Two moist static energy budgets to understand intraseasonal atmospheric variability

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with contributions from

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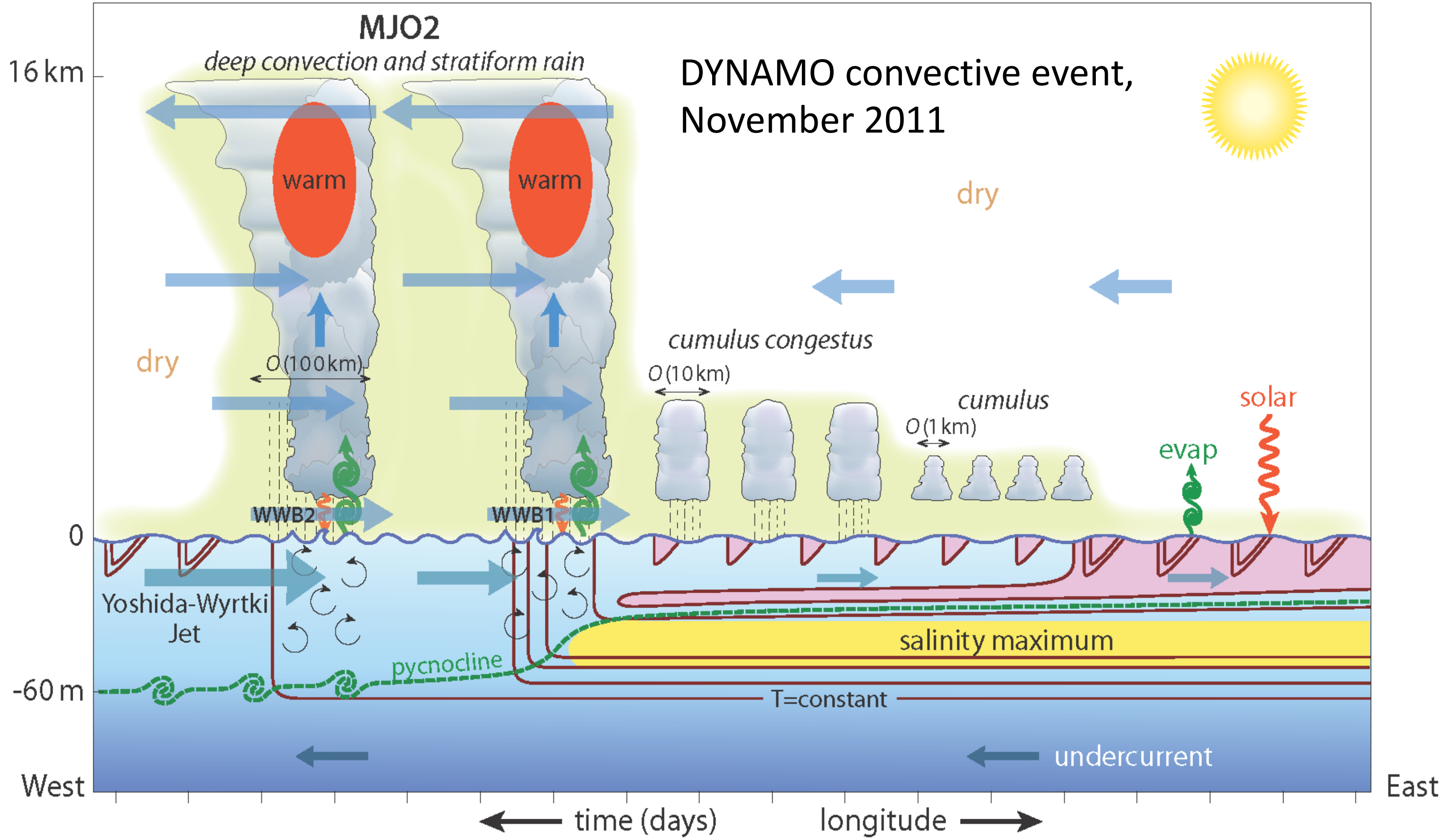
Office of Naval Research

image from NASA GSFC

Energy scales of air-sea interaction



Moum et al. 2014

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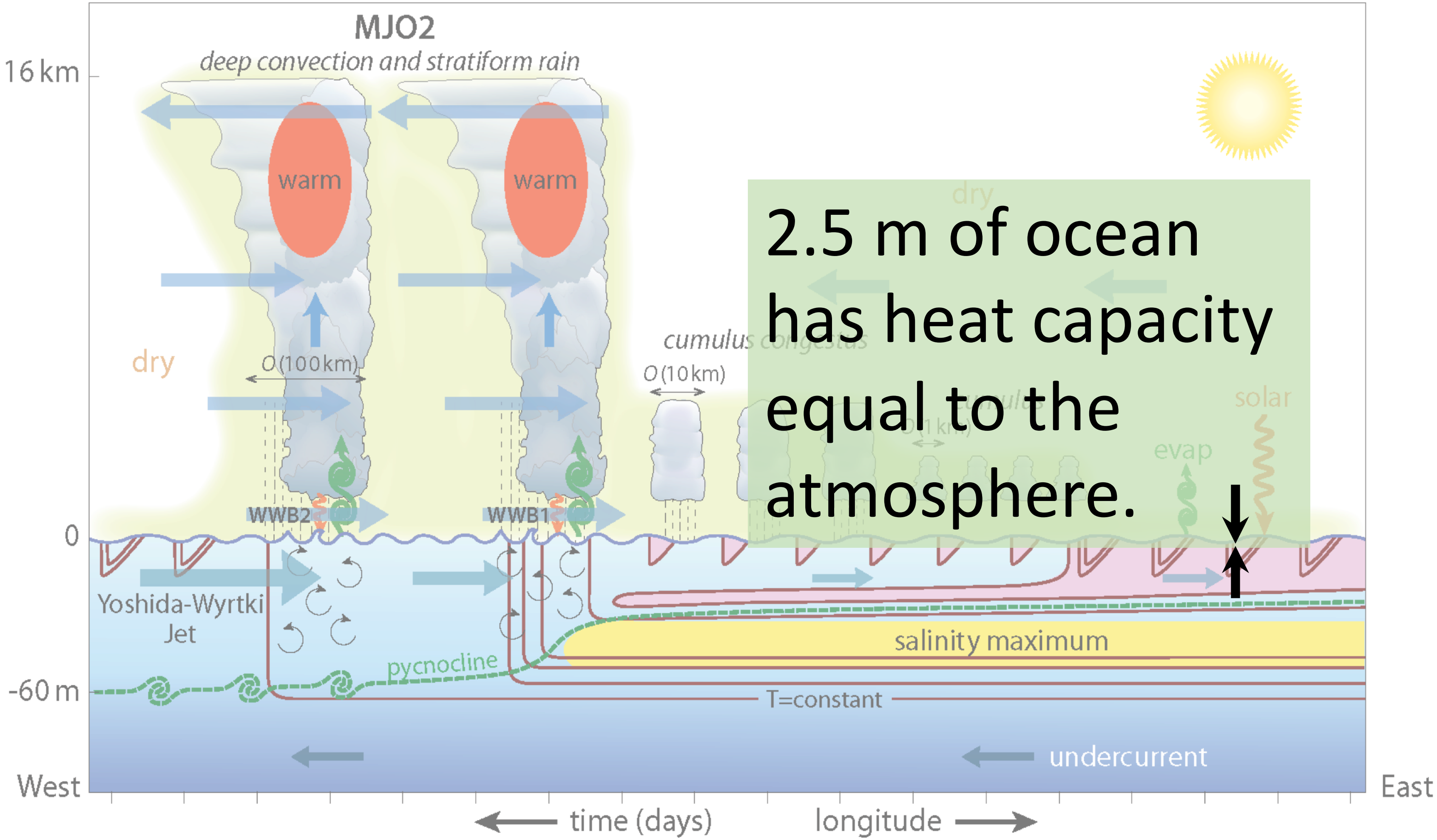
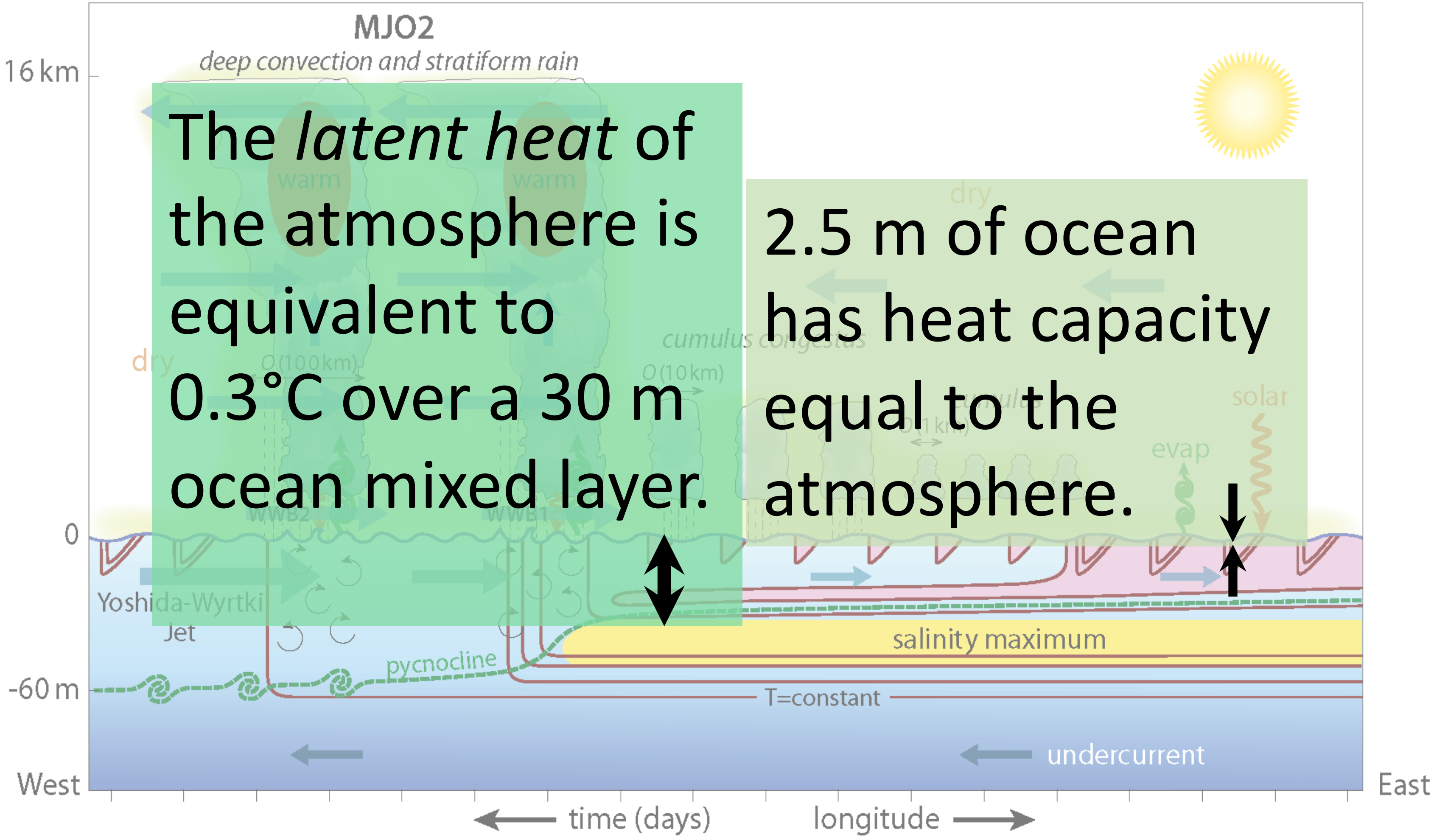


2.5 m of ocean has heat capacity equal to the atmosphere.

Moum et al. 2014

Energy scales of air-sea interaction



The *latent heat* of the atmosphere is equivalent to 0.3°C over a 30 m ocean mixed layer.

2.5 m of ocean has heat capacity equal to the atmosphere.

Moum et al. 2014

A tale of two moist static energy (MSE) budgets

1. Subcloud mixed layer moist static energy (MSE) budget

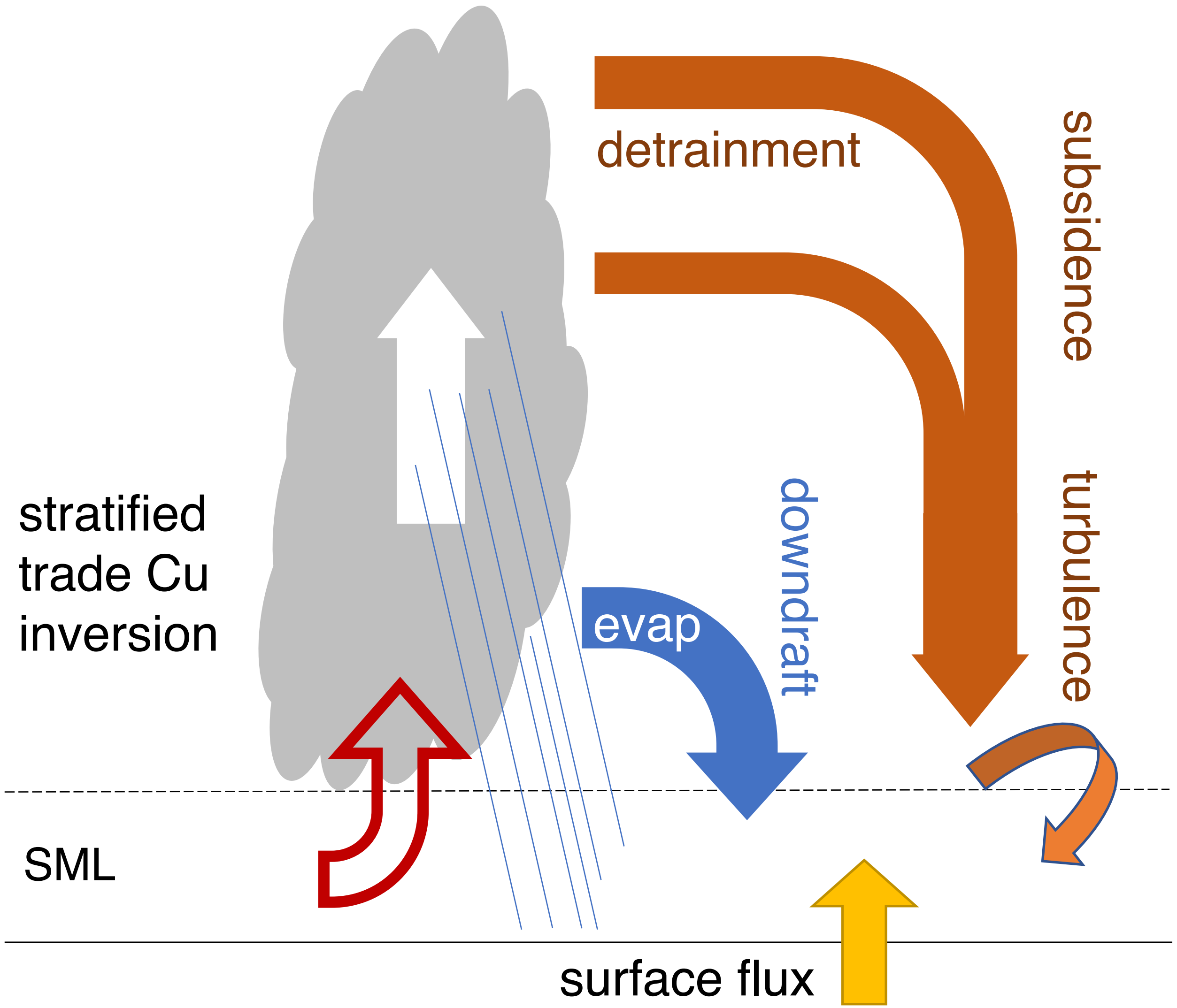
2. Tropospheric MSE budget

A tale of two moist static energy (MSE) budgets

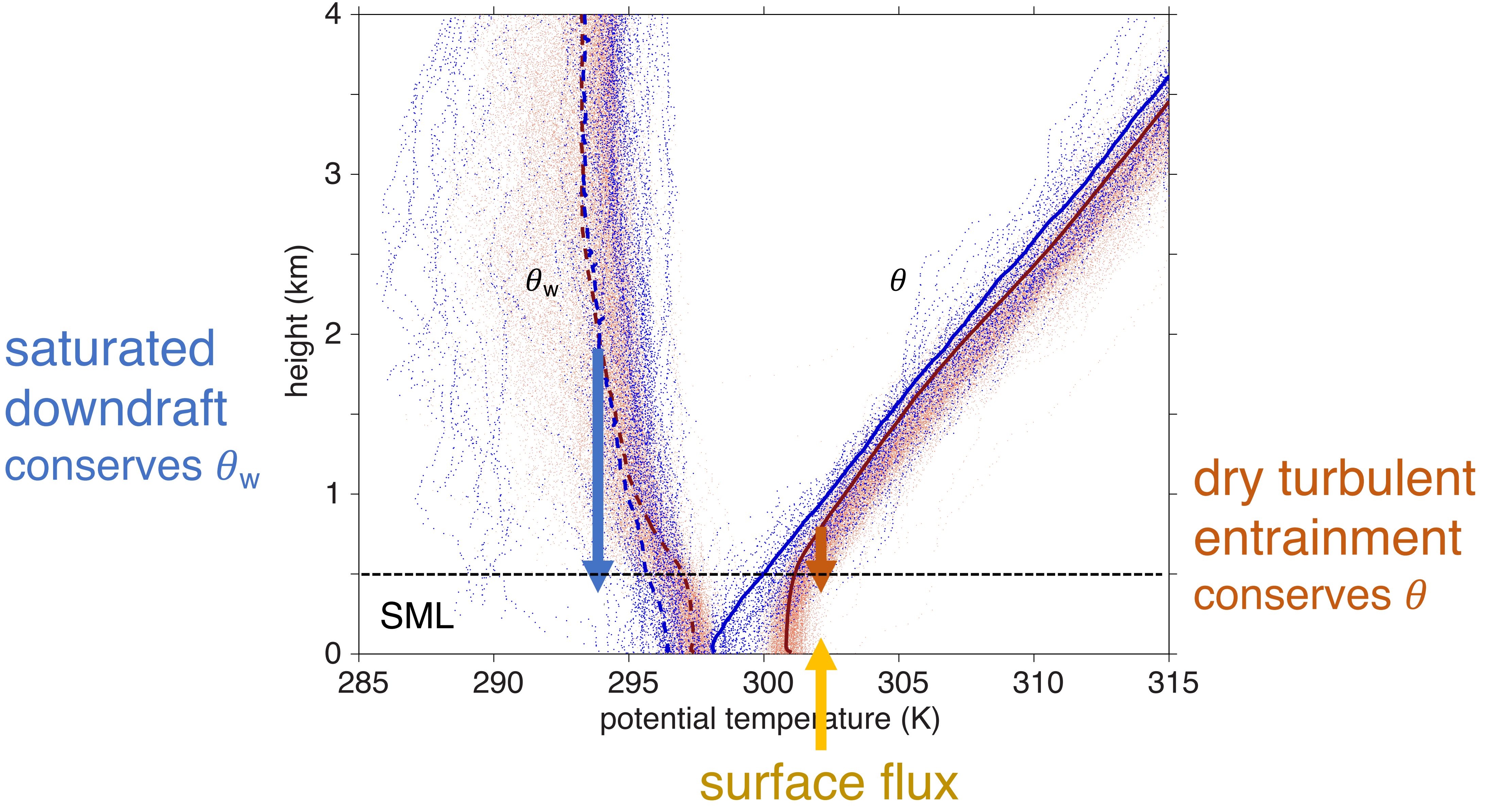
1. Subcloud mixed layer moist static energy (MSE) budget
   - Mixing line analysis gives information on the subcloud thermodynamic equilibrium. (de Szoeke 2018)
2. Tropospheric MSE budget

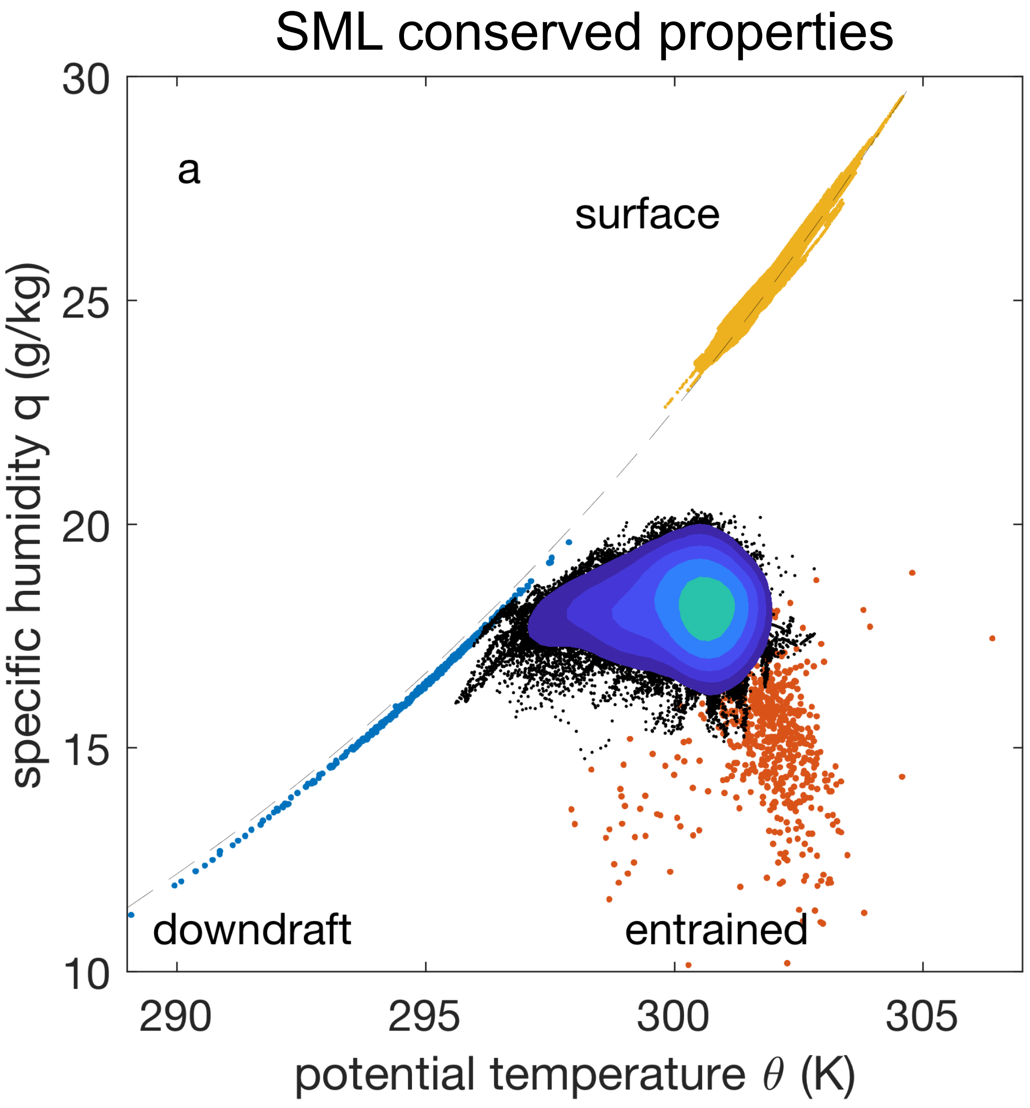
1. The subcloud mixed layer (SML) is the MSE source for moist convection.

- Evaporative *downdrafts* inject cold air into the SML.
- *Turbulence* entrains warm dry air.
- How do *turbulence* and *convective clouds* affect these fluxes?
- What is the flux of MSE into the trade cumulus cloud base?

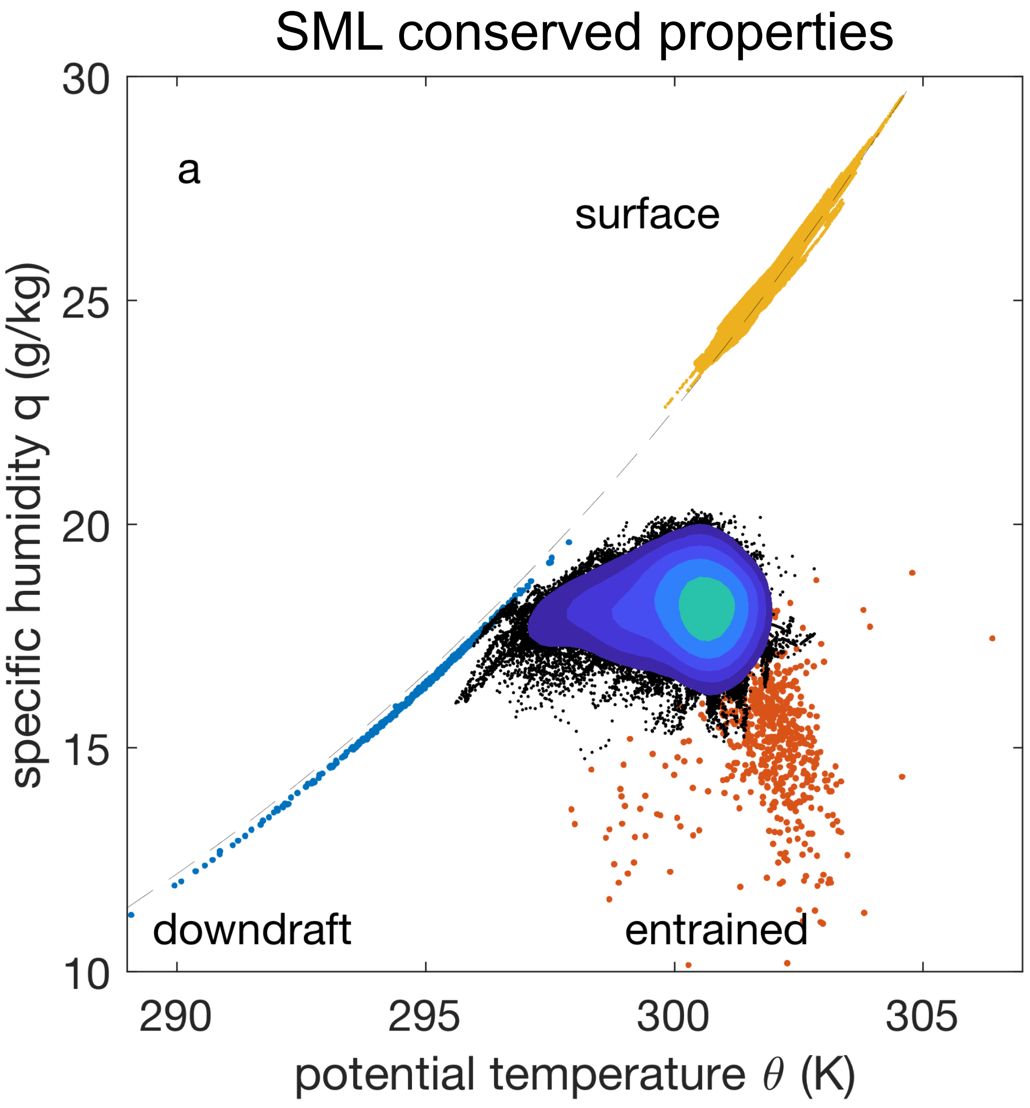


Budgets of θ, q distinguish convective downdrafts from entrained air.





SML conserved properties
a
surface
downdraft
entrained
specific humidity q (g/kg)
potential temperature θ (K)
10
15
20
25
30
290
295
300
305



Express each boundary layer observation as a mixture of downdraft, entrained, and surface air.

Mixing of conserved variables $\boldsymbol{\theta}$ and q

$$\begin{pmatrix} \theta_d & \theta_{en} & \theta_s \\ q_d & q_{en} & q_s \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} f_d \\ f_{en} \\ f_s \end{pmatrix} = \begin{pmatrix} \theta_{ML} \\ q_{ML} \\ 1 \end{pmatrix}$$

$$\begin{pmatrix} \theta_d - \theta_{en} & \theta_s - \theta_{en} \\ q_d - q_{en} & q_s - q_{en} \end{pmatrix} \begin{pmatrix} f_d \\ f_s \end{pmatrix} = \begin{pmatrix} \theta_{ML} - \theta_{en} \\ q_{ML} - q_{en} \end{pmatrix}$$

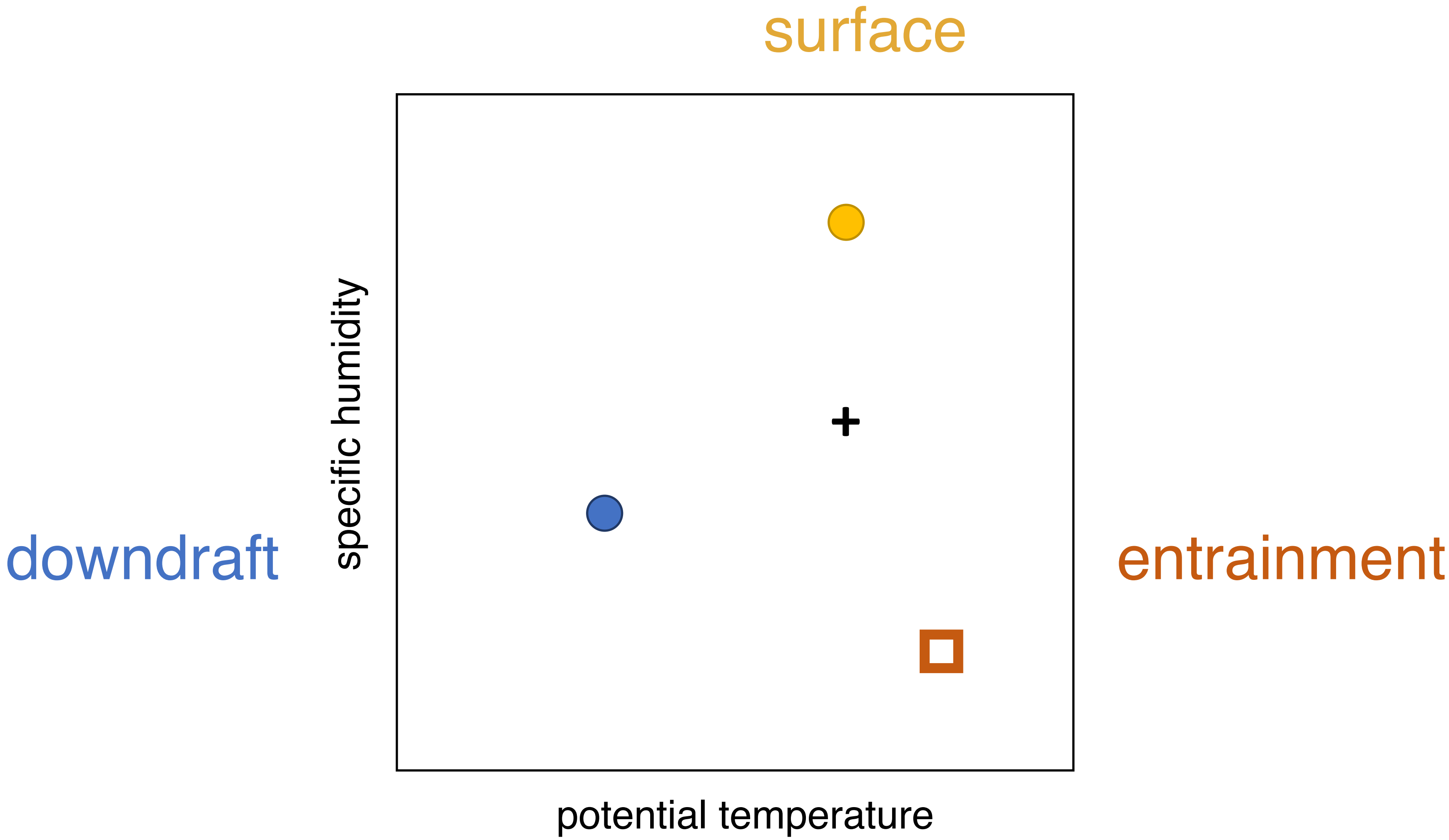
source $\mathbf{S}$ fraction $\boldsymbol{f}$ mixture $\boldsymbol{m}$

$$\boldsymbol{S f} = \boldsymbol{m}.$$

Solve for fractions by inverting source matrix:

$$\boldsymbol{f} = \mathbf{S}^{-1}\boldsymbol{m}$$

From conserved variables to mixing fraction



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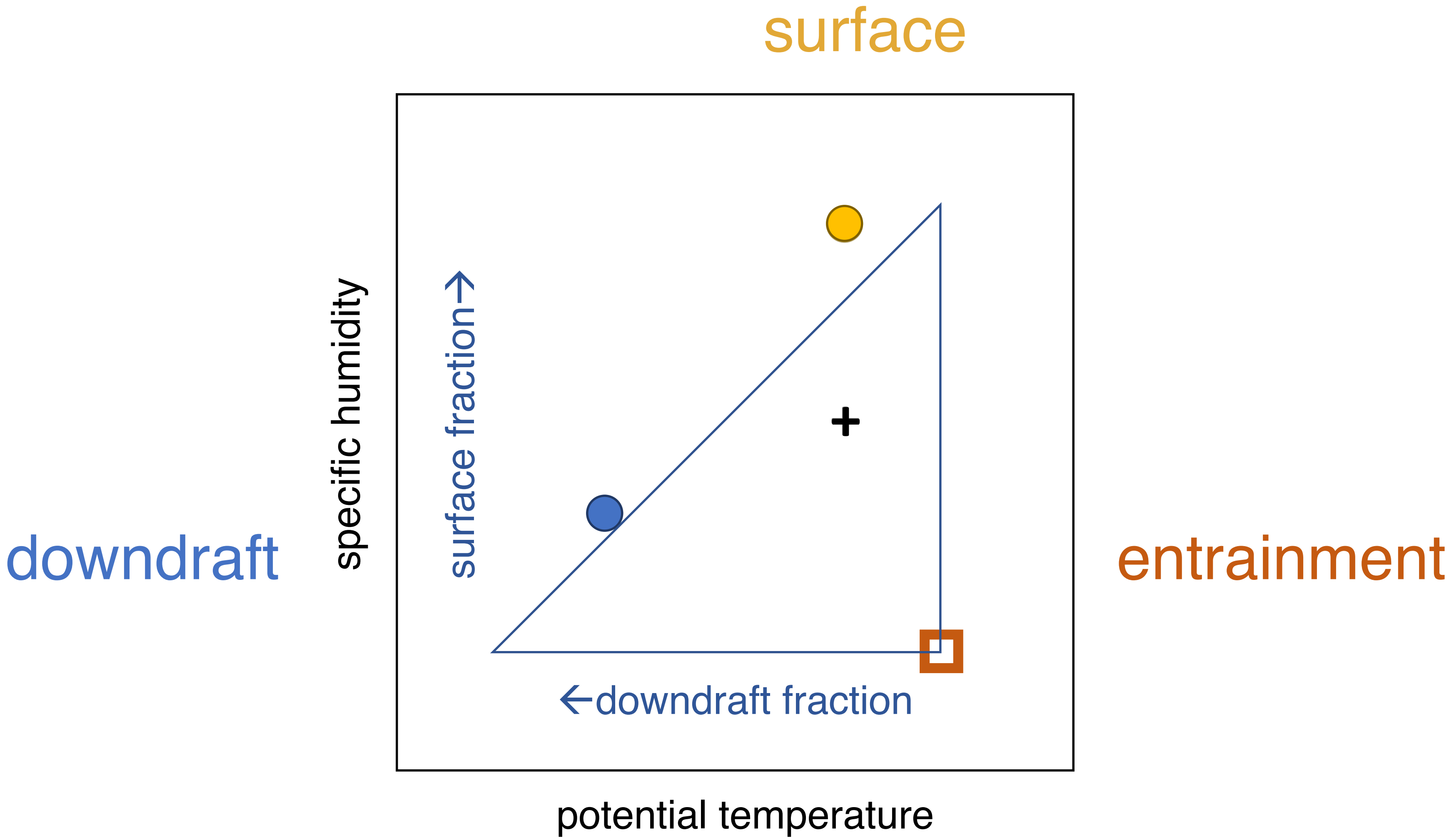

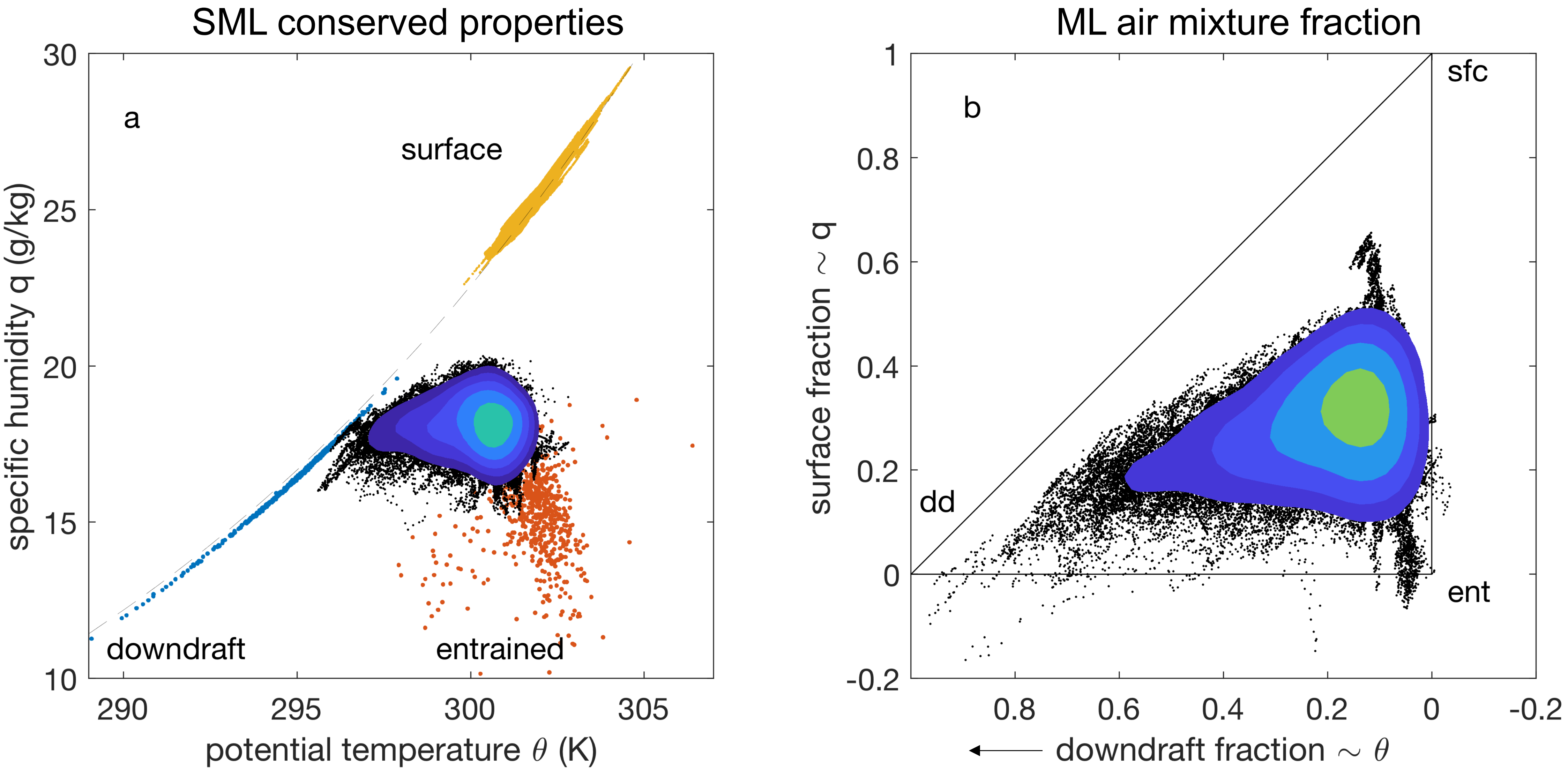
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specific humidity q (g/kg)
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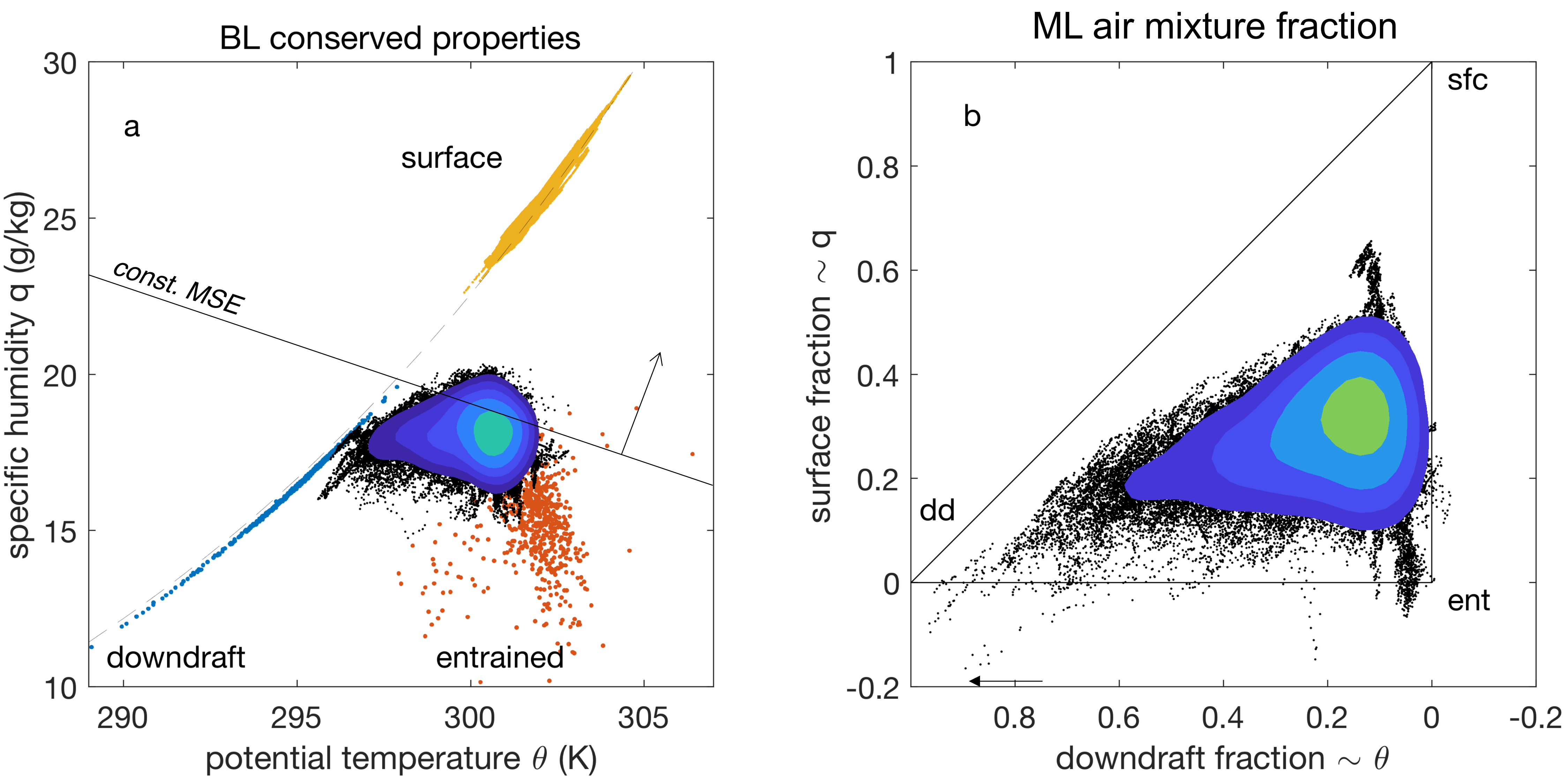
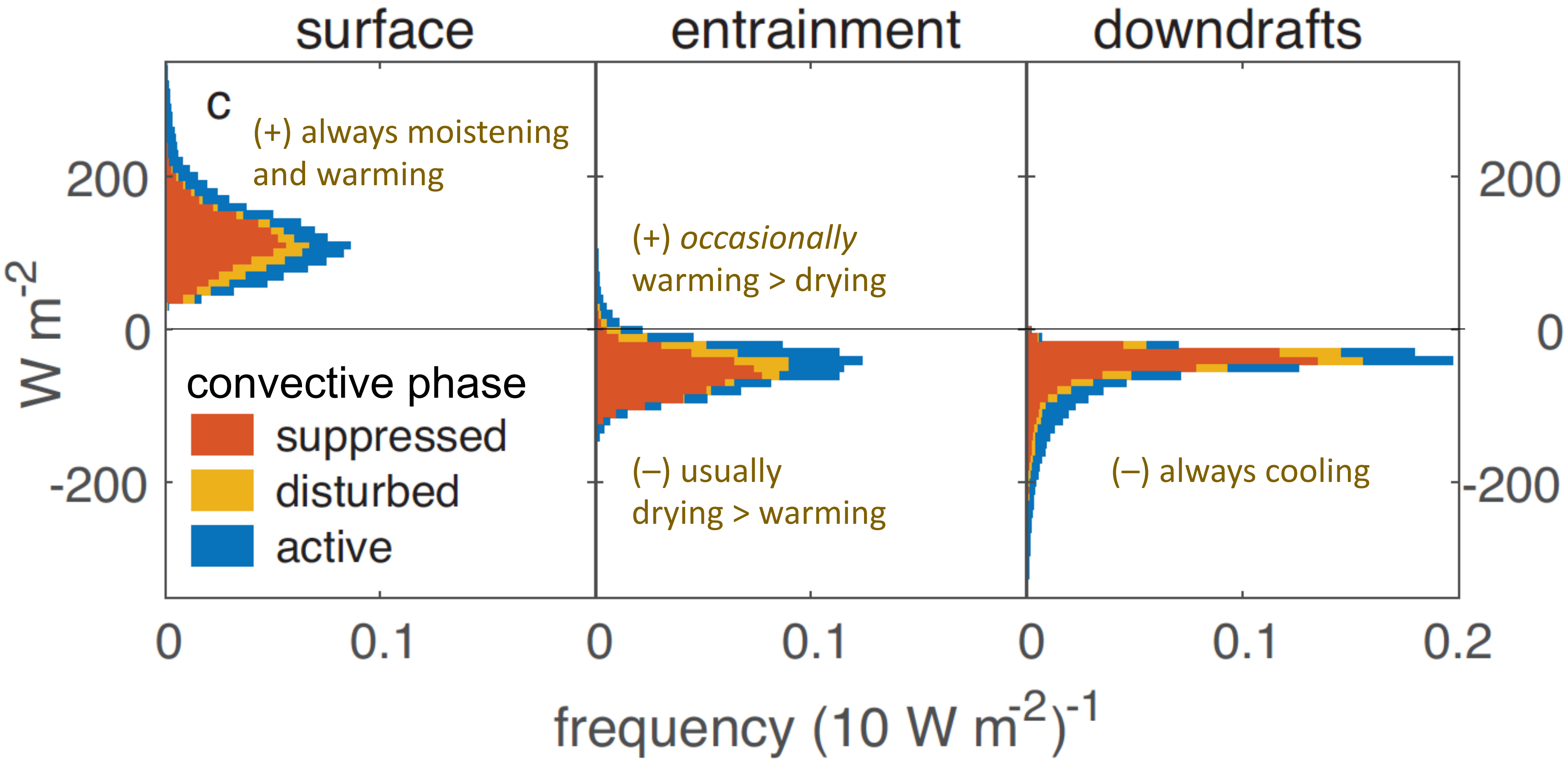
10
15
20
25
30
290
295
300
305
ML air mixture fraction
b
sfc
dd
ent
surface fraction ~ q
downdraft fraction ~ θ
-0.2
0
0.2
0.4
0.6
0.8
1
0.8
0.6
0.4
0.2
0
-0.2

θ, q fluxes uniquely determine MSE fluxes.



→ Boundary layer MSE fluxes



A tale of two moist static energy (MSE) budgets

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   - Downdrafts and entrainment balance surface flux warming.

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2. Tropospheric MSE budget

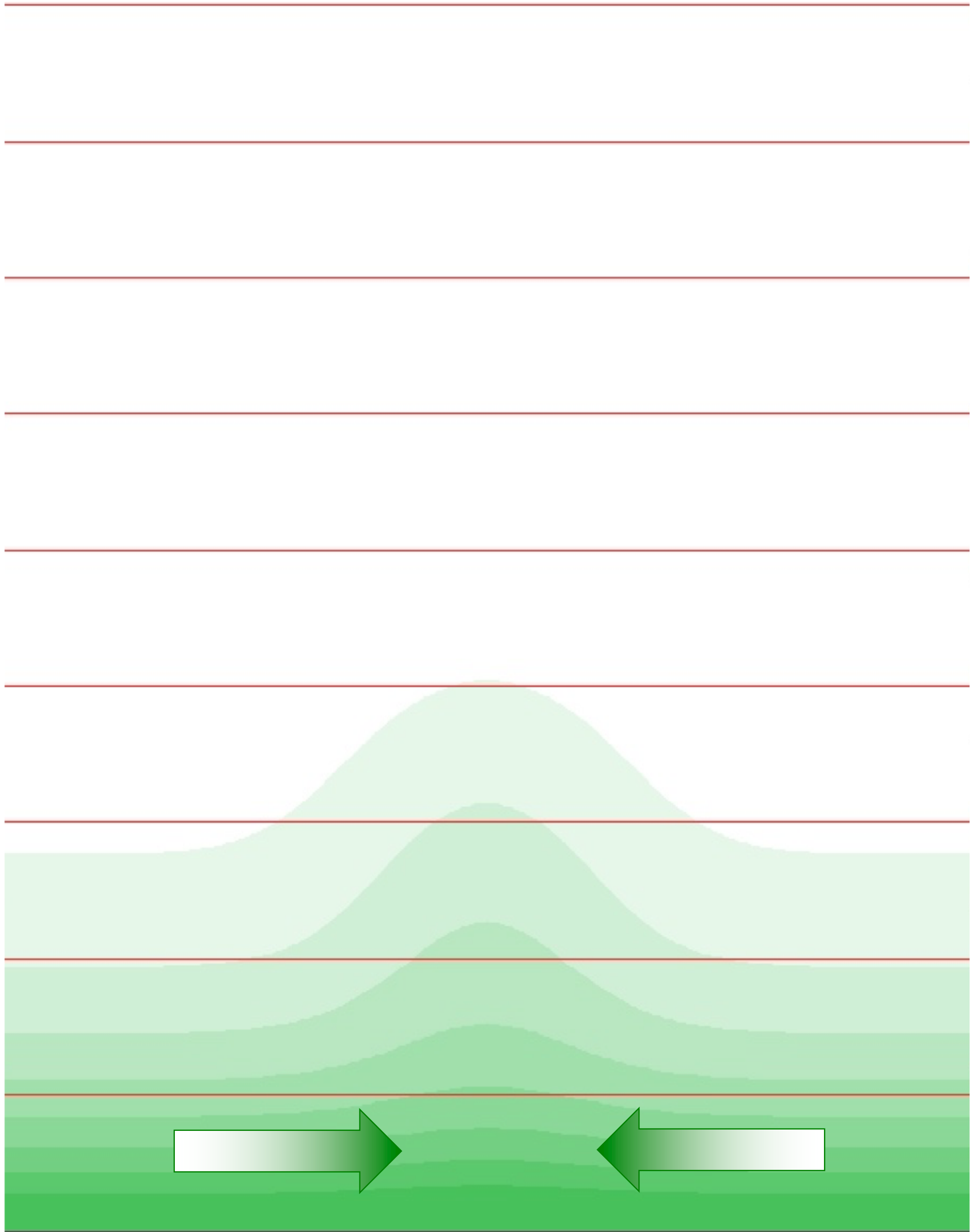
Mechanisms by which ocean heat content and SST affect synoptic and intraseasonal convection:

a) Surface MSE flux

b) Balanced moisture convergence over warm SST

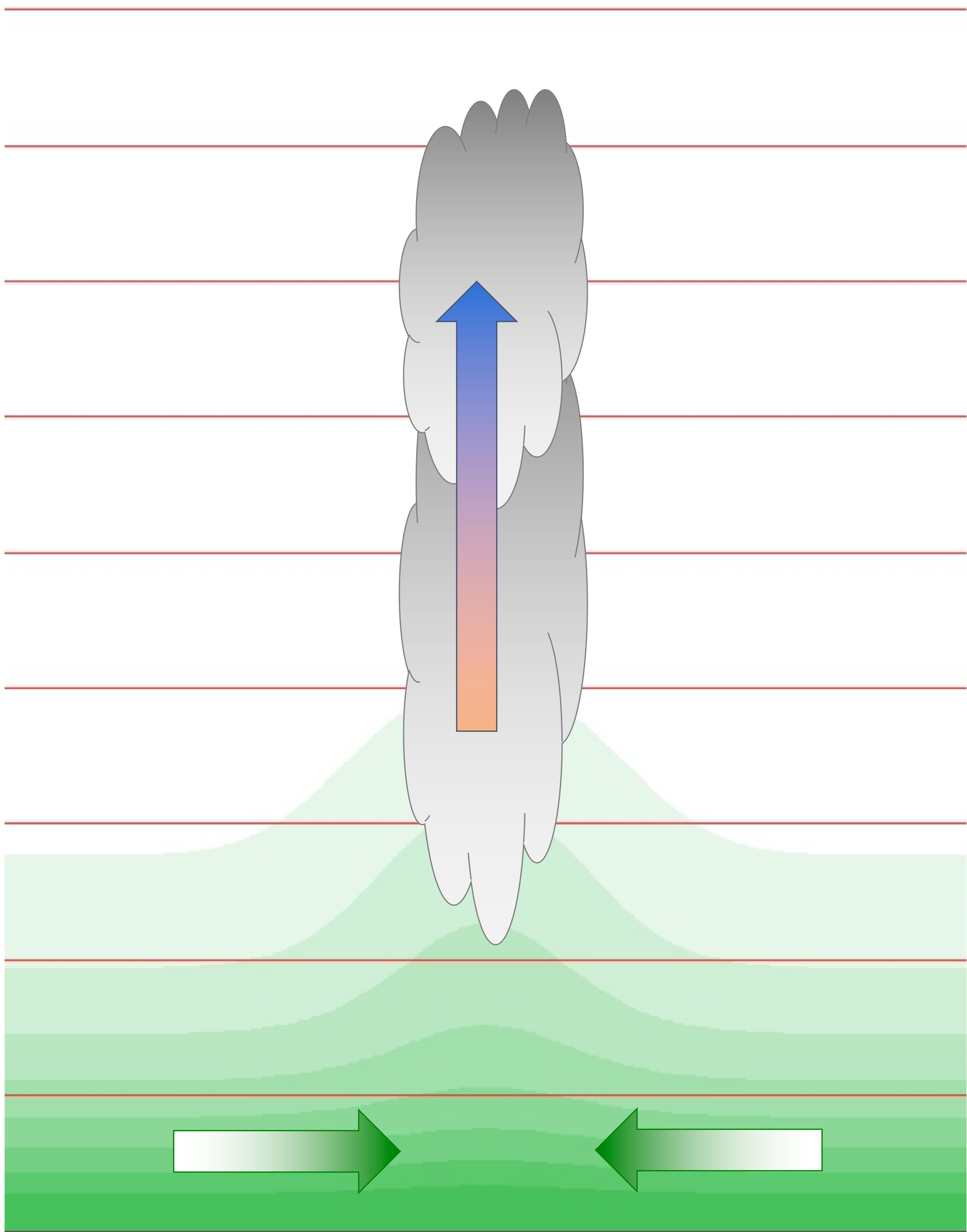
Quasi-equilibrium, moist static energy, and moisture modes

- *T* profile near radiative-convective equilibrium.



Quasi-equilibrium, moist static energy, and moisture modes

- *T* profile near radiative-convective equilibrium.
- Latent heating from precipitation balanced by adiabatic rising.
  (Riehl and Malkus 1958)



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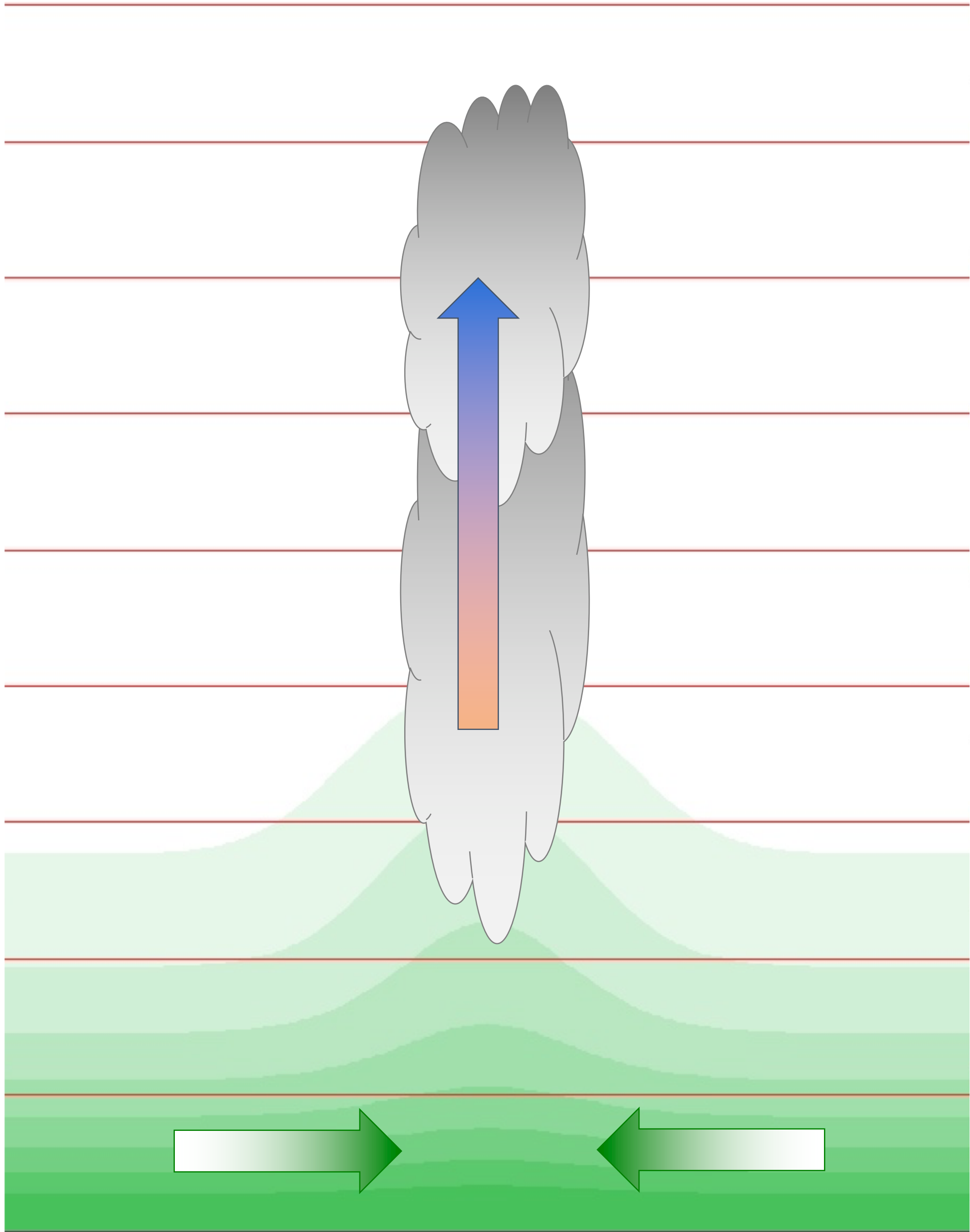
- Column moist static energy (MSE)

$$h = c_p T + gz + Lq$$

links heat sources to circulation.



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- Column moist static energy (MSE)

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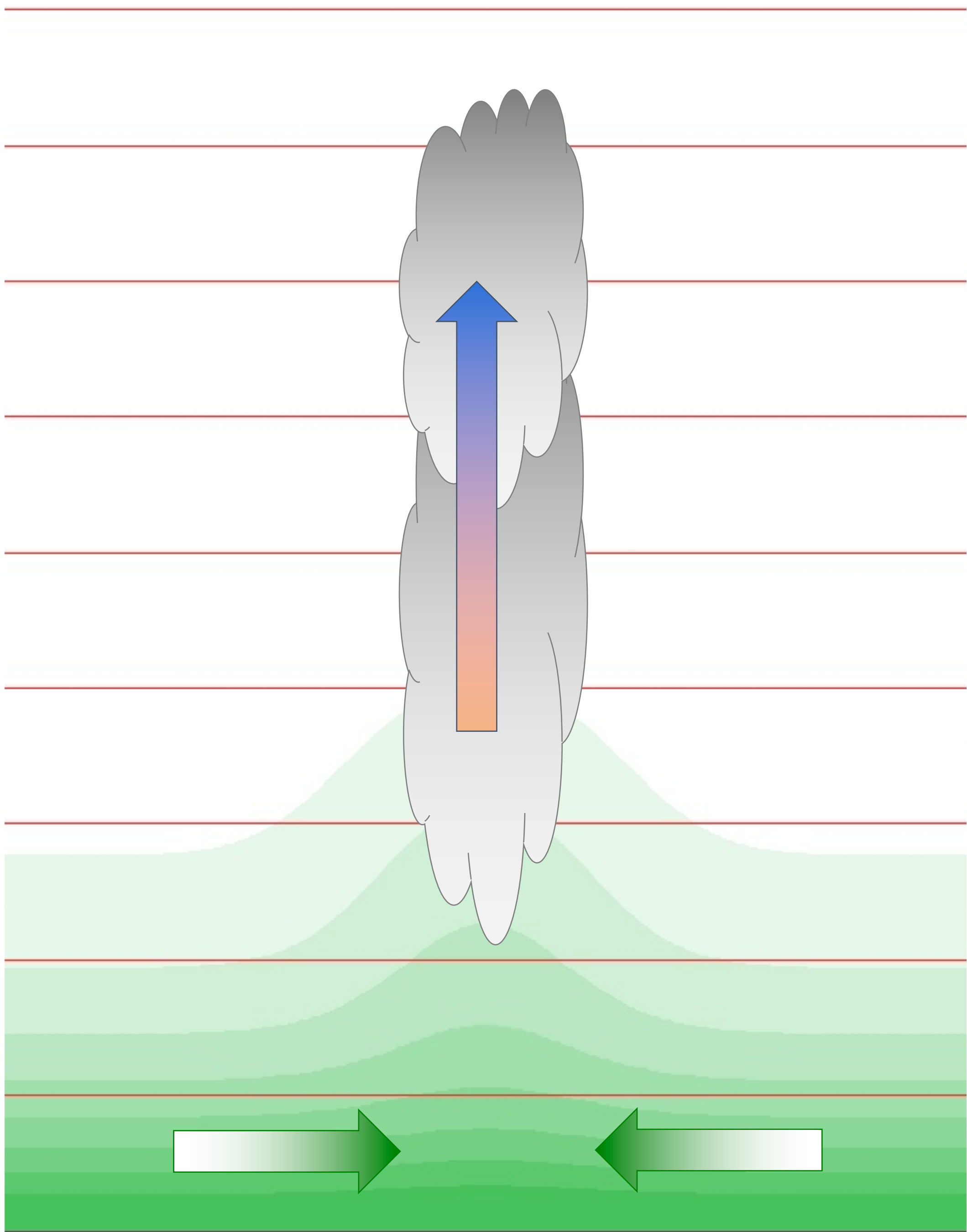
links heat sources to circulation.

- Temperature gradients are weak in the tropics so MSE variations result from variations in moisture q.
- Convergence of *moisture* central to tropical circulation.



Tropospheric humidity budget

3-D advection of humidity

$$\mathbf{u} \cdot \nabla q = \boldsymbol{u} \cdot \nabla_{\mathrm{h}} q + \frac{\partial(\omega q)}{\partial p} - q\frac{\partial \omega}{\partial p}$$

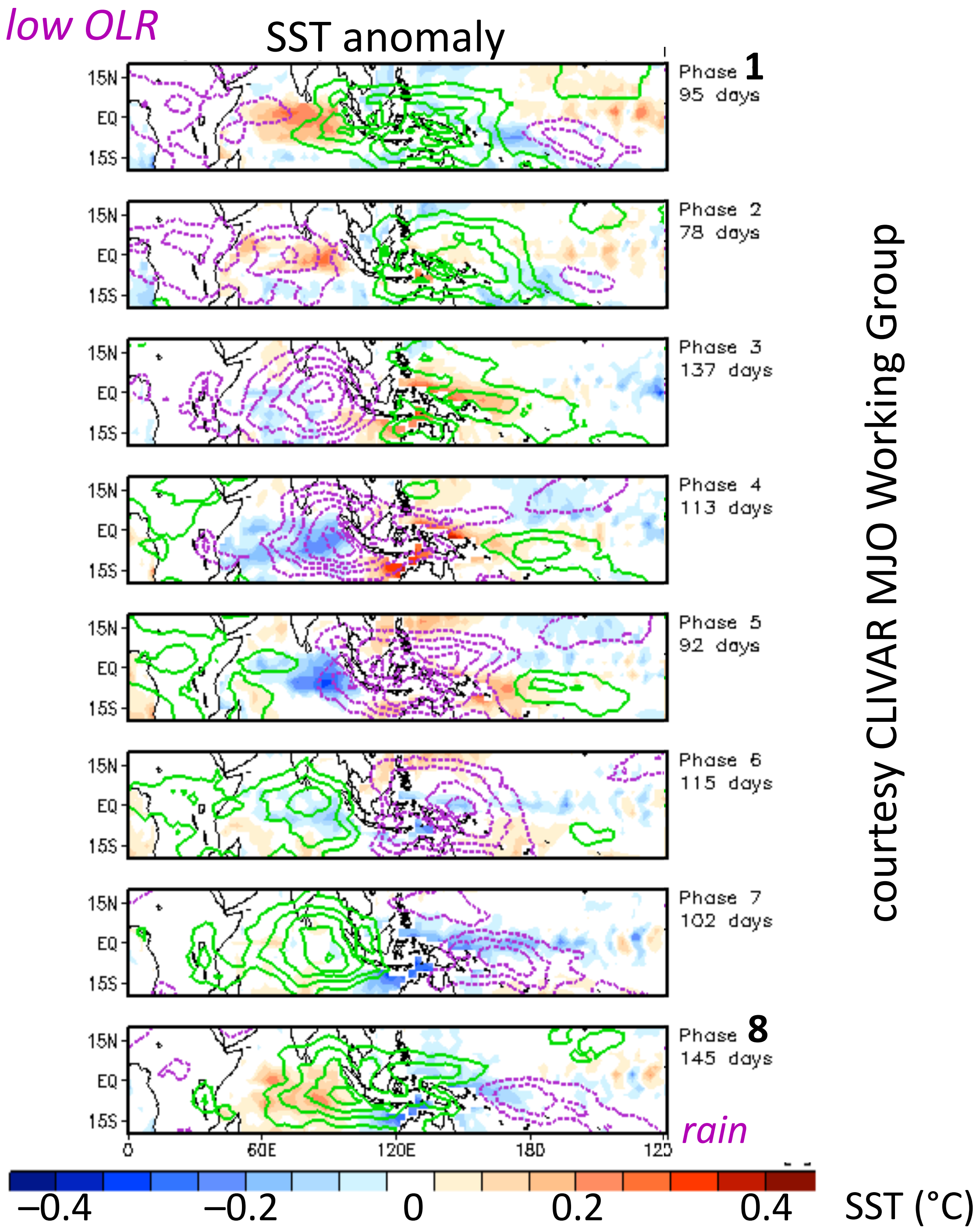
$$\frac{\partial \omega}{\partial p} + \nabla_{\mathrm{h}} \cdot \boldsymbol{u} = 0$$

$$\mathbf{u} \cdot \nabla q = \boldsymbol{u} \cdot \nabla_{\mathrm{h}} q + \frac{\partial(\omega q)}{\partial p} + q(\nabla_{\mathrm{h}} \cdot \boldsymbol{u})$$

integrating from p_{sfc} to $p = 0$,

$$\int_0^{p_{\mathrm{sfc}}} \mathbf{u} \cdot \nabla q = \int_0^{p_{\mathrm{sfc}}} [\boldsymbol{u} \cdot \nabla_{\mathrm{h}} q + q(\nabla_{\mathrm{h}} \cdot \boldsymbol{u})]\, dp$$

small dominant



courtesy CLIVAR MJO Working Group

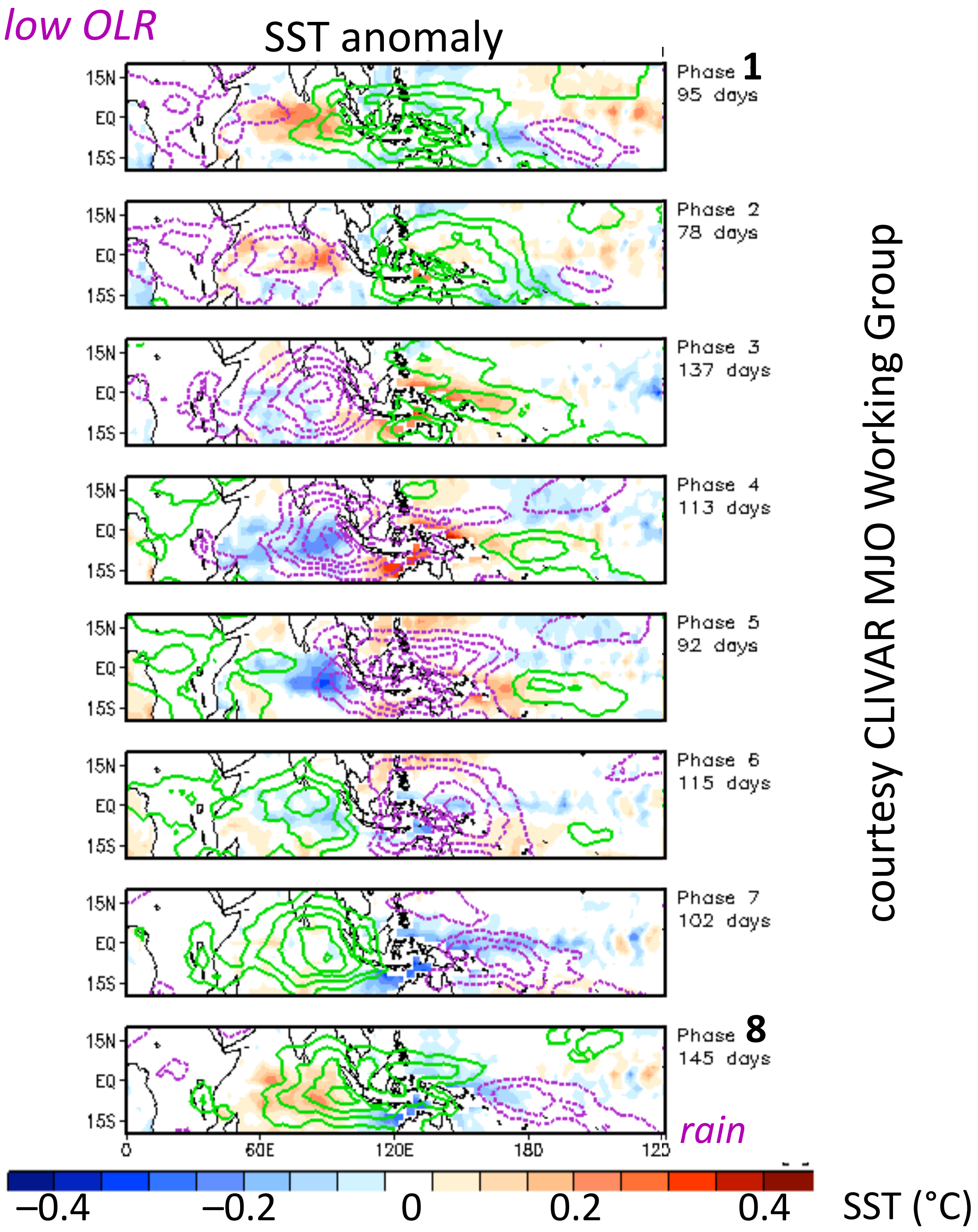
Question

Does **±0.2 °C SST anomaly** associated with the MJO also affect it by…

a) enhancing air-sea fluxes?

or

b) inducing hydrostatic pressure that drives frictional moisture convergence?



Question

Does the MJO SST anomaly

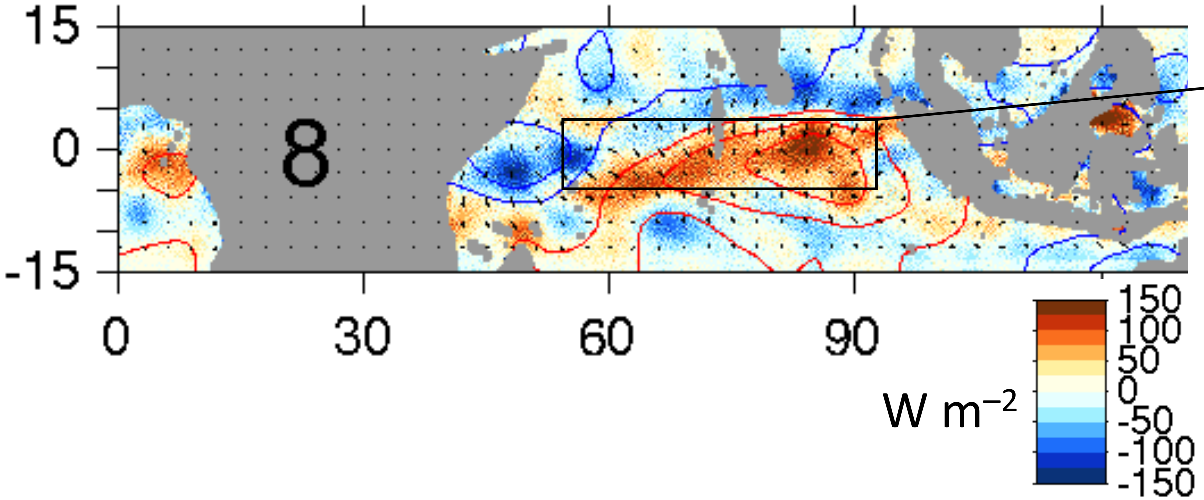
a) enhance air-sea fluxes?

b) induce hydrostatic moisture convergence?

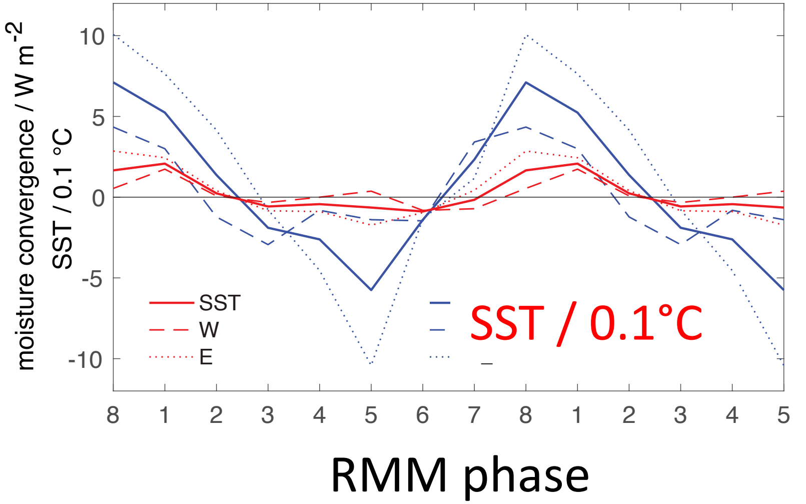
Answer

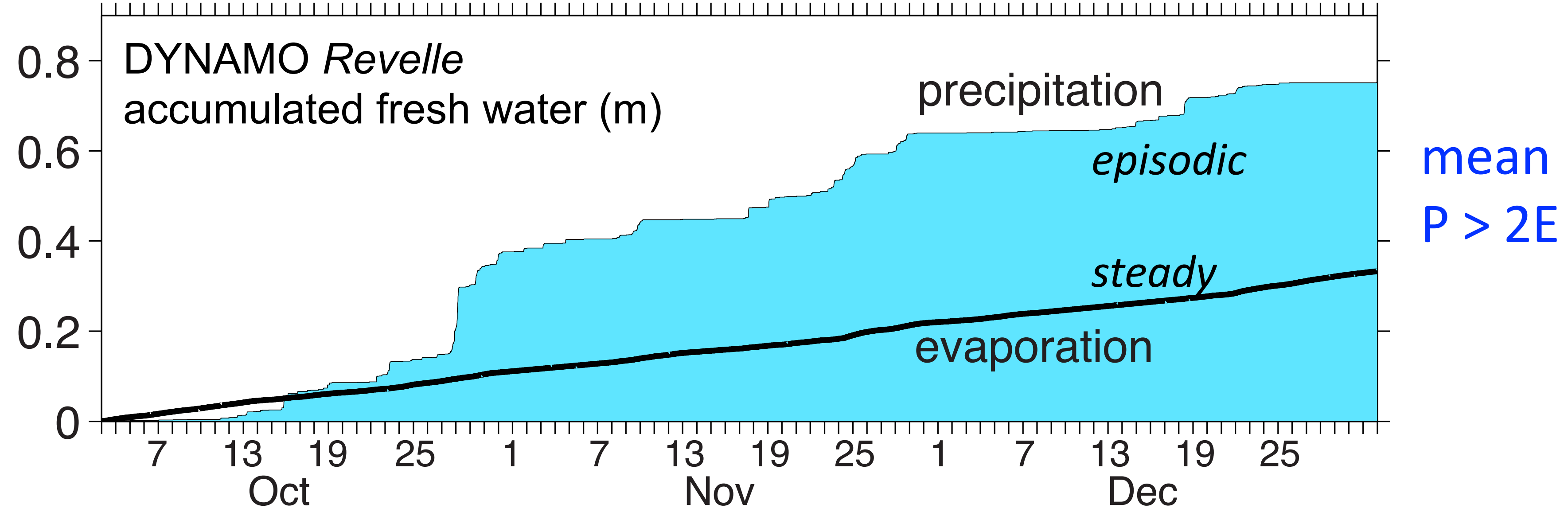
A little. SST’ brings small evaporation anomaly closer to convection. (DeMott et al. 2016)

Yes. ±8 W m^{-2} averaged over the equatorial Indian Ocean.



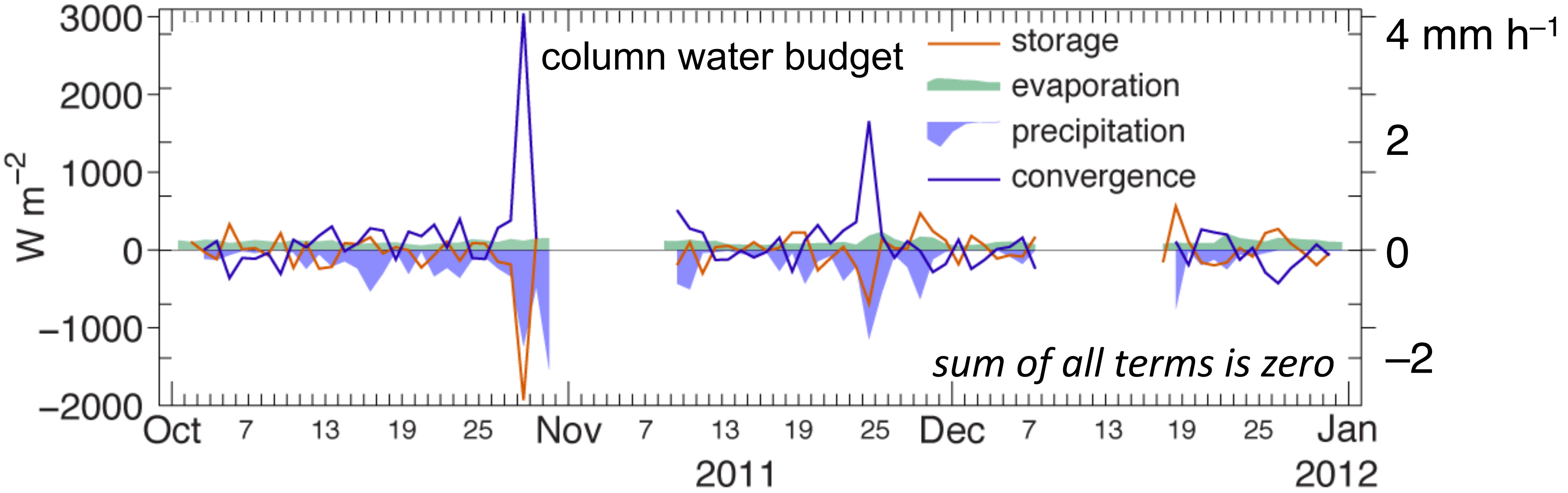
moisture convergence / W m^{-2}





Local evaporation does not explain precipitation mean or anomalies.

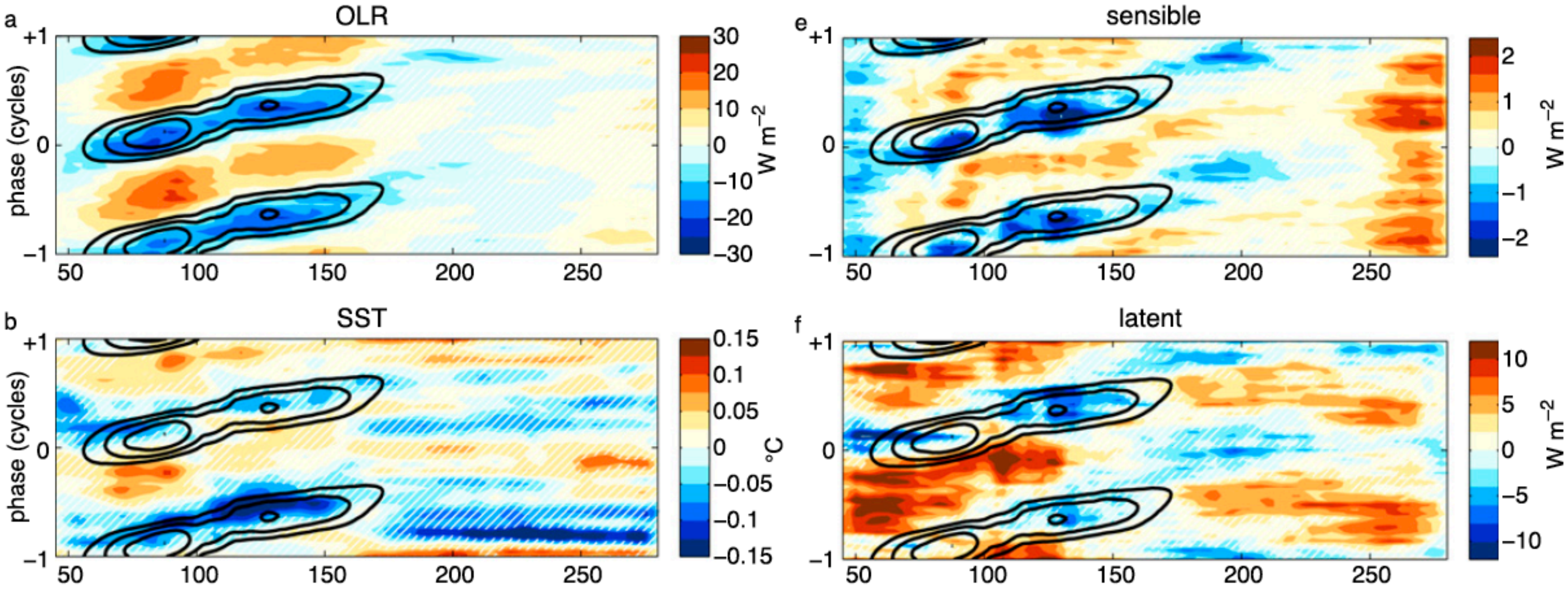
→ precipitation requires nonlocal moisture convergence



outgoing longwave radiation

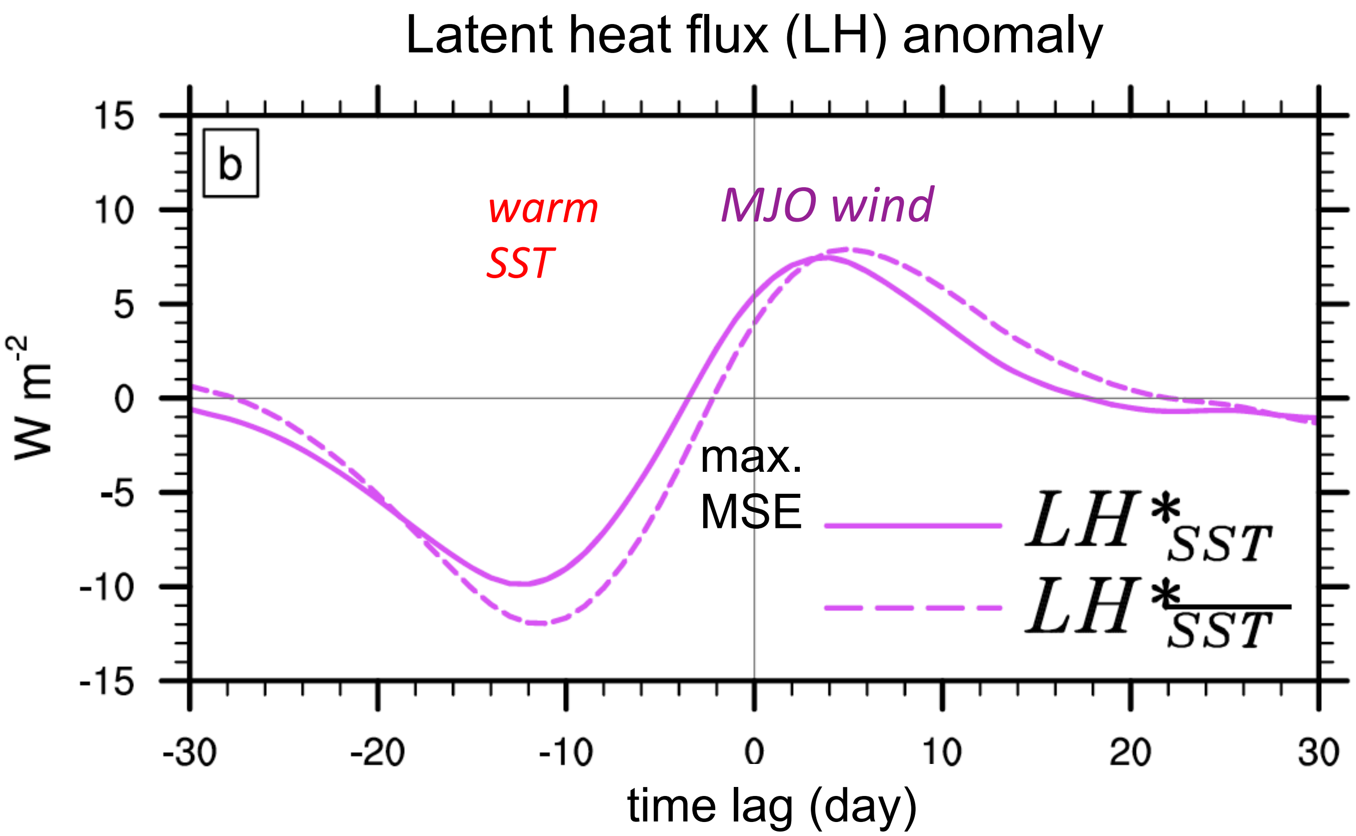
SST

surface fluxes

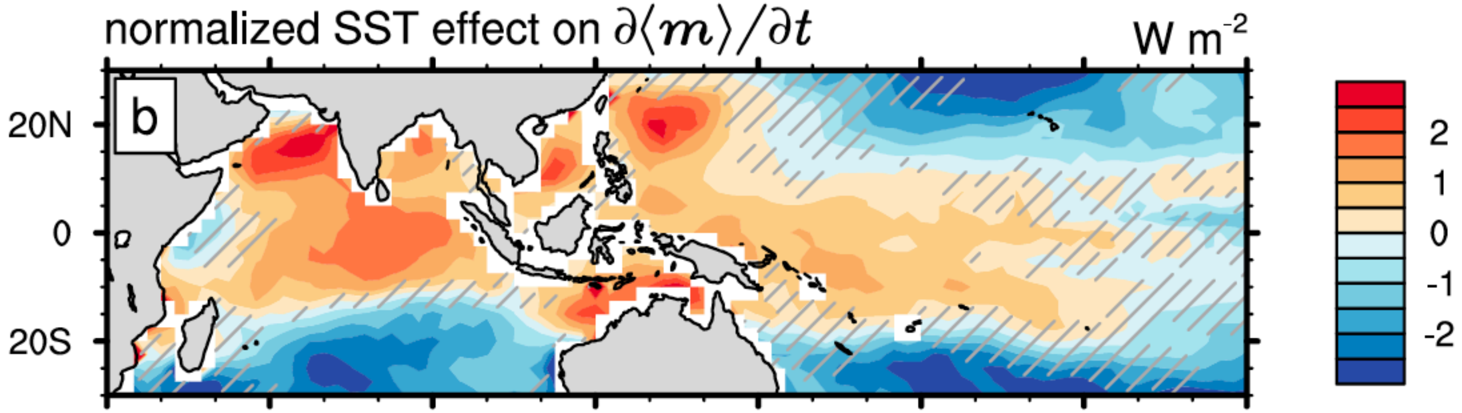


de Szoeke et al. 2015

Warm before convection,
SST quickly cools
under strong fluxes



- LH is earlier and less weak before MJO because of warmer SST.
- LH decays faster because of SST cooling.



- SST increases MSE tendency by 1-2 W m^{-2}

De Mott et al. 2016

a) Effect of MJO SST anomalies on air-sea flux is small.

- Surface flux variability is driven mostly by wind.
- SST is out of phase with sea-air temperature difference and surface fluxes.
- Local evaporation is insufficient for column moisture anomalies or precipitation.
- Mean rain, MJO variability, and storms all require nonlocal moisture convergence.
- However, even small MSE sources may compensate MSE export and destabilize moisture modes.

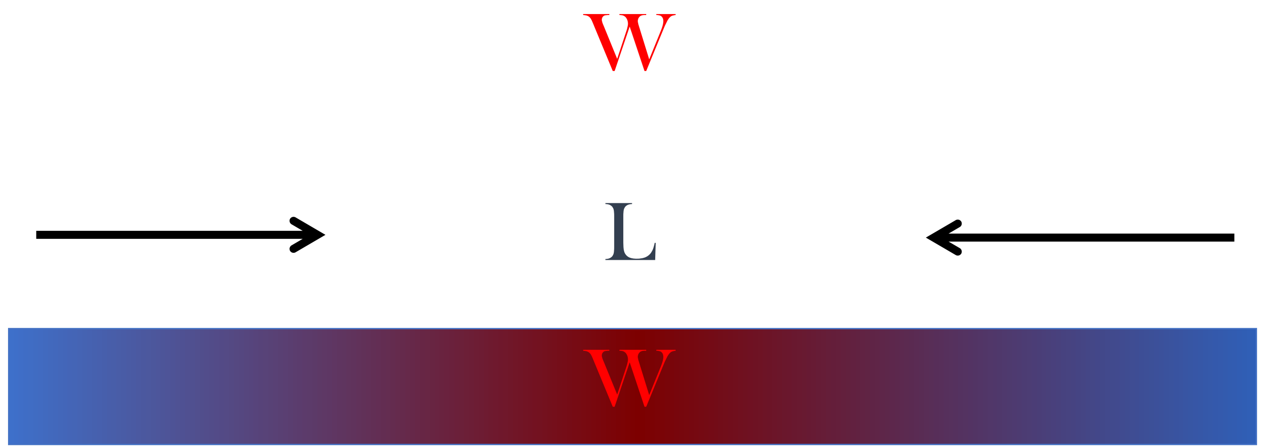
b) Does the SST anomaly induce hydrostatic pressure whose gradient drives frictional moisture convergence?

Flux anomalies are small, but suppose on intraseasonal time scales **boundary layer maintains thermal equilibrium with SST.**

Then low pressure drives mass and moisture convergence over warm SST.
(e.g. Lindzen and Nigam 1987)

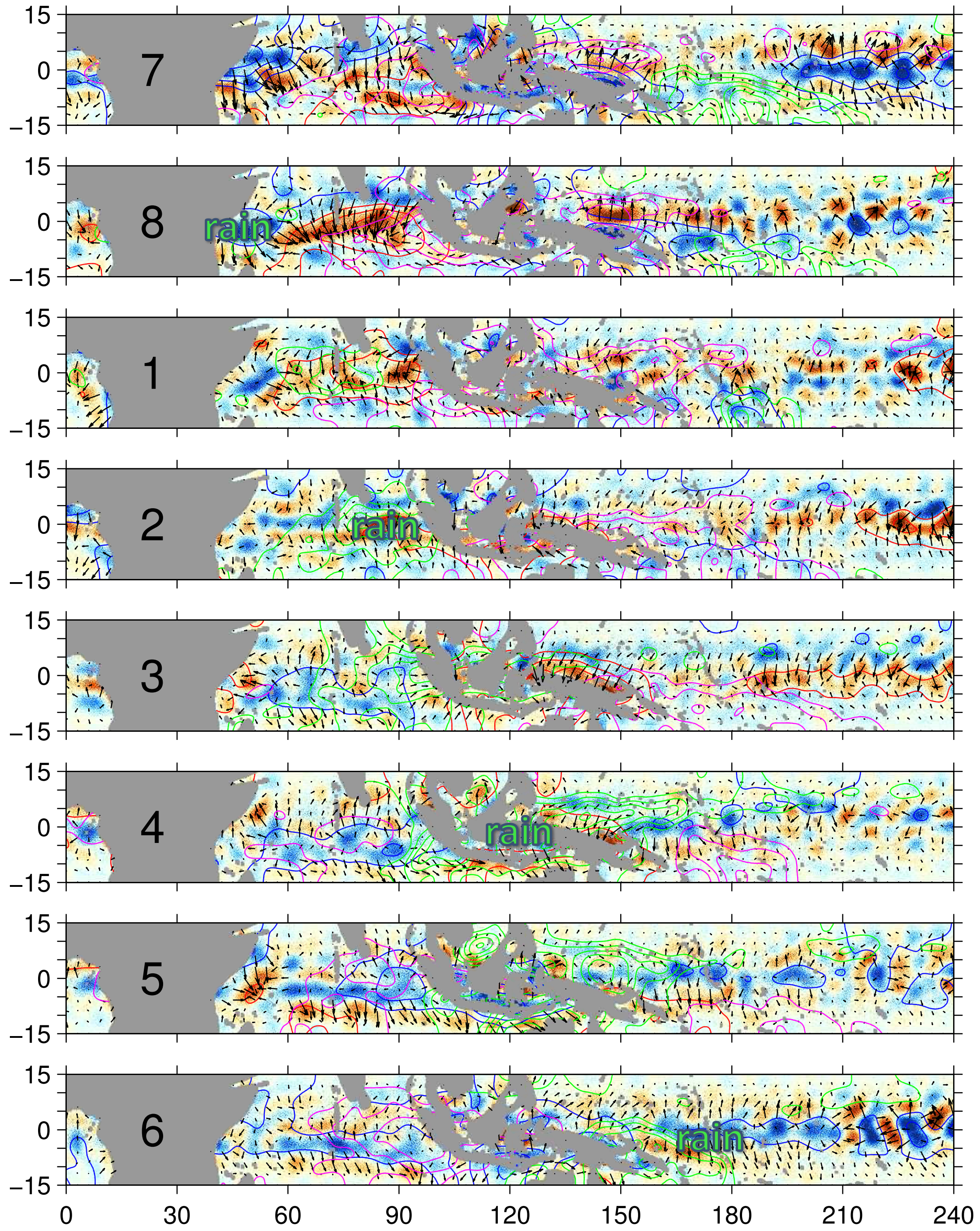
$$p' \propto -\mathrm{SST}'$$

$$-\nabla\cdot\mathbf{u}' \sim -\nabla^2\mathrm{SST}'$$



MJO SST-induced winds

- Compute *SST-induced* wind and divergence
  - with Back and Bretherton (2009) model.
- Composite TRMM microwave SST
  - Real-time Multivariate MJO index (RMM, Wheeler and Hendon 2004).
  - November-April, |RMM|>1.
- Filter with 120-day, 3.5-degree running means.
- Compute induced pressure for each RRM phase’s SST pattern.

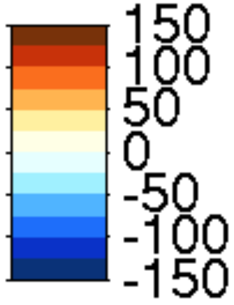


Composite |RMM| > 1, November-April

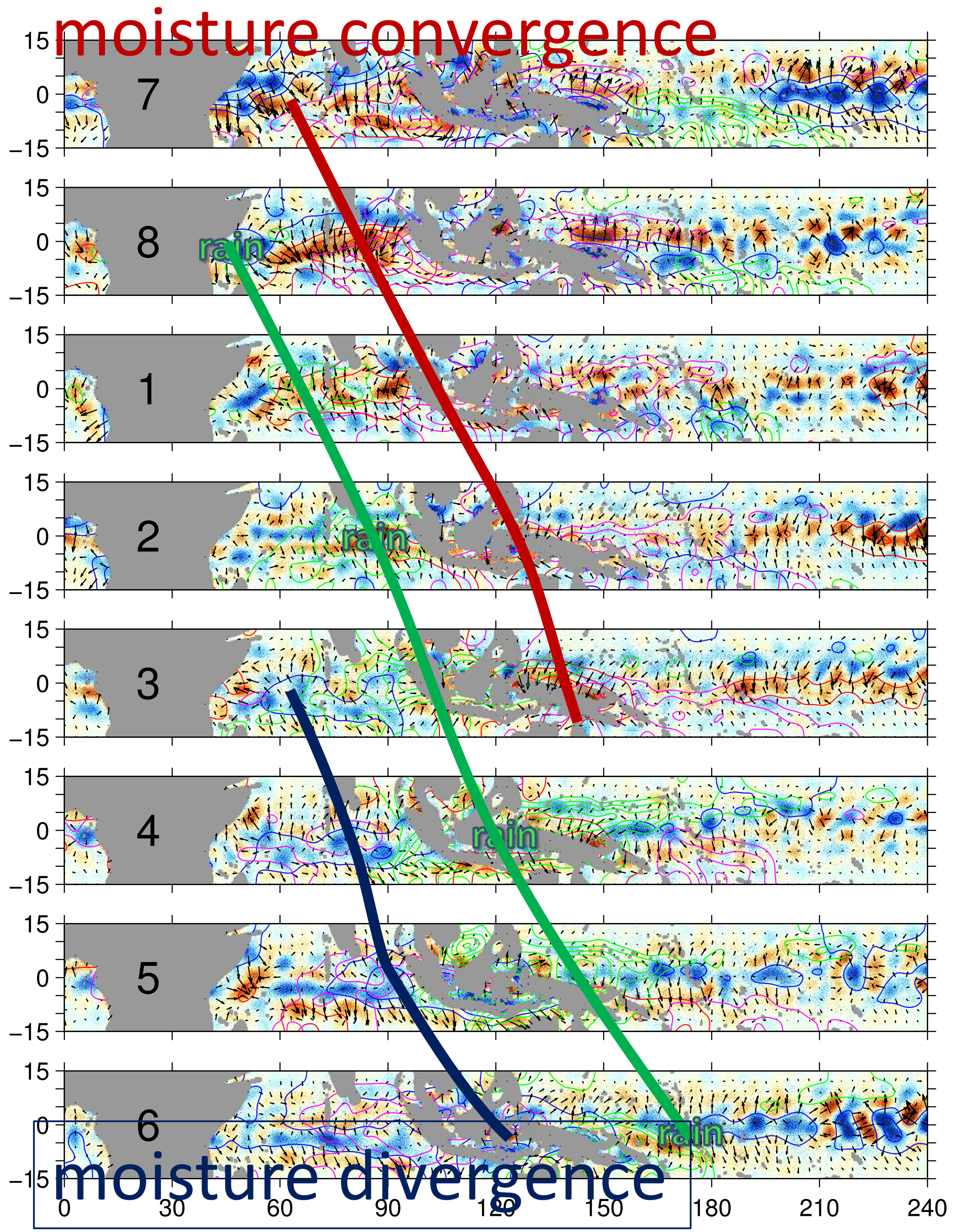
SST anomaly
(0.05 °C)

+red
–blue

induced **vapor convergence**
(W m^{-2})



rain
dry



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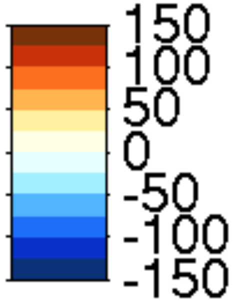
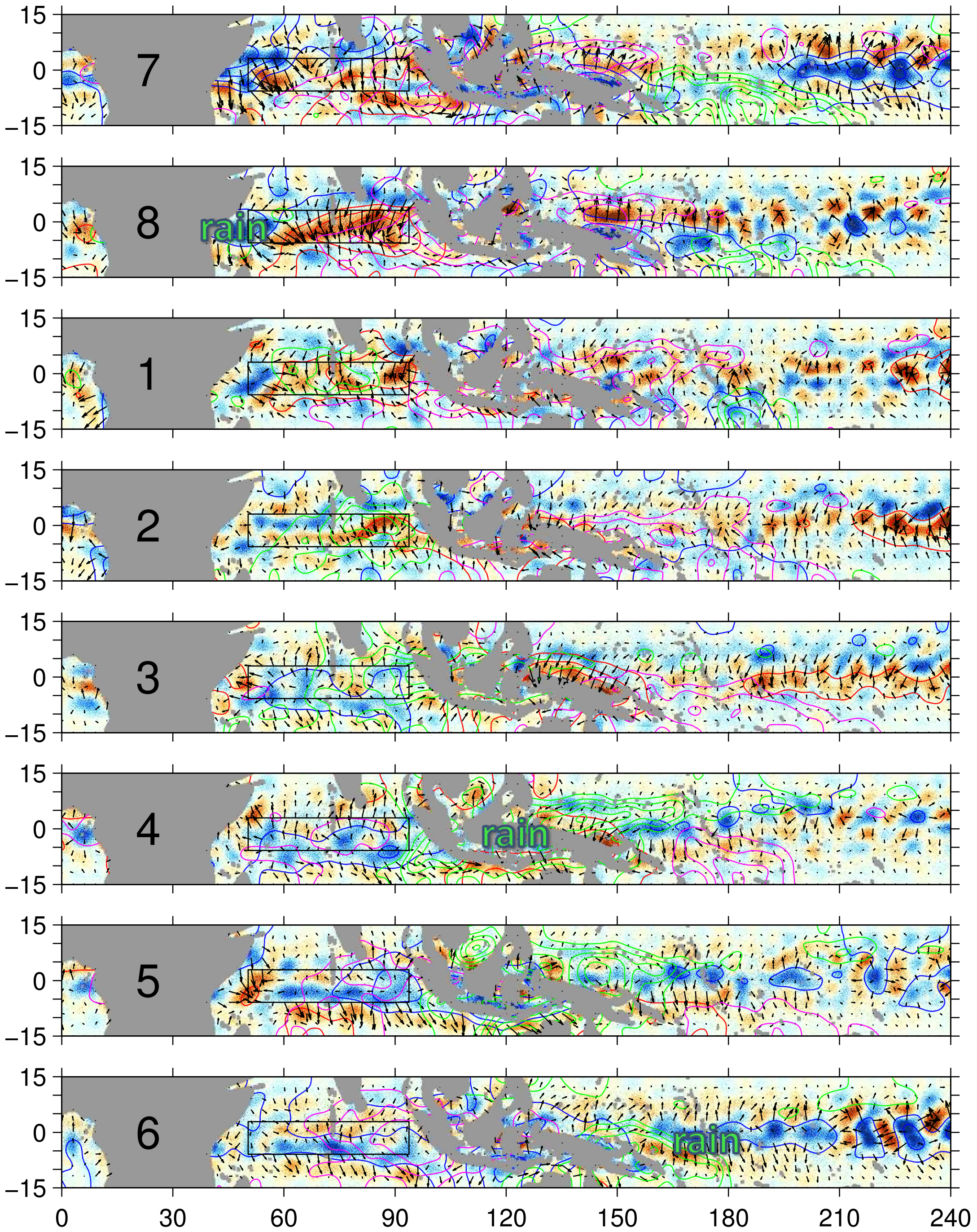


rain
dry



Composite |RMM| > 1, November-April

SST anomaly
(0.05 °C)

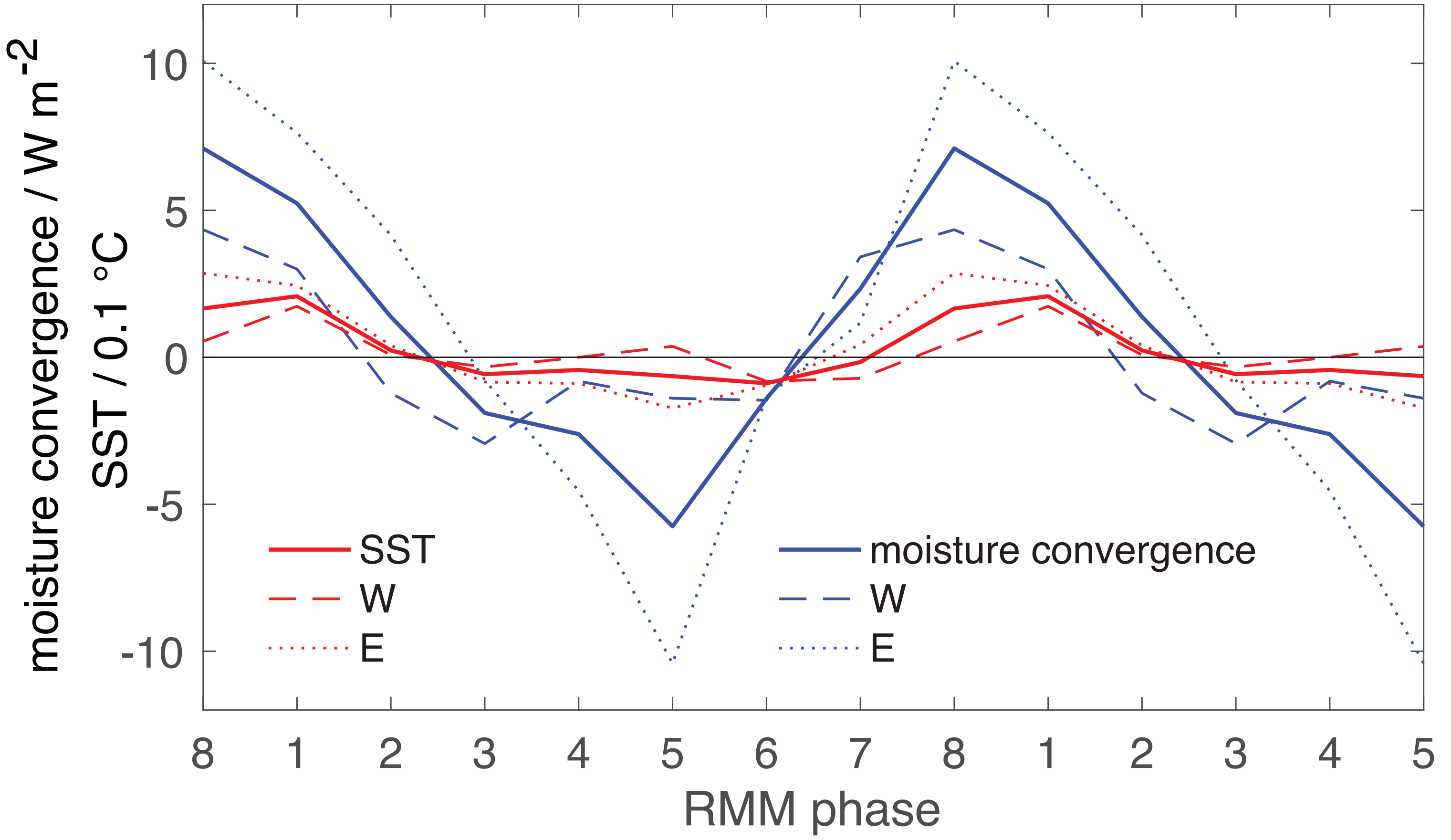
+red
–blue

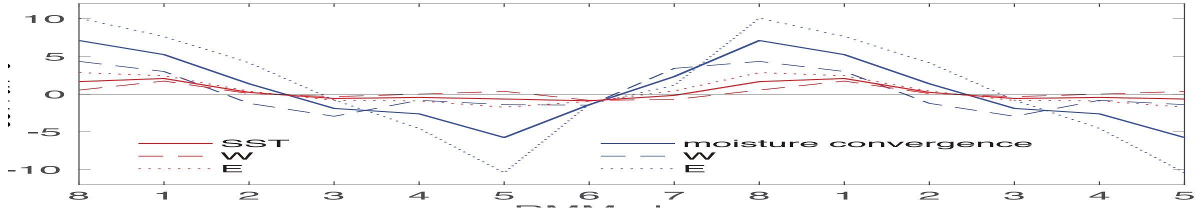
induced **vapor convergence**
(W m^{-2})

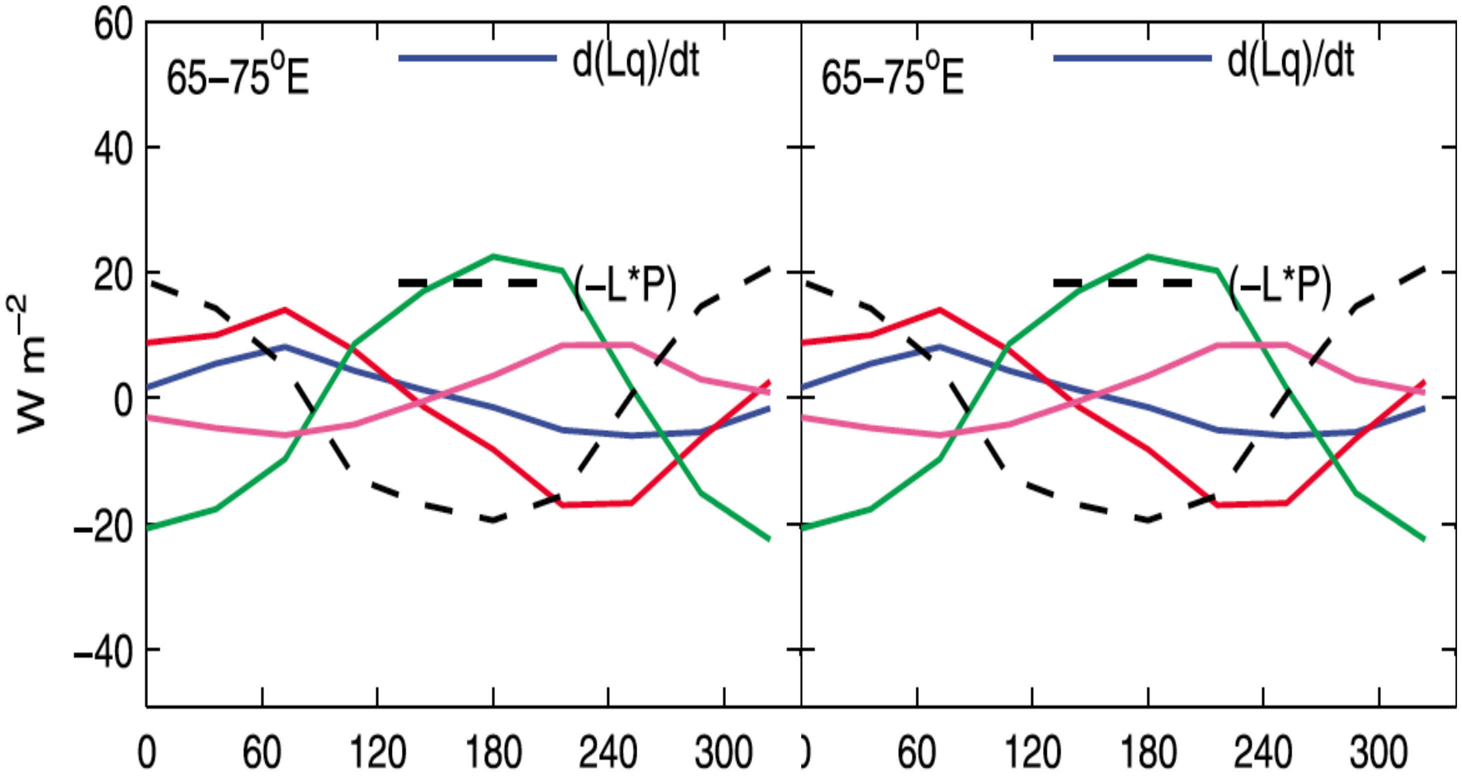
rain
dry

|RMM|>1 Nov-Apr Indian Ocean (50-95°E) ±5°N

moisture convergence (W m^{-2}), SST x 10 (°C)







MJO phase (degrees)

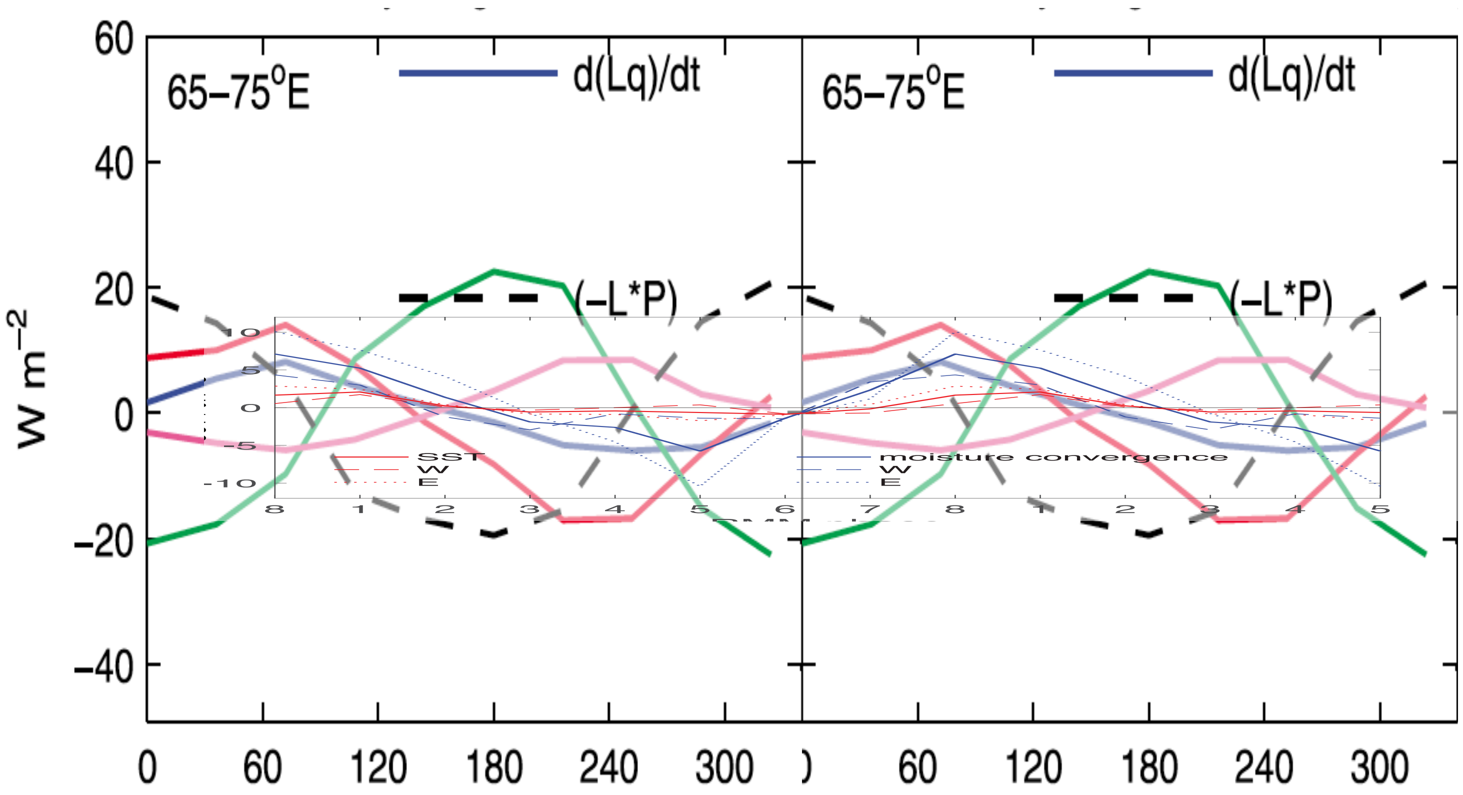
SST-induced convergence

is same magnitude as:

moisture tendency

ERA-I reanalysis

(Kiranmayi and Maloney 2011)



MJO phase (degrees)

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is same magnitude as:

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ERA-I reanalysis

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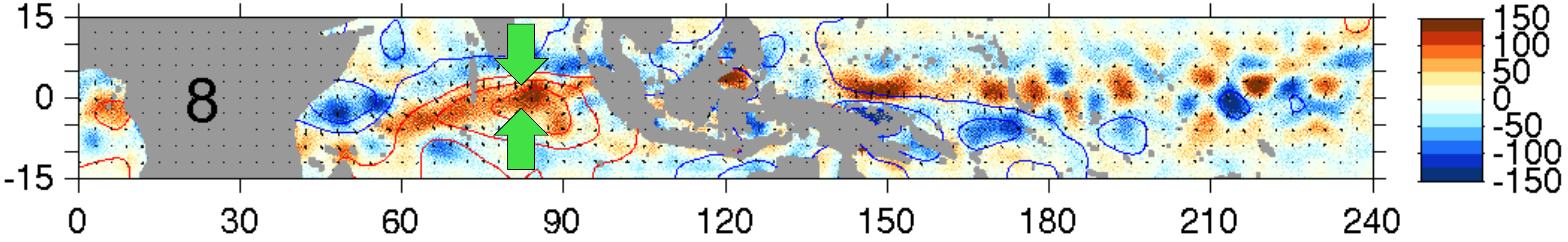
SST-induced BL moisture convergence

- Explains a significant fraction of moisture advection.
  8 W m^{-2} average equatorial (±5°N) Indian Ocean MSE convergence.
  40 W m^{-2} in some phases & locations.
- Is systematically 10-20 days ahead of MJO convection in Indian Ocean.
  in RMM phases 7, 8, and 1.

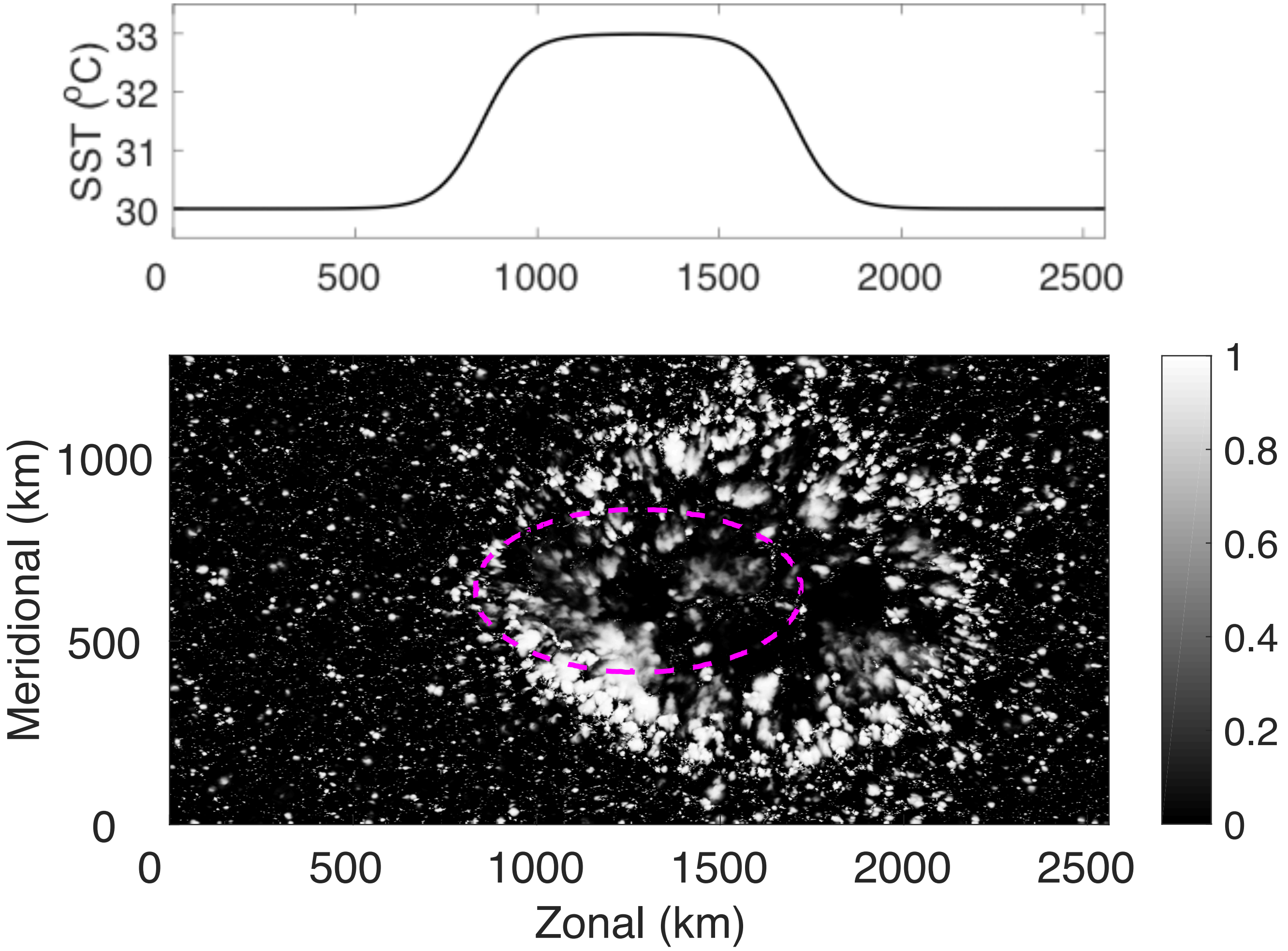


Indian tropical atmosphere *inhales* before the convective phase of the MJO.

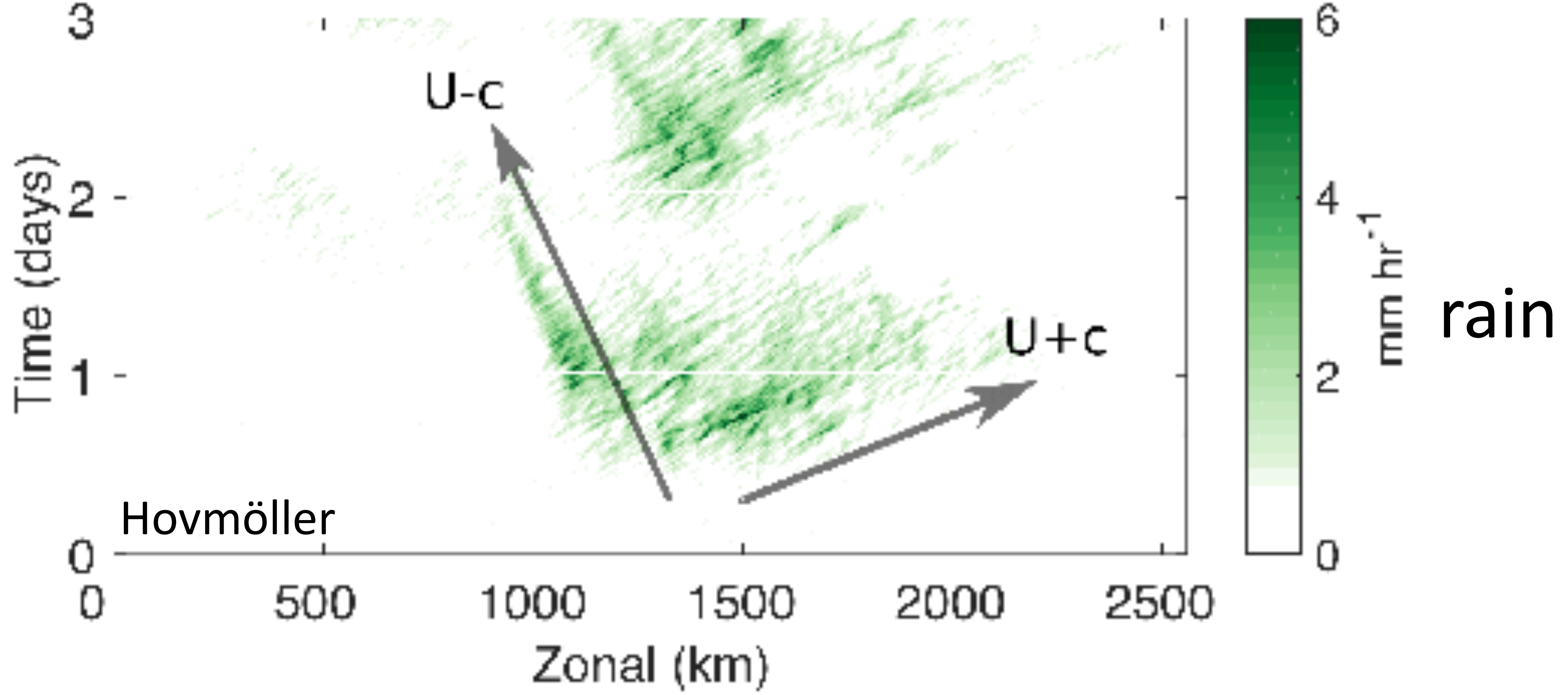
Response to a mesoscale warm SST patch

First triggered by SST, clouds self-organize and propagate away from a warm patch.

(Skyllingstad et al. 2019)



Response to a mesoscale warm SST patch



Mean wind and convective fronts propagate away from SST patch, selecting resonant scales.

(Skyllingstad et al. 2019)

Summary

1. Surface flux, entrainment, and convective downdrafts maintain the subcloud boundary layer near equilibrium.

2. Local evaporation is 2x too small to balance precipitation.
   - storms require even more (5-10x) moisture.

3. Circulations in balance with hydrostatic SST-induced pressure gradients induce significant moisture and MSE convergence before intraseasonal convection.
   - Wind and convective organization select scales of interaction.

Postscript: effective mixing depth

$$T_t = \lambda Q$$

T	mixed layer temperature	$\lambda = \left(\rho c_p h\right)^{-1}$	
Q	net heat flux divergence	h	mixed layer depth

Take a [**spatial** average], e.g. of a scale resolved by satellite or model.

$$[T_t] = [\lambda][Q] + [\lambda' Q']$$

measured only by process experiment

$$\lambda_{\mathrm{eff}} = \frac{[T_t]}{[Q]} = [\lambda] + \frac{[\lambda' Q']}{[Q]}$$