

# **Atmospheric Stability and weakening of tropical circulation**

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Global water vapor budget (Held and Soden 2006):

$$P \approx Mq$$

$$\rightarrow \delta P \approx M \delta q + q \delta M$$

thermodynamic dynamic

$P$ : precipitation

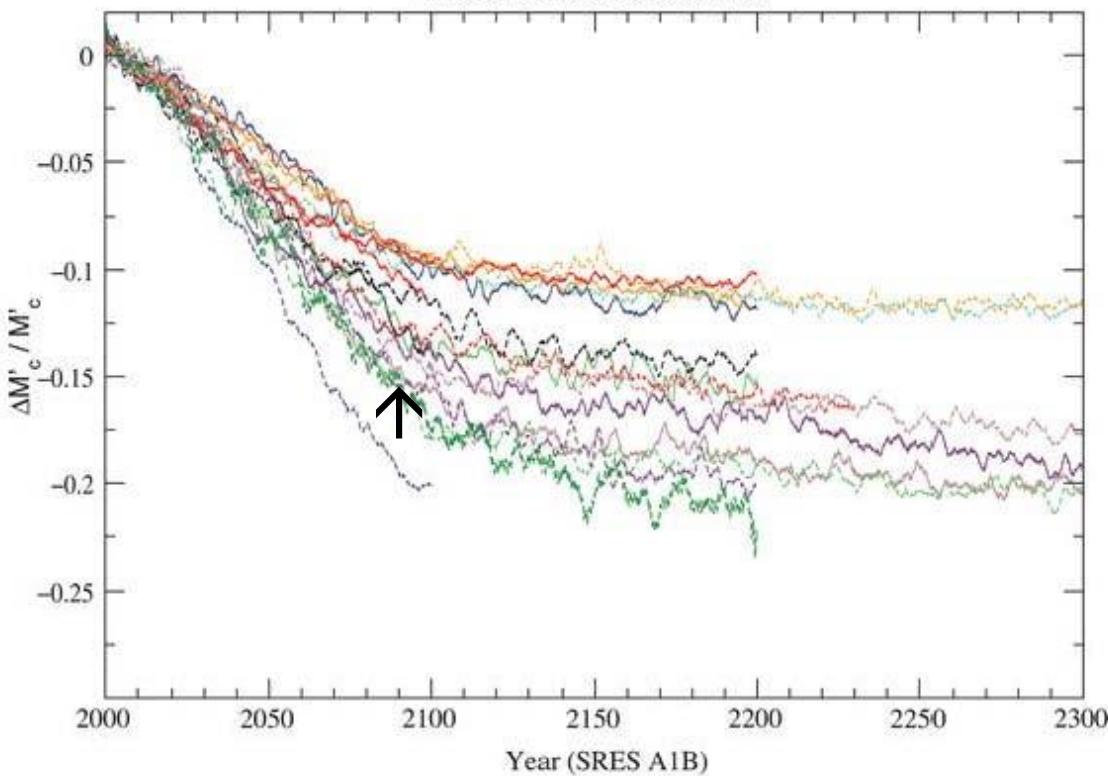
$M$ : mass flux;  $q$ : PBL water vapor

(a) Atmospheric Water vs. Temperature

(b) Precipitation vs. Temperature

(b)

Inferred Convective Mass Flux



7.5% in  $q$  per  $1^\circ\text{C}$  T  
(Clausius-Clapeyron) →  
thermodynamic component

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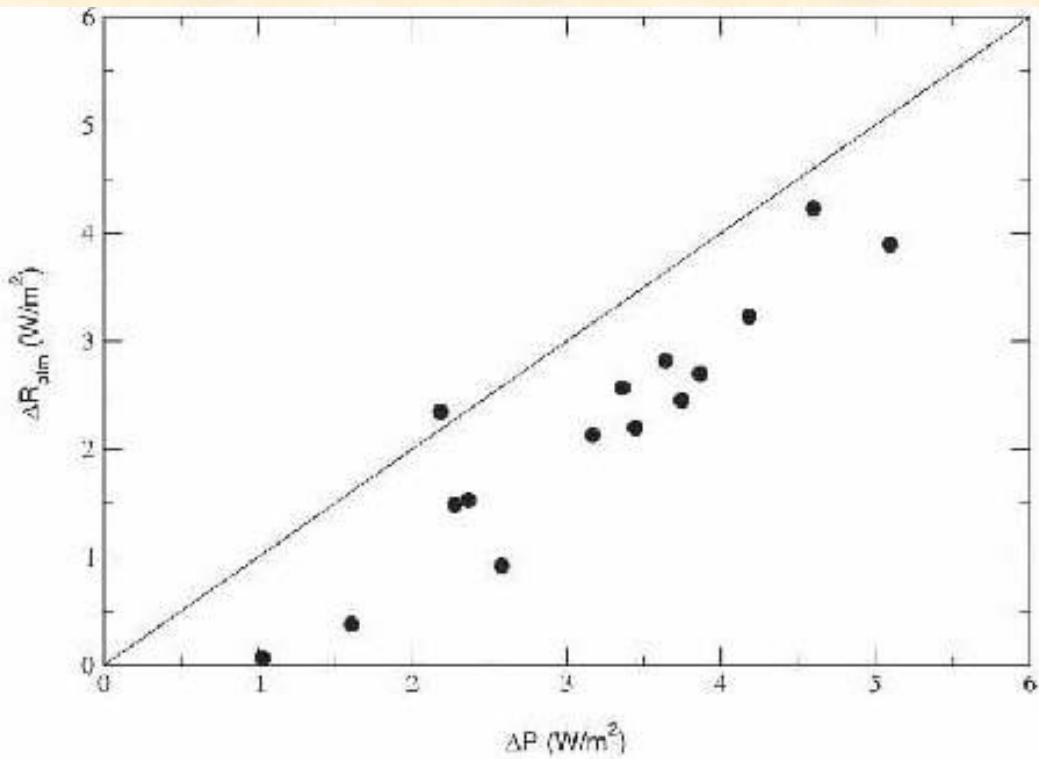
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(d) Radiative Cooling vs. Precipitation

Vecchi and Soden (2007)

In global average,  $P = E$

$P \approx LW + SW$  (assuming  $H$  is small)

$$\frac{\delta P}{P} \quad \text{increases at 1-3% per } 1^\circ\text{C T}$$

$$\frac{\delta q}{q} \quad \text{increases at 7.5% per } 1^\circ\text{C T}$$

$$\rightarrow \frac{\delta M}{M} < 0 \quad ?$$

→ NO

# Vertically integrated water vapor budget

$$P - E \approx -\langle \nabla \cdot v q \rangle$$

convergence of moisture flux

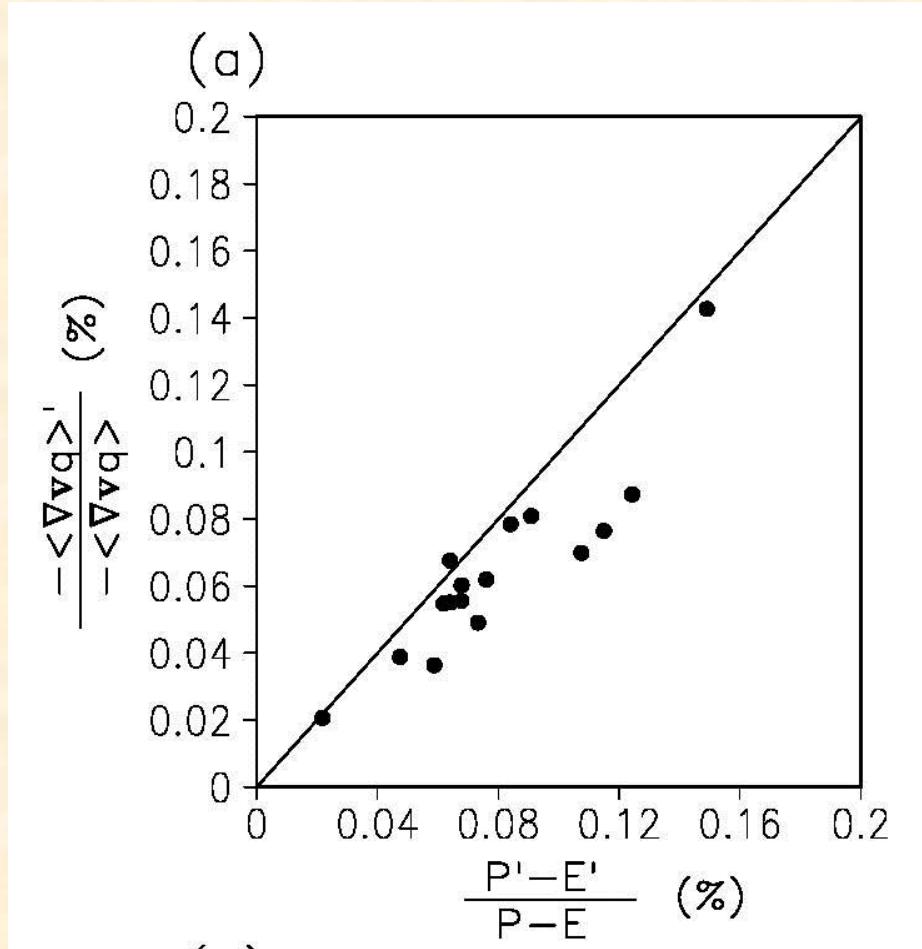
$P$ : precipitation;  $E$ : evaporation

$q$ : water vapor (moisture);  $v$ : horizontal velocity

$\omega$ : vertical velocity;  $\langle \rangle$ : vertical integration

# Vertically integrated water vapor budget

$$\frac{(P - E)'}{P - E} \approx \frac{-\langle \nabla \cdot v q \rangle'}{-\langle \nabla \cdot v q \rangle}$$



$$P' - E' \approx -\langle \omega \partial_p q' \rangle' - \langle v \cdot \nabla q' \rangle'$$

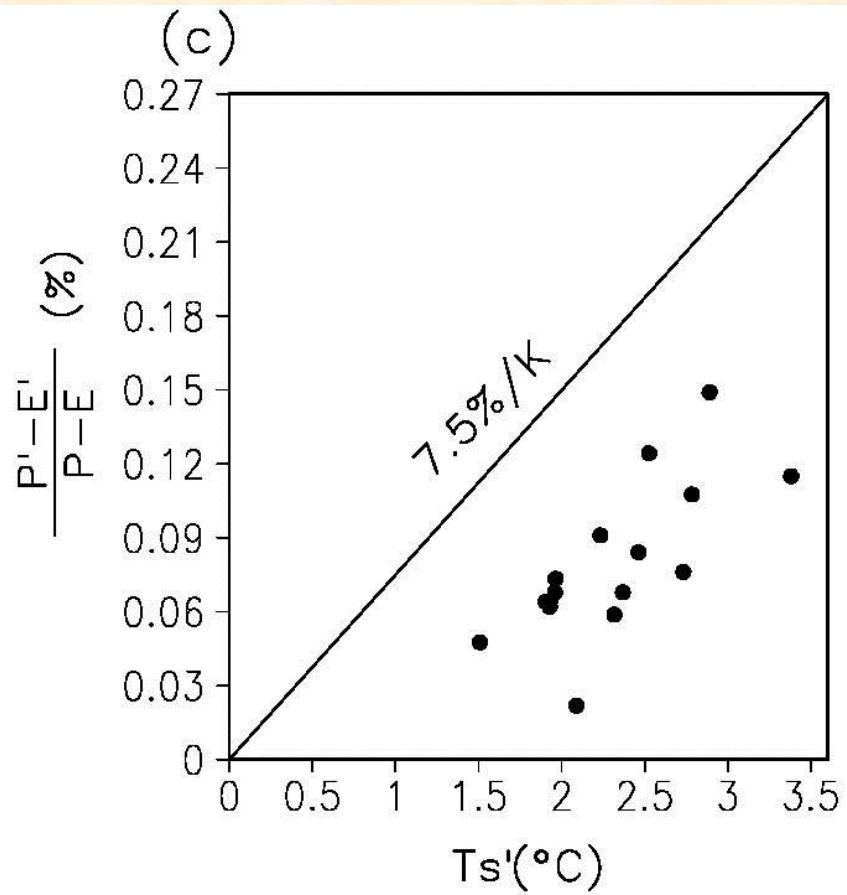
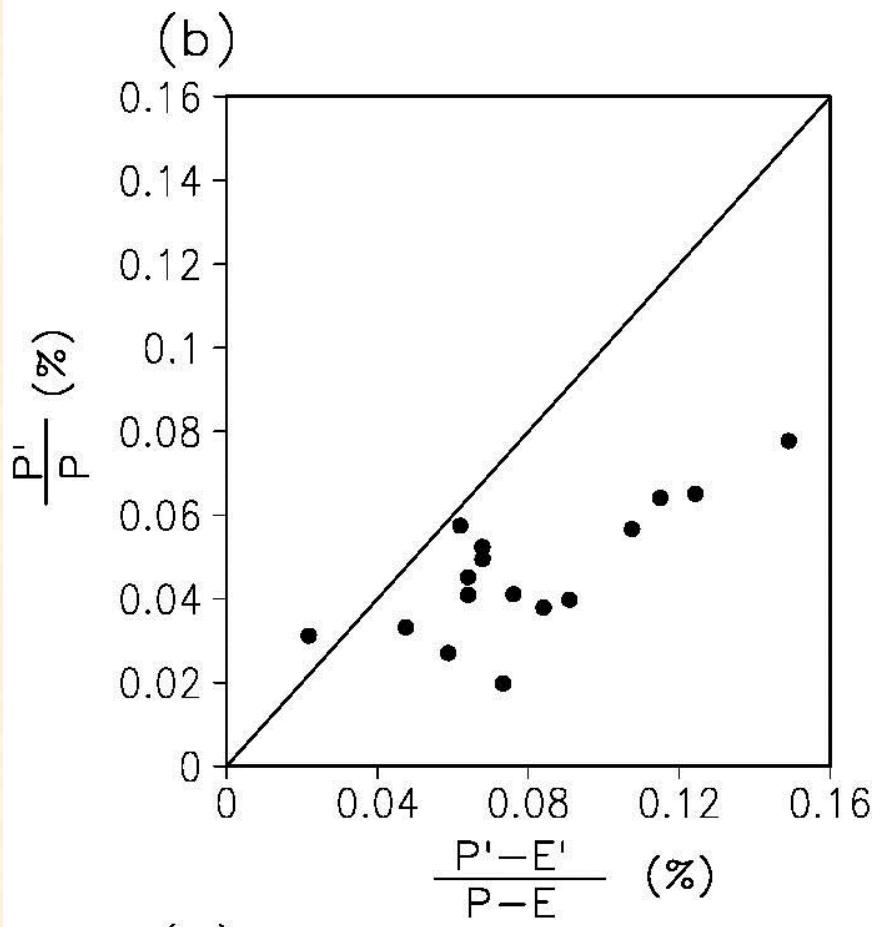
vertical advection      horizontal advection

$$\rightarrow P' - E' \approx -\langle \bar{\omega} \partial_p q' \rangle - \langle \omega' \partial_p \bar{q} \rangle - \langle v \cdot \nabla q' \rangle'$$

thermodynamic      dynamic

$$\rightarrow \frac{P' - E'}{\bar{P} - \bar{E}} \approx \frac{-\langle \bar{\omega} \partial_p q' \rangle}{-\langle \nabla \cdot v q \rangle} + \frac{-\langle \omega' \partial_p \bar{q} \rangle}{-\langle \nabla \cdot v q \rangle}$$

$$\frac{P'}{\bar{P}} \approx \frac{\delta q}{\bar{q}} + \frac{\delta M}{\bar{M}}$$

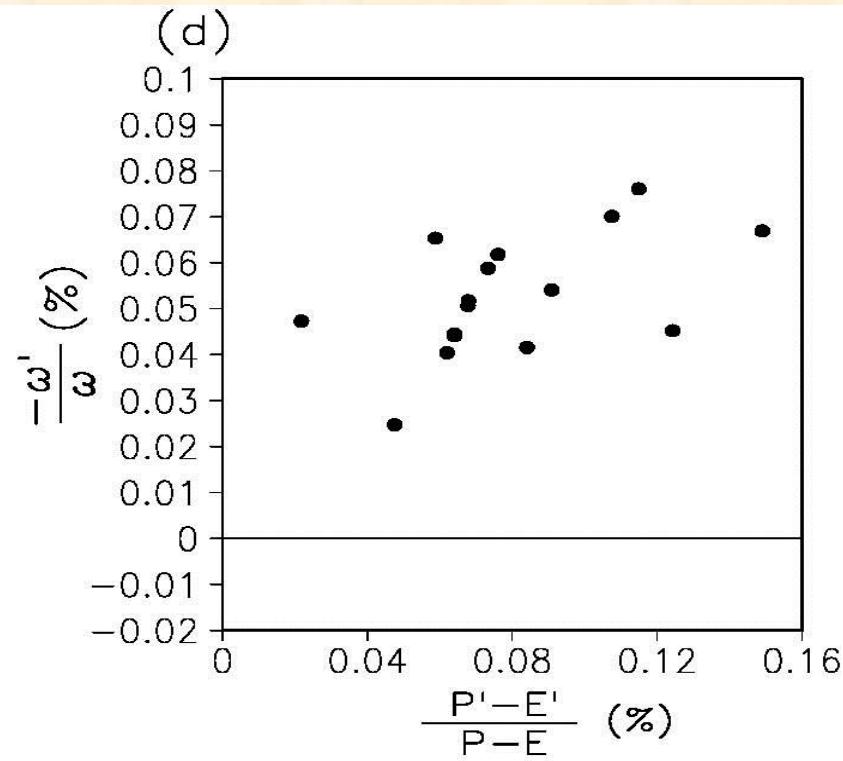


→  $\frac{P'}{\bar{P}} < \frac{(P-E)'}{P-E} < 7.5\%$

$$\frac{P' - E'}{\bar{P} - \bar{E}} \approx \frac{-\langle \bar{\omega} \partial_p q' \rangle}{-\langle \nabla \cdot v \bar{q} \rangle} + \frac{-\langle \omega' \partial_p \bar{q} \rangle}{-\langle \nabla \cdot v \bar{q} \rangle}$$

$$\frac{P' - E'}{\bar{P} - \bar{E}} < 7.5\% \sim \frac{-\langle \bar{\omega} \partial_p q' \rangle}{-\langle \nabla \cdot v \bar{q} \rangle}$$

$\rightarrow \frac{-\langle \omega' \partial_p \bar{q} \rangle}{-\langle \nabla \cdot v \bar{q} \rangle} < 0$  : a weakening of tropical circulation



$$\frac{P' - E'}{\bar{P} - \bar{E}} \approx \frac{-\langle \bar{\omega} \partial_p q' \rangle}{-\langle \nabla \cdot v \bar{q} \rangle} + \frac{-\langle \omega' \partial_p \bar{q} \rangle}{-\langle \nabla \cdot v \bar{q} \rangle}$$

$\downarrow$                      $\downarrow$                     ↙  
 No constraint       $\leq 7.5\%$  in  $q$  per  $1^\circ\text{C T}$

$>0$  or  $<0$

7.5% in  $q$  per  $1^\circ\text{C T}$

$$\frac{P'}{\bar{P}} \approx \frac{\delta q}{\bar{q}} + \frac{\delta M}{\bar{M}}$$

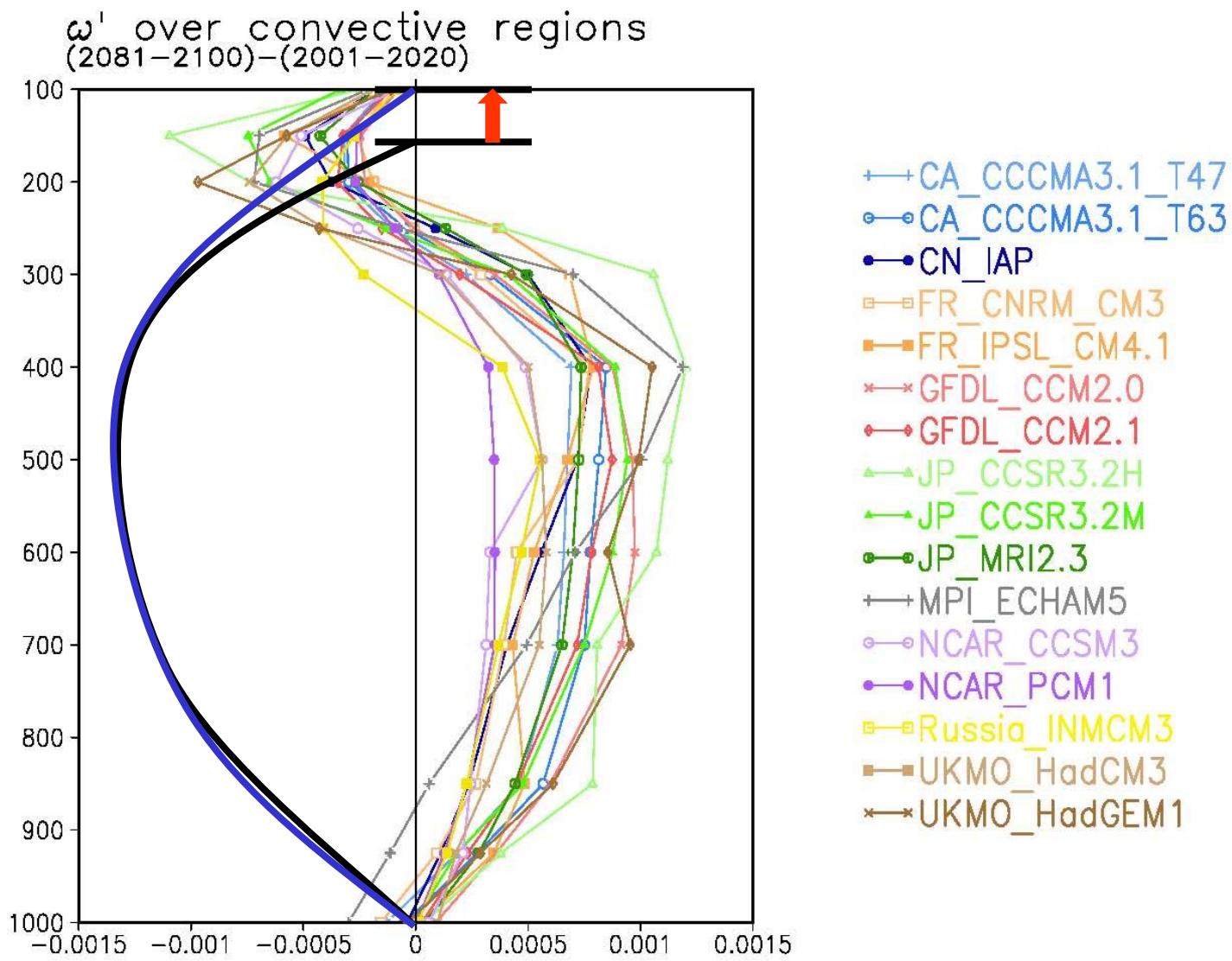
$\uparrow$                     ↘  
 $\downarrow$

1-3% in  $P$  per  $1^\circ\text{C T}$

$<0$

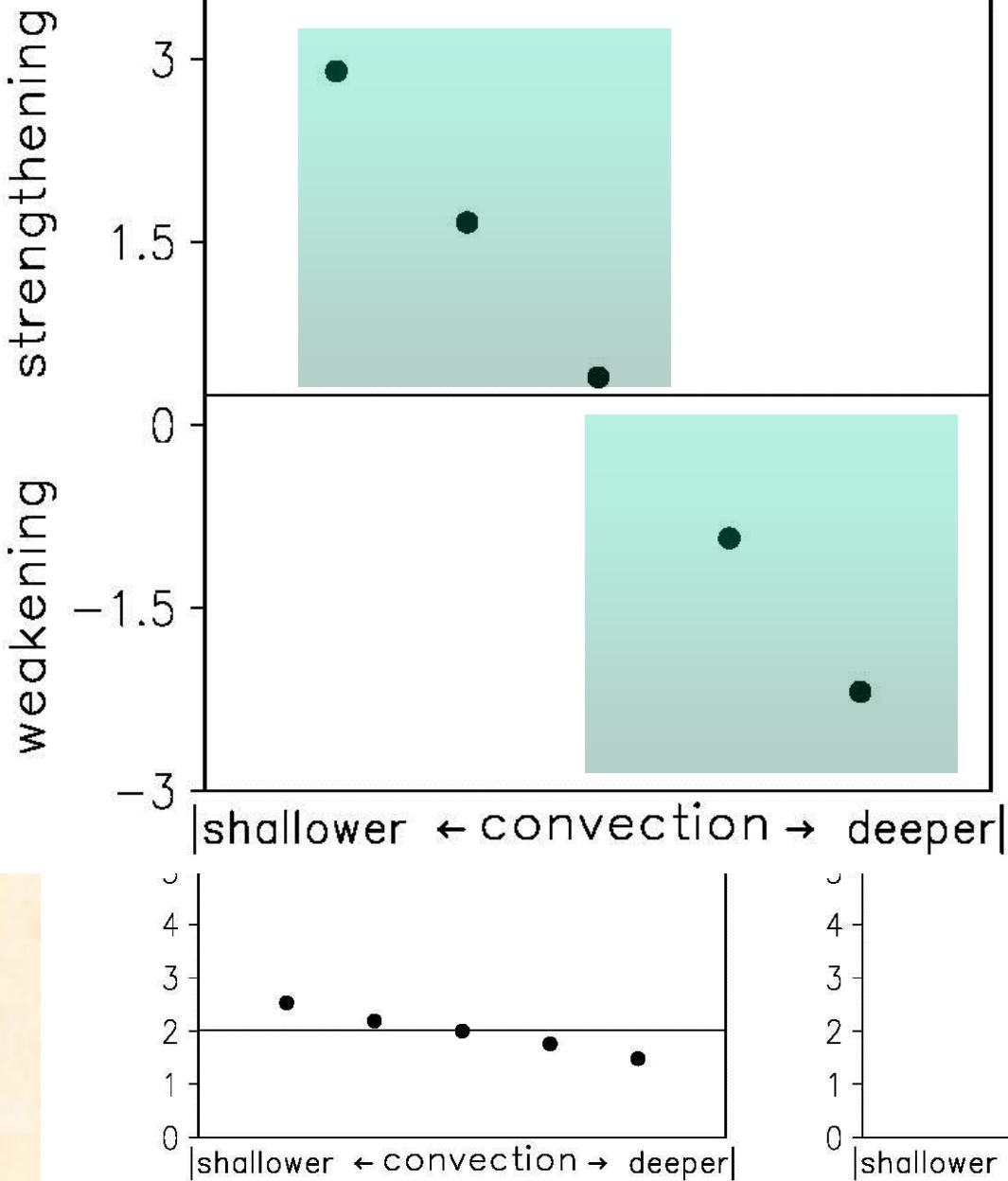
(controlled by energy budget)

# Effect of convection depth

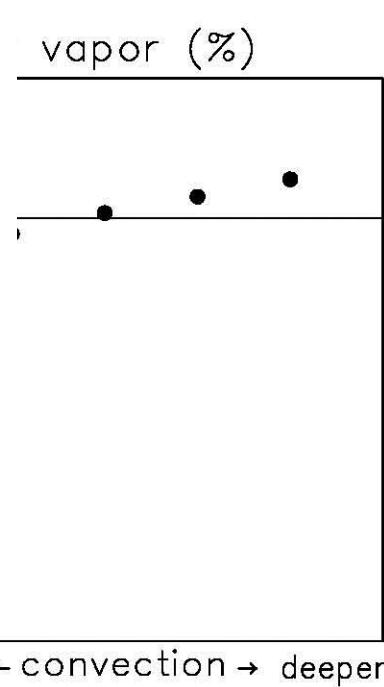


→ deepening of convection: ~ 2.5-3.4%

(a) tropical circulation (%)

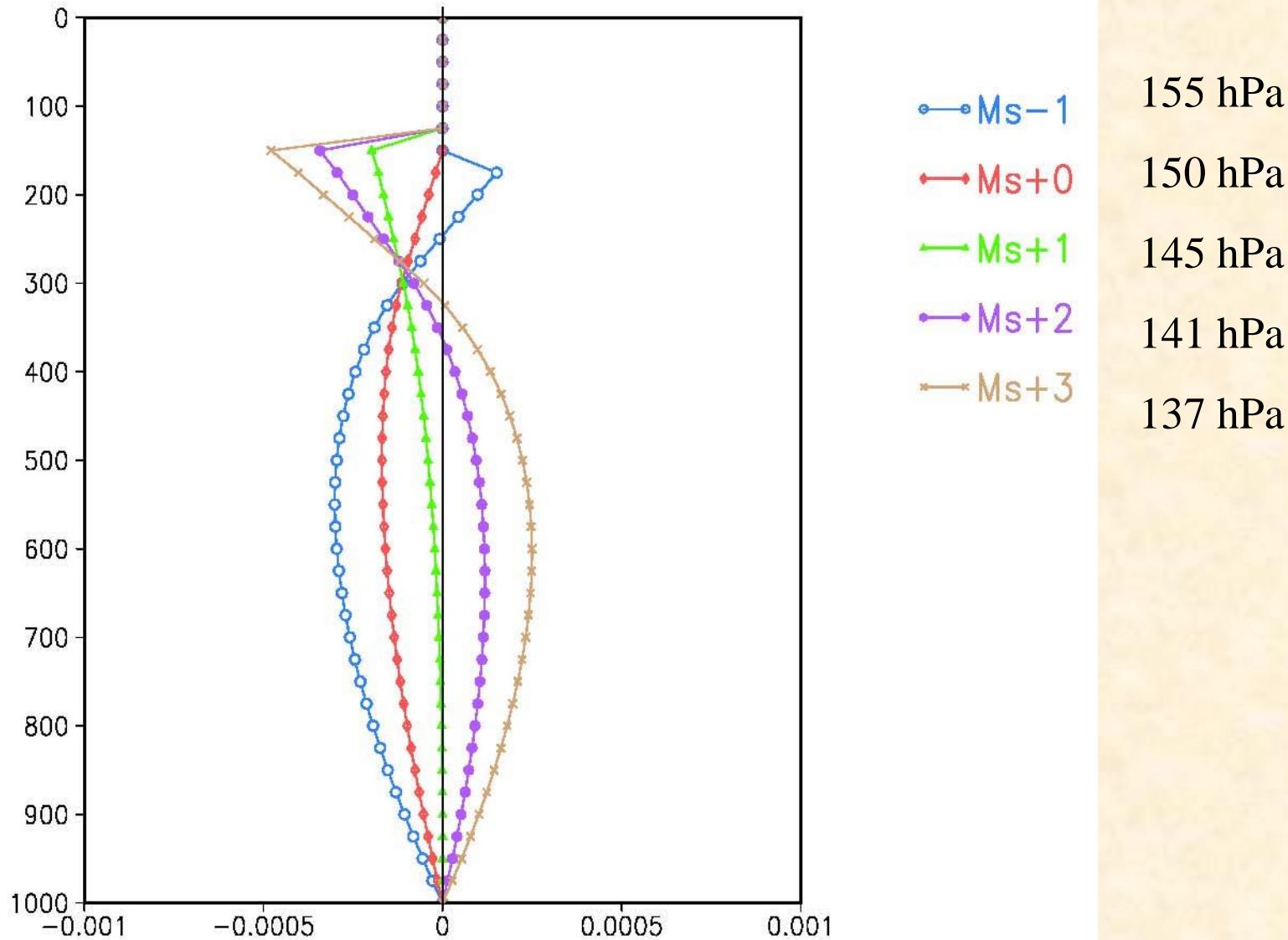


Convection top:  
155 hPa ~ 137 hPa  
(-1.2% ~ 3.3%)



Chou and  
Chen 2009

## $\omega'$ over convective regions



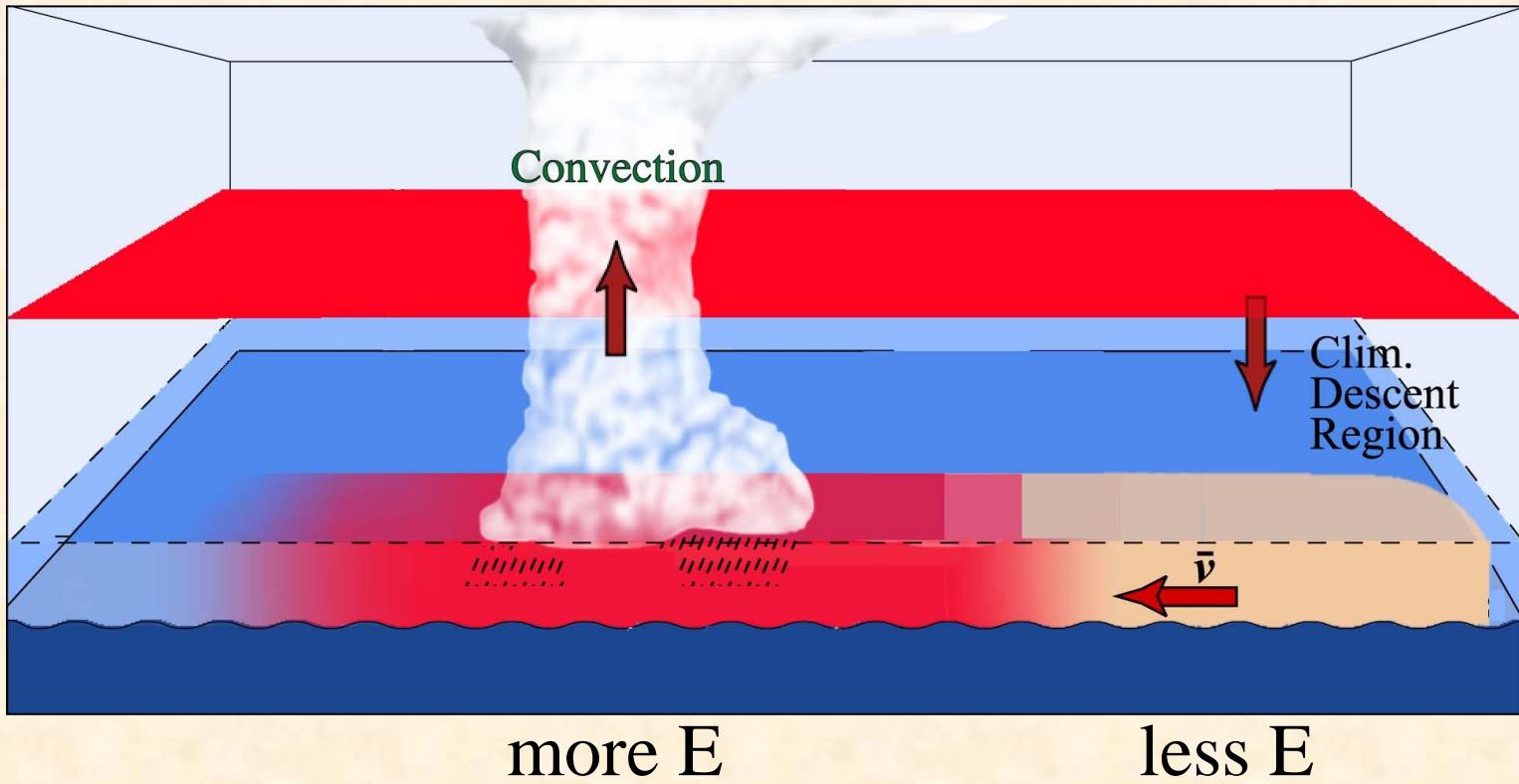
shallow ← → deeper

term	$M_s-1$	$M_s+0$	$M_s+1$	$M_s+2$	$M_s+3$
global $P'/\bar{P}$	<b>0.0253</b>	<b>0.0219</b>	<b>0.0200</b>	<b>0.0176</b>	<b>0.0148</b>
global $E'/\bar{E}$	0.0245	0.0217	0.0200	0.0181	0.0156
global $q'/\bar{q}$	<b>0.0695</b>	<b>0.0724</b>	<b>0.0761</b>	<b>0.0790</b>	<b>0.0821</b>
$\omega'/\bar{\omega}$ at 500 hPa	<b>0.0408</b>	<b>0.0166</b>	<b>-0.0072</b>	<b>-0.0287</b>	<b>-0.0492</b>
$P' - E'/\bar{P} - \bar{E}$	0.0906	0.0695	0.0476	0.0284	0.0088
$-\langle \nabla \cdot \mathbf{v} q \rangle' / -\langle \nabla \cdot \bar{\mathbf{v}} \bar{q} \rangle$	0.0906	0.0695	0.0478	0.0285	0.0089
$-\langle \mathbf{v} \cdot \nabla q \rangle' / -\langle \nabla \cdot \bar{\mathbf{v}} \bar{q} \rangle$	-0.0111	-0.0063	-0.0039	-0.0003	0.0018
$-\langle \omega \partial_p q \rangle' / -\langle \nabla \cdot \bar{\mathbf{v}} \bar{q} \rangle$	0.1017	0.0758	0.0517	0.0288	0.0221
$-\langle \bar{\omega} \partial_p q' \rangle / -\langle \nabla \cdot \bar{\mathbf{v}} \bar{q} \rangle$	0.0531	0.0572	0.0621	0.0638	0.0662
$-\langle \omega' \partial_p \bar{q} \rangle / -\langle \nabla \cdot \bar{\mathbf{v}} \bar{q} \rangle$	0.0418	0.0183	-0.0032	-0.0249	-0.0459
$P'/\bar{P}$	0.0376	0.0305	0.0252	0.0196	0.0153
$E'/\bar{E}$	-0.0099	-0.0044	0.0050	0.0117	0.0211

$$\frac{P' - E'}{\bar{P} - \bar{E}} \approx \frac{-\langle \bar{\omega} \partial_p q' \rangle}{-\langle \nabla \cdot \bar{\mathbf{v}} \bar{q} \rangle} + \frac{-\langle \omega' \partial_p \bar{q} \rangle}{-\langle \nabla \cdot \bar{\mathbf{v}} \bar{q} \rangle}$$

thermodynamic  
dynamic

# Deeper convection



$$P' \approx E' - \langle \nabla \cdot v q \rangle'$$

- Reduced upward motion; Less convergence of moisture flux
- more evaporation

# Vertically integrated moist static energy budget

$$\langle \omega' \partial_p \bar{h} \rangle \approx -\langle \bar{\omega} \partial_p h' \rangle - \langle \mathbf{v} \cdot \nabla (T + q) \rangle' + F^{net'}$$

shallow ← → deeper

term	$M_s-1$	$M_s+0$	$M_s+1$	$M_s+2$	$M_s+3$	
$\langle \omega' \partial_p \bar{h} \rangle / \langle \bar{\omega} \partial_p h \rangle$	0.0375	0.0149	-0.0067	-0.0303	-0.0501	ascent
$-\langle \bar{\omega} \partial_p h' \rangle / \langle \bar{\omega} \partial_p h \rangle$	<b>0.1259</b>	<b>0.0819</b>	<b>0.0368</b>	<b>-0.0030</b>	<b>-0.0464</b>	stability
$-\langle \mathbf{v} \cdot \nabla (q + T) \rangle' / \langle \bar{\omega} \partial_p h \rangle$	-0.0401	-0.0412	-0.0562	-0.0542	-0.0648	
$F^{net} / \langle \bar{\omega} \partial_p h \rangle$	-0.0011	0.0092	0.0340	0.0453	0.0691	

→ The deeper (shallow) convection,  
 the more stable, larger values, (unstable, smaller  
 values) the atmosphere

# Under quasi-equilibrium closure

$$\langle \omega \partial_p h \rangle = M \nabla \cdot v_1$$

where

$$M = -\langle \Omega \partial_p h \rangle \quad \text{gross moist stability}$$

$$\nabla \cdot v_1 \quad \text{divergence (baroclinic winds)}$$

$\Omega$ : typical profile of vertical velocity for deep convection

horizontal advection

$$\langle \omega' \partial_p \bar{h} \rangle \approx -\langle \bar{\omega} \partial_p h' \rangle - \langle v \cdot \nabla (T + q) \rangle' + F^{net'}$$

atmospheric  
stability

net energy input



$$\nabla \cdot v'_1 \approx \frac{1}{\bar{M}} [-M \nabla \cdot \bar{v}_1 - \langle v \cdot \nabla (T + q) \rangle' + F^{net'}]$$



$$\frac{\nabla \cdot v'_1}{\nabla \cdot \bar{v}_1} \approx -\frac{M'}{\bar{M}}$$

# Gross moist stability

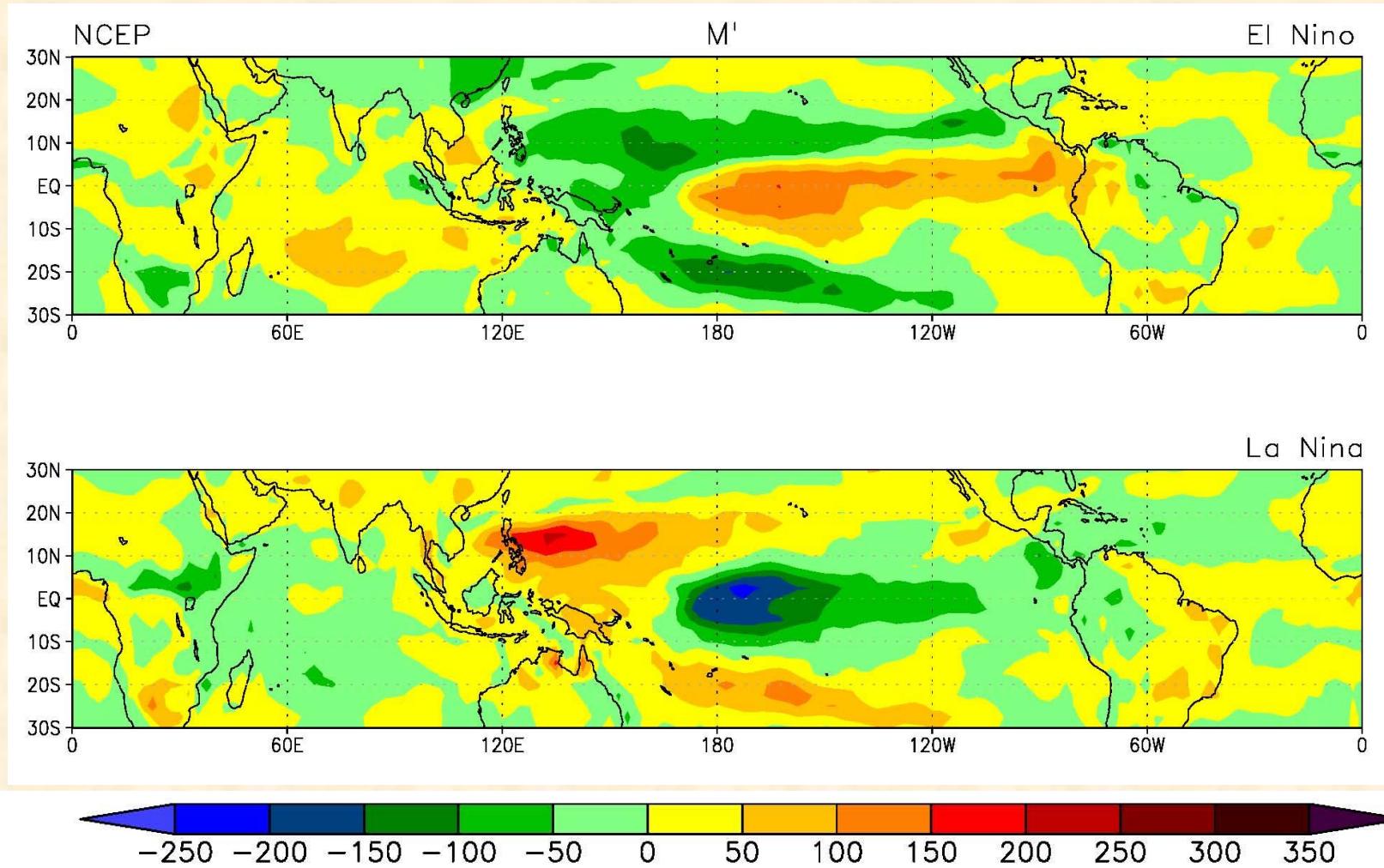
$$M = -\langle \Omega \partial_p h \rangle$$

$$= M(T, q, p_t)$$

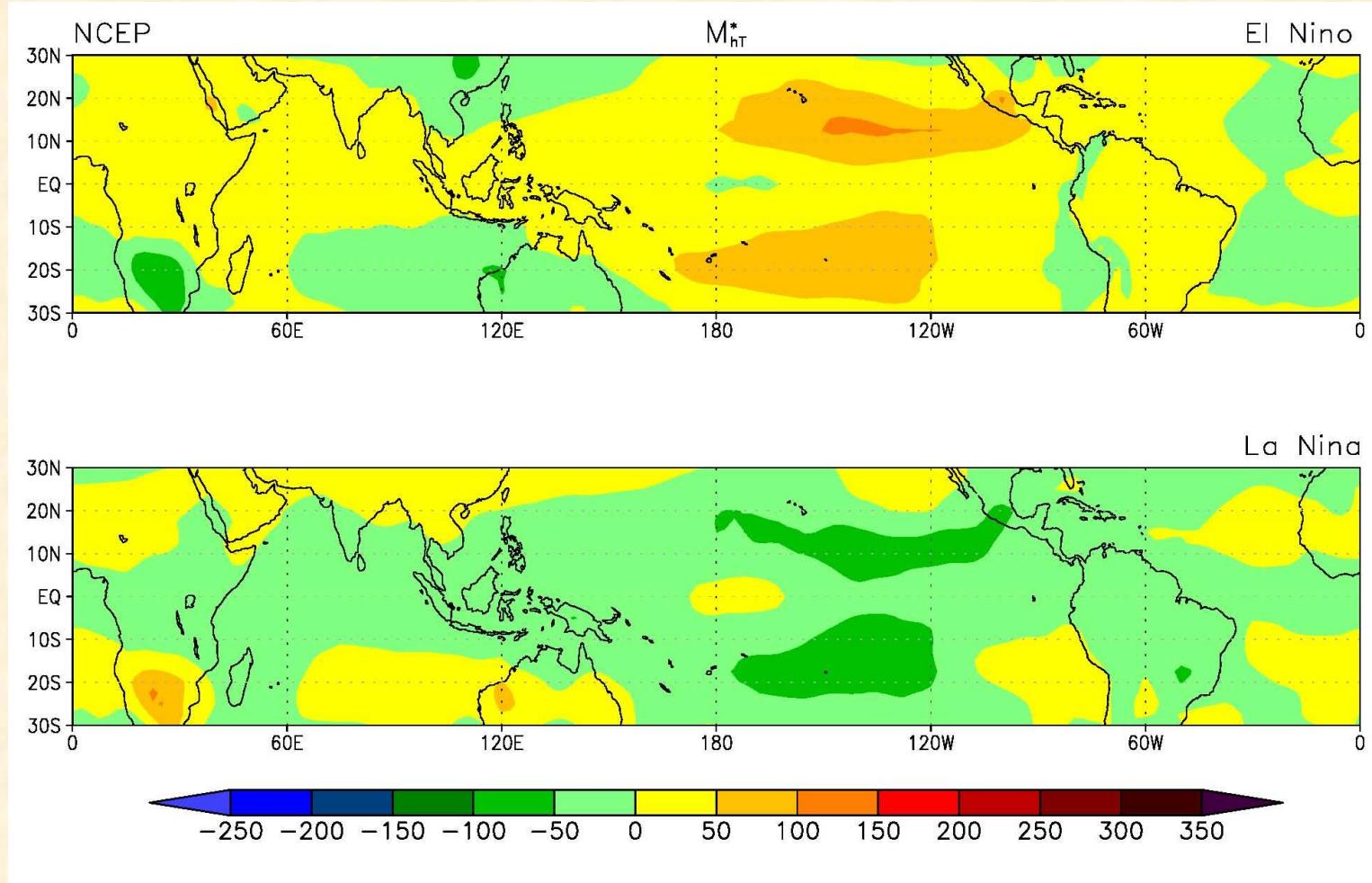
$$= M(\bar{T}, \bar{q}, \bar{p}_t) + M(T', \bar{q}, \bar{p}_t) + M(\bar{T}, q', \bar{p}_t) + M(\bar{T}, \bar{q}, p'_t) + \Delta M$$

$$= \tilde{M} + M_{hT}^* + M_{hq}^* + M_{pt}^* + \Delta M$$

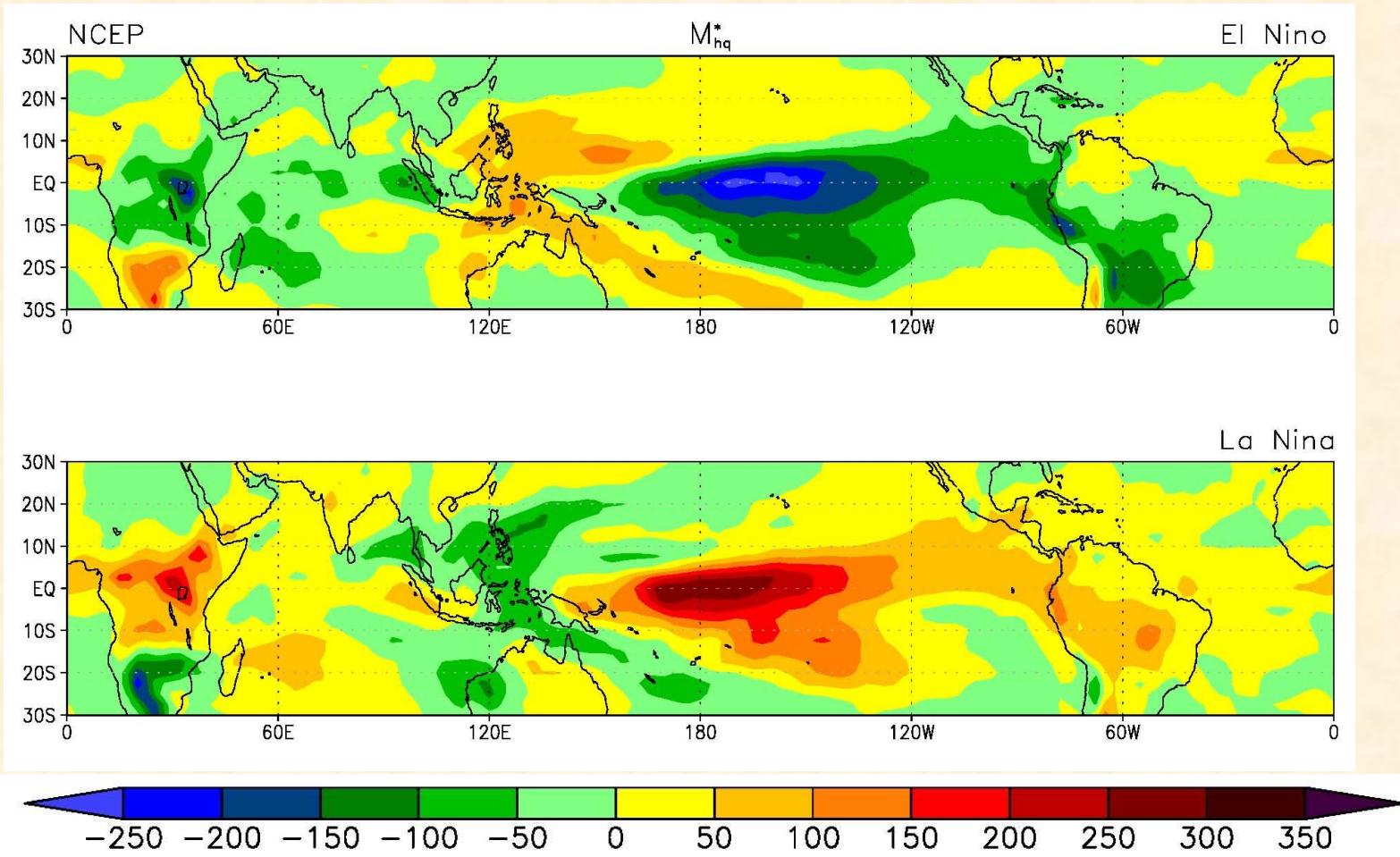
# ENSO



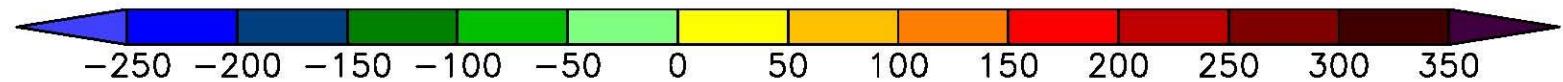
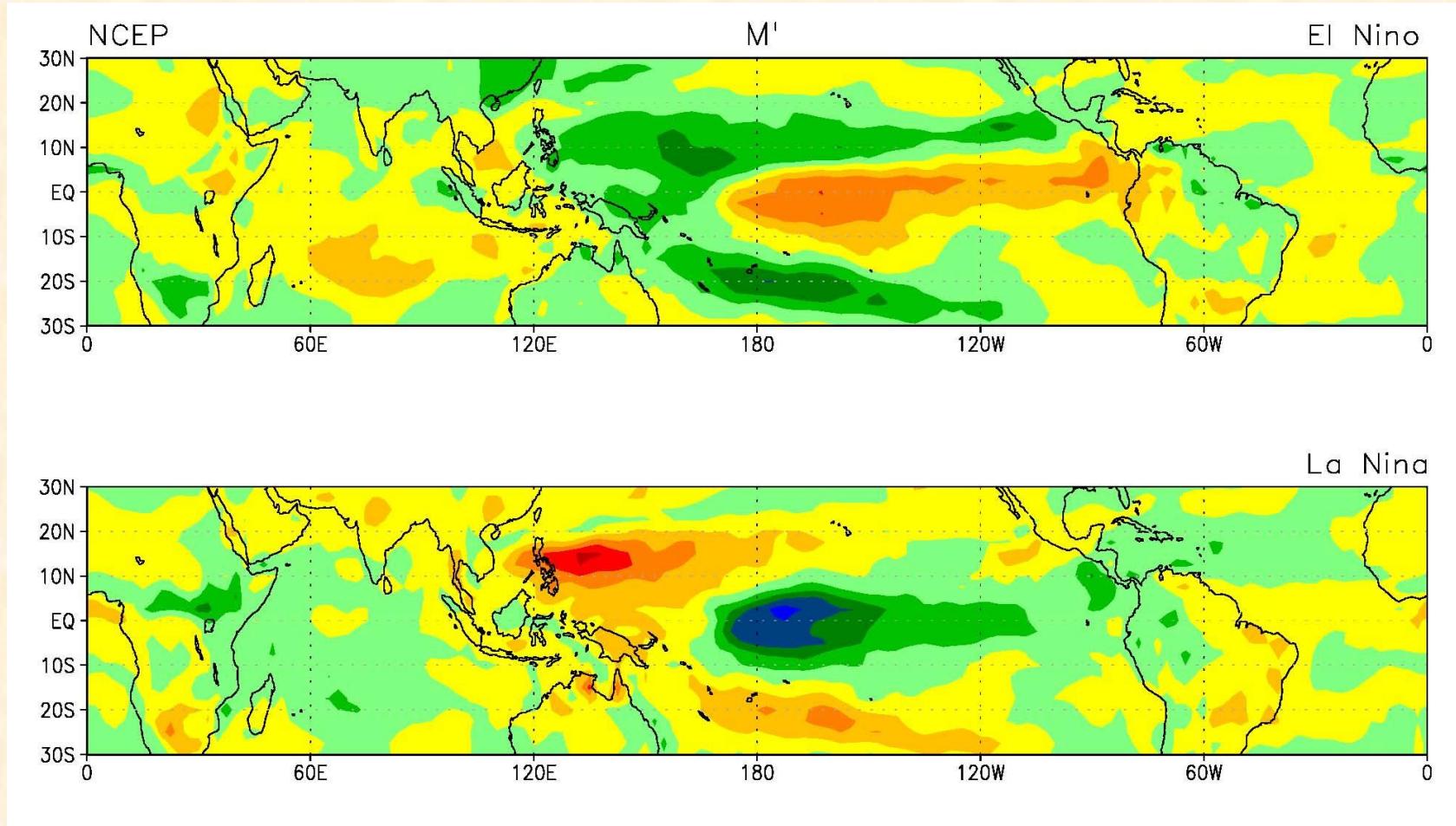
$$M_{hT}^*$$



$$M_{hq}^*$$



$$M_{pt}^*$$



# Conclusion

- Slower increase of rainfall and faster increase of water vapor → no guarantee for weakening of tropical circulation
- Effect of convection depth: the deeper (shallower) convection, the weaker (stronger) the circulation  
→ inconsistent among observed strength of tropical convection
- Gross moist stability  $M$ : an index to measure atmospheric stability

Chou and Chen, 2010, J. Climate, 23, 3019-3030.