

# CLIMATE OF EARTH-LIKE PLANETS WITH AND WITHOUT OCEAN HEAT TRANSPORT ORBITING A RANGE OF M AND K STARS

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## Introduction:

The mean surface temperature of a planet is now acknowledged as insufficient to surmise its full potential habitability. Advancing our understanding requires exploration with 3D general circulation models (GCMs), which can take into account how gradients and fluxes across a planet's surface influence the distribution of heat, clouds, and the potential for heterogeneous distribution of liquid water. Here we present 3D GCM simulations of the effects of alternative stellar spectra, instellation, model resolution, and ocean heat transport, on the simulated distribution of heat and moisture of an Earth-like planet (ELP).

## Model:

We use the ROCKE3D (Resolving Orbital and Climate Keys of Earth and Extraterrestrial Environments with Dynamics), a generalized version of the NASA Goddard Institute for Space Studies (GISS) GCM, which is a well-known community Earth System Model routinely used to simulate the Earth's recent past, current, and future climates. We forced the GCM configured for the 1850 preindustrial Earth with different stellar spectral irradiances, with non-interactive atmospheric chemistry ("NINT" configuration of ModelE, (Schmidt et al., 2014)). The model was run at  $4^\circ \times 5^\circ$  with 20 vertical layers until equilibrium, with and without ocean heat transport (OHT). The ocean configurations included a 100 m slab ocean with q-fluxes set to zero ("q0"), and a 13-layer 1000 m deep fully dynamic ocean ("d1000").

**Stellar spectra and top-of-the-atmosphere instellation:** We forced the GCM with radiation spectra for the Sun-Earth (relative instellation, stellar constant=1366 W/m<sup>2</sup>), the K2V star HD22049, the M1V Kepler-186, and the M3.5V AD Leo, and the M4V GJ876 (Figure 1).

**Results:** Because of the red-shifted spectral energy distributions of HD22049 and Kepler-186, there is greater absorption by O<sub>3</sub> and H<sub>2</sub>O and an increased stellar radiation heating rate in the upper atmosphere. This leads to non-monotonic trends: from the G2V Sun to M1V Kepler-186, the planet initially warms, but with the redder stars M3.5V AD Leo and M4V blackbody, the planet cools. Ocean heat transport, instead of moderating the stellar effect, instead ac-

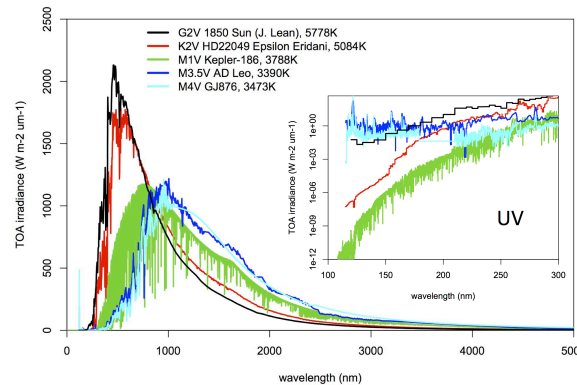


Figure 1. Five stellar spectra top-of-the-atmosphere irradiance used to force the GISS GCM ROCKE3D. Credits: G2V Sun: Judith Lean (measured); K2V HD22049: Segura et al. (2003) (measured); M1V Kepler-186: Von Paris (pers. comm.) (modeled); M3.5V AD Leo: Segura et al. (2005) (measured); M4V GJ876: Aki Roberge ( $\leq 1000$  nm measured,  $>1000$  nm black-body).

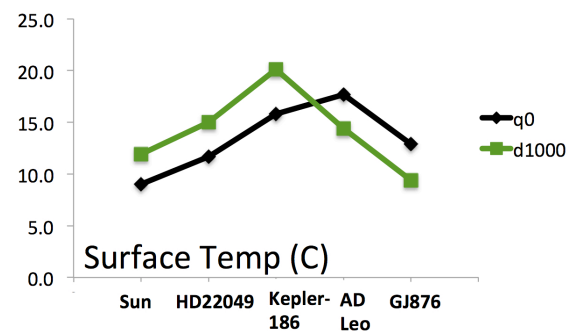
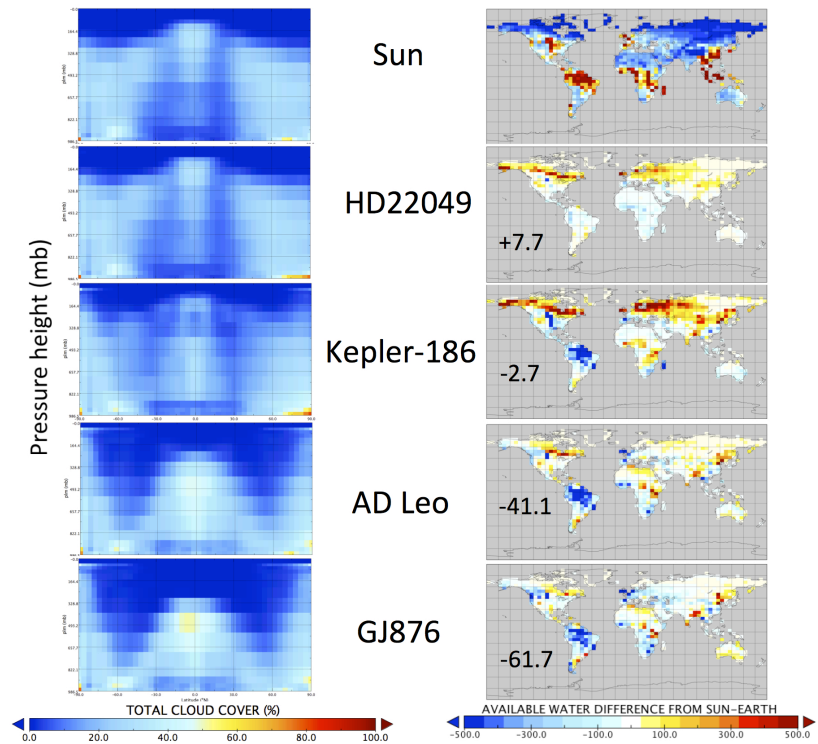


Figure 2. Non-monotonic mean global surface temperature trends with stellar spectral shift to redder, accelerated rather than damped by ocean heat transport.

celerates these trends (Figure 2).

With redder stars, the increased static stability of the atmosphere leads to reduced deep moist convection, weakening of mid-latitude storms, and a loss of high clouds in the mid-latitudes (Figure 3). This leads to greater emission to space from lower altitude, decreased surface temperature, less poleward heat transport by storms, and thus sea ice expands, surface albedo increases, and the planets cools with the reddest stars. Because of the resulting greater atmospheric stability, precipitation is steadily reduced with the M stars (Figure 3). The K star HD22049 produces a "sweet spot" of clement conditions, warmer and more uniformly available liquid water across land for life, thus improving the potential detectability of surface biosignatures.

Figure 3. Left: Total cloud cover percent by pressure height vs. latitude shows loss of mid-latitude high clouds with the reddest stars. Right: Available liquid land water relative to the G2V Sun, increases with the K star HD22049, then decreases with redder stars due to reduced precipitation because of increased atmospheric stability of the atmosphere.



#### References:

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