Quantifying Air-sea Interactions in the Tropics

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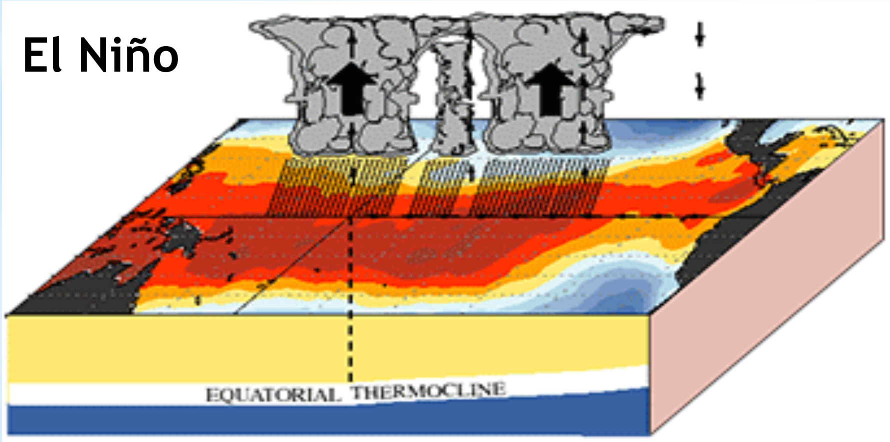
Air-sea interaction

Outside the tropics:
Atmospheric variability generated internally within the atmosphere.

In the tropics:
SSTs regulate the atmosphere.



http://forum.weatherzone.com.au/ubbthreads.php/topics/1050469/40

How strong is the SST forcing of convection?

"Although SSTs in excess of 27.5^{o}C are required for deep convection to occur, the intensity of convection appears to be insensitive to further increases in SST."

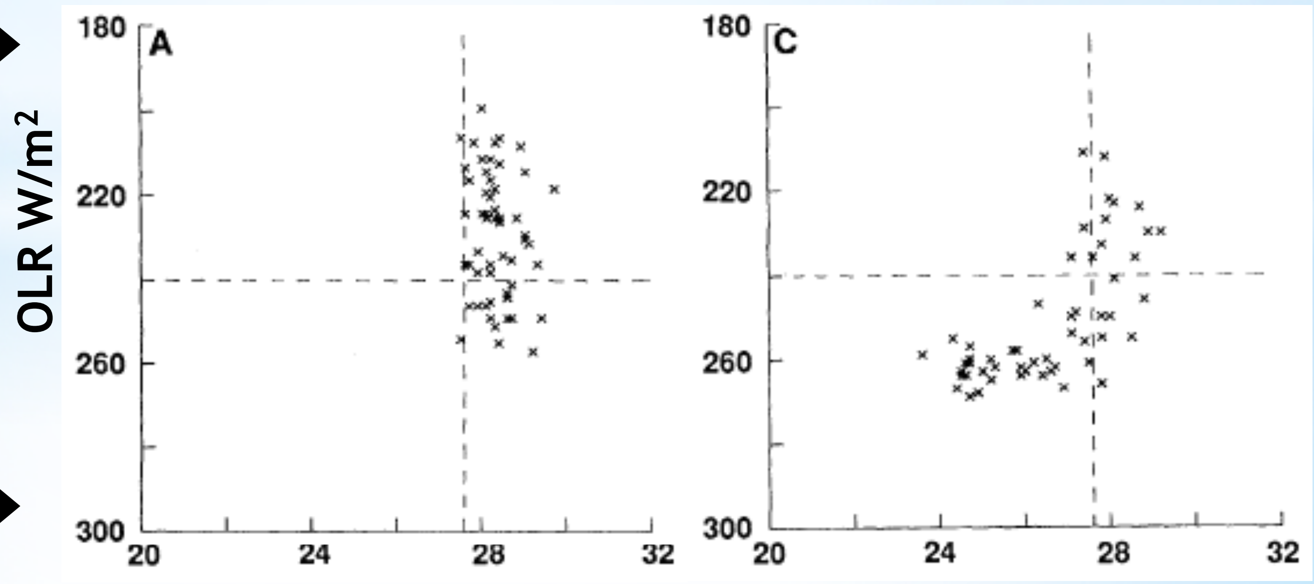
-- Graham and Barnett 1987, *Science*

strong convection →

weak convection →

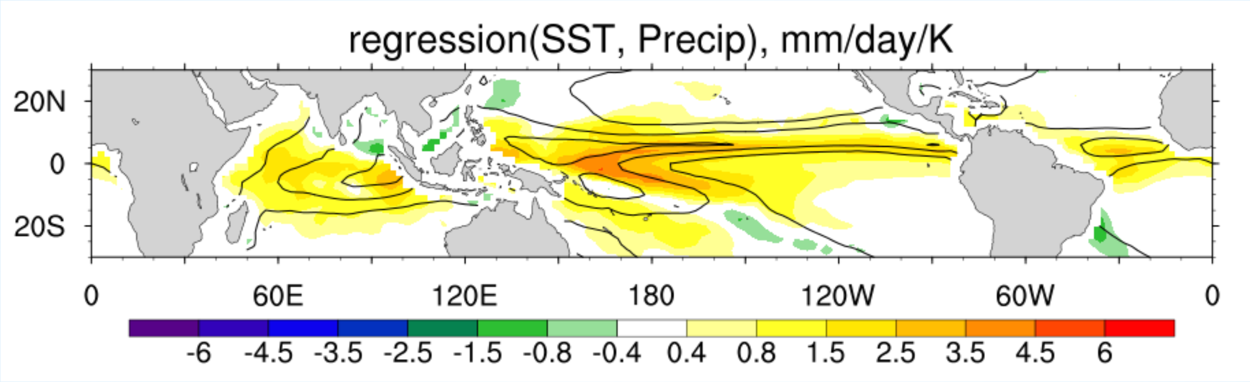
SST > 27.5^{o}C

SST ~ 27.5^{o}C



SST ^{o}C

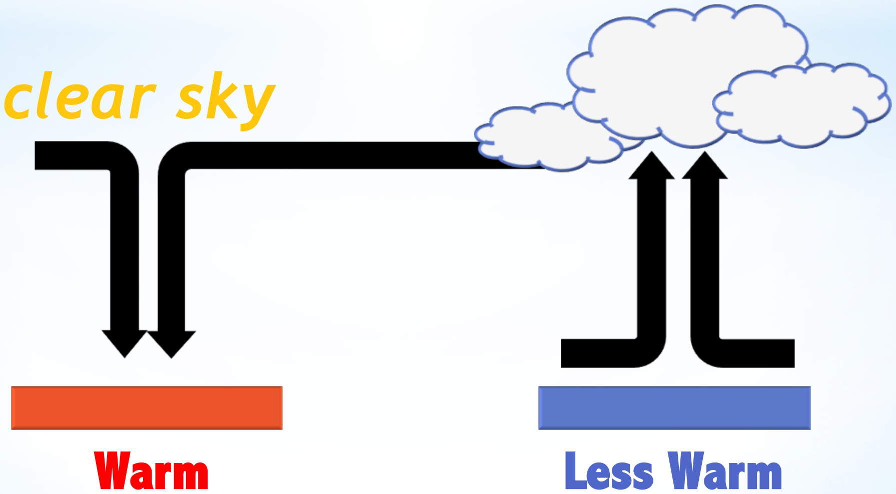
Lack of SST forcing over warm pool?



Lau et al. 1997, *J. Climate*

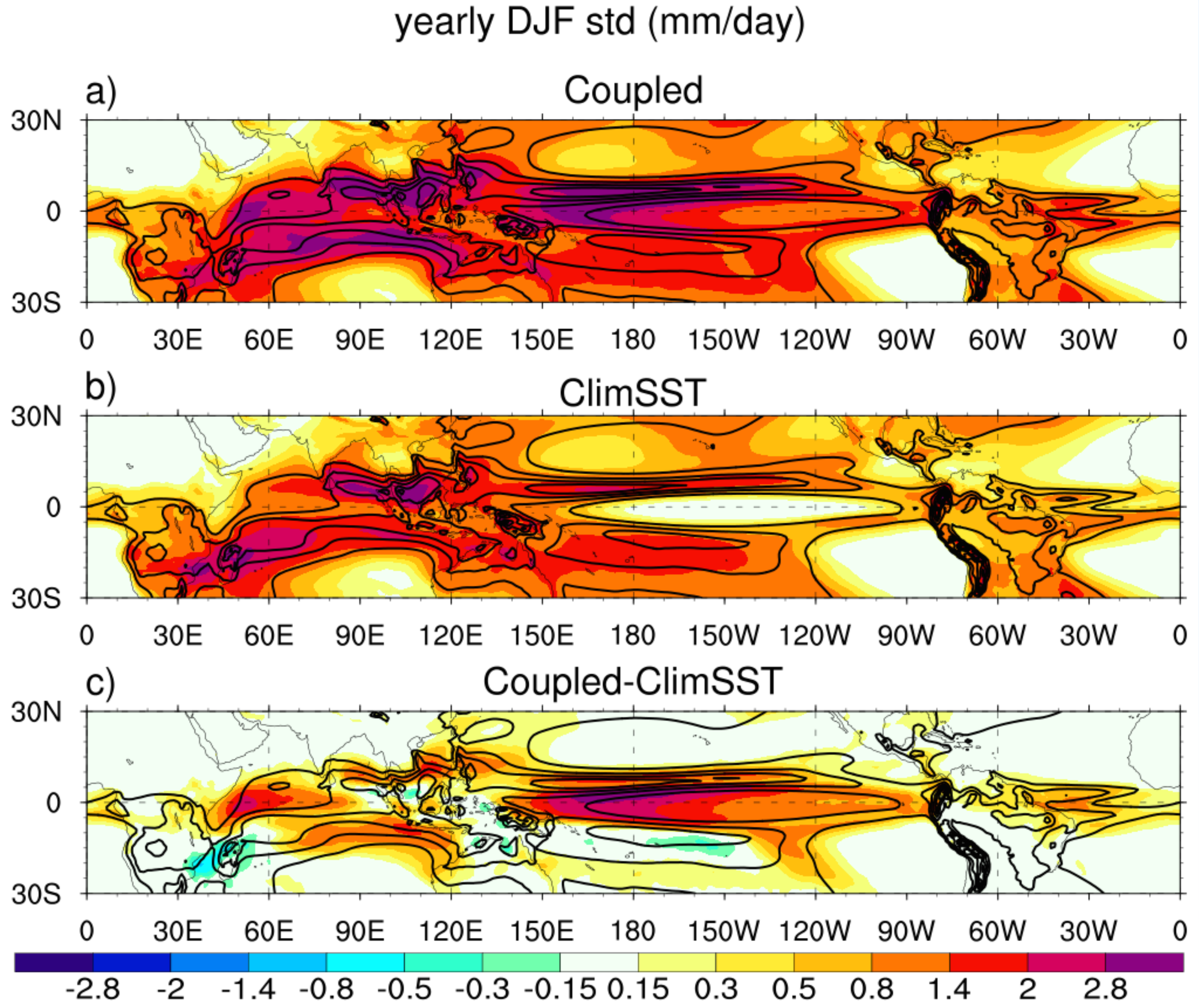
Large-scale remote forcing?

Waliser and Graham 1993, *J. Climate*; Zhang 1993, *J. Climate*; Waliser 1996 *J. Climate*



SST forcing in coupled systems

$$P = P(SST) + F_P$$



Atmospheric intrinsic

Ocean driven

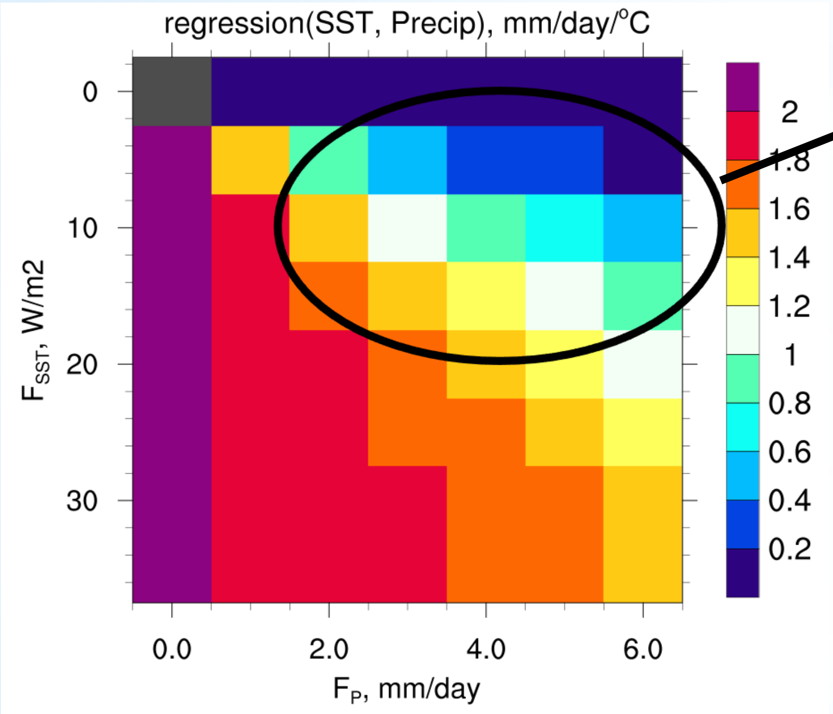
He et al. 2017 *J. Climate*

SST forcing in coupled systems

$$P = a \cdot SST + F_P$$

$$\frac{dSST}{dt} = \frac{1}{c_p \rho_w H}(b \cdot P + F_{SST})$$

a=2 (mm/day)/^{o}C; b=-3 (W/m^2)/(mm/day)



If F_P is large and F_{SST} is small (e.g., ITCZ), it would appear in a coupled system that the SST forcing is much less than 2 (mm/day)/^{o}C.

SST forcing in an uncoupled system

$$P = a \cdot SST + F_P$$

$$\frac{dSST}{dt} = \frac{1}{c_p \rho_w H}(b \cdot P + F_{SST})$$

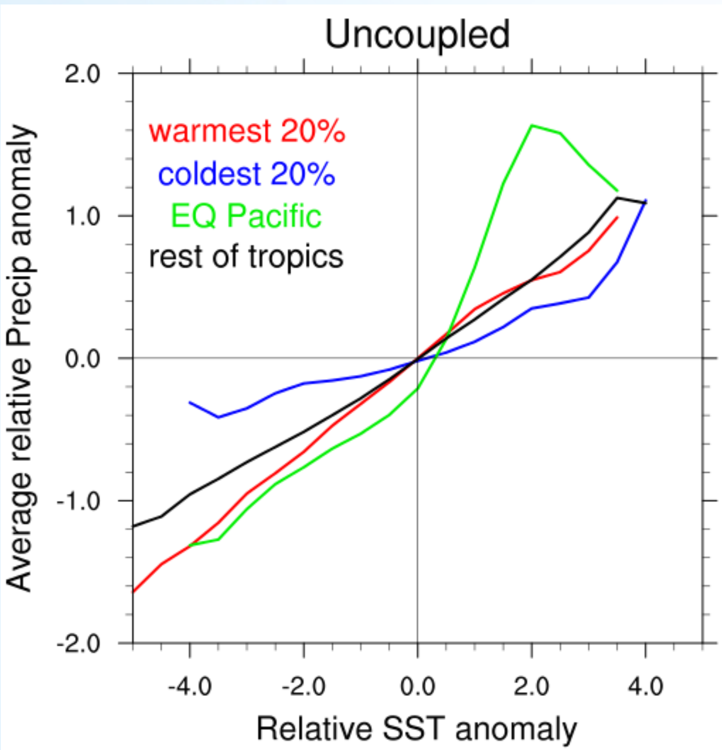
Coupled GFDL-FLOR

↓ *SST anomalies*

Atmosphere-only GFDL-FLOR

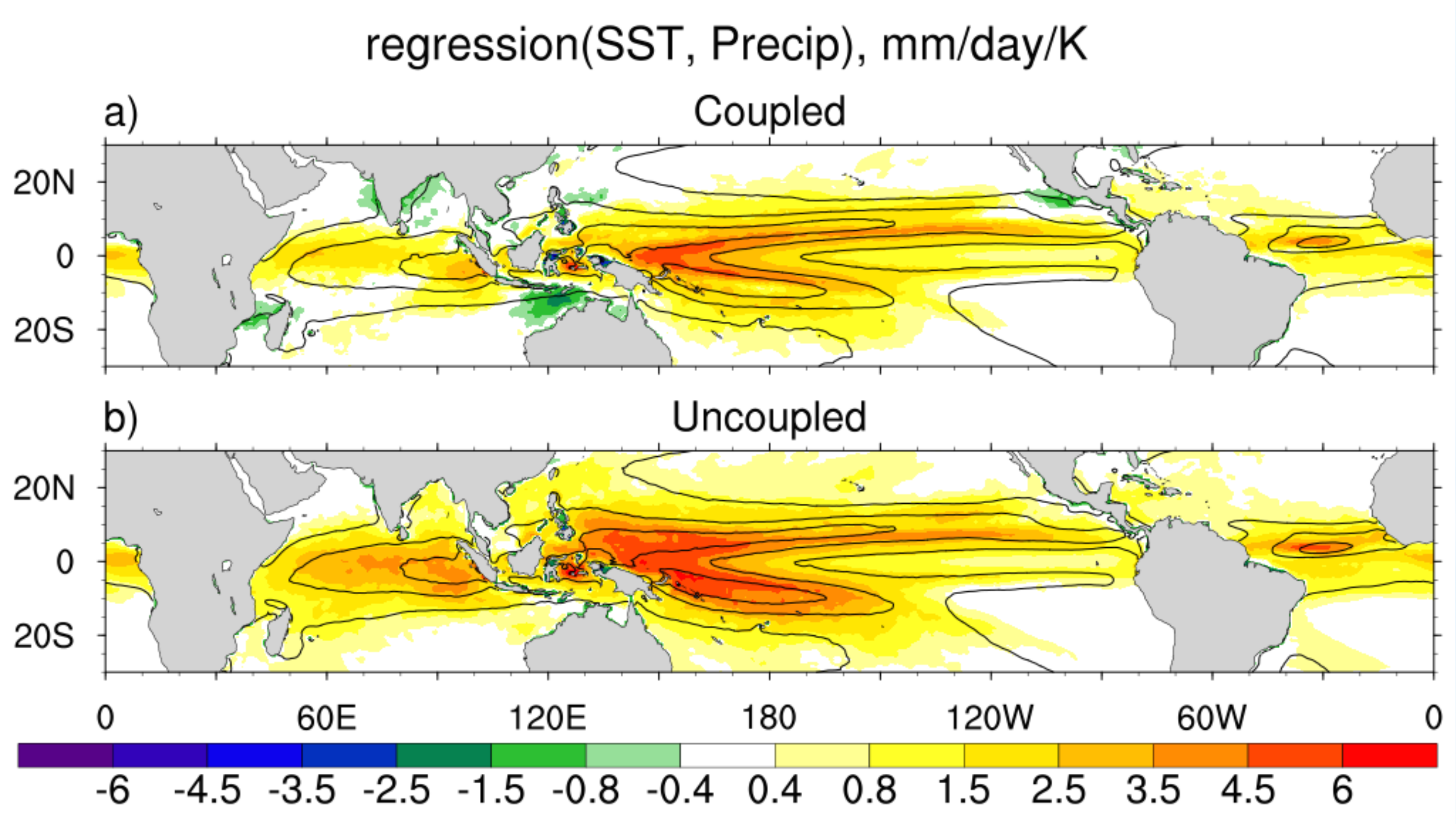
run for 200 years

Assume linearity and solve for regression coefficient, *a*.



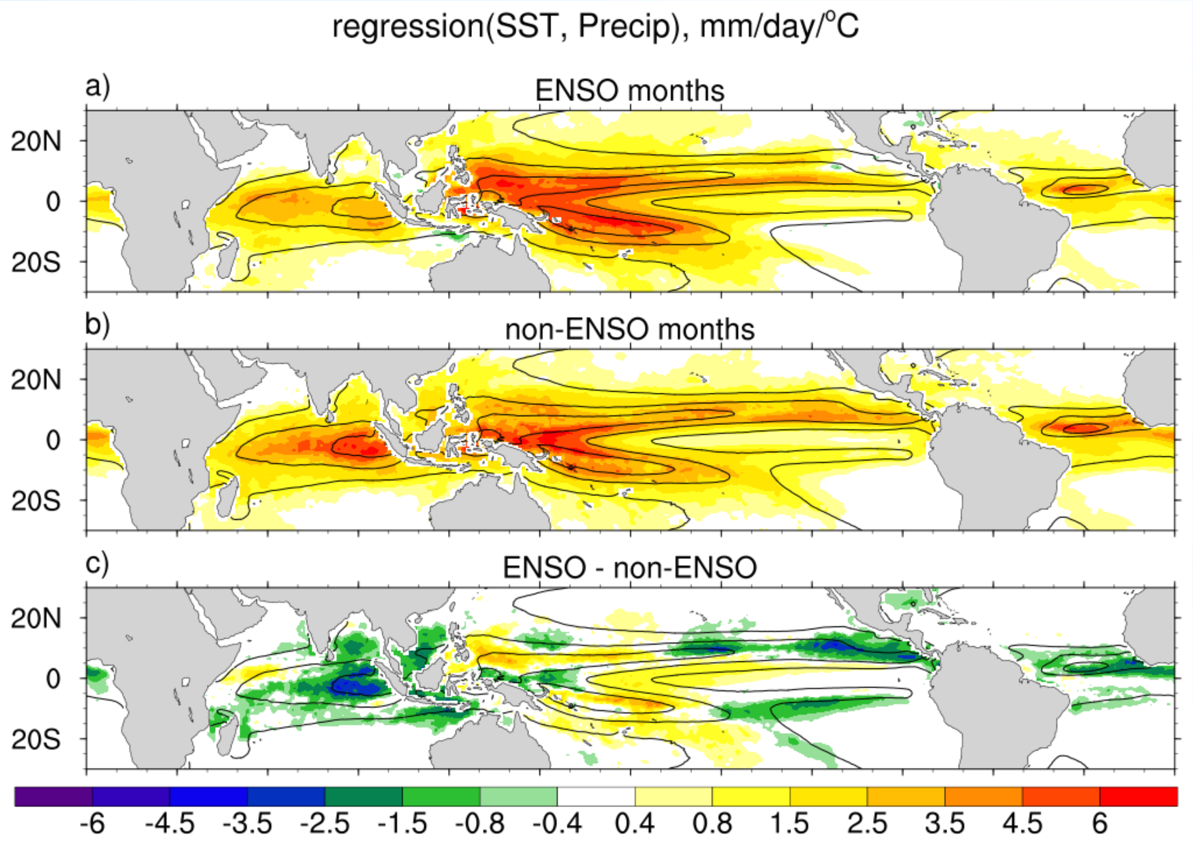
$$relative\_anomaly = \frac{anomaly}{std}$$

Coupled vs. Uncoupled



Local vs. non-local SST forcing

$$P = P(local\_SST) + P(remote\_SST) + F_P$$



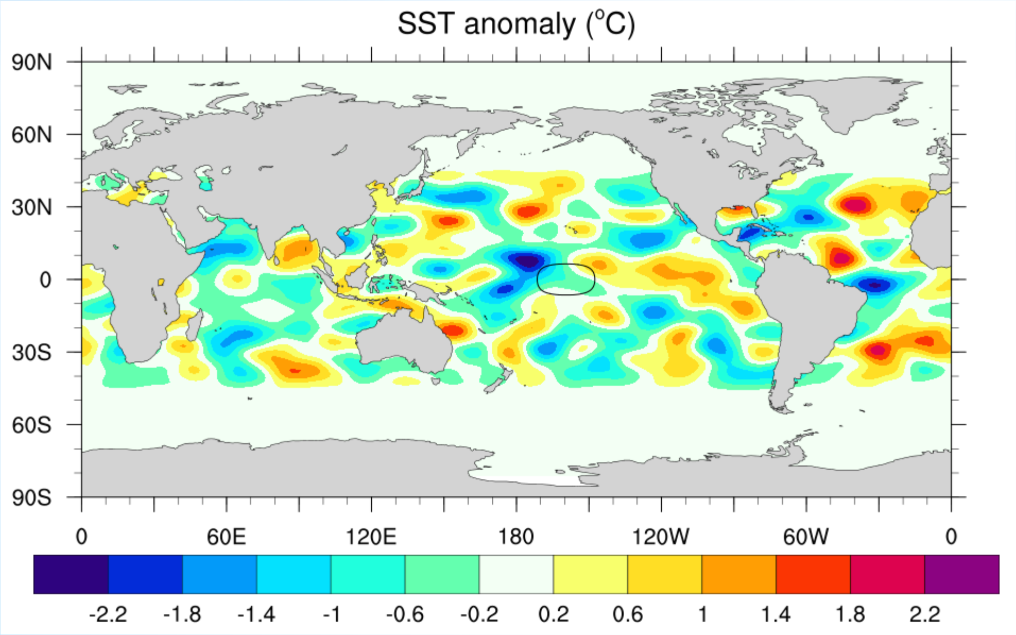
- The point-wise regression largely reflects precipitation response to local SST forcing.

Random SST forcing

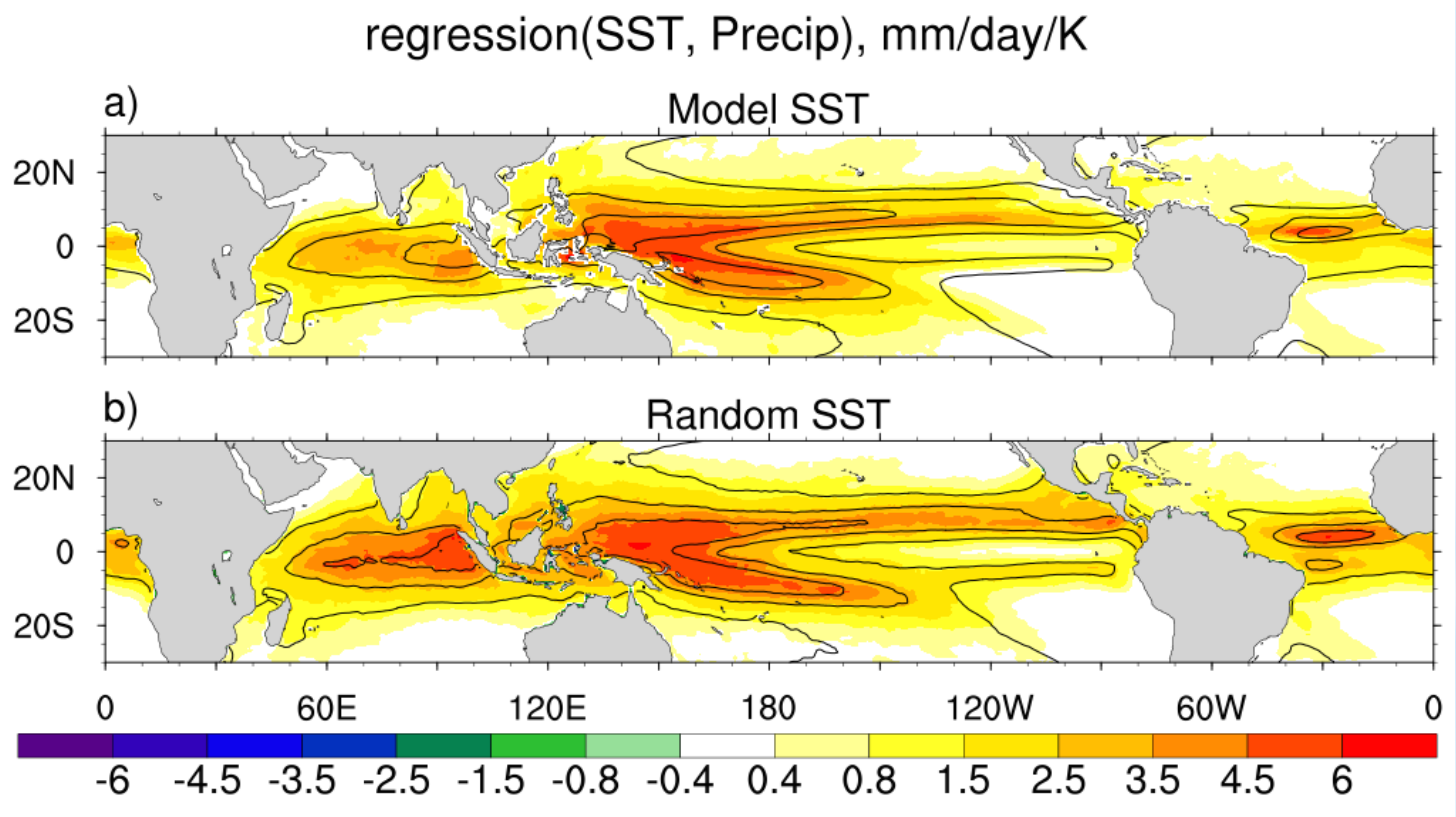
Apply a random SST forcing at each grid point (i) that is not correlated with the other grid points.

$$SST_i(x,y) = B_i \cdot \cos^2\left(\frac{\pi}{2}\frac{y-y_i}{y_w}\right) \cdot \cos^2\left(\frac{\pi}{2}\frac{x-x_i}{x_w}\right)$$

$$y_w = 8^o; x_w = 15^o \qquad B_i = WhiteNoise$$

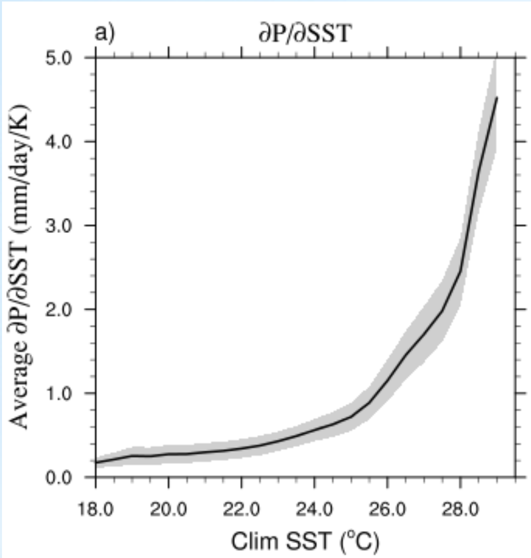


Random SST forcing



- The point-wise regression is largely independent of the spatial structure of SST anomalies.

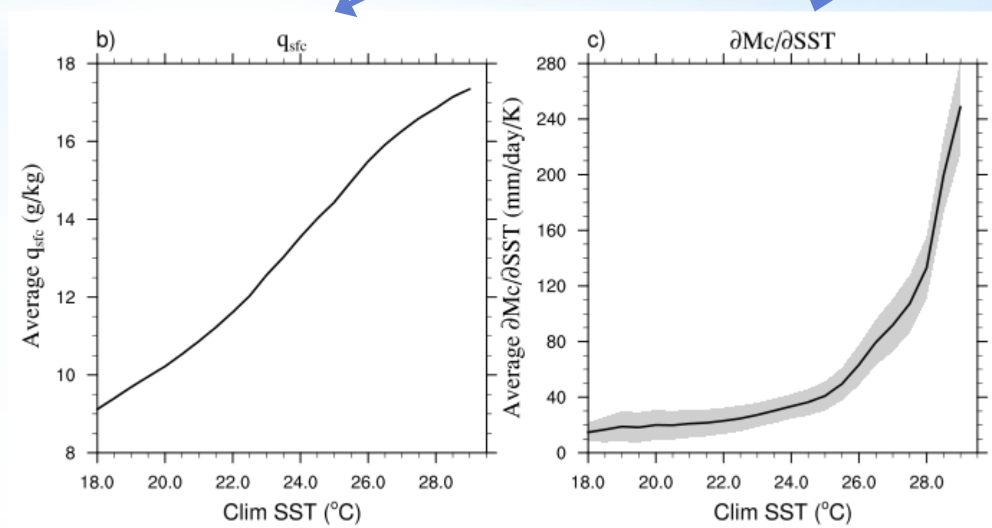
What determines ∂P/∂SST?



$$P = q_{sfc} \cdot Mc \qquad \left(Mc = \frac{P}{q_{sfc}}\right)$$

$$\frac{\partial P}{\partial SST} = \frac{\partial P}{\partial q_{sfc}} \cdot \frac{\partial q_{sfc}}{\partial SST} + \frac{\partial P}{\partial Mc} \cdot \frac{\partial Mc}{\partial SST}$$

$$\frac{\partial P}{\partial SST} = Mc \cdot \frac{\partial q_{sfc}}{\partial SST} + q_{sfc} \cdot \frac{\partial Mc}{\partial SST}$$



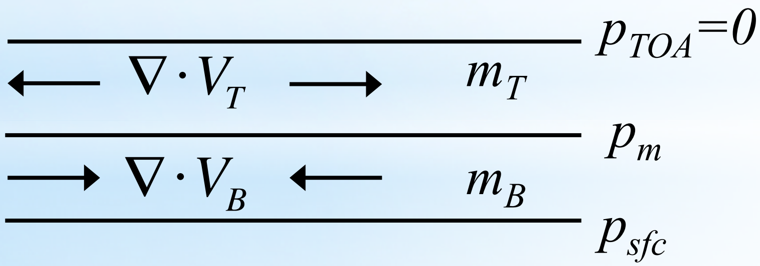
What determines ∂Mc/∂SST?

- **Moist Static Energy Model** (Neelin and Held 1987, *J. Climate*)

$$m = s + L\cdot q \qquad s = C_p\cdot T + \Phi$$

$$\int \nabla\cdot(mV) = F_{sfc} - F_{TOA}$$

$$\int m\cdot(\nabla\cdot V) + \cancel{\int V\cdot(\nabla m)} \approx F_{sfc} - F_{TOA}$$



$$\nabla\cdot V_B = \int_{p_m}^{p_{sfc}} \nabla\cdot V\,\frac{dp}{g} = -\nabla\cdot V_T$$

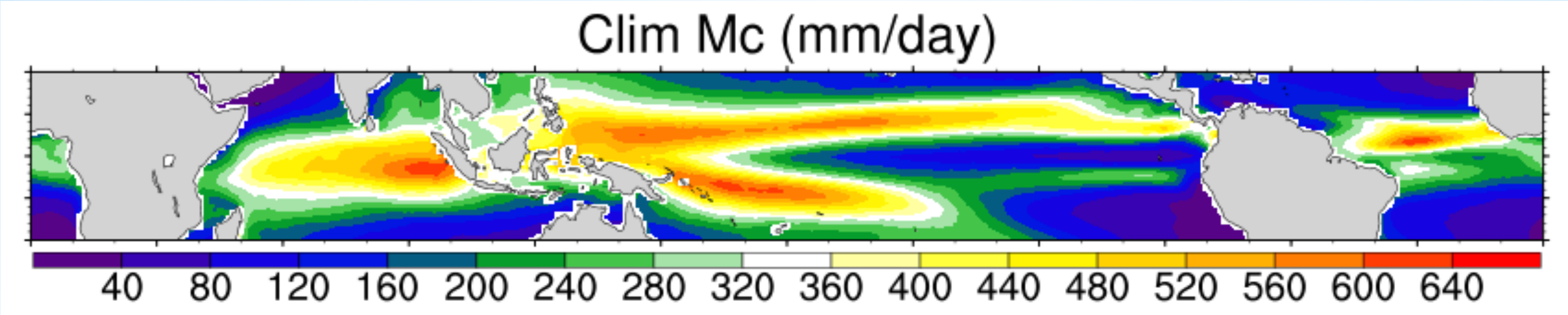
$$\Delta m = m_T - m_B$$

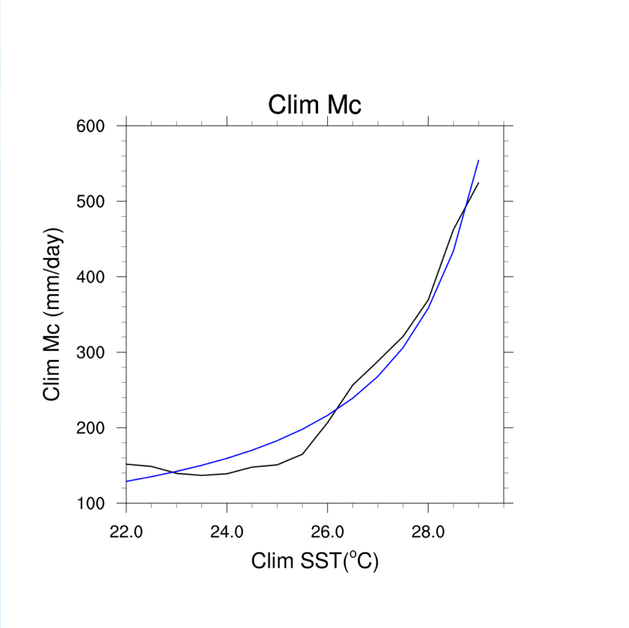
$$-\Delta m\nabla\cdot V_B \approx F_{sfc} - F_{TOA}$$

$$-\nabla\cdot V_B \approx \frac{F_{sfc} - F_{TOA}}{\Delta m}$$

What determines ∂Mc/∂SST?

$$Mc \propto -\nabla \cdot V_B \approx \frac{F_{sfc} - F_{TOA}}{\Delta m}$$





$$Mc \propto \frac{F}{\Delta m} = \frac{F}{s_T + \cancel{L \cdot q_T} - s_B - L \cdot q_B} \approx \frac{F}{\Delta s - L \cdot q_B}$$

$$q_B = \alpha \cdot q_{sat}(T_B) \approx 80\% \cdot q_{sat}(SST - 1.5^oC)$$

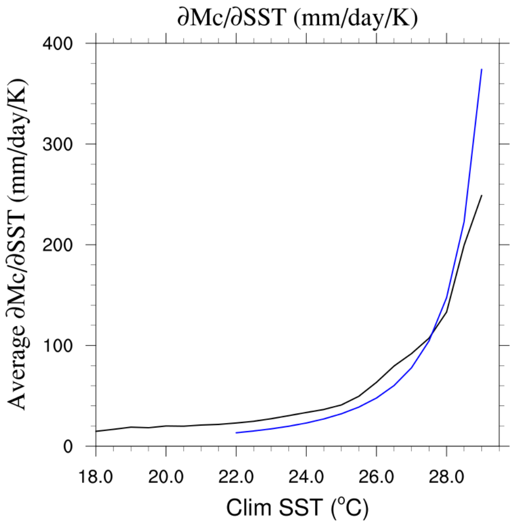
$$\Delta s = 5.0 \times 10^4 J/kg$$

What determines ∂Mc/∂SST?

$$Mc \propto \frac{F}{\Delta s - L \cdot q_B}$$

$$\frac{\partial q_B}{\partial SST} = q_B \cdot 7\% / {}^{o}C$$

$$\frac{\partial Mc}{\partial SST} \propto \frac{F \cdot L \cdot q_B \cdot 7\% / {}^{o}C}{(\Delta s - L \cdot q_B)^2}$$



- As the base *SST* increases, $L \cdot q_B$ increases exponentially towards Δs.

Summary so far …

* Simultaneous SST-convection relationships from coupled systems, including observation, are inadequate for quantifying SST forcing.
* SST forcing of convection is a monotonically increasing function of the base SST.
* Uncoupled simulations can be ideal tools for quantifying SST forcing.

Coming next …

* Is the uncoupled SST forcing consistent with what's happening in coupled systems? $(P = a \cdot SST + F_P)$
* What do these uncoupled air-sea relationships teach us about the coupled air-sea relationships?

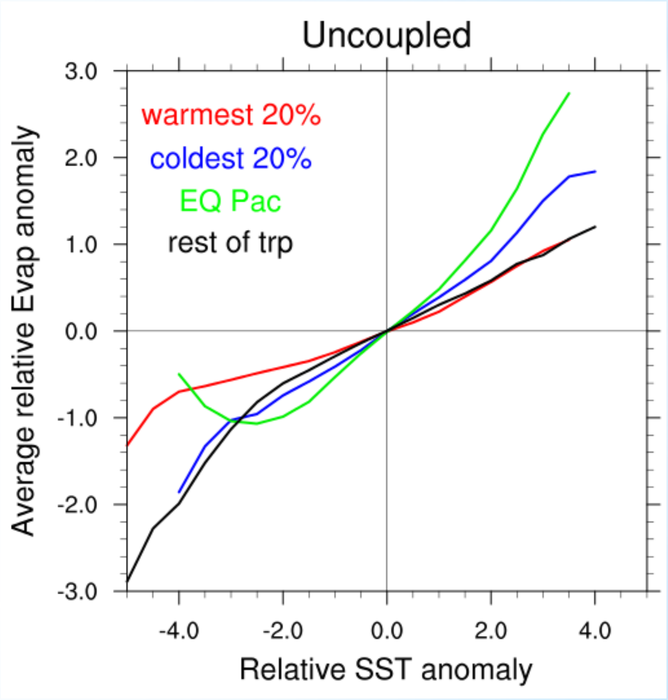
Quantifying Evap and SH sensitivity

$$P = \frac{\partial P}{\partial SST} \cdot SST + F_P$$

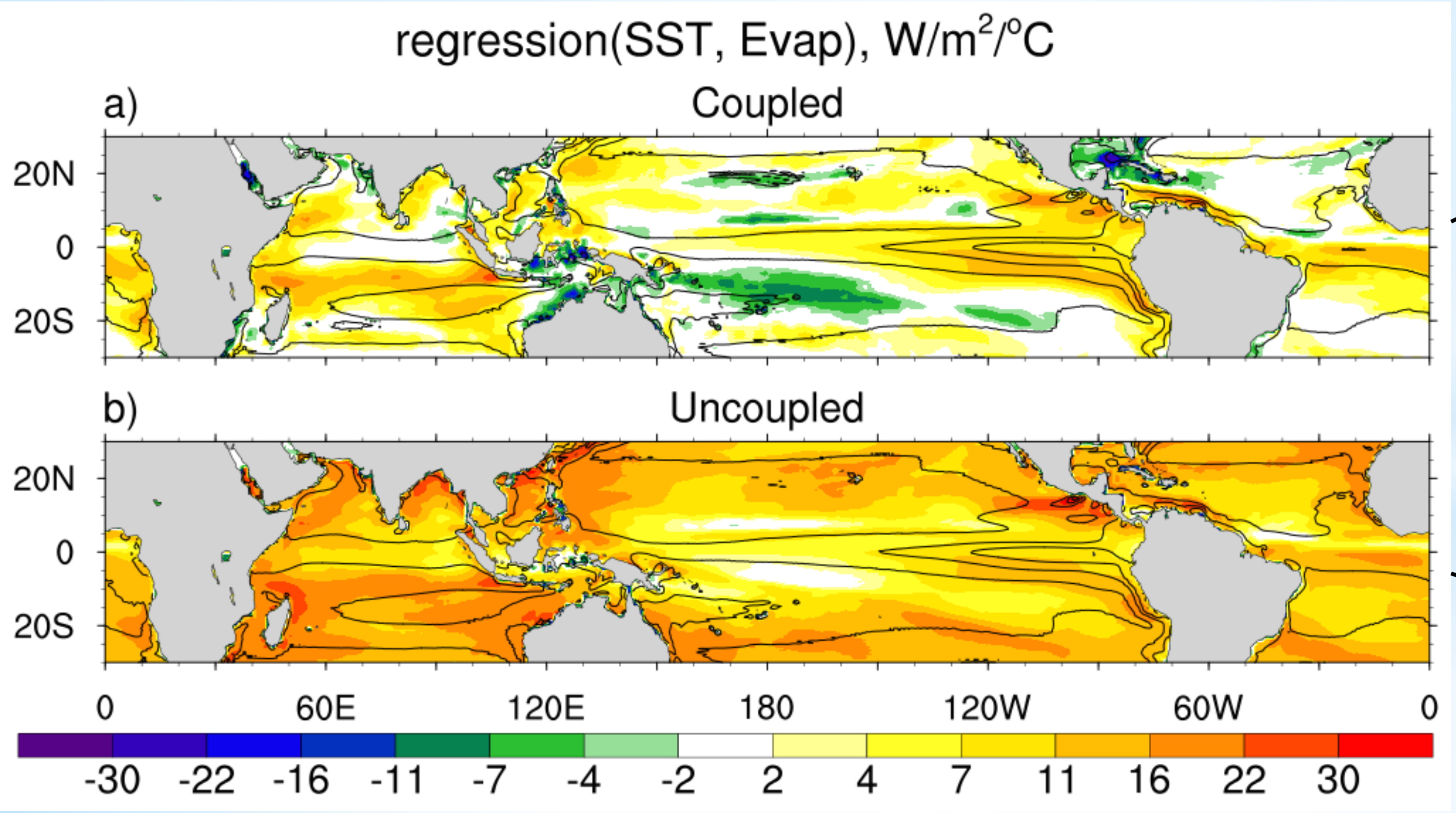
$$E = \frac{\partial E}{\partial SST} \cdot SST + F_E \qquad SH = \frac{\partial SH}{\partial SST} \cdot SST + F_{SH}$$

$$\frac{dSST}{dt}$$

Estimate Evap sensitivity from *uncoupled* run based on regression (SST, Evap).



Coupled vs. Uncoupled



SST forcing
& Evap feedback

SST forcing only

What determines ∂E/∂SST?

$$E = L \cdot \rho_a \cdot C_D \cdot U \cdot [q_{sat}(SST) - rh \cdot q_{sat}(SST - dT)]$$

$$\gamma = L / (R_v \cdot SST^2)$$

$$E = L \cdot \rho_a \cdot C_D \cdot U \cdot (1 - rh \cdot e^{-\gamma \cdot dT}) \cdot q_{sat}(SST)$$

1. only consider the Clausius-Clapeyron change in q_{sat} to changes in SST, while assuming U, rh and dT do not change.

$$\left(\frac{\partial E}{\partial SST}\right)_{CC} = \frac{\partial E}{\partial q_{sat}} \cdot \frac{\partial q_{sat}}{\partial SST} = \frac{\partial E}{\partial q_{sat}} \cdot \gamma \cdot q_{sat} = \gamma \cdot E$$

What determines ∂E/∂SST?

$$E = L \cdot \rho_a \cdot C_D \cdot U \cdot (1 - rh \cdot e^{-\gamma \cdot dT}) \cdot q_{sat}(SST)$$

2. consider changes in U, rh and dT in response to changes in SST.

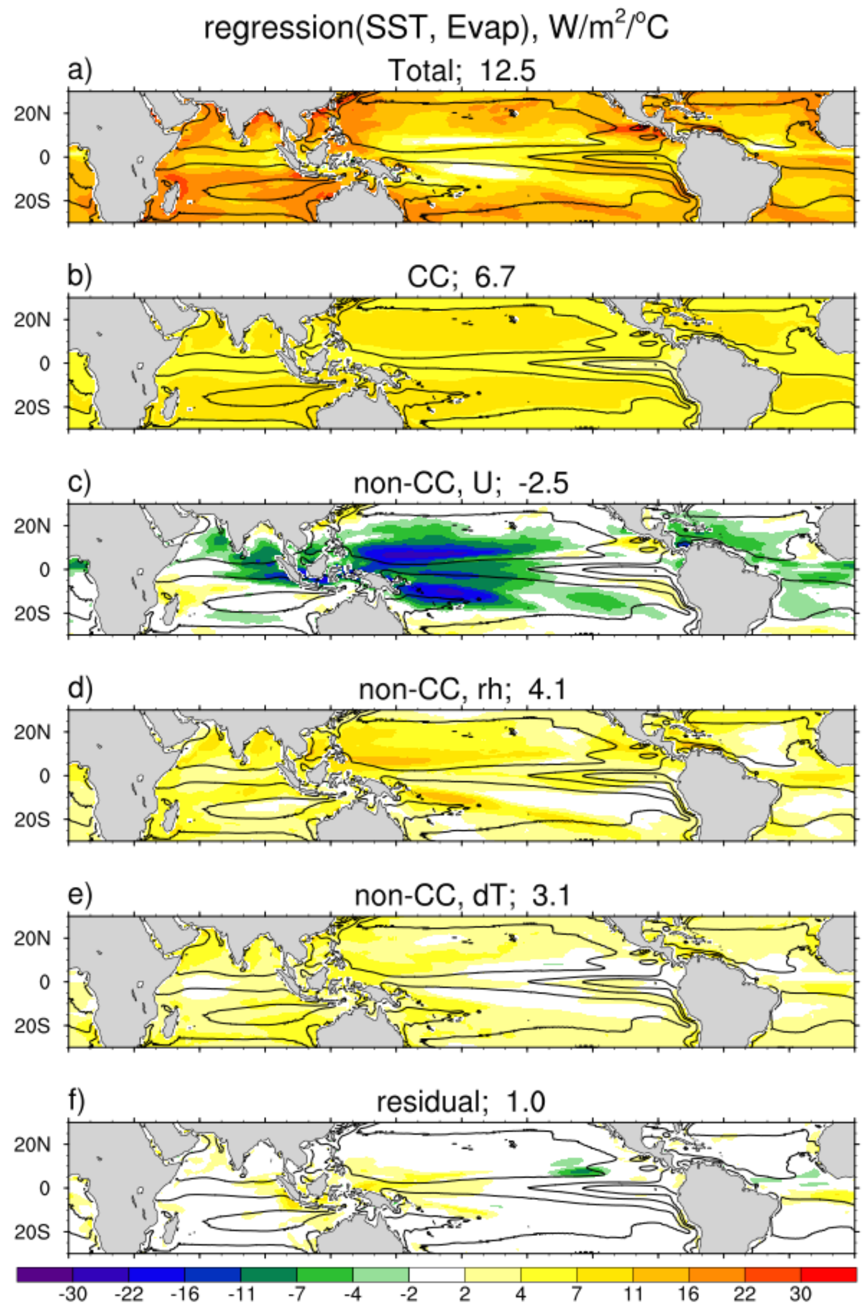
$$\left(\frac{\partial E}{\partial SST}\right)_{non-CC} = \frac{\partial E}{\partial U} \cdot \frac{\partial U}{\partial SST} + \frac{\partial E}{\partial rh} \cdot \frac{\partial rh}{\partial SST} + \frac{\partial E}{\partial dT} \cdot \frac{\partial dT}{\partial SST}$$

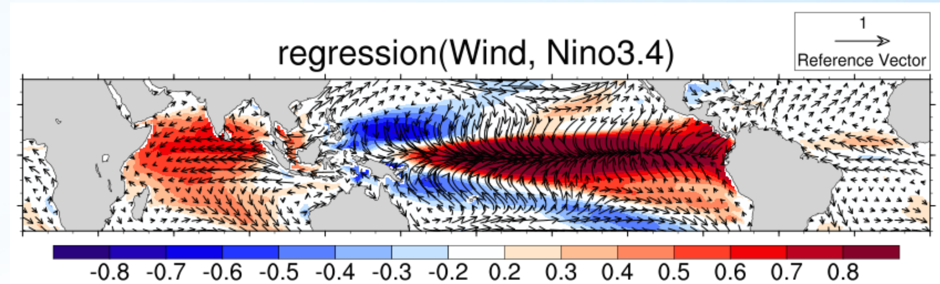
$$\frac{\partial E}{\partial U} = \frac{E}{U}$$

$$\frac{\partial E}{\partial rh} = -L \cdot \rho_a \cdot C_D \cdot U \cdot q_{sat}(Ta)$$

$$\frac{\partial E}{\partial dT} = L \cdot \rho_a \cdot C_D \cdot \gamma \cdot U \cdot rh \cdot e^{-\gamma \cdot dT} \cdot q_{sat}(SST)$$

What determines ∂E/∂SST?

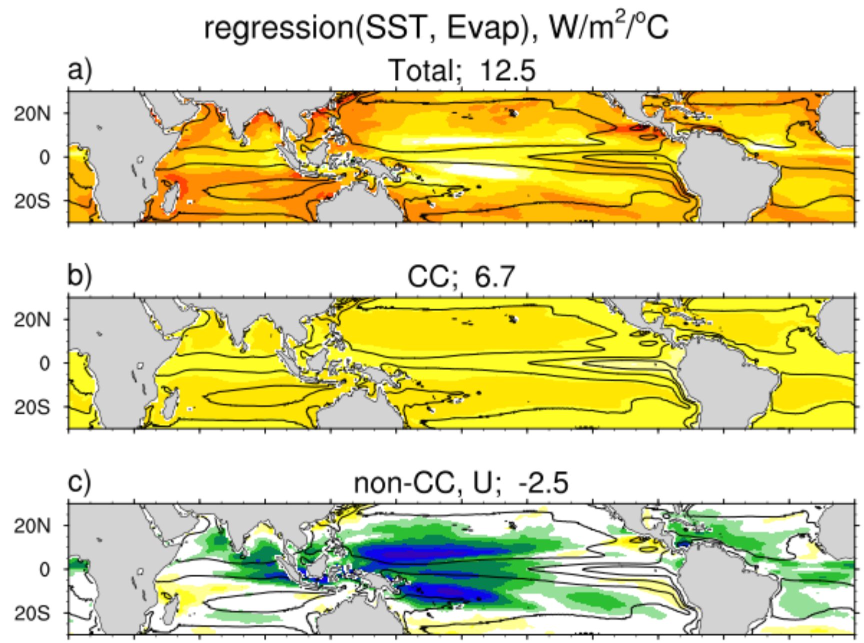


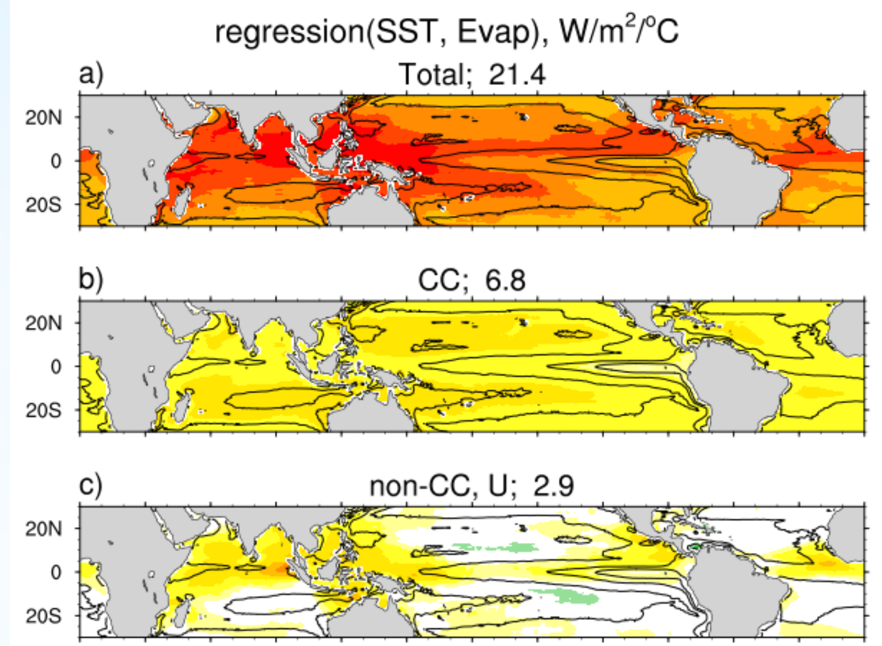


Deep tropics: cold, dry downdraft

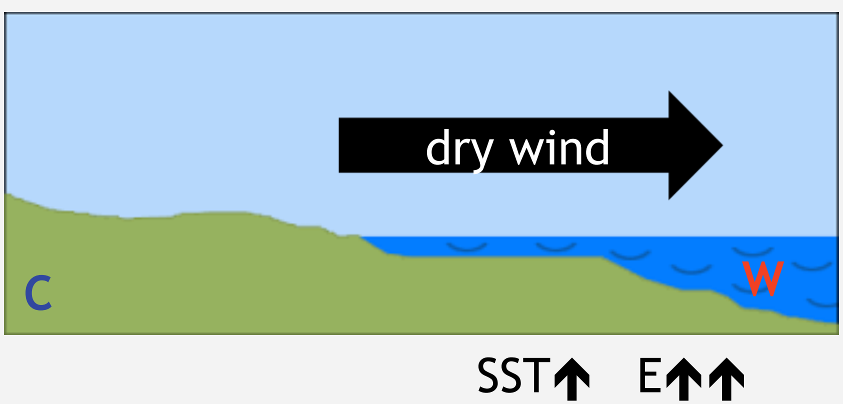
Subtropics: weaker air-sea coupling

Model SST vs. Random SST forcing

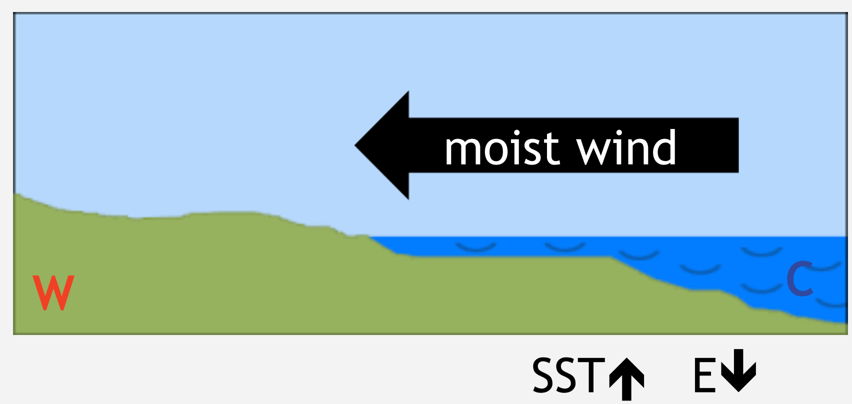


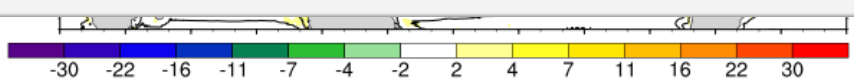


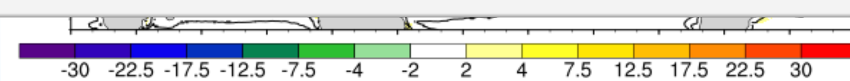
dry season



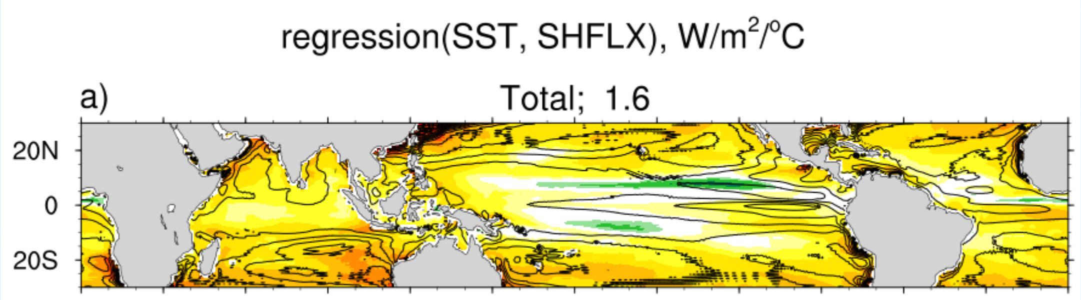
wet season



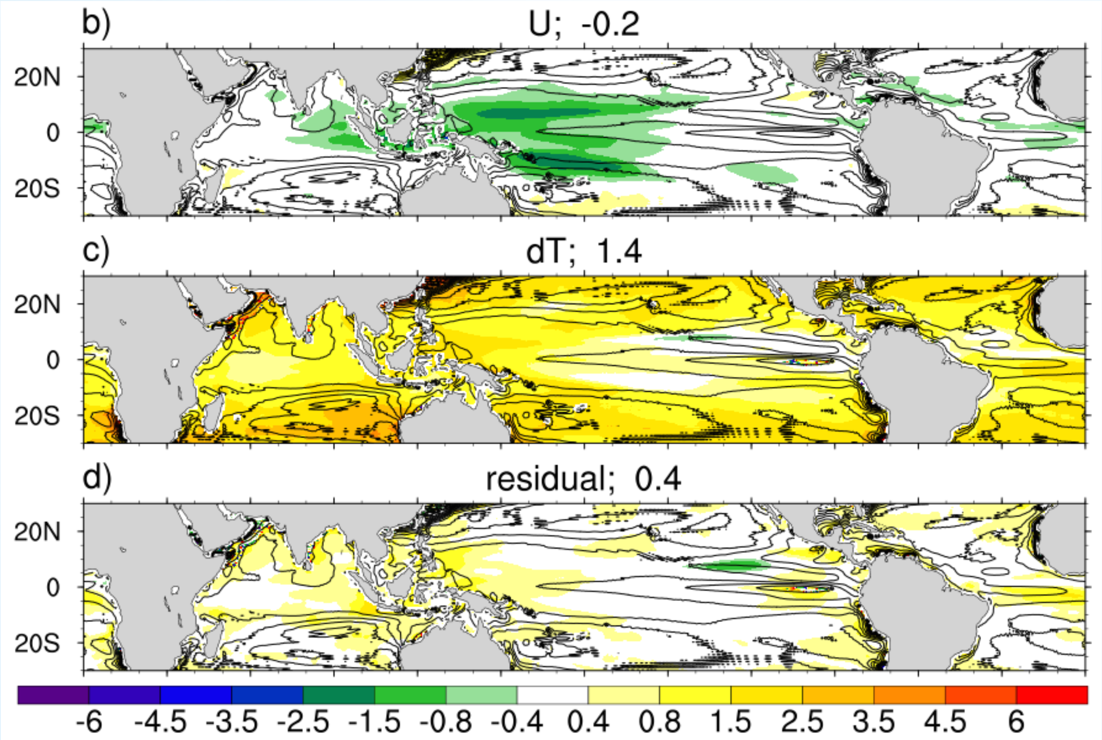




SH sensitivity to SST variability



$$SH \approx \rho_a \cdot C_D \cdot U \cdot dT \longrightarrow \frac{\partial SH}{\partial SST} = \frac{\partial SH}{\partial U} \cdot \frac{\partial U}{\partial SST} + \frac{\partial SH}{\partial dT} \cdot \frac{\partial dT}{\partial SST}$$



Summary for Evap and SH …

* Evaporation and SH sensitivity to SST variability should also be estimated from uncoupled systems.
* Evaporation and SH sensitivity is lowest in the off equatorial Pacific, due to the surface wind response.
* The spatial structure of SST anomalies is important for Evaporation and SH sensitivity.

A framework for air-sea interaction

$$P = \frac{\partial P}{\partial SST} \cdot SST + F_P$$

$$E = \frac{\partial E}{\partial SST} \cdot SST + F_E$$

$$SH = \frac{\partial SH}{\partial SST} \cdot SST + F_{SH}$$

$$SW = C_{SW} \cdot P$$

$$C_{sw} = regression(P, SW)$$

$$\frac{\partial SST}{\partial t} = \frac{1}{c_p \rho_w H}(SW + LW - E - SH + F_{SST})$$

- Quantify atmospheric sources of SST variability.

$$LW = \beta \cdot SST - 4 \cdot \alpha \cdot \overline{\overline{SST}}^3 \cdot SST$$

ENSO forcing

(Waliser and Graham 1993, *J. Climate*)

Tropical SST variability

$$\frac{dSST}{dt} = \frac{1}{c_p \rho_w H}(SW + LW - E - SH + F_{SST})$$

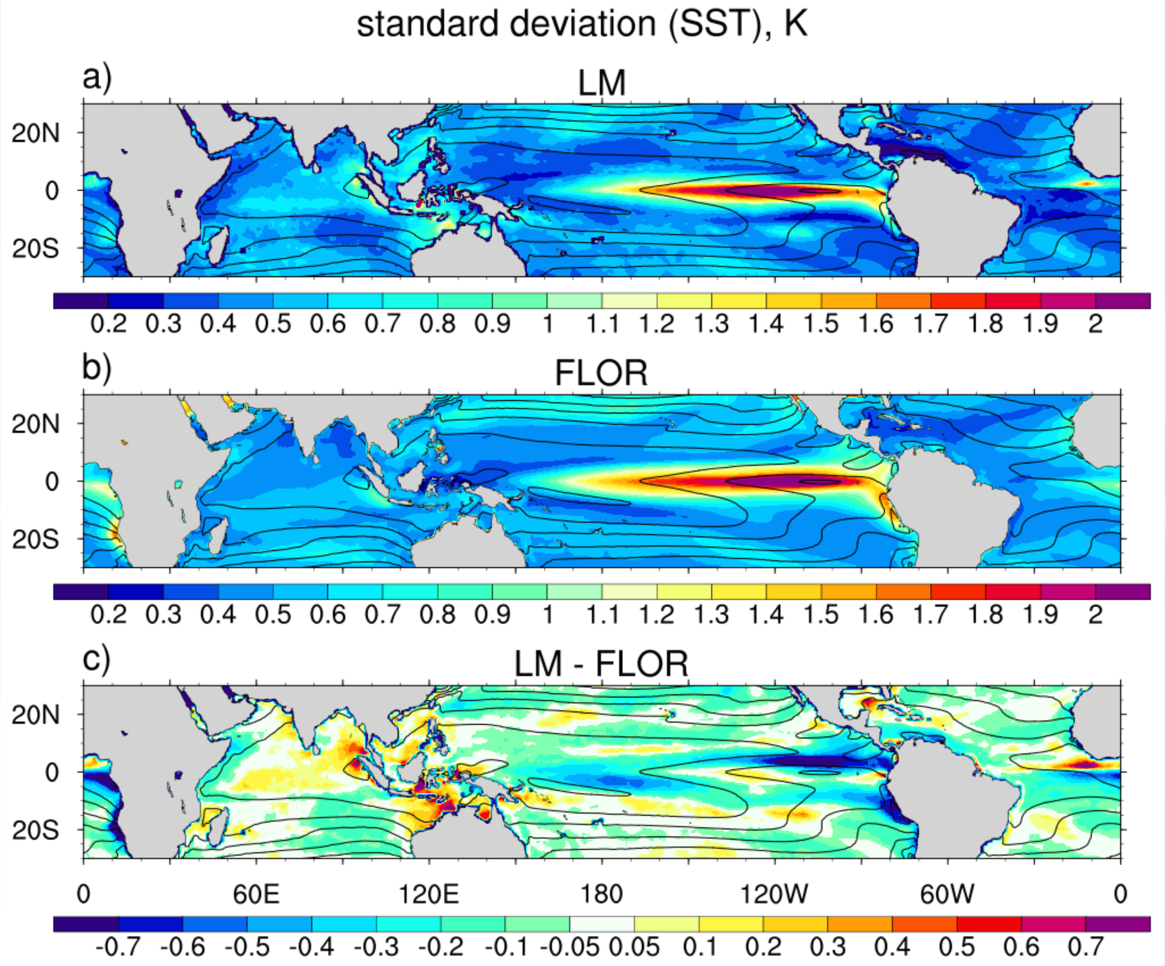
$$P = \frac{\partial P}{\partial SST} \cdot SST + F_P$$

$$E = \frac{\partial E}{\partial SST} \cdot SST + F_E$$

$$SH = \frac{\partial SH}{\partial SST} \cdot SST + F_{SH}$$

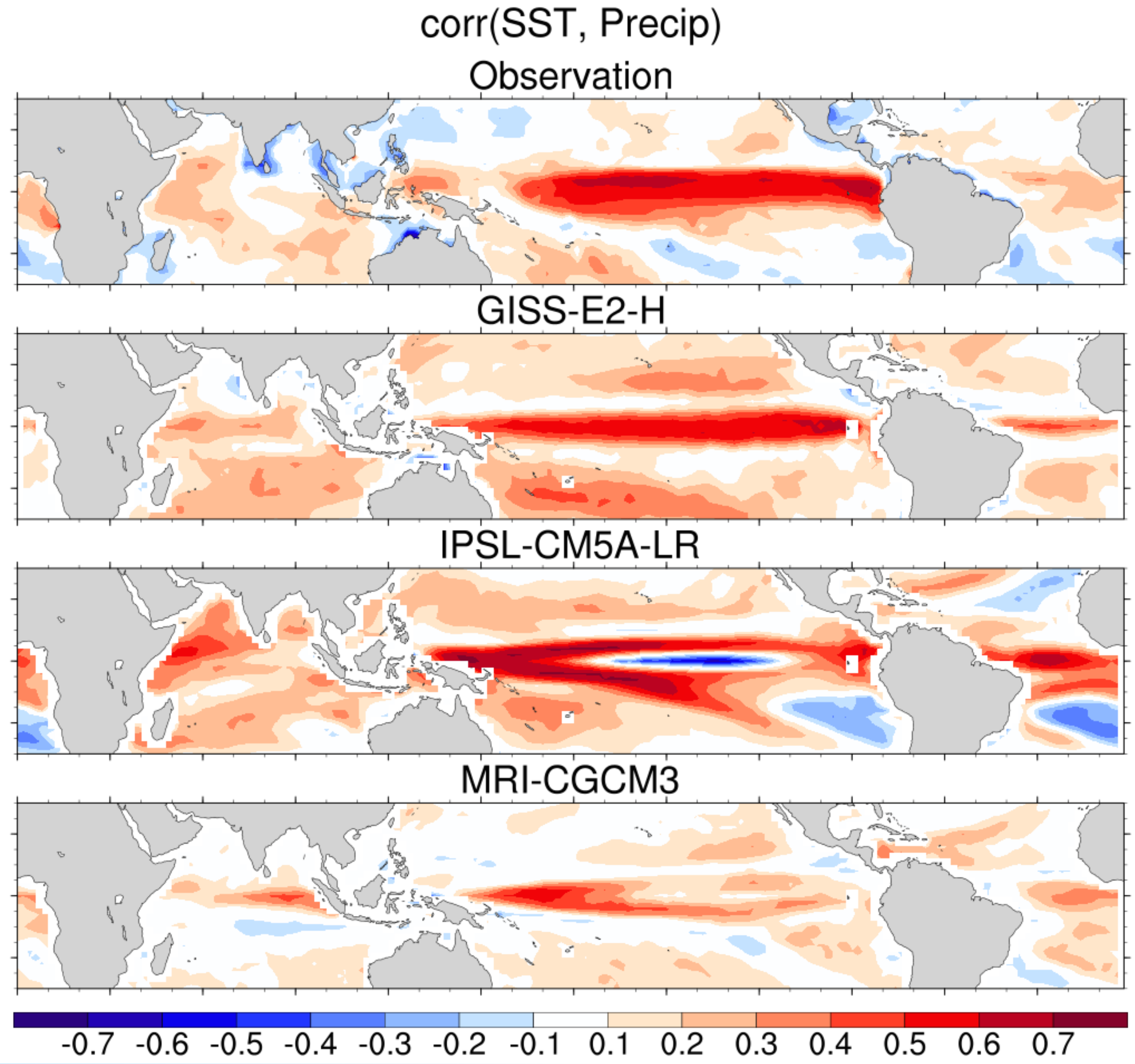
$$LW = \beta \cdot SST - 4 \cdot \alpha \cdot \overline{\overline{SST}}^3 \cdot SST$$

$$SW = C_{SW} \cdot P$$



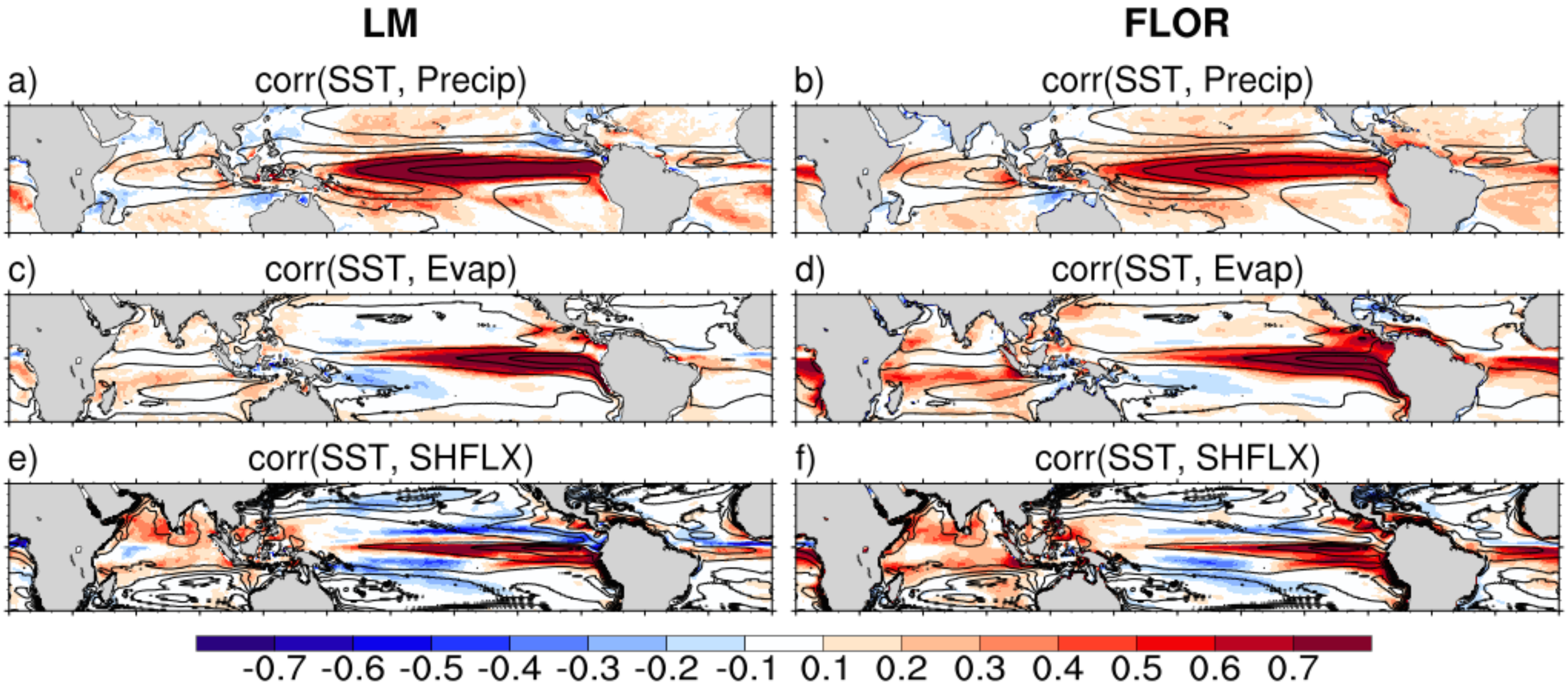
- LM simulates tropical SST variability reasonably well.

Local air-sea relationship



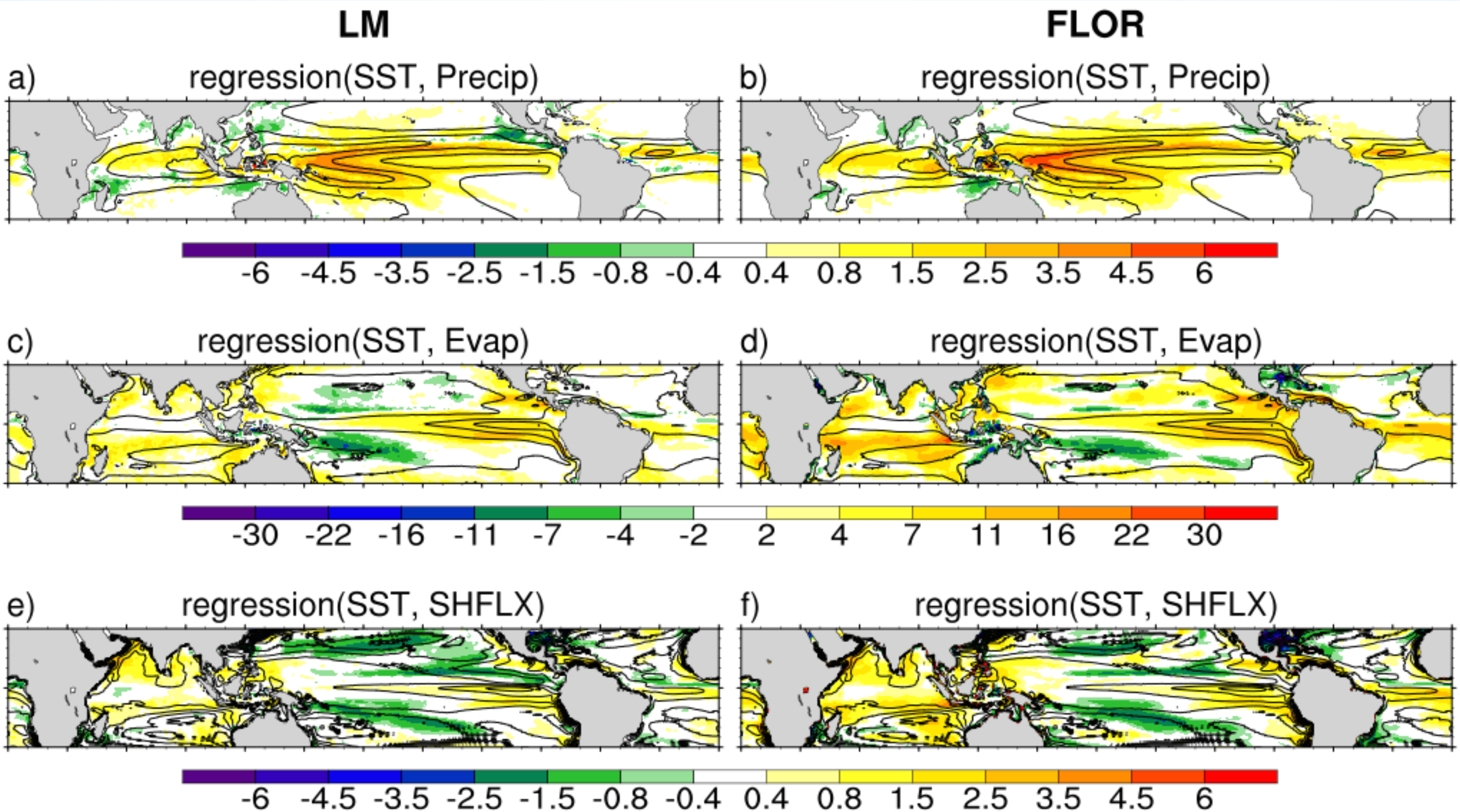
- Large biases in the simulation of air-sea relationship from current CGCMs.

Local air-sea relationship



- LM reasonably represents the local air-sea relationship from the CGCM.

Local air-sea relationship



- LM reasonably represents the local air-sea relationship from the CGCM.

Summary I

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* SST forcing of convection is a monotonically increasing function of the base SST.
* Uncoupled simulations can be ideal tools for quantifying SST forcing.

Summary II

* Evaporation and SH sensitivity to SST variability should also be estimated from uncoupled systems.
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* The spatial structure of SST anomalies is important for Evaporation and SH sensitivity.

Thank you