Atmospheric Stability and weakening of tropical circulation

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Global water vapor budget (Held and Soden 2006):

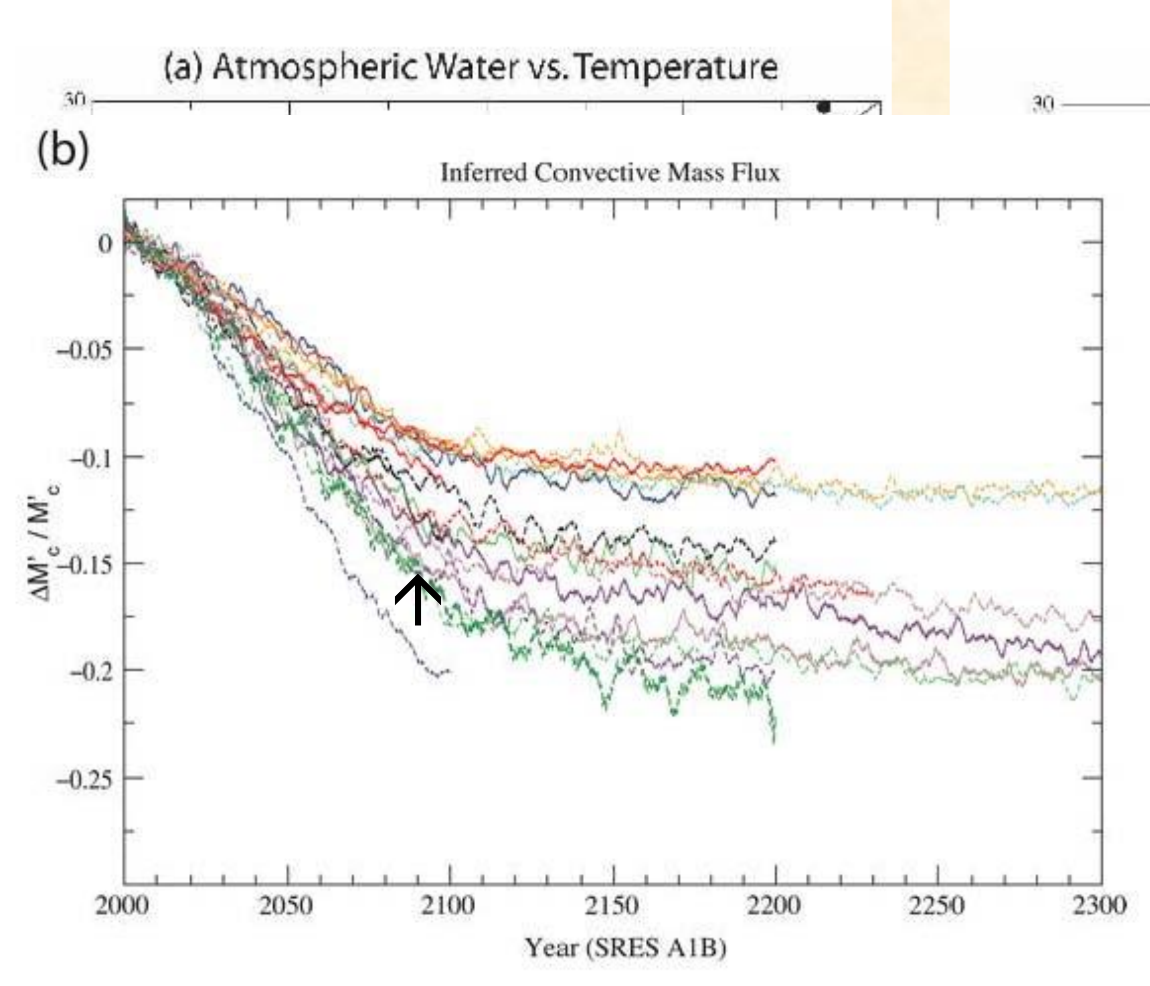
$$P \approx Mq$$

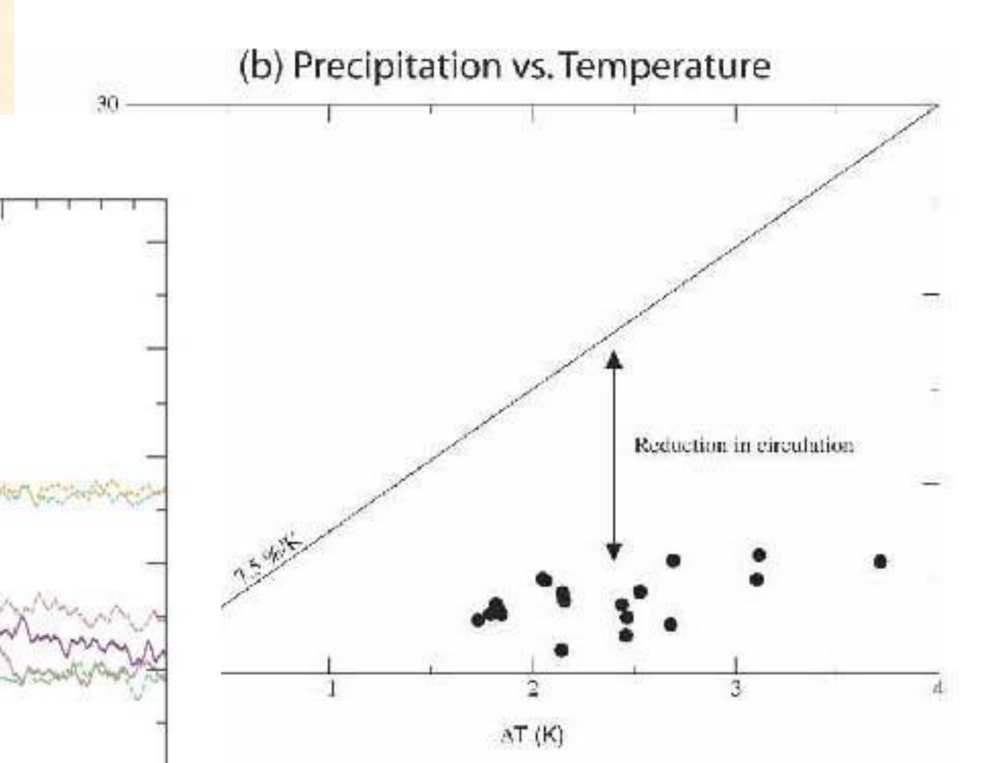
$$\Rightarrow \quad \delta P \approx M\delta q + q\delta M$$

thermodynamic   dynamic

P: precipitation

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





➔ <0

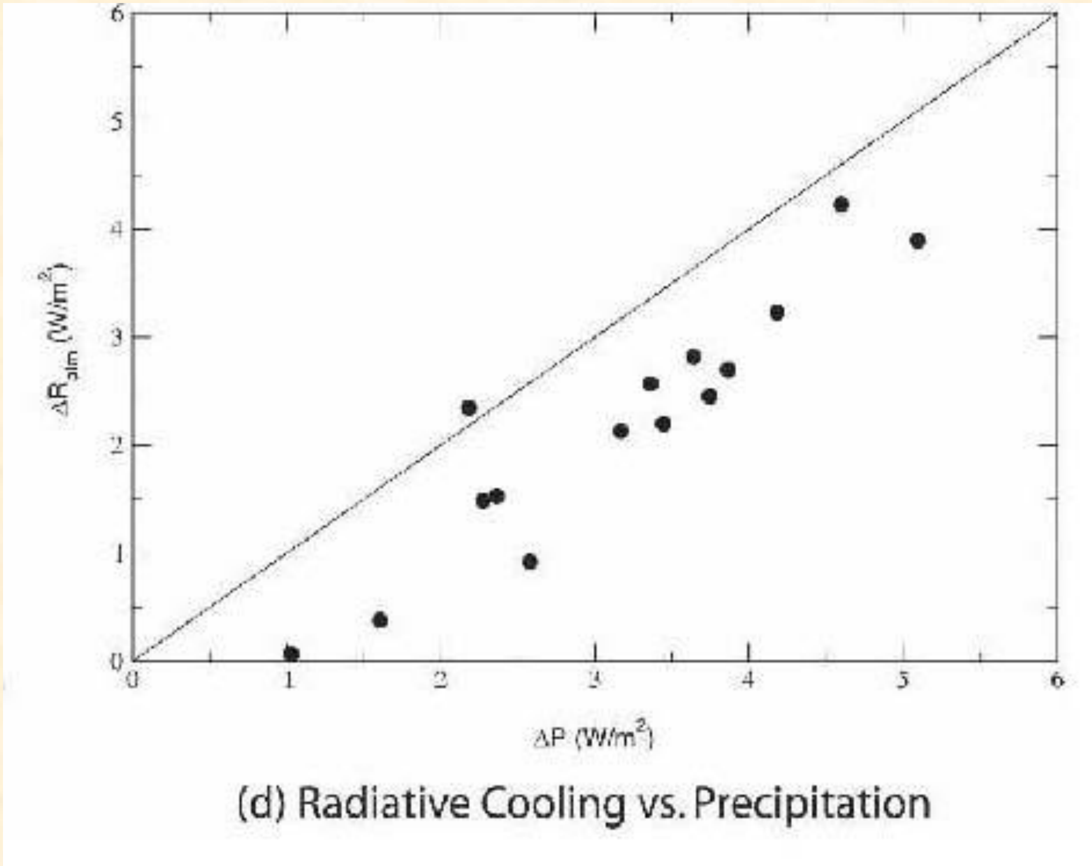
➔ slowing of tropical circulation→ dynamic component

-

↓

7.5% in q per 1℃ T (Clausius-Clapeyron)→ thermodynamic component

Held and Soden (2006); Vecchi and Soden (2007)



(d) Radiative Cooling vs. Precipitation

Vecchi and Soden (2007)

In global average, $P = E$

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

$$\frac{\delta P}{P}$$ increases at 1-3% per 1℃ T

$$\frac{\delta q}{q}$$ increases at 7.5% per 1℃ T

➔ $$\frac{\delta M}{M} < 0$$?

➔ **NO**

Vertically integrated water vapor budget

$$P - E \approx -\langle \nabla \cdot vq \rangle$$

convergence of moisture flux

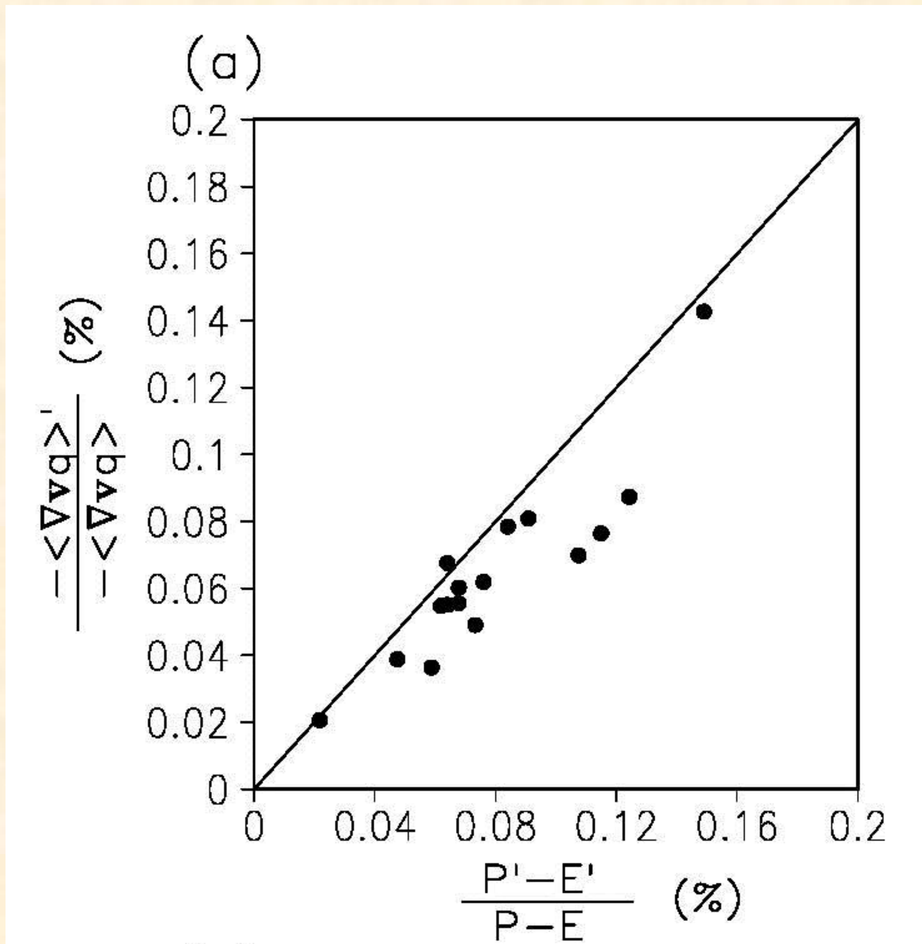
P: precipitation; E: evaporation

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

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

Vertically integrated water vapor budget

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



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

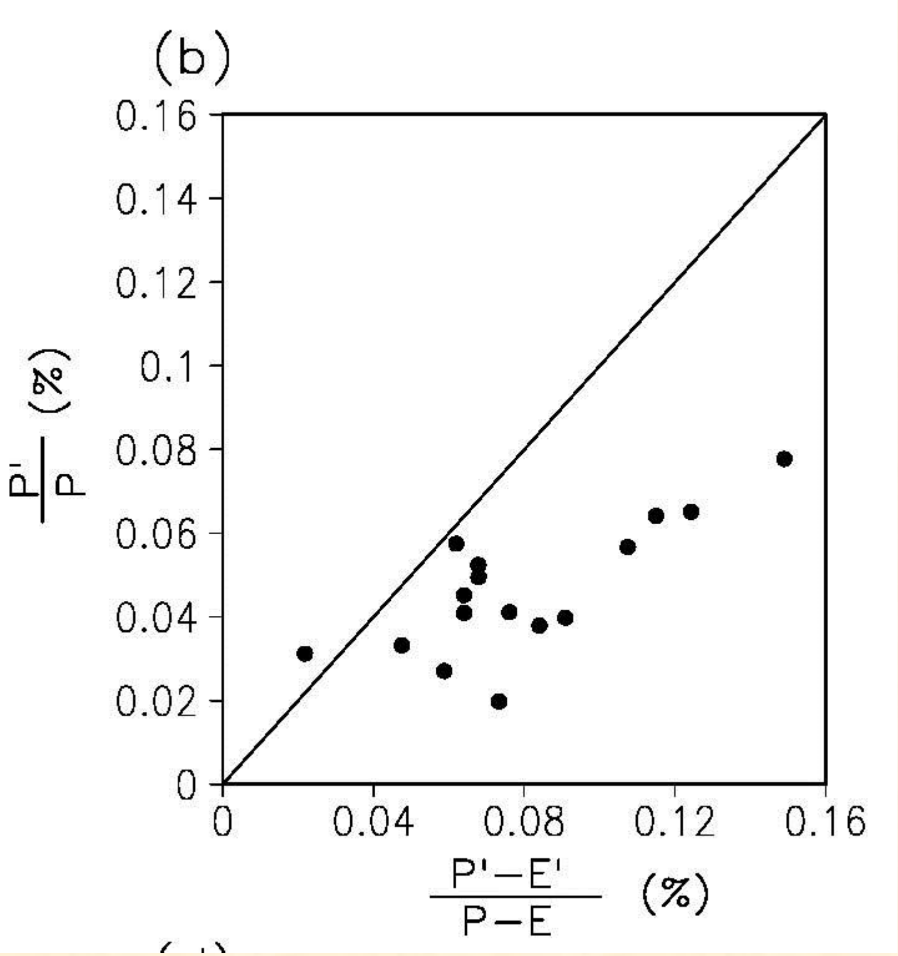
vertical advection horizontal advection

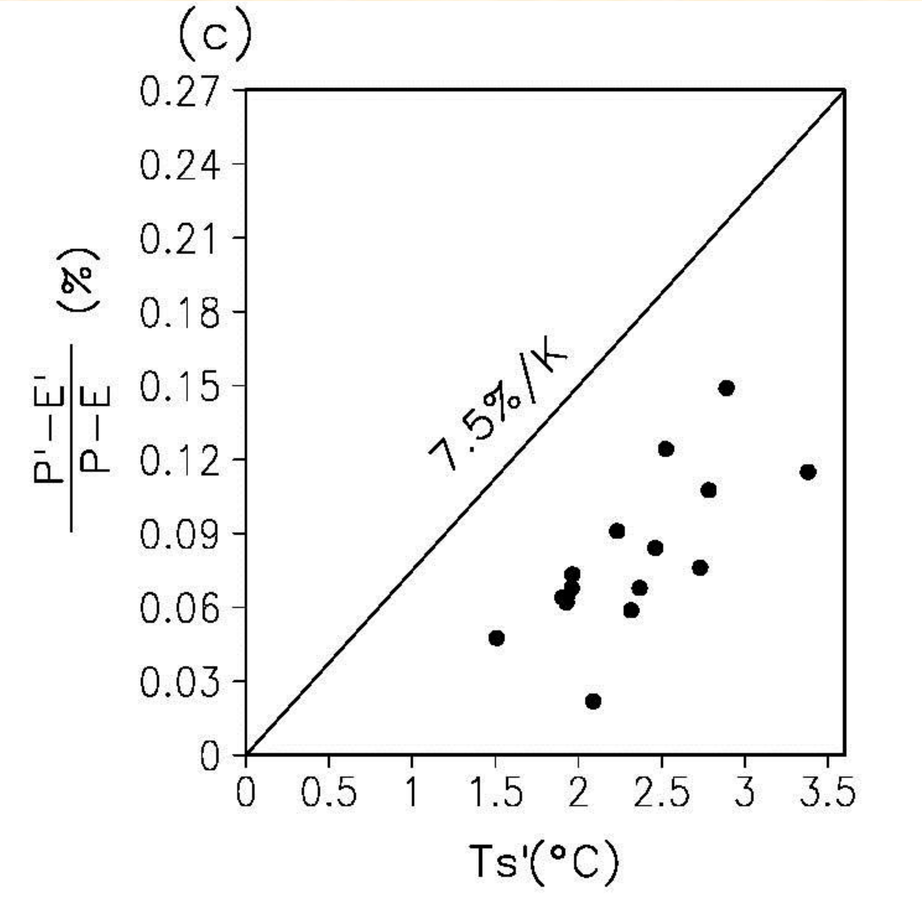
$$\rightarrow \quad P' - E' \approx -\langle \overline{\omega} \partial_p q' \rangle - \langle \omega' \partial_p \overline{q} \rangle - \langle v \cdot \nabla q \rangle'$$

thermodynamic dynamic

$$\rightarrow \quad \frac{P' - E'}{\overline{P} - \overline{E}} \approx \frac{-\langle \overline{\omega} \partial_p q' \rangle}{-\langle \nabla \cdot \overline{vq} \rangle} + \frac{-\langle \omega' \partial_p \overline{q} \rangle}{-\langle \nabla \cdot \overline{vq} \rangle}$$

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



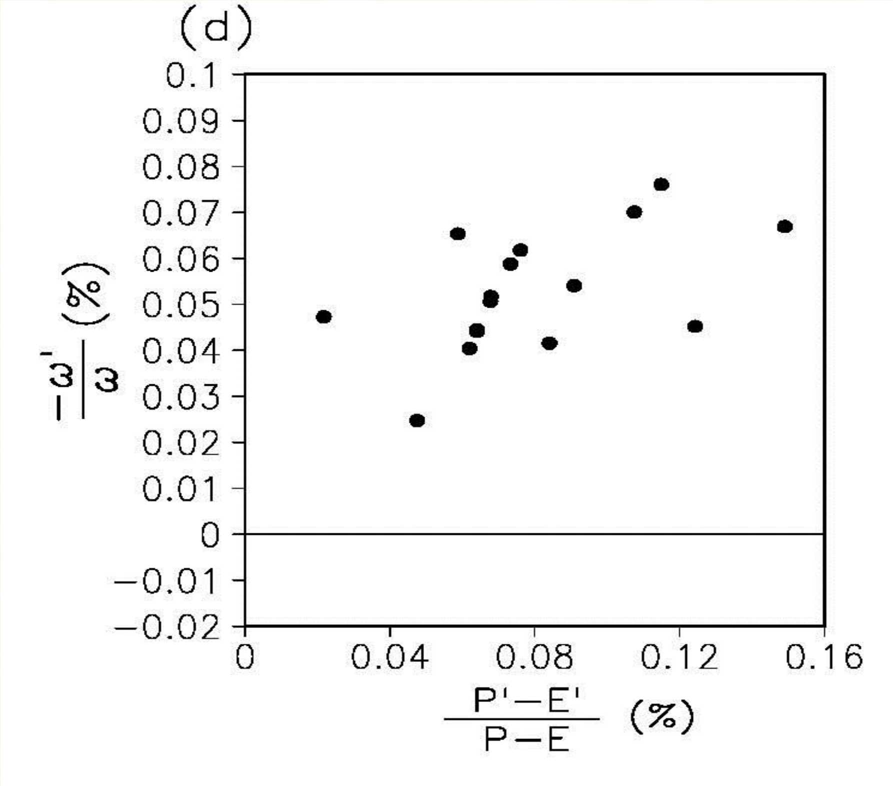


$$\rightarrow \quad \frac{P'}{\overline{P}} < \frac{(P-E)'}{\overline{P-E}} < 7.5\%$$

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

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

➔ $\frac{-\langle\omega'\partial_p\overline{q}\rangle}{-\langle\nabla\cdot\overline{\overline{vq}}\rangle} < 0$:a weakening of tropical circulation



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

↓ No constraint

↓ ≤ 7.5% in q per 1℃ T

↘ >0 or <0

7.5% in q per 1℃ T ↑

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

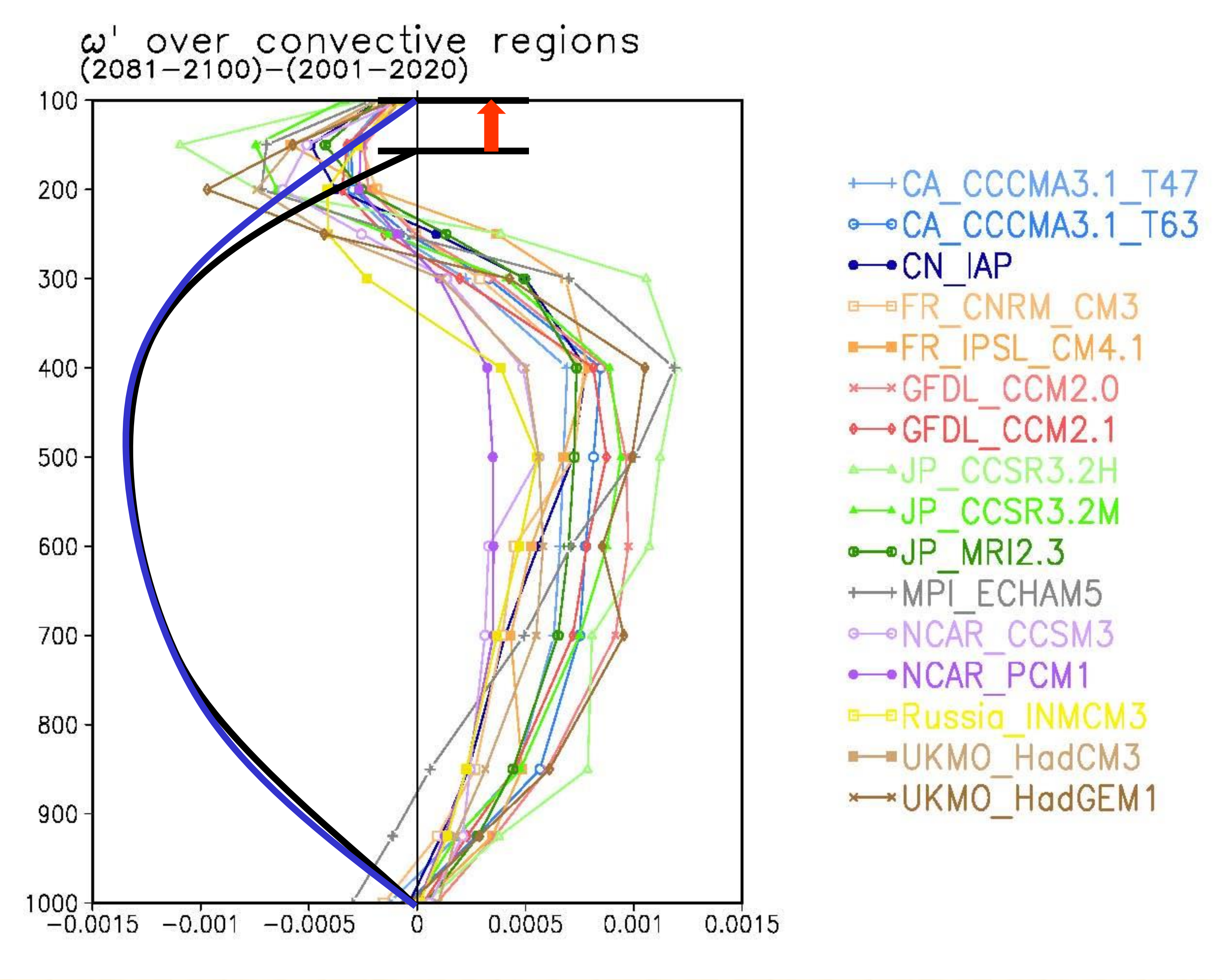
↘ <0

↓

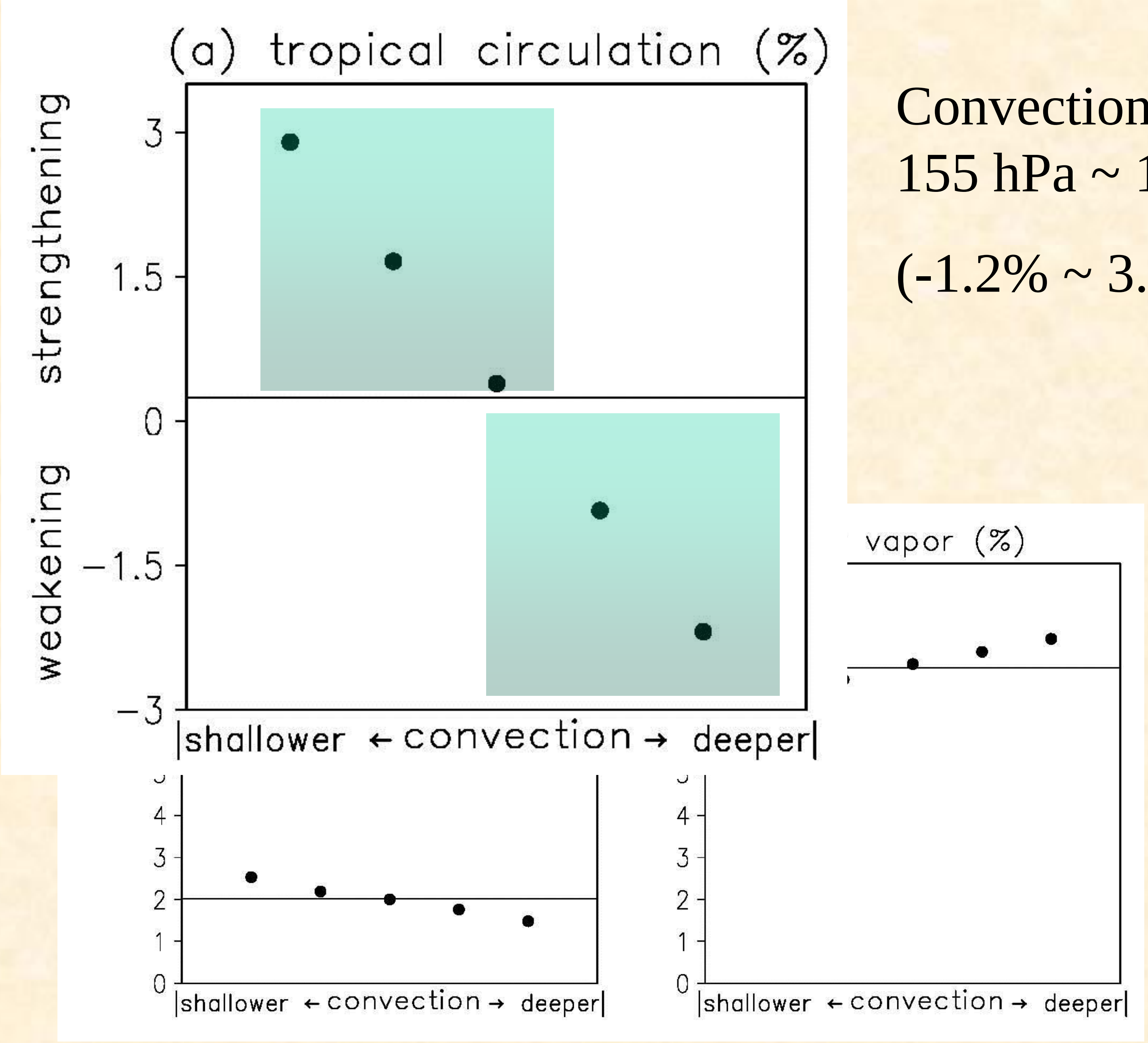
1-3% in P per 1℃ T

(controlled by energy budget)

Effect of convection depth



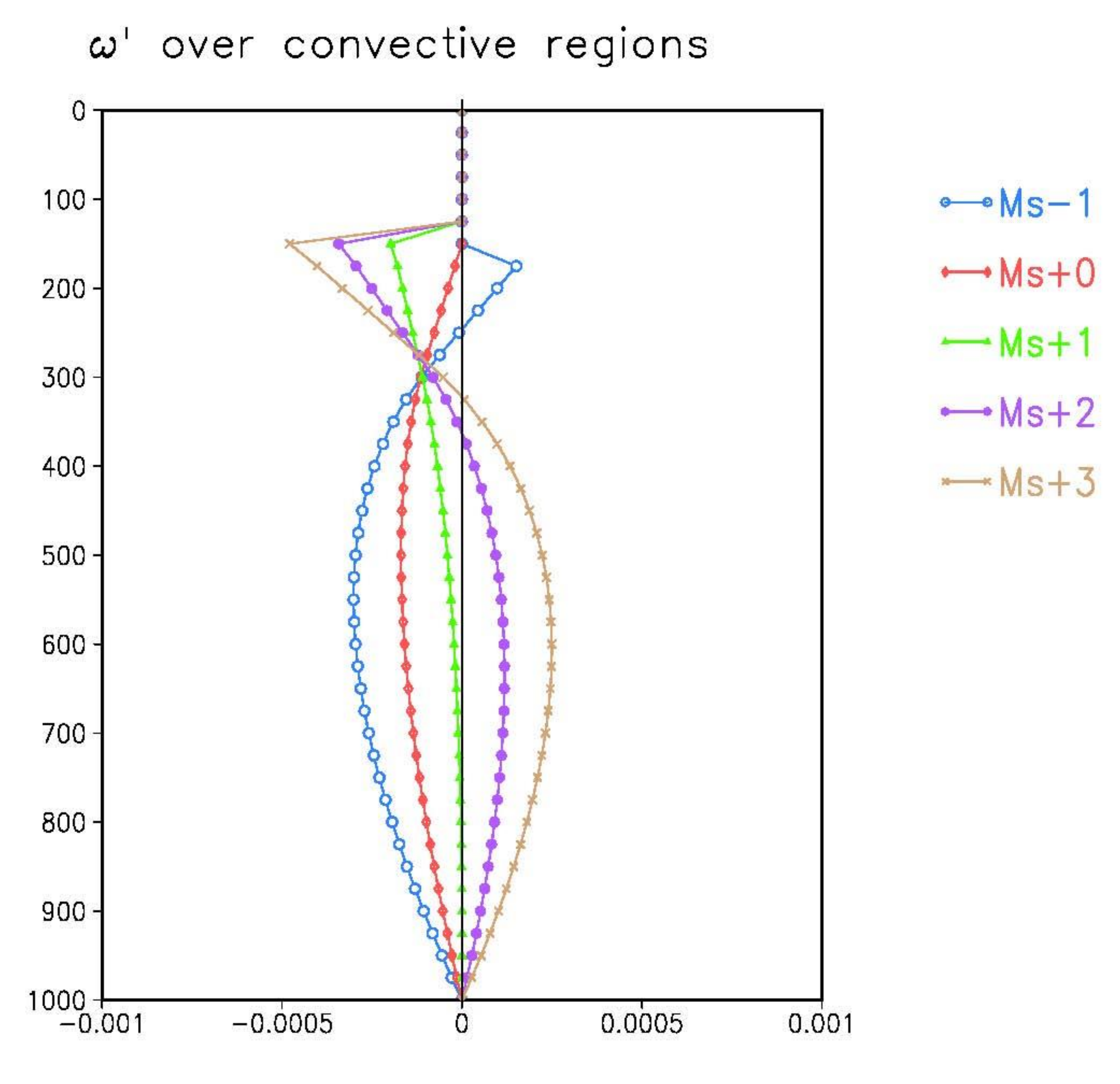
➔ deepening of convection:~ 2.5-3.4%



Convection top:
155 hPa ~ 137 hPa

(-1.2% ~ 3.3%)

Chou and Chen 2009



155 hPa

150 hPa

145 hPa

141 hPa

137 hPa

shallower← →deeper

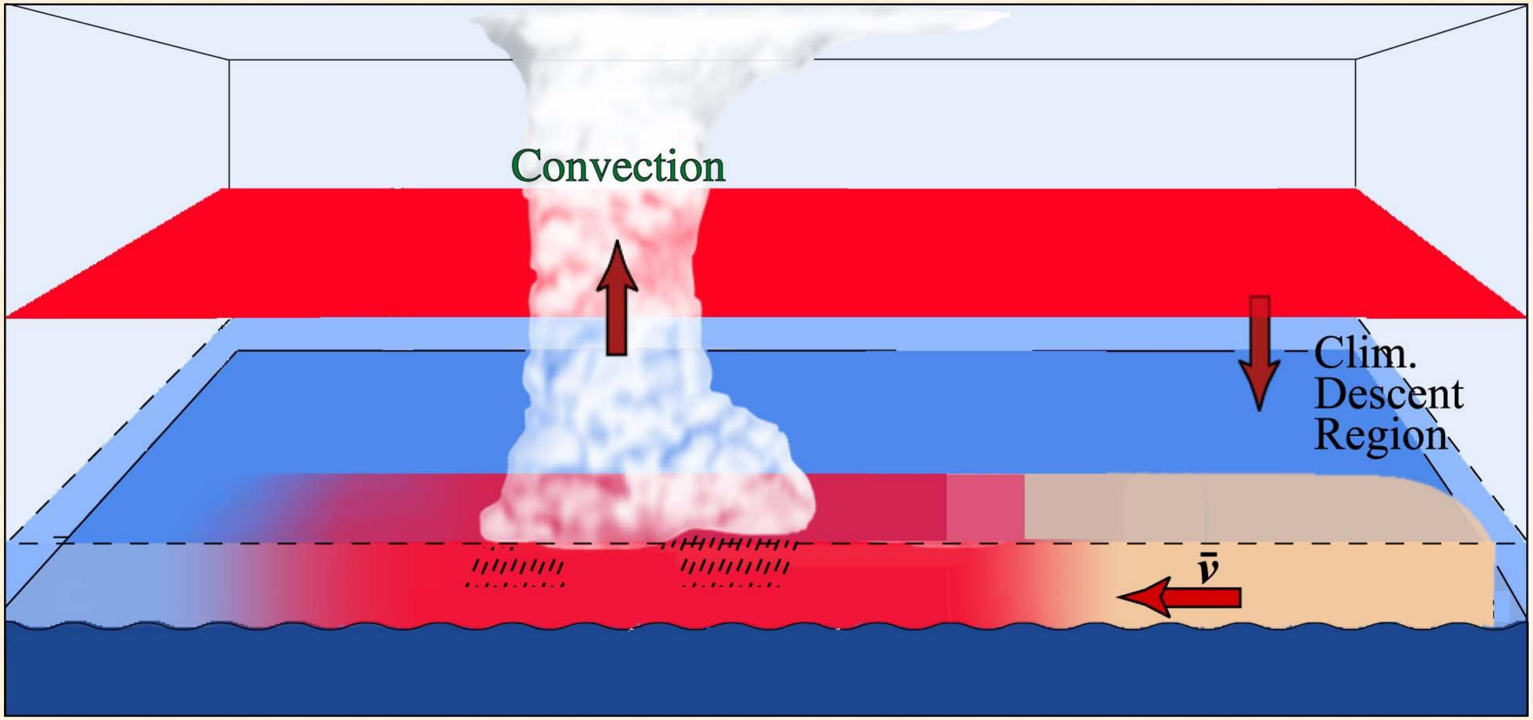
term	M_s-1	M_s+0	M_s+1	M_s+2	M_s+3
global $P'/\bar{P}$	**0.0253**	**0.0219**	**0.0200**	**0.0176**	**0.0148**
global $E'/\bar{E}$	0.0245	0.0217	0.0200	0.0181	0.0156
global $q'/\bar{q}$	**0.0695**	**0.0724**	**0.0761**	**0.0790**	**0.0821**
$\omega'/\bar{\omega}$ at 500 hPa	**0.0408**	**0.0166**	**-0.0072**	**-0.0287**	**-0.0492**
$P' - E'/\bar{P} - \bar{E}$	0.0906	0.0695	0.0476	0.0284	0.0088
$-\langle\nabla\cdot\mathbf{v}q\rangle'/-\langle\nabla\cdot\overline{\mathbf{v}q}\rangle$	0.0906	0.0695	0.0478	0.0285	0.0089
$-\langle\mathbf{v}\cdot\nabla q\rangle'/-\langle\nabla\cdot\overline{\mathbf{v}q}\rangle$	-0.0111	-0.0063	-0.0039	-0.0003	0.0018
$-\langle\omega\partial_p q\rangle'/-\langle\nabla\cdot\overline{\mathbf{v}q}\rangle$	0.1017	0.0758	0.0517	0.0288	0.0221
$-\langle\bar{\omega}\partial_p q'\rangle/-\langle\nabla\cdot\overline{\mathbf{v}q}\rangle$	0.0531	0.0572	0.0621	0.0638	0.0662
$-\langle\omega'\partial_p\bar{q}\rangle/-\langle\nabla\cdot\overline{\mathbf{v}q}\rangle$	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

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

thermodynamic

dynamic

Deeper convection



more E less E

$$P' \approx E' - \langle \nabla \cdot vq \rangle'$$

—Reduced upward motion; Less convergence of moisture flux

—more evaporation

Vertically integrated moist static energy budget

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

shallower ← → deeper

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

➔The deeper (shallower) 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

$M = -\langle \Omega \partial_p h \rangle$ gross moist stability

$\nabla \cdot v_1$ divergence (baroclinic winds)

Ω: 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

➔

$$\nabla \cdot v_1' \approx \frac{1}{\bar{\bar{M}}} [-M' \nabla \cdot \bar{v}_1 - \langle v \cdot \nabla (T + q) \rangle' + F^{net'}]$$

➔

$$\frac{\nabla \cdot v_1'}{\nabla \cdot \bar{v}_1} \approx -\frac{M'}{\bar{\bar{M}}}$$

Gross moist stability

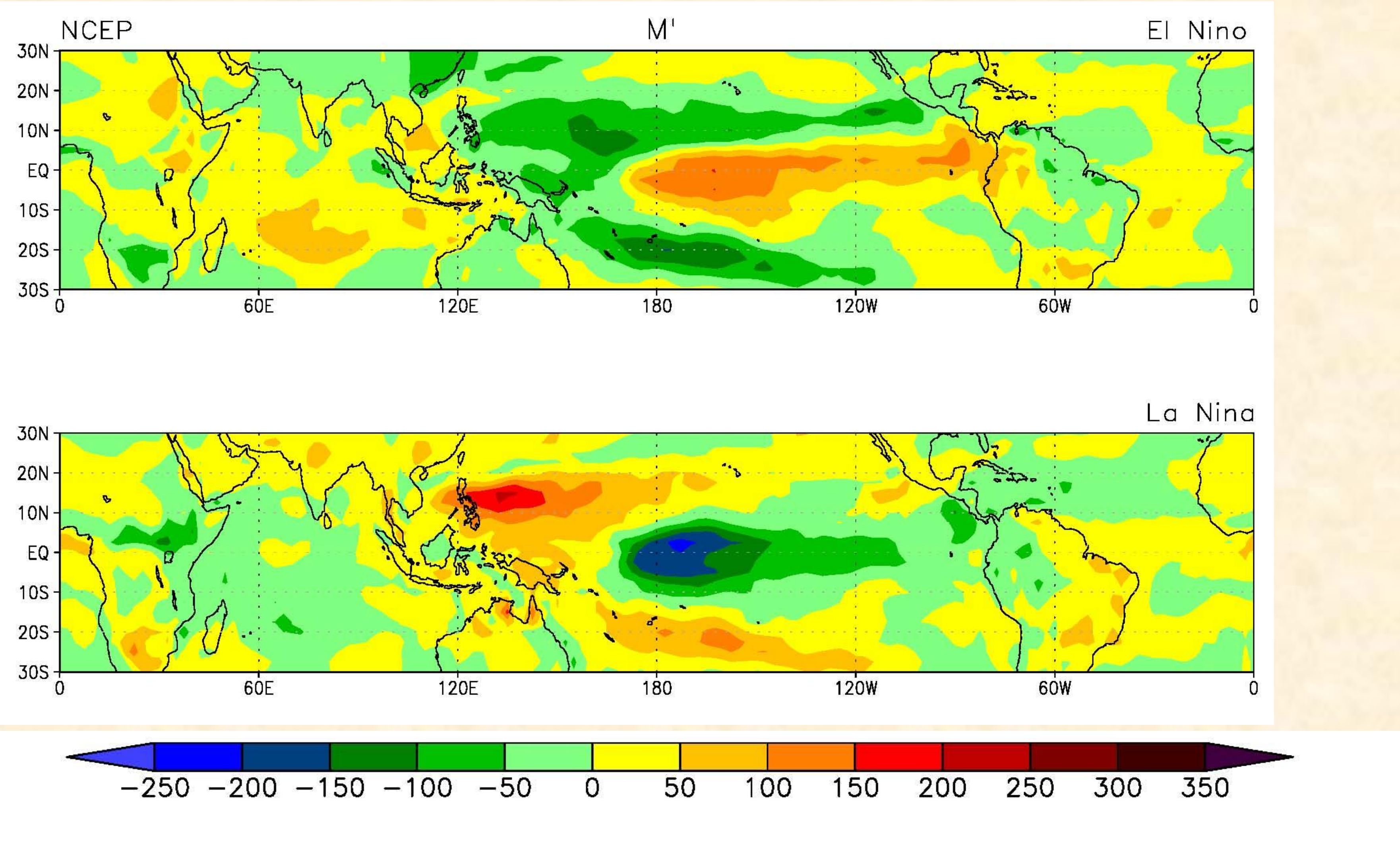
$$M = -\langle \Omega \partial_p h \rangle$$

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

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

$$= \widetilde{M} + M^*_{hT} + M^*_{hq} + M^*_{pt} + \Delta M$$

ENSO


NCEP
M'
El Nino
30N
20N
10N
EQ
10S
20S
30S
0
60E
120E
180
120W
60W
0
La Nina
−250
−200
−150
−100
−50
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100
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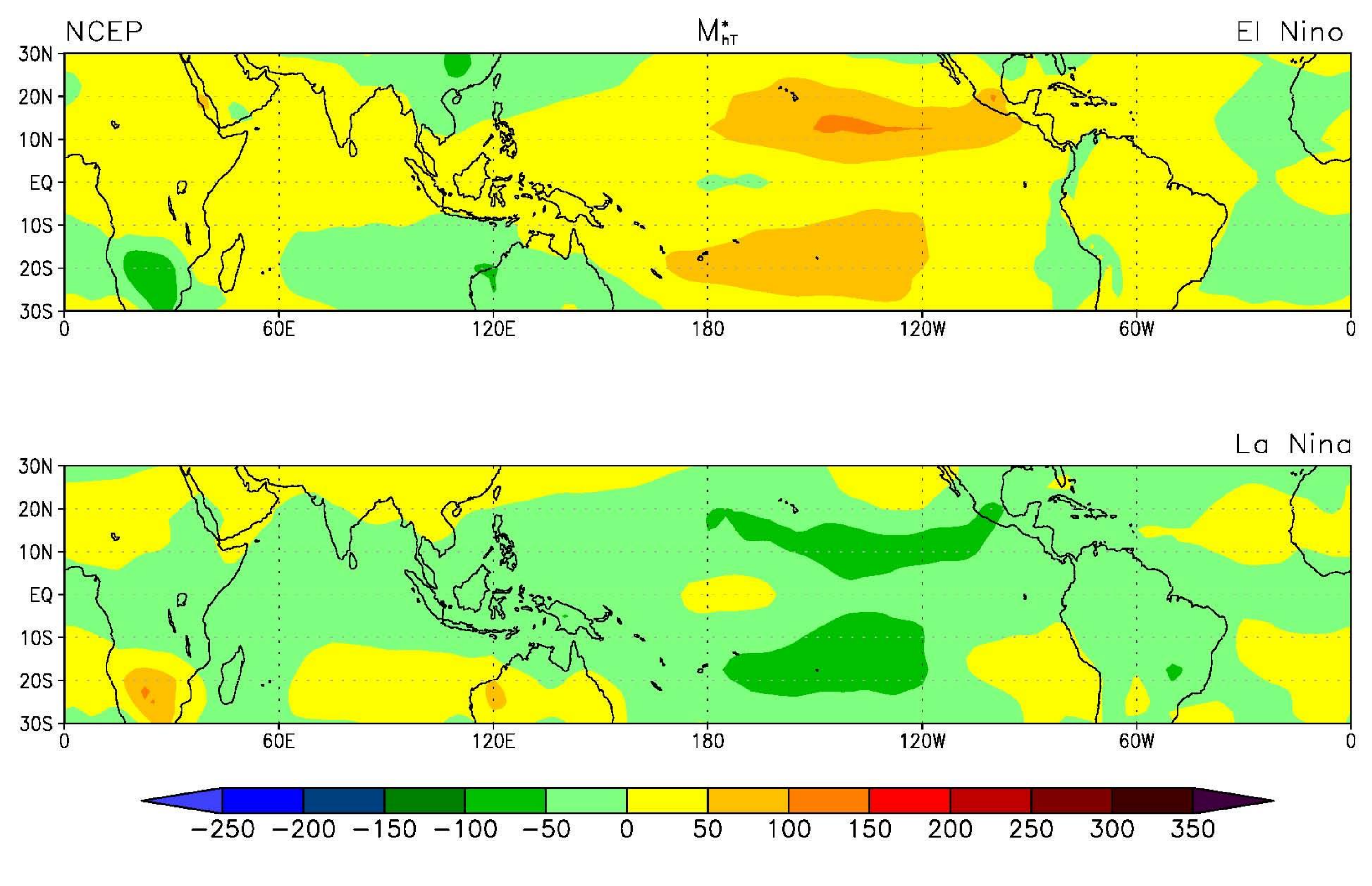
200
250
300
350

M^*_{hT}



NCEP
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30N
20N
10N
EQ
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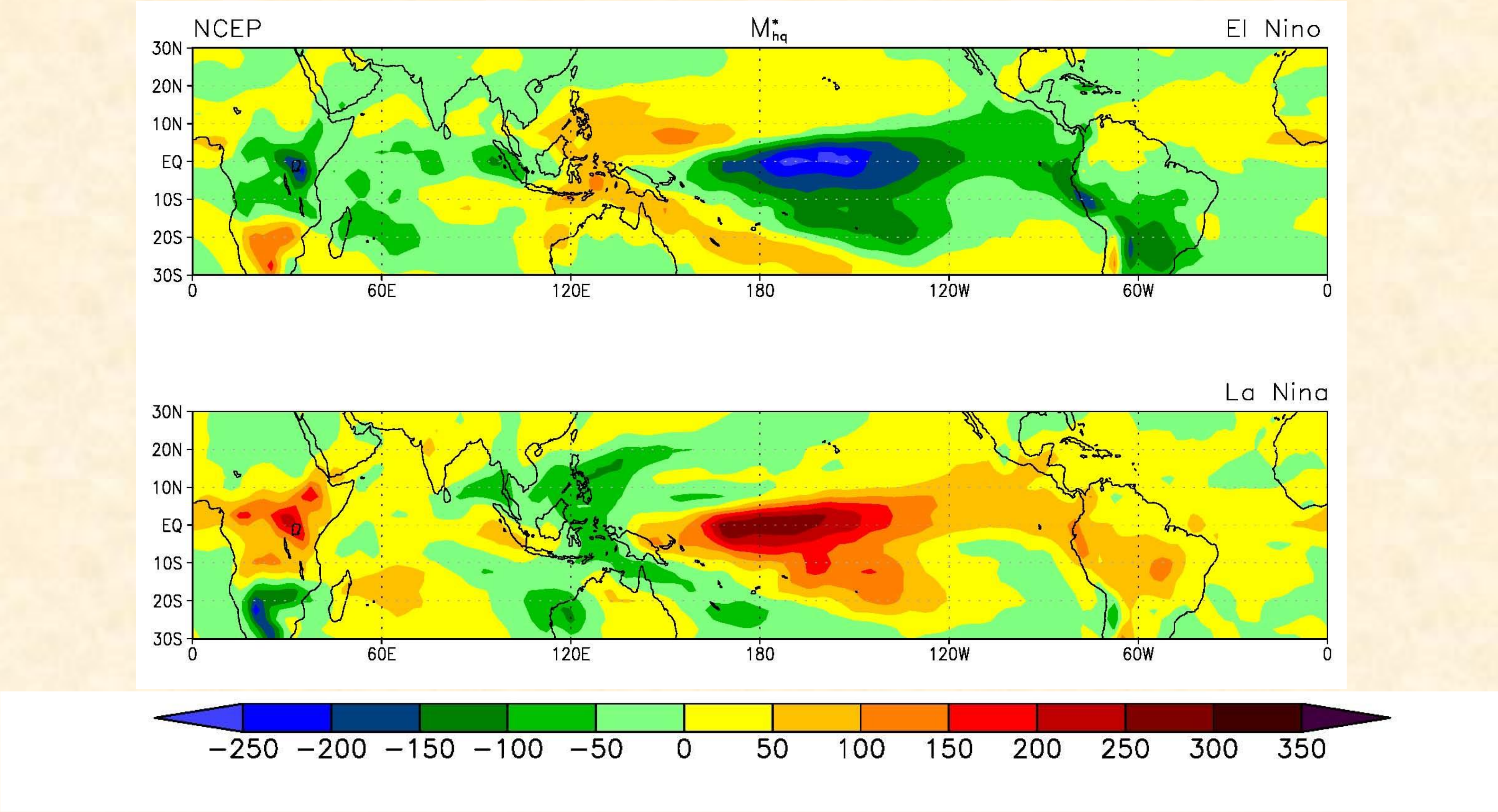
20S
30S
0
60E
120E
180
120W
60W
−250 −200 −150 −100 −50 0 50 100 150 200 250 300 350

M^*_{hq}



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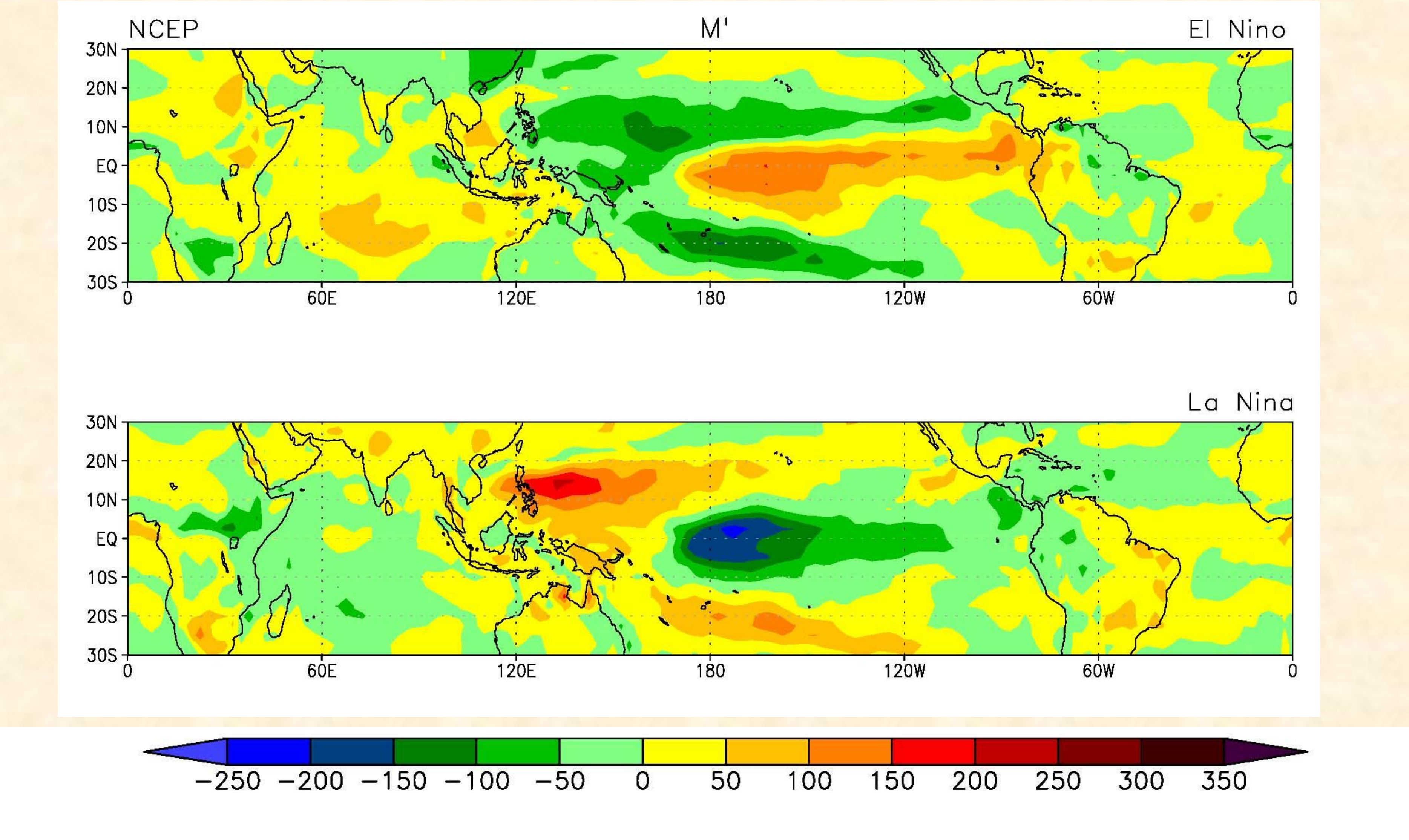
$$M^*_{pt}$$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Conclusion

- 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.