COLUMBIA CLIMATE SCHOOL
LAMONT-DOHERTY EARTH OBSERVATORY

The spectral roots of hydrologic sensitivity: why warmer atmospheres rain more

Robert Pincus
Lamont-Doherty Earth Observatory

Warmer atmospheres rain more

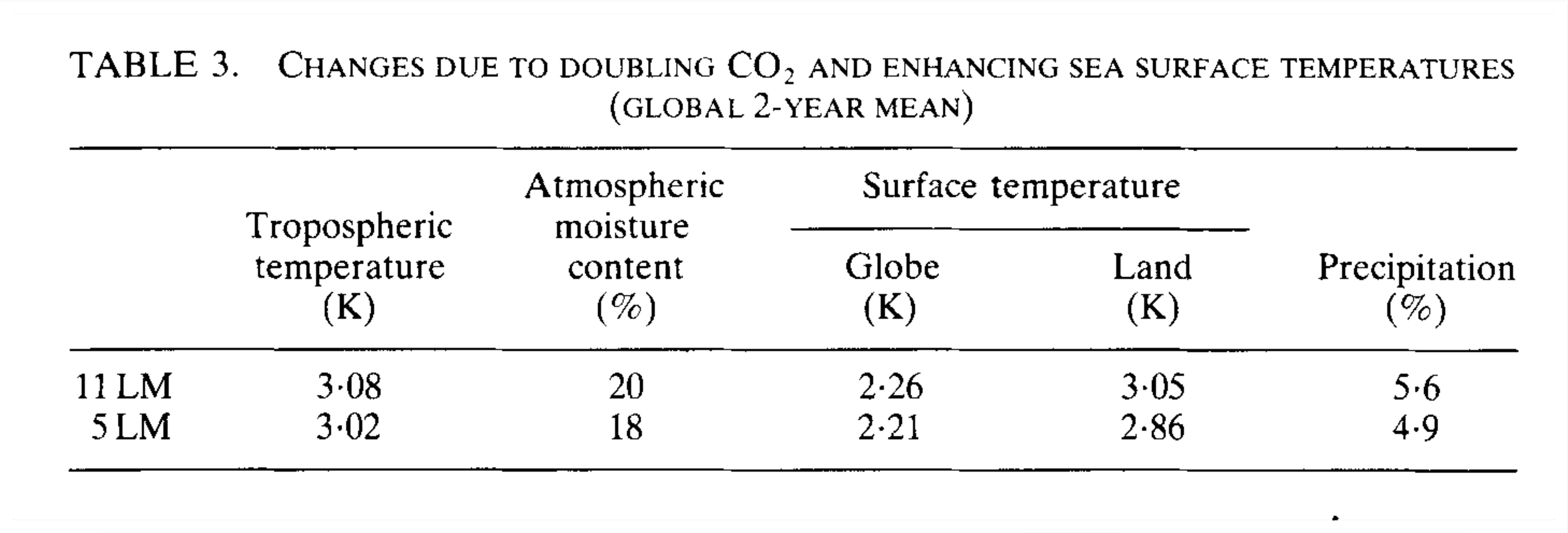
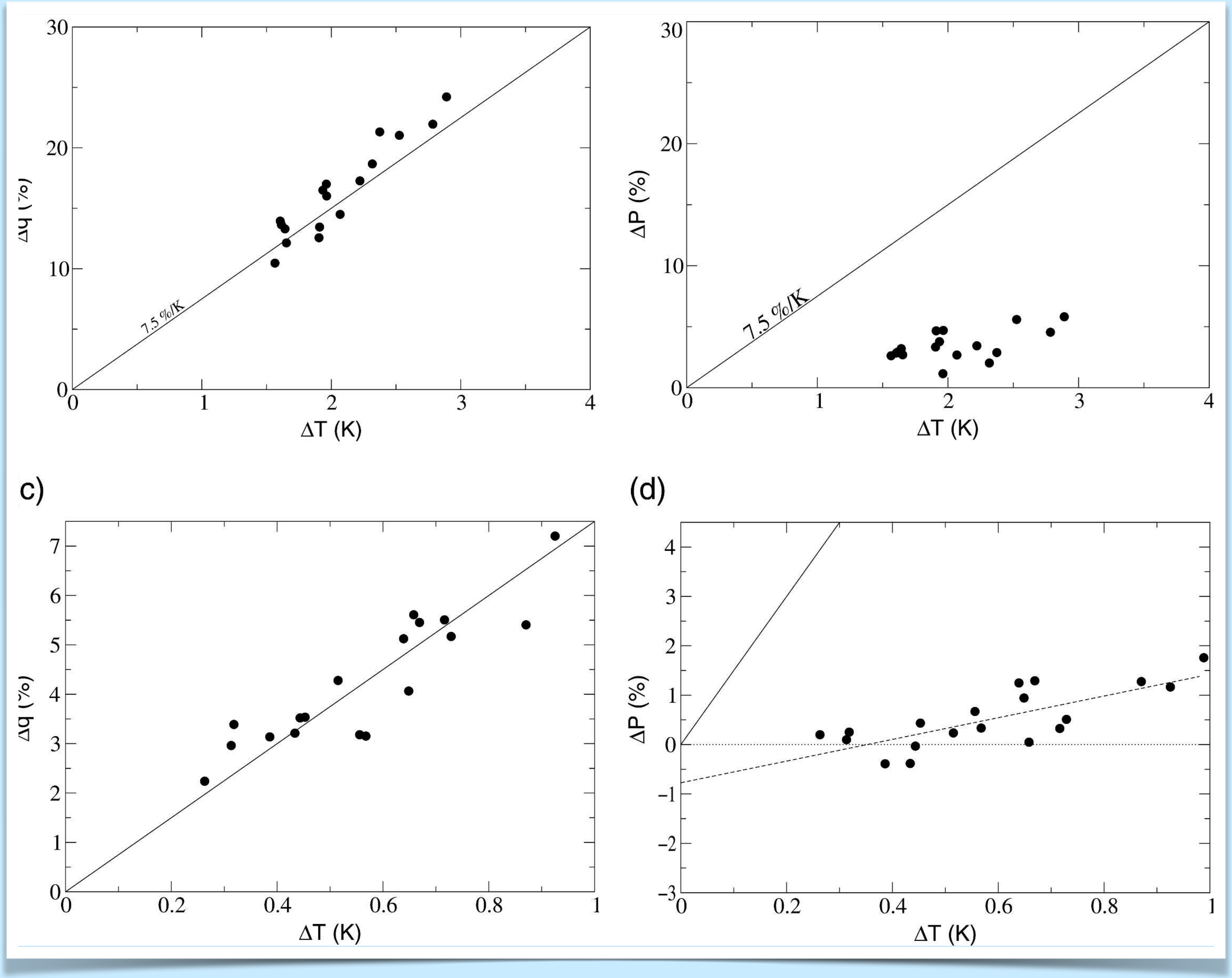


TABLE 3. CHANGES DUE TO DOUBLING CO_2 AND ENHANCING SEA SURFACE TEMPERATURES (GLOBAL 2-YEAR MEAN)

	Tropospheric temperature (K)	Atmospheric moisture content (%)	Surface temperature		Precipitation (%)
			Globe (K)	Land (K)	
11 LM	3·08	20	2·26	3·05	5·6
5 LM	3·02	18	2·21	2·86	4·9

Mitchell et al. 1987, 10.1002/qj.49711347517

Warmer atmospheres rain more



Held and Soden 2006, 10.1175/JCLI3990.1

Energy conservation and global rainfall

Water balance within the atmosphere requires

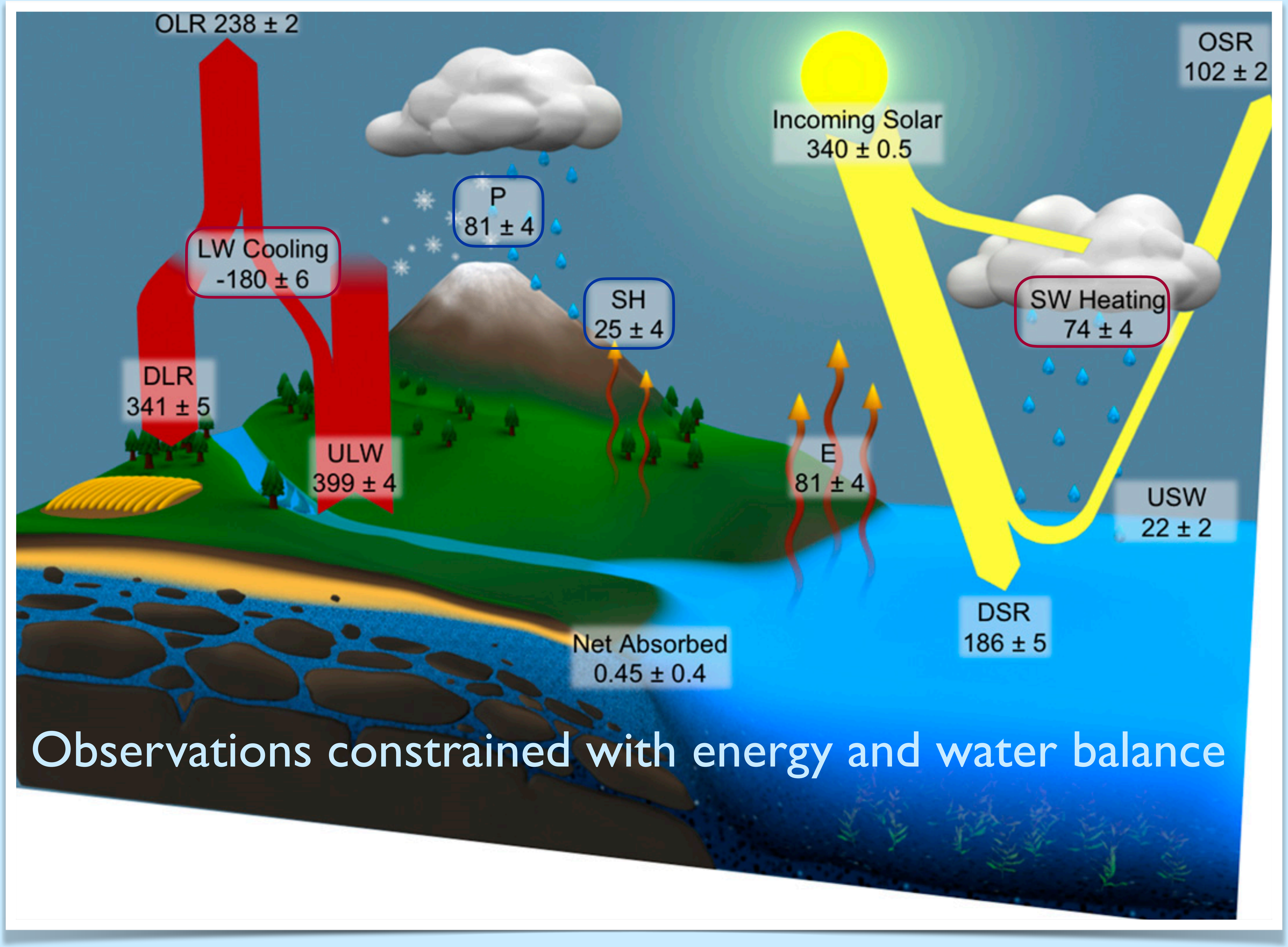
Surface evaporation - surface precipitation = 0

Energy balance within the atmosphere requires

Net atmospheric radiative heating + latent heat flux + sensible heat flux = 0
or, in energy units,

$$H_{\mathrm{SW}} - Q_{\mathrm{LW}} + L_{\mathrm{v}}P + SHF = 0$$

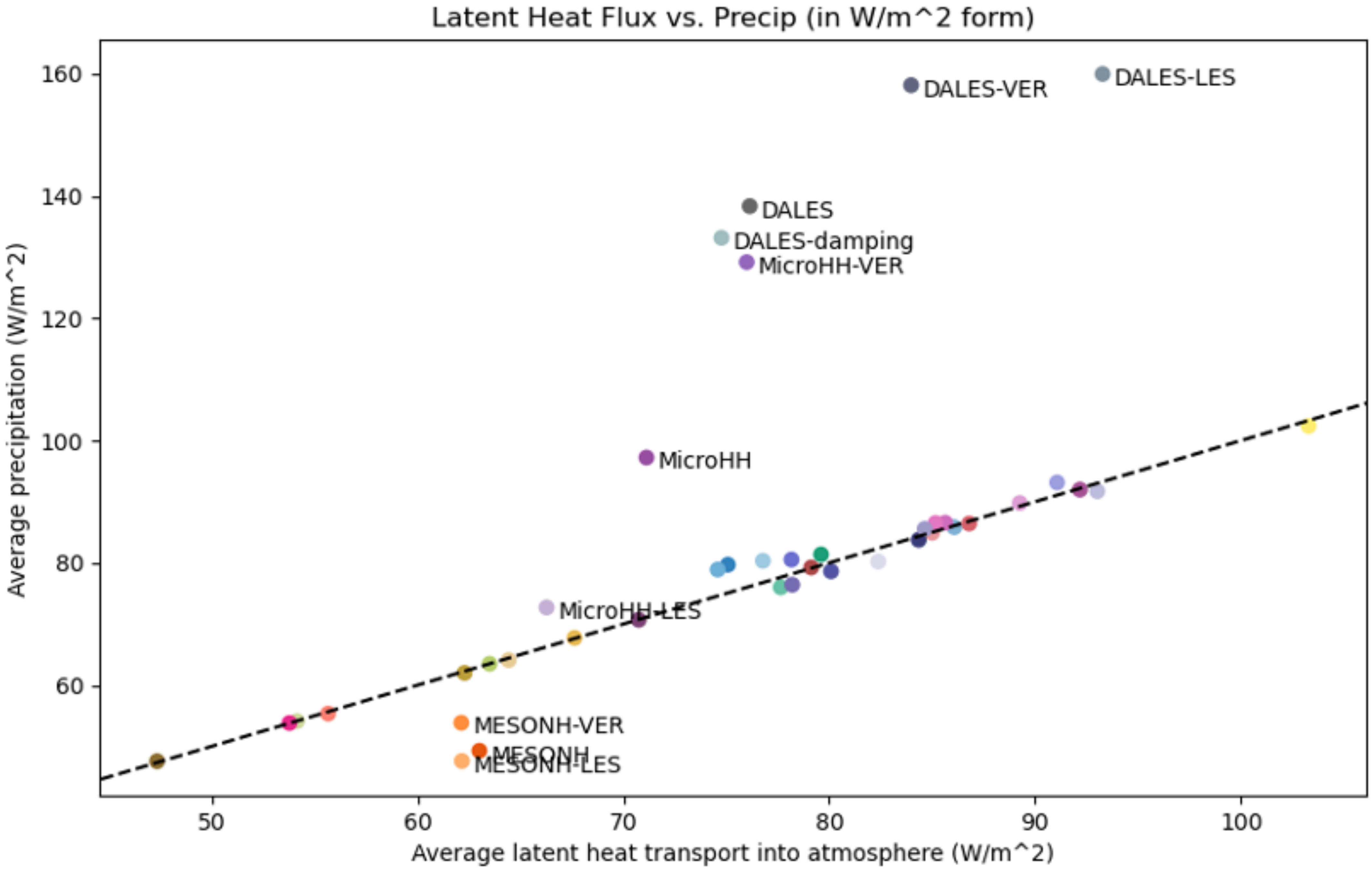
In Earth's atmosphere $H_{\mathrm{SW}} \ll |Q_{\mathrm{LW}}|$ and $L_{\mathrm{v}}P \ll SHF$



Observations constrained with energy and water balance

L'Ecuyer et al 2015: 10.1175/JCLI-D-14-00556.1

(Results from RCEMIP - beware diagnostics)



Graham O’Donnell/Allison Wing

Radiation change constrains precipitation change with temperature

How does precipitation with temperature (what is the "hydrologic sensitivity")?

$$L_{\mathrm{v}}\frac{dP}{dT_S} = \frac{dQ_{\mathrm{LW}}}{dT_S} - \frac{dH}{dT_S} - \frac{dSHF}{dT_s}$$

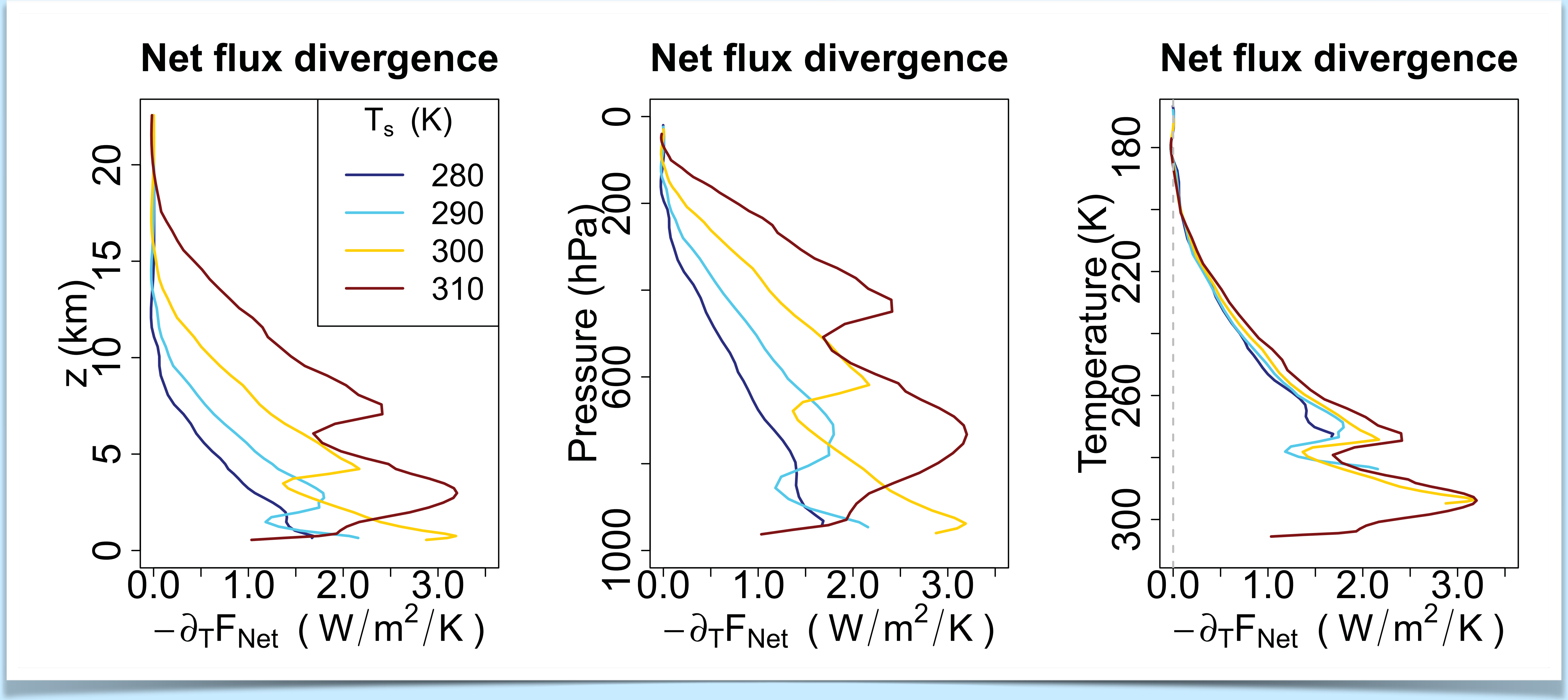
In climate change simulations latent heat fluxes often decrease a little with temperature but to first order

$$L_{\mathrm{v}}\frac{dP}{dT_S} \approx \boxed{\frac{dQ_{\mathrm{LW}}}{dT_S}} - \frac{dH}{dT_S} \sim \frac{dQ_{\mathrm{LW}}}{dT_S}$$

Can we understand $\frac{dQ_{\mathrm{LW}}}{dT_S}$?

(Spoiler alert: everything depends on radiative transfer and water vapor thermodynamics)

“The atmosphere deepens in temperature coordinates”



Jeevanjee and Romps 2018, 10.1073/pnas.1720683115

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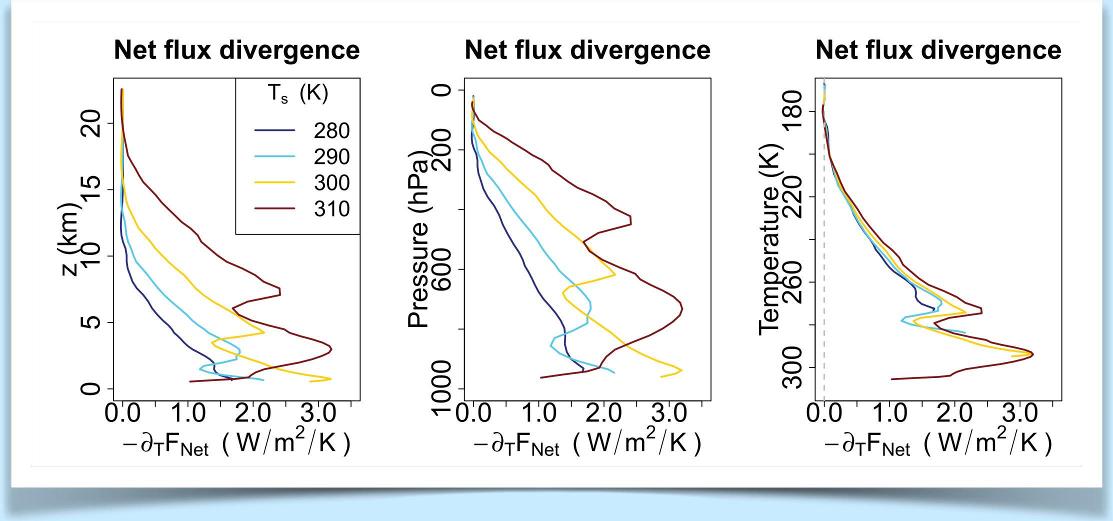
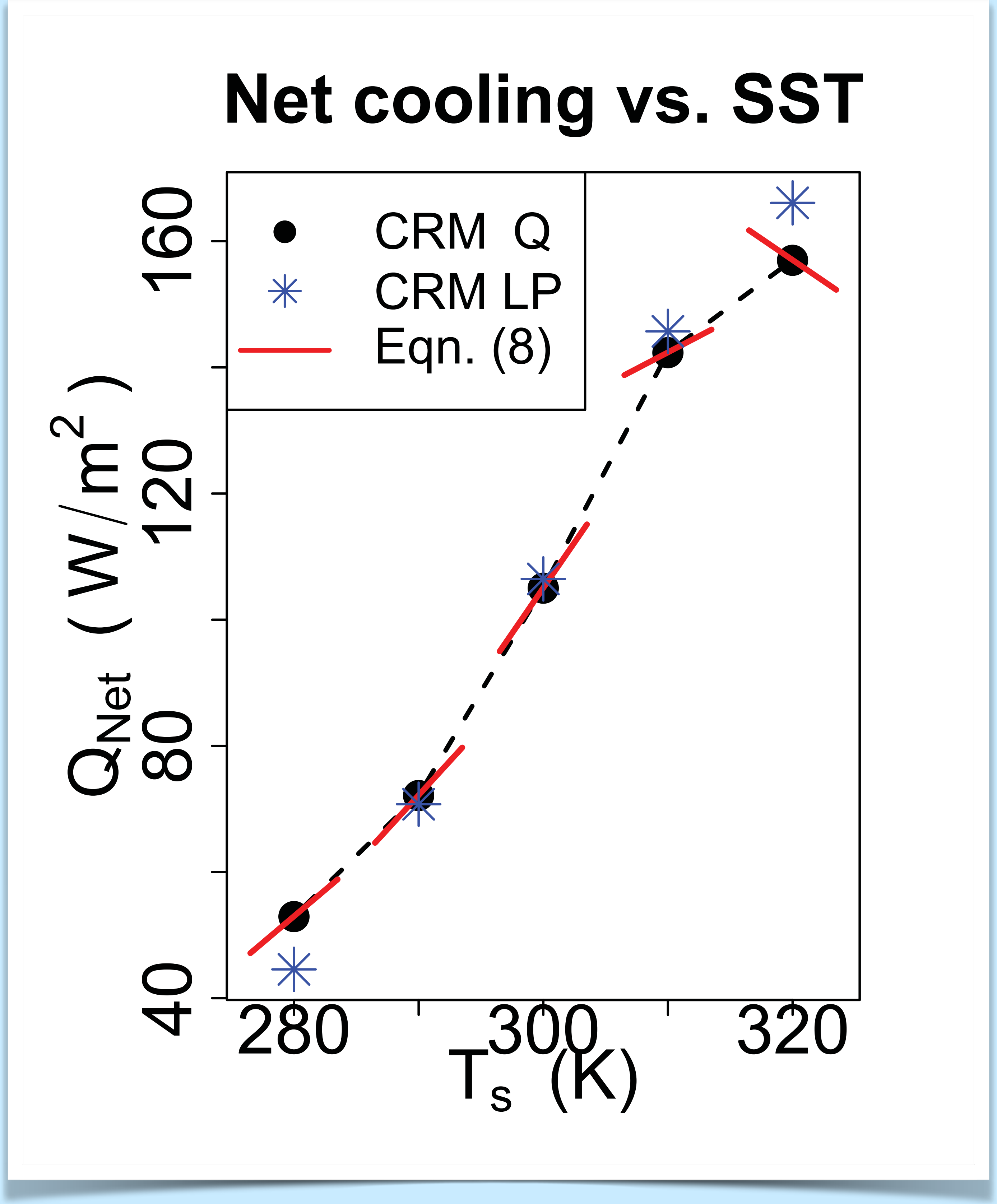




Jeevanjee and Romps 2018, 10.1073/pnas.1720683115

An explanation: Simpson's "law"

To the extent that

The absorption coefficient of water vapor is constant with T, p and

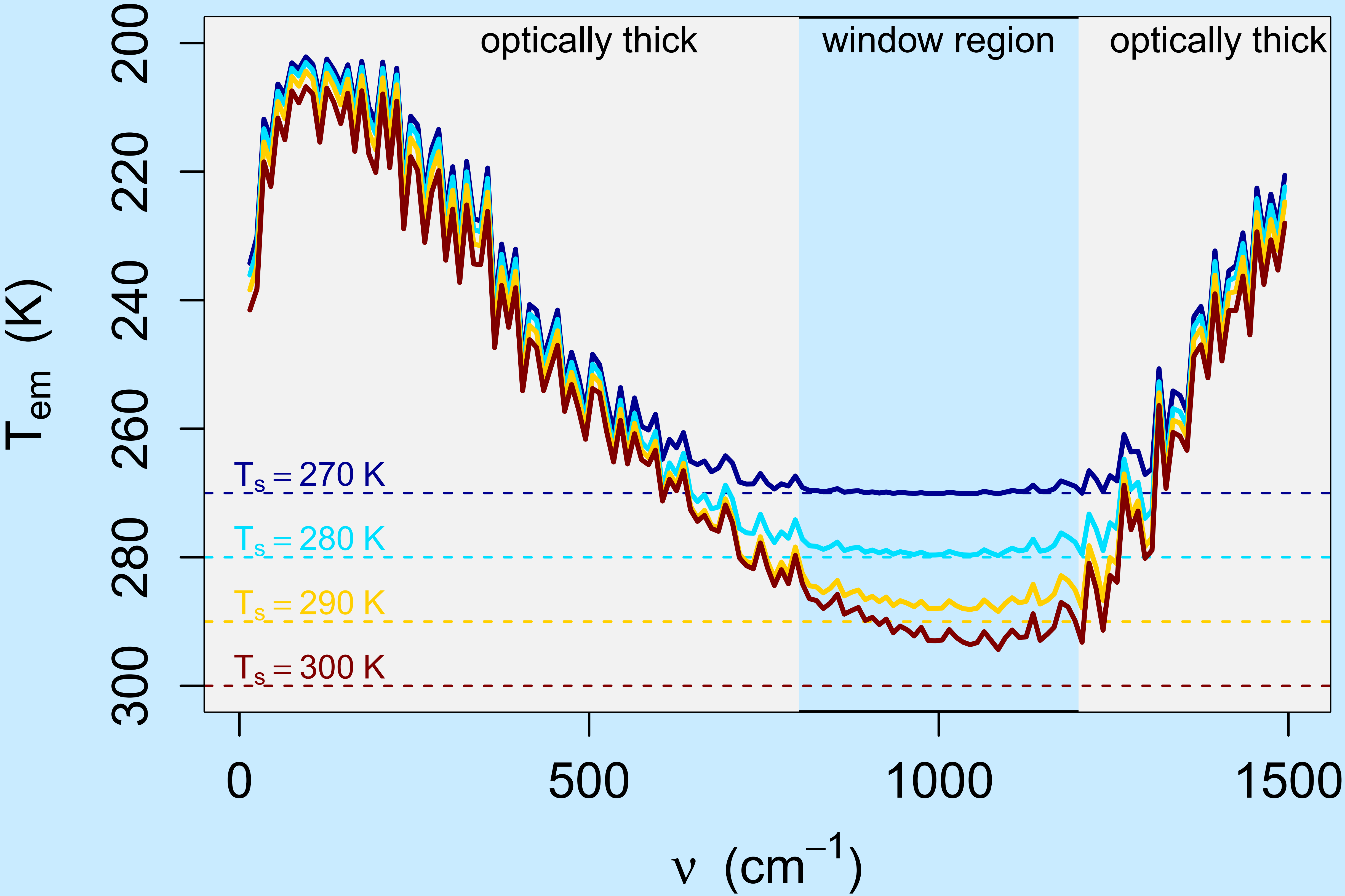
Water vapor path depends only on local temperature

Then

Water vapor optical depth is a function of temperature so

Cooling by water vapor is independent of temperature in optically thick regions

An explanation: Simpson's "law"



Jeevanjee et al. 2021 10.1029/2021GL093699

The atmosphere cools to space and warms from the surface

The monochromatic flux divergence across the whole atmosphere is

$$Q_\nu = \int_0^{\tau_\nu^*} \pi B_\nu(T(\tau_\nu))e^{-\tau_\nu} d\tau_\nu - \int_0^{\tau_\nu^*} \pi(B_\nu(T_s) - B_\nu(T(\tau_\nu)))e^{-(\tau_\nu^* - \tau_\nu)} d\tau_\nu$$

i.e. by cooling to space and heating from the surface at each τ

[You can get here by using the solutions to Schwartchild's equation for up and down flux to compute net flux

$$Q_\nu = (F_\nu^-(0) - F_\nu^+(0)) - (F_\nu^-(\tau^*) - F_\nu^+(\tau^*))$$]

“Hydrologic sensitivity” is dominated by changes in cooling to space

The change in total flux divergence with surface temperature is

$$\frac{dQ_\nu}{dT_s} = \frac{d}{dT_s}\int_0^{\tau_\nu^*} \pi B_\nu(T(\tau_\nu))e^{-\tau_\nu}d\tau_\nu - \cancel{\frac{d}{dT_s}\int_0^{\tau_\nu^*} \pi(B_\nu(T_s) - B_\nu(T(\tau_\nu)))e^{-(\tau_\nu^*-\tau_\nu)}d\tau_\nu}$$

because surface exchanges are small and get smaller at higher T_s

$$\approx \pi B_\nu(T(\tau_\nu))e^{-\tau_\nu}\frac{d\tau_\nu}{dT_s} + \pi \cancel{\int_0^{\tau_\nu^*} \frac{d}{dT_s}B_\nu(T(\tau_\nu))e^{-\tau_\nu}d\tau_\nu}$$

because cooling is dominated by water vapor and “Simpson’s law”

$$\approx \pi B_\nu(T(\tau_\nu))\frac{d\epsilon}{dT_s}$$

Remember emissivity is bounded by $0 \leq \epsilon \leq 1$

… in spectral regions where opacity changes with temperature

Emission from the atmosphere is dominated by water vapor and carbon dioxide

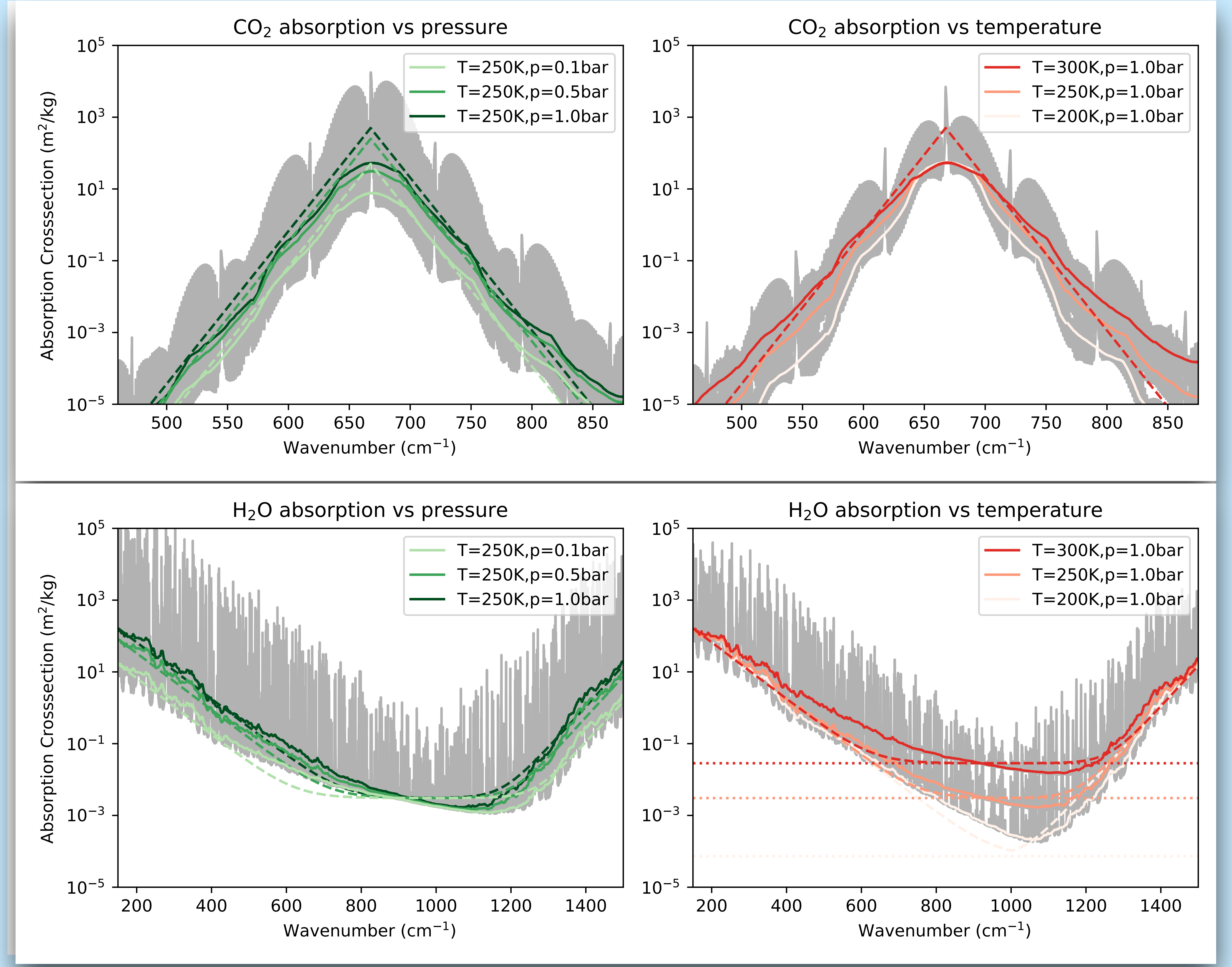
$$\tau_\nu = \tau_{\nu,\mathrm{CO}_2} + \tau_{\nu,\mathrm{H_2O}} = \tau_{\nu,\mathrm{CO}_2} + Dk_{\nu,\mathrm{H_2O}} WVP$$

neglecting pressure broadening and self-continuum

So that

$$\frac{dQ_\nu}{dT_s} = e^{-\tau_{\nu,\mathrm{CO}_2}} \left(\pi B_\nu(T_s) \frac{d \ln WVP}{dT_s} \tau_{\nu,\mathrm{H_2O}} e^{-\tau_{\nu,\mathrm{H_2O}}} \right)$$

Complicated spectroscopy can be usefully idealized



Koll et al 2023, doi:10.1175/JAS-D-22-0178.

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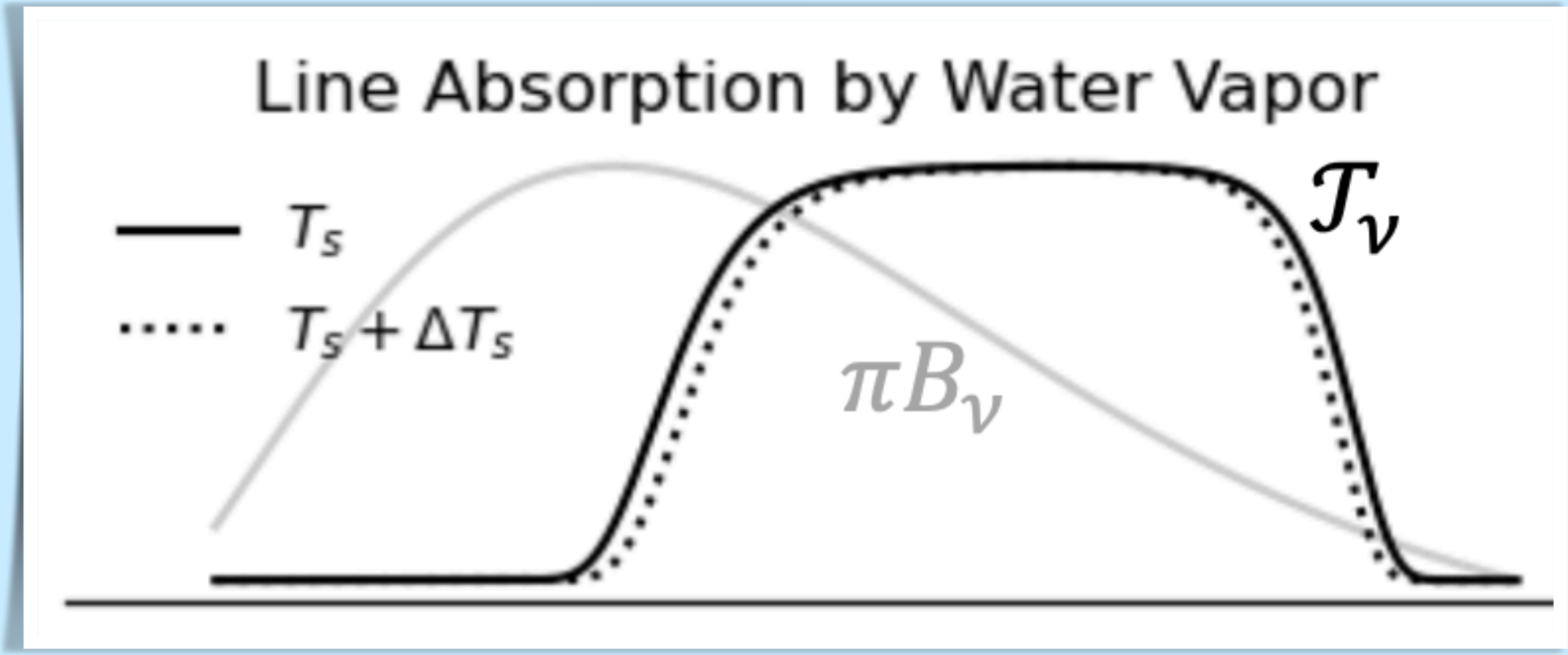
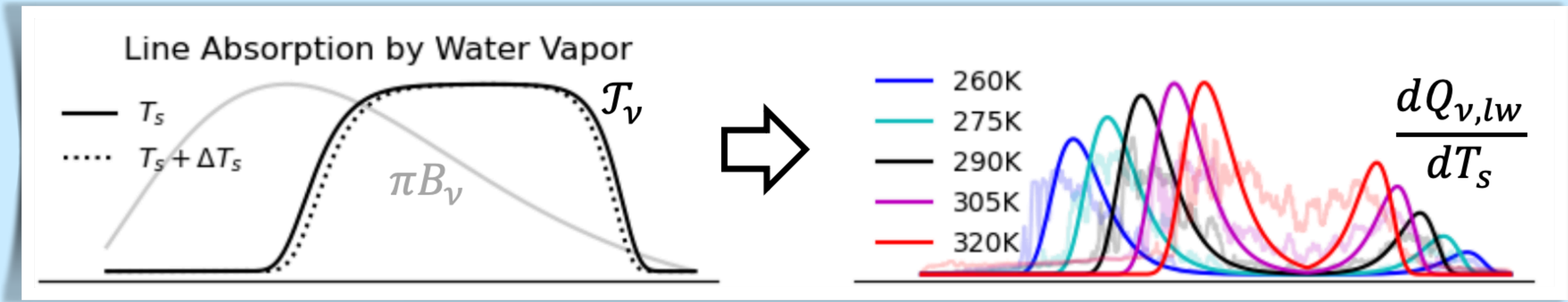
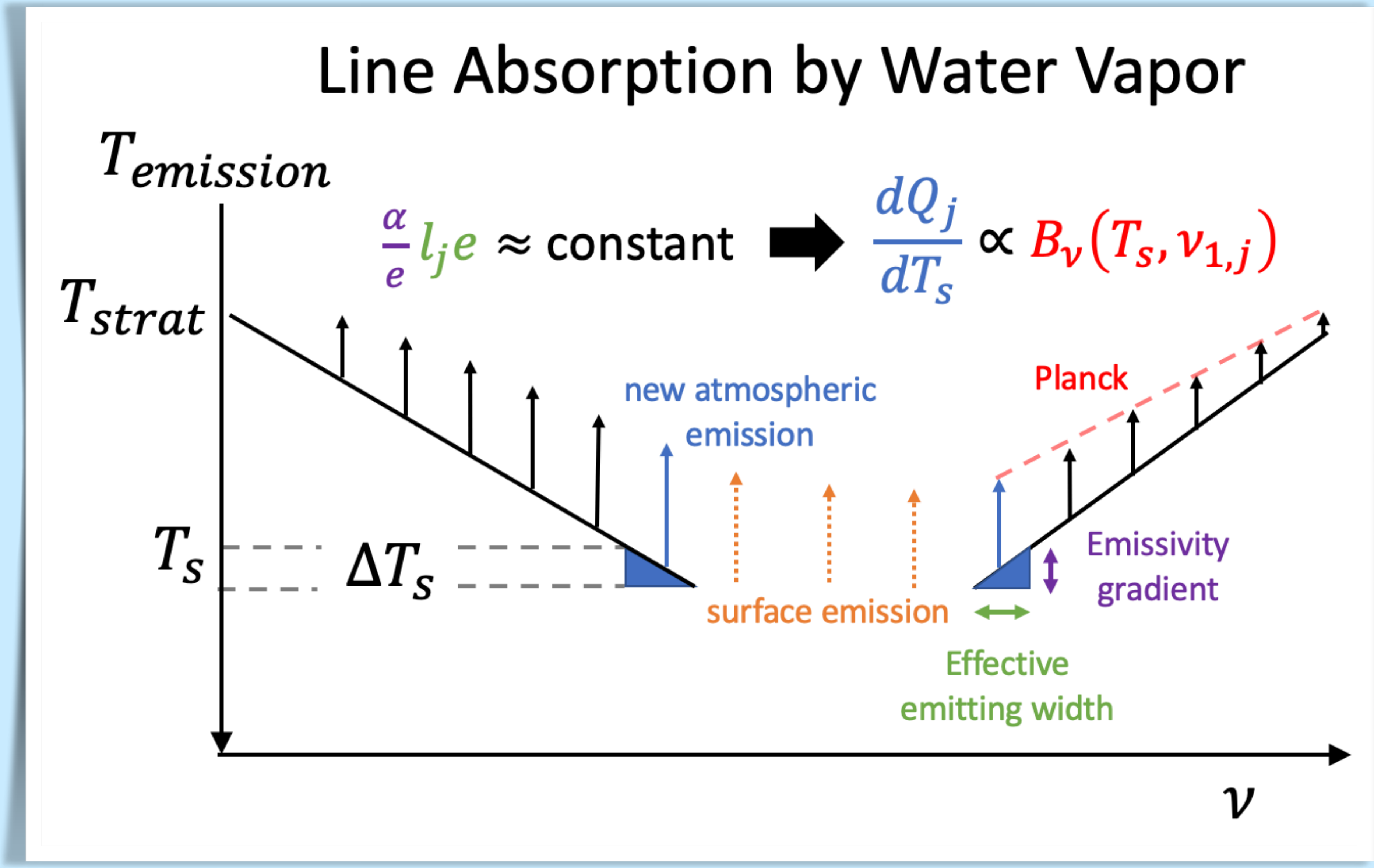
Each source of absorption - water vapor lines, water vapor continuum, carbon dioxide - adds interesting physics

Hydrologic sensitivity results from the closing water vapor window

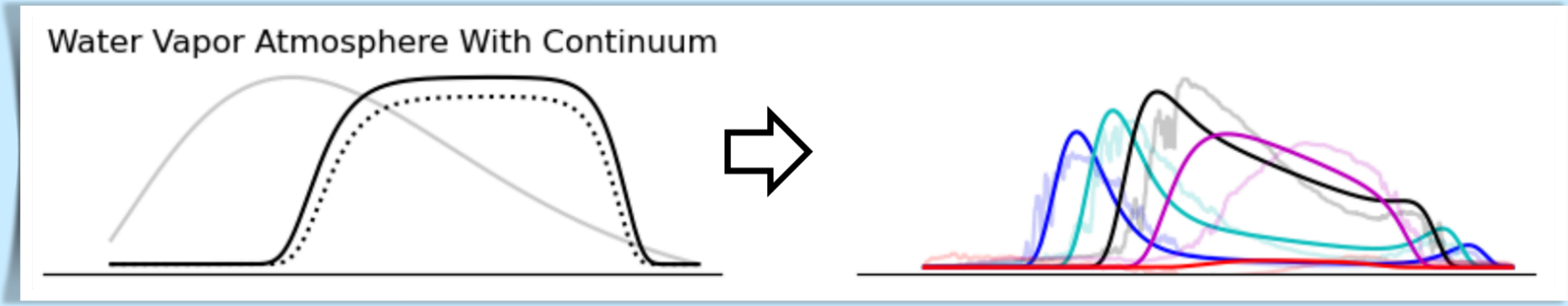


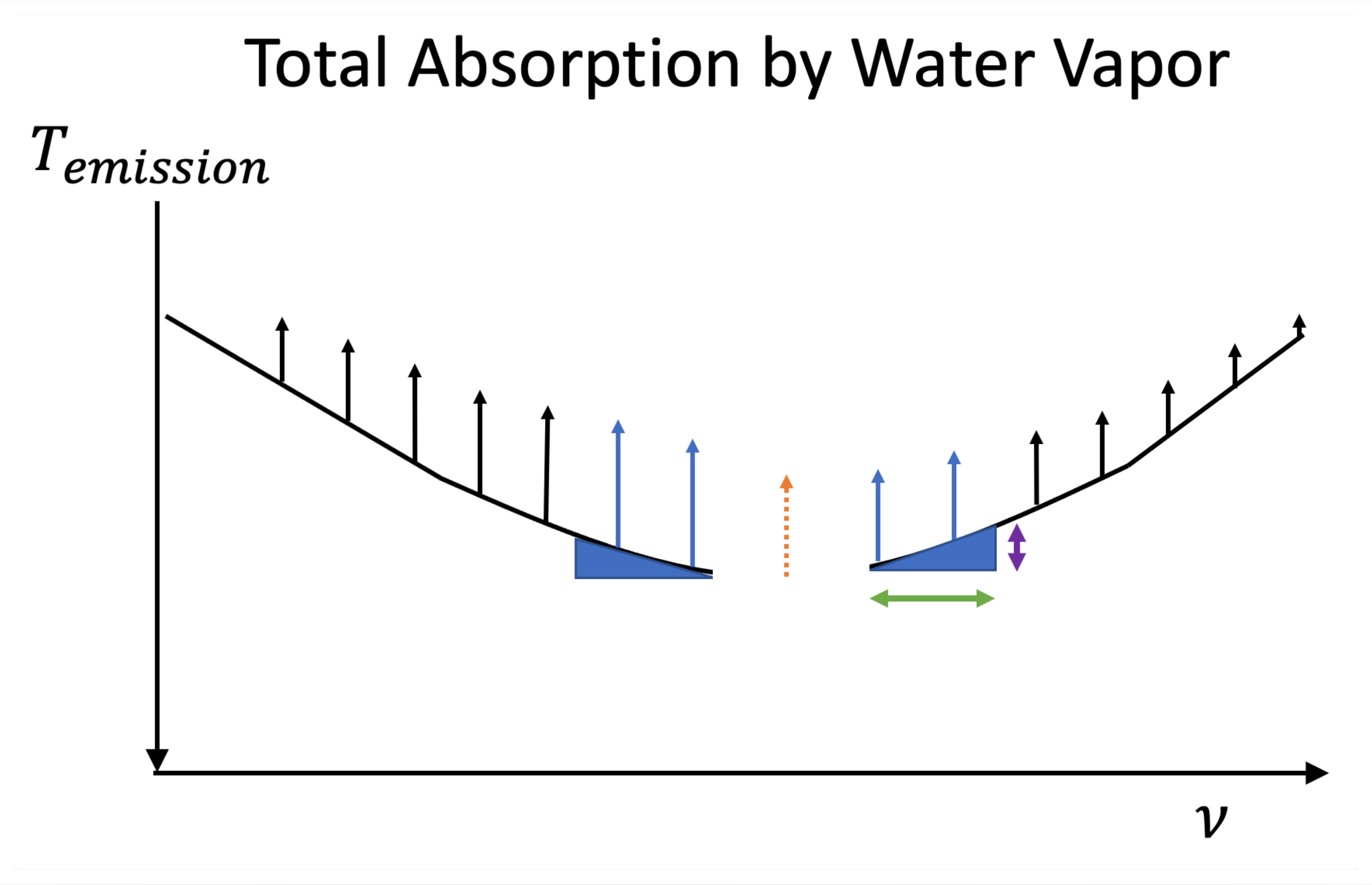
Hydrologic sensitivity results from the closing water vapor window





The window darkens as it closes





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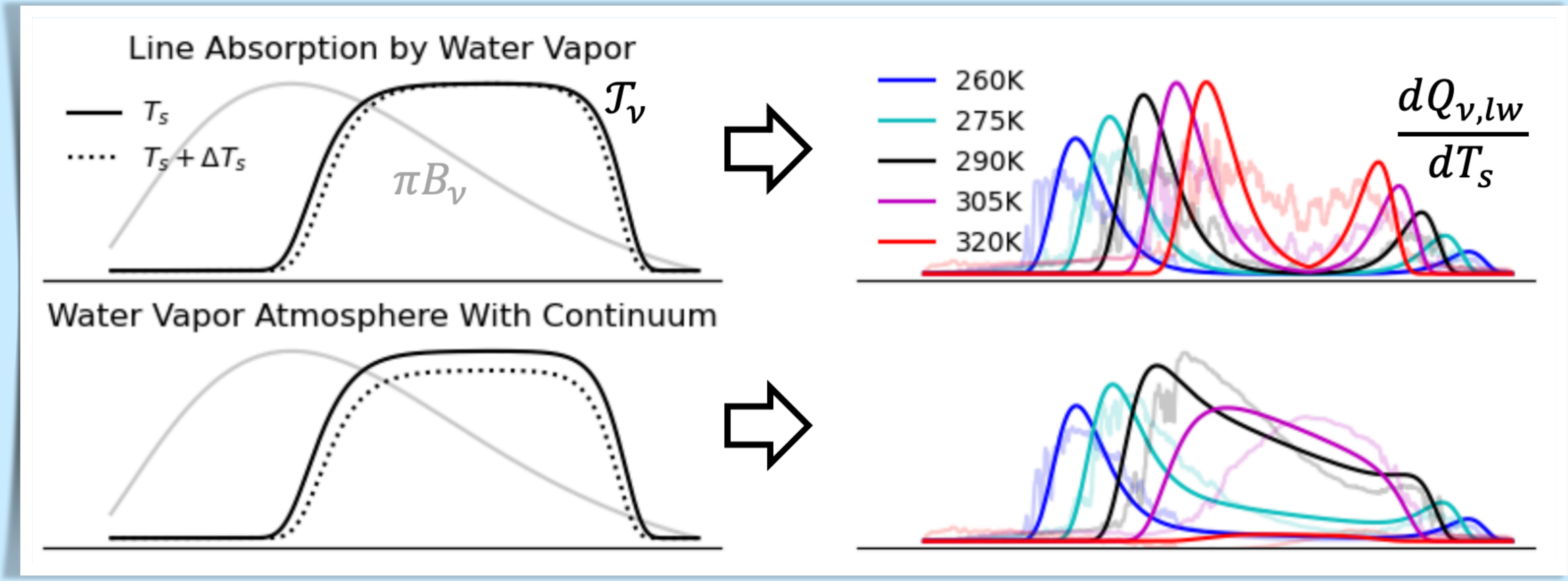
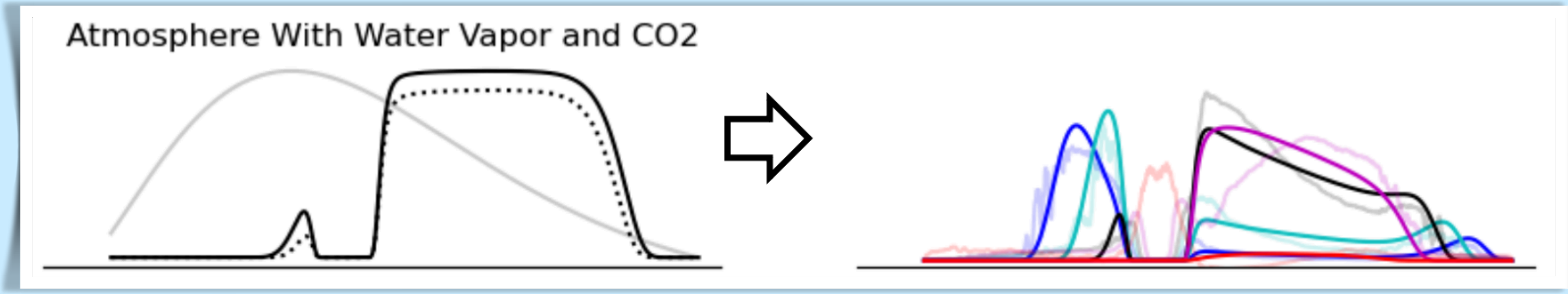
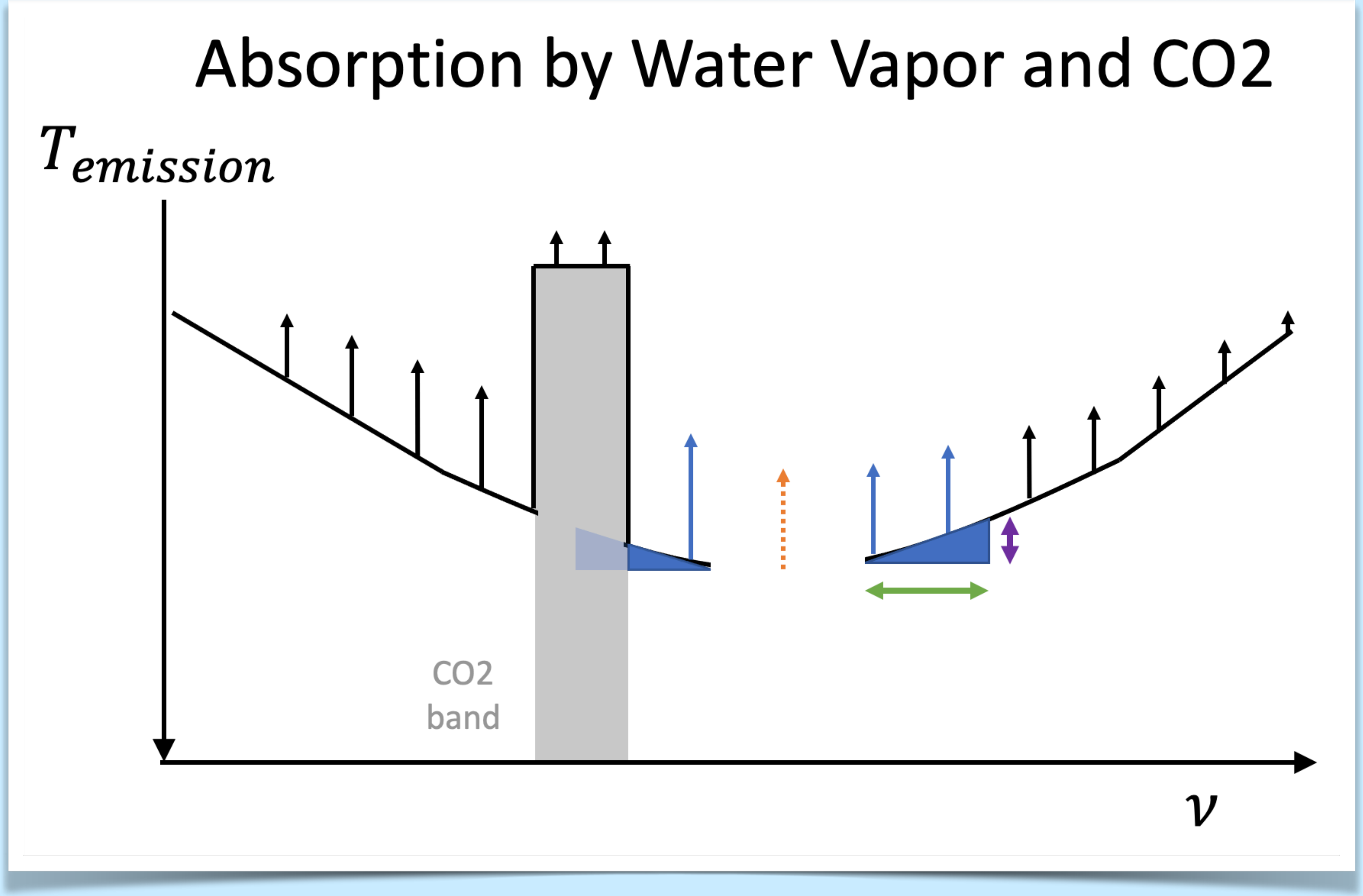


The window darkens from the edges, then the whole window goes opaque at once, introducing stronger temperature dependence

One the whole window is opaque it's out of play

Carbon dioxide masks, with another temperature dependence





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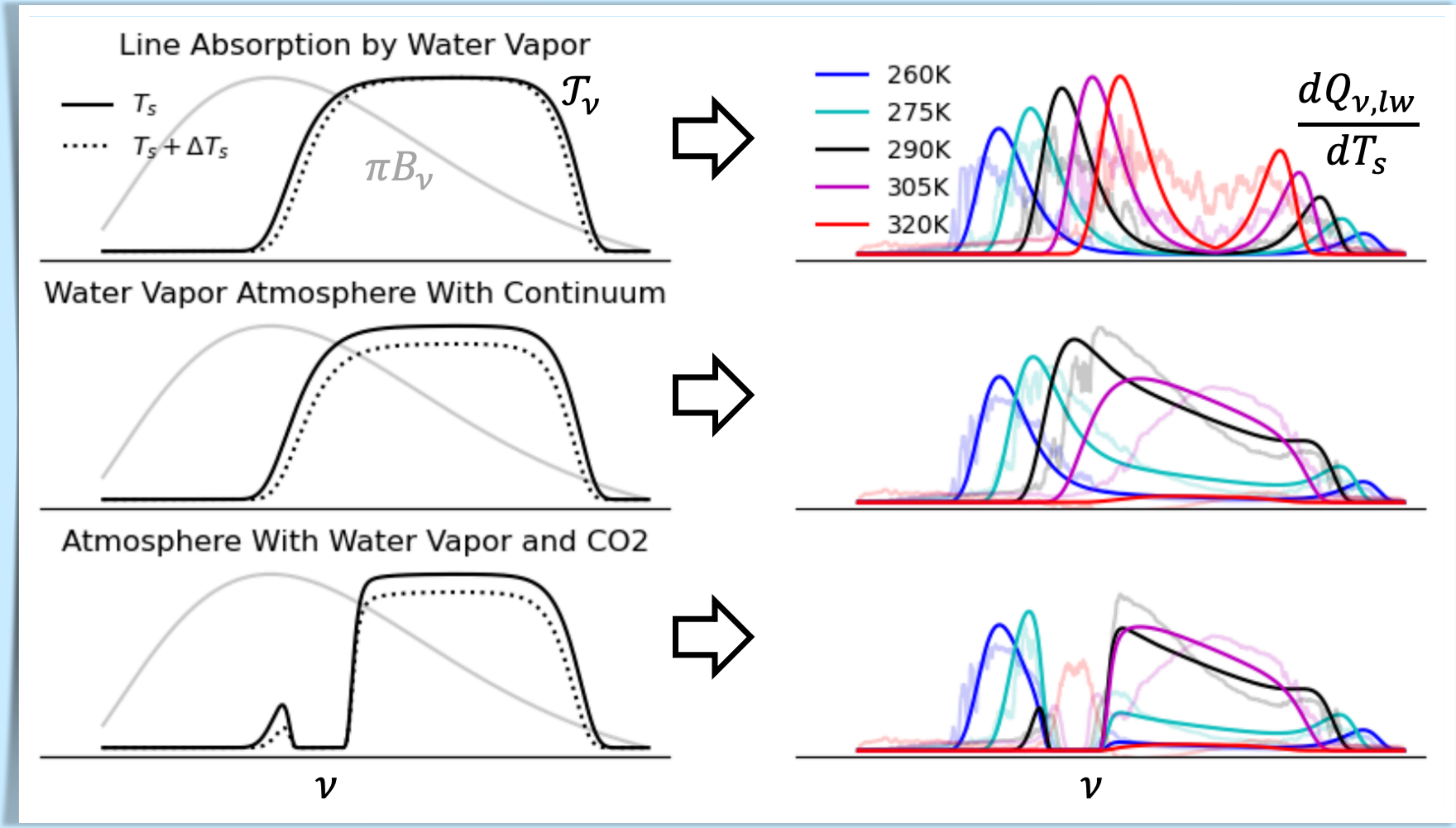
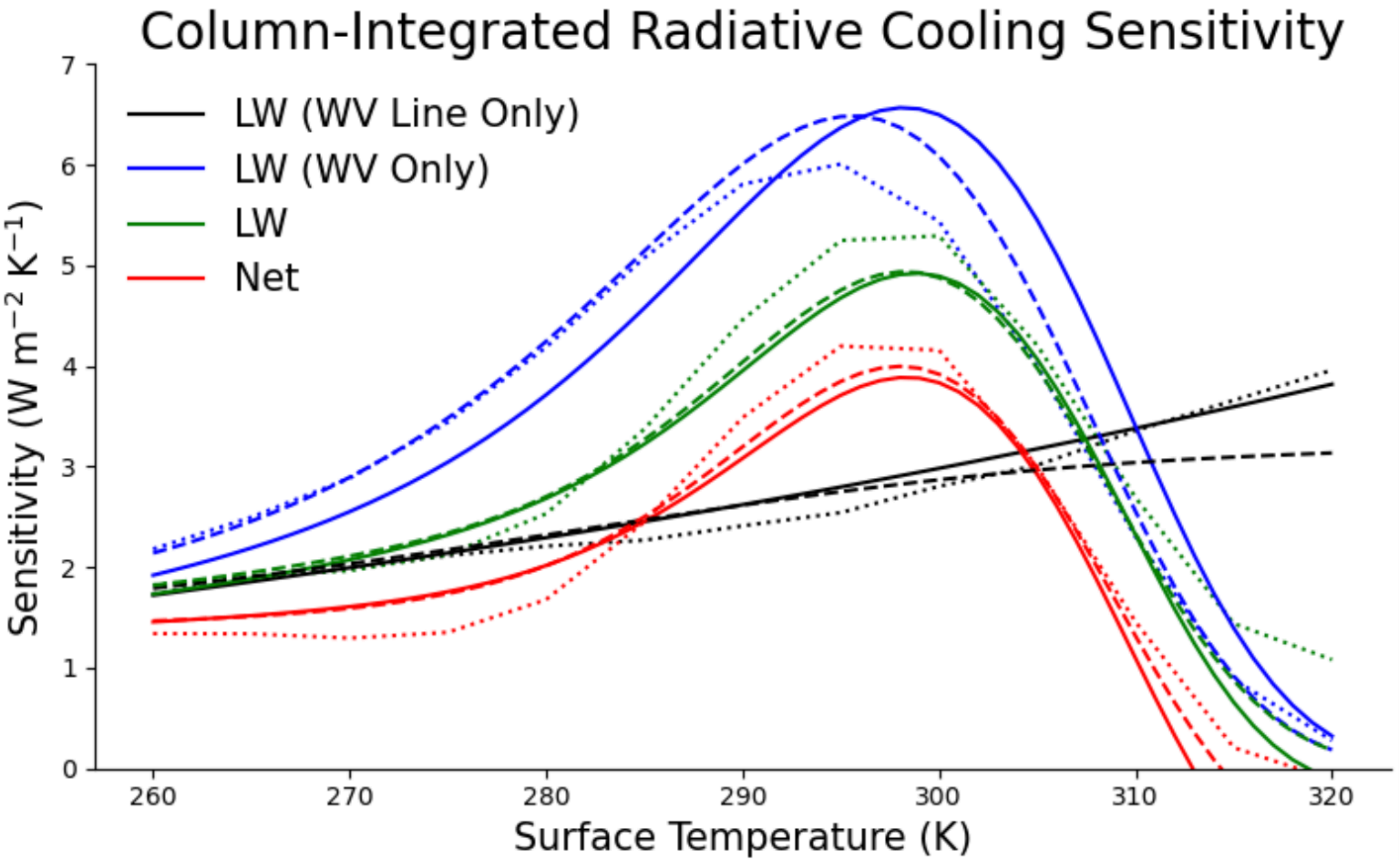
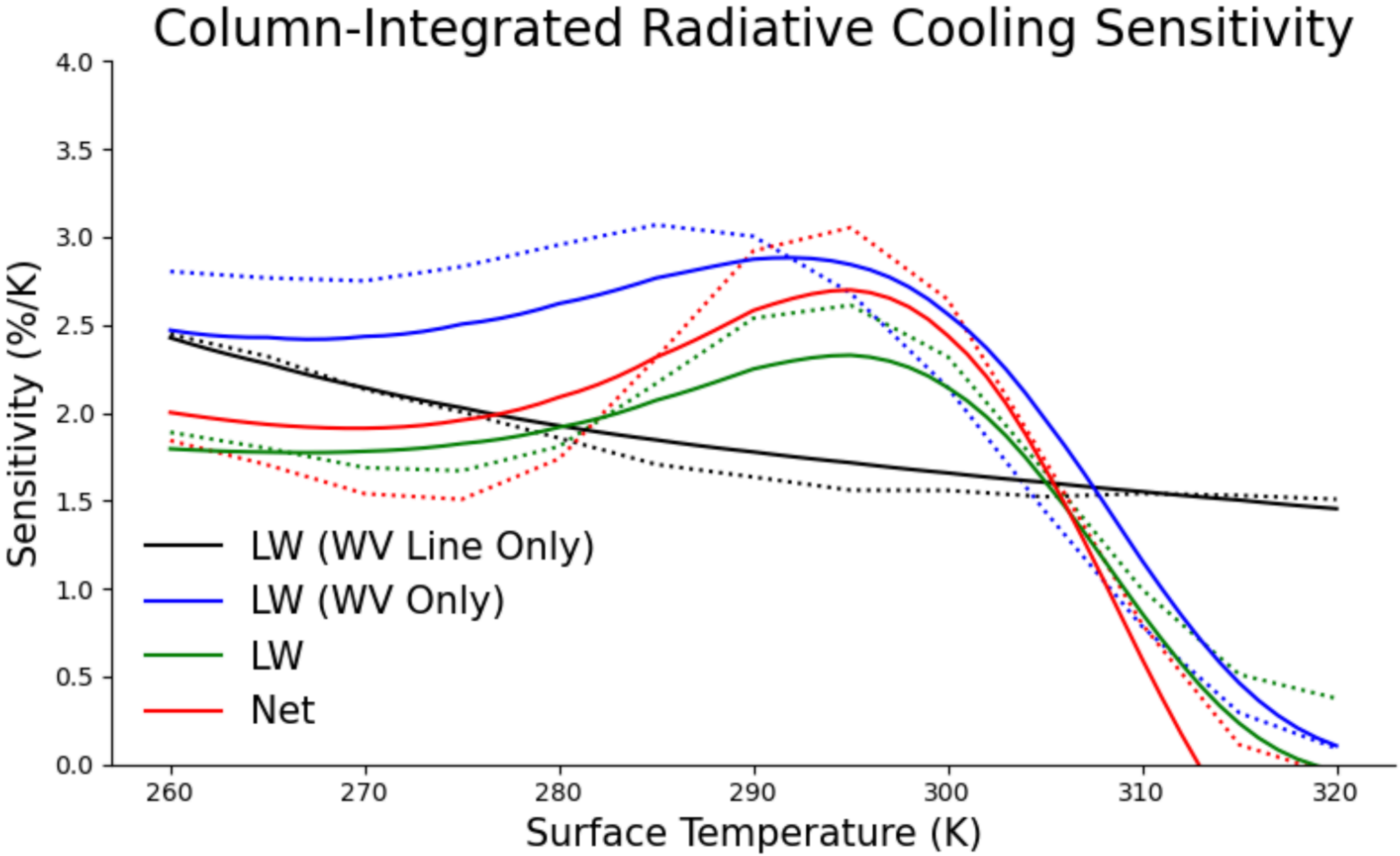



Column-Integrated Radiative Cooling Sensitivity
LW (WV Line Only)
LW (WV Only)
LW
Net
Sensitivity (W m^{-2} K^{-1})
0
1
2
3
4
5
6
7
260
270
280
290
300
310
320
Surface Temperature (K)


Column-Integrated Radiative Cooling Sensitivity
Sensitivity (%/K)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
260
270
280
290
300
310
320
Surface Temperature (K)
LW (WV Line Only)
LW (WV Only)
LW
Net

Hydrologic sensitivity is a consequence of spectroscopy

The atmosphere rains more with surface temperature not because it warms but because it warms and moistens simultaneously

The scale of hydrologic sensitivity is set by the surface Planck function and shaped by the spectroscopy of water vapor and carbon dioxide

Hydrologic sensitivity peaks at ~298K and drops off quickly at higher temperatures

From theory to models

Shortwave heating also increases with warming, damping sensitivity

Changes in sensible heat fluxes modify hydrological sensitivity

Partly addressed by considering cooling in the free atmosphere

Clouds can mask changes in atmospheric emission and/or lower the apparent surface temperature

CO_2 forcing damps these already-small estimates

It's unclear how to integrate across varying temperatures

… but hydrologic sensitivity atmospheric component of the climate feedback and models can be understood in the same framework