ATMOSPHERIC CIRCULATIONS OF TERRESTRIAL PLANETS ORBITING LOW MASS STARS

A Dissertation in
Meteorology
by
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ABSTRACT

Atmospheres of planets orbiting low mass stars have properties unlike those typically studied by climatologists. One of the most glaring differences is that the rotation is “trapped” for planets orbiting within the habitable zone of the star. This lack of a typical “day” changes these planets’ dynamics. Previous work includes that of Gareth Williams and Manoj Joshi. Joshi discussed planets with 10-day orbits only. Williams focused on planets with differing rotation rates, but still rotating relative to their star. Here, tidally locked planets with a variety of orbital periods ranging from 1 to 100 days are discussed. The GENESIS model is used to simulate these planets, and the data are analyzed for waves, energy fluxes, and habitability. The major components of the energy fluxes are the mean meridional circulation (i.e., the Hadley cell) and stationary eddies in the form of a wave number 1 stationary Rossby wave. A transition point in the atmospheric circulation is identified for orbital periods between 100 hours and 101 hours for dry planets. For the wet planets, the transition occurs near 96-hour rotation period. This transition occurs when the Rossby radius of deformation approaches the planet’s radius and is associated with the increasing importance of the wave number two stationary eddy as the Rossby radius approaches the planetary radius.

The most habitable dry planet is found to be the 2400-hour orbiter. For the wet planets, the 24-hour rotator is most habitable. The most habitable wet planet is the 24-hour rotator, with the least habitable wet planet being the 2400-hour rotator. The difference in the rotation period of the most habitable planets between the dry planets and the wet planets is caused by the availability of water vapor as a greenhouse gas, the added
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1.1 Introduction

Recently, planets not much larger than Earth have been discovered in M-star systems (von Bloh, 2008). The expectation is that Earth-size planets will be found in the near future (Basri et al. 2005). In the light of this expectation, the probability of an Earth-like planet to be habitable is dependent on numerous factors. The first is whether the planet is within the habitable zone of its parent star. Kasting et al. (1993) lay out the expectation for where a planet needs to be located in a star system for it to possibly have liquid water at the surface. In that paper, the habitability of planets orbiting low-mass stars is called into question because the location of the planet within the tidal locking radius of its star might cause the planet not to rotate and lead to atmospheric collapse. This idea that tidally locked planets might not be habitable was first expressed by Dole (1964). Atmospheric collapse is the condensation and deposition of atmospheric constituents to the point where the atmosphere no longer exists. Atmospheric collapse results in a planet covered partially with an ice sheet and no extant atmosphere. Joshi (1997) found that atmospheric collapse does not occur using an IGCM (intermediate general circulation model). More recently, the probability that M-star planets will receive
volatiles (like water) during their formation and retaining them throughout the bombardment period has been called into question (Lissauer, 2007). These problems are acknowledged here, but that does not discourage us from proceeding, as nature may have found ways around them. Hence, this study focuses on how the habitability of a terrestrial planet orbiting a low-mass star depends on the atmospheric circulation of the planet. In this chapter, tidal locking is discussed in a broad sense and then the rationale for looking at the particular tidal locking ratio that is focused on here is given. Then, the different star types addressed by this research are discussed. Finally, the previous works on the atmospheric circulations of planets with differing rotation rates are discussed, with special attention paid to those that are most applicable to the present study.

1.2 Tidal Locking

There are many tidal locking resonances into which a planet can be locked. All of these situations involve planets that have their rotation rates slowed by their parent stars and other bodies. This slowing of rotation occurs because of tidal dissipation. For the earth, most of the tidal dissipation occurs along the shoreline of the oceans as the earth rotates under the Moon and Sun. This gives the earth a tidal dissipation factor ($Q^{1/2}$) of ~13 (Kasting et al., 1993). For the planets modeled here, there is no shoreline. Because of this lack of shoreline for the ocean to push against (or lack of ocean in the dry case), we choose a tidal dissipation factor of 100, following Kasting (1993) and Burns (1986). The tidal locking radius is calculated with the formula (Peale, 1977 and Kasting, 1993):
Here, $r_T$ is the tidal locking radius, $P_0$ is the original rotation period of the planet (here 13.5 hr, as in Kasting et al. 1993), $t$ is the time period from formation (here 4.5 Ga (Giga-annum = $10^9$ Earth years)), $Q^{-1}$ is the solid body plus ocean specific dissipation function (here 100), and $M$ is the mass of the star. This formula is used to compute the tidal locking radii given in Figure 1-1. Using a time length of 4.5 Ga is decided based on the

\[
    r_T = 0.027 \left( \frac{P_0}{Q} \right)^{1/6} M^{1/3}.
\]

Figure 1-1: Tidal Locking Distance for stars 4.5 Ga of age and the planet’s Earth Equivalent Distance (EED) in Astronomical Units for typical main sequence stars and low-mass stars. The corresponding orbital period at the EED, in hours, versus stellar mass. The stellar mass ($M_{\text{star}}$) is given compared to the Sun’s mass ($M_{\odot}$). The expected EED and period are calculated for the typical main sequence star relation.
present age of the earth. The tidal locking radius of a given star will increase in time, as demonstrated by the time term in the equation. As the star system ages, the tidal locking radius increases. Presently, the Sun’s tidal locking radius is between Mercury and Venus in our own solar system. Mercury orbits in a 3:2 resonance with the Sun, where it orbits twice for three rotations of the planet; hence, it avoids tidal locking even though it is within the tidal locking radius.

The focus of this study is on planets that are tidally locked. These planets were thought to be totally uninhabitable until recently (Joshi 1997 and Joshi 2003). In Joshi (1997), atmospheric collapse was shown not to occur for planets with atmospheres of more than 100 millibars of surface pressure. Also, it was shown that the planet will be ice free for a CO$_2$ - H$_2$O atmosphere with CO$_2$ concentrations in excess of 1 bar for a planet at the Earth Equivalent Distance. The Earth Equivalent Distance for a star was the orbital radius around a star where a planet receives the same amount of solar insolation as the present Earth (1365 W m$^{-2}$). The model used in that study was the SGCM (described in Joshi 1995 and James and Gray 1986). The atmosphere had a grey radiation scheme with modeling of the condensation of CO$_2$. The rotation rate was based on that of Titan ($4.5\times10^{-6}$ s$^{-1}$, which corresponds to a rotation period of about 16 days). The model was spun up for 1620 Earth days.

In Joshi (2003), the atmospheric circulations of tidally locked planets in 10 day orbits were studied. The model used in that study was the IGCM, which is described in Forster (2000). The radiation scheme included cloud effects, evaporation, transportation and precipitation of water with a T21 (5.5°) horizontal resolution and 22 layers in the vertical. The stellar insolation was 1376 W m$^{-2}$ and the star was set as a M5 star at 20%
solar mass ($M_\oplus$) with the planet orbiting at ~0.1 AU. The stellar spectrum was the same as the sun, and the same assumption is made here. It is known that the stellar spectrum depends on the stellar mass, but the shift in the spectrum between stars and its effect on the atmospheric circulation is small compared with the difference incurred by the absence of a diurnal heating cycle like that on Earth. The Joshi (2003) atmospheres included ozone. The rotation rate was set to the same as Earth’s. Joshi’s planets had differing surface features; totally dry, ocean planet, and half ocean/half land with a continent filling the northern hemisphere (hereafter, the northern continent run). The wet planet (hereafter called the aquaplanet) had a swamp ocean and was shown to have a temperature range of 30°C to -30°C. The dry planet showed a temperature range of 80°C to -70°C. The northern continent run showed a temperature range between these two extrema as the ocean has a mitigating effect on the variability of the land surface temperature.

### 1.3 Stars

Stars are classified according to their color, which is a function of their surface temperature, and their luminosity, which is a function of their mass. The hotter a star is, the bluer the star appears, and the cooler a star is, the redder the star appears. The larger a star is, the brighter it appears, while smaller stars appear dimmer. This paper deals with only two classes of stars, M-stars and K-stars. These stars are chosen because planets within their habitable zone (as defined by Kasting et al. 1993), must orbit within the tidal locking radius of the star within 4.5 Ga of formation. This tidal locking induces
interesting effects on the atmospheric circulations of these planets that cannot be captured by simplified 1D and 2D models.

1.3.1 M Stars

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 billion years 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. However, the habitable zones of these stars lie very close to the star, which may stymie life on their surfaces because of x-ray emissions from the star sterilizing the surface, or the stellar wind sputtering away the atmosphere (Lammer et al 2007, and Khodachenko et al 2007), impact erosion of the atmosphere (Scalo et al 2007), or a lack of volatiles (Lissauer 2007). The chances that one or more of these things will occur decrease as the star increases in mass because the habitable zone is further away for larger stars.

1.3.2 K Stars

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. Only late K-stars (on the less massive side of the range) have habitable zones within their tidal locking radii. Planets within the
habitable zones of these stars experience only a very low chance of any of the conditions that might plague planets orbiting M-stars because of the large distance between the star and the habitable zone. Also, K-stars have less active chromospheres than M-stars which lead to fewer and weaker flares from the K-stars. But, due to this large orbital distance between the star and the planet, the planets tidally locked to K-stars will rotate more slowly than those tidally locked to M-stars. Also, even though the planets are expected to be tidally locked, the planet may have properties different enough from those modeled so as to preclude tidal locking, which will act, in general, to make the planet even more habitable than seen here. These conditions include orbital resonances with other planets in the system, spin-orbital resonances, and tidal dissipation rates different from those expected. All of these conditions allow a planet to avoid becoming tidally locked, and, if it is in the habitable zone, to increase its habitability.

1.4 Earth Equivalent Distance and Orbital Period

The calculation of the Earth Equivalent Distance (EED) is based on data from the isochrone 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 2MASSJHK, with circumstellar dust turned off. The initial mass function is lognormal from Chabrier (2001). The age is 4.55 Ga with Z = 0.01900. The luminosity is related to the radius of the semimajor axis of an orbiting body through the flux relation Eq. 1.2
Here, \( F \) is the flux at a given distance \( a \), from a star with luminosity \( L \). But, the flux is same at the Earth as the planets here, so Eq. 1.3 must hold

\[
L_{\text{star}} = \left( \frac{a_{\text{planet}}}{a_{\text{Earth}}} \right)^2 L_S. \tag{1.3}
\]

Here \( a_{\text{planet}} \) is the semimajor axis of the planet (or the EED) in AU (Astronomical Unit = the distance from the Earth to the Sun = \(149,598,000 \) kilometers) and \( a_{\text{Earth}} \) is the semimajor axis of the Earth in AU. Finally, the EED is used to calculate the orbital period via Kepler’s Third Law of Planetary Motion: Eq. 1.4

\[
\left( \frac{EED}{a_{\text{Earth}}} \right)^3 \left( \frac{M_S}{M_{\text{star}}} \right) = \left( \frac{P_{\text{planet}}}{P_{\text{Earth}}} \right)^2. \tag{1.4}
\]

Here, \( P_{\text{planet}} \) is the orbital period of the planet in Earth years, and \( P_{\text{Earth}} \) is the orbital period of the Earth in Earth years for a typical main sequence star.

### 1.5 Circulations

The modeled planets are forced with a constant, non-zonal insolation that is at a maximum at the equator. It is expected that the circulations will have some component that reasonably resembles the solution in Gill (1982). Gill (1982) demonstrated with an analytical model that a fixed heating on an equatorial beta-plane will perturb the system such that both Kelvin waves and planetary waves are formed. The characteristics of a Kelvin wave are flow parallel to and symmetric about the equator. The surface flow in...
this Kelvin wave was easterly, moving toward the heating. The Kelvin waves propagated eastward away from the disturbance at speed \(c\) and decay at rate \(r\), with decay through momentum transfer between levels through cumulus activity or “cumulus friction”. The planetary waves had meridional (north-south) flow and propagated westward at a speed one-third that of the Kelvin wave, but continuing at the same decay rate. Because of the meridional motion of the planetary wave, there was poleward motion at the point of heating. This resulted in a cyclonic center to the west of the heating. The vertically rising air at the source propagated through the waves and sinks. From there, the air returned along the surface. Because of the difference in distance traveled by the waves, more points eastward of the source felt the effects of the disturbance than those westward of the source. This set of circumstances help form the Walker circulation in the Pacific Ocean.

Williams (1982) studied the differences in atmospheric circulation of planets rotating at different rates using a GCM. The study focused on planets with a flat, uniformly moist surface of zero heat capacity rotating relative to their parent star and it excluded all ice-related processes. The radiative heating and cooling calculations were performed using normal annual mean distribution of albedo, ozone, carbon dioxide and cloud cover for the earth. The rotation rates ranged from 8 times present earth rotation to no rotation. Starting from no rotation, as the rotation rate increased, the planet developed zonally flowing super-rotating jets near the poles. As the rotation rate was increased further, these jets strengthened and moved equatorward. As the rotation rate was increased further, the jets continued to move equatorward and strengthen, with secondary jets developing poleward of the initial jets pair. The study also examined the effects of
obliquity, and the diurnal period. This study shows that the basic physics of the atmosphere on Earth are representative of the basic atmospheric physics of all planetary atmospheres.

Another study that investigated the changes in atmospheric circulations with rotation rate was Del Genio (1987). In Del Genio et al (1987), the rotation rates ranged from 2/3 earth’s rotational period to 256 times its rotational period. It was shown that there are atmospheric circulation regime changes at 4 day rotational periods. We expect to see this transition in the present study, as well. They showed that the Rhines scale, the Richardson number (both geostrophic and cyclostrophic), and the Burger number all reach a minimum around 4 days rotational period. The Rhines scale is the ratio of the scale of the turbulent eddies to the observed horizontal scale. This Rhines number shows the importance of turbulent eddies to the observed atmospheric circulation. The Richardson number is the ratio of vertical to horizontal potential temperature contrast. The difference between the geostrophic and cyclostrophic Richardson numbers is the inclusion of the Rossby number in the geostrophic Richardson number. This inclusion of the Rossby number adds the strength of the Coriolis effect to the Richardson number. Overall, the Richardson number indicates the relative importance of vertical and horizontal heat transport in balancing differential diabatic heating. The Burger number is the square of the ratio of the deformation to the observed horizontal scale. The Rhines and Burger numbers together indicate which process (turbulent eddies or the deformation radius) sets the eddy horizontal scale.

The model used in Del Genio’s study was a simplified version of GISS Model 1 GCM. The hydrologic cycle was suppressed to expose the basic dynamics of the
circulations. We have done a similar thing here for the same reason (see Chapter 2). The energetics in Del Genio’s model shifted from baroclinic to quasi-barotropic when the Rossby radius of deformation reached planetary scale as the rotation rate decreased. As the Rossby radius of deformation increased, the Hadley cell expanded poleward and replaced eddies as the primary large scale transport mechanism. This expansion of the Hadley was accompanied by the poleward shift of the jet stream and baroclinic zone. Also, the equator-pole temperature contrast decreased. The jet strength was a maximum at the 8 day rotation period. This was accompanied by a switch in the eddy momentum transport from poleward to equatorward. The tropospheric static stability decreased in the tropics and increased in the midlatitudes with increasing rotation period, but the global static stability remained constant. The spectrum of the kinetic energy of the eddies shifted to lower wavenumber with increasing rotation period, reaching wavenumber 1 at 8 days rotation period.

Williams (1988a,b) were two more thorough papers that analyze the circulation regimes of planets rotating at rates faster and slower than the earth. In these papers, the influence of rotation rate on moist and dry atmospheres under a variety of conditions (axisymmetric, oblique, diurnal heating, drag-free surfaces, interior heated surfaces, and regular surfaces) was studied. The circulations were interpreted in terms of a combination of standard symmetric-Hadley (SH) and quasi-geostrophic (QG) theories. The circulations were described as combinations of the natural Hadley circulation, the quasi-Hadley circulation, a QG latitudinally asymmetric wave dispersion that gives a poleward, jet-traversing momentum transport circulation, and a QG symmetric wave dispersion that gives a jet-converging momentum transport circulation. The quasi-Hadley
circulation is only seen in the moist atmospheres because the quasi-Hadley circulation takes into account the latent heating of the atmosphere from cloud formation. For slow rotators (rotation period < 4 days), the natural Hadley circulation dominates in moist atmospheres, overlapping QG latitudinally asymmetric and quasi-Hadley elements dominate in the midrange (rotation period between 1 and 2 days), and overlapping QG latitudinally asymmetric wave dispersion, QG symmetric wave dispersion, and quasi-Hadley circulations dominate in the high range (rotation periods < 1 day). The dry atmospheres were similar in all cases except that they lack a quasi-Hadley circulation.

Kinetic energy was highest in the 8 day rotator for the moist cases and the 2 day rotator for the dry cases. Rossby waves propagate more easily in the moist cases than in the dry cases because of the extra energy imparted to the atmosphere through latent heating.

This present study builds on those of Williams, Del Genio and Joshi. The present study extends Williams’ studies to tidally locked planets while still feeling the effect of the Coriolis force, and extends Joshi’s work to include planets rotating at different rotation periods.

Spiegel (2007) challenged the assertion that a planet’s average surface temperature must be above 273K to be habitable. Using an energy balance model, they studied the spatial and temporal variation in habitability of Earth-like planets. The study showed that the habitability of Earth-like planets that are not tidally locked depends on rotation rate and surface features, such as land/ocean fraction and that the habitability of a planet cannot be solely determined from the average surface temperature. This work continues the study of Spiegel in a 3d model and examines the applicability of the idea of partial habitability to tidally locked planets.
The remainder of this thesis is organized as follows. Chapter 2 discusses the atmospheric circulations of dry planets. Chapter 3 discusses the atmospheric circulations of ocean planets. Chapter 4 describes the carbonate silicate cycle and its affects on the atmosphere and habitability of tidally locked planets. And Chapter 5 concludes the study with a summary of the work done here, and its relevance in the light of the previous works.
Chapter 2

Dry Planets

2.1 Introduction

Although atmospheric composition is an important component in determining the atmospheric circulation and, thereby, the habitability of a planet, these type of data are not capable of being collected in the near future. The focus of this study is to determine to the first order how the lowest-order climate of a planet depends on its orbital parameters; therefore, this research aims to gain insight into the lowest-order constraints on the probability of a terrestrial planet being habitable based solely on the easily observed orbital characteristics.

As discussed in the previous chapter, previous work in this area includes the studies of Williams (1982, 1988), Del Genio (1987) and Joshi (2003). The work of Williams (1982, 1988) and Del Genio (1987) has already determined the circulations for planets orbiting far from their parent star. However, for low mass stars, habitable planets will be near their parent stars, placing them within the tidal locking radius of the stars. Tidally locking a planet to its parent star does not necessarily affect the atmospheric circulation, as long as the planet still rotates relative to its parent star. However, in the 1:1 tidal locking case, this rotation relative to the parent star does not occur. Therefore, these planets were not addressed by either Williams or Del Genio. Joshi (2003) studied a
tidally locked planet with a ten day orbit, but he did not examine other orbital periods and rotation rates.

The purpose of this chapter is to fill the parameter space remaining with regard to tidally locked terrestrial planets, examining their lowest-order climatology and expected habitability based on their differing rotation rates.

In section 2.2, the methods and models used in this study are discussed. In section 2.3, a planet that rotates every 24 hours and that is not tidally locked is discussed as a representation of earth under the conditions specified in section 2.2. In section 2.4, tidally locked planets are discussed. In section 2.5, a transition between circulation regimes is explored and its impact on habitability is discussed. Section 2.6 discusses the habitability of these planets. In section 2.7, the chapter is concluded, discussing the research presented here in light of previous work and expectations for future work.

2.2 Methods

In this study, a global circulation model (GCM) is used to simulate the circulations of dry, tidally locked planets orbiting within the habitable zones of their parent stars.

2.2.1 Planetary and Orbital Characteristics

The modeled planets are perfect spheres with the mass and radius of the earth. The surface is entirely land with no ocean, with flat topography at zero elevation. There
is no vegetation, and the ratio of soil sand: silt: clay is 33:33:34 everywhere. The gravitational acceleration is 9.81 m s\(^{-2}\) at the surface, the same as for Earth.

In all experiments described here, the solar constant is fixed at 1365 W m\(^{-2}\), and the pattern of solar radiation is assumed to be invariant in time, consistent with complete tidal locking at a ratio of 1 orbit to 1 rotation. The subsolar point is assumed to be at 90\(^\circ\)E longitude (Figure 2-1). A circular orbit is specified with no seasons (zero obliquity, zero eccentricity, zero precession). These assumptions are reasonable for tidally locked planets.

Table 2-1: The orbital characteristics for the planets modeled. The characteristics for the EED and \(M_{\text{star}}/M_{\odot}\) are based on the Mass-Luminosity Relation for typical main sequence stars \(\left(\frac{M_{\text{star}}}{M_{\odot}} = \left(\frac{L_{\text{star}}}{L_{\odot}}\right)^{2/3}\right)\).

<table>
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<th>Rotation Period (hr)</th>
<th>(\Omega) (rad/s)</th>
<th>(\frac{M_{\text{star}}}{M_{\odot}})</th>
<th>(\frac{M_{\text{star}}}{M_{\odot}})</th>
<th>EED (AU)</th>
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<tr>
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<tr>
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<td>0.104</td>
<td>0.019</td>
<td></td>
</tr>
<tr>
<td>96</td>
<td>1.82x10(^{-5})</td>
<td>0.120</td>
<td>0.024</td>
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</tr>
<tr>
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<td>1.75x10(^{-5})</td>
<td>0.122</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>101</td>
<td>1.73x10(^{-5})</td>
<td>0.122</td>
<td>0.025</td>
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<td>1.000</td>
<td>1.000</td>
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</tr>
</tbody>
</table>
2.2.2 Atmospheric Characteristics

The assumed atmosphere is similar to that of Earth in mass and composition. The surface pressure is 1 bar. The atmospheric carbon dioxide concentration is set to 345 ppmv, with zero concentrations for other greenhouse gases. The balance of the atmosphere is composed entirely of nitrogen (N$_2$) and oxygen (O$_2$). These simplifications are made so that the underlying atmospheric dynamics are easier to diagnose and explain.

2.2.3 Model Description

The experiments described below use the GENESIS version 2.3 GCM, composed 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$^\circ$), both for the atmosphere and surface models.

The surface module includes multilayer models of soil (Pollard and Thompson, 1995). 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. Heat diffusion is included with the diffusion coefficient, $k$, dependent on the different soil components.

The standard GENESIS v2.3 GCM was adapted for this study by adding the ability to (i) set the inertial rotation rate in the Coriolis terms for atmospheric and sea-ice dynamics, (ii) set the day length for solar radiation, including an option for no temporal variation (tidal locking), and (iii) optionally initialize the atmosphere and soil to
completely dry conditions. The coding added to the model to create these additions was minor in scale, but necessary to the success of this study.

2.2.4 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 periods (in Earth hours. i.e., 3600 sec) are 24-hr, 48-hr, 72-hr, 96-hr, 120-hr, 240-hr, and 2400-hr, following the curve shown in Figure 1-1. Though the earth rotates every 23 hr 56 min, the rotation periods are all compared to a 24-hr rotator for ease in calculation. These curves were determined from the tidal dissipation equation given in Peale (1977). In addition, a non-tidally locked control experiment was performed with solar radiation period and inertial rotation period both set to 24 hours. Also, simulations were performed at rotation periods of 99, 100, 101, and 102 hours. These model runs analyze the transition between the fast rotating regime and the slow rotating regime. 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 daily (once every 24 hr) model 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. It was necessary to reduce the GCM time step to 10 minutes (from its standard value of 30 minutes) to preserve numerical stability with the stronger atmospheric winds resulting from tidally locked solar radiation.

2.2.5 Flux decomposition

The momentum equations in sigma-coordinates (Washington and Parkinson, 2005) are
and

\[ \frac{\partial p}{\partial \sigma} = -\rho g \frac{\partial z}{\partial \sigma}. \tag{2.3} \]

Here \( u \) is the zonal wind component, \( v \) is the meridional wind component, \( \rho \) is the air density, \( f \) is the Coriolis forcing, \( a \) is the planetary radius, \( \phi \) is the latitude, \( \lambda \) is the longitude, \( p \) is the atmospheric pressure, \( z \) is the height, \( \sigma \) is the sigma vertical coordinate, \( F \) is the frictional forcing in the zonal or meridional direction, and \( g \) is the gravitational forcing. These equations are generic large-scale atmospheric equations. GCM codes use essentially equivalent, but often slightly different forms of these equations, for numerical reasons. The GENESIS model is fully described by Pollard and Thompson (1995b). The planets were spun up from an isothermal resting state, changing only the Coriolis forcing term for each model run.

Stationary waves are excited through atmospheric interaction with surface features, like mountains, that constantly force the atmosphere in a consistent way or through localized heat sources, like ocean warm pools. Since the planets here are tidally locked (aside from the control) and, therefore have an uneven distribution of solar radiation in the zonal direction, the stationary wave flux is expected to play an important role. In contrast, transient waves are excited through baroclinic instability. These
Transient eddies are the major weather producers here on Earth. These wave fluxes are analyzed through Fourier transforms in time and space to determine the relative importance of the waves for energetic and momentum distribution in the different model runs. The nomenclature used here is taken from Peixoto and Oort (1992) wherein an overbar (\(\bar{\cdot}\)) denotes the temporal average, the brackets ([ ]) denote zonal average, the prime (\(\prime\)) denotes perturbation from the temporal mean, and the asterisk (\(*\)) denotes perturbation from the zonal mean. So, each variable has a time mean (\(\bar{A}\)), a time perturbation (\(A'\)), a zonal mean ([A]), and a zonal perturbation (\(A^*\)). These are used to denote the circulations that transport heat and momentum around the planet through advection. \([\bar{A}\bar{B}]\) is the total zonally and temporally averaged (hereafter, called the mean) flux, which is the sum of \([A\bar{B}]\), the flux due to the mean meridional circulation (MMC), \([A'B']\), the flux due to the transient mean meridional circulation, \([A^*B^*]\), the flux due to the stationary eddies, and \([A'^*B'^*]\), the flux due to the transient eddies.

2.3 Dry Earth

For future comparison, a planet rotating once every 24 hours without being tidally locked was modeled first. The mean fields are shown in Figure 2-2. The mean potential temperature field (Figure 2-2a) shows strengthening static stability (increasing vertical gradient of potential temperature) as one moves poleward around a zone of higher instability (decreased vertical gradient of potential temperature) in the tropics. This zone of lower static stability in the tropics will hereafter be called the potential temperature...
Figure 2-2: a) The mean potential temperature field in K. The area with potential temperature above 300 K is shaded. 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\(^8\) kg s\(^{-2}\) 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) in J m\(^{2}\) s\(^{-1}\) horizontally and J cPa m\(^{-3}\) s\(^{-1}\) vertically relative to the given arrow of 5x10\(^3\) J m\(^{2}\) s\(^{-1}\) (or J cPa m\(^{-3}\) s\(^{-1}\)) and the transient eddy heat flux convergence (contoured at 10 and then the contour interval is 100) in 10\(^{-5}\) J m\(^{-3}\) s\(^{-1}\). d) The transient eddy zonal momentum flux (vectors) in m\(^{2}\) s\(^{-2}\) horizontally and m cPa s\(^{-2}\) vertically relative to the given arrow of 50 m\(^{2}\) s\(^{-2}\) (or m cPa s\(^{-2}\)) and the transient eddy zonal momentum flux convergence contoured at a contour interval of 1x10\(^{-5}\) m s\(^{-2}\). e) The mean meridional circulation (MMC) heat flux (vectors) in J m\(^{2}\) s\(^{-1}\) horizontally and J cPa m\(^{-3}\) s\(^{-1}\) vertically relative to the given arrow of 5x10\(^5\) J m\(^{2}\) s\(^{-1}\) (or J cPa m\(^{-3}\) s\(^{-1}\)) and the MMC heat flux convergence (contoured at 1000 and then the contour interval is 1000) in 10\(^{-5}\) J m\(^{-3}\) s\(^{-1}\). f) The MMC zonal momentum flux (vectors) in m\(^{2}\) s\(^{-2}\) horizontally and m cPa s\(^{-2}\) vertically relative to the given arrow of 100 m\(^{2}\) s\(^{-2}\) (or m
cPa s$^{-2}$) 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$^{-1}$. Throughout this paper, the shaded areas denote areas of negative quantities unless otherwise stated.

well. For this study, the well is delineated as the area with potential temperatures greater than 300 K because this potential temperature defines the tropical well in the control.

Without water, the transfer of energy through the atmosphere is all accomplished through adiabatic processes. The only diabatic processes allowed are the absorption of stellar energy by the surface and atmosphere, the turbulent transfer of heat from the surface to the atmosphere, and long-wave radiational cooling of the atmosphere by CO$_2$ and the surface.

This planet shows a pair of zonal jets at 200 hPa at 30° latitude, as is seen in Figure 2-2b in the filled contours with zonal wind speeds in excess of 20 m s$^{-1}$. The jets seen here are realistic in their strength. A Hadley cell is seen in the average zonal wind field as easterly (negative) winds at the equator bracketed by westerlies located near 20° latitude. The subtropical jet forms at the poleward end of the Hadley cell, near 20° latitude which is a narrower region than that seen on Earth. Some of the reasons for this difference between the control run and the present Earth are the absence of topography and oceans in the control, which act to force stationary eddies, maintain the surface air temperature through the heat capacity of water, and add latent heat to the system. The contours of the average mass stream function (Peixoto and Oort, 1992) show a strong Hadley cell with weaker Ferrel cells poleward of the strong Hadley cell circulations. These are known to be Ferrel cells because their circulations are thermally indirect, as opposed to the nearby thermally direct Hadley cells, with the signs changing between the
Ferrel cell and the nearby Hadley cell. A thermally direct circulation has rising air in the warm sector and sinking air in the cool sector. This type of circulation is denoted by positive values for the mass stream function in the northern hemisphere and negative values in the southern hemisphere. A thermally indirect cell has rising air in the cool sector and sinking air in the warm sector. This type of circulation is denoted by negative values for the mass stream function in the northern hemisphere and positive values in the southern hemisphere. The weak polar cells may also be seen in this figure, as evidenced by the surface easterlies poleward of 45° latitude.

The momentum and energy fluxes from different mechanisms are now examined to establish what mechanisms might be causing the circulation patterns seen here. For the control, only the MMC (the Hadley cell) and the transient eddies make important contributions to the circulation. The strong Hadley cell is seen in Figure 2-2b. Here, the heat flux of the transient eddies is seen as vectors in Figure 2-2c, and the convergence of the flux is contoured. Convergence is denoted by solid contours while divergence is denoted by dashed contours. The transient eddy heat flux is negative for most of the atmosphere, with heat moving up and poleward. This transport of energy is especially strong near the surface between 20° and 40° latitude. This is consistent with the transient eddies being strongest in the mid-latitudes.

The transient eddy zonal momentum flux convergence (Figure 2-2d) directly above the equator shows convergence. Note also that the zonal momentum flux of the transient eddies is divergent in the subtropics and convergent near 40° latitude at 200 hPa. This transient eddy momentum flux convergence and the surface westerlies seen in Figure 2-2b between 20° and 45° latitude identify the polar front. On the present Earth
the polar front jet lies near 60° latitude. The difference here is most likely caused by the lack of water vapor in the atmosphere and surface topography. Because of the close proximity of the subtropical and polar front jets in this run, it is difficult to judge the poleward extent of the subtropical jet and the equatorward extent of the polar front jet in the figure. So the jets seen in Figure 2-2b are a combination of the subtropical and polar jets seen on earth.

Figure 2-2e shows the MMC heat flux. Note the convergence, divergence, convergence triplet over the equator, and the triplet’s reversal in the rest of the tropics. The triplet is the result of converging air at the surface, rapidly rising and cooling air in the mid-levels, and converging air aloft. The reversal in the rest of the tropics shows sinking air aloft diverging, converging and warming in the mid-levels and diverging air at the surface. This combination of triplets makes up the vertical branches of the previously mentioned Hadley cell. Combining the tropical reversed triplet and another convergence, divergence, convergence triplet in the mid latitudes results in the Ferrel cell circulation. Poleward of the Ferrel cell, another triplet is seen which shows the circulation of the polar cell.

Figure 2-2f shows the MMC zonal momentum flux. The MMC zonal momentum flux converges near 20° latitude and near 200 hPa. This convergence aloft shows the location of the subtropical jet. On present Earth, the subtropical jet is located near 30° latitude. The difference seen here is most likely due to the lack of water vapor and topography in this model.

The adiabatic warming and cooling term (Figure 2-2g) shows strong cooling in the equatorial atmosphere bracketed by weaker warming near 20° latitude. This
corresponds to the Hadley cell circulation seen in Figure 2-2b. Another area of warming lies poleward of the cooling, which corresponds to the Ferrel cell circulation. The cooling seen at the poles corresponds with the polar cell.

The stationary wave contribution is ignored because localized heat sources and topography are absent; therefore, the stationary wave contribution is negligible. In summary, some minor differences between the present Earth and the control are expected due to the simplifications made, but the overall circulation is reasonably well simulated.

2.4 Tidally locked cases

2.4.1 24 hour orbiter

The first case discussed is the 24 hour orbiter. This case is not quite physical because the stellar mass required for an orbital period of 24 hours (~0.01 $M_{\text{Sun}}$) is below the hydrogen burning limit of 0.08 $M_{\text{Sun}}$; 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 given in Figure 2-3a. Here, two separate jet streams are seen, as opposed to the single jet stream seen in the control run. The more equatorward jet stream lies near 10° latitude with the secondary jet stream near 70° latitude. These jet streams are analogous to the subtropical and polar jet streams seen on present Earth, respectively. However, the subtropical jet stream seen in this run is more equatorward than the subtropical jet seen on Earth which lies near 30° latitude. Also, the polar jet seen in this run is more poleward than the polar
jet seen on present Earth which lies near 60° latitude. So, this tidally locked run looks different from the control in the distribution of the jet streams. The jet streams for this tidally locked case are also stronger than the jet streams in the control case. The jet

Figure 2-3

Figure 2-3: a,c,e,g,i) The zonally and temporally averaged (filled) zonal wind velocity in m s\(^{-1}\) for the 24, 72, 96, 120, and 2400 hour orbiters, respectively. The contour interval is 5 m s\(^{-1}\) and the color is based on the key given in Figure 2-3a. Black contours of the mass stream function in 10\(^9\) kg s\(^{-2}\), with contours of 0, 1, 2, 5, 10, 15, 20, and 25. b,d,f,h,j) The corresponding zonally and temporally averaged potential temperature in K for each case at contours of 10 K. The area with potential temperature above 300 K is shaded.
streams here attain average speeds greater than 60 m s$^{-1}$ for the subtropical jet and greater than 30 m s$^{-1}$ for the polar jet, while the jet stream in the control case does not sustain average speeds greater than 30 m s$^{-1}$. The surface easterlies in the tropics also show differences between the control and this tidally locked case. In the control, these easterly winds extend from the equator to 20° latitude and reach to the top of the atmosphere. In the tidally locked case, the surface easterlies are broader, extending from the equator to near 45° latitude, but they are also shallower, reaching to only the 800 hPa pressure level. The mass stream function is also seen in Figure 2-3a. Here, a strong Hadley cell is seen in the tropics, a weak Ferrel cell is seen in the mid-latitudes, and a strong polar cell is seen in the high latitudes. The strong polar cell and weak Ferrel cell seen here are different from the control run where the Ferrel cell was strong and the polar cell was weak. The Hadley cell is slightly weaker in the tidally locked case than in the control, but has a broader reach (beyond 40° latitude) than in the control, in which it reached only 20° latitude.

In Figure 2-3b, it is shown that there is a high vertical and horizontal gradient in the mean potential temperature field. The tidally locked planet is much more stable than the control run, and the slope of the isentropes is much gentler in the tidally locked case than in the control run. The 300 K isentrope does not touch the surface anywhere in the tidally locked planet, unlike in the control, where the 300 K isentrope touches the surface near 10° latitude.

To understand the differences between the control and the tidally locked planet, the meridional and vertical fluxes of heat and momentum are displayed in Figure 2-4.
Figure 2-4:  a) The transient eddy heat flux b) The transient eddy zonal momentum flux c) The stationary eddy heat flux d) The stationary eddy zonal momentum flux e) The MMC heat flux f) The MMC zonal momentum flux and g) The adiabatic energy term for the 24 hour tidally locked planet.  The transient eddy heat flux convergence is contoured at $10 \times 10^3$ J m$^{-3}$ s$^{-1}$ and then the contour interval is $50 \times 10^3$ J m$^{-3}$ s$^{-1}$ with a reference vector for the flux of $1 \times 10^5$ J m$^{-2}$ s$^{-1}$ horizontally (J cPa m$^{-3}$ s$^{-1}$ vertically). The transient eddy zonal momentum flux convergence is contoured at $1 \times 10^{-5}$ m s$^{-2}$ with a reference vector for the flux of $100$ m$^2$ s$^{-2}$ horizontally (cPa m s$^{-2}$ vertically). The stationary eddy heat flux convergence is contoured at $10 \times 10^3$ J m$^{-3}$ s$^{-1}$ and then the contour interval is $50 \times 10^3$ J m$^{-3}$ s$^{-1}$ with a reference vector for the flux of $1 \times 10^5$ J m$^{-2}$ s$^{-1}$ horizontally (J cPa m$^{-3}$ s$^{-1}$ vertically). The stationary eddy zonal momentum flux convergence is contoured at $1 \times 10^3$ J m$^{-3}$ s$^{-1}$ and then the contour interval is $5$ m s$^{-2}$ with a reference vector for the flux of $200$ m$^2$ s$^{-2}$ horizontally (cPa m s$^{-2}$ vertically). The MMC heat flux convergence is contoured at $10 \times 10^3$ J m$^{-3}$ s$^{-1}$, and then the contour interval is $50 \times 10^3$ J m$^{-3}$ s$^{-1}$ with a reference vector for the flux of $4 \times 10^5$ J m$^{-2}$ s$^{-1}$ horizontally (J cPa m$^{-3}$ s$^{-1}$ vertically). The MMC zonal momentum flux is contoured at 1 m s$^{-2}$ and then the contour interval is 5 m s$^{-2}$ with a reference vector of 200 m$^2$ s$^{-2}$ horizontally (cPa m s$^{-2}$ vertically). The adiabatic term is contoured at 0.02 J kg$^{-1}$ s$^{-1}$. 
Using this figure, the relative importance of the transient eddies, the stationary eddies and the MMC can be determined. Here, the stationary eddies are shown to play an important role in the circulation of heat and momentum through the atmosphere.

The transient eddy heat flux (Figure 2-4a) shows a similar setup to the control run (Figure 2-2c). Much of the atmosphere has a divergent heat flux, with weak areas of convergent heat flux in the tropics and polar regions. There are some differences, as well. The control run has weaker negative heat flux convergence than the tidally locked case, and, a second maximum in divergence is seen near 60° latitude in this simulation which is not seen in the control. The heat flux convergence in the tropics acts to increase the slope of the isentropes, while the divergence in the subtropics and midlatitudes acts to decrease their slope. The low-level convergence tends to increase the vertical potential temperature gradient (increasing the static stability near the surface) while the divergence in the mid levels acts to decrease this gradient.

The transient eddy zonal momentum flux (Figure 2-4b) bears little resemblance to the control (Figure 2-2d). A few areas show similar characteristics: the convergence seen in the low-level tropics and the upper-level convergence, for example. However, other characteristics are very different. In the polar regions, the control shows strong zonal momentum divergence, while in the tidally locked case, the polar regions show weak convergence. Also, the two distinct lobes of strong divergence seen in the control near 20° latitude are absent from the tidally locked case. In the control, areas of transient eddy momentum flux convergence were the location for the polar front jet. Here, the jets are not located in areas of transient eddy momentum flux convergence in the tropics and subtropics. Instead, these areas of convergence move some of the zonal momentum
poleward for use in the secondary jet stream. In the high latitudes, the convergent areas are closely associated with the secondary jet stream. Also, the large divergent region in the mid latitudes seems closely associated with the region of low zonal wind speed.

The stationary eddy heat flux (Figure 2-4c) has no equivalent in the control. This is because the control has no zonal change in forcing. This lack of forcing results in an environment where stationary eddies cannot develop. For the tidally locked planet, the stationary eddy heat flux convergence shows alternating areas of convergence and divergence, with divergence in the equatorial region, convergence in the tropics, divergence in the mid-latitudes, convergence near 60° latitude and divergence in the polar regions. The low-level subtropical and midlatitude divergence acts to decrease the potential temperature gradient horizontally along the surface, carrying low potential temperature air into the tropics. The convergence in the tropics acts to aid in smoothing the potential temperature gradient even more, allowing the potential temperature at the surface to become very low for its location. Comparing this heat flux convergence with the transient eddy and MMC heat flux convergences, it is apparent that all three of these motions have nearly the same strength and, thereby, are equally important in the distribution of heat around the planet.

The stationary eddy zonal momentum flux (Figure 2-4d) again has no equivalent in the control run and for the same reason. The equatorial region shows low-level convergence underlying mid-level divergence with upper-level convergence aloft. Comparing this figure to Figure 2-4f, a similar but opposite setup is seen. Where the stationary eddy momentum flux shows convergence, the MMC shows divergence, and vice versa. This interaction extends into the tropics but not into the mid-latitudes.
Instead, in the mid- and upper latitudes, the transient eddy (Figure 2-4 b) convergence and divergence aloft act in opposition to the stationary eddy divergence and convergence in the mid and upper latitudes, respectively. The stationary eddy zonal momentum flux convergence in the high altitudes over the equator seen here will become important in later simulations for the development of an equatorial jet. Here, the stationary eddy zonal momentum flux convergence over the equator acts to draw zonal momentum toward the equator. In the high latitudes, the jet streams are aided in development by the stationary eddies. Here, the convergence seen near 60° latitude seems to be the source for the zonal momentum drawn into the polar jet by the transient eddies. Again, all three circulations have about the same magnitude and, therefore, are important in determining the circulation.

The MMC heat flux (Figure 2-4e) shows strong resemblance to the MMC heat flux in the control (Figure 2-2e). There is convergence at low-levels, divergence at mid-levels and convergence aloft over the equator. There is also a secondary triplet of divergence, convergence, and divergence, respectively, near 20° latitude. However, that is where the similarities end. The mid-latitudes are dominated by convergence, whereas the control had another convergence, divergence, convergence triplet. And the polar regions are dominated by divergence, where the control had another divergence, convergence, divergence triplet. The triplet in the tropics acts to increase the vertical potential temperature gradient high aloft and near the surface while decreasing the gradient in the mid-levels. This setup should result in a steep slope for the isentropes that decreases with height. This is precisely what is seen in Figure 3-3b. In the subtropics, the opposite is true: the divergence is aloft and at the surface acts to decrease the vertical
potential temperature gradient, while the convergence in the mid levels acts to increase the vertical potential temperature gradient. This acts to decrease the slope of the isentropes. Again, this effect is seen in Figure 2-3b.

The MMC zonal momentum flux (Figure 2-4f) is very different from the control (Figure 2-2f). The control has divergence in the lowest level equatorial region, with convergence aloft. The tidally locked planet, on the other hand, has convergence in the low-levels and divergence aloft over the equator. Near 20° latitude, both cases show divergence near the surface and convergence aloft. In both cases, these areas of convergence aloft show the location and forcing for the subtropical jet. Outside of the tropics, the MMC zonal momentum flux is weak for the tidally locked planet while the control shows a much greater forcing for the circulation. The MMC zonal momentum flux convergence in the subtropics is the direct source for the zonal momentum in the primary jet stream. It also plays an indirect role in the creation of the secondary jet stream by supplying the zonal momentum to the stationary eddies in the midlatitudes which supply the zonal momentum to the transient eddies in the high latitudes.

The adiabatic warming and cooling (Figure 2-4g) is strongest in the tropics. This agrees with the control (Figure 2-2g) which shows the same distribution in the tropics. However, the tropical warming near 20° latitude and the equatorial cooling are both weaker in the tidally locked planet than in the control. The control shows weak cooling throughout the atmosphere near 40° latitude which is not seen in the tidally locked case. Instead, there is weak warming in the tidally locked planet run. The poles are also different, with atmospheric warming throughout the polar regions in the control. By contrast, where the tidally locked planet shows cooling except at the lowest levels.
For the control run, only two major components are involved in the heat and momentum fluxes: transient eddies and the MMC. When the planet is tidally locked around its parent star, the circulation becomes more complex as a third player, the stationary eddies, becomes important as well. The interplay between these three circulations should have a pronounced effect on the surface temperature and, thereby, the habitability of the tidally locked planets.

2.4.2 Other Tidally Locked Planets

In addition to the 24-hour orbiter case, Figure 2-3 shows the mean zonal wind speed, mass stream function and potential temperature for the 48-hour case, the 96-hour case, the 120-hour case and the 2400-hour case. Taken altogether, these cases run the full gamut from the smallest M-stars to the low mass end of the K-stars. Because the change in spectral distribution of the incident radiation has been ignored (as discussed previously), these simulations demonstrate the changes that occur in the circulation due to only changing the strength of the Coriolis effect. The low-mass end of the K-stars was chosen as a cut off for this study because planets orbiting at the EED around stars of mass greater than 0.62 \( M_{\text{Sun}} \) are not likely to be tidally locked.

The mean zonal wind speed shows the location of the jet streams and the tropical easterlies. The mean zonal wind speed shows a pair of jets with the 24 hour orbiter (Figure 2-3a). Increasing the orbital period to 48 hours (Figure 2-3c) shows that this pair of jets has become a single jet between 40° and 60° latitude with an average speed greater than 50 m s\(^{-1}\). The tropical easterlies are still present, extending from the equator to
beyond 40° latitude. Increasing the orbital period to 96 hours (Figure 2-3e) increases the speed of the single jet to above 70 m s\(^{-1}\) with tropical easterlies still present.

Increasing the orbital period to 120-hours (Figure 2-3g) brings abrupt changes. The single jet in the mid-latitudes has disappeared, and an equatorial jet has appeared. This equatorial jet extends from the equator to beyond 40° latitude with wind speeds in excess of 60 m s\(^{-1}\). Also, the tropical easterlies have disappeared. Equatorial super-rotation cannot exist without an equatorial wave source. According to Hide (1969), equatorial super-rotating jets are most likely the sinks that develop as a result of horizontal advection of energy and angular momentum from higher latitudes toward the equator. These equatorial jets are sinks only for kinetic energy and angular momentum, as Suarez and Duffy (1993) showed that poleward heat transport still occurs within an equatorial super-rotating jet regime. They also showed that initiation of a super-rotating equatorial jet solution within a non-super-rotating atmosphere occurs when the tropical heating by eddies surpasses a value at which the conventional circulation becomes unstable. Getting a planet out of a super-rotating regime was found to be impossible once the super-rotating regime had been established, even when the tropical heating that initiated the super-rotating circulation was discontinued. Instead, they found a hysteresis effect with multiple steady states. They found that the propagation characteristics of the transient eddies had changed, decreasing “their easterly contribution to the low-latitude momentum budget”. Saravanan (1993) states that “waves generated by the eddy heating produce a sudden transition to super-rotation” through breakdown of the restoring mechanism. This results in a super-rotating circulation “where the weak westerly torque produced by eddy heating balances the easterly torque due to the weak meridional
circulation.” So, the transition between an Earth-like circulation and a circulation with an equatorial jet should be rapid, it should require strong stationary eddy heating at the equator, and the transition should be facilitated by a decrease in the equator-to-pole temperature gradient. In this study, tidal locking provides the strong stationary eddy heating. Decreasing the rotation rate (increasing the rotation period) results in a lower equator-to-pole temperature gradient (as seen in Figure 2-3). The rapidity of the transition and the resilience of the base circulations to transitional forcing will be examined later in this chapter.

Increasing the orbital period to 2400-hours (Figure 2-3i) 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 (1988). In general, as rotation rate decreases, the meridional scale of the jets and MMC increases. However, none of the dry cases of Williams (1988) showed an equatorial super-rotating jet. In fact, the only cases in that study which had an equatorial super-rotating jet were moist and fast rotating. Here, the transition between separate hemispheric jets and equatorial super-rotating jets actually occurs in slow, dry cases. Therefore, the equatorial super-rotating jet must be a result of the zonal asymmetry in the forcing and denotes a change between two circulation regimes. Here, the regimes will be referred to as fast rotating if they have Earth-like circulations and slow rotating if they have an equatorial super-rotating jet.

The mass stream function shows the relative strengths of the Hadley cell, the Ferrel cell, and the polar cells. In the 24-hour orbiter case (Figure 2-3a), a Hadley cell, a weak Ferrel cell, and a strong polar cell are seen. In the 48-hour orbiter (Figure 2-3c), the
Hadley cell has strengthened, the Ferrel cell has weakened and shrunk, and the polar cell has strengthened and expanded. In the 96-hour orbiter (Figure 2-3e), the Hadley cell has strengthened more, the Ferrel cell has strengthened and expanded, and the polar cell has weakened and shrunk. In the 120-hour orbiter (Figure 2-3g), abrupt changes have occurred. The Hadley cell has weakened. The Ferrel cell has strengthened and expanded to the poles, and the polar cell is not seen. The 2400-hour orbiter (Figure 2-3i) continues these changes, with a strengthened Hadley cell and a strengthened and expanded Ferrel cell. Interestingly, the extent of the Hadley does not change much between the runs with the 0 contour near 40° latitude denoting the poleward extent of the Hadley cell.

The potential temperature field shows the stability of the atmosphere. For relatively rapidly rotating (24-hr, 48-hr, and 96-hr) planets, the 300 K isentrope lies near 350 hPa in the polar regions and slopes down to near 900 hPa in the equatorial atmosphere (Figure 2-3b, d, f). The slope decreases with increasing rotation period. Also, the 300 K isentrope becomes flatter in the tropics as the rotation period increases. As the rotation period is increased to 120-hr (Figure 2-3h), the isentropes become flatter throughout the atmosphere. The 300 K isentrope starts near 550 hPa in the polar regions (as opposed to 350 hPa in the faster rotators) and descends to near 900 hPa. This is an example of the flatness of the isentropes. Increasing the orbital period to 2400-hr (Figure 2-3j) decreases the slope to nearly zero, with the 300 K isentrope remaining near 900 hPa for all latitudes.

The stationary wave structure for the tidally locked cases is displayed in Figure 2-5. In the fast rotating cases, an upper-level Rossby anticyclone can be seen to the west of the substellar point, and Kelvin waves are seen to the east of the substellar point. This
The 200 hPa and 850 hPa eddy geopotential heights and winds for the 24 (a,b), 72 (c,d), 96 (e,f), 120 (g,h), 2400 (i,j) hour rotators. The contour interval in the first column (200 hPa) is 100 m with wind vectors relative to the 100 m s$^{-1}$ arrow below panel g. The contour interval in the second column (850 hPa) is 50 m with wind vectors relative to the 50 m s$^{-1}$ arrow below panel h.

setup is similar to that seen in Gill (1982). However, the Rossby waves seen here to the east of the heating are not part of the Gill solution. In the lower levels, the tropical Rossby cyclone (which is seen in Gill) appears to have merged with an extratropical cyclone (which is not seen in Gill). The similarities between this study and Gill make sense because of the location of the forcing is approximately the same for the two studies.
However, the surface area coverage is different between the two models. Gill was restricted to the tropics, whereas here the entire planetary atmosphere comes into play, thereby allowing for the formation of a secondary Rossby wave and an extratropical cyclone. Also, in the Gill solution, the background flow was zero, whereas that is not the case here because of the strong momentum flux convergence by the stationary waves.

The slow rotating cases, especially the 120-hr case, show very little meridional tilt. They have greater wave amplitude than in the fast rotating cases, which implies that resonant-like behavior may be present. This resonant behavior may be a response to the zonal wave-number 1 heating projecting onto one of the normal modes of Laplaces’ tidal equations over a sphere (Longuet-Higgins, 1968) as the Rossby radius of deformation approaches the planetary radius. In Figure 2-5, the stationary wave structure for the 120-hr simulation shows characteristics of both the westward propagating Type 1 gravity wave and the Type 2 Rossby wave with $s = 1$, $\nu = 2$, and $\epsilon = 1$, where the notation is as in Longuet-Higgins. A Type 2 wave with these values should have a phase speed of $-63$ m s$^{-1}$. The absolute value of this phase speed is approximately equal to the value of the zonal mean of the zonal wind speed of the 120-hr case. Because the zonal mean of the zonal wind speed is not zero, then the westward propagation of the waves that would ordinarily occur for these waves is compensated for by the zonal wind. Therefore, an ordinarily westward propagating wave becomes a stationary wave.
2.4.3 Characteristic numbers

Several numbers in meteorology can be used to characterize the planetary circulations seen here. These numbers include the Rossby radius of deformation, the Rossby number, the scale height, and the Richardson number.

The Rossby radius of deformation, $\lambda_R$, is “the horizontal scale at which rotation effects become as important as buoyancy effects” (Gill, 1982). For this study, the equatorial Rossby radius of deformation is used. Its formulation is given by Eq. 2.4

$$\lambda_R = \sqrt{\frac{N \ast H}{2\beta}}. \quad 2.4$$

Here, $H$ is the scale height, and $\beta$ is the change in the planetary vorticity in the meridional direction. The Brunt-Väisälä frequency, $N$, is defined as Eq. 2.5

$$N \equiv \sqrt{\frac{g}{\theta} \frac{\partial \theta}{\partial z}}. \quad 2.5$$

Here $g$, 9.81 m s$^{-2}$, is the acceleration due to gravity, and $\theta$ is the potential temperature.

The scale height is defined as Eq. 2.6

$$H = \frac{R \bar{T_S}}{Mg}. \quad 2.6$$

Here, $R$ is the ideal gas constant, 8.314 J K$^{-1}$ mol$^{-1}$, $T_S$ is the surface temperature, and $M$ is the molecular mass of the air. Here 28 g mol$^{-1}$ is used because the atmosphere is almost entirely composed of nitrogen. Normally, $\lambda_R$ is defined in the midlatitudes as Eq. 2.7

$$\lambda_R = \frac{NH}{f}. \quad 2.7$$
Here, $H$ and $N$ are defined as above, and $f$ is the Coriolis parameter, which depends on latitude. For comparison, the midlatitude Rossby radius of deformation is listed in Table 2-2 as $L_R$.

From these tables, large changes in both the dimensionless and dimensional numbers are seen either between the 96-hr and 120-hr or in the trends of the numbers as this transition is approached. The average surface temperature increases from the 24-hr orbiter to the 96-hr orbiter, then drops sharply between the 96-hr and 120-hr orbiters and then increases again from the 120-hr orbiter to the 2400-hr orbiter. The maximum zonal wind speed increases from the 24-hr orbiter to the 96-hr orbiter and then decreases from the 120-hr orbiter to the 2400-hr orbiter. The scale height increases from the 24-hr

Table 2-2: The atmospheric characteristics for the planets modeled. The Earth’s radius is 6,378.137 km.

<table>
<thead>
<tr>
<th>Rotation Period (hr)</th>
<th>B (m$^{-1}$ s$^{-1}$)</th>
<th>N (s$^{-1}$)</th>
<th>H (km)</th>
<th>$\lambda_R$ (km)</th>
<th>$L_R$ (km)</th>
<th>mean $T_s$ (K)</th>
<th>$u_{max}$ (m s$^{-1}$)</th>
<th>$\psi_{max}$ (kg m$^{-3}$ s$^{-1}$)</th>
<th>$\psi_{max}$ (kg m$^{-3}$ s$^{-1}$)(secondary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>2.29x10$^{-11}$</td>
<td>1.48x10$^{-2}$</td>
<td>7.94</td>
<td>1547</td>
<td>1333</td>
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orbiter to the 96-hr orbiter, drops for the 120-hr orbiter, and then increases from the 120-hr orbiter to the 2400-hr orbiter. The Brunt-Väisälä frequency decreases from the 24-hr orbiter to the 96-hr orbiter, then increases dramatically for the 120-hr orbiter, and then decreases from the 120-hr orbiter to the 2400-hr orbiter. All of these changes occur near the 96 – 120-hr orbiter transition seen above. Looking for a cause for this transition, the Rossby radius of deformation seems to be a likely culprit. As the Rossby radius of deformation approaches a length equal to one-half of the planetary radius, the ability for full wavelengths of the wave-number-1 stationary wave to fit around a latitude circle decreases. When the Rossby radius of deformation equals one half of the planetary radius, then only one wave-number-1 stationary wave can exist around a latitude circle. By increasing the Rossby radius of deformation further, the energy that would have gone into the wave-number-1 stationary wave will begin to be passed into the wave-number-2 stationary wave. Continuing to increase the Rossby radius of deformation causes the lower wave-number stationary waves not to fit, resulting in the energy going into higher wave-numbers. This point will be revisited in Section 2.5.

2.4.4 Horizontal structure

Now that the mean meridional circulation patterns have been discussed, what are the effects of tidal locking on the zonal circulations? How does the non-zonally symmetric heating effect the atmospheric circulation? What are the energy consequences of having a stationary heat source? To address these questions, the horizontal structure of the circulation is examined.
2.4.4.1 Potential Temperature

It is of interest to examine the potential temperature variation among the simulated planets. The mean potential temperature field for the control is shown in Figure 2-6: a,c,e,g,i) The time averaged 200 hPa potential temperature and wind vectors for 24, 48, 96, 120 and 2400 hour rotators. The contour interval is 2K with the 350K contour darkened and all the vector lengths are relative to the arrow given below the column of 200 m s\(^{-1}\). b,d,f,h,j) The corresponding 1000 hPa potential temperature and wind vectors with contours of potential temperature of 10K with the 300 K contour darkened and the vectors are relative to the vector given below the column of 25 m s\(^{-1}\).
Figure 2-2b. The potential temperature does not vary longitudinally on this planet because rotation evens out the solar energy absorption along any latitude. However, for the tidally locked planets, this zonal symmetry does not occur, because the planet does not rotate relative to the parent star. As can be seen in Figure 2-6, the potential temperature field varies with longitude for these planets. All of these planets have potential temperature fields that vary with longitude; however, as the rotation rate slows, the latitudinal variation at 200 hPa decreases (Fig. 2-6 a,c,e,g, and i), but the 1000 hPa potential temperature fields maintain most of their longitudinal variation throughout. The difference in the 200 hPa fields is caused by the changing rotation rate, which changes the strength of the Coriolis effect. As the Coriolis effect decreases, the Rossby deformation radius increases. This increase in the Rossby deformation radius allows the Hadley cell to extend further poleward. Since the Hadley cell is associated with not only surface easterlies, but also uniform potential temperatures aloft, a smaller gradient in the potential temperature field at 200 hPa is expected as the Hadley cell expands (Del Genio and Suozzo, 1987). The 1000 hPa potential temperature field does not show this same decreased gradient, however. Instead, the potential temperature field at 1000 hPa displays the distribution of the solar insolation modified by the low-level wind field. Here, the dawn terminator corresponds to an anomaly in the potential temperature field for rotation periods less than 100 hours. This anomaly is a decrease in the potential temperature along meridians as the equator is approached. Instead of having concentric circles of decreased potential temperature radiating outward from the central maxima, as in the slowly rotating planets, the quickly rotating planets demonstrate a noticeable decrease in potential temperature along the equator on the dawn side. This decrease in
the potential temperature is caused by the cooler air rushing toward the substellar point from the antistellar point along the equator.

Figure 2-7: The total zonal flux of sensible heat for the (a) 24-hr, (b) 72-hr, (c) 96-hr, (d) 120-hr, and (e) 2400-hr rotators (vectors) and convergence (contours). Areas of divergence are shaded. These values have been averaged meridionally. The reference vector for the plots is $5 \times 10^6$ J m$^{-2}$ s$^{-1}$ horizontally (J cPa m$^{-3}$ s$^{-1}$ vertically). The contour interval is $500 \times 10^3$ J m$^{-3}$ s$^{-1}$. 

...
2.4.4.2 Zonal Flux of Energy

On the present Earth, the zonal flux of sensible heat is negligible. This is because the diurnal heating decreases the zonal gradient in temperature. On tidally locked planets, this sensible heat flux is important in advecting energy from the sunlit side to the dark side. In Figure 2-7, the sensible heat is calculated using Eq. 2.8

\[ E_s = \rho c_p T. \]  

Here, \( \rho \) is the density in kg m\(^{-3} \), \( c_p \) is the specific heat of air at constant pressure (1004 J K\(^{-1} \) kg\(^{-1} \)) and \( T \) is the air temperature in K. Then, the meridional and temporal averages are taken to get the values that are plotted. Figure 2-7a (the 24-hr orbiter) shows the divergence and convergence of the sensible heat flux. Here, there is convergence of sensible heat in the region between the substellar point to the antistellar point. This location for the convergence is expected because the hottest temperature on the planet is at the substellar point, whereas the antistellar point is near the coldest temperature on the planet. So, there should be convergence of sensible heat flux as warmer air is advected into colder areas. Correspondingly, the divergence of sensible heat flux in the region between the antistellar point and the substellar point is also expected for the same reason. Intriguingly, the only other case that shows this same behavior is the 120-hr case (Figure 2-7d). The 48-hr orbiter and the 96-hr orbiter show divergence near the dusk terminator (180° longitude) and convergence near the dawn terminator (0° longitude). Therefore, the warm air does not penetrate far onto the dark side and, correspondingly, the cold air does not penetrate far onto the sunlit side. The 48-hr orbiter actually has another set of areas of convergence and divergence on the dark side that is not seen in any other case.
Figure 2-8: The total zonal flux of potential energy for the (a) 24-hr, (b) 72-hr, (c) 96-hr, (d) 120-hr, and (e) 2400-hr rotators (vectors) and convergence (contours). Areas of divergence are shaded. These values have been averaged meridionally. The reference vector for the plots is $5 \times 10^6$ J m$^{-2}$ s$^{-1}$ horizontally (J cPa m$^{-3}$ s$^{-1}$ vertically). The contour interval is $50 \times 10^3$ J m$^{-3}$ s$^{-1}$.

The 2400-hr shows a convective circulation with convergence in the low-levels over the substellar point and divergence in the upper-levels over the substellar point. On the dark side, the convergence of sensible heat aloft and corresponding divergence of sensible heat in the low-levels shows the sinking motion associated with the convective circulation.
The divergence of the zonal flux of sensible heat on the dark side of the planet is difficult to explain with radiant flux alone. The zonal potential energy flux must be examined as well. In Figure 2-8, the potential energy is calculated from Eq. 2.9

\[ E_p = g \rho z \]  

Here, \( g \) is the gravitational acceleration, \( \rho \) is the density and \( z \) is the geopotential height. In Figure 2-8, adiabatic warming of the air through vertical motion transforms potential energy into sensible heat energy and adiabatic cooling reverses the process. Divergent regions of sensible heat flux are also regions of divergent potential energy flux with some minor differences.

### 2.4.4.3 Equatorial Circulation

The changes in the Rossby wave tilt across the transition also have an impact on the equatorial circulation. In Figure 2-9, the equatorial circulations for two cases, a fast rotator and a slow rotator, are shown. Also displayed are the circulations along the substellar and the antistellar longitudes. The equatorial circulations show some similarities and some differences. The equatorial circulations are quite similar over the substellar point (90°E longitude). Rising motion carries heat energy upward by convection into the upper atmosphere. This convection can be seen as the nearly vertical isentropes over the substellar point in both Figure 2-9a and Figure 2-9b. On the unlit portion of the planet, the two cases are different. In the fast rotator case (Figure 2-9a), isentropes on the unlit side are nearly flat, while isentropes on the unlit side of the slow rotator show curvature. This curvature has a large impact on the circulations. Ordinarily,
air will retain its potential temperature in the absence of diabatic energy gains or losses.

This resistance to change implies that the wind vectors should be parallel to the
isentropes, provided no diabatic heating or cooling occurs. However, diabatic cooling occurs on the unlit side of the planet through radiant cooling. Therefore, the air cools and its potential temperature decreases with time so that a component of the wind field extends toward lower isentropes. In general, as altitude increases, so does potential temperature. Therefore, the cooling air associated with lower potential temperature should move to lower altitudes. But, for the slow rotator case, the isentropes are curved in such a way that wind flowing parallel to the isentropes actually rises rather staying at the same altitude. Because the air resists changing potential temperature, the wind flows mostly parallel to the isentropes. So, when the isentropes are curved upward, the air begins moving upward as well, resulting in upward vertical motion on the dark side of the planet.

In Figure 2-9c and Figure 2-9d, the circulations for the substellar longitude (90°E) are shown. The two circulations look similar, with rising air near the equator. However, the circulations differ in the mid- and upper latitudes. The fast rotator shows strong upward motion in the equatorial atmosphere, with a pair of vortices bracketing the rising motion near 600 hPa and 20° latitude. Poleward of these vortices, downward motion is seen. The flow is poleward in the upper-levels above 200 hPa, whereas the lower levels show equatorward flow throughout the mid and high latitudes. The slow rotator (Figure 2-9d) displays very different characteristics. The upward flow in the tropics is weaker and less centralized than in the fast rotator case. The fastest upward motion is near 20° latitude, whereas the fastest upward motion was over the equator in the fast rotator case. The vortices are weaker, lower in the atmosphere (near 800 hPa) and more poleward (near 40° latitude) than in the fast rotator case. The flow is poleward at all but the lowest
levels (below 800 hPa). The surface area with potential temperature above 300 K reaches to 60° latitude and is wider than in the fast rotator case, in which it reaches to 50° latitude.

In Figure 2-9e and Figure 2-9f, the circulations for the antistellar longitude (90°W) are shown. Here, continuations of the differences seen over the substellar longitude are seen. For the fast rotator, the equatorward flow on the sunlit side has become poleward flow on the dark side. The flow at the equator is downward, with some slight upward motion in the tropics above 500 hPa. The 300 K isentrope descends to 900 hPa at the equator from a high near 350 hPa at the poles. For the slow rotator, the poleward flow on the sunlit side has become equatorward flow on the dark side. As mentioned above, the curvature of the isentropes in the slow rotator case leads to upward air motion at the equator, which is different from in the fast rotator case. In the fast rotator case, the minimum potential temperature is found at the poles. For the slow rotator case, the minimum potential temperature is found near 60° latitude, not at the poles. This collocates the minimum potential temperature at the surface with the center of the upper-level vortices seen in Figure 2-5g and the lower level vortices seen in Figure 2-5h.

2.5 Abrupt transition and multiple equilibria

For the 24-hr and 96-hr runs, the behavior of the transient eddy flux is similar to that of the control, earth-like run, indicating that the transient wave behavior (ie. the weather) is not so different from that of the earth. The same can be said about the mean
meridional circulation. However, the wave momentum flux characteristics change significantly between the 96-hr and 120-hr rotators. Here, the abruptness of this transition and what process is responsible for the transition are examined. To this end, the model was run using a binary search algorithm to find the rotation periods between which the transition occurs. It was expected that the transition would involve a transition state between the two regimes, with traits of both regimes commingled. However, this was not the case. The transition occurs between the rotation periods of 100 hours and 101 hours and a transition state displaying characteristics of both regimes is not seen.

Figure 2-10: The average zonal wind speed at 200 hPa above the equator for different rotation periods. All parameters are calculated from simulations spun up from rest except those that cross the transition. Across the transition, the initial conditions are the final conditions for the previous simulation along the same line.
The 100-hr rotator resembles the 96-hr rotator and the 101-hr rotator resembles the 120-hr rotator. This rapid transition between regimes, though it may vary slightly depending on the model initialization and the physics of the model, is expected to be robust in its abruptness. The robustness of this transition results from the nature of the transition. We postulate that the transition is caused by the saturation of the stationary eddy scale. This

**Figure 2-11**

Figure 2-11: 200 hPa height contours and wind vectors for the decreasing rotation rate series of simulations: a) 100-hr initial conditions, b) 101-hr, c) 220-hr, and d) 221-hr. The contour interval is 500m and the vectors are relative to the reference of 100 m s\(^{-1}\).
saturation occurs because the Rossby waves no longer fit on the planet without
interfering with each other. This lack of room for the Rossby waves is shown by the
Rossby radius of deformation. As the planetary rotation period increases, the Rossby
radius of deformation approaches the planetary radius, and the Rossby waves increase in
size and decrease in number until only one wave may fit on the planet. After that point,
any increase of the rotation period will begin forcing smaller Rossby waves (those with

Figure 2-12

Figure 2-12: 200 hPa height contours and wind vectors for the increasing rotation rate
series of simulations: a) 101-hr initial conditions, b) 100-hr, c) 93-hr, and d) 92-hr. The
contour interval is 500m and the vectors are relative to the reference vector of 100 m s\(^{-1}\).
higher wave numbers) preferentially because of the lack of space for any more low wave number waves. This effect was predicted by Del Genio (1987).

So, the transition is quite abrupt when starting from a non-rotating, non-circulating initial condition. However, if the planet’s atmosphere is already circulating in one of the two regimes, how slow (fast) does the rotation need to be in order to cause a change to the other circulation regime? To determine the effect of slowing down (or speeding up) the rotation rate, the planets were spun up from rest at 100-hr (101-hr) circulation for 3 years to create the initial conditions. From there, the planet’s rotation period was increased (decreased) and integrated for 3 years until the transition occurred. If the planet’s rotation period was changed too quickly, a premature transition occurred. To negate this effect, the transition was validated by increasing (decreasing) the rotation period by 1 hour until the transition actually occurred. For the fast rotating planets, increasing the rotation period resulted in a transition at a 221-hr rotation period (Figure 2-10). In Figure 2-11, the effects of slowing the rotation rate are shown. The 100-hr circulation (Figure 2-11a) was used as the initial conditions for the slow down. Note the pair of subtropical jet streams and the nearly negligible zonal variation in the height contours that are characteristics of the fast rotating regime. The 101-hr circulation (Figure 2-11b) shows that the transition did not occur at the same rotation period as starting from a non-circulating initial condition. Note that there is very little change in the geopotential height contours between Figure 2-11a and Figure 2-11b. Figure 2-11c shows the 220-hr circulation. This displays the initial condition for the 221-hr circulation that did cause a transition. Note the very different appearance of the circulation from the 100-hr circulation, even though it lies within the same regime. Figure 2-11d displays the
221-hr circulation after the transition. Note the pair of vortices on the dark side of the planet and the strong equatorial jet between them: these are defining characteristics of the slow rotating regime. For the slow rotating planets, decreasing the rotation period resulted in hysteresis, as well. Figure 2-12 shows the effects of increasing the rotation rate. Figure 2-12a displays the 101-hr initial condition for the speed up. Note the pair of vortices on the dark side of the planet and the equatorial superrotation that are characteristics of the slow rotating regime. In Figure 2-12b, the 100-hr circulation is shown to demonstrate that the transition did not occur at the same location as in the spin up from the non-circulating atmosphere. Figure 2-12c shows the 93-hr circulation that was the initial condition for the 92-hr circulation that did transition. Note that, unlike when the rotation rate was slowed in the previous series, the regime does not show much change prior to the circulation that transitioned. Figure 2-12d shows the 92-hr circulation after the transition. Note the zonal nature of the height contours and the jet stream near 50° latitude, which are defining characteristics of the fast rotating regime. So, the transition is metastable, with the transition occurring at different rotation rates dependent on the circulation prior to the change of rotation rate.

2.6 Habitability

Given the previous discussion on the circulation of these tidally locked planets, we can ask: Does the habitability of a planet depend on the atmospheric circulation? And, does the strong equatorial super-rotation play an important role in determining the zonal extent of the habitable region? We know that the meridional scale increases as the
rotation rate decreases. Does this have an impact on the meridional extent of the habitable region? How does the habitable region change at the transition?

As the planets studied here have no water, they are not technically habitable.

Figure 2-13

Figure 2-13: The habitable surface areas of the planets with (a) 12 hour, (b) 24 hour, (c) 48 hour, (d) 72 hour, (e) 96 hour, (f) 100 hour, (g) 101 hour, (h) 120 hour, (i) 240 hour, and (j) 2400 hour orbital period. The outer unlabeled line denotes the 0°C average temperature isotherm and the inner unlabeled line denotes the 50°C average temperature isotherm. The area between these two lines denotes the surface area of the planet that is habitable at some point during the run, the habitable area (HA). The other two bold lines are the 0°C minimum annual temperature isotherm and the 50°C maximum annual temperature isotherm as labeled. The area between these two lines is shaded and denotes the areas on the planet where animals can exist at all times during the run, the continuously habitable area (CHA).
However, it is still of interest to know the extent of surface areas with temperatures tolerable for animal life, partly because in later chapters these simulations will be used to compare with simulations of more habitable planets. The habitable regions of the planets are diagnosed by calculating the average surface temperature contours. The area between 0°C and 50°C average surface temperature is defined as the habitable area (HA), as this is the temperature range at which animals can exist on Earth (Ward and Brownlee, 2003). A second habitable area where the minimum temperatures do not fall below 0°C and the maximum temperatures do not exceed 50°C is defined as the continuously habitable area (CHA). This region corresponds more or less to the tropics on present Earth. Both the habitable areas and the continuously habitable areas on each planet are shown in Figure 2-13. Other habitable ranges which have much less strict limits were considered, but were determined to be less interesting for this discussion. (The upper temperature limit for microbial life on Earth is above 130°C (Kashefi and Lovley, 2003), but GCM simulations such as those described here shed little light on whether this condition is met.) The continuously habitable region is shaded in Figure 2-13 for all of the planets. The difference between the HA and CHA is caused by weather systems that move through the atmosphere, bringing extreme temperature variations with them. The variation of temperature in some places on some of the planets is enough that a location can have a temperature minimum below 0°C and a temperature maximum above 50°C (see Figure 2-13a). These temperature variations occur on a time scale of days, often changing rapidly between cold and warm conditions. As the rotation period of the planets increases, the CHA approaches the HA because the strength of the pressure gradient force and the temperature gradient between the lit and unlit sides decrease.
Also, as the rotation period increases, the Hadley cell expands, decreasing the temperature gradient meridionally, which results in a more temperate climate over a larger area. The circulation regime change in the atmospheric dynamics also plays a crucial role in the shape and size of the surface habitable region. The fast rotating regime has a surface habitable region resembling a backwards D (Figure 2-13 a,b,c,d,e,f). In the slow rotating regime, the habitable region takes on an annular shape like that seen in

Figure 2-14: The habitable surface area of the planets dependent on their rotation period. The HA for the fast rotators are pink dots and the slow rotators are blue dots. In general, the greater the rotation period, the greater the habitable area on the surface. However, this axiom does not hold true when crossing over the transition. It is clearly seen that the 100 hour rotator has much greater habitable surface area than the 101 hour rotator. This drastic change in habitable area is due to the shift in the circulation regimes. This trend holds true for the CHA as well, with the CHA of the fast rotators plotted with green triangles and the CHA for the slow rotators plotted as blue squares.
Figure 2-13(g,h,i,j), which increases in size as the rotation rate decreases (increasing rotation period). This increase of habitability with increasing rotation period in the slow rotating planets implies that stronger equatorial super-rotation is not good for the planet’s habitability.

According to this study, the most habitable worlds are the slowly orbiting, more distant, tidally locked planets orbiting late M-stars and early K-stars (see Figure 2-14). This result was unexpected, as our hypothesis was that the most habitable worlds would be the close in fast rotators orbiting early M-stars. From a detectability standpoint, this puts a slight damper on the possibility of finding a truly habitable terrestrial planet by the radial velocity method (the most common method used to find extrasolar planets) in the near future, as the most easily found planets are those that are close in. However, from an atmospheric survivability standpoint, this is good news, because close in planets may suffer more from atmosphere erosion through strong impact erosion of their atmospheres and atmospheric sputtering by the stellar wind, especially as M-stars become increasingly active as their masses decrease.

2.7 Discussion

The results shown in this chapter demonstrate that the rotation period of a planet is important in the atmospheric dynamics and habitability of a tidally locked planet. For the most part, the circulations of the planets change only slightly between adjacent runs. However, two significant transitions are observed in the circulation regimes. The first
occurs between the 96-hr and 120-hr rotations. The second occurs between the 240-hr and 2400-hr rotations.

The first transition occurs as the Rossby radius of deformation approaches one half of the planetary radius. After this point, we postulate that the wave-number-1 stationary waves cannot fit around a latitude circle. So, wave-number-2 stationary waves are preferentially excited. Increasing the Rossby radius of deformation further excites higher and higher order wave-numbers.

The second transition occurs as the Coriolis effect weakens. Eventually, the Coriolis effect becomes so weak that it has almost no influence on the circulations of any weather perturbation smaller than the planetary scale. After this point, the circulation takes on the form of a convection cell where the horizontal pressure gradient force is not balanced by any other force. The exploration of this second transition is a topic for a different paper.

Will there be a similar transition on water-planets? Are the transitions seen here also seen in water-covered planets at the same rotation periods? Are water-covered planets more or less habitable (in terms of surface temperature) than the dry planets discussed in this chapter? These questions will be addressed in chapter 3.
Chapter 3

Aquaplanets

3.1 Introduction

In the previous chapter, dry, waterless planets were discussed. In this chapter, wet, water-covered planets (hereafter called aquaplanets) are discussed. The circulations of these planets in some ways resemble the circulations of their dry counterparts, but in other ways they do not appear similar at all. Joshi (2003) showed that aquaplanets have more temperate climates than the corresponding dry planets. Introducing an ocean increases the heat capacity of the surface compared to the dry planet case. The inclusion of water vapor in atmosphere acts to increase the greenhouse effect, allowing for warmer temperatures on the dark side of the planet. Also, the latent heat energy deposited in the atmosphere by condensation of water vapor increases the available energy in the atmosphere.

In section 3.2, the methods and models used in this study are discussed. In section 3.3, a planet that rotates every 24 hours and that is not tidally locked is discussed as a representation of earth under the conditions specified in section 3.2. In section 3.4, the tidally locked planets are discussed.
3.2 Methods

In this study, a global circulation model (GCM) is used to simulate the circulations of wet-covered, tidally locked planets orbiting within the habitable zone of low-mass stars.

3.2.1 Planetary and Orbital Characteristics

The simulated planets are perfect spheres with the mass and radius of the earth. The surface is entirely ocean with no land. There is no vegetation. The gravitational acceleration is 9.81 m s\(^{-2}\) at the surface.

In all experiments described here, the solar constant is 1365 W m\(^{-2}\), and the pattern of solar radiation is invariant in time, representing complete tidal locking at a ratio of 1 orbit to 1 rotation, with the subsolar point at 90\(^{\circ}\)E longitude (Figure 2-1). A circular orbit is specified with no seasons (zero obliquity, zero eccentricity, zero precession). As mentioned in Chapter 2, these assumptions are reasonable for tidally locked planets.

3.2.2 Atmospheric Characteristics

The assumed planetary atmospheres are similar to that of Earth in mass and composition but greenhouse gases aside from carbon dioxide (CO\(_2\)), which is kept at a constant Earth-like value, and water vapor, which is determined by the model, are not present. The surface pressure is 1 bar. The atmospheric carbon dioxide concentration is
set to 345 ppmv, with zero concentrations for other greenhouse gases. The balance of the
atmosphere is composed entirely of nitrogen (N$_2$) and oxygen (O$_2$). These simplifications
are made so that the effects of water vapor on the underlying atmospheric dynamics are
easier to diagnose and explain.

### 3.2.3 Model Description

The experiments described below use the GENESIS version 2.3 GCM, composed
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$^\circ$), both for the atmosphere and surface
models.

The surface module includes a 50 m slab ocean (Pollard and Thompson, 1995). This ocean does not circulate, but allows heat energy diffusion throughout. Also, any sea
ice that forms is allowed to move in the wind.

The standard GENESIS v2.3 GCM was adapted for this study by adding the
ability to (i) set the inertial rotation rate in the Coriolis terms for atmospheric and sea-ice
dynamics, (ii) set the day length for solar radiation, including an option for no temporal
variation (tidal locking), and (iii) optionally initialize the atmosphere and soil to
completely dry conditions. The coding added to the model to create these additions was
minor in scale, but necessary to the success of this study.
3.2.4 Numerical Experiments

A suite of 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. As in the dry planet simulations discussed in Chapter 2, the periods (in Earth hours, i.e., 3600 sec) are 24-hr, 48-hr, 72-hr, 96-hr, 120-hr, 240-hr, and 2400-hr, following the curve shown in Figure 1-1. Though the earth rotates every 23 hr 56 min, the rotation periods are all compared to a 24-hr rotator for ease in calculation. These curves were determined from the tidal dissipation equation given in Peale (1977). In addition, a non-tidally locked experiment was performed with solar radiation period and inertial rotation period both set to 24 hours to be used as an Earth-like 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 runs are initialized with a surface ocean or with no atmospheric moisture, and so they develop atmospheric water vapor, clouds and precipitation. It was necessary to reduce the GCM time step to 10 minutes (from its standard value of 30 minutes) to preserve dynamical stability with the stronger atmospheric winds resulting from tidally locked solar radiation.
3.3 Wet Earth

3.3.1 General Circulation

For comparison, a planet rotating once every 24 hours without being tidally locked is modeled. The mean fields are shown in Figure 3-1. In Figure 3-1a, the mean potential temperature and equivalent potential temperature are shown. The potential temperature field shows a marked decrease in vertical gradient as compared to its dry counterpart. This difference in vertical gradient is illustrated by the fact that the spacing between the isentropes is larger than in the dry control. This decrease in gradient corresponds with a decrease in static stability. Also, the slope of the 300 K isentrope is much gentler and smoother than in the dry control (Figure 2-2b). Here the isentrope descends from near 350 hPa at the poles to the surface near 15° latitude at a near constant slope. In the dry case, the 300 K isentrope is near 250 hPa and stays near that altitude until it reaches 40° latitude. From there, the 300 K isentrope descends rapidly through the atmosphere to reach the surface near 10° latitude. Equivalent potential temperature \((\theta_e)\) is calculated from the potential temperature \((\theta)\) as follows:

\[
\theta_e = \theta e^{\frac{L_e Q}{c_p T}}. \tag{3.1}
\]

Here, \(L_e\) is the latent heat of fusion for water, \(Q\) is the mixing ratio of water, \(c_p\) is the specific heat at constant pressure for air, and \(T\) is the air temperature. The equivalent potential temperature takes the latent heat capacity of water into account in determining the stability of an air parcel. Because the air carries moisture, the air parcel acts as if it
Figure 3-1: a.) The mean potential temperature and equivalent potential temperature fields for the control “wet earth” in K (black and red contours, respectively). The area with potential temperature above 300 K is shaded. b.) Mean zonal wind in filled contours of 10 m s\(^{-1}\). The black contours are the mass stream function in \(10^9\) kg s\(^{-2}\) as defined by Peixoto and Oort (1992) contoured at 0.1, 1, 2, and then a contour interval of 5. c.) The transient eddy heat flux (vectors) in J m\(^2\) s\(^{-1}\) horizontally and J cPa m\(^3\) s\(^{-1}\) vertically relative to the given arrow of \(2 \times 10^3\) J m\(^2\) s\(^{-1}\) (or J cPa m\(^3\) s\(^{-1}\) ) and the transient eddy heat flux convergence with a contour interval of \(50 \times 10^{-5}\) J m\(^{-3}\) s\(^{-1}\). d.) The transient eddy zonal momentum flux (vectors) in m\(^2\) s\(^{-2}\) horizontally and m cPa s\(^{-2}\) vertically relative to the given arrow of \(50\) m\(^2\) s\(^{-2}\) (or m cPa s\(^{-2}\) ) and the transient eddy zonal momentum flux convergence with a contour interval of \(1 \times 10^{-5}\) m s\(^{-2}\). e.) The mean meridional circulation (MMC) heat flux (vectors) in J m\(^2\) s\(^{-1}\) horizontally and J cPa m\(^3\) s\(^{-1}\) vertically relative to the given arrow of \(1 \times 10^5\) J m\(^2\) s\(^{-1}\) (or J cPa m\(^3\) s\(^{-1}\) ) and the MMC heat flux convergence contoured at 1000 and then a contour interval of \(5000\) in \(10^{-5}\) J m\(^{-3}\) s\(^{-1}\). f.) The MMC zonal momentum flux (vectors) in m\(^2\) s\(^{-2}\) horizontally and m cPa s\(^{-2}\) vertically relative to the given arrow of \(50\) m\(^2\) s\(^{-2}\) (or m cPa s\(^{-2}\) ) and the MMC zonal momentum flux convergence with a contour interval of \(1 \times 10^{-5}\) m s\(^{-2}\). g.) The adiabatic warming (positive) and cooling (negative) by the MMC in contours of \(0.02\) J kg\(^{-1}\) s\(^{-1}\). Throughout this paper, the shaded areas denote areas of negative quantities unless otherwise stated.
has a higher potential temperature than it actually has. The more moisture the atmosphere holds, the greater the difference between $\theta_e$ and $\theta$. This difference between potential temperature and equivalent potential temperature affects the atmospheric circulation. In the mean equivalent potential temperature field, the 300 K equivalent isentrope begins at the same place in the poles, but descends toward the surface at a faster rate, hitting its most equatorward point near 65° latitude and 800 hPa. From there, the equivalent isentrope moves poleward to reach the surface near 70° latitude. Based on the equivalent potential temperature field, the planet is even less statically stable than predicted by the mean potential temperature field.

For the water-covered control, the circulation is similar to the dry control. In Figure 3-1b, the mean zonal wind speed is shaded. A single jet is present, as in the dry control. The jet is stronger than in the dry control and is slightly higher in the atmosphere. The surface easterlies in the tropics do not have the same height extent as in the dry control, but the polar easterlies extend higher into the atmosphere, almost to 500h Pa. The mass stream function is contoured and shows that the Hadley cell and the Ferrel cell are weaker. In the dry case, a single Ferrel cell was confined to between 20° and 40° latitude, whereas, in this aquaplanet case, two Ferrel cells are present: a small, weak one between 30° and 40° latitude, and second, broader cell poleward of 60° latitude. Between these two Ferrel cells, there is a weak direct thermal circulation. So, on the present Earth and on the dry, 24-hr rotator, the circulation is three-celled, (Figure 2-3b), whereas on the wet, 24-hr rotator, the circulation is four-celled (Figure 3-1b). Hence, the distribution of circulation cells on a planet is partially a function of the surface characteristics.
In Figure 3-1c, the mean transient eddy heat flux is shown by vectors and the convergence of that flux is contoured. Convergence is denoted by solid contours, while divergence is denoted by dashed contours. In general, the regions of divergence and convergence match up with the dry planet. However, the area of divergence above the equator is thinner in the wet case, with areas of both convergence and divergence aloft. These extra regions of divergence and convergence are not seen in the dry case. Also, transient eddy heat flux is weaker than in the dry case, especially in the tropics and mid-latitudes.

In Figure 3-1d, the mean transient eddy zonal momentum flux is shown as a field of vectors. The convergence (solid) and divergence (dashed) of this zonal momentum flux are contoured. Here, the transient eddies and mean meridional circulation dominate the circulation, as in the dry case (Figure 2-2d). Also, as in the dry case, at high altitudes the transient eddies draw zonal momentum from the tropics and deposit zonal momentum into the extratropics near 40° latitude. Note that the vectors point not only poleward, but upward, as well. This transport of zonal momentum by the transient eddies accounts for some of the appearance of the jets in Figure 3-1b. The equatorial region of divergence is larger than in the dry case, extending to near 40° latitude in the wet case. The region of convergence is further poleward, correspondingly, extending from near 40° latitude to near 70° latitude. The poles show divergence, just as in the dry case, except that the region is smaller.

In Figure 3-1e, the MMC heat flux is displayed as vectors, with convergence contoured. The equatorial region shows a triplet of convergence in the low-levels, divergence in the mid-levels and convergence aloft. Opposing triplets radiate away from
the equator, extending from 10° latitude to 40° latitude, then reversing sign and extending from 40° latitude to 70° latitude, and reversing sign once more to extend from 70° latitude to the pole. Again, this pattern is like that seen in the dry case, except that some of the triplets are wider and some triplets are narrower than in the dry case. The MMC heat flux is weaker than in the dry case.

In Figure 3-1f, the MMC zonal momentum flux is displayed as vectors, with its convergence contoured. In general, this case resembles the dry case. Low level convergence at the equator is overlain by mid-level convergence. In the rest of the tropics, low-level convergence is overlain by mid-level divergence. The convergence aloft again dictates the location of the subtropical jet. However, this convergence is stronger than that of the transient eddies, meaning that the subtropical jet is more closely associated with this convergence than that of the transient eddies. In the mid and upper latitudes, the locations of the major areas of convergence and divergence resemble that of the dry case, except that the tropical mid-level divergence extends to near 40° latitude, as compared to near 30° latitude like in the dry case.

In Figure 3-1g, the adiabatic warming and cooling follows the same pattern as in the dry case. However, the warming in the equatorial region is weaker than in the dry case, and the corresponding cooling in the tropics and mid-latitudes is weaker, as well.

Figure 3-2 displays the total energy flux of the atmosphere for the control aquaplanet. The latent heat flux (Figure 3-2a) shows divergence between ~10°S and 10°N latitude, convergence between 10° and 40° latitude, divergence between 40° and 70° latitude, and convergence at the poles. The lowest latitude divergence is results from
the increasing upward motion of the air around the equator shown in the Hadley cell. As the air rises, it cools, which forces the water vapor in the air to condense and fall out as
rain. So, regions of latent heat flux divergence should be regions of increased rainfall. This condensation decreases the latent heat energy by converting it to sensible heat. That’s why the sensible heat flux divergence (Figure 3-2b) is so strong in the middle atmosphere in this region. The convergence throughout the equatorial region in the potential energy (Figure 3-2c) is a response to the rising motion in the region. The rising branch of the Hadley cell carries low-level air upward, increasing its potential energy. Finally, near the top of the atmosphere, this upward motion ceases, creating the region of strong convergence. The convergence of the latent heat flux between 10° and 40° latitude underlies the descending branch of the Hadley and Ferrel cells. Descending air decreases in potential energy, leading to the divergence of potential energy in this region. Descending air warms adiabatically, so the sensible heat increases and shows in the figure as convergence. With the air warming as it descends, the air increases its saturation vapor pressure with respect to water, allowing for a higher dew point and increased water vapor in the air once the atmosphere comes near a water vapor source, which acts to increase the latent heat showing up in the figure as latent heat convergence. So, the regions of latent heat flux convergence should be regions of increased evaporation as well.

Figures 3-2 d, e, and f, show the average rainfall rate, the average fractional cloud cover, and the average evaporation rate for all points, respectively. Note, that there is very little variation in these fields zonally, but there is quite a bit of variation meridionally. In Figure 3-2c, a region of low rainfall rates (below 4 mm s\(^{-2}\)) is seen near 40° latitude. This location corresponds with the convergent region in the latent heat energy flux in Figure 3-2a. The region of highest rainfall rates occurs near the equator,
between ~10°S and 10°N latitude. This region is also the location of the strongest latent heat flux divergence, so areas of latent heat flux divergence have low rainfall rates and regions of latent heat flux convergence have high rainfall rates. Figure 3-2e shows the average fractional cloud cover. The minimum occurs around 30° latitude with coverage less than 60% and maxima in the poles and the equatorial regions above 80%. The regions of higher cloud cover correspond to areas of latent heat flux divergence and the regions of low cloud cover correspond to regions of latent heat flux convergence. Figure 3-2f shows the evaporation rate around the globe. The highest evaporation rate occurs between 10° and 40° latitude at more than 6 mm s$^{-1}$, with the lowest evaporation rates in the polar latitudes with a rate below 2 mm s$^{-1}$. There is a local minimum in the equatorial regions with an evaporation rate below 4 mm s$^{-1}$. The difference in the evaporation rate between the two cloudiest areas (the equator and the poles) comes about because of the spheroidal nature of the planet. As the latitude increases, the sunlight hits the planet at a more indirect angle. This lowering of the angle decreases the amount of energy available to evaporate the water. So, the cloud cover, rainfall rate, and evaporation rate can be approximated through looking at the latent heat flux, as long as latitude is taken into account.
3.4 Tidally Locked Cases

3.4.1 24 Hour Orbiter

The first case discussed is the 24-hr orbiting aquaplanet. Again, this case is not quite physical, for the same reasons as in Chapter 2, but it is useful for comparison to the

Figure 3-3: (a,c,e,g,i) The zonal wind speed (m s$^{-1}$) (shaded) with 10 m s$^{-1}$ contour interval. Overlain is the mass streamfunction contoured at $10^9$ kg s$^{-2}$. (b,d,f,h,j) The zonal potential temperature field in K with black contours of 10K and shaded for potential temperature above 300 K. Overlain is the equivalent potential temperature with red contours of 10K. For the 24 (a,b), 72 (c,d), 96 (e,f), 120 (g,h), and 2400 (i,j) hour rotators.
control wet earth. The planet’s mean zonal wind speed is shown in Figure 3-3a. Here, a single jet stream develops, as in the aquaplanet control. This jet stream has a much higher maximum average speed than in the control (148 m s\(^{-1}\) for the present simulation compared to 51 m s\(^{-1}\)) for the aquaplanet control. This single jet stream is different in appearance from the two jet streams in the corresponding dry planet (Figure 2-3a), which also has a lower maximum speed (91 m s\(^{-1}\)). The depths of the easterlies at the equator and near the poles are different in this simulation and that of the control aquaplanet. The equatorial easterlies penetrate to near 400 hPa at the equator in the aquaplanet control, and that is the deepest penetration. Here, the penetration of the equatorial easterlies is only to around 800 hPa on average with slightly deeper penetration (to 700 hPa) near 20° latitude. Near the poles, the control aquaplanet has easterlies that approach 700 hPa at 80° latitude. In the present simulation, the full atmosphere from 70° latitude poleward shows easterly winds. These results are different from the corresponding dry planet, as well, in that the easterlies there do not penetrate nearly so far into the atmosphere. In the aquaplanet control, multiple Ferrel cells, a Hadley cell, and a weak polar cell are seen in each hemisphere. The present simulation shows a Hadley cell and a pair of weaker Ferrel cells.

The mean potential temperature field for the 24-hr aquaplanet (Figure 3-3b) shows differences from the aquaplanet control (Figure 3-1a). In this simulation, the 300 K isentrope does not reach the surface at any point. Also, the vertical gradient of both potential temperature and equivalent potential temperature are much greater than in the control aquaplanet. This corresponds to the atmospheres being more statically stable with regard to both dry convection and moist convection. The isentropes slope less
steeply than in the aquaplanet control. The 300 K equivalent isentrope does reach the
ground, but it does not experience the poleward bend seen in the control, and it reaches
the ground much further equatorward. When compared with the corresponding dry
planet (Figure 2-3b), differences are seen as well. The isentropes are more gently sloped
throughout the atmosphere, and the vertical gradient is much lower in the present
simulation than in the 24-hr dry planet run.

As in Chapter 2, the meridional and vertical fluxes of heat and momentum are
discussed to understand the differences between the control and the tidally locked planet.
In this chapter, the meridional and vertical fluxes of latent heat will also be discussed
because the introduction of water vapor into the atmosphere makes this a key player in
the movement of heat through the atmosphere.

The transient eddy heat flux (Figure 3-4a) shows both similarities to and
differences from the control aquaplanet. The similarities include the presence of low-
level convergence outside of the tropics, mid-level divergence that stretches from pole to
pole, and a region of mid-level convergence in the equatorial region. The differences
include an order of magnitude increase in the convergence and the strength of the
transient eddy heat flux in this simulation over the aquaplanet control. Also, the weak
divergence seen aloft in the control over the equator and the convergence in the upper
latitudes seen aloft in the control aquaplanet are not seen in this simulation. When the
dry 24-hr planet (Figure 2-4a) is compared to the present simulation, again, there are
similarities and differences. Similarities include: the transient eddy heat flux
convergence, the nearly pole-to-pole region of divergence in the mid- and upper
atmosphere, the convergence near the surface in the mid- and upper latitudes, and the
Figure 3-4: a) The transient eddy heat flux b) The transient eddy zonal momentum flux c) The stationary eddy heat flux d) The stationary eddy zonal momentum flux e) The MMC heat flux f) The MMC zonal momentum flux and g) The adiabatic energy term for the 24-hr tidally locked planet. The transient eddy heat flux convergence has a contour interval of $10 \times 10^{-3}$ J m$^{-3}$ s$^{-1}$ with a reference vector for the flux of $2.5 \times 10^{4}$ J m$^{-2}$ s$^{-1}$ horizontally (J cPa m$^{-3}$ s$^{-1}$ vertically). The transient eddy zonal momentum flux convergence is contoured at $1 \times 10^{-5}$ m s$^{-2}$ with a reference vector for the flux of $25$ m$^2$ s$^{-2}$ horizontally (cPa m s$^{-2}$ vertically). The stationary eddy heat flux convergence has a contour interval of $10 \times 10^{-3}$ J m$^{-3}$ s$^{-1}$ with a reference vector for the flux of $5 \times 10^{4}$ J m$^{-2}$ s$^{-1}$ horizontally (J cPa m$^{-3}$ s$^{-1}$ vertically). The stationary eddy zonal momentum flux convergence has a contour interval of $1 \times 10^{-5}$ m s$^{-2}$ with a reference vector for the flux of $100$ m$^2$ s$^{-2}$ horizontally (cPa m s$^{-2}$ vertically). The MMC heat flux convergence has a contour interval of $10 \times 10^{-3}$ J m$^{-3}$ s$^{-1}$ with a reference vector for the flux of $2 \times 10^{5}$ J m$^{-2}$ s$^{-1}$ horizontally (J cPa m$^{-3}$ s$^{-1}$ vertically). The MMC zonal momentum flux has a contour interval of $1 \times 10^{-5}$ m s$^{-2}$ with a reference vector of $100$ m$^2$ s$^{-2}$ horizontally (cPa m s$^{-2}$ vertically). The adiabatic term is contoured at $0.02$ J kg$^{-1}$ s$^{-1}$. 
convergent region aloft over the equator. However, differences exist in the strength of the convergence (this simulation has a lower maximum convergence), the low-level convergence (which runs pole-to-pole in the dry simulation, but only extends from the pole to 20° latitude, whereupon the transient eddy flux of heat becomes divergent near the ground), and the much deeper convergence over the poles in the present simulation than in the dry simulation. As in the dry simulation, the convergence over the equator acts to increase the slope of the isentropes, whereas the divergence in the mid latitudes acts to lessen the slope of the isentropes.

The transient eddy zonal momentum flux (Figure 3-4b) shows quite a few differences and a couple of similarities to the aquaplanet control. The similarities include the divergence above the equator and the divergence around 20°. Also, the convergence high aloft over the equator and near 40° latitude is similar. Differences between the two include the much more chaotic looking transient eddy zonal momentum flux and convergence regions in the present simulation as opposed to the aquaplanet control. There are very definite regions where the momentum is being deposited and where the momentum is being drawn in from in the aquaplanet control that are not seen in the present simulation. Also, the regions of convergence and divergence are much weaker than in the control. The present simulation does not resemble the 24-hr dry planet much at all in the distribution of convergent regions or transient eddy zonal momentum flux strength. Again, as in the dry case, the transient eddy zonal momentum flux does not significantly affect the jet stream location. Here, the convergence aloft near 40° latitude seems to indicate that a jet stream should be present, but it is overpowered by the other fluxes.
The stationary eddy heat flux has no equivalent in the aquaplanet control. However, this simulation can be compared to the 24-hr dry simulation (Figure 2-4c). Here, convergence in the low-level equator sloping poleward with height is seen in both simulations. Upper atmosphere divergence in the equatorial and mid-latitude regions is present in both simulations. Differences include the polar divergence seen in the dry simulation that does not appear in the present simulation. The divergence over the equator is weaker in the present simulation than in the dry simulation. In fact, the dry simulation has stronger convergence overall than the present simulation. There is convergence at surface for the present simulation that is not seen in the dry simulation between 40° and 60° latitude. The divergence in the mid levels over the equator acts to decrease the meridional gradient of potential temperature, while the convergence in the subtropics acts to increase the slope of the isentropes. Both effects can be seen clearly in Figure 3-3b.

The stationary eddy momentum flux is very different throughout most of the atmosphere from the 24-hr dry simulation (Figure 2-4d). Some of the few commonalities between the two are the upper-level convergence in the mid- to high latitudes (which are not quite in the same location), the mid- to upper-level polar divergent regions, and the surface region of convergence over the equator. Some of the major differences include the low-level polar regions where the present simulation shows divergence, and the dry simulation convergence, the upper atmosphere above the equator where the present simulation shows divergence and the dry simulation convergence, and the convergence seen in the dry simulation in the tropical mid-levels which is not seen in the present simulation. As in the transient eddy zonal momentum flux figure, the stationary eddy
flux convergence shows that there should be a secondary jet high aloft over 40° latitude which is not seen. However, the maximum wind speed in the low-levels at 40° latitude corresponds to the convergence of the stationary eddy zonal momentum flux there.

The MMC heat flux is shown in Figure 3-4e. The convergence in the mid levels over the equator acts to draw higher potential temperatures downward, increasing the potential temperature near the surface. The divergence in the mid levels over the tropics acts to decrease the isentrope slope through the tropics. And the convergence in the subtropics increases the slope of the isentropes.

The MMC momentum flux is shown in Figure 3-4f. Here, the upper-level acquisition and deposition of momentum is seen in the tropics as divergence and convergence of the momentum flux. The strong divergence high aloft over the equator separates the jet stream and overrules the zonal momentum flux convergence caused by both the transient eddies and the stationary eddies. Also, the zonal momentum flux convergence aloft indicates the location of the strong jet stream in the high levels over the subtropics. The low-level convergence over the equator forms a secondary jet that is super-rotating and equatorial, but it weaker and at a lower level than the primary subtropical jet in the slow rotating circulation regime.

The adiabatic term (Figure 3-4g) shows many similarities to the control. The locations of cooling and warming air are very similar. The difference between the two lies in the strength in the mid-levels of the atmosphere. The circulation in the control aquaplanet is much stronger through the mid levels than the present simulation.

Unlike the previous chapter, the planets modeled here have surface oceans that contribute water vapor to the atmosphere. The effect of this water vapor is to increase the
greenhouse effect, increase the albedo of the planet through cloud formation, and increase the heat capacity of the atmosphere. Figure 3-5a displays the mean latent heat flux and

Figure 3-5

Figure 3-5: a) The mean latent heat flux (vectors) and convergence (contours) for the 24-hr aquaplanet. The reference vector is $1 \times 10^6$ J m$^{-2}$s$^{-1}$ horizontally (J cPa m$^{-3}$ s$^{-1}$ vertically) and the contour interval is $10 \times 10^{-3}$ J m$^{-3}$ s$^{-1}$. b) The mean sensible heat flux (vectors) and convergence (contours). The reference vector is $1 \times 10^6$ J m$^{-2}$s$^{-1}$ horizontally (J cPa m$^{-3}$ s$^{-1}$ vertically) and the contour interval is $5 \times 10^{-3}$ J m$^{-3}$ s$^{-1}$. c) The mean potential energy flux (vectors) and convergence (contours). The reference vector is $1 \times 10^6$ J m$^{-2}$s$^{-1}$ horizontally (J cPa m$^{-3}$ s$^{-1}$ vertically) and the contour interval is $5 \times 10^{-3}$ J m$^{-3}$ s$^{-1}$. d) The average rainfall rate in mm s$^{-1}$. It is contoured at 5 mm s$^{-1}$ and then a contour interval of 10 mm s$^{-1}$ with grey areas denoting regions of rainfall exceeding 1 mm s$^{-1}$. e) The average fractional cloud cover. The contour interval is 0.1 with grey areas denoting regions of cloud cover exceeding 0.5. f) The average evaporation rate in mm s$^{-1}$ contoured at 1 mm s$^{-1}$ and then a contour interval of 5 mm s$^{-1}$.
its convergence. In this figure, the strong convergence at the surface is caused by the addition of water vapor through evaporation, and the strong divergence aloft is due the condensation of that water vapor to form clouds, which releases the latent heat to become sensible heat (Figure 3-5b). The mean divergence aloft for all latitudes indicates that clouds cover much of the planet most of the time (see Figure 3-5e), and there is no set latitude with mostly clear skies, as seen in the control (Figure 3-2a). The mean convergence at the surface means that there is no set latitude for evaporation. Instead, much of the surface has water vapor evaporating into the atmosphere much of the time (see Figure 3-5f).

The mean sensible heat flux and convergence is displayed in Figure 3-5b. The strong divergence in the tropics is caused by two related mechanisms. The first is the transformation of latent heat to sensible heat through condensation of water vapor. The second is rising motion. In the subtropics, the convergence develops through sinking motion (as was seen in Figure 3-4g) which causes the air to warm adiabatically, increasing the sensible heat.

Figure 3-5c displays the mean potential energy flux and convergence. The first thing to note is the chaotic nature of this figure. There is no set latitude for increase or decrease of potential energy. This means that rising motion and sinking are intermixed on latitude circles within the simulation, resulting in a very chaotic distribution of mean potential energy.

Figure 3-5d shows the average precipitation rate. Any area with a precipitation rate greater than 1 mm s\(^{-1}\) is shaded. The most obvious feature of this figure is the white v-shaped pattern. As everything with a precipitation rate greater than 1 mm s\(^{-1}\) is shaded,
this means that these areas are the locations of the least precipitation. This is very
different from the minimum precipitation bands in the control which are confined to a
latitude band. The second feature to note is the area of heavy precipitation just to the east
of the substellar point. This area of heavy precipitation is the result of the strong
convection at the substellar point. Interestingly, a second area of heavy precipitation
occurs on the dark side of the planet over the antistellar point. The precipitation here
must be dynamically forced because there is no orography or diabatic heating occurring
here.

Figure 3-5e shows the average fractional cloud cover. Areas with fractional cloud
cover greater than 50% are shaded. Here, the areas of low precipitation are seen as areas
of low cloud cover. The most persistent cloud cover is at the same location as the
heaviest precipitation. There are areas directly poleward of this cloudy area that are clear
most of the time. These areas have low enough precipitation rates to be nearly white in
Figure 3-5d (they look speckled). These must be the areas of sinking motion
corresponding to the strong rising motion at the substellar point. Comparing this location
with the mean potential energy field (Figure 3-c), the cause of chaotic nature of that field
becomes apparent because the sinking motion (less clouds) and rising motion (more
clouds) do occur in the latitude band which shows up as the chaotic potential energy
field.

The average evaporation rate is shown in Figure 3-5f. As should be expected, the
major areas of evaporation are also areas of low cloudiness, and the dark side of the
planet has very low evaporation rates. Note that the area just west of the substellar point
has very high evaporation rates as well. This is a recovery area for the low humidity air
coming from the dark side of the planet that is warming rapidly as it approaches the subellar point. Another thing to note is that some evaporation does occur on the dark side of the planet. This is probably caused by warm air on the sunlit side moving across the terminator and retaining enough energy to evaporate water from the surface ocean.

3.4.2 Other Tidally Locked Planets

In addition to the 24-hr orbiter case, Figure 3-3 shows the mean zonal wind speed, mass stream function and potential temperature for the 48 hour case, the 96 hour case, the 120 hour case and the 2400 hour case. As in Chapter 2, these cases run the full gamut from the smallest M-stars to the low mass end of the K-stars.

The mean zonal wind speed shows the location of the jet streams and the tropical easterlies. The mean zonal wind speed shows a single jet near 20° latitude. For the 24-hr aquaplanet, this jet has speeds over 120 m s⁻¹ (Figure 3-3a). Increasing the orbital period to 48 hours (Figure 3-3c) shows that this single jet has moved poleward to between 20° and 40° latitude. The average speed is still greater than 100 m s⁻¹, and the tropical easterlies are still present, extending from the equator beyond 40° latitude. Increasing the orbital period to 96 hours (Figure 3-3e) increases the speed of the single jet slightly, with speeds above 100 m s⁻¹ still present, and it moves the jets even further poleward, to 40° latitude. The tropical easterlies have all but disappeared aside from some easterlies near 20° latitude, with weak polar easterlies also present. Increasing the orbital period to 120 hours (Figure 3-3g) brings even more changes. The single jet in the mid-latitudes has disappeared and an equatorial jet has appeared. This equatorial jet extends from the
equator to beyond 40° latitude with wind speeds in excess of 60 m s$^{-1}$. See Chapter 2 for a discussion of equatorial jets. Also, the tropical easterlies have disappeared and are replaced with polar easterlies that extend from the subtropics to the poles. Increasing the orbital to 2400 hours (Figure 3-3i) shows more changes. The equatorial jet has weakened significantly to just over 5 m s$^{-1}$, and easterly winds cover the surface.

The mass stream function shows the relative strengths of the Hadley cell, the Ferrel cell, and the polar cells. In the 24-hr aquaplanet (Figure 3-3a), a Hadley cell, and two Ferrel cells are seen. A weak polar cell lies between the Ferrel cells. In the 48-hr aquaplanet (Figure 3-3c), the Hadley cell has expanded, one of the two the Ferrel cells has disappeared, the other Ferrel cell has weakened, and the polar cell has disappeared. In the 96-hr aquaplanet (Figure 3-3e), some major changes have occurred. The Hadley cell has expanded further, the Ferrel cell has strengthened, moved upward and expanded equatorward, and the polar cell has reappeared underneath the Ferrel cell. In the 120-hr aquaplanet (Figure 3-3g), the changes in the 96-hr aquaplanet seem to have disappeared. The Hadley cell has expanded further. The Ferrel cell has expanded and moved back towards the ground. A weak secondary Ferrel cell has appeared below the primary Ferrel cell and the polar cell is not seen. The 2400-hr aquaplanet (Figure 3-3i) continues these changes with a strengthened Hadley cell and a strengthened and expanded Ferrel cell. Interestingly, the extent of the Hadley does not change much between the runs with 40° latitude denoting the poleward extent of the Hadley cell in all but the 24-hr aquaplanet simulation.

The potential temperature field shows the stability of the atmosphere. The greater the vertical gradient of potential temperature is, the more stable the atmosphere is. Also,
a tighter horizontal gradient of potential temperature means that meridional mixing is weaker. In the 24-hr aquaplanet simulation (Figure 3-3b), the 300 K isentrope lies near 600 hPa in the polar regions, increases in height slightly through the subpolar region, and then slopes gently toward 900 hPa, its lowest height over the equator. The vertical gradient of potential temperature is greater than in the control, which indicates that the 24-hr aquaplanet simulation is more statically stable than the control. Higher static stability denotes that dry convection is more difficult to initiate and to maintain in this atmosphere than in the control. Increasing the rotation period to 48 hours draws the 300 K isentrope upward to near 400 hPa in the polar regions, which then slopes down to near 900 hPa in the equatorial atmosphere (Figure 3-3d). This increase in slope with rotation period is opposite from the result in Chapter 2 for the fast rotators. The vertical gradient of potential temperature has increased, meaning the static stability has also increased. Increasing the rotation period to 96 hours decreases the slope, with the 300 K isentrope maintaining the same height in the poles and descending to near 800 hPa in the tropics. Increasing the rotation period to 120 hours (Figure 3-3h) draws the 300 K isentrope downward in the polar regions to near 500 hPa with a low point of 800 hPa in the tropics. Finally, the 2400-hr aquaplanet (Figure 3-3j) shows nearly flat isentropes with height, with the 300 K isentrope near 750 hPa for all latitudes.

Now that the static stability of the dry atmosphere has been addressed, the stability of the moist atmosphere may now be discussed. In moist atmospheres, the equivalent potential temperature is much more important in determining the resistance of an atmosphere to convection than the potential temperature. In the 24-hr aquaplanet simulation (Figure 3-3b), the 300 K equivalent isentrope intersects the surface near 40°
latitude. This may be compared with the 300 K isentrope, which does not get to the surface. Also, note the steep slope of the equivalent isentropes in the subtropics. This slope shows that the moist static stability is greatly reduced in these regions. This indicates that moist convection is rather easy to initiate in these regions. For the other two relatively rapid rotators, the 48-hr and 96-hr aquaplanets (Figure 3-3d,f), the slope decreases while encompassing more of the atmosphere. The 300 K equivalent isentrope intersects the surface near 30° latitude, with slight increases in the moist static stability overall. In the 120-hr aquaplanet simulation (Figure 3-3h), the 300 K equivalent isentrope intersects the surface near 10° latitude, with a gentle slope upward to near 600 hPa at the poles, and with the moist static stability increasing further. Finally, the 2400-hr aquaplanet (Figure 3-3j) displays nearly flat equivalent isentropes with the 300 K equivalent isentrope slightly below the 300 K isentrope. This is the moistest statically stable atmosphere simulated. However, it is also the least horizontally stable atmosphere as well, which allows easy mixing at any level.

The stationary wave structure for the tidally locked cases is displayed in Figure 3-6. In the 24-hr and 48-hr aquaplanet simulations (Figure 3-6a,c), the upper-level Rossby anticyclone can be seen overlying the substellar point, and Kelvin waves are seen to the east of the substellar point. This setup is similar to that seen in Chapter 2 and that seen in Gill (1982). However, while these aquaplanet simulations show many similarities to their Chapter 2 counterparts, a shift westward is seen in all of the equatorial waves, along with a shift eastward for all the extratropical waves. This same shift is seen in the low-levels as well. The tropical Rossby cyclone has moved westward while the extratropical
cyclone has moved eastward. Referring back to Figure 3-3, the reason for the shift becomes clear. In the dry planet simulations, the zonal wind speeds were much lower than for the corresponding aquaplanets. Also, the polar winds are easterly or weakly westerly in the aquaplanet simulations, whereas the dry planets had much stronger westerly winds in the high latitudes. The 96-hr aquaplanet shows major differences from its dry counterpart. In the aquaplanet simulation, very little meridional tilt is seen, and
the wave amplitude is much higher than in the previous fast rotating simulations. Therefore, the resonant behavior seen in Chapter 2 that developed in the slow rotating regime is also present in the 96-hr aquaplanet simulation. This means the transition for the aquaplanets occurs at a faster rotation rate than on the dry planets. For the rest of the aquaplanets, there is very little difference between the aquaplanets and their corresponding dry planets.

### 3.4.3 Dimensionless Numbers

The dimensionless numbers used here were described in Chapter 2. The Rossby radius of deformation seems to be the most important characteristic number in determining the circulation regime of an atmosphere. In Chapter 2, the transition between the fast rotators and the slow rotators was found to occur near a Rossby deformation radius of 3000 km. In the previous section, the 96-hr aquaplanet appears to have characteristics of the slow rotators. Looking at the Rossby radius of deformation, it

<table>
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<tr>
<th>Rotation Period (hr)</th>
<th>N (s(^{-1}))</th>
<th>(\beta) (m(^{-1})s(^{-1}))</th>
<th>(\lambda_R) (km)</th>
<th>(L_R) (km)</th>
<th>Mean (T_s) (K)</th>
<th>(H) (km)</th>
<th>(u_{max}) (m s(^{-1}))</th>
<th>(\psi_{max}) (kg m(^{-3})s(^{-1}))</th>
<th>(\psi_{max}) (secondary) (kg m(^{-3})s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>0.01451</td>
<td>2.29x10(^{-11})</td>
<td>1598</td>
<td>1011</td>
<td>281.2</td>
<td>8.048</td>
<td>148.3</td>
<td>6.281</td>
<td>3.007</td>
</tr>
<tr>
<td>48</td>
<td>0.01491</td>
<td>1.14x10(^{-11})</td>
<td>2275</td>
<td>1072</td>
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<td>7.939</td>
<td>113.0</td>
<td>5.52</td>
<td>2.121</td>
</tr>
<tr>
<td>72</td>
<td>0.01539</td>
<td>7.62x10(^{-12})</td>
<td>2805</td>
<td>3329</td>
<td>267.7</td>
<td>7.796</td>
<td>117.3</td>
<td>10.13</td>
<td>8.71</td>
</tr>
<tr>
<td>96</td>
<td>0.01643</td>
<td>5.72x10(^{-12})</td>
<td>3374</td>
<td>5964</td>
<td>269.6</td>
<td>7.986</td>
<td>141.5</td>
<td>5.67</td>
<td>2.441</td>
</tr>
<tr>
<td>120</td>
<td>0.01664</td>
<td>4.57x10(^{-12})</td>
<td>3803</td>
<td>7575</td>
<td>268.2</td>
<td>8.027</td>
<td>111.1</td>
<td>3.437</td>
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<tr>
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<td>5376</td>
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<td>261.8</td>
<td>7.979</td>
<td>80.2</td>
<td>8.718</td>
<td>6.186</td>
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<td>7.861</td>
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<td>12.78</td>
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<tr>
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<td>7.906</td>
<td>62.31</td>
<td>8.488</td>
<td>1.455</td>
</tr>
</tbody>
</table>
is apparent that the 96-hr aquaplanet is firmly beyond the transition point between the fast rotating regime and the slow rotating regime. So, it makes sense that the 96-hr aquaplanet shows characteristics of the slow rotating regime.

3.4.4 Horizontal Structure

Now that the mean meridional circulation patterns have been discussed for the aquaplanets, what are the effects of tidal locking on the zonal circulations? How does the non-zonally symmetric heating affect the atmospheric circulation? What are the energy consequences of having a stationary heat source? How does latent heat change the circulations? To address these questions, the horizontal structure of the circulation is examined.

3.4.4.1 Potential temperature

It is of interest to examine the potential temperature variation among the planets. The mean potential temperature field for the control is shown in Figure 3-1b. The potential temperature field for the control aquaplanet does not vary latitudinally because the diurnal heating of the planet smoothes out all variation in the east-west direction. For the tidally locked planets, this diurnal heating does not occur. Instead, the location of the substellar point does not change, resulting in a zonally asymmetric circulation. In Figure 3-7, the potential temperature at 200 hPa and 1000 hPa is shown. The 200 hPa potential temperature field shows the upper-level circulation while the 1000 hPa potential
temperature field essentially shows the surface temperature range, corrected for pressure differences. As in Chapter 2, all of the planets show some zonal variation in potential temperature. At 200 hPa (Figure 3-7a,c,e,g, and i), the amount of variation in the potential temperature field decreases with rotation rate. However, the zonal variation is greatest for the 96-hr aquaplanet. Also, within this field, the existence and extent of the waves seen in Figure 3-6 at 200 hPa is also apparent. At 1000 hPa (Figure 3-7b,d,f,h, and j), the zonal variation potential temperature does not change much as the rotation period changes. Instead, the shape, size and distribution of the isentropes change as a result of the wind field (shown). Because the surface is water-covered instead of land-covered as in Chapter 2, the heat capacity of the surface plays a role in the shape of the isentropes. In Chapter 2, the proximity of the terminator had a noticeable effect on the curvature of the isentropes, with a strong potential temperature gradient across the terminator especially for the fast rotators. Here, the terminator does not have the same strong effect. Instead, the wind field has the strongest effect on the isentropic gradient. This effect is especially strong for the 24-hr aquaplanet (Figure 3-7b).

3.4.4.2 Zonal Flux of Energy

In the dry planet cases, the energy in the system was only in three forms: sensible, kinetic and potential. The movement of energy around the planet through these forms of energy is easily inferred from the circulations and did not warrant discussion in the last chapter. In the aquaplanet cases, there is a fourth energy source: latent heat from the evaporation and condensation of water. To understand how the energy circulates in these
aquaplanet cases, the latent heat must be taken into account. Because the distribution of this latent energy is not easily inferred from the circulations, the mean latent energy and the mean sensible energy and the mean potential energy are shown in Figure 3-5. The latent energy is calculated from Eq. 3.2

\[ E_L = QL_c \rho \nu. \]
Here, $E_L$ is the latent energy flux, $Q$ is the water vapor mixing ratio, $L_c$ is the latent heat of condensation for water ($2.5 \times 10^6 \text{ J kg}^{-1}$), $\rho$ is the density, and $v$ is the meridional wind speed. The sensible energy flux is calculated from Eq. 3.3

$$E_S = c_p v \rho dT.$$  \hspace{1cm} 3.3
Figure 3-9: The meridionally averaged potential energy flux and convergence for a) the 24-hr aquaplanet, b) the 72-hr aquaplanet, c) the 96-hr aquaplanet, d) the 120-hr aquaplanet, and e) the 2400-hr aquaplanet. The reference vector $5 \times 10^6$ J m$^{-2}$ s$^{-1}$ horizontally (J cPa m$^{-3}$ s$^{-1}$) and the contour interval is $50 \times 10^{-3}$ J m$^{-3}$ s$^{-1}$.

Here, $v$ and $\rho$ are the same as above. $E_S$ is the sensible energy flux, $c_p$ is the specific heat at constant pressure for air (1004 J K$^{-1}$ kg$^{-1}$), and $dT$ is the air temperature minus the global average air temperature. The potential energy flux is calculated from Eq. 3.4

$$E_p = g \rho g v.$$  \hspace{2cm} 3.4
Here, $v$ and $\rho$ are the same as above. $E_P$ is the potential energy flux, $g$ is the acceleration due to gravity (here, 9.81 m s$^{-2}$), and $z$ is the height.

Figure 3-8 displays the meridional mean sensible heat flux and convergence for the aquaplanets. Note that in the first three simulations, the flux is dominated by the zonal flux with very little vertical flux. In the last two simulations, the vertical flux has
some visible impact, especially near the substellar point, that is not apparent in the first
three simulations. In all simulations, the substellar point shows some of the strongest
convergences of sensible heat, as would be expected because of the strong illumination
there. However, some other regions have strong sensible heat flux which is not expected.
Even within the same regime, the strongest convergence aloft and at the surface are not
the same between different simulations. In fact, the closest resemblance to any of these
simulations is the corresponding dry planet. Even then, it is the slower rotating 120-hr
and 2400-hr that bear the closest resemblance to their dry planet counterparts. For all of
the figures, divergence denotes rising motion with adiabatic cooling and latent heat gain.
Convergence denotes sinking motion with adiabatic warming. Convergence at the
surface denotes warming through radiant absorption from the ground when located above
the substellar point. As may be seen by comparing Figure 3-8 with Figure 3-9, the
sensible heat flux is offset by the potential energy flux.

Figure 3-10 displays the meridionally averaged latent heat flux and its
convergence. The first thing to note is that the latent heat flux is 10% as strong as the
sensible heat flux. The second thing to note is that all of the simulations have the
strongest latent heat flux convergence at or near the substellar point and at this point the
flux is upward. This convergence is caused by the warming of the air as it moves over
the illuminated portion of the planet, warming and gathering water vapor along the way.
Directly above this point of strong convergence is an area of divergence. This area of
divergence denotes the loss of latent heat energy through condensation and subsequent
cloud formation. Other convergent regions aloft denote the movement of more humid air into areas of less humid air, increasing the latent heat in that region.
3.4.4.3 Equatorial Circulation

The transition discussed in Chapter 2 for dry planets also occurs for the aquaplanets. However, the rotation period at which the transition occurs is lower for the aquaplanets than for the dry planets. This can be seen by comparing Table 3-1 with Table 2-2. In Chapter 2, the transition occurred when the Rossby radius was between 3000 and 3300 km in the dry simulations (which corresponds to rotation periods between 100 and 101 hours). In the aquaplanet simulations, this range of Rossby radii actually occurs between the 96 hour rotation period and the 72 hour rotation period. Therefore, we expect the transition to occur within this range. As previously seen, this is indeed the case. In Figure 3-7, the circulations of the 72-hr aquaplanet clearly resemble those of the 24-hr aquaplanet: the tilted Rossby waves are clearly in evidence, as expected for an aquaplanet in the fast rotation regime. On the other hand, the circulations of the 96 hour aquaplanet resemble those of the 120 hour aquaplanet with no Rossby wave tilt, as would be expected for an aquaplanet in the slow rotation regime. This figure is comparable with Figure 2-5 and shows the same relationship across the transition.

In Figure 3-11, the average equatorial, substellar, and antistellar circulations are shown. This figure again shows the same relationship across the transition as in the dry simulations (Figure 2-9).

3.4.4.4 Clouds

Unlike the dry planets, the aquaplanets have the capacity for weather in their atmospheres. So, it is of interest to know where clouds develop, where precipitation falls,
and where water vapor is evaporated back to the atmosphere. Because these planets have zonal variability in temperature, and insolation, it is expected that the planets will also have zonally variable cloud cover, precipitation, and evaporation. Also, because these planets are water-covered, the location of ice sheets and their thickness is important in
understanding their surface variability. The major regions of evaporation and precipitation can be approximated from the ice sheet distribution and the fractional cloud cover. Areas of high cloudiness are also areas of heavy precipitation, whereas relatively low cloud areas that are ice-free are areas of increased evaporation. Close proximity to the substellar point also increases the evaporation rate.

For the aquaplanets, the cloud and ice distributions all vary greatly between the different simulations (Figure 3-12). The cloud distribution (Figure 3-7, first column) shows the regions where the latent heat of the water vapor in the air is converted to sensible heat through condensation. Here, the general trend is for lessening cloud coverage on the dark side of the planet as the rotation period increases. This effect is caused by the weakening wind field as the rotation period increases. As the wind field weakens, the ability of the wind to advect atmospheric characteristics such as temperature and humidity far from the source region diminishes, causing cloud formation to remain closer to the site where the water vapor was first evaporated. This lower ability of warm air to advect into cooler areas also decreases the habitability of the planet. The ice coverage (Figure 3-12, second column) shows the regions where liquid water is available at the surface. The ice coverage shown here is in near equilibrium and does not change significantly over the final year of the simulation. In these regions, higher evaporation rates are attainable. Some evaporation may occur over the ice sheets, but the evaporation rates there are much lower than over the open ocean. Ice-covered areas are important for the habitability of a planet in that ice is the only hard surface in these simulations available for development of detectable life forms. Unfortunately, to maintain the ice
The habitability of aquaplanets (Figure 3-13) follows a very different trend than the dry planets (c.f. Figure 2-14). For the aquaplanets, the habitable area decreases with increasing rotation period, as opposed to the trend for dry planets where the habitable

3.5 Habitability

The habitability of aquaplanets (Figure 3-13) follows a very different trend than the dry planets (c.f. Figure 2-14). For the aquaplanets, the habitable area decreases with increasing rotation period, as opposed to the trend for dry planets where the habitable
Figure 3-14: The habitable surface areas of the planets with (a) 24 hour, (b) 48 hour, (c) 72 hour, (d) 96 hour, (e) 120 hour, (f) 240 hour, and (g) 2400 hour orbital period. The outer unlabeled line denotes the 0°C average temperature isotherm. The area inside this contour denotes the surface area of the planet that is habitable at some point during the run, the habitable area (HA). The other bold line is the 0°C minimum annual temperature isotherm. The area inside this contour is shaded and denotes the areas on the planet where animals can exist at all times during the run, the continuously habitable area (CHA).

area increases with increasing rotation period, in general. The fast rotating planets have a steeply sloping trend for their habitable surface area, while the slowly rotating aquaplanets have a much more gently sloping trend in their habitable surface areas. The 24-hr aquaplanet has the greatest amount of habitable area, and the 2400-hr aquaplanet...
has the least amount of habitable surface area. The shape of the habitable areas (Figure 3-14) matches the shape of the ice-free area shown in Figure 3-12. The shapes shown here are most likely caused by the movement of ice across the surface of the ocean forced by the surface wind. The stronger the surface wind blows, the faster the ice moves from the dark side to the sunlit side, forcing the ice to melt. This prevents a thick ice sheet from forming on the dark side of the planet, and enables the HA and CHA to cross the terminator, as seen in the faster rotating planets.

3.6 Discussion

In answer to one of the questions posed in Chapter 2: the transition in circulation regimes does occur for aquaplanets. However, the transition occurs at a lower rotation period (faster rotation rate) than for the dry planets, between 72 hour and 96 hour rotation periods, as opposed to 100 to 101 hours for the dry planets. Aquaplanets have larger habitable surface areas than the corresponding dry planets as a result of their larger surface heat capacity and rates of latent heat transfer. Interestingly, the trends in habitability for aquaplanets have opposite signs to that for the dry planets, with the HA of the aquaplanets decreasing for increasing rotation period (decreasing rotation rate).

In the past two chapters, idealized planets with no topography, no geochemical cycles and homogenous surface conditions have been simulated. In the next chapter, Earth-like planets with a parameterized carbonate-silicate cycle, and realistic topography with continents, oceans, and mountains will be simulated to demonstrate the effect of
continental distribution and the carbonate-silicate cycle on the atmospheric circulations and habitability of planets.
4.1 Introduction

The calculations presented so far represent only a small subset of the possible range of tidally locked M-star planets. Most importantly, such planets could be located either closer in or farther out in the habitable zone than is present Earth. Their surface temperatures should then depend both on their distance from the parent star and on the greenhouse gas concentrations in their atmospheres. Planets located farther out in the habitable zone would be expected to accumulate more CO\textsubscript{2} in their atmospheres, because their surfaces would be colder (other things being equal) and so the rate of removal of CO\textsubscript{2} by weathering of silicates should be slower (Walker et al., 1981; Kasting et al., 1993). Also, the topography is important because the silicate weathering rate depends on runoff. Increasing the runoff will act to increase the silicate weathering rate. The greater the silicate weathering rate, the lower the atmospheric carbon dioxide concentration at the balance point will be. And lowering the atmospheric carbon dioxide concentration should lower the average surface temperature.
4.2 Methods

4.2.1 Atmospheric Constituents

The trace greenhouse gas concentrations were set to present earth levels for all simulations, with water vapor and carbon dioxide allowed to vary between simulations. The methane concentration was 1.714 ppmv. The N$_2$O concentration was 0.311 ppm. Also included are CFC$_{11}$ and CFC$_{12}$ at concentrations of 0.280 ppt and 0.503 ppt, respectively. The water vapor concentration is determined by the model. The atmospheric carbon dioxide concentration is set to 355 ppm for the control simulations. In the carbonate-silicate cycle simulations, CO$_2$ was allowed to vary over a wide range, from 1 to 1,000,000 ppmv.

4.2.2 Topography

The surface topography used for this study is the present Earth land and ocean distribution scaled to T31 resolution. This land distribution was chosen to provide an easy comparison to atmospheric concentrations of CO$_2$ on the present Earth.

4.2.3 Model Description

For this study, we used GENESIS version 3.0, which has updated CO$_2$ absorption coefficients from CCM3. These updated absorption coefficients allow for the
atmospheric CO\textsubscript{2} concentrations to vary over a much greater range, from 0 bars to 0.1 bars. Otherwise, the code is the same as in the previous chapters.

### 4.2.4 Numerical Experiments

A suite of experiments was performed varying the top of the atmosphere solar insolation and the substellar point with a constant orbital period of 240 hrs (10 days). The 240 hr orbital period was chosen for comparison with the work of Joshi (2003). Two substellar points were chosen, one at 0° latitude and 0° longitude (hereafter referred to as the Atlantic Basin) (Figure 4-1a) and the other at 0° latitude and 180° longitude (hereafter referred to as the Pacific Basin) (Figure 4-1b). The top of the atmosphere solar insolation was specified as 100% present Earth solar insolation (1365 W m\textsuperscript{-2}). First, a tidally locked planet with an invariant atmospheric CO\textsubscript{2} concentration of 355 ppm with present Earth solar insolation was modeled for each of the substellar points. Both control simulations were integrated for 10 years.
4.3 Results

This section is divided into two parts. The first section describes the control simulations while the second section describes the variant CO₂ simulation results.

4.3.1 Invariant CO₂

The invariant carbon dioxide model simulations are shown in Figure 4-1. For these runs, the atmospheric carbon dioxide concentration was fixed at 355 ppm. These runs are not in carbonate-silicate cycle balance. Instead, these runs display the consequence of changing the substellar point, and subsequently, the land mass distribution that receives direct solar heating. For the simulations here and afterward, the continental area is constant; however, the amount of land surface that is habitable

Figure 4-2: The 200 hPa geopotential heights and wind vectors for the a) Atlantic Basin simulation and the b) Pacific Basin simulation. Vectors are relative to the arrow below each figure at 100 m s⁻¹. Contours are at 100 m intervals. Green areas denote the location of landmasses.
changes. So, in addition to the HA and CHA, we calculate the LHA and LCHA, which are the *land habitable area* and *land continuously habitable area*. These two new parameters are important because the development of a civilization like that on Earth depends on the availability of habitable land surface areas. This concept also comes into play in the “animal habitable zone” defined by Ward and Brownlee (2002) in their book *Rare Earth*.

For both the Atlantic Basin simulation (Figure 4-2a) and the Pacific Basin simulation (Figure 4-2b), the upper-level atmospheric circulations look like the 240-hr orbiter simulations for both the dry planet and the aquaplanet. So, the overall circulation is not affected greatly by the presence of topography. However, some small stationary Rossby waves are seen over the continental areas in both cases.

Figure 4-3 shows the mean annual surface temperature for both the Atlantic Basin
Figure 4-3: The simulation (Figure 4-3a) and the Pacific Basin simulation (Figure 4-3b). In the previous chapters, the region between 0°C and 50°C was circular. Here, because of the topography, this region is not entirely circular. Also, the lowest temperatures were collocated with the upper-level vortices in both the dry planet and the aquaplanet cases. The current simulations show that the temperature distribution depends on the topography below the vortices. In the Atlantic Basin simulation, the coldest temperature in the northern hemisphere is located west of the northern hemisphere vortex near Kamchatka. In the Pacific Basin simulation, the coldest temperature is located in Europe. The hottest temperatures for both the dry planet and the aquaplanet were located at the substellar point. In the Atlantic Basin simulation shown here, the hottest temperature is in South America, not the substellar point. This shift westward from the substellar point is caused by the lack of water vapor in the air coming over the Andes from the unlit side of the planet. This lack of water vapor prevents clouds from forming over South
America, thereby allowing the stellar insolation to penetrate to the surface. The substellar point is located over the Atlantic Ocean, which allows water to evaporate, forming clouds which block the incoming stellar insolation. In the Pacific Basin simulation, the hottest surface temperature is in Australia, not at the substellar point. Again, the surface temperatures are hottest over land areas, except in this case there are no mountains to further decrease the water vapor.

The HA for these simulations is shown in Figure 4-4. By definition, the HA covers the same area as the blue area in Figure 4-3 for the same run. The HA is then further refined into LHA, CHA, and LCHA. Each of these has their own connotations. The CHA includes tropical climes where almost any organism can readily survive. Areas in the HA that are not in the CHA are temperate climes that require hardier organisms. The LCHA includes tropical climes located on continents that are ideal for the development of animal life and civilizations. The LHA includes temperate climes located on continents to which civilizations might spread after initial development in the LCHA.

4.3.2 Variable CO₂ simulations

After running the control simulations, we used a binary search code to find the CO₂ concentration that balances the carbonate-silicate cycle for a given solar insolation and substellar point. Each simulation with a different CO₂ amount was allowed to run for 10 years: then the annual mean surface temperature and runoff distribution at that time was used to estimate the silicate weathering rate. The CO₂ outgassed from volcanoes is
set to the present Earth value of 6.8 x 10^{12} moles C/year (Donnadieu et al., 2006). Land areas that have average surface temperatures between 0°C and 35°C are assumed to weather at the ambient surface temperature. Any land below 0°C is assumed to have zero runoff, and hence zero weathering. Any land for which the local average surface temperature is above 35°C is assumed to have the same weathering rate as land at 35°C. This qualification ensures that the land will not weather chemically faster than it can weather physically. (Tropical soils today are already heavily chemically weathered, suggesting that physical weathering becomes limiting at surface temperatures roughly equal to those in the present tropics.) Then, the CO$_2$ output from the volcanoes (which is set to a constant) and the CO$_2$ drawdown rate (calculated from the surface temperature and runoff) are compared. The CO$_2$ weathering rate is calculated from an equation in Walker, et al (1981) where Eq. 4.1

$$\frac{dCO_2}{dt} = \frac{1}{2} \oint S \cdot zwei \left( \frac{[CO_2]}{[CO_2]_0} \right)^3 \cdot \left( \frac{runoff}{runoff_0} \right) \cdot e^{\frac{T-T_0}{17.7}}. \quad 4.1$$

Here, $S$ (8.4543 x 10^{-10} C s^{-1} m^{-2}) is the present Earth silicate weathering rate per unit area; $runoff$ is the annual mean runoff rate at a grid point (which is calculated from the model output); $zwei$ is a factor used to calibrate to the surface area in a grid box that is weatherable; $T$ is the annual mean temperature at a grid point; $T_0$ is the reference temperature for the silicate weathering rate (here, 288K); $[CO_2]$ is the atmospheric concentration of carbon dioxide; $runoff_0$ is a reference globally averaged runoff amount determined from running GENESIS under present Earth conditions (0.665 mm d$^{-1}$); and $[CO_2]_0$ is the CO$_2$ concentration for used for determining the runoff amount (355 ppm). The global integral of the product is halved because only half of the CO$_2$ used in the
reaction goes into carbonates, while the rest is lost back to the atmosphere when calcium carbonate is precipitated. If outgassing is greater than weathering, the next CO$_2$ concentration chosen is higher than the current CO$_2$ concentration, whereas if outgassing is less than weathering, the next CO$_2$ concentration is lower than the present CO$_2$ concentration. When the change in CO$_2$ between one run and the next is less than 10% of the previous run, we conclude that the carbonate silicate cycle is nearly balanced, and so we have found the optimum CO$_2$ level for that configuration.

In the Atlantic Basin simulation, the carbonate-silicate cycle balanced at a CO$_2$ concentration between 7 and 12 ppm. The actual CO$_2$ concentration shown here is 7 ppm. This is only ~2% the present Earth atmospheric concentration. This level of atmospheric carbon dioxide is below the limit at which terrestrial plants can photosynthesize (10 ppm CO$_2$ for the hardiest C$_4$ plants (Caldeira and Kasting, 1992)); hence, none of this planet would be habitable for any photosynthetic life present on the Earth today. The reason the concentration is so low is because the substellar point is over the Atlantic Basin (Figure 4-1a). With the substellar point in this location, a large amount of land area is illuminated and, consequently, surface temperatures and weathering rates are very high. Note that major mountain ranges, like the Himalayas and the Andes, are illuminated in this simulation. The insolation warms the surface such that when it rains, the silicate rocks are easily weathered, drawing down the CO$_2$ concentration in the atmosphere.

In the Pacific Basin simulation, by contrast, the carbonate-silicate cycle balanced at a CO$_2$ concentration between 59,068 ppm and 60,311 ppm, which corresponds to a
CO₂ partial pressure of ~0.060 bar. The actual CO₂ concentration in this simulation is 60,311 ppm. This is nearly 200 times higher than the atmospheric CO₂ concentration on present Earth. The reason is that the substellar point is over the middle of the Pacific Ocean, so there is little continental landmass in the region where the solar insolation is high (as seen in Figure 4-1b). This lack of landmass leads to a need for larger atmospheric CO₂ concentrations in order to keep the landmasses on the dark side of the planet warm enough for liquid water to flow and to thereby weather the continents.

Although the carbon dioxide concentration is different from both the dry planet and the aquaplanet cases previously studied, the atmospheric circulations (Figure 4-5a,b) closely resemble those cases. Although the overall circulations bear close resemblance to the circulations seen before for the 10 day orbiters, the contoured 200 hPa geopotential heights and the 200 hPa wind vectors show topographically forced waves from the landforms present which are apparent in the figures. Specifically, the location of the Andes and the Rocky Mountains can be seen as a wave in the upper-levels over South
America and North America, respectively, in both simulations. Also in both simulations, there are waves in the vortices in the southern hemisphere as the contours cross from ocean to land near Antarctica. In the Pacific Basin simulation, waves can be seen over Asia, denoting the presence of the Himalayas.

The average surface temperature fields for these variable-CO$_2$ simulations are shown in Figure 4-6a,b. Areas in blue have average temperatures above 0°C, which makes these areas more likely to have liquid water present. The locations of the warmest and coldest areas on each planet are approximately the same for these planets and their respective controls discussed above. However, the global average surface temperatures and the global temperature ranges are very different (Table 4-1). The Atlantic Basin simulation decreased in all parameters except temperature range when compared to the 355 ppm control simulation. The lowered carbon dioxide concentration decreased the greenhouse effect, decreasing the global average temperature. As a consequence of the
lowered temperatures, the HA, CHA, LHA, and LCHA all decreased, but not drastically. The decreased greenhouse effect also allowed the temperature range to increase. The Pacific Basin simulation increased in all parameters except temperature range when compared to the 355 ppm control Pacific Basin simulation. The heightened carbon dioxide concentration increased the greenhouse effect, increasing the global average temperature. This warmer temperature is especially seen on the dark side of the planet, where the lowest temperatures are much higher than in the other simulations. This can be seen as a lack of isotherms on the unlit portion of the planet in Figure 4-6b when compared with Figure 4-6a. The temperature range decreased because of the increased greenhouse effect. Because of the increased temperatures, the HA, CHA, LHA, and LCHA all increased, with the LCHA and LHA doubling for the variable CO$_2$ simulation (Table 4-1).

Table 4-1: Average Surface Temperature and its range for the planets in chapter 4.

<table>
<thead>
<tr>
<th>Substellar Point Location</th>
<th>Carbon Dioxide Concentration (ppm)</th>
<th>Average Surface Temperature (°C)</th>
<th>Average Surface Temperature Range (°C)</th>
<th>HA ($x10^{14}$ m$^2$)</th>
<th>CHA ($x10^{14}$ m$^2$)</th>
<th>LHA ($x10^{14}$ m$^2$)</th>
<th>LCHA ($x10^{14}$ m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic Basin</td>
<td>355</td>
<td>254</td>
<td>104.20</td>
<td>1.50</td>
<td>1.47</td>
<td>0.70</td>
<td>0.69</td>
</tr>
<tr>
<td>Pacific Basin</td>
<td>355</td>
<td>260.4</td>
<td>94.98</td>
<td>1.57</td>
<td>1.48</td>
<td>0.28</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>60,311</td>
<td>281.6</td>
<td>80.89</td>
<td>2.83</td>
<td>2.46</td>
<td>0.69</td>
<td>0.46</td>
</tr>
</tbody>
</table>

The HA, CHA, LHA, and LCHA are shown in Figure 4-7a,b for their respective simulations. For the Atlantic Basin simulation, the HA, CHA, LHA, and LCHA have all decreased compared to the control. This is caused by the decreased concentration of carbon dioxide in the atmosphere required for carbonate-silicate cycle balance. But, because the control only has 355 ppm of CO$_2$, the present simulation looks much like the
control (Figure 4-4a). Notable differences include the Northern Atlantic Ocean, the HA on the South American continent, and the Ural Mountains on the Eurasian continent. For the Pacific Basin simulation, the HA, CHA, LHA, and LCHA have all increased compared to the control. This is a result of the increased concentration of carbon dioxide in the atmosphere required for carbonate-silicate balance. The carbon dioxide concentration builds in the atmosphere until the silicate weathering rate balances the rate of carbon dioxide outgassing from volcanoes. This increase in carbon dioxide concentration in the atmosphere increases the surface habitable area over the control at 355 ppm. The HA expands to include all of Australia (where only a portion of was habitable before), and much larger chunks of the Eurasian, North American, and South American continents. The Antarctic and Arctic regions also become partially habitable. Even Africa, which is nearly at the antistellar point, gains some habitability. So, increasing the CO₂ concentration decreases the global temperature range on the planet by

Figure 4-7: The HA (dark blue), the CHA (light blue), the LHA (green), and the LCHA (yellow) for the a) Atlantic Basin simulation and the b) Pacific Basin simulation. Black areas denote continental areas that are inhospitable and white areas denote frozen ocean areas. Areas that are in the LHA, CHA and LCHA are also in the total HA. Areas in the LCHA are also in the total LHA and total CHA.
increasing the temperature on the dark side of the planet. This brings about habitable areas on the dark side of the planet.

4.4 Conclusion

If Earth were tidally locked around a star with a 10-day orbital period with present Earth insolation, the habitable surface area would depend on the location of the substellar point. Moving the substellar point near or over a continent will decrease the carbon dioxide concentration in the atmosphere by increasing the rate of silicate weathering. Lowering the atmospheric carbon dioxide concentration decreases the greenhouse effect, which lowers the surface temperature globally. This global decrease in surface temperature results in a decrease in the habitable surface area, as all of the modeled planets are already cold, on average, compared to modern Earth. Moving the substellar point away from continental areas increases the carbon dioxide concentration, which results in an increase in the average surface temperature. This increase in average surface temperature may or may not increase the habitable surface area depending on the planet’s location in the Habitable Zone (HZ) of its star. If the planet is far out in the HZ, then increasing the CO$_2$ concentration should increase the habitable surface area through increasing surface temperatures. However, if the planet is close to the star in the HZ, then increasing the CO$_2$ concentration may actually decrease the habitable surface area by increasing surface temperatures.

The planets modeled here are located at the 1 A.U. equivalent distance from their parent star, which puts the planets close to the inner edge of the habitable zone for the
star. We know that planets may exist at any distance from their parent star, so future work should include planets at different distances from their parent stars.
In this work, the atmospheric dynamics of tidally locked planets was explored. The dynamics are dominated by the stationary eddies and mean meridional circulation. These dynamics are different from those of the present Earth in that the present Earth is dominated by the mean meridional circulation and transient eddies. As the rotational period increases, the stationary eddies expand to the size of the planet. Beyond this point, the Rossby radius of deformation continues to increase, but the preferred stationary eddy wavenumber moves from the #1 wavenumber to higher wavenumbers. The transition of the stationary eddies to wavenumbers greater than 1 occurs above a rotation period of 100 hours for the dry planets and near 96 hours for the aquaplanets.

Also, the habitability of these planets based on rotation period has been constrained for planets at the Equivalent Earth Distance with Earth-like CO₂ concentrations. All of these planets are habitable to some degree. Based solely on average surface temperature (Figure 5-1), only the 24-hr and the 48-hr rotating aquaplanets are habitable by traditional standards of habitability, i.e. having an average surface temperature above freezing (273 K). According to Joshi (1997), the surface temperature and habitability are only secondarily dependent on the rotation rate. Here, by contrast, we find that the surface temperature and habitability depend strongly on the rotation rate (Figure 5-1). As expected, the mean temperature increased for the
aquaplanets over the dry planets while the mean temperature range decreased with the addition of water to the model. The water and water vapor in the model increased the greenhouse effect, added clouds and ice (with the associated increase in albedo), added oceans (with the associated decrease in albedo and the higher surface heat capacity), and added latent heat to the atmosphere through condensation. Also, the albedo varies between the different planets (Table 5-1). The albedo is nearly constant across the dry planets, but varies more widely across the aquaplanets because of cloud and ice cover. Even though the albedo is higher for the aquaplanets, they retain more heat as a consequence of the increased concentration of greenhouse gases in their atmospheres.
Table 5-1: The average temperature, the minimum mean temperature, the maximum mean temperature, the planetary albedo and the IR greenhouse effect for the idealized planets.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Average Temperature (K)</th>
<th>Minimum Mean Temperature (K)</th>
<th>Maximum Mean Temperature (K)</th>
<th>Planetary Albedo</th>
<th>IR Greenhouse Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>245.6</td>
<td>156.2</td>
<td>356.5</td>
<td>0.2889</td>
<td>0.9464</td>
</tr>
<tr>
<td>48</td>
<td>237.5</td>
<td>170.3</td>
<td>352.2</td>
<td>0.289</td>
<td>0.9353</td>
</tr>
<tr>
<td>72</td>
<td>250.5</td>
<td>165.5</td>
<td>350.2</td>
<td>0.289</td>
<td>0.9353</td>
</tr>
<tr>
<td>96</td>
<td>250.3</td>
<td>171.7</td>
<td>349.5</td>
<td>0.289</td>
<td>0.9353</td>
</tr>
<tr>
<td>TRANSITION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>242.4</td>
<td>156.1</td>
<td>353.1</td>
<td>0.2891</td>
<td>1.03</td>
</tr>
<tr>
<td>240</td>
<td>251</td>
<td>196.8</td>
<td>349.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2400</td>
<td>262.6</td>
<td>227.2</td>
<td>347.5</td>
<td>0.2892</td>
<td>0.7765</td>
</tr>
<tr>
<td>Control</td>
<td>282.6</td>
<td>210.1</td>
<td>307.6</td>
<td>0.2714</td>
<td>0.686</td>
</tr>
<tr>
<td>Wet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>281.2</td>
<td>240.6</td>
<td>320.7</td>
<td>0.3844</td>
<td>0.6617</td>
</tr>
<tr>
<td>48</td>
<td>274.4</td>
<td>225.5</td>
<td>316.3</td>
<td>0.3991</td>
<td>0.7206</td>
</tr>
<tr>
<td>72</td>
<td>267.7</td>
<td>206</td>
<td>308.2</td>
<td>0.4156</td>
<td>0.7671</td>
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<tr>
<td>TRANSITION</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>96</td>
<td>269.6</td>
<td>196.8</td>
<td>316.2</td>
<td>0.3851</td>
<td>0.7732</td>
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<tr>
<td>120</td>
<td>268.2</td>
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<td>313.7</td>
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<td>240</td>
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<td>0.8626</td>
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<tr>
<td>2400</td>
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<td>235.8</td>
<td>296.7</td>
<td>0.4743</td>
<td>0.7909</td>
</tr>
<tr>
<td>Control</td>
<td>295.6</td>
<td>278.6</td>
<td>304.6</td>
<td>0.3079</td>
<td>0.556</td>
</tr>
<tr>
<td>Atlantic Basin</td>
<td>7 ppm</td>
<td>250.5</td>
<td>204.8</td>
<td>316.3</td>
<td>0.4175</td>
</tr>
<tr>
<td></td>
<td>355 ppm</td>
<td>254.3</td>
<td>210.4</td>
<td>315.3</td>
<td>0.415</td>
</tr>
<tr>
<td>Pacific Basin</td>
<td>355 ppm</td>
<td>260.1</td>
<td>216.3</td>
<td>311.3</td>
<td>0.4007</td>
</tr>
<tr>
<td></td>
<td>60,000 ppm</td>
<td>283.6</td>
<td>255.7</td>
<td>323.9</td>
<td>0.3232</td>
</tr>
</tbody>
</table>

caused by the inclusion of water vapor. The infrared greenhouse effect is the ratio of outgoing top of the atmosphere infrared flux to the flux determined from the Stefan-Boltzmann law at the surface. Here again, the impact of water vapor is seen as the ratio is lower for the aquaplanet than in the corresponding dry planet except in the 2400-hr case. The partial habitability of the planets ranges from as high as 65% for the 24-hr
rotating aquaplanet to as low as 19% for the 24 hour rotating dry planet (Figure 5-2).

Even though the dry planets are not habitable by definition because they have no surface water, they are included here for comparative purposes. Surprisingly, the predicted habitable surface areas do not include the terminator (as predicted in Joshi 1997) for the dry planets. Instead, the habitable areas are solely located on the sunlit side of the planets (Figure 2-12). For the aquaplanets, the terminator forms part (but not all) of the surface habitable areas for some, but not all, cases (Figure 3-17). Here, the impact of rotation period is strongly evident, with habitable areas that cross (but do not necessarily parallel) the terminator (e.g., the 24 hour rotating aquaplanet) or habitable areas that lie parallel to the terminator.

Figure 5-2

![Graph showing habitable surface area percentage vs. rotation period for different types of planets.](image)

**Figure 5-2:** The percentage of the surface area that is habitable for all of the idealized planets.
(but do not cross) the terminator (e.g., the 2400 hour rotating aquaplanet). We expect that the partial habitability of real planets will fall between that of the dry planet and that of the wet planet, although the habitability should not scale linearly with surface ocean coverage. Instead, we expect the distribution of continents to have a strong effect on the habitability (cf. Earth with Rodinia vs. Earth with Pangaea).

The results for the carbonate-silicate cycle study show that land mass distribution can have a very powerful impact on the habitability of a planet through the carbonate-silicate cycle. Large landmasses that are illuminated by the parent star act as sinks for atmospheric CO$_2$, which decreases the habitability of the planet and increases the temperature extremes on the planet’s surface. Large bodies of water illuminated by the parent star do not have this problem (because of the absence of silicate minerals in seawater) and allow the planet’s atmospheric CO$_2$ to build up to high levels, increasing the habitable surface area. Unfortunately, the habitable land area does not change nearly so much between the different landmass distributions as the habitable area because much of the land remains unlit, leaving it cooler and less habitable than land on the sunlit side of the planet. But, the increased atmospheric CO$_2$ concentration does decrease the extremes of temperature, creating more marginally habitable surface area (areas with average temperatures slightly below 0°C and low variability in temperature) keeping the promise that if a tidally locked terrestrial planet has plate tectonics operating, the planet will be much more habitable than previously thought. This result combined with previous results show that tectonically active planets (those with an active carbon cycling system) within the habitable zone of their stars should have liquid water at their surface at some point of their evolution, regardless of their orbital characteristics.
Future work could concentrate on allowing the oceans to circulate, allowing the eccentricities to be different and evolve, allowing the obliquities to evolve, and changing land mass amounts.
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VITA

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Adam Robert Edson was born on September 10th, 1979 to Paul Edson and Marla Edson in Sinclairville, NY. He was the third born of four brothers. In his senior year, he took up square dancing. He graduated from Cassadaga Valley High School in 1997 as the salutatorian of his class. In the fall of 1997, he took up square dance calling as well. Also in the fall of 1997, he began study at Jamestown Community College, from which he graduated summa cum laude in the spring of 1999 with an A.S. in Mathematics and Science. During his time there, he worked for the college tutor center, “Main Street”, where he helped fellow students gain insight and understanding in the sciences and mathematics. In the fall of 1999, he began study at the State University of New York at Brockport. He graduated magna cum laude in the spring of 2001 with a B.S. in Meteorology. During his time there, he was a teaching assistant in the introductory level meteorology course. From June 2001 to January 2004, he was employed by Condor Reliability Services of San Diego, CA as a weather observer at the Rochester International Airport. In the fall of 2003, he began study at the Pennsylvania State University under Dr. Peter Bannon. He received his M.S. in Meteorology in the spring of 2006 for his paper, “Nonlinear atmospheric adjustment to momentum forcing” which was published in the Journal of the Atmospheric Sciences in 2008. In the summer of 2006, he began study with Dr. James Kasting and Dr. Sukyoung Lee. During his time at Penn State, he met and married his favorite square dance partner, Riann. He received his Ph.D. in Meteorology and Astrobiology in the fall of 2008 on his thesis, “Atmospheric circulations of tidally locked terrestrial planets orbiting low mass stars”. Then he joined the staff of ITT Visual Information Services as a programming consultant.