Tracking Tropical Cyclones in High-Resolution GCM Simulations of TRAPPIST-1e with Varying Atmospheric CO2

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Summary:

We conducted simulations of aquaplanet tidally locked versions of TRAPPIST-1e with sufficient spatial resolution to permit tropical cyclogenesis. We examined low-pressure storms to determine if they were analogous to tropical cyclones on Earth and found that their locations agreed broadly with predictions from Earth-based environmental favorability metrics.

Background

Tropical cyclones are well-studied climate phenomena on Earth characterized by fast winds and heavy rainfall that are often modeled as as heat engines [1-2]. Tropical cyclones also can impact the observable properties of planets by affecting the transport of water vapor to low pressures along with cloud cover and resulting outgoing longwave radiation [3-4]. Since hurricanes are expected to form on exoplanets [5-6], it is imperative to study how planetary properties can affect their presence, structure, and strength.

Methods

In order to investigate cyclogenesis on idealized exoplanet simulations, we used the ExoCAM GCM [7] to model tidally locked versions of TRAPPIST-1e (with 1 bar of nitrogen, varying levels of atmospheric CO2 along with water vapor set by Clausius-Clapeyron assuming an aquaplanet surface) orbiting a low mass M-dwarf, We used TempestExtremes [8] in order to investigate low pressure areas that could be tropical cyclones. We examined storm structure through both 2D maps along with azimuthally averaged 2D structure. The cyclones with the longest duration in each of the three were investigated further. The environmental favorability metrics we used for comparison to cyclone locations were absolute vorticity, ventilation-reduced maximum potential intensity [2, 6, 9-11], and the product between those two.

Cyclone Structure

Both of the .1 and .01 bar model cyclones display cyclonic winds surrounding a low pressure minima along with an inflow of radial winds near the surface and an outflow of radial winds near their top (see Figure 1). The .01 bar storms on average had smaller radii in comparison to the .1 bar case. Both cyclones possess a clear saturated center with a tower of vertical humidity near the core (see Figure 2). The vertical storm structure found in [5] were used for comparison. Cyclones found within this study demonstrate broad agreement with cyclones found in other studies as well as those seen on Earth.

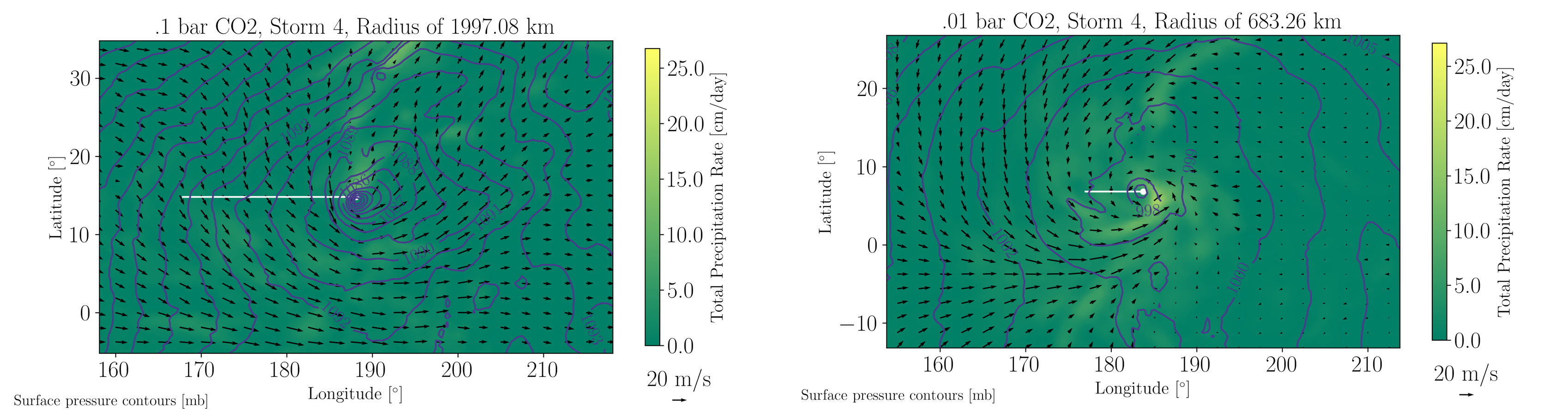

Fig 1: Individual cyclones from the .1 bar (left) and .01 bar (right) models. The filled contours display precipitation (inches/day), the line contours display surface pressure (in Pa), and the quivers display surface winds (in m/s). The solid white line represents the cyclone radii determined by azimuthally averaging the surface winds until the average value fell below 8 m/s.

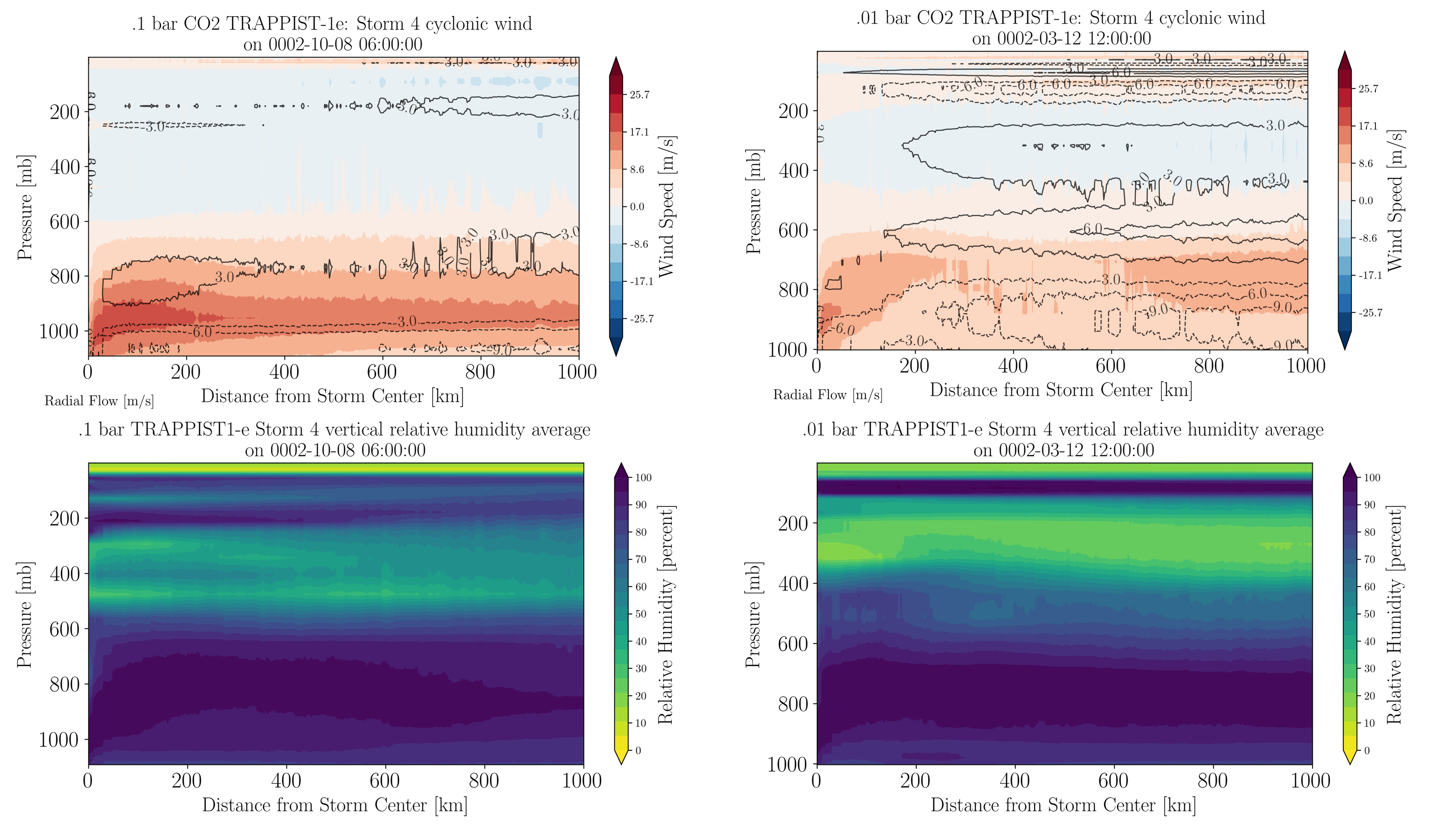

Fig 2: Vertical structure for the previous two cyclones created through azimuthal averages at each pressure. The radial distance from the tracked cyclone center is plotted along the x-axis (in km) and pressure is plotted along the y-axis (in mbar). The plots on the top show the wind structure with cyclonic winds in the filled contours while the line contours display the radial winds. Positive tangential wind speed values represent cyclonic winds while negative values represent anti-cyclonic winds. The dotted lines represent inward flow (towards the center) while the solid lines display outward flow. The plots on the bottom display relative humidity (in %).

Cyclone Locations and Qualities

When comparing the models against one another, it can be seen that all of the models have cyclones developing near the substellar point in a given region that depends on the wind patterns of the model. For the cyclones themselves, neither model has any cyclones that meet the wind threshold for being defined as a hurricane [12]. This is likely the result of the lesser stellar irradiation that TRAPPIST-1e receives in comparison to that of Earth. This would mean less energy can be funneled into the cyclones to allow them to reach the hurricane threshold. We find that the environmental favorability metrics can reasonably predict the locations of cyclone formation within each model, but there is less agreement in the .1 bar case. This is likely due to the stronger equatorial jet seen near the substellar point which will push tropical cyclones away from favorable regions of formation. It can be seen in both cases that the product between the absolute vorticity and ventilation reduced maximum potential intensity best predicts the locations of the cyclones This suggests that while even though the ventilation-reduced maximum potential intensity and absolute vorticity metrics were designed for Earth, their predictions could carry over onto exoplanets. These findings also agree with previous studies investigating tropical cyclogenesis on exoplanet GCMs [13]. Notably, we also find that the novel metric of a product of the ventilation-reduced maximum potential intensity and absolute vorticity provides a better predictor of tropical cyclone location, implying that it may be relevant for Earth tropical cyclone studies as well.

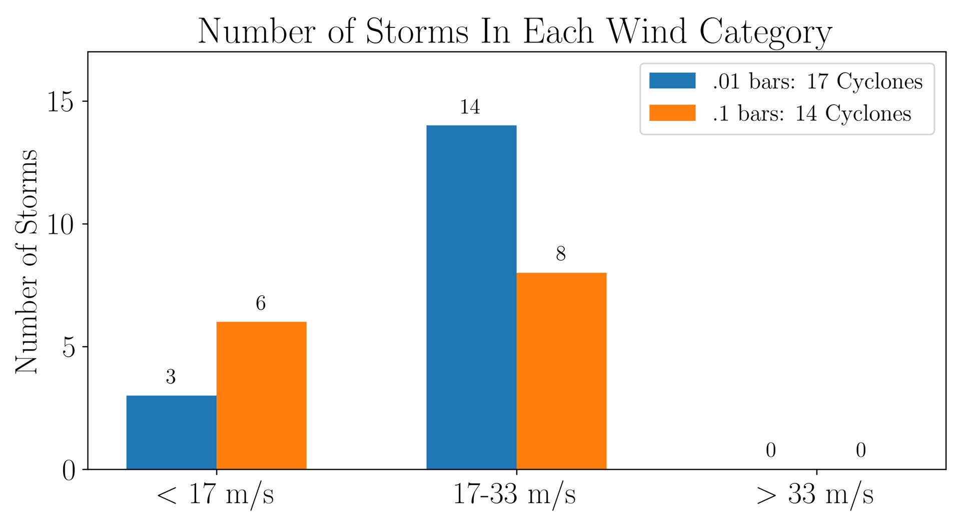

Fig 3: Histogram plot of the number of cyclones that have maximum wind speed in each respective category (hurricane-like, storm-like, and depression-like from right to left)

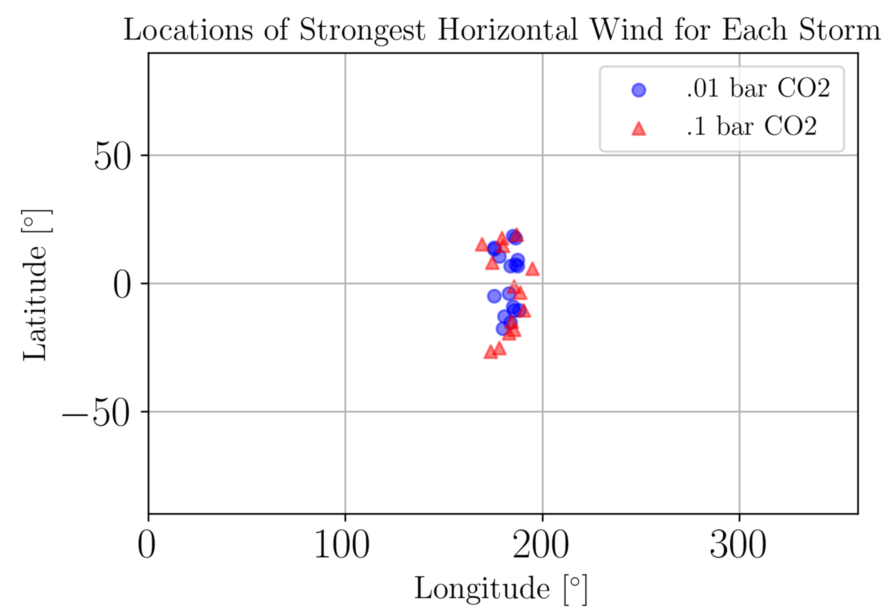

Fig 4: Location of each cyclone at which it achieved the greatest horizontal wind speed. The blue circles are cyclones found within the .01 bar CO2 case, and the red triangles are cyclones found in the .1 bar CO2 case.

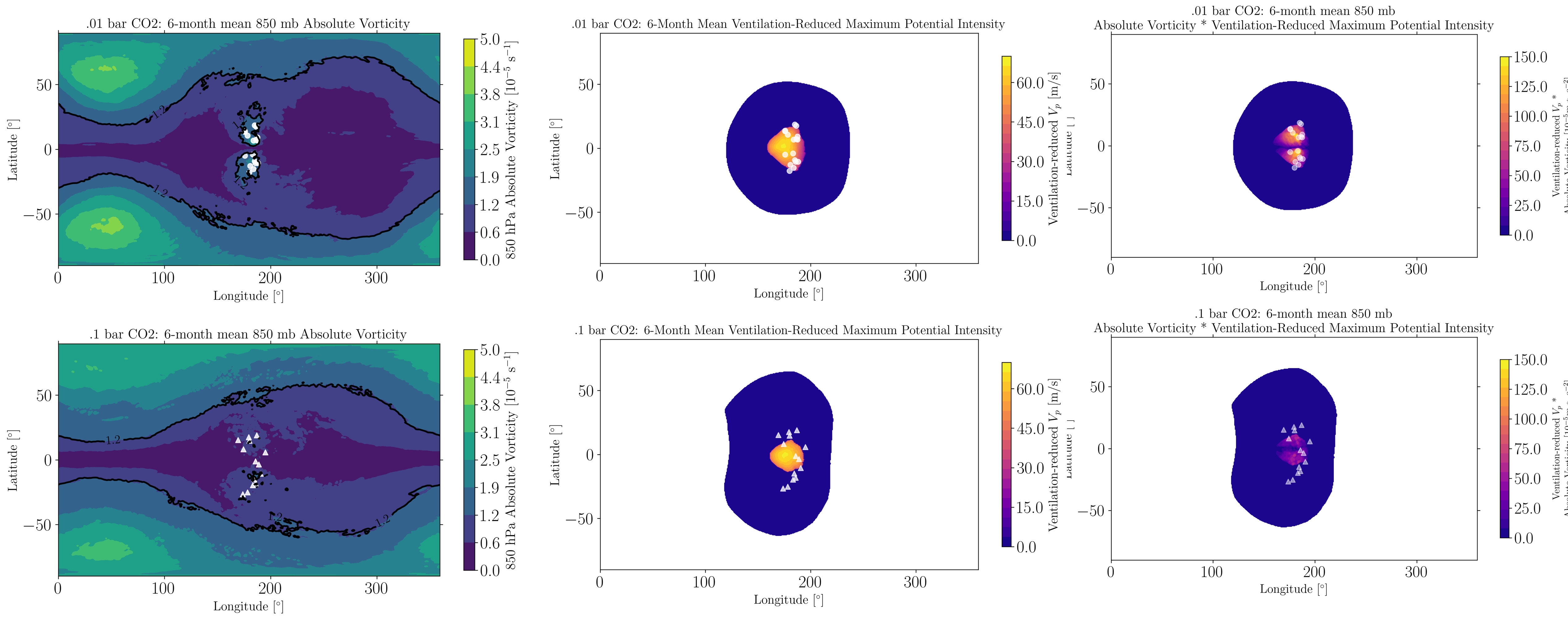

Fig 5: 6-month average environmental favorability metrics with tracked cyclone points overlayed in white. The left column is absolute vorticity. The middle column is ventilation reduced maximum potential intensity, and the right column is the product between the previous two variables. We find good agreement between environmental favorability metrics and tracked cyclone locations.

Next Steps

At this moment, we are continuing this approach with additional GCM simulations of specific exoplanets. We also expanding this study to investigate additional iterations of TRAPPIST-1e with varying atmospheric conditions. Hopefully, by building up a sample of differing exoplanets and atmospheric conditions, we can build a better intuition as to what the climate and atmospheric activity of these planets may be.

1) Applying these cyclone investigation tools and metrics to different models and input conditions, especially considering specific nearby rocky exoplanets (TRAPPIST-1e, Proxima Centauri b, LP 890-9c).

2) Investigating how the presence of tropical cyclones on exoplanets would impact their observable properties.

[1] Emanuel (2003), Annual Review of Earth and Planetary Sciences, 31, 75. [2] Chavas (2017), Journal of Atmospheric Sciences, 74, 2989. [3] Pierrehumbert (1995), Journal of Atmospheric Sciences, 52, 1784. [4] Wing (2019), Current Climate Change Reports, 5, 1. [5] Yan & Yang (2020), Astronomy and Astrophysics, 643, A37. [6] Komacek et al. (2020), The Astrophysical Journal, 898, 115. [7] Wolf et a. (2022), The Planetary Science Journal, 3, 7. [8] Ullrich et al. (2021), Geoscientific Model Development, 14, 5023 [9] Bister & Emanuel (2002), Journal of Geophysical Research (Atmospheres), 107, 4801. [10] Tang & Emanuel (2012), Bulletin of American Meteorological Society, 93, 1901. [11] Hoogewind et al. (2020) Journal of Climate, 33, 1725. [12] Jialin Lin, T. Q., & Klotzbach, P. 2022, Atmosphere-Ocean,728. [13] Garcia et al. [2024] The Astrophysical Journal.