

Investigating the Dynamics of Hothouse Earth Climates with a Simplified GCM

Matthew McKinney¹ and Jonathan Mitchell¹

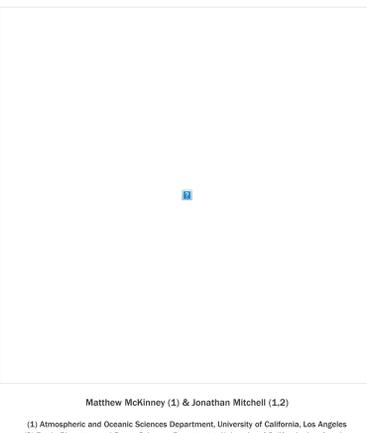
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Abstract

There are records of past Earth climates that were ice-free all the way to the poles (Barron 1983), which can be described as “hothouse” climates. These hothouse climates can be contrasted with an “all-tropics” planet, where the tropics are defined by the atmospheric dynamics, i.e. the Hadley Cell extent (Faulk et al. 2017). This classification is thus primarily dependent on a planet’s rotation, rather than its ice-free extent or surface temperatures. We investigate the parameter space between Earth and an all-tropics world using the open-source GCM Isca, developed by Vallis et al (2018). We take an Earth analog and perform a parameter sweep in two dimensions: global reservoir depth (10m, 1m, 1cm) and rotation period (8 days, 4 days, 1 day). The sweep will allow us to explore the effects of surface liquid coverage and large-scale atmospheric circulation on an Earth-like climate. To better represent the distribution of surface water, we utilize the surface hydrology scheme developed by Faulk et al. (2020) for the Titan Atmosphere Model. In this presentation we provide a status report and analysis of initial findings.

Investigating the Dynamics of Hothouse Earth Climates with a Simplified GCM



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INTRODUCTION

What is a Hothouse Earth?
 • An Earth-like planet with no permanent ice, even at the poles.
 • Limited inventory of surface liquids, such that most of the condensable is in the atmosphere as vapor.
 Real-World Comparison
 • The Saturnian moon Titan is a close analog to a hothouse Earth.
 • Both with limited and condensable methane, but most of it is in the atmosphere as vapor (Lorenz et al. 2008; Ponnada & Griffith 2010).
 • The surface has no permanent methane ice, with the poles instead dominated by methane lakes (Sofka et al. 2007).
 • Titan has weak rotation, allowing its tropics to extend from pole to pole, effectively an all-tropics world (Faulk et al. 2017).

METHODS

Research Hypothesis
 • Our hypothesis is that an Earth-like planet with similar parameters to Titan will have similar dynamics and climatology.

Experimental Approach
 • We use the open-source Global Climate Model (GCM) Isca, developed by Vallis et al. (2018), and add the surface hydrology scheme from the Titan Atmosphere Model (TAM), developed by Faulk et al. (2020).
 • Each experiment varies two parameters in three values, for 9 individual experiments:

1. Initial surface water depth in each grid cell, with the possible values: 10m, 1m, 10cm
2. Rotation period, with the possible values: 1 Earth-day, 4-days, 8 days.

Universal Settings
 • All experiments use Isca's built-in full Boussinesq convection scheme.
 • Large-scale condensation with no supercooled.
 • Constant planetary albedo of 0.3.
 • Flat global topography with runoff.

RESULTS 1: SURFACE WATER & HUMIDITY

• For low-level humidity on Earth, we expect to see higher specific humidity in the tropics where temperatures are highest.
 • In a Titan-like state, this is reversed, with the highest specific humidities at the poles where temperatures are coolest.

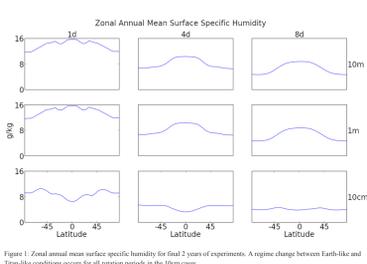


Figure 1: Zonal annual mean surface specific humidity for final 2 years of experiments. A regime change between Earth-like and Titan-like conditions occurs for all rotation periods for all water depths in the 10cm cases.

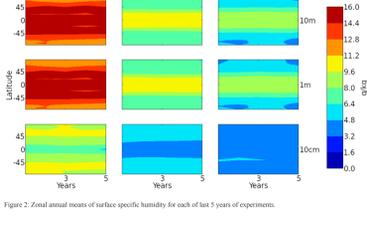


Figure 2: Zonal annual means of surface specific humidity for each of last 5 years of experiments.

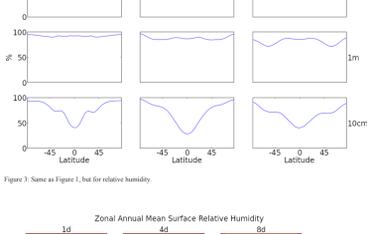


Figure 3: Same as Figure 1, but for relative humidity.

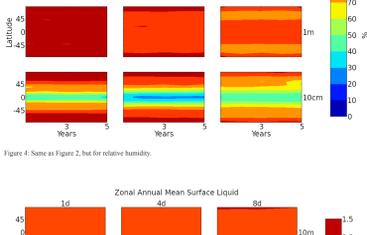


Figure 4: Same as Figure 2, but for relative humidity.

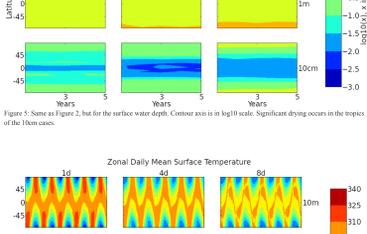


Figure 5: Same as Figure 2, but for the surface water depth. Contour axis is in log10 scale. Significant drying occurs in the tropics of the 10cm cases.

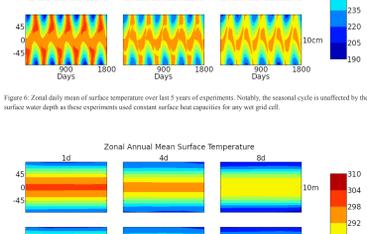


Figure 6: Zonal daily mean surface temperature over last 5 years of experiments. Notably, the seasonal cycle is unaffected by the surface water depth as these experiments used constant surface heat capacities for any wet grid cell.

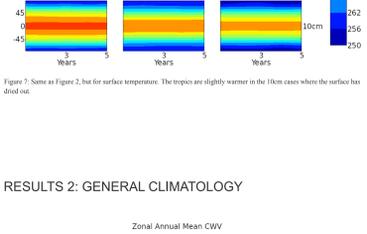


Figure 7: Same as Figure 2, but for surface temperature. The tropics are slightly warmer in the 10cm cases where the surface has dried out.

RESULTS 2: GENERAL CLIMATOLOGY

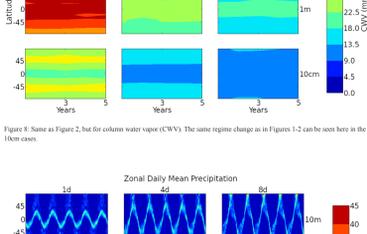


Figure 8: Same as Figure 2, but for column water vapor (CWV). The same regime change as in Figures 1-2 can be seen here in the 10cm cases.

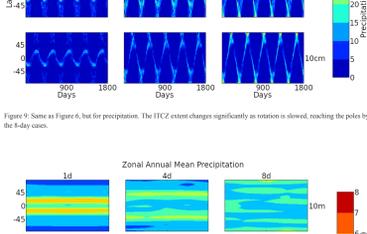


Figure 9: Same as Figure 6, but for precipitation. The ITCZ extent changes significantly as rotation is slowed, reaching the poles by the 8-day cases.

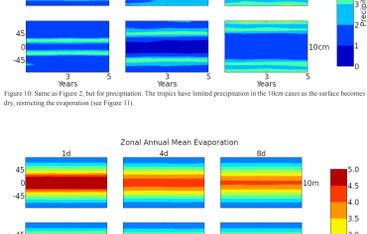


Figure 10: Same as Figure 2, but for precipitation. The tropics have limited precipitation in the 10cm cases as the surface becomes dry, restricting the evaporation (see Figure 11).

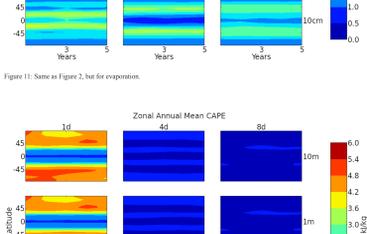


Figure 11: Same as Figure 2, but for evaporation.

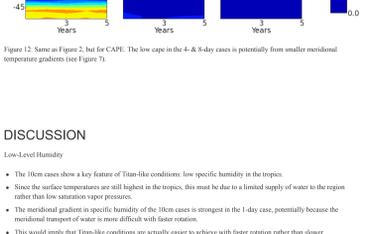


Figure 12: Same as Figure 2, but for CAPE. The low CAPE in the 4- & 8-day cases is potentially from smaller meridional temperature gradients (see Figure 7).

DISCUSSION

Low-Level Humidity
 • The 10cm cases show a key feature of Titan-like conditions, low specific humidity in the tropics.
 • Since the surface temperatures are still highest in the tropics, this must be due to a limited supply of water to the region rather than low saturation vapor pressures.
 • The meridional gradient in specific humidity of the 10cm cases is strongest in the 1-day case, potentially because the meridional transport of water is more difficult with faster rotation.
 • This would imply that Titan-like conditions are actually easier to achieve with faster rotation rather than slower.

General Climate Tendencies
 • The precipitation plots in Figure 9 demonstrate the effect of rotation on ITCZ extent. The ITCZ extends poleward as the rotation slows to 4 days, and reaches the poles by 8 days, matching the results of Faulk et al. (2017).
 • The poleward extent of the ITCZ is one way to limit water in the tropics, however the lowest tropical rainfall for the 10cm experiments is in the 4-day case rather than the 8-day case (Figure 10).
 • The same 4-day case also sees the most surface drying, which suggests there may be a non-monotonic relation between the rotation period and surface moisture in the tropics.

CONCLUSIONS AND FUTURE WORK

Our initial conclusions are that Earth with Titan-like parameters does show some Titan-like characteristics. In addition, some Titan-like characteristics may not require all of Titan's parameters, and may even be accounted by Earth-like parameters.
 We will need to expand on the parameters covered in our experiments to fully test the hypothesis. This will include deeper/shallower initial surface depths and slower/faster rotation, plus an additional parameter.

The new parameter is a saturation vapor pressure coefficient, which will be referred to as "cof". This coefficient is applied to the Clausius-Clapeyron (CC) equation to change the resultant saturation vapor pressure for a given temperature. Its default value is 1, meaning to change to the output of the CC equation.
 This parameter will allow us to change the amount of water that can be contained by the atmosphere, to see if this is important in generating Titan-like climatology. Methane on Titan has a higher volatility than water on Earth, allowing it to reach CWV of ~5m (Ponnada & Griffith 2010). Adjusting the cof can allow an Earth-like atmosphere to hold a similar amount of water.

We will also include the full TAM hydrology scheme, which is outlined below in Figure 13. Our experiments so far have only isolated the surface runoff, excluding all subsurface processes.

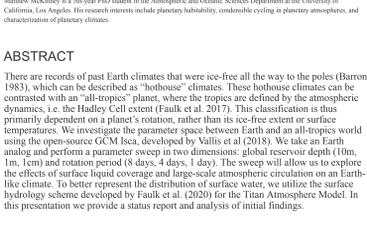


Figure 13: Outline of TAM hydrology scheme as described in Faulk et al. 2020. The scheme includes both surface runoff (R) and infiltration (I), plus subsurface transport (R2) and evaporation directly from the subsurface table (E).

AUTHOR INFORMATION

Matthew McKinney is a 5th-year PhD student in the Atmospheric and Oceanic Sciences Department at the University of California, Los Angeles. His research interests include planetary habitability, condensable cycling in planetary atmospheres, and characterization of planetary climates.

ABSTRACT

There are records of past Earth climates that were ice-free all the way to the poles (Barron 1983), which can be described as "hothouse" climates. These hothouse climates can be contrasted with an "all-tropics" planet, where the tropics are defined by the atmospheric dynamics, i.e. the Hadley Cell extent (Faulk et al. 2017). This classification is thus primarily dependent on a planet's rotation, rather than its ice-free extent or surface temperatures. We investigate the parameter space between Earth and an all-tropics world using the open-source GCM Isca, developed by Vallis et al. (2018). We take an Earth analog and perform a parameter sweep in two dimensions: global reservoir depth (10m, 1m, 1cm) and rotation period (8 days, 4 days, 1 day). The sweep will allow us to explore the effects of surface liquid coverage and large-scale atmospheric circulation on an Earth-like climate. To better represent the distribution of surface water, we utilize the surface hydrology scheme developed by Faulk et al. (2020) for the Titan Atmosphere Model. In this presentation we provide a status report and analysis of initial findings.

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