# Convergence zones in seasonally-varying Hadley cells: What is the role of boundary layer dynamics?

Simona Bordoni
California Institute of Technology

Frontiers in Oceanic, Atmospheric and Cryospheric Boundary Layers,
Kavli Institute for Theoretical Physics, UCSB, May 23 2018

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Collaborators: S. Faulk, S. Hill, A. Lobo, J. Mitchell, T. Schneider, H.-H. Wei

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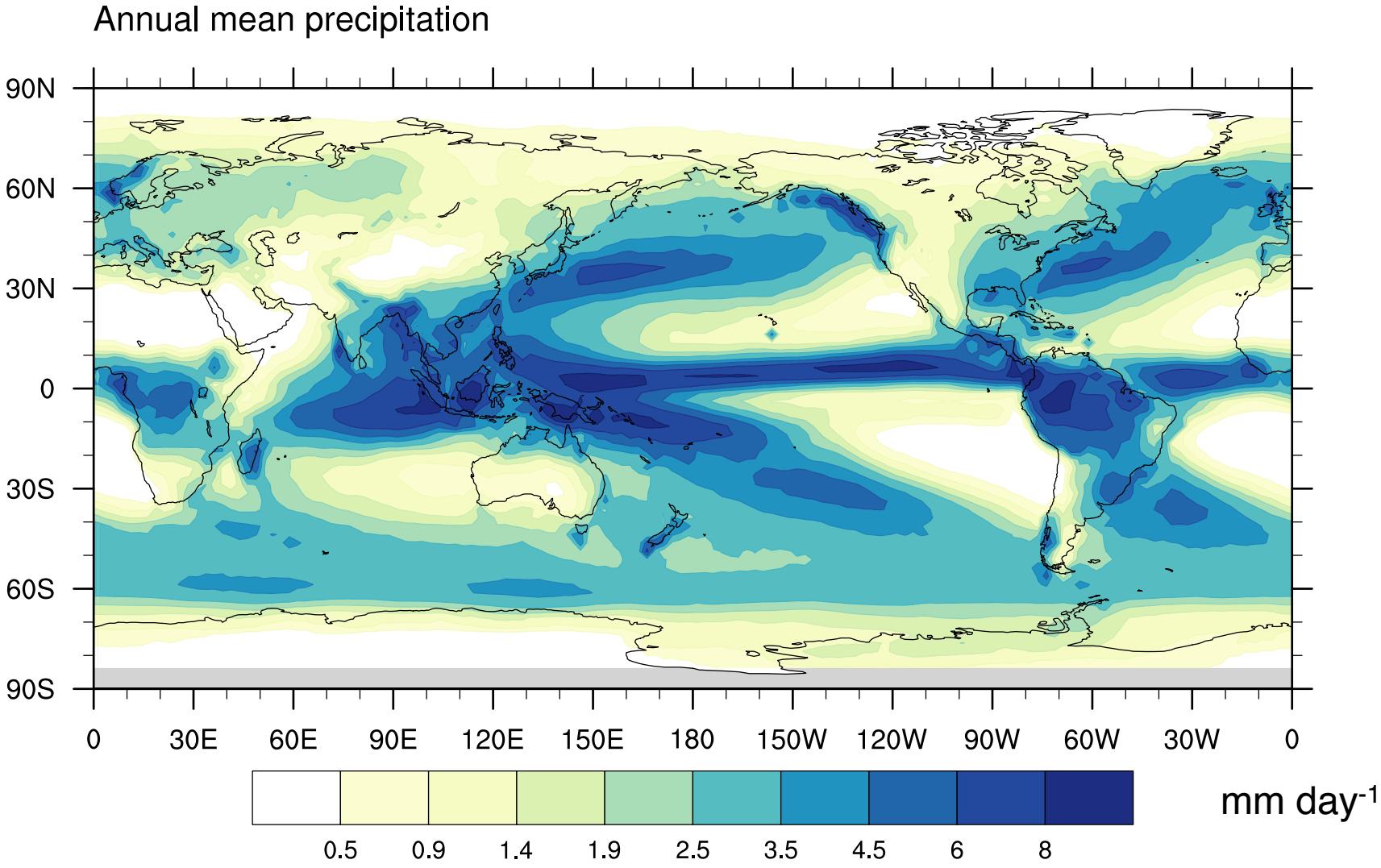
# Annual mean precipitation over the Earth's surface




*Data source*: GPCP

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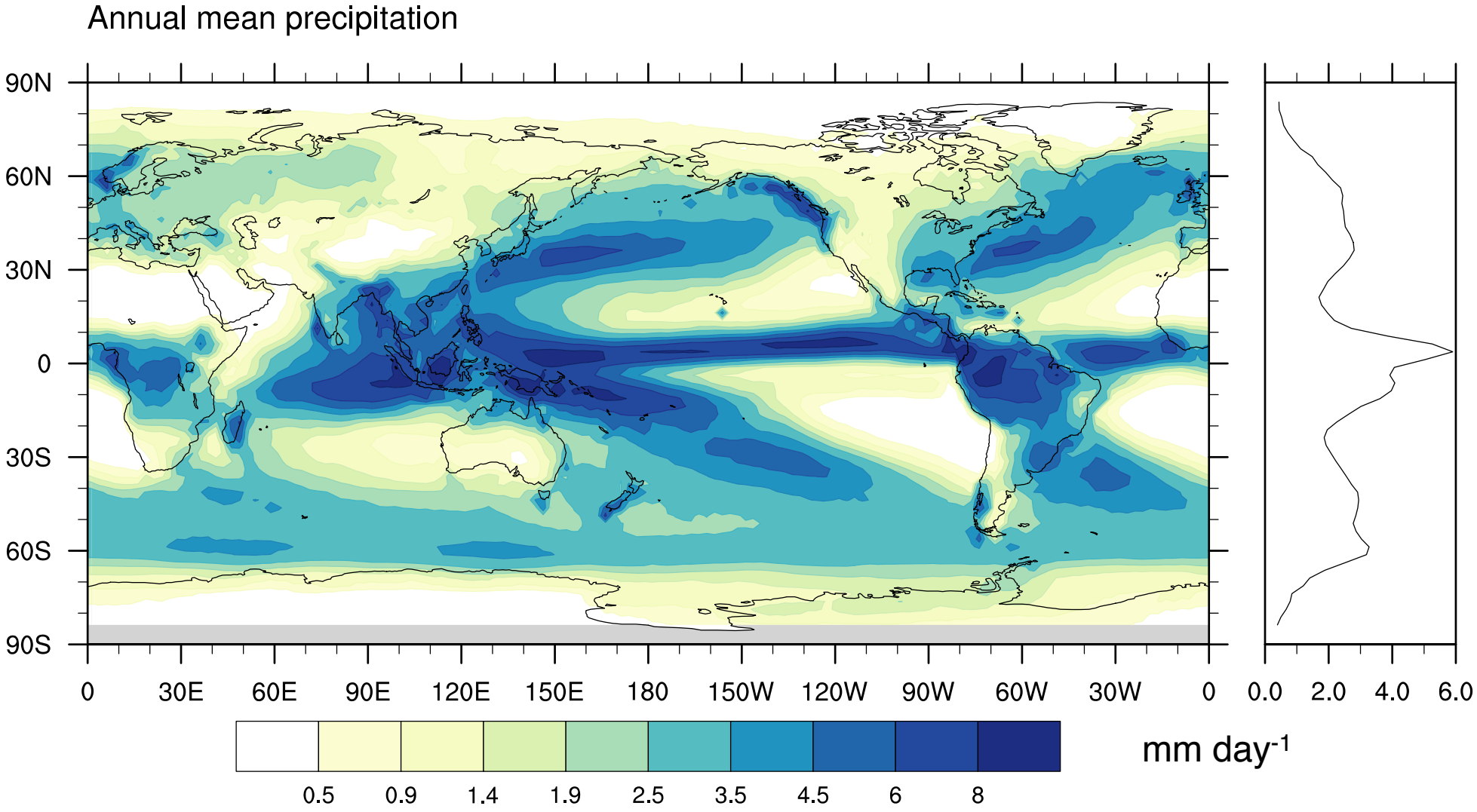


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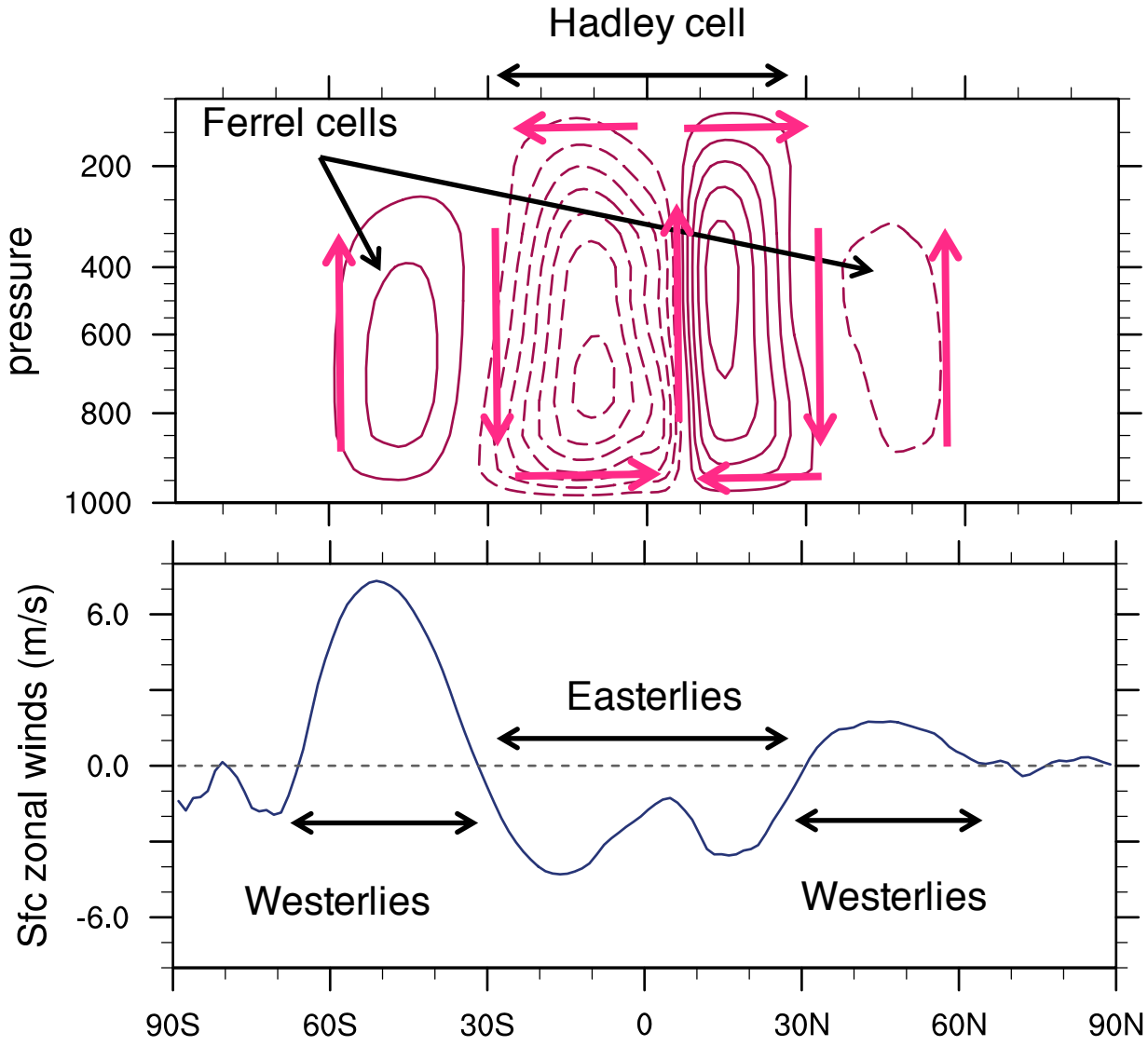
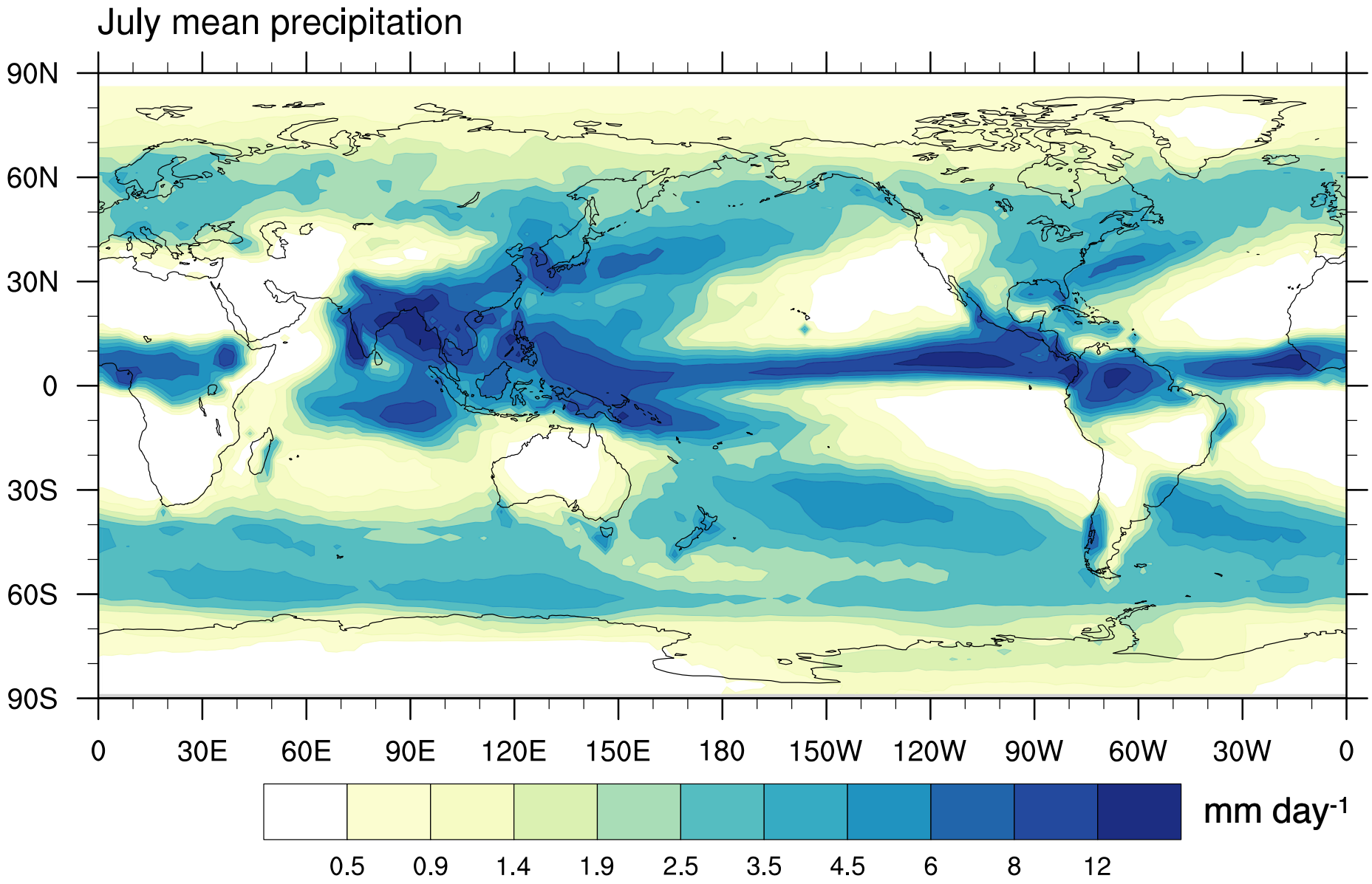
Why is the ITCZ north of the equator?

# Precipitation is tied to the atmospheric overturning




*Data source*: ERA-40 Reanalysis

# But there are large seasonal migrations

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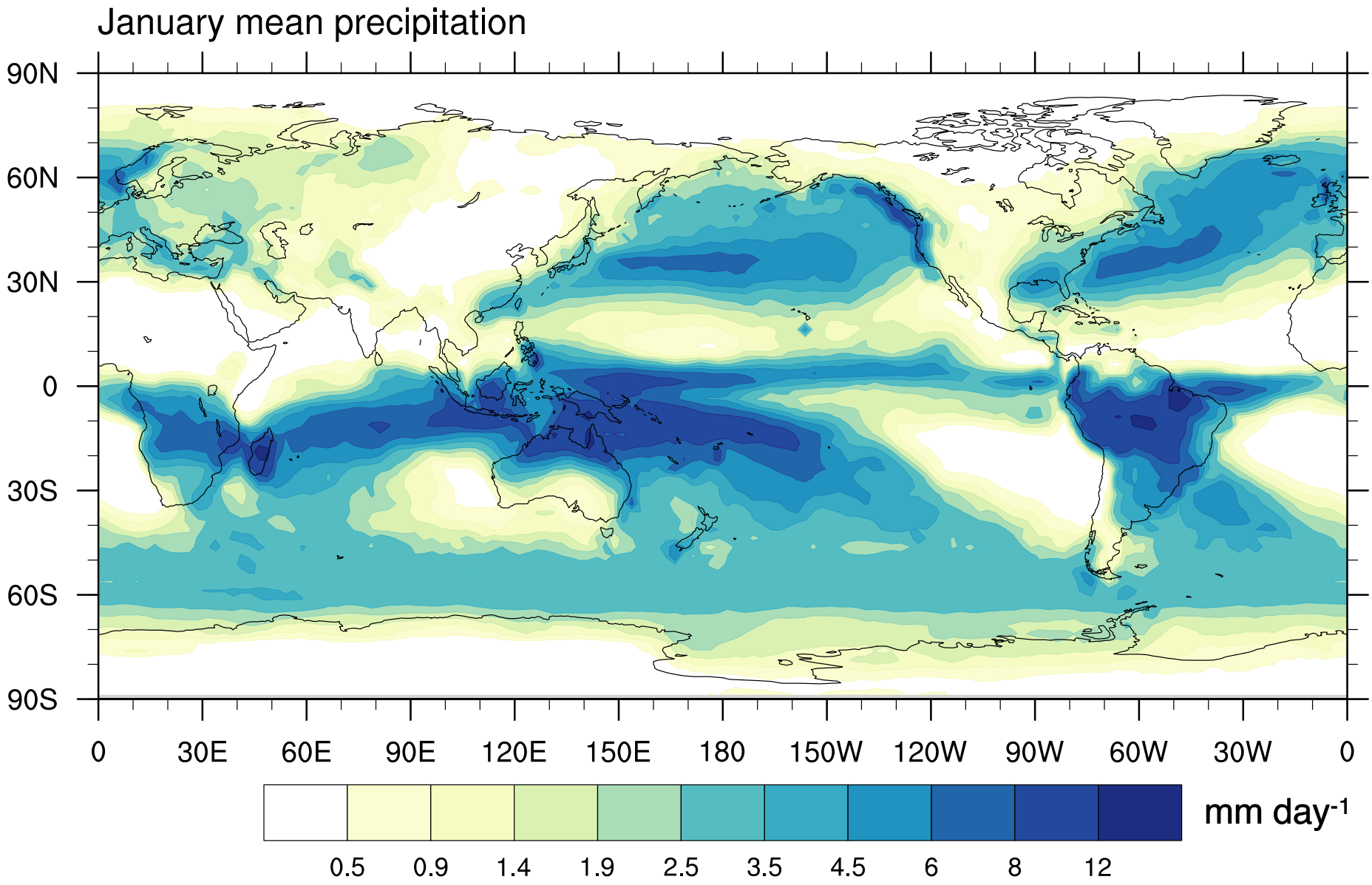


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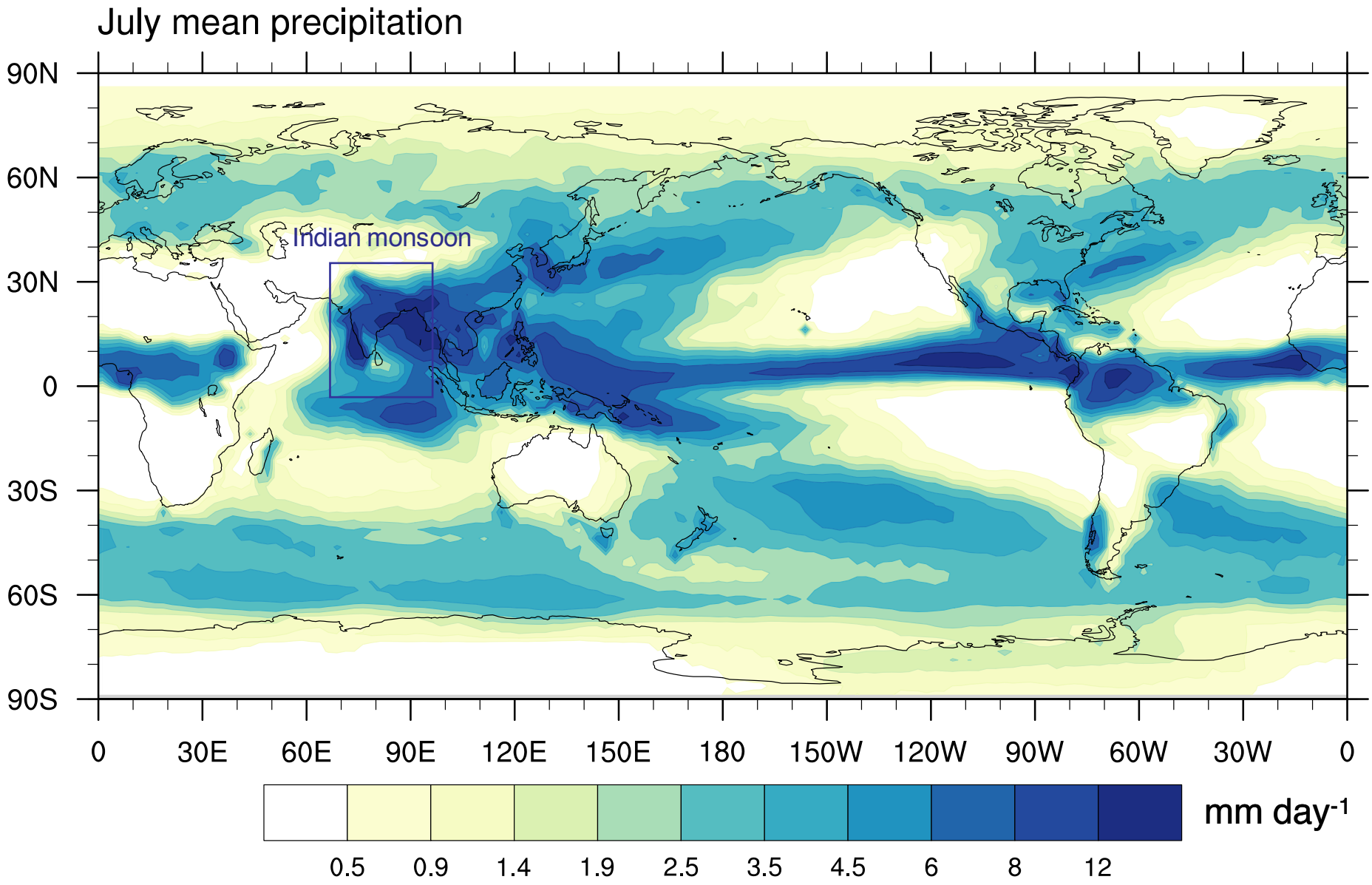


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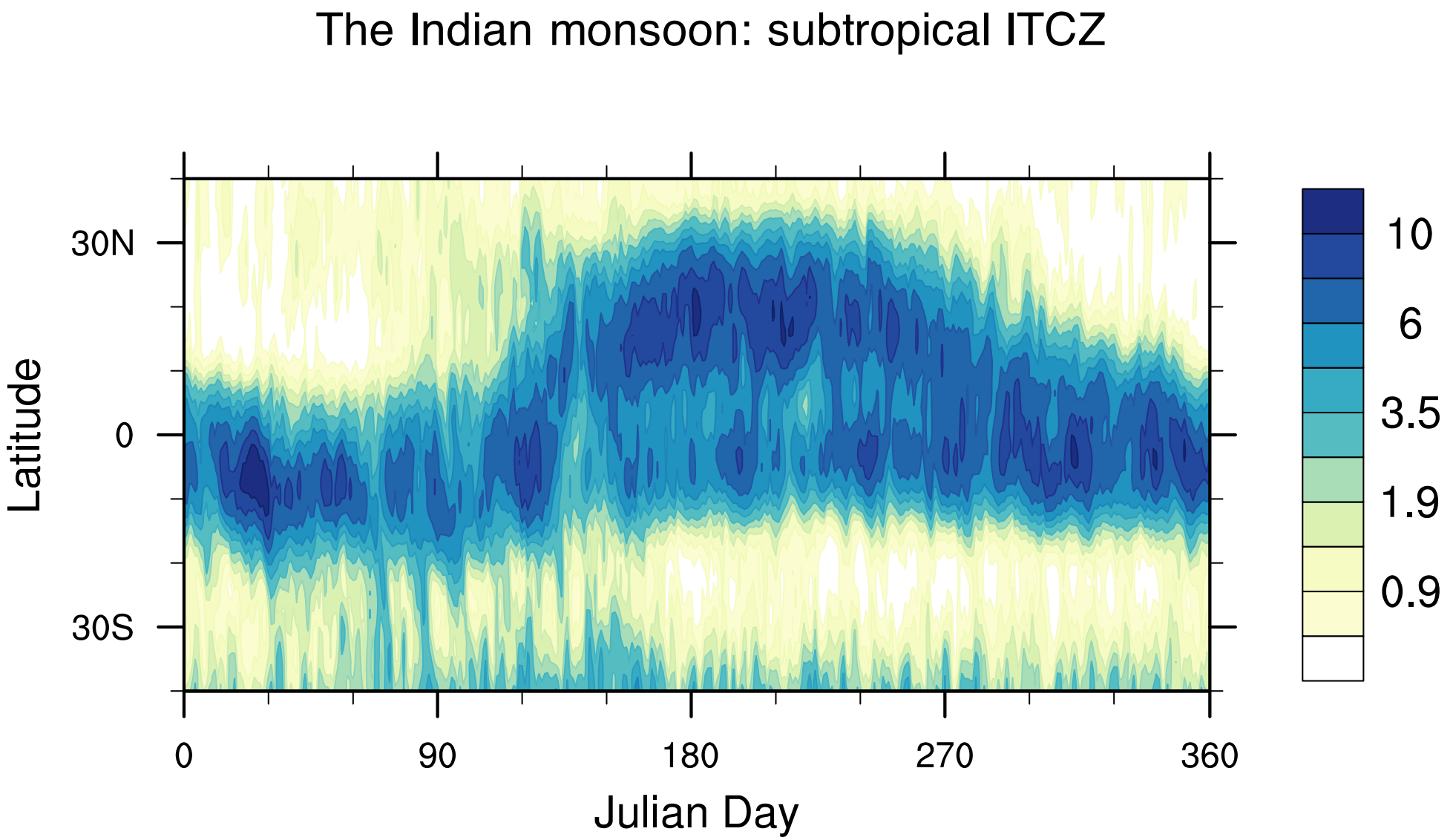
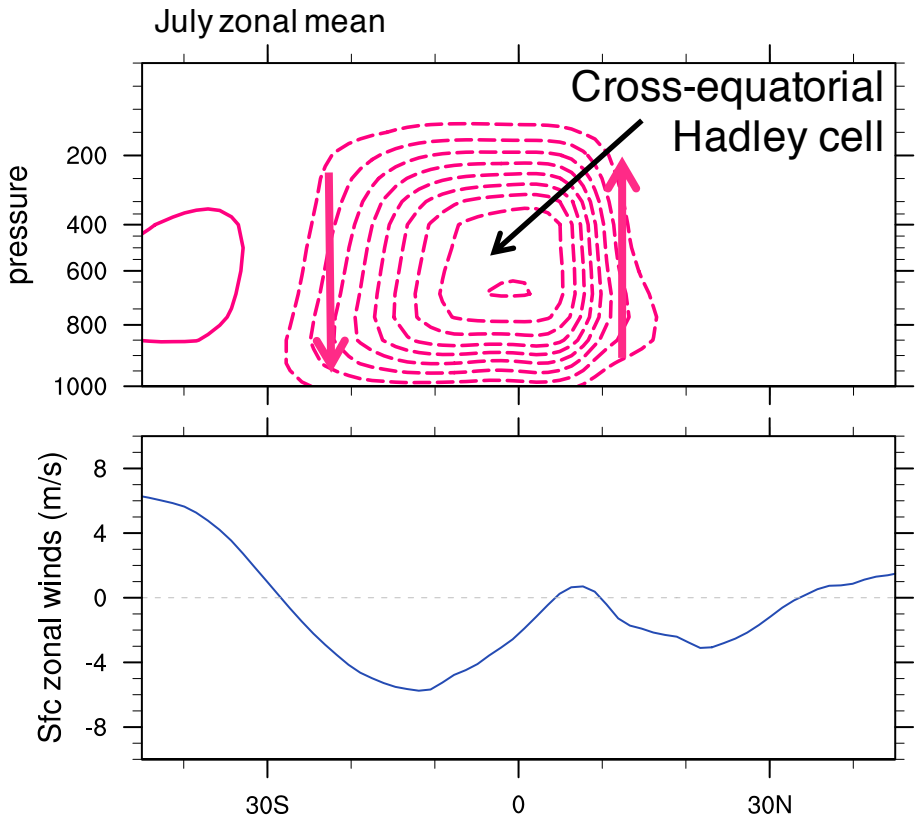
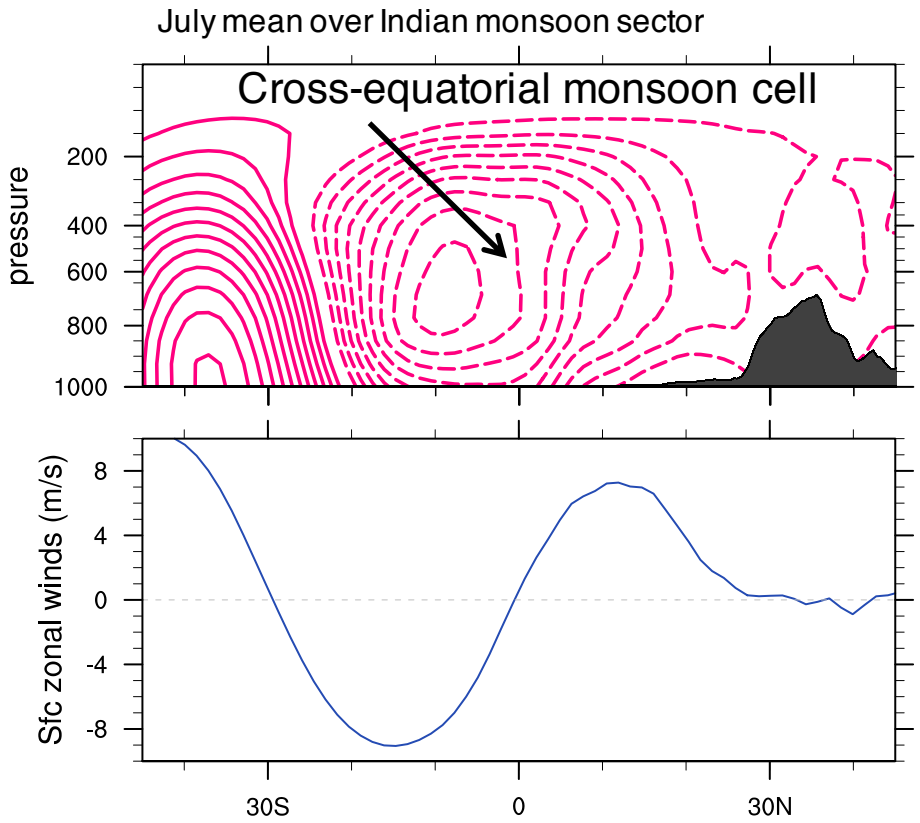



*Data source*: GPCP 1DD

# The Indian monsoon: regional cross-equatorial Hadley cell

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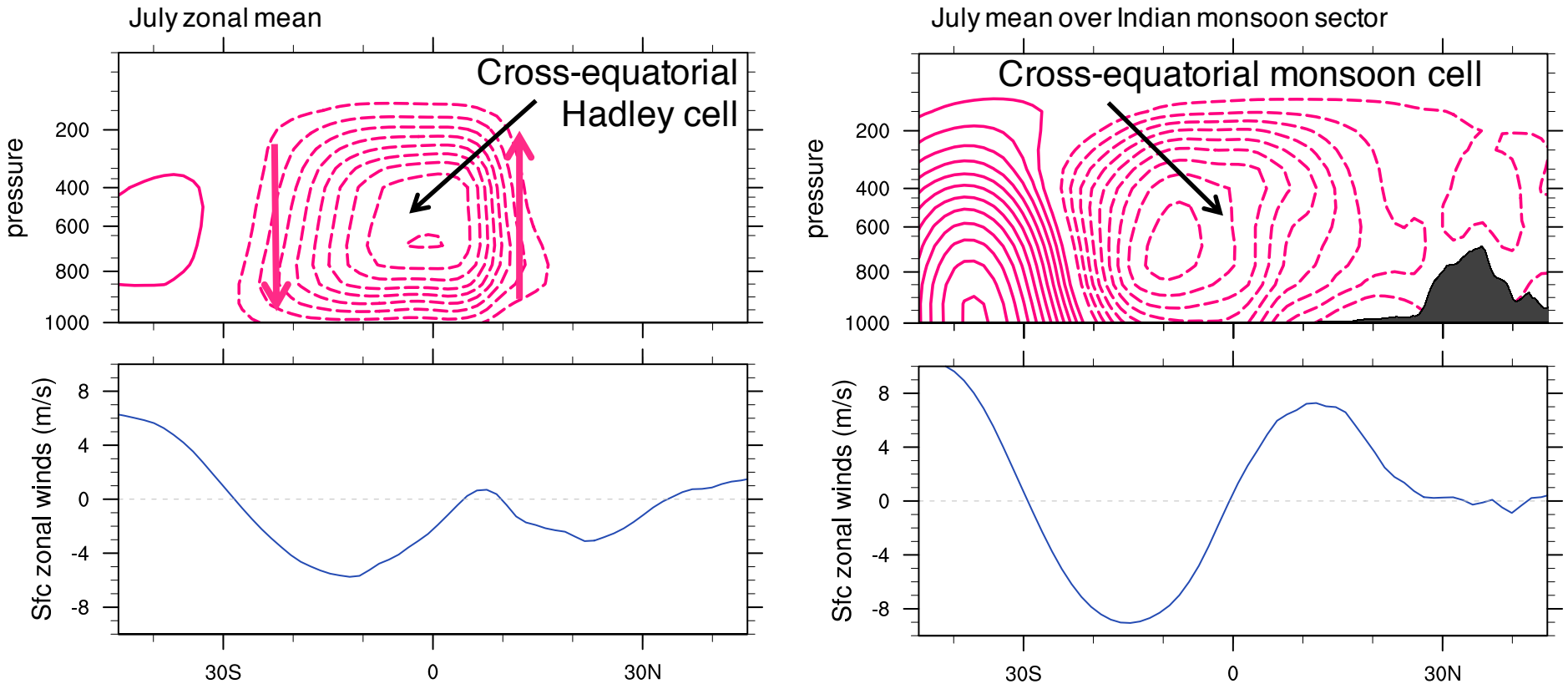


Monsoon circulations are cross-equatorial Hadley circulations that project strongly on the solstice zonal mean

e.g, Bordoni & Schneider (2008), Walker, Bordoni & Schneider (2015), Walker & Bordoni (2016)

# Theories for ITCZ position

1) Thermodynamic theories:
   - Convective QE predicts ITCZ to be just equatorward of the maximum in lower-level moist static energy (local forcing)
   - Atmospheric energy budget emphasizes anti-correlation between the cross-equatorial atmospheric energy transport and the ITCZ location (remote forcing)

2) Dynamic theories:
   - Angular-momentum conserving theories of Hadley cells
   - Boundary-layer momentum budget

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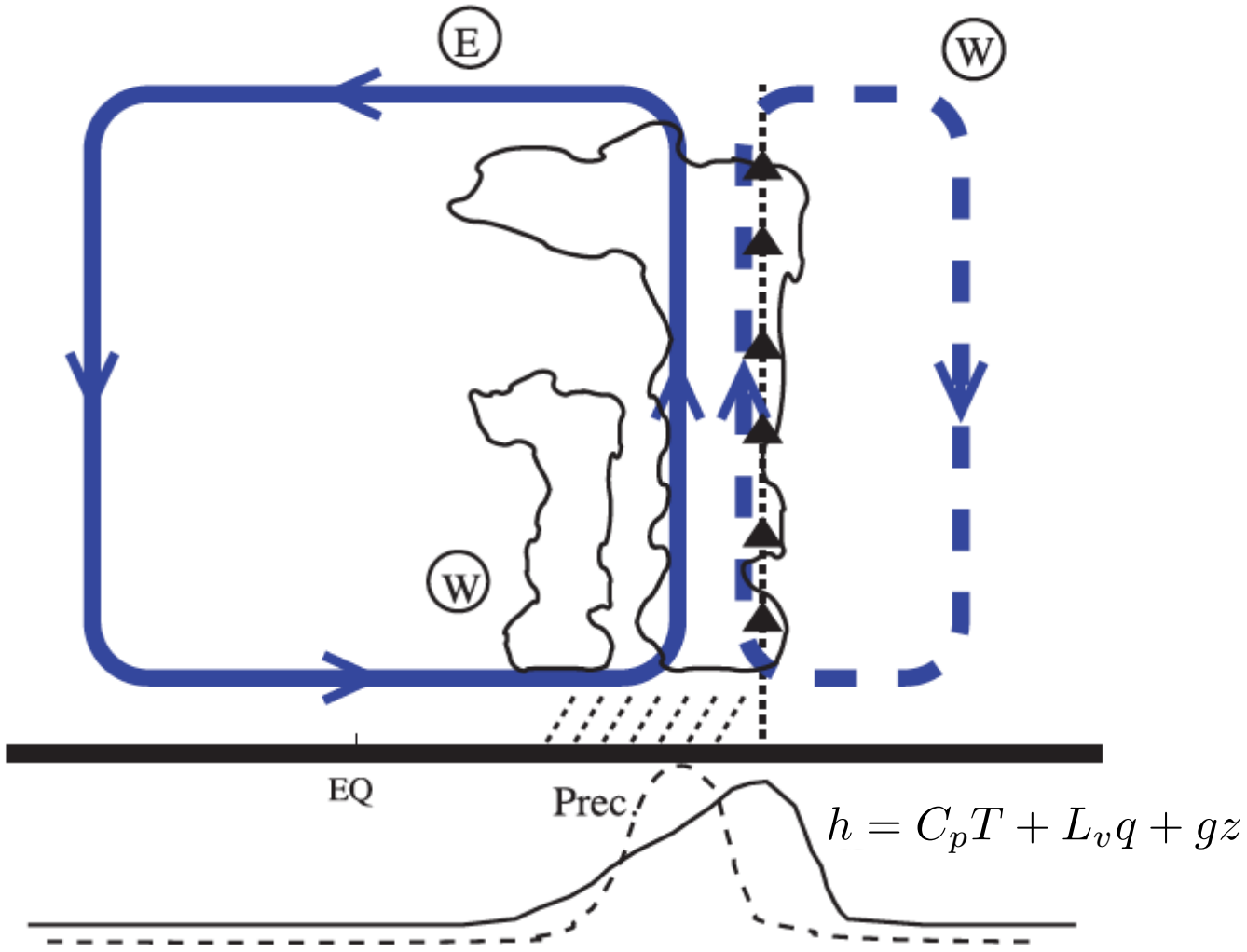
# Convective QE view




e.g., Emanuel et al. (1994), Emanuel (1995), Prive and Plumb (2007), Nie et al. (2010)

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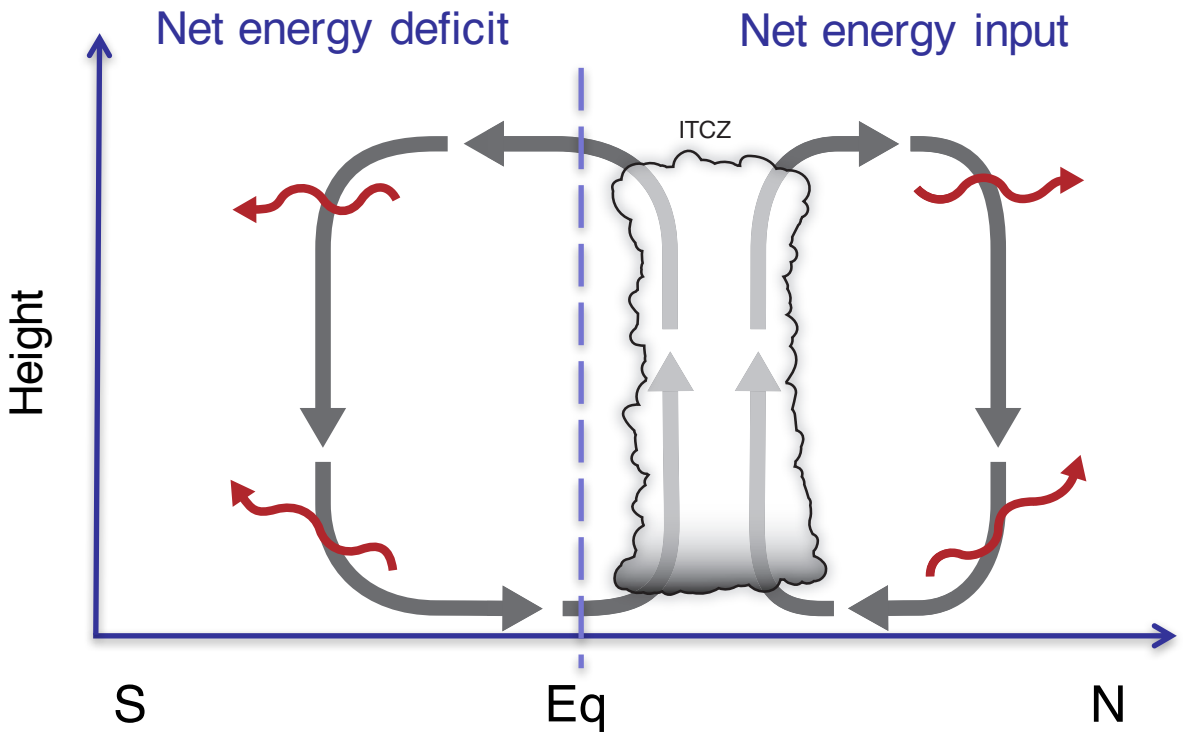
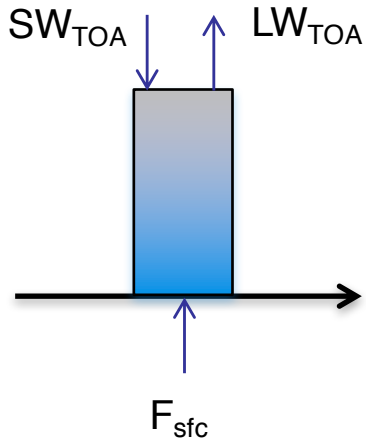
# Atmospheric energy budget




Adapted from Schneider et al. 2014

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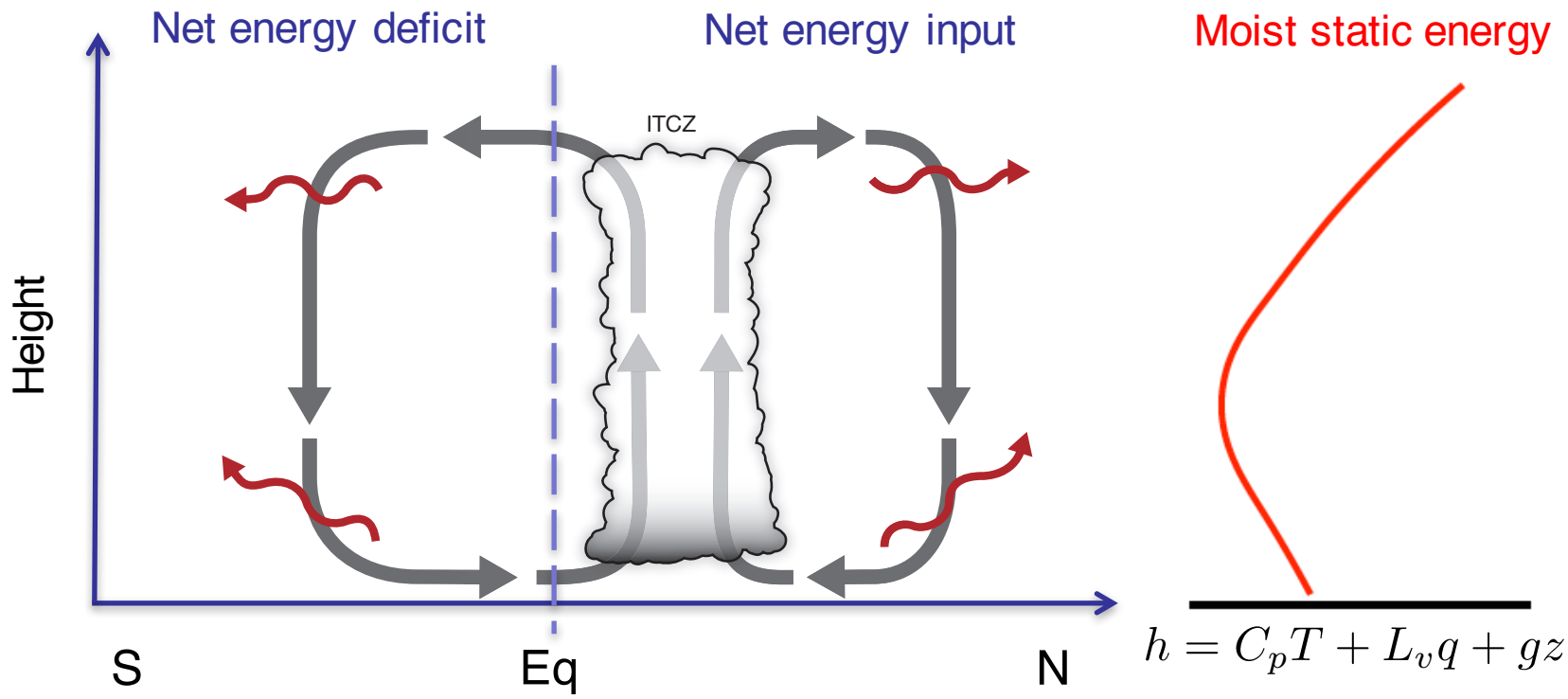


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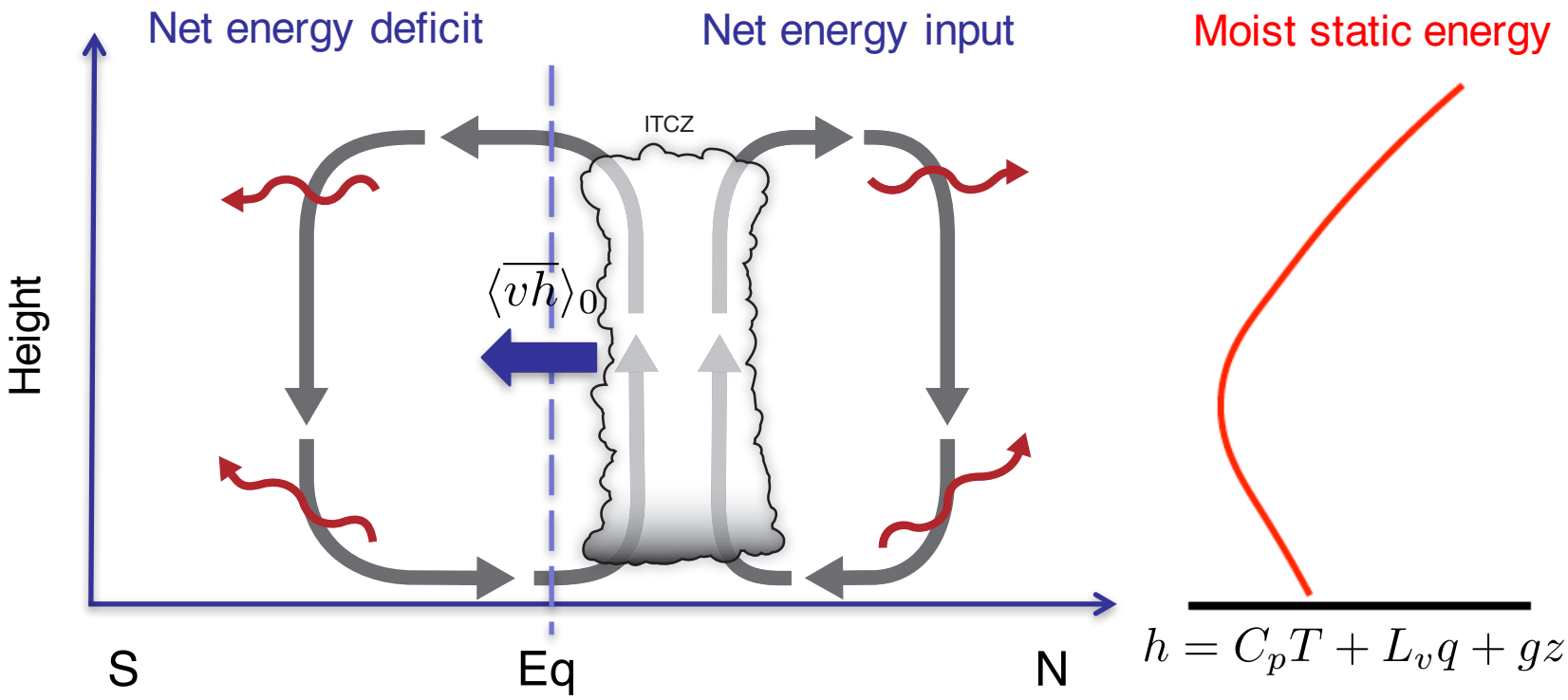


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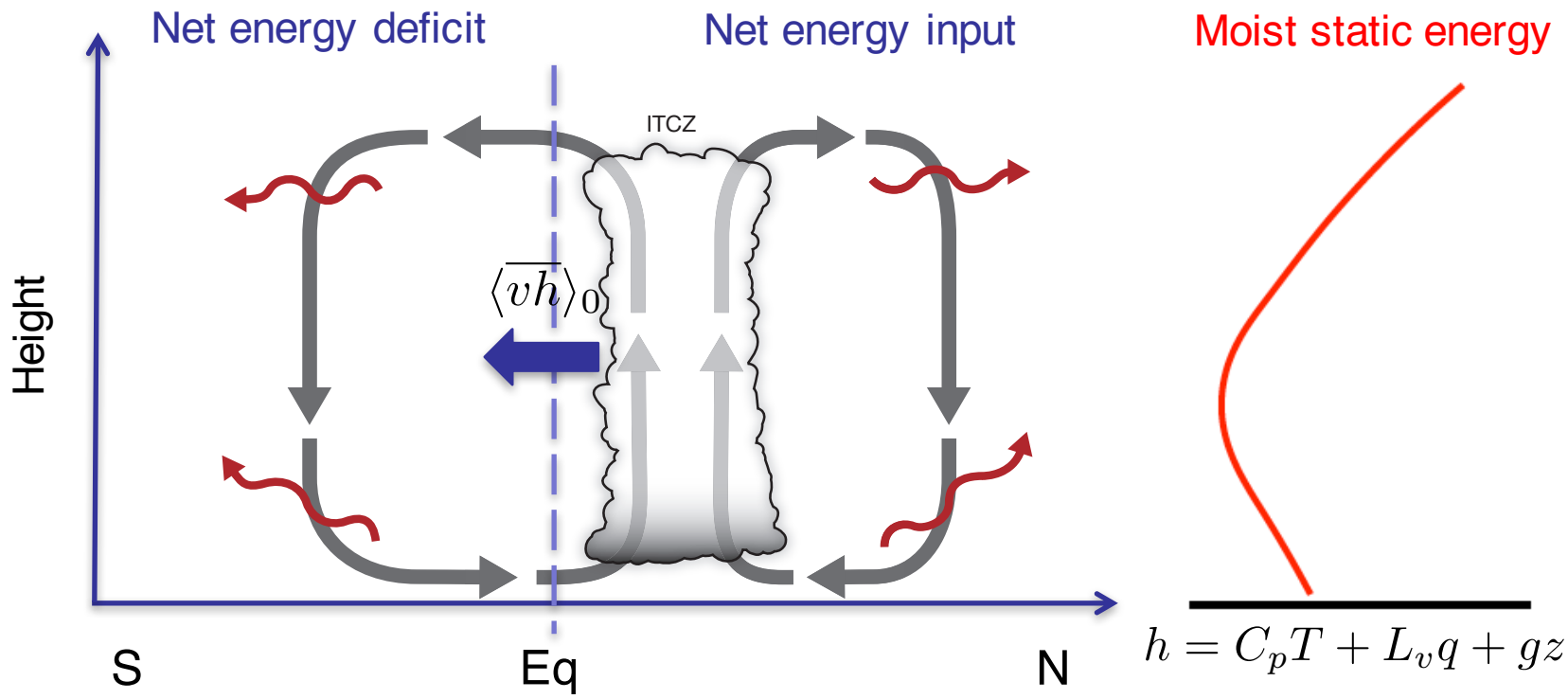
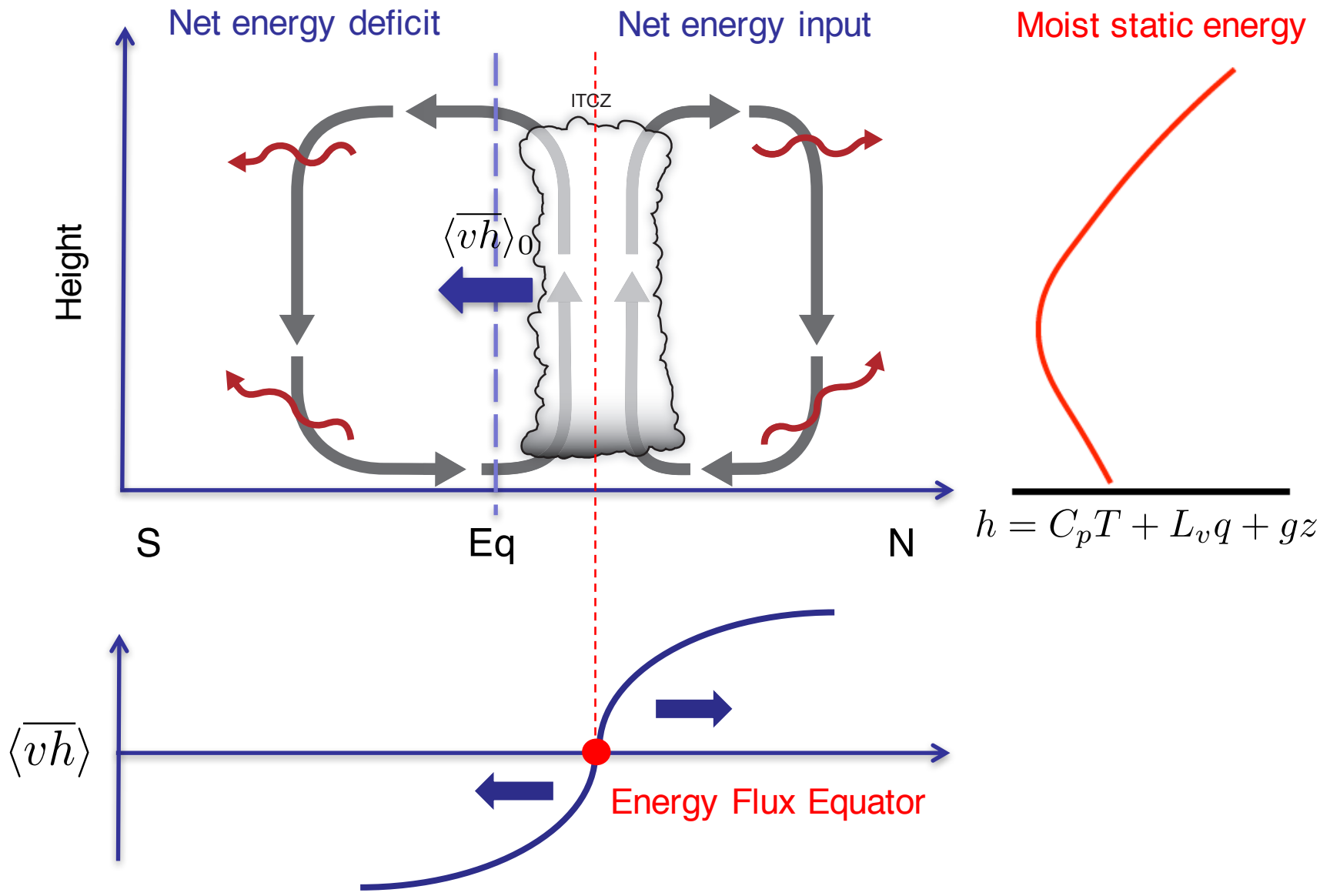



ITCZ position is anti-correlated with the cross-equatorial energy transport $\langle \overline{vh} \rangle_0$

e.g., Kang et al. 2008, Hwang and Frierson 2012, Donohoe et al. 2013, Bischoff and Schneider 2014

# Atmospheric energy budget

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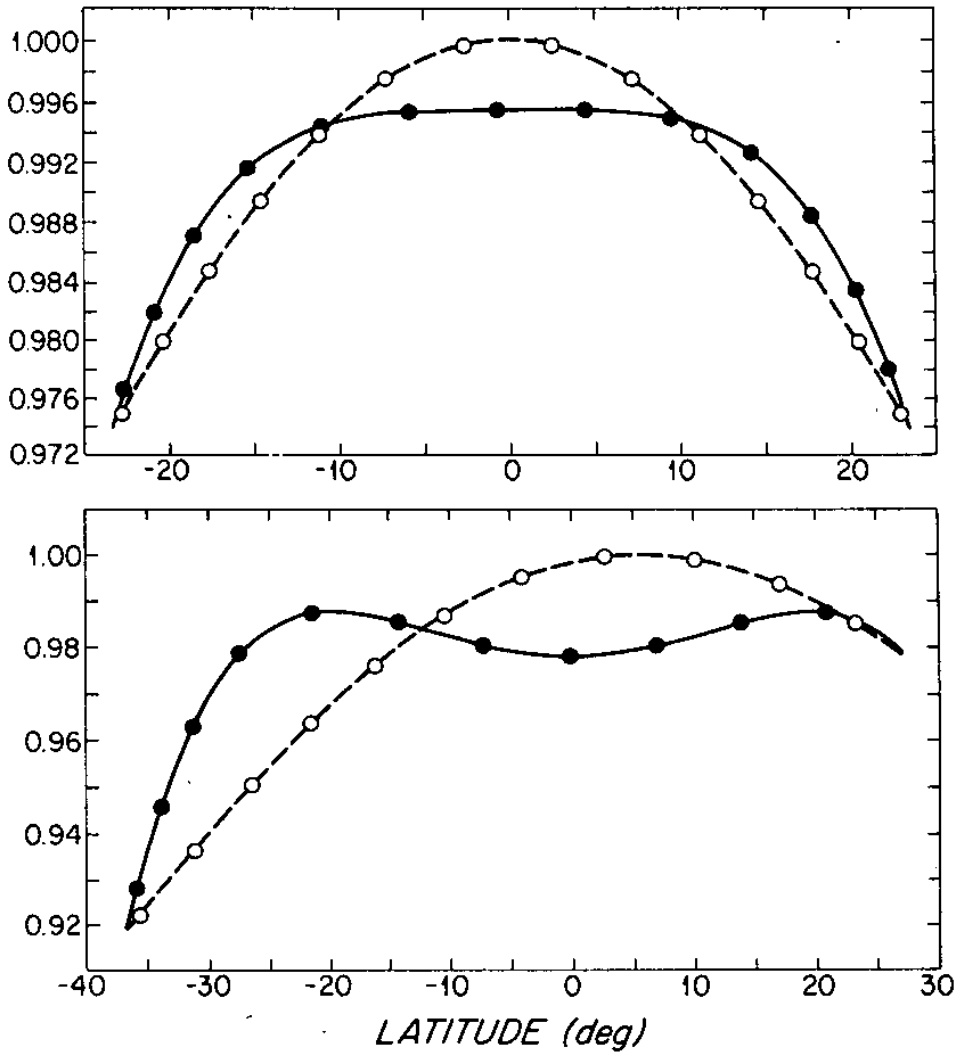
# Angular momentum conserving theories




$$\phi_H \propto \frac{1}{\Omega a}$$

$$\phi_H \propto \Omega^{-\frac{2}{3}}$$

e.g., Held and Hou (1980), Lindzen and Hou (1988), Caballero et al. (2008)

# Theories for ITCZ position

1) Thermodynamic theories:
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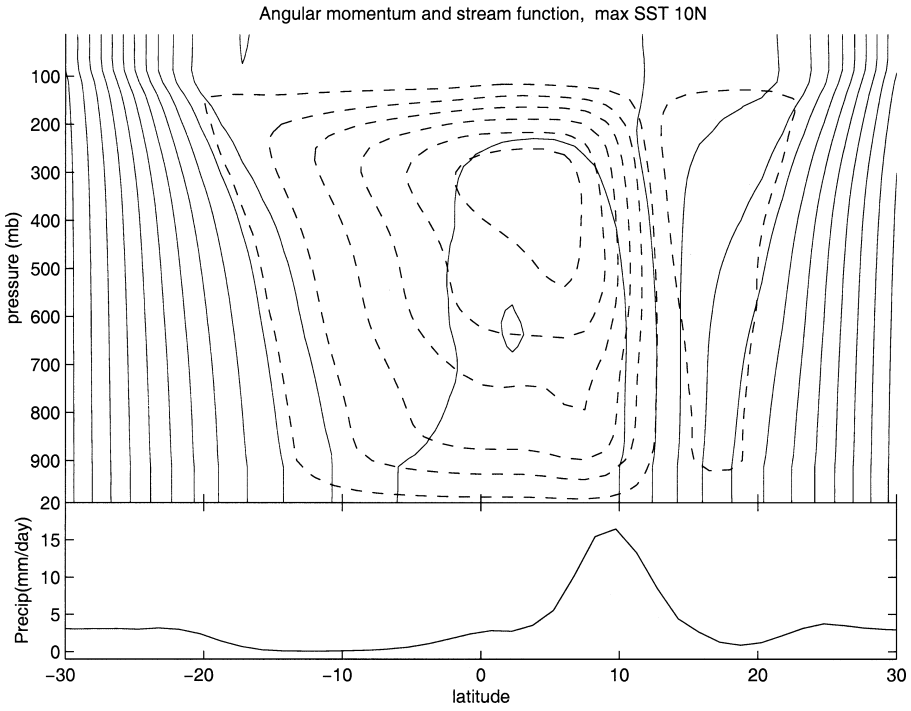
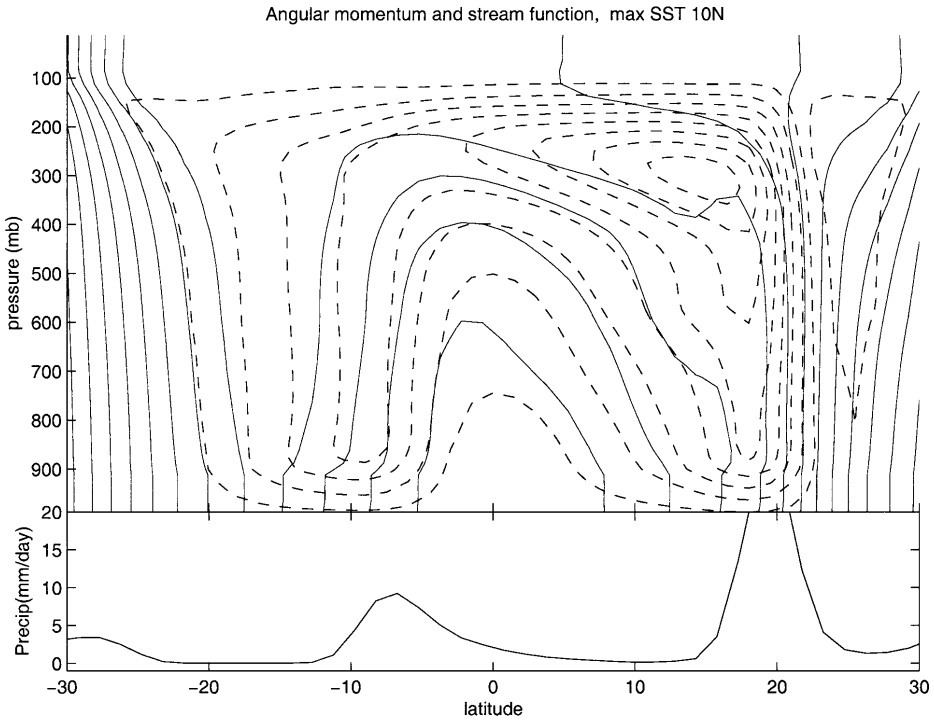
# Boundary-layer momentum budget



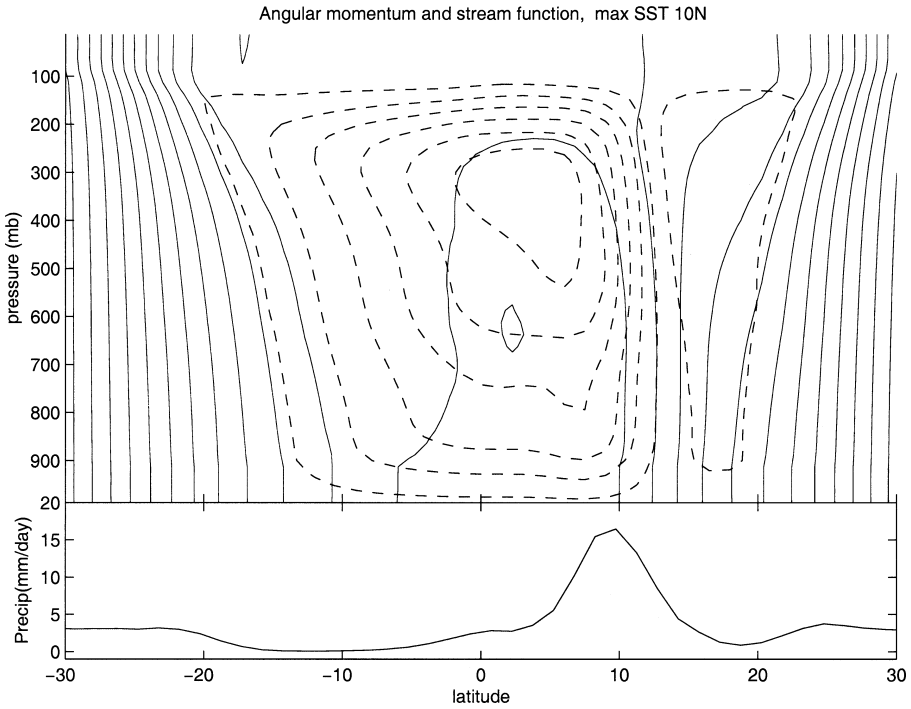




Cross-equatorial mass flux in boundary layer is constrained by the BL momentum budget

Pauluis 2004

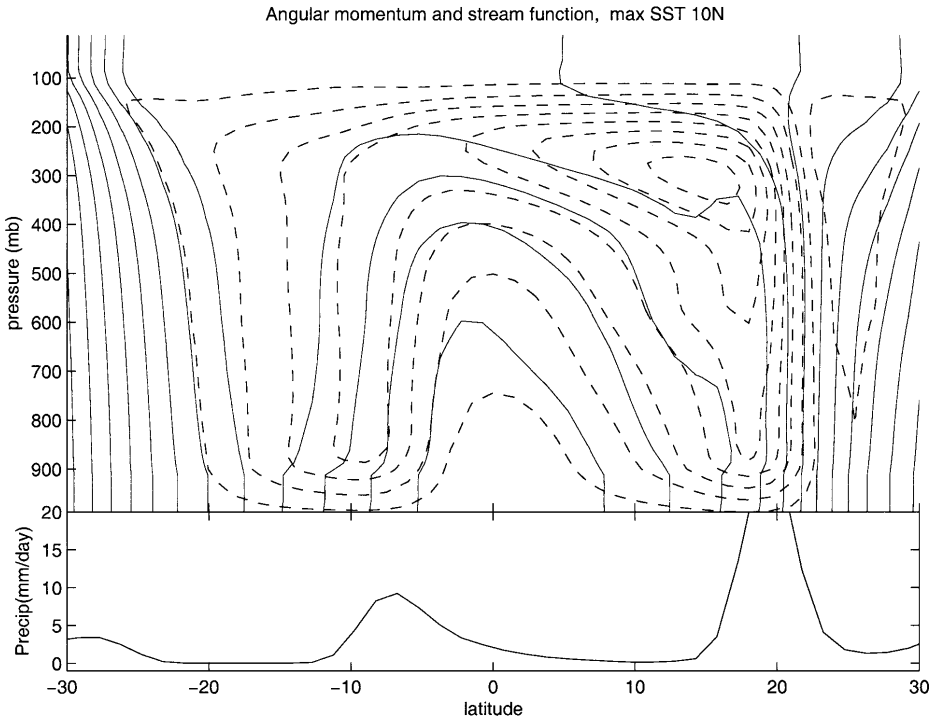
# Boundary-layer momentum budget

## Deep BL and/or strong T gradient




Single ITCZ

## Shallow BL and/or weak T gradient




Pauluis 2004

# Boundary-layer momentum budget

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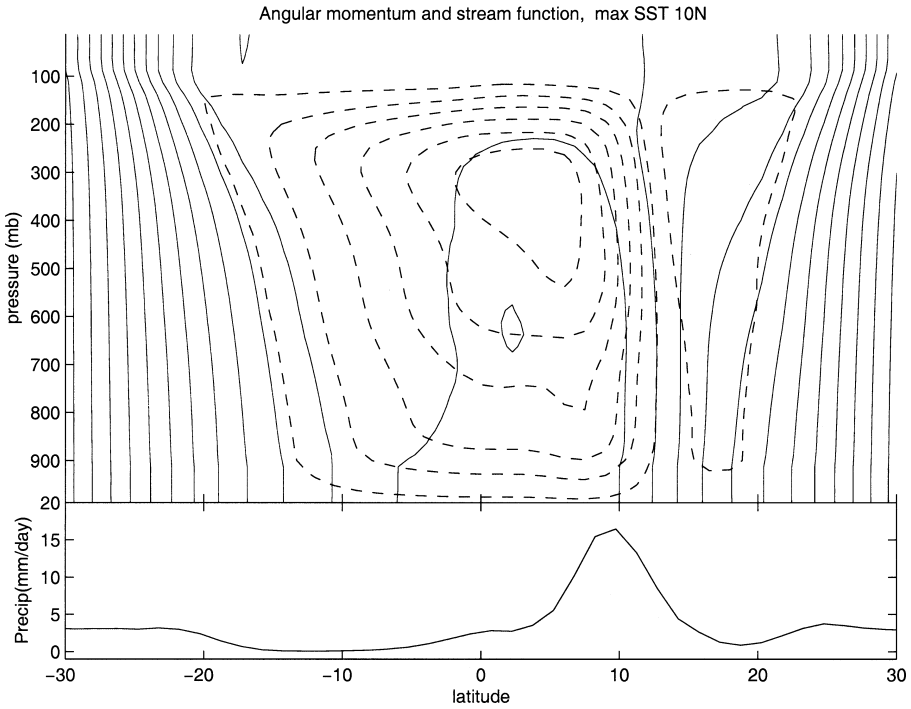


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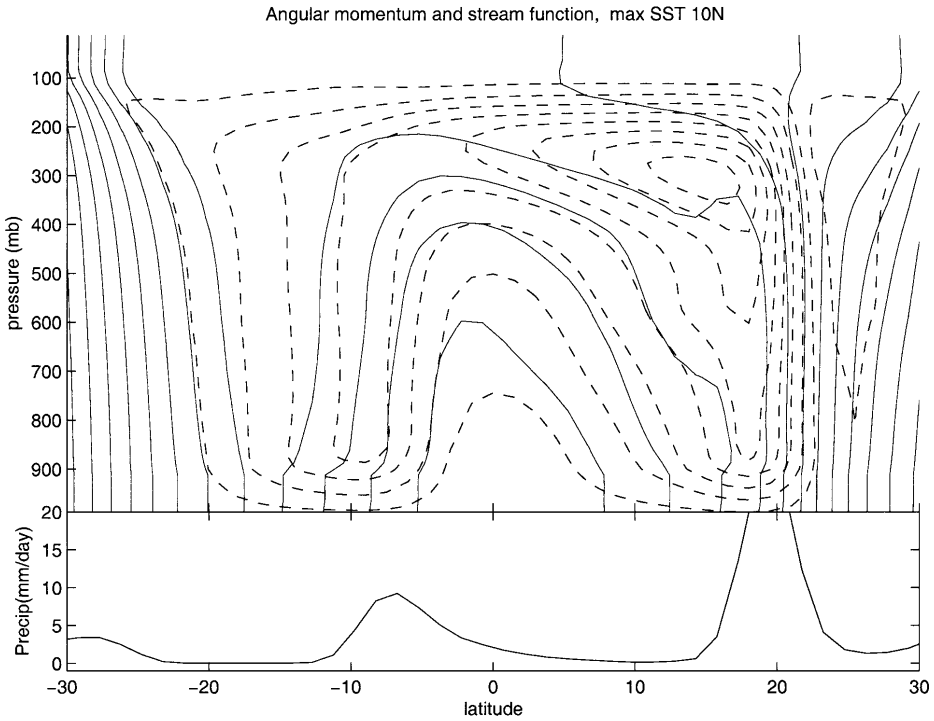


Double ITCZ

Pauluis 2004

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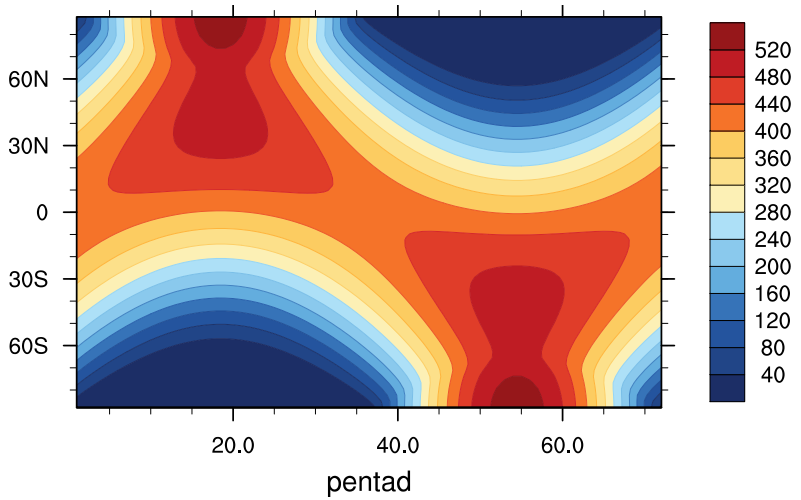
Is there really no role for BL dynamical constraints on the ITCZ position?

# Simulations with an aquaplanet GCM

Model: Idealized Caltech GCM (e.g, O'Gorman and Schneider 2008, Bordoni and Schneider 2008)

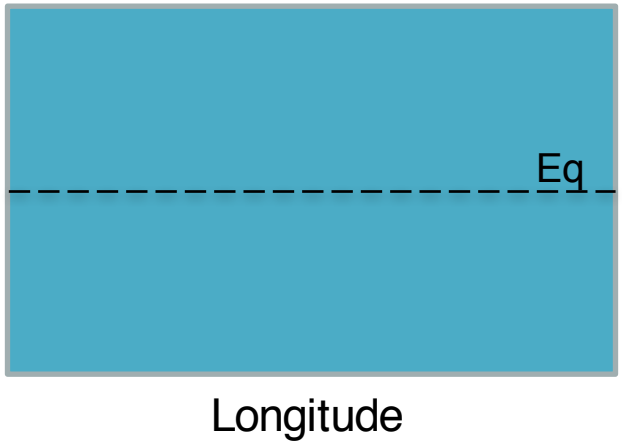
- Simplified Betts-Miller convection scheme;
- Grey radation (no clouds, no water vapor feedback);
- Slab ocean;
- Seasonal cycle of insolation with 360 days



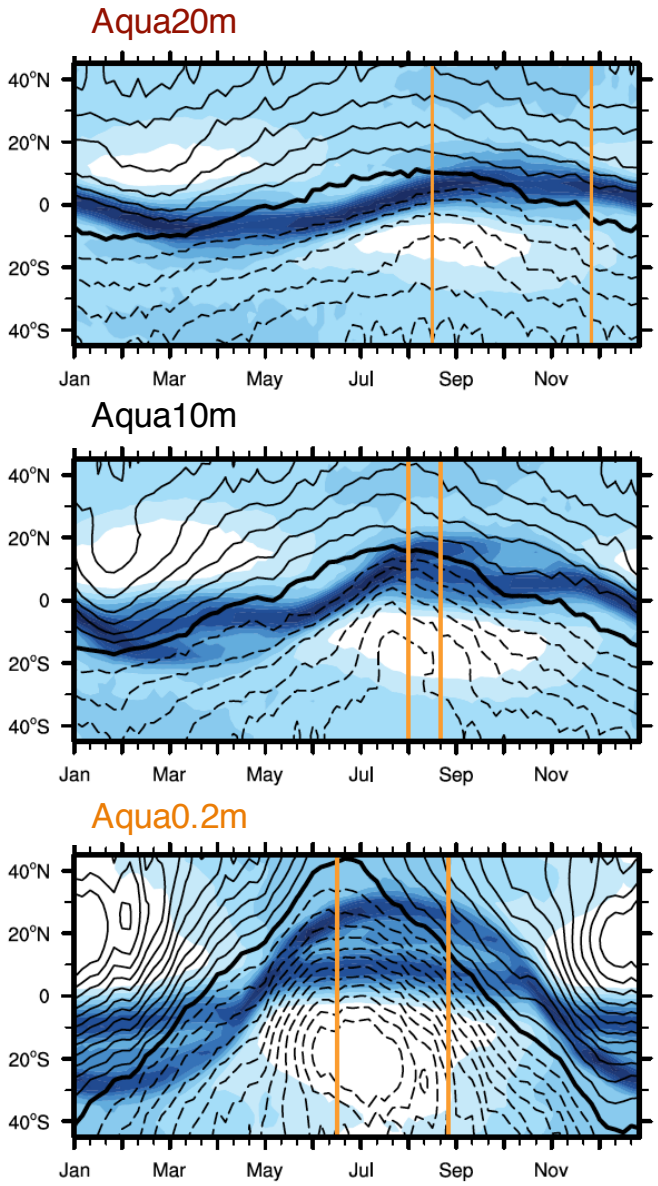

Experimental design:

- Aquaplanet with different mixed layer depths (Aqua20m, Aqua10m, Aqua0.2m)

**Mixed layer depth: 20/10/0.2 m**



# Simulations with an aquaplanet GCM

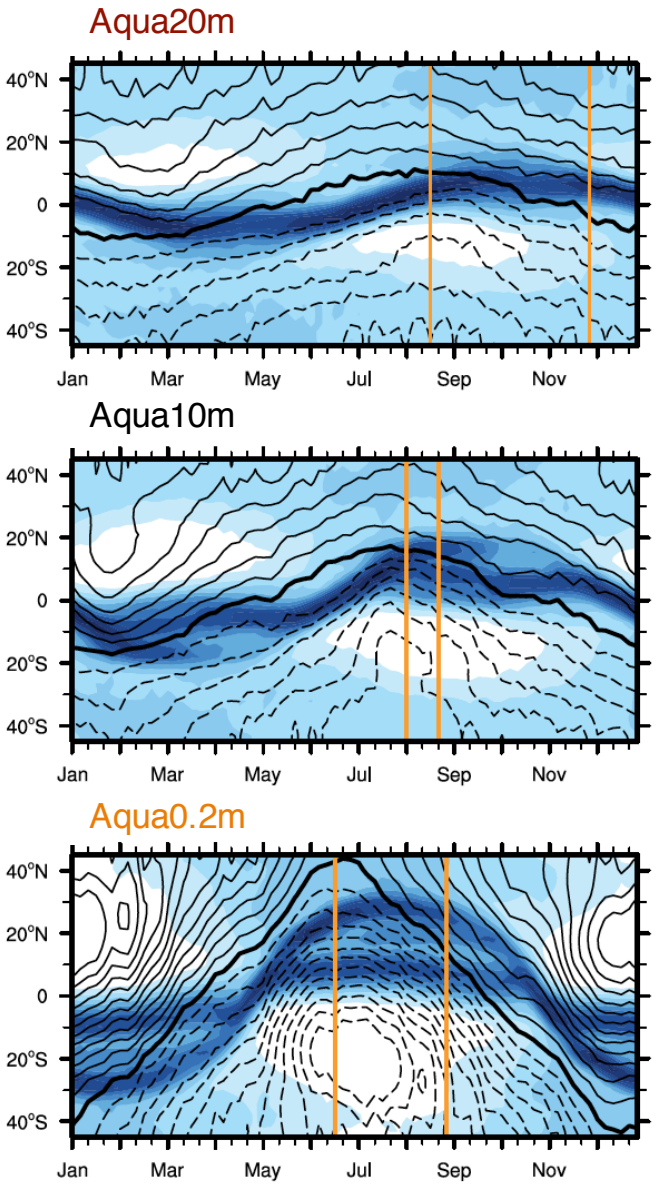



Contour: $\langle \overline{vh} \rangle$

Shading: Precip

Wei and Bordoni 2018, *in press*

# Simulations with an aquaplanet GCM



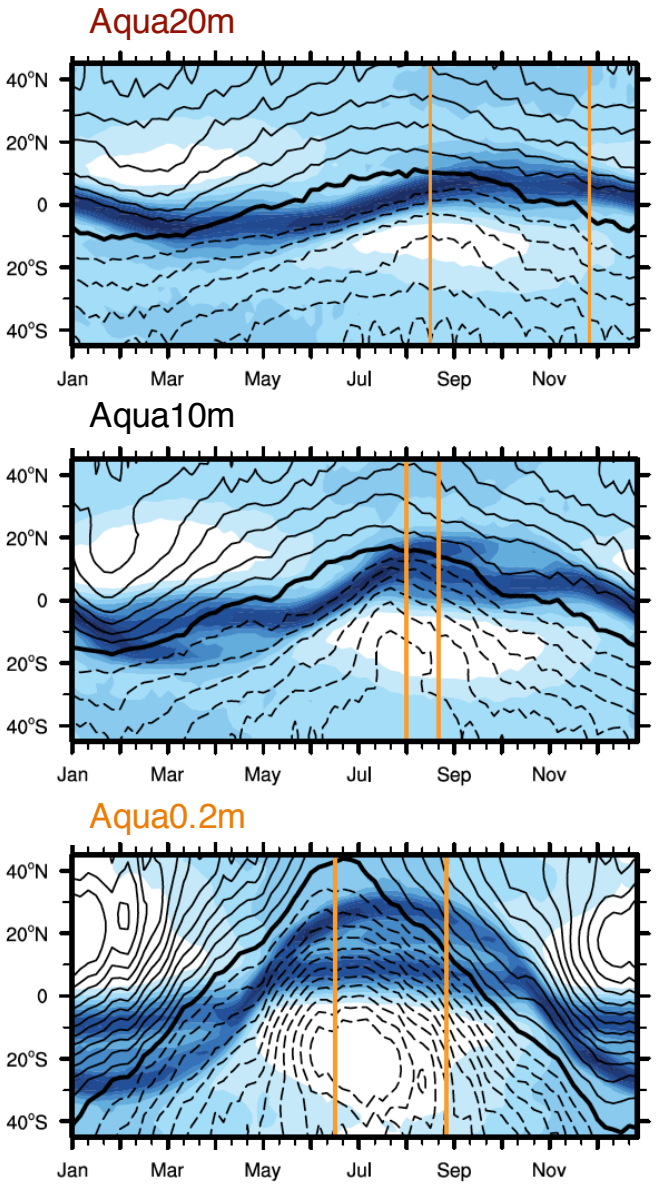

The EFE always leads the ITCZ, even in the simulation with the shallowest mixed layer depth

Contour: $\langle \overline{vh} \rangle$

Shading: Precip

Wei and Bordoni 2018, *in press*

# Simulations with an aquaplanet GCM




Latitude

| Phase (day) | EFE | $P_{max}$ | EFE-$P_{max}$ |
|---|---|---|---|
| Aqua20m | 136 | 198.55 | **-62.55** |
| Aqua10m | 121.9 | 162.45 | **-40.55** |
| Aqua0.2m | 90.65 | 119.1 | **-28.45** |

Contour: $\langle \overline{vh} \rangle$

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Wei and Bordoni 2018, *in press*

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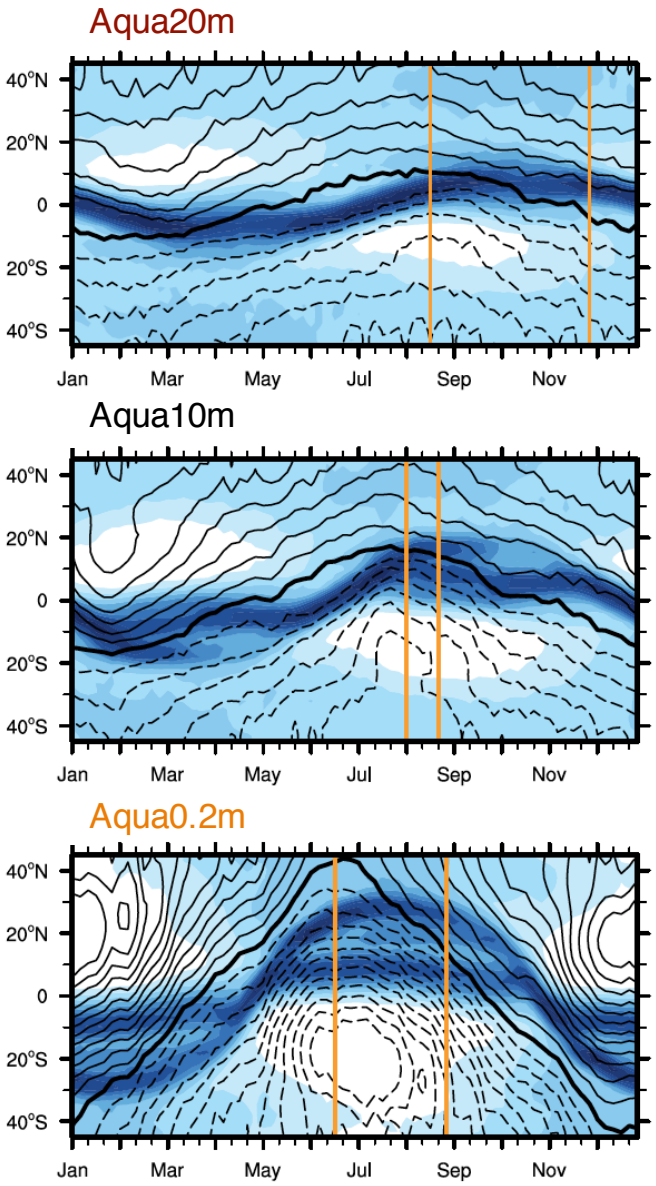


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There are times during the seasonal cycle when EFE and ITCZ reside on opposite sides of the equator.

Contour: $\langle \overline{vh} \rangle$

Shading: Precip

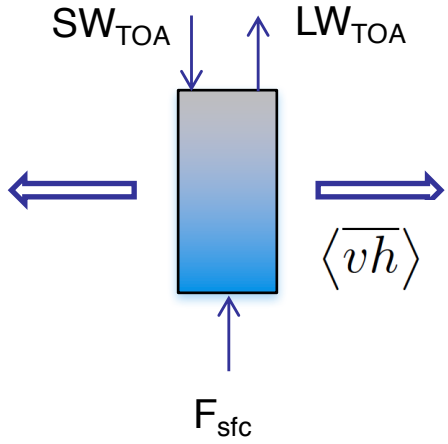
Wei and Bordoni 2018, *in press*

# Seasonal cycle of EFE and ITCZ

Energy budget

$$\partial_y \left\langle \overline{vh} \right\rangle = R - F_{\text{surf}} = F^{\text{net}} - \frac{\partial \left\langle \overline{e} \right\rangle}{\partial t} = NEI_{\text{eff}}$$

Strong divergence occurs in regions of positive net energy input




Wei and Bordoni 2018, *in press*

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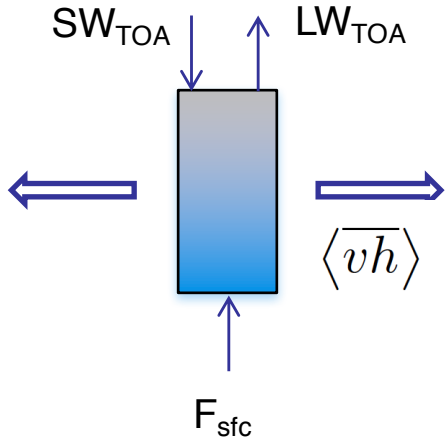


Strong divergence occurs in regions of positive net energy input

Energy flux equator is a meridional integral measure

$$\begin{aligned}
\langle \overline{vh} \rangle_{T,\phi_{EFE}} &= 2\pi \int_{SP}^{\varphi_{EFE}} \text{NEI}_{\text{eff}} cos\phi a^2 d\phi \\
&= 2\pi \int_{\phi_{EFE}}^{NP} \text{NEI}_{\text{eff}} cos\phi a^2 d\phi \\
&= 0.
\end{aligned}$$

Wei and Bordoni 2018, *in press*

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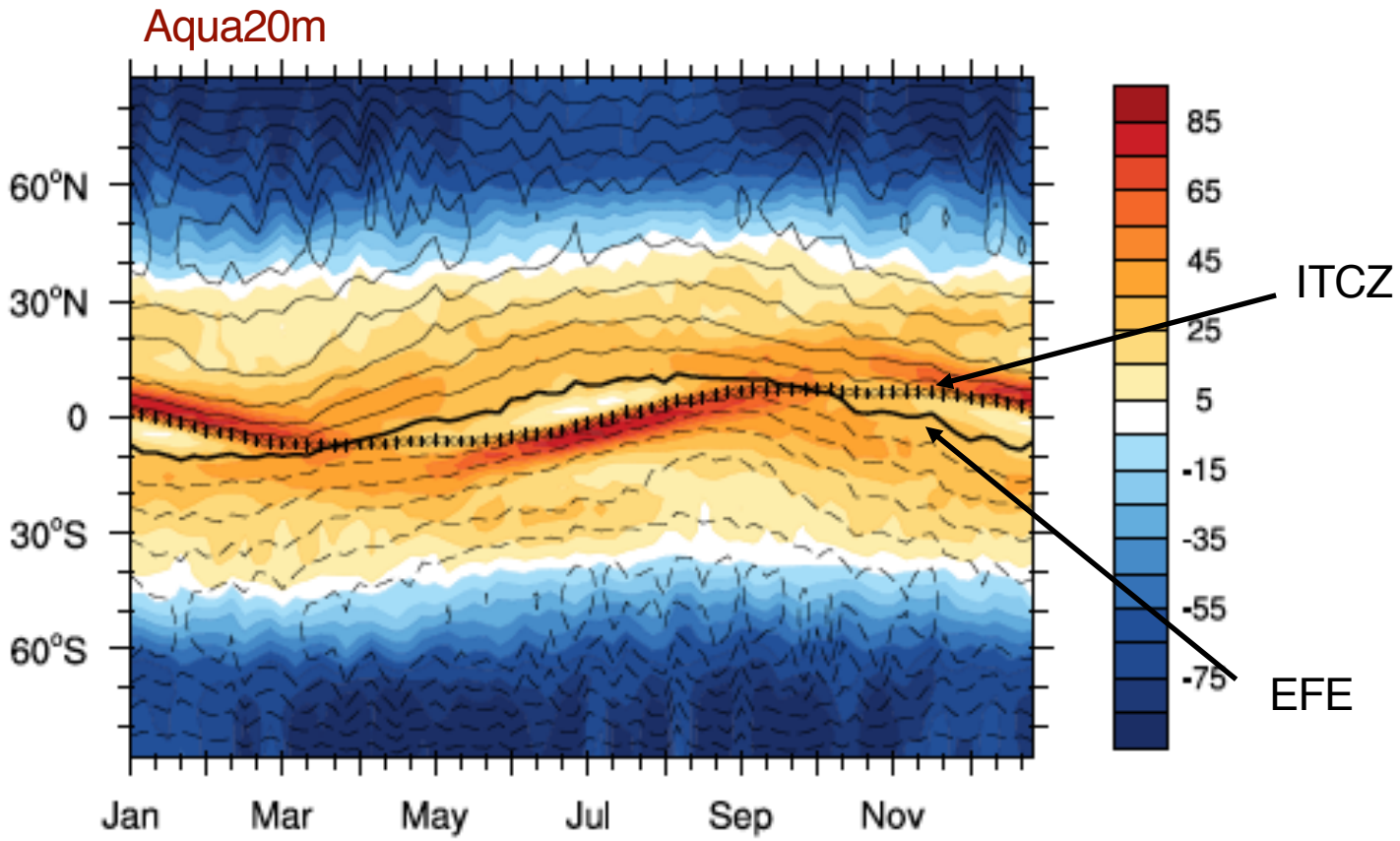


Contour: $\langle \overline{vh} \rangle$

Shading: $NEI_{eff}$

Wei and Bordoni 2018, *in press*

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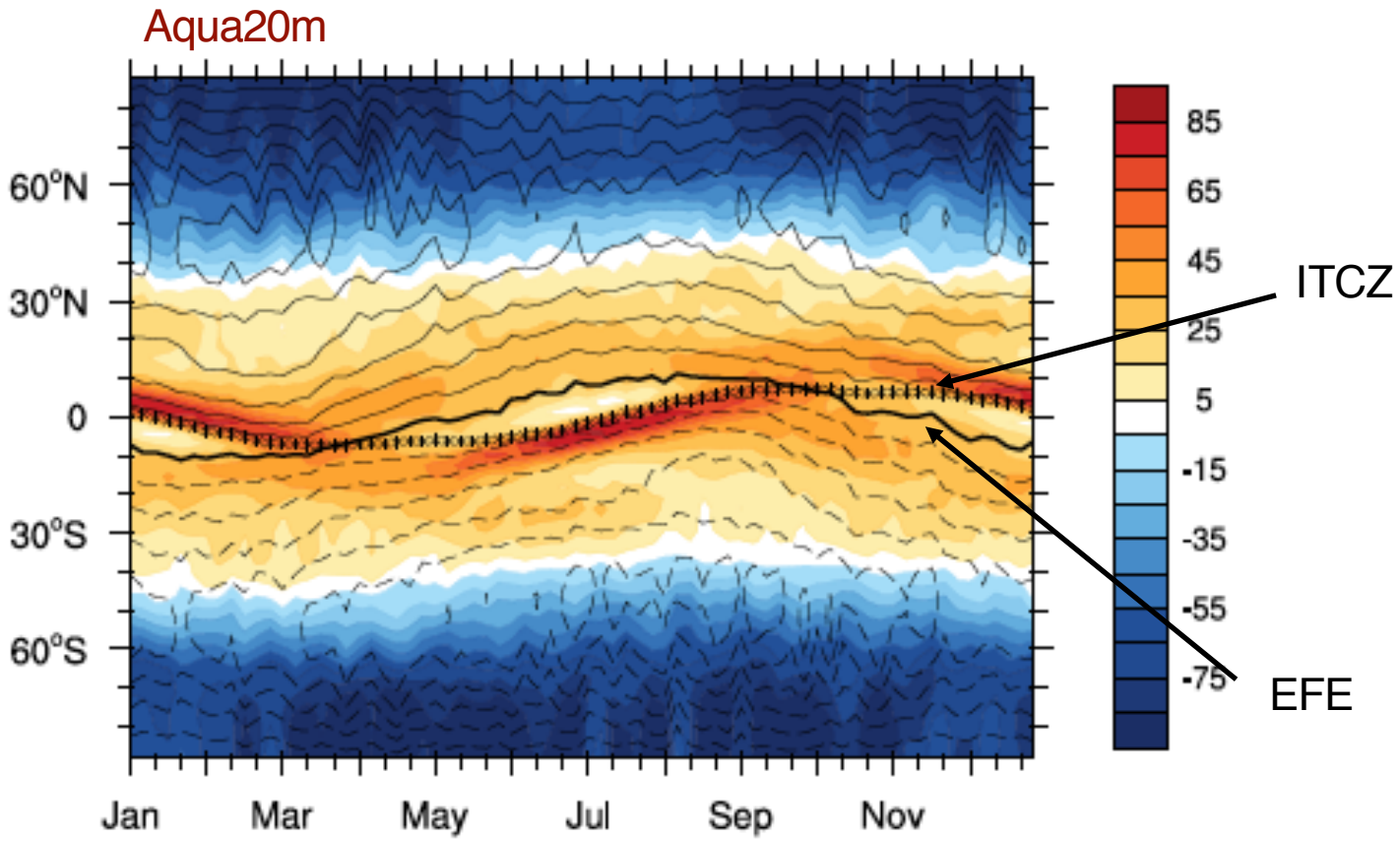
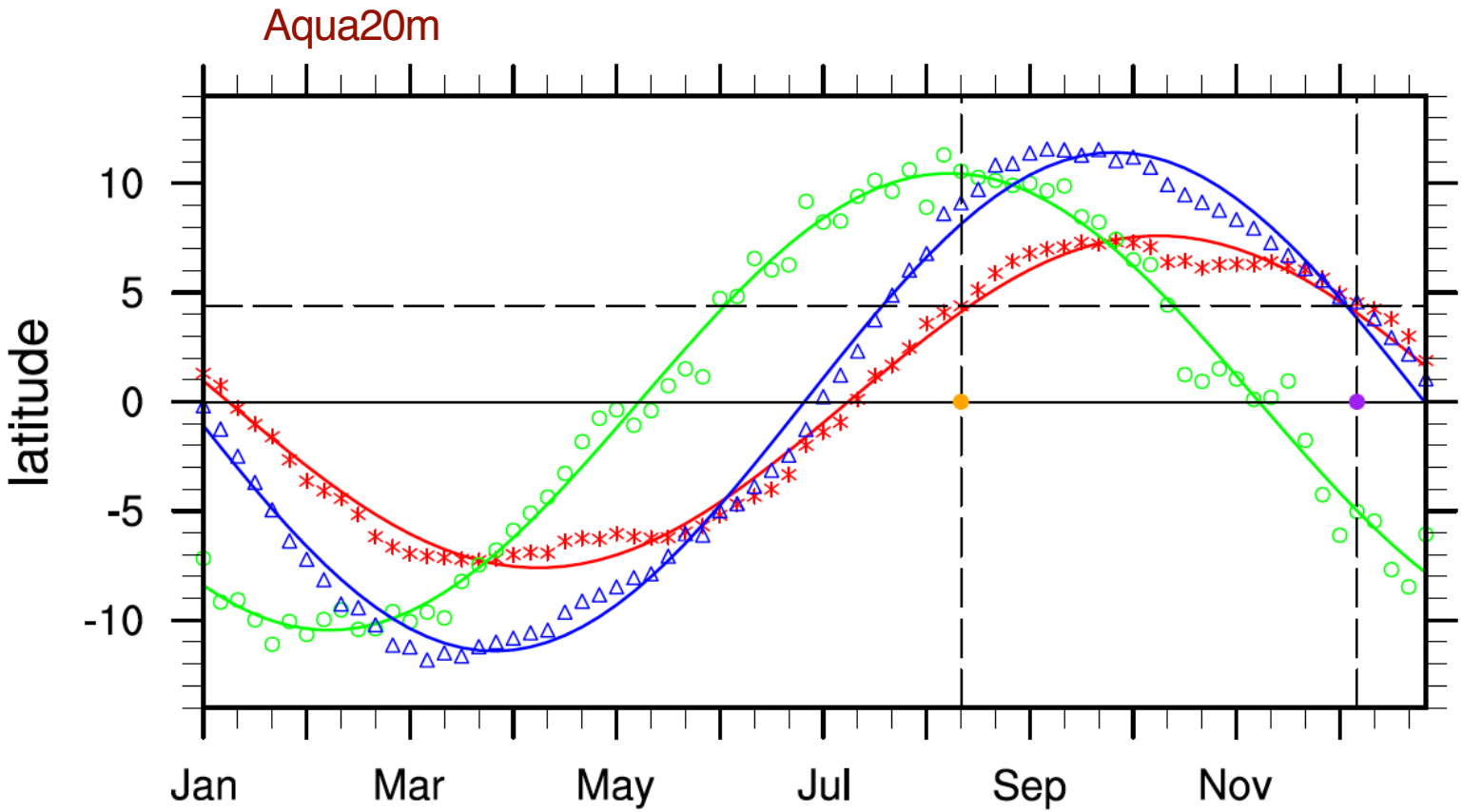



Phase offset between EFE and ITCZ arises from phase offset between insolation and surface temperature

Wei and Bordoni 2018, *in press*

# What happens when EFE and ITCZ are in opposite hemisphere?




EFE

Poleward boundary of the cross-equatorial Hadley cell

ITCZ

Wei and Bordoni 2018, *in press*

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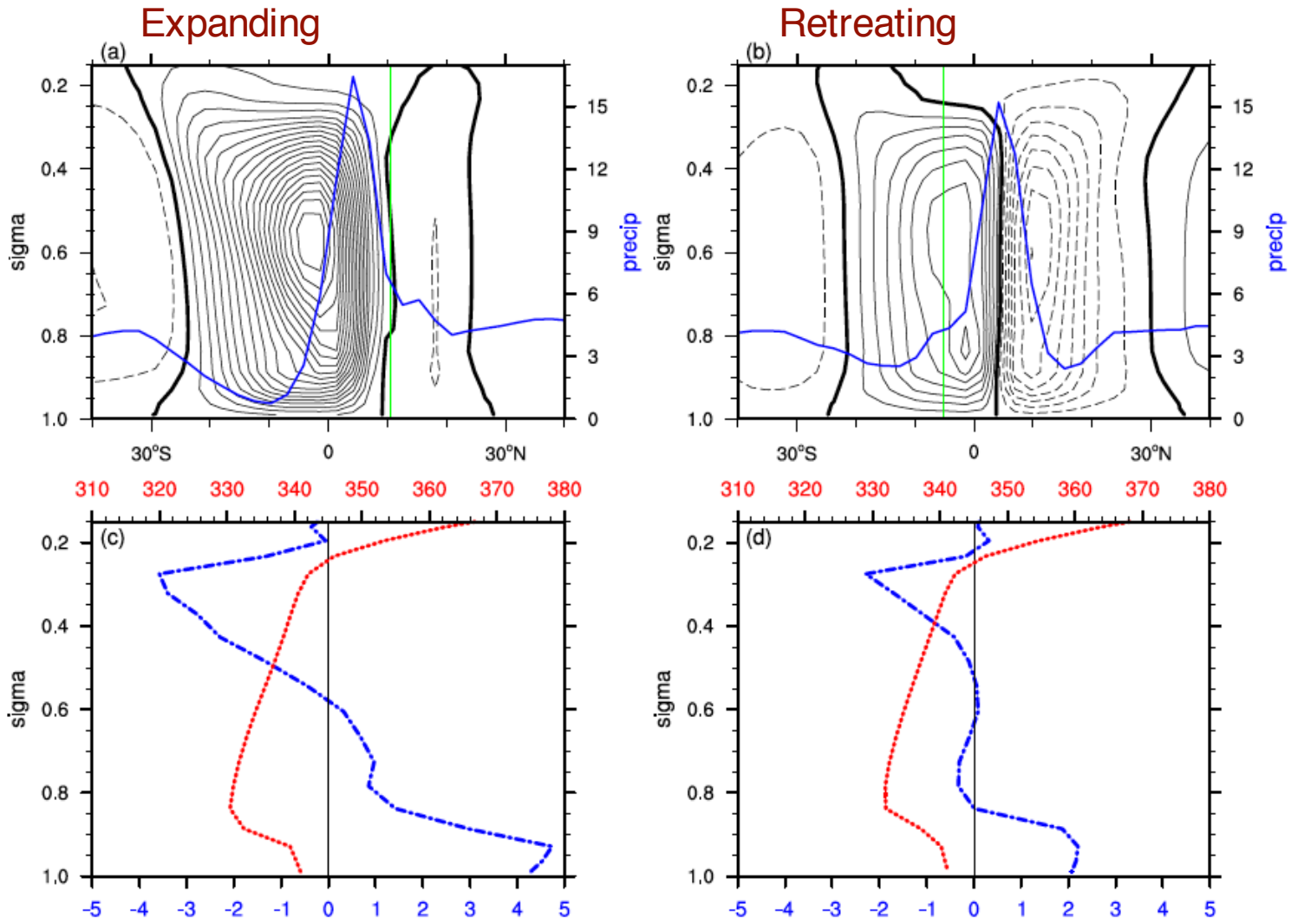


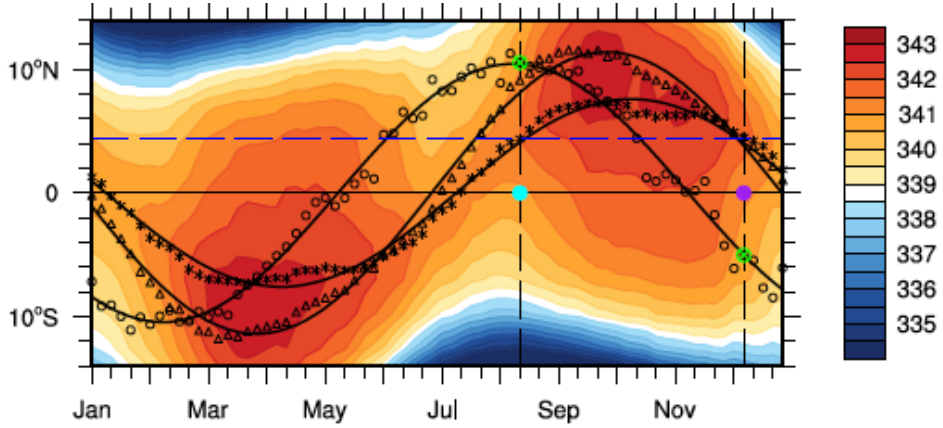

Meridional velocity

MSE

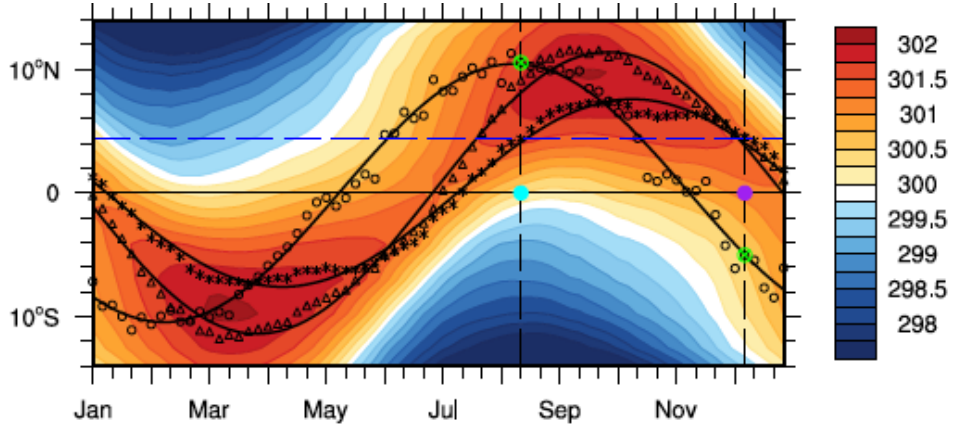
Wei and Bordoni 2018, *in press*

# Role for BL dynamics?

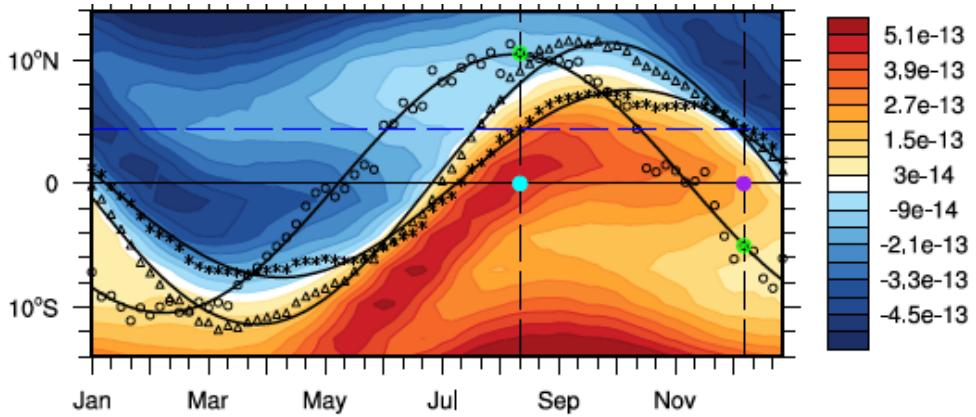
Near-surface T




Near-surface MSE




T gradient

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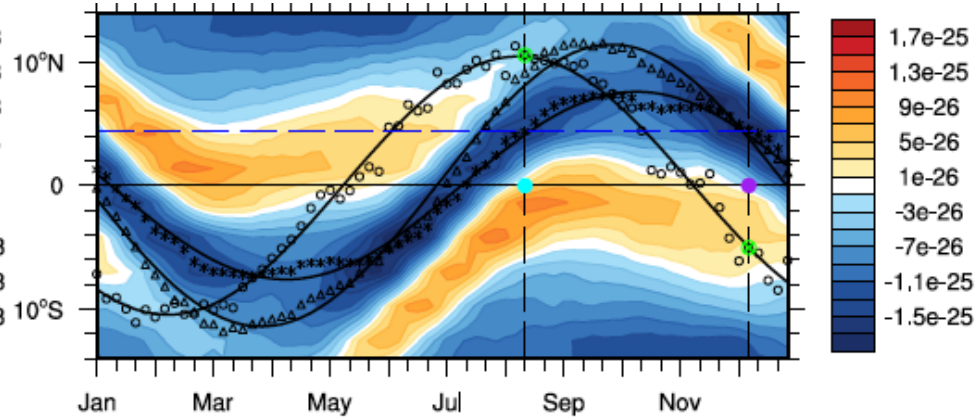


Wei and Bordoni 2018, *in press*

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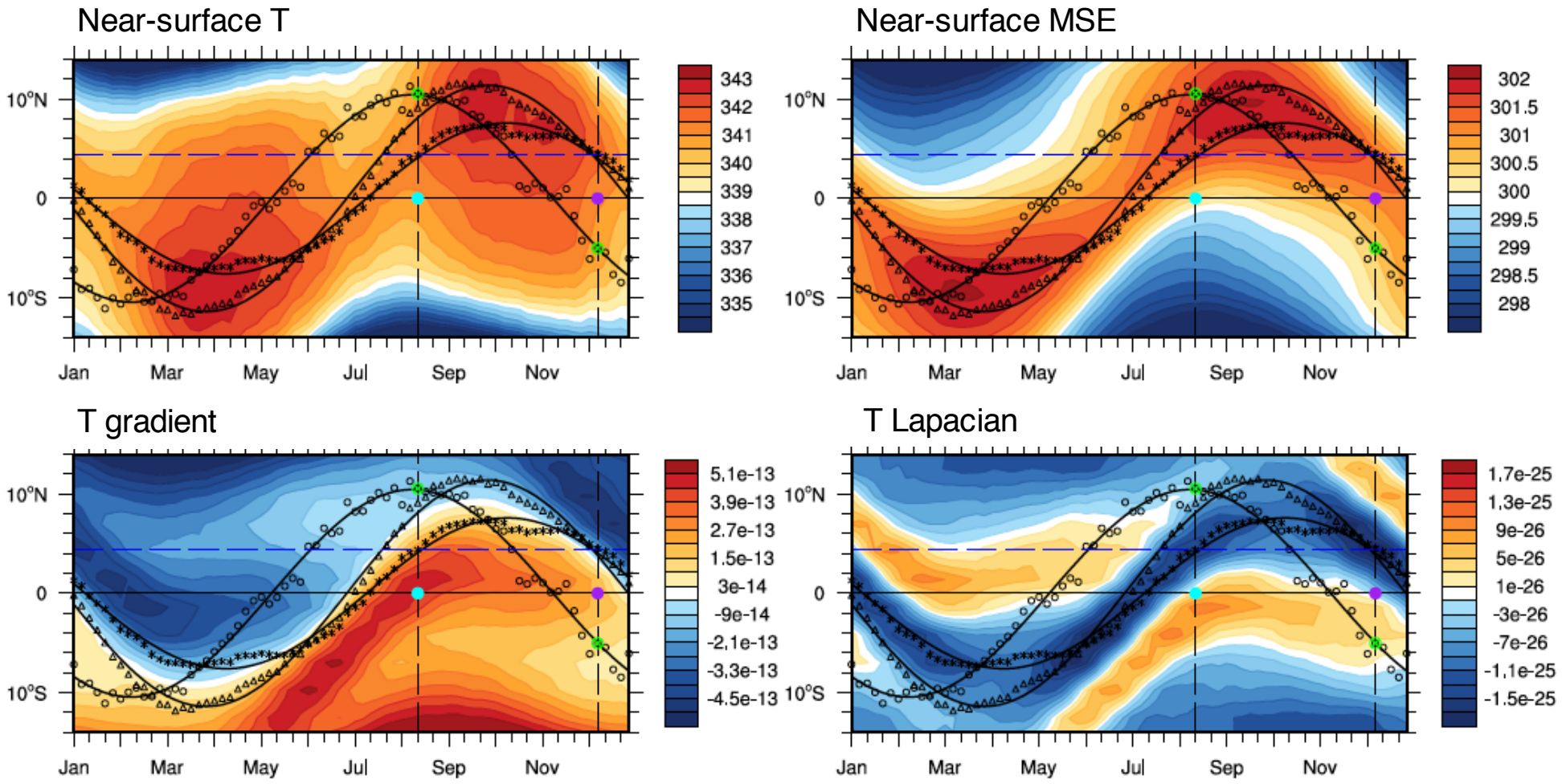
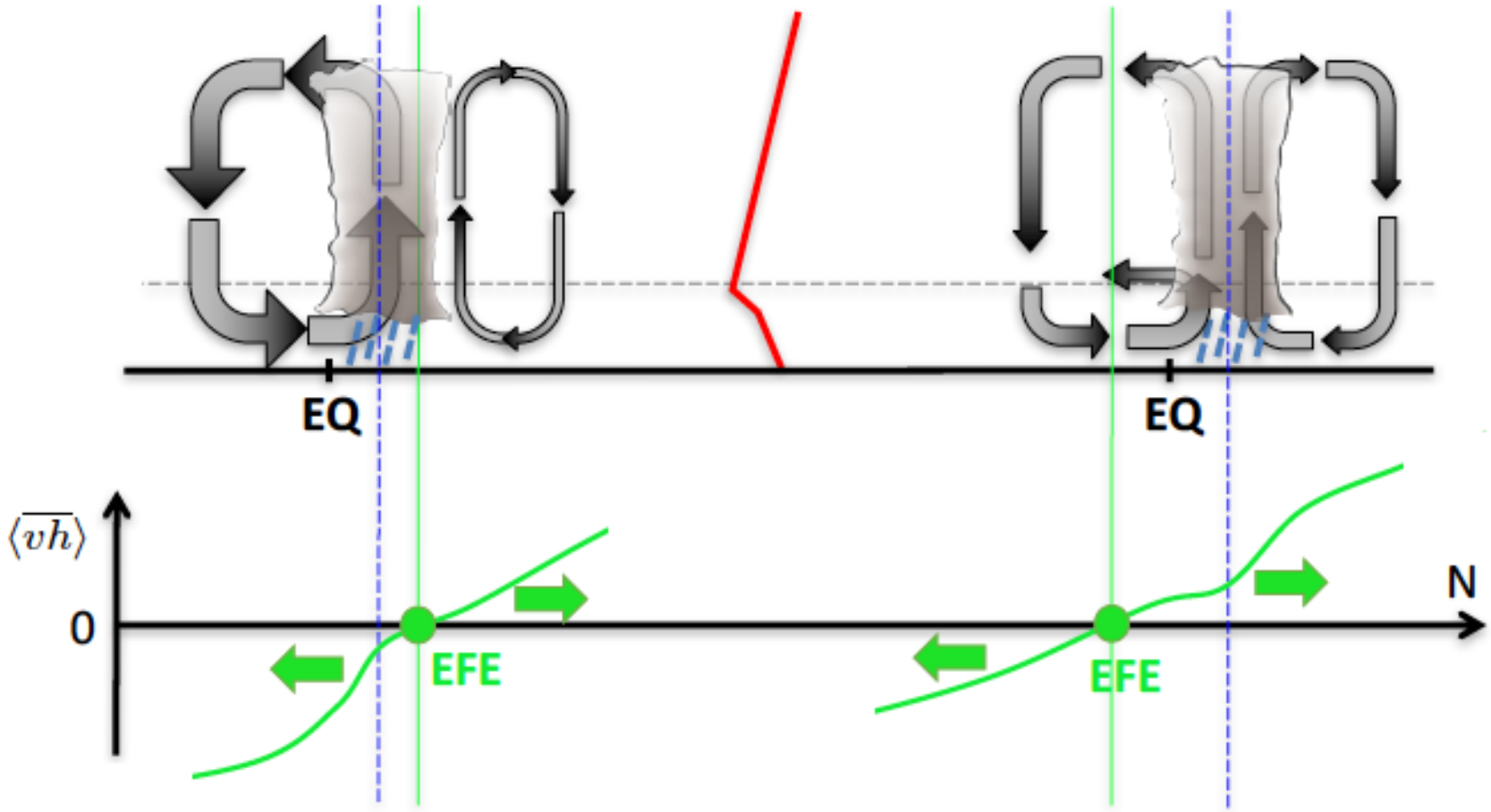



Stronger Laplacian of temperatures favors more bottom-heavy vertical profiles (e.g., Back and Bretherton 2006)

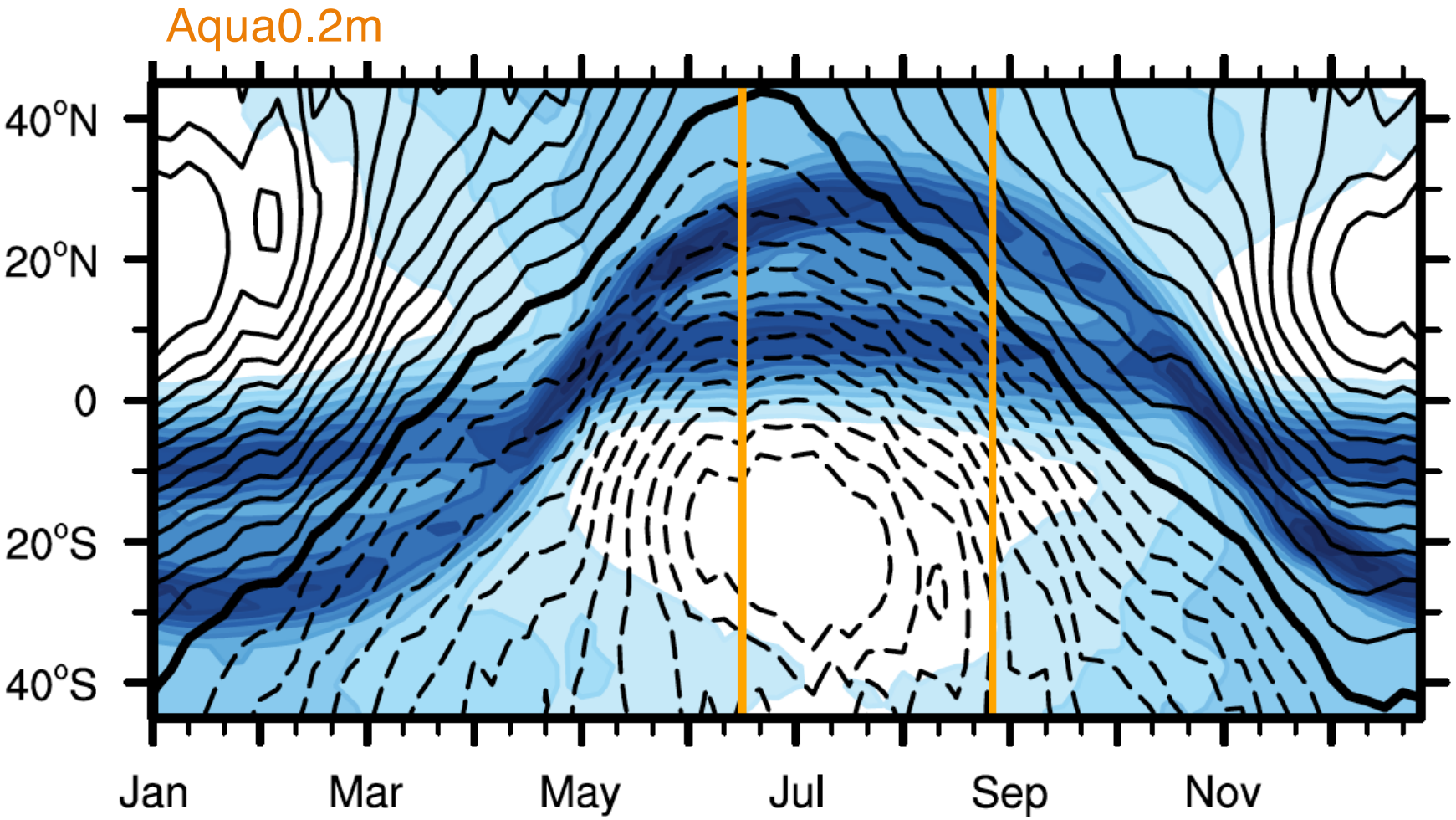
Wei and Bordoni 2018, *in press*

# Summary

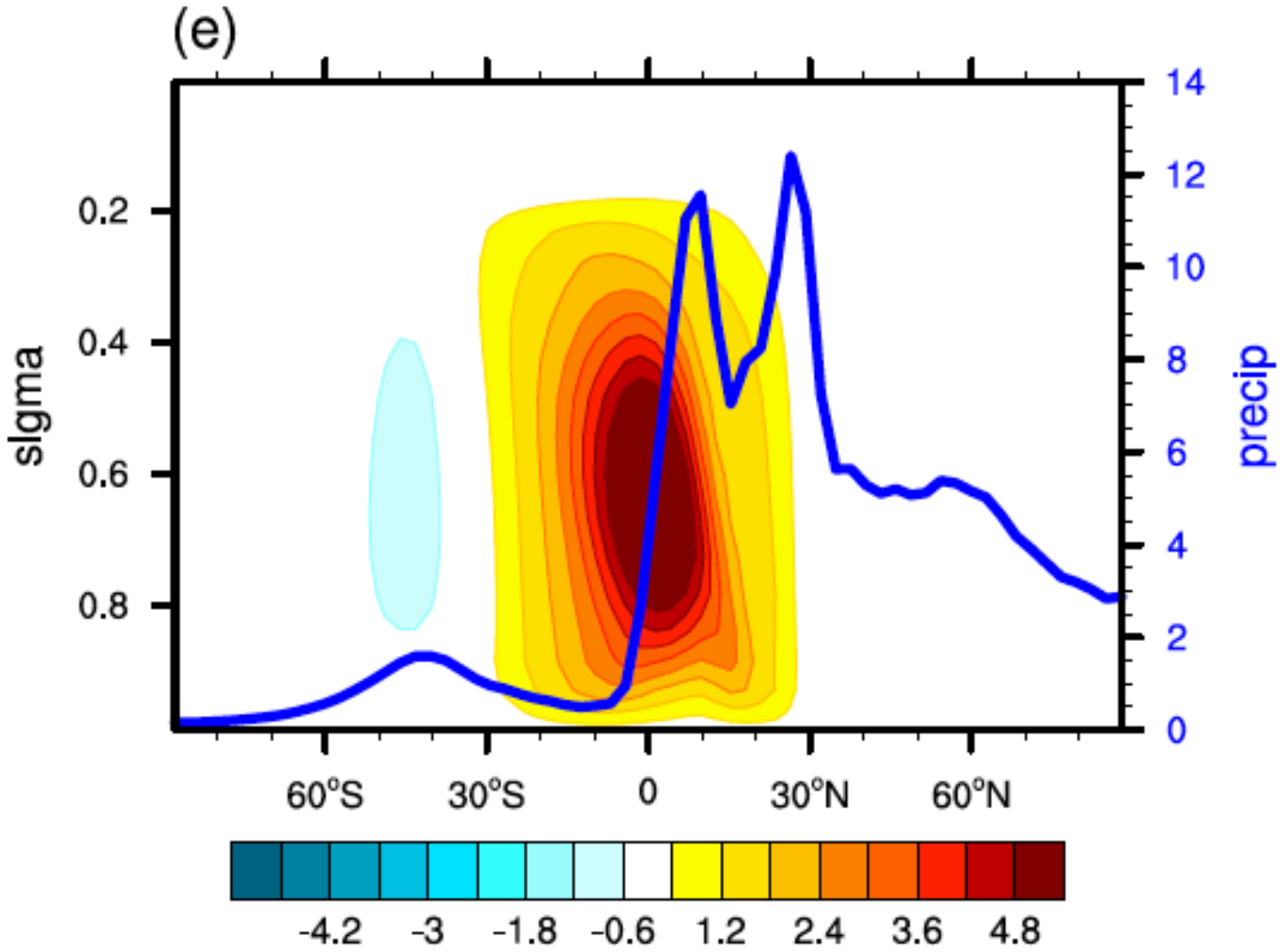



Importance of changes in efficieny of energy transport through changes in vertical circulation structure on seasonal timescales

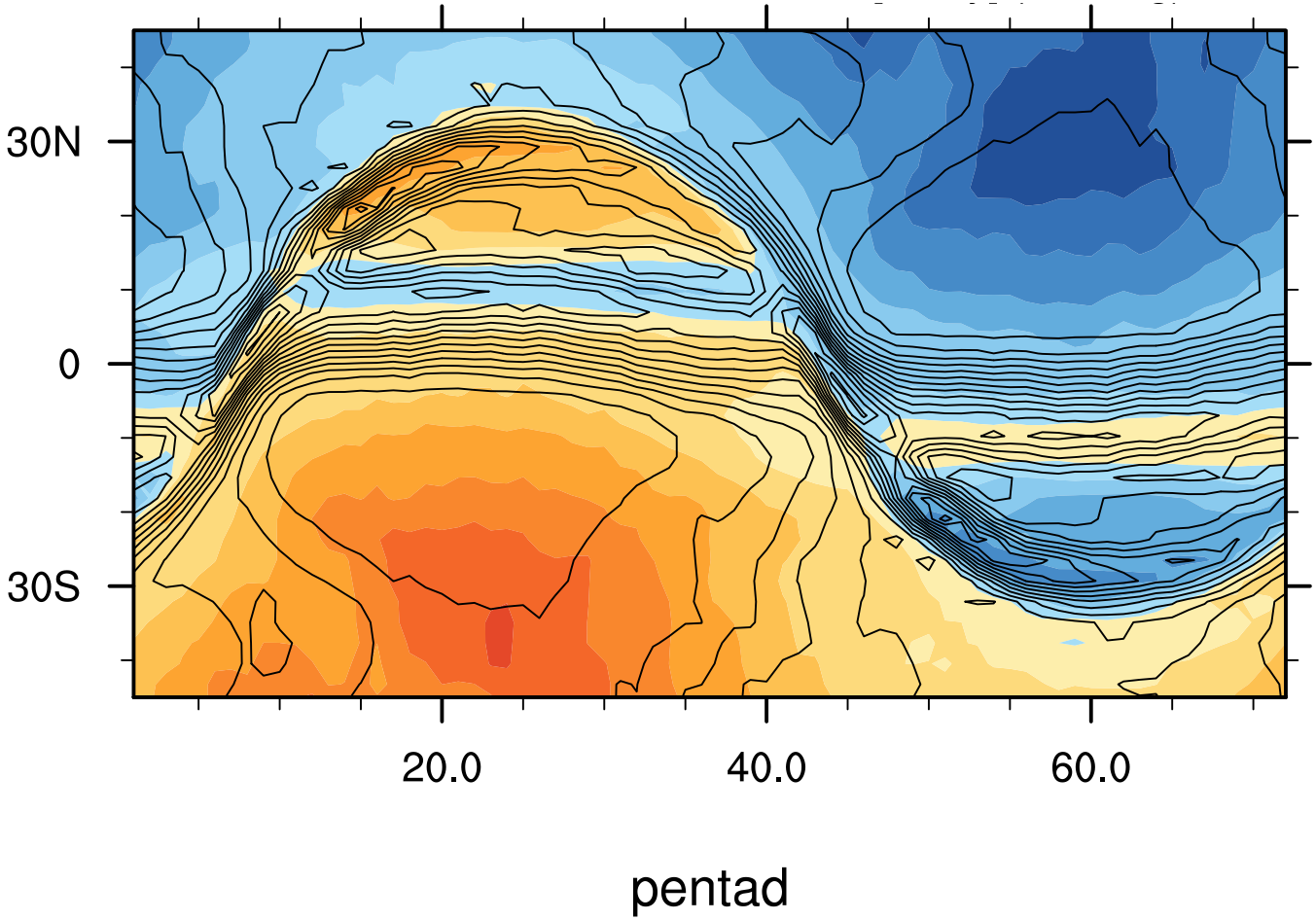
# Is the ITCZ always controlled by MSE maximum?



# Double ITCZ and jumping behavior



# Role of temperature gradients



# Conclusions

- Controls on ITCZs are still unclear;
- Thermodynamics theories do not always control the ITCZ position;
- Dynamical factors do play a role;
- Consideration of boundary layer dynamics might prove useful to understand ITCZ migrations.