EAPS 53600: Introduction to General Circulation of the Atmosphere

Spring 2020

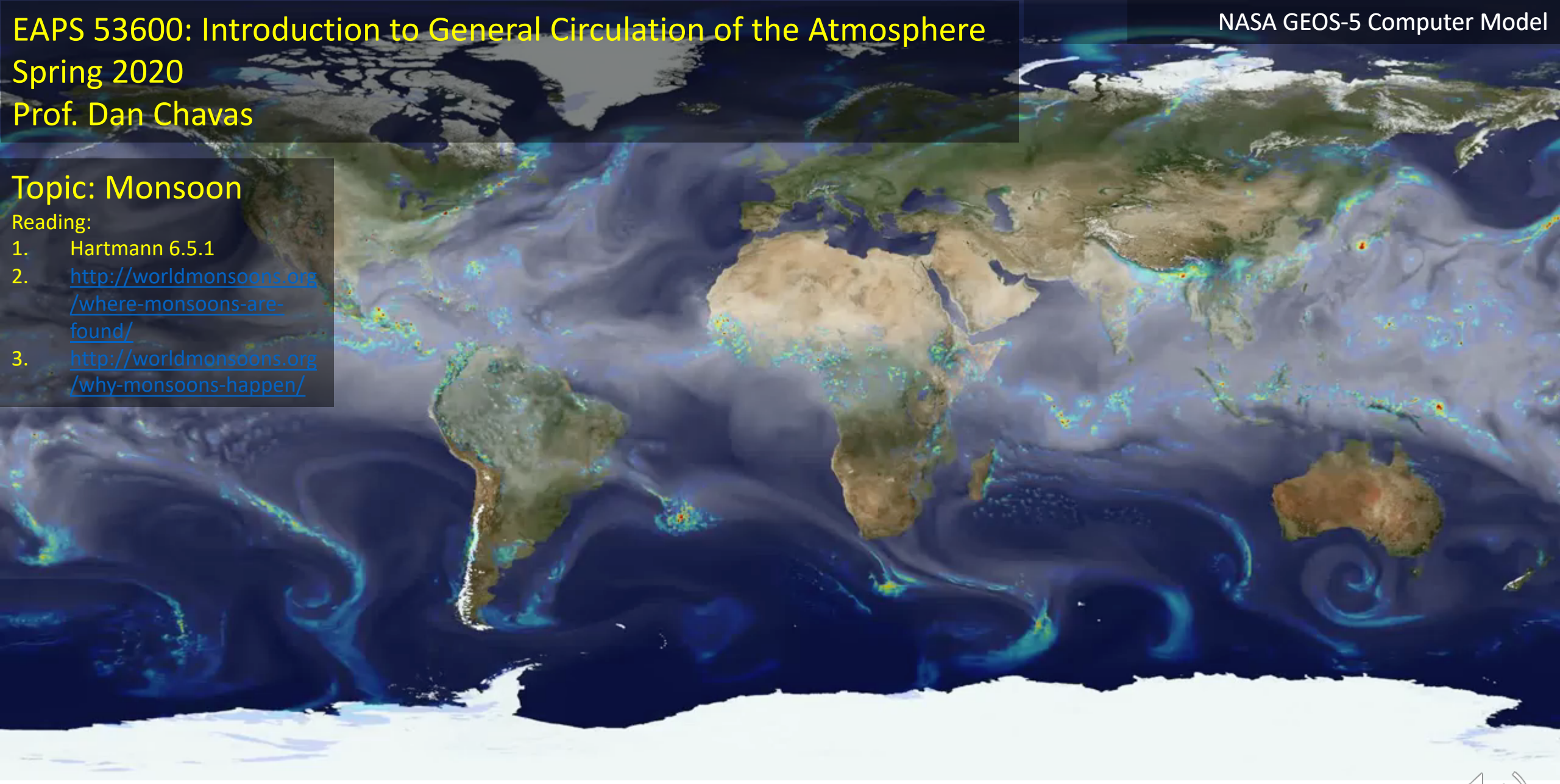
Prof. Dan Chavas

NASA GEOS-5 Computer Model

Topic: Monsoon

Reading:

1. Hartmann 6.5.1
2. http://worldmonsoons.org/where-monsoons-are-found/
3. http://worldmonsoons.org/why-monsoons-happen/



White: total precipitable water (brigher white = more water vapor in column)

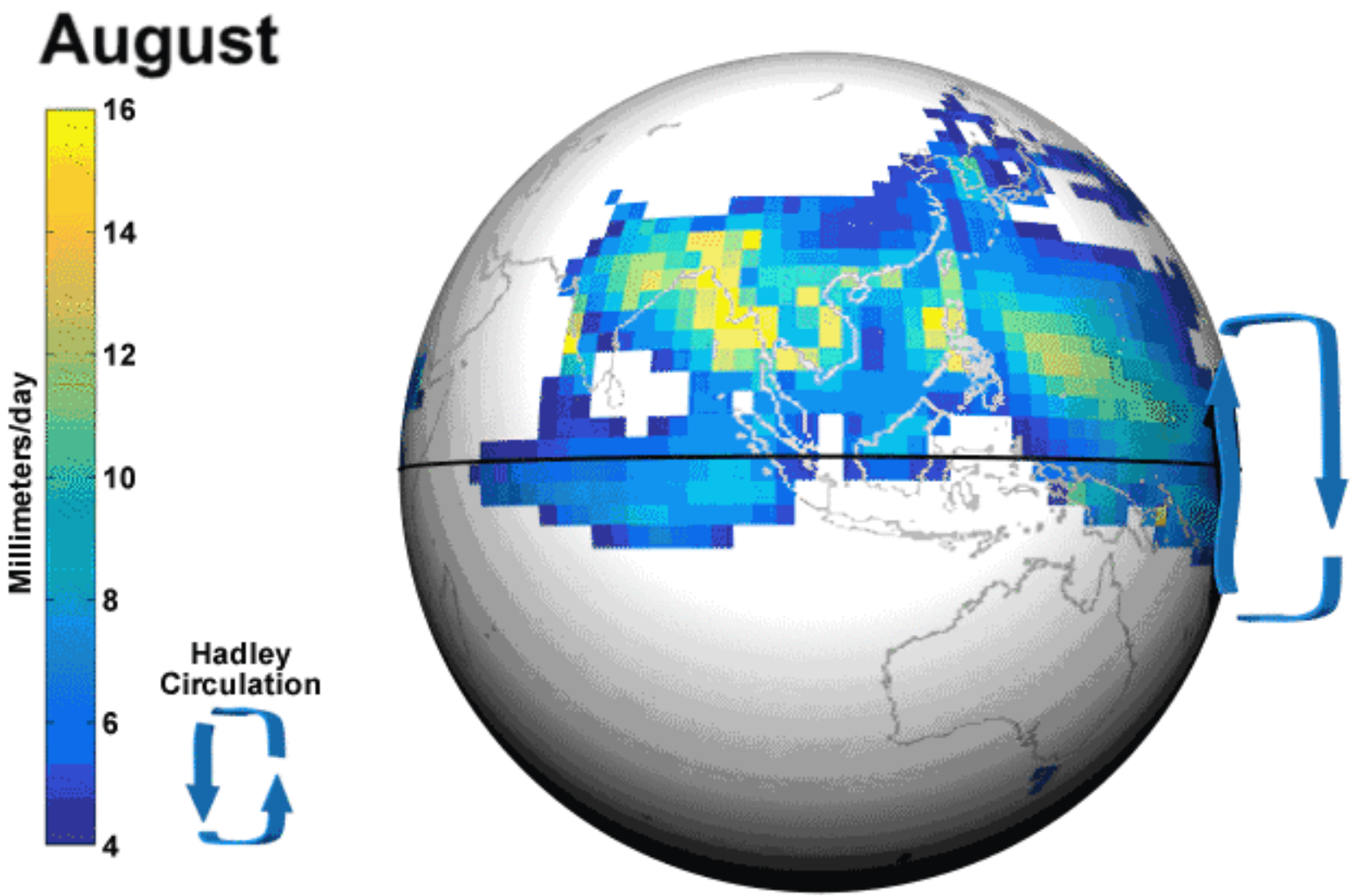
Colors: precipitation rate ($0 - 15\,\frac{mm}{hr}$, red=highest)

Source: https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=30017

Learning outcomes for today:

- **Describe what a monsoon is and where/when they occur on Earth**
- **Explain the theory for why monsoons suddenly start and end**
- **Explain the theory for why land-ocean contrast contributes to its sudden onset**

https://www.youtube.com/watch?v=CR7KL6KSlx4



http://worldmonsoons.org/why-monsoons-happen/

Lindzen and Hou (1988) JAS
Figure 9

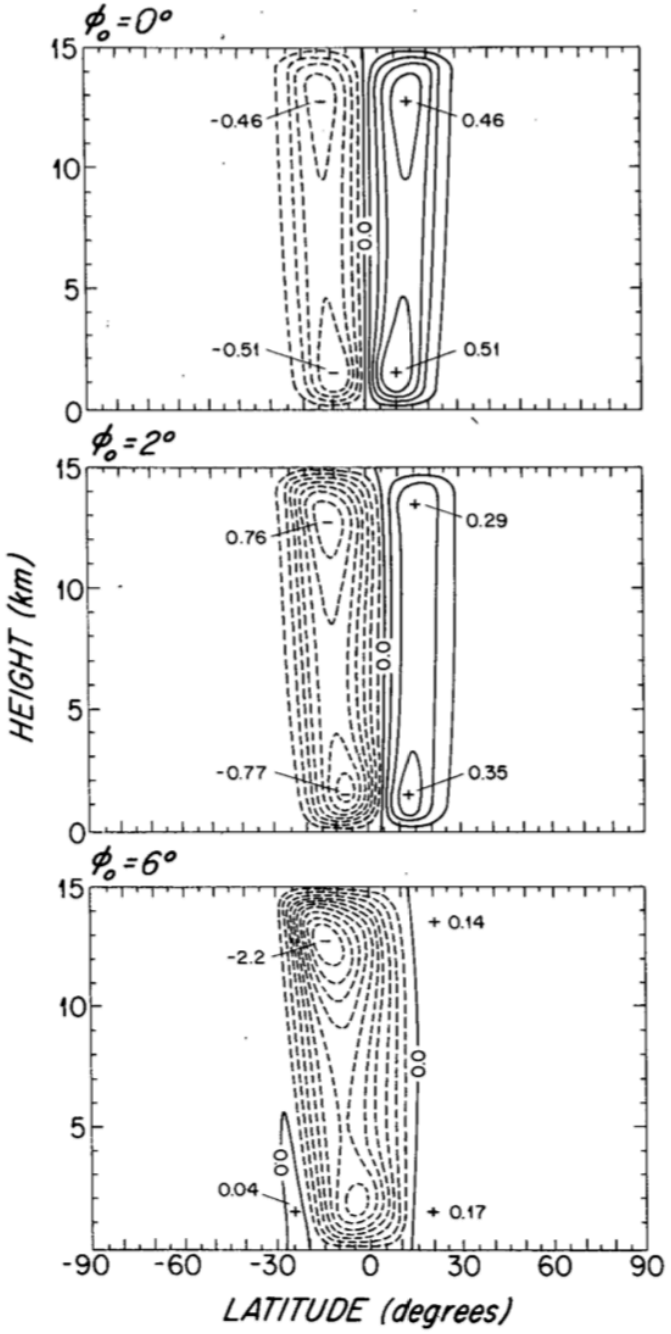


FIG. 9. Numerical model results for ψ for (a) $\phi_0 = 0°$, (b) $\phi_0 = 2°$, and (c) $\phi_0 = 6°$. Units are in 10^{10} kg s^{-1} and the contour interval is 0.1×10^{10} kg s^{-1} for (a) and (b); twice this value for (c).

Why does the Monsoon <u>suddenly</u> start and end?

Why does the Monsoon suddenly start and end?

Plumb and Hou (1992, JAS)

A theory for how subtropical heating causes a sudden transition to a Hadley overturning cell

We consider the response of a zonally symmetric atmosphere to a thermal forcing that is localized in the subtropics. Specifically, the equilibrium temperature distribution has a local subtropical peak and is flat elsewhere, including at the equator. On the basis of inviscid steady-state theory, it is argued that the response to such forcing is one of two distinct types. Below a threshold forcing the atmosphere adopts a steady state of thermal equilibrium with no meridional flow. With supercritical forcing, this state breaks down and a strong meridional circulation is predicted. The threshold forcing value is that at which the absolute vorticity of the zonal flow (in gradient balance with the equilibrium temperatures) vanishes at the upper boundary. These inviscid predictions are tested in a zonally symmetric numerical model; while the model viscosity shifts the threshold and otherwise modifies the response, the threshold is clearly evident in the model behavior.

Plumb, R.A. and Hou, A.Y., 1992. The response of a zonally symmetric atmosphere to subtropical thermal forcing: Threshold behavior. *Journal of the atmospheric sciences*, *49*(19), pp.1790-1799.

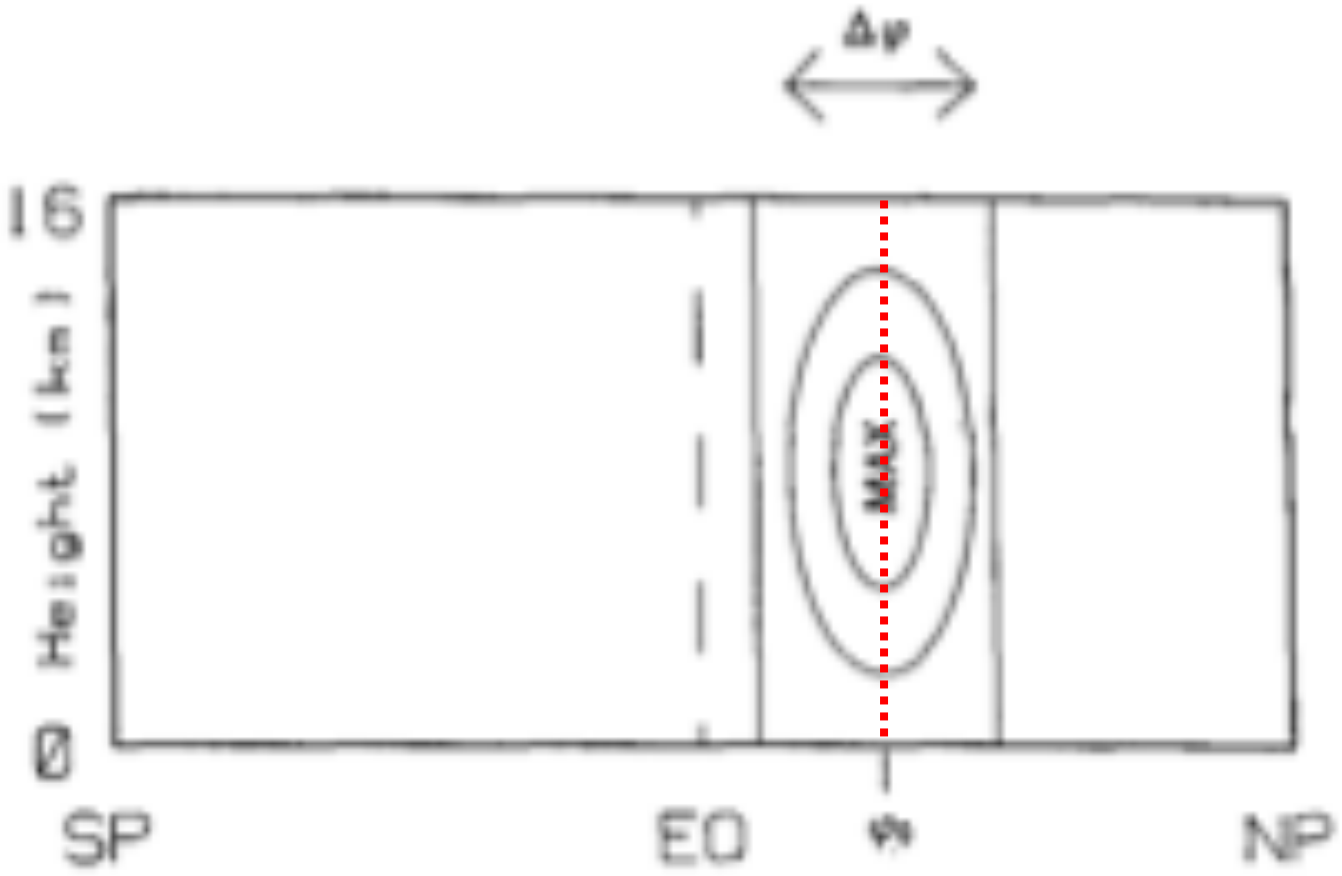


FIG. 1. Latitude–height distribution of equilibrium temperature in the model experiments. Contours are at 0, 1/3, and 2/3 of maximum value; T_e is zero outside the outer contour.

They use:
$\phi_0 = 25^o$
$\Delta\phi = 15^o$

Weak heating (max θ = 3 K), very weak overturning

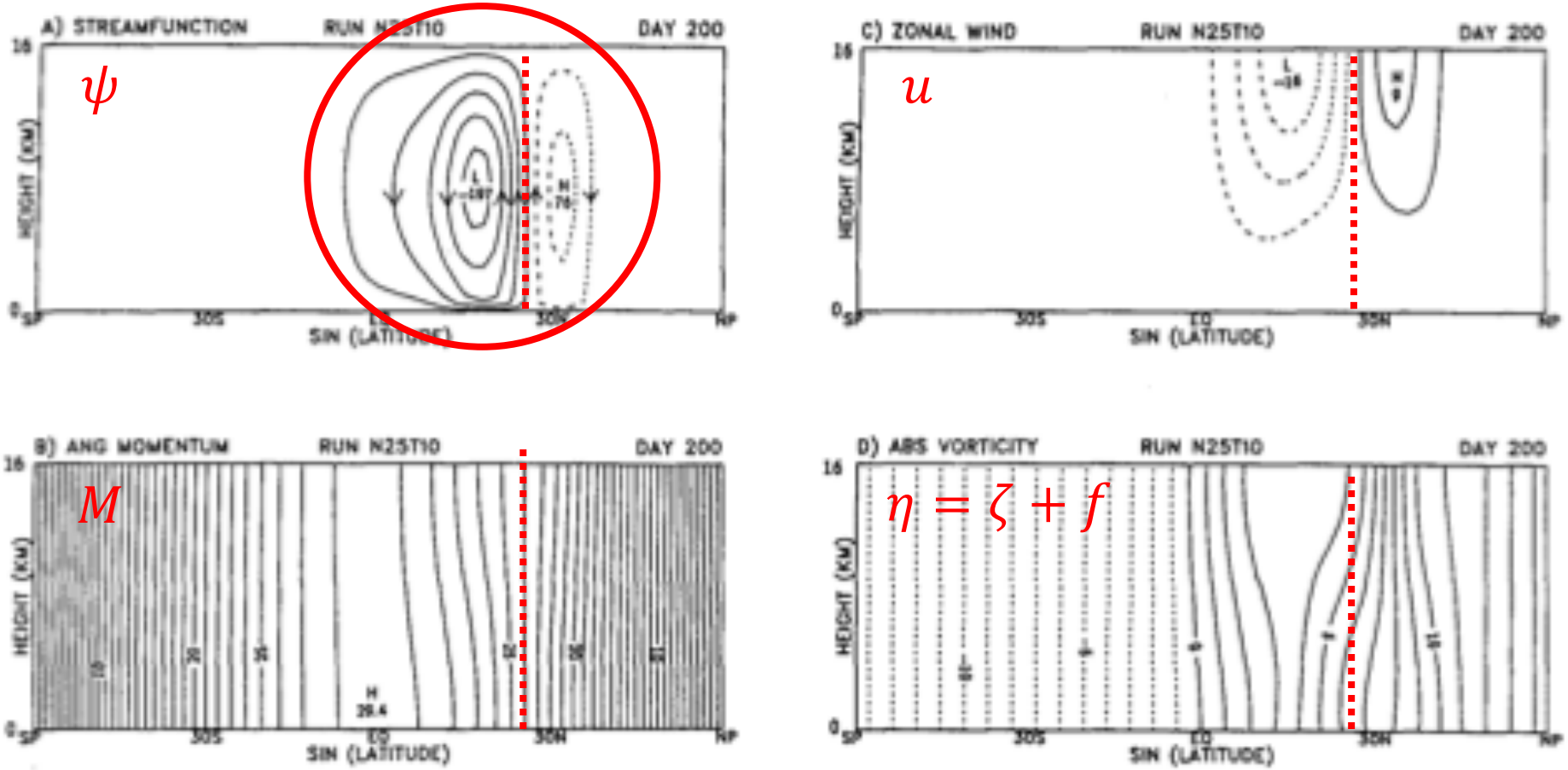
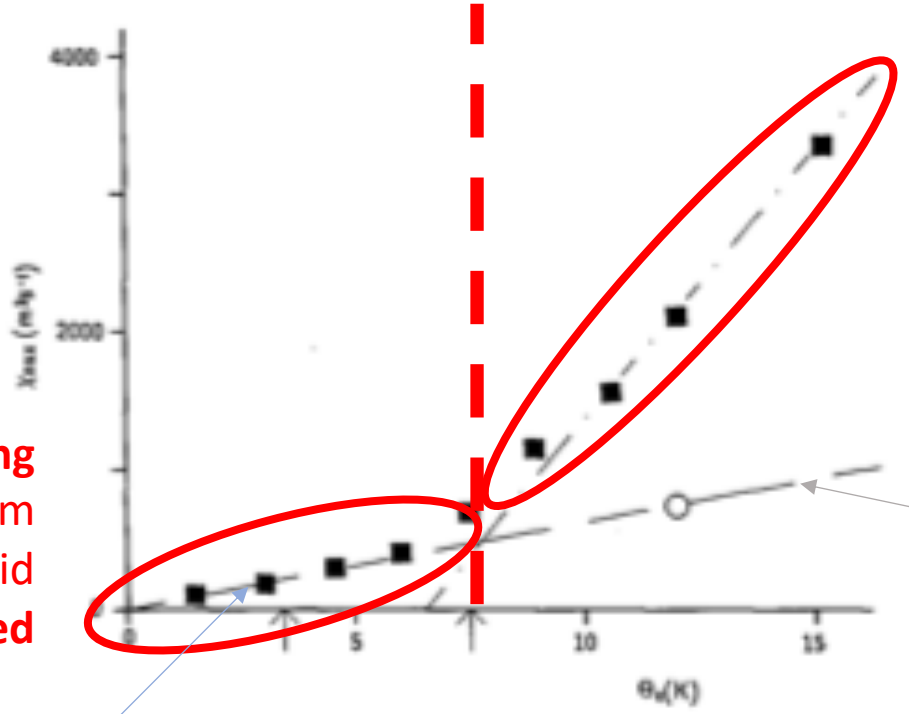


FIG. 2. Solution for Θ_e = 3.0 K after 200 days of integration (by which time the flow is almost steady). Shown are (a) streamfunction χ ($m^2 s^{-1}$; contour interval 40 $m^2 s^{-1}$), (b) angular momentum density M ($10^8 m^2 s^{-1}$; contour interval $1 \times 10^8 m^2 s^{-1}$), (c) zonal wind u ($m s^{-1}$; contour interval 5 $m s^{-1}$) and (d) absolute vorticity ζ_a ($10^{-5} s^{-1}$; contour interval $1 \times 10^{-5} s^{-1}$). In (b) and (d), the contour values include zero, so the contours (interval Δ) are at 0, $\pm\Delta$, $\pm 2\Delta$, etc.; in (a) and (c), the zero line is not plotted, the contour values being $\pm\Delta/2$, $\pm 3\Delta/2$, etc.

Threshold behavior: off-equatorial Hadley cell will form if the sub-tropical forcing is strong enough

Super-critical forcing
Radiative-convective equilibrium solution is not allowed
Angular momentum conserving (AMC) solution must apply instead
Strong Hadley cell overturning

Sub-critical forcing
Radiative-convective equilibrium solution is valid
No Hadley cell overturning required



Linearized solution
(RCE only; AMC not allowed)

FIG. 4. Dependence of the maximum value of the steady streamfunction χ on the forcing amplitude Θ_e. The squares show points determined from results of the complete, nonlinear model. The circle shows a result from the linearized model, and the dashed line the linear dependence of χ_{max} on Θ_e. The steeper, dash–dot, line is drawn by eye and has no other significance. The two arrows show the theoretical value of Θ_e at which the TE solution becomes irregular; the left arrow is for the inviscid case, the right arrow for $\nu = 2.5\ m^2\ s^{-1}$ according to the linear model results.

(Note: a very weak Hadley cell still forms that is driven by viscous mixing)

What governs this threshold behavior?

Strong heating (max θ = 12.1 K) – LINEAR SOLUTION ONLY: Hadley/AMC solution is not allowed

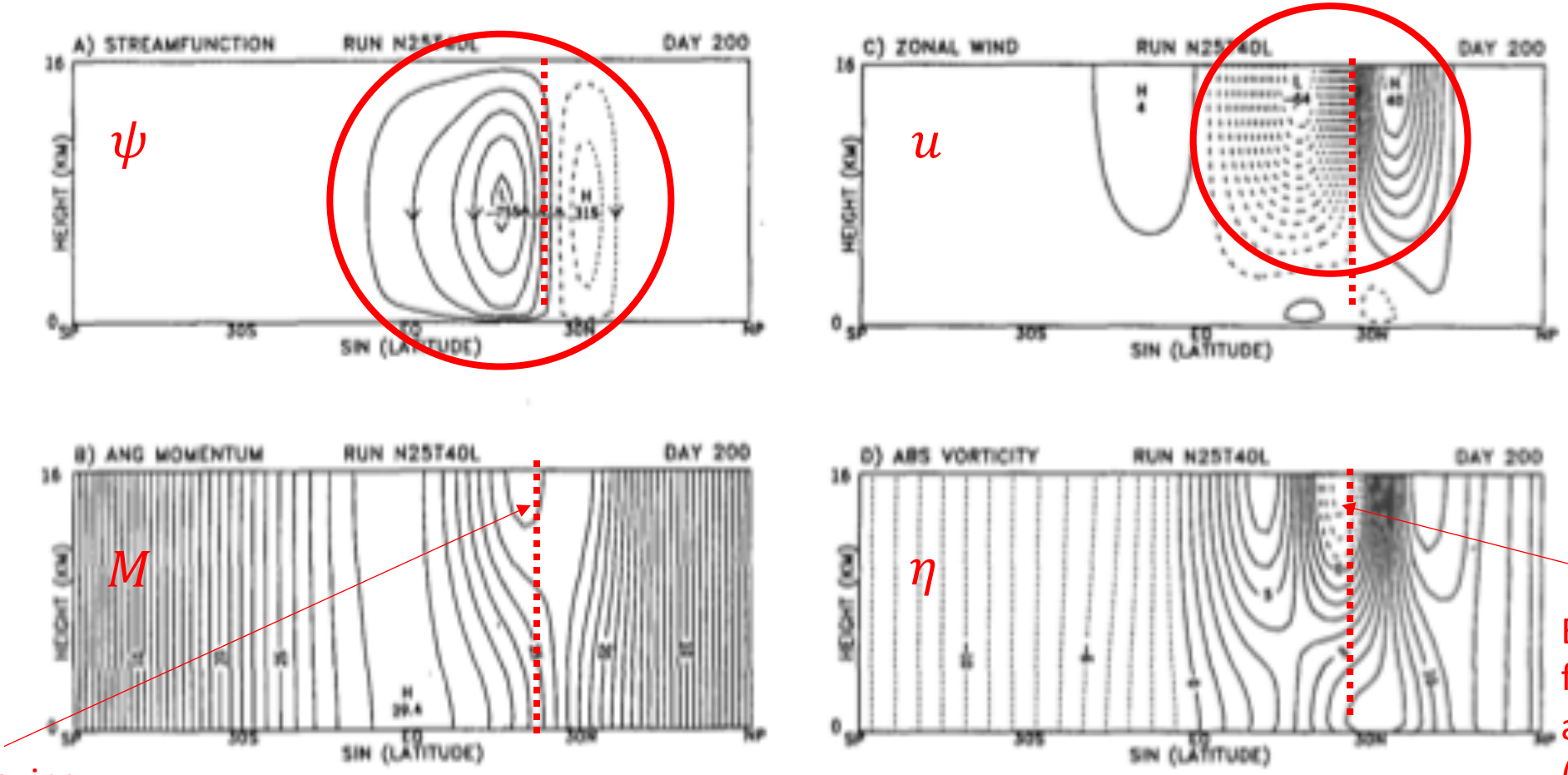


FIG. 3. Solution from the linearized model for θ_v = 12.1 K after 200 days of integration. Layout as for Fig. 2. Contouring is as for Fig. 2 except that the contour interval in (a) is 160 m^2 s^{-1} (i.e., four times that of Fig. 2).

$\eta < 0$ (NH)

Equivalently: the flow has negative absolute vorticity (flow that conserves its M will have $\eta = 0$). This is **inertially unstable** – it is *not* a valid steady state solution.

M **increases** moving north or south from ϕ_0. **This is impossible** – there is no source of M in the free troposphere! (Hide's theorem)

The thermal equilibrium solution violates the laws of physics.

An angular-momentum-convserving overturning circulation must form!

Strong heating (max θ = 12.1 K), very strong overturning

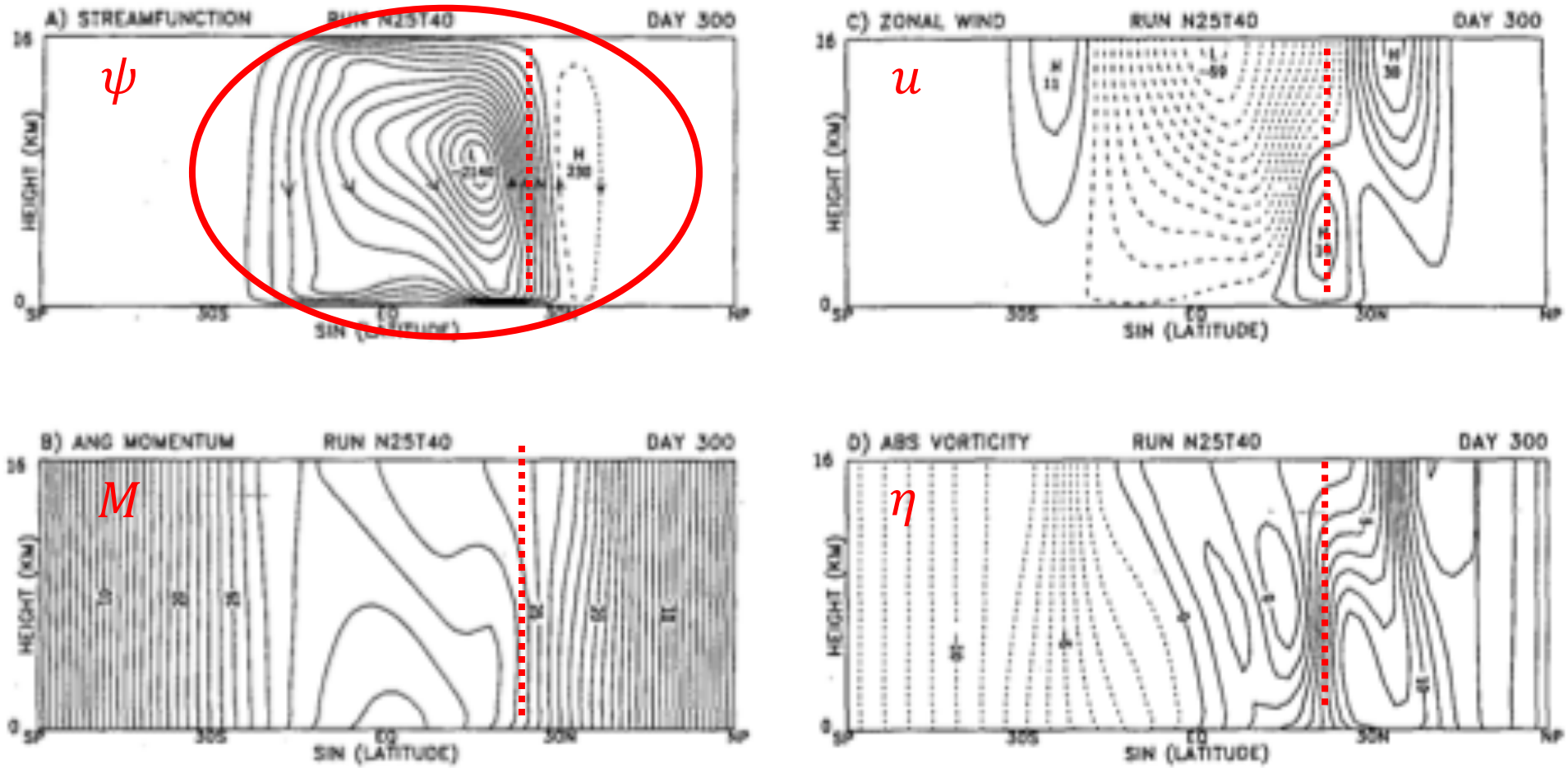


FIG. 5. Solution for Θ_e = 12.1 K after 300 days of integration (by which time the flow is almost steady). Layout as for Fig. 2. Contouring is as for Fig. 2 except that the contour interval in (a) is 160 $m^2 s^{-1}$ (i.e., four times that of Fig. 2a and the same as that of Fig. 3a).

This solution is valid!

- M now increases monotonically with latitude
- $\eta > 0$ everywhere (NH)

What defines this threshold behavior?

If $\eta_{TE} < 0$ anywhere: super-critical, Hadley/AMC cell must form.

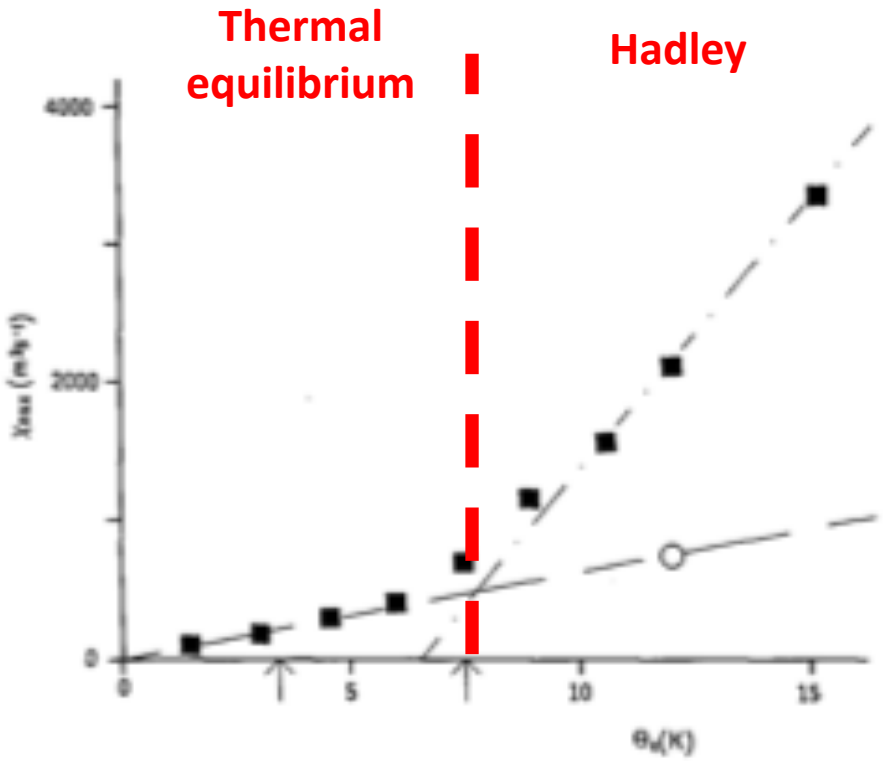
(Same argument as in Held-Hou theory)

$$-\frac{1}{2}\frac{gD}{T_0}\frac{1}{\cos\varphi}\frac{\partial}{\partial\varphi}\left[\frac{\cos^3\varphi}{\sin\varphi}\frac{\partial\hat{T}_e}{\partial\varphi}\right] < 2\Omega^2 a^2 \sin\varphi \cos^2\varphi \qquad (8)$$

everywhere; this will be satisfied if the forcing is weak, broad, and/or far from the equator. When (8) is violated, however, the TE solution is untenable, and it is expected that the response must take the form of an AMC solution somewhere in the region of the forcing (though not all the way to the poles).

It might appear that an alternative prediction is that the AMC solution is always possible. However, in the Appendix we present a proof that this solution cannot be realized whenever the TE solution is regular. Therefore, we predict that only the TE solution can exist when (8) is satisfied and only the AMC solution when it is not. Thus, (8) represents a transition from TE to AMC behavior.

Threshold behavior: off-equatorial Hadley cell will form if the sub-tropical forcing is strong enough



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Why is land-ocean contrast important for the monsoon?

Why is land-ocean contrast important for the monsoon?

Privé and Plumb (2007, JAS)

A theory for how the monsoon is drawn inland over a sub-tropical continent.

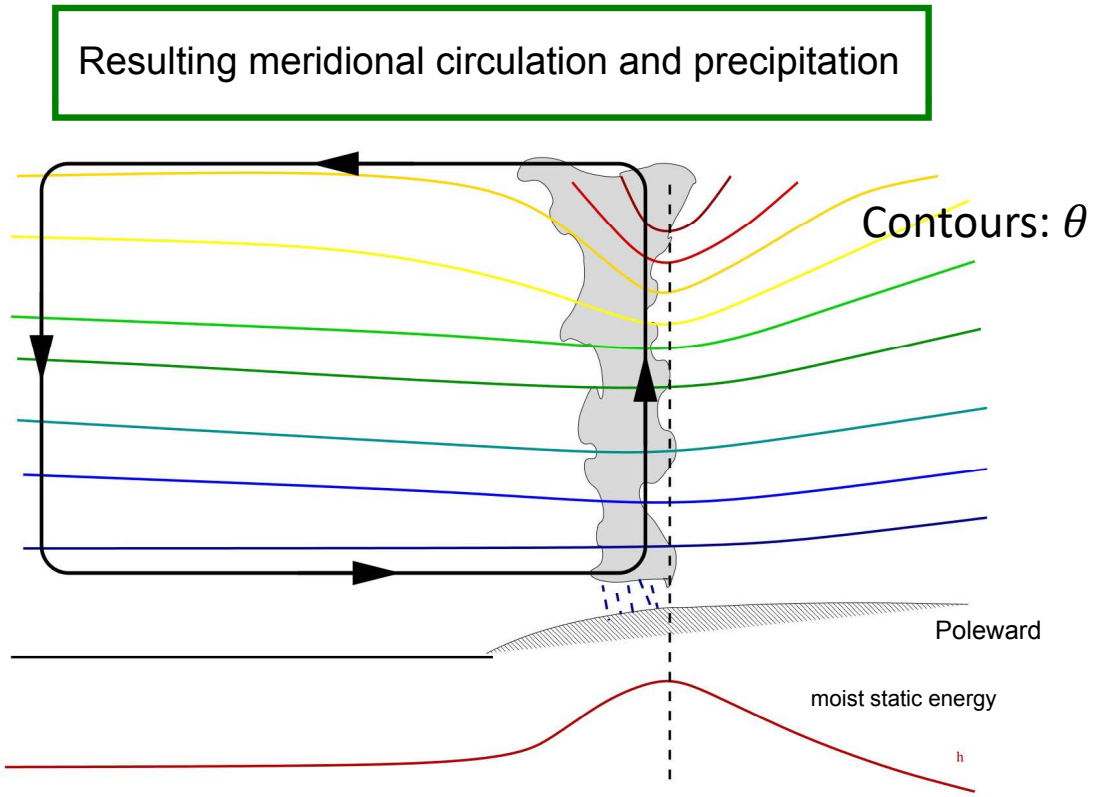
The applicability of axisymmetric theory of angular momentum conserving circulations to the large-scale steady monsoon is studied in a general circulation model with idealized representations of continental geometry and simple physics. Results from an aquaplanet setup with localized subtropical forcing are compared with a continental case. It is found that the meridional circulation that develops is close to angular momentum conserving for cross-equatorial circulation cells, both in the aquaplanet and in the continental cases. The equator proves to be a substantial barrier to boundary layer meridional flow; flow into the summer hemisphere from the winter hemisphere tends to occur in the free troposphere rather than in the boundary layer. A theory is proposed to explain the location of the monsoon; assuming quasiequilibrium, the poleward boundary of the monsoon circulation is collocated with the maximum in subcloud moist static energy, with the monsoon rains occurring near and slightly equatorward of this maximum. The model results support this theory of monsoon location, and it is found that the subcloud moist static energy distribution is determined by a balance between surface forcing and advection by the large-scale flow.

Privé, N.C. and Plumb, R.A., 2007. Monsoon dynamics with interactive forcing. Part I: Axisymmetric studies. *Journal of the atmospheric sciences*, *64*(5), pp.1417-1430.

Moist static energy (per unit mass):

$$h = gz + C_p T + L_v r_v \quad \left[\frac{J}{kg}\right]$$

Theory: peak overturning (and precipitation) follows the maximum in boundary layer moist static energy



Source: MIT OCW 12.811 Spring 2011, Kerry Emanuel (via Nikki Privé)

What's special about land?

- **Land has a small capacity to retain energy.**
- Thus, energy input to the surface (solar) is rapidly transferred to the atmosphere (sensible+latent)
- **Moving towards summer**: solar heating rapidly increases = **surface energy fluxes from land to air rapidly increases**

Why does land poleward of ocean matter?

- Air rises near peak in boundary layer moist static energy $h_{b,max}$ ("quasi-equilibrium")
- $\boldsymbol{h_{b,max}}$ **shifts inland** as **surface heat flux is increased**
- **Air** flowing inland from ocean has smaller h_b and **must travel farther inland** for surface fluxes to increase h_b to $h_{b,max}$

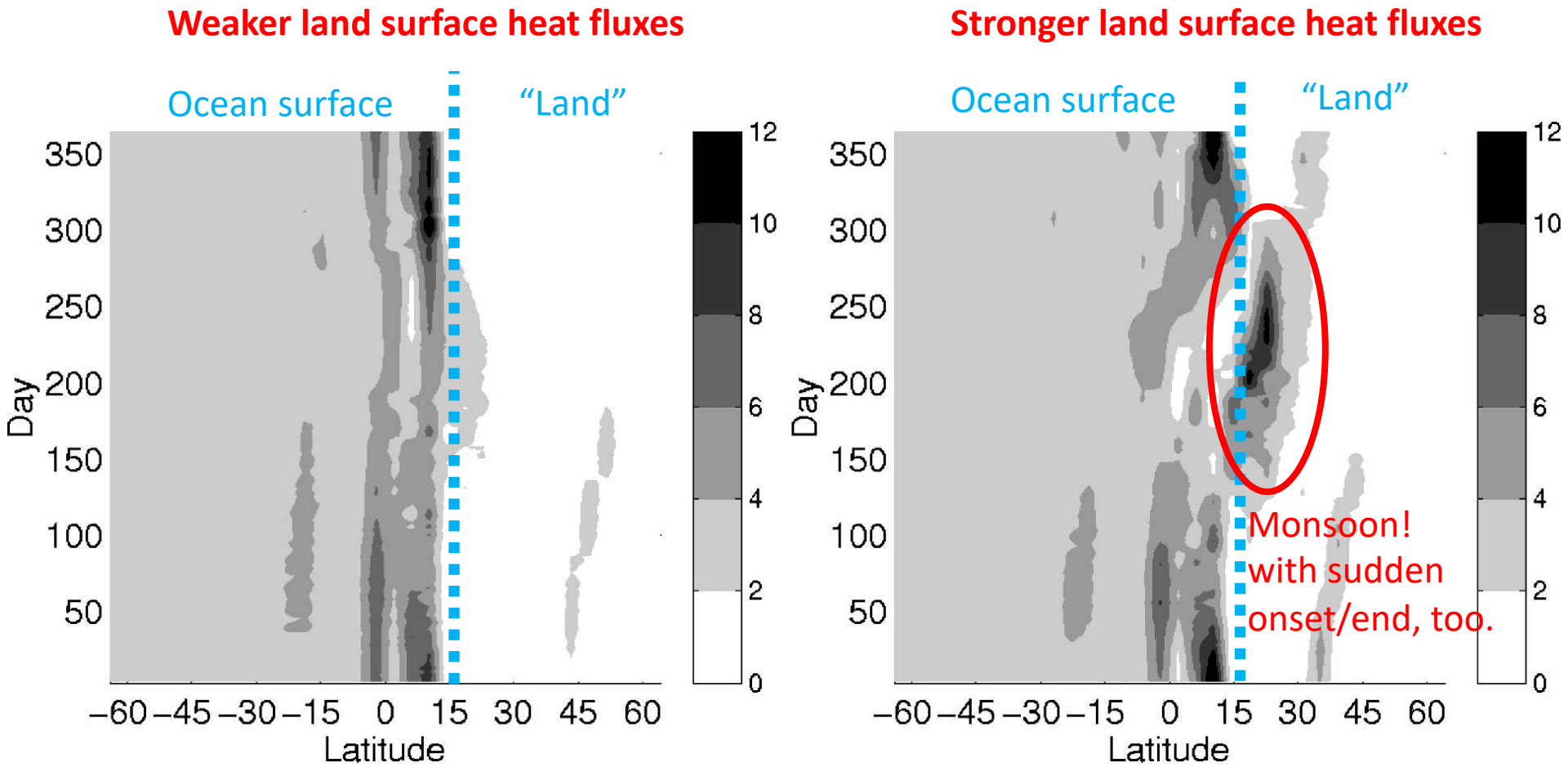
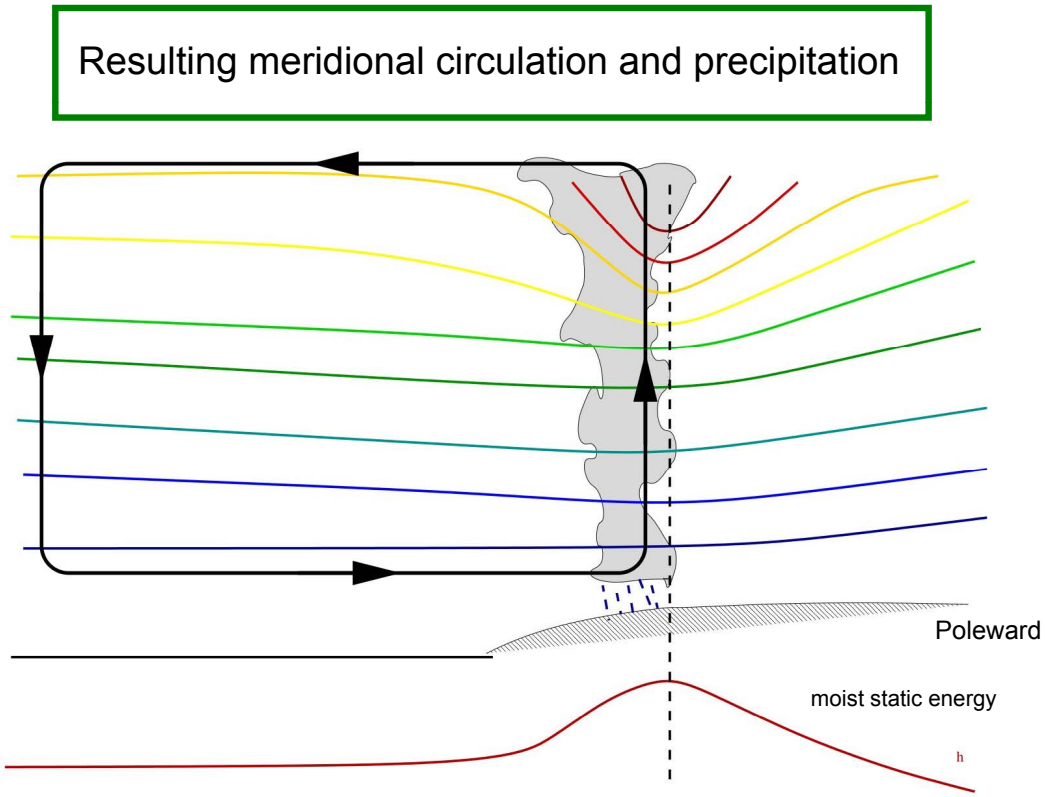


FIG. 8. Hovmoeller diagram of precipitation for seasonal cases, with contour interval of 2.0 mm day^{-1}. (left) Maximum summer land forcing THF_0 = 130 W m^{-2}; (right) maximum summer land forcing THF_0 = 150 W m^{-2}. Day zero occurs at winter solstice; data are averaged over 4 yr of model integration.

Why is land-ocean contrast important for the monsoon?



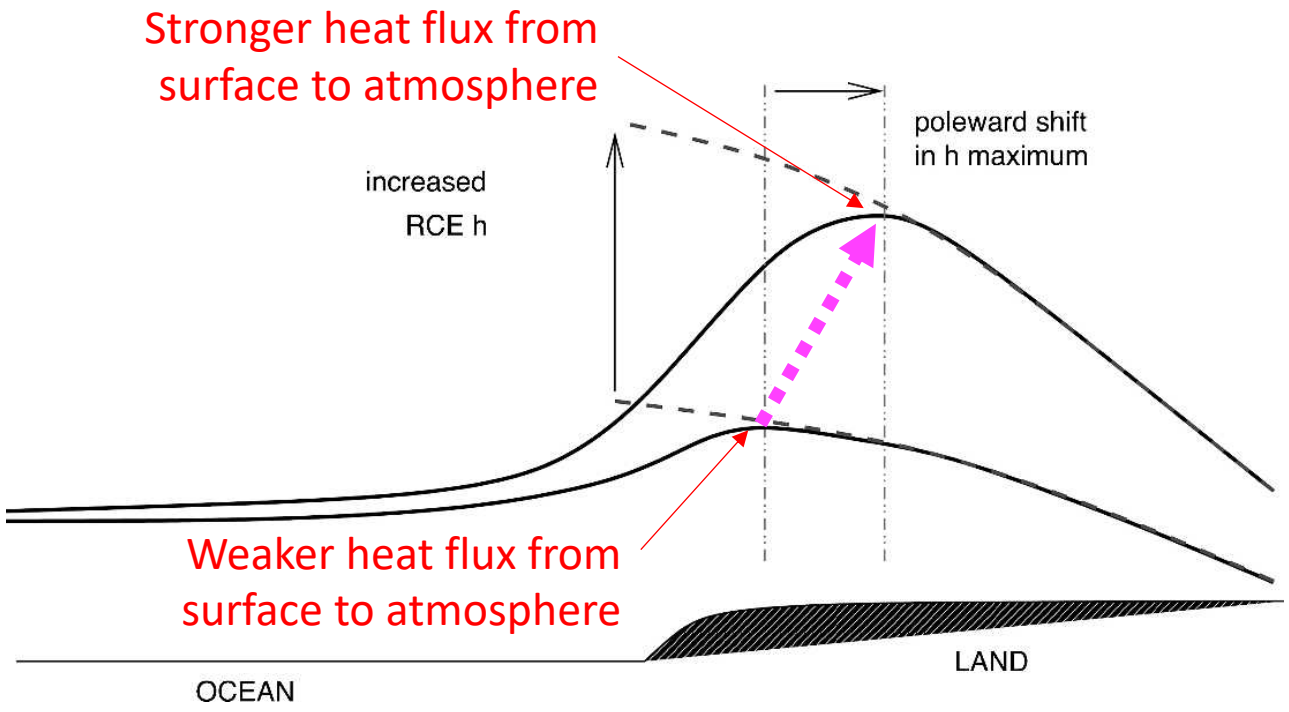
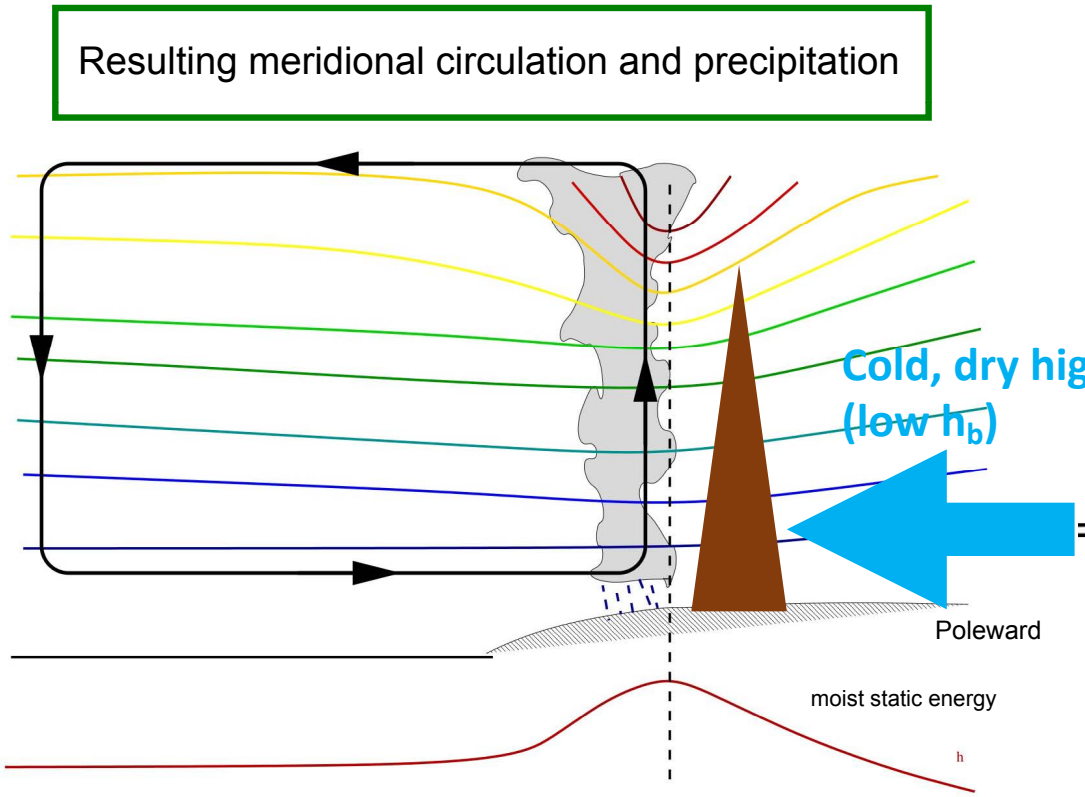
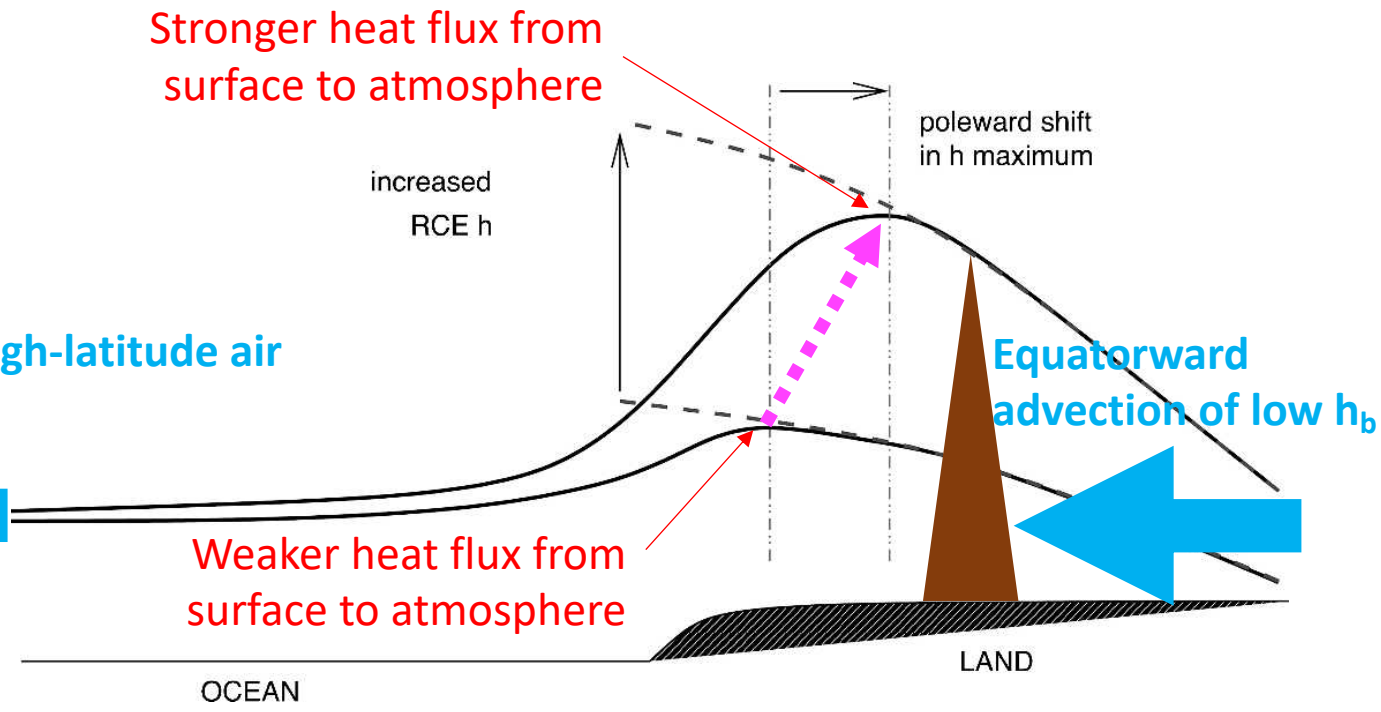


FIG. 11. Schematic diagram of subcloud moist static energy. Dashed line shows radiative convective equilibrium h_b; solid line shows h_b in the presence of a large-scale circulation. As the surface forcing is increased, the radiative–convective equilibrium h_b also increases over the land, but not over the adjacent ocean. Poleward-flowing air from the ocean requires greater heating to reach the RCE equilibrium h_b, and the h_b maximum shifts inland.

Topography is also important for <u>insulating</u> the monsoon region from cold/dry air





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Topography "insulates" the warm moist monsoonal air – i.e. it prevents it from mixing with cold+dry air. This flux of low-h_b air would **offset** the enhanced surfaces that brings the monsoon inland.

Topography is also important for insulating the monsoon region from cold/dry air

Boos and Kuang (2010, Nature)

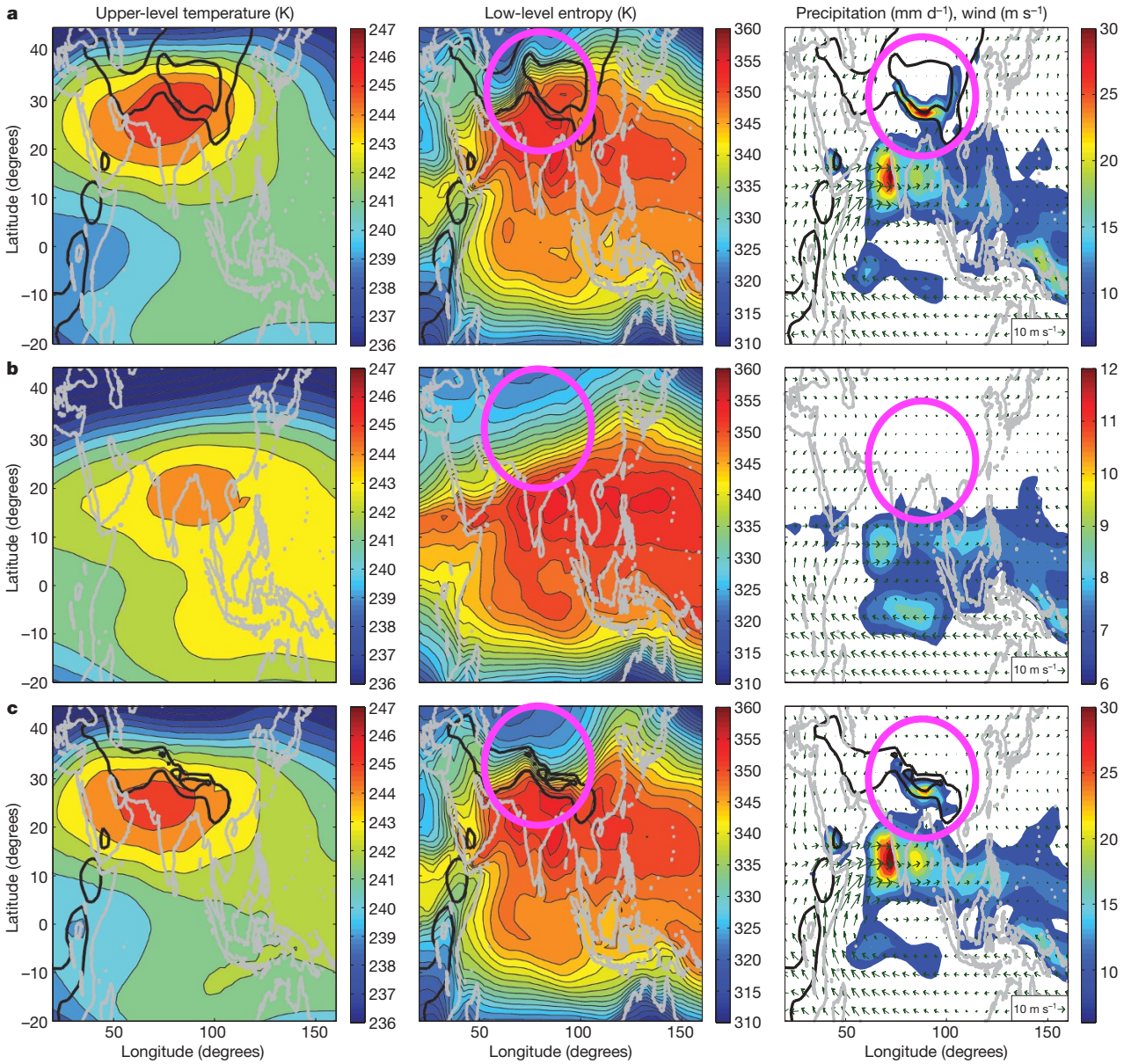

Figure 3 | Thermodynamic structure, precipitation and wind from the atmospheric model. All panels are for June–August and as in Fig. 1 but for the model run with **a**, standard topography, **b**, no elevated topography, and **c**, surface elevations north of the Himalayas set to zero.

Himalayan plateau (black contours)

Monsoon!

Himalayan plateau removed

Inland h_b reduced (sub-critical)

No monsoon!

Only southern "wall" of Himalayas retained

Monsoon again!

Boos, W.R. and Kuang, Z., 2010. Dominant control of the South Asian monsoon by orographic insulation versus plateau heating. *Nature*, *463*(7278), pp.218-222.

Now go to Blackboard to answer a few questions about this topic!