EPSC Abstracts
Vol. 14, EPSC2020-664, 2020, updated on 17 Oct 2021
https://doi.org/10.5194/epsc2020-664
Europlanet Science Congress 2020

EXO-ATMOS: A scalable grid of hypothetical planetary atmospheres

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Summary: As part of the NASA Frontier Development Lab, we implemented a parallelized cloud-based exploration strategy to better understand the statistical distributions and properties of potential planetary atmospheres. Starting with a modern-day Earth atmosphere, we iteratively and incrementally simulated a range of atmospheres to infer the landscape of the multi-parameter space, such as the abundances of biological mediated gases that would yield stable (non-runaway) planetary atmospheres on Earth-like planets around solar-type stars. Our current dataset comprises of 124,314 simulated models of earth-like exoplanet atmospheres and is available publicly on the NASA Exoplanet Archive. Our scalable approach of analysing atmospheres could also help interpret future observations of planetary atmospheres by providing estimates of atmospheric gas fluxes and temperatures as a function of altitude, and thereby enable high-throughput first-order assessment of the potential habitability of exoplanetary surfaces.

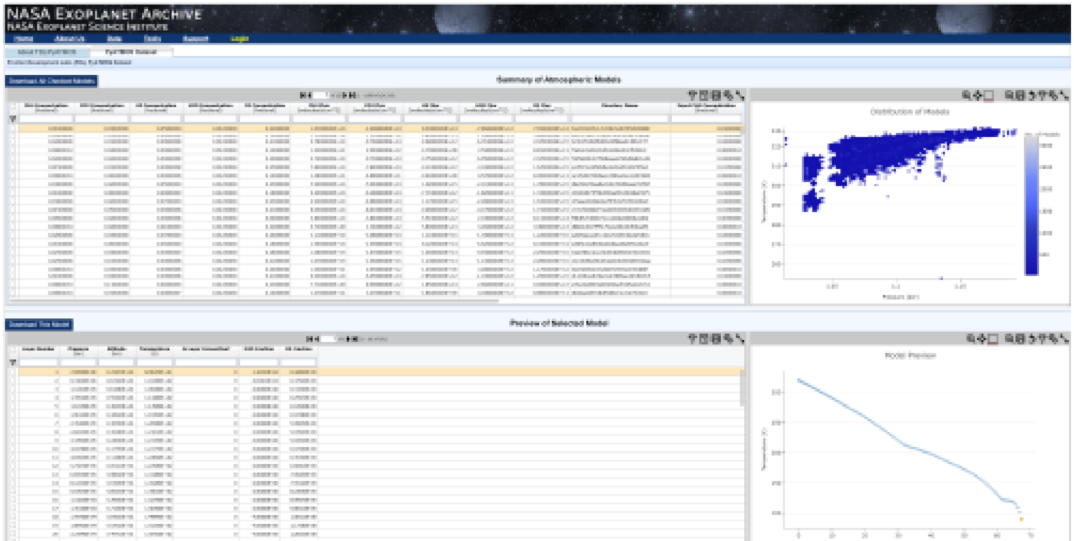
Introduction: The NASA Frontier Development Laboratory (FDL) is an annual science accelerator that focuses on applying machine learning and large-scale computing to challenges in space science and exploration (Cabrol et al. 2018). FDL engages interdisciplinary teams of computer scientists and space science domain experts and tasks them to solve problems that are valuable to NASA and humanity's future. We implemented a cloud-based strategy to better understand the statistical distributions of habitable planets and life in the universe and layout an avenue to characterize the potential role of biological regulation of planetary atmospheres.

We simulated a range of atmospheres to infer the landscape of the multi-parameter space, such as the abundances of biological mediated gases that would yield stable (non-runaway) planetary atmospheres on Earth-like planets around solar-type stars. Our scalable tool, once coupled to a generalized ecosystem model, could help derive estimates of the biological mediated atmospheric gas fluxes and help constrain the type and the extent of exobiology on exoplanets based on the remotely detected atmospheric compositions.

Method: Our team generated data for a wide variety of hypothetical biospheres to scope out the plausible range of habitable atmospheres and metabolisms that could be present in the universe. We implemented a cloud-based massively parallelized procedural parameter search for a wide range of planetary atmospheres. Since existing tools were not capable of broad parameter scans, we streamlined the ATMOS 1-D atmospheric simulation code developed by the NASA Virtual Planetary Laboratory (Arney et al. 2016, Meadows et al. 2016). and produced a package for the community called PyAtmos (https://github.com/PyAtmos). This package dramatically increases the usability and accessibility of the ATMOS 1-D software across a range of platforms.

We then used PyAtmos on the Google Cloud Platform in an automated and scalable procedure to search the parameter space of atmospheric compositions. Our search considered the relative concentrations of greenhouse gases such as methane, carbon dioxide and water. 124,314 different atmospheres were simulated and then analyzed to establish if the planetary surface temperatures and fluxes of gases were compatible with conditions that could maintain a liquid water inventory on the planetary surface.

Results: The dataset of planetary atmospheres we have generated can be used for training machine learning models to bootstrap the ATMOS code. It is an open-source dataset (https://exoplanetarchive.ipac.caltech.edu/cgi-bin/FDL/nph-fdl?atmos) available for the community to understand distributions of habitability parameters such as surface temperatures and free energy available to life on different classes of atmosphere bearing planets.



All of these are based around an Earth-like planet that orbits a star similar to the Sun, but with different gas mixtures in their atmospheres. A parameter space of possible atmospheres was scanned by varying the concentrations of six gases - Carbon dioxide, Oxygen, Water, Methane, Hydrogen and Nitrogen.

In future work, we plan to include parameters such as star type, planet size and distance from the host star when evaluating the range of different atmospheres that may be habitable. The scalability of our framework provides a mechanism to incorporate complex biogeochemical and global climate models to better understand the co-evolution of the atmosphere and biosphere (e.g. Chopra et al. 2016, Gebauer et al. 2017, Nicholson et al. 2018, Lineweaver et al. 2018). Analyses of such multi-dimensional datasets will enable better interpretations of future observations of exo-atmospheres and biosignatures by upcoming telescopes (Fuji et al. 2018).

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