Thermospectric constraint on Earth’s tropopause temperature

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EGU

30 April 2025

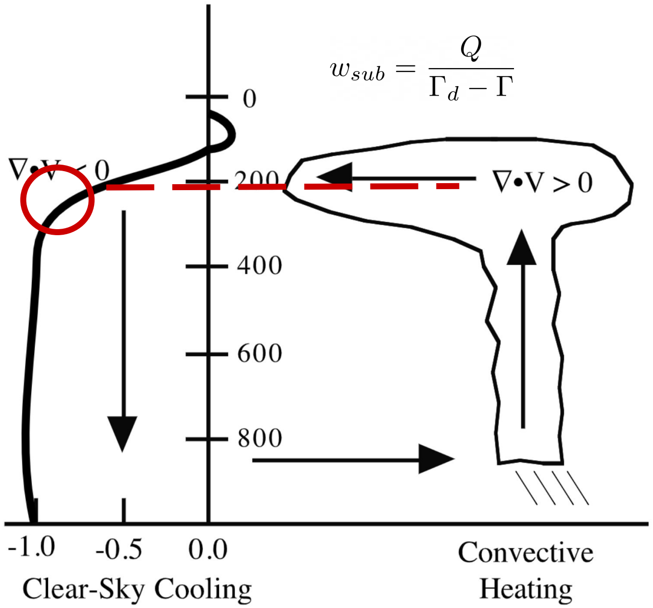
The tropopause is the boundary between the troposphere and the stratosphere

- **The tropopause separates two regions with qualitatively different heat budgets**
  - Troposphere exhibits a balance between net radiative cooling and heating from convection and eddies
  - Stratosphere is close to radiative equilibrium (zero net radiative cooling)

- **The tropopause is important because it is a boundary condition for CO_2 forcing, hurricane intensity, CAPE, the water vapor feedback, stratospheric water vapor…**

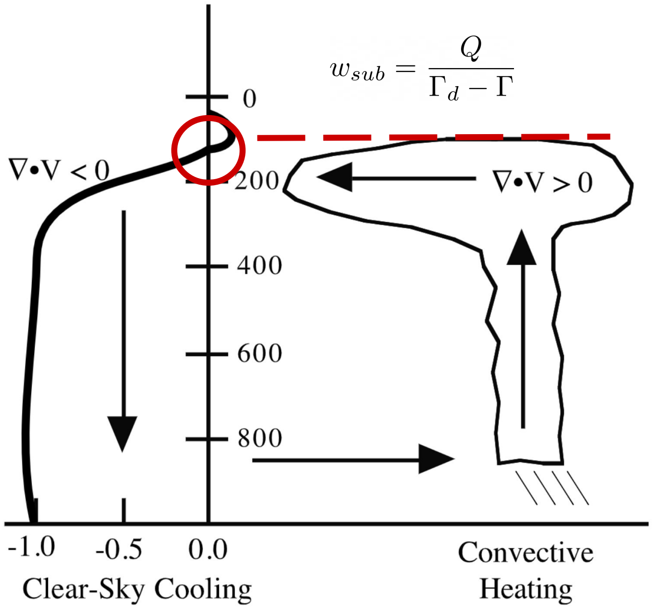
Vertical motions are linked to radiative cooling and water vapor

Convective outflow linked with sharp decline in radiative cooling profiles



Hartmann and Larson, 2002

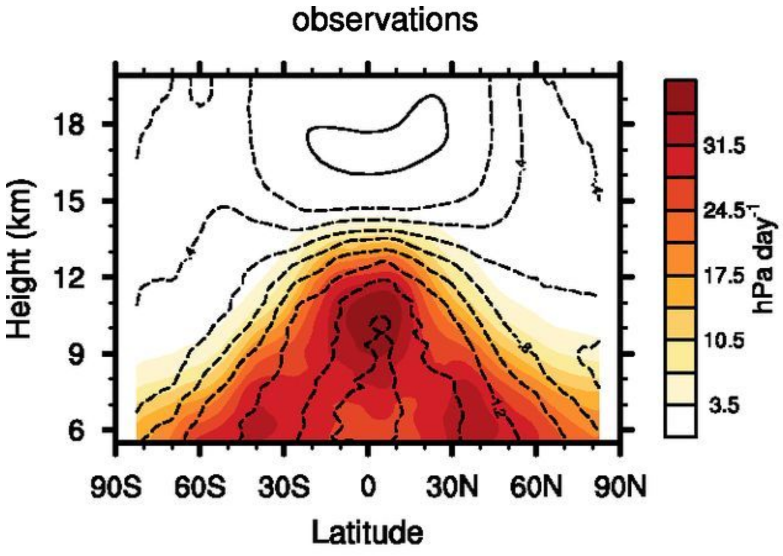
Convective top linked with zero point of radiative cooling



Hartmann and Larson, 2002

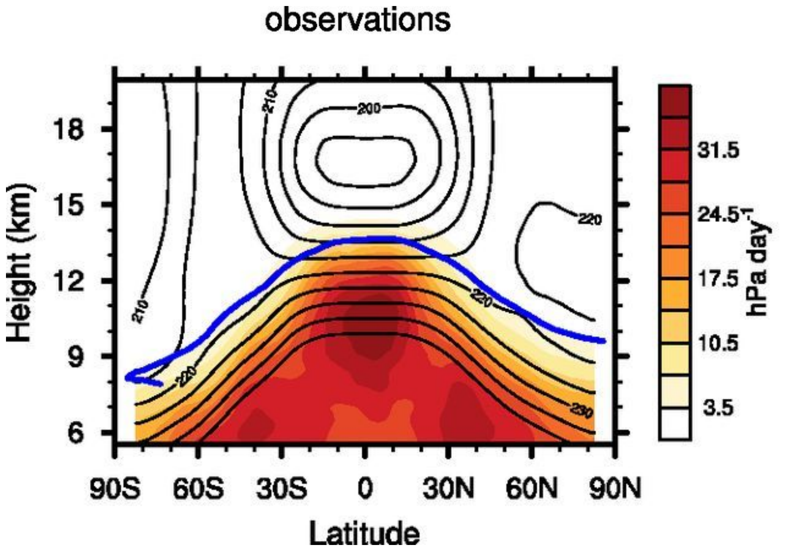
Vertical motions are linked to radiative cooling and water vapor

Diabatic Mass flux (shading) **linked with radiative cooling** (contours) **across the globe**



Thompson and Bony, 2017

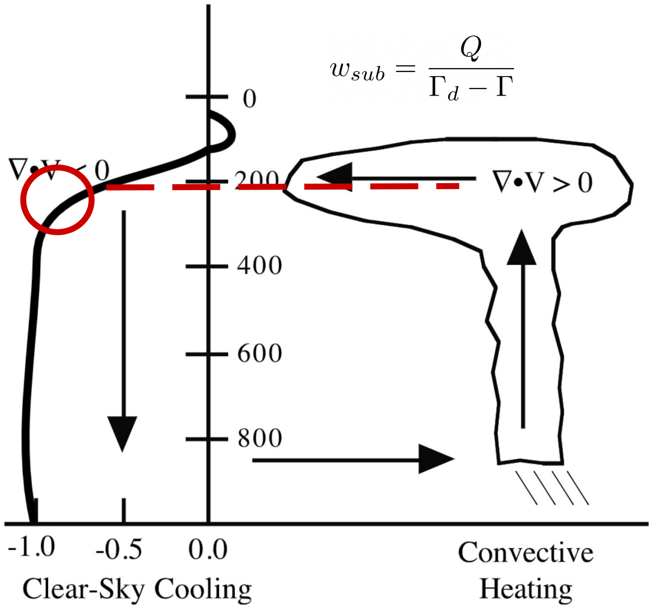
Diabatic Mass flux (shading) **linked with temperature** (contours) **and water vapor** (blue) **across the globe**



Thompson and Bony, 2017

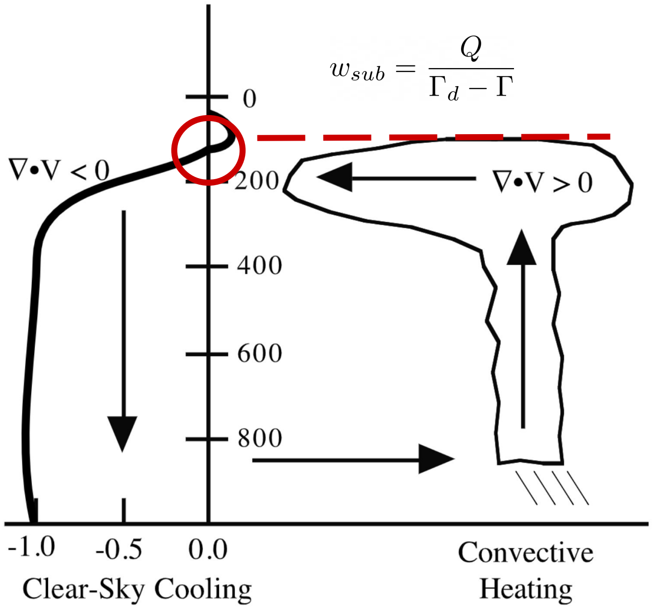
Anvil clouds are thermodynamically constrained — perhaps the tropopause too?

Fixed Anvil Temperature (FAT)



Hartmann and Larson, 2002

Fixed Tropopause Temperature (FiTT)?



Hartmann and Larson, 2002

Water vapor is thermodynamically constrained — perhaps the tropopause too?

Questions:

1. **Can we make make the FiTT hypothesis quantitative?**
2. **Can we predict tropopause temperature and its change with warming?**
3. **Can we see and explain FiTT in a hierarchy of models?**

Thermodynamics is not enough, we need spectroscopy

When does water vapor stop cooling to space? How little water vapor is too little to emit?

$$\tau_{H_2O}(\nu, z) = \int_z^\infty \kappa_{H_2O}(\nu) \frac{p}{p_{\mathrm{ref}}} \rho_{H_2O} dz'$$

$$\tau_{H_2O}(\nu, T_{\mathrm{em}}) = 1$$

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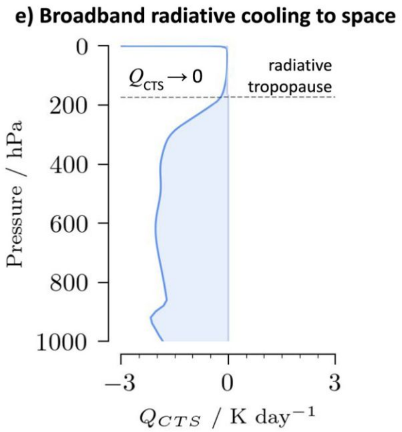

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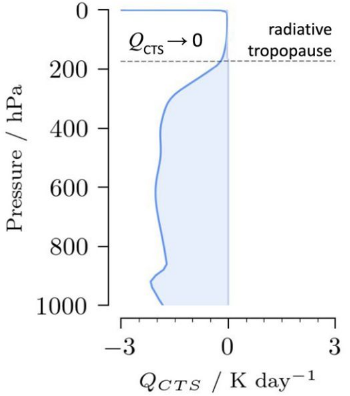
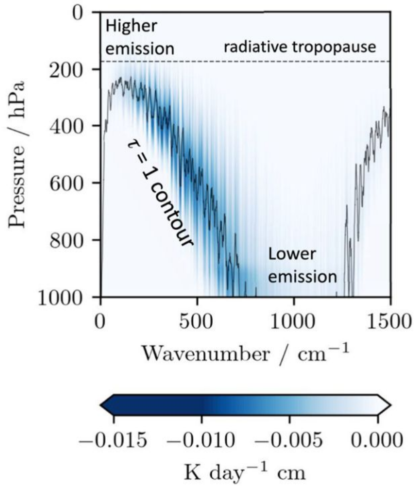
e) Broadband radiative cooling to space



d) Spectrally resolved radiative cooling to space



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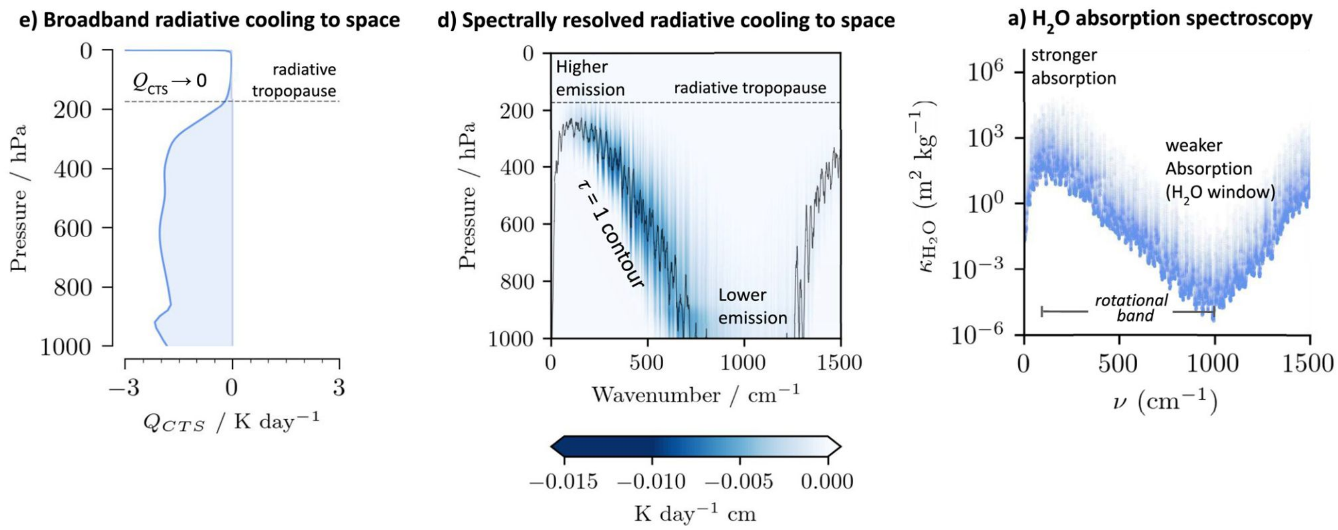

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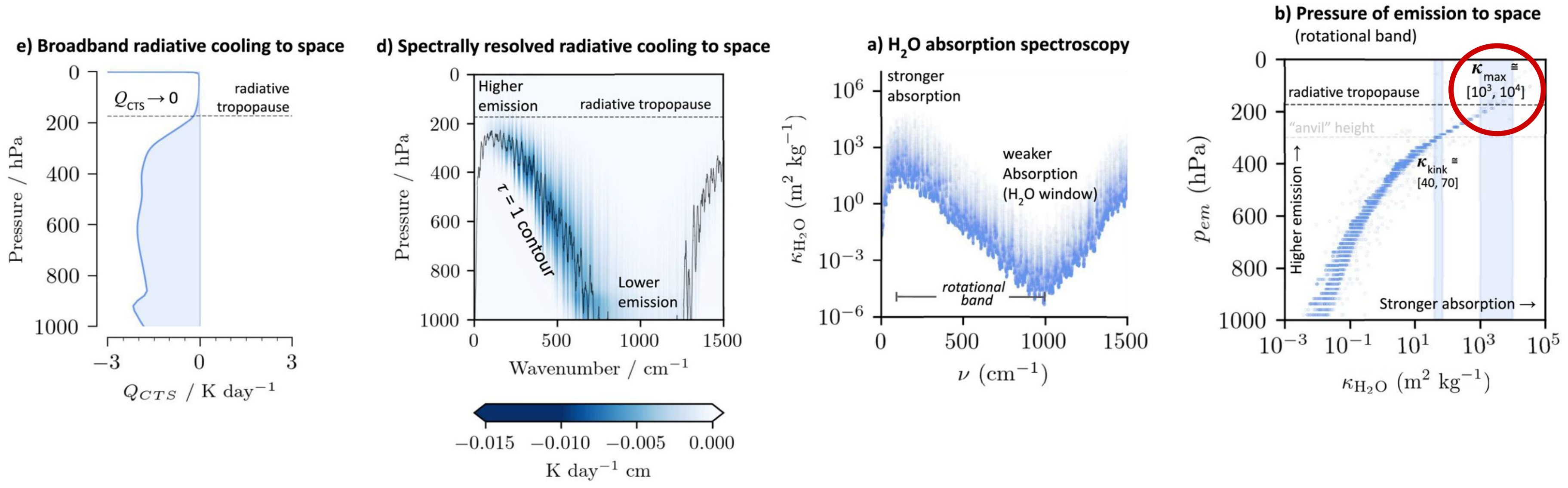

The thermospectric constraint can predict T_{tp} and its change with warming

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$$\Rightarrow \quad T_{em}(\kappa_{H_2O}) = \frac{T^*}{W\left(\frac{T^*}{T_{ref}}(D \cdot \mathrm{RH} \cdot M_v \cdot \kappa_{H_2O})^{R_d \Gamma / g}\right)}$$

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$$\boxed{T_{tp} = T_{em}(\kappa_{max}) \approx 188\ \mathrm{K}}$$

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$$\boxed{\frac{dT_{tp}}{dT_s} = \frac{T_{tp}}{T_s} \frac{1}{\frac{LR_d\Gamma}{gR_vT_{tp}} - 1} \approx 1/7}$$

(from pressure broadening)

The thermospectric constraint can predict T_{tp} and its change with warming

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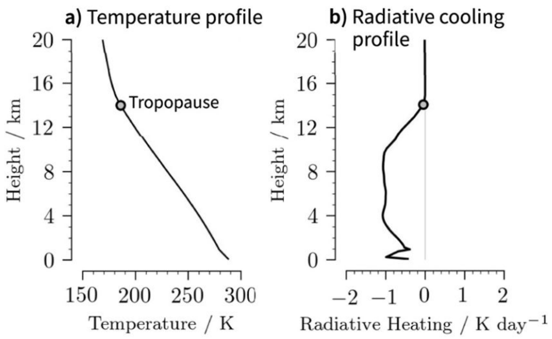
$$\boxed{\left.\frac{d \ln \rho_{H_2O}}{dT}\right|_{T_{tp}} = \frac{L}{R_v T_{tp}^2} = 16\% \text{ K}^{-1} \Longrightarrow \text{4 K to double } \rho_{H2O}}$$

Testing the thermospectric constraint

Use the Isca Single Column Model (SCM)

Control simulation

(T_s = 290 K , RH = 70%, κ scaling = 1)



Vallis et al, 2018
https://execlim.github.io/IscaWebsite/index.html

The model is configured with a correlated-k radiation scheme (RRTM), a boundary layer turbulence profile, and a simplified representation of moist convection (the simple Betts-Miller scheme).

Prescribed SSTs and RH. 280 ppmv CO_2. No O3.

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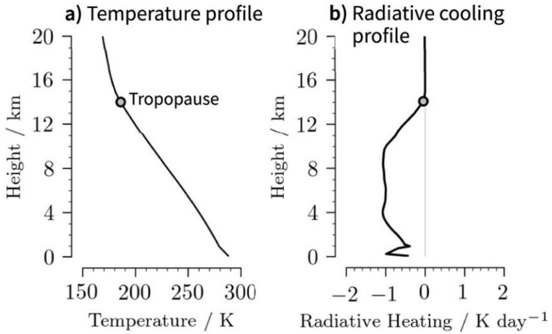

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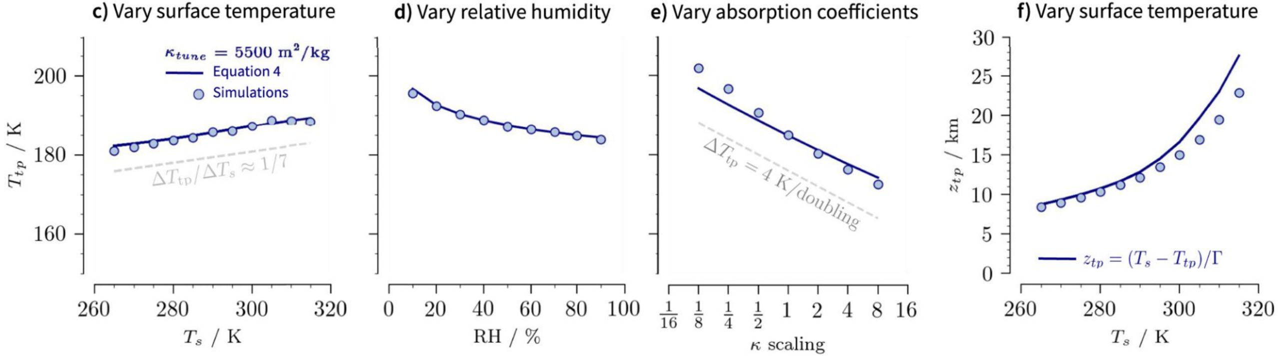
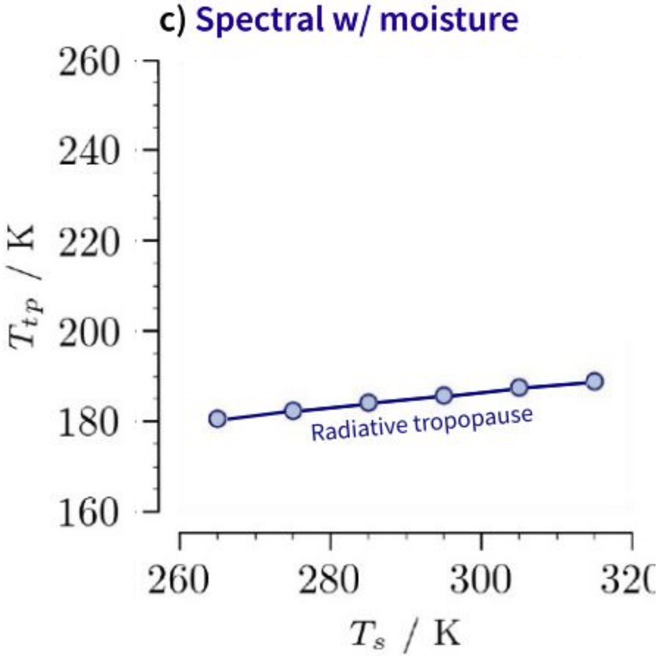
Testing theory against simulations



Moisture is essential for a fixed temperature; Spectroscopy is essential for getting the *right* temperature



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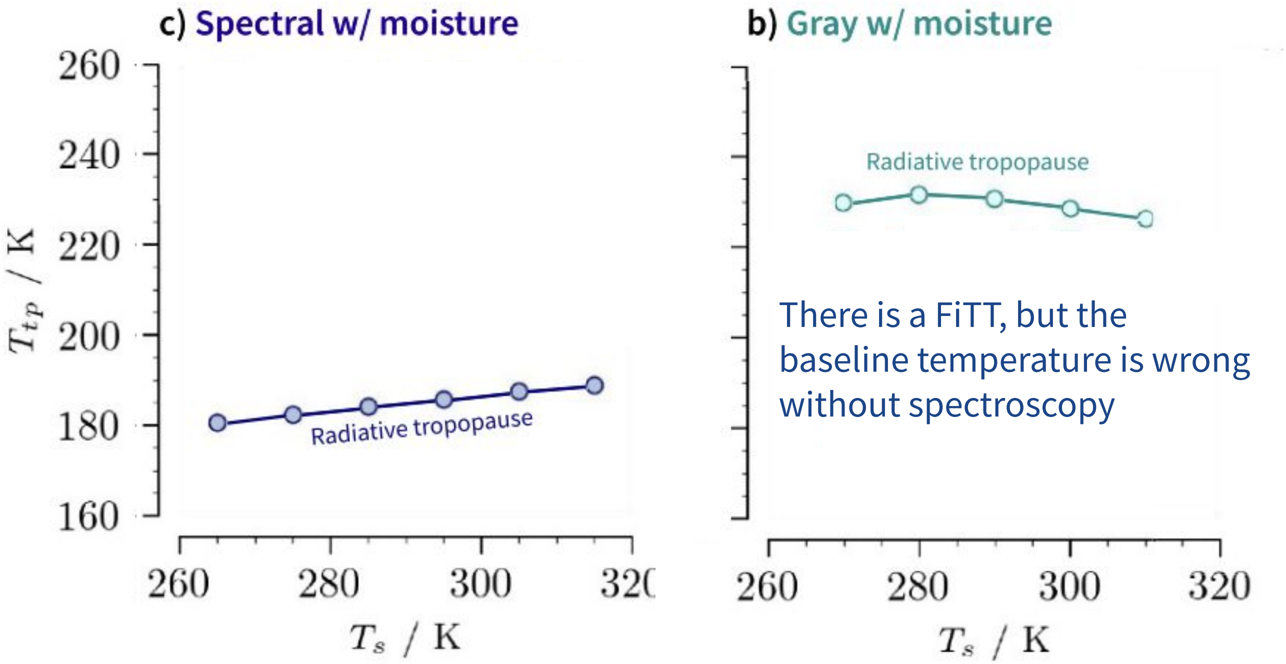
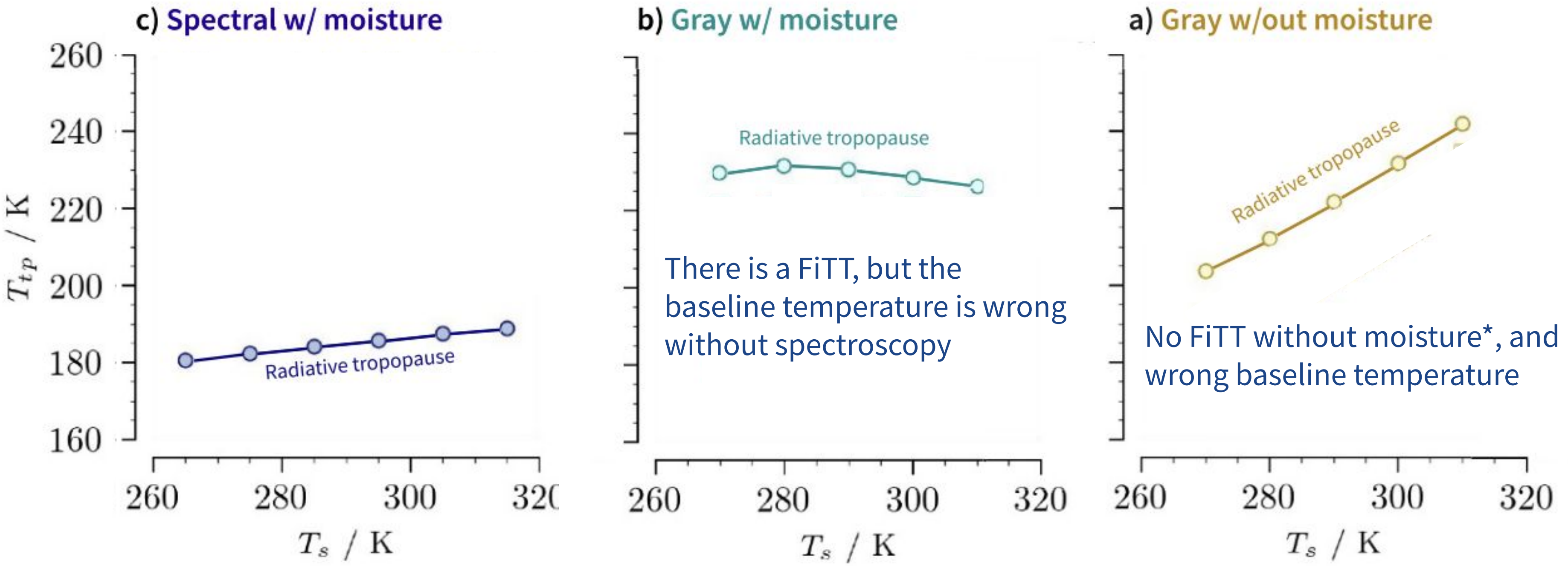


There is a FiTT, but the baseline temperature is wrong without spectroscopy

Moisture is essential for a fixed temperature; Spectroscopy is essential for getting the *right* temperature



*For the global warming driven by insolation or prescribed SSTs

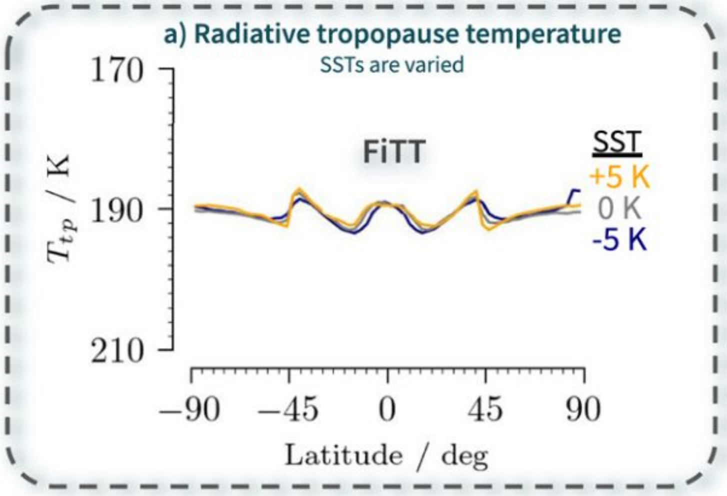
Testing the thermospectric constraint and comparing tropopauses

Use the Isca General Circulation Model (GCM)

$$T_s(\phi) = \begin{cases} 300(1 - \sin^2(3\phi/2)) \text{ K}, & \text{for } -\pi/3 < \phi < \pi/3 \\ 273 \text{ K}, & \text{otherwise}, \end{cases}$$

Radiative Tropopause

Using -0.2 K day^{-1} criterion



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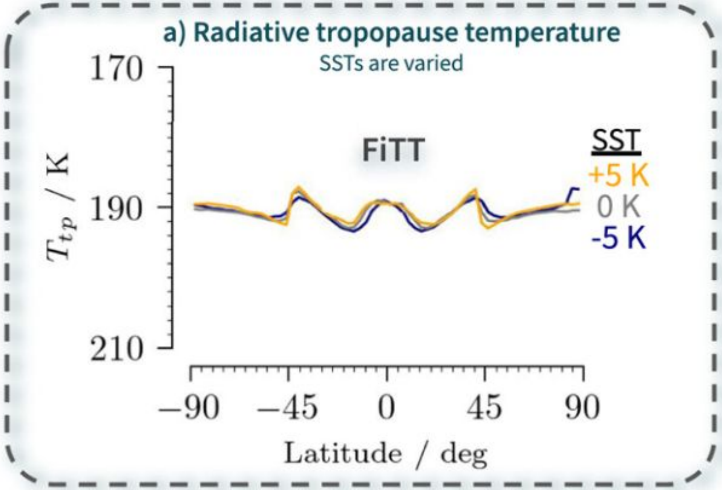
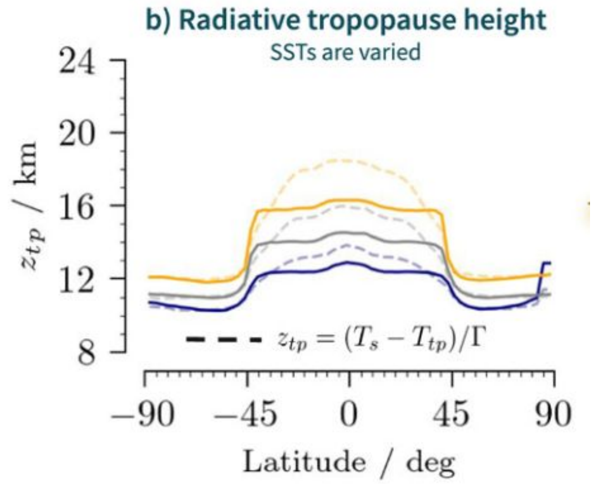


Partially explains the rising tropopause

$\Rightarrow$



Insights in the radiative tropopause carry over to the lapse rate tropopause

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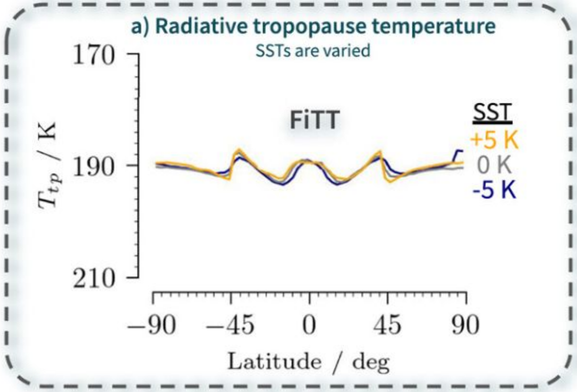
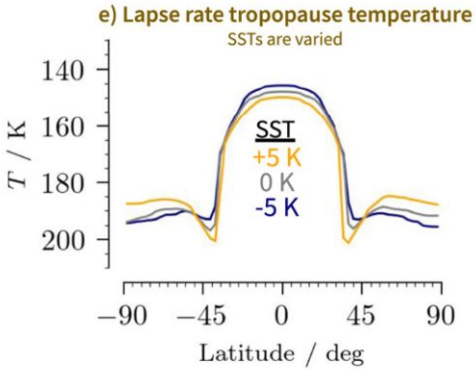


Lapse Rate Tropopause

Using 5 K km^{-1} criterion



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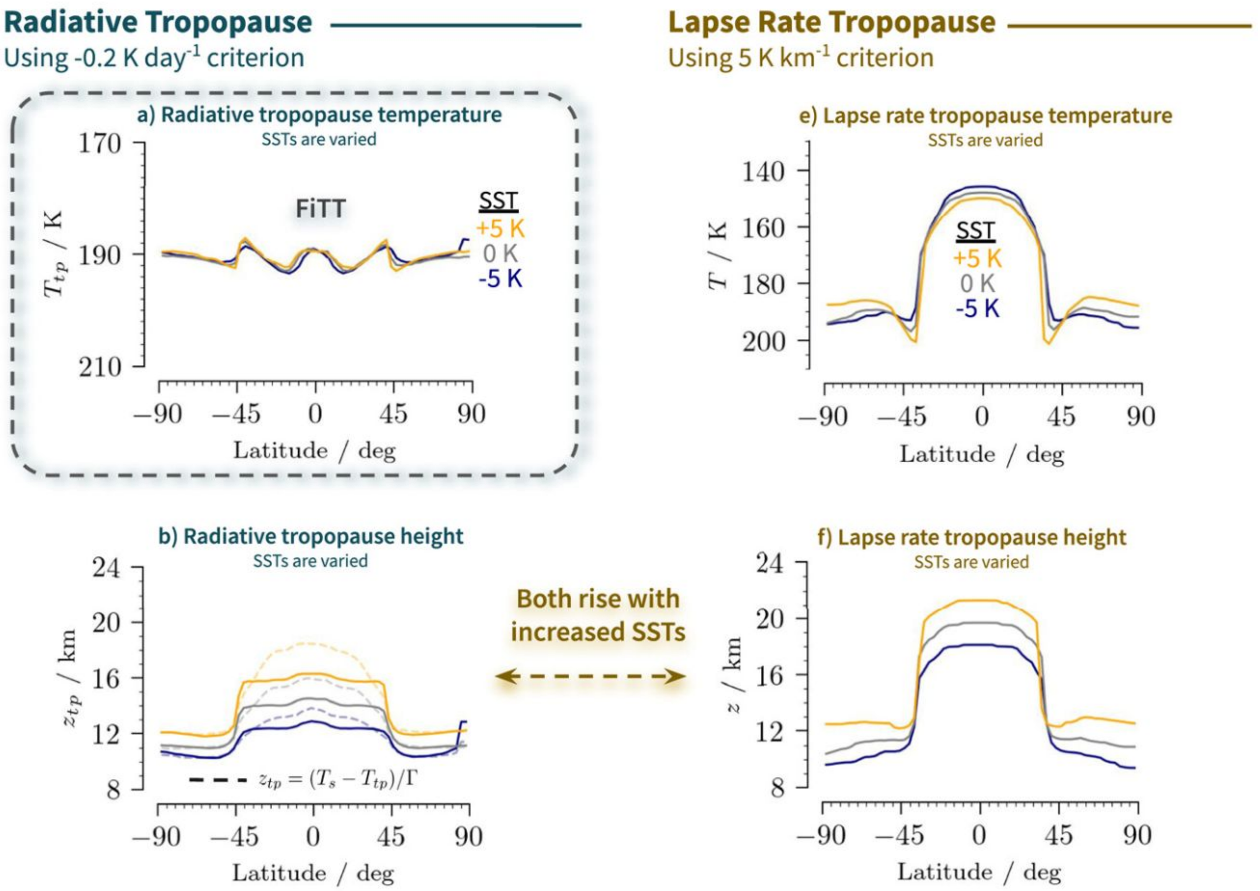

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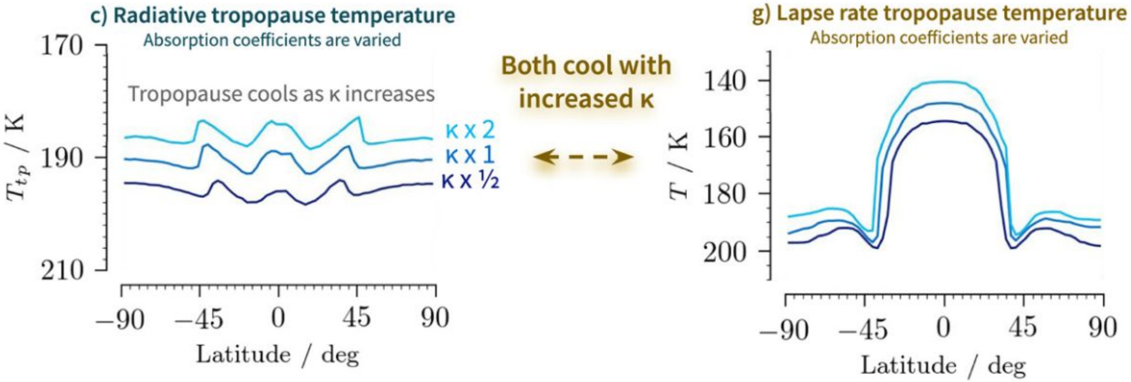

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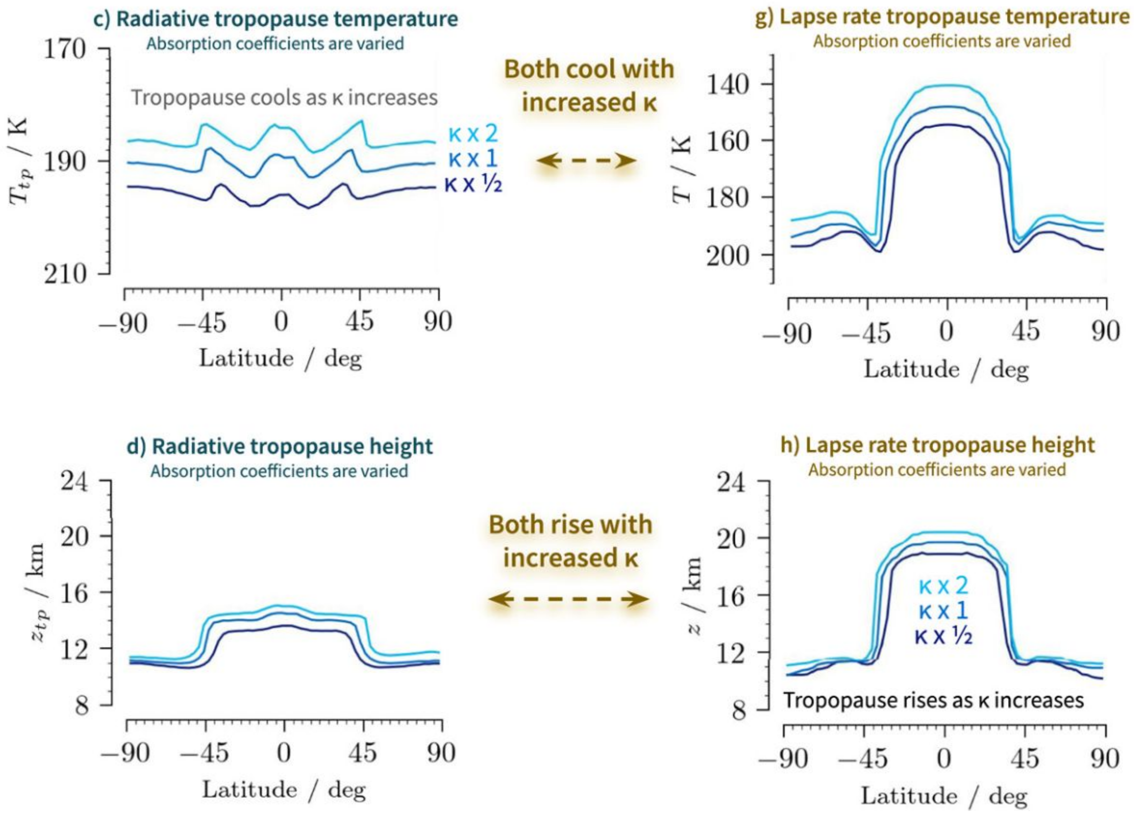

Conclusions

Questions

- Can we make make FiTT quantitative? Can we predict tropopause temperature and its change with warming? Can we see FiTT in a hierarchy of models?

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Takeaways

- A hierarchy of climate models exhibit a FiTT

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- It is the combination of water vapor thermodynamics and spectroscopy that allows a quantitative understanding of the tropopause.

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Takeaways

- A hierarchy of climate models exhibit a FiTT

- It is the combination of water vapor thermodynamics and spectroscopy that allows a quantitative understanding of the tropopause.

- This constraint limits the vertical extent of Earth's general circulation, showing that small scale physics has large scale impacts.

To learn more

AGU Advances

RESEARCH ARTICLE

10.1029/2024AV001206

Peer Review The peer review history for this article is available as a PDF in the Supporting Information.

Water Vapor Spectroscopy and Thermodynamics Constrain Earth's Tropopause Temperature

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[1]Now at LMD/IPSL, Sorbonne Université, CNRS, Paris, France, [2]Department of Mathematics and Statistics, University of Exeter, Exeter, UK, [3]Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA

The Paper

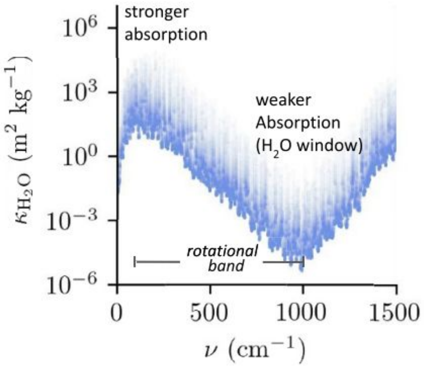
- Explores the thermospectric constraint in more detail and compares to other longstanding constraints based on TOA energy balance and gray radiation

About me

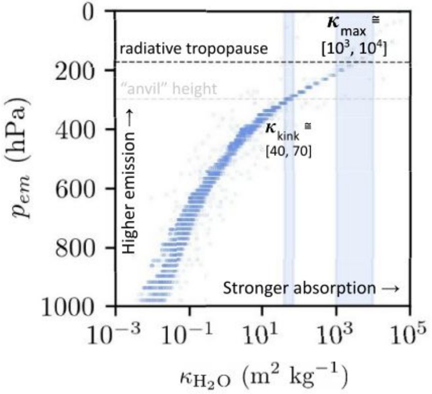
- Looking for assistant professor / lecturer positions

The connection between H_2O spectroscopy, radiative cooling, and the tropopause

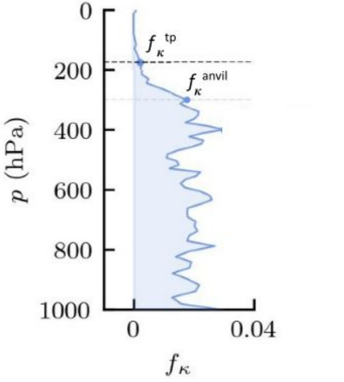
a) H_2O absorption spectroscopy



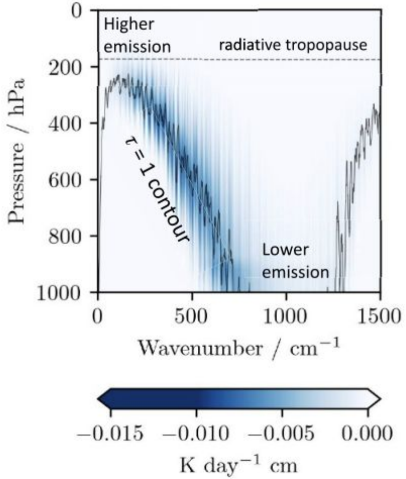
b) Pressure of emission to space (rotational band)



c) Density of wavenumbers emitting to space (rotational band)



d) Spectrally resolved radiative cooling to space



Takeaways

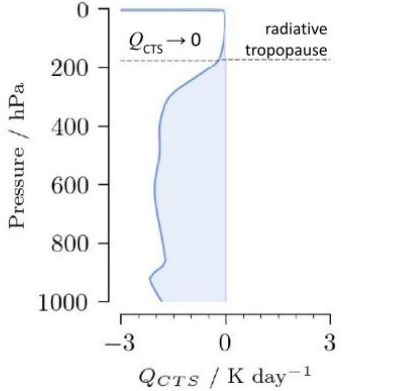
$$Q_{\mathrm{CTS}}(p) \sim f_\kappa(p)$$

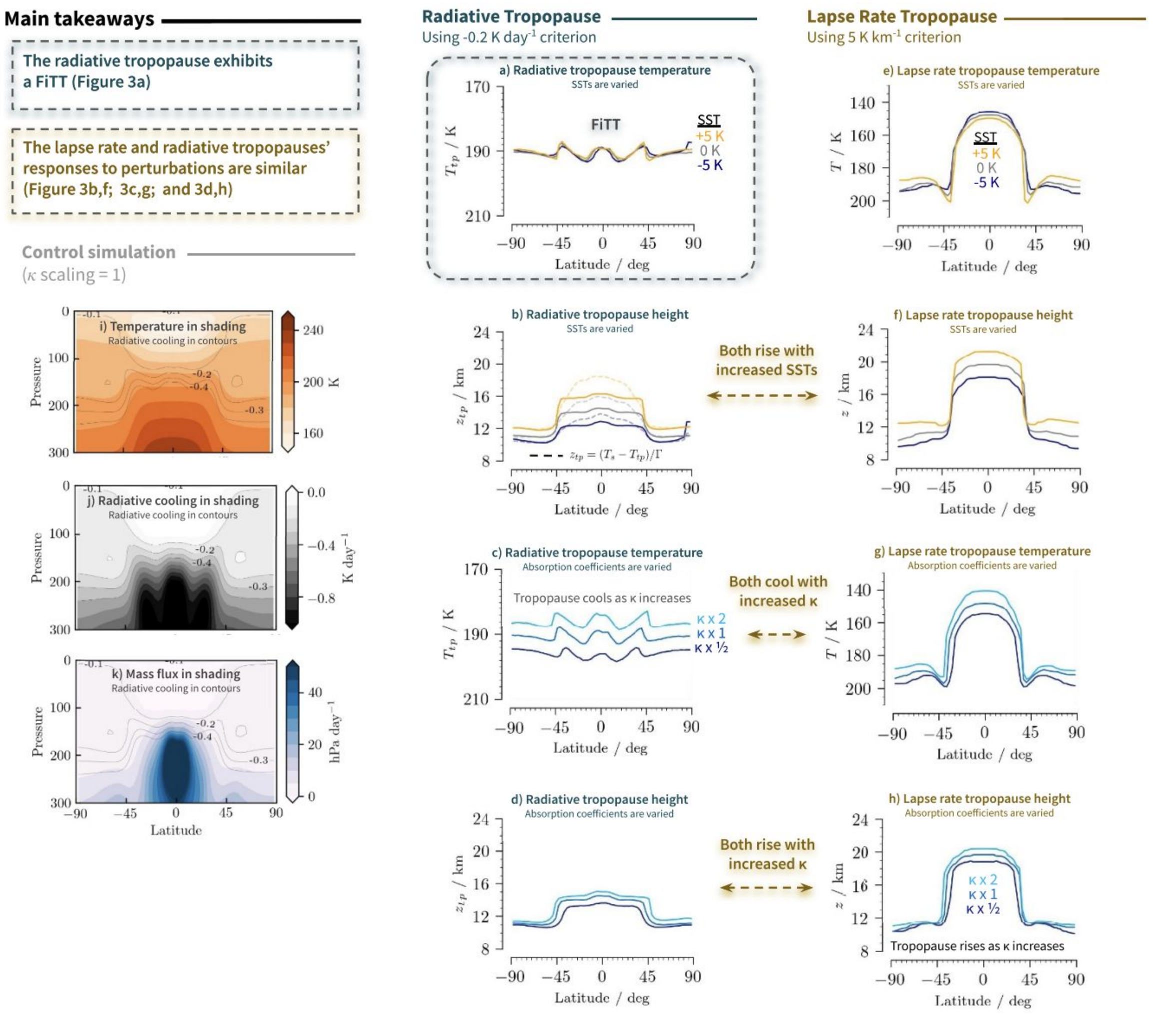
→ Figure 1c,e

$$\kappa_{\max} \approx [10^3, 10^4]\ \mathrm{m^2\ kg^{-1}}$$

→ Figure 1b

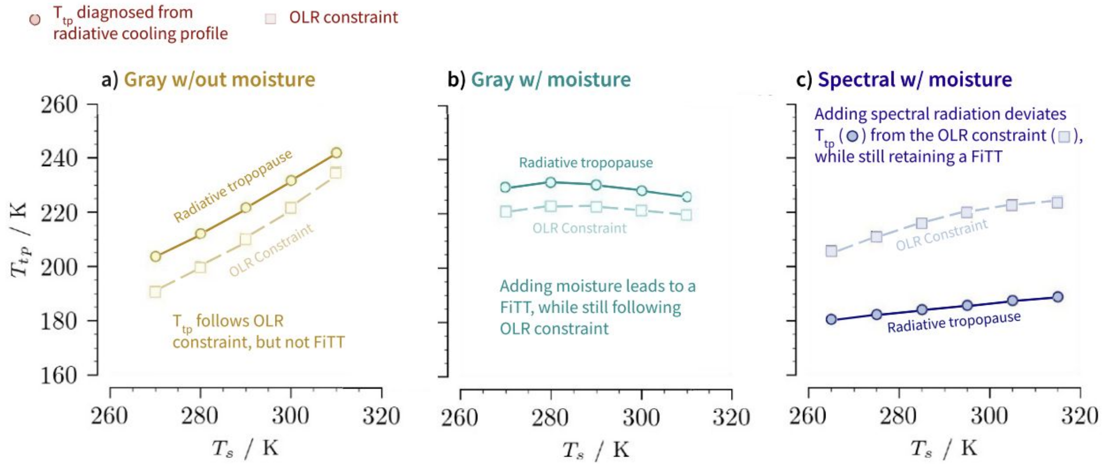
e) Broadband radiative cooling to space



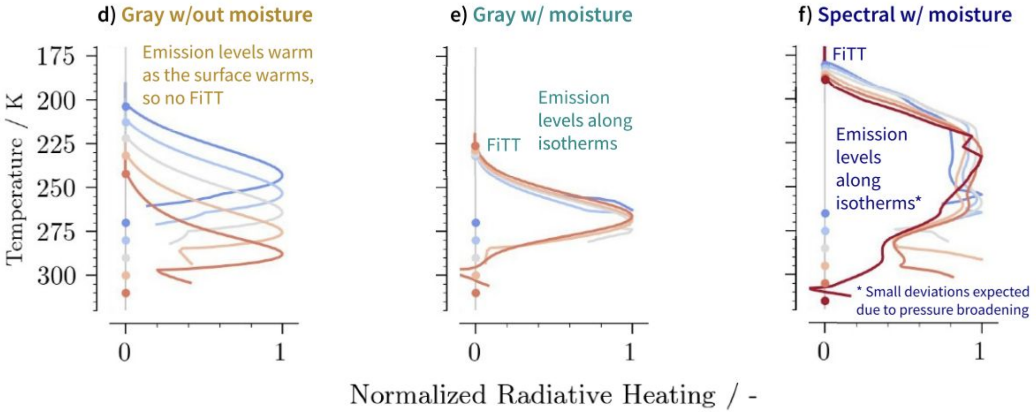


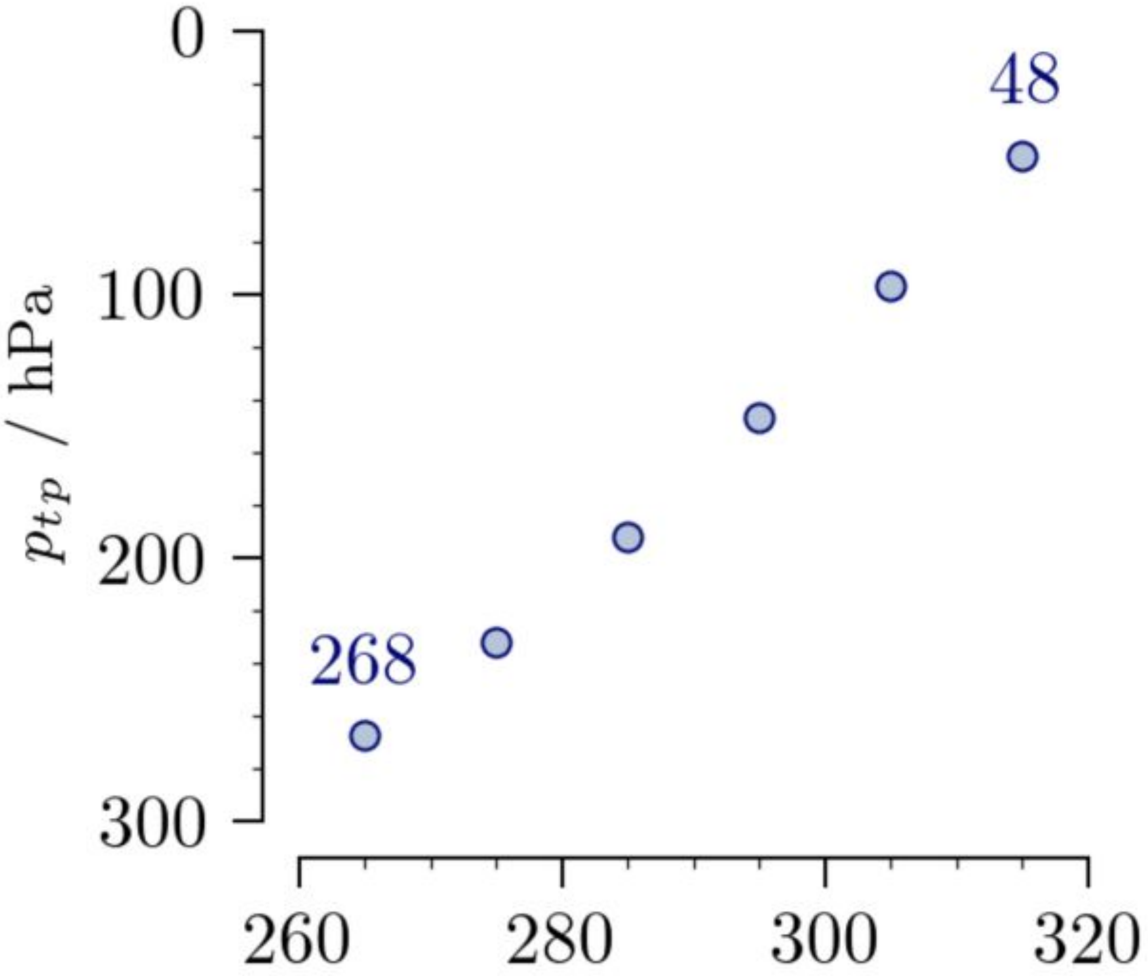
Main takeaways
The radiative tropopause exhibits a FiTT (Figure 3a)
The lapse rate and radiative tropopauses' responses to perturbations are similar (Figure 3b,f; 3c,g; and 3d,h)
Control simulation
(κ scaling = 1)
i) Temperature in shading
Radiative cooling in contours
j) Radiative cooling in shading
Radiative cooling in contours
k) Mass flux in shading
Radiative cooling in contours
Pressure
Latitude
K
K day^{-1}
hPa day^{-1}
Radiative Tropopause
Using -0.2 K day^{-1} criterion
a) Radiative tropopause temperature
SSTs are varied
FiTT
SST
+5 K
0 K
-5 K
T_{tp} / K
Latitude / deg
b) Radiative tropopause height
SSTs are varied
z_{tp} / km
$z_{tp} = (T_s - T_{tp})/\Gamma$
c) Radiative tropopause temperature
Absorption coefficients are varied
Tropopause cools as κ increases
κ x 2
κ x 1
κ x ½
d) Radiative tropopause height
Absorption coefficients are varied
Both rise with increased SSTs
Both cool with increased κ
Both rise with increased κ
Lapse Rate Tropopause
Using 5 K km^{-1} criterion
e) Lapse rate tropopause temperature
SSTs are varied
T / K
f) Lapse rate tropopause height
SSTs are varied
z / km
g) Lapse rate tropopause temperature
Absorption coefficients are varied
h) Lapse rate tropopause height
Absorption coefficients are varied
Tropopause rises as κ increases

Testing the OLR constraint

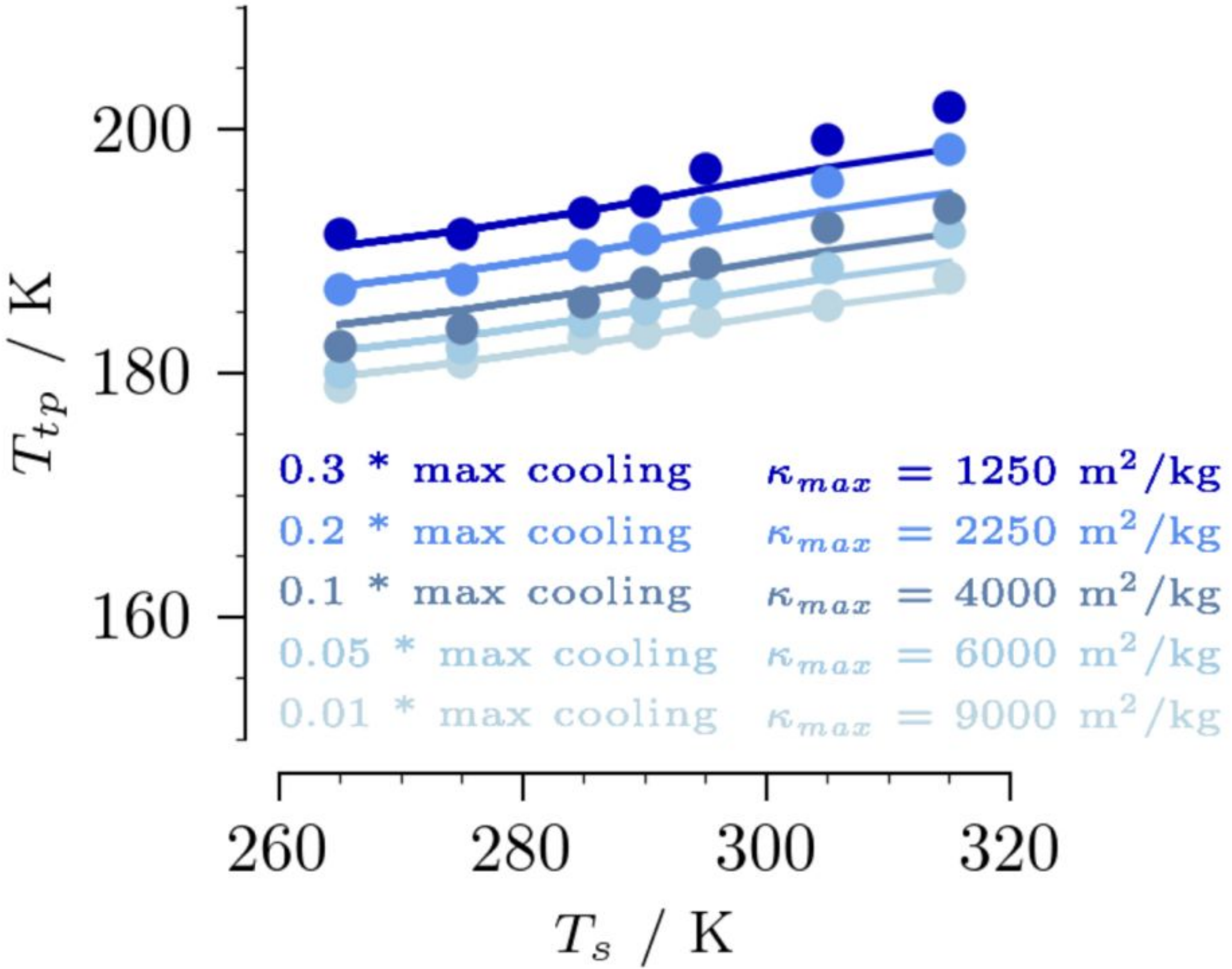


Comparing behavior of emission levels

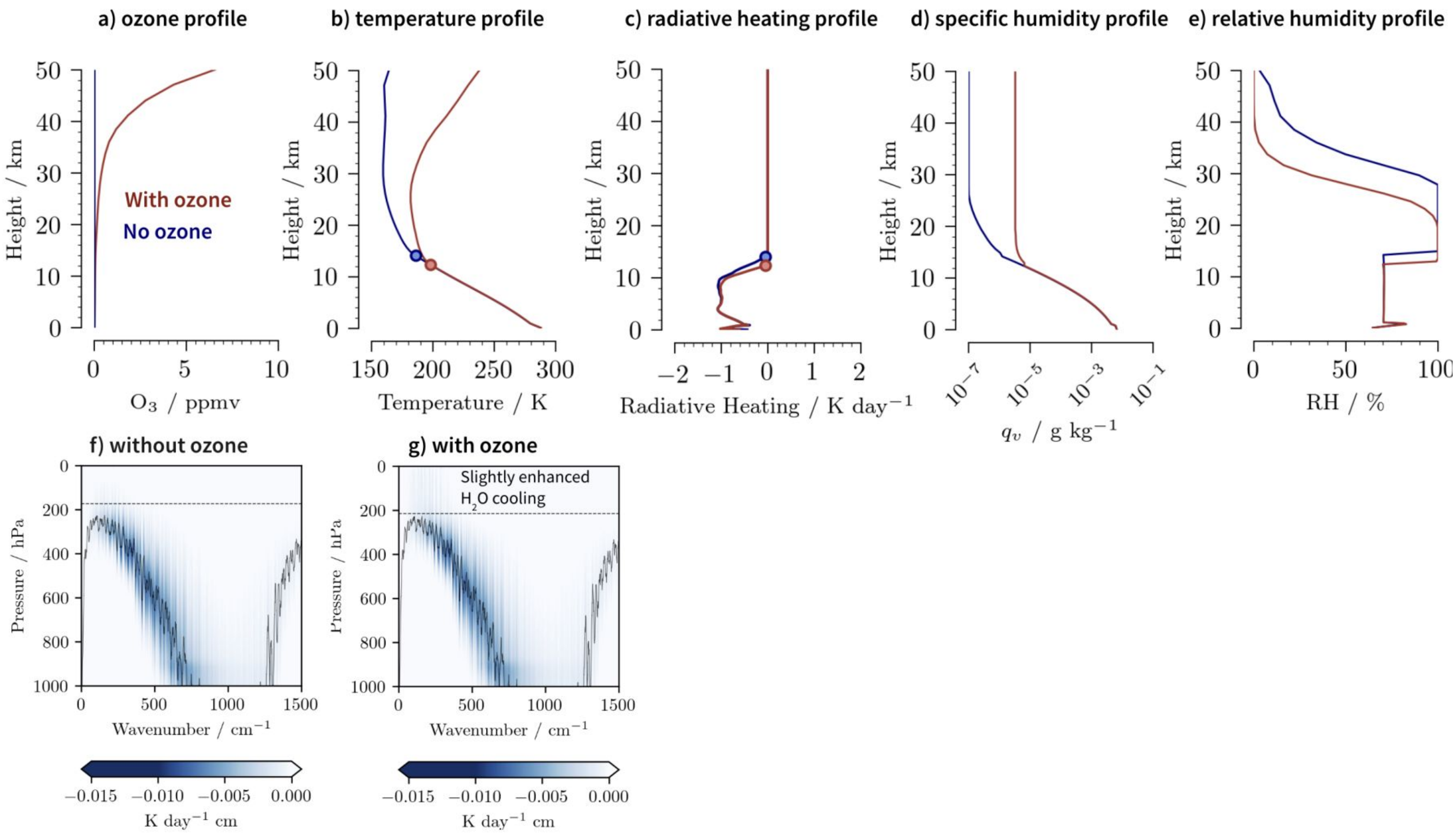




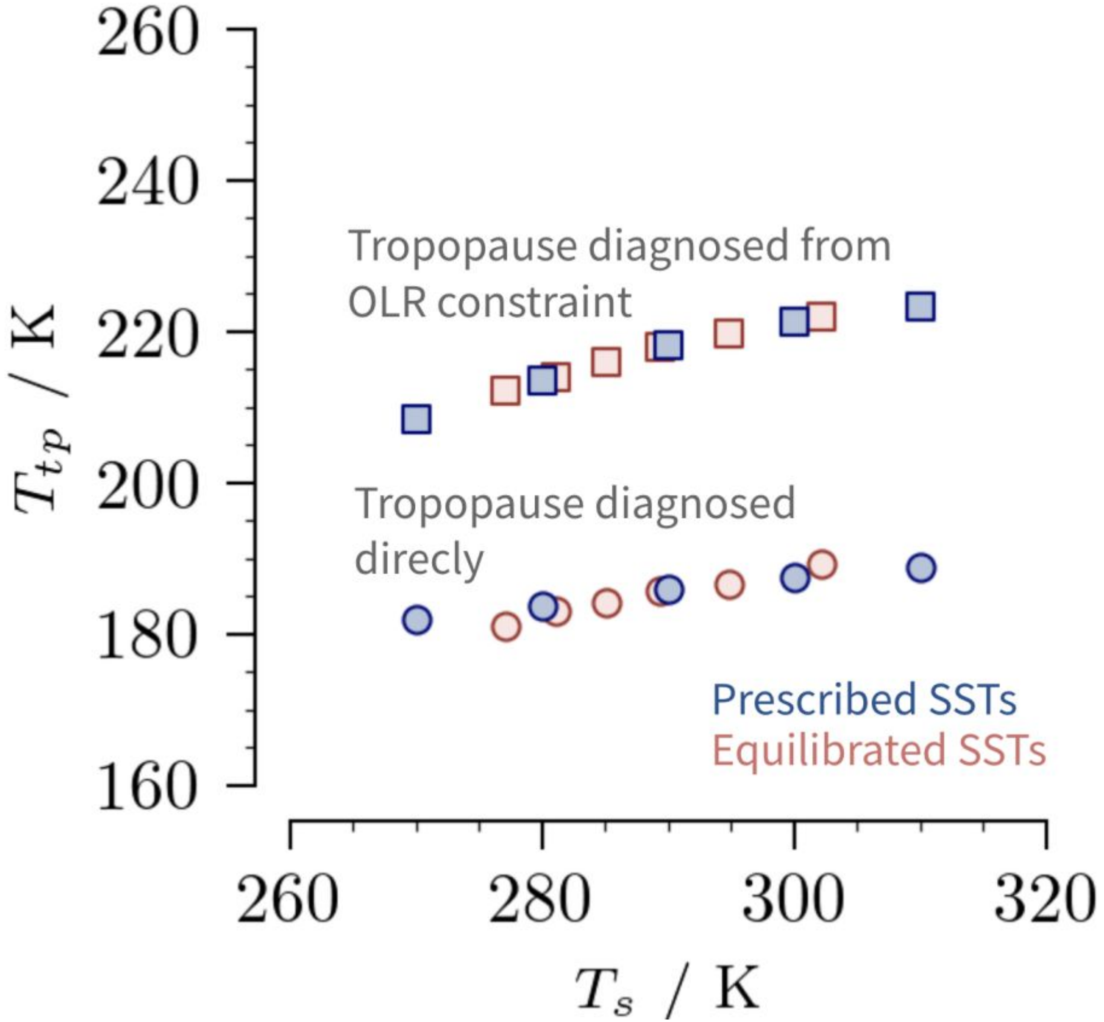
0
100
200
300
p_{tp} / hPa
48
268
260
280
300
320



200
180
160
T_{tp} / K
0.3 * max cooling κ_{max} = 1250 m^2/kg
0.2 * max cooling κ_{max} = 2250 m^2/kg
0.1 * max cooling κ_{max} = 4000 m^2/kg
0.05 * max cooling κ_{max} = 6000 m^2/kg
0.01 * max cooling κ_{max} = 9000 m^2/kg
260
280
300
320
T_s / K

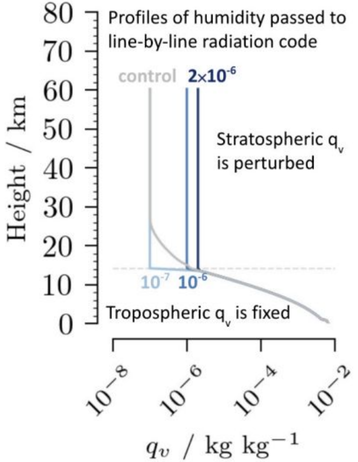


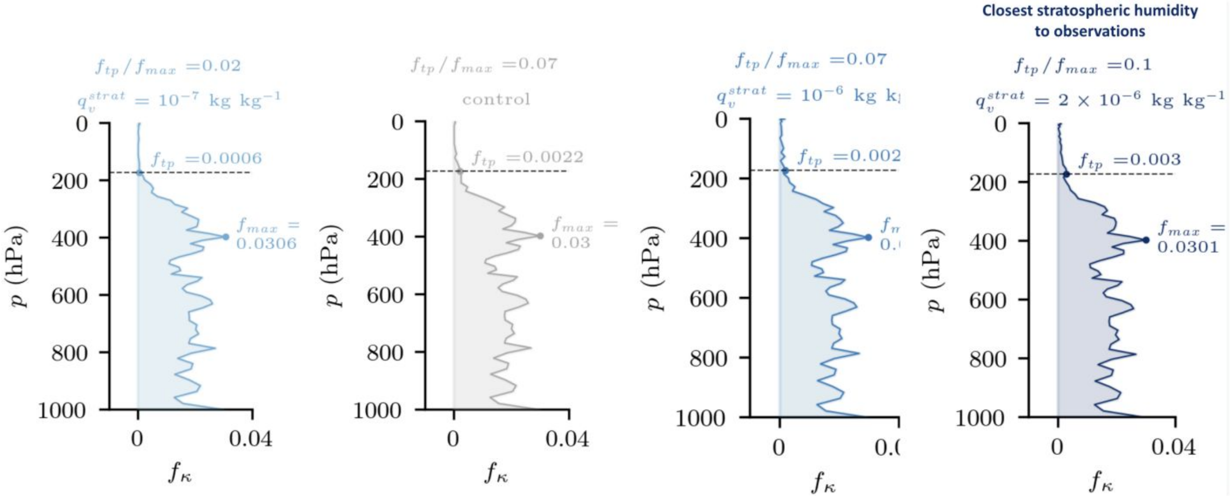
a) ozone profile
b) temperature profile
c) radiative heating profile
d) specific humidity profile
e) relative humidity profile
With ozone
No ozone
Height / km
O3 / ppmv
Temperature / K
Radiative Heating / K day−1
qv / g kg−1
RH / %
f) without ozone
g) with ozone
Slightly enhanced
H2O cooling
Pressure / hPa
Wavenumber / cm−1
K day−1 cm



Tropopause diagnosed from OLR constraint
Tropopause diagnosed direcly
Prescribed SSTs
Equilibrated SSTs
T_{tp} / K
T_s / K
260
240
220
200
180
160
260
280
300
320

Validation of Theory's Assumptions about Stratospheric Water





$$\tau_{\mathrm{H_2O}}(\kappa_{\mathrm{H_2O}}, T) \approx \underbrace{\kappa_{\mathrm{H_2O}} \frac{p}{p_{\mathrm{ref}}}}_{\text{spectroscopy}} \underbrace{M_{\mathrm{v}} \mathrm{RH} \exp\left(-\frac{L}{R_{\mathrm{v}} T}\right)}_{\text{water vapor path}},$$

$$T_{\mathrm{tp}} = (\mathrm{OLR}/2\sigma)^{1/4} \quad \text{(OLR constraint)},$$