Understanding the Hydrologic Cycle Response to Climate Change
2. Precipitation

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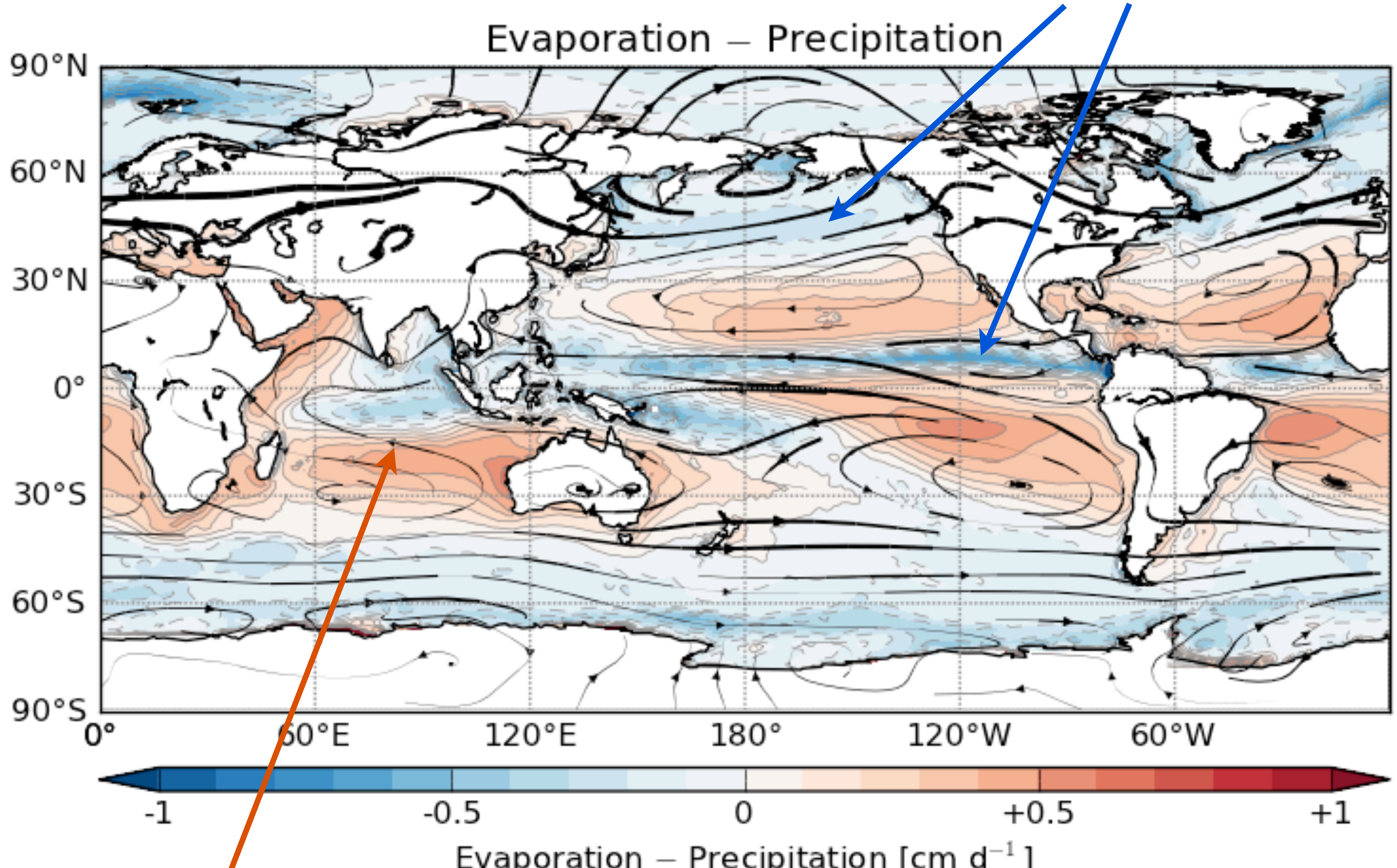
Evaporation – Precipitation

Although regional imbalances can be quite large, evaporation and precipitation are approximately equal in the global mean

precipitation is large over the tropics and in the midlatitude storm tracks



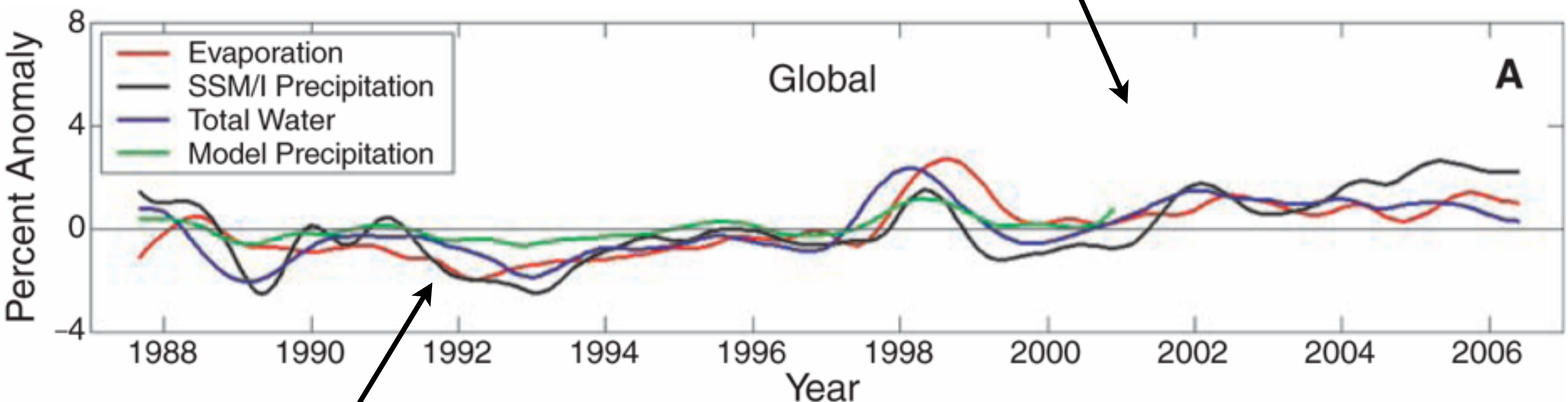
evaporation is large over the subtropical oceans

Data: Climate Forecast System Reanalysis

Given what we've learned about how water vapor changes, how do you expect precipitation to change?

Given what we've learned about how water vapor changes, how do you expect precipitation to change?

Satellite observations of precipitation and evaporation have approximately the same temporal variability as total column water vapor...



Observed time series suggests that the sensitivity of precipitation to temperature changes is about 7% K^{-1}...

Wentz et al. 2007

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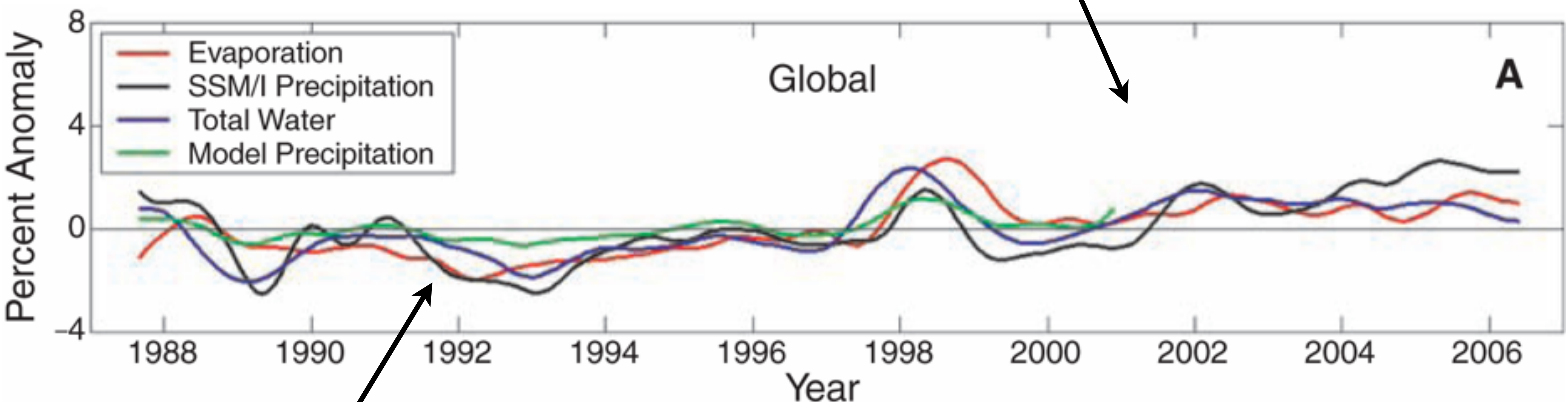

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...Clausius-Clapeyron?

Wentz et al. 2007

Given what we've learned about how water vapor changes, how do you expect precipitation to change?

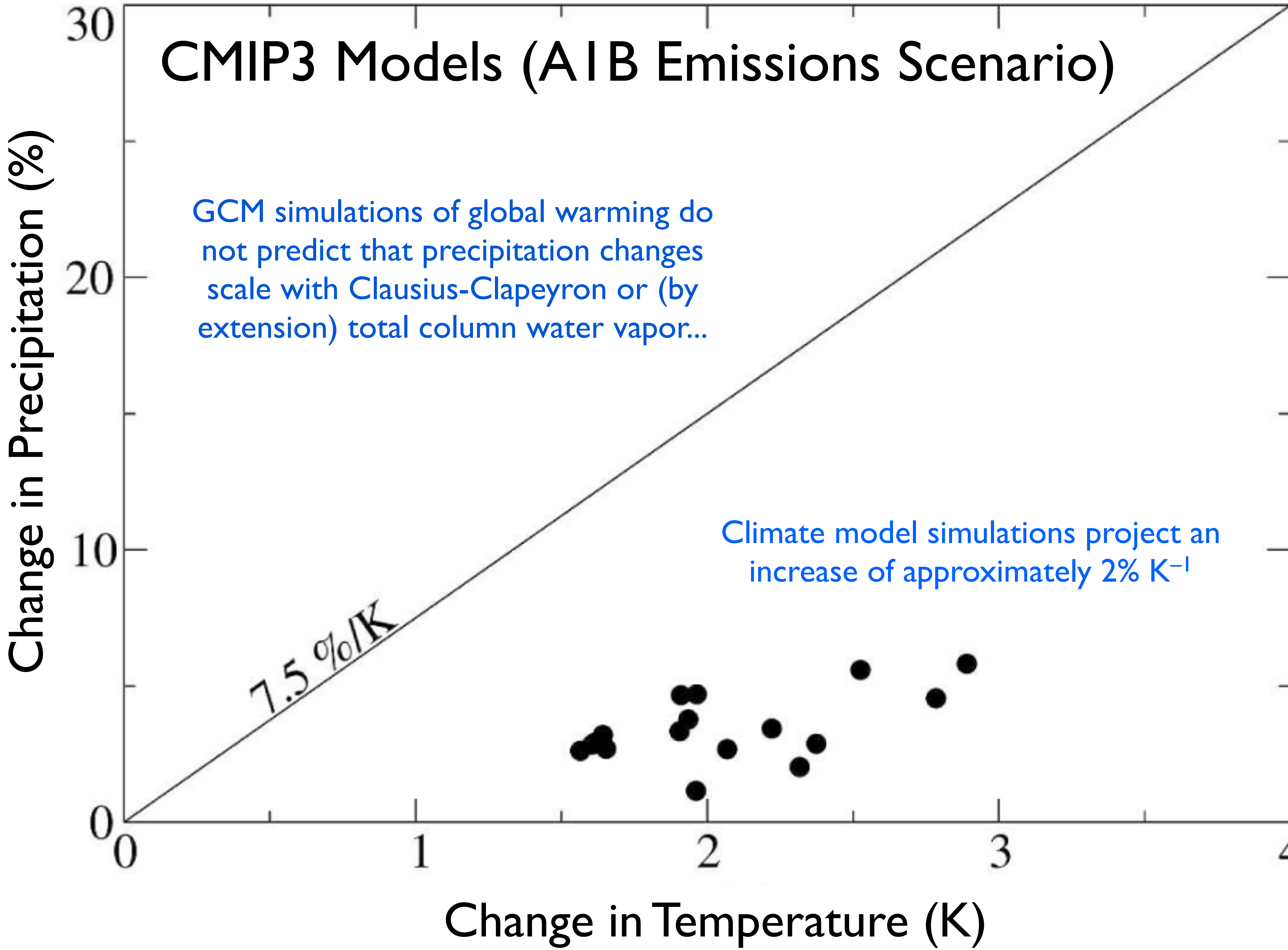
Satellite observations of precipitation and evaporation have approximately the same temporal variability as total column water vapor

But wait...

Observed time series suggests that the sensitivity of precipitation to temperature changes is about 7% K^{-1}...

...Clausius-Clapeyron?

Wentz et al. 2007



Held and Soden 2006

ΔP	Precipitation	source
~3.4% K^{-1}	$2{\times}CO_2$	CMIP2 Models (slab ocean) Allen & Ingram 2002
~2.2% K^{-1}	20^{th} century	CMIP3 Models (20C3M) Held & Soden 2006
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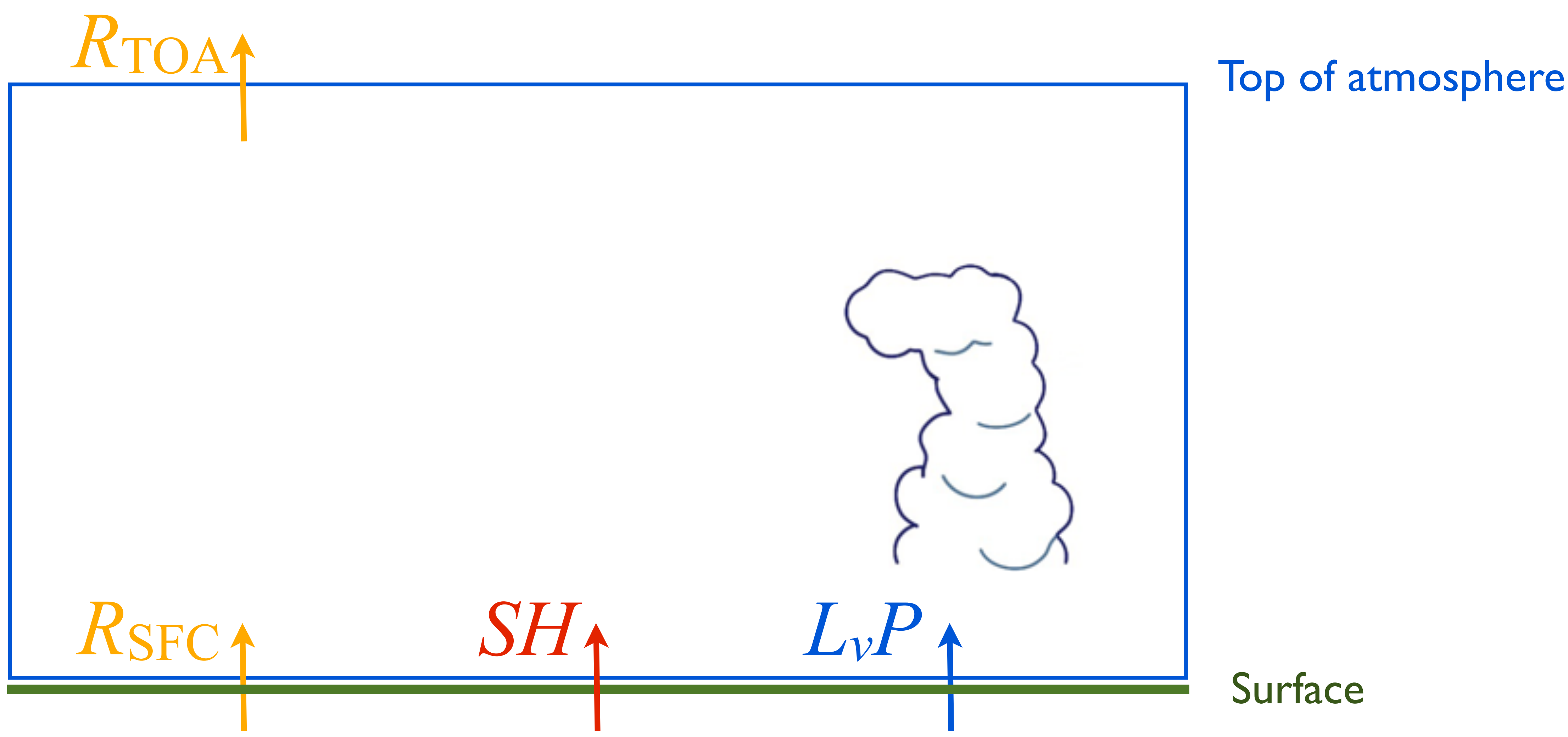
Global Atmospheric Energy Balance

We can think of evaporation and precipitation as energy fluxes and then compute the atmospheric energy budget



$$L_v P = R_{\mathrm{TOA}} - R_{\mathrm{SFC}} - SH$$

Global Atmospheric Energy Balance

net radiative flux at the top of the atmosphere

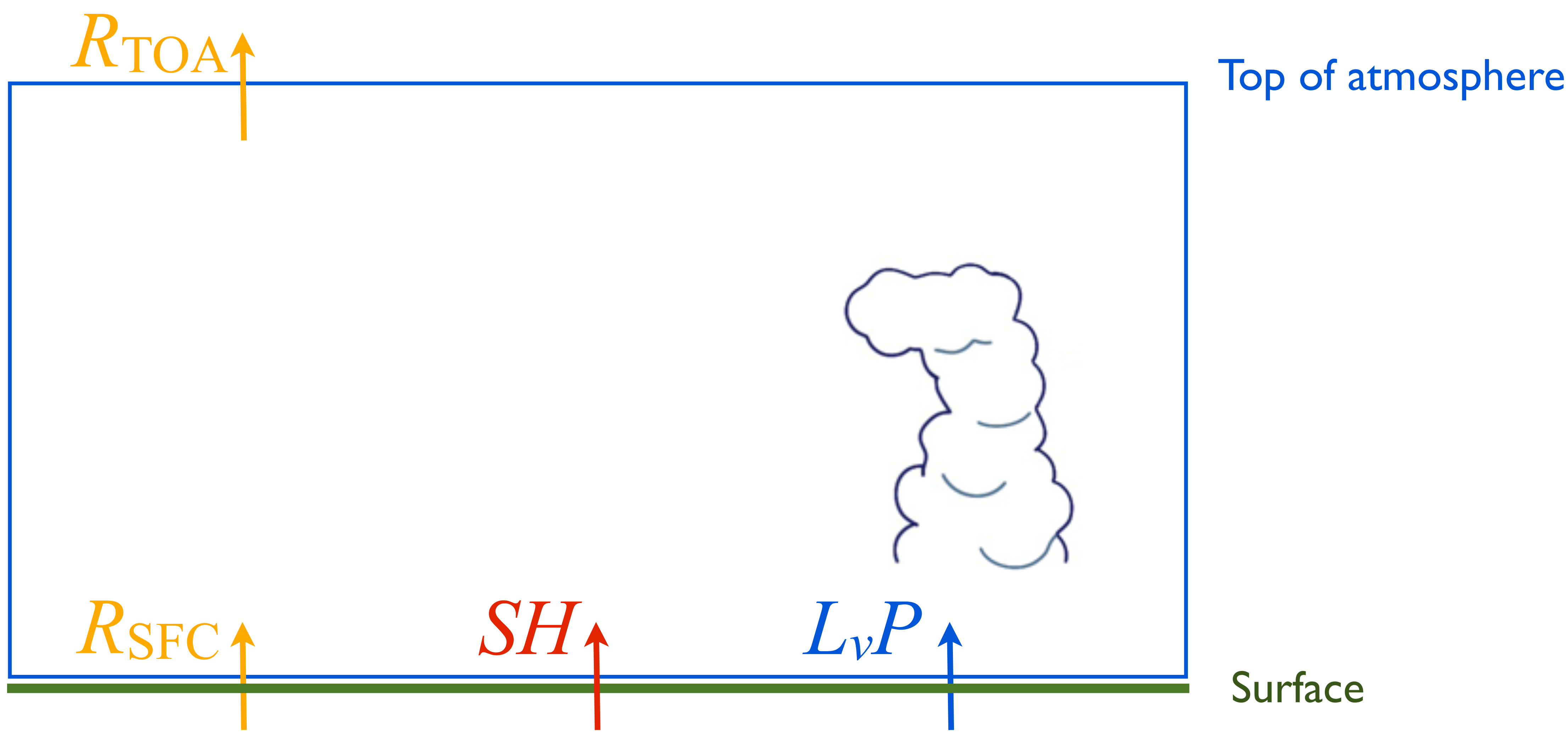
sensible heat flux into the atmosphere

latent heating of the atmosphere

net radiative flux at the base of the atmosphere

$$L_v P = R_{\mathrm{TOA}} - R_{\mathrm{SFC}} - SH$$

Global Atmospheric Energy Balance



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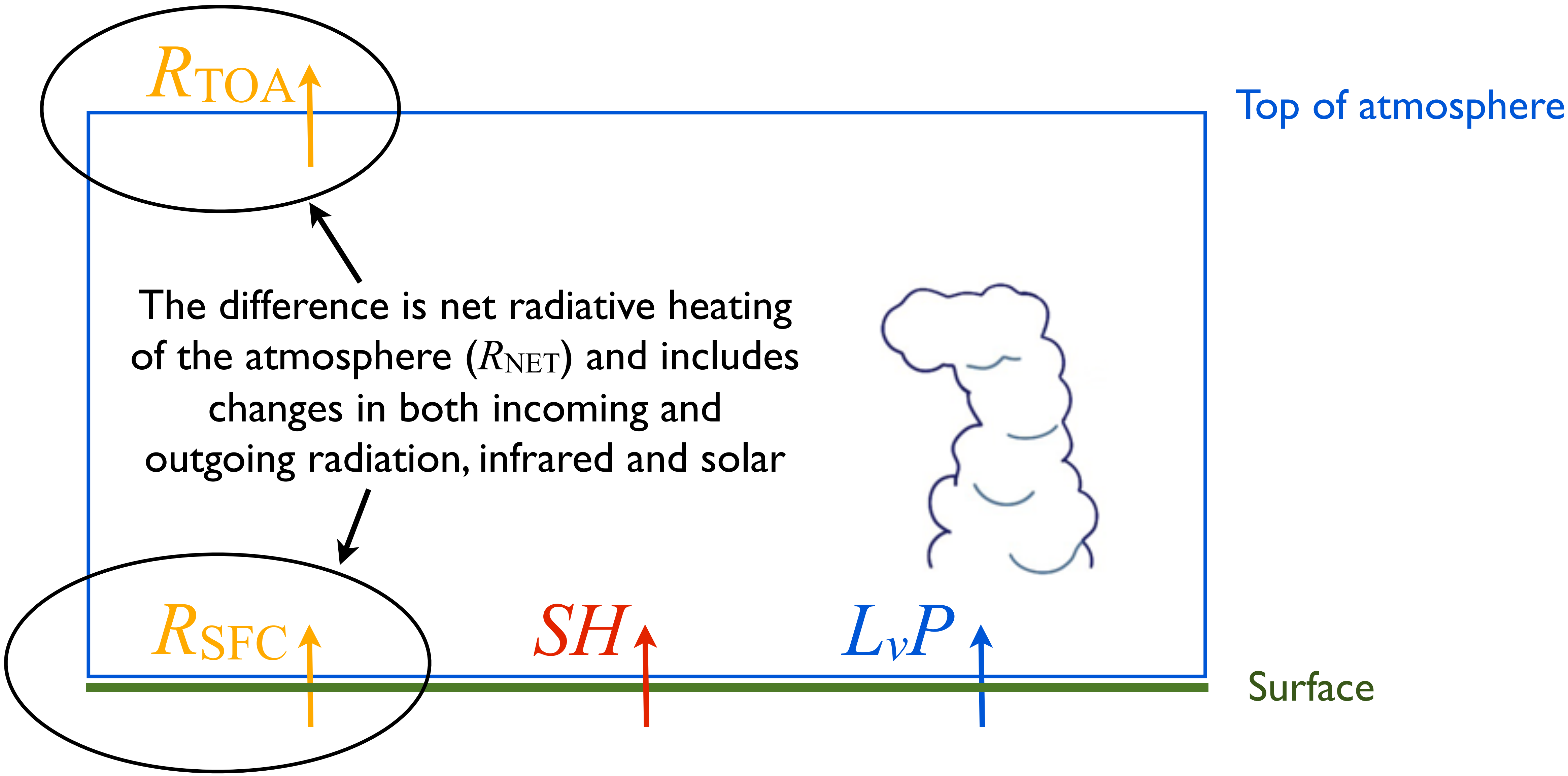
Global Atmospheric Energy Balance



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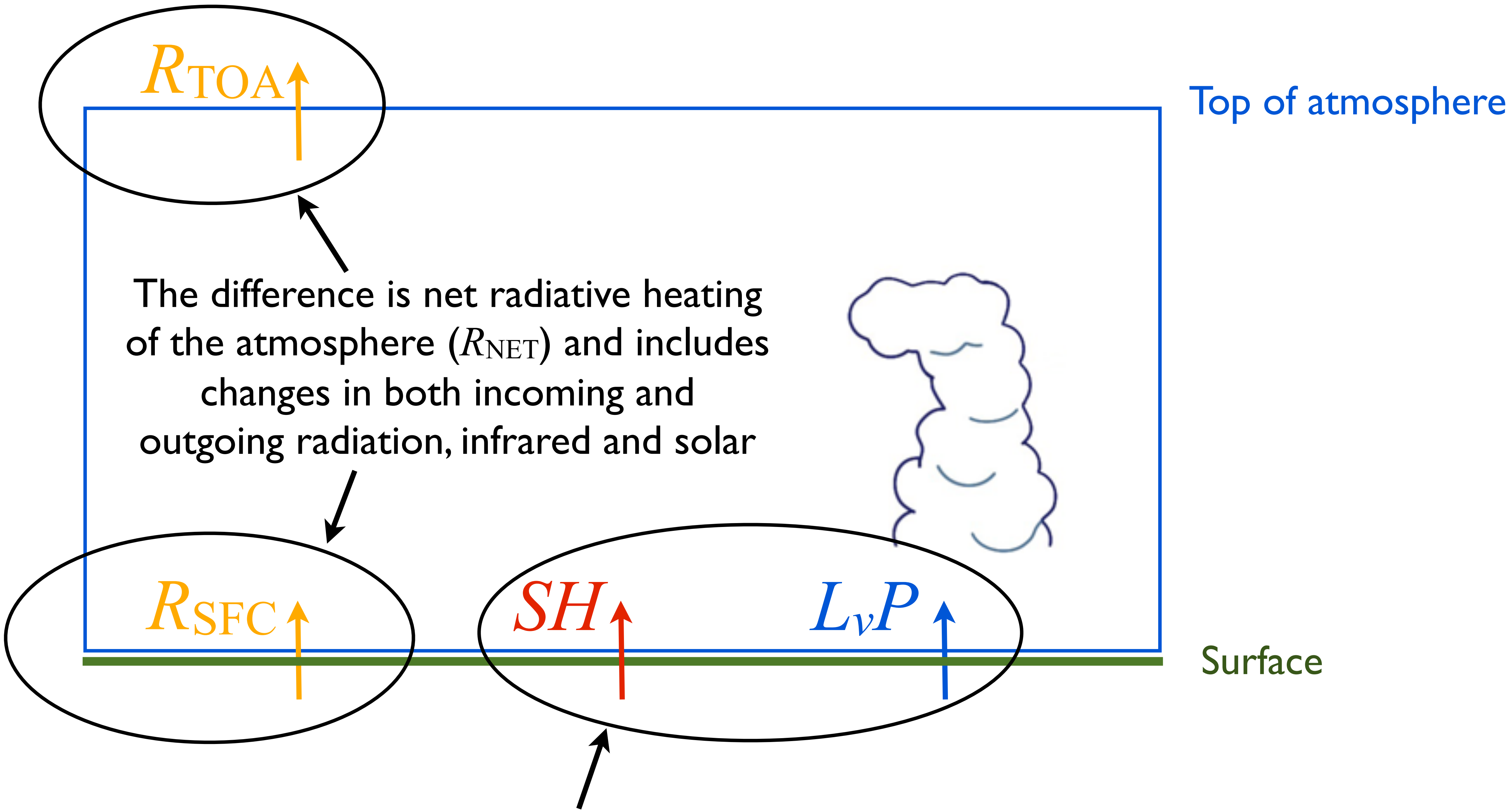
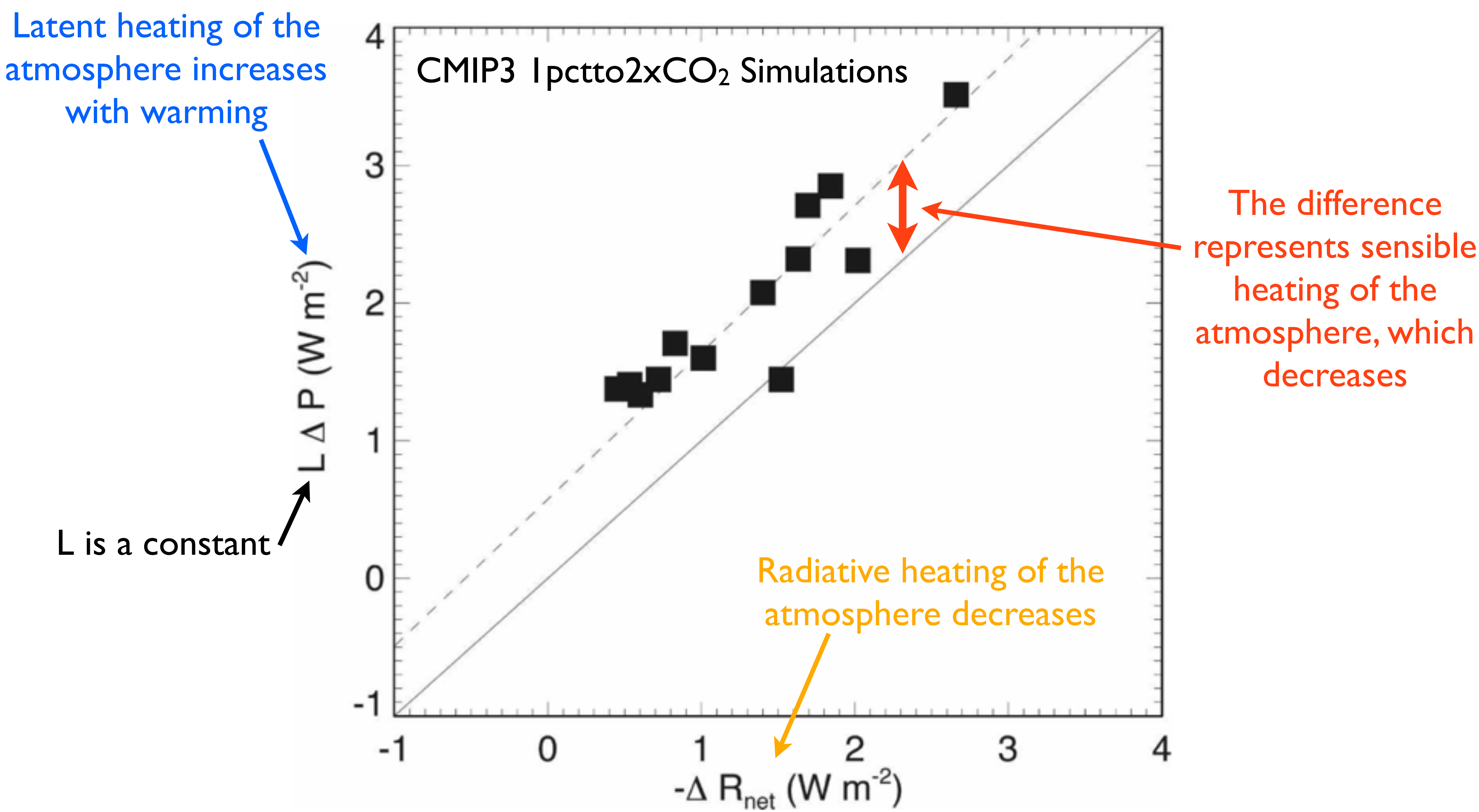
Global Atmospheric Energy Balance



Combined must balance R_{SFC} and R_{NET}, but the Bowen ratio SH/L_vP may also change

$$L_vP = R_{\text{TOA}} - R_{\text{SFC}} - SH$$

Global Atmospheric Energy Balance

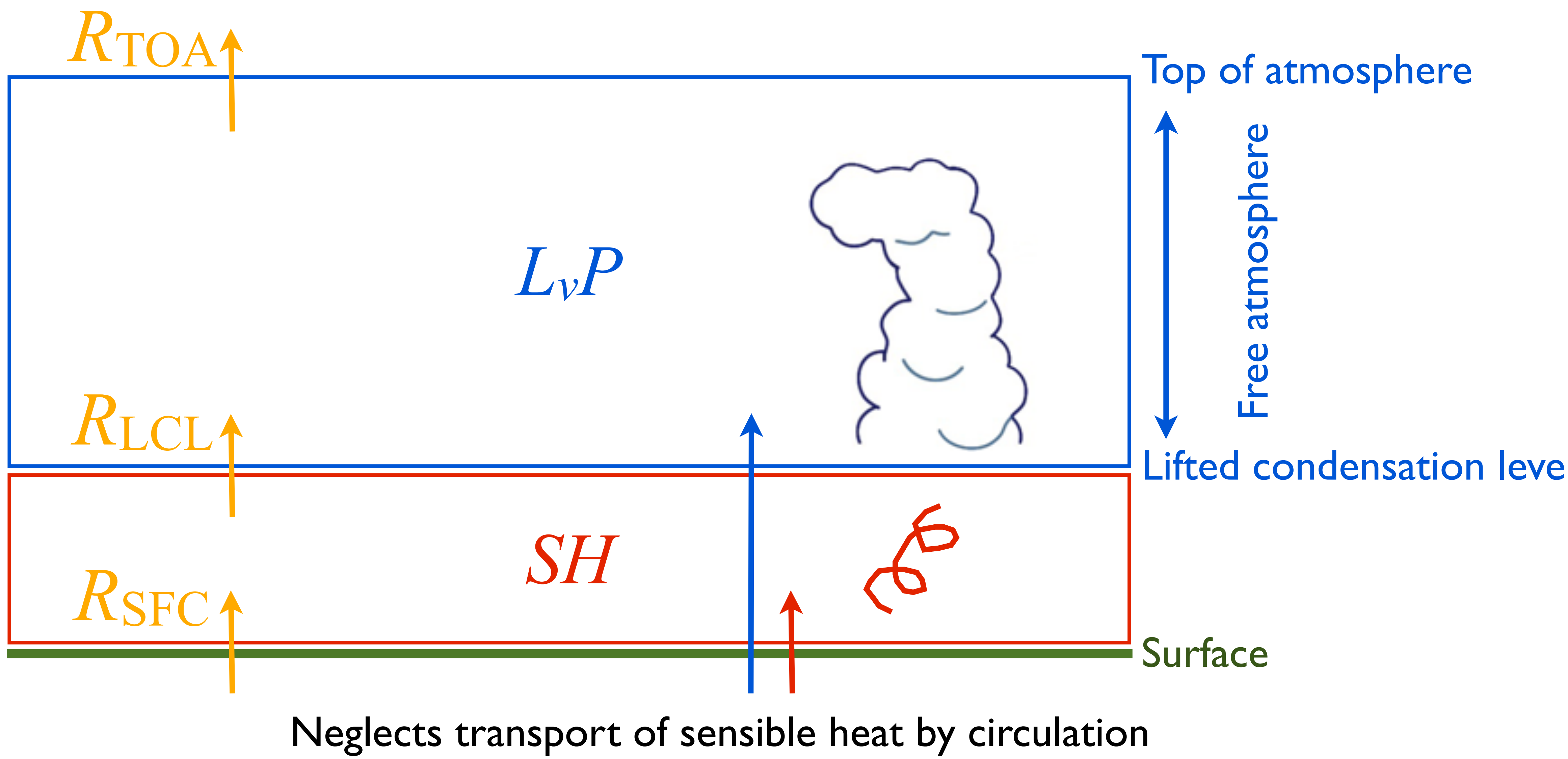


Precipitation increases when the atmosphere loses energy and decreases when the atmosphere gains energy

Stephens and Ellis 2008

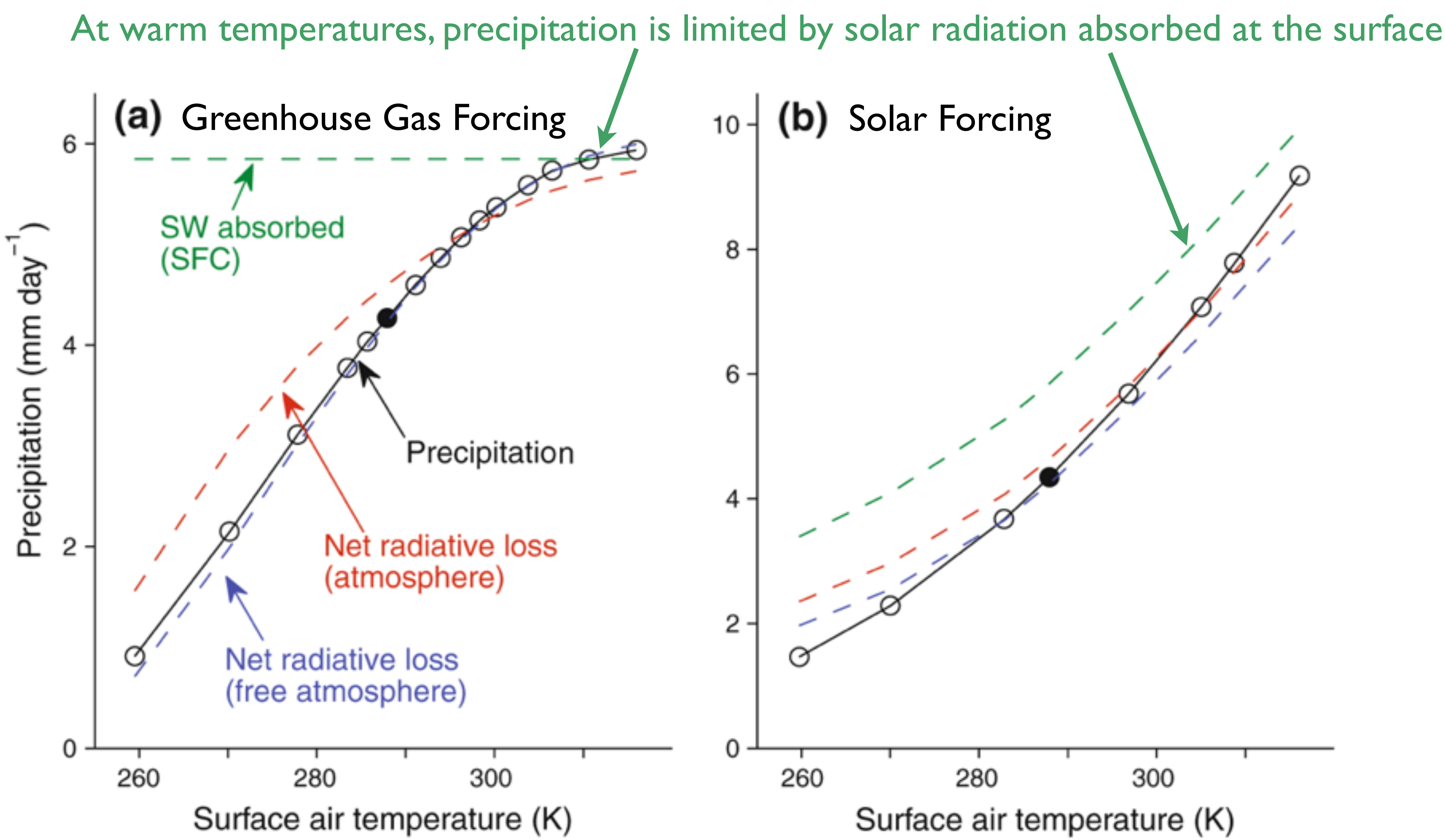
Global Atmospheric Energy Balance

If sensible and latent heating (condensation) occur in separate regions of the atmosphere, we can simplify the constraint:



$$L_v P \doteq R_{\mathrm{TOA}} - R_{\mathrm{LCL}}$$

Global Atmospheric Energy Balance

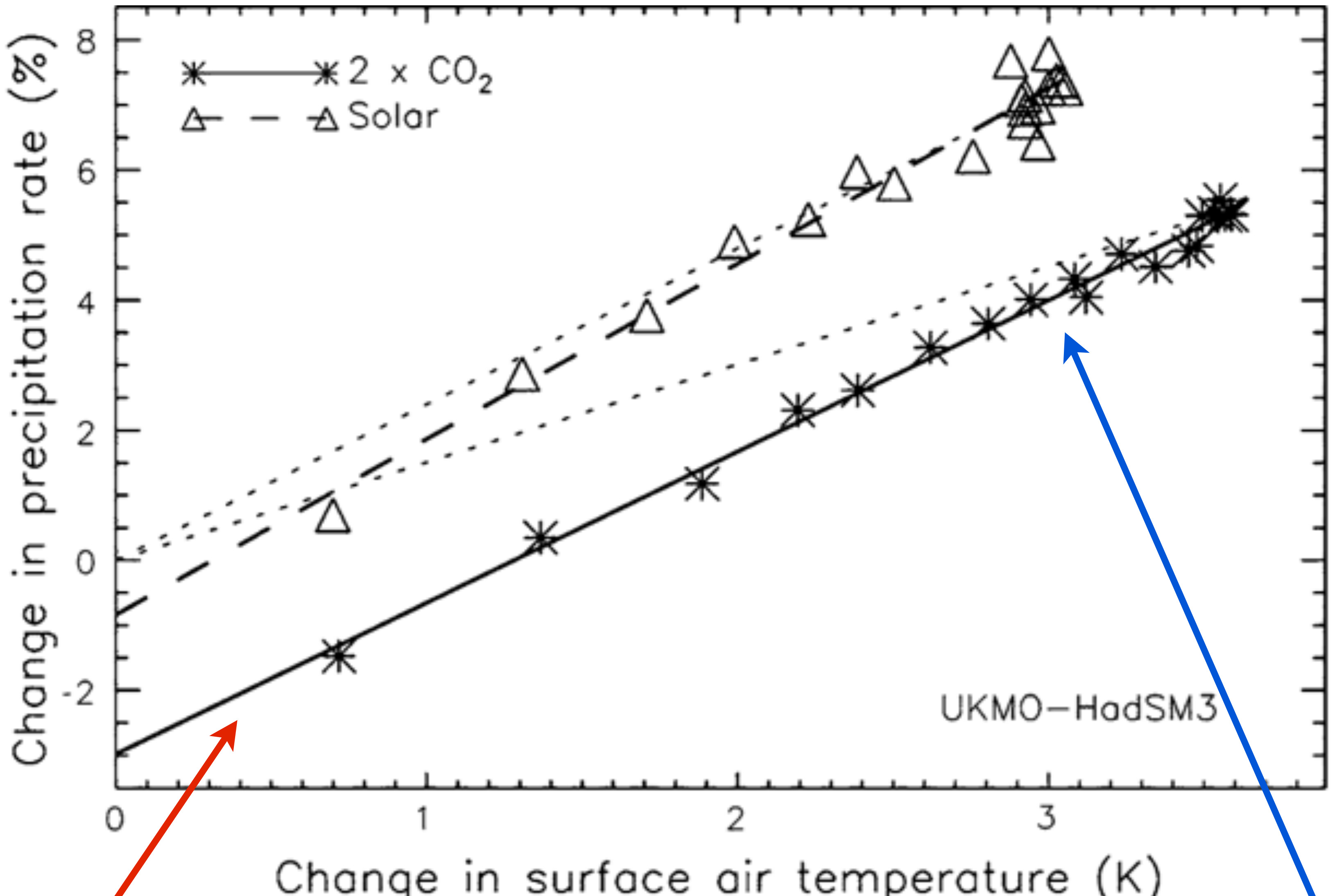


The net radiative heating of the free atmosphere provides a more accurate constraint than that of the entire atmosphere

O'Gorman et al. 2012

Transient Sensitivity to Different Forcings

Initial response followed by gradual adjustment of precipitation to an instantaneous increase in greenhouse gases or solar radiation



Initial decrease indicates an increase in the radiative heating of the atmosphere

Linear increase reflects the effects of the gradual increase in temperature that follows the abrupt change in radiative forcing

Andrews et al. 2009

Decomposing the Precipitation Response

The linear relationship between temperature and precipitation suggests that the response can be decomposed into different parts

"Slow" response

"Fast" response

k is a constant

$$L_v \Delta P = k \Delta T + G$$

Temperature-dependent response

Temperature-independent response (initial forcing)

Andrews et al. 2009

Transient Sensitivity to Different Forcings

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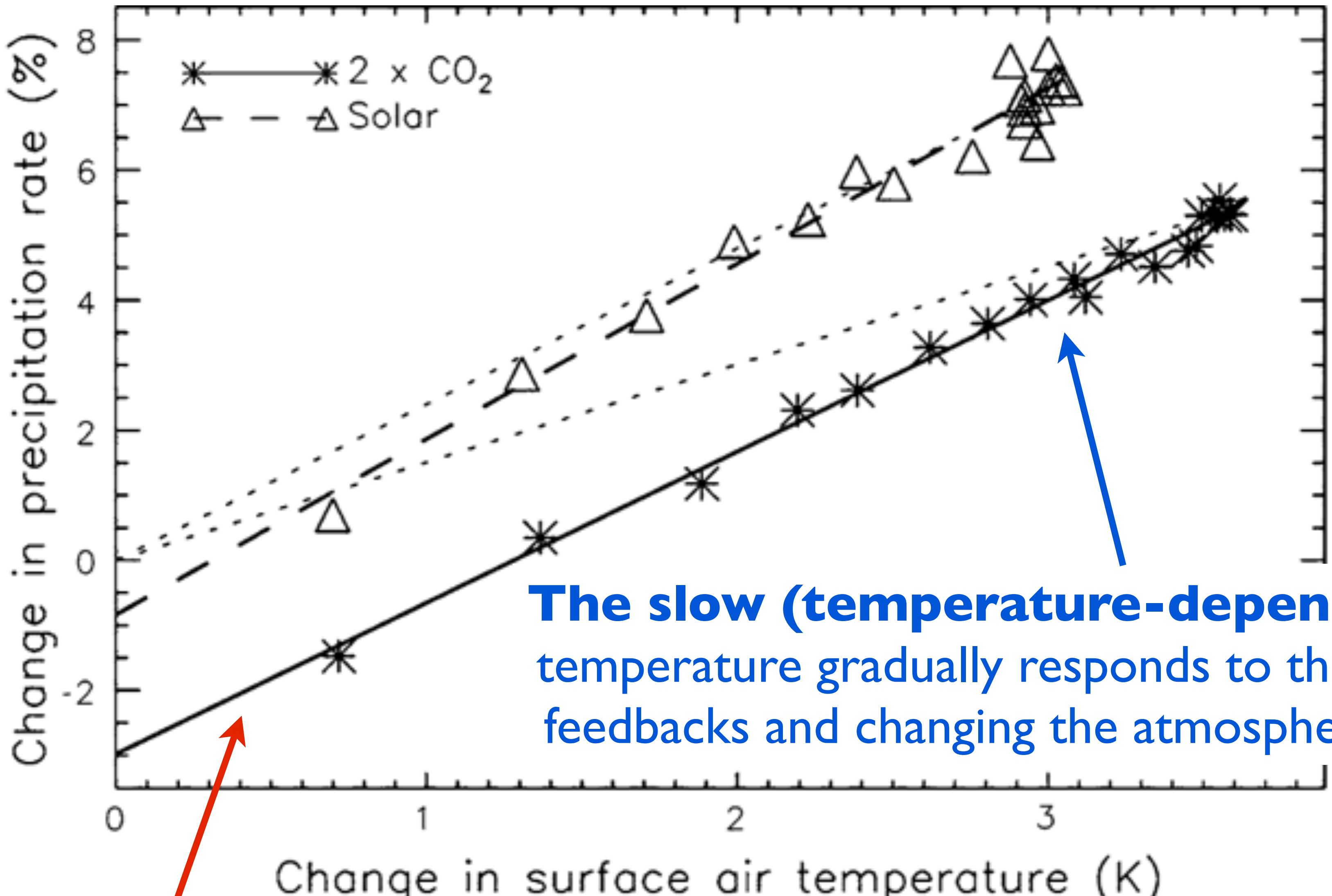
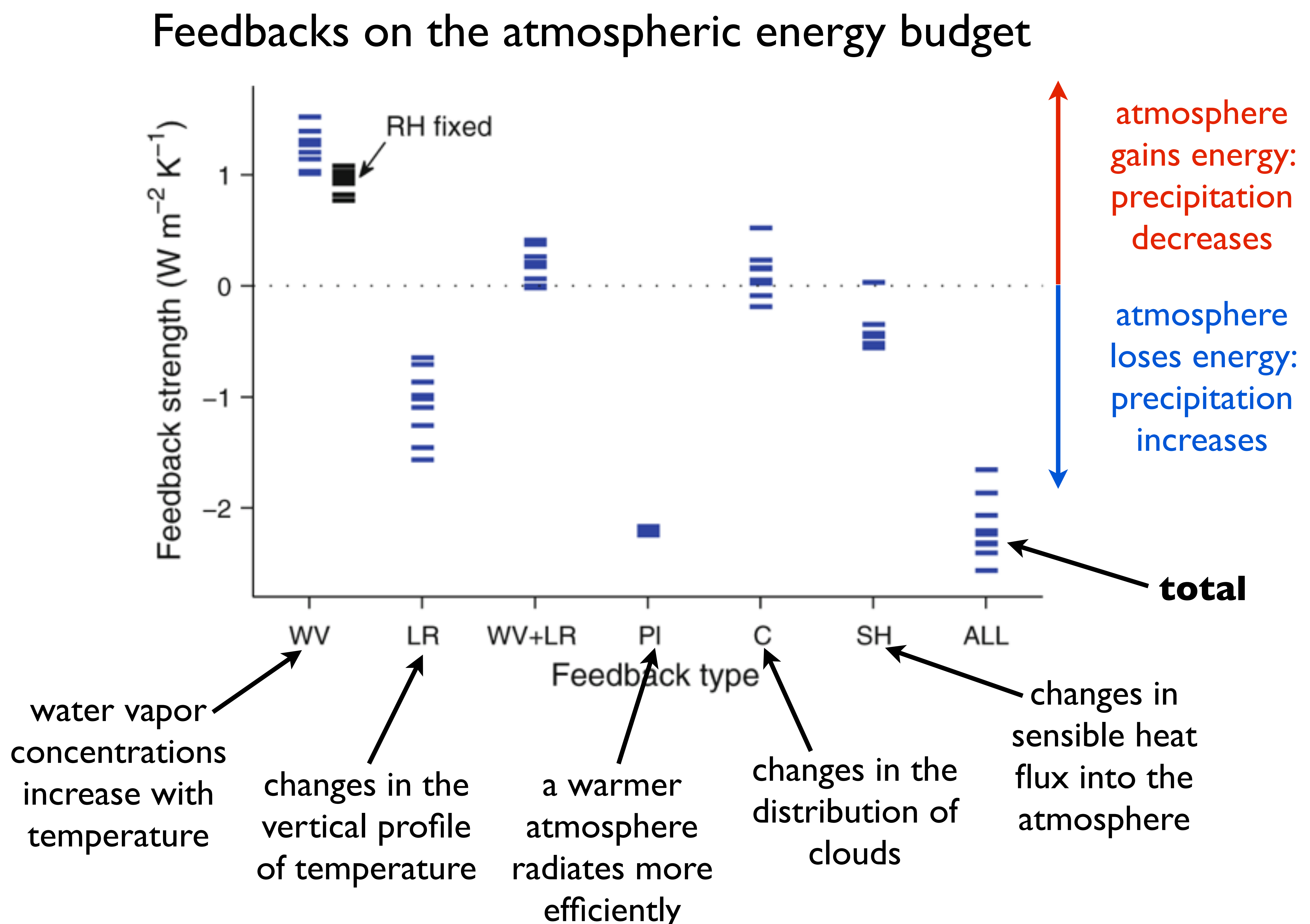


The slow (temperature-dependent) response:
temperature gradually responds to the forcing, activating feedbacks and changing the atmospheric energy balance

The fast (temperature-independent) response:
an increase in carbon dioxide or solar radiation initially increases the radiative heating of the atmosphere, reducing precipitation

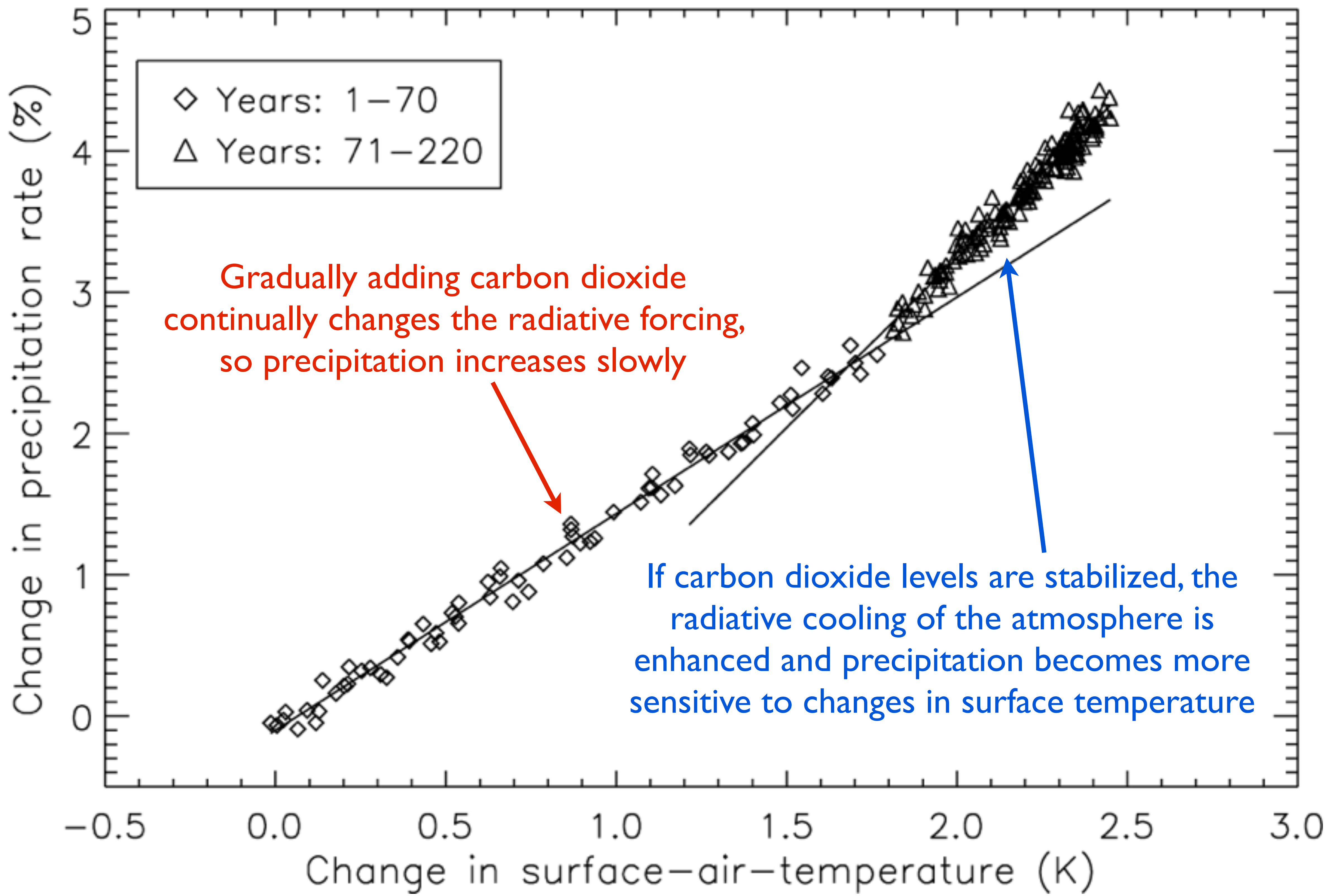
Andrews et al. 2009

The Temperature-Dependent Response

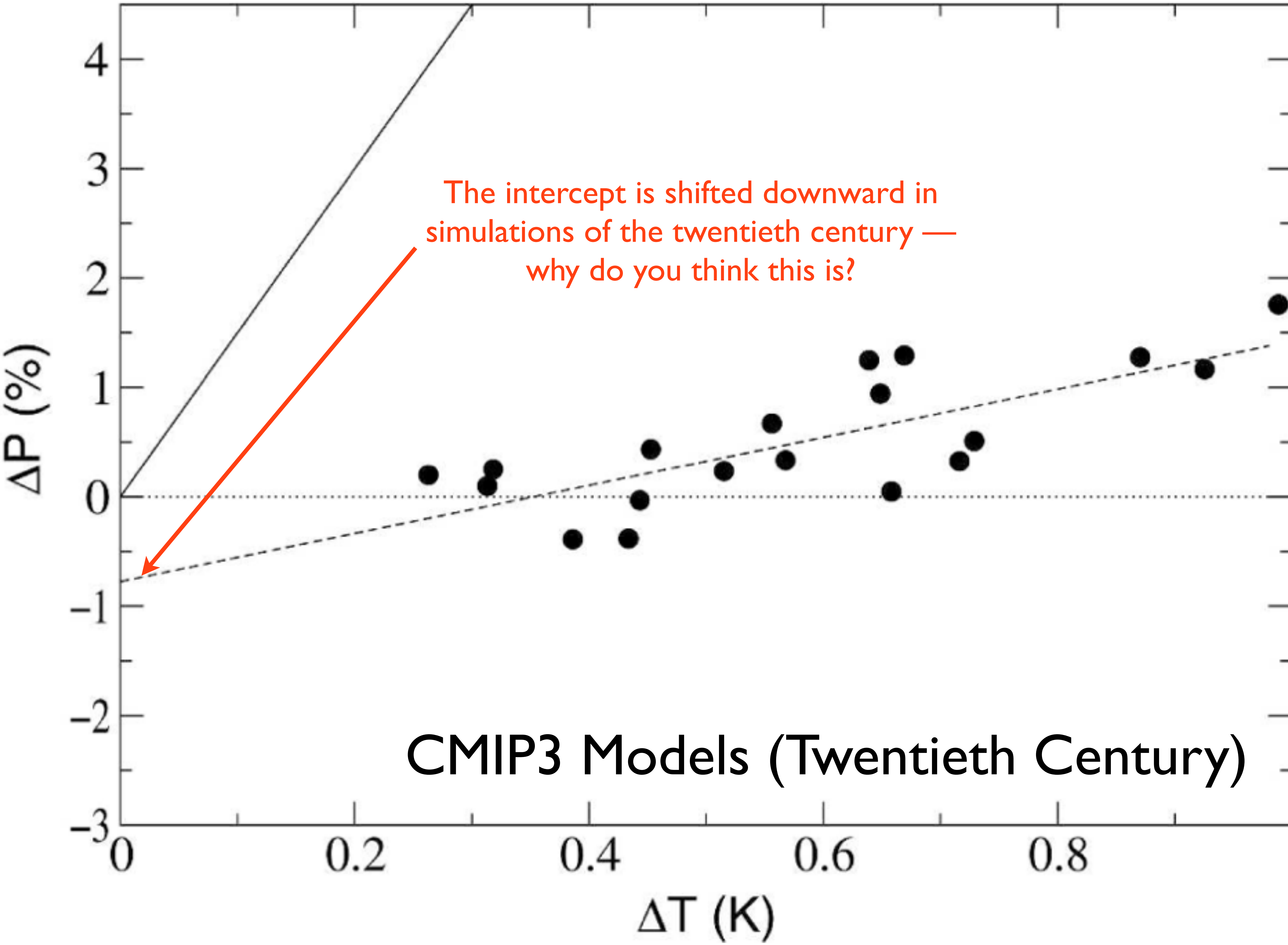


O'Gorman et al. 2012

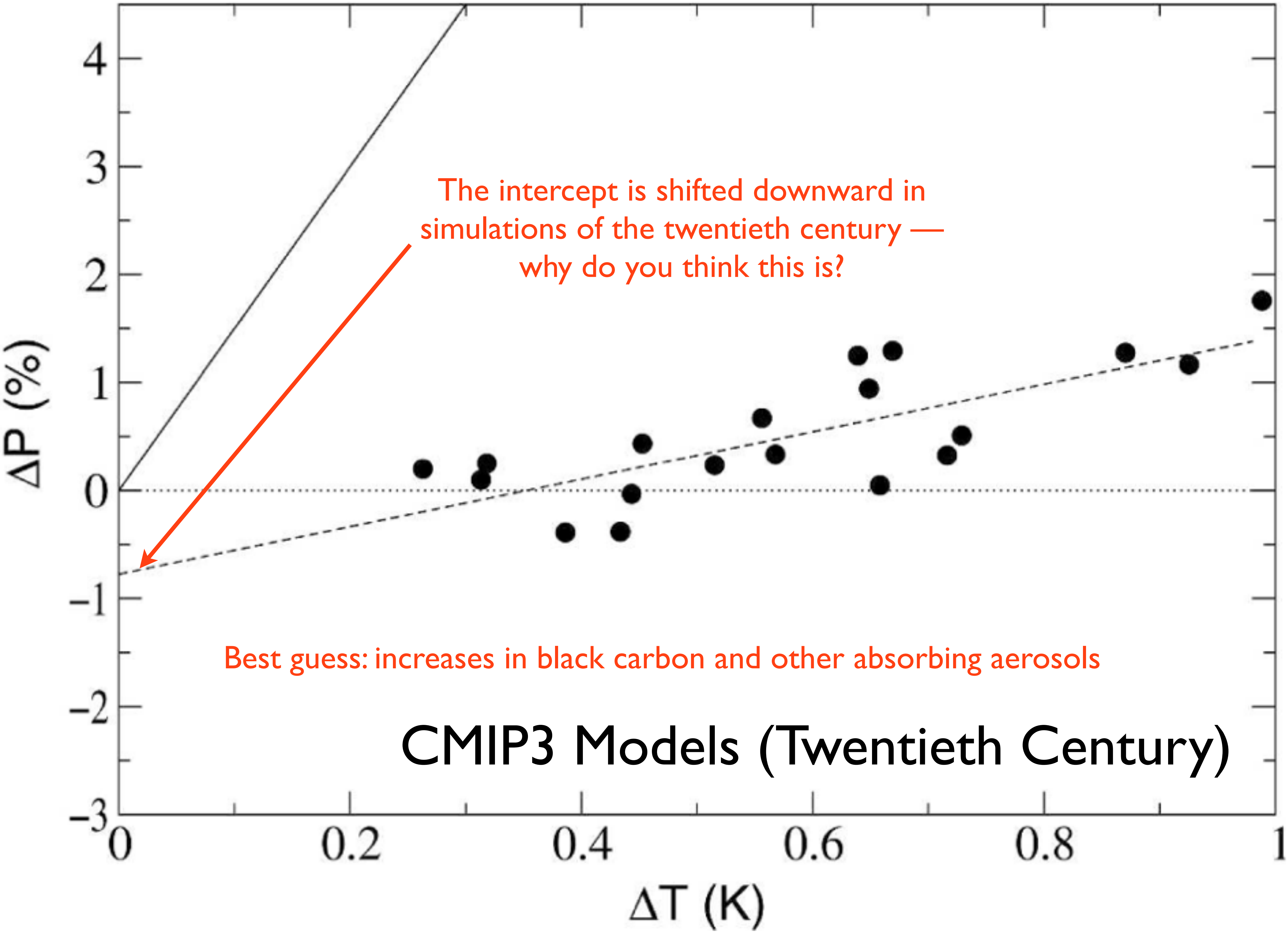
Transient vs. Equilibrium Response



Andrews and Forster 2010



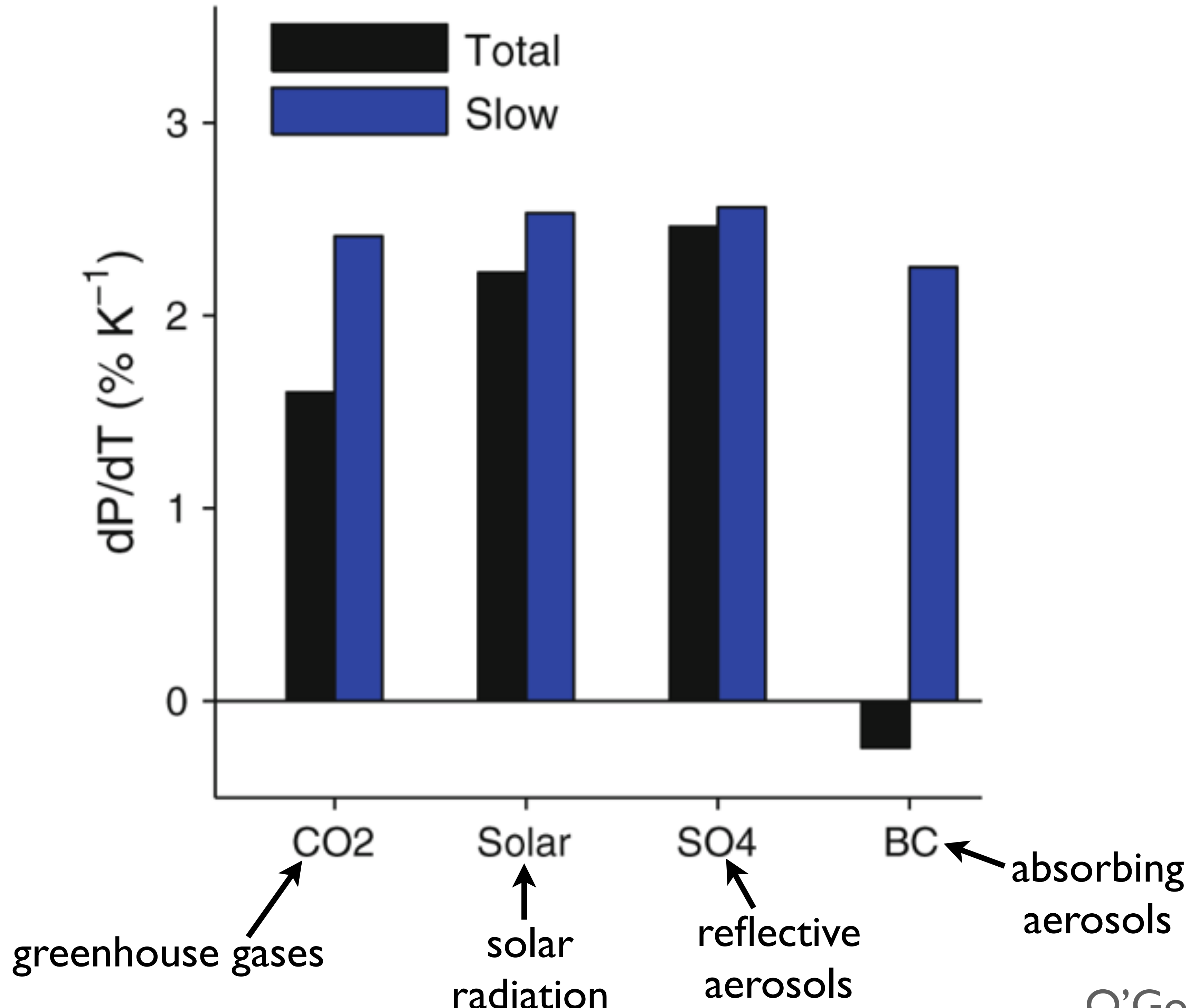
Held and Soden 2006



Held and Soden 2006

Dependence on the Type of Forcing

The total response of precipitation to temperature change depends on the forcing agent, even though the temperature-dependent response is similar

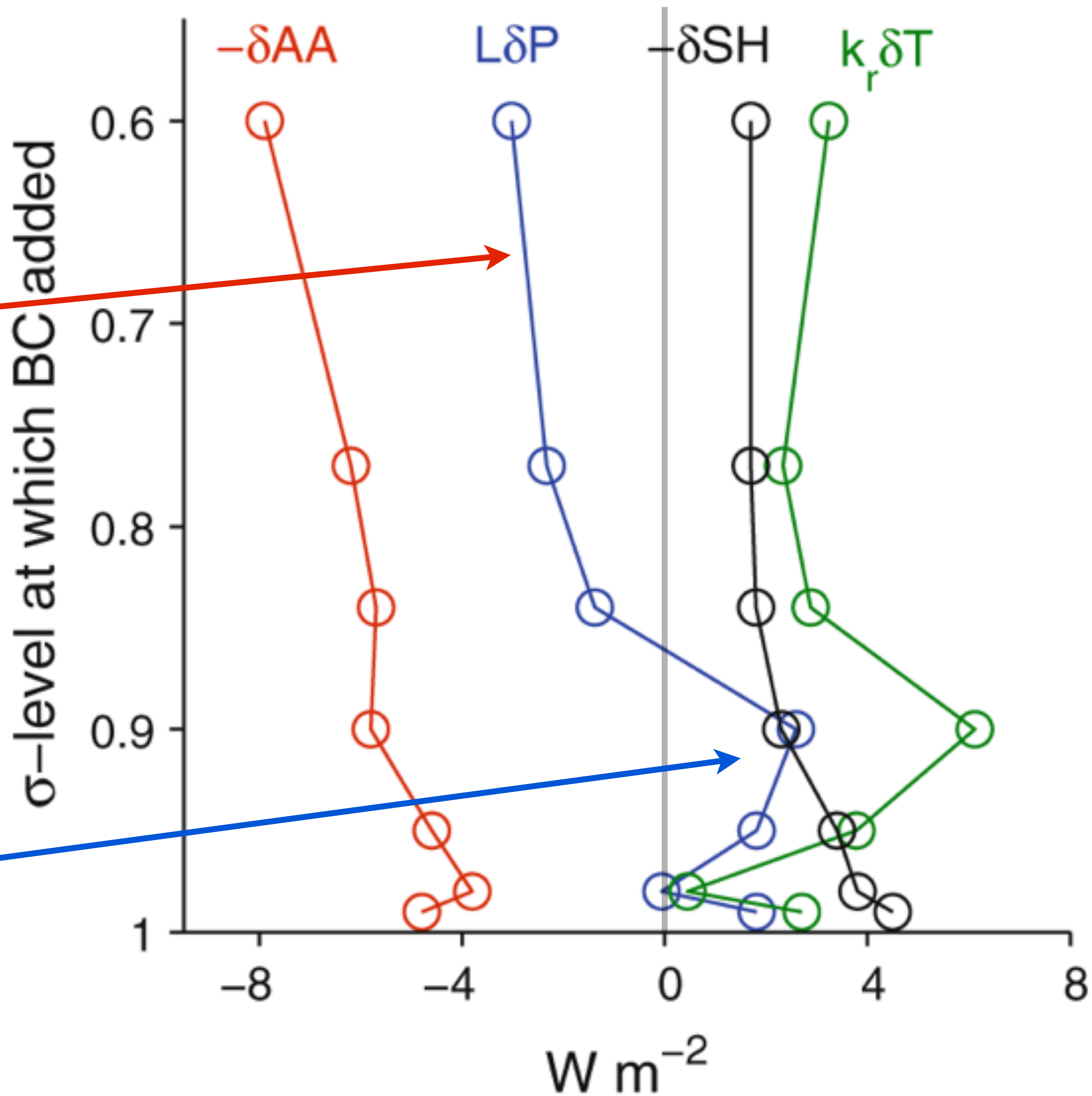


O'Gorman et al. 2012

Effects of Absorbing Aerosols

Adding black carbon higher in the atmosphere tends to reduce precipitation

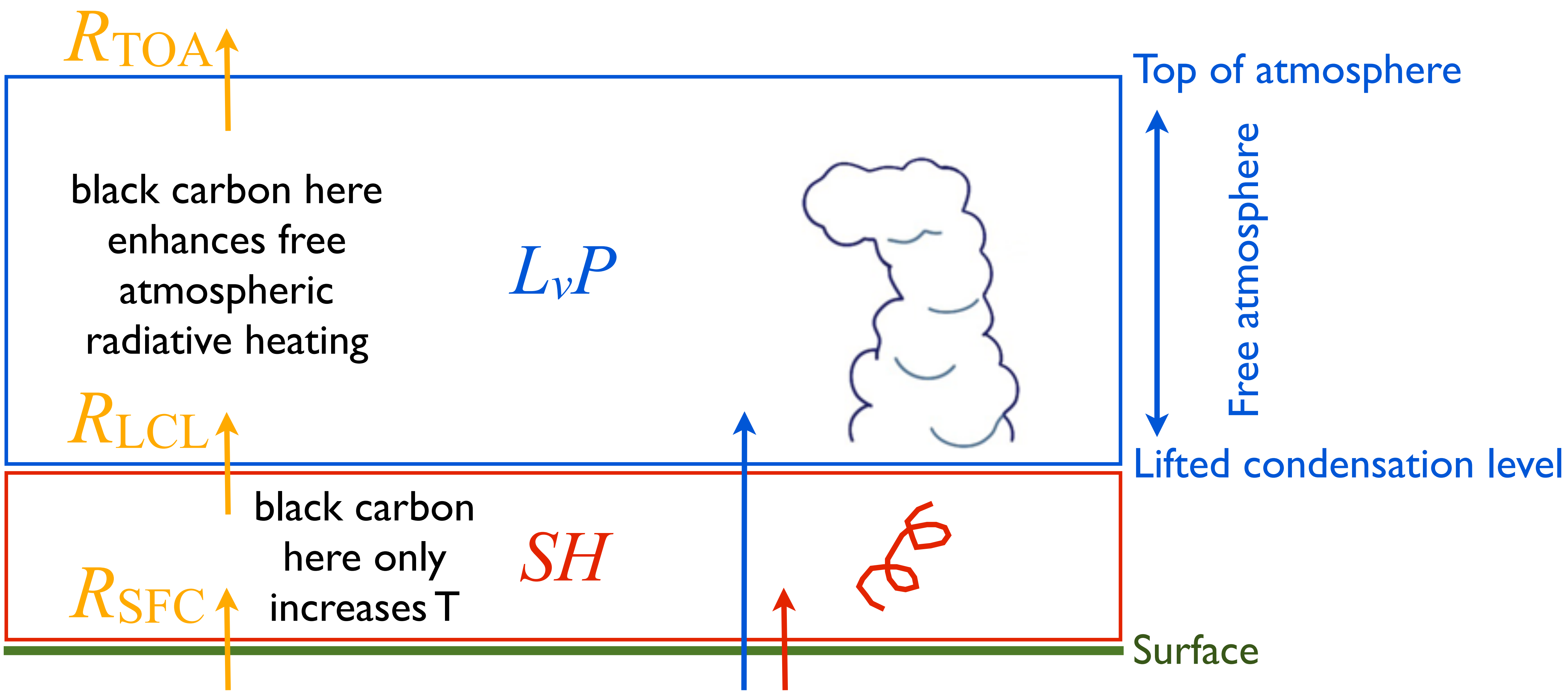
Adding black carbon in the boundary layer tends to increase precipitation



O'Gorman et al. 2012

Global Atmospheric Energy Balance

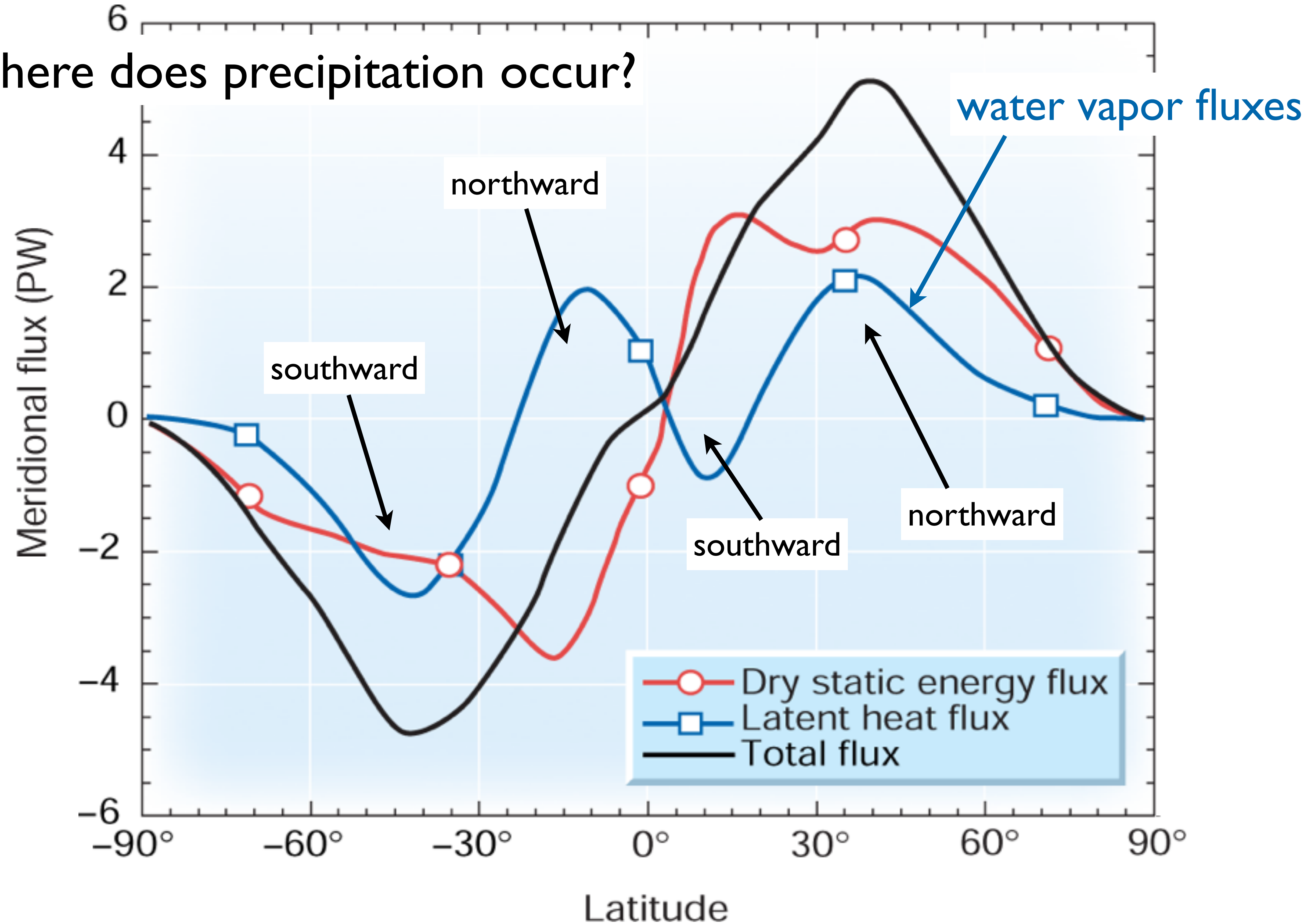
Increasing black carbon in different regions of the atmosphere has different effects on the energy budget



$$L_vP = R_{TOA} - R_{LCL}$$

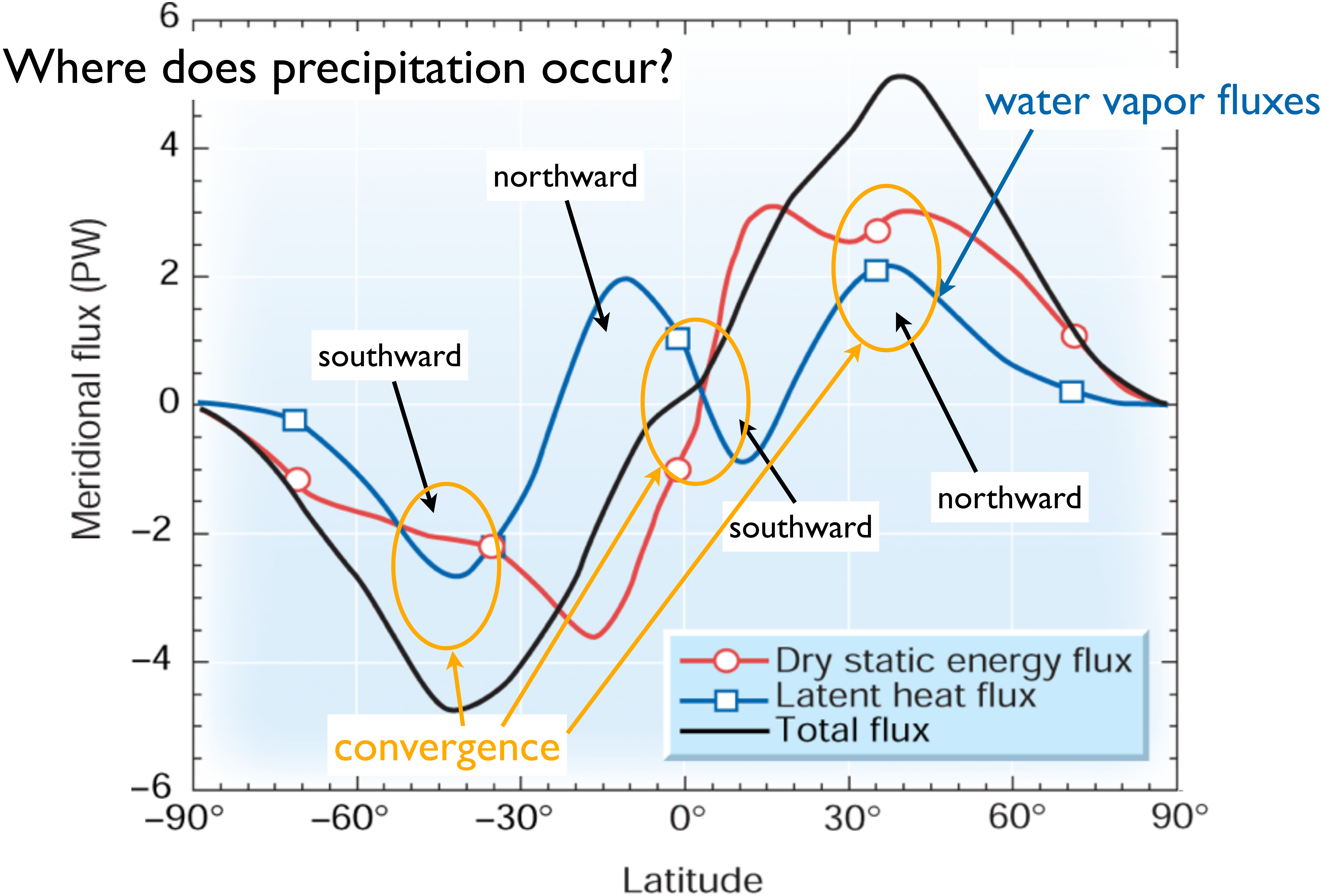
Water Vapor Fluxes and Precipitation

Where does precipitation occur?



Pierrehumbert 2002

Water Vapor Fluxes and Precipitation



Pierrehumbert 2002

Water Vapor Fluxes and Precipitation

density

meridional velocity

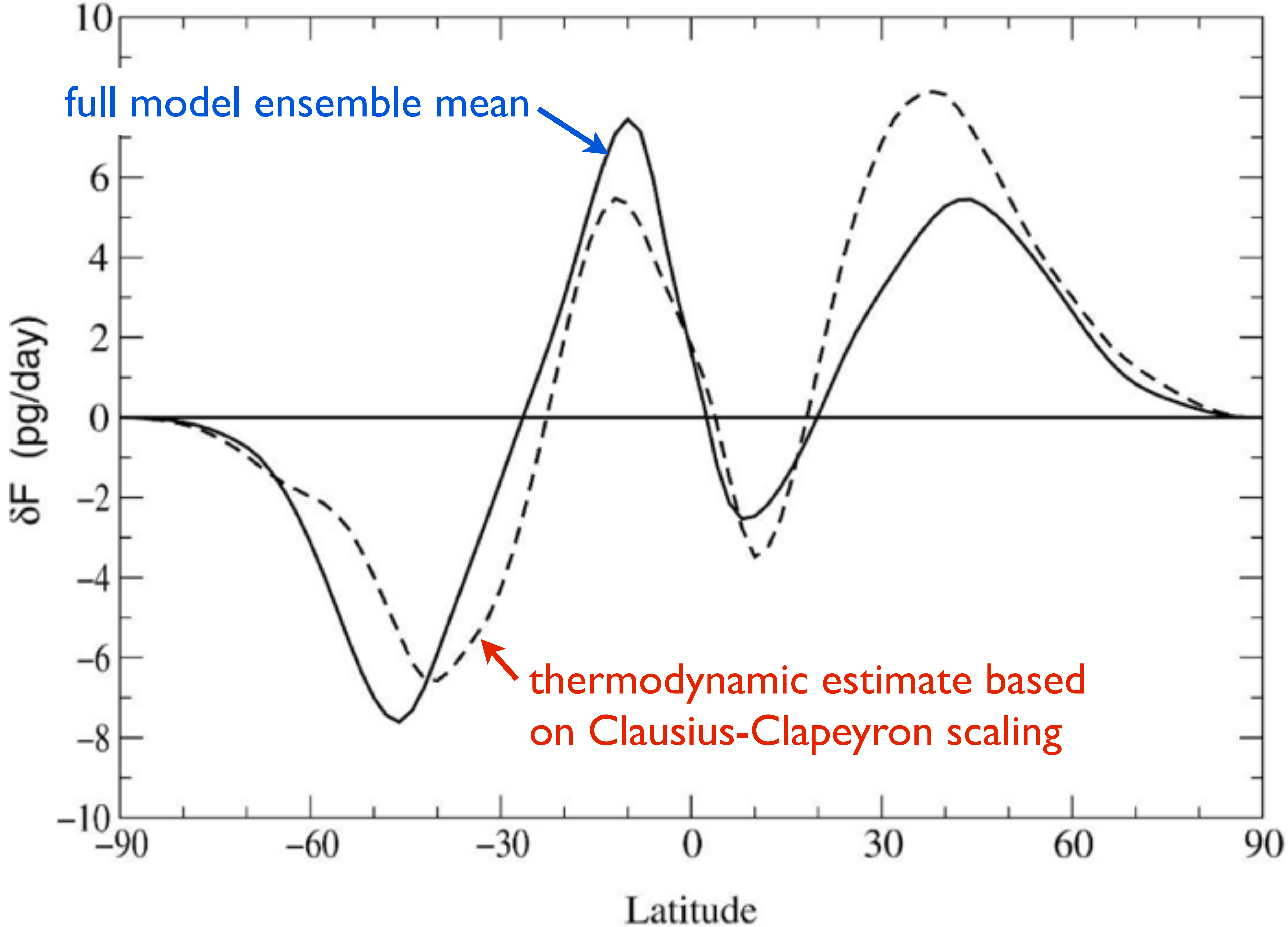
$$F = \rho V L_v q$$

specific humidity [kg kg^{-1}]

If no changes in circulation, fluxes follow Clausius-Clapeyron:

$$\frac{\delta F}{F} \approx \frac{\delta e_s}{e_s} \approx \alpha \delta T$$

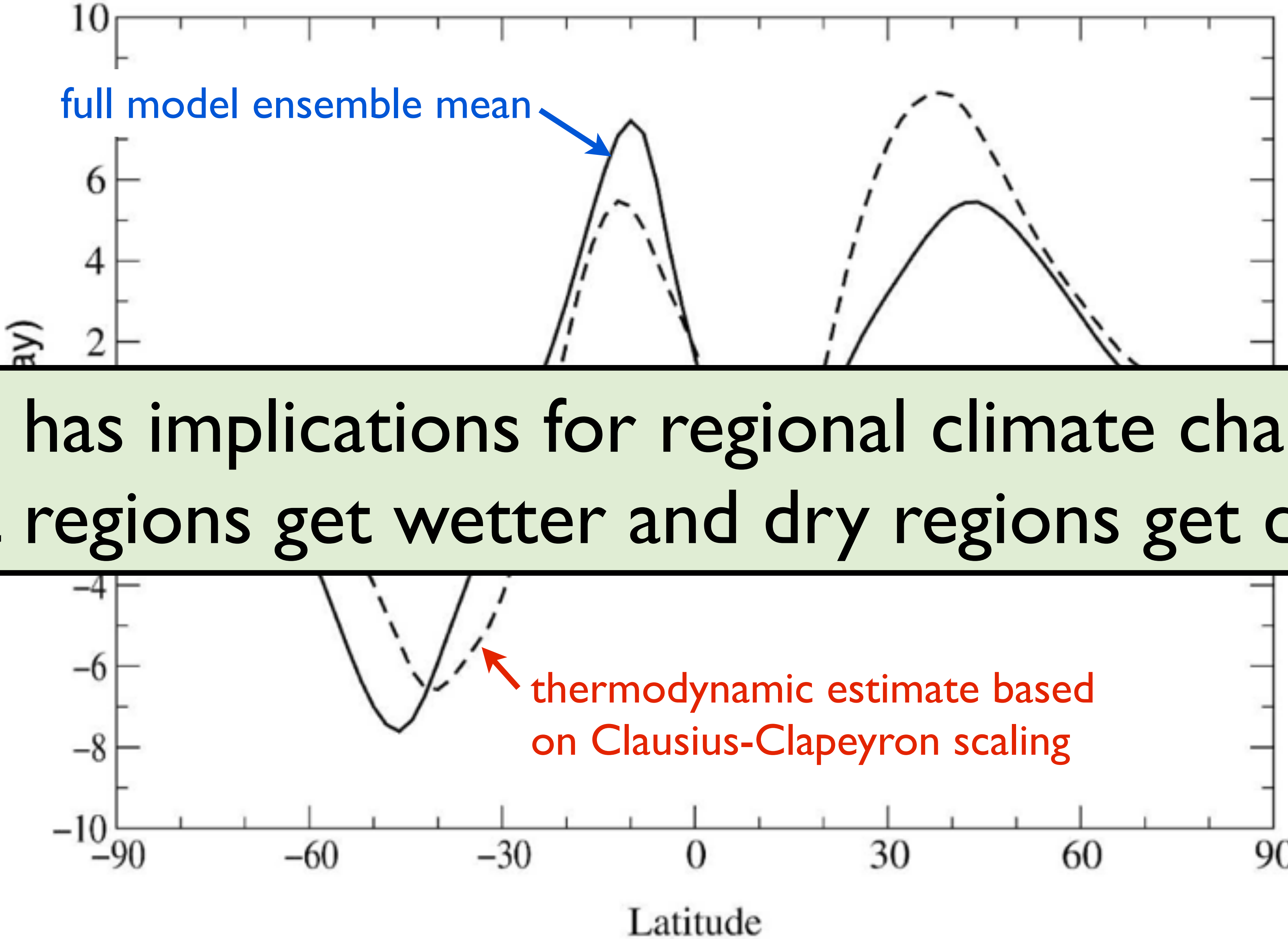
Projected Changes in Water Vapor Flux



Climate model simulations suggest that Clausius-Clapeyron scaling is a useful approximation for water vapor fluxes

Held and Soden 2006

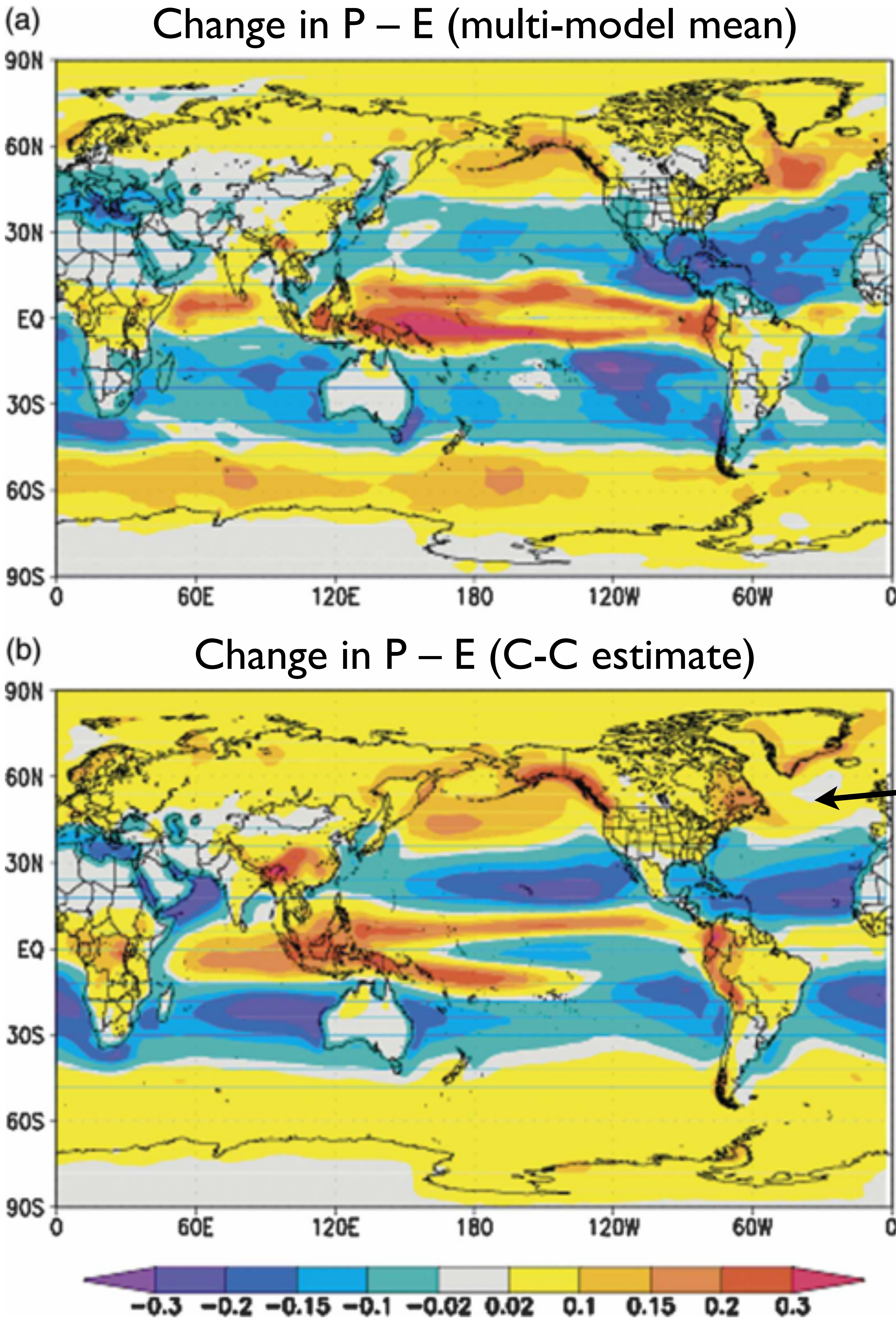
Projected Changes in Water Vapor Flux



This has implications for regional climate changes: wet regions get wetter and dry regions get drier

Climate model simulations suggest that Clausius-Clapeyron scaling is a useful approximation for water vapor fluxes

Held and Soden 2006



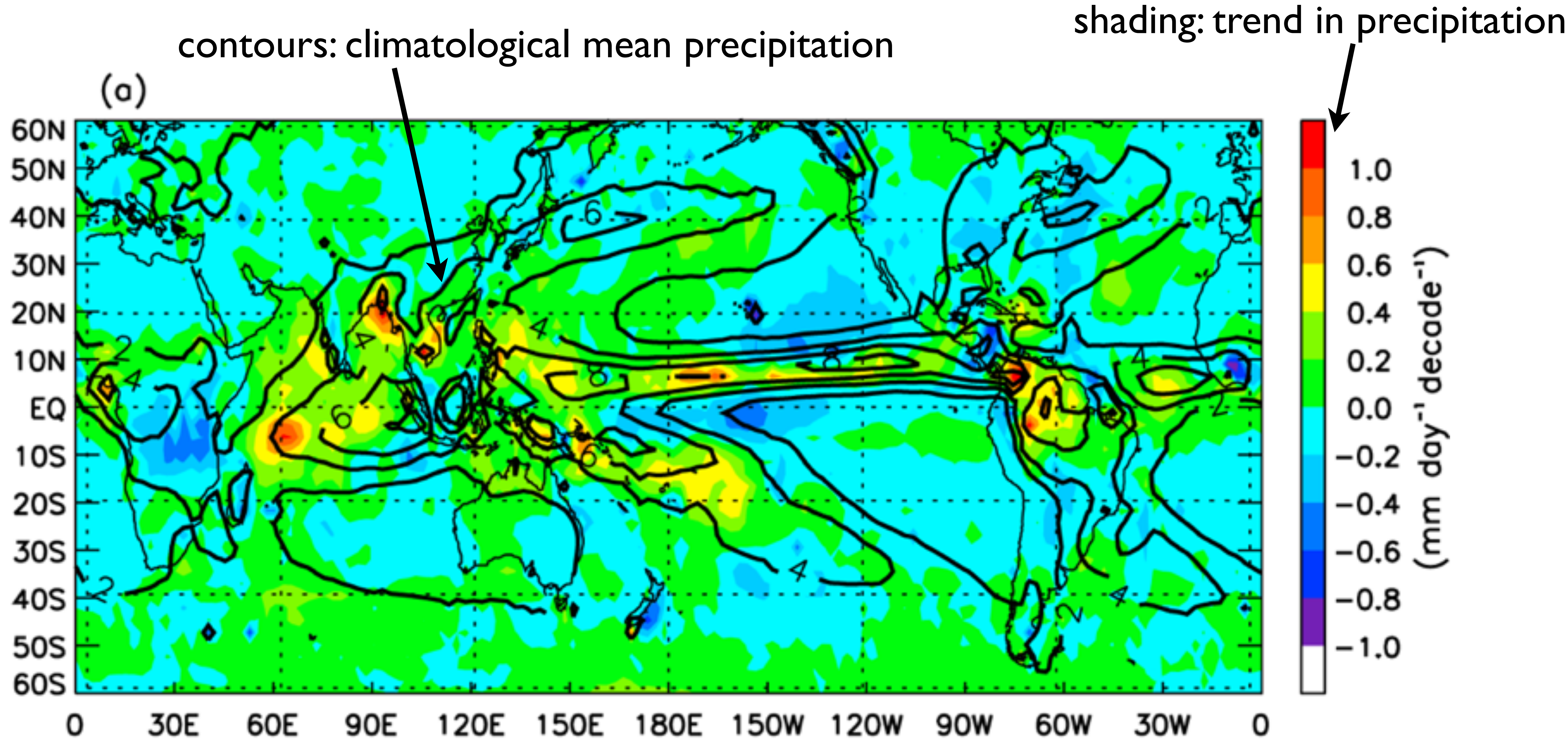
The extent of the agreement between GCM simulations and estimates based on Clausius-Clapeyron scaling suggests that "wet gets wetter, dry gets drier" is a useful starting point for understanding regional changes in precipitation

The thermodynamic estimate of changes in P–E based on Clausius-Clapeyron scaling exactly represents "wet gets wetter, dry gets drier":

$$\Delta(P-E) = 0.07(P-E)\Delta T$$

Held and Soden 2006

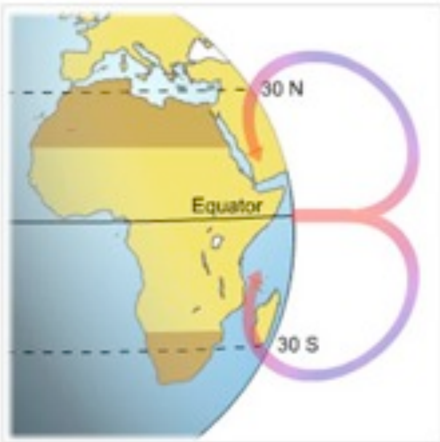
Observed Precipitation Changes (1979–2007)



Observed trends in precipitation over the past three decades are also consistent with this idea, especially in the tropics

Zhou et al. 2011

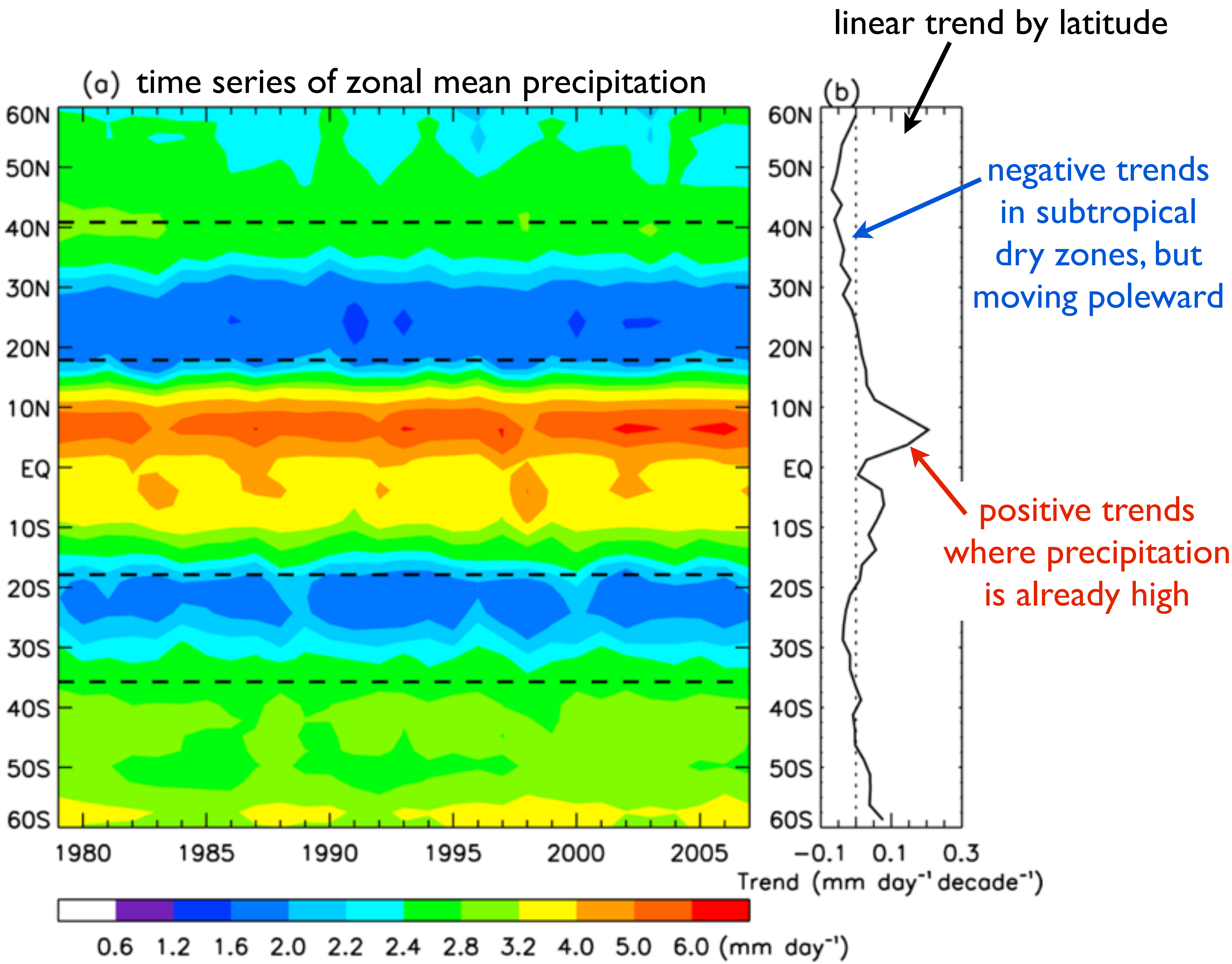
Changes in the Hadley Cell (1979–2007)



descending air

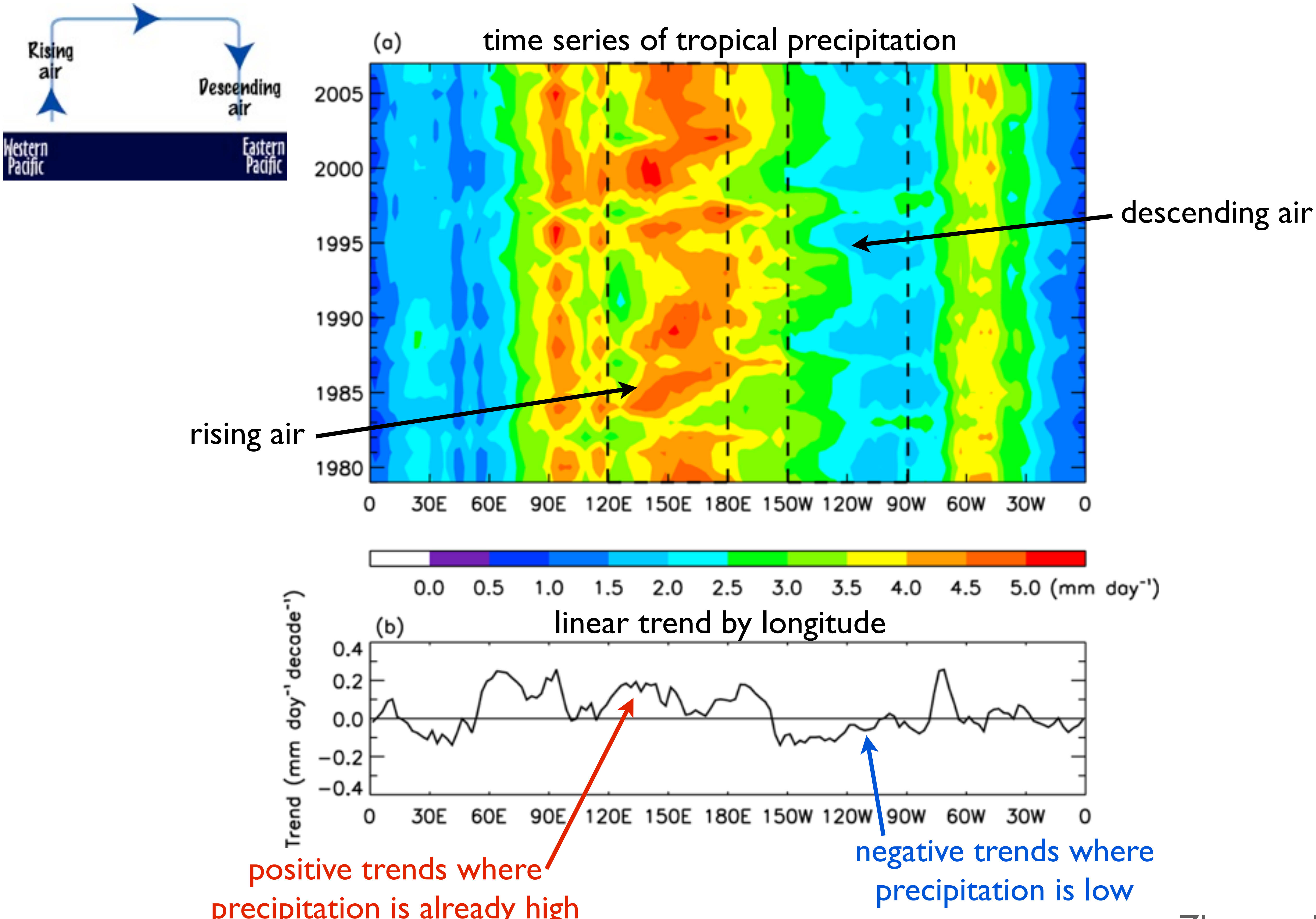
rising air

descending air



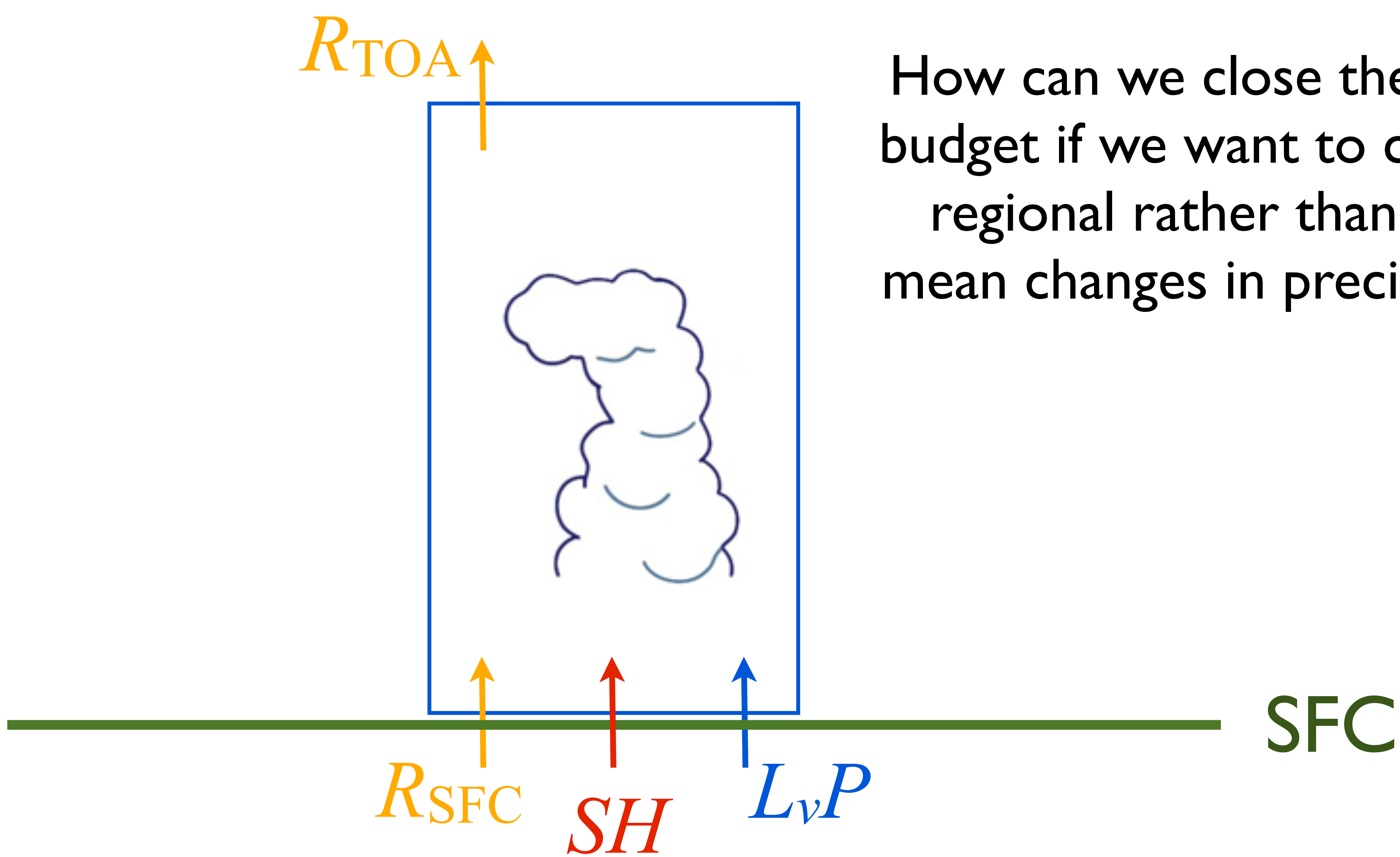
Zhou et al. 2011

Changes in the Walker Cell (1979–2007)



Zhou et al. 2011

The Energetics of Regional Precipitation Change



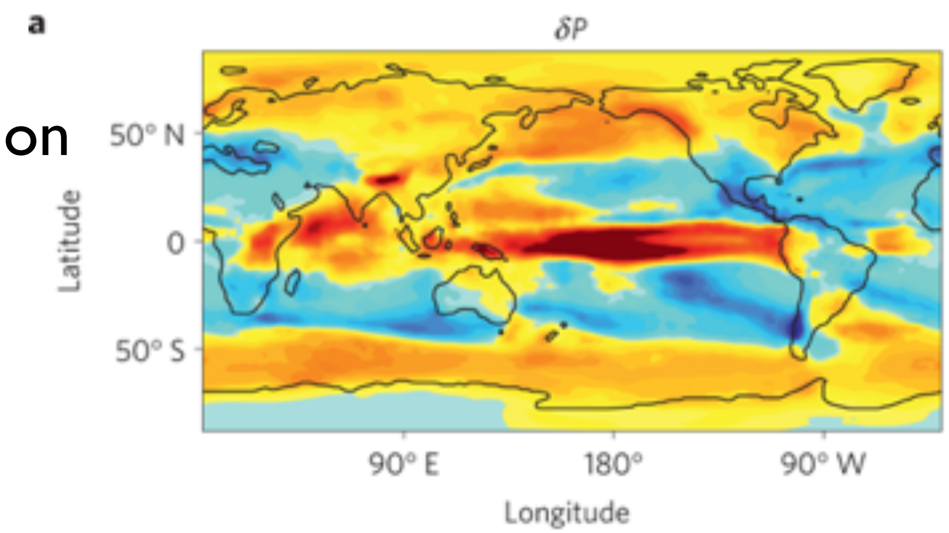
How can we close the energy budget if we want to constrain regional rather than global mean changes in precipitation?

$$L_vP = R_{\mathrm{NET}} - SH + \cdots$$

The Energetics of Regional Precipitation Change

The spatial distributions of changes in radiation and sensible heat don't look much like precipitation...

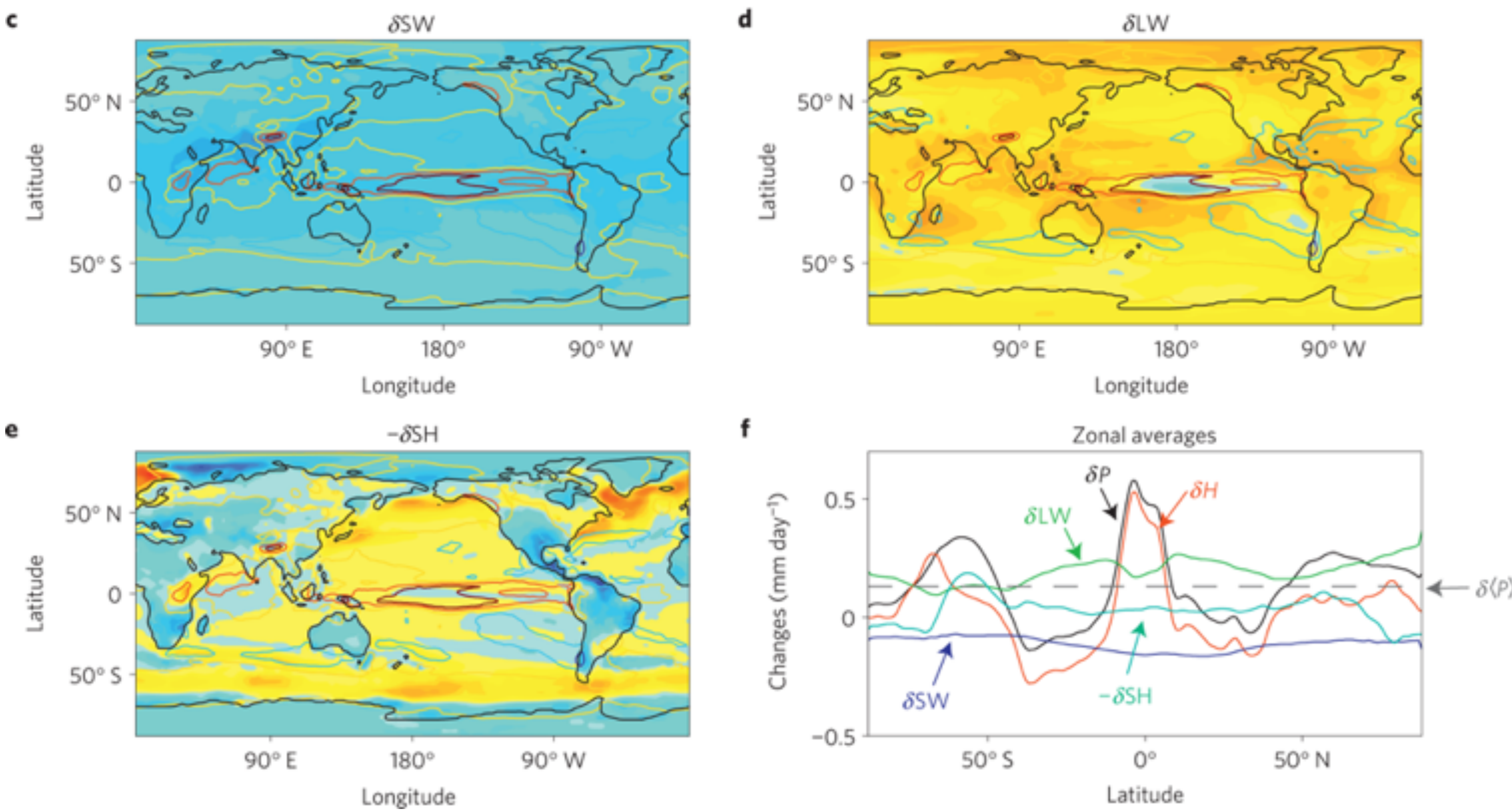
precipitation



solar radiation

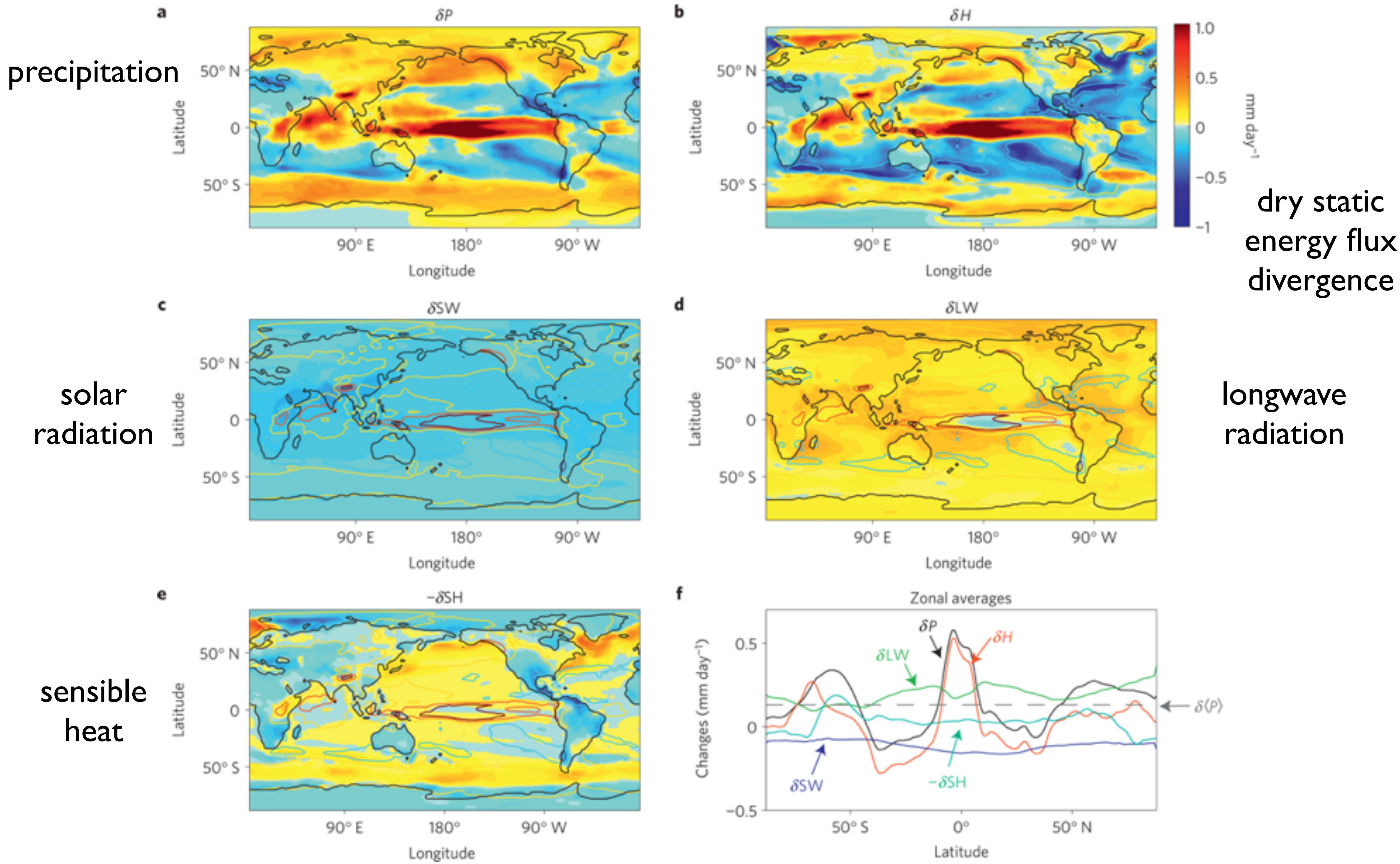
longwave radiation

sensible heat



Muller and O'Gorman 2011

The Energetics of Regional Precipitation Change



Muller and O'Gorman 2011

Dry Static Energy

thermal energy
(sensible heat)

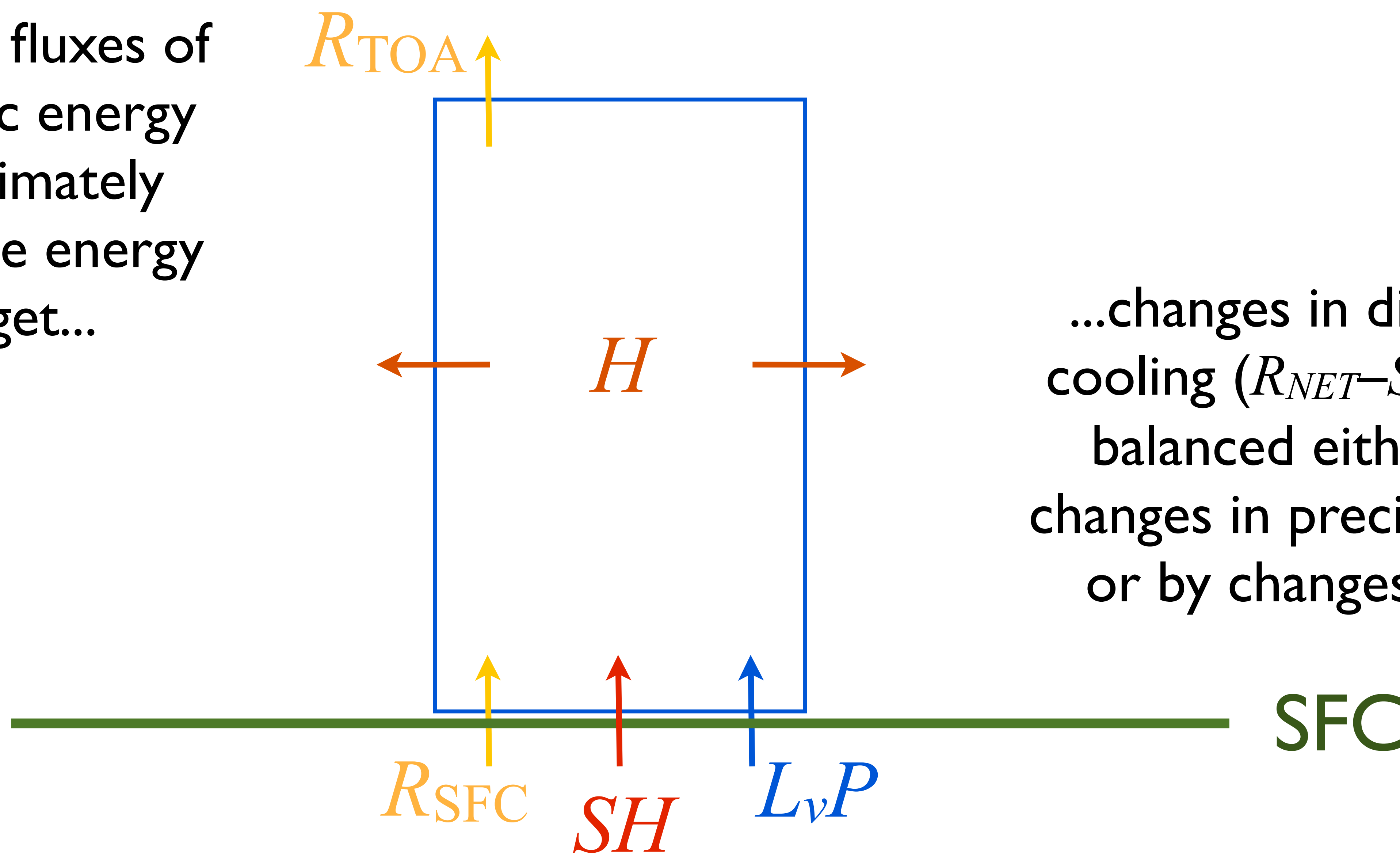
$$h = c_p T + gz$$

potential energy

Fluxes of dry static energy can be due to either the mean circulation or eddies (such as synoptic weather systems)

The Energetics of Regional Precipitation Change

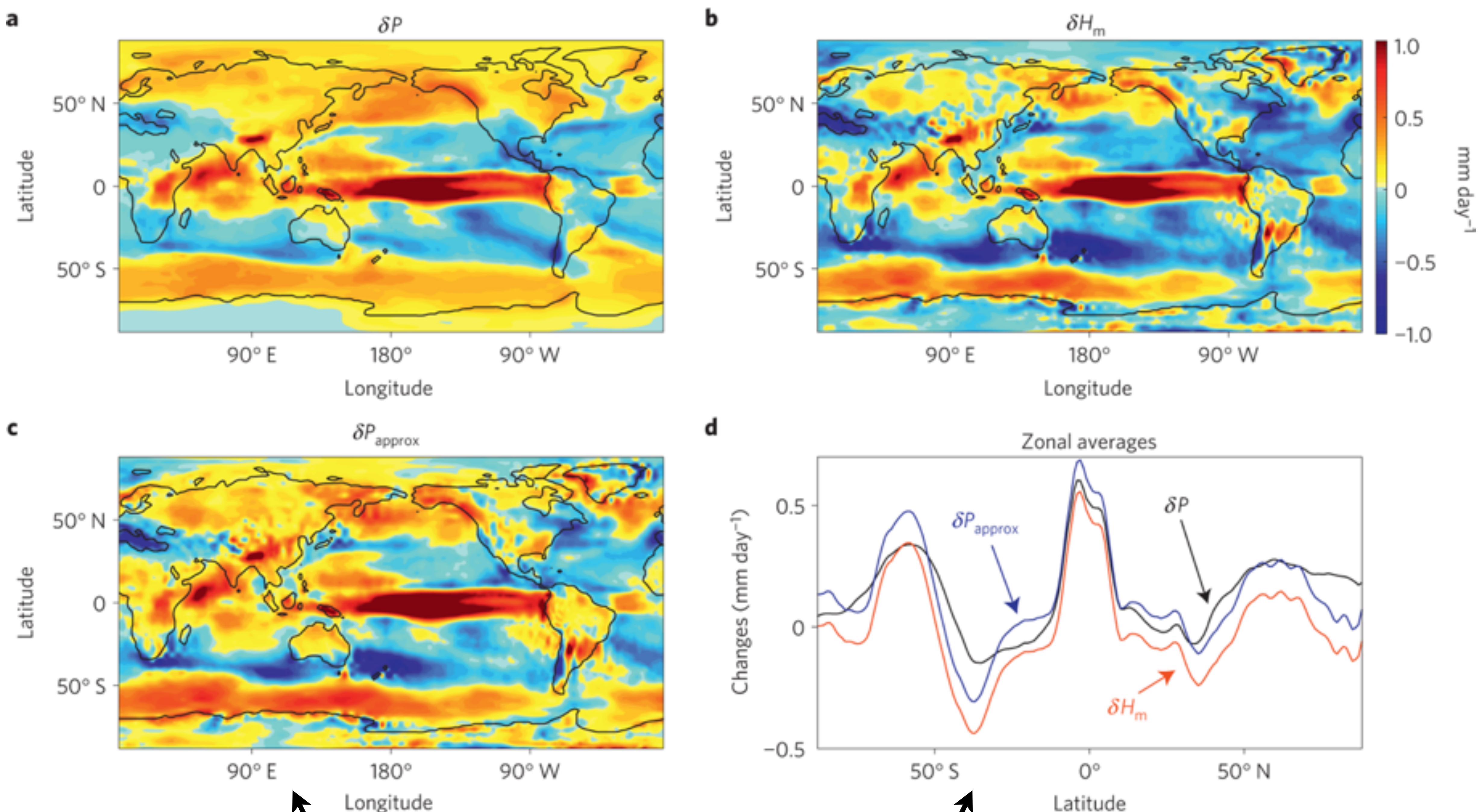
Including fluxes of dry static energy approximately closes the energy budget...



...changes in diabatic cooling (R_{NET}–SH) are balanced either by changes in precipitation or by changes in H

$$L_v P = R_{\mathrm{NET}} - SH + H$$

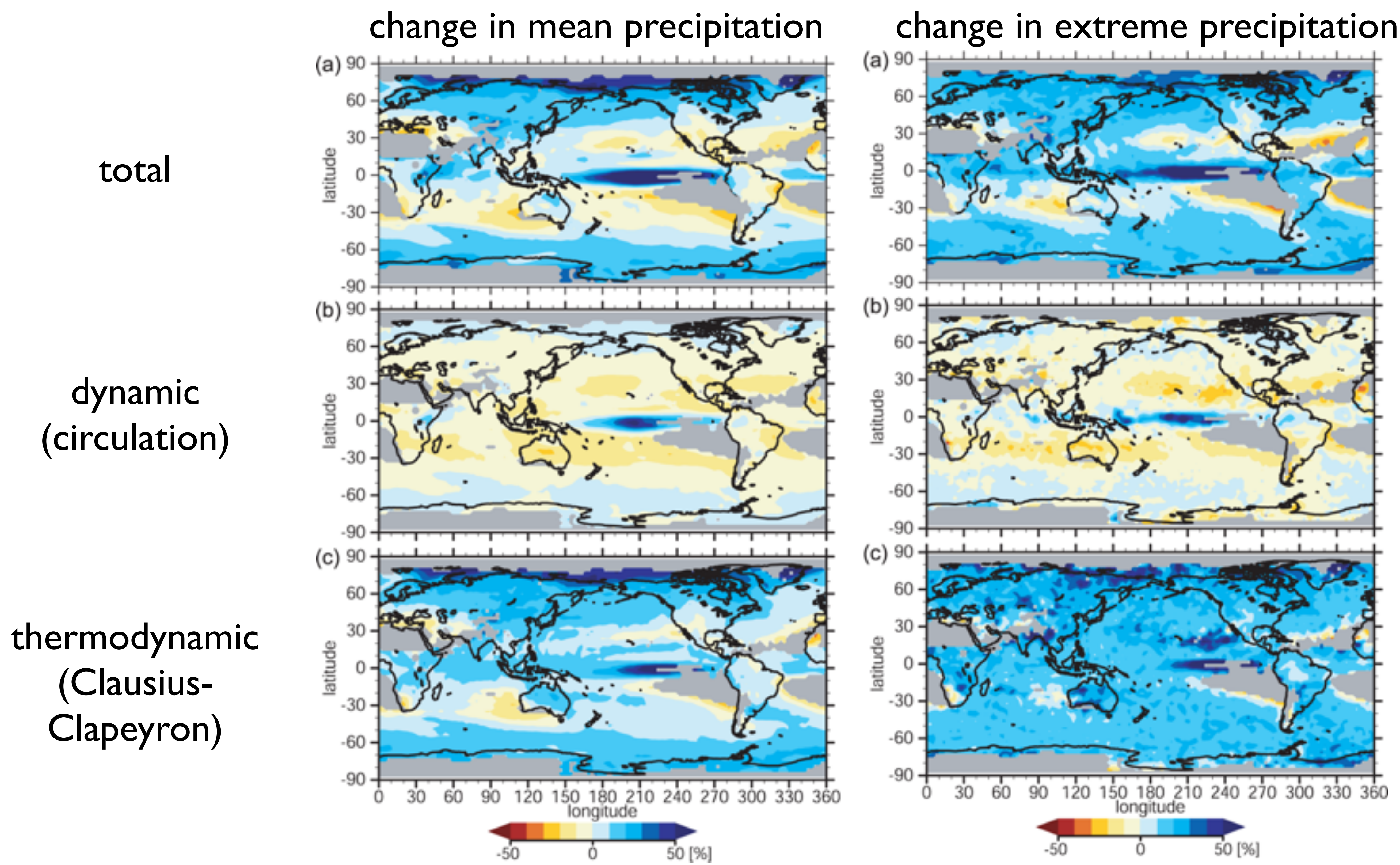
The Energetics of Regional Precipitation Change



This energetic constraint provides a reasonable approximation of the distribution of changes in precipitation

Muller and O'Gorman 2011

Changes in Precipitation Extremes in a GCM



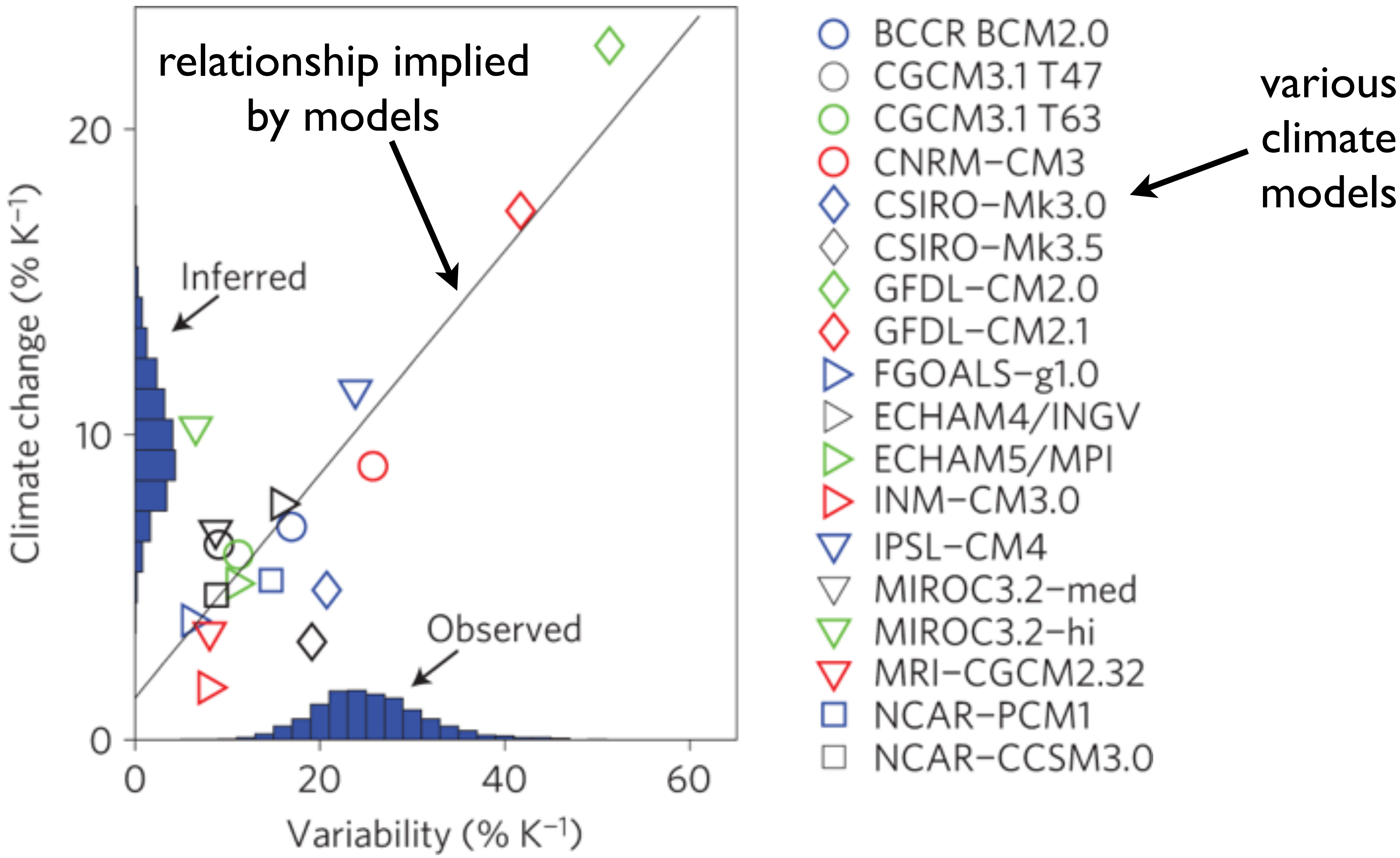
The intensity of extreme events increases more than mean precipitation, mainly due to increases in water vapor

Emori and Brown 2011

Constraining Changes in Tropical Extremes

Models do not agree on changes in tropical extremes: 0–30% K^{-1}

estimate of about 10% K^{-1} also holds for tropical land areas, where the effects of extreme precipitation events can be severe



Use relationships between recent variability and climate model projections to constrain future changes to 6–14% K^{-1}

O'Gorman 2012

Summary

- Global mean precipitation changes are not tightly constrained by temperature, although temperature changes do appear to dominate water vapor flux changes
- Changes in precipitation are constrained by the energy budget of the atmosphere, especially the free atmosphere
- There are substantial differences between climate model and observational estimates of precipitation sensitivity to changes in temperature, and even between various observational estimates
- Most data sources suggest a sensitivity of 1–3% K^{-1}
- Regional changes in precipitation largely reinforce existing patterns: wet regions get wetter, while dry regions get drier
- These regional changes can also be understood from an energy budget perspective by including transport of dry static energy
- The occurrence of extreme precipitation events is expected to increase more rapidly than mean precipitation