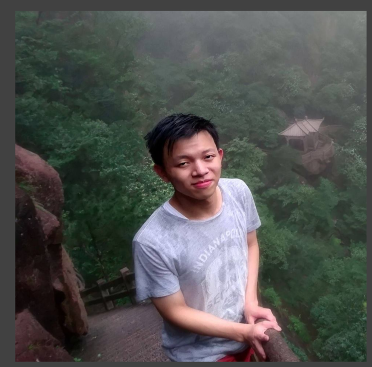
Modeled 3-D Biosignatures from Proxima Centauri b



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Proxima Centauri b is one of the most promising extrasolar terrestrial planets to search for potential biomarkers due to its proximity to Earth and relatively high planet to stellar luminosity ratio. These factors create a prime target for follow-up characterization efforts by e.g., *James Webb Space Telescope* and/or directing imaging. High-resolution, 3-D model predictions of atmospheric biosignatures however, are not currently available in the community. Here we use the CESM1 WACCM, a high-top coupled climate-chemistry general circulation model, to simulate the circulation, photochemistry, and stratospheric chemistry of Proxima b. From our equilibrium simulations with boundary conditions consistent with Proxima b observations (i.e., mass, radius, heliocentric distance, etc.) and a stellar spectrum consistent with its host star, we find increased mixing ratios and lifetimes for biogenic compounds (e.g., CH4, N2O, and CH3Cl) in the stratosphere. Whereas these biogenic gases are typically concentrated at the equator on Earth, they are dispersed across the mid-latitudes and even to the poles of Proxima b. Our initial analysis suggests that these characteristics are the result of a markedly energized stratospheric circulation regime and altered photochemistry, both of which are the consequence of enhanced UV and IR radiative forcing relative to Earth. Model simulated global distribution and longer lifetimes of biomarkers suggest that Proxima b's molecular absorption and observational windows are potentially greater than anticipated. These results indicate enhanced prospects for detecting signals of life on Proxima b and/or other M-dwarf planets, conclusions consistent with prior studies using 1-D models.

Why Proxima b?

- Closest known exo-planetary system
- Nearly Earth-sized and resides in the liquid water habitable zone
- Well characterized, relatively high resolution of the host star (Proxima Cen) spectra available
- Host star is a late-dwarf; it has a lower bolometric luminosity, allows better chance to resolve the atmosphere of the attending planet
- M-dwarf star is the most abundant type of stars
- Characterization efforts (JWST, HabEx) will likely measure planets orbiting M-dwarfs

Model & Data

- The Community Earth System Modeling (CESM) 1.2 Whole Atmosphere Community Climate Model (WACCM)
- Developed by National Center for Atmospheric Research (NCAR)
- Atmosphere component includes full stratospheric-mesospheric chemistry, coupled with circulation and climate
- No known applications to exoplanets
- Stellar spectrum is downloaded from the Virtual Planetary Laboratory site (vpl.astro.washington.edu/spectra/stellar/)

Model Details: 1.9°x2.5° horizontal resolution 66 vertical levels Active atmosphere and slab ocean components Inactive/prescribed land and sea-ice components Use of MOZART: model for ozone and related chemical Tracers 57 chemical species linked by ~250 reactions	Sensitivity Experiments: Altered stellar spectra and planetary radius 1. Earth - Solar spectra 2. Proxima b 1 - Quiescent Proxima Spectra 3. Proxima b 2 - Active Proxima` Spectra All other parameters such as planetary mass, gravity, and density assume Earth-like values
Boundary Conditions: Zero orbital obliquity and eccentricity Earth's continental configuration/topography Pre-industrial atmospheric composition Bolometric solar flux of 1365 W/m^2	Data Extraction: All results are run to equilibrium and are averaged over 20 years simulation time. Spectral data are normalized for planets at 1 AU.

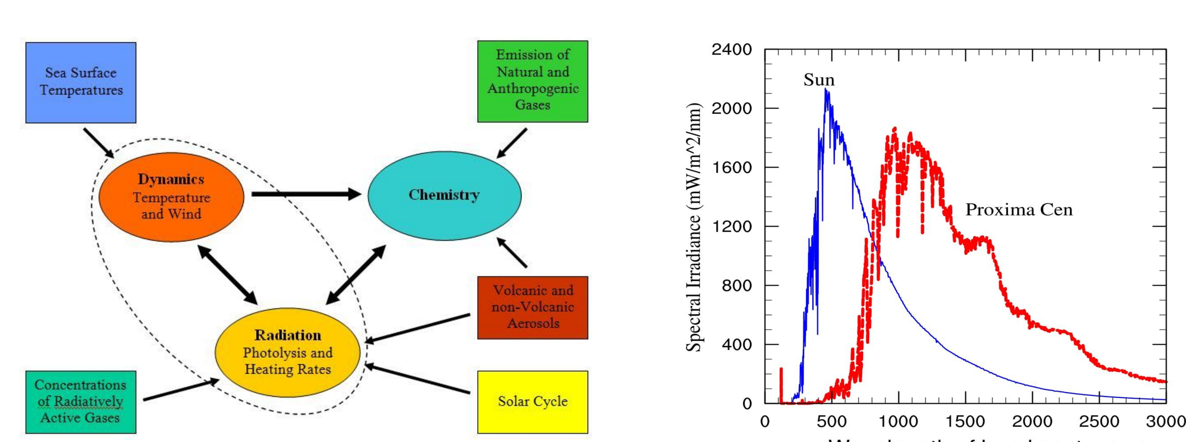

Figure 1. The basic schematic of typical chemistry-climate models and the stellar spectral energy disrtribution (SED) of the Sun and Proxima Cen.

Different Ozone Concentrations due to altered UV environments

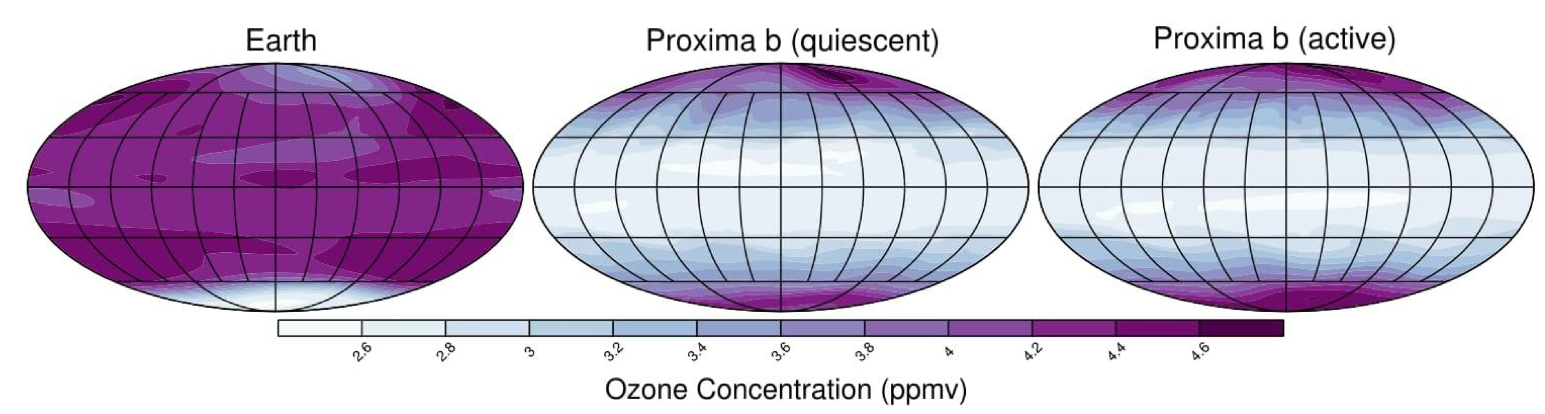

Figure 2. Ozone mixing ratio at 150 mbar as a function of latitude and longitude for various input stellar spectra. Only a small increase is measured in the 1600-2100 Angstrom region of the spectrum between the quiet and active spectra, resulting in little difference between the two planet scenarios. On the other hand, substantial changes are seen between the Earth and Proxima b, primarily stemming from the altered amount of UV irradiation from the respective host stars. Interactions between oxygen and impinging UV photons (photolysis) which in turn results in the altered ozone mixing ratios initiates a chain of chemical reactions that affects the presence of various biogenic compounds.

- The amount of stratospheric ozone present depends on the incident stellar spectral energy distribution and stellar activity
- These effects are not meridionally uniform
- Little difference is observed between a quiet host star and an active one
- Difference between planetary radii has little effect on chemistry

Abundance and Distribution of Biosignatures for M-dwarf planets

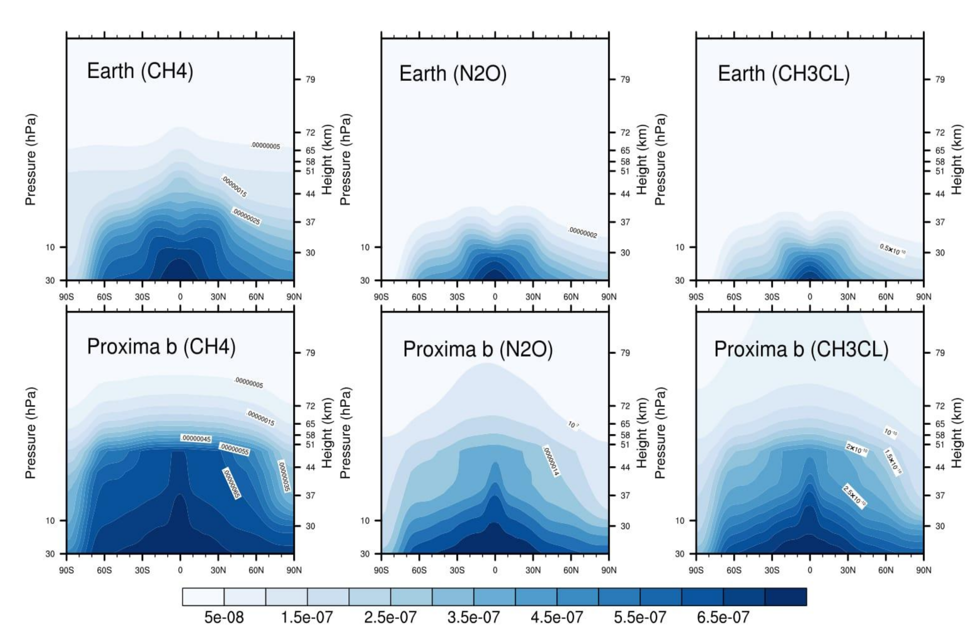

Figure 3. Zonal mean mixing ratios of CH4, N2O, and CH3Cl as functions of altitude and latitude. Apart from abundance increase found by 1-D models, we also find changes in the meridional distribution of these biosignatures. Whereas these gases are typically concentrated at the equator on Earth, they are dispersed across the mid-latitudes and even to the poles of Proxima b. Such behaviors indicate that mechanisms that may change the distribution of various biosignatures, beyond purely photochemical and eddy-diffusion processes calculated in 1-D models.

$$O_3 + h\nu(\lambda_{<3100\ nm}) \rightarrow O_2 + O(D')$$
$$O(D') + H_2O \rightarrow 2OH$$
$$CH_4 + OH \rightarrow CH_3 + H_2O$$
$$CH_3 + O_2 + M \rightarrow CH_3O_2 + M$$

- Consistent with 1-D models, higher concentrations of CH4, N2O, and CH3Cl are found
- These gases extend to higher altitudes and latitudes
- Although photochemistry plays the dominant role, spectral-driven circulation may also be important

Effects on energy budget and heat transport

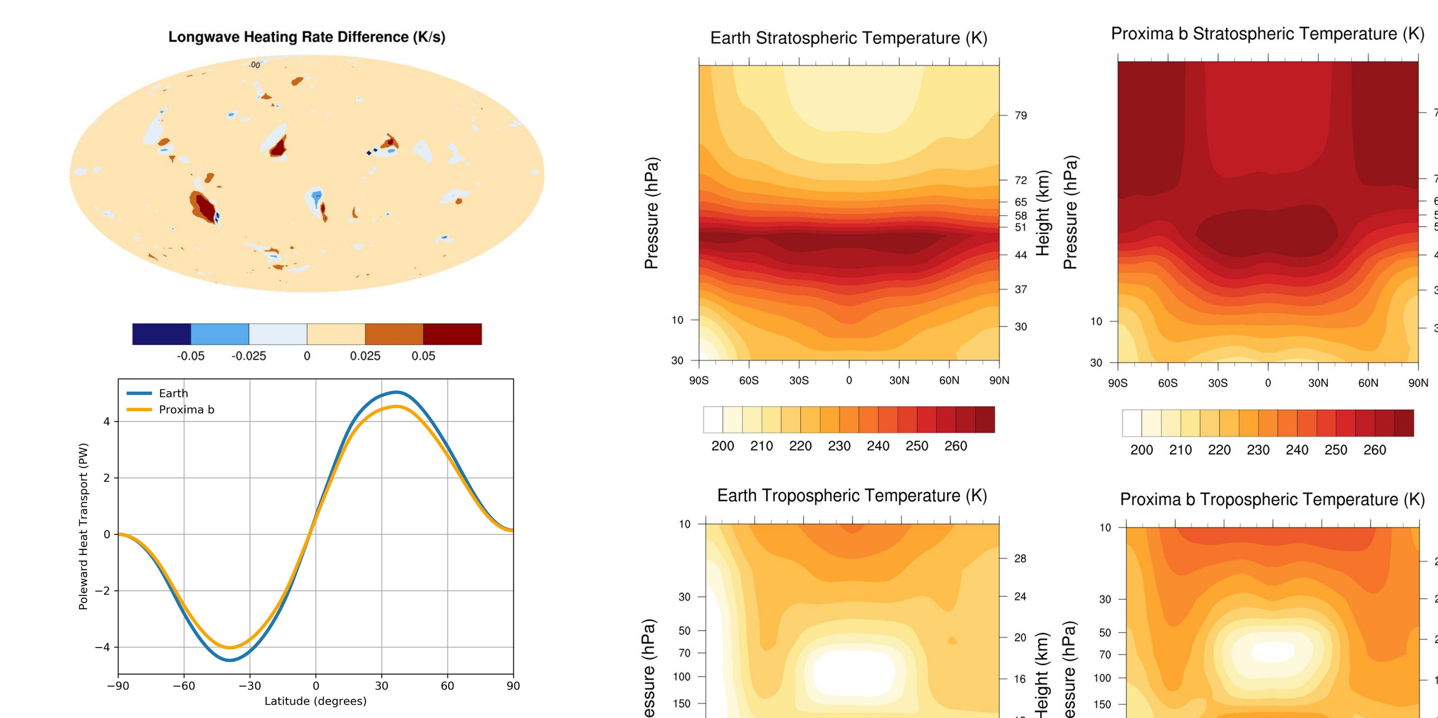

Figure 4. Longwave heating difference, heat transport (top), and atmospheric temperatures (right) for Earth and Proxima b. The diagrams show evidence for decreased heat transport, caused by more isothermal stratospheres.

- Enhanced radiative heating by species e.g. CH4 and H2O are caused by increased of the NIR/IR spectral region of M-dwarfs
- Evidence for decreased poleward heat transport are observed; this effect is tied to the more isothermal stratosphere due to increase radiative heating
- These effects indicate that single-column models are insufficient in capturing the full behavior of atmospheric chemistry

Observational Implications & Future Work

Main Caveats:

1) Fixed surface to atmosphere gas fluxes
2) Modern Earth atmospheric compositions

Future simulations will investigate other factors that may influence observational best-practices:

1) Planetary rotation period
2) Seasonality
3) Diurnal cycles of plants

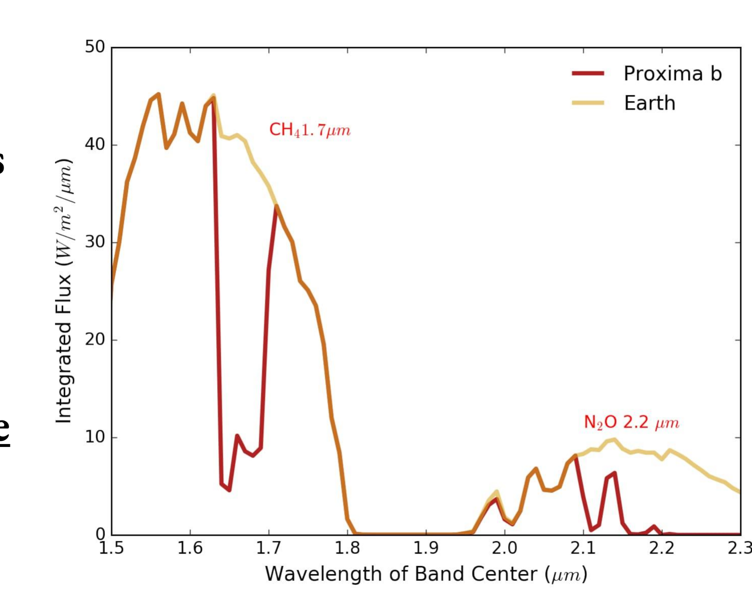

Figure 5. Model spectra of Earth and Proxima b (TOA flux) generated by SBDART radiative transfer model, using GCM model data as inputs. The preliminary spectral results are consistent with those using 1-D models in that we also find deep CH4 features at 1.7 microns for the model orbiting cooler stars.

[1] Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, Icarus, 101, 108 [2] Kreidberg, L., Loeb, A., 2016, ApJL, 832, 1 [3] Liu, S.C., Donahue T.M., et al., 1976, JGR, 81, 18 [5] Meadows, V. S., Reinhard, C.T., et al., 2017, arXiv [6] Rugheimer, S., Kaltenegger, L., Segura, A., et al., 2015, ApJ, 809, 57 [7] Sagan, C., Thompson, et al., 1993, Nature, 365, 715 [9] Turbet, M., Leconte, J., Selsis, F., et al. 2016, A\&A, 596, A11 [10] Yang, J., Cowan, N. B., \& Abbot, D. S. 2013, ApJL, 771, L45 [11] Fujii, Y., Del Genio, A. D., Anderson, D.S., 2017, arXiv}.