Moist dynamics of tropical convection zones in monsoons, teleconnections and global warming

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- Leveraging a theoretical framework from convective qu equilibrium, moist static energy budget, + ….
- Monsoon aspect: what limits seasonal movement of deep convection zones over continents?
- Tropical regional precipitation anomalies associated wit changes in deep convection zones: including drought regions in both El Niño & global warming cases. Mechanisms? Similarities?

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 ⟨ ⟩

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

⟨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
≈ (measure of divergence)
x gross moist stability

Net energy flux into column

Moist static energy $h = s + q$

Quasi-equilibrium schemes

Manabe et al 1965; Arakawa & Schubert 1974; Moorthi & Suarez 1992; Randall & Pan 19

Posit that bulk effects of convection tend to establish statistical equilibrium among buoyancy-related fields

Approach here depends on **convection** tending to **constrain vertical structure of temperature** field.

For now: **Smoothly posed convective adjustment**

Convective heating: (Betts 1986; Betts & Miller 1986)

$$Q_c = (T^c - T)/\tau_c$$

τ_c time scale of convective adjustment

T_c convective profile; may interact with h_b

h_b atm boundary layer (ABL) moist static energy

T^c typically moist adiabat or closely related

Can be expanded about a reference state, T_r^c

$$T^c = T_r^c(p) + A(p)\, T_1^c + \text{higher order}$$

$A(p)$ vertical dependence of the moist adiabat perturbation

T_1^c incl. ABL adjustment by downdrafts to satisfy energy constraint

Tends to reduce CAPE (convective available potential energy)

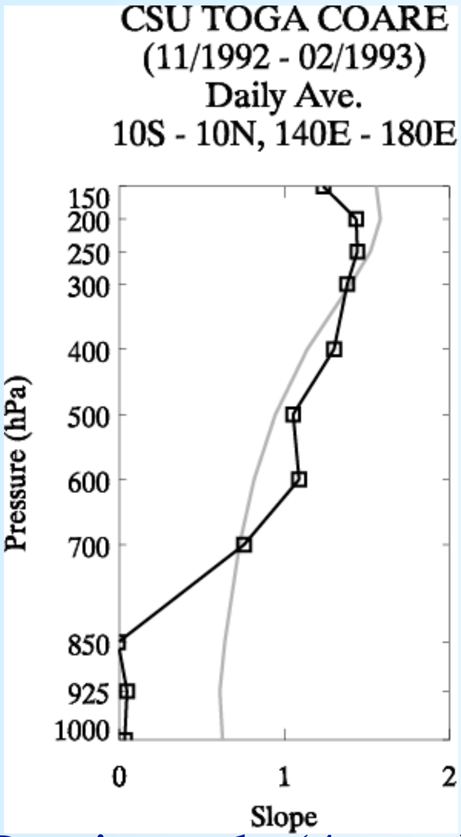
Vertical structure of temperature variations

See also, e.g., Xu and Emanuel 1989; Fu et al 1994; Brown and Bretherton 1997; Sobel et al 2004

- Regressions of Temp. on 850-200 hPa Ave. Temp. (square
- Same for reversible moist adiabats over similar range (grey

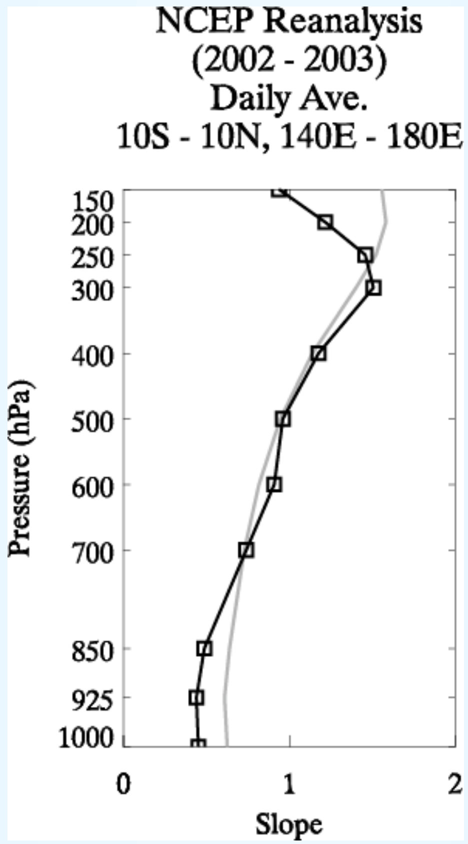
Daily, COARE Domain

Monthly, tropical av

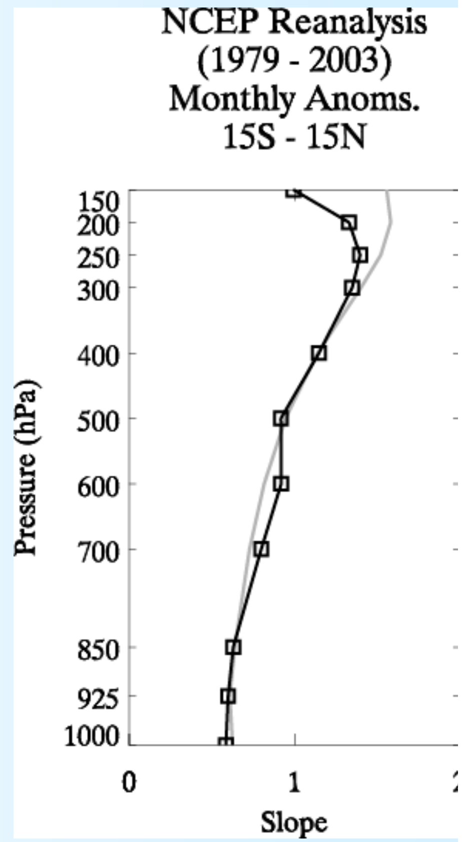


Rawinsonde (4 mon)

[Ciesielski et al (2003) data]



NCEP (2 yr)



NCEP (24 yr)

Courtesy, C. Holloway

Analytical solution under quasi-equilibrium convective constraints

If T constrained to be close to QE temp T^c

$$T \approx T^c \approx \underline{T_r^c + A(p)T_1^c}$$

Primitive equations, momentum + hydrostatic:

$$(\partial_t + D_m)v + f\mathrm{k} \times v = -\kappa \nabla \int_p^{p_o} T d \ln p + \nabla \phi_o$$

$$\approx -\kappa \int_p^{p_o} \underline{A(p)} d \ln p \nabla \underline{T_1^c} + \nabla \phi_o$$

baroclinic pressure gradients have strongly constrained vertical structure

Analytic solution in deep convective regions (cont.)

Vertical structure of baroclinic pressure gradients $\Rightarrow$ structure of baroclinic wind V_1. With barotropic component $\Rightarrow$ $\quad \boldsymbol{v} = \boldsymbol{v}_o(x,y,p,t) + V_1(p)\boldsymbol{v}_1(x,y,t)$

Continuity eqn. $\Rightarrow$ $\quad \omega = \Omega_1(p)\, \nabla\cdot\boldsymbol{v}_1$

The moist static energy eqn. becomes

$$(\partial_t + \mathcal{D})(\hat{T} + \hat{q}) + M\nabla\cdot\boldsymbol{v}_1 = F_{net}$$

where M is the gross moist stability $\quad M = \langle \Omega \partial_p h \rangle$

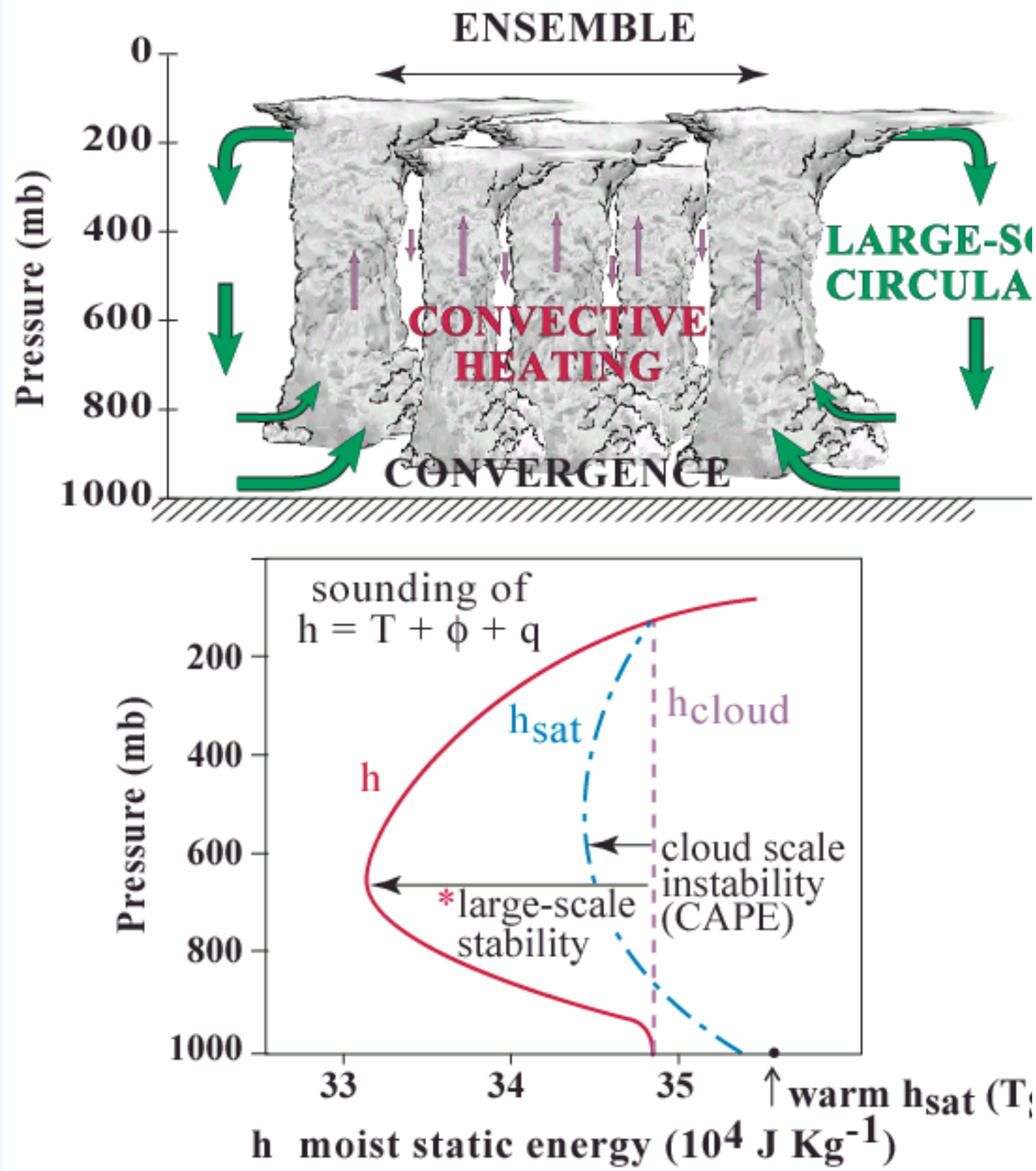
NB: Have not yet used convective closure on moisture.

Neelin 1997; Yu et al 1998; Neelin and Zeng 20

Moist convection interacting with large-scale dynamic

- **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

Have approx. analytic solution for convective regions:

Extend to full nonlinearity, non-convective regions,…

Use analytic solutions for leading basis functions in Galerkin expansion in vertical

$$T = T_r(p) + \sum_{k=1}^{K} a_k(p) T_k(x, y, t) + T_R,$$

- **Horizontal gradients of *T* matter; specify reference stat $T_r(p)$ to improve accuracy.**
- **Simplest case: 1 basis function in *T*, *q***

  Extra basis function for external mode ⇒ 2 in *v*

Neelin and Zeng (2000

Quasi-equilibrium Tropical circulation model:

- Primitive equations projected onto vertical basis functions fro
  convective quasi-equilibrium analytical solutions
- for Betts-Miller (1986) convective scheme, accurate vertical structure in deep convective regions for low vertical resolutio
- 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:

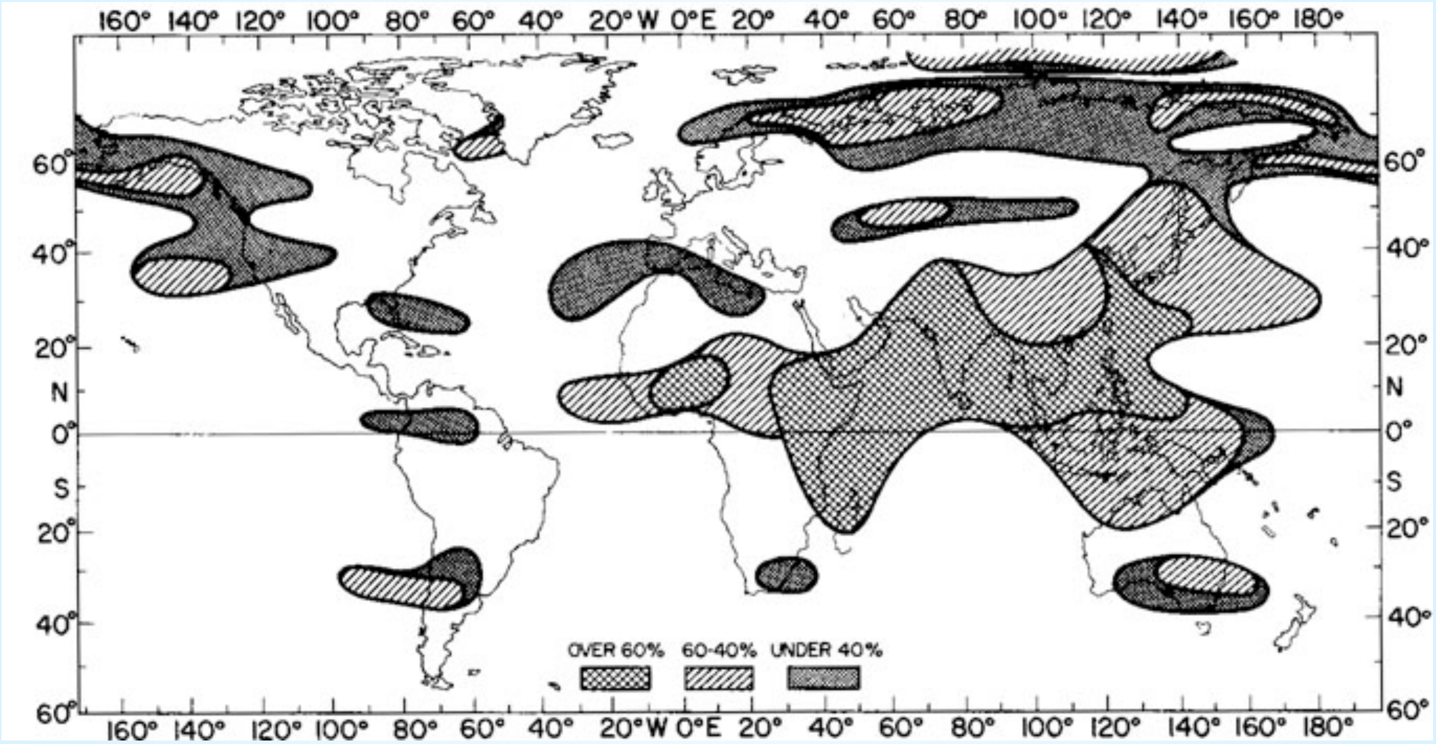
- 1 soil moisture layer; evapotranspiration with stomatal/root resistance dep. on surface type (e.g., forest, desert, grassland)
- low heat capacity; Darnell et al 1992 albedo

- http://www.atmos.ucla.edu/~csi/QTCM

Dynamics of summer monsoon convective zones

- Seasonal movement of deep convection zones over continents
- Dynamical mechanisms mediating land-ocean contrast?
- Given the large insolation extending poleward over continents, w do deep convection zones not extend farther poleward?
- Do mechanisms affecting convection zones differ from continent continent?
- QTCM 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

Wind-based vs. precip. regime-based monsoon definiti

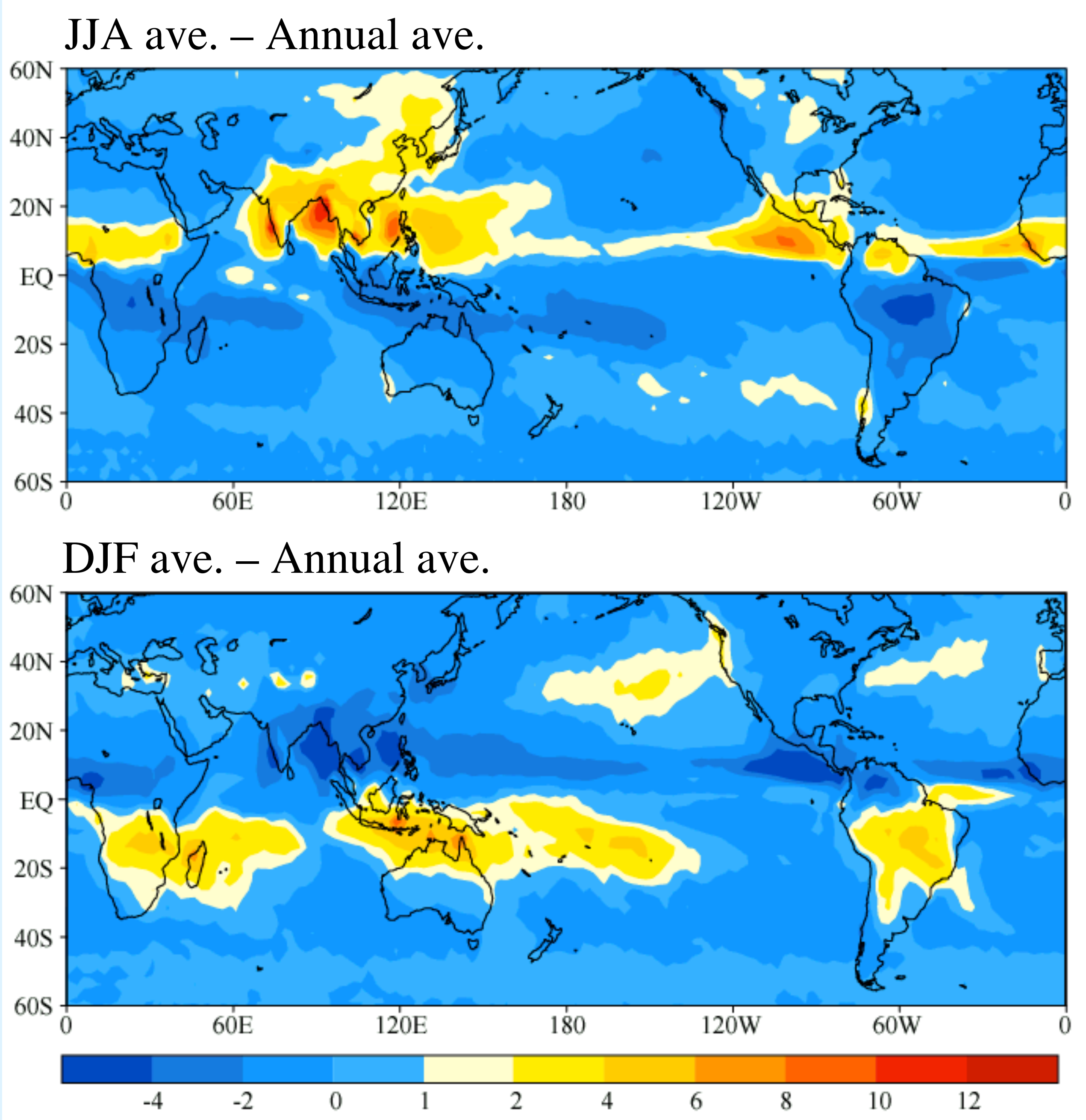


Freq. of surface wind direction; Khromov (1957); from Ramage (1971)

Pronounced summer precip maximum; sfc low; upper level high and outflow, … (e.g., Tang and Reiter 1984; Barlow et al 1998; Higgins et al 1998; Zhou and Lau 1998; Yu and Wallace 2000; …)

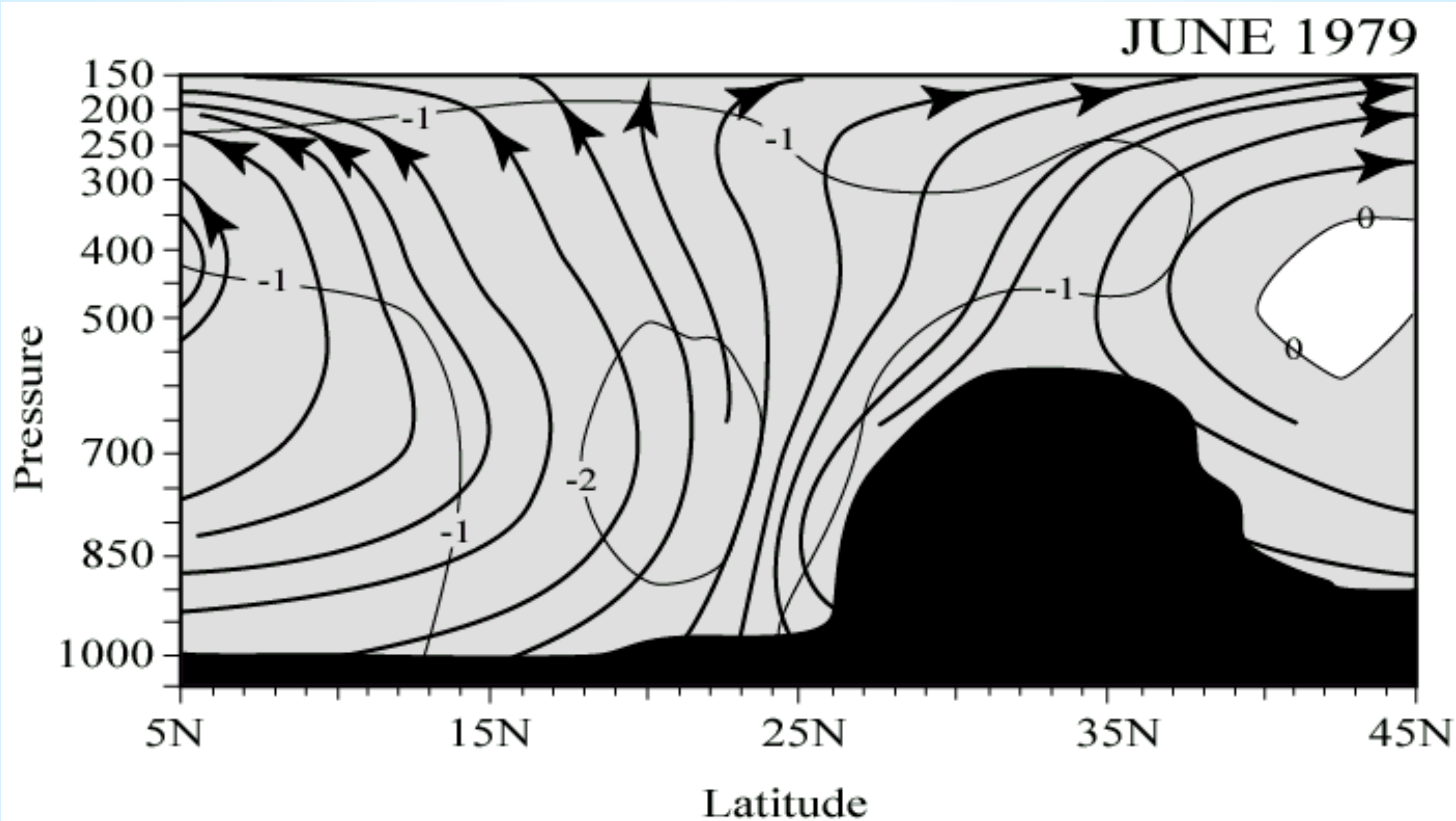
i.e., characteristics of seasonal arrival of deep convection zone

Seasonal precipitation minus Annual Average



mm/day

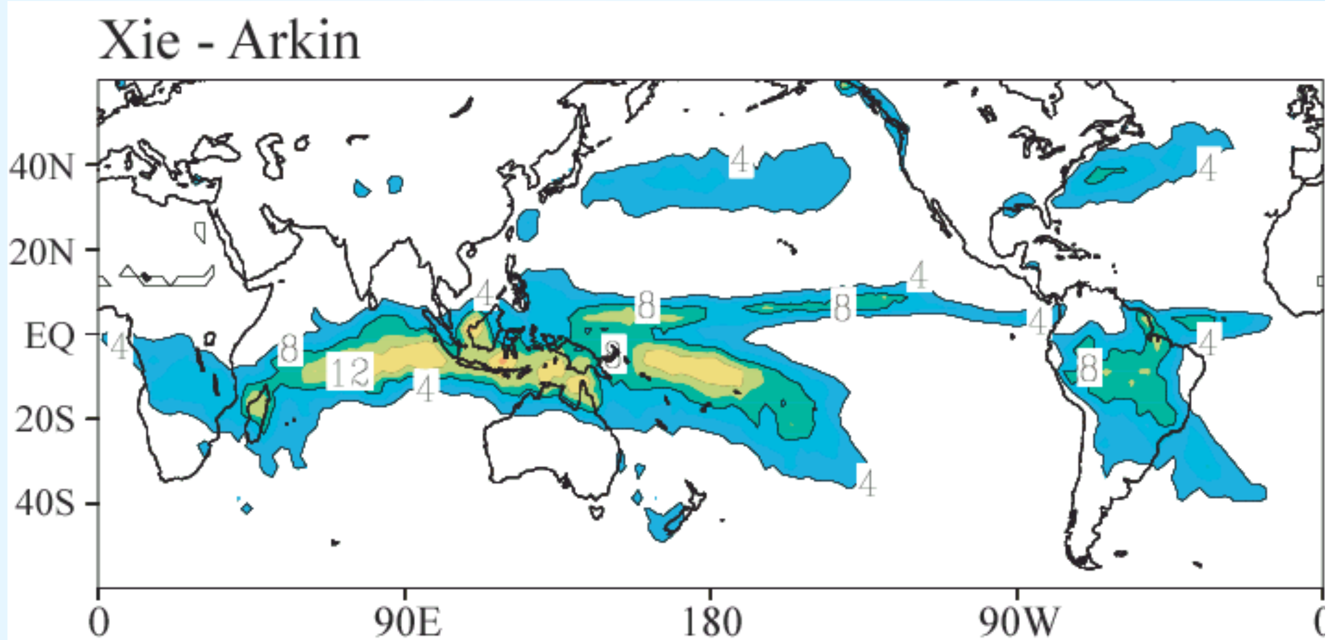
Latitude-height cross section at 90E from Bay of Ben
across Tibetan Plateau (shaded regions are rising motion



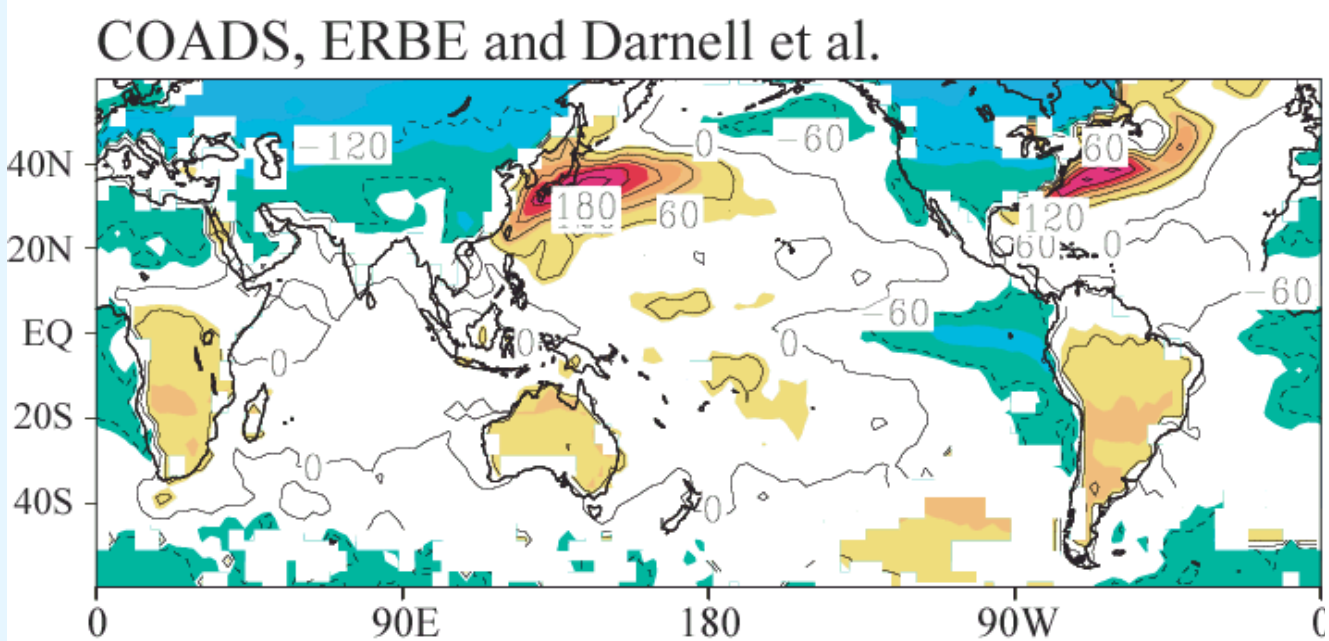
From Yanai et al. (1

Observed climatology January

Precipitation



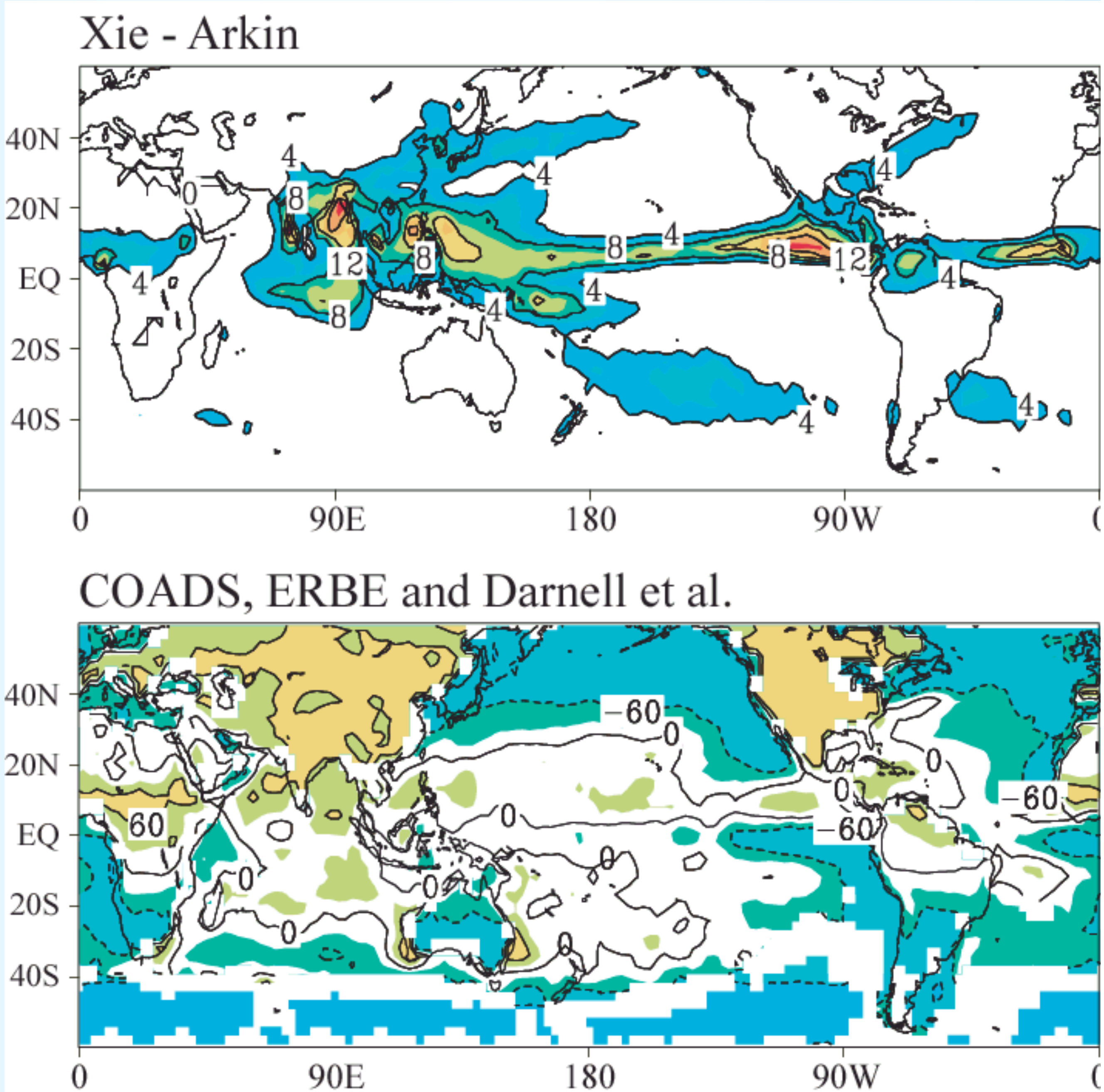
Net Flux into the atmosphere



Observed climatology July

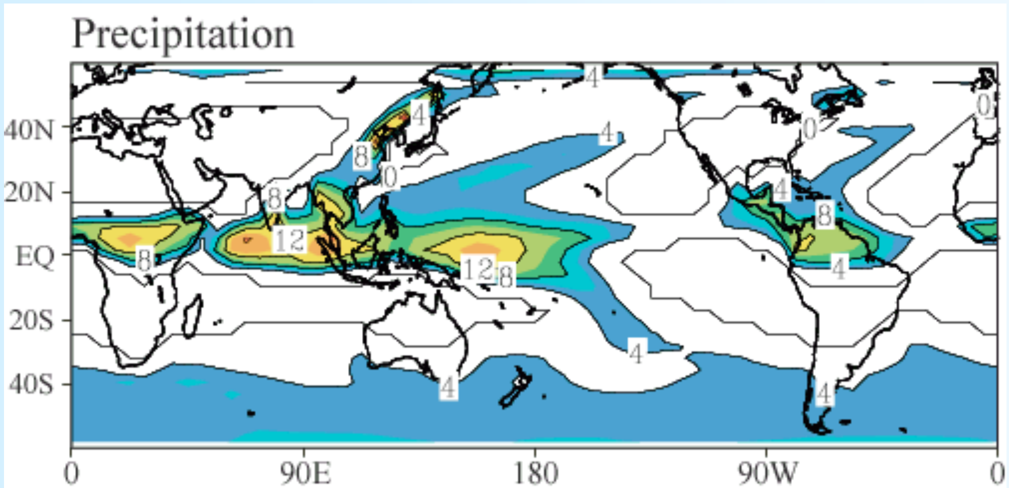
Precipitation

Net Flux into the atmosphere

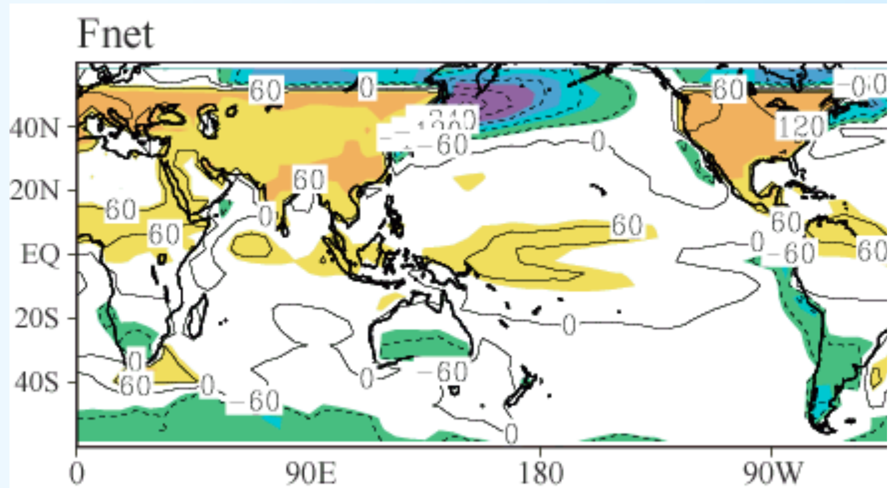


QTCM climatology July
(coupled to a mixed-layer ocean)

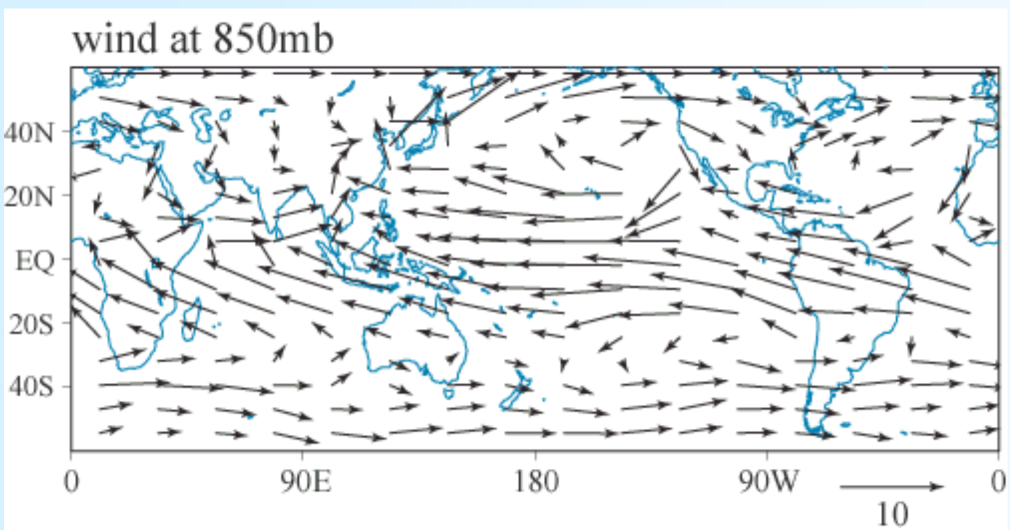
Precipitation



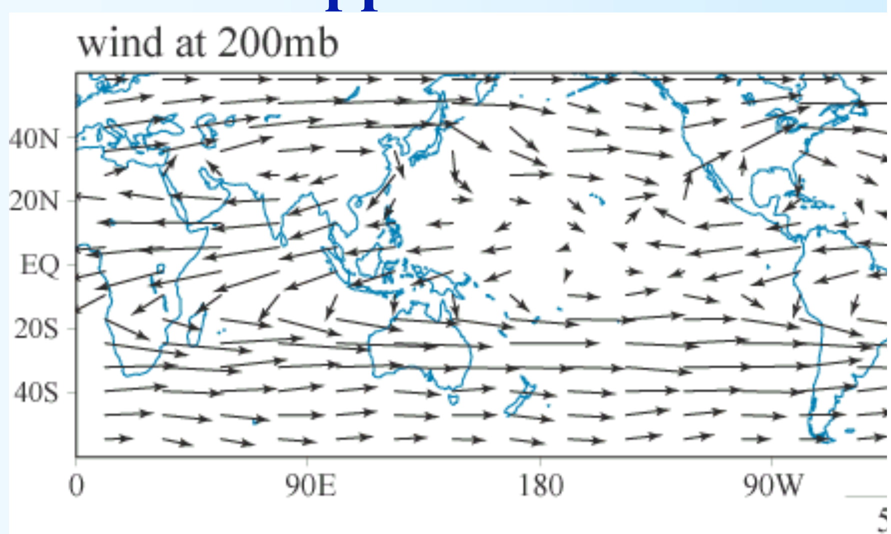
Net flux into atmosphere



Low-level wind



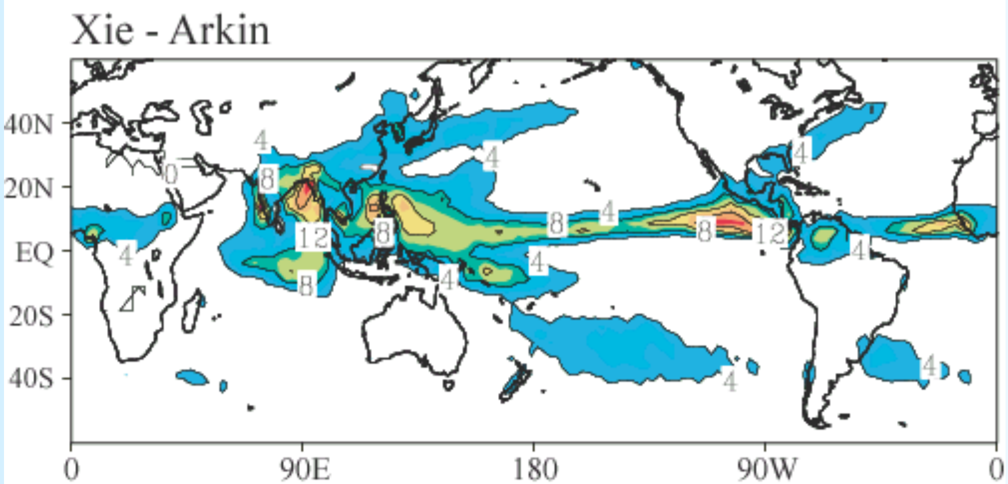
Upper-level wind



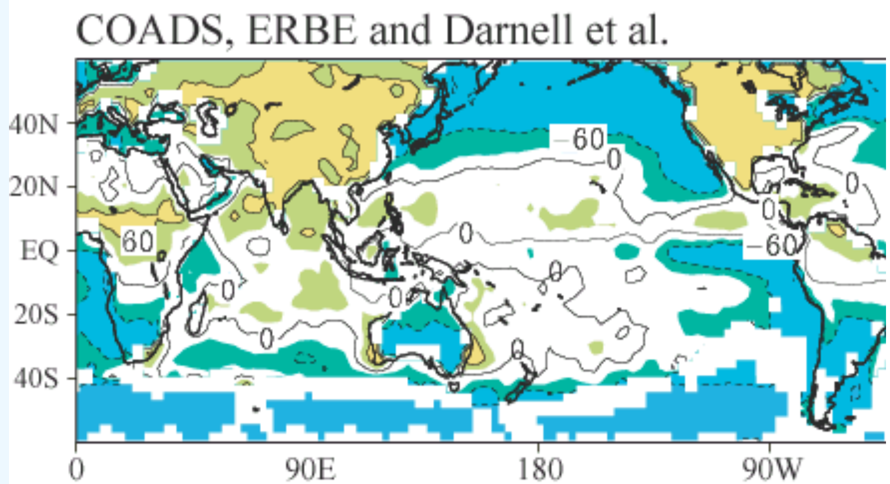
QTCM1

Observed climatology July

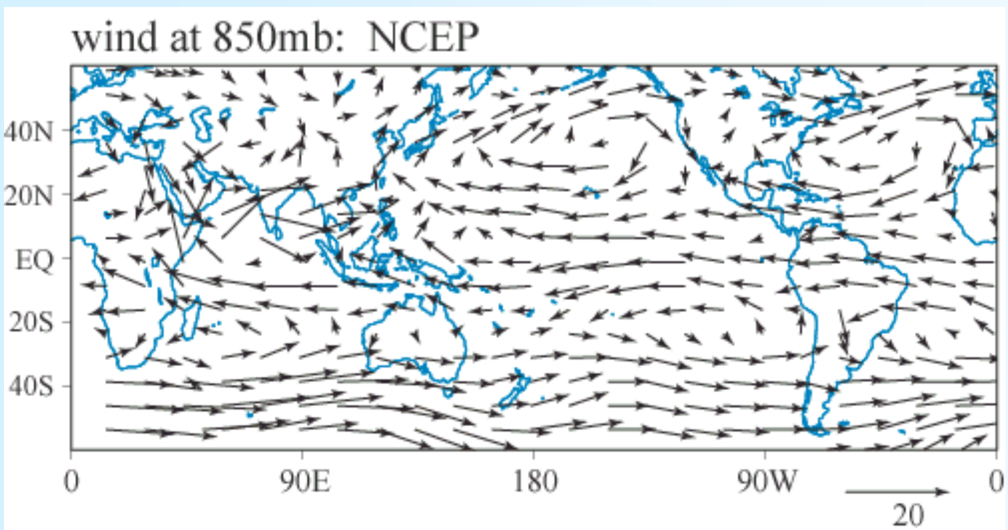
Precipitation



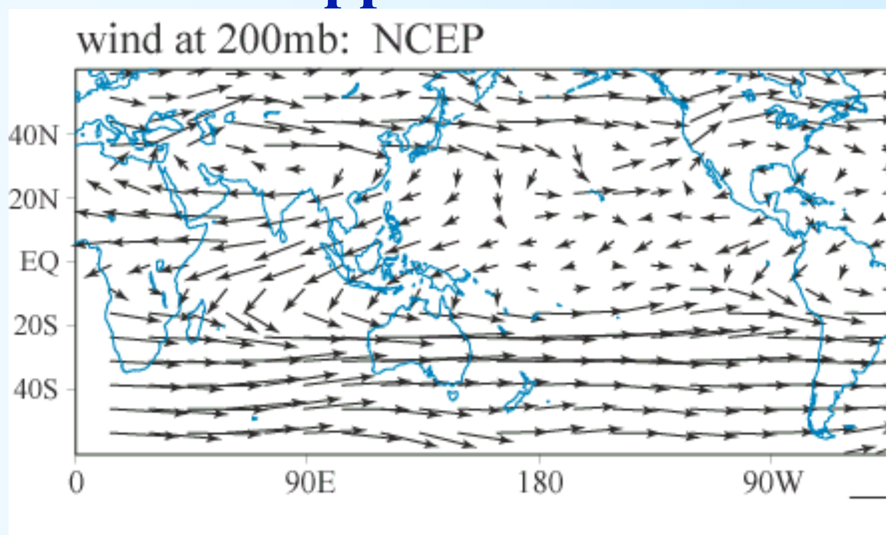
Net flux into atmosphere



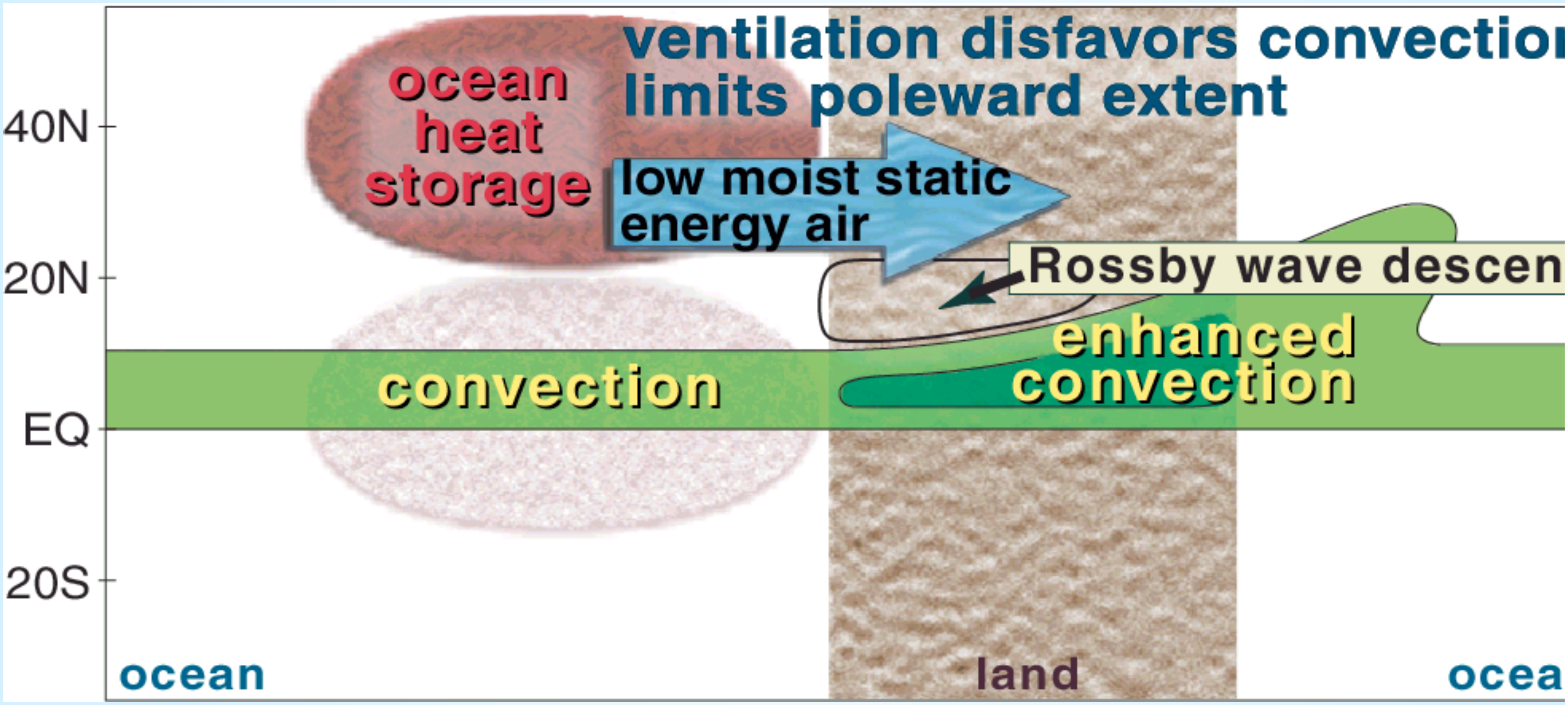
Low-level wind



Upper-level wind



Ventilation and the "interactive Rodwell-Hoskins" mechanism



Chou, Neelin and Su 2

The “ventilation mechanism”

- **import of low moist static energy air from ocean where heat storage opposes summer warming**
- **oceanic air: cooler 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**

Chou, Neelin and Su 2

The "interactive Rodwell-Hoskins mechanism"

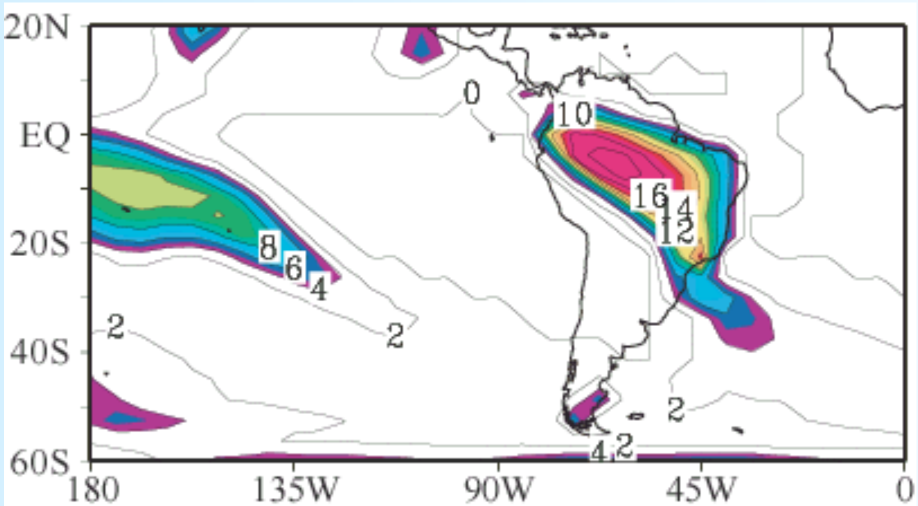
- Rodwell and Hoskins (1996): imposed convective heating in Asia gives Rossby wave descent pattern to west, enhancing deserts.
- when convection is interactive: associated flow feeds back on heating, creating characteristic convection/dry region pattern
  - » we emphasize feedback (convection ⇔ baroclinic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

Chou, Neelin and Su

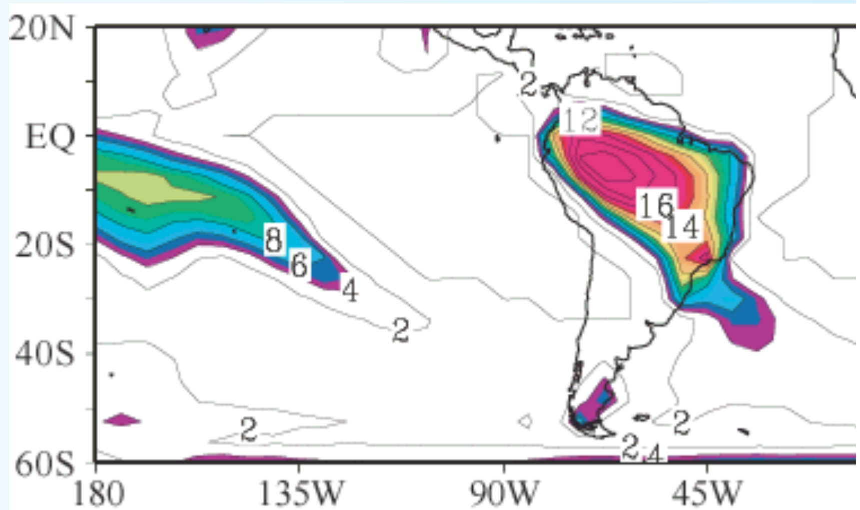
South American region case (observed albedo) Jan

Precipitation

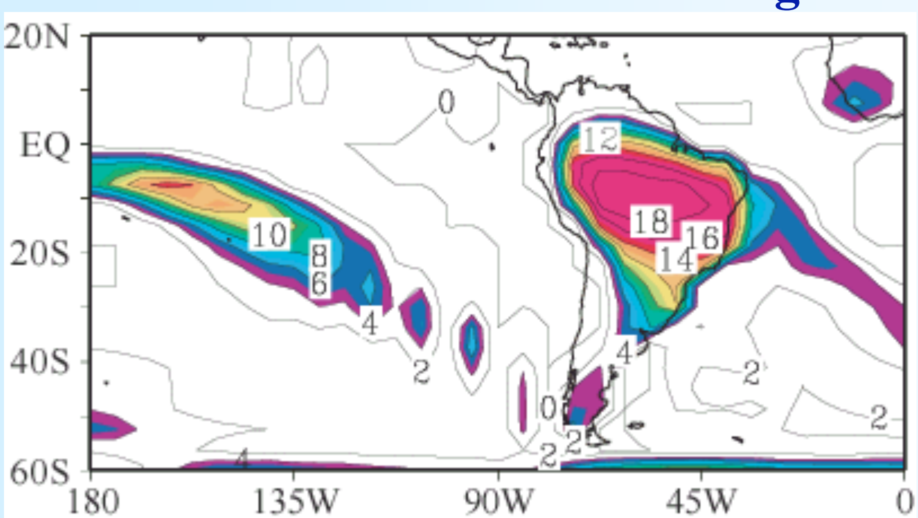
Control



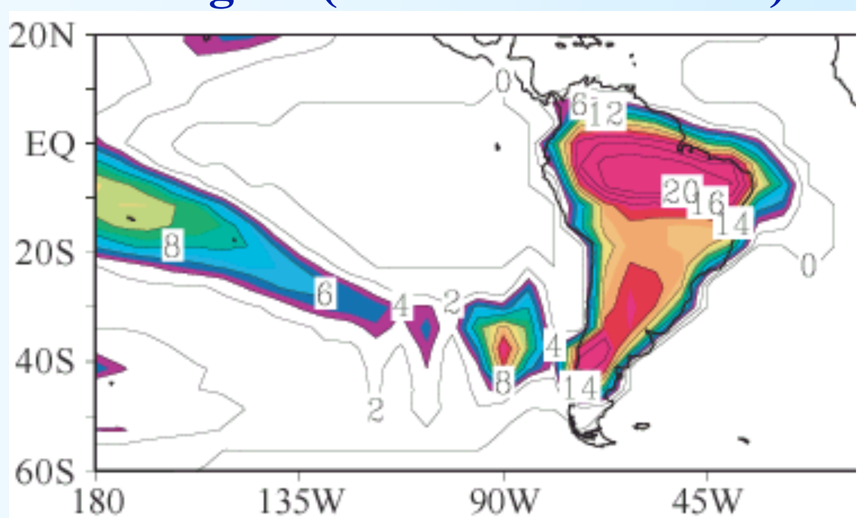
Saturated soil moisture over South American region



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



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



Chou and Neelin

Refinement of experimental design

1. Consistent treatment of v_χ :

- Irrotational (purely divergent) wind component v_χ
- Non-divergent wind component v_ψ

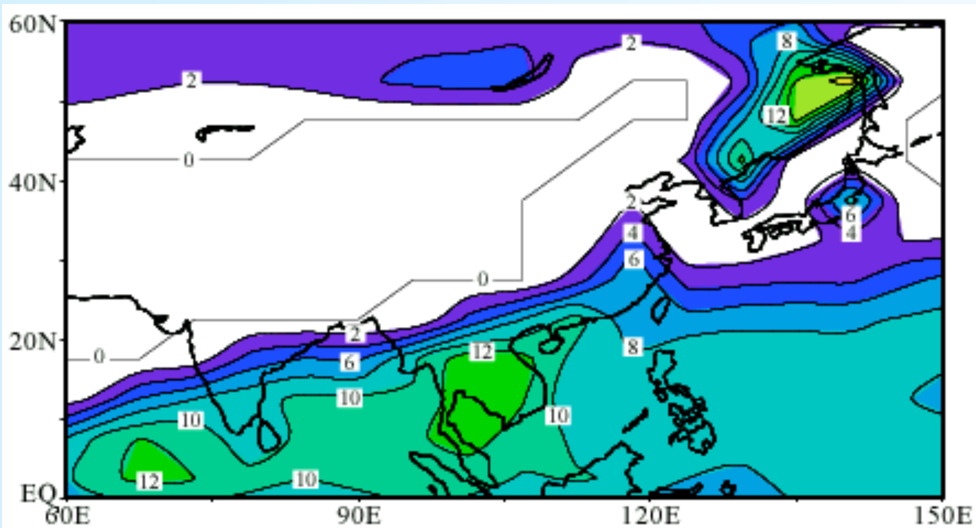
➢ "No ventilation" = suppress $v_\psi \cdot \nabla T,\ v_\psi \cdot \nabla q$

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

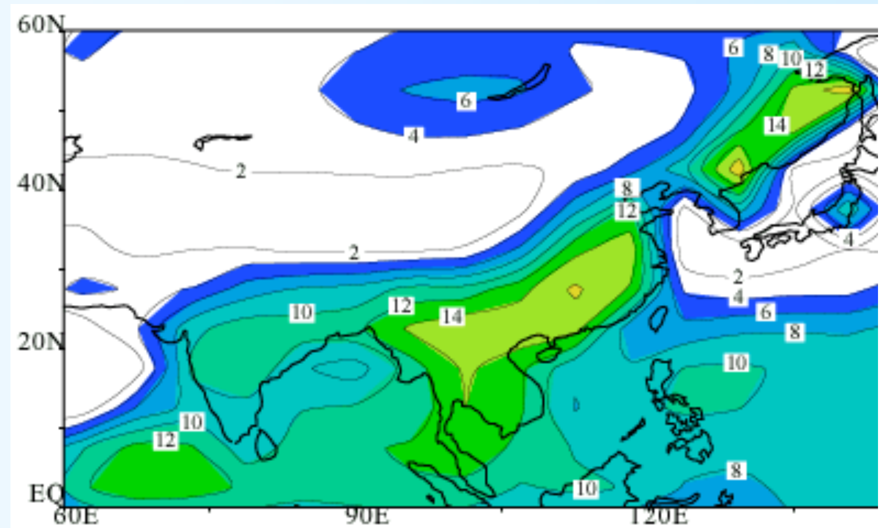
Asian region case – July

Precipitation

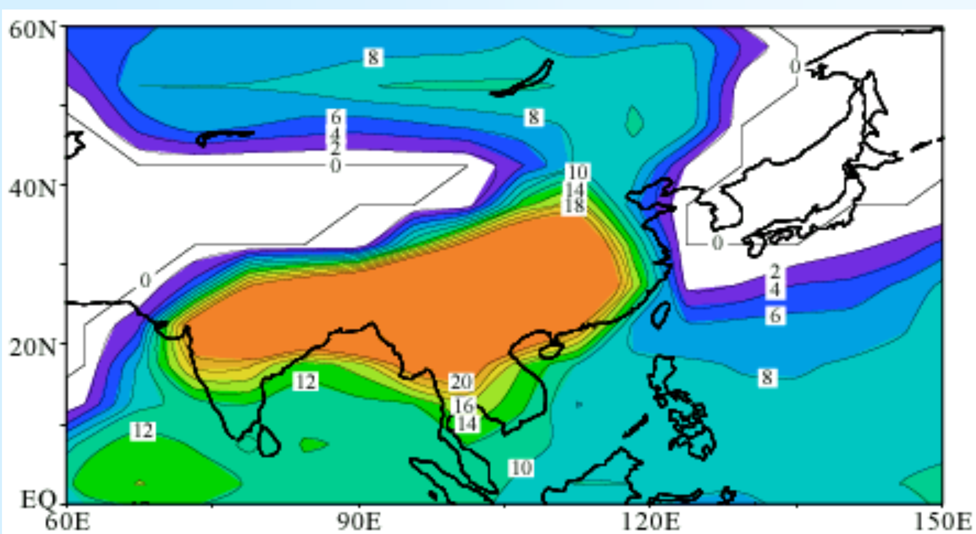
Control



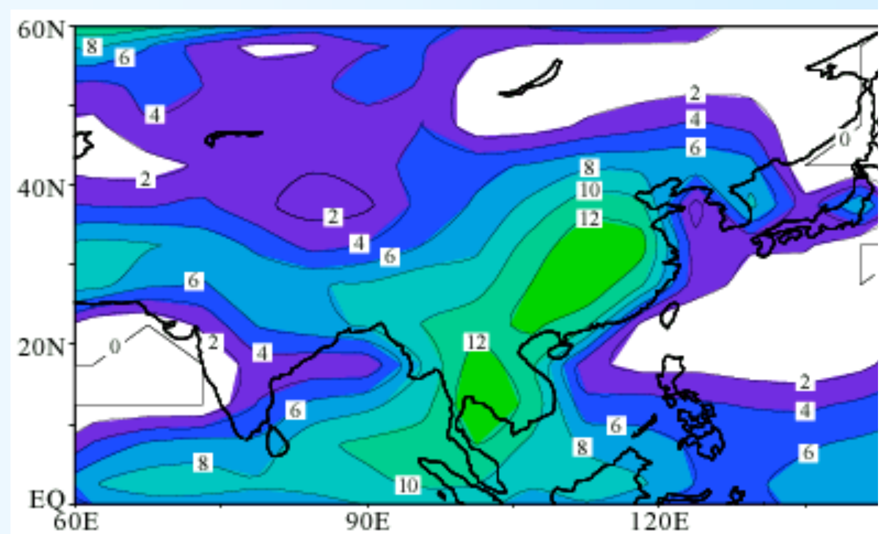
Saturated soil moisture



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



No β-effect: f = constant



QTCM v2.3

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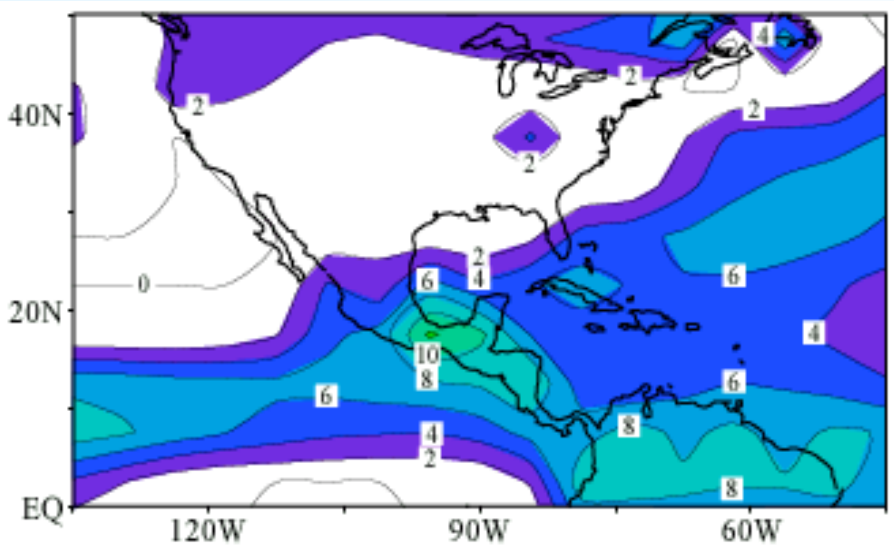
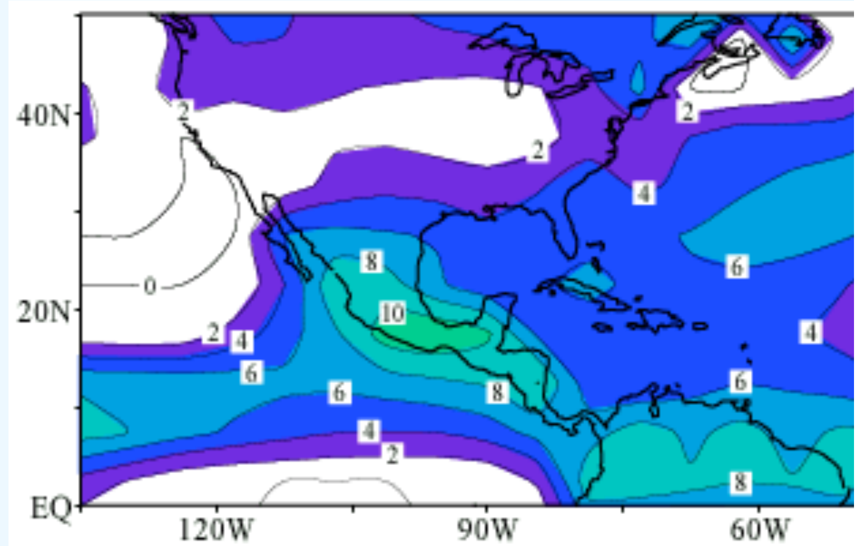
North American region case

July Precipitation

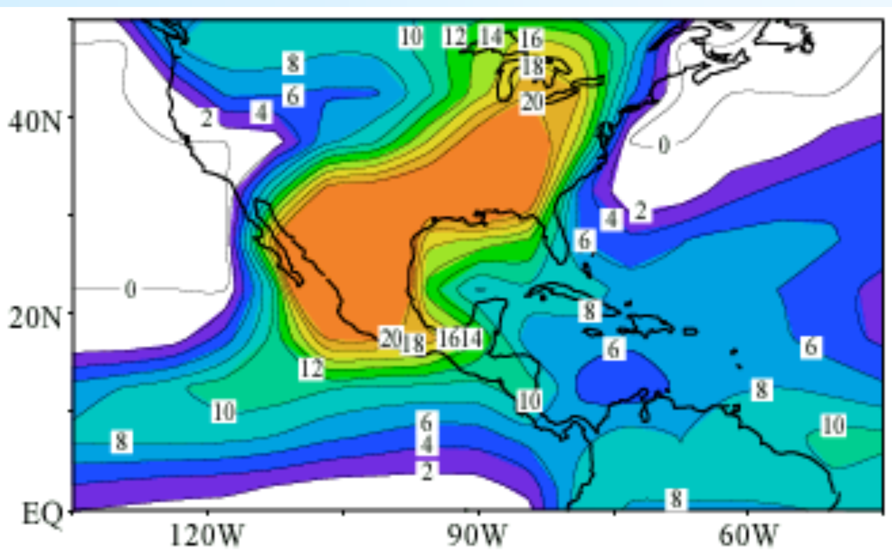
Control



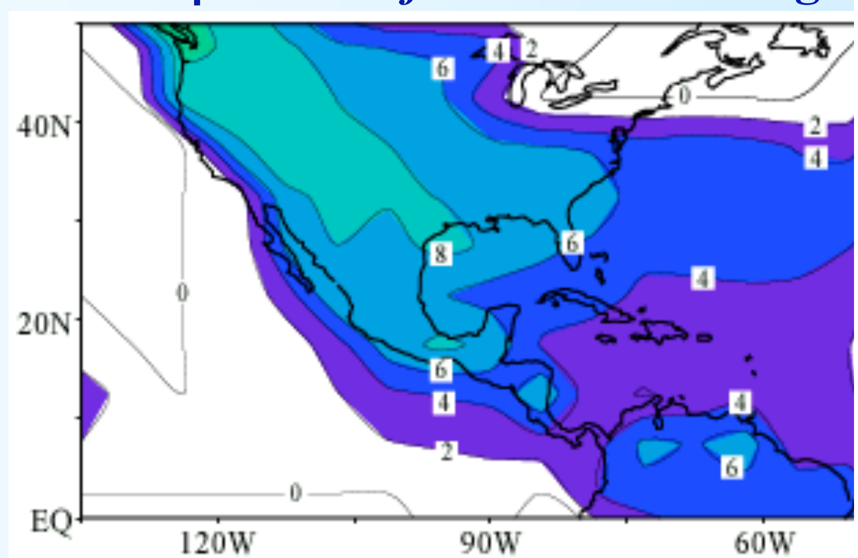
Saturated soil moisture



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



No β-effect: f = constant in regio



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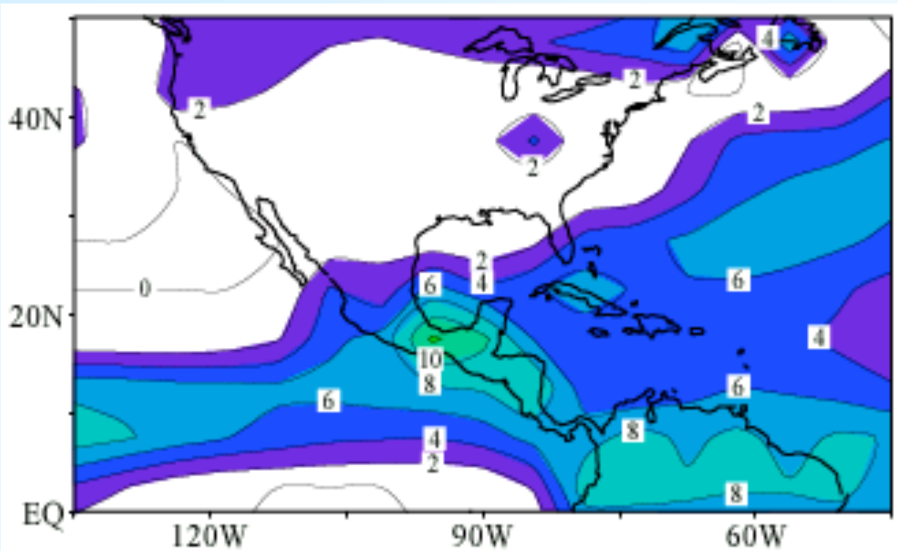
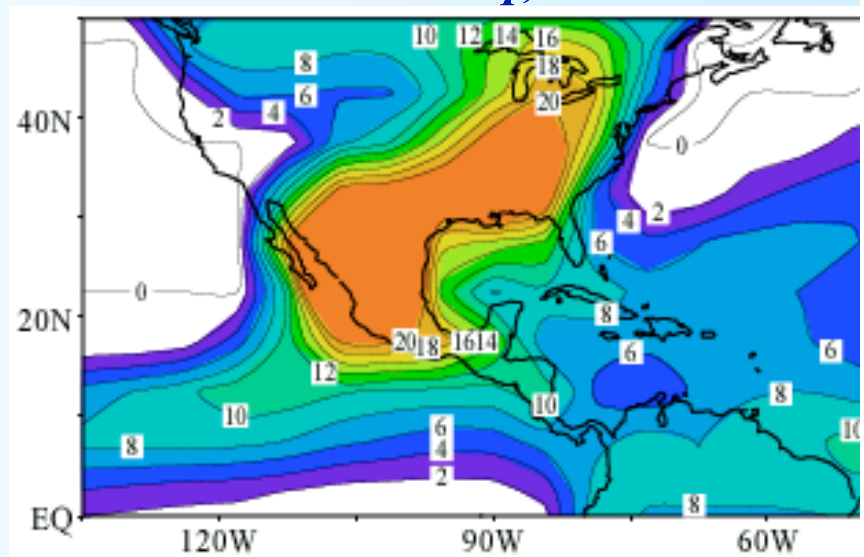
North American region case

July Precipitation

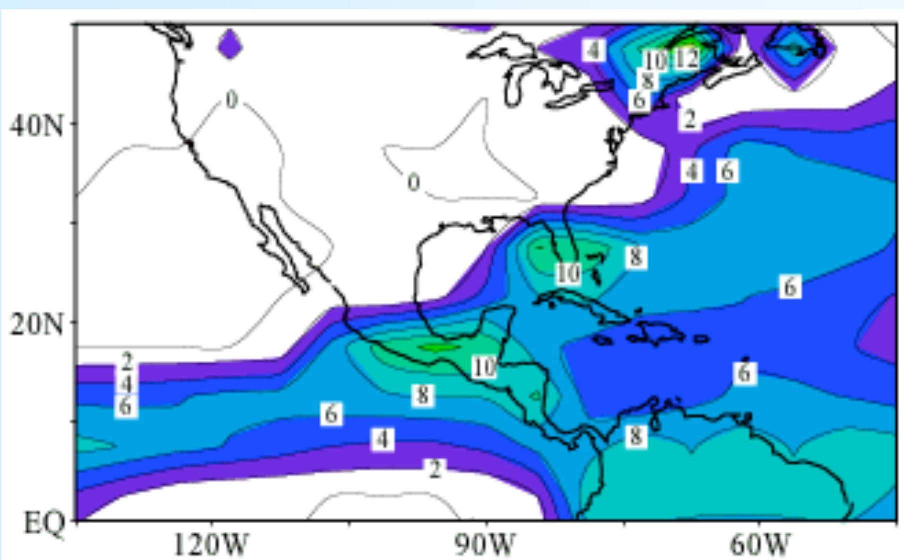
Control



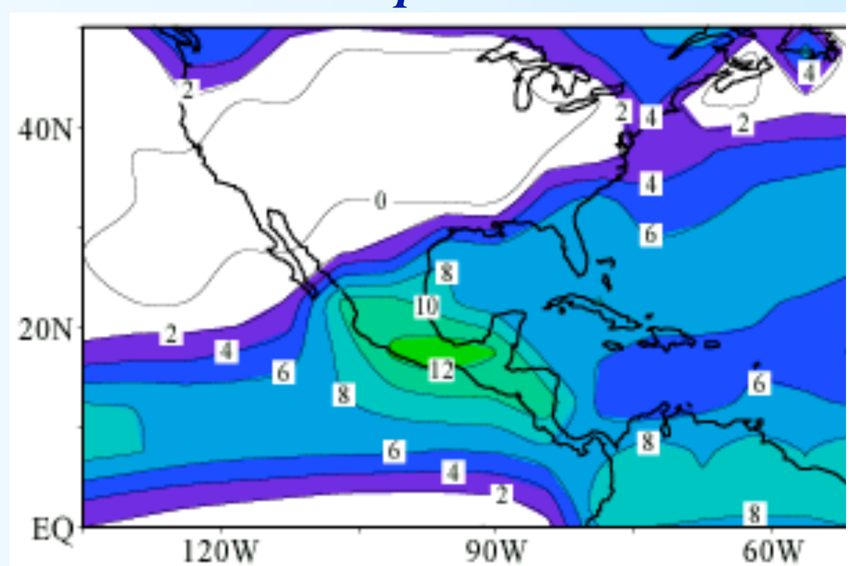
No ventilation: $v \bullet \nabla q$, $v \bullet \nabla T$ set to ze



No *T* ventilation



No *q* ventilation



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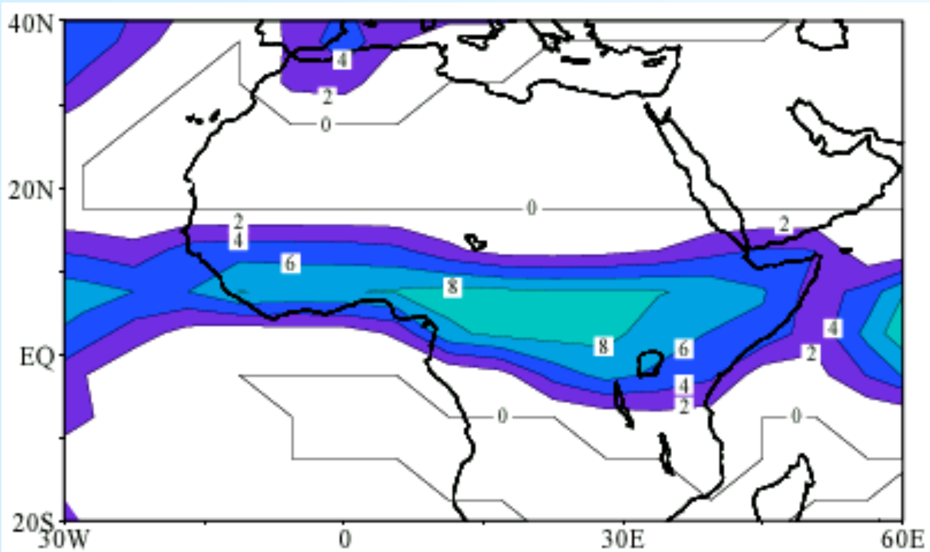
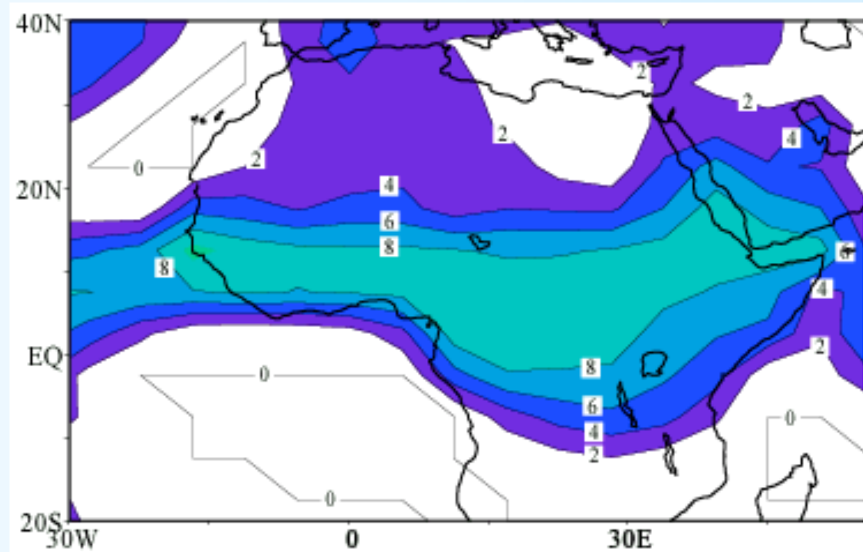
African region case (observed albedo) July

Precipitation

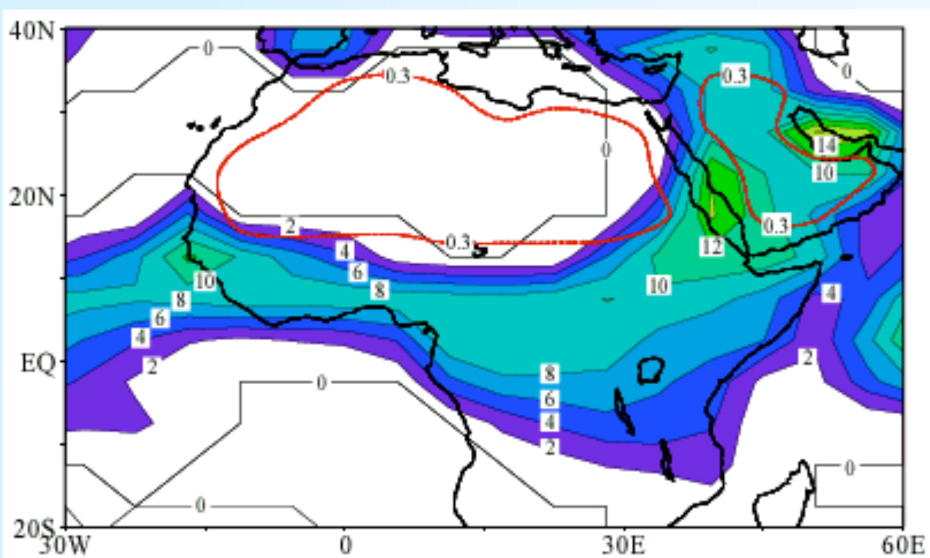
Control



Saturated soil moisture

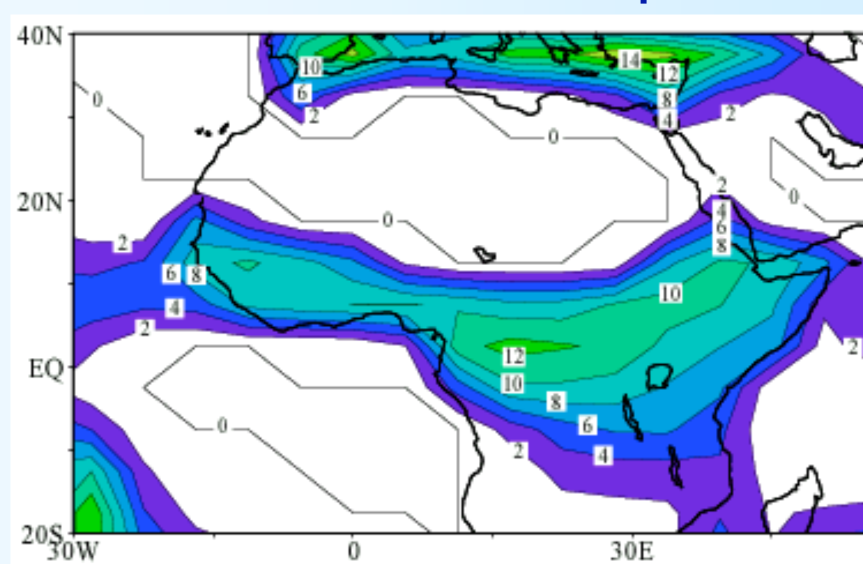


No ventilation: $v \cdot \nabla q$, $v \cdot \nabla T$ set to zero



(red contour: albedo = 0.3)

No ventilation and no β-effect:



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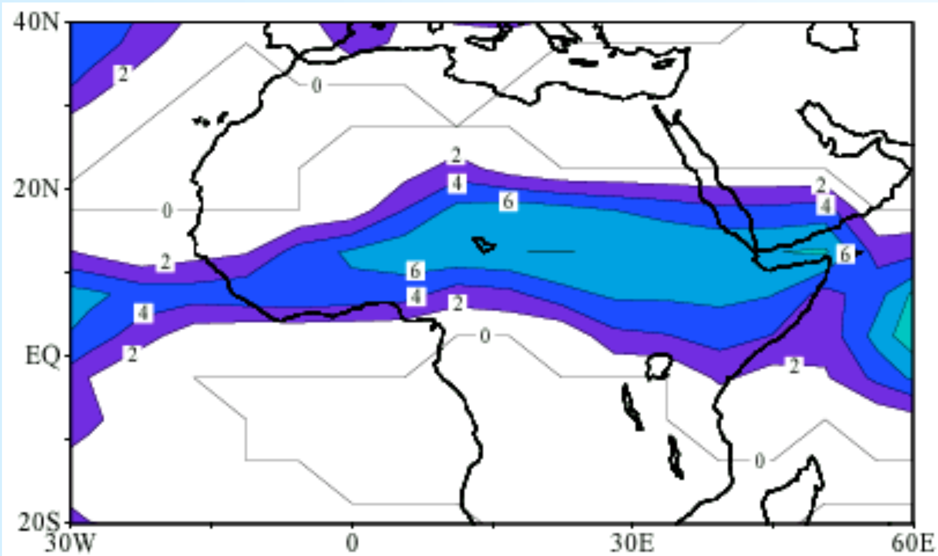
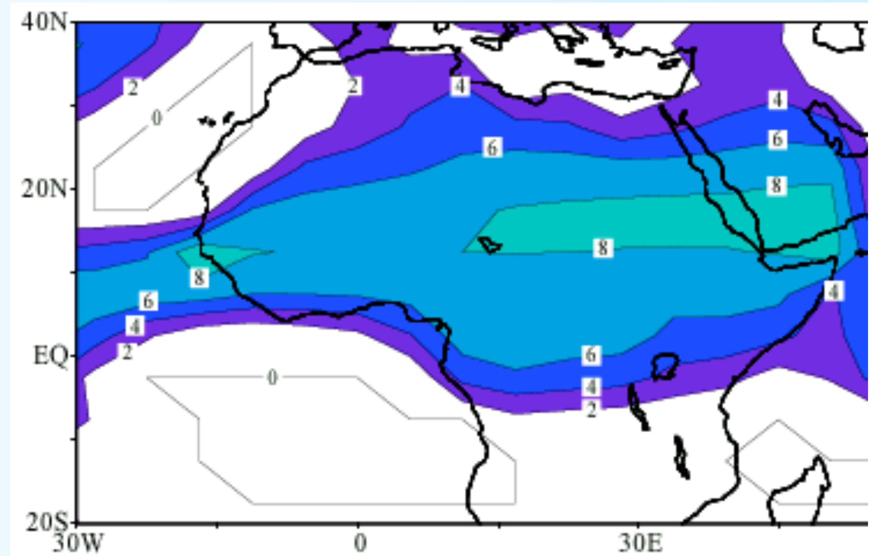
African region constant albedo case (0.26 over Africa) Jul

Precipitation

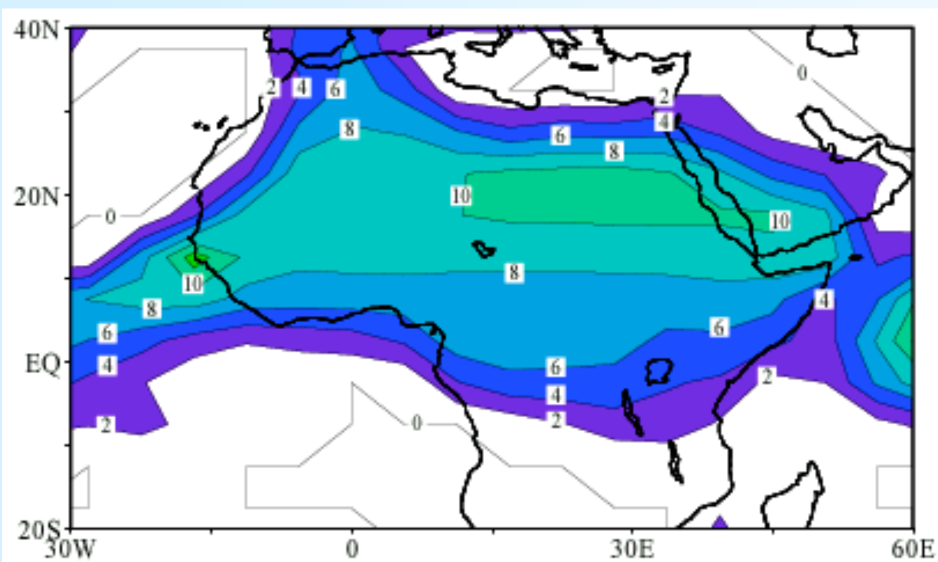
Control



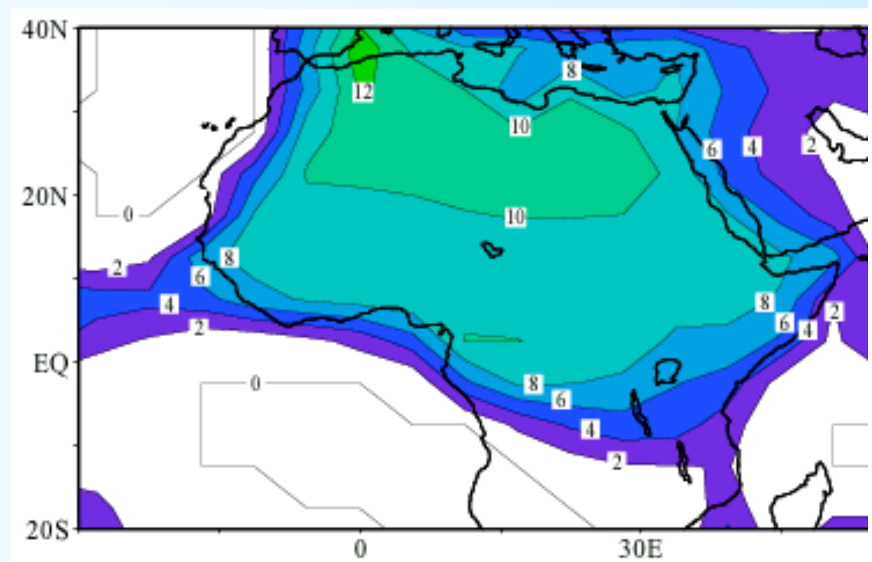
Saturated soil moisture



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



No ventilation and no β-effect:



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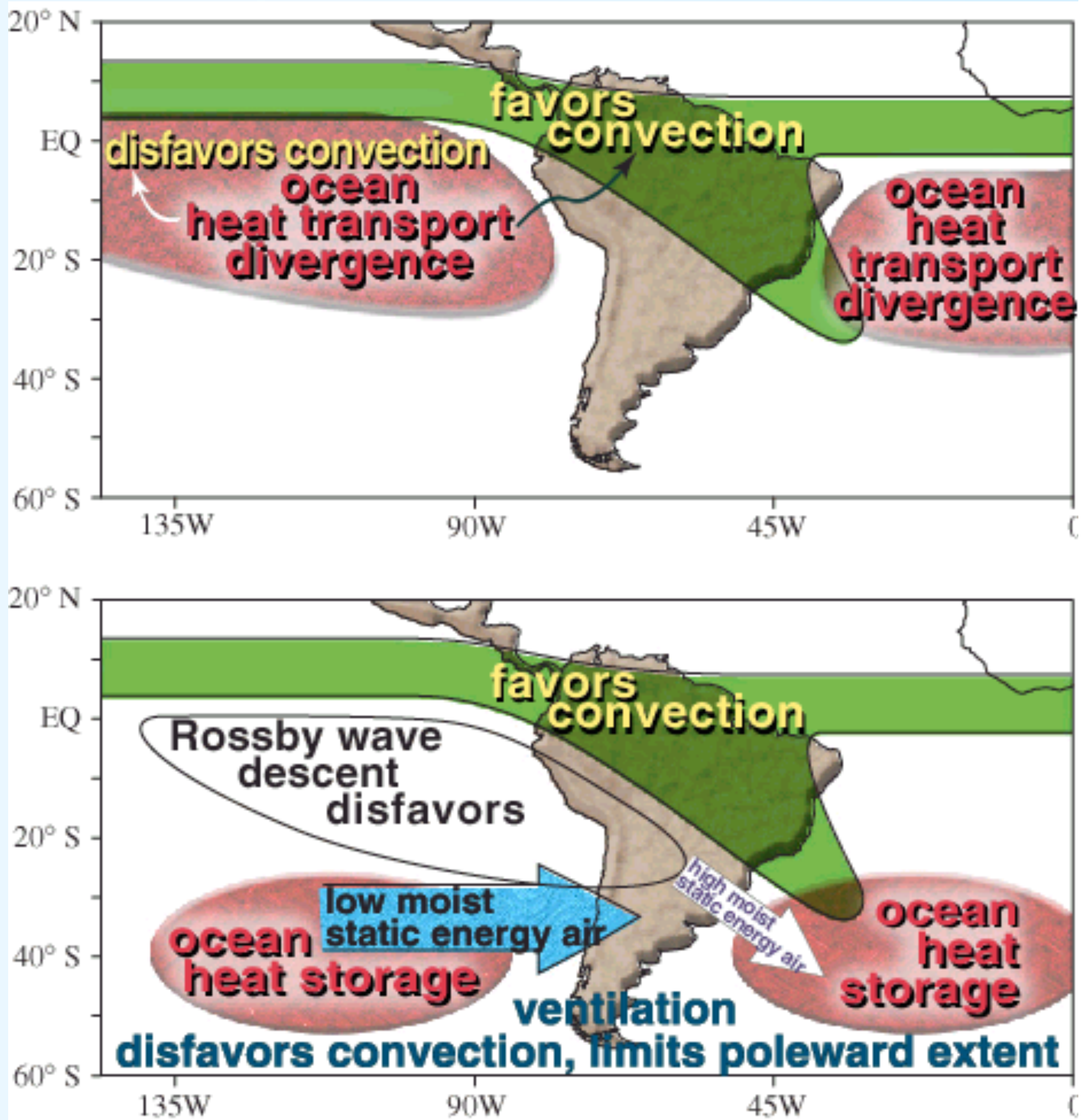
Mechanisms affecting convective zones (S. American ca

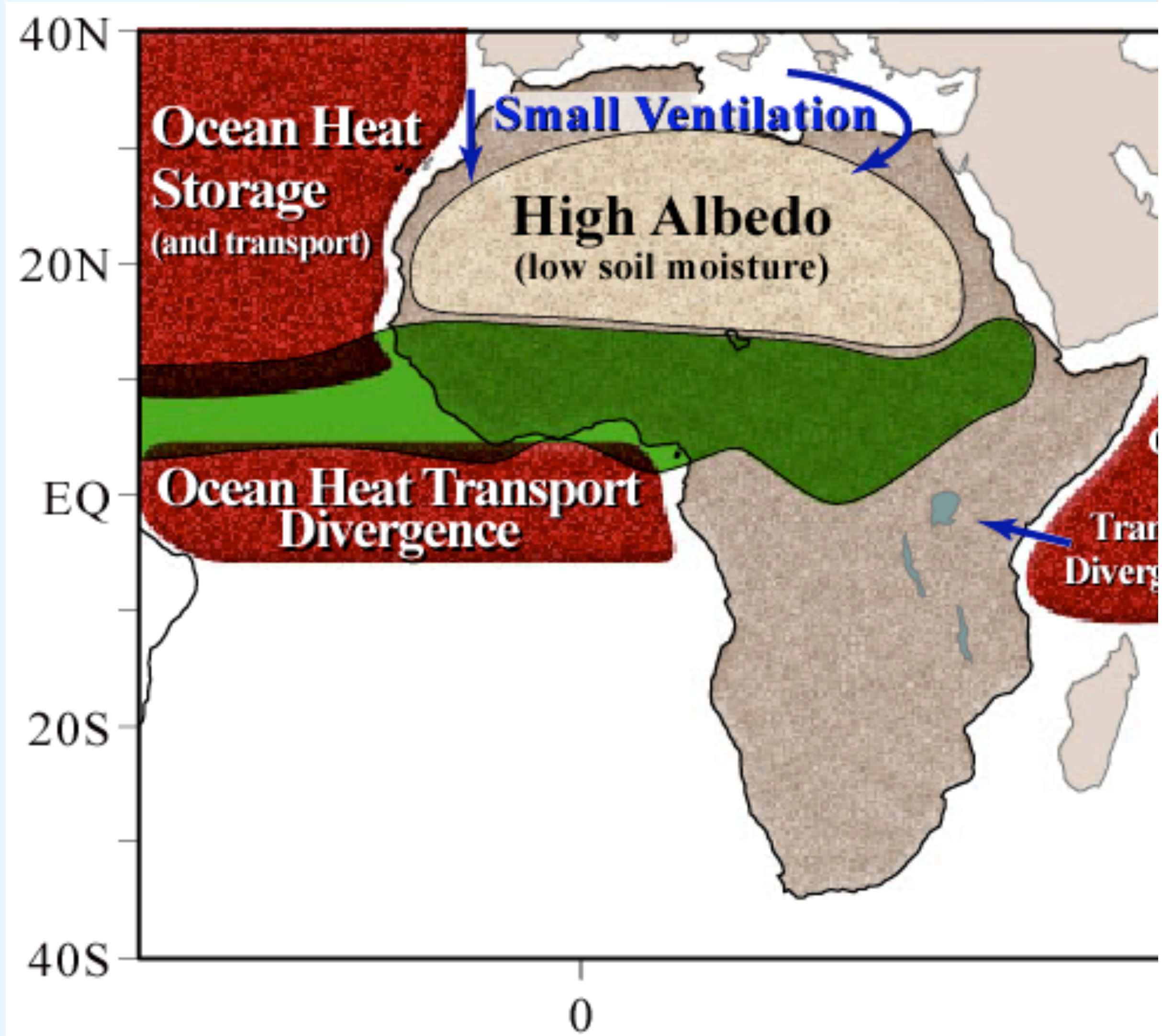
Ocean heat transport out of the tropics

Ventilation and the interactive Rodwell-Hoskins mechanism



African northern summer monsoon climatology

- Albedo is leading effect on poleward extent of convection
- Dynamical mechanisms:
  - affect margin of convective zone
  - take over if albedo gradient is flattened

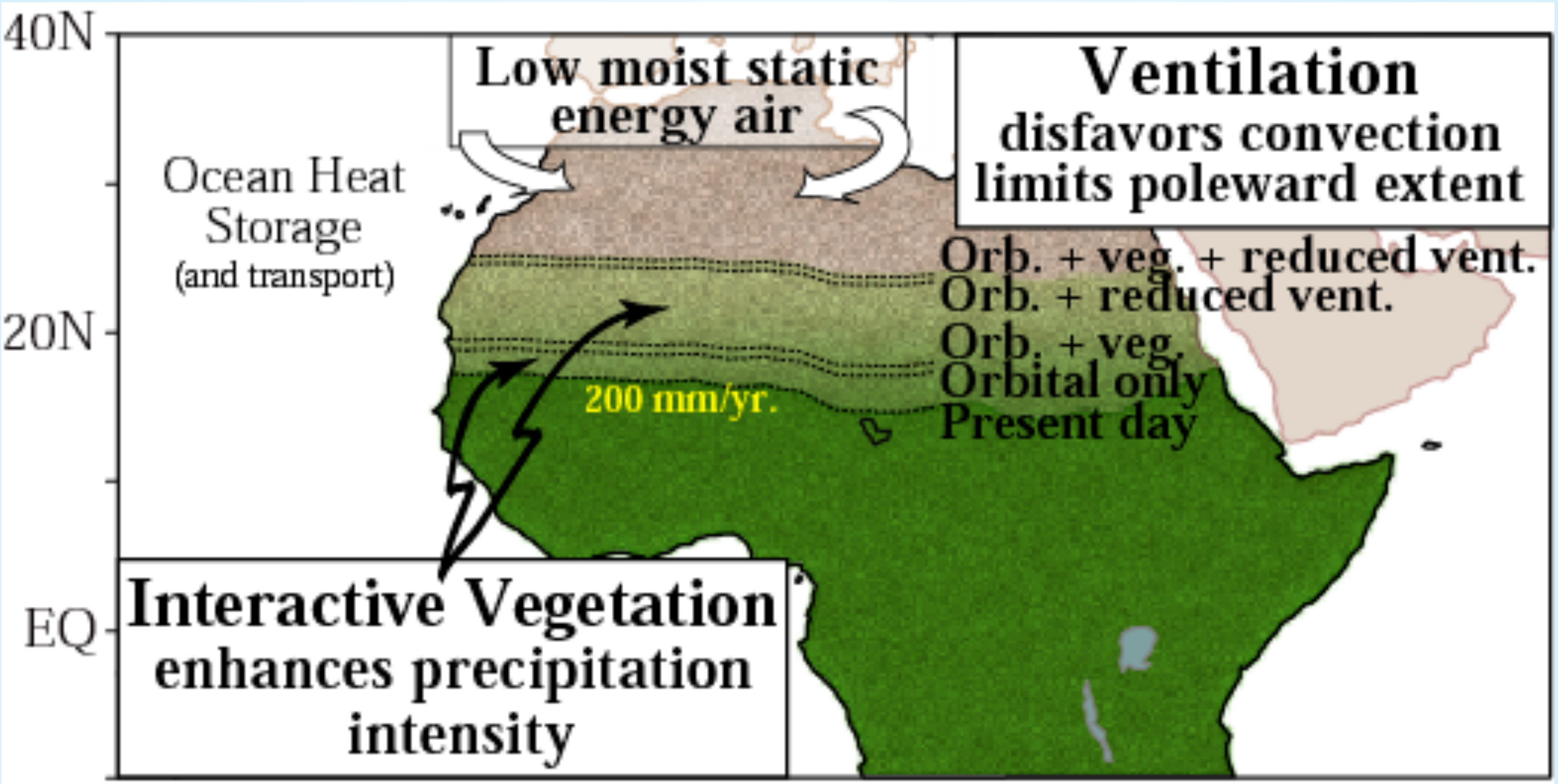


African monsoon & mid-Holocene (6kaBP) green Saha

- Paleo Model Intercomp Proj (PMIP): orbital parameter change => small monsoon boundary shift (Joussaume et al 1999) rel to pollen data (Jolly et al 1998; Prentice & Webb 1998)
- LMD and ECHAM GCMs with same interactive veg model yield different results (DeNoblet et al 2000)

- QTCM expts with grass-like albedo over Sahara (Su et al, in prep) & interactive vegetation (Hales et al, in prep)
- Ventilation opposes rise of moisture; may not increase enough to reach increase in trop temp.
- Reduced ventilation expts: e.g. reduce advection affecting q anomalies rel. to control; or reduce ventilation in control and 6kaBP cases

African mid-Holocene 6kabp monsoon Schematic of QTCM - SVeg expts.

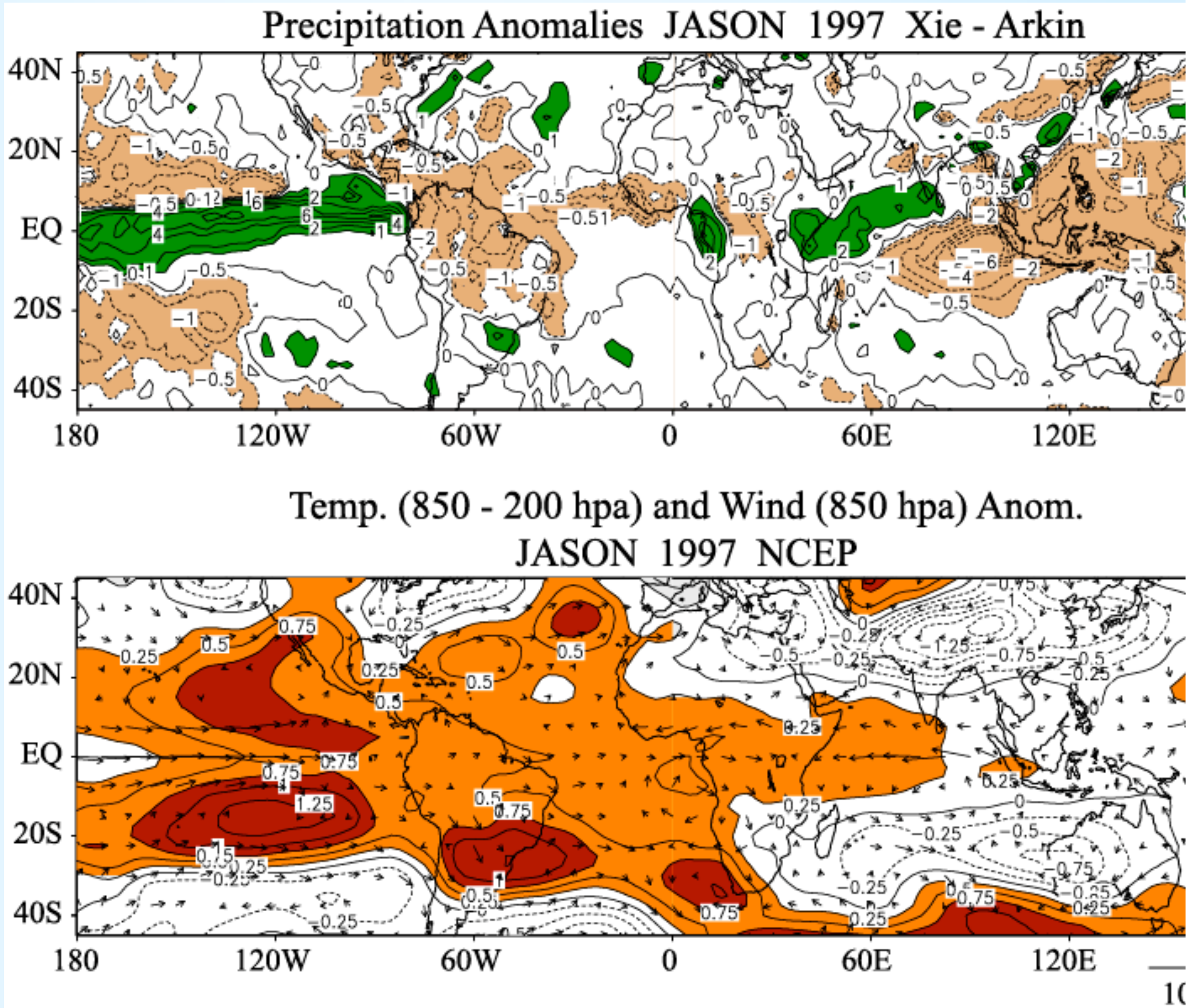


Mechanisms for regional precipitation anomalies teleconnections and global warming

- Tropical regional precipitation anomalies associated with changes in deep convection zone including drought regions in both El Niño & global warming cases. Mechanisms? Similarities

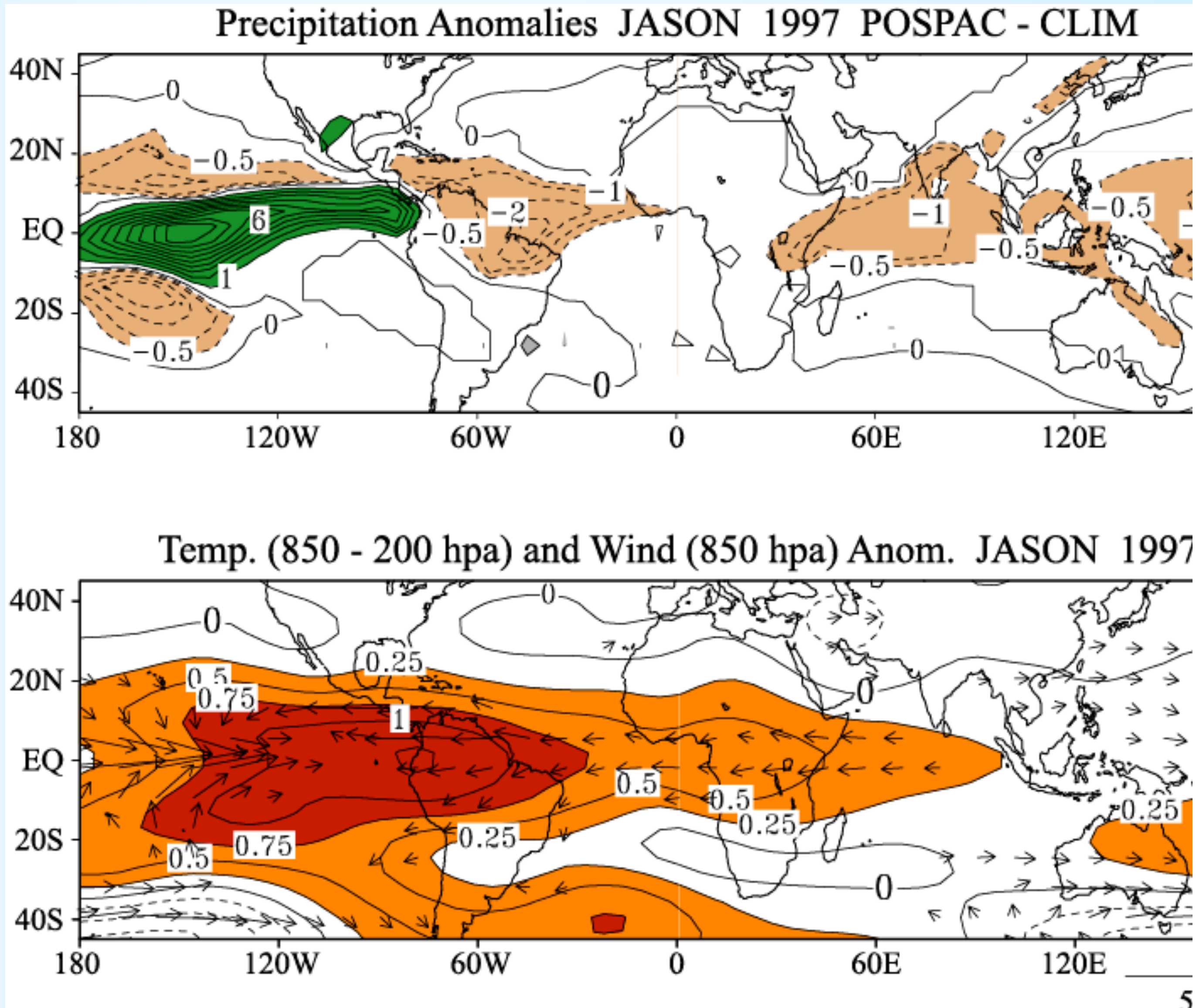
Observed anomalies during July-Nov 1997

Tropospheric Temperature



Neelin et al 2003; Neelin and Su 2004 su

QTCM anomalies forced by Pacific positive SST anomalies July-Nov 1997



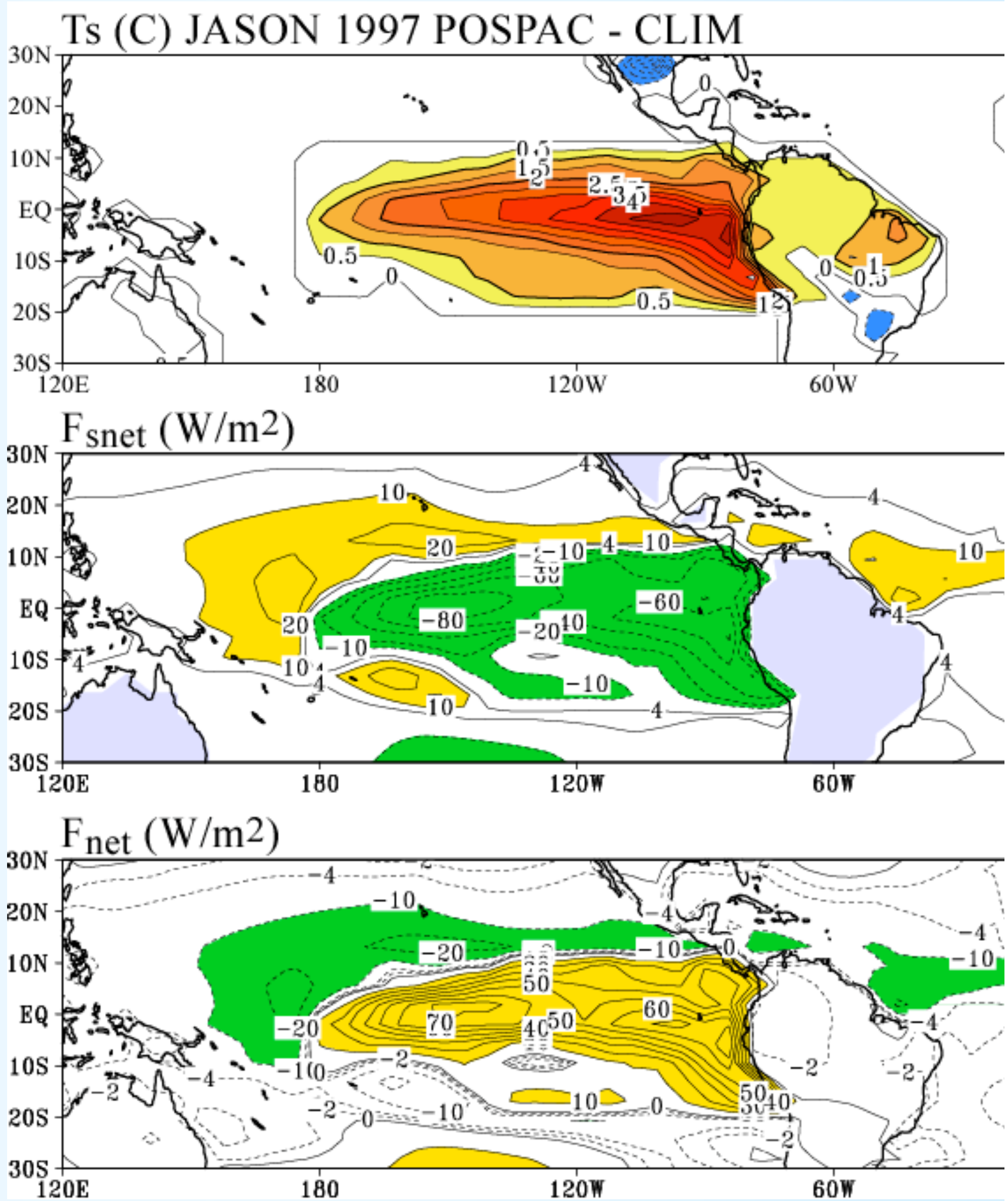
Tropospheric Temperature

QTCM POSPAC-Fluxes

Surface temperature

Net surface flux

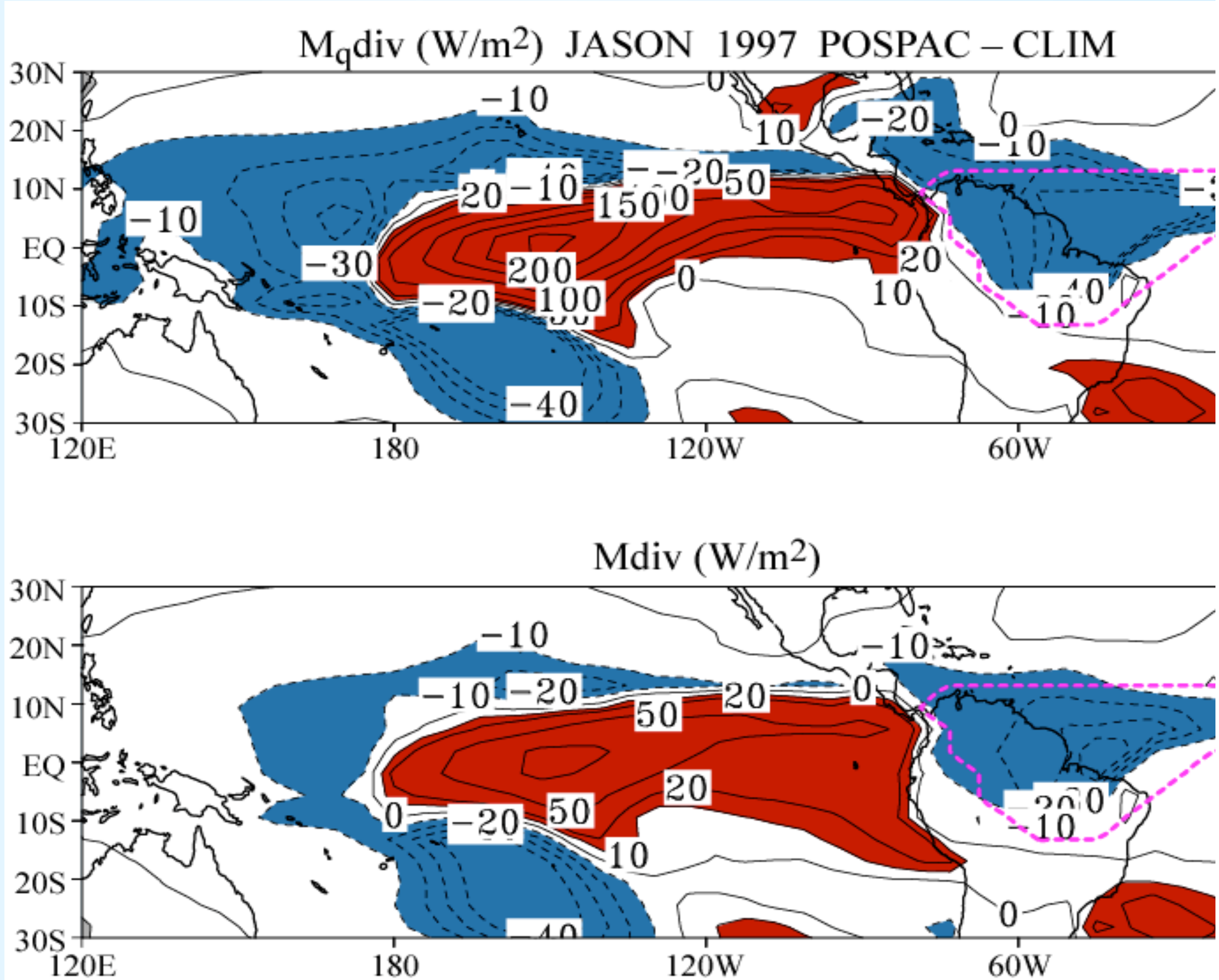
Net flux into atmospheric column



QTCM July-Nov 1997: Anomaly budget contributions

Moisture convergence $M_q \nabla \cdot v$ (by divergent flow)

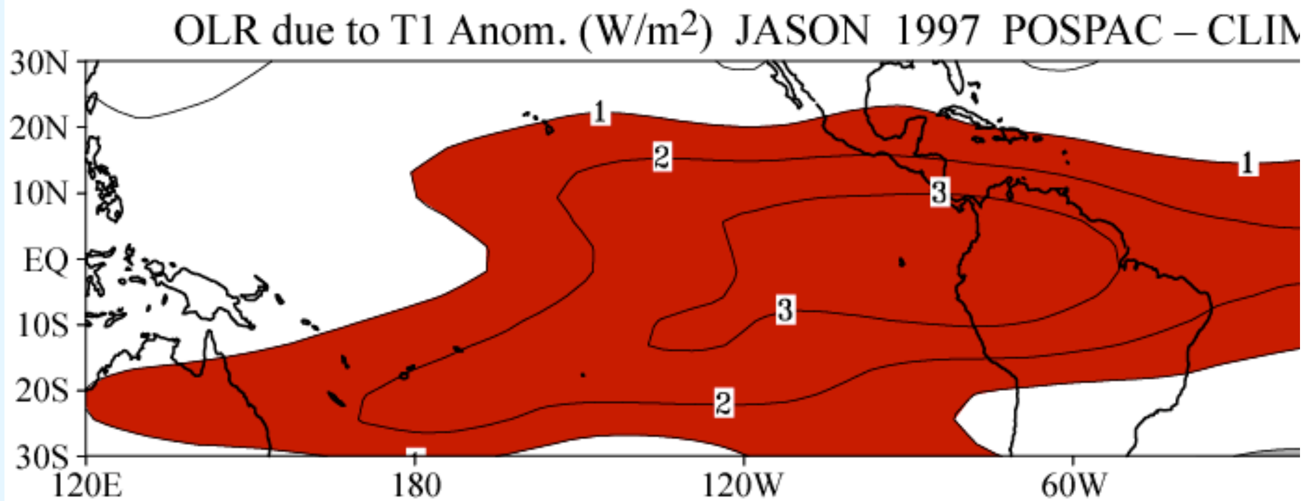
Moist static energy divergence* $M \nabla \cdot v$



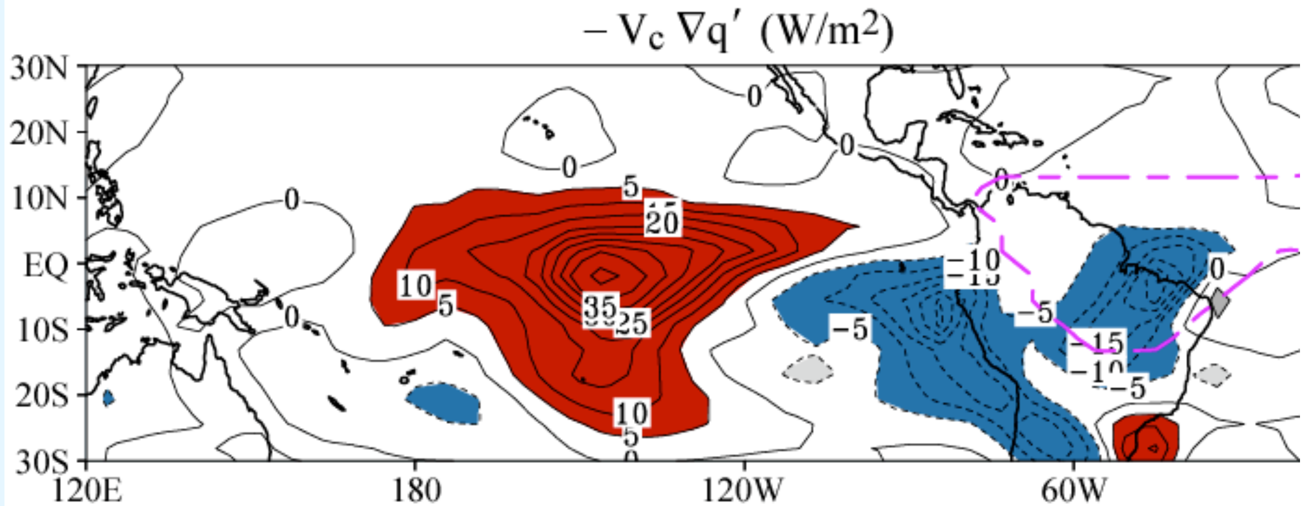
* **Gross moist stability $M=M_s-M_q$ is an effective stability that include partial cancellation of adiabatic cooling by diabatic heating**

QTCM July-Nov 1997: Anomaly budget contributions

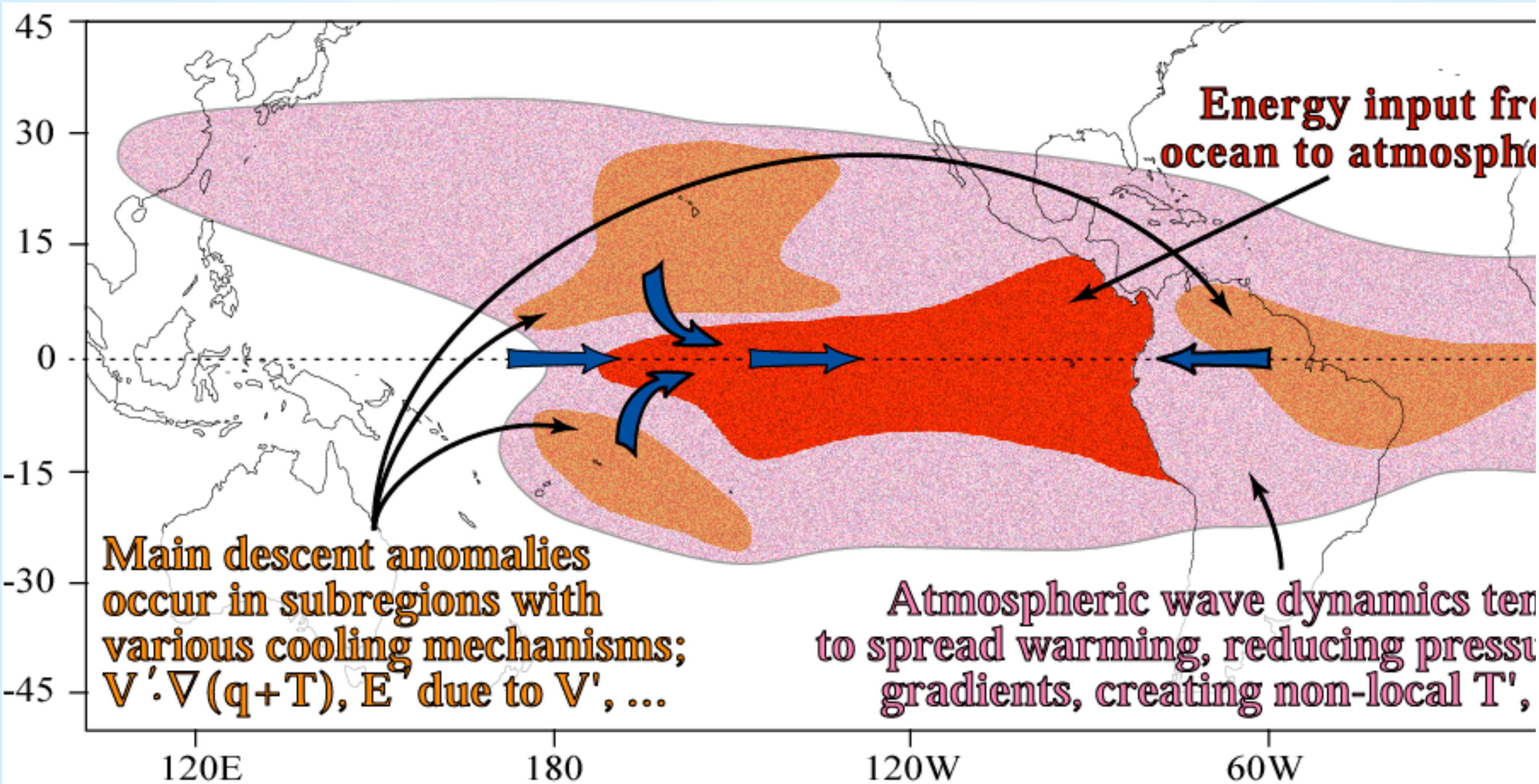
Radiative cooling anom. (top of atmosphere) due to temp. anom.



Mean wind advection of moisture anomaly
$\bar{v} \cdot \nabla q'$

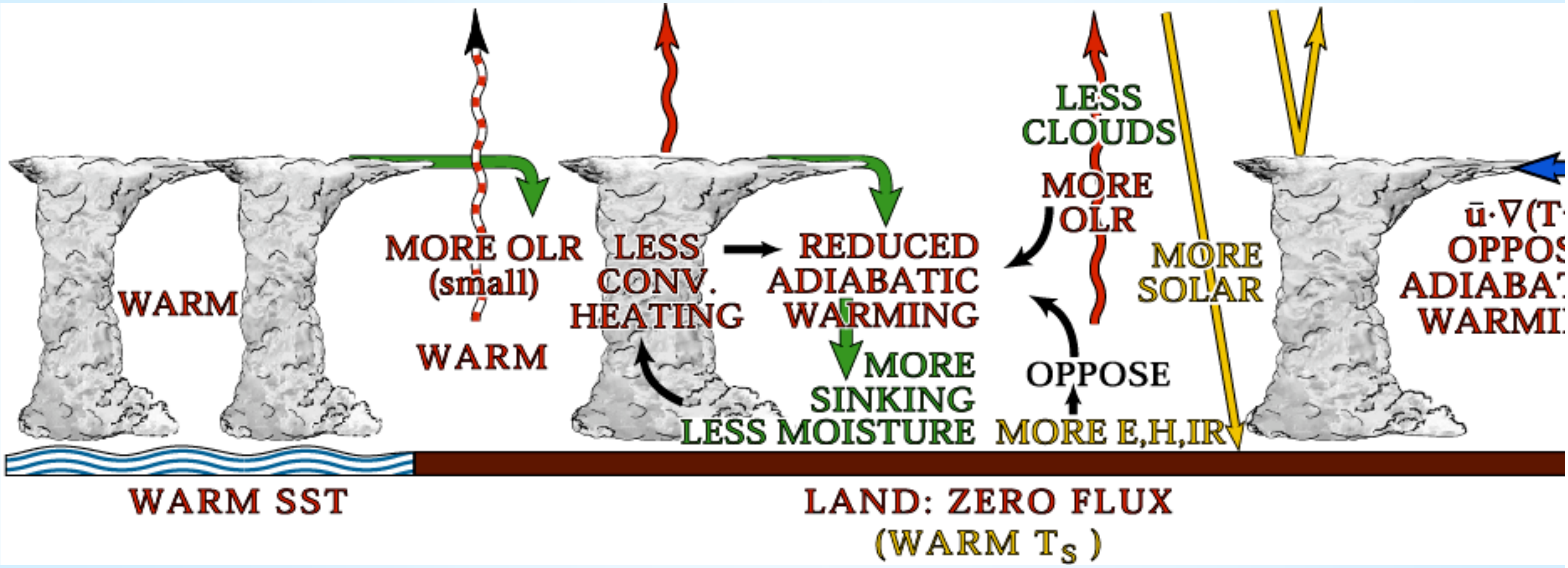


ENSO teleconnections to regional precip. anomalies



Su & Neelin,

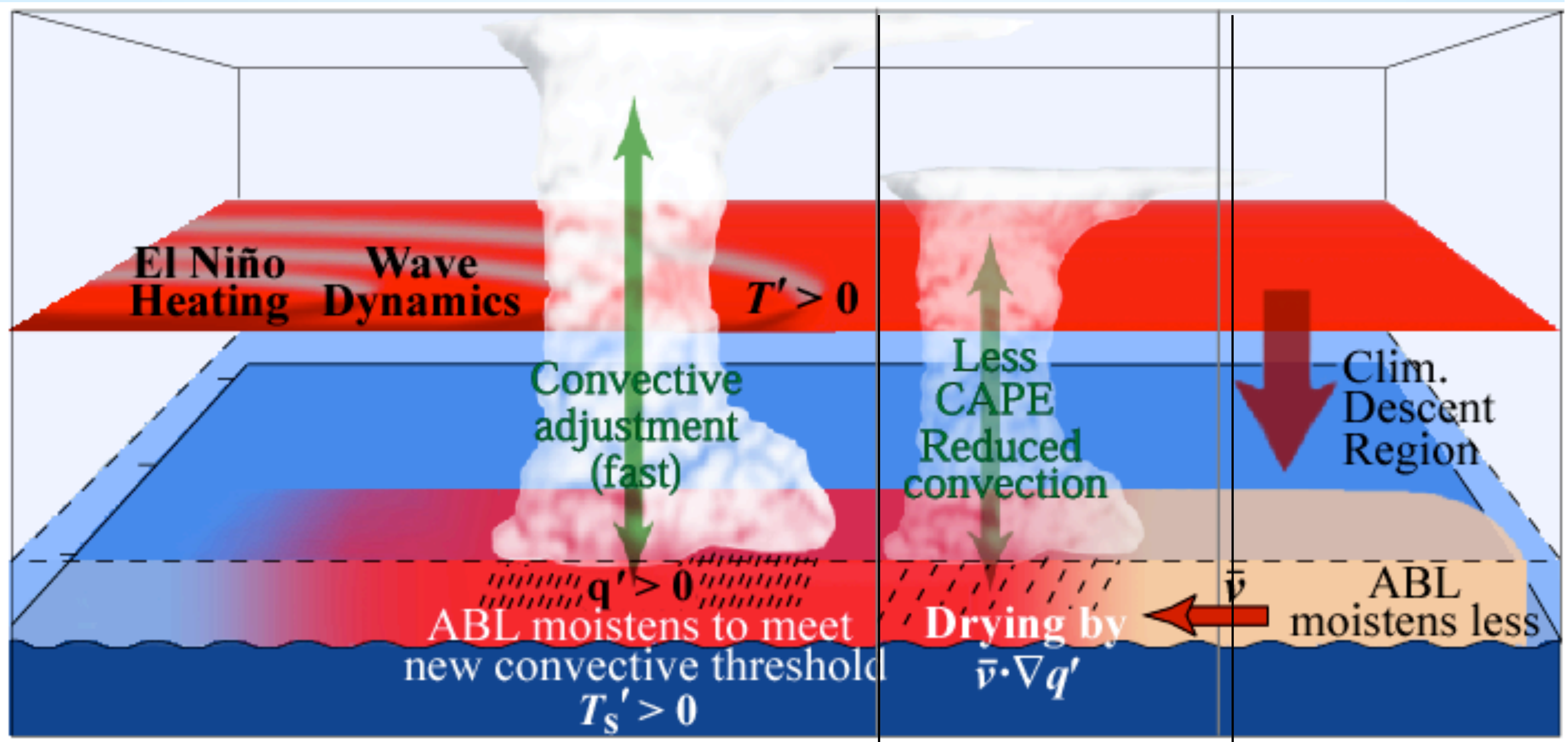
ENSO teleconnections to regional precip. anomalies



- a small zoo of mechanisms with moist convective and clo
  radiative feedbacks

Zeng & Neelin 1999; Giannini et al 2001; Su et al 2001; Bretherton & Sobel 200
Chiang and Sobel 2002; Chiang et al 2002; Su and Neelin 2002; Neelin et al 200
Neelin and Su 2004 subm…

The "upped-ante" mechanism



Margin of convective zone with $\bar{v}$ inward from dry region

Neelin, Chou & Su,

QTCM experiments suppressing upped-ante mechanism

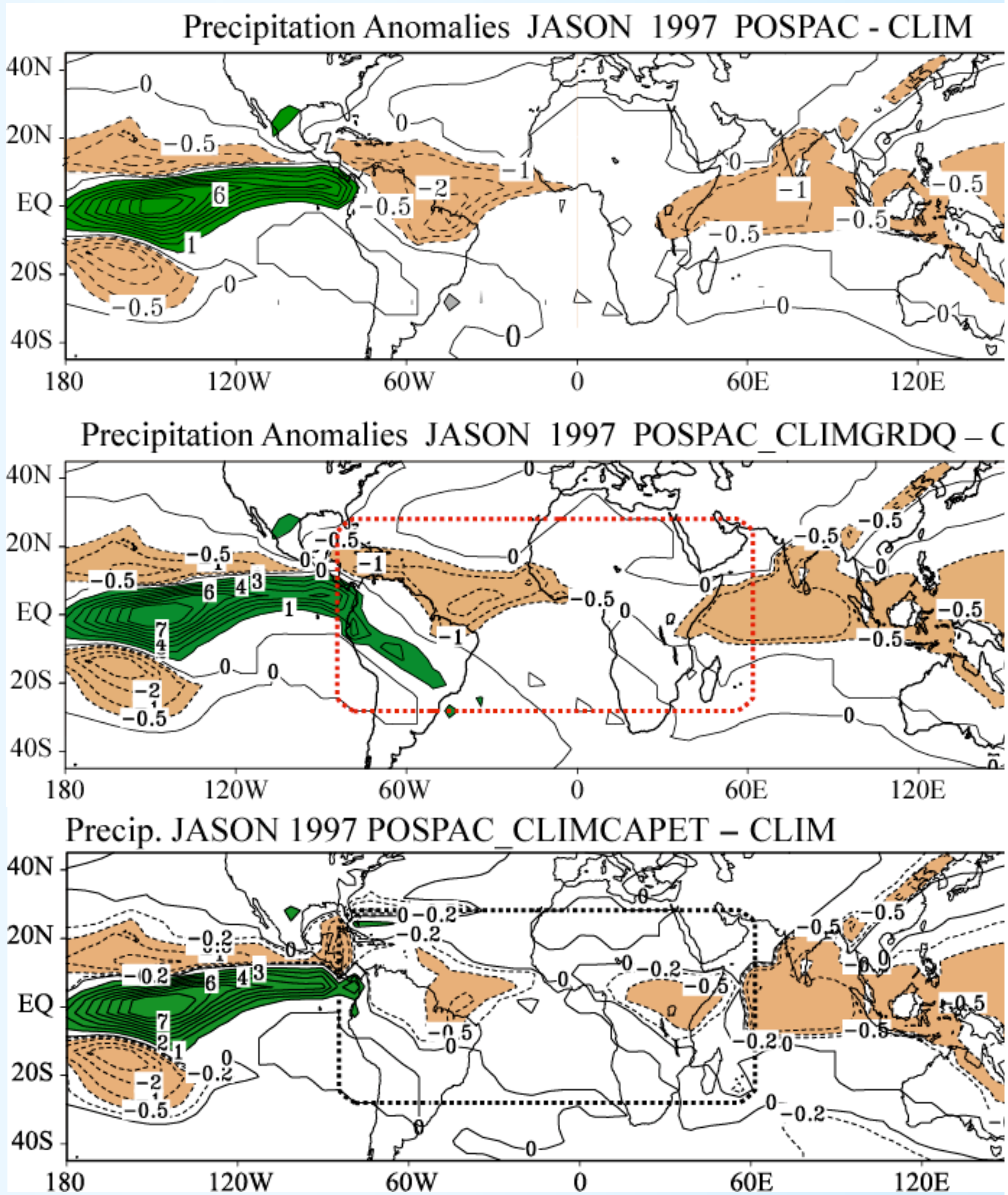
Precipitation Anomalies

Control

Anomaly ( )′ term suppressed in region:

$(v \cdot \nabla q)'$

T' **contribution to CAPE**



Other mechanisms

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

Perturbation MSE budget + **ocean mixed layer / land**

$$\bar{M}\,\nabla\cdot v' = -M'\,\nabla\cdot\bar{v} - (v\cdot\nabla q)' - c\partial_t T'_s + F^{net'}_{top} + (v\cdot\nabla T)' \ldots$$

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

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

Upped-ante (↑ $-(\bar{v}\cdot\nabla q)'$)

Anomalous GMS (↑ $\nabla\cdot v(-M')$)

Rad cooling, $(v\cdot\nabla T)$, ocean transp, … (↑ $\ldots$)

GMS multiplier effect (↑ $\bar{M}_q/\bar{M}$)

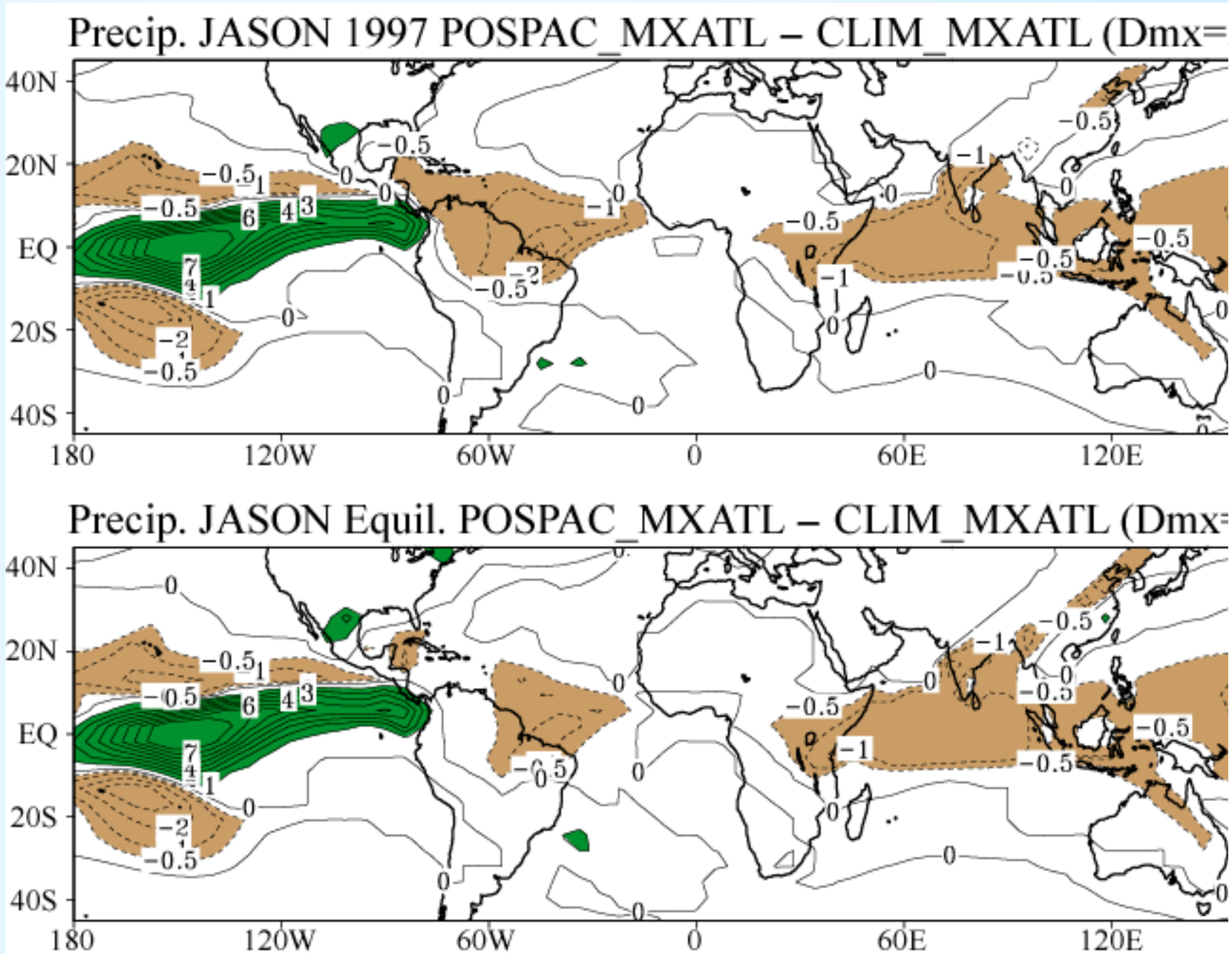
SST disequilibrium (↑ $c\partial_t T_s'$)

Mixed layer ocean in Atlantic: 1st year vs equilibrium

Precipitation anomalies

- Positive 1997 El Nino Jul.-Nov. SST anom in Pacific: tropical Atlantic 50m ML SST is adjusting

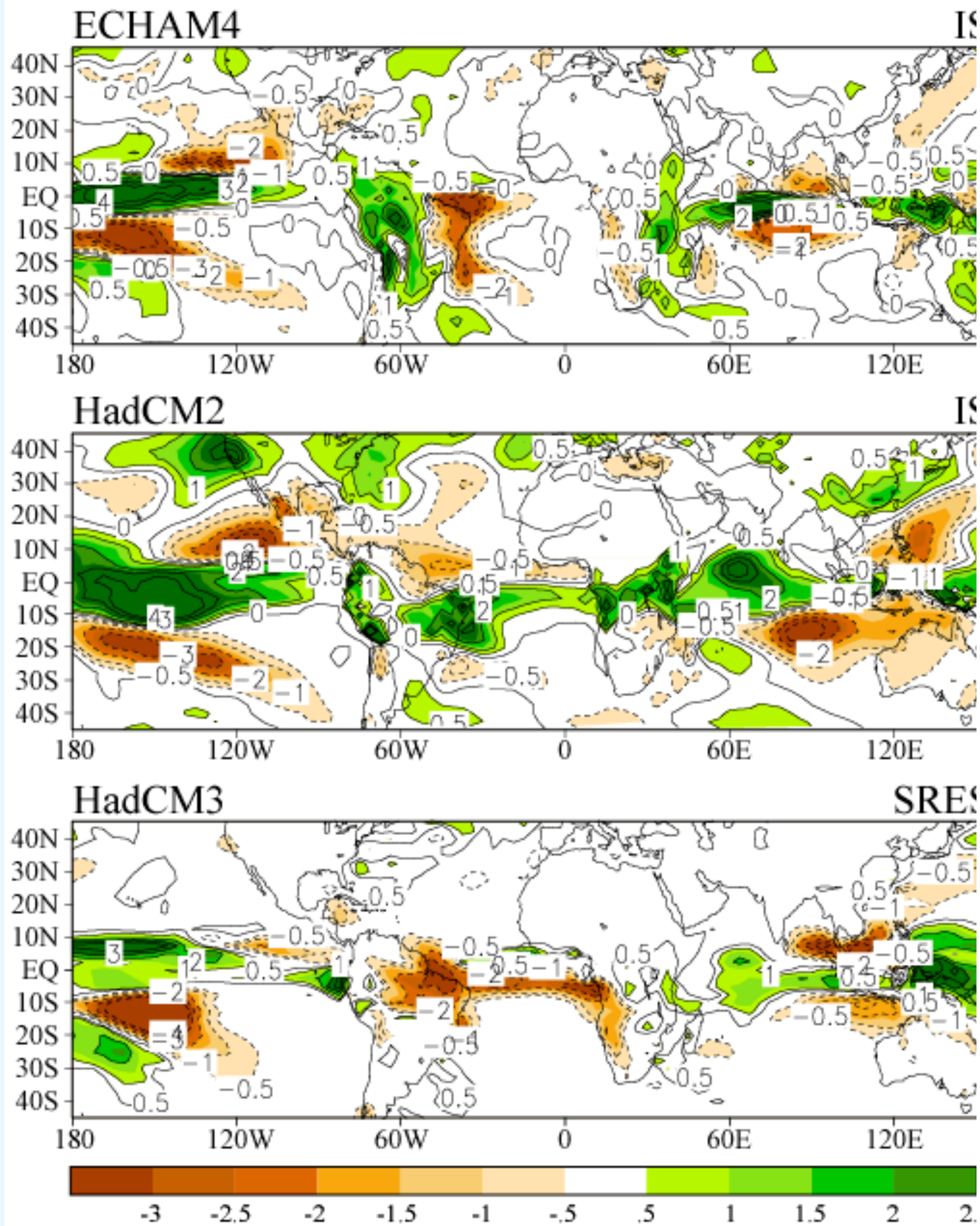
- Long term equilibrium with El Nino SST anom artificially sustained



(anomalies relative to climatology of ML Atlantic, clim. SST elsewhere)

Global Warming case: GCM Precip. Anom.

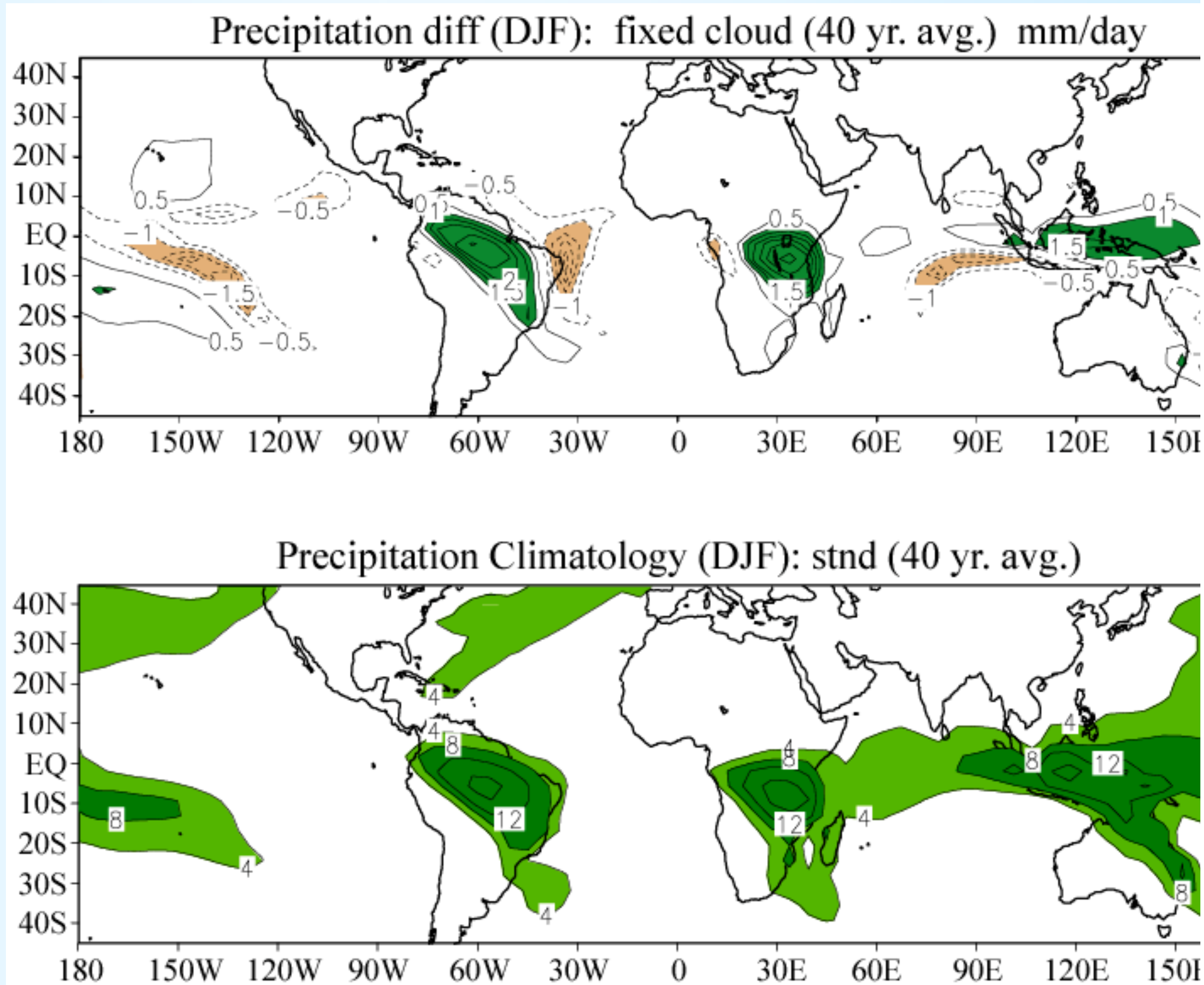
DJF precip. anom.
Three GCM
Greenhouse gas
scenarios for
2070-2090
rel. to 1961-1990 clim



QTCM doubled CO_2 experiments
Qflux mixed-layer ocean

Dec - Feb
Precip change

Dec - Feb
QTCM Precip
climatology

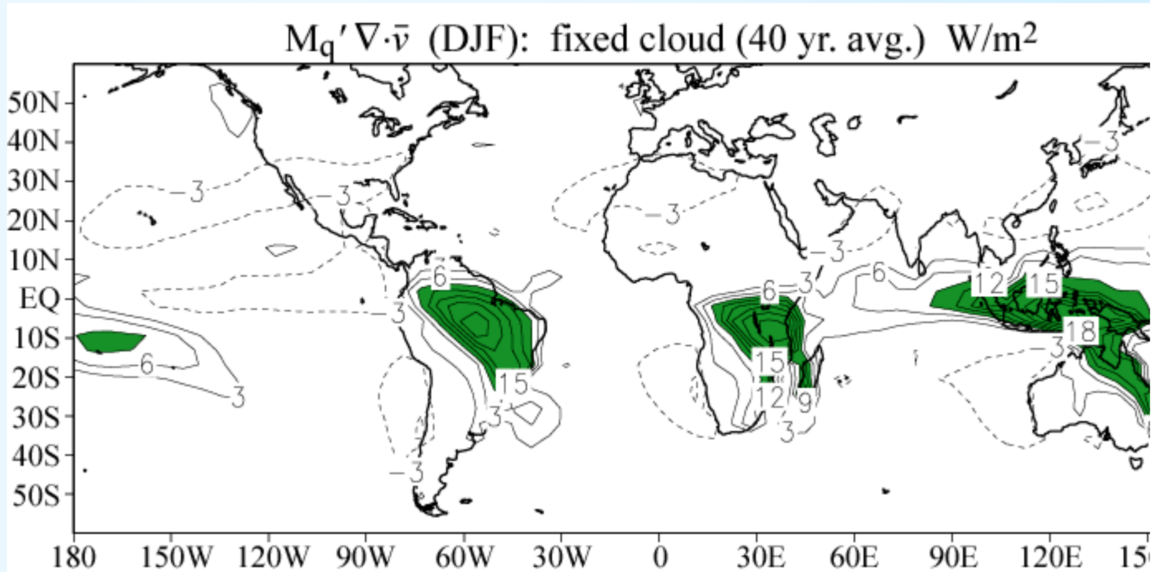


Neelin et al 2003; Chou & Neelin 2

QTCM doubled CO_2 experiments
Moisture budget contributions

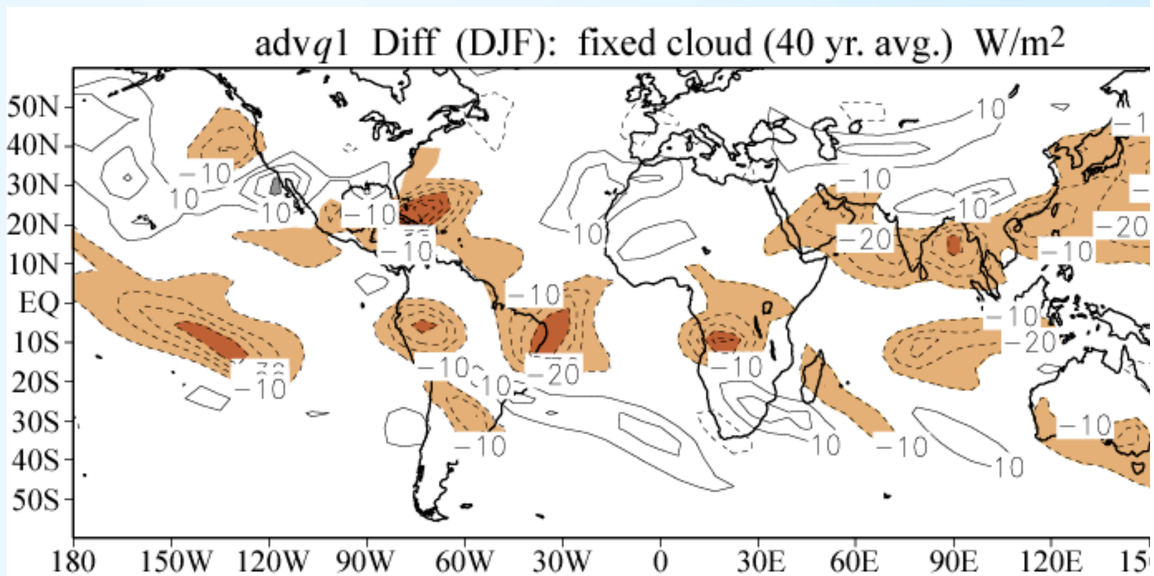
$M_q{}' \nabla \cdot \bar{v}$

Anomalous moisture convergence due to moisture anom. q'



$(v \cdot \nabla q)'$

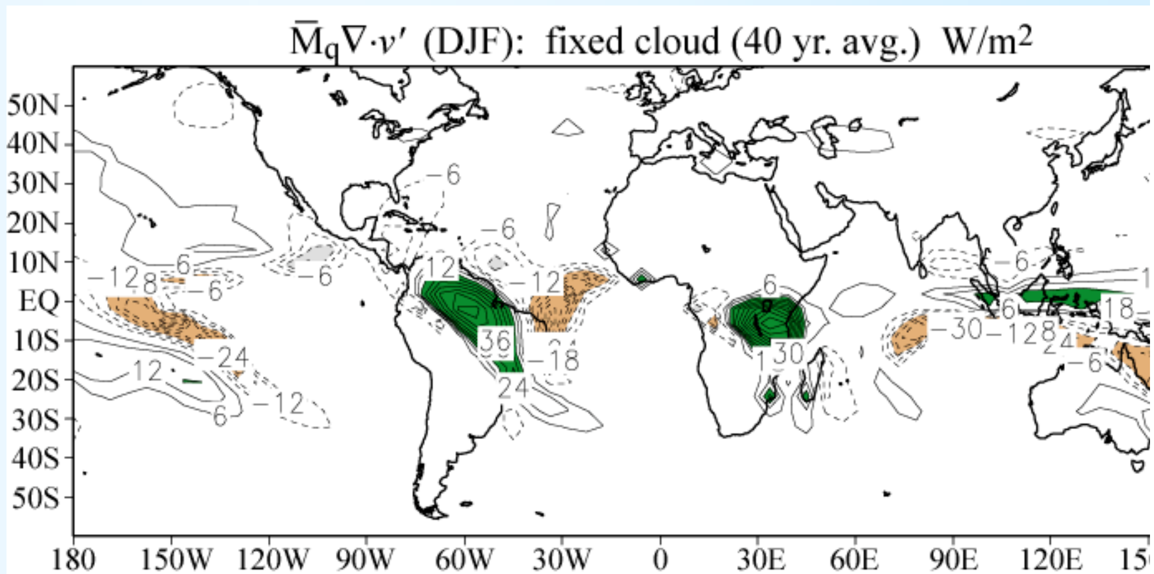
Anomalous moisture advection



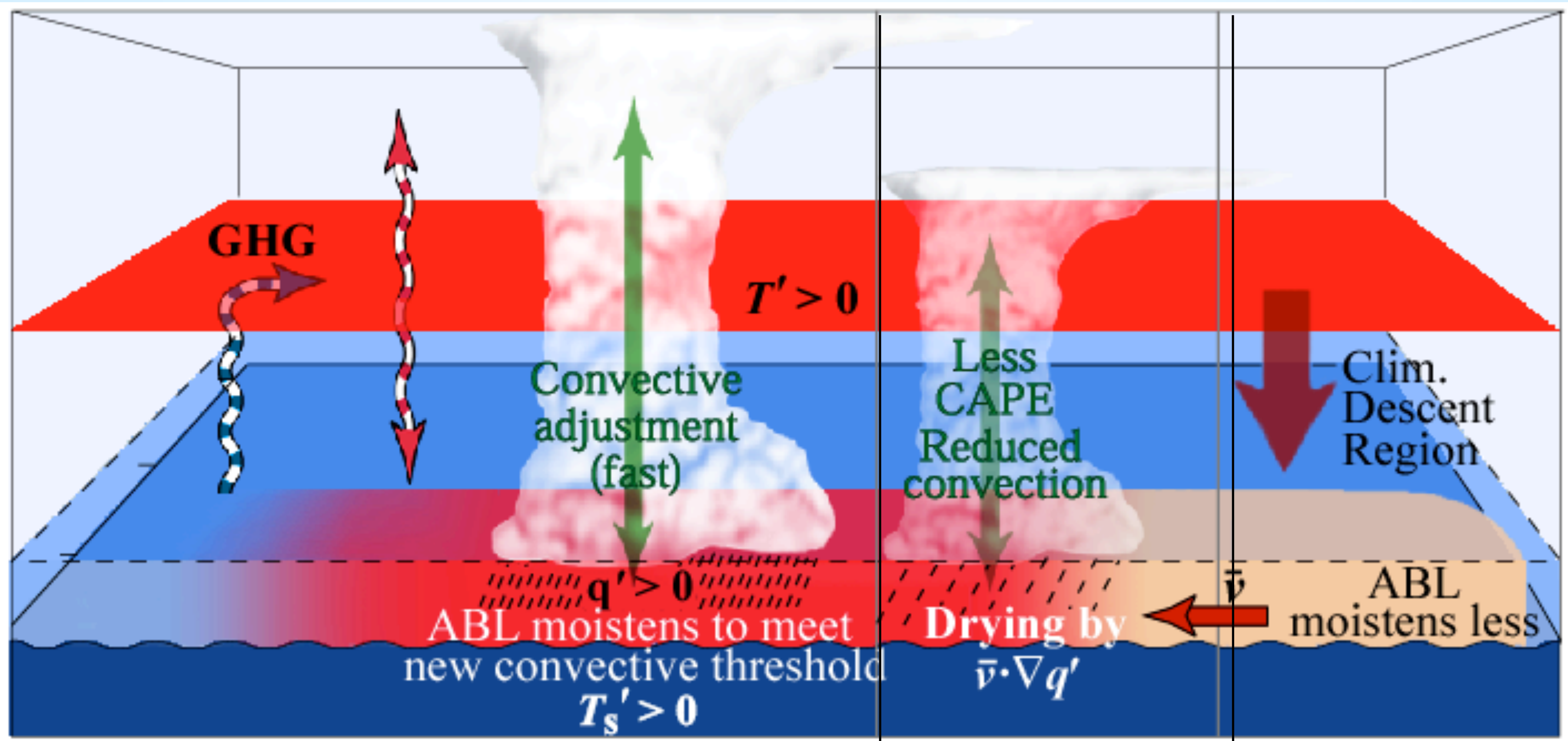
QTCM doubled CO_2 experiments
Moisture budget contributions

$\overline{M}_q \nabla \cdot v'$

Anomalous moisture convergence due to anomalous divergence (GMS multiplier effect feedback)



The "upped-ante" mechanism



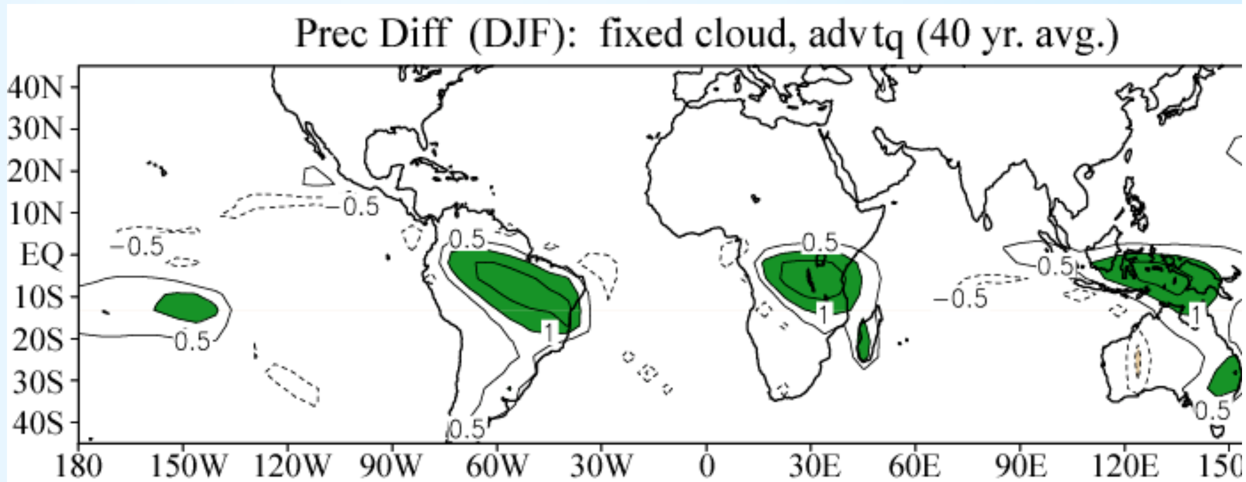
Margin of convective zone with $\bar{v}$ inward from dry region

Neelin, Chou & Su,

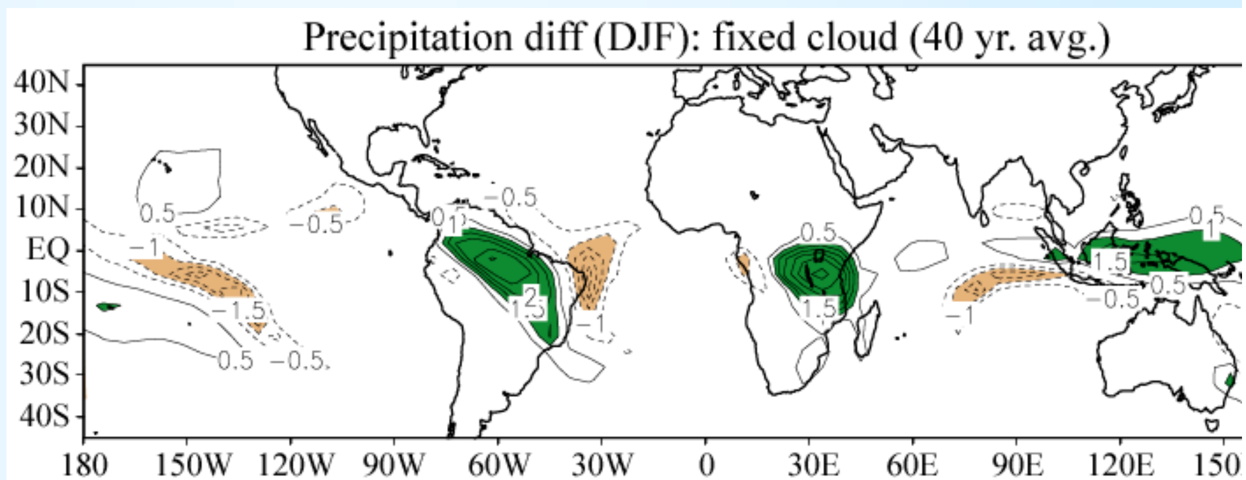
QTCM $2xCO_2$ Expt. suppressing change in moistur advection

(testing the upped-ante mechanism)

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

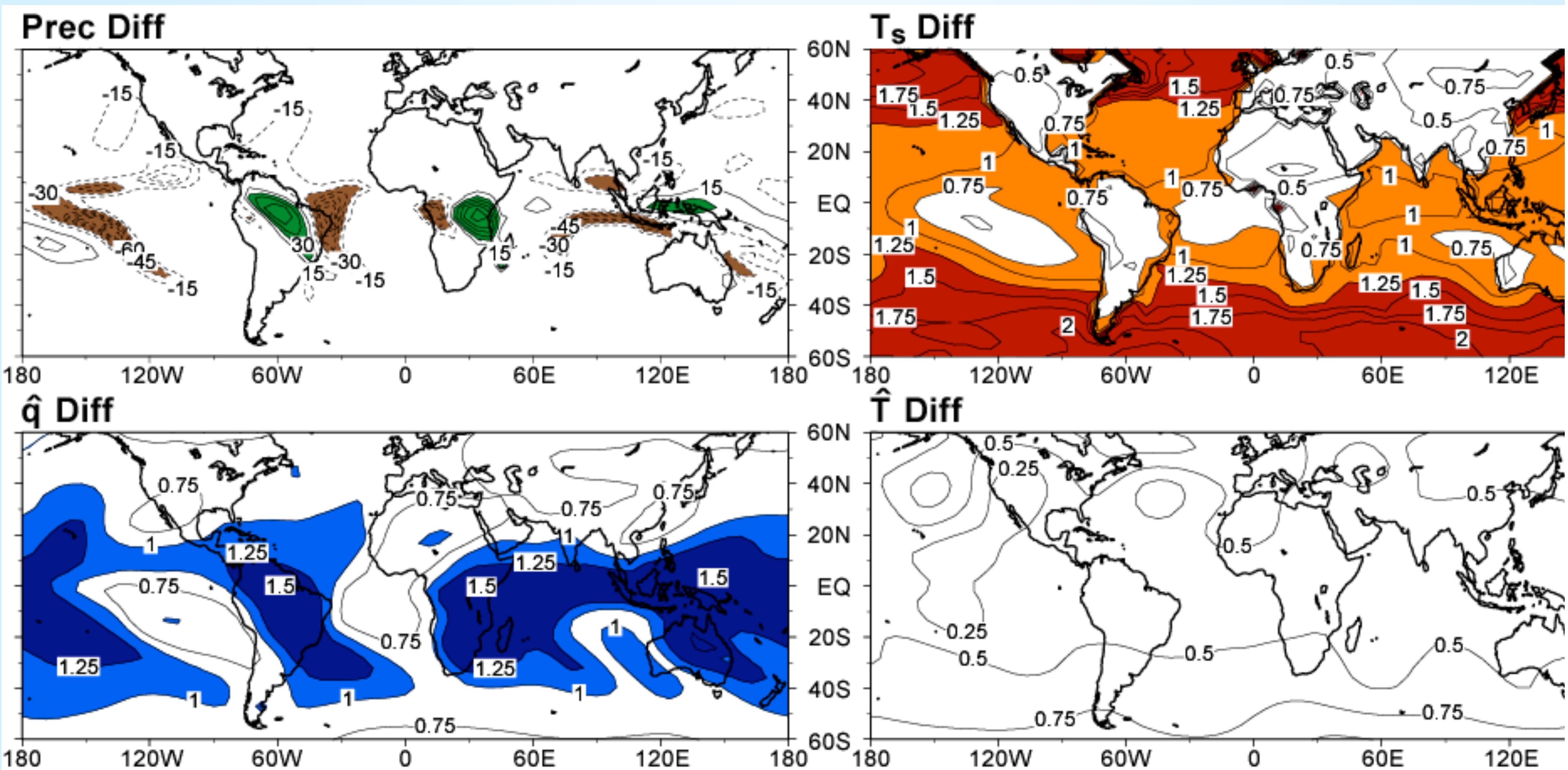


Control
$2xCO_2$ Precip. change



Response to imposed T change in CAPE

- $T' = 1.5$ C added to temperature only inside convection scheme
- Mimicks 2xCO_2 moisture and regional precip response
- DJF Precip (W/m^2), surface temp, moisture (K), tropospheric mean te



Anomalous Gross Moist Stability (M′) mechanism

- Moist Static Energy transport by divergent flow ≈ $M\nabla\cdot v$
- $M = M_s - M_q$

increases with increasing moisture, tends to reduce M

may partially compensate if cloud top rises

- $\bar{M}\nabla\cdot v' + M'\nabla\cdot \underline{v} = F'_{net} - (v\cdot\nabla q)' + \ldots$

reduced

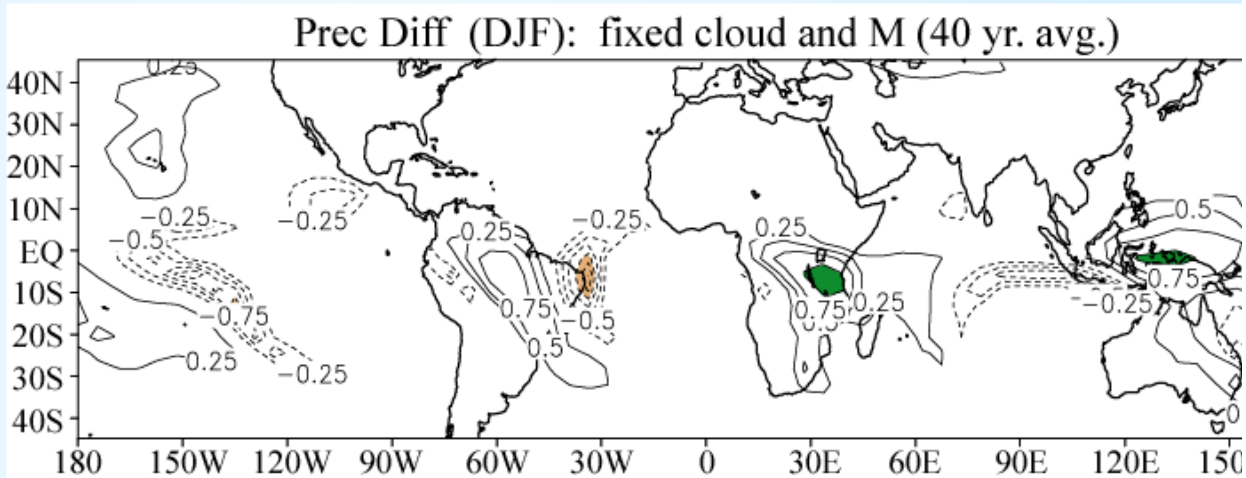
increases to compensate

- $P' \approx \frac{\bar{M}_q}{\bar{M}}\nabla\cdot \underline{v}(-M')$
- Mechanism increases convergence & precip. in strong convergence zones: "rich-get-richer"

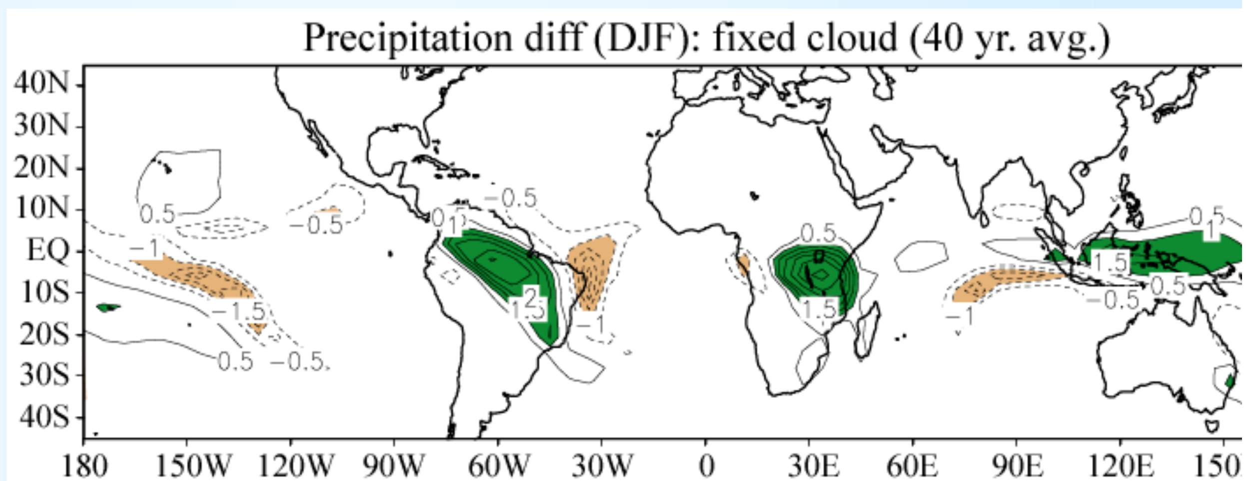
QTCM 2xCO_2 Expt. suppressing change in gross moi stability, M

(testing the M′ mechanism)

Experiment
2xCO_2 Precip. change
(mm/day)



Control
2xCO_2 Precip. change

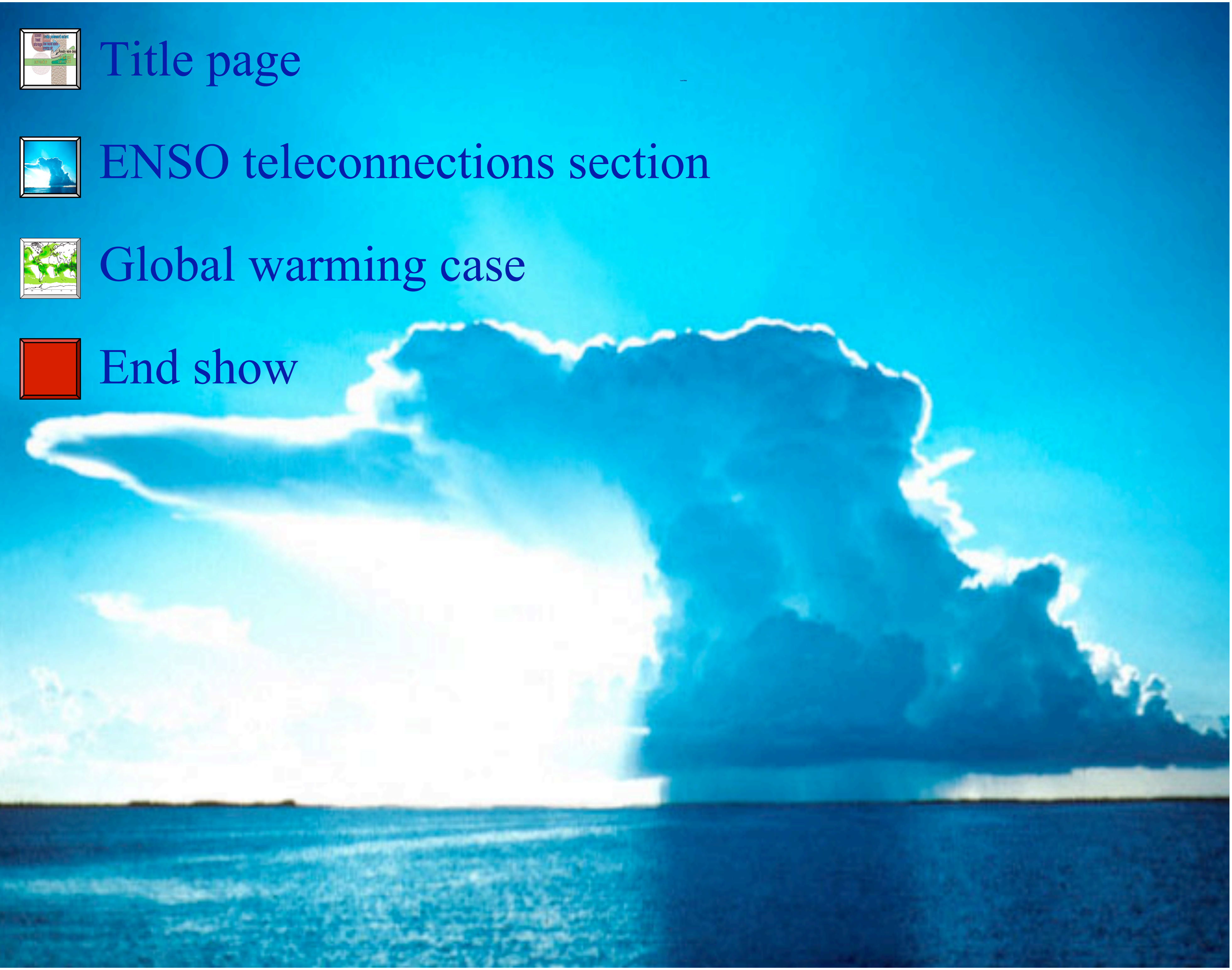


Summary: Regional precip. Teleconn./global warmin

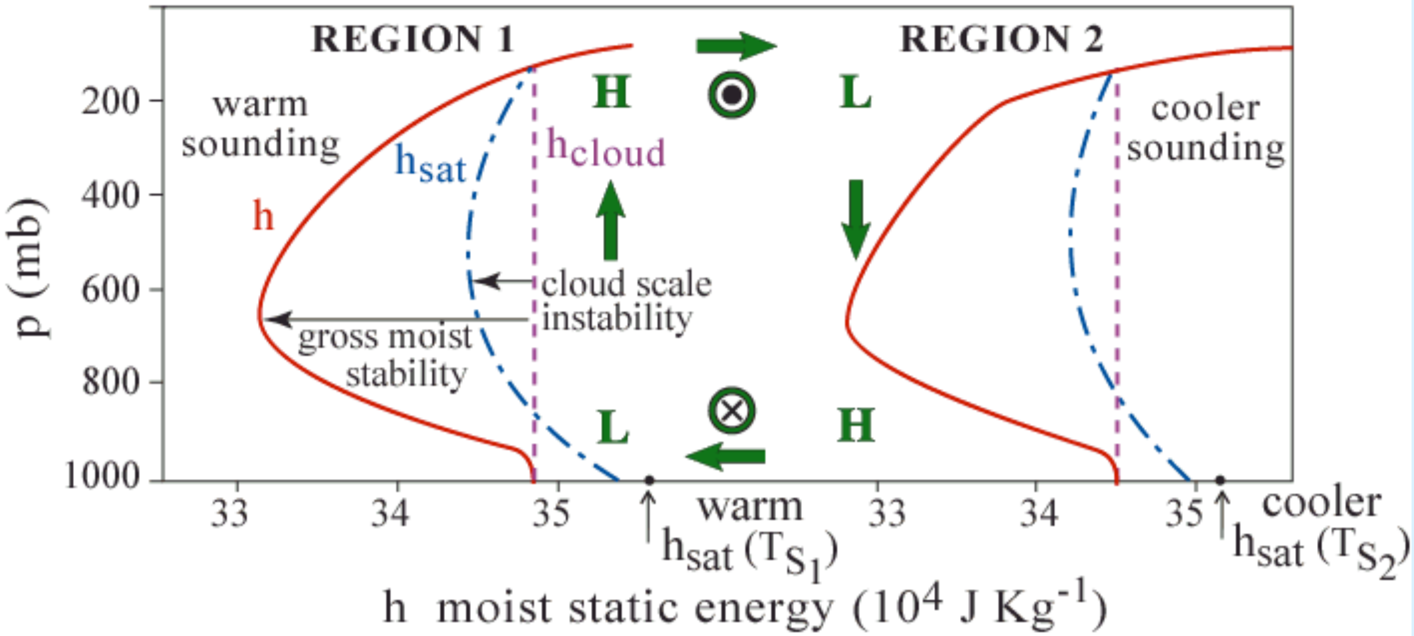
- tropical regional precipitation anomalies in ENSO teleconnect case ⇒ a handful of contributing mechanisms
- $2XCO_2$ case, mixed-layer ocean case ⇒ set of mechanisms wi some cross-over to ENSO case
- the "upped-ante mechanism":
  - substantial negative precip. anomaly regions in both cases
  - drought occurs at margins of convection zones with climatolog wind inflow from dry zone into convection zone
- the "anomalous gross moist stability (M') mechanism":
  - contributes positive precipitation changes in strong precipitatio regions in global warming case (but theory for M' very poor)
- Surface heat fluxes & SST′ important only when SST is in disequilibrium (∂_t SST or ocean transport anom.)

Regional precip. anom. relation to monsoon case

- $\boldsymbol{v_\psi} \cdot \nabla(\boldsymbol{q}, \boldsymbol{T})$ terms: strong impact on precip/precip anomalies d
  to role in moist static energy budget
  - partial cancellation of adiab. cooling & diab. heating ⇒ smal
  - M_q/M large ⇒ GMS multiplier effect
  - oppose precip in parts of trop convg zones & limit poleward ex
  - role in upped-ante mechanism; involves QE to not QE transitio
- role of QE mediation: moisture rel to T of free troposphere vs
  imported q
- F_{net}: favorable but not sufficient in monsoon; small in land ano
  - ocean heat storage & transport ⇒ ocean land contrast in monso
    contrib. some Atl. negative precip. anoms. in ENSO case


Title page
ENSO teleconnections section
Global warming case
End show

Q_c constrains temperature through deep column
→ baroclinic pressure gradients



Neelin 1997

Model Summary – QTCM equations

$$\partial_t \boldsymbol{v}_1 + \mathcal{D}_{V1}(\boldsymbol{v}_0, \boldsymbol{v}_1) + f\boldsymbol{k} \times \boldsymbol{v}_1 = -\kappa \nabla T_1 \text{ - stress}$$

$$\partial_t \boldsymbol{v}_0 = \ldots \; \textit{(barotropic component)}$$

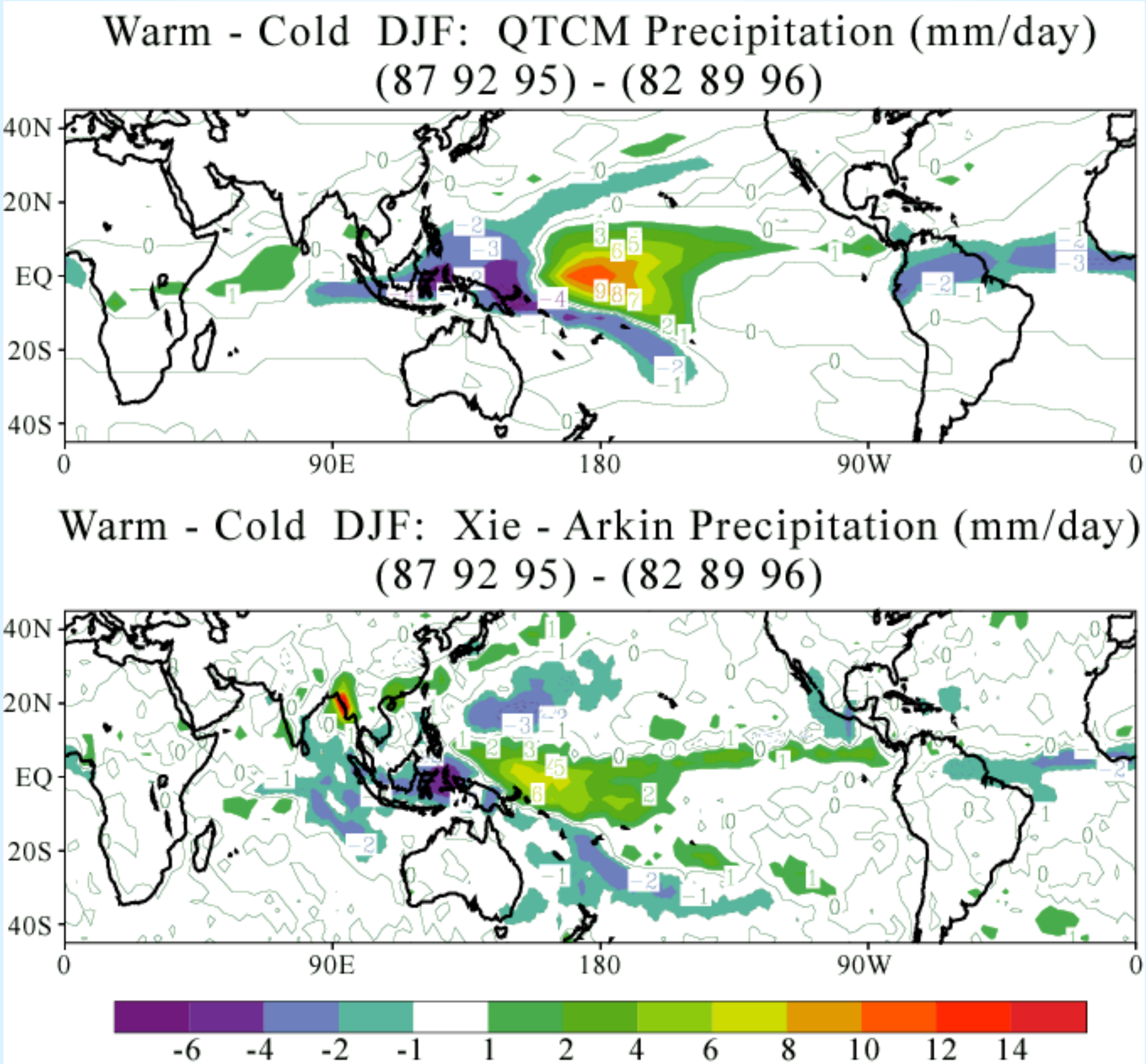
$$\hat{a}_1(\partial_t + \mathcal{D}_{T1})T_1 + M_{S1}\nabla\cdot\boldsymbol{v}_1 = \langle Q_c \rangle + \text{Rad} + H$$

$$\hat{b}_1(\partial_t + \mathcal{D}_{q1})q_1 + M_{q1}\nabla\cdot\boldsymbol{v}_1 = \langle Q_q \rangle + E$$

Moisture sink and convective heating

$$-\langle Q_q \rangle = \langle Q_c \rangle = \varepsilon_c(q_1 - T_1)$$

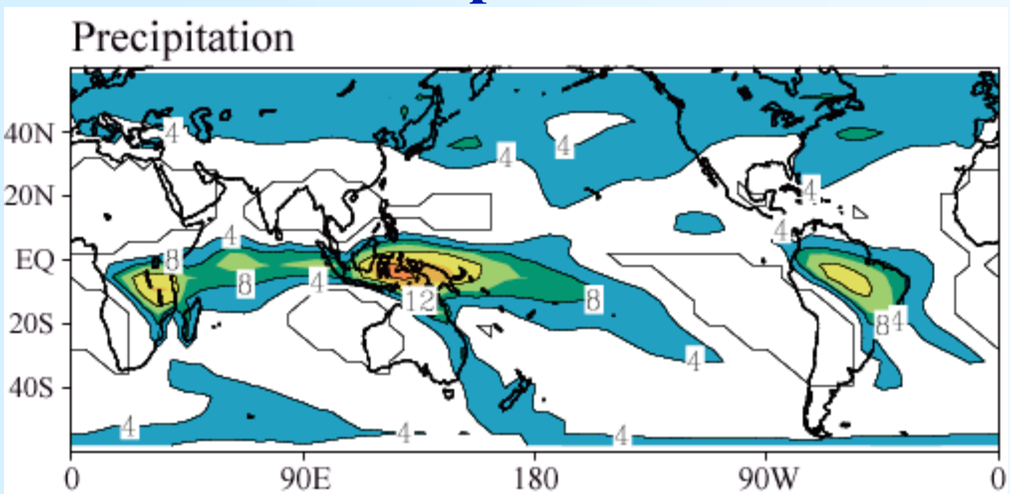
ENSO Composite (DJF)



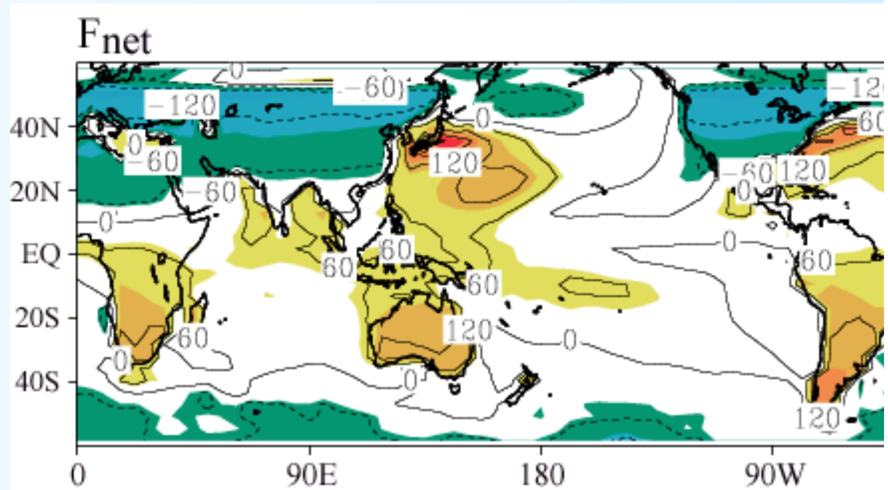
Zeng, Neelin and Chou 2000 QTCM1 V2.0

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

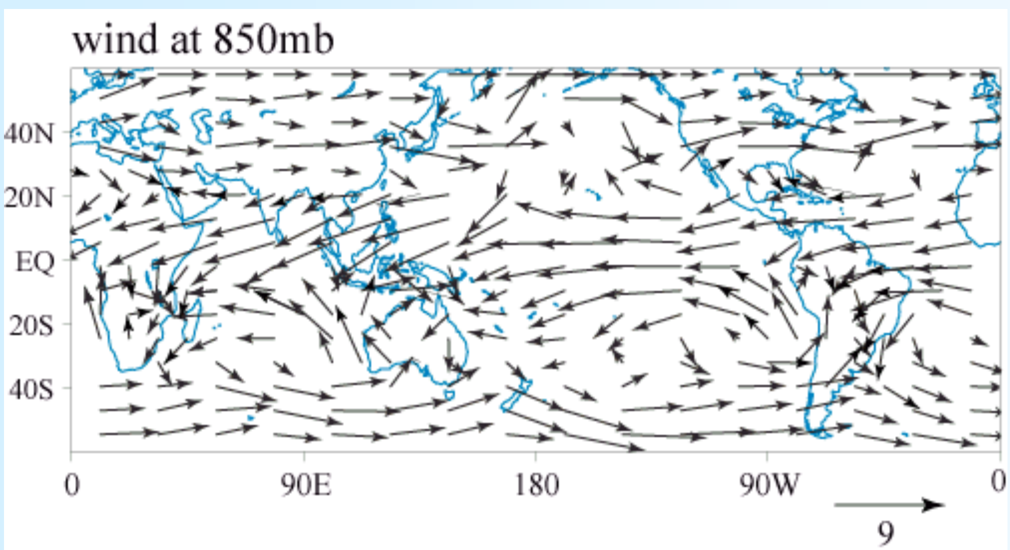
Precipitation



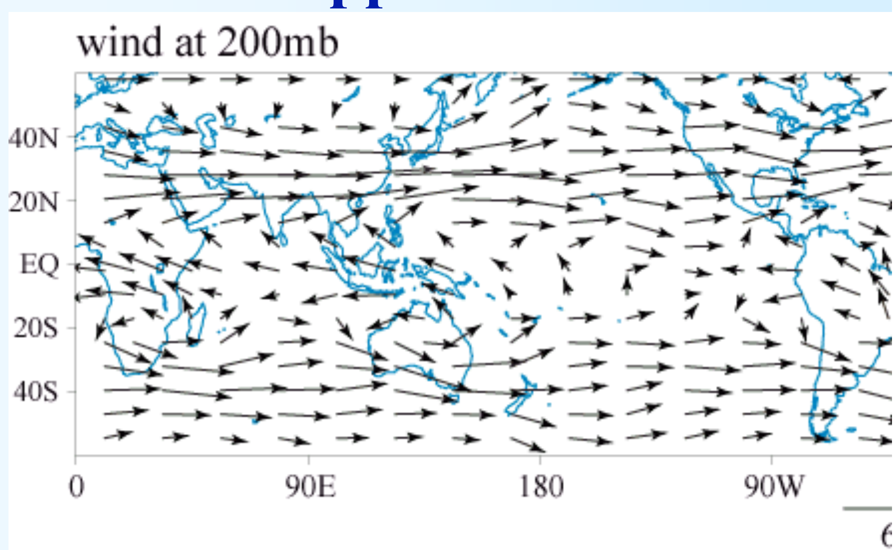
Net flux into atmosphere



Low-level wind



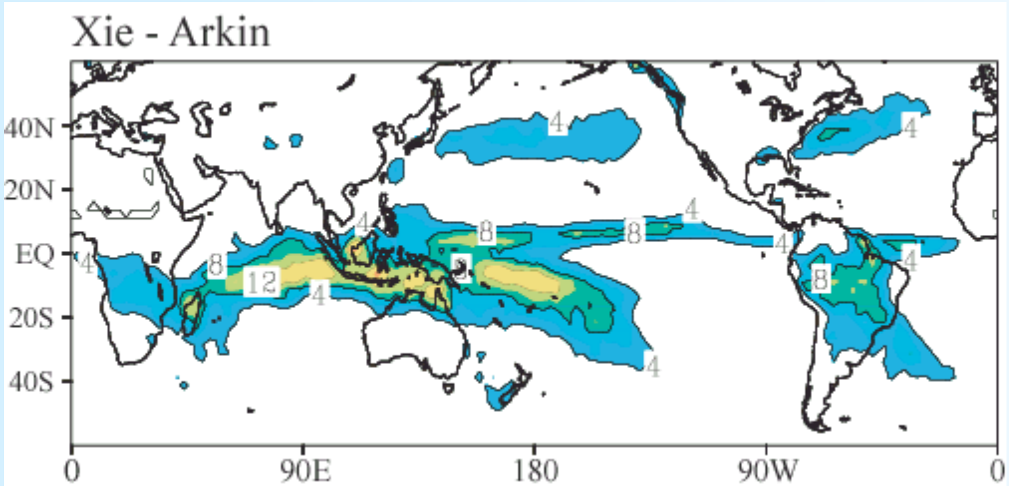
Upper-level wind



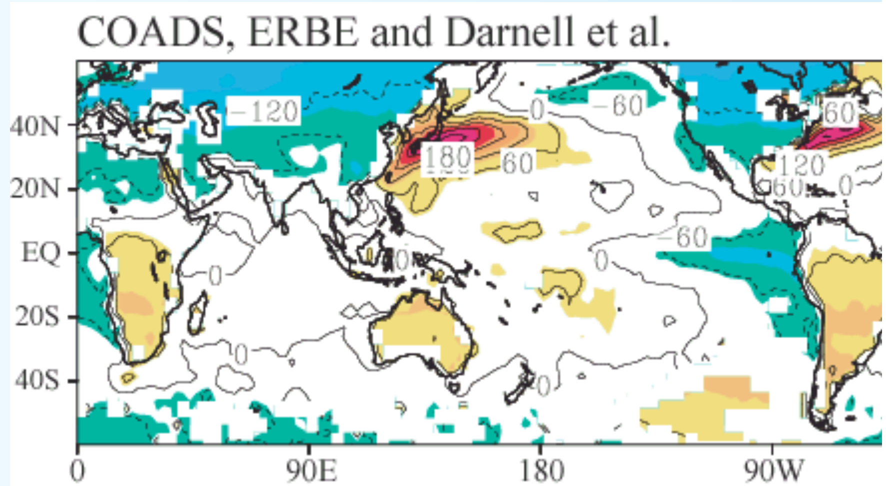
QTCM1

Observed climatology January

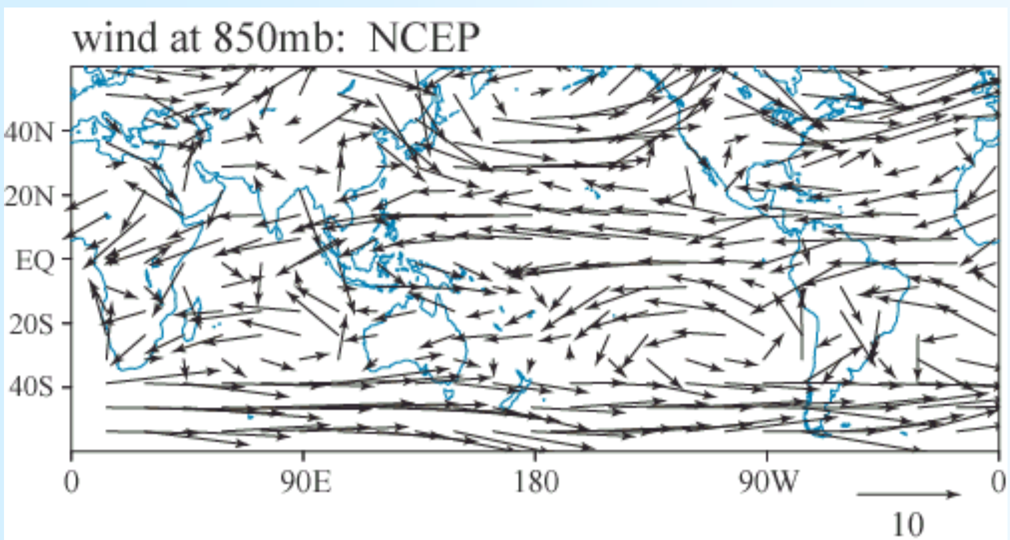
Precipitation



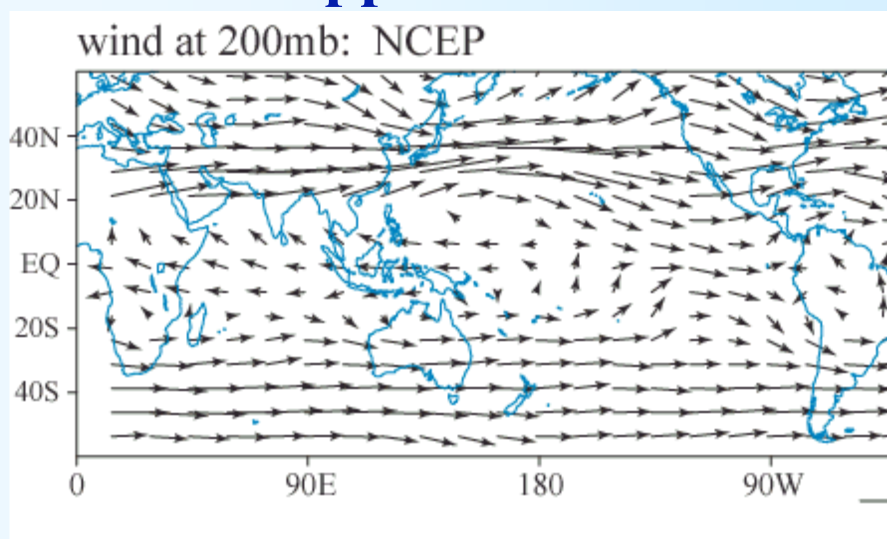
Net flux into atmosphere



Low-level wind

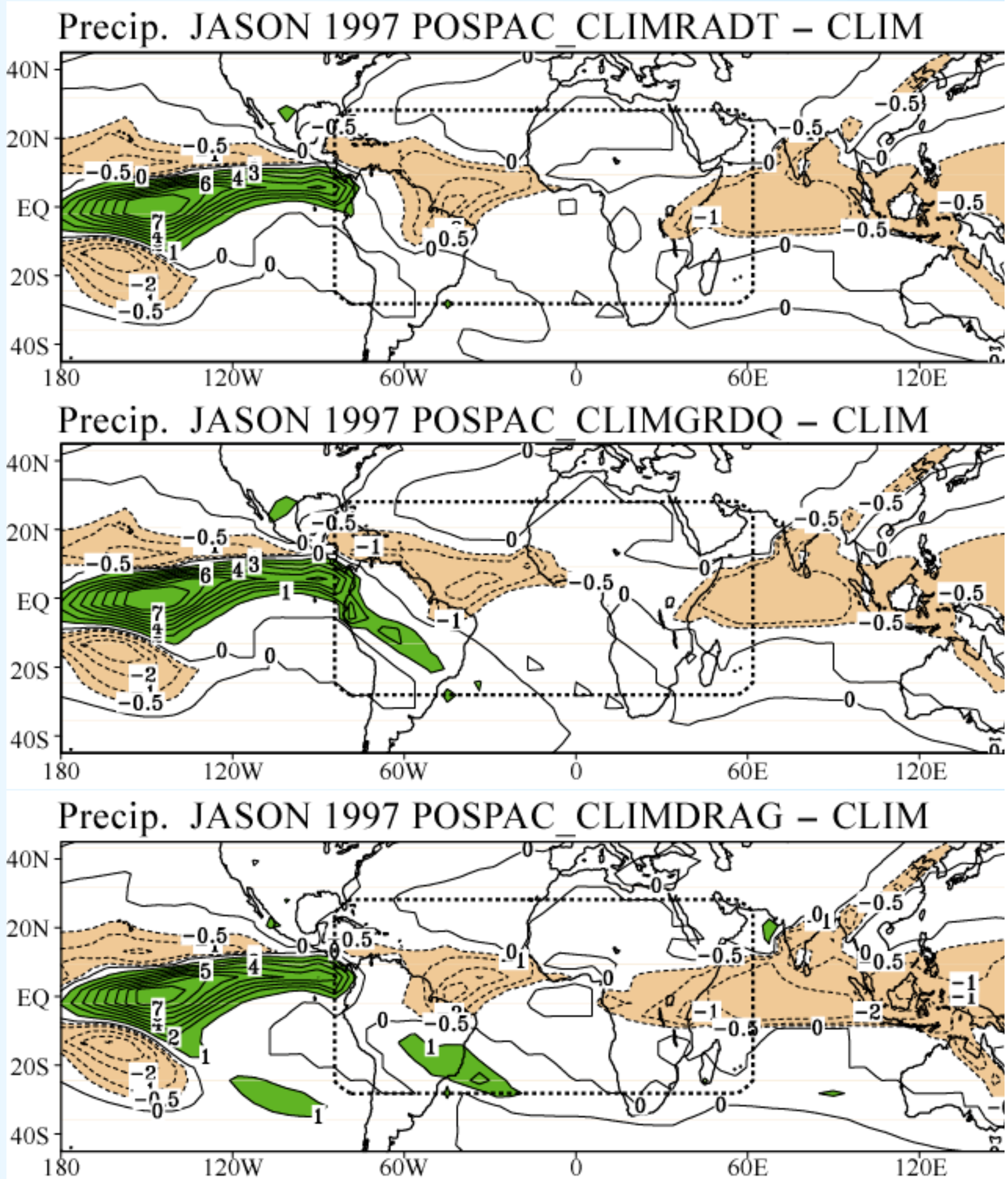


Upper-level wind



QTCM experiments suppressing various mechanisms

Precipitation Anomalies
Anomaly $(\ )'$ term
suppressed in region:



T' radiative effects

$(v \cdot \nabla T)'$

$(surface\ stress)'$