Interactive comment on "TRAPPIST-1 Habitable Atmosphere Intercomparison (THAI). Motivations and protocol" *by* Thomas Fauchez et al.

Daniel D.B. Koll (Referee)

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This is an interesting proposal for a exoplanet GCM (global climate model) intercomparison. I am a fan of the general idea and the project's open nature – given the booming interest in the field, model intercomparisons such as this one will be playing an important ongoing role. I also think the experimental setup is generally appropriate, but clarifications on the overall design and on some of the modeling choices would be helpful. See below.

We would like to thank the reviewer Daniel D.B Koll for his kind words and his helpful and insightful review of our manuscript. We have deeply considered the points brought up by the referee in the revisions to paper. Our reply is detailed below.

***Major comments: - What plans do the authors have for an online presence to share necessary input files as well as model outputs? In particular, it is not clear to me how participants who are interested in submitting a model would obtain the necessary host star spectrum. I would also strongly encourage the authors to make their main out- put netcdfs publicly available (=not on a personal/professional website) so that model developers or graduate students will still be able to access the results five years from now. Github sounds like an easy option. Similarly some of the co-authors, e.g., the ROCKE3D team, have been doing great work in making their files available to the rest of the community, which might also be feasible here.**

We have set up this repository hosted at NASA: https://thai.emac.gsfc.nasa.gov/dataset/thai

The outputs from all the models in the intercomparison will be hosted there. The stellar spectrum used will only be in the dataset. Data will be accessible to download by anyone, and upload will be possible with authorized IP address for scientists whose want to contribute to the intercomparison with their own GCM.

We have added a statement about this in the revised manuscript:

"THAI model outputs and the TRAPPIST-1 stellar spectrum will be progressively uploaded during the intercompaison and will be available at : https://thai.emac.gsfc.nasa.gov/dataset/thai"

- To understand the likely-important impact of cloud parameterizations, what about a version of Hab1/Hab2 that still includes water vapor/latent heating effects but disables the radiative effects of clouds (see Yang et al 2019)? This setup should be easy to implement in most GCMs.

This is a very interesting suggestion that will help to interpret our differences due to cloud physical processes without having the radiative effects of clouds. However, our objective is not to fully understand all the differences between the models but to understand how the first order differences impact the observables from synthetic spectra. The co-authors have debated considerably to arrive at the five configuration chosen for this intercomparison. At this point we would rather not add more required configurations to this intercomparison. However, time permitting amongst participating parties, we encourage the exploration of different configurations and parameters not explicitly include at present.

We add this statement before the conclusion:

"Note that while additional simulations with a simple Newton cooling model, a 1-D column model, or with cloud radiative effects disabled would help to better understand the differences due to the dynamical cores and cloud physics, they will also dramatically increase the computationnal time, amount of data and effort. Yet, THAI aims to be easily reproducible and not time consuming in order to reach many GCM user groups. The five simulations propose in THAI should be enough to understand the main differences between the GCMs and their impact on the observable. THAI could also be used as a benchmark for a future GCM intercomparison that will specifically aim to understand the finest differences between the models."

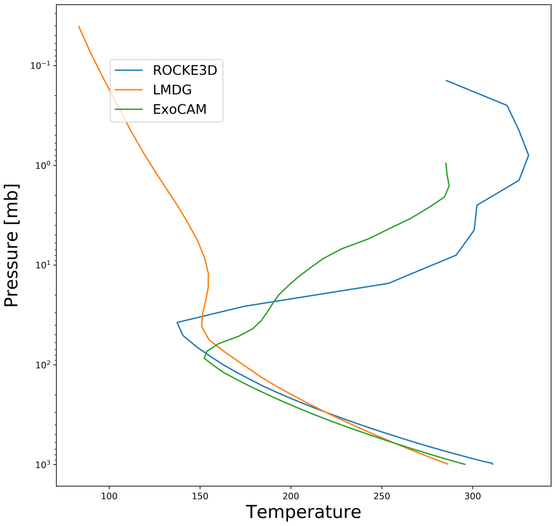
Also a THAI workshop is currently being planned around fall 2020 to discuss about THAI results and their perspectives.

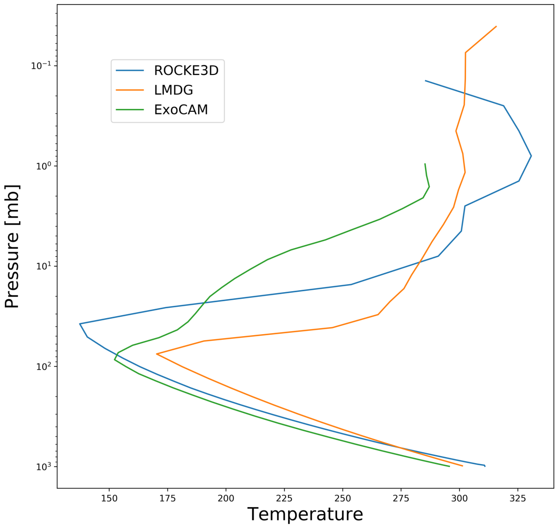
- I know that this is not easily done with many GCMs, but adding a 1D single col- umn case to the intercomparison would be very useful for isolating differences due to clearsky radiative transfer. These differences can be far from negligible (see Yang et al, 2016), and at least some of the models in this study should be able to run in 1D. Even if a 1D intercomparison isn't feasible here, calling for such an option would at least be a useful sign to model developers.

We agree with referee #1 that comparison using a 1D single column model could be useful to isolate difference due to clearsky radiative transfer. However, all GCMs do not have a 1d single column version. Also the cloud-free cases Ben1/Ben2 can also allow such radiative transfer comparison.

- For the pure N2 case, do the authors still want models to include N2-N2 collision- induced absorption or is this supposed to be an atmosphere that is completely trans- parent? For an intercomparison, the latter case would presumably be interesting. How- ever, I'd think that a zero-opacity atmosphere might easily lead to numerical issues (first, some radiation codes just crash if run with zero optical thickness; second, a zero- or low-opacity atmosphere might become extremely warm, because it is still heated by sensible heat fluxes on the dayside but can't easily shed the heat via radiative cooling, leading to potential further numerical issues). If such issues arose during the study, it would be worth discussing how participating models have dealt with them.

Yes we have included N2-N2 CIA in our simulations otherwise the atmosphere is indeed transparent and numerical issue arise. Also, we have noticed that when lacking an efficient radiative coolant in the high atmosphere like CO_2, N_2-N_2 mid-IR absorption warms the stratosphere and creates an inversion. The figure below shows a comparison between LMD-G, ROCKE-3D and ExoCAM average temperature profiles. In the left panel mid-IR N_2-N_2 was omitted in LMD-G, but included in the two other models. In the right figure N_2-N_2 has been included in the three models and we can see the temperature inversion occurring between 30-100 mb.





In section 3.1, when presenting Ben2 we have added: *"Note that N_2 -N_2 CIA should be included to avoid a fully transparent atmosphere and associated numerical instabilities."*

***Minor comments: - Figure 1, bottom row: add global-mean albedos somewhere on this figure?**

- Page 7: the intercomparison fixes albedos, but what about sea ice dynamics?

There is no dynamic ocean nor dynamic sea ice included since only ROCKE-3D is able to use such parameterizations.

- Page 7: do the Hab1 and Hab2 cases with a zero-ocean-heat-transport slab ocean reach steady state on the nightside? In particular, does the sea ice thickness asymp- tote to a finite value?

This is a level of details we reserve for the second part of the study when we will compare the outputs of each of the models.

- Page 9 "should have reached radiative equilibrium" To what precision, in W/m2? Also, the global-mean top-of-atmosphere radiative equilibrium will be dominated by the warm dayside. The nightside could take much longer to reach equilibrium (smaller flux = longer equilibration timescale). Have the authors looked at the nightside surface bud- get, to see if it reaches equilibrium?

This is an important question, however this question depends on the model itself. As described in Way et a.l, (2017), ROCKE-3D considers radiative equilibrium at a precision of 0.2 W/m^2. But other models may never reach such level of radiative equilibrium. Also, sometimes it requires other diagnostics such as surface temperature, sea ice extension, etc. to determine whether or not the model reached convergence. Therefore, we prefer to remain agnostic concerning the threshold for radiative equilibrium and leave it up to the user to determine the convergence.

- Page 11 "LMD-G is available upon request." From whom?

We add: "LMD-G is available upon request from Martin Turbet (martin.turbet@lmd.jussieu.fr) and François Forget (francois.forget@lmd.jussieu.fr)"

***Technical comments: - Abstract, l.3: "... may soon be able to characterize, through transmission spectroscopy, the atmospheres of rocky exoplanets..." Why emphasize transits over other techniques that the manuscript mentions later on (e.g., emission spectra or phase curves)? The results of this work will be interesting more broadly.**

We modify this sentence into: *"through transmission, emission and reflection spectroscopy, the atmospheres of rocky exoplanets"*

- Abstract, l.14 "The four test cases included two land planets composed of pure N2 and pure CO2, respectively..." ... pure N2 and pure CO2 *atmospheres*, ...

Done

- P2, l.6-7: "... and represent nearly 20% of astronomical objects in the stellar neigh- borhood of the Sun. " Interesting! Citation?

it is actually 15 %: "Cantrell, J. R., Henry, T. J. & White, R. J. The solar neighborhood XXIX: the habitable real estate of our nearest stellar neighbours. *Astron. J.* **146,** 99 (2013)."

We have updated the 20 % to 15 % and added (Cantrell et al., 2013) as a reference.

- P6, l.7: "because all the models do not include CO2 condensation" - because not all the models include X, or because all the models do not include X?

"because not all the models include X" thank you.

- P7, l.29: " to much the model" - typo, too.

Done.

- P7, l. 30: "disable the gravity waves" - the gravity wave parameterization in the strato- sphere? The dynamical cores should still be resolving some internal gravity waves.

Yes, the gravity wave parameterization in the stratosphere (sub-grid). Thank you for pointing this out, we have modified the paragraph in:

"We also ask the contributing scientists to disable the sub-grid gravity wave parameterizations in their model. Indeed, all the models do not have implemented a gravity wave parameterization and some have prescribed or predicted gravity wave formation, tuned for Earth topography and meteorology. Therefore, to avoid differences in atmospheric dynamics especially above the tropopause, we recommend to not include the sub-grid gravity wave parameterizations in this

intercomparison. Gravity waves whose wavelengths are greater than the model grid are explicitly resolved in the models and do not need to be modified."

- Page 8, Table 2: molecular air mass is referring to the dry background gases only?

Yes only for dry gases, we add "(dry)" in the "molecular air mass" row of Table 2.

- Page 8, Table 2: momentum roughness length and heat roughness length are missing units.

Good catch. Both are in meter.

Done.

Interactive comment on "TRAPPIST-1 Habitable Atmosphere Intercomparison (THAI). Motivations and protocol" *by* Thomas Fauchez et al.

Anonymous Referee #2

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This brief paper describes a protocol for inter comparing GCMs for TRAPPIST-1e in anticipation of future observations. The goal is to determine the differences in climate states when the models are run under similar configurations. These states can be related to spectra or thermal phase curves anticipated from future observations such as JWST. Four GCMs have signed on so far but only preliminary results are available; more detailed analysis will follow. This is a good idea and should be a useful effort.

The biggest uncertainty is the mass and composition of the atmosphere. The only constraint seems to be that HST observations do not favor an extended H2 atmosphere for TRAPPIST-1e. Thus, heavier atmospheres consisting mainly of N2 and CO2 are considered. The models are configured to sort out the effects of the dynamical core, physical packages, and moist processes. This is achieved by comparing four different runs for each model with different surface and atmospheric conditions. The approach seems reasonable and should give the authors a good start on what will surely be a challenging but stimulating research project.

We would like to thank the reviewer for their positive words and their helpful comments, which have allowed us to make improvements to our manuscript. We have addressed each of the referee's comments below and noted the resulting changes we have made to the paper.

The authors might consider a few things.

1. If the goal is to determine the differences in model climate states with similar run configurations, it is not clear how model numerics will be separated from model physics. Different dynamical cores running at different resolutions with different numerical schemes will produce different climates. How does one distinguish these differences from those due to real physical processes? I think BEN1/BEN2 should get at some of this but not all of it. Perhaps one way is to run with simple Newtonian cooling using a common relaxation field and time constant.

We agree with referee #2 that a simulation with "Newtonian cooling" is an interesting idea. However, this increases the load of simulations to perform and we think that in order to have this intercomparison working in a reasonable time frame, the number of simulations should be low.

Also, the goal of this intercomparison is not to understand exactly why those models differ but to understand how these differences can have an impact on the observables from synthetic spectra. The four simulations we propose cover a large enough parameter space to answer this question. He have added the paragraph below before the conclusion:

”Note that while additional simulations with a simple Newton cooling model, a 1-D column model, or with cloud radiative effects disabled would help to better understand the differences due to the dynamical cores and cloud physics, they will also dramatically increase the computational time, amount of data and effort. Yet, THAI aims to be easily reproducible and not time consuming in order to reach many GCM user groups. The five simulations propose in THAI should be enough to understand the main differences between the GCMs and their impact on the observable. THAI could also be used as a benchmark for a future GCM intercomparison that will specifically aim to understand each differences between the models.”

2. Once that is clarified then an even more daunting task is to isolate changes due to different physics prescriptions. Is the intent to go to that level of detail or to describe what the differences are without analyzing the reasons? Some brief discussion about this would be helpful.

What we are looking for with this intercomparison is the most important effects between the models, the ones that can have a first order impact on the climate. We therefore do not consider subtle effects due to the numerical schemes, resolution etc. As mentioned in our answer to referee #2 first question, the objective is to quantify the impact of the model differences on the observables, not to understand all the differences between the models which would require another experimental protocol.

3. With suppressed CO2 condensation nightside surface temperatures are likely to be much warmer than when condensation is included. Without latent heat release atmospheric temperatures will cool and the surface must warm to maintain energy balance. Feedbacks related to moist processes may be affected and this may complicate the interpretation.

We agree with referee #2 about the potential effect of disabling CO_2 condensation. However, this is something we have to set up in the future because not all the models include CO_2 condensation. For a similar reason we did not consider ocean heat transport (OHT). In the future, we hope that CO_2 condensation and OHT will be integrated in all the models.

4. The radiative effects of clouds, both CO2 and H2O, can be very different between models. Runs with passive clouds might help isolate those effects. Of course, this adds to the analysis work (as does running with Newtonian cooling), but it is a point worth considering.

Disabling the radiative effects of clouds has also been suggested by referee #1. We agree that this is a very interesting suggestion. However, as also mentioned in the answer of the first question of referee #2, this would increase the number of simulations required for the intercomparison. As an example, Hab1, Hab1* and Hab2 require about 65Gb of data each. Running the model with the radiative effects of clouds disable would require starting new simulations from the initial conditions. We believe that in order to be successful, the number of simulations in THAI should stay small (we already have 5) with the objective to stay focused on understanding the impact of the differences on the observable. A paragraph added before the conclusion discusses about this.

“Note that while additional simulations with a simple Newton cooling model, a 1-D column model, or with cloud radiative effects disabled would help to better understand the differences due to the dynamical cores and cloud physics, they would also dramatically increase the computational time, amount of data and effort. THAI aims to be easily reproducible and not time consuming in order to reach many GCM user groups. The five simulations propose in THAI should be enough to

understand the main differences between the GCMs and their impact on the observables. THAI could also be used as a benchmark for future GCM intercomparisons that specifically aim to understand each differences between the models.”

5. The authors hope to add more models into the mix which will increase the workload. Recognizing that this is not a proposal, it still begs the question of having adequate support and manpower to do the work. Is there?

The first author, Thomas Fauchez, has a NASA SEEC proposal funded to work on this project with two THAI members as co-Is (Ravi Kopparapu, Mike Way). Therefore, we think that we have the adequate resources to successfully perform this intercomparison.

Also a THAI workshop is currently being planned around fall 2020 to discuss about THAI results and their perspectives (this is now mentioned in the revised version of the conclusion):

“The results of the comparison of these four models will be given in a second paper and a THAI workshop is planned for fall 2020.”

TRAPPIST-1 Habitable Atmosphere Intercomparison (THAI). Motivations and protocol

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Abstract. Upcoming telescopes such as the James Webb Space Telescope (JWST), the European Extremely Large Telescope (E-ELT), the Thirty Meter Telescope (TMT) or the Giant Magellan Telescope (GMT) may soon be able to characterize, through transmission**, emission or reflection spectroscopy,** the atmospheres of rocky exoplanets orbiting nearby M dwarfs. One of the most promising candidates is the late M dwarf system TRAPPIST-1 which has seven known transiting planets for which Transit Timing Variation (TTV) measurements suggest that they are terrestrial in nature, with a possible enrichment in volatiles. Among these seven planets, TRAPPIST-1e seems to be the most promising candidate to have habitable surface conditions, receiving $\sim 66\%$ of the Earth's incident radiation, and thus needing only modest greenhouse gas inventories to raise surface temperatures to allow surface liquid water to exist. TRAPPIST-1e is therefore one of the prime targets for JWST atmospheric characterization. In this context, the modeling of its potential atmosphere is an essential step prior to observation. Global Circulation Models (GCMs) offer the most detailed way to simulate planetary atmospheres. However, intrinsic differences exist between GCMs which can lead to different climate prediction and thus observability of gas and/or cloud features in transmission and thermal emission spectra. Such differences should preferably be known prior to observations. In this paper we present a protocol to inter-compare planetary GCMs. Four testing cases are considered for TRAPPIST-1e but the methodology is applicable to other rocky exoplanets in the Habitable Zone. The four test cases included two land planets composed of pure

N_2 and pure CO_2 **atmospheres,** respectively, and two aqua planets with a modern Earth and a CO_2 rich composition. Currently, there are four participating models (LMDG, **ROCKE-3D**, ExoCAM, UM), however this protocol is intended to let other teams participate as well.

1 Introduction

M dwarfs are the most common type of stars in our galaxy and rocky exoplanets orbiting M dwarf stars will likely be the first to be characterized with upcoming astronomical facilities such as the James Webb Space Telescope (JWST). Ultra-cool dwarfs (T < 2700 K) are a sub-stellar class of late M-dwarfs and represent nearly 15% of astronomical objects in the stellar neighborhood of the Sun **(Cantrell et al., 2013)**. Their smaller size compared to other stellar types allows easier detection of rocky exoplanets in close orbits, and this potential was recently realized by the discovery of the TRAPPIST-1 system (Gillon et al., 2016, 2017). Located about 12 pc away TRAPPIST-1 has seven known planets, and is one of the most promising rocky-planet systems for follow-up observations due to the depths of the transit signals (Gillon et al., 2017; Luger et al., 2017). Transit Timing Variation (TTVs) measurements of the TRAPPIST-1 planets suggest a terrestrial composition likely enriched in volatiles, and possibly water (Grimm et al., 2018). Also, it has been found that three planets (TRAPPIST-1 e, f and g) are in the habitable zone (HZ, Kopparapu et al., 2013) where surface temperatures would allow surface water to exist (Gillon et al., 2017; Wolf, 2017, 2018; Turbet et al., 2018).

TRAPPIST-1 is an active M dwarf star (O'Malley-James and Kaltenegger, 2017; Wheatley et al., 2017; Vida and Roettenbacher, 2018) which offers an environment very hostile to the survival of planetary atmospheres. However, Bolmont et al. (2017) and Bourrier et al. (2017) argued that depending on their initial water contents, the TRAPPIST-1 planets could have retained some water presently. Assuming that this water has remained in sufficient quantity, TRAPPIST-1e may be able to maintain habitable conditions (locally or globally around the planet) through a very large set of atmospheric configurations (Wolf, 2017; Turbet et al., 2018; Grootel et al., 2018, and references therein). The first attempt to characterize those planets through transmission spectroscopy has been conducted by de Wit et al. (2016, 2018) using the Hubble Space Telescope (HST) for the six innermost planets. Their analysis suggests that the TRAPPIST-1 planets do not have a cloud/haze free H_2 dominated atmosphere and that a large set of high mean molecular weight atmospheres are possible, such as thick N_2, O_2, H_2O, CO_2, or CH_4 dominated atmospheres. Using laboratory measurements and models Moran et al. (2018) have also shown that H_2 dominated atmospheres with cloud/haze can also be ruled out. Note that the uncertainties of these HST observations were very large, on the order of hundreds of parts per million (ppm) and further investigations with future facilities such as JWST (Barstow and Irwin, 2016; Morley et al., 2017) will be needed to determine the nature of atmospheres heavier than hydrogen.

Upstream of future JWST characterization of TRAPPIST-1e, it is important to derive constraints on its possible atmosphere to serve as a guideline for the observations. For this purpose, 3-D Global Climate Models (GCMs) are the most advanced tools (Wolf et al., 2019). However, GCMs are very complex models and their outputs can vary from one model to another for a variety of reasons. GCM intercomparisons have been widely used by the Earth science community. For instance the Coupled Model Intercomparison Project (CMIP) initiated in 1995 and currently in its version 6 (Eyring et al., 2016), focuses on the differences in GCM responses to forcings for anthropogenic climate change. While exoplanets receive considerable attention from climate modelers, and atmospheric data from Earth-like worlds may be imminent, to our knowledge only one intercomparison of planetary GCMs has been published (Yang et al., 2019). They found significant differences in global surface temperature between the models for planets around M-dwarf stars due to differences in atmospheric dynamics, clouds and radiative transfer. However, Yang et al. (2019) concerns planets near the inner edge of the HZ and focuses on highly idealized planetary configurations. Note that another model intercomparison have been run for the exoplanet community: the Palaeoclimate and Terrestrial Exoplanet Radiative Transfer Model Intercomparison Project (PALAEOTRIP). The protocol of this experiment is described in Goldblatt et al. (2017) and aims to compare a large variety of radiation codes used for paleoclimate or exoplanets sciences, to identify the limit conditions for which each model can produce accurate results. Information and timeline about PALEOTRIP can be found at http://www.palaeotrip.org/.

The motivation behind the TRAPPIST Habitable Atmosphere Intercomparison (THAI), is to highlight differences among GCM simulations of a confirmed exoplanet, TRAPPIST-1e, that is potentially characterizable in the near term (with JWST or ground-based facilities), and to evaluate how these differences may impact our interpretations of retrievals of its atmospheric properties from delivered observables. Our objective is also to provide a clear protocol intended for other GCMs to join the intercomparison, which is therefore not only limited to the GCMs presented in this paper. Results of the intercomparison will be presented in a following paper. In this paper, the motivations, including a presentation of TRAPPIST-1e and of the GCMs, are presented in section 2. In section 3 we present the THAI protocol describing all the parameters to be set up in the GCM. In Section 4, we list the model parameters to be provided in order for a given model to be comparable to other GCM simulations. A summary is given in section 5.

2 TRAPPIST-1e climate simulation and motivations

2.1 Motivations for a planetary GCM intercomparison

Global Climate Models (GCMs) are 3-dimensional numerical models designed to represent physical processes at play in planetary atmospheres and surfaces. They are the most sophisticated way to model the atmospheres and oceans of real planets. GCMs can be seen as a complex network of 1-D time-marching climate models connected together through a dynamical core (see description below). Each 1-D column contains physical parameterizations for radiative transfer, convection, boundary layer processes, cloud macroscale and microscale physics, aerosols, precipitation, surface snow and sea ice accumulation, and other processes, at varying levels of complexity.

The motivation behind this experimental protocol is to evaluate how some of the differences between the models can impact the assessment of the planet's habitability and its observables through transmission spectroscopy and thermal phase curves with upcoming observatories such as JWST. The intercomparison protocol was designed to evaluate three possible sources of differences between the models listed below:

1. The dynamical core:
   The dynamical core is a numerical solver of the hydrodynamic equations on the (rotating) planetary sphere. It calculates the winds that transport atmospheric gases, clouds, aerosols, sensible and latent heat, and momentum from one atmospheric column to another.

2. The radiative transfer:
   Each model has its own radiative transfer working assumptions and may use different spectroscopic databases and even different versions of the same spectroscopic database (e.g., HITRAN), collision-induced absorption (CIA), line-by-line versus correlated-k distribution (Lacis and Oinas, 1991), line cutoff, spectral resolution, etc.

3. The moist physics:
   The treatment of water in all of its thermodynamic phases is critical for the simulation of habitable planets. In particular cloud and convection process are a significant source of differences between climate models, and these differences are often exacerbated when modeling exoplanets around M-dwarf stars (Yang et al., 2014, 2019).

Note that a particular emphasis will be given on the differences of cloud properties between the models because they may have a large impact on the strength of the spectral signatures simulated by current radiative transfer tools (Fauchez et al., 2019). Yet a sufficient understanding of 3D cloud fields is needed to provide realistic observational constraints to observers. It is therefore crucial to address these potential differences between the GCMs.

Four GCMs (in their planetary version) are initially onboard THAI:

1. the Laboratoire de Météorologie Dynamique - Generic model (LMDG, Wordsworth et al., 2011, a review paper on the model is currently under preparation),

2. the Resolving Orbital and Climate Keys of Earth and Extraterrestrial Environments with Dynamics (ROCKE-3D, Planet 1.0 version derived from the NASA GISS Model E, Way et al., 2017),

3. the Exoplanet Community Atmospheric Model (ExoCAM [1], derived from the CAM4 NCAR model, Neale, 2010),

4. the Met Office Unified Model (UM, Mayne et al., 2014; Boutle et al., 2017).

By publishing our protocols in advance of the intercomparison work, we hope that other teams will also use this protocol to compare their own GCM with the four GCMs of this study.

2.2 The TRAPPIST-1e benchmark

TRAPPIST-1e is up to now one of the best habitable planet candidates for atmospheric characterization through transmission spectroscopy with JWST. Therefore, it is also an obvious candidate for an experimental protocol for GCM intercomparison. In Table 1 we summarize the TRAPPIST-1e parameters used in the THAI project based on Grimm et al. (2018).

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[1] Available on Github, https://github.com/storyofthewolf/ExoCAM

Available from NCAR, http://www.cesm.ucar.edu/models/cesm1.2/

Table 1. TRAPPIST-1 stellar spectrum and TRAPPIST-1e planetary parameters from Grimm et al. (2018)

Star & spectrum	2600 K BT Settl with Fe/H = 0
Planet	TRAPPIST-1e
Insolation	900 $W.m^{-2}$
Rotation period	6.1 days
Orbital period	6.1 days
Mass ($M_\oplus$)	0.772
Radius ($R_\oplus$)	0.910
Density ($\rho_\oplus$)	1.024
Gravity ($g_\oplus$)	0.930

3 The THAI Protocol

3.1 Atmospheric configurations

For THAI, we have chosen a set of four planetary configurations with increasing complexity. We have chosen to start with benchmark cases of dry-land planets with N_2- and CO_2-dominated atmospheres respectively, which will allow us to assess atmospheric dynamical + boundary layer, and CO_2 radiative transfer differences. Next we conduct aquaplanet simulations of N_2 and CO_2 dominated atmospheres respectively, providing characteristic cold and warm habitable states for TRAPPIST-1e. By gradually increasing the complexity of our simulations, we hope to be able to parse out meaningful differences between atmospheric dynamical + boundary layer, radiative transfer, and moist physical processes. The motivation for each of these cases is described below:

- Benchmark case 1 (Ben1): In this case, constituted of 1 bar of N_2 only, the purpose is to test the differences of the planetary boundary layer (PBL) schemes, the dynamical core and the associated heat redistribution between the different models. **Note that N_2-N_2 CIA should be included to avoid a fully transparent atmosphere and numerical instabilities.**

- Benchmark case 2 (Ben2): In this case, constituted of 1 bar of CO_2, we test the PBL schemes and dynamical core differences as well as the CO_2 radiative transfer.

- Habitable case 1 (Hab1): In this case, constituted of a modern Earth-like atmosphere of 1 bar of N_2 and 400 ppm of CO_2, the dynamical core, the clouds and atmospheric processes are tested together. It is also the most widespread benchmark for habitable planets in the literature (Barstow and Irwin, 2016; Morley et al., 2017; Lincowski et al., 2018).

- Habitable case 2 (Hab2): In this case, constituted of 1 bar of CO_2, the dynamical core, the CO_2 radiative transfer assumption and the clouds and atmospheric processes are tested. This case is likely representative of the early Earth (during the Hadean epoch), early Venus, and early Mars, at a time when Martian valley networks and lakes were formed (Haberle et al., 2017; Kite, 2019).

In each case, it is crucial to start each simulation with the same initial conditions. The simplest approach is then to start with an isothermal atmosphere. For THAI, we fixed the initial surface and atmosphere temperature at 300 K. The atmospheric configurations for the two benchmark (dry land) cases and two habitable cases are listed in Table 2, first horizontal block. Note that for Ben2 initial results indicate that some models feature cold trap temperatures on the night-side slightly below the CO_2 condensation point at 1 bar (194 K). However, because **not all** the models include CO_2 condensation, it should be disabled in the models that allow it. Ben2 is thus to be viewed as a idealization for the sake of study. Initial results indicate that Hab1 is representative of a cool, largely ice covered world but with liquid water in the substellar region. Hab2 is significantly warmer than Hab1, owing to a strong CO_2 greenhouse effect and the water vapor greenhouse feedback, and is representative of a temperate habitable world. The amount and variability of clouds and the strength of the atmospheric processes should be enhanced providing a more challenging comparison than in Hab1.

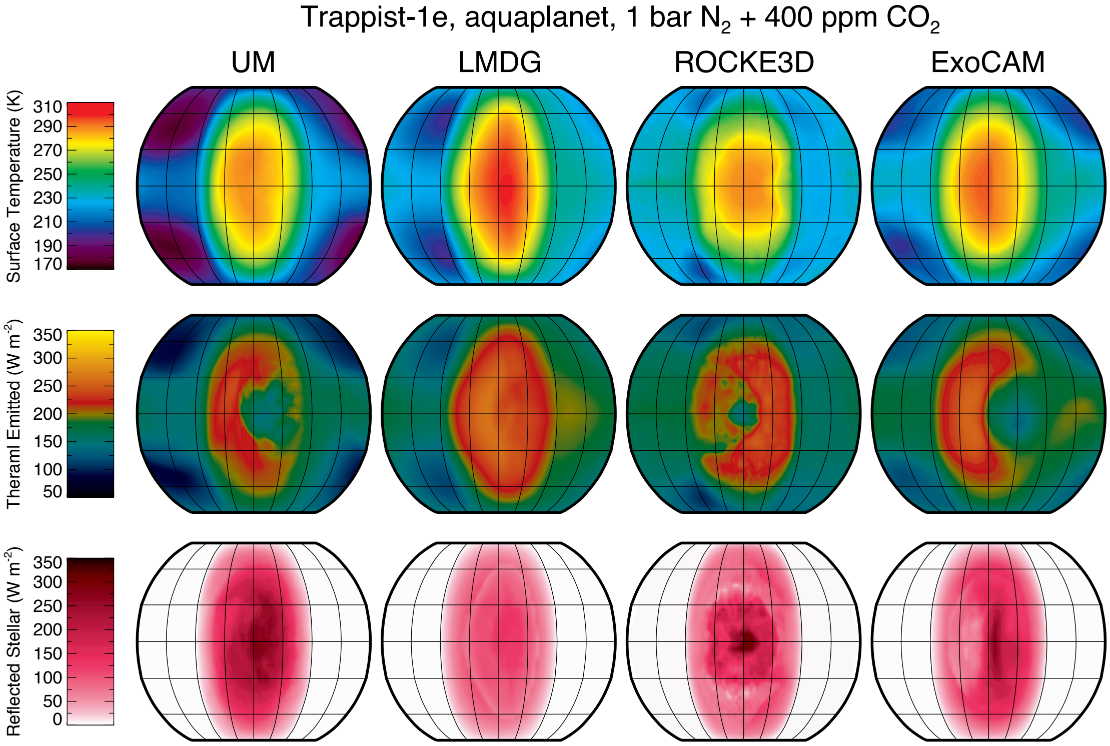

Figure 1. Surface contours for surface temperature, thermal emitted radiation (TOA) and reflected stellar radiation (TOA) for "Hab1" simulated by the four GCMs: the UK Met Office United Model (UM), the Laboratoire Météorologie Dynamique Generic model (LMDG), the Resolving Orbital and Climate Keys of Earth and Extraterrestrial Environments with Dynamics (ROCKE-3D), and the National Center for Atmospheric Research Community Atmosphere Model version 4 modified for exoplanets (ExoCAM).

In Fig. 1 we show results from preliminary simulations on case "Hab1" conducted with four different GCMs; UM, LMDG, ROCKE-3D and ExoCAM. We show surface contours for surface temperature, thermal emitted radiation (TOA) and reflected stellar radiation (TOA). We can see significant differences in the maximum, minimum and mean values of these parameters between the models. For such a complex atmosphere it is difficult to disentangle the effects leading to these differences. However, it seems clear that the patterns of thermal emitted and reflected stellar TOA fluxes are strongly influenced by the cloud patterns produced by each respective model. Here we have shown preliminary outputs to demonstrate the feasibility of the described experiments. In depth analysis of these simulations will be discussed in a following manuscript in preparation.

3.2 Surface

The surfaces considered in THAI (Table 2, second horizontal block) are simple. The land planets (Ben1 & Ben2) are covered by sand with a subsurface depth of at least 3 m with a constant albedo of 0.3. The ocean planets (Hab1 & Hab2) are fully covered by a 100 m deep slab (no horizontal heat transport) ocean. The ocean albedo is fixed at 0.06 and the ice and snow albedos are fixed at a constant value of 0.25. Note that the sea ice/snow albedo parameterization is a common source of discrepancy between the models. Some models, like ROCKE-3D, account for the spectral dependence of the sea ice albedo over multiple bands and variations due to snowfall, aging, depth and melt ponds while other models, such as LMDG, compute the wavelength-dependent albedo of water ice / snow from a simplified albedo spectral law, calibrated to get an ice / snow bolometric albedo of ~ 0.25 around an ultra-cool star like TRAPPIST-1 (Joshi and Haberle, 2012; von Paris et al., 2013; Shields et al., 2013). Differences in sea ice albedo have been found to have a large impact on planetary climate and habitability (Turbet et al., 2018). However, for the sake of this intercomparison, this discrepancy can be easily avoided by fixing the sea ice and snow albedo at a constant bolometric value of 0.25.

3.3 Model spatial resolutions and time steps.

The model spatial resolution is an important parameter because every process taking place at a sub-grid level would be parameterized and those parameterizations often diverge between the models. Similarly the model time steps control the numerical stability and accuracy. However, the choices for those are fundamental to how each model operates under a given parameterization and arbitrary fixing these parameters may prevent some model to correctly and fairly perform the intercomparison. In addition, models should be compared using the specifications that they commonly use for exoplanet studies. Therefore, for the sake of the THAI, we do not impose the model spatial resolution nor time steps. Note that we however recommend (but this is not a requirement) the radiative time step (a parameter much more flexible than the others among the models) to be set up at 1800 s. This value should provide a good coupling of the radiation with temporal changes to the atmosphere without slowing down too much the model.

We also ask the contributing scientists to disable the sub-grid gravity wave parameterizations in their model. Indeed, all the models do not have implemented a gravity wave parameterization and some have prescribed or predicted gravity wave formation, tuned for Earth topography and meteorology. Therefore, to avoid differences in atmospheric dynamics especially above the tropopause, we recommend to not include the sub-grid gravity wave parameterizations in this intercomparison. Gravity waves whose wavelengths are greater than the model grid are explicitly resolved in the models and do not need to be modified.

Note that under the requirements of the protocol, the atmospheric simulation of TRAPPIST-1e may actually not represent what each individual model can simulate with all their parameterizations fully activated. This is especially true for the sea ice and snow albedo parameterization. Therefore, complementary to the Hab1 case, we propose the Hab1* which should be simulated with the commonly used model parameterizations fully activated. Therefore, only the requirements on the atmospheric composition (1 bar of N_2 and 400 ppm of CO_2) and the planet and star properties of Table 1 are constrained for Hab1*.

Table 2. THAI experimental protocol.

Case	Ben1	Ben2	Hab1	Hab2
		Atmospheres		
Composition	1 bar N_2	1 bar CO_2	1 bar N_2 + 400 ppm CO_2	1 bar CO_2
Molecular air mass **(dry)**	28	44	28	44
Initial state	Isothermal 300 K		Isothermal 300 K	
		Surfaces		
Type	Land only		Ocean planet	
Composition	Sand		Slab ocean	
Albedo	0.3		Liquid water: 0.06 Ice/snow: 0.25	
Heat capacity (J/m^3/K)	$2 \cdot 10^6$		$4 \cdot 10^6$	
Thermal inertia (J/m^2/K/s^2)	2000		12000	
Momentum roughness length (m)	0.01		0.01	
Heat roughness length (m)	0.001		0.001	
Depth of the subsurface / ocean (m)	> 3		100	
Cautions:	disable **sub-grid** gravity wave **parameterization** disable CO_2 condensation			

4 Outputs

To compare the difference between models of a particular (instantaneous) output variable, both the average and standard deviation over the specified frequency and number of orbits for the case will be computed. Four categories of outputs frequently used in climate simulations have been selected: radiation, surface, atmospheric profiles and clouds. The radiation outputs are the outgoing longwave radiation (OLR) and absorbed shortwave radiation (ASR) for clear and cloudy skies, also commonly known as emitted thermal and absorbed stellar fluxes, respectively, both at the top of the atmosphere (TOA). The surface outputs are the temperature map, the downward total SW flux and net LW flux and the open ocean fraction (for Hab1/Hab1* & Hab2 only). The atmosphere outputs are the temperature and the U, V and W wind speed profiles. Finally, the cloud outputs For Hab1/Hab1* & Hab2 are the water vapour and cloud condensed water and ice integrated columns, and the cloud profiles of the cloud fraction and the mass mixing ratio for the liquid, ice and both combined. Also in these two cases, the spatial and temporal variability is much weaker than in Hab1/Hab1* & Hab2. Therefore, to mitigate the amount of data we choose to only output data for ten consecutive orbits (with a 6 hour output frequency). Concerning Hab1/Hab1* & Hab2, we can see in Figure

2 that weather patterns modulate the surface temperature and cloud water column of Hab1 on a period nearly equal to 10 orbits. Also Hab2 (hotter than Hab1) has a more efficient heat transport and is therefore more homogeneous in temperature but the cloud variability is very important. Therefore, more orbits (100) are needed in order to smooth out this variability. A summary of the output parameters is given in Table 3.

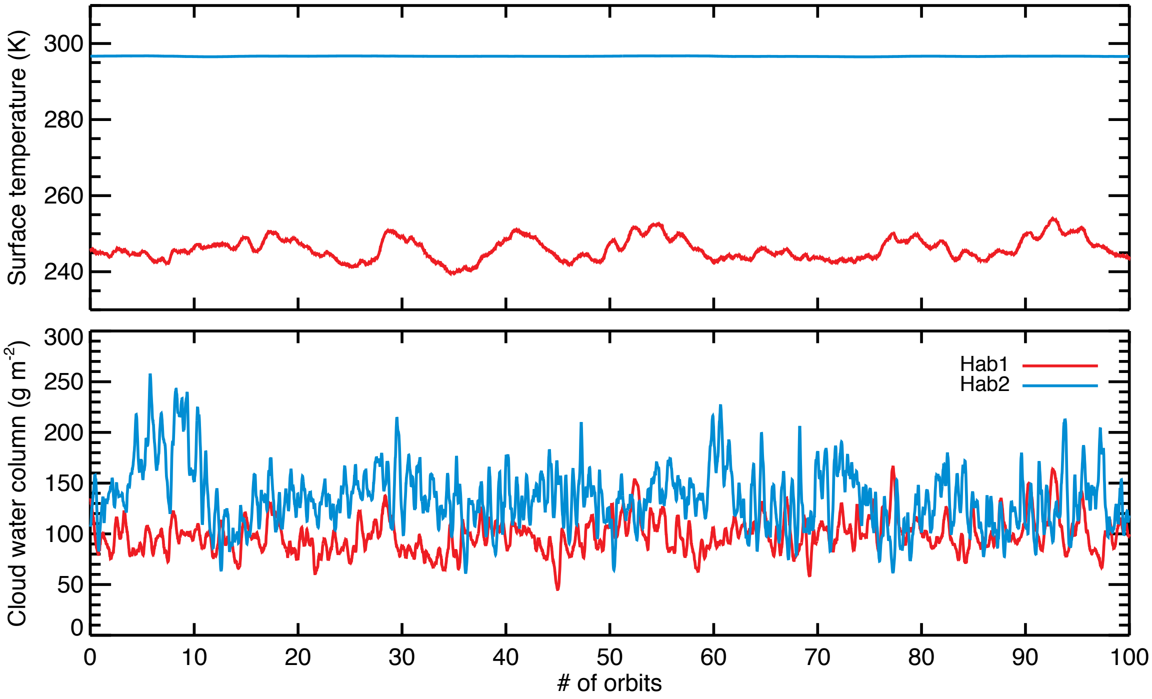

Figure 2. Globally averaged surface temperature (top panel) and cloud water column (bottom panel) as a function of the number of orbits for Hab1 & Hab2 simulated with ExoCAM (Wolf and Toon, 2015). Surface temperature for Hab1 and cloud water column for the 2 cases vary by a couple of tens of percents on a timescale of 10 orbits due to weather patterns.

All the simulations should have reached radiative equilibrium at TOA. To facilitate comparison between each GCM, we ask the contributing scientists to provide their output in netCDF format.

Table 3. Instantaneous fields to be output by the GCM. For each diagnostic, the mean value and the standard deviation are computed from data output at the specified frequency and number of orbits for the case. OLR and ASR correspond to outgoing longwave radiation (at TOA) and absorbed shortwave radiation (at TOA), respectively, SW and LW correspond to shortwave and longwave, respectively, CF corresponds to cloud fraction and MMR at mass mixing ratio.

<table>
<tr><th>Case</th><th>Ben1</th><th>Ben2</th><th>Hab1/Hab1*</th><th>Hab2</th></tr>
<tr><td>Number of orbits</td><td>10</td><td>10</td><td>100</td><td>100</td></tr>
<tr><td>Frequency (hours)</td><td>6</td><td>6</td><td>6</td><td>6</td></tr>
<tr><td colspan="5">2D maps</td></tr>
<tr><td>Radiation</td><td colspan="4">OLR (clear/cloudy)</td></tr>
<tr><td></td><td colspan="4">ASR (clear/cloudy)</td></tr>
<tr><td>Surface</td><td colspan="4">temperature map</td></tr>
<tr><td></td><td colspan="4">downward total SW flux</td></tr>
<tr><td></td><td colspan="4">Net LW flux</td></tr>
<tr><td></td><td>∅</td><td>∅</td><td colspan="2">open ocean fraction</td></tr>
<tr><td>Clouds</td><td>∅</td><td>∅</td><td colspan="2">total/liquid/ice/vapor column</td></tr>
<tr><td colspan="5">Vertical profiles</td></tr>
<tr><td>Atmospheric profiles</td><td colspan="4">temperature</td></tr>
<tr><td></td><td colspan="4">U, V , W wind speed</td></tr>
<tr><td></td><td colspan="4">heating rates (SW/LW)</td></tr>
<tr><td></td><td>∅</td><td>∅</td><td colspan="2">specific + relative humidity</td></tr>
<tr><td>Cloud profiles</td><td>∅</td><td>∅</td><td colspan="2">CF (total/liquid/ice) [%]</td></tr>
<tr><td></td><td>∅</td><td>∅</td><td colspan="2">MMR (total/liquid/ice) [kg/kg]</td></tr>
</table>

The main objective of THAI is to highlight how differences in atmospheric profiles produced by each GCM are going to impact the predictions of atmosphere detectability and observational constraints for habitable planet targets such as TRAPPIST-1e (Morley et al., 2017; Fauchez et al., 2019). Therefore, in addition to the parameters of Table 3, we will emphasize the differences between the models in term of the planet's climate and habitability with a particular attention on the cloud coverage. Also, the objective will be to identify and quantify the differences on the simulated JWST observations, through simulated transmission spectra (in NIRSpec prism and MIRI LRS ranges) and thermal phase curves (in MIRI LRS range) due to the differences of atmospheric profiles (temperature, pressure and gas mixing ratios) output by each GCM. The planetary spectrum generator (PSG, Villanueva et al. (2018)) will be used to simulate transmission and emission spectra. The comparison of the spectra for Hab1 & Hab2 cases will therefore highlight the sensitivity of model characteristics to predict transmission spectra of habitable planets.

Note that while additional simulations with a simple Newton cooling model, a 1-D column model, or with cloud radiative effects disabled would help to better understand the differences due to the dynamical cores and cloud physics, they would also dramatically increase the computationnal time, amount of data and effort. THAI aims to be easily reproducible and not time consuming in order to reach many GCM user groups. The five simulations propose in THAI should be enough to understand the main differences between the GCMs and their impact on the observables. THAI could also be used as a benchmark for future GCM intercomparisons that specifically aim to understand each differences between the models.

5 Summary

THAI is an intercomparison project of planetary GCMs focused on the exciting new habitable planet candidate, TRAPPIST-1e. Because rocky exoplanets in the Habitable Zone of nearby M dwarfs have the highest chance to be the first Earth-size exoplanets to be characterized with future observatories, TRAPPIST-1e is currently the best benchmark we could think of to compare the capability of planetary GCMs. In this first paper we have presented the planet and GCM parameters to be used in this experiment which already has four GCMs onboard (LMDG, ROCKE-3D, ExoCAM and UM), but we hope more GCMs will join the project. The results of the comparison of these four models will be given in a second paper **and a THAI workshop is planned for fall 2020**.

Code availability. ExoCAM (Wolf and Toon, 2015) is available on Github, https://github.com/storyofthewolf/ExoCAM. The Met Office Unified Model is available for use under licence, see http://www.metoffice.gov.uk/research/modelling-systems/unified-model.ROCKE-3D is public domain software and available for download for free from https://simplex.giss.nasa.gov/gcm/ROCKE-3D/. Annual tutorials for new users take place annually, whose recordings are freely available on line at https://www.youtube.com/user/NASAGISStv/playlists?view=50&sort=dd&shelf_id=15. LMD-G is available upon request **from Martin Turbet (martin.turbet@lmd.jussieu.fr) and François Forget (francois.forget@lmd.jussieu.fr)**.

Data availability. **THAI model outputs and the TRAPPIST-1 stellar spectrum will be progressively uploaded during the intercompaison and will be available at: https://thai.emac.gsfc.nasa.gov/dataset/thai**

Competing interests. No competing interests are present.

Author contribution

T.J.F. lead the THAI project and has written the manuscript. E.T.W ran the simulation for Fig 1. and plotted the figures. Every author contributed to the development of the THAI protocol, to the discussions and to the editing of the manuscript.

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