Mean precipitation change from newly emitting spectral regions

A spectrally-resolved analytical model to explore hydrological sensitivity

Sean Cohen

Robert Pincus

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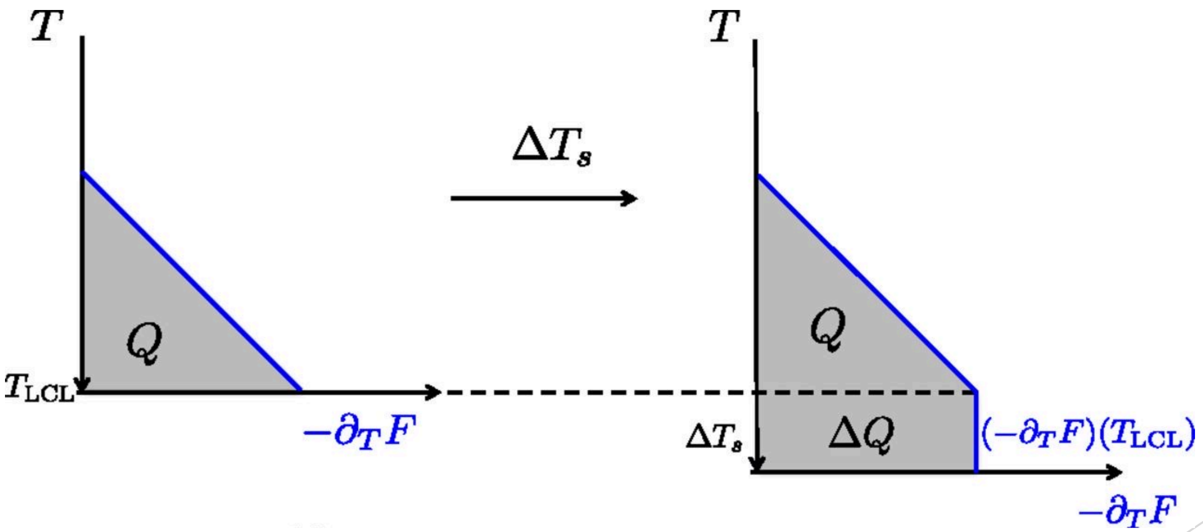
Mean precipitation is energetically constrained by radiative cooling

- In the absence of large-scale circulation, convective heating is primarily balanced by radiative cooling.

$$Hydrological\ Sensitivity \approx Radiative\ Cooling\ Sensitivity$$

- Clausius-Clapeyron ties water vapor to temperature, so flux divergence is T_S-invariant (Simpson's law).
- Thus, a warmer surface temperature simply adds a "new layer" of water vapor near the surface (Jeevanjee and Romps 2018).



Hydrological sensitivity is proportional to local radiative cooling rate

- The radiative cooling rate at a temperature level T is proportional to the hydrological sensitivity when T is the surface temperature.

$$\mathcal{H}_\nu(T) = -\frac{g}{c_p}\frac{dQ_\nu}{dT_s}\bigg|_{T=T_s}\frac{dT}{dp}$$

- If we assume a vertically constant radiative cooling rate, we obtain the canonical 2%/K value for hydrological sensitivity.

$$\frac{d\ln Q_\nu}{dT_s} \approx \frac{1}{\Gamma(T_s)H} \approx \frac{1}{(6km/K)(8km)} \approx 2\%/K$$

- **Thus, the mechanisms that drive the tropospheric radiative cooling rate to be nearly constant are the same mechanisms that yield the canonical scaling for hydrological sensitivity.**

Can we use a spectral framework to understand these underlying mechanisms?

An idealized spectral framework for hydrological sensitivity

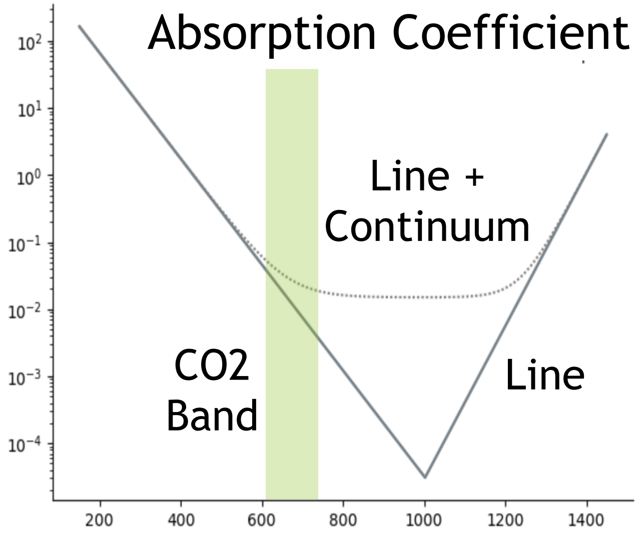
- Beginning with the radiative transfer equations, we assume:
  - Clear-skies
  - Longwave only
  - Vertically constant RH

  Line-by-line assumptions

  - Cooling dominated by water vapor
  - Neglect pressure broadening
  - Idealized mass-absorption coefficient

$$\frac{dB_\nu(T(\tau))}{dT_s} \approx 0$$

Idealized Mass-Absorption Coefficient



Wavenumber

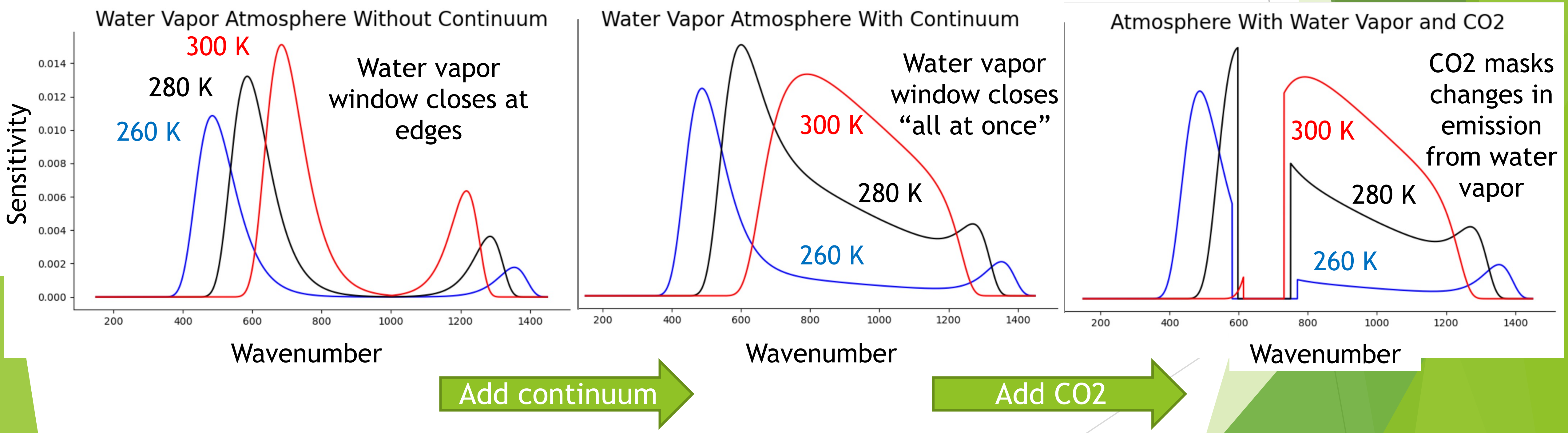
- **Hydrological sensitivity stems from changes in atmospheric transmission with surface temperature.**

$$\frac{dQ_\nu}{dT_s} \approx B_\nu(T_s)\frac{d\mathcal{T}_\nu}{dT_s}$$

- We compare our idealized model with line-by-line calculations in PyARTS.

Mean rainfall changes when atmospheric transmission changes

- Spectrally-resolved hydrological sensitivity reveals the wavenumbers where atmospheric transmission changes most with surface temperature.



Stefan-Boltzmann sets the magnitude of hydrological sensitivity

- In a water atmosphere without a continuum, broadband transmission sensitivity is nearly T_s-invariant:

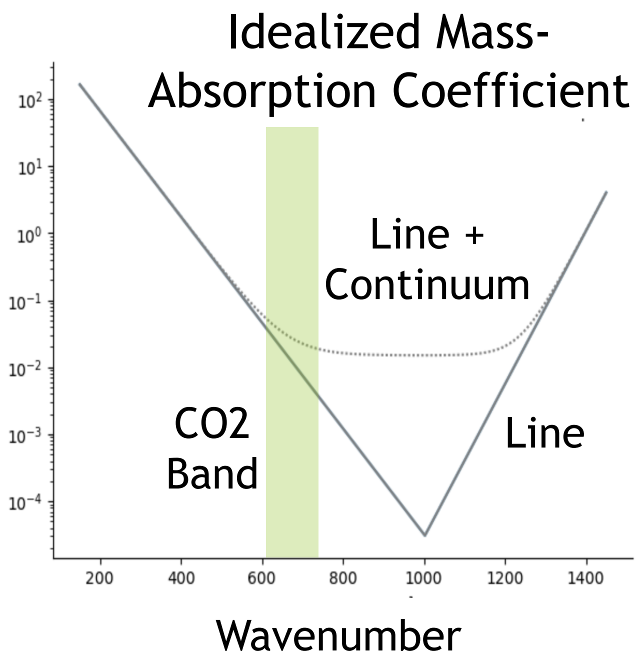
$$\frac{dQ_\nu}{dT_s} \approx B_\nu(T_s)\frac{d\mathcal{T}_\nu}{dT_s} \approx \frac{\sigma T_s^4}{\Delta\nu}\int_{\nu_{rot}}^{\nu_{v-r}} \frac{d\mathcal{T}_\nu}{dT_s} d\nu = constant \cdot T_s^3$$

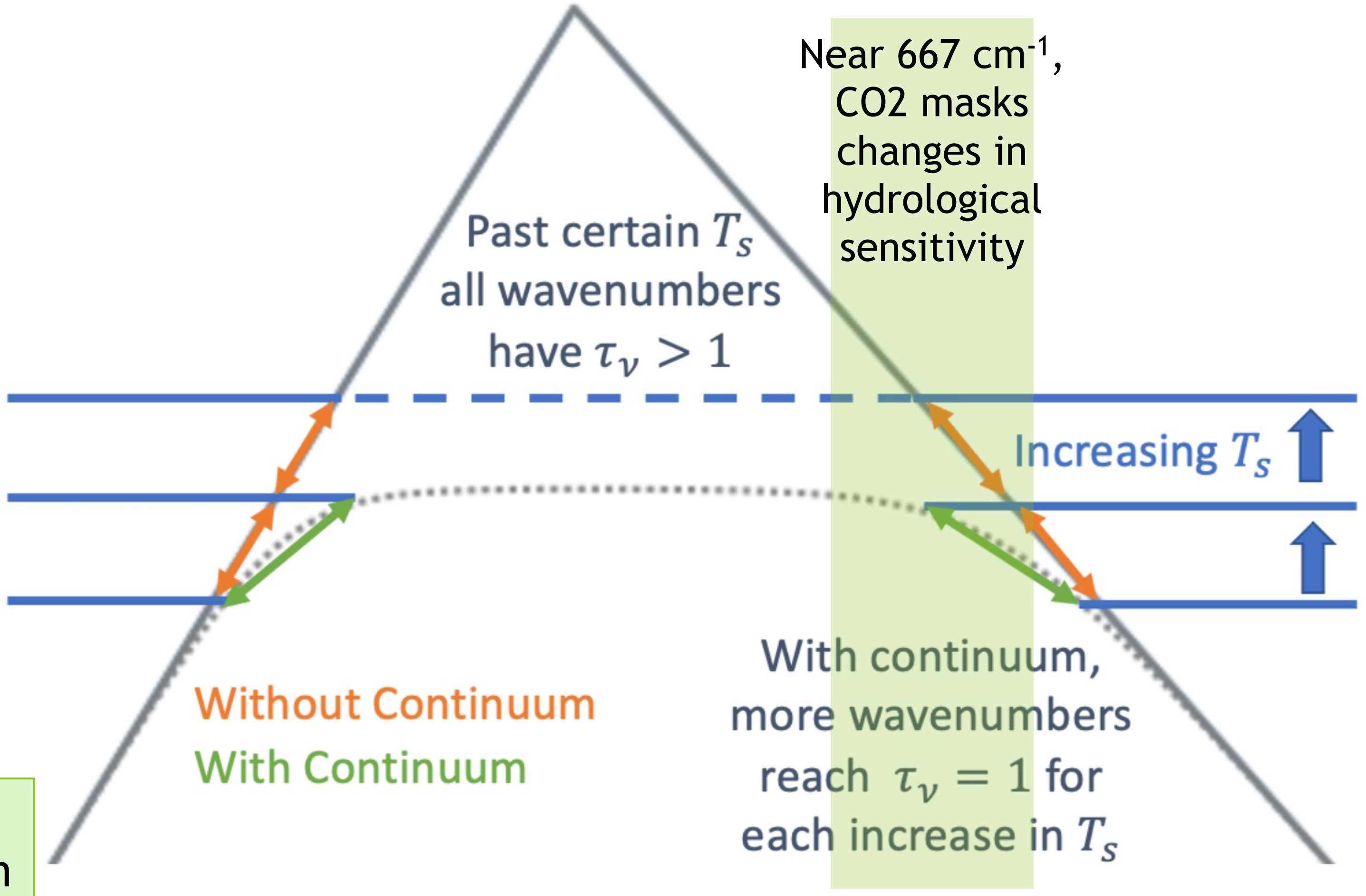
- Due to Stefan-Boltzmann, $Q \propto {T_s}^4$, yielding:

$$\frac{d\ln Q_\nu}{dT_s} \approx \frac{4T_s^3}{T_s^4 - T_{strat}^4} \approx 2\%/K$$

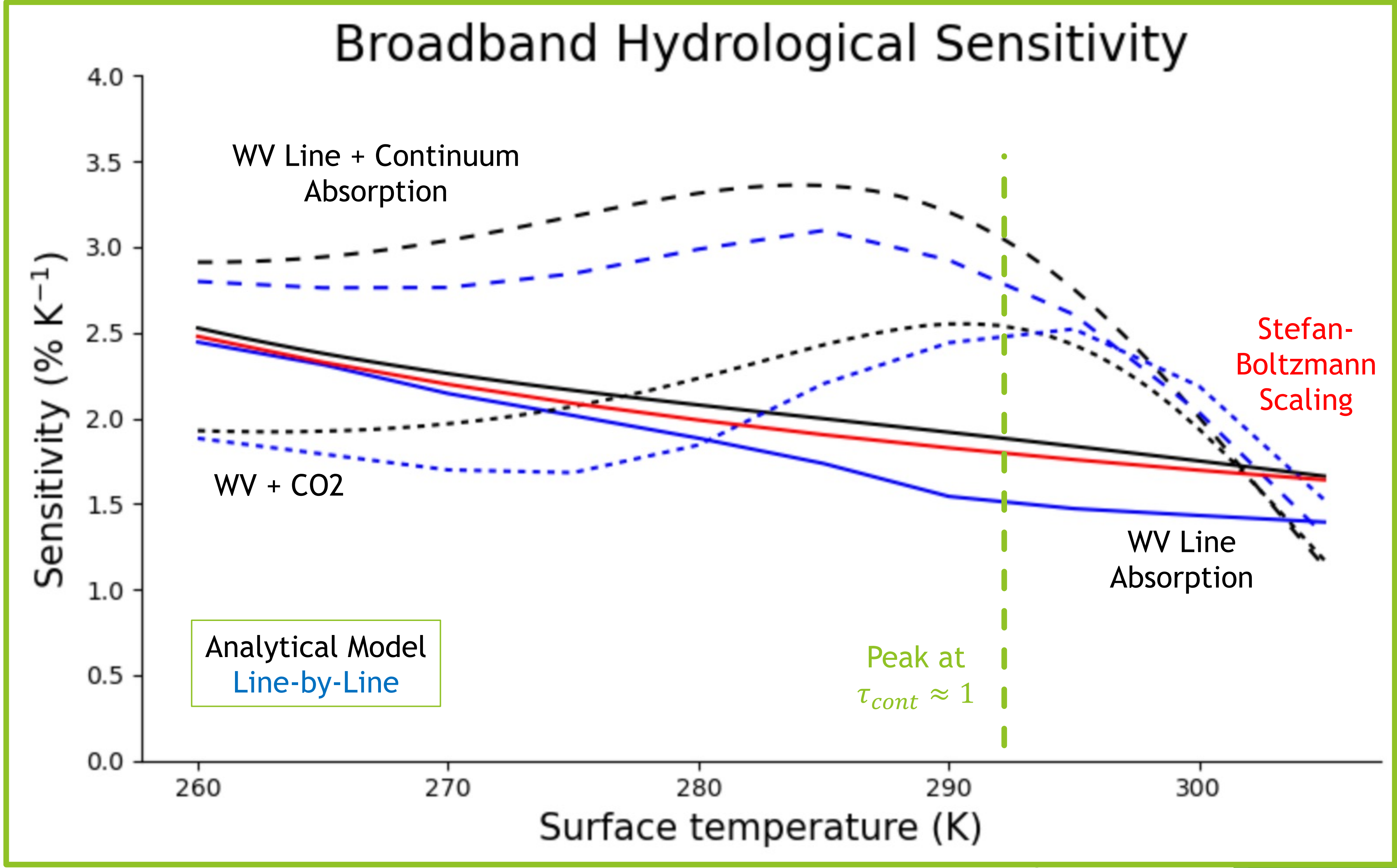
- The “symmetry” of the water vapor window causes atmospheric transmission to change at a near constant rate with T_s, making Stefan-Boltzmann the 1st order driver of hydrological sensitivity.

The water vapor continuum causes hydrological sensitivity to peak at subtropical surface temperatures





Hydrological sensitivity peaks when the optical depth of the water vapor continuum is approximately unity, near $T_s \approx$290K


Broadband Hydrological Sensitivity
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Sensitivity (% K^{-1})
260
270
280
290
300
Surface temperature (K)
WV Line + Continuum
Absorption
WV + CO2
Stefan-
Boltzmann
Scaling
WV Line
Absorption
Analytical Model
Line-by-Line
Peak at
$\tau_{cont} \approx 1$

Summary: The spectral roots of hydrological sensitivity

- Hydrological sensitivity is proportional to local radiative cooling rate.
- Mean rainfall changes when atmospheric transmission changes.
- Stefan-Boltzmann sets the magnitude of hydrological sensitivity.
- The water vapor continuum causes hydrological sensitivity to peak at subtropical surface temperatures.

$$\frac{dQ_\nu}{dT_s} \approx B_\nu(T_s)\frac{d\mathcal{T}_\nu}{dT_s}$$