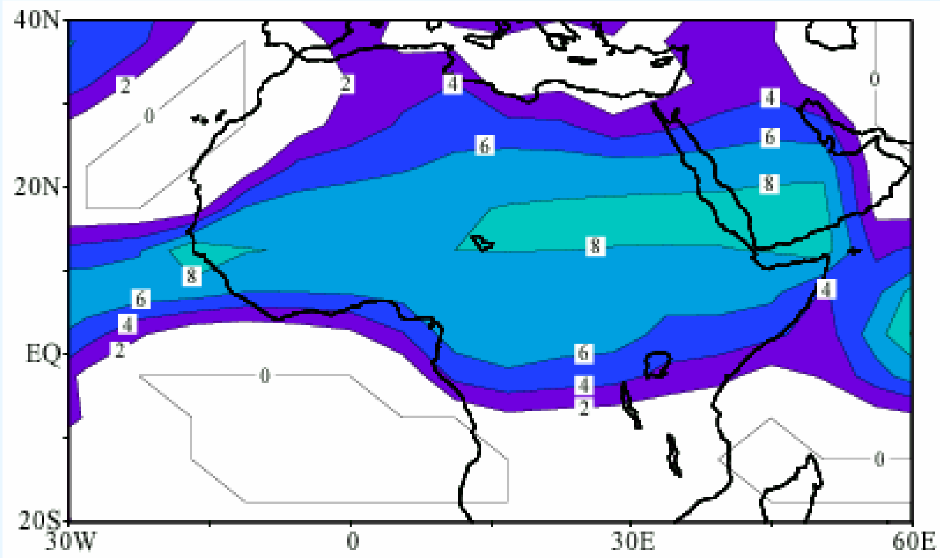
African region constant albedo case (0.26 over Africa) July

Precipitation

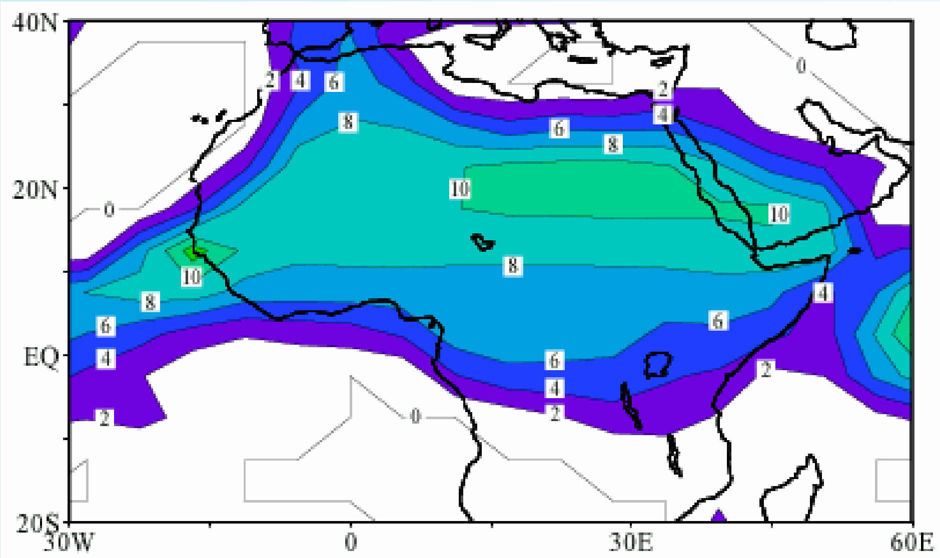
Control



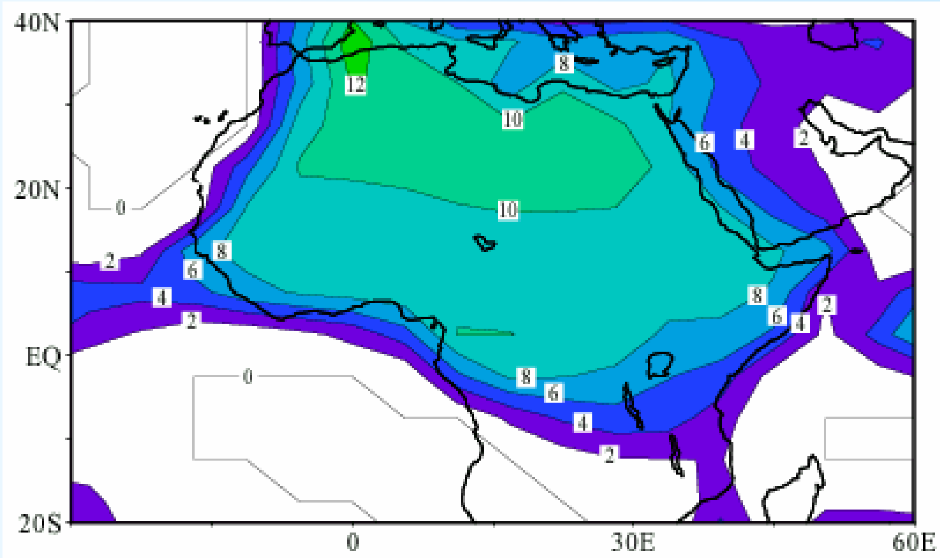
Saturated soil moisture



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



No ventilation and no β-effect:



Chou and Neelin 2003

Summary: (General/Idealized Continent)

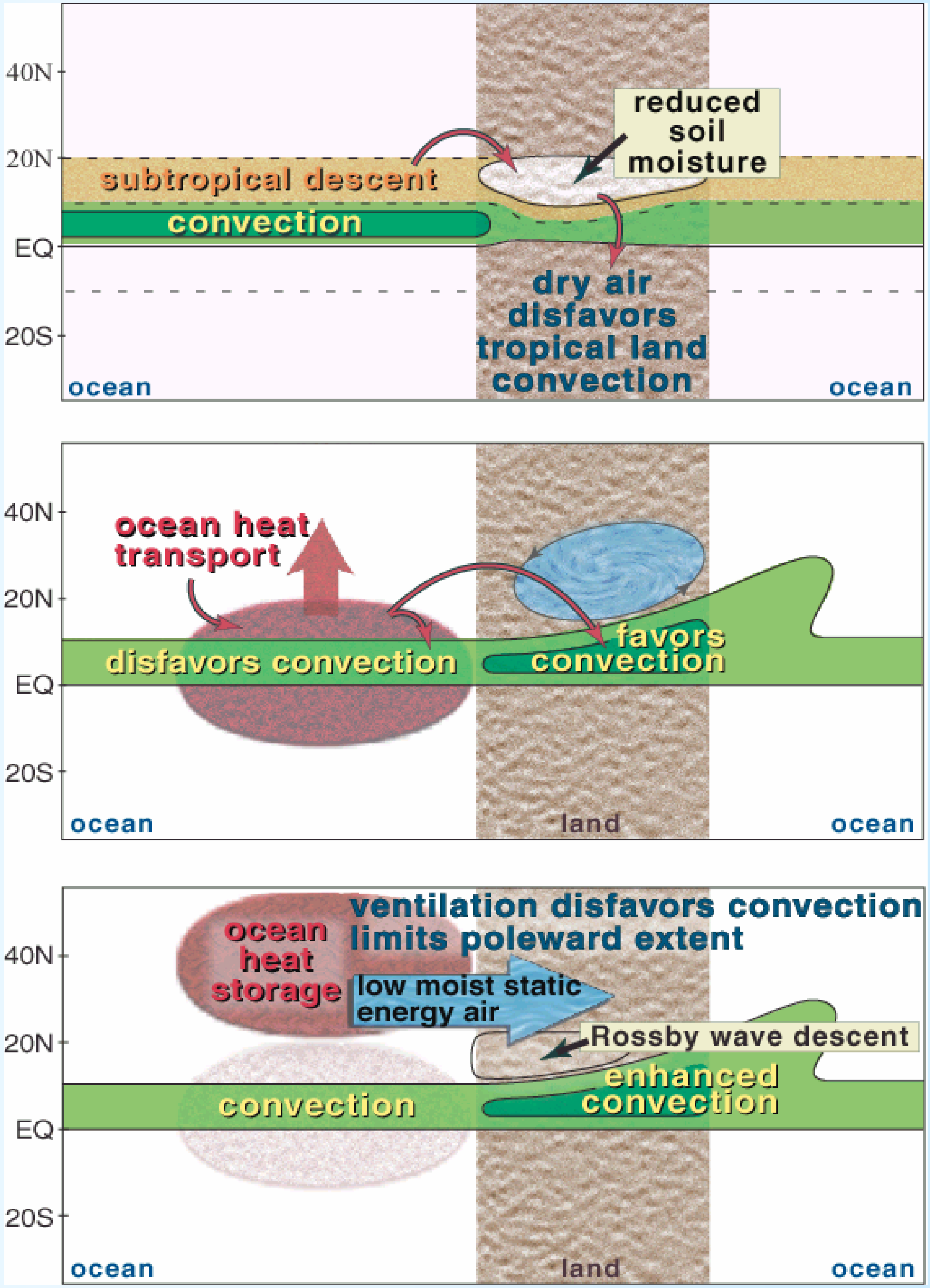
Ventilation	Interactive Rodwell-Hoskins mechanism
• import of low moist static energy air from ocean where heat storage keeps cool » balances heating of midlatitude continent » limits poleward extension of summer monsoon convection » produces east-west asymmetry	• Rossby wave div/convergence pattern interacts with convection » eastern continent convection favored » western continent convection disfavored (eastern favored)
Soil moisture	**Ocean heat transport**
• drying tendency in subtropical descent region » contributes to limiting poleward extent of convection » tropical continent convection disfavored	• tropical ocean cooled by transport » tropical continent convection favored

Mechanisms affecting continental convective zones

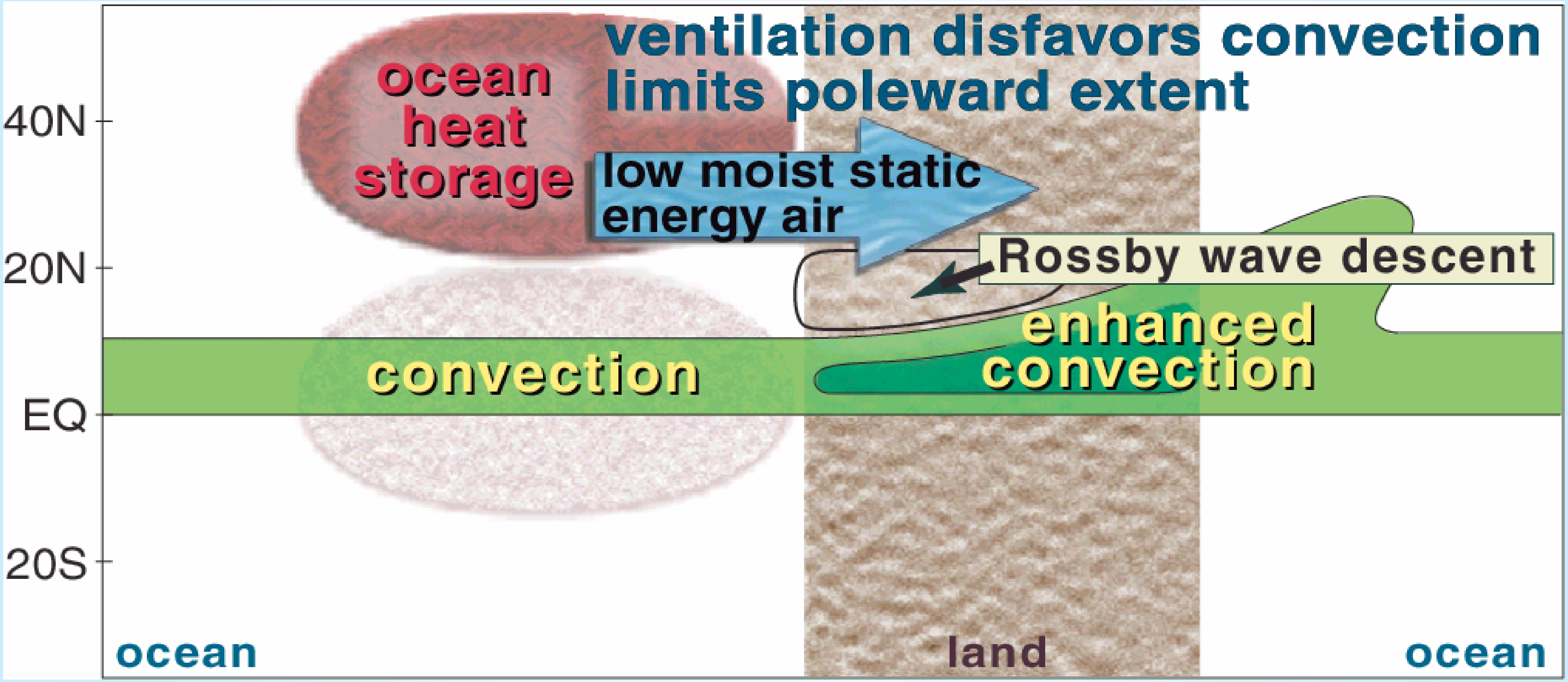
Soil moisture feedbacks

Ocean heat transport out of the tropics

Ventilation and the interactive Rodwell-Hoskins mechanism



Ventilation and the interactive Rodwell-Hoskins mechanism



- **Observed estimate of net energy flux Fnet into atmospheric column: positive Fnet extends much further poleward than convective zone**
- **Dynamical factors limit poleward extension of summer convective zone**

South America

- Ventilation and interactive Rodwell-Hoskins (IRH) mechanism important
- Both affect NW-SE tilt of convergence zone
- Soil moisture feedback secondary

North America

- Ventilation strongly affects poleward extent of convergence zone
- IRH mechanism a major dynamical influence favoring dryer southwestern continent
- Ventilation by either of $\mathbf{v}_\psi \cdot \nabla T$, $\mathbf{v}_\psi \cdot \nabla q$ can prevent poleward extension of convergence zone

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. $\boldsymbol{v}_{\psi}\cdot\nabla \boldsymbol{q}$ 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]

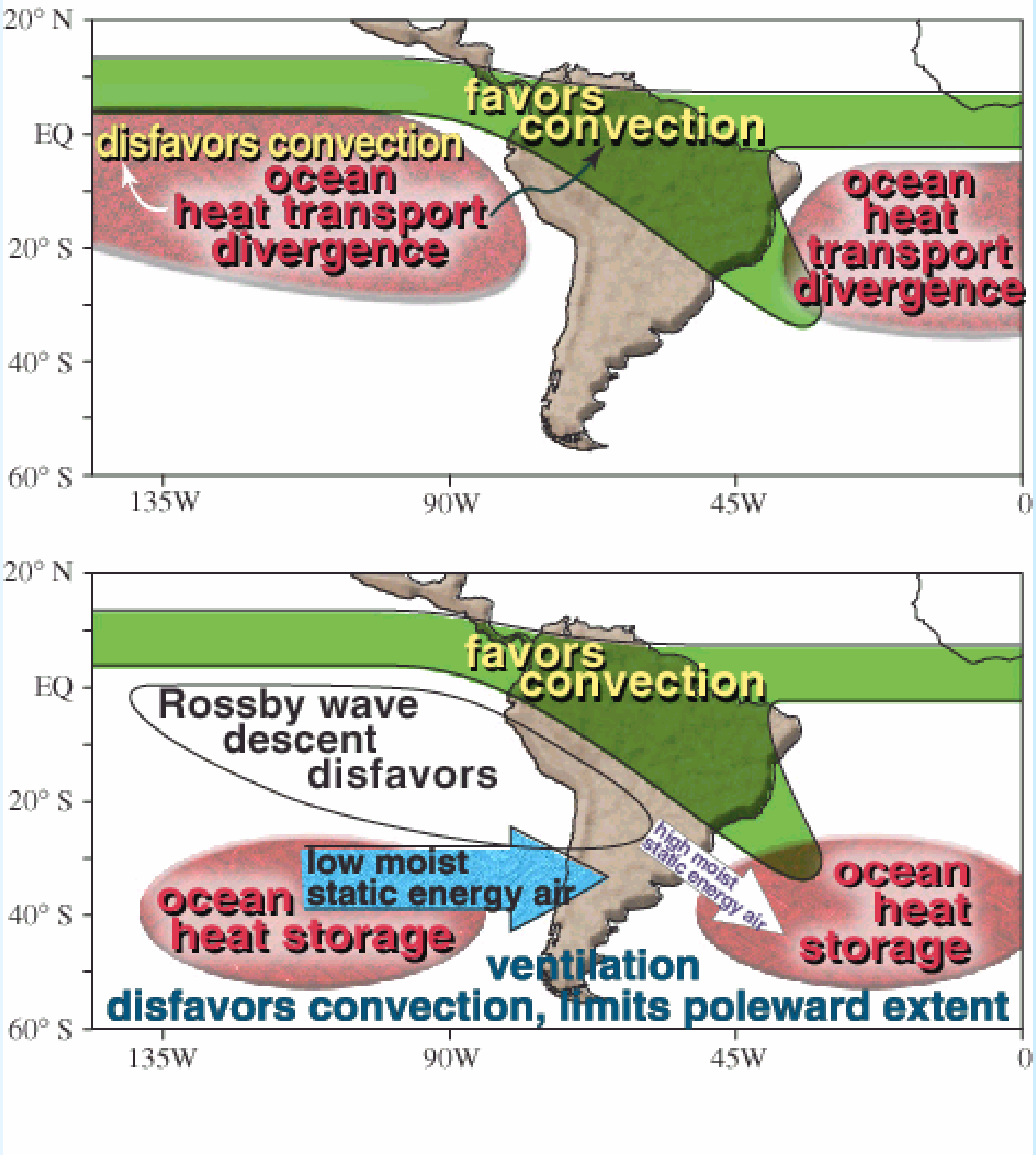
Africa

- 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 Fnet into atmospheric column, positive Fnet extends much further poleward than convective zone
- QTCM mixed-layer ocean with Q-flux “heat transport”
- Caveats: No topography, North American precipitation imperfect

Summary: N. & S. America (2)

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