Time Variability in 3D Atmospheric GCM Models for Ultra-Hot Jupiters

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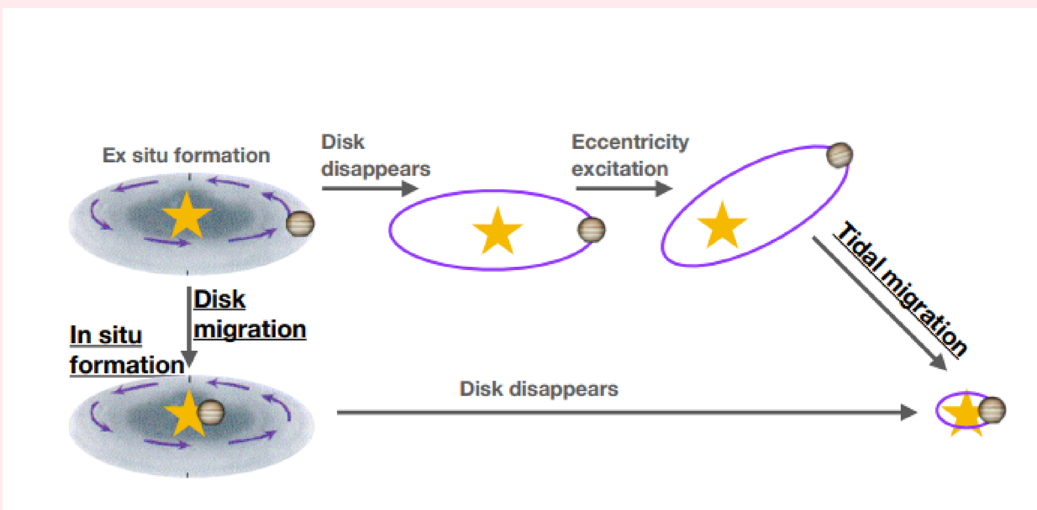
I . Background

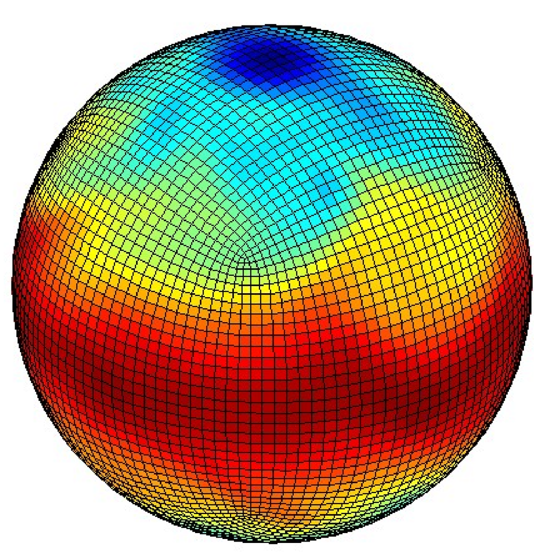
- Hot Jupiters are **gas giant** exoplanets that orbit very close to their host stars, often completing an orbit in just a few days[1].
- They likely form farther from the star and migrate inward through mechanisms like **disk migration** or **high-eccentricity migration.[1]**



- Because they are **tidally locked**, they have a **permanent day-side and night-side**, creating strong temperature gradients and dynamic atmospheres.
- This project focuses on **WASP-121b**, to explore how its atmospheric properties change over time.
- WASP-121b is an ultra-hot Jupiter located about **0.025 AU** from its host star, completing an orbit every **~1.27 days.** Its close proximity makes it a strong candidate for studying extreme atmospheric dynamics[3]

II. Modeling

In this project, we use the **MIT General Circulation Model** (MITgcm) to simulate the atmospheric dynamics. Originally built for Earth's oceans and atmosphere, MITgcm is adapted here for exoplanetary atmospheres.[2]



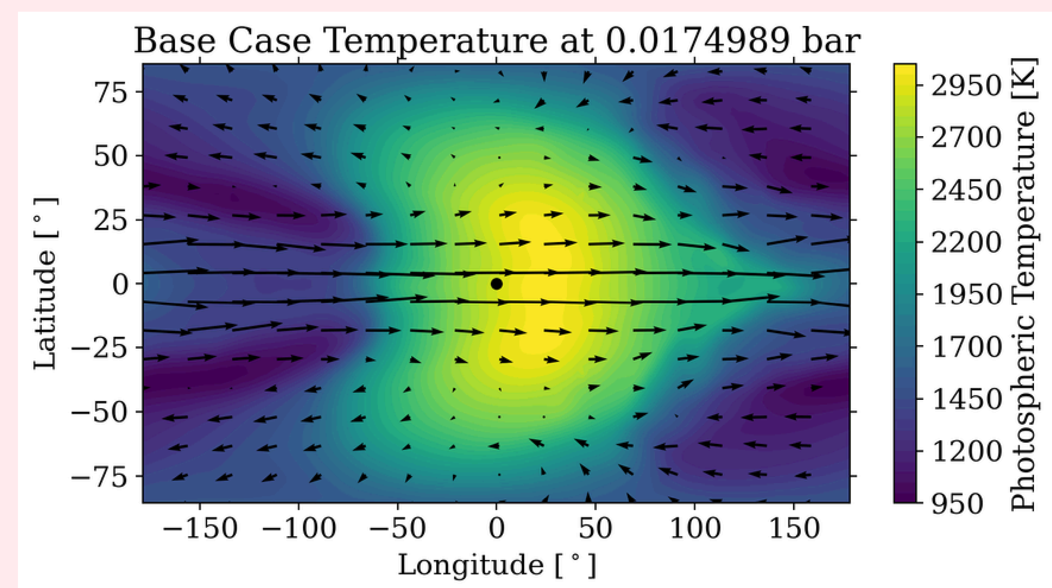
- **Coupled Physics Approach** : Combines fluid dynamics (Navier-Stokes) with radiative transfer to model wind and temperature change.
- **Simplifying Assumptions:** Assumes a thin, hydrostatically balanced atmosphere with constant gravity, modelingonly a local atmospheric section

III. Research

We investigated how temperature evolves over time and varies across different regions of WASP-121b's atmosphere using our base case simulation. Our goal was to understand this variability and how pressure levels influence atmospheric dynamics.

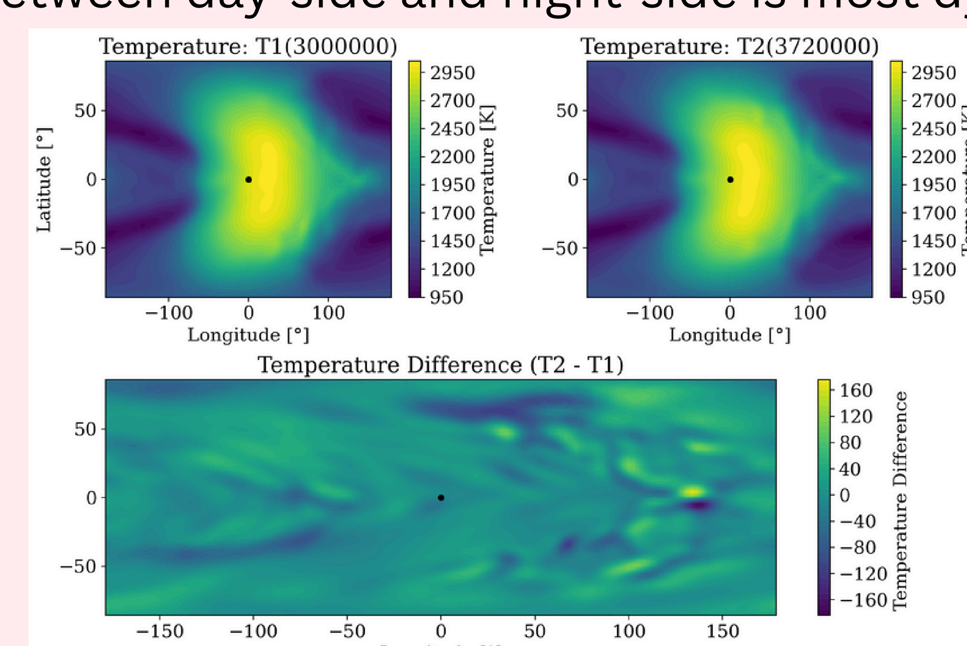
- **Base Temperature Map**

This plot shows the temperature level of **~0.017 bar**. We observe a **strong day-night contrast** driven by extreme stellar irradiation and planetary rotation. This prolonged exposure on the dayside results in higher temperatures near the substellar point

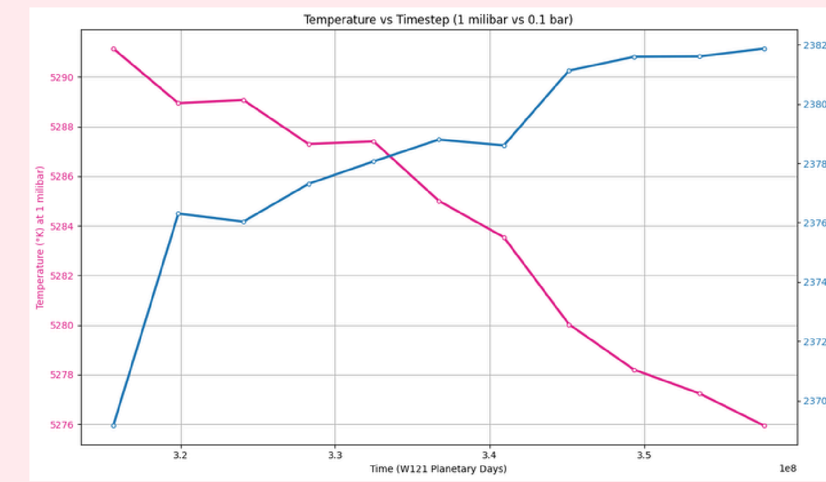


- **Temperature Difference over Time**

The **two plots** show a temperature map for each of these **distinct timesteps**, while the **main plot** compares the **temperature maps at two different timesteps**. It reveals the most significant changes occur near the terminator, where the transition between day-side and night-side is most dynamic.



- **Time Variability at Different Pressure Levels**

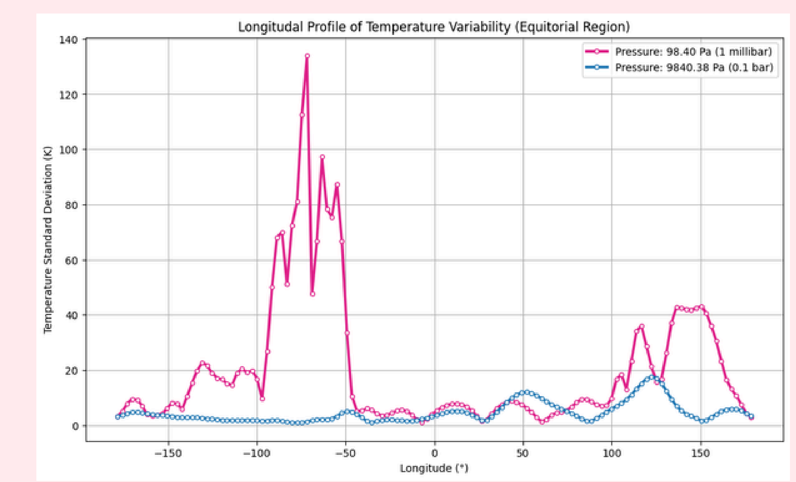


These line plots show the **temperature evolution at the substellar point for two different pressure levels**:

- At **1 millibar**, a higher pressure level, we see a steady/constant decrease in the temperature over time.
- At **0.1 bar**, which is a lower pressure level, we see a steady/constant increase in the temperature over time

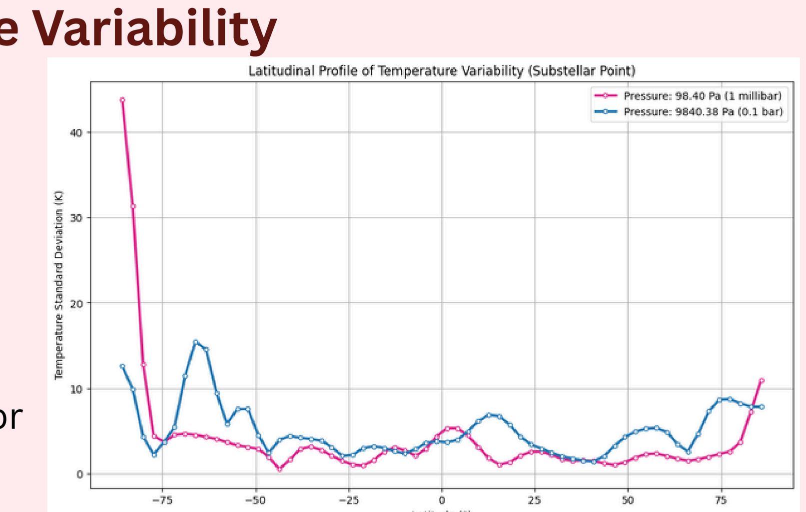
- **Longitudinal Profile of Temperature Variability**

This plot shows the **standard deviation of temperature** along **longitude** at the **equator** for two pressure levels. Variability peaks near the **terminators**, where day and night regions meet, especially in the upper atmosphere (1 mbar). **Deeper layers exhibit less variability** due to **longer radiative timescales.**



- **Latitudal Profile of Temperature Variability**

This plot shows how **standard deviation of temperature** along **latitude** at the **substellar point** for two pressure levels. Variability is **highest near** the **poles** and **drops significantly** near the **equator**, suggesting more **stable temperatures** in **equatorial regions**. The peak at high latitudes may reflect dynamic instabilities or flow over the poles.



IV. Conclusions & Next Steps

- Our results highlight strong **temperature variability** at the **terminators** and **relatively stable conditions near the equator**, especially at **higher pressures**.
- **Differences** in variability **across pressure levels** indicate **vertical atmospheric structure** and **circulation dynamics**.
- Our next steps include **increasing the number of timesteps** for better temporal resolution and **expanding the study** to other exoplanets for comparative analysis.

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References

[1] Fortney et al, 2021.
[2] MITgcm Held–Suarez Atmosphere Overview, MITgcm Documentation
[3] NASA Exoplanet Archive. (2024). WASP-121b Overview.