Upward shift of the general circulation in response to climate warming

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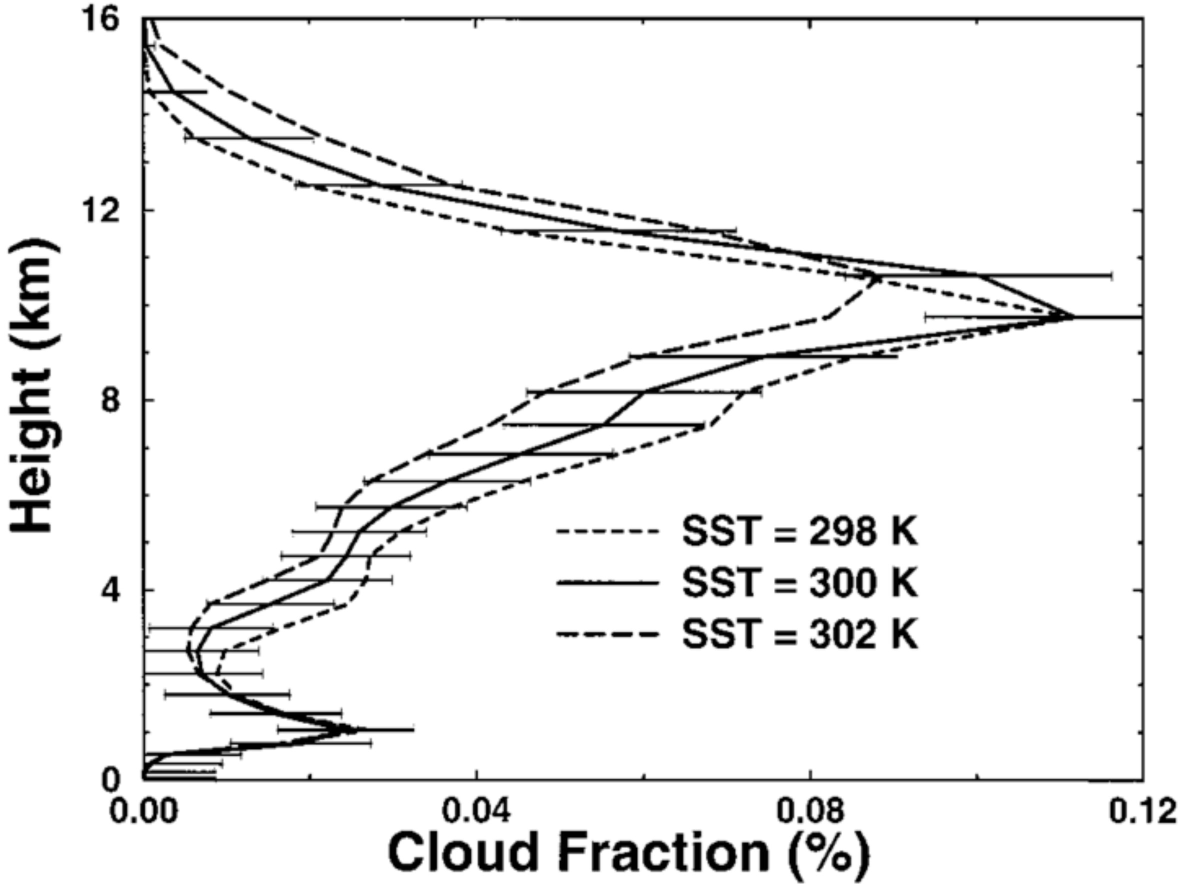
Many aspects of circulation shift upwards with warming in CRM and GCM simulations



Radiative convective equilibria in cloud resolving model

Tompkins and Craig, J. Climate, 1999

Upward shift with warming

- Is the upward shift a property of the moist governing equations?

- If so, can we use it to predict the vertical structure of the response of the general circulation to warming?

Upward-shift transformation

Given a (time-dependent) solution to the primitive equations:

$$u\;(\lambda, \phi, p)$$

Can we find another transformed solution that is shifted upwards:

$$u'(\lambda, \phi, p) = u(\lambda, \phi, \beta p)$$

...where β >1 corresponds to an upward shift

Transformed solution: Dry primitive equations

$$u'(\lambda, \phi, p) = u(\lambda, \phi, \beta p)$$
$$v'(\lambda, \phi, p) = v(\lambda, \phi, \beta p)$$

$$\omega'(\lambda, \phi, p) = \frac{\omega(\lambda, \phi, \beta p)}{\beta}$$

$$T'(\lambda, \phi, p) = T(\lambda, \phi, \beta p)$$

...where $\beta > 1$ corresponds to an upward shift

cf. Garner JAS 2007

Transformed solution: Dry primitive equations

$$u'(\lambda, \phi, p) = u(\lambda, \phi, \beta p)$$

$$v'(\lambda, \phi, p) = v(\lambda, \phi, \beta p)$$

$$\omega'(\lambda, \phi, p) = \frac{\omega(\lambda, \phi, \beta p)}{\beta}$$

Weakening of vertical velocities

$$T'(\lambda, \phi, p) = T(\lambda, \phi, \beta p)$$

...where $\beta > 1$ corresponds to an upward shift

Moist primitive equations are more difficult

$$u'(\lambda, \phi, p) = u(\lambda, \phi, \beta p)$$

$$v'(\lambda, \phi, p) = v(\lambda, \phi, \beta p)$$

$$\omega'(\lambda, \phi, p) = \frac{\omega(\lambda, \phi, \beta p)}{\beta}$$

Pot. temp. offset

$$T'(\lambda, \phi, p) = T(\lambda, \phi, \beta p) \boxed{- \Delta\theta\Pi(\beta p)}$$

$$\boxed{\mathcal{R}(\lambda, \phi, p) = \mathcal{R}(\lambda, \phi, \beta p)}$$

Relative humidity

$$\Pi = (p/p_0)^{\frac{R}{C_p}}$$

Moist transformed solution valid for saturated and unsaturated motions

Valid if:

$$\Delta\theta = \left(\frac{\beta - 1}{\beta}\right)\left(\frac{R_v}{L_v}\right)T\theta$$

which ensures saturation specific humidity transforms correctly

$$q_s'(x, y, p) = q_s(x, y, \beta p)$$

But then need $T\theta$ approximately constant....

Radiative cooling term

Also need radiative cooling to shift upwards:

$$\dot{Q}'_{rad}(p) = \dot{Q}_{rad}(\beta p)$$

Some support from FAT hypothesis
(Hartmann & Larson, 2002)

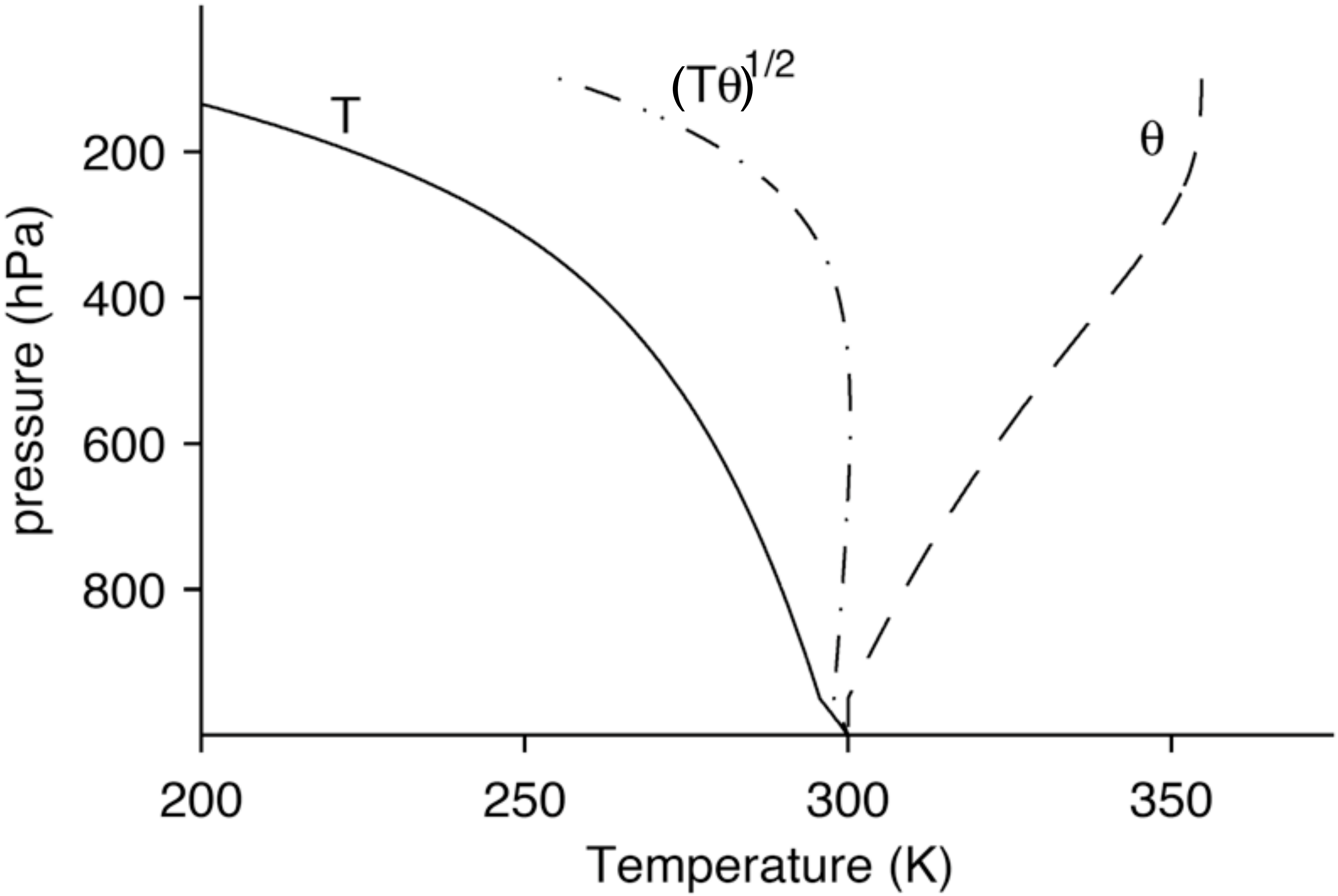
Remaining free parameter β is set by the change in near-surface temperature

$$\delta T_{BL} \simeq (\beta - 1)\left[p\frac{\partial T}{\partial p} - e_s\frac{dT}{de_s}\right]$$

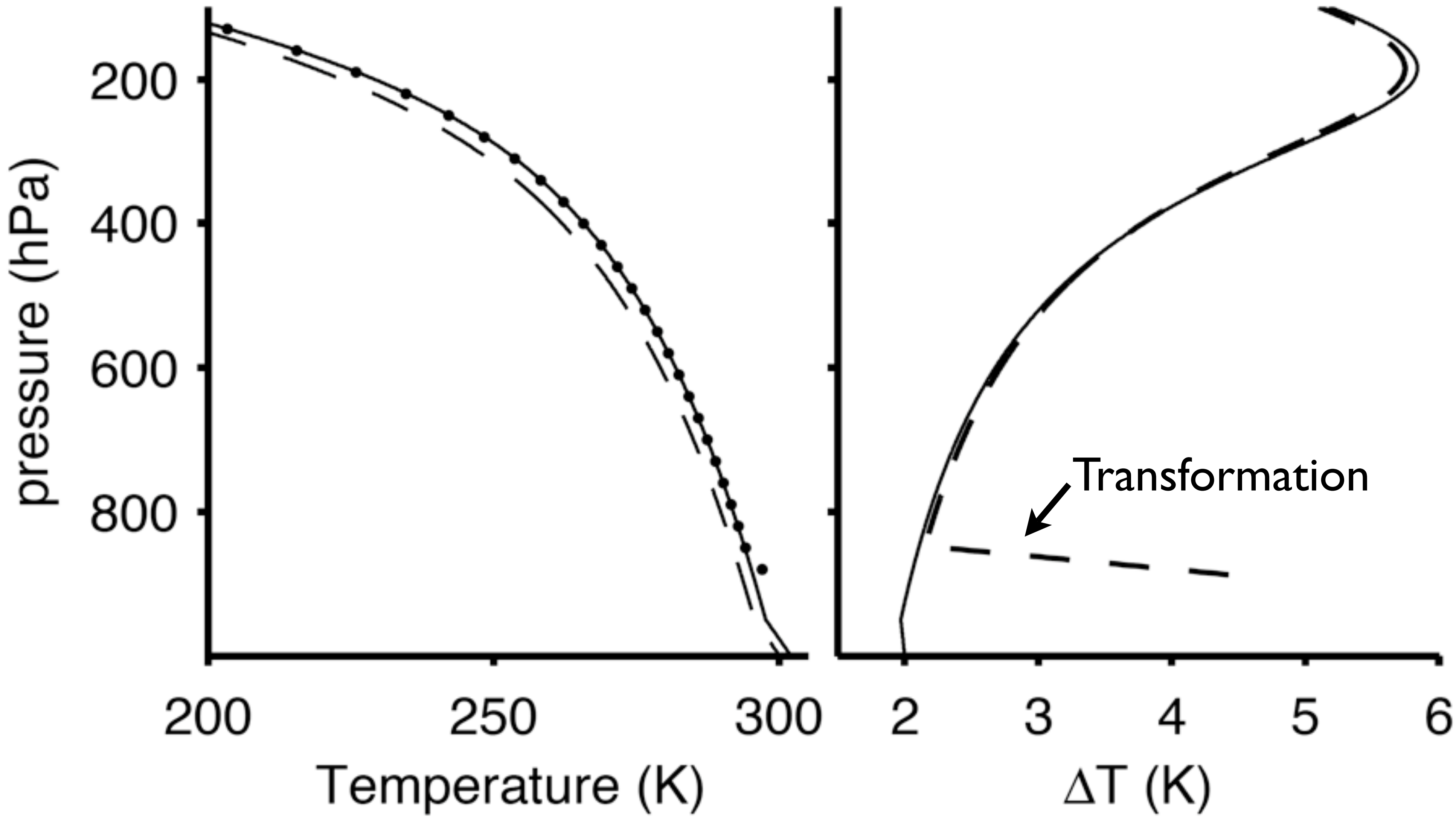
$$\frac{\beta - 1}{\delta T} \approx 0.05\ \mathrm{K}^{-1}$$

Other surface boundary conditions may not be satisfied

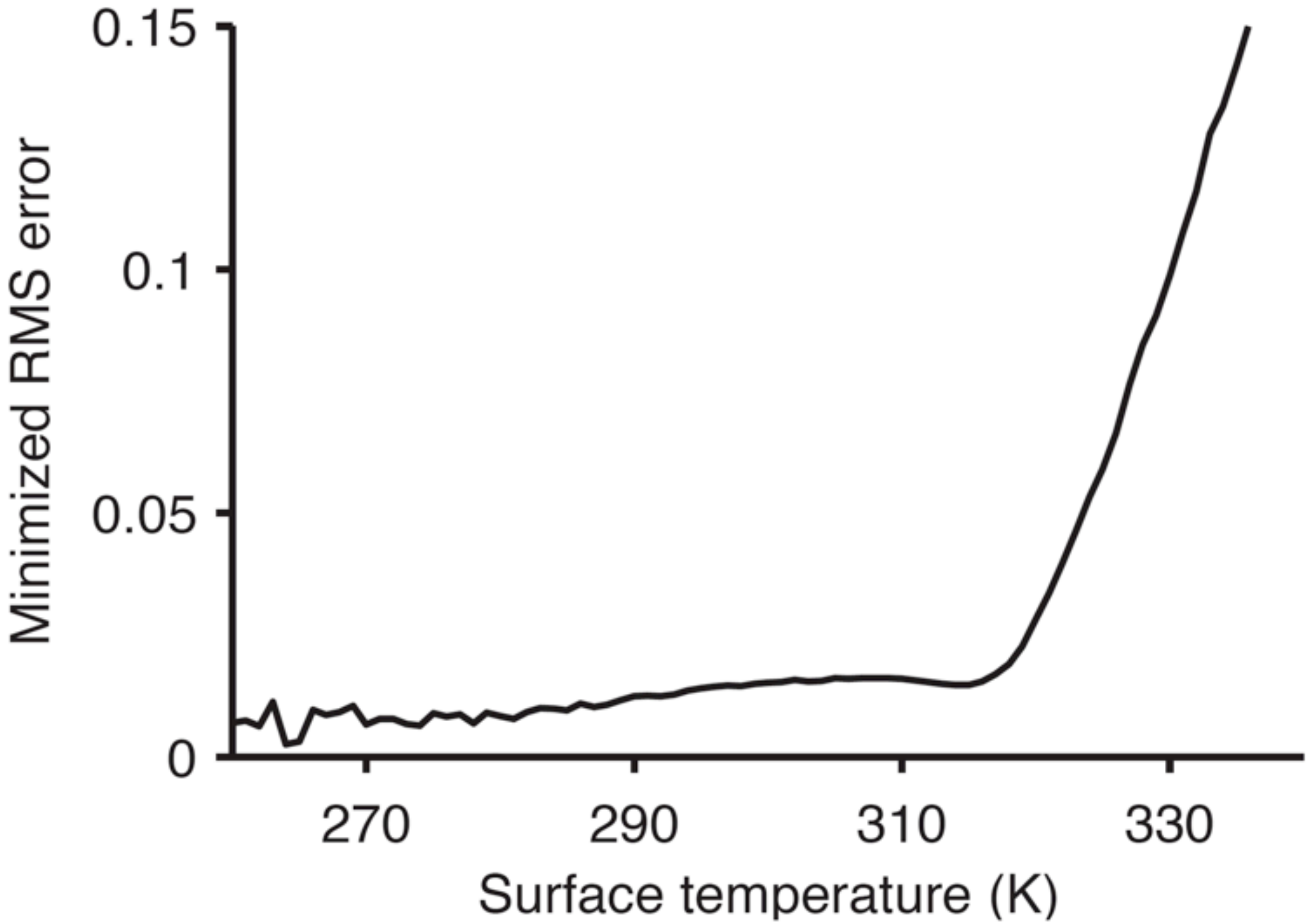
First test: pseudoadiabatic parcel ascents



Transformation reproduces pseudoadiabatic parcel ascent under 2K increase in SST



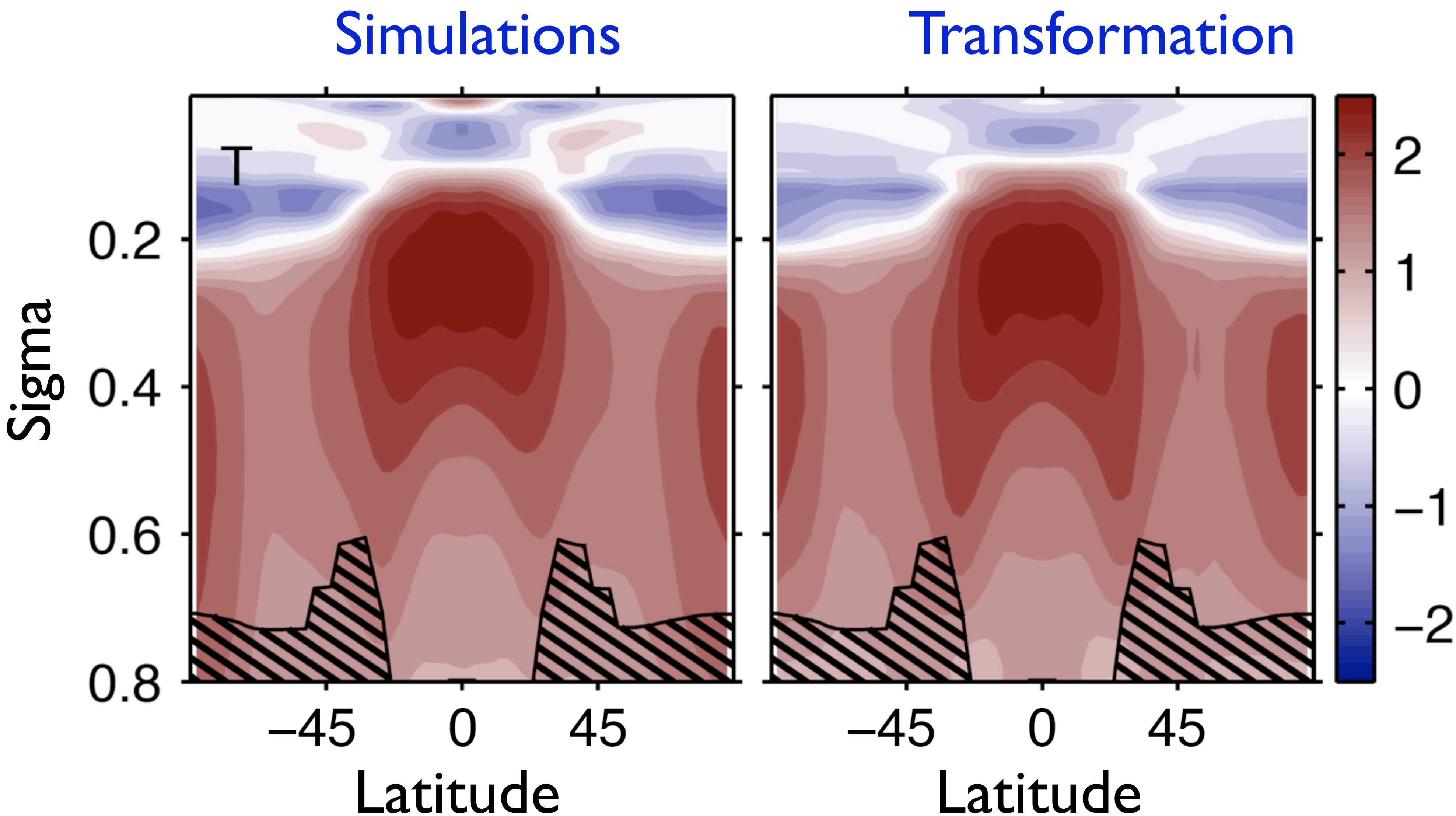
Error small (<2%) except for very high temperatures



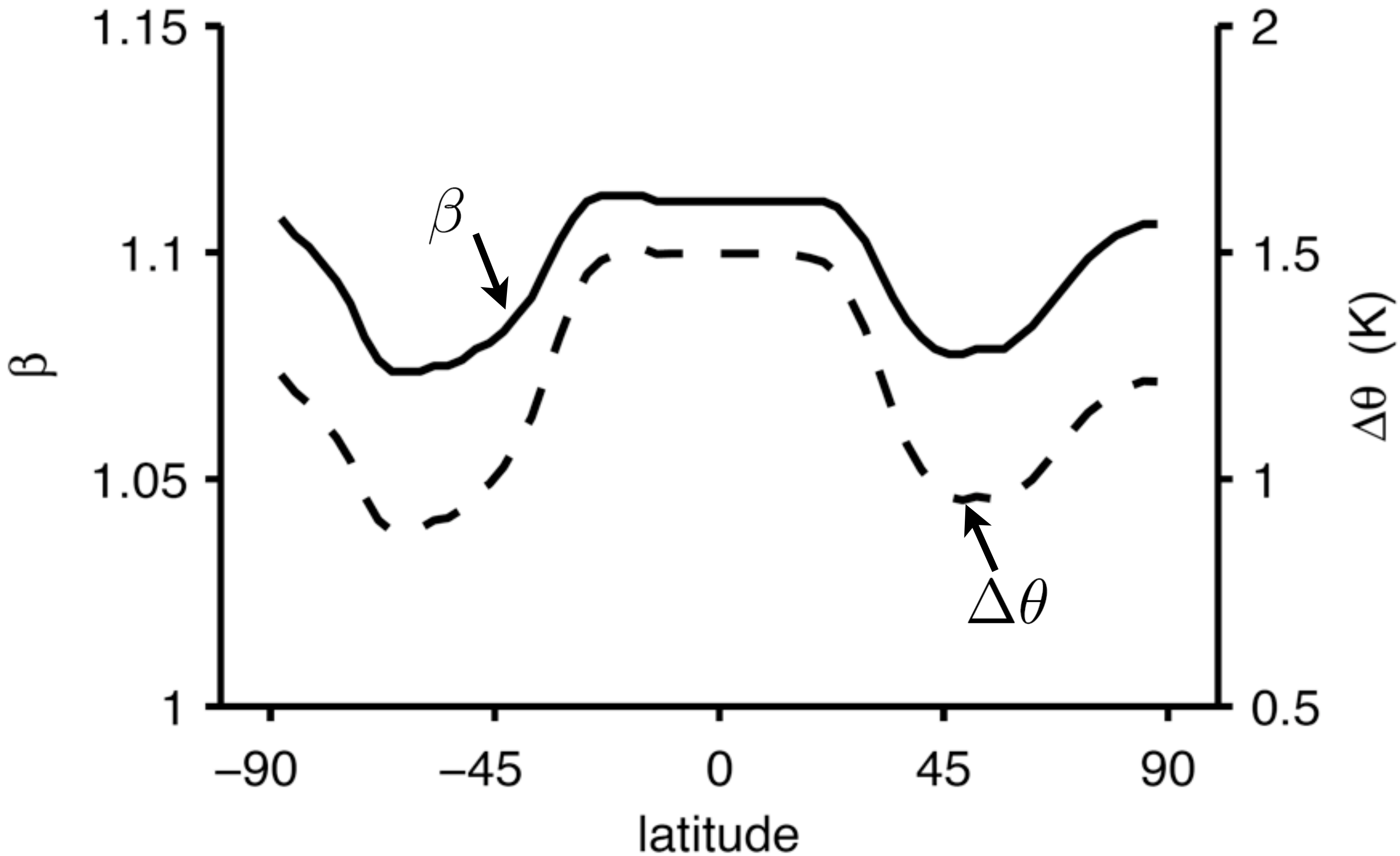
Apply to simulations with idealized moist GCM

- Aquaplanet with prescribed SST distribution a function of latitude
- GFDL dynamical core, Betts-Miller like convection (Frierson 2007), no clouds or ice
- Idealized radiation scheme that conforms to upward shift transformation (radiative cooling a function of specific humidity)
- Increase SST by 2K

Idealized GCM: change in temperature (K)

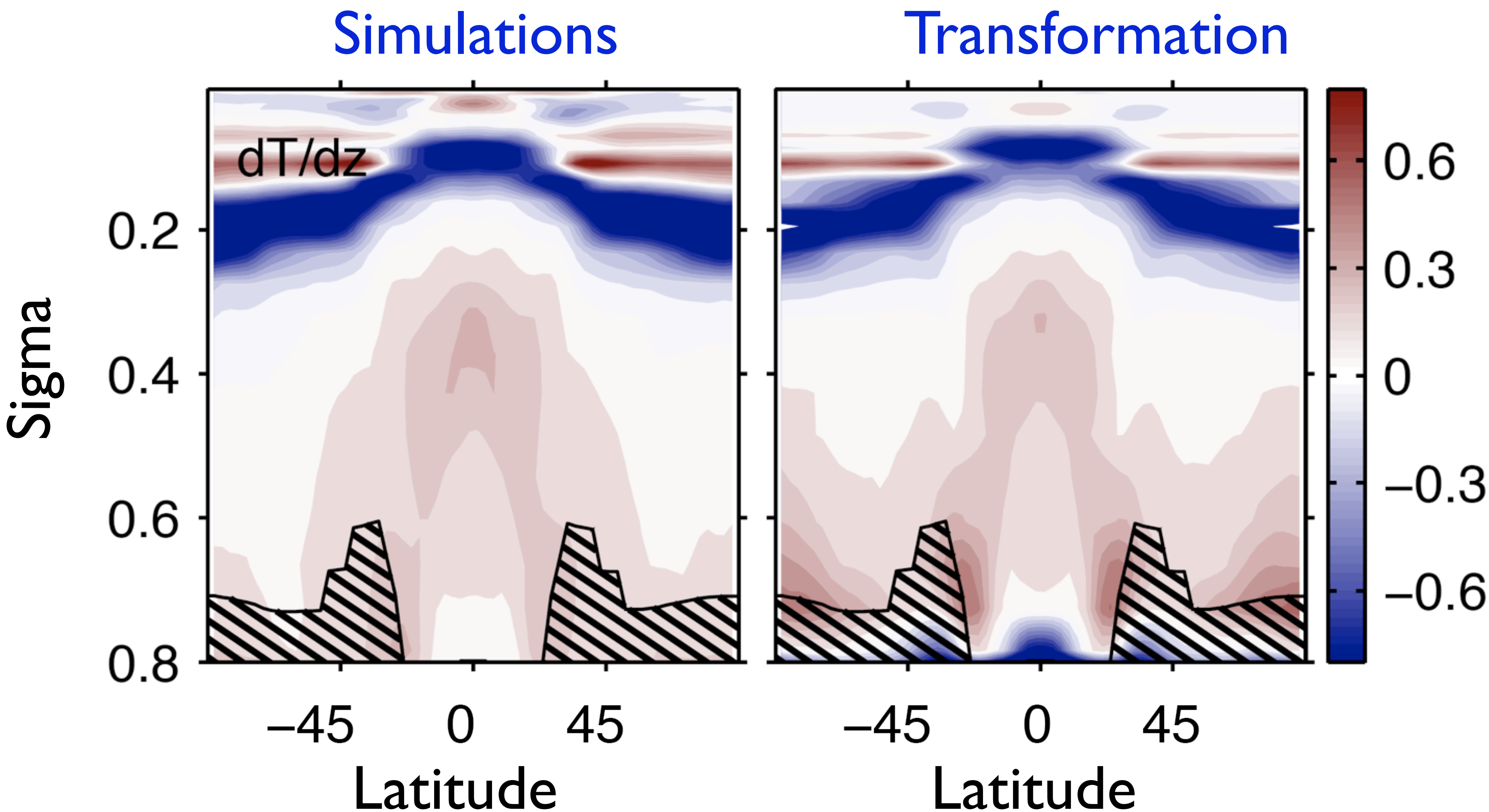


Fit β at each latitude

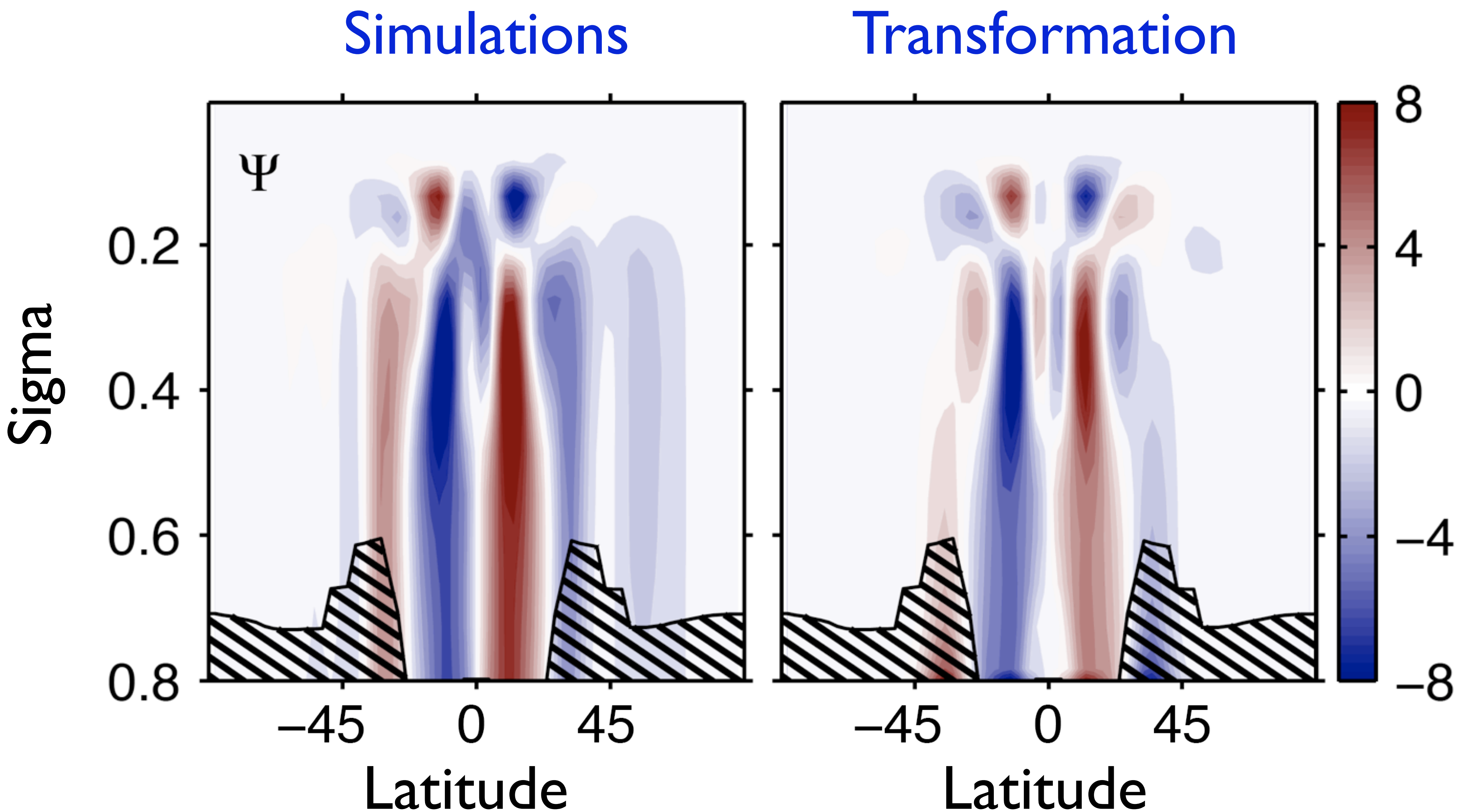


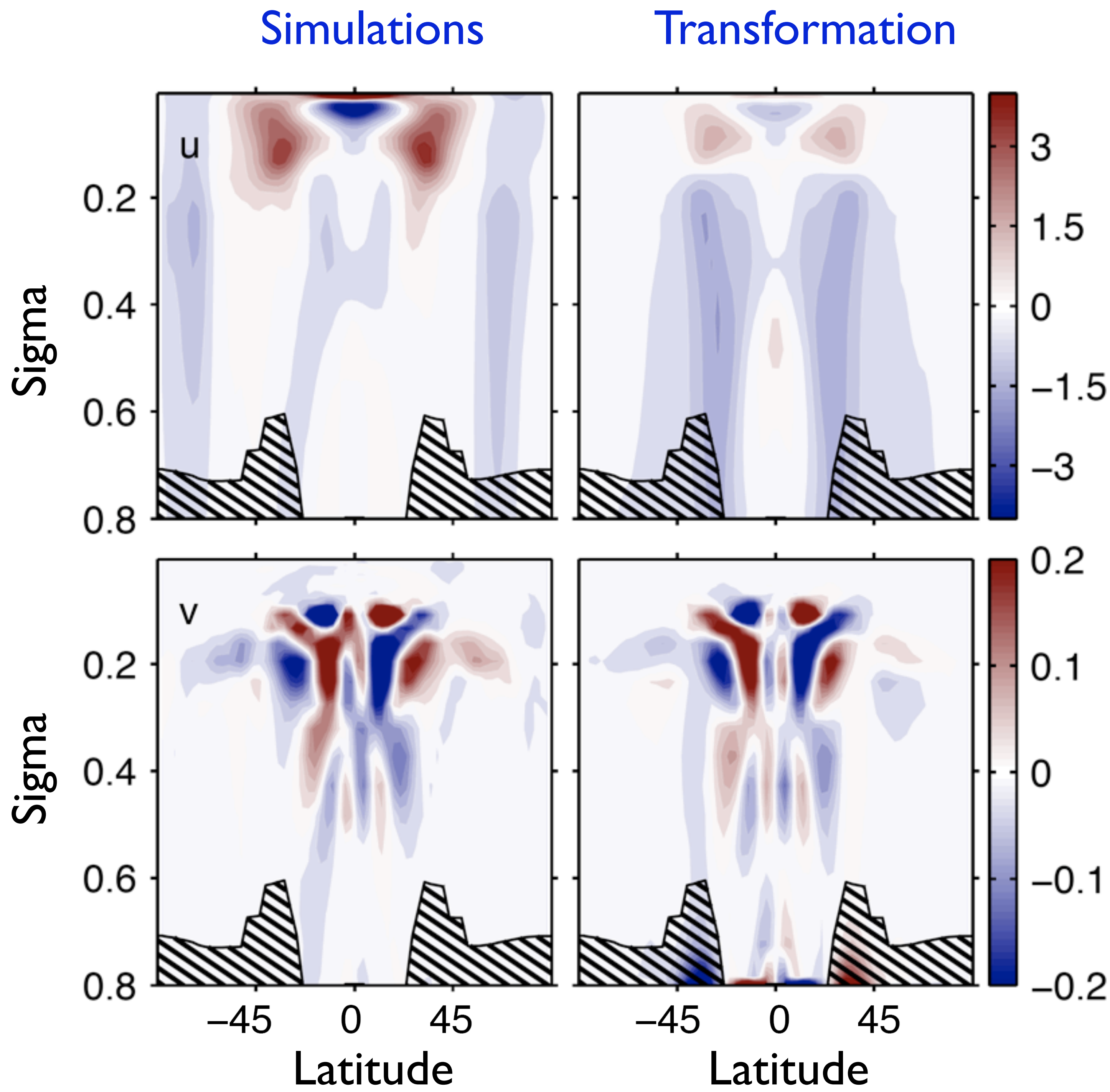
$$\Delta\theta = \left(\frac{\beta - 1}{\beta}\right)\left(\frac{R_v}{L_v}\right) T\theta$$

Changes in lapse rate (K/km) mostly reproduced



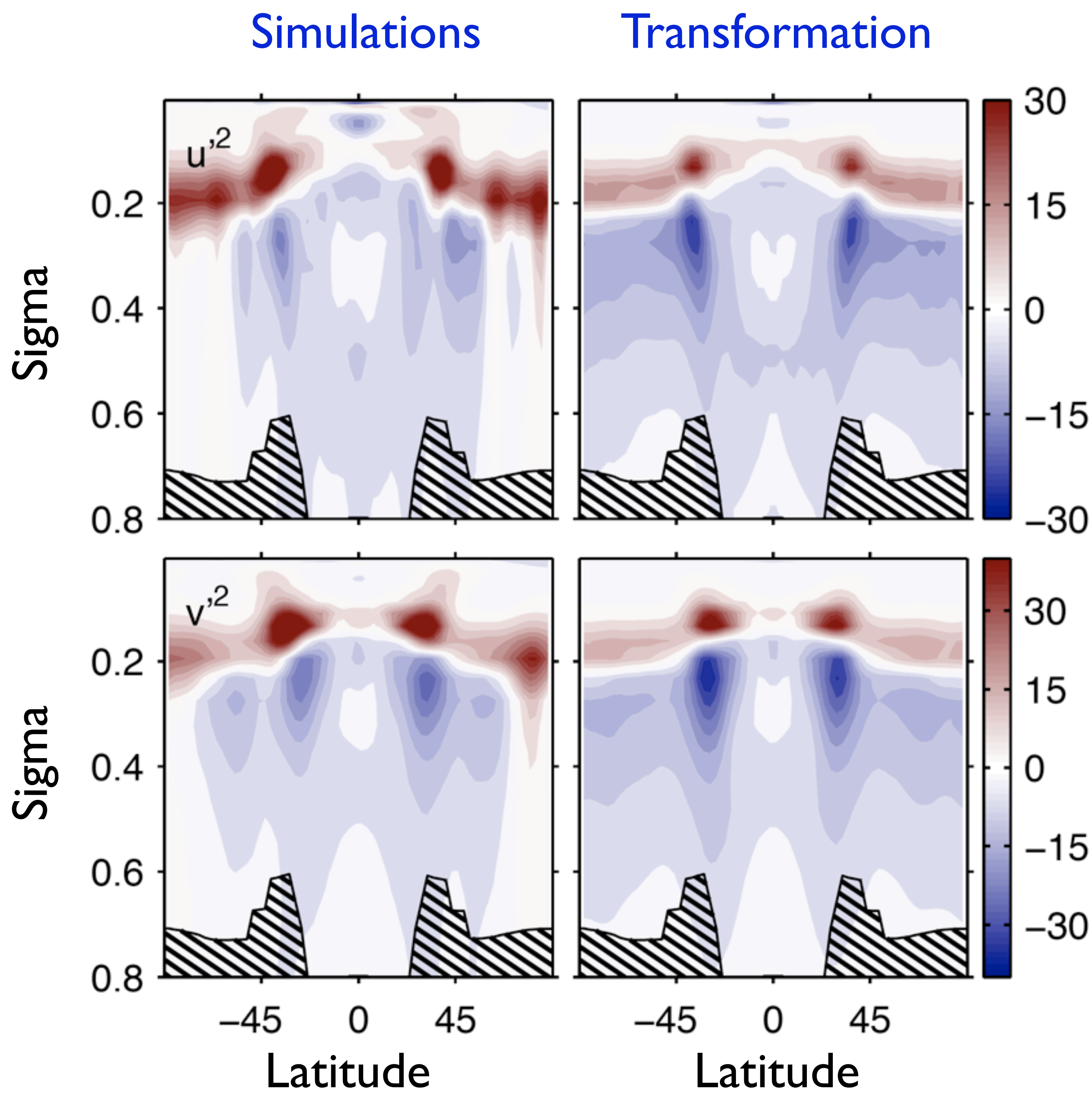
Captures weakening in streamfunction (10^9 kg s^{-1})





Problem with zonal wind (m/s)

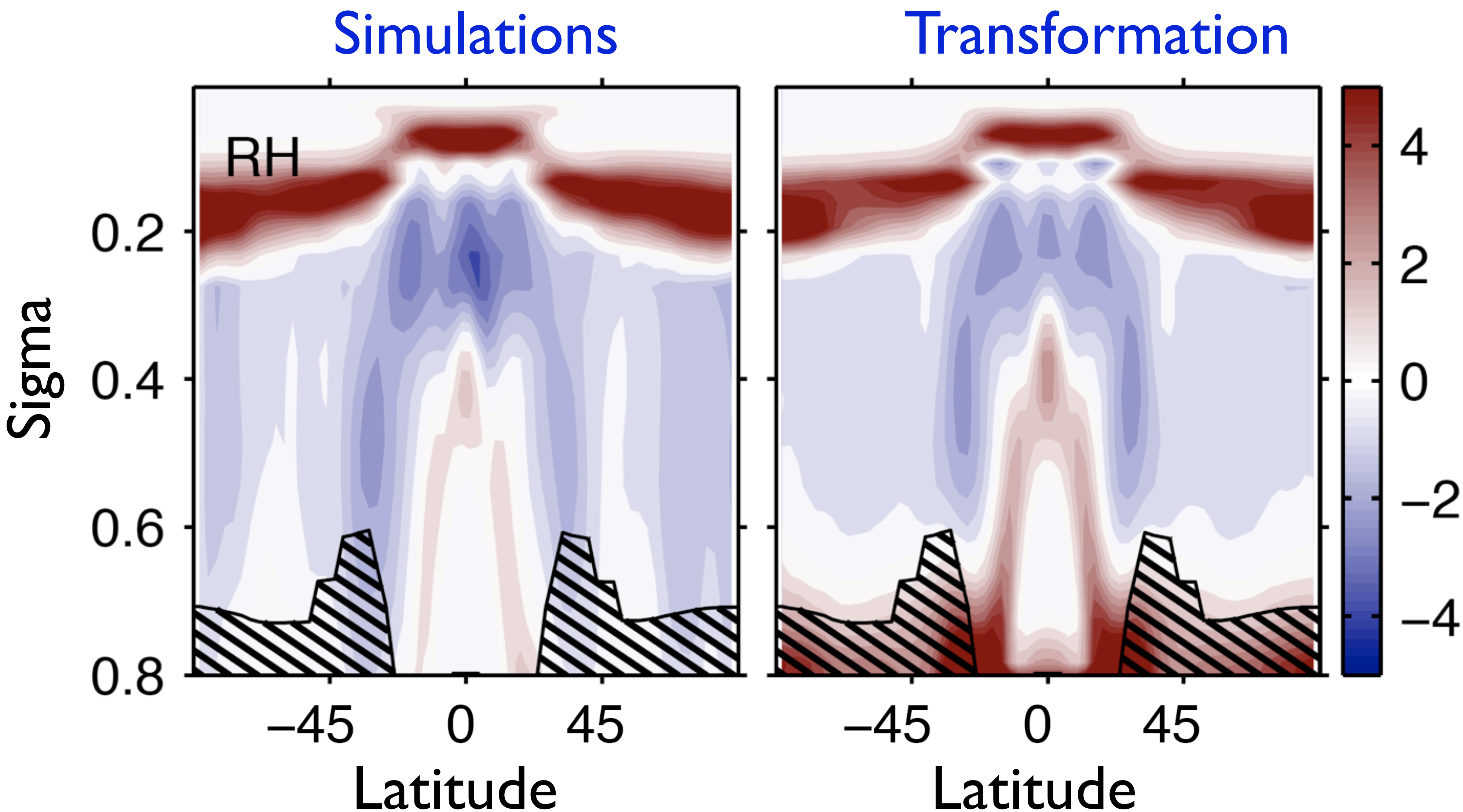
Meridional wind (m/s) is well captured



Zonal wind variance (m^2s^{-2}) mostly captured

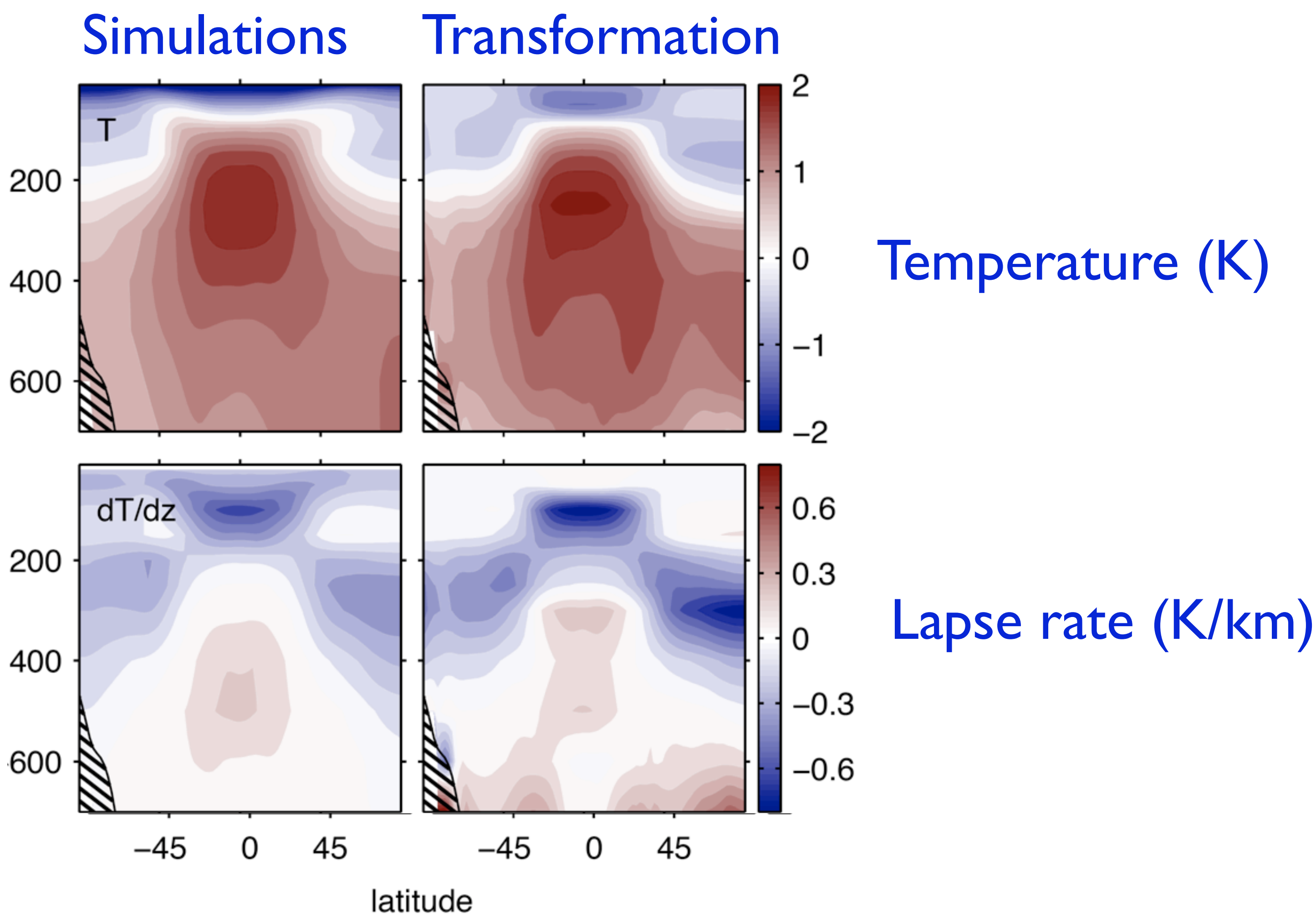
Meridional wind variance (m^2s^{-2}) mostly captured

Detailed changes in relative humidity are captured

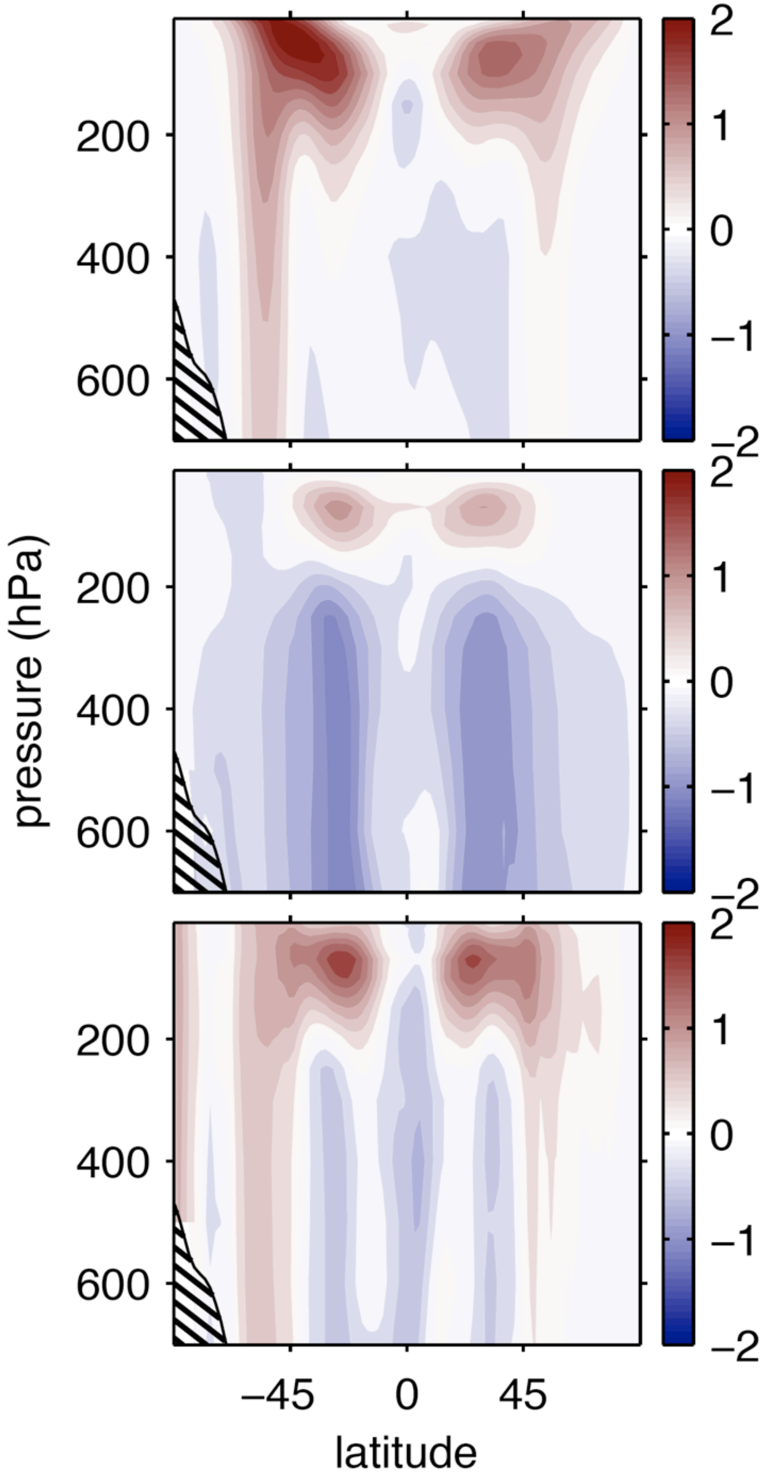


Next apply to CMIP3 simulations under A1B

CMIP3 multimodel mean: similar to idealized GCM but worse agreement in lower troposphere



Zonal wind (m/s) error is mostly barotropic



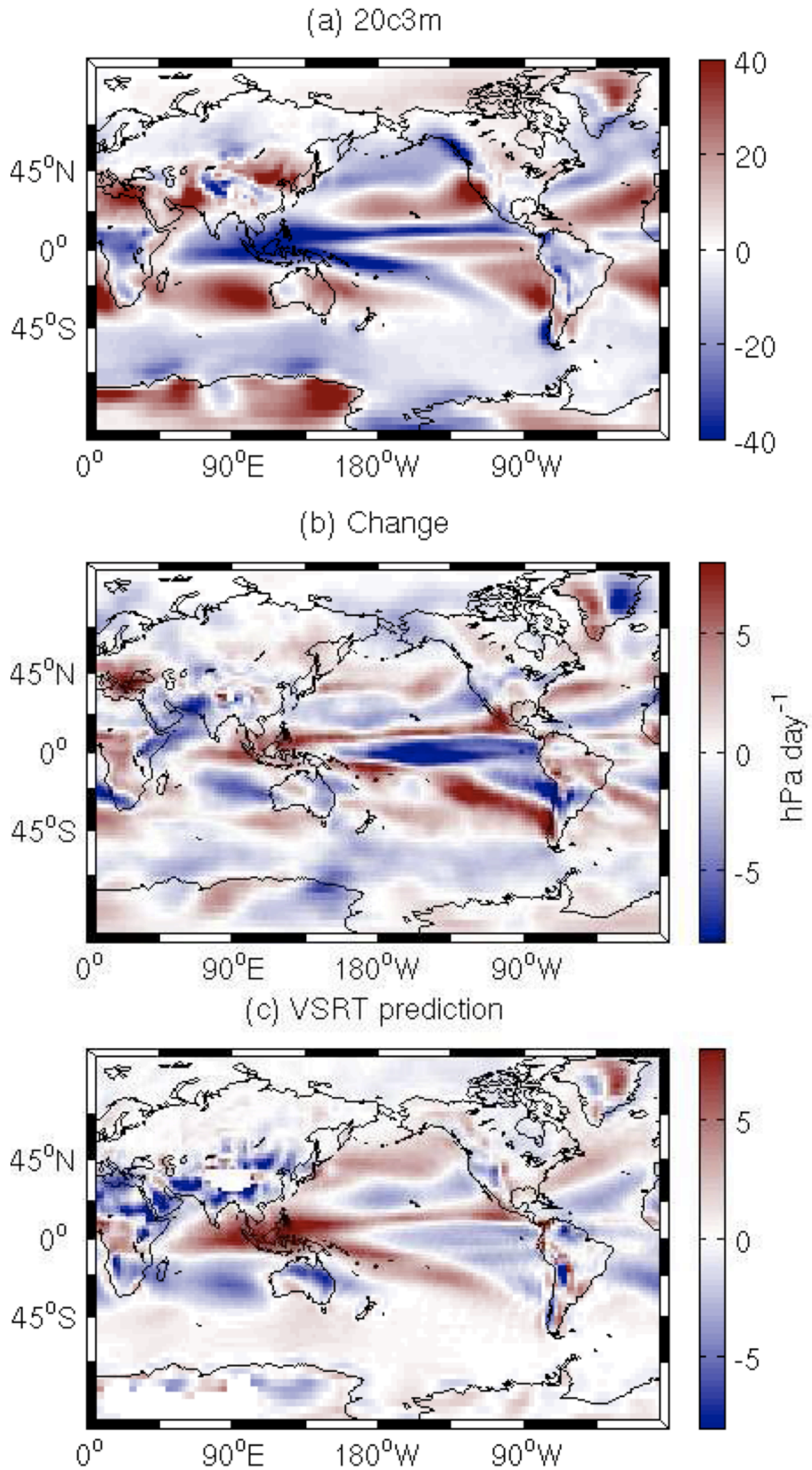
Simulations

Transformation

Transformation + barotropic adjustment

$$\hat{u}(\phi, p) = u(\phi, \beta p) + \Delta u(\phi)$$

Weakening of pressure vertical velocity(hPa/day)



20th century

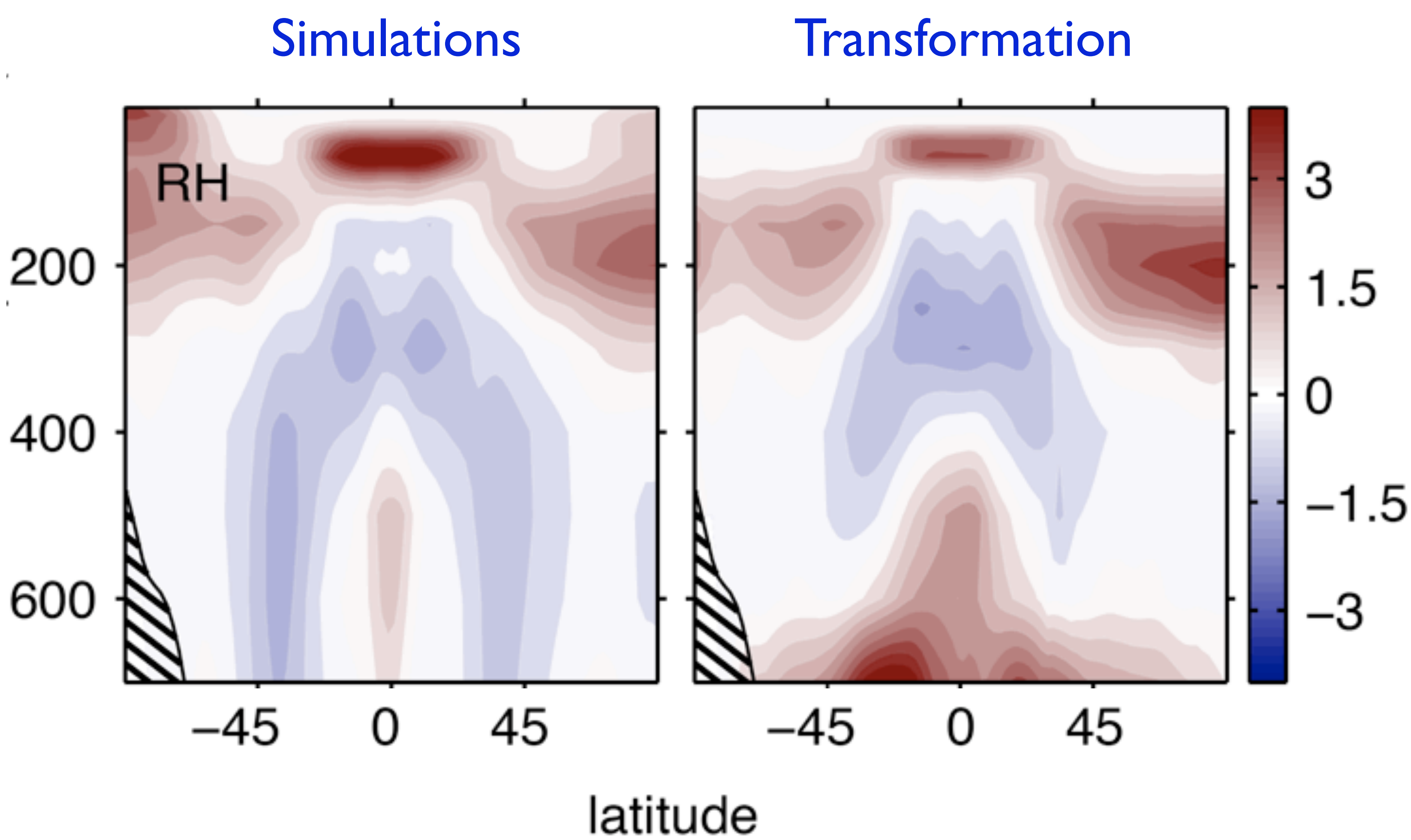
Simulated change

Transformation

$$\omega'(\lambda, \phi, p) = \frac{\omega(\lambda, \phi, \beta p)}{\beta}$$

$$\frac{\beta - 1}{\delta T} \approx 0.05 \ \mathrm{K}^{-1}$$

Relative humidity changes captured in middle and upper troposphere



Conclusions

- Upward shift a robust response to warming in many variables in both GCMs and CRMs

- Found upward-shifted solution for moist primitive equations
  - Temperature is not just shifted upwards
  - Pressure vertical velocity weakens with warming

- Captures many features of vertical structure of response; Provides framework (based on governing equations) to analyze circulation response more generally