Understanding climate evolution through spectral trends analysis: comparative study of IASI and climate model simulations

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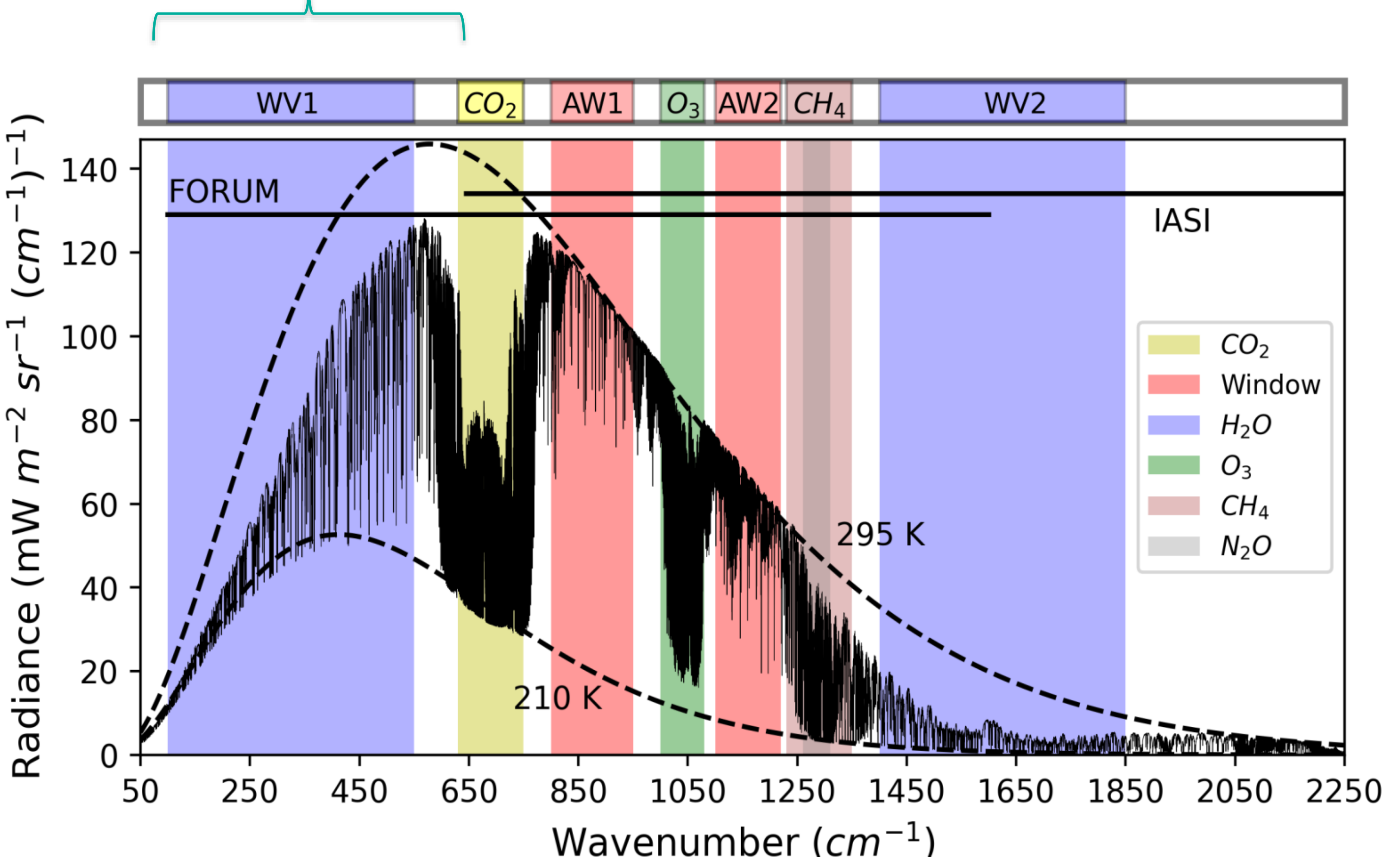
Why do we study the Earth Emission Spectrum?

PREFIRE (2024) and FORUM (2027)



Simulated Earth emission spectrum computed by σ-IASI Radiative transfer model (Della Fera et al. 2023)

The Outgoing Longwave Radiation (OLR) spectrum is determined by surface and atmospheric properties.

It implicitly contains the fingerprints of all the most relevant climate variables (surface properties, GHGs gases, clouds)

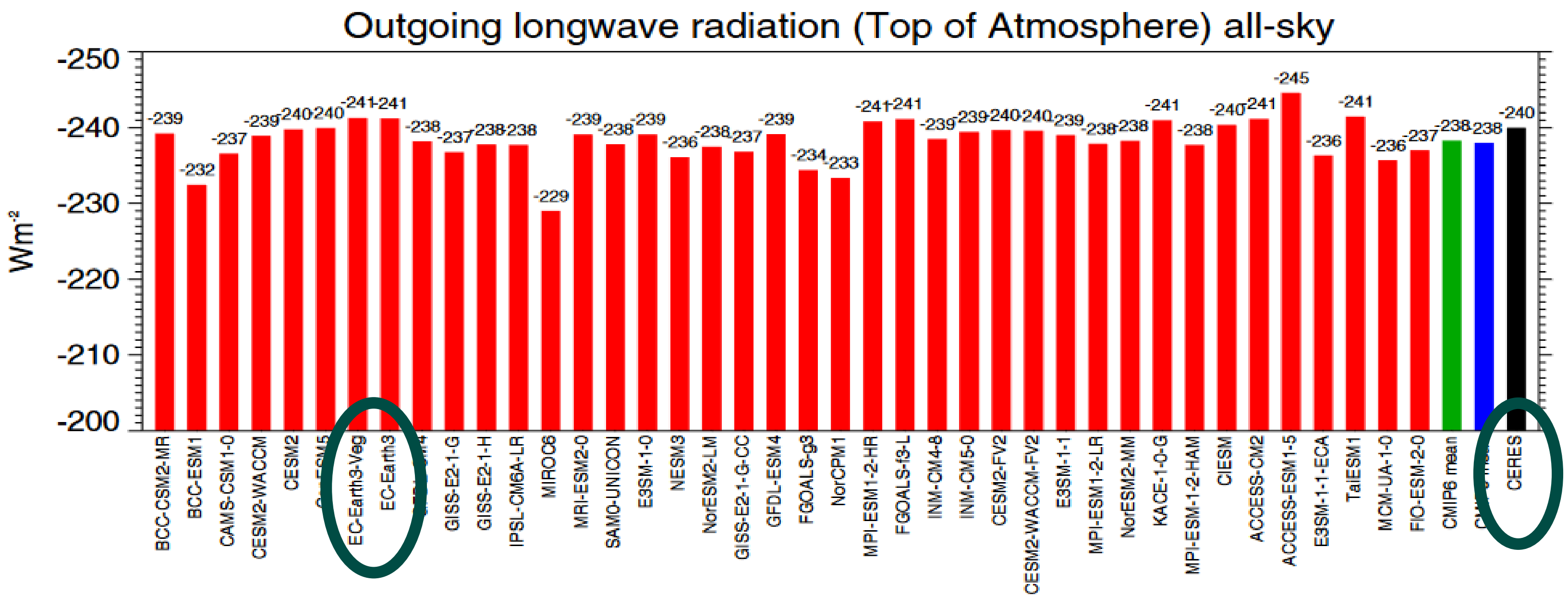
Observed and simulated OLR fluxes

Flux

Radiance

$$F = \int_{100}^{2500} d\nu \int_{0}^{2\pi} d\phi \int_{0}^{\pi/2} d\theta L_{\nu}(\theta, \phi) \cos(\theta) \sin(\theta)$$

Climate models just provide fluxes



ECE OLR = 241 W/m2

CERES OLR = 240 W/m2

From Wild 2020

Only 8 out of 40 CMIP6 models outside the 2σ observational uncertanty

Limitations of the comparison:
1) Climate models are tuned on CERES values
2) Spectral compensating errors

Radiance from models: a new tool for the EC-Earth

COSP module (link between climate model and RTM)

Temperature, humidity, clouds, etc.

σ-*IASI*

Radiances IASI/FORUM

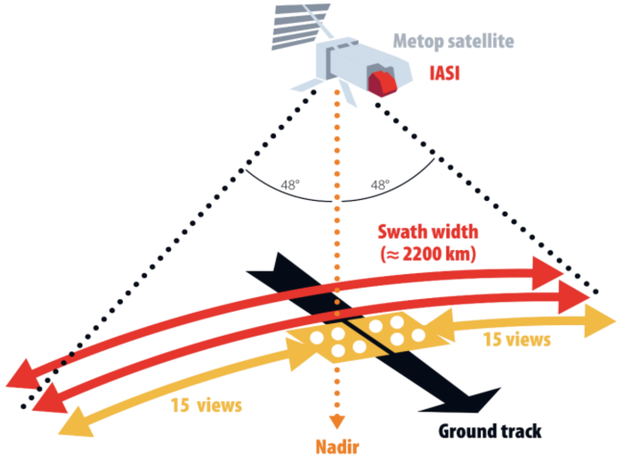
12 years (2008 – 2019) Spectral comparison ECE vs IASI over the ocean

Objectives:

Test climate model and highlight spectral biases

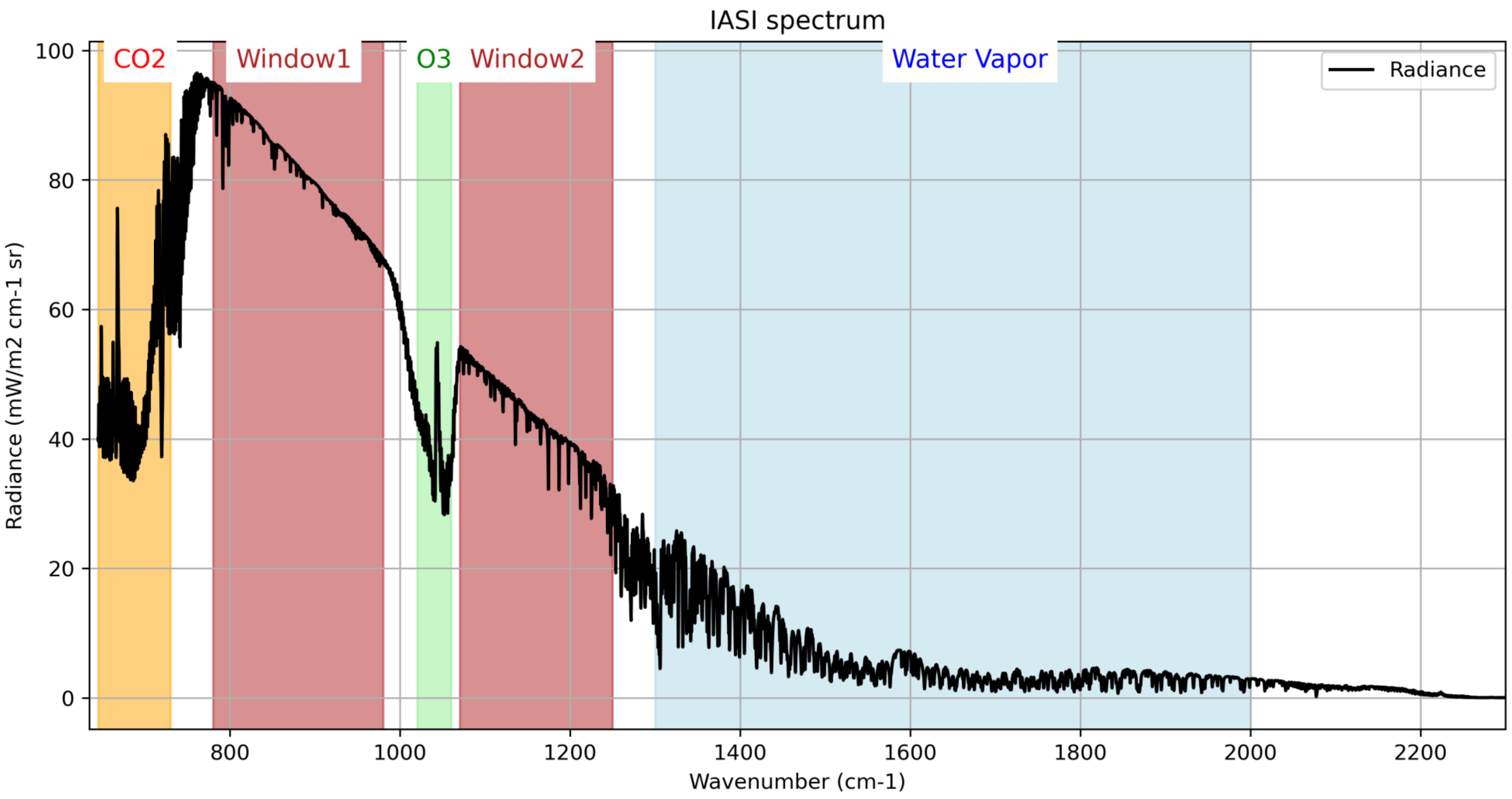
Describe the evolution of climate variables in models and observations

IASI (Infrared Atmsospheric Saunding Interferometer)



- Launch : 2006
- Orbits: 14 orbits per day (equatorial crossing times 9:30 AM and PM)
- Spectral range: 645-2760 cm^{-1}
- Spectral resolution : 0.25 cm-1

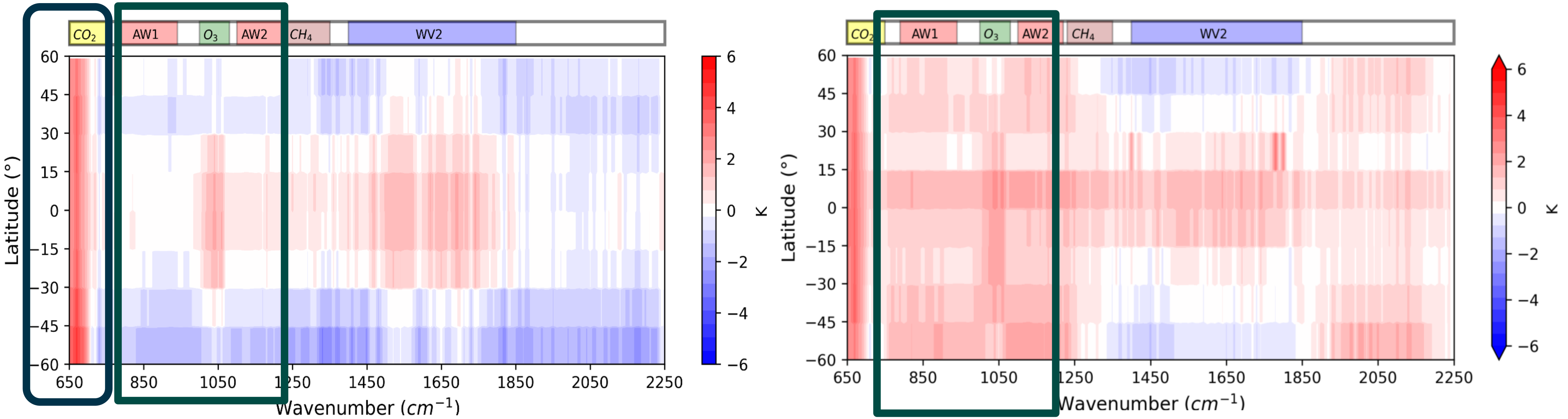
IASI measured spectrum



Spectral biases in the EC-Earth model

ECE-IASI (Ocean 60°N, 60°S)

CLEAR-SKY (2008 – 2019) | ALL-SKY (2008 – 2019)



- Positive temperature bias in stratosphere (CO2 core band, 3.5 K) and Negative temperature bias in troposphere (CO2 wing band, 1 K) (Della Fera et al. 2023 GMD)
- Maximum impact of cloud on radiation falls in the atmospheric windows (AW1, AW2)
- EC-Earth underestimates cloud cover relative to ISCCP observation but overestimates the cloud optical depth. The results is a too strong cloud cooling effect in ECE (Lacagnina et al. 2014)

Spectral trends analysis

$$R(t, b_0, \mathbf{c}, \mathbf{d}) = b_0 t + \sum_{i=1}^{8}\left(c_i \cos\left(\frac{2\pi t}{T_i}\right) + d_i \cos\left(\frac{2\pi t}{T_i}\right)\right)$$

R: spectral radiance for a specific channel

b0, ci, di are the fitting parameters. The terms in the sum represent the periodic oscillations with period Ti. In Ti we include annual (12 months), semi-annual (6 months), and other characteristic atmospheric periodicities of 3, 4, 8, 9, 24 and 36 months (Whitburn et al. 2021)

$$\Delta\mathbf{R}_t = \mathbf{J}_t \Delta\mathbf{x}_t$$

ΔR_t:
Monthly radiance anomalies

Monthly anomalies are computed by subtracting from the monthly radiance mean R_t the monthly long-term mean over the period 2008-2019

J_t:
Jacobian or spectral kernel

$$\mathbf{J}_t = \frac{\partial \mathbf{R}_t}{\partial \mathbf{x}_t}$$

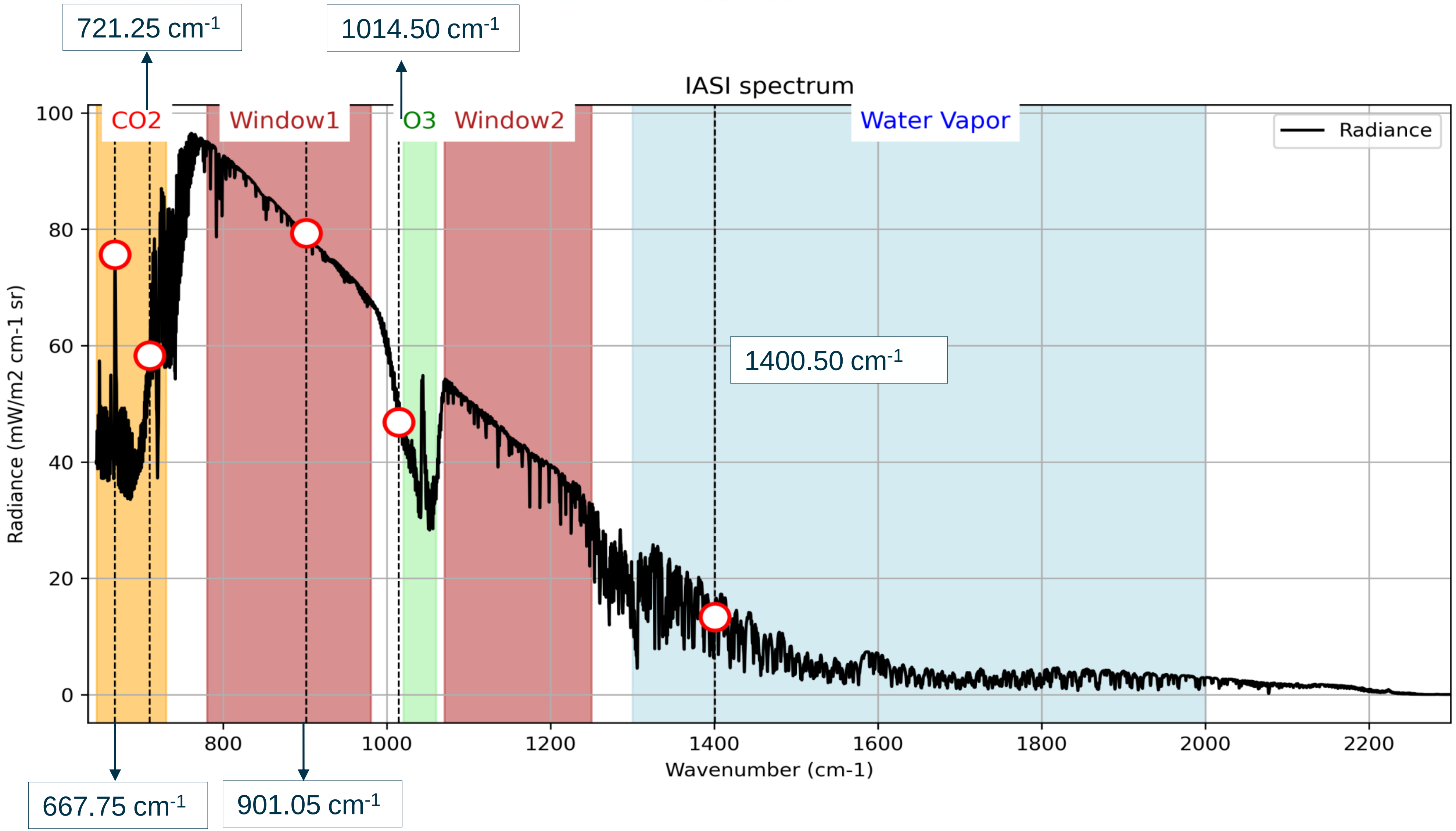
Computed with RTTOV on 17 pressure levels, starting from ERA5 profiles

Δx_t:
Monthly variables anomalies

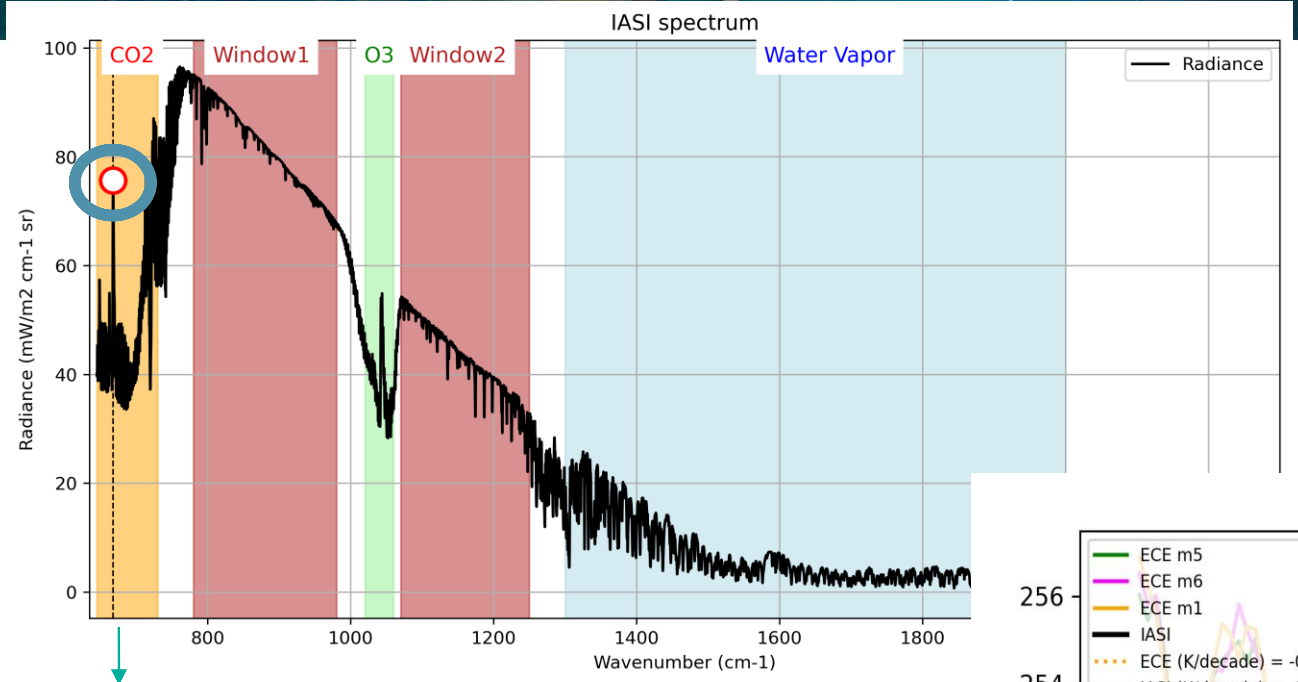
$$\mathbf{x} = \begin{pmatrix} \mathbf{T}(p) \\ \mathbf{x}_{CO_2}(p) \\ T_s \\ \mathbf{q}(p) \\ \mathbf{x}_{O_3}(p) \\ \mathbf{x}_{cloud(p)} \end{pmatrix}$$

$$\Delta R_t = \frac{\partial R_t}{\partial T_t}\Delta T_t + \frac{\partial R_t}{\partial T_{st}}\Delta T_{st} + \frac{\partial R_t}{\partial q_t}\Delta q_t + \frac{\partial R_t}{\partial x_{CO_2}}\Delta x_{CO_2} + \frac{\partial R_t}{\partial x_{O_3}}\Delta x_{O_3} + \frac{\partial R_t}{\partial cloud_t}\Delta cloud_t + Residual$$

Spectral trends analysis: selected channels

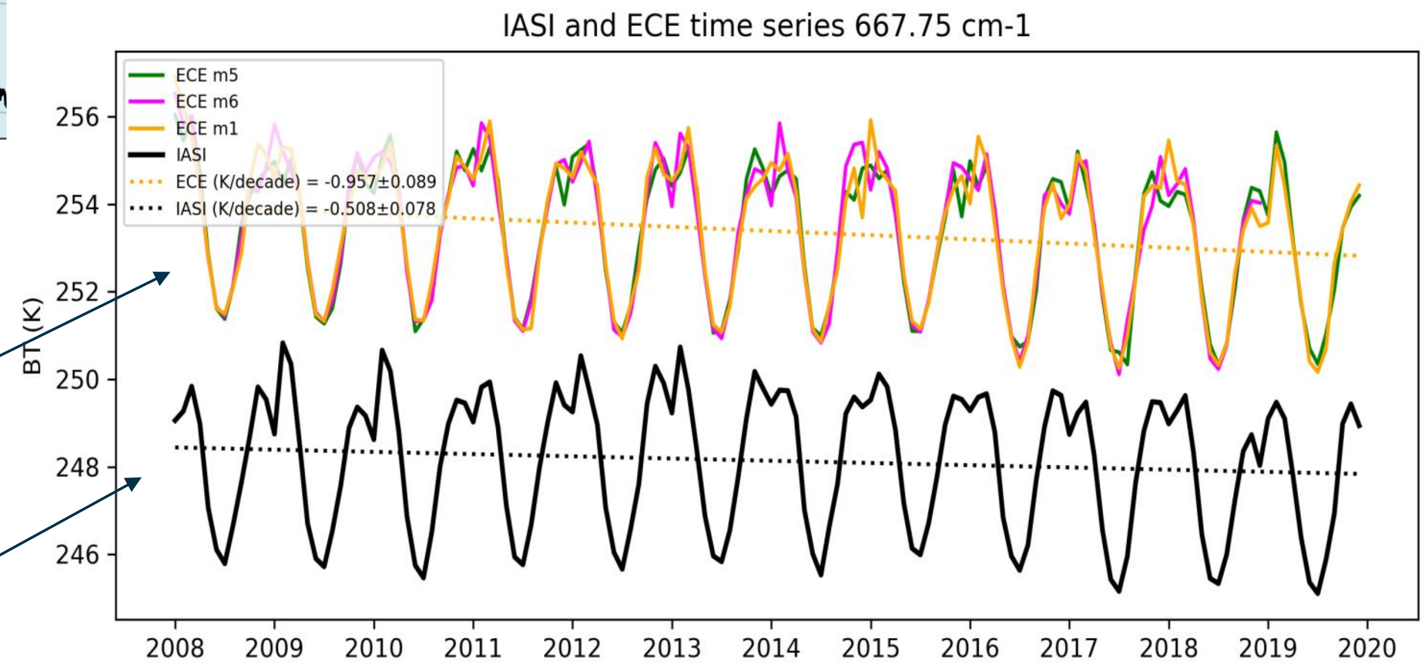


Spectral trends analysis at 667.75 cm^{-1}



667.75 cm^{-1}

1) **WARM BIAS of ECE** climate model
2) **NEGATIVE TREND** both in IASI and ECE with ECE showing a more pronounced negative trend

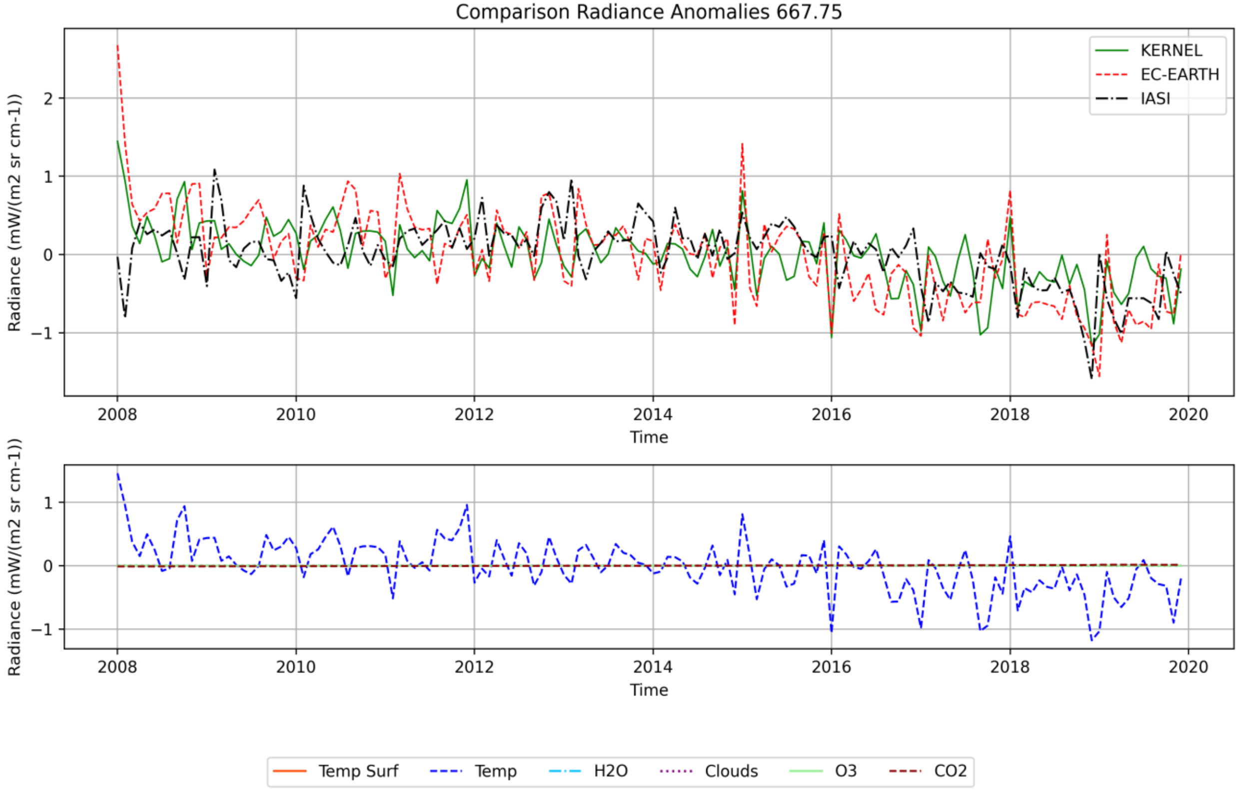


ECE SIMULATIONS

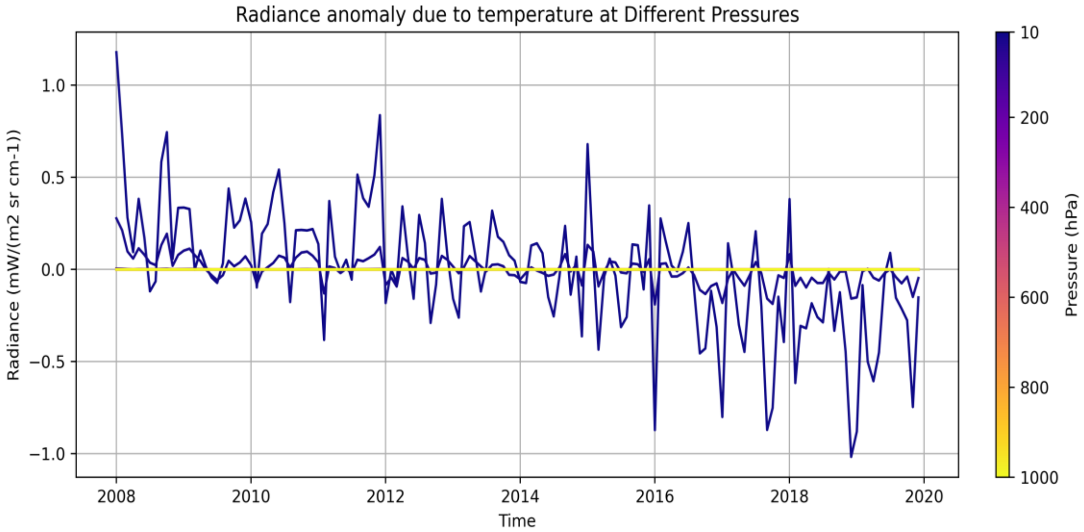
IASI

Spectral trend attribution at 667.75 cm^{-1}

$$\Delta R_t = \frac{\partial R_t}{\partial T_t}\Delta T_t + \frac{\partial R_t}{\partial T_{st}}\Delta T_{st} + \frac{\partial R_t}{\partial q_t}\Delta q_t + \frac{\partial R_t}{\partial x_{CO_2}}\Delta x_{CO_2} + \frac{\partial R_t}{\partial cloud_t}\Delta cloud_t + Res$$



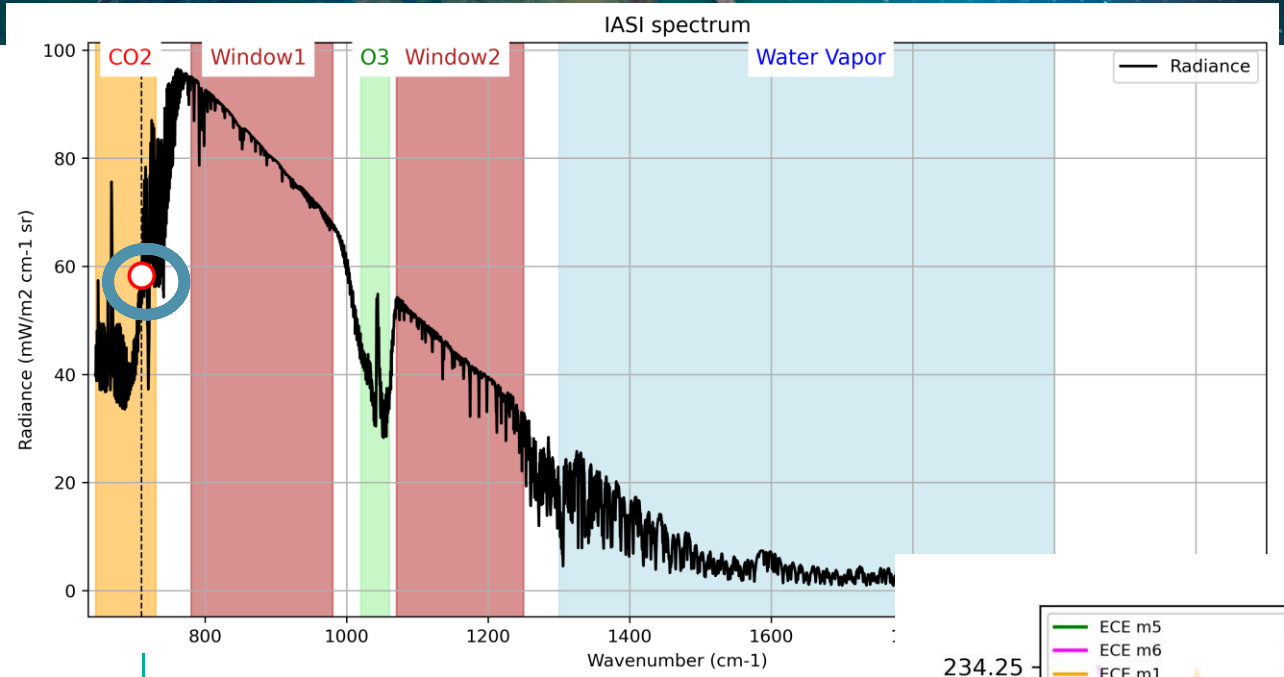
At which atmospheric levels does the temperature contribute the most to radiance trends?



The downward trend can be entirely accounted for by the impact of stratospheric temperatures

Climate signal: **Stratosphere is cooling**

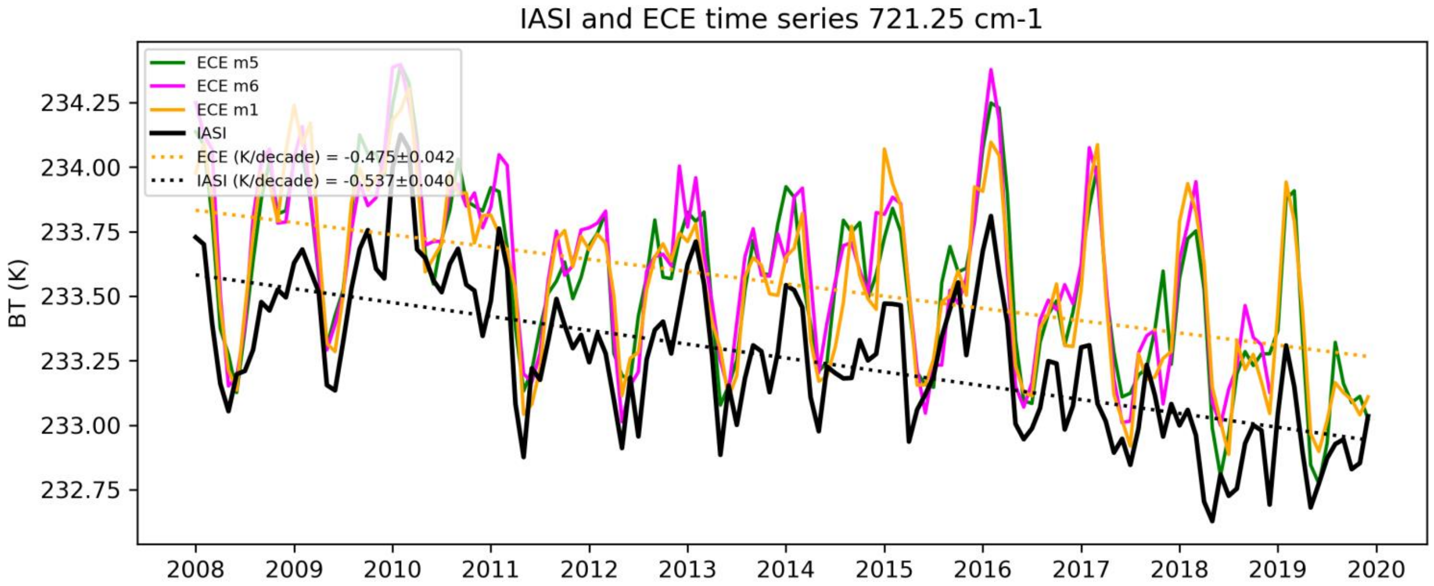
Spectral trends analysis at 721.25 cm^{-1}



721.25 cm^{-1}

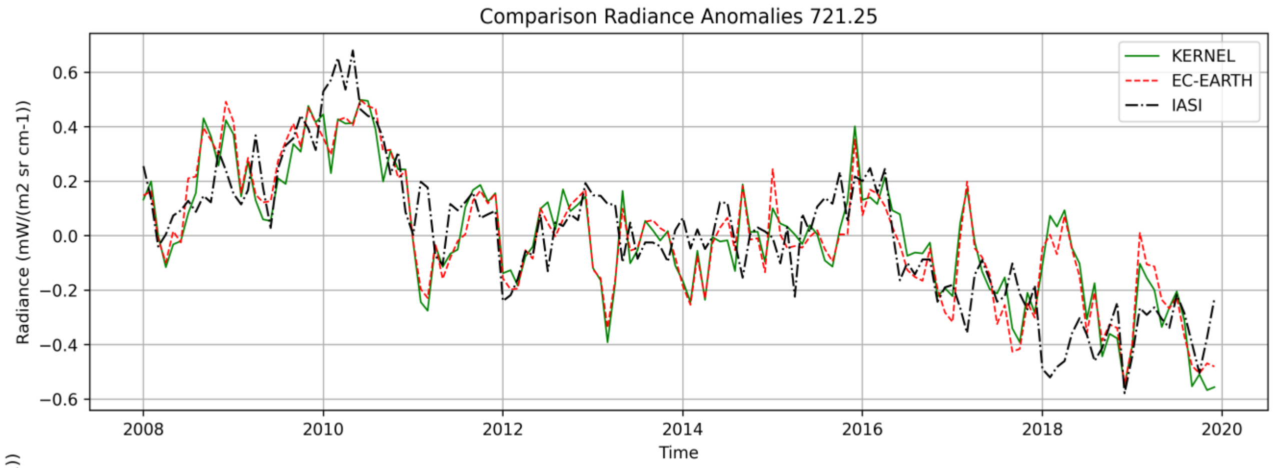
1) **SMALL WARM BIAS** of the ECE model
2) **NEGATIVE TREND**

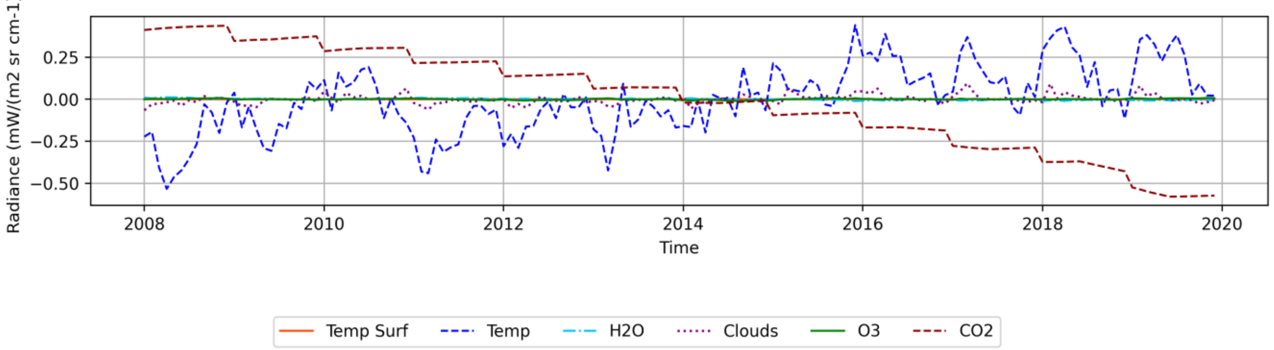
Brightness temperature is decreasing in the wing of the CO2 band.
Good agreement between IASI and ECE trends



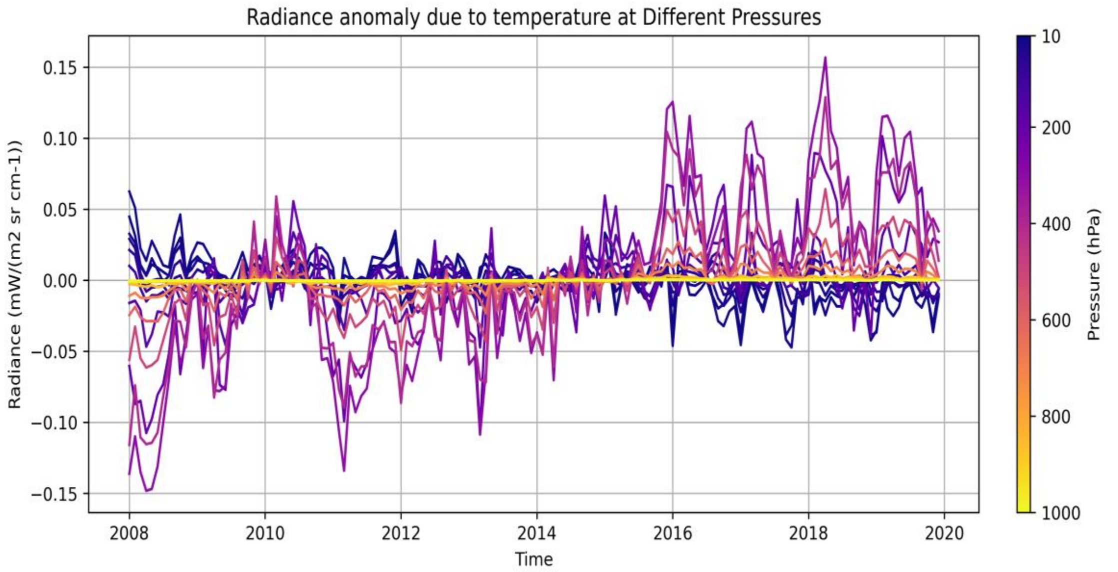
Spectral trend attribution at 721.25 cm^{-1}

$$\Delta R_t = \frac{\partial R_t}{\partial T_t}\Delta T_t + \frac{\partial R_t}{\partial T_{st}}\Delta T_{st} + \frac{\partial R_t}{\partial q_t}\Delta q_t + \frac{\partial R_t}{\partial x_{CO_2}}\Delta x_{CO_2} + \frac{\partial R_t}{\partial cloud_t}\Delta cloud_t + Res$$





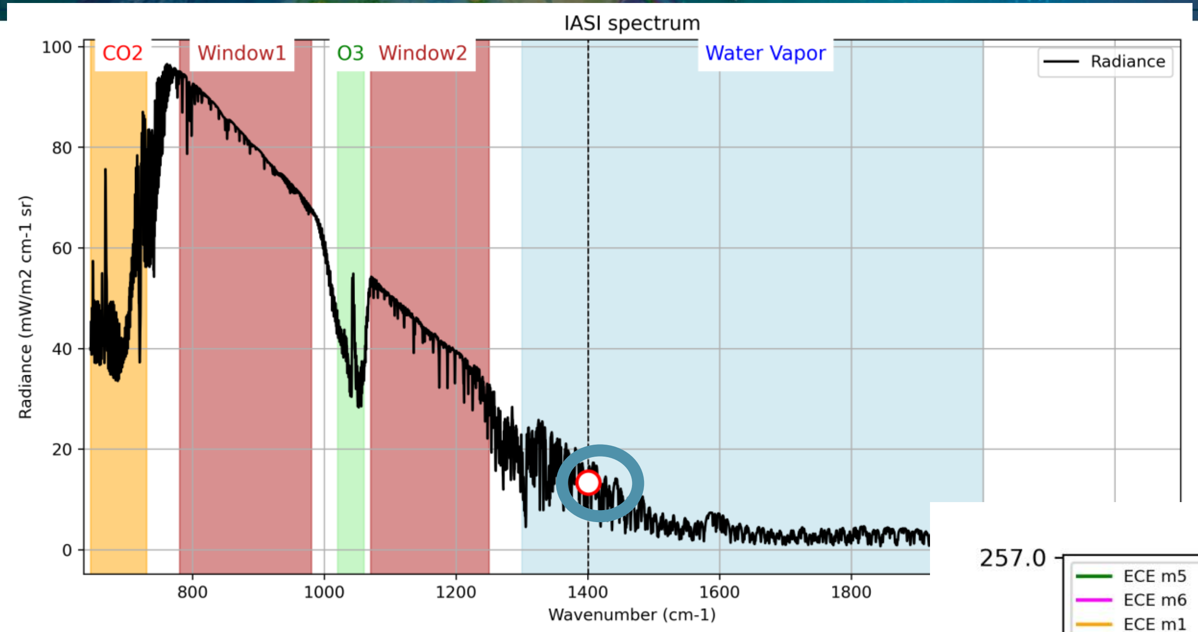
$\frac{\partial R_t}{\partial T_t}\Delta T_t$ at different pressures



The trend is primarily influenced by tropospheric temperature and CO2 concentration. The rising CO2 concentration tends to trap more energy within the system.

High troposphere **is warming** while stratosphere is cooling

Spectral trends analysis at 1400.50 cm^{-1}

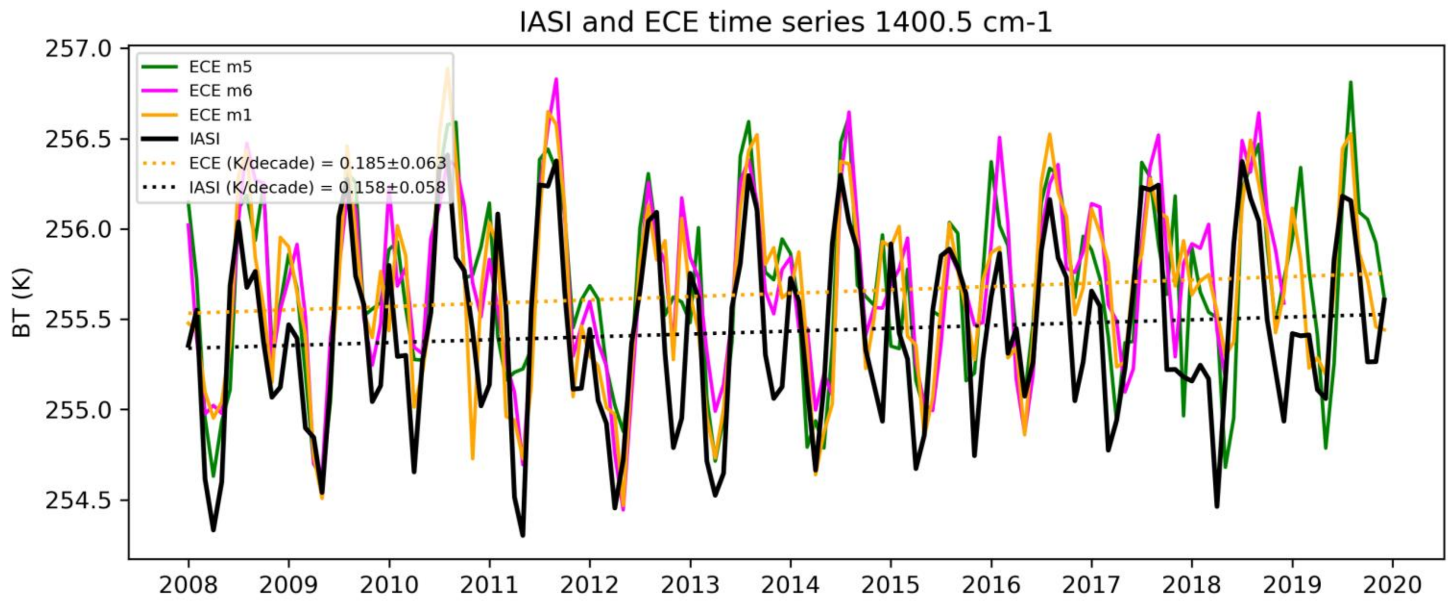


1400.50 cm^{-1}

NEAR ZERO TREND

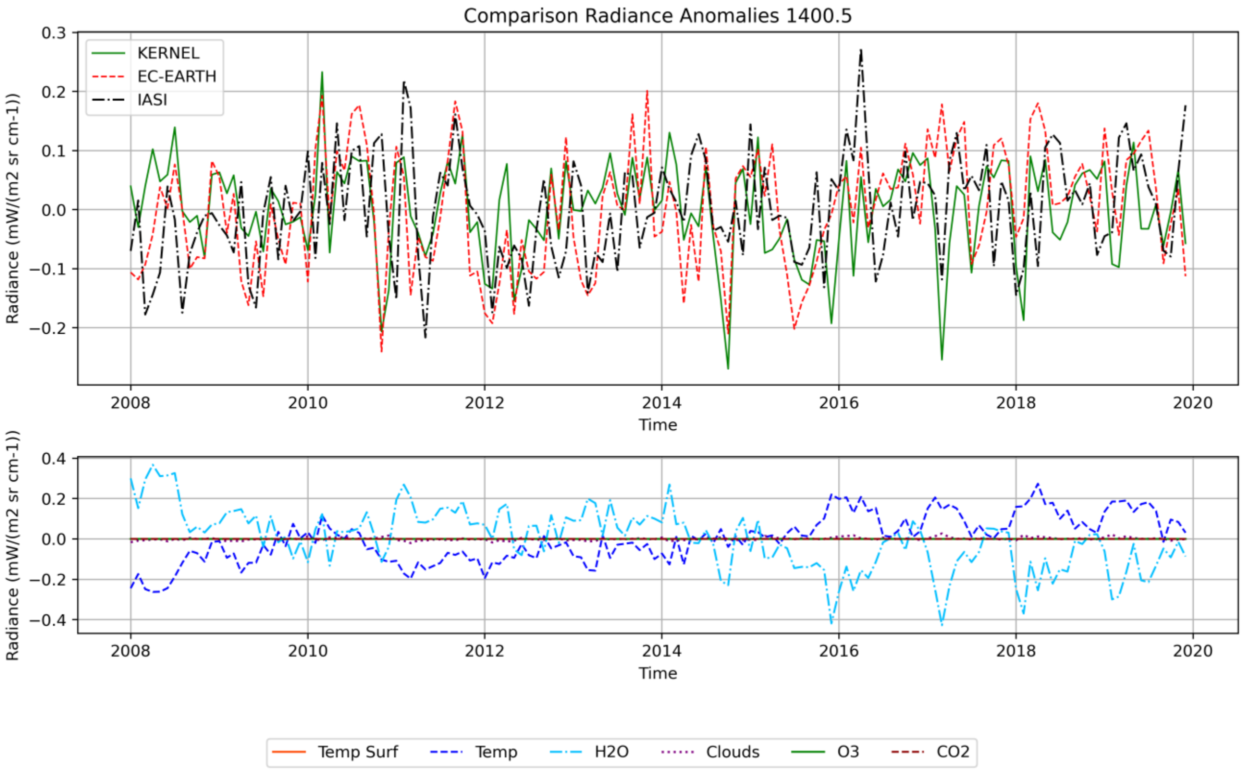
The trend is nearly zero, with a slight positive trend in ECE and IASI measurements.

Positive bias found in ECE simulation



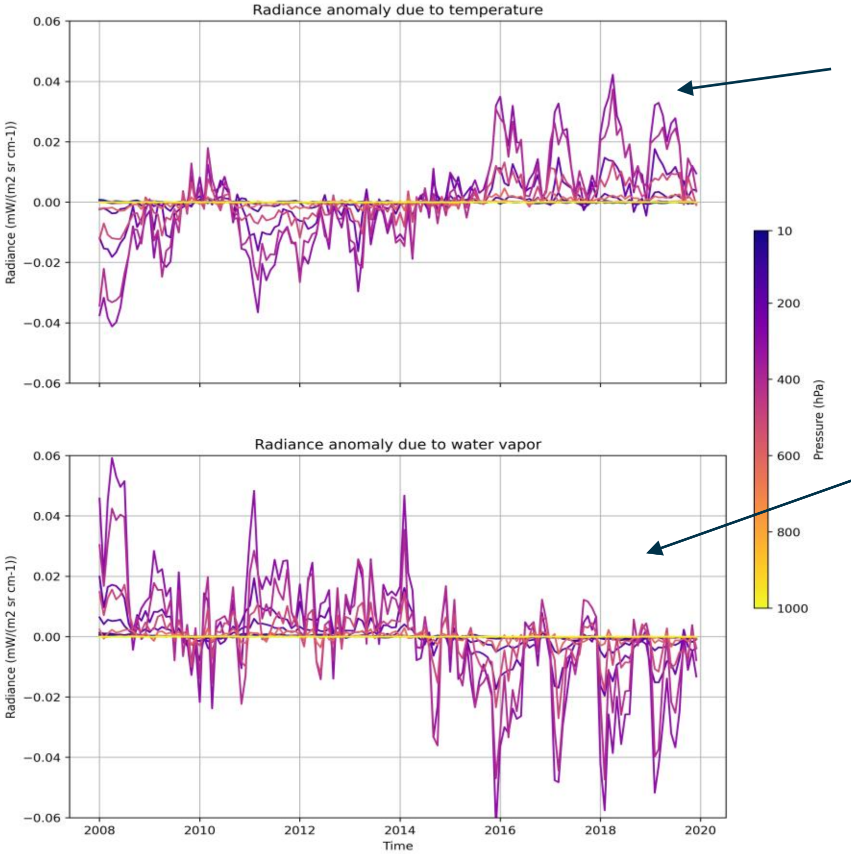
Spectral trend attribution at 1400.50 cm^{-1}

$$\Delta R_t = \frac{\partial R_t}{\partial T_t}\Delta T_t + \frac{\partial R_t}{\partial T_{st}}\Delta T_{st} + \frac{\partial R_t}{\partial q_t}\Delta q_t + \frac{\partial R_t}{\partial x_{CO_2}}\Delta x_{CO_2} + \frac{\partial R_t}{\partial cloud_t}\Delta cloud_t + Res$$



Climate signal: **Water vapor concentration** in the high troposphere is increasing

The trend approaches zero due to the balancing effects of tropospheric temperature and water vapor concentration, which exert opposing influences.



$$\frac{\partial R_t}{\partial T_t}\Delta T_t$$

$$\frac{\partial R_t}{\partial q_t}\Delta q_t$$

CONCLUSIONS

The spectral dimension in climate studies is crucial to highlight the climatology and the evolution of key climate variables, to characterize relevant driving climate mechanisms and to identify biases in climate model simulations.

Through a comparison of mean values over a 12-year period, we have identified model bias in specific spectral bands:

- Positive temperature bias in CO_2 core band (3.5 K)
- Negative temperature bias in CO_2 wing band (1 K)
- Positive temperature bias in Atmospheric Windows (EC-Earth underestimates cloud cover)

From the trend and radiances anomalies analysis we can trace back to the variables that determine the trend and explain the bias:

- The stratosphere is experiencing cooling, consistent across both observations and simulations.
- Even though the troposphere is warming (resulting in more radiation reaching the top of the atmosphere), a negative radiance trend is observed in the CO_2 band, attributed to the increasing concentration of CO_2.
- The effects of water vapor and approaches zero.

Thank you for the attention!

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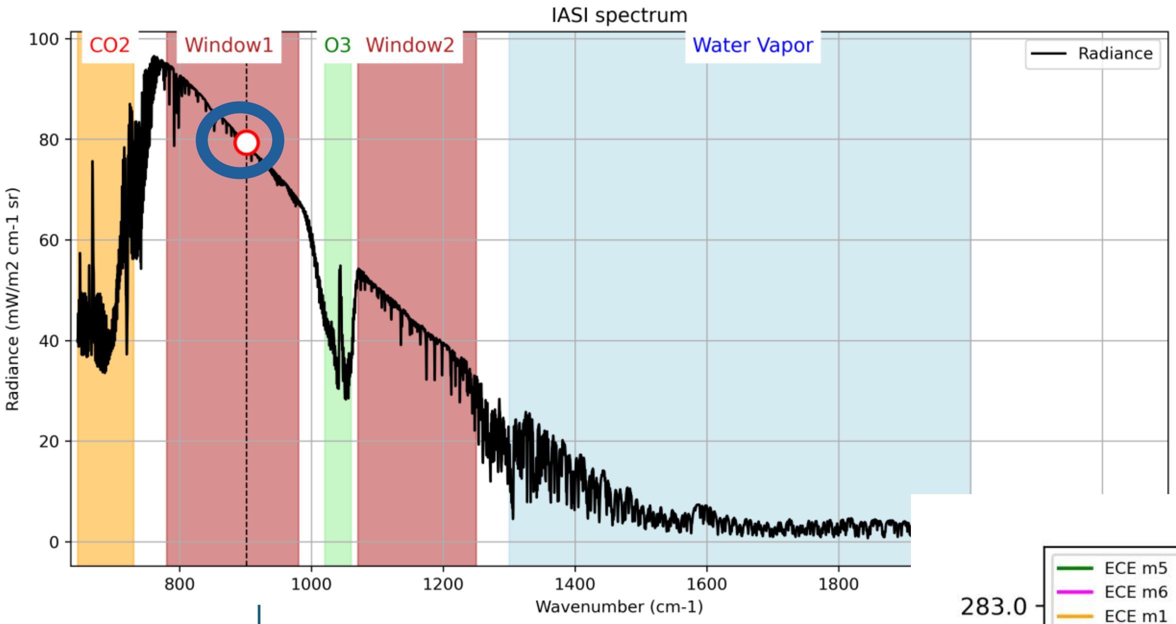
- Even though the troposphere is warming (resulting in more radiation reaching the top of the atmosphere), a negative radiance trend is observed in the CO_2 band, attributed to the increasing concentration of CO_2.
- The effects of water vapor and temperature on radiation balance out in the water vapor bands, resulting in a trend that approaches zero.

Thank you for the attention!

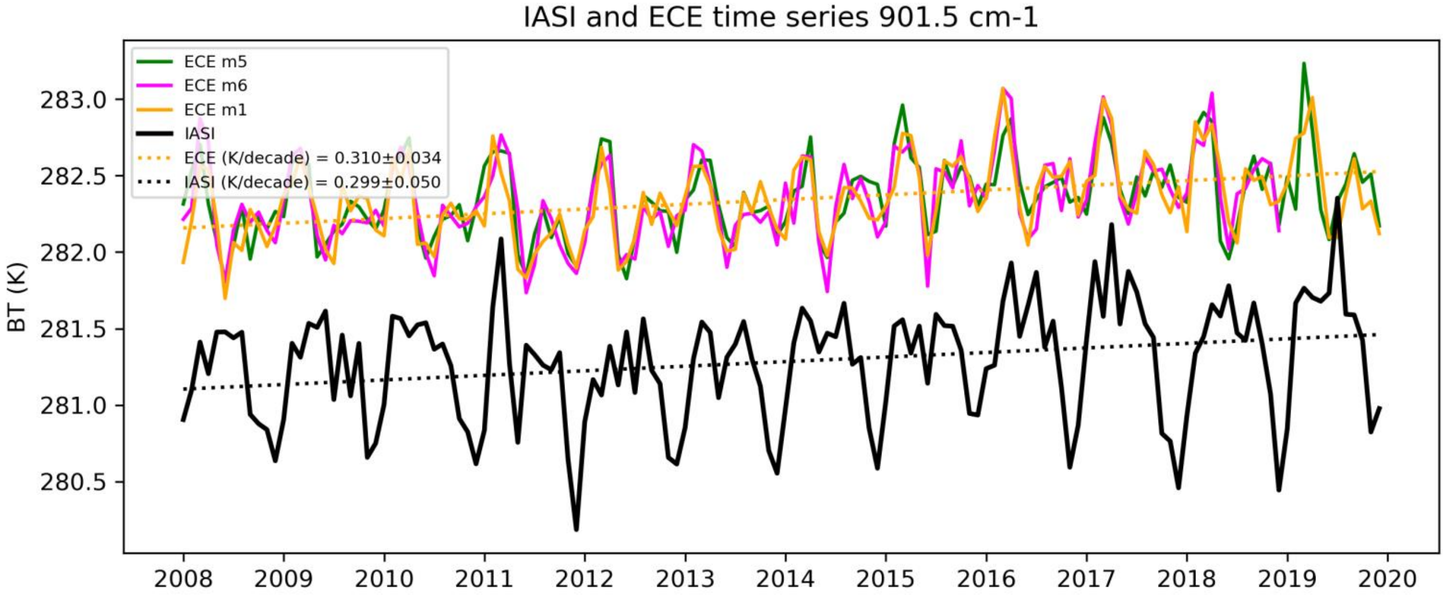
Spectral trends analysis at 901.50 cm^{-1}



901.50 cm^{-1}

POSITIVE TREND

Positive trend in the BTs sensitive to surface
The model exhibits a positive bias, largely attributable to clouds, but the trend aligns closely with that observed in IASI data.



Spectral trend attribution

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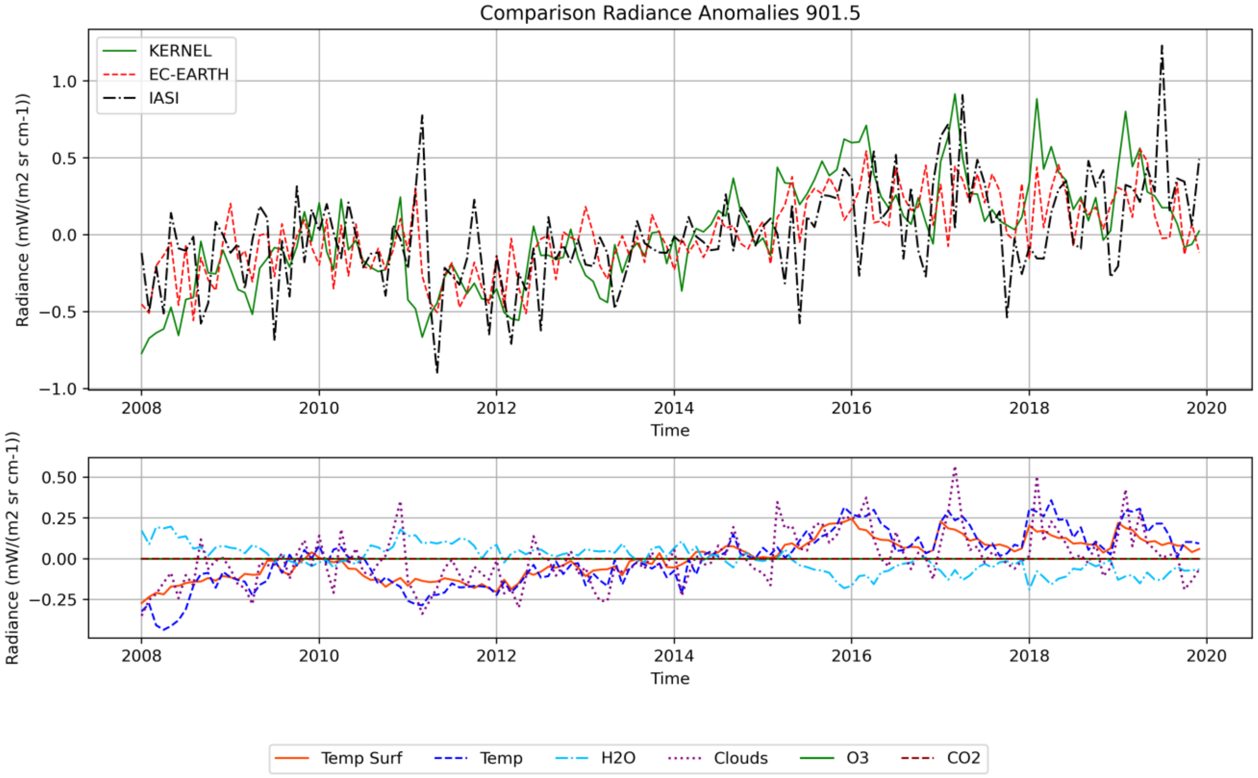
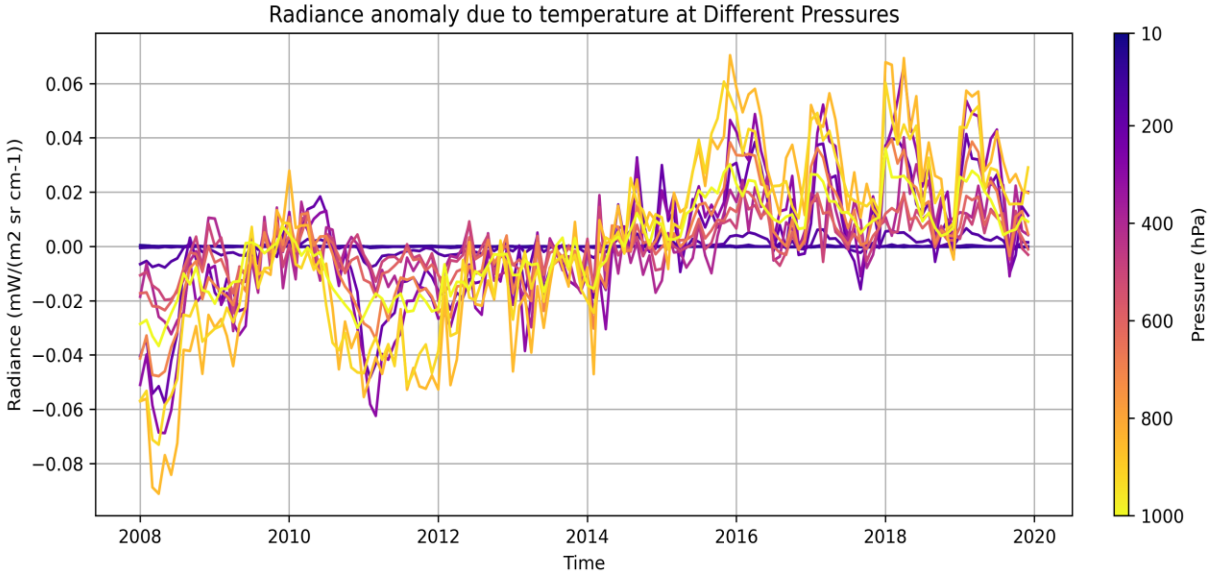
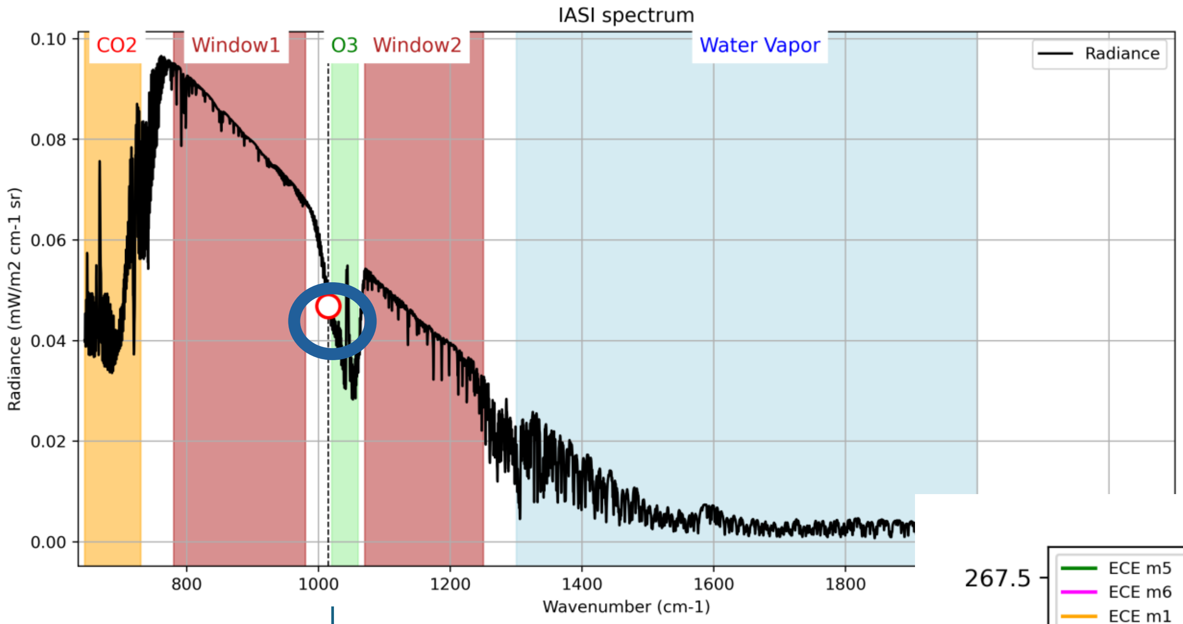




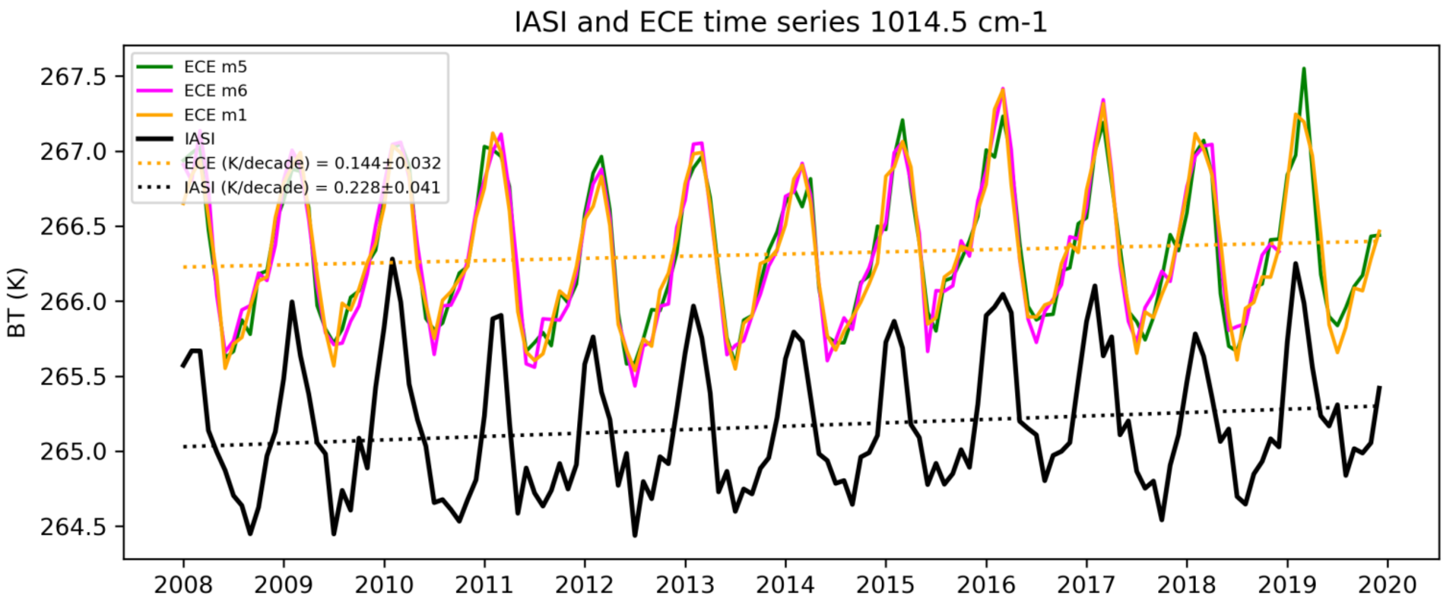
The predominantly positive trend is attributed to tropospheric and surface temperatures. However, water vapor acts to attenuate this positive trend

Climate signal: **Low Troposphere and Surface temperature are increasing**

Spectral trends analysis at 1014.50 cm^{-1}



1014.50 cm^{-1}



Spectral trend attribution

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