Equilibrium Temperatures and Albedos of Habitable Earth-Like Planets in a Coupled Atmosphere-Ocean GCM

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Introduction

The potential habitability of exoplanets is typically categorized using the nominal equilibrium temperature(T^n_{eq}) for a planet with an Earth-like planetary (Bond) albedo of 0.3 or 0 (e.g., [1], [2]). T^n_{eq} requires knowledge only of the luminosity of the host star and the planet's distance from it. As an indicator of habitability, though, it leaves much to be desired because albedos of other planets can be very different, and because surface temperature exceeds equilibrium temperature by the amount of the atmosphere's greenhouse effect. Attempts to account for these have been made using 1-D models [3], but these models do not properly account for clouds, sea ice and atmospheric and ocean dynamics.

The question thus arises: Given a large number of candidate habitable planets and resource limits that allow only a few to be observed intensely to characterize their atmospheres, how should the choices be made?

GCM Experiments

3D global climate models (GCMs) can address these issues, but they are computationally expensive and thus only a limited number of GCM exoplanet studies have been carried out to date. We use the GISS ROCKE-3D GCM [4] to determine whether predictions more useful than those based on T^n_{eq} can be obtained for ***Earth-like*** exoplanets with information that will be available for every known exoplanet. Our GCM couples the atmosphere to a dynamic ocean, which is necessary for a realistic assessment of habitability for planets with oceans.

A large ensemble of simulations that vary every possible external parameter to represent all possible habitable planets does not yet exist. Instead, we use an "ensemble of opportunity" of 29 simulations already conducted with ROCKE-3D, all for 1 bar N_2 atmospheres with CO_2, some with CH_4, and all with a surface water reservoir:

Proxima Centauri b [5]: 10 experiments varying incident stellar flux, greenhouse gas concentrations, ocean salinity, spin-orbit configuration, and fractional ocean coverage.

GJ 876 [6]: 4 aquaplanet experiments that vary incident stellar flux.

Ancient Venus [7]: 3 experiments for different insolations.

Ancient Earth [8]: 6 experiments, 3 Archean with different greenhouse gas amounts,1 Paleoproterozoic, 1 Neoproterozoic and 1 Cretaceous.

Earth inner edge approach [9]: 5 cases varying insolation and rotation.

Kepler 1649-b analog: Idealized with weaker instellation than the actual planet and slow synchronous rotation.

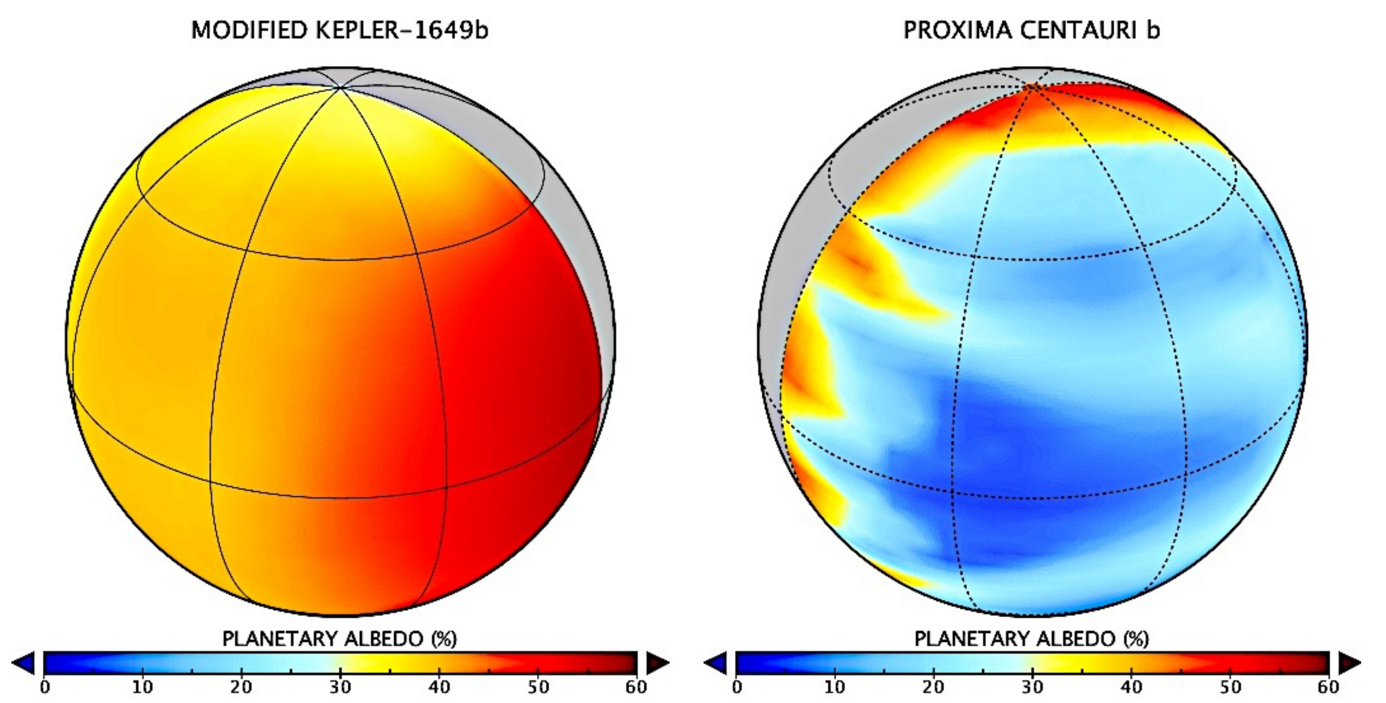

Fig. 1. *Planetary albedo maps for the (left) modified Kepler-1649b and (right) Proxima Centauri b GCM simulations.*

Fig. 1 illustrates two major controls on planetary albedo that cause planets to deviate from Earth's A = 0.3. The modified Kepler-1649b shows a consistent GCM feature of synchronously but slowly rotating planets: Rising air on the dayside that creates optically thick convective clouds and a high albedo (A = .42). Proxima Centauri b also has bright dayside clouds but less so due to its weak instellation (.65 times Earth's). Its albedo is lower than Earth's (A = .23) because of the very cool star it orbits. Proxima Centauri's mostly near-IR emission is strongly absorbed by H_2O and CO_2, reducing the impact of the clouds. Kepler-1649b also orbits a cool star, but the instellation is so strong (1.4 times Earth's) that the cloud albedo effect dominates.

A Simple Prediction of Planetary Albedo

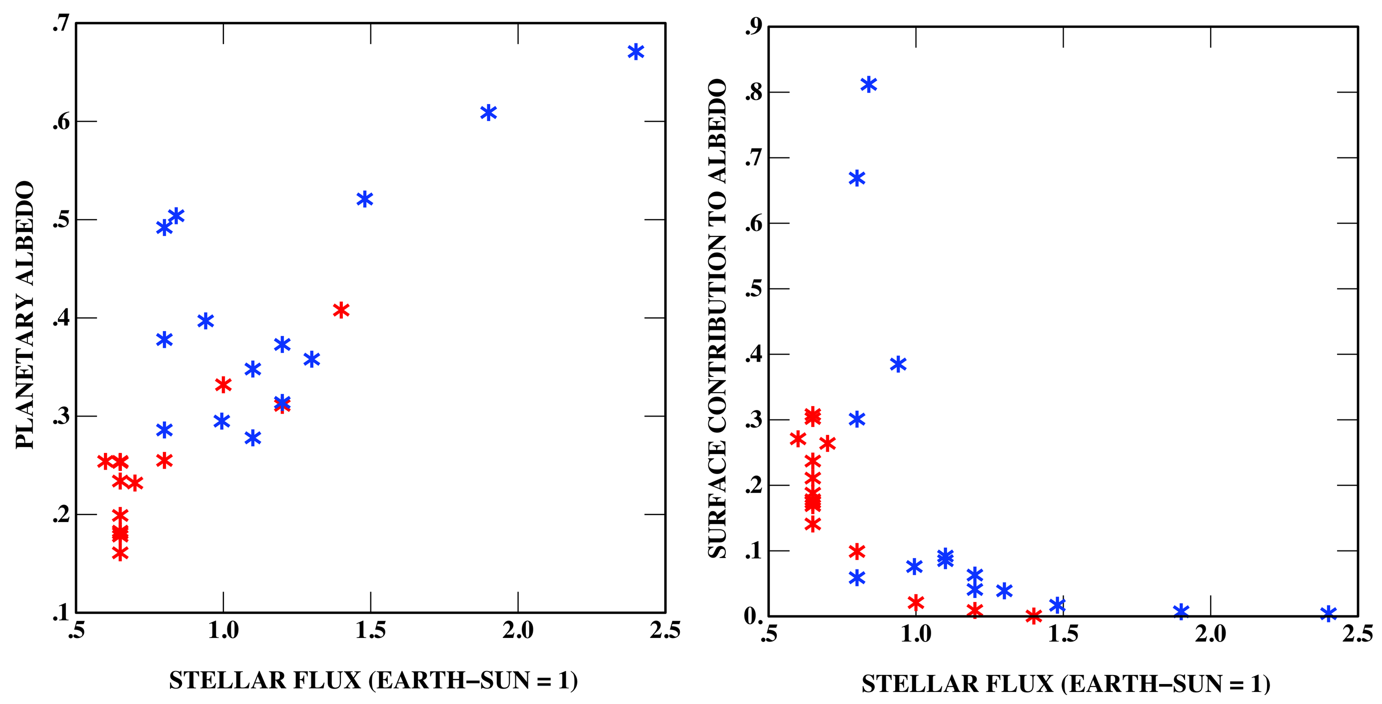

Fig. 2. *(Left) Bond albedo and (right) surface fractional contribution to albedo vs. normalized incident stellar flux S0X. Blue/red = warm/cool star.*

Fig. 2 (left) shows that A and S0X (incident stellar flux relative to the solar constant S_o) are highly correlated for the ensemble. A < 0.3 is limited to planets more weakly irradiated than Earth with only one exception. This suggests that ***S0X and stellar temperature (T_{star}), known quantities for any exoplanet, might be used to predict A***, subject to several caveats:

•The exception mentioned above is for a 16 d rotation period, non-tidally locked planet with S0X = 1.1 that is not dominated by a day-night circulation. This also occurs for synchronously rotating planets with short rotation periods, which are not yet represented in our ensemble.

•High A occurs for weakly irradiated planets orbiting the Sun because sea ice and snow, not clouds, control A on snowball planets. In Fig. 2 (right), it can be seen that the surface contribution to Bond albedo (calculated using the approach of [10]) is significant only for S0X <1. Our ensemble does not yet include thick CO_2 "maximum greenhouse" atmospheres, which will deviate from the behavior seen in Fig. 2.

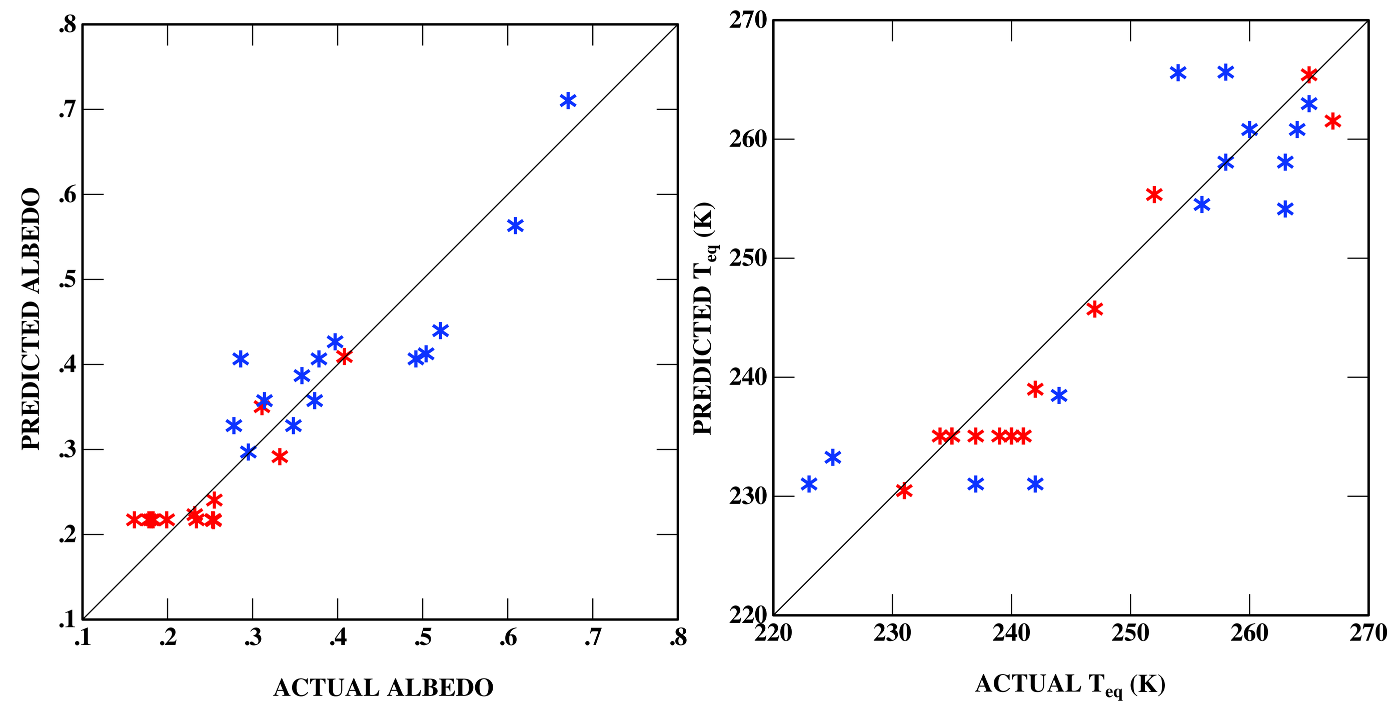

Fig. 3. *Left: Predicted vs. actual planetary albedo. Right: Predicted vs. actual equilibrium temperature. 1:1 lines are also shown for reference.*

With these caveats in mind, we predict Bond albedo A^p with two simple regressions of GCM planetary albedo A against S0X and T_{star}, one for cloud-dominated and another for surface-dominated planets:

$$A^p = .2941\ S0X + .0126\ T'_{star} - .0107 \qquad (S0X \geq 1)$$
$$A^p = .1210\ S0X + .2894\ T'_{star} - .0575 \qquad (S0X < 1)$$

(where $T'_{star} = T_{star}/4500$) and use it to predict equilibrium temperature T^p_{eq}. The left panel of Fig. 3 shows the predicted vs. actual A. For the usual assumption A=0.3, the RMS error in A across our ensemble is 0.12. Using the regression above, the RMS error is reduced to 0.06.

The predicted equilibrium temperature is

$$T^p_{eq} = [S_o(1-A^p)S0X/4\sigma]^{1/4}$$

where S_o = 1361 W/m² is the incident solar flux on Earth and σ is the Stefan-Boltzmann constant. The right panel of Fig. 3 shows predicted vs. actual T_{eq}. The RMS error in T_{eq} using A^p is 6 K, vs. 15 K for A = 0.3.

References: [1] Borucki et al. (2012) *ApJ* 745:10; [2] Anglada-Escude et al. (2016) *Nature* 536: 47; [3] Selsis et al. (2007) *A&A* 476:1373; [4] Way et al. (2017) *ApJSS* 231:12; [5] Del Genio et al. (2017), *AsBio* subm., arXiv:1709.02051; [6] Fujii et al. (2017), *ApJ* 848;100; [7] Way et al. (2016), *GRL.* 43:8376; [8] Sohl et al. (2017), *ApJ* in prep.; [9] Way et al. (2015), arXiv:1511.07283; [10] Donohoe & Battisti (2011) *J. Clim.* 24:4402; [11] Wolf (2017), *ApJL* 839:L1; [12] Turbet et al. (2017) *A&A* subm., arXiv:1707.06927; [13] Fujii et al. (2017) *ApJ* 848:100; [14] Kopparapu et al. (2017) *ApJ* 845:5; [15] Bean et al. (2017) *ApJL* 841:L24.

How Well Does T_{eq} Predict Surface Temperature?

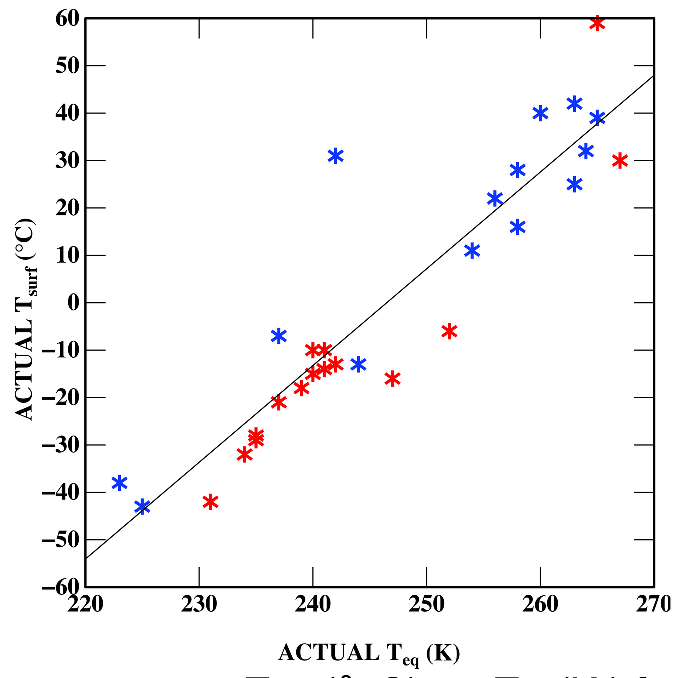

Fig. 4. Surface temperature T_{surf} (° C) vs. T_{eq} (K) for the GCM ensemble.

There is a strong relationship between T_{eq} and T_{surf} (Fig. 4), except for our Archean Earth with highly elevated CO_2 and CH_4, a much warmer planet with a strong greenhouse effect. A linear regression of T_{surf} vs. T_{eq} (line in Fig. 4) predicts T_{surf} with a 11.4° C RMS error. In units of K for T_{surf}:

$$T_{surf} = T_{eq} + 1.0415\ T_{eq} - 230.06 = T_{eq} + G_a,$$

where G_a is the greenhouse effect. Rearranging terms,

$$G_a = 1.0415(T_{eq} - T^E_{eq}) + G^e_a$$

where G^E_a = 35 K is G_a of Earth for T^E_{eq} = 254.6 K. This expression indicates that G_a (and thus T_{surf}) increase ~4% faster than T_{eq}, most likely because H_2O increases with temperature. The regression above predicts *A = 0.3* and *T_{surf} = 16.6° C* for Earth, close to observed. For Mars, a planet with little surface water, it is less successful (*-93° C*, vs. *-59° C* observed). For Proxima b it predicts *-23° C* vs. *-10* to *-32° C* for the GCM.

Using our S0X + T_{star}-based predictor T^p_{eq} to predict T^p_{surf} gives an RMS T_{surf} error of 17.6° C. Using T_{eq} for A=0.3, the RMS error is 32.8° C.

Predictions for Everyone's Favorite Exoplanets

Potential successes:

•Kepler-186 f (S0X 0.32, T_{star} 3755 K): T^p_{surf} = -102° C. This planet is unlikely to be habitable at the surface, a potential snowball.

•Kepler-452 b (S0X 1.11, T_{star} 5757 K): T^p_{surf} = 24° C. Potentially Earth-like, unless its size (1.5 R_E) makes it a mini-Neptune.

•LHS 1140 b (S0X 0.46, T_{star} 3131 K): T^p_{surf} = -61° C. Perhaps barely habitable if it has several bars of CO_2.

•TRAPPIST-1 e (S0X 0.66, T_{star} 2559 K): T^p_{surf} = -17° C. Habitable. A GCM [11] finds T_{surf} = -32 to +56 ° C depending on composition.

•TRAPPIST-1 f (S0X 0.38, T_{star} 2559 K): T^p_{surf} = -75° C. Likely a snowball if it has water. [11] finds -63° C but [12] is able to sustain liquid.

•GJ 273 b (S0X 1.06, T_{star} 3382 K): T^p_{surf} = 22° C. Potentially a warm Earth-like planet if it is rocky.

•GJ 3293 d (S0X 0.59, T_{star} 3480 K): T^p_{surf} = -38° C. Borderline habitable, a colder analog of Proxima Centauri b if it is rocky.

•K2-3 d (S0X 1.5, T_{star} 3896 K): T^p_{surf} = 41° C. Inner edge planet, borderline habitable, maybe a moist greenhouse [13,14].

•GJ 625 b (S0X 2.1, T_{star} 3499 K): T^p_{surf} = 35° C. Inner edge, moist greenhouse planet?

A likely failure:

•TRAPPIST-1 d (S0X = 1.14, T_{star} = 2559 K): T^p_{surf} = 28° C. [11] finds this to be a runaway planet. The prediction fails due to rapid rotation.

Conclusions and Future Work

✧A simple predictor of exoplanet habitability that uses only information available for any exoplanet (S0X, T_{star}) predicts T_{surf} with useful error bars for a wide range of GCM-simulated ***Earth-like*** exoplanets

✧Some needed improvements: (1) a predictor for the regime of low albedo, rapidly rotating close-in planets; (2) a predictor for thick CO_2 maximum greenhouse planets, e.g., see the proposal of [15].

✧The expanding library of GCM simulations for many models argues for a community effort to derive the most robust possible predictor.