Simulations of transit spectra of Hot Jupiters in the wavelength range of the CARMENES infrared channel (0.96-1.7μm)

A. Sánchez-López[1], M. López-Puertas[1], B. Funke[1], P. J. Amado[1], L. M. Lara[1] and M. Salz[2]

[1]Instituto de Astrofísica de Andalucía, CSIC, Spain

[2]Hamburger Sternwarte, Universität Hamburg, Hamburg, Germany

Abstract

Transmission spectroscopy in the primary transit of an exoplanet has proven to be very useful for obtaining information of exoplanet atmospheres from both ground-based facilities and space telescopes. The Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs (CARMENES) instrument has started being operative in early 2016 and here, we explore its capabilities for extracting information about Hot Jupiter atmospheres taking advantage of its ultra-stability, wide spectral interval (0.52–1.7 μm), and high spectral resolution (R=82000). We present some preliminary results of our simulations of the primary transit transmission spectra of HD 189733b in the 1-1.7 μm spectral range where several molecules, such as water vapour, carbon monoxide, carbon dioxide and methane, have strong ro-vibrational bands. Sensitivity studies are presented for the range of expected concentrations of these species, as well as for the expected range of temperature profiles. Our simulations have been performed using the line-by-line Karlsruhe Optimized and Precise Radiative Transfer Algorithm (KOPRA) adapted for exo-atmospheres.

1. Introduction

- HD 189733b is a **Hot Jupiter** exoplanet orbiting an orange dwarf star (K1.5V). It is one of the most studied exoplanets and, in the next months, the **CARMENES** instrument will obtain **high resolution primary transit spectra.** These will be used to **search for atmospheric molecules such us H_2O, CO and CH_4.**
- Here we describe the **tools and methods** we use for the **simulation of its transmission spectra** for **several P,T profiles** and molecule **volume mixing ratios ('vmr'**: abundance of one component of a mixture relative to that of all other components) and present results on: a) **validations** of our radiative transfer calculations; b) show the **effects of changing p-T profiles and vmr**; c) simulations of **low-resolution HST/WFC3 observations** and d) simulations of **high-resolution CARMENES data in the same spectral range.**

Table 1.2	CARMENES Parameters
Wavelength coverage (Δλ)	VIS: 0.52-0.96 μm, NIR: 0.96-1.7 μm
Spectral Resolution (R)	VIS: 94,600; NIR: 80,400
Working Temperature (T_{work})	VIS: 285.00 ± 0.05 K; NIR: 140.00 ± 0.05 K

2. Tools and Methods

2.1 Concept of 'Change in Transit Depth' ([1] and [2]):

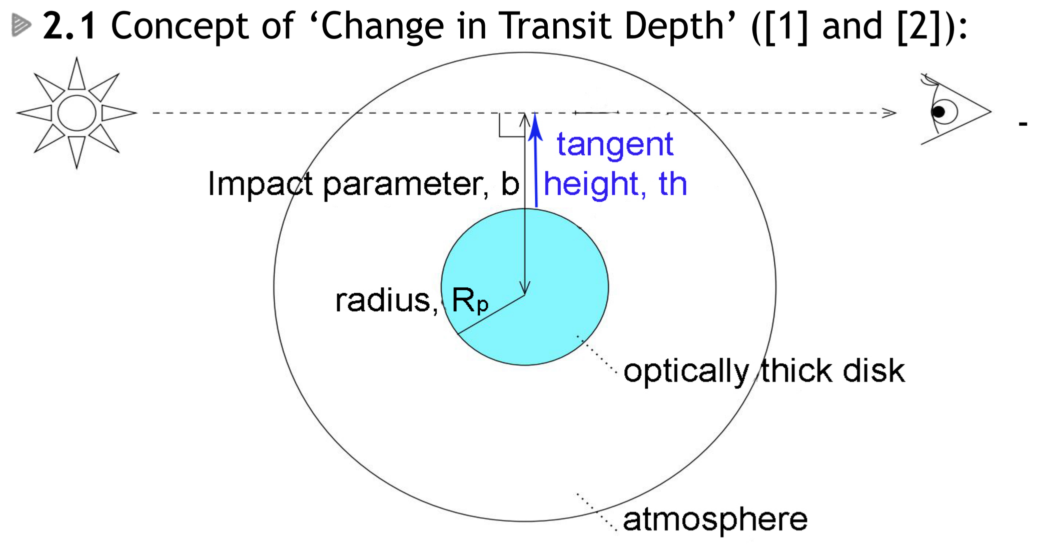


Fig.2 adapted **from [1]:** Transmission of starlight through the planetary limb. The planet itself (in blue, **p > 1 bar**) is optically thick at all wavelengths. The scale is distorted for clarity.

- See [1] for a complete derivation of the magnitude **Change in transit depth**

$$ctd = -\frac{\Sigma_\lambda}{\pi R_s^2}, \quad \text{Eq.1}$$

where the atmospherical absorption is:

$$\Sigma_\lambda = \int_{R_p}^{b_{max}} 2\pi b db \left[1 - e^{-\tau_\lambda(b)}\right] \quad \text{Eq.2}$$

and b = R_p+ tangent height (**'th'** above the "solid surface", see Fig.2).

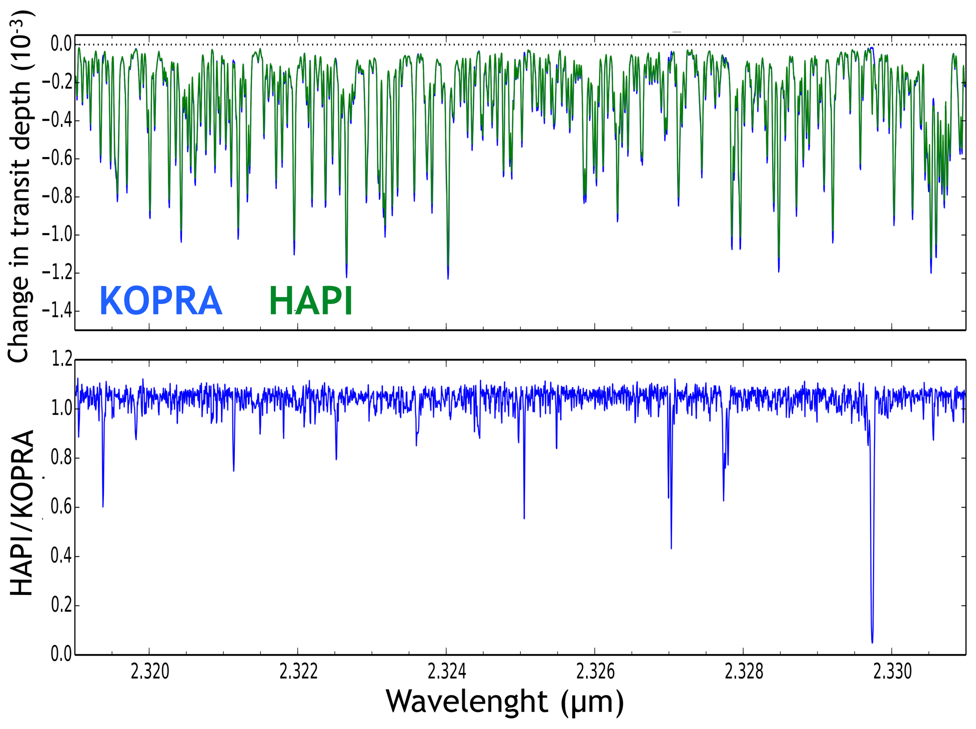
2.2 Karlsruhe Optimized and Precise Radiative Transfer Algorithm, **KOPRA** [3]:

- Line-by-line radiative transfer model
- Kuntz implementation of the Humlicek algorithm for the Voigt line-shape.
- Interface for generic NLTE-model GRANADA (switched off for this work)
- Supports vibrational and rotational non-LTE
- Computes spectra and Jacobians for LTE and non-LTE
- User-defined parameters:
  - Accuracy of absorption coefficient calculation (and number of lines)
  - Accuracy of frequency integration
  - Interfering species to be included (and altitude range)

3. Comparison between KOPRA and a HAPI-based code calculations

- Hitran Application Programming Interface (HAPI): (a) Line-by-line data from HITRANonline; (b) computes high-resolution spectral simulations (absorption coefficients and radiance, transmission and absorption spectra); (c) Choice of **Instrumental Line Shape (ILS)** to simulate experimental data.

Fig3: Comparison between both codes for a **water vapor** simulation in an isothermal atmosphere 1500K with a vmr of $1 \cdot 10^{-4}$ and a boxcar ILS (0.01 cm^{-1}).



- Good agreement between KOPRA and HAPI calculations. Both codes calculate almost the same spectral transit depth.
- Differences:
  1. Absorption base level: Due to different atmospheric grids and R_p values used.
  2. Missing line in HAPI code (2.329μm).
  3. Small differences (<5%) in transit depth of weak absorption lines.

4. Comparison between spectroscopic databases

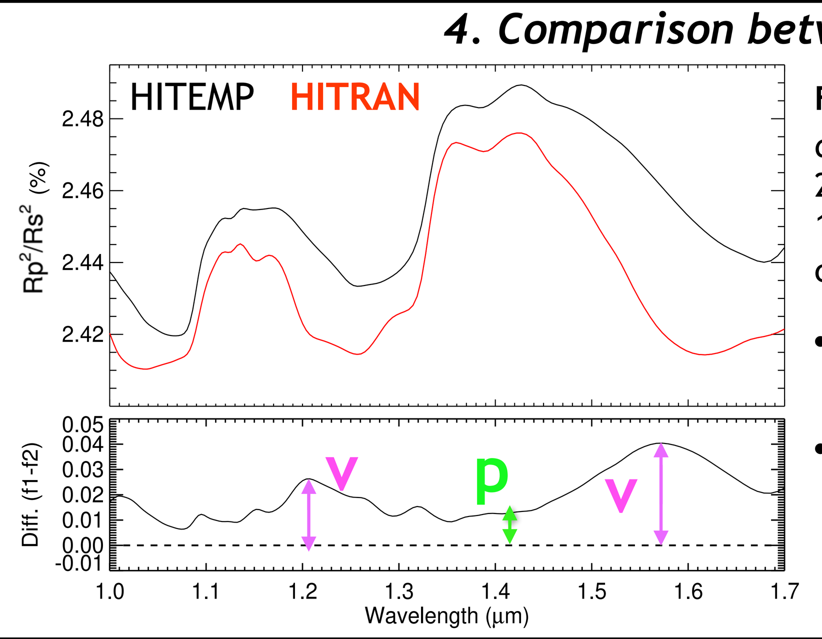


Fig4: Comparison of the spectrum ratio (-Eq.1 + R_p^2/R_s^2, as described in [1]) obtained using the HITEMP 2010 and HITRAN 2012 spectroscopic databases. An isothermal atmosphere at 1500K, H_2O vmr of 1×10^{-4} and a gaussian ILS of FWHM=100 cm^{-1} have been used.

- **HITEMP includes more lines and therefore is more absorbent.**
- Note that **the peak to valley amplitude is significantly reduced using HITEMP** due to stronger absorption in the valleys (pink arrow) with respect to the band heads (green arrow).

5. Modeling the HST/WFC3's HD 189733b Transmission Spectra

- Theoretical atmospheric models used to simulate the HST/WFC3 (FWHM=100 cm^{-1}) data (based on [4]).

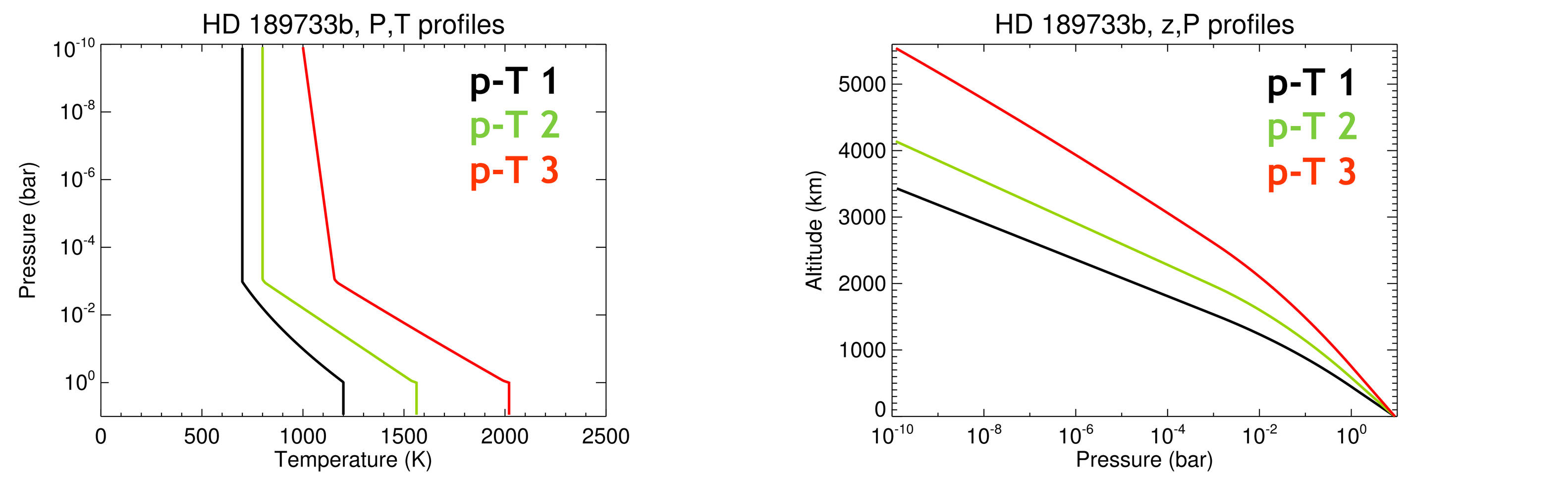
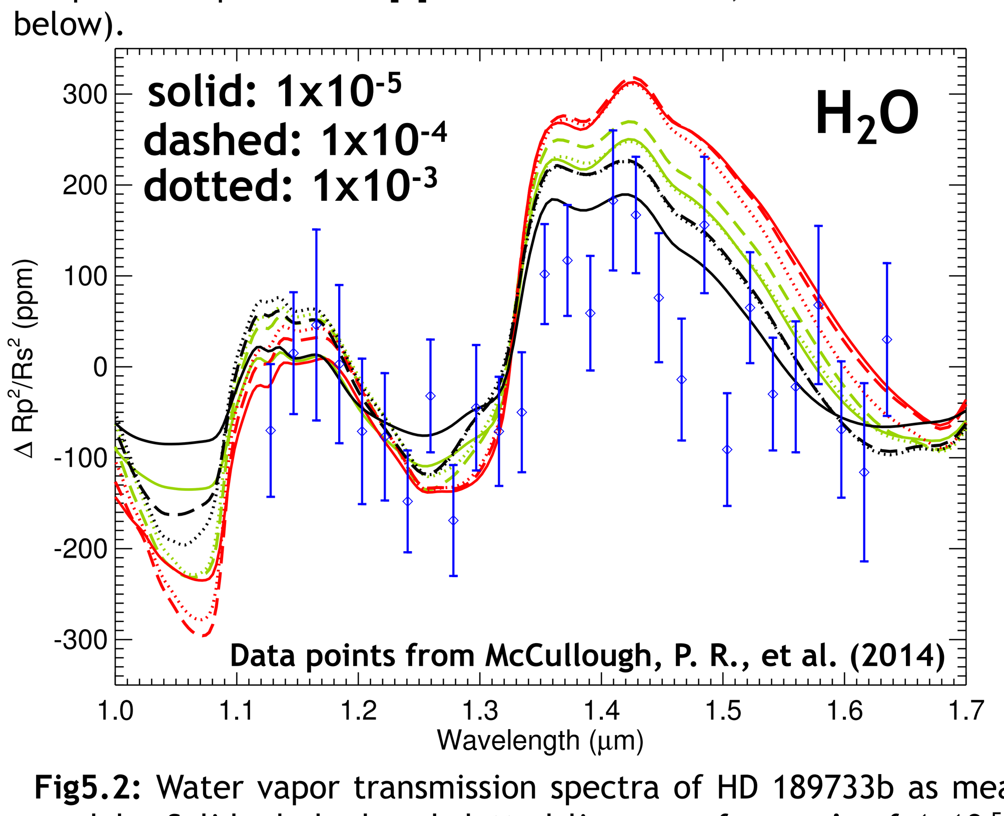


Fig5.1: Atmospheric p-T profiles used in the simulations in Figs 5.2, 6.1 and 6.2. Profiles 2 and 3 similar to dayside temperature profiles in [4]. Profile 1 is colder, more suited for the HST/WFC3 transmission measurements (see below).



- Dayside **P,T profiles of [4]** are **too hot to match the HST/WFC3 transmission data** for the planetary limb atmosphere. Maybe this is partly because of the use of different spectroscopic linelists.
- The **best fits** to the data are given by the **colder profile** and vmr of 1×10^{-5} (**solid black line**) or vmr of 1×10^{-4} (**dashed black line**). A vmr of 6.3×10^{-6} as suggested by [6] might be too low to reproduce the peak-to-valley amplitude (perhaps due to different linelists).
- Large **cross-talk between** the **p-T** profile and the **H_2O abundance** (see Fig.6.2).

Fig5.2: Water vapor transmission spectra of HD 189733b as measured by HST/WFC3 compared to our theoretical models. Solid, dashed and dotted lines are for vmr's of 1×10^{-5}, 1×10^{-4}, 1×10^{-3}, respectively. Colors indicate the temperature profile as in Fig.5.1.

6. Simulation of the transmission as seen by CARMENES

- Model atmospheres in Fig.5.1 are used to simulate the transmission spectrum with the CARMENES high spectral resolution (see Table 1.2) in order to explore its capability to a) **identify trace gases as CO,** and b) **constrain** the **p-T** and H2O **abundance.**

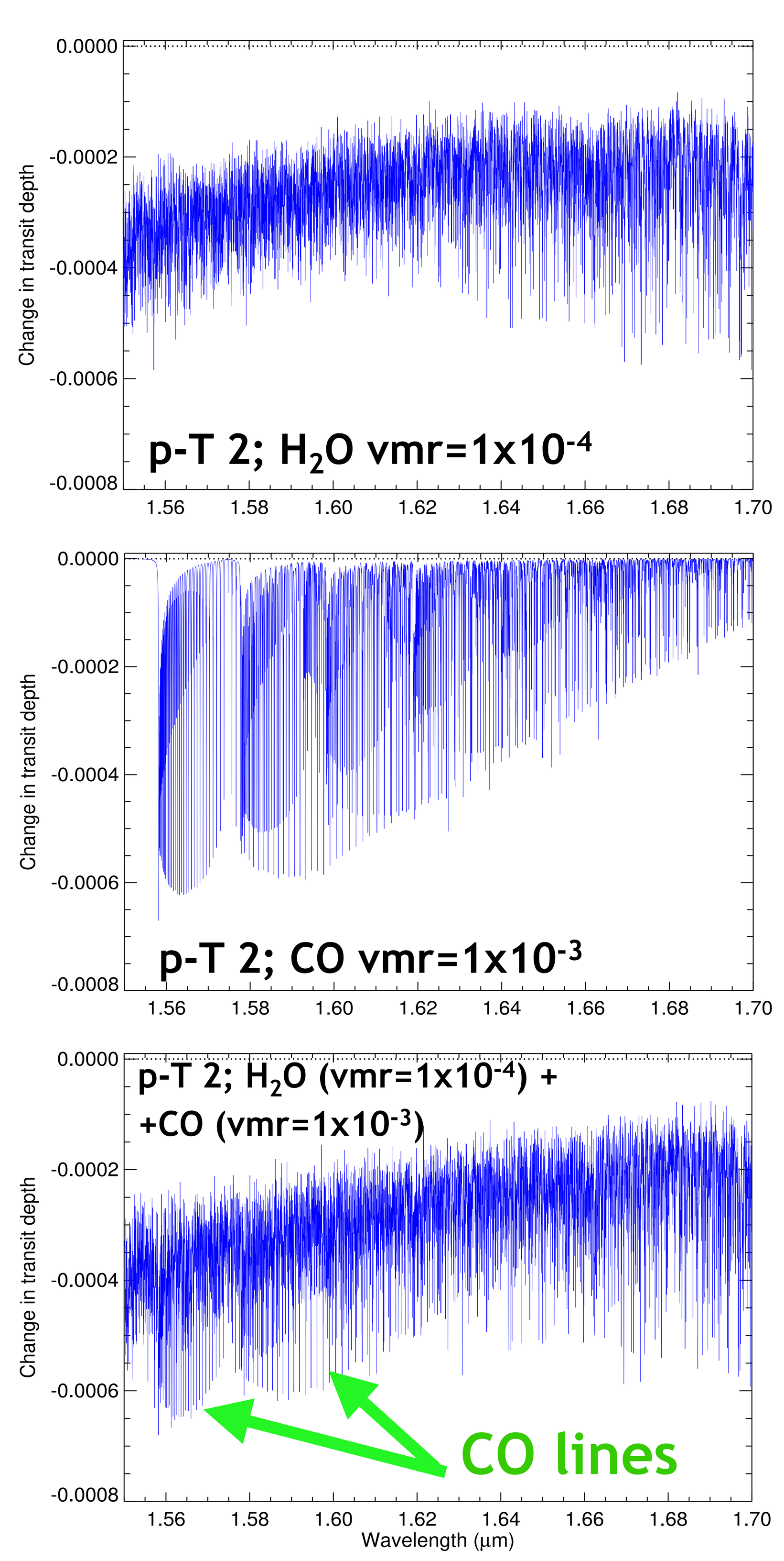


Fig6.1: Simulated transmission spectra of HD 189733b at the CARMENES spectral resolution of 0.1 cm^{-1} for the intermediate p-T profile 2, H_2O vmr of 1×10^{-4} and CO vmr of 1×10^{-3}.

- The CARMENES high-resolution transmission spectrum likely allows us to **identify CO lines along with water vapour.**

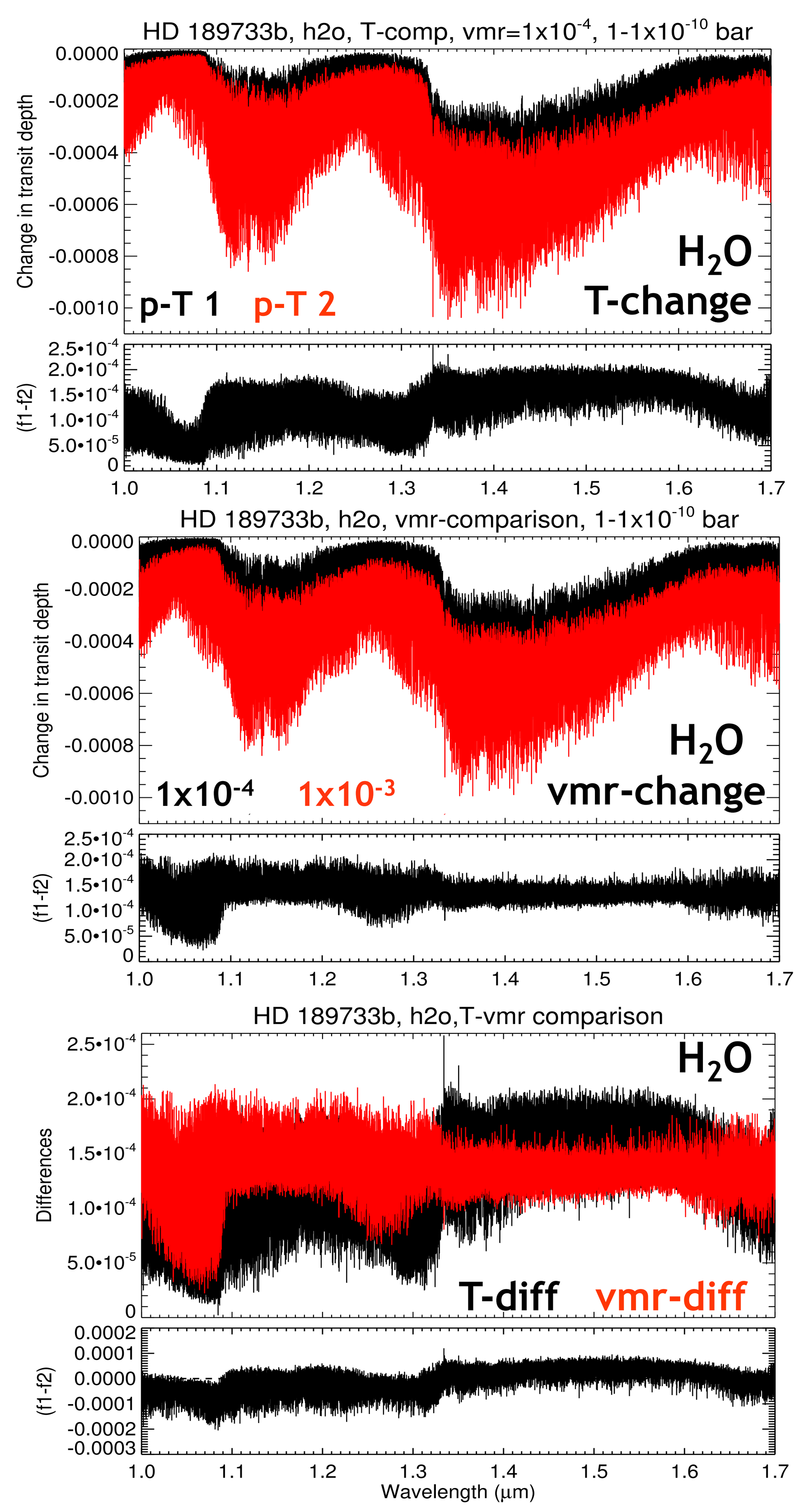


Fig6.2: Analysis of the effect of changing temperature or H_2O volume mixing ratio.

- Changing **vmr increases the absorption uniformly.** Changing T has a **stronger impact on the deepest absorption band.** This could help decrease the huge **cross-talk between T** (several hundred K) **and H_2O abundance** (spanning 3 orders of magnitude).

7. Conclusions and Future Work

- **Reduction of the the peak-to-valley** amplitude using **HITEMP 2010 compared to HITRAN 2012.**
- **Dayside T,P profiles from [4] are too hot to match** the HST/WFC3 observations of the **limb atmosphere.**
- The **best fits** to the **HST/WFC3 data** are given by the **colder p-T profile** and **H_2O abundance of 1×10^{-5} or 1×10^{-4}.**
- The large **cross-talk** between the **p-T profile** and **H_2O abundance is reproduced** in our **HST/WFC3 simulations.**
- **Molecular detection of CO** in the high-resolution transmission spectra of CARMENES might be **possible.**
- **CARMENES** might **help decrease the large cross-talk** between T and water vapour abundance.

Future Work:
- Study **different P,T profiles** to find the **best fits to HST/WFC3 data.**
- Characterize the **telluric contamination of the Earth's atmosphere** and its removal.
- Perform similar studies for other exoplanets, such as **HD 209458b.**

8. References

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