Atmospheric circulations of terrestrial planets orbiting low-mass stars

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Contents lists available at ScienceDirect

Icarus journal homepage: www.elsevier.com/locate/icarus

Icarus xxx (2010) xxx–xxx

ARTICLE IN PRESS

Circulations and habitable zones of planets orbiting low-mass stars are investigated. Many of these planets are expected to rotate synchronously relative to their parent stars, thereby raising questions about their surface temperature distributions and habitability. We use a global circulation model to study idealized, synchronously rotating (tidally locked) planets of various rotation periods, with surfaces of all land or all water, but with an Earth-like atmosphere and solar insolation. The dry planets exhibit wide variations in surface temperature: >80 °C on the dayside to <-110 °C on the nightside for the 240-h rotator, for example. The water-covered aquaplanets are warmer and exhibit narrower ranges of surface temperatures, e.g., ~40 °C to ~60 °C for the 240-h orbiter. They also have a larger habitable area, defined here as the region where average surface temperatures are between 0 °C and 50 °C. This concept has little relevance for either dry or aquaplanets, but might become relevant on a planet with both land area and oceans.

The circulations on these tidally locked planets exhibit systematic changes as the rotation period is varied. However, they also reveal abrupt transitions between two different circulation regimes and multiple equilibria. For the dry planet, the transition occurs between a 4-day and a 5-day period, while for the aquaplanet, it occurs between a 3-day and a 4-day period. For both dry and aqua planets, this transition occurs when the Rossby deformation radius exceeds half the planetary radius. Further investigation on the dry planet reveals that multiple equilibria exist between 100- and 221-h periods. These multiple equilibria may be relevant for real planets within the habitable zones of late K and M stars, because these planets are expected to have rotation periods between 8 and 100 Earth days.

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1. Introduction

Within the past few years, planets not much larger than Earth, so-called “superEarths”, have been discovered in orbit around nearby M stars (Udry et al., 2007; Von Bloh et al., 2008). Earth-size M-star planets may be found within the near future (Basri et al., 2005). These planets are expected to have very different atmospheric circulations than those seen on Earth because many of them are expected to be synchronously rotating, that is, they should always exhibit the same side to their parent star. As discussed further below, planets can also be tidally locked without rotating synchronously, but we will not concern ourselves with this issue here, and we will henceforth use the two terms interchangeably. Dole (1964) speculated that, because of tidal locking, the atmospheres of M-star planets might freeze out (or “collapse”) on the planet’s nightside, leaving only a thin noncondensable atmosphere. This might preclude surface habitability, as nowhere on the planet would there be enough atmosphere to support life.

Recent studies have been more optimistic about the habitability of M-star planets. By performing calculations with an intermediate-resolution general circulation model, Joshi et al. (1997) showed that atmospheric collapse should not occur in most circumstances because the atmospheric circulation can transport enough heat to keep the nightside relatively warm. Specifically, he showed that atmospheres with more than 100 millibars of surface pressure were protected from this fate, if they received the same amount of solar insolation as does the present Earth (1365 W m⁻²). The model used in this case employed a simple gray atmosphere radiation scheme and assumed a 16-day orbit period, which is appropriate for an Earth-like planet orbiting a 0.35 solar mass star. Joshi (2003) used a more detailed 3-D climate model to study tidally locked planets in 10-day orbits around an M5 star (0.2 Ms). This study showed that increasing the planet’s surface water coverage decreased the surface temperature range and that the most habitable region was expected to be near the terminator.
More recently, other authors have pointed out that M-star planets may receive few volatiles (including water) during their formation (Lissauer, 2007), and they may have difficulty in retaining them because of impact erosion (Scalo et al., 2007) and significant flare activity on M stars, combined with the probable absence of a planetary magnetic field (Lammer et al., 2007; Khodachenko et al., 2007). M-star planets remain interesting, however, because it may be possible to study them in the near future from the James Webb Space telescope (JWST) using transit spectroscopy (Gardner et al., 2007). We might even find that all the negative predictions about M-star habitability are wrong.

The primary goal of this study is to follow up on the above previous efforts to examine habitability and atmospheric circulation of M-star planets, focusing on their sensitivities to planetary rotation period. Previous modeling studies have shown that changes in rotation period can cause substantial changes in atmospheric circulation patterns. Hence, different circulation regimes may prevail on planets around stars of different masses. (Recall that we are interested only in those planets which receive Earth-like solar insolation. This links the orbital distance and period, and hence the planet’s rotation rate, directly to the stellar mass.) In calculations that bear indirectly on this question, Williams and Holloway (1982) and Williams (1988a,b) used a global circulation model (GCM) to study the effect of rotation rate on atmospheric circulation for planets with a flat surface of zero heat capacity, rotating relative to their parent star (unlike the planets studied here). As the rotation rate was increased from zero, super-rotating zonal jets emerged near the poles. With further increases in the rotation rate (up to eight times that of Earth), these jets strengthened and moved equatorward, and eventually secondary jets developed poleward of the initial pair (Williams and Holloway, 1982).

Williams (1988b) found that for slow rotators (rotation period >4 days), the circulation is dominated by zonally symmetric, overturning Hadley circulation with equatorward wave action forcing the super-rotation. For faster rotators (rotation periods between 1 and 2 days), zonally asymmetric eddies were found to play a greater role. Del Genio and Suozzo (1987), using a simplified version of the GISS GCM, found that as the rotation rate was decreased, the Hadley cell, baroclinic zone, and zonal jets all expanded poleward, and the equator-to-pole temperature contrast decreased. It is reasonable to expect that these changes would influence the existence and/or extent of the habitable zone.

While these previous studies provide important guidance, the present study should not be expected to yield the same results. The tidally locked planets considered here exhibit a huge zonal contrast in radiative heating between the dayside and nightside. This stationary (with respect to the surface of the planet) heating field is expected to generate a planetary-scale wave response. Gill (1982) studied equatorial wave response to a localized tropical heating and found that it was dominated by Rossby waves to the west, and an equatorially trapped Kelvin wave to the east, of the heating. This wave response can alter the tropical Hadley circulation. Moreover, because the Rossby waves can propagate poleward (Jin and Hoskins, 1995), depending on background flow conditions, the extratropical circulation can also be influenced by these thermally forced stationary waves.

This present study builds on this previous work by extending Williams’ studies to tidally locked planets and by extending Joshi’s work to include planets rotating at different rates, and thus to Earth-like planets orbiting different classes of stars. We calculate circulation patterns in tidally locked M-star planet atmospheres using the GENESIS 3-D general circulation model (Thompson and Pollard, 1997). Our results confirm Joshi’s earlier prediction that such planets can efficiently transport heat around to their nightsides. We also show that there is a rich spectrum of dynamical behavior in such atmospheres that depends on the planet’s rotation rate, and hence on its distance from its parent star. Section 2 provides a background for the phenomenon of tidal locking, types of stars, and the relationship between Earth equivalent distance and orbital period. The GCM is described in Section 3. The circulations from the dry model are described in Section 4, while those from the moist model are presented in Section 5. The simulated habitable zone is discussed in Section 6, and concluding remarks follow in Section 7.

2. Model parameters and assumptions

2.1. Tidal locking

Before describing our climate model, we briefly discuss the phenomenon of tidal locking. Tidal locking occurs when a planet’s rotation rate is slowed by tidal dissipation. Tidal dissipation is a function of the parameter $Q$, which is the inverse of the specific dissipation function for the planet as a whole (solid body plus ocean). For Earth, most of the tidal dissipation occurs along the shoreline of the oceans as the planet rotates under the Moon and Sun. This gives the modern Earth a low $Q$ value ($\sim 13$) (Kasting et al., 1993), meaning that the tidal dissipation rate is high. However, this dissipation must be anomalously high, even for Earth, because if one extrapolates back in time it leads to the prediction that the Moon formed only 1.5 byr (billion years) ago. Earth’s tidal dissipation rate must have been lower in the past as a consequence of different configurations of continents and ocean basins. For the planets modeled here, there is either no ocean (for the dry planets) or no shoreline (for the wet ones); hence, we use $Q = 100$, following Kasting et al. (1993) and Burns (1986). The tidal locking distance, $r_T$, is calculated from the formula (Peale, 1977; Kasting et al. (1993) with adjustments suggested in Dobrovolskis (2009)).
Here, $P_0$ is the original rotation period of the planet (taken as 13.5 h, as in Kasting et al. (1993)), $t$ is the time period from formation (here assumed to be 4.5 byr), and $M$ is the mass of the star. All quantities are in cgs (centimeter, grams, seconds) units. Stars younger (older) than 4.5 byr will have smaller (larger) tidal locking radii. Results for stars of different masses are shown in Fig. 1. Within our own Solar System, Mercury avoids synchronous rotation even though it is within the Sun's tidal locking radius because it is caught in a 3:2 spin–orbit resonance. Such locking depends explicitly on the relatively high orbital eccentricity of Mercury, which is maintained by its gravitational interaction with other planets, especially Venus. This might happen in other planetary systems, as well, if the outer planets pump up the eccentricities of the inner ones. Planets that are locked in spin–orbit resonances should exhibit climates which are intermediate in nature between synchronous and rapid rotators. Here, we focus on synchronously rotating planets, which are the most different from our own rapidly rotating Earth, and the most subject to climate unpredictability.

Note that the results of our study do not depend on the accuracy of Eq. (1). Tidal locking distances are inherently difficult to calculate because of uncertainties in dissipation rate ($1/Q$). The tidal locking radius merely provides an estimate of which stellar types are susceptible to this phenomenon.

2.2. Types of stars

Stars are classified according to their surface temperature and luminosity, both of which are functions of their mass. The most massive stars are O stars and the least massive stars are M stars. Between these two extremes, the star types in order of decreasing size are B, A, F, G (e.g. the Sun), and K. Hot, blue stars toward the beginning of this sequence are brighter and more massive than cool, red stars toward the end. (We are concerned here with dwarf, or main sequence, stars, not with giant stars, which can be bright and cool simultaneously.) M stars and late (small) K-stars both have habitable zones that lie within the tidal locking radius defined in Eq. (1) (Kasting et al., 1993).

M stars are the smallest stars capable of fusing hydrogen within their cores. These stars range in size from 8% to 50% of the solar mass. These stars are expected to have a life span of 100 byr or longer on the main sequence, prior to their eventual dimming and dying. This longevity gives plenty of time for life to begin and evolve on the surface of planets within their habitable zones.

K-stars are the next largest star type. They range in size from 50% to 80% of the solar mass. Early K-stars (on the more massive side of the range) have habitable zones that are outside of their tidal locking radii and will not be studied here. Planets orbiting K-stars should experience few of the problems that might plague planets orbiting M stars because of the larger distance between the star and the habitable zone and because K-stars are less active than M stars. Potentially habitable tidally locked planets around K (rotation rates between 1020 h and ~1600 h) stars will also rotate more slowly than those around M stars (rotation rates between ~200 h and ~1020 h). As we will see, this causes their atmospheric circulation patterns to be quite different.

2.3. Earth equivalent distance and orbital period

In all calculations presented here, we put the planet at the Earth equivalent distance (EED) from its parent star, that is, the distance at which it would receive the same amount of stellar radiation as does Earth. This distance is unique for each star, as it depends only on the star's luminosity, which in turn depends on stellar mass. The calculation of the EED is based on luminosity data given by Girardi (2008). The isochrone is developed from Marigo et al. (2008) with Bonatto et al. (2004) for 2MASS-specific details, and the photometric system is 2MASSJK, with circumstellar dust turned off. The initial mass function is lognormal from Chabrier (2001). The age of the star is 4.55 Ga with $Z = 0.01900$. These parameters define the mass-luminosity relation of low-mass stars. In general, the luminosity of a star is proportional to its mass; however, the actual relation is not constant across the spectrum of stars examined here. The orbital radius of the planet is related to the stellar luminosity through the flux relation

$$F = \frac{L}{4\pi a^2}$$

(2)

Here, $F$ is the flux at a given distance $a$, from a star with luminosity $L$. But, the flux is by construction the same as at Earth, so Eq. (3) must hold:

$$L = \left( \frac{a_{\text{planet}}}{a_{\text{Earth}}} \right)^2$$

(3)

Here $a_{\text{planet}}$ is the semimajor axis of the planet (or the EED) in AU (1 Astronomical Unit = the mean distance from the Earth to the Sun = 149,598,000 km), $a_{\text{Earth}} = 1$ AU, and $L_S$ is the luminosity of the Sun. Finally, the EED is used to calculate the orbital period via Kepler's Third Law:

$$\left( \frac{\text{EED}}{a_{\text{Earth}}} \right)^3 \left( \frac{M_S}{M} \right) = \left( \frac{P_{\text{planet}}}{P_{\text{Earth}}} \right)^2$$

(4)

Here, $M$ is the mass of the star, $M_S$ is the mass of the Sun, $P_{\text{planet}}$ is the orbital (and rotational) period of the planet in Earth years, and $P_{\text{Earth}} = 1$ year. This relationship is shown in Fig. 1.

3. Methods

Like other models that have been used previously to study tidally locked planets, our model makes some simplifying assumptions. Most importantly, the stellar spectrum is assumed to be unchanged from that of the Sun, and the planet’s general atmospheric composition is unchanged from that of Earth (79% N2, 21% O2, 345 ppm CO2, but no ozone). Neither of these assumptions is likely to be valid for a real M-star planet; however, this allows us readily...
to compare our predicted atmospheric circulation patterns both with previous studies and with that of modern Earth.

In order to elucidate the underlying dynamical processes, we first discuss the atmospheric circulations of completely dry planets. In the following section, we study the circulations of completely ocean-covered planets.

subsection 3.1 Model description

The numerical experiments described below use the GENESIS v2.3 GCM, which consists of a spectral atmospheric general circulation model coupled to multilayer models of vegetation, soil and land ice, and snow (Thompson and Pollard, 1997). The GCM grid for this study is spectral T31 resolution (~3.75°), for both the atmosphere and surface models.

For the dry planets, the surface module includes multilayer models of soil (Pollard and Thompson, 1995a,b). The soil model extends from the surface to a depth of 4.25 m, with layer thicknesses increasing from 5 cm at the top to 2.5 m at the bottom. Vertical heat diffusion is included, and the diffusion coefficient depends on soil texture. For this study, the soil is 33% sand, 33% silt, and 33% clay. For the aquaplanets, the surface module includes a 50-m slab ocean (Pollard and Thompson, 1995a,b). This ocean does not circulate, but includes linear horizontal heat diffusion, with the coefficient chosen best to fit modern Earth climate. Also, any sea ice that forms is allowed to move in the wind. All of the surface is no-slip. In all runs, the atmosphere is devoid of water, but water vapor is allowed to accumulate in the atmosphere, clouds are allowed to form, and precipitation to fall in the aquaplanet simulations. The standard GENESIS v2.3 GCM was adapted for this study by adding the ability (i) to set the inertial rotation rate in the Coriolis terms for atmospheric and sea-ice dynamics, (ii) to set the day length for solar radiation, including an option for no temporal variation (tidal locking), and (iii) optionally to initialize the atmosphere and soil to completely dry conditions.

subsection 3.2 Numerical experiments

A suite of numerical experiments was performed with increasing inertial rotation periods (i.e., with decreasing Coriolis parameters). For tidally locked planets, these correspond to the planet’s orbital period around its parent star. The modeled periods for the dry planets are 24, 48, 72, 96, 120, 240, and 2400 h. Figure 1 and Table 1 show how these rotation periods are related to orbital distance and stellar mass. Although the Earth rotates every 23 h 56 min, the rotation periods are all compared to a 24-h rotator for ease in calculation. In addition, a non-tidally locked control experiment was performed with solar radiation period and inertial rotation period both set to 24 h. Additional simulations were performed at rotation periods of 99, 100, 101, and 102 h for the dry planets more carefully to analyze the transition between the fast-rotating regime and the slow-rotating regime. Unlike for the control experiment, the solar insolation for the tidally locked planets has a strong zonal asymmetry (Fig. 2). In each experiment, the model was spun up for 3 Earth years (1095 days) from an initially isothermal state of 274 K at rest, after which instantaneous data were recorded for an additional Earth year, as described below. The runs were initialized with no surface or atmospheric moisture, so the simulations remained completely dry throughout with no water vapor, clouds, precipitation or soil moisture. For numerical stability reasons, it was necessary to reduce the GCM time step to 10 min (from its standard value of 30 min) because of the stronger atmospheric winds resulting from tidally locked solar radiation (Fig. 5b, d, and f).

For the aquaplanets, the same rotation periods were assumed, but the dynamical transition region was not studied in as much detail. As discussed later, the transition for the aquaplanets was not as abrupt, and, combined with the results from the dry planets, further exploration was not seen as necessary. Again, a non-tidally locked experiment with a 24-h day was performed as a control. In each experiment, the model was spun up for at least 20 Earth years (7300 days) from an initially isothermal state of 274 K at rest, after which instantaneous daily model data was recorded for an additional Earth year as described below. The GCM time step was again set to 10 min.

4. Dry planets

subsection 4.1 Dry Earth

For comparison, a planet rotating once every 24 h without being tidally locked was modeled first in a standard Earth simulation. As can be seen in the mean field (Fig. 3), the main features of the observed general circulation on Earth are evident in this simulation. The potential temperature field exhibits realistic surface values, with the largest meridional gradient in the extratropics. This mean zonal wind shows a pair of zonal jet streams (areas of high zonal wind speed) at 200 hPa at 30° latitude (Fig. 3b), which are realistic in their strength. In each hemisphere, a Hadley cell is seen with a sinking branch approximately at 20° latitude which is narrower than that seen in the observations. This difference may be caused by the static stability of the model’s tropical atmosphere being too small, as can be seen in the steep isentropic slope in the tropics.

The momentum and heat fluxes from different mechanisms are also examined to establish what mechanisms might be causing the simulated circulation patterns. For the control, because stationary forcings are absent, only the mean meridional circulation (MMC) and the transient eddies make important contributions to the circulation. The transient eddy heat flux is strongest in the mid-latitudes, where it transports heat both upward and poleward (Fig. 3c). Although the MMC carries a substantial amount of heat in the tropics, its poleward heat flux decreases rapidly in the extratropics. The transient eddy zonal momentum flux convergence coincides with the jet, indicating that the jet is driven by the transient eddies (Fig. 3e). These characteristics are consistent with the behavior of the observed transient eddy and the MMC fluxes of heat and momentum. The adiabatic warming and cooling term (Fig. 3g) shows strong cooling in the equatorial atmosphere, bracketed by weaker warming near 20° latitude. This corresponds to the Hadley cell circulation seen in Fig. 3b. Another area of warming, which lies poleward of the cooling, corresponds to the Ferrel cell circulation. The cooling seen at the poles corresponds with the polar cell.

In summary, some minor differences between the present Earth and the control are expected because of the simplifications made, but the overall circulation is reasonably well simulated.
4.2. Tidally locked cases

The first case discussed is the 24-h orbiter. This case is not quite physical because the stellar mass ($\sim 0.01 \, M_{\odot}$) required for an orbital period of 24 h at the Earth-equivalent distance is below the hydrogen burning limit of 0.08 $M_{\odot}$; however, this case highlights the differences between a tidally locked planet and the non-tidally locked control planet shown above without introducing any other variables. The planet’s mean zonal wind speed is shown in Fig. 4a. Here, two separate jet streams are seen in each hemisphere.

Fig. 2. Top of the atmosphere solar insolation in W m$^{-2}$ for the tidally locked cases. The maximum is located at the substellar point and has been set to Earth’s top of the atmosphere solar insolation of 1365 W m$^{-2}$. The contour interval is 100 W m$^{-2}$.

Fig. 3. Simulation results for the control case (dry Earth). (a) The mean potential temperature field in degrees Celsius. The area with potential temperature above 0°C is shaded. Throughout this paper, the shaded areas denote areas of negative quantities unless otherwise stated. (b) Mean zonal wind for the control “dry earth” in filled contours of 10 m s$^{-1}$. The black contours are the mass stream function in 10$^9$ kg s$^{-1}$ as defined by Peixoto and Oort (1992) with contours of 0.1, 1, 2, and then a contour interval of 5. (c) The transient eddy heat flux (vectors with maximum length 2954 J m$^{-2}$ s$^{-1}$ and 1.988 kPa m$^{-2}$ s$^{-1}$) and the transient eddy heat flux convergence (contoured at 10 and then the contour interval is 100) in 10$^5$ J m$^{-2}$ s$^{-1}$. (d) The transient eddy zonal momentum flux (vectors with maximum length 3.09 m$^{-2}$ s$^{-1}$ and 0.011 kPa m s$^{-1}$) and the transient eddy zonal momentum flux convergence contoured at a contour interval of $1 \times 10^{-5}$ m s$^{-2}$. (e) The mean meridional circulation (MMC) heat flux (vectors with maximum length 264,320 J m$^{-2}$ s$^{-1}$ and 1970 J kPa m$^{-2}$ s$^{-1}$) and the MMC heat flux convergence (contoured at 1000 and then the contour interval is 1000) in 10$^5$ J m$^{-2}$ s$^{-1}$. (f) The MMC zonal momentum flux (vectors with maximum length 0.53 m$^{-2}$ s$^{-1}$ and 53 kPa m s$^{-1}$) and the MMC zonal momentum flux convergence (contoured at a contour interval of $1 \times 10^{-5}$ m s$^{-2}$). (g) The adiabatic warming (positive) and cooling (negative) by the MMC in contoured at 0.05 J kg$^{-1}$ s$^{-1}$. 

as opposed to the single jet stream seen in the control run. The horizontal structure of this stationary wave (Fig. 5a) in the tropics exhibits Gill-type (Gill, 1982) Rossby wave gyres to the west of the heating. The low-latitude jet in Fig. 4a is a manifestation of this Rossby wave gyre. The wave structure in Fig. 5a suggests that the extratropical Rossby waves propagate into the tropics in the eastern part of the heating. Evidence that these waves are forced by the heating can also be seen in the surface wind field (Fig. 5b). The fact that the surface circulation is in the opposite direction from the upper tropospheric circulation indicates a locally thermally forced circulation response (Gill, 1982).

Fig. 4b shows that the slope of the isentropes for the tidally locked planets is much gentler than that in the control run in the tropics and in mid-latitudes. For example, between the equator and 60° latitude, in the control run, the 300-K isentrope intersects the ground and the 300-hPa surface, while for the 24-h tidally locked case, it spans only 900-hPa and 600-hPa surfaces. Because the net zonal mean diabatic heating is identical between these two cases, this difference in the stratification can ultimately be attributed to the additional dynamical processes driven by the stationary wave. As the rotation period is increased to 72 and then to 96 h (Fig. 4d and f), the isentropic slope continues to weaken between the equator and 40° latitude while it remains essentially constant in higher latitudes. For the 120-h case (Fig. 4h), not only does the isentropic slope continue to decline in lower latitudes, but it also becomes smaller in higher latitudes. Increasing the rotation period to 2400 h (Fig. 4j) reduces the slope to nearly zero. Thus, we observe that the isentropic slope generally declines as the rotation rate is reduced. As the isentropic slope is reduced, the zonal mean equatorial surface potential temperature decreases.

Increasing the orbital period from 24 to 72 h (Fig. 4b) shows that the pair of jets has become a single jet between 40° and 60° latitude, with an average speed greater than 50 m s⁻¹. The horizontal structure (Fig. 5c) indicates that this change in the jet structure is associated with an increase in the meridional scale of the stationary wave. This scale increase can be understood in terms of the Rossby radius of deformation, defined as

\[ \lambda_R = \frac{N}{f} \]

outside the equatorial region. In the equatorial β-plane, the Rossby radius of deformation takes on the form

\[ \lambda_R = \sqrt{\frac{NH}{2\beta}} \]

where \( N \) is the Brunt–Väisälä frequency \( (N \equiv \sqrt{\frac{g}{H}}) \), \( H \) is the scale height, \( f \) is the Coriolis parameter, and \( \beta \) is the meridional variation of \( f \). The scale height is defined as \( H = \frac{RT_s}{Mg} \), where \( R \) is the ideal gas constant, \( 8.314 \text{ J K}^{-1} \text{ mol}^{-1} \), \( T_s \) is the global mean surface temperature, and \( g \) is the gravitational acceleration.

\[ \text{Fig. 4.} \quad (a, c, e, g, \text{ and } i) \text{ The zonally and temporally averaged (filled) zonal wind velocity in m s}^{-1} \text{ for the 24, 72, 96, 120, and 2400-h orbiters, respectively. The contour interval is 5 m s}^{-1}. \text{ Black contours of the mass stream function in} \times 10^8 \text{ kg s}^{-1} \text{, with contours of 0, 1, 2, 5, 10, 15, 20, and 25.} \quad (b, d, f, h, \text{ and } j) \text{ The corresponding zonally and temporally averaged potential temperature in K for each case at contours of} \times 10\degree \text{C. The area with potential temperature above} \times 0\degree \text{C is shaded.} \]
temperature, and \( M \) is the molecular mass of the air. Here, \( M = 28 \text{ g mol}^{-1} \) is used because the atmosphere is composed mostly of nitrogen. As can be seen in Eq. (5), \( \omega_0 \) is inversely proportional to the rotation rate while Eq. (6) shows that \( \omega_0 \) decreases with increasing rotation rate in the equatorial region as well. Therefore, if the stationary wave can be scaled by \( \omega_0 \), the wave scale is expected to increase as the rotation rate decreases. Consistent with this interpretation, as the orbital period is increased to 96 h, the meridional scale of the stationary wave further increases (Fig. 4e). Though this relation is seemingly straightforward, the inclusion of the Brunt–Väisälä frequency (which makes a statement about the atmospheric stability) and the scale height make it impossible to estimate the rotation period at which the transition would occur.

Increasing the orbital period to 120 h (Fig. 4g) brings abrupt changes. This abrupt transition will be examined further later in this section. Increasing the orbital period to 2400 h (Fig. 4i) leads to still more changes. The equatorial jet weakens significantly to just over 5 m s\(^{-1}\), and easterly winds cover the surface. The findings for the Hadley cell are consistent with the calculations shown by Williams (1988a,b). However, none of the dry cases of Williams (1988a,b) showed an equatorial super-rotating jet because there was no equatorial wave source in that study. Here, the equatorial wave is forced by the differential solar heating between the day and night hemispheres.

The potential temperature field at 1000 hPa shows that the low-level wind field redistributes the heat from the Sun. In the fast-rotating cases, an anomaly in the potential temperature field occurs near the dawn terminator where the distribution of potential temperature does not follow equisolar lines (lines of constant solar energy input). The surface wind field indicates that this decrease in potential temperature is caused by cooler air advecting toward the substellar point from the antistellar point along the equator (Fig. 5b, d, and f).

4.3. Abrupt transition and multiple equilibria

For the 24-h and 96-h runs, the behavior of the transient eddy flux is similar to that of the control, Earth-like run, indicating that the transient wave behavior (i.e. the weather) is not so different from that of Earth. The same can be said about the mean meridional circulation. As mentioned earlier, however, the circulation changes dramatically between the 96-h and 120-h rotators.

An abrupt circulation change between the Earth-like state (as in the control run) and the equatorially super-rotating state (as in Fig. 4g) was previously found in two-level primitive equation models (Suarez and Duffy, 1992; Saravanan, 1993). Saravanan (1993) gradually varied a localized symmetric wavy equatorial heat source and found that an Earth-like state abruptly transitions to
a super-rotating state as the heating becomes stronger than a threshold value. This is consistent with the angular momentum constraint that equatorial super-rotation can only arise from an equatorial wave source (Hide, 1969). In this study, tidal locking provides the wavy heating and, while the heating rate is fixed, the rotation rate is varied. Therefore, slowing the rotation rate, as we have done in our study, plays a dynamically equivalent role to increasing the heating rate, as in Saravanan (1993).

To test whether the transition between the 96-h and 120-h rotators is as abrupt as that exhibited by the previous two-level model studies, intermediate values of the rotation rate were examined. We found that the transition is indeed abrupt, as it occurs between the rotation periods of 100 h and 101 h. The 100-h rotator resembles the 96-h rotator and the 101-h rotator resembles the 120-h rotator.

As is common in the nonlinear phenomena of abrupt transition (e.g., ice-albedo feedback process of a Snowball Earth (Budyko, 1969) or the oceanic thermohaline circulation (Stommel, 1961)), we found that the above abrupt dynamical transition also exhibits hysteresis and multiple equilibria. To examine the impact of the initial condition on the final equilibrated circulation state, the planets were spun up from rest at 100-h (101-h) circulation for 3 years to create the initial conditions. From there, the planet’s rotation period was increased (decreased) by one hour and integrated for 3 years. This length of time is ample to see the transition because it is more than the amount of time necessary to spin up the atmosphere from rest to an equilibrated state; also, longer iterations did not show any sign of transition after much longer (~50 years) of iteration. If the transition did not occur by the end of this 3-year period, using this final state as the new initial state, we performed another integration with a larger (smaller) value of rotation period. When the rotation period was gradually increased in this manner, the dynamical transition no longer occurred between 100 and 101 h; instead, it occurred at a 221-h rotation period (Fig. 6). The slight rise at ~110 h rotation period is due to a sudden change in rotation rate, after that point, changes of only 1 h per run are mandated to determine the extent of the hysteresis. A sudden change in rotation rate is not an expected occurrence. Thus, the dynamical system exhibits a strong hysteresis effect. Similarly, decreasing the rotation period also resulted in hysteresis. Suarez and Duffy (1992) and Saravanan (1993) found that their multiple equilibria solution was metastable in the sense that the second solution, obtained with the other state as the initial condition, collapsed to the first solution that was obtained with the resting initial state. We have not explored this possibility in detail because it is tangential to this study. However, given the similarities between our results and those of the previous two studies, we suspect that our solutions are also likely to be metastable.

Although examining a precise mechanism for this transition is beyond the scope of this study, we postulate that it is associated with the saturation of the stationary eddy scale. Table 2 shows that as the planetary rotation period increases, the Rossby radius of deformation approaches the planetary radius. At the transition periods, 100 and 101 h, we see that values for these two radii are very close to each other. As the meridional scale of the stationary wave approaches the size of the planet, the wave cannot ‘fit’, and so poleward propagation is no longer allowed. Indeed, the 120-h case shows very little meridional tilt (Fig. 5g). In addition, the wave amplitude is much greater than that in the faster-rotating cases, suggesting that resonant-like behavior may be present. In this case, the resonant behavior may arise in response to the zonal wave-number-1 heating projecting onto one of the normal modes of Laplace’s tidal equations (Longuet-Higgins, 1968).

The hysteresis that occurs from a slower to a faster rotator, or vice versa, may be relevant for a planet if it is subjected to tidal drag. Because the drag slows the rotation of a planet, two planets with an identical rotation rate may have substantially different circulations if one of them had experienced a relatively stronger tidal drag in its past.

5. Aquaplanets

We now consider aquaplanets, with oceans covering their entire surfaces. The zonal mean circulations of these planets in some ways resemble those of the corresponding dry planets, including the latitudinal ranges of surface easterlies and westerlies, the extent of the Hadley cells, and the position of the upper tropospheric zonal jets (not shown). The exception is the 96-h case: this case is different because the dynamical transition discussed for the dry planets occurs between 72- and 96-h rotators. As a result, the 96-h aquaplanet run resembles the 120-h dry run (compare Fig. 7 with Fig. 5).

For the dry planets, the transition occurs when \( \lambda_R \) is between 3000 and 3300 km (which correspond to rotation periods of 100 and 101 h, respectively). In the aquaplanet simulations, this range of \( \lambda_R \) actually occurs between the 96-h and the 72-h rotation periods (see Table 3). Therefore, we expect the transition to occur within this range, which is indeed the case. This difference in the value of \( \lambda_R \) in turn, is consistent with the aquaplanets having higher static stability (not shown).

The most notable difference between the dry planets and aquaplanets is the surface potential temperature (which is close to the actual surface temperature). Consistent with the findings by Joshi (2003), the present experiments also reveal that aquaplanets have more temperate climates than the corresponding dry planets. Although the presence of an ocean increases the seasonal heat capacity of the surface compared to the dry planet case, this is not relevant for tidally locked planets. The relevant effects are (i) additional thermal radiative greenhouse warming caused by atmospheric water vapor on both the sunlit and dark sides of the aquaplanet and (ii) additional heat transport from the sunlit to the dark side, both by latent heat flux in the atmosphere (Fig. 8) and by heat transfer.
diffusion in the slab ocean. These more than counteract the net cooling effect of increased planetary albedo caused by clouds and sea ice (Table 4). These influences of water on the shape, size and distribution of 1000-hPa potential temperature variations are apparent in Fig. 7. For dry planets, the proximity of the terminator had a noticeable effect on the curvature of the isentropes: the potential temperature gradient was strong across the terminator, especially for the fast rotators. Here, the terminator has much less effect, producing more uniform distributions.

For the aquaplanets, the cloud and sea-ice distributions vary significantly between the different simulations (Fig. 9). In general, cloud cover decreases and sea ice thickens and expands on the nightside of the planet as the rotation period increases. These trends are consistent with weakening low-latitude zonal winds as the rotation period increases (Fig. 7), allowing nightside temperatures to cool, and more water vapor to condense out near the terminator before being advected further into the nightside.

### Table 2

<table>
<thead>
<tr>
<th>Rotation period (h)</th>
<th>β (km⁻¹s⁻¹)</th>
<th>N (s⁻¹)</th>
<th>H (km)</th>
<th>Z₀ (km)</th>
<th>T₀ (K)</th>
<th>uₘₐₓ (m s⁻¹)</th>
<th>ψₘₐₓ (10⁹ kg s⁻¹)</th>
<th>ψₘₐₓ (10⁹ kg s⁻¹) (secondary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 (Control)</td>
<td>2.29 × 10⁻⁵</td>
<td>0.00767</td>
<td>7.451</td>
<td>1060</td>
<td>732</td>
<td>270.4</td>
<td>44.95</td>
<td>17.11</td>
</tr>
<tr>
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<td>0.0148</td>
<td>7.941</td>
<td>1547</td>
<td>1333</td>
<td>233.9</td>
<td>91.29</td>
<td>11.45</td>
</tr>
<tr>
<td>48</td>
<td>1.14 × 10⁻⁵</td>
<td>0.0143</td>
<td>7.974</td>
<td>2153</td>
<td>2638</td>
<td>237.5</td>
<td>92.13</td>
<td>12.94</td>
</tr>
<tr>
<td>72</td>
<td>7.62 × 10⁻⁶</td>
<td>0.014</td>
<td>7.993</td>
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<td>3914</td>
<td>238.1</td>
<td>96.56</td>
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</tr>
<tr>
<td>96</td>
<td>5.72 × 10⁻⁶</td>
<td>0.014</td>
<td>8.019</td>
<td>3017</td>
<td>5245</td>
<td>239.1</td>
<td>94.54</td>
<td>15.12</td>
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<td>100</td>
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<td>0.014</td>
<td>8.024</td>
<td>3078</td>
<td>5465</td>
<td>239.1</td>
<td>92.87</td>
<td>15.52</td>
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<tr>
<td>101</td>
<td>5.43 × 10⁻⁶</td>
<td>0.017</td>
<td>7.866</td>
<td>3381</td>
<td>6546</td>
<td>230.1</td>
<td>111.6</td>
<td>9.51</td>
</tr>
<tr>
<td>120</td>
<td>4.57 × 10⁻⁶</td>
<td>0.0163</td>
<td>7.938</td>
<td>3626</td>
<td>7573</td>
<td>233.6</td>
<td>101.1</td>
<td>10.5</td>
</tr>
<tr>
<td>240</td>
<td>2.29 × 10⁻⁵</td>
<td>0.0145</td>
<td>8.084</td>
<td>4895</td>
<td>13845</td>
<td>243.3</td>
<td>71.76</td>
<td>12.08</td>
</tr>
<tr>
<td>2400</td>
<td>2.29 × 10⁻⁷</td>
<td>0.0127</td>
<td>8.138</td>
<td>14,550</td>
<td>122,125</td>
<td>257.5</td>
<td>25.08</td>
<td>17.72</td>
</tr>
</tbody>
</table>

Fig. 7. The eddy geopotential height field and winds for the 200 hPa at 24-h (a), 72-h (c), 96-h (e), 120-h (g), and 2400-h (i) aquaplanets. The contour interval is 100 m. The longest vectors are 40.5861 m s⁻¹, 25.0633 m s⁻¹, 75.5554 m s⁻¹, 104.114 m s⁻¹, and 26.2511 m s⁻¹ respectively. (b, d, f, h, and j) The respective 1000 hPa potential temperature field (contours) and wind field (vectors). The contour interval is 10°C. The longest vectors are 15.1856 m s⁻¹, 13.6400 m s⁻¹, 11.9463 m s⁻¹, 11.6883 m s⁻¹, and 12.8542 m s⁻¹ respectively.
6. Surface temperatures and habitability

In this section, we examine surface temperatures of the idealized planets and address the question of their habitability. Our dry planets are almost certainly not habitable, by definition, and our aquaplanets could be habitable virtually everywhere if the ocean is deep enough not to freeze to the bottom on the nightside. So, this discussion is actually more relevant to the question of what would happen if we included some land area in our aquaplanet simulations. With this thought in mind, we define the habitable area of a planet as the region in which the average surface temperature is between 0°C and 50°C. We keep this discussion brief because the simulations described here cover only a small region of parameter space for tidally locked planets, and thus have only limited implications for M-star planet habitability. More detailed calculations in this area would necessarily involve a range of orbital distances, atmospheric compositions, and continental configurations, along with more sophisticated models for ocean heat transport. In particular, the simple oceanic slab with linear heat diffusion used here is very simple, and overlooks possible effects of gyral or deep ocean overturning circulations. However, its use captures the basic additional heat transport from warm to cold hemispheres, presumably a good first-order approximation for a wide range of planets, and has allowed the exploration of much wider parameter ranges than would have been possible with an ocean general circulation model.

The global mean temperature is higher for the aquaplanets than for the dry planets (Fig. 10 and Table 4), as a consequence of the greenhouse effect of water vapor and additional latent and oceanic heat transports, which more than offset the increased albedo caused by clouds and sea ice (Table 4). However, the albedo may play an important role in explaining the dependency of the mean surface temperature on the rotation rate. Fig. 10 shows that as rotation period increases, the mean temperature increases for the dry planets, while it decreases for the aquaplanets. We suggest that these trends are caused by strengthening meridional overturning for dry planets (which homogenizes planetary temperatures more efficiently, Fig. 5), and weakening low-latitude zonal winds for aquaplanets (which allows expanded sea-ice extent and thicker cloud cover on the sunlit side, Fig. 7). While surface temperatures may be inferred from the 1000-hPa potential temperatures given in Figs. 5 and 7, they are shown explicitly (and more clearly) for Table 3.

Table 3

<table>
<thead>
<tr>
<th>Rotation period (h)</th>
<th>β (km s⁻¹)</th>
<th>N (s⁻¹)</th>
<th>H (km)</th>
<th>L (km)</th>
<th>Mean, Tₘ (K)</th>
<th>Ṽ₁ (10⁹ kg s⁻¹)</th>
<th>Ṽₘₗ (secondary) (10⁹ kg s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 (Control)</td>
<td>2.29 × 10⁻³</td>
<td>0.01072</td>
<td>7.906</td>
<td>1354</td>
<td>295.6</td>
<td>62.31</td>
<td>8.488</td>
</tr>
<tr>
<td>24</td>
<td>2.29 × 10⁻³</td>
<td>0.01451</td>
<td>8.048</td>
<td>1598</td>
<td>281.2</td>
<td>148.3</td>
<td>6.281</td>
</tr>
<tr>
<td>48</td>
<td>1.14 × 10⁻³</td>
<td>0.01491</td>
<td>7.939</td>
<td>2275</td>
<td>274.4</td>
<td>113</td>
<td>5.52</td>
</tr>
<tr>
<td>72</td>
<td>7.62 × 10⁻⁶</td>
<td>0.01539</td>
<td>7.796</td>
<td>2805</td>
<td>267.7</td>
<td>117.3</td>
<td>10.13</td>
</tr>
<tr>
<td>96</td>
<td>5.72 × 10⁻⁶</td>
<td>0.01643</td>
<td>7.986</td>
<td>3374</td>
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<td>5.67</td>
</tr>
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<td>0.01664</td>
<td>8.0277</td>
<td>3803</td>
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<td>80.2</td>
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<td>2400</td>
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<td>0.0155</td>
<td>7.861</td>
<td>16,116</td>
<td>259.3</td>
<td>23.02</td>
<td>12.78</td>
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</table>

Fig. 8. The meridionally averaged latent heat flux and convergence for (a) the 24-h aquaplanet, (b) the 72-h aquaplanet, (c) the 96-h aquaplanet, (d) the 120-h aquaplanet, and (e) the 2400-h aquaplanet. The longest vectors are 207.095 kJ m⁻² s⁻¹ and 103.133 kJ cPa m⁻³ s⁻¹, 143.355 kJ m⁻² s⁻¹ and 149.490 kJ cPa m⁻³ s⁻¹, 150.834 kJ m⁻² s⁻¹ and 275.677 kJ cPa m⁻³ s⁻¹, 200.030 kJ m⁻² s⁻¹ and 407.495 kJ cPa m⁻³ s⁻¹, and 67.047 kJ m⁻² s⁻¹ and 179.321 kJ cPa m⁻³ s⁻¹, respectively.
In general, the aquaplanets have more area in which the average surface temperature is within the assumed limits of habitability. Dry planets and aquaplanets exhibit an intriguing dichotomy with respect to increasing the rotation rate. As the dry planets spin faster, the habitable surface area decreases, whereas the opposite trend is found for the aquaplanets. This is the same dichotomy as seen for mean surface temperature. The suggested cause is also the same, namely, a change in the large-scale wind patterns, as discussed above.

<table>
<thead>
<tr>
<th>Simulation (dry or wet)</th>
<th>Rotation period (h)</th>
<th>Minimum mean temperature (K)</th>
<th>Average temperature (K)</th>
<th>Maximum mean temperature (K)</th>
<th>Planetary albedo</th>
<th>IR greenhouse effect</th>
</tr>
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<tr>
<td>Dry</td>
<td>24 (Control)</td>
<td>210.1</td>
<td>282.6</td>
<td>307.6</td>
<td>0.2714</td>
<td>0.686</td>
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<td></td>
<td>24</td>
<td>156.2</td>
<td>245.6</td>
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<td>0.9464</td>
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<td></td>
<td>48</td>
<td>170.3</td>
<td>237.5</td>
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<td></td>
<td>72</td>
<td>165.5</td>
<td>250.5</td>
<td>350.2</td>
<td>0.289</td>
<td>0.9353</td>
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<tr>
<td></td>
<td>96</td>
<td>171.7</td>
<td>250.3</td>
<td>349.5</td>
<td>0.289</td>
<td>0.9353</td>
</tr>
<tr>
<td>Transition</td>
<td>120</td>
<td>156.1</td>
<td>242.4</td>
<td>353.1</td>
<td>0.2891</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>196.8</td>
<td>251</td>
<td>349.9</td>
<td>0.2892</td>
<td>0.7765</td>
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<tr>
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<td>2400</td>
<td>227.2</td>
<td>262.6</td>
<td>347.5</td>
<td>0.2892</td>
<td>0.7765</td>
</tr>
<tr>
<td>Wet</td>
<td>24 (Control)</td>
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<td>0.3079</td>
<td>0.556</td>
</tr>
<tr>
<td></td>
<td>24</td>
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<tr>
<td></td>
<td>48</td>
<td>225.5</td>
<td>274.4</td>
<td>316.3</td>
<td>0.3991</td>
<td>0.7206</td>
</tr>
<tr>
<td></td>
<td>72</td>
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<td>267.7</td>
<td>308.2</td>
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<tr>
<td>Transition</td>
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<td>196.8</td>
<td>269.6</td>
<td>316.2</td>
<td>0.3851</td>
<td>0.7732</td>
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<tr>
<td></td>
<td>120</td>
<td>211</td>
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<tr>
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<td>261.8</td>
<td>307.8</td>
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<td></td>
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<td>296.7</td>
<td>0.4743</td>
<td>0.7909</td>
</tr>
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</table>

Fig. 11. Surface temperatures in degrees Celsius for the 120-h (a and c) and the 2400-h (b and d) orbiters under dry planet (a and b) and aquaplanet (c and d) conditions. The contour interval is 10°C. For the dry planet in the 2400-h orbit (panel b), nightside temperatures are everywhere greater than −80°C.

The transition between the fast rotators and slow rotators also affects habitability by altering the transfer of heat between the dayside and the nightside. For dry planets, increasing the rotation rate generally increases heat transfer from the dayside to the nightside by increasing the strength of the zonal winds. However, near the slow/fast transition, the slow-rotating regime, with its dominant stationary waves, is more efficient at transferring energy from the dayside to the nightside. For the aquaplanets, the dependence of habitable surface area on rotation rate is lessened because the surface winds are stronger, and hence planetary wave activity is less important.
In summary, our calculations support Joshi’s suggestion that tidally locked planets could be habitable, as we also find that atmospheric heat transport is sufficient to keep the dark side of the planet relatively warm. But, as mentioned above, our calculations cover only a limited range of parameter space, and hence are more relevant to questions of atmospheric dynamical regimes than they are to the question of planetary habitability.

Fig. 9. The average total fractional cloud cover for (a) the 24-h aquaplanet, (c) the 72-h aquaplanet, (e) the 96-h aquaplanet, (g) the 120-h aquaplanet, and (i) the 2400-h aquaplanet. The contour interval is 0.1 with shaded regions having fractional cloud coverage of 0.5 and greater. The ice coverage (shaded), and ice depth (contours) for (b) the 24-h aquaplanet, (d) the 72-h aquaplanet, (f) the 96-h aquaplanet, (h) the 120-h aquaplanet, and (j) the 2400-h aquaplanet. Shaded areas have ice at least 1 cm thick and the contour interval is 5 m. These sea-ice distributions are in near-equilibrium, and do not change significantly over the final year of the simulations.

In this work, the atmospheric dynamics of tidally locked planets were explored as a function of rotation period. The dynamics are dominated by the stationary eddies that arise from the east–west contrast in radiative heating between the dayside and the nightside. As the rotational period increases, the stationary eddies expand to the size of the planet. Beyond this point, an abrupt transition occurs in the circulation pattern. For the dry planets, this transition occurs between 96- and 120-h periods, while for the aquaplanets, the transition occurs between 72- and 96-h periods. For the dry planets, additional calculations show that multiple equilibria exist between 100- and 221-h periods.

As expected, the mean temperature of the aquaplanets is greater than that of the dry planets because of the added greenhouse effect of water vapor. Conversely, the temperature contrast between sunlit and nightsides decreases for aquaplanets because of additional atmospheric latent and oceanic diffusive heat transport. The planetary albedo varies more widely across the aquaplanets because of cloud and ice cover. Intriguingly, dry planets warm substantially with increasing rotation period, while aquaplanets cool. The dry planet trend is caused by increased meridional mixing on the more slowly rotating planets, which reduces large-scale...

Fig. 10. The average surface temperature of the dry planets and aquaplanets. Also shown are the average surface temperatures for the dry planet control run (dry Earth), the aquaplanet control run (wet Earth) and the present Earth (present Earth).

7. Concluding remarks

In this work, the atmospheric dynamics of tidally locked planets were explored as a function of rotation period. The dynamics are dominated by the stationary eddies that arise from the east–west contrast in radiative heating between the dayside and the nightside. As the rotational period increases, the stationary eddies expand to the size of the planet. Beyond this point, an abrupt transition occurs in the circulation pattern. For the dry planets, this transition occurs between 96- and 120-h periods, while for the aquaplanets, the transition occurs between 72- and 96-h periods. For the dry planets, additional calculations show that multiple equilibria exist between 100- and 221-h periods.

As expected, the mean temperature of the aquaplanets is greater than that of the dry planets because of the added greenhouse effect of water vapor. Conversely, the temperature contrast between sunlit and nightsides decreases for aquaplanets because of additional atmospheric latent and oceanic diffusive heat transport. The planetary albedo varies more widely across the aquaplanets because of cloud and ice cover. Intriguingly, dry planets warm substantially with increasing rotation period, while aquaplanets cool. The dry planet trend is caused by increased meridional mixing on the more slowly rotating planets, which reduces large-scale...
temperature contrasts and raises the mean surface temperature. In the aquaplanet cases, the trend is reversed because the low-latitu
dude zonal winds are weaker on more slowly rotating planets, which allows sea ice to expand across the terminator.

In conclusion, even though none of these idealized planets are habitable by human standards, the present study supports previ
ous conclusions that tidally locked planets within the habitable zone of their parent star can be warm enough to support liquid water at their surface, and may, in turn, support life. We have, of course, still looked at only a small portion of parameter space for possible extrasolar planets. Future studies should examine other factors, including atmospheric composition, planet location within
the habitable zone, and different land–sea distributions.

Acknowledgments

The authors would like to thank Charles Anderson for his help in displaying the circulations in three dimensions, as it helped greatly with the description of the circulations. The authors also wish to acknowledge the use of IDL for analysis and graphics in this paper.

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