Climate Outcomes of Earth-similar Worlds as a Function of Obliquity and Rotation Rate

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Abstract

A set of simulations with a 3D global climate model are performed to investigate the roles of obliquity and rotation period in the habitability of Earthlike exoplanets. The simulations cover the obliquity–rotation parameter space, from 0° to 90° in obliquity and 1–128 days in rotation period. The simulated global mean temperatures arewarmer at 45° obliquity with fast rotations, due to the modification of the greenhouse effect from the spatial redistribution of clouds and water vapor. The slow-moving insolation–cloud mechanism, previously found in simulations with slow rotations and zero obliquity, also produces a cooling trend from intermediate obliquity to high obliquity, with the coldest climate occurring at 90° obliquity for all rotation periods. At low obliquities and fast rotation, persistent snow and sea ice can form, producing cooler temperatures. A Climate Habitability metric is defined, based on temperature and precipitation, which compares well with observations when applied to a simulation using Earth’s obliquity and rotation. Over a wider range of obliquity and rotation period, the Climate Habitability ranges from 10% to 70% of the terrestrial area. Overall, the simulated global mean surface temperature shows a much larger spread across the range of simulated rotation periods at 45° obliquity compared to 0° obliquity. Therefore, we conclude that 3D exoplanet simulations using intermediate obliquities (e.g., 45°) instead of 0° will reveal a wider range of possible climate conditions for specific orbital configurations. In addition, Earth’s climate habitability can increase by 25% if the obliquity increases from 23°5 to 45°.

Unified Astronomy Thesaurus concepts: Exoplanet atmospheric variability (2020); Planetary climates (2184)

1. Introduction

The question of whether any of the currently known terrestrial planets could support life has attracted great interest within the scientific community and among the general public. To first order, the potential for a planet to support life is based on estimates of the planet’s equilibrium temperature, given the planet’s radius (typically constrained to ~5% by transit depth; Fulton & Petigura 2018), its distance from the star (typically constrained to within 1%, by measuring the planet’s orbital period and stellar mass; Akesson et al. 2013; Kane 2014), and an assumed average global albedo (usually poorly constrained observationally; von Paris et al. 2016). Calculations of exoplanet equilibrium temperatures have thus given rise to lists of known exoplanets that could have surface temperatures allowing for the presence of liquid water (Kane et al. 2016).

However, the true picture of an exoplanet’s potential for life — and the available niches for living organisms—is much more complex than the estimated equilibrium temperature might imply. The habitability of our own living world depends on an intricate web of strongly nonlinear processes and dynamic feedback loops that govern the Earth’s climate across many different timescales (Neelin 2011), and these processes interact with one another to manifest the Earth’s ever-evolving, oftentimes nondeterministic, global climate variations (Zachos et al. 2001; Tyrrell 2020). For example, variations in the Earth’s orbital and rotational dynamics cause changes in both the intensity and spatial-temporal distribution of insolation (Berger 1978), which in turn impacts the length and intensity of the seasons, thereby leading to new atmospheric circulation patterns (Williams & Holloway 1982), which alter the distribution of snow and ice on the Earth’s surface, leading to changes in greenhouse gas concentrations in the atmosphere (Foster et al. 2017; Milanković 1941). As a result, our own planet has experienced climatic states ranging from snowball Earth events to ice-free, fully vegetated greenhouses—within just the past 700 million yr (Fairchild & Kennedy 2007; Huber et al. 2018).

In this paper, we explore planetary habitability within the traditional circumstellar habitable zone, by modeling climate outcomes for planets that are near twins of the Earth, but that have different combinations of day length (rotation rate) and axial tilt (obliquity). To assess exoplanet climate outcomes over the rotation–obliquity phase space, we use the ROCKE-3D generalized global climate model (GCM) developed at the NASA Goddard Institute for Space Studies (GISS; Way et al. 2017). A 3D GCM uses mathematical equations to simulate the general circulation of the atmosphere and oceans and to describe (1) the conservation of energy, mass, moisture, and momentum, and (2) the equation of state relating temperature and pressure. In addition, 3D GCMs such as ROCKE-3D use parameterizations of a vast array of other climate processes, such as cloud formation, convection, precipitation, formation of sea ice, soil and vegetation interactions with the atmosphere, etc. In addition, 3D GCMs such as ROCKE-3D coupled to dynamic ocean models reveal how the inclusion of more realistic ocean circulation and heat transport can dramatically alter our perspective of a planet’s habitability potential...
With radiative time steps that are an hour or less, and dynamic time steps as short as a few minutes, GCMs are also capable of responding to diurnal forcings and simulating seasonal climate changes. GCMs also provide a view of the geographic distribution of surface temperature and rainfall, enabling us to examine what portion of the planet can sustain liquid water, and for what period of time.

To account for the dependence of habitability on the spatial distribution of temperature and/or precipitation on the exoplanets, we define Temperature Habitability, Precipitation Habitability, and Climate Habitability based on surface temperature, precipitation, and the combination of both for each of the 3D simulations. The Temperature Habitability uses the classical above-freezing temperature for the existence of liquid water as the criterion for the habitability threshold, is defined as the fraction of the year with monthly temperatures above 0°C, and bears a value between 0 and 1. Jansen et al. (2019) used similar criteria in their calculation of the global distribution of “fraction habitability” from all their simulations with zero obliquity. For our simulations with obliquity variations from 0° to 90°, applying the above-freezing temperature threshold to the 12 month climatological temperatures accounts for seasonal animal migrations as adaptations to shifts of habitability (Figure 1, lower right). The Precipitation Habitability is defined according to the threshold of 30 cm (12 inches) of accumulative annual total precipitation and bears a value of 0 or 1. Applying this threshold to the observations of annual total precipitation during 1980–2010 (Willmott & Matsuura 2018) identifies regions that correspond to the major deserts around the globe (Figure 1, middle right). We define the Climate Habitability as the fraction of the year with monthly temperatures above 0°C and annual precipitation above 30 cm, which is essentially the product of the Temperature Habitability and the Precipitation Habitability (Figure 1, top left). The Climate Habitability derived from observations of terrestrial air temperature and precipitation during 1980–2010 (Willmott & Matsuura 2018) demonstrates that it provides a reasonable estimate of the global distribution of surface quality for life, with 0 Climate Habitability in the desert regions, perfect Climate Habitability in the tropical rain forest regions, and partial Climate Habitability in the midlatitude regions that many animals need to adapt to via seasonal migrations. A comparison between the derived Climate Habitability and Temperature Habitability from observations shows that the Climate Habitability has a better fit with the observed global distribution of surface quality for life by removing the desert regions in the subtropics and subarctic zone (Figure 1, right).

Previous studies suggest that large obliquities and strong obliquity variations can be a mechanism for expanding the outer edges of traditional habitability zones. Using a 1D Energy Balance Model (EBM), Spiegel et al. (2009) show that the severe climate with large-amplitude seasonal variations in high-obliquity exoplanets can also maintain seasonally and regionally habitable conditions. Using a different 1D EBM, Armstrong et al. (2014) show that large and rapid obliquity oscillations can suppress the ice-albedo feedback, increasing the outer edge of the habitable zone, therefore such exoplanets are more likely to be habitable than those with negligible oscillations, such as Earth. Using 3D exoplanet simulations, Colose et al. (2019) investigated the response of exoplanet climates to two different obliquities at 20° and 75° in an aquaplanet configuration (i.e., no continents) and found that the exoplanet climates appear to be warmer with higher obliquity. In addition, 3D exoplanet simulations have shown that planets exhibit a cooler climate with a slower rotation period as a result of the increase of the planetary albedo due to the expansion of the clouds from the tropics to the polar regions (Yang et al. 2014). More recently, Jansen et al. (2019) and Guzewich et al. (2020) used a different 3D GCM to explore climate variation with rotation and stellar insolation, and demonstrated a similar result to Yang et al. (2014), with the climates becoming cooler as the rotation period increases. None of these studies explored variation with obliquity, and used either zero or modern Earth values for obliquity. Since Colose et al. (2019) only investigated two different obliquities, more studies are needed to obtain the full response of exoplanet climates to obliquity variations from 0° to 90°, along with variations of rotational periods. In this study, we perform a complete set of 3D simulations to explore the impact of obliquity on the surface climate of Earth-similar planets, whose size, atmosphere, and insolation are equivalent to the Earth’s, but with different obliquity and rotation periods, to study how a wide variety of planetary parameters impact habitability for Earthlike exoplanets.

The remainder of this paper is structured as follows. In Section 2, we describe the configuration of the 3D exoplanet climate model and the experiment setup, which covers the 2D obliquity–rotation parameter space. In Section 3, we describe the simulation results, with a focus on the dependence of the exoplanet climate on obliquity. In Section 4, we describe the results for the dependence of the Climate Habitability on obliquity and rotation period. We conclude in Section 5, with a discussion of the implications of our study for experiment setups of 3D exoplanet models for habitability studies.

2. Methods

2.1. Configuration of 3D Exoplanet Climate Model (ROCKE-3D)

The model we use in this study is the Resolving Orbital and Climate Keys of Earth and Extraterrestrial Environments with Dynamics Planetary GCM (ROCKE-3D), developed at NASA’s GISS (Way et al. 2017). ROCKE-3D is a generalized version of the GISS ModelE2-R coupled ocean–atmosphere GCM (Schmidt et al. 2014), with additions and modifications that allow for exoplanetary and ancient Earth paleoclimate scenarios, particularly where surface and atmospheric boundary conditions are markedly different from the present day. Improvements to the calendaring system have also made ROCKE-3D adaptable for studies of the effects of varied spin–orbit configurations (Way et al. 2017), and the addition of a SOCRATES radiation scheme (Edwards 1996; Edwards & Slingo 1996) allows the model to simulate planetary climates using different incident stellar spectra (Way et al. 2017). These options enable exoplanet scientists to explore how exoplanet climates are impacted by the combined effects of many potential parameters, and they have been used to run ROCKE-3D for ancient Venus and Mars, water worlds orbiting M stars, and modern Earths having higher insolation and altered atmospheric chemistry (e.g., Way et al. 2018; Del Genio et al. 2019; Jansen et al. 2019).

The atmosphere in ROCKE-3D uses 40 vertical layers with a top at 0.1 hPa. Prognostic variables in ROCKE-3D are
calculated using the conservation equations for mass, energy, momentum, and moisture, and include hundreds of variables, such as air temperature, water vapor, pressure, winds, clouds, rain and snow in the atmosphere, salinity, temperature, current and sea ice distribution in the ocean, and surface temperature, albedo, and snow depth over the land. All our simulations use the computationally efficient resolution of $4^\circ \times 5^\circ$ (lat x lon), which is computationally efficient. It is noteworthy, however, that ROCKE-3D utilizes a second-order differencing scheme in the momentum and mass equations and a unique quadratic upstream scheme for heat and moisture advection, which implicitly increases the absolute model resolution to enable a more accurate depiction of processes on smaller scales (Schmidt et al. 2006). The ocean model is a fully coupled dynamic ocean, with 13 vertical layers down to a possible depth of 5000 m (Russell et al. 1995). Another option for the ocean model (the “bathtub” ocean) is to run the coupled dynamic ocean with a depth of 1360 m, only utilizing the upper 10 layers in ROCKE-3D (Way et al. 2018). The continental layout and land topography are roughly those of modern Earth, with a surface albedo of 0.2, as a rough average of a clay and sand mix. The surface albedo will be modified by accumulated snow cover. All simulations use the insolation values for modern Earth. We refer the reader to Way et al. (2017, 2018) for a full description of the atmosphere, ocean, land, and sea ice components of ROCKE-3D, as well as its current and near-future capabilities as a community model for studying planetary and exoplanetary atmospheres.

We use a baseline version of ROCKE-3D, known as Planet_1.0, with the “bathtub” ocean configuration for all the simulations in this study, which allows the model to come into a steady climate state (“radiative equilibrium”) much faster (~600 model years) than it would with the full-depth ocean. The throughput of the ROCKE-3D simulation with 44 cores is ~0.5 hr per model year, and a typical ROCKE-3D run with 600 model years takes ~300 hr (~two weeks) to complete. We use

**Figure 1.** Spatial distribution of the Climate Habitability, Precipitation Habitability, and Temperature Habitability derived from observations of terrestrial air temperature and precipitation during 1980–2010 (Willmott & Matsuura 2018; right column), and ROCKE-3D simulations with 25° obliquity and 1 day rotation (left column). Climate Habitability: the fraction of the year with monthly temperatures above 0°C and annual precipitation above 30 cm (top); Precipitation Habitability: annual precipitation above 30 cm (middle); Temperature Habitability: the fraction of the year with monthly temperatures above 0°C (bottom). The Temperature Habitability ranges between 0 and 1 as a consequence of the strong seasonality in the mid–high latitudes of the northern hemisphere.
to slow rotations (16–128 days) and from intermediate obliquity to high obliquity (45°–90°)—in particular, the coldest climate falls at 90° obliquity for all rotations (2–128 days); and (3) a general cooling trend from fast rotations to slow rotations is interrupted by a warming episode near 16 days of rotation for low obliquities (0°–15°). Figure 3 shows the annual mean surface temperature from nine simulations, with three rotational periods from fast to slow rotations (2, 8, and 128 days) and three obliquities from low to high obliquity (0°, 45°, and 90°). The warmest surface temperature with 45° obliquity/2 days of rotation exhibits an above-zero annual mean temperature globally, except for high-elevation regions over Greenland, Eastern Antarctica, and the Tibetan Plateau. The cooler climates in high-obliquity or slow-rotation simulations exhibit a warm ocean–cold continent pattern, with above-freezing surface temperatures in coastal regions. It is notable that the polar regions in the Arctic and Southern Ocean are only below freezing and ice-covered in a narrow obliquity–rotation parameter space with low-obliquity and fast–intermediate rotations. Figure 4 shows the global mean values of four key climate parameters that characterize three major climate mechanisms that are responsible for the temperature distributions in the obliquity–rotation parameter space: (1) the obliquity-driven modification of the greenhouse effect (the “obliquity–greenhouse mechanism”), where the insolation seasonal variation in fast rotators modifies the spatial distribution of clouds and water vapor, leading to stronger longwave radiation feedback at 45°; (2) according to the shortwave cloud radiative forcing, there is enhanced cloud cooling under slow-moving insolation forcing (the “slow-moving insolation–cloud mechanism”), with slow rotations or high obliquities that are responsible for the cold climates in this obliquity–rotation parameter space; and (3) as will be shown in Section 3.4, the snow–ice fraction exhibits great reductions around 16 days of rotation with low obliquities, due to the expansion of the Hadley cell into the polar region (the “Hadley cell–polar ice mechanism”), which is responsible for the warming episodes in this parameter space. In Sections 3.2–3.4 below, we will provide further discussion of each of the three mechanisms.

3.2. Warmest Climate Occurs at 45° Obliquity for Fast Rotations

Generally, the global water vapor amount is expected to be tightly controlled by the temperature, as the saturation vapor pressure of water is a strong function of temperature via the Clausius–Clapeyron relation. Because of this first-principles relationship, the water vapor amount is viewed as a response to temperature, with the average water vapor increasing by roughly 7% per °C for typical temperatures in the present-day Earth atmosphere (Held & Soden 2006). The increased water vapor then increases the greenhouse effect, inducing feedback to the radiative forcing that can lead to additional warming beyond the initial temperature response.

This relationship between the average water vapor and temperature generally holds for spatially constant radiative forcings (such as increasing carbon dioxide concentration), but it does not hold for spatially varying forcing or temperature responses (Back et al. 2013; Rose & Rencurrel 2016). Increasing the obliquity introduces a strong spatially varying forcing through the seasonal variation of solar insolation. The insolation pattern modifies the distribution of the water vapor regionally, modifying the strength of the water vapor feedback to slow rotations (16–128 days) and from intermediate obliquity to high obliquity (45°–90°)—in particular, the coldest climate falls at 90° obliquity for all rotations (2–128 days); and (3) a general cooling trend from fast rotations to slow rotations is interrupted by a warming episode near 16 days of rotation for low obliquities (0°–15°). Figure 3 shows the annual mean surface temperature from nine simulations, with three rotational periods from fast to slow rotations (2, 8, and 128 days) and three obliquities from low to high obliquity (0°, 45°, and 90°). The warmest surface temperature with 45° obliquity/2 days of rotation exhibits an above-zero annual mean temperature globally, except for high-elevation regions over Greenland, Eastern Antarctica, and the Tibetan Plateau. The cooler climates in high-obliquity or slow-rotation simulations exhibit a warm ocean–cold continent pattern, with above-freezing surface temperatures in coastal regions. It is notable that the polar regions in the Arctic and Southern Ocean are only below freezing and ice-covered in a narrow obliquity–rotation parameter space with low-obliquity and fast–intermediate rotations. Figure 4 shows the global mean values of four key climate parameters that characterize three major climate mechanisms that are responsible for the temperature distributions in the obliquity–rotation parameter space: (1) the obliquity-driven modification of the greenhouse effect (the “obliquity–greenhouse mechanism”), where the insolation seasonal variation in fast rotators modifies the spatial distribution of clouds and water vapor, leading to stronger longwave radiation feedback at 45°; (2) according to the shortwave cloud radiative forcing, there is enhanced cloud cooling under slow-moving insolation forcing (the “slow-moving insolation–cloud mechanism”), with slow rotations or high obliquities that are responsible for the cold climates in this obliquity–rotation parameter space; and (3) as will be shown in Section 3.4, the snow–ice fraction exhibits great reductions around 16 days of rotation with low obliquities, due to the expansion of the Hadley cell into the polar region (the “Hadley cell–polar ice mechanism”), which is responsible for the warming episodes in this parameter space. In Sections 3.2–3.4 below, we will provide further discussion of each of the three mechanisms.

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Table 1

Obliquity, Rotation Periods, Run Length, and Global Mean Surface Temperature for the 70 Experiments on the Obliquity–Rotation Grids

| Obliquity (degrees) | Rotation (Earth days) | Run Length (model years) | Global $T$ ($^\circ$C) | Obliquity (degrees) | Rotation (Earth days) | Run Length (model years) | Global $T$ ($^\circ$C) |
|---------------------|-----------------------|--------------------------|------------------------|---------------------|-----------------------|--------------------------|------------------------|
| 0                   | 1                     | 800                      | 11.1                   | 0                   | 16                    | 700                      | 12.1                   |
| (10)                | 1                     | 800                      | 11.7                   | (8)                 | 16                    | 700                      | 12.2                   |
| 15                  | 1                     | 1000                     | 12.6                   | 15                  | 16                    | 800                      | 12.3                   |
| (20)                | 1                     | 600                      | 14.0                   | 30                  | 16                    | 600                      | 13.0                   |
| (25)                | 1                     | 600                      | 15.4                   | 45                  | 16                    | 600                      | 11.9                   |
| 30                  | 1                     | 800                      | 17.2                   | (55)                | 16                    | 800                      | 10.7                   |
| (40)                | 1                     | 1000                     | 19.0                   | 60                  | 16                    | 700                      | 10.1                   |
| 45                  | 1                     | 600                      | 19.6                   | 75                  | 16                    | 600                      | 8.6                    |
| (50)                | 1                     | 1000                     | 19.7                   | 90                  | 16                    | 600                      | 8.0                    |
| 0                   | 2                     | 600                      | 10.4                   | (0)                 | 24                    | 600                      | 10.9                   |
| 15                  | 2                     | 1100                     | 10.8                   | (17)                | 24                    | 700                      | 11.1                   |
| 30                  | 2                     | 600                      | 15.1                   |                     |                       |                          |                        |
| 45                  | 2                     | 1000                     | 16.7                   | 0                   | 32                    | 600                      | 9.8                    |
| 59                  | 2                     | 600                      | 14.0                   | 15                  | 32                    | 700                      | 9.8                    |
| 75                  | 2                     | 600                      | 10.8                   | 30                  | 32                    | 600                      | 9.1                    |
| 90                  | 2                     | 500                      | 9.6                    | 46                  | 32                    | 500                      | 8.2                    |
|                     |                       |                          |                        |                     |                       |                          |                        |
| 0                   | 4                     | 400                      | 9.1                    | 75                  | 32                    | 600                      | 6.4                    |
| (8)                 | 4                     | 500                      | 9.0                    | 90                  | 32                    | 600                      | 6.1                    |
| 15                  | 4                     | 600                      | 9.1                    |                     |                       |                          |                        |
| 31                  | 4                     | 600                      | 13.3                   | 0                   | 64                    | 400                      | 7.0                    |
| 45                  | 4                     | 1000                     | 13.6                   | 17                  | 64                    | 500                      | 6.8                    |
| 60                  | 4                     | 1000                     | 11.0                   | 30                  | 64                    | 400                      | 6.6                    |
| 75                  | 4                     | 600                      | 8.8                    | 45                  | 64                    | 400                      | 6.5                    |
| 90                  | 4                     | 600                      | 8.0                    | 60                  | 64                    | 400                      | 6.2                    |
|                     |                       |                          |                        |                     |                       |                          |                        |
| (0)                 | 6                     | 600                      | 6.2                    | (82)                | 64                    | 500                      | 5.9                    |
| (17)                | 6                     | 600                      | 8.0                    | 90                  | 64                    | 300                      | 5.8                    |
| 0                   | 8                     | 600                      | 7.9                    | 0                   | 128                   | 300                      | 6.5                    |
| (8)                 | 8                     | 600                      | 8.2                    | 15                  | 128                   | 300                      | 6.3                    |
| 15                  | 8                     | 600                      | 9.2                    | 30                  | 128                   | 300                      | 6.0                    |
| 30                  | 8                     | 600                      | 12.6                   | (35)                | 128                   | 500                      | 6.0                    |
| 45                  | 8                     | 600                      | 12.7                   | 44                  | 128                   | 500                      | 5.9                    |
| 60                  | 8                     | 600                      | 10.5                   | 60                  | 128                   | 300                      | 5.6                    |
| 75                  | 8                     | 600                      | 8.8                    | 75                  | 128                   | 300                      | 5.2                    |
| 90                  | 8                     | 600                      | 8.0                    | 90                  | 128                   | 600                      | 5.0                    |
| (0)                 | 12                    | 600                      | 10.1                   |                     |                       |                          |                        |
| (17)                | 12                    | 700                      | 11.0                   |                     |                       |                          |                        |
from the Clausius–Clapeyron limit. This mechanism works only for fast-rotation periods, because rotational dynamics (e.g., Coriolis forces) are needed to produce zonal structures in the atmosphere, such as the Hadley cell or midlatitude storm tracks. Likewise, cloud distributions will follow similar patterns, contributing to the modulation of the greenhouse effect locally through their longwave radiative effects.

The combined effects of spatially varying patterns of water vapor and cloud responses result in an obliquity-driven modification of the greenhouse effect that produces the maximum global mean surface temperature at 45° obliquity for fast rotators. For 0° or 90° obliquity, the insolation is more concentrated in the tropics or polar regions, respectively. The water vapor (Figure 5, middle column) and associated downward longwave radiation (Figure 5, right) also tend to be confined in those regions. For 45° obliquity, the insolation and the associated downward longwave radiation are more uniformly distributed around the globe. As a result, the global average of the water vapor at 45° obliquity is 22.9 kg m⁻², which is 20% and 37% more than that at 0° (19.1 kg m⁻²) and 90° obliquity (16.7 kg m⁻²), respectively. This is associated with stronger water vapor feedback, in which the global average of the downward longwave radiation at the surface at 45° obliquity is 341.2 W m⁻², which is 8% and 13% more than that at 0° (314.6 W m⁻²) and 90° obliquity (301.7 W m⁻²), respectively.

3.3. Coldest Climate Occurs at 90° Obliquity for All Rotations

The general cooling trend from intermediate rotation to slow rotation and from intermediate obliquity to high obliquity can be attributed to enhanced shortwave radiation reflection by clouds in climates with slow rotation or high obliquity. In both cases—slow rotation or high obliquity—the “migration” of the substellar point over the exoplanet surface is slower, due to the long diurnal cycle or extreme seasonality, respectively. Previous studies have shown that this slow migration of insolation over the planet’s surface creates clouds that can reflect the insolation more efficiently than the clouds resulting from the fast migration of insolation (Yang et al. 2014; Way et al. 2018). For example, Figure 6 (left to right) shows a comparison of the local insolation, shortwave cloud radiative forcing, and cloud water and ice path, between three climates (top to bottom) resulting from intermediate rotation (8 days, 0° obliquity and 90° obliquity) and slow rotation (128 days, 0° obliquity) at month 12 of year 600 of the simulation. The shortwave cloud radiative cooling will be largest in the regions with thick clouds, where the total cloud water and ice path is large (Figure 6, middle column versus right column). Compared with the 8 day rotation periods, the slow migration of insolation forcing in the 128 day rotation period results in both higher local insolation intensity and higher spatial correlation between the insolation maxima and cloud formation, which increases the shortwave cloud radiative cooling. For cases with high obliquity, the insolation movement is less affected by the rotation rates during the summer seasons, which results in slow movements of insolation forcing over the polar region that induce the similar effect of enhanced cloud cooling. Figure 6 (middle row versus bottom row) shows the simulation with 90° obliquity and 8 day rotation periods exhibiting a similar collocation of strong localized insolation forcing and cloud formation at the northern hemisphere polar region, which results in much larger cloud radiative cooling than in the low-obliquity simulation (Figure 6, middle row versus top row).
3.4. Nonlinear Temperature Response to the Increase in Rotations at Low Obliquities

The nonlinear trend of the warming episode between 8 and 16 days of rotation at low obliquity (Figure 2) is due to the surface warming associated with the expansion of the Hadley cell. The extent of the Earth’s Hadley cell is primarily determined by the Rossby radius of deformation (Schneider 1977), which is typically on the order of 1000 km for the Earth’s atmosphere at 1 day of rotation. Similar relationships have also been found in other terrestrial planets in the solar system in observational and modeling studies (Williams & Holloway 1982; Rees & Garrett 2019). When the rotation period increases from 2 to 16 days (Figure 7, left), the Hadley cell reaches the polar regions, due to the increase in the Rossby radius of deformation, from synoptic to planetary scale (Del Genio & Suozzo 1987; Way et al. 2018), and the associated poleward atmospheric heat transport melts the sea ice and snow in both polar regions (Figure 7, right). The loss of surface snow and ice decreases the planetary albedo, which then produces the warmer equilibrium climate state at this rotation rate. The warming episode occurs only at low obliquities, because at larger obliquities the insolation is much higher in polar regions, which prevents polar ice from forming (Figure 3).

4. Dependence of Habitability on Obliquity and Rotation

4.1. Climate Habitability Simulation in ROCKE-3D

In this section, we utilize the Temperature Habitability, the Precipitation Habitability, and the Climate Habitability as the climate descriptors relevant to habitability in order to examine the overall trends for Earth-similar worlds in the obliquity—rotation parameter space. The modeled Temperature Habitability, Precipitation Habitability, and Climate Habitability in ROCKE-3D exhibit reasonable agreement with those derived from the observations (Figure 1, left versus right). For example, the spatial pattern of the Temperature Habitability is very similar...
between ROCKE-3D and the observations, with Greenland and Antarctica being the only region with nearly zero habitability. For the Precipitation Habitability, ROCKE-3D captures the major deserts in the northern hemisphere, including the Sahara Desert, the Arabian Desert, the Gobi Desert, and the Syrian Desert, but fails to reproduce the desert regions in the southern hemisphere, such as the Great Victoria Desert (Australia) and the Kalahari Desert (Africa), probably due to the low resolution of the model which cannot resolve the fine details of the air–sea interactions in those regions.

4.2. Climate Habitability Maximizes at Intermediate Obliquity for Faster Rotations

Figure 8 shows the global mean of the modeled Climate Habitability as well as the contributions from the Precipitation Habitability and Temperature Habitability to the 70 ROCKE-3D experiments in the obliquity–rotation parameter space. For the Temperature Habitability (Figure 8, lower right), the pattern resembles that of the global mean temperature in Figure 2, with lower habitability at high obliqui- ties or slow rotations and higher habitability around 45° obliquity at fast rotations as well as around the warming at 16 days of rotation with low obliquities. One exception is the warmer annual temperature, with lower habitability at 0° obliquity than at 90° obliquity for slow rotations of 64 and 128 days. This is because even though the 90° obliquity produces colder temperatures than 0° obliquity, the higher seasonality associated with the 90° obliquity produces partial habitability during the warm season. In contrast, 0° obliquity with slow rotations of 64 and 128 days produces below-freezing temperatures and near-zero habitability year round, due to the lack of seasonality.

For the Precipitation Habitability, this shows sharp differences between the low and middle–high obliqui- ties, since it is mostly lower than 0.6 for 0°–15° obliquity, but quickly increases to over 0.7 for obliquity of 30° or higher, and it can be as high as 0.99 with obliquity of 90° and a rotation period of 128 days (Figure 8, lower left). The higher Precipitation Habitability with obliquity of 30° or higher is attributed to the increased seasonality that brings the annual precipitation over the 30 mm yr\(^{-1}\) threshold. For 0°–15° obliquity, a minimum of the Precipitation Habitability occurs at around 8 days of rotation, due to the disappearance of precipitation in the midlatitude associated with the expansion of the Hadley cell into the polar regions (Figure 7).

There are four major results for the Climate Habitability. First, the combined temperature and precipitation effects (Figure 8, top, and Figure 9) resemble the Temperature Habitability for obliquity of 30° and higher, since the precipitation is not a limiting factor for the obliquities in this range. As such, the largest Climate Habitability amounts to ~0.7 around 45° obliquity for fast rotations, due to the warmest temperature at this obliquity–rotation parameter space (Figure 2). Second, for obliquity of 15° and lower, the Climate Habitability is limited by both the Temperature Habitability and, more importantly, the lower Precipitation Habitability, which result in the minimum Climate Habitability at 0° obliquity for almost all rotation periods, and the overall lowest Climate Habitability of ~0.1 at the 128 day rotation period and...
Figure 6. The mechanism of enhanced cloud cooling from slow-moving insolation forcing. Left column: local incoming solar radiation (W m\(^{-2}\)); middle column: shortwave cloud radiative forcing (W m\(^{-2}\)); right column: cloud water and ice path (kg m\(^{-2}\)). Top row: month 12 of year 600 in the simulation with 8 day rotation periods and 0° obliquity; middle row: month 6 of year 600 in the simulation with 8 day rotation periods and 90° obliquity; bottom row, month 12 of year 300 in the simulation with 128 day rotation periods and 0° obliquity.

Figure 7. The mechanism of Hadley cell–driven snow/ice melting in simulations with 0° obliquity and rotation periods of 2 (top row) and 16 days (bottom row). Left column: stream function of atmosphere; right column: snow/ice fraction.
0° obliquity (Figure 9, bottom left). Third, even at the lowest Climate Habitability, at 0° obliquity and a 128 day rotation period, there are still year-round habitable locations at coastal regions around the globe, due to the favorable temperature and precipitation impact from the ocean. Lastly, the expansion of the Hadley cell increases the Temperature Habitability through the warming of the polar region, but decreases the Precipitation Habitability due to the disappearance of midlatitude storm tracks. Therefore, the higher temperature around the 16 day rotation period with low obliquities does not result in higher Climate Habitability, because of the low Precipitation Habitability in this obliquity–rotation parameter space.

5. Discussion

In this study, we have demonstrated the critical role of obliquity and rotation period on the habitability of Earthlike exoplanets. These parameters can be responsible for a difference in Climate Habitability by a factor of 7, with the potential habitable area based on surface temperature and precipitation ranging from 10% of the terrestrial area of the exoplanet, with 0° obliquity and 128 days of rotation, to 70%, with 45° obliquity and 1 day of rotation.

The range of the modeled Climate Habitability associated with the obliquity mostly depends on three climate dynamics: (1) the obliquity-driven modification of the greenhouse effect; (2) enhanced cloud cooling under slow-moving insolation forcing; and (3) polar snow/ice loss from the expansion of the Hadley cell. The obliquity-driven modification of the greenhouse effect is responsible for the warmest global surface temperature at 45° obliquity for fast rotations. The enhanced cloud cooling under slow-moving insolation forcing modulates the planetary albedo through the formation of middle-level clouds and produces the coldest surface temperature at 90° obliquity. The melting of polar snow and ice is also responsible for the nonlinear warming episode around 16 days of rotation with low obliquities, when the expansion of the Hadley cell reaches the polar regions. All three climate dynamics are robust features of Earthlike exoplanets; therefore, the simulation results from ROCKE-3D should be applicable to Earthlike exoplanets in general.
Previous studies with variations of rotational periods and $0^\circ$ obliquity have shown that the planetary rotation rate can have a great impact on accurate estimates of the habitable zone, due to the dependence of the global surface temperature on rotation (Yang et al. 2014; Way et al. 2018; Jansen et al. 2019). Our set of 70 experiments on the obliquity–rotation parameter space has enabled us to quantify the impact of obliquity and rotation period on the global mean surface temperature. Figure 10 (top left) shows that the global temperature spread due to variations of rotation is mostly controlled by the highest temperature at the fastest rotation, with the largest spread of the global mean temperature occurring at $45^\circ$ obliquity ($\sim 13^\circ$C), which is more than twice the spread at $0^\circ$ obliquity ($\sim 5^\circ$C). In terms of the role of obliquity, the largest spread of the global mean temperature occurs at 1 day of rotation ($\sim 8^\circ$C), and decreases with the rotation period (Figure 10, right). Therefore, within the obliquity–rotation parameter space in our investigation, our results show that varying obliquity through the full range produces the largest spread of the global temperature at 1 day rotation periods, and varying the rotation produces the largest spread of the global temperature at $45^\circ$ obliquity. One important implication of Figure 10 is that simulations exploring climate outcomes for various rotation periods should also sample a variety of obliquities, or choose a midrange obliquity (e.g., $45^\circ$), in order to more fully sample the spread in the resulting global surface temperatures. Sets of simulations with the obliquity fixed at $0^\circ$ do not fully elucidate the range of temperature outcomes for a given set of rotation periods. We conclude that 3D exoplanet simulations that are used to explore the range of possible climate conditions will benefit from the usage of $45^\circ$ obliquity instead of $0^\circ$ obliquity.

These temperature spreads imply that the Habitable Zone range depends on spin–orbit parameters. We note that 3D GCM simulations are not able to characterize longer-timescale climate variations, from coupling to cryospheric or geochemical processes that modify the surface topography (e.g., ice sheets) or atmospheric composition (e.g., silicate weathering). An accurate estimate of the Habitable Zone must account for all of these processes. For example, Haqq-Misra et al. (2016) used a 1D EBM coupled to models of geological processes that modify the atmospheric CO2 and an ice-albedo feedback mechanism in order to explore the “limit cycles” where the climate oscillates between globally glaciated and warm extremes. Their results showed that the outer regions of the Habitable Zone could be very susceptible to limit cycles for plausible ranges of volcanic outgassing and weathering, and that limit cycles would effectively reduce the size of the Habitable Zone. However, it is possible that regional or seasonal climate conditions could produce locally habitable conditions, which are not modeled by EBMs. A full quantification of the Habitable Zone edge would require fully coupled models in all conditions, which is a challenging computational effort. Nevertheless, 3D GCMs are useful for detailed explorations of planetary climates at snapshots in time, and are necessary for understanding the spatial variation of habitability within a given climate.
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Data availability: the globally averaged climatology data presented in Figures 2, 4, 8, and 10 are available on Zenodo: doi:10.5281/zenodo.6468807. 2D maps (in an equal-angle latitude–longitude grid, native to ROCKE-3D) of temperature and precipitation are also included, for the nine selected simulation configurations shown in Figure 9, along with the one simulation performed with Earth’s rotation period and obliquity.

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**References**

Akeson, R. L., Chen, X., Ciardi, D., et al. 2013, *PASP*, 125, 989
Armstrong, J. C., Barnes, R., Domagal-Goldman, S., et al. 2014, *AsBio*, 14, 277
Back, L., Russ, K., Liu, Z., et al. 2013, *JCli*, 26, 8781
Berger, A. L. 1978, *JAtS*, 35, 2362
Colose, C. M., Del Genio, A. D., & Way, M. J. 2019, *ApJ*, 884, 138
Del Genio, A. D., Brain, D., Noack, L., & Schaefer, L. 2020, Planetary Astrobiology (Tucson, AZ: Univ. Arizona Press), 419
Del Genio, A. D., & Sussman, R. J. 1987, *JAsS*, 44, 973
Del Genio, A. D., Kiang, N. Y., Way, M. J., et al. 2019, *ApJ*, 884, 75
Edwards, J. M. 1996, *JAsS*, 53, 1921
Edwards, J. M., & Slingo, A. 1996, *QJRMS*, 122, 689
Fairchild, I. J., & Kennedy, M. J. 2007, *Jgsoc*, 164, 895
Foster, G. L., Royer, D. L., & Lunt, D. J. 2017, *NatCo*, 8, 14845
Fulton, B. J., & Petigura, E. A. 2018, *AJ*, 156, 264
Guzewich, S. D., Lustig-Yaeger, J., Davis, C. E., et al. 2020, *ApJ*, 893, 140
Haqq-Misra, J., Kopparapu, R. K., Batalha, N. E., Harman, C. E., & Kasting, J. F. 2016, *ApJ*, 827, 120
Held, I. M., & Soden, B. J. 2006, JCLI, 19, 5686
Huber, B. T., MacLeod, K. G., Watkins, D. K., & Coffin, M. F. 2018, GPC, 167, 1
Jansen, T., Scharf, C., Way, M., & Del Genio, A. 2019, ApJ, 875, 79
Joshi, M. 2003, AsBio, 3, 415
Kane, S. R. 2014, ApJ, 782, 111
Kane, S. R., Hill, M. L., Kasting, J. F., et al. 2016, ApJ, 830, 1
Merlis, T. M., & Schneider, T. 2010, JAMES, 2, 13
Milanković, M. 1941, Canon of Insolation and the Ice-age Problem (Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem) (Belgrade: Israel Program for Scientific Translations), https://openlibrary.org/books/OL5275634M/Canon_of_insolation_and_the_ice-age_problem
Neelin, J. D. 2011, Climate Change and Climate Modeling (Cambridge: Cambridge Univ. Press), https://assets.cambridge.org/9780521841573_frontmatter/9780521841573_frontmatter.pdf
Rees, K. N., & Garrett, T. J. 2019, ApJ, 879, 126
Rose, B. E. J., & Rencurrel, M. C. 2016, JCLI, 29, 4251
Russell, G. L., Miller, J. R., & Rind, D. 1995, AtO, 33, 683
Schmidt, G. A., Ruedy, R., Hansen, J. E., et al. 2006, JCLI, 19, 153
Schmidt, G. A., Kelley, M., Nazarenko, L., et al. 2014, JAMES, 6, 141
Schneider, E. K. 1977, JAIS, 34, 280
Spiegel, D. S., Menou, K., & Scharf, C. A. 2009, ApJ, 691, 596
Tyrrell, T. 2020, ComEE, 1, 61
von Paris, P., Gratier, P., Bordé, P., & Selsis, F. 2016, A&A, 587, A149
Way, M. J., Del Genio, A. D., Aleinov, I., et al. 2018, ApJS, 239, 24
Way, M. J., Aleinov, I., Amundsen, D. S., et al. 2017, ApJS, 231, 12
Williams, G. P., & Holloway, J. L. 1982, Natur, 297, 295
Willmott, C. J., & Matsuura, K. 2018, Terrestrial Air Temperature and Precipitation: Monthly and Annual Time Series (1900–2017), v5.01, http://climate.geog.udel.edu/~climate/html_pages/download.html
Wolf, E., Kopparapu, R., Airapetian, V., et al. 2019, Astro2020: Decadal Survey on Astronomy and Astrophysics, 2020, 177
Yang, J., Boué, G., Fabrycky, D. C., & Abbot, D. S. 2014, ApJL, 787, L2
Zachos, J., Pagani, M., Sloan, L., Thomas, E., & Billups, K. 2001, Sci, 292, 686