Effects of Variable Eccentricity on the Climate of an Earth-like World

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Abstract

The \textit{Kepler} era of exoplanetary discovery has presented the astronomical community with a cornucopia of planetary systems that are very different from the one that we inhabit. It has long been known that Jupiter plays a major role in the orbital parameters of Mars and its climate, but there is also a long-standing belief that Jupiter would play a similar role for Earth if not for the Moon. Using a three-dimensional general circulation model (3D GCM) with a fully coupled ocean, we simulate what would happen to the climate of an Earth-like world if Mars did not exist, but a Jupiter-like planet was much closer to Earth’s orbit. We investigate two scenarios that involve the evolution of the Earth-like planet’s orbital eccentricity from 0 to 0.283 over 6500 years, and from 0 to 0.066 on a timescale of 4500 years. In both cases we discover that they would maintain relatively temperate climates over the timescales simulated. More Earth-like planets in multi-planet systems will be discovered as we continue to survey the skies and the results herein show that the proximity of large gas giant planets may play an important role in the habitability of these worlds. These are the first such 3D GCM simulations using a fully coupled ocean with a planetary orbit that evolves over time due to the presence of a giant planet.

Key words: astrobiology – planets and satellites: atmospheres – planets and satellites: terrestrial planets

1. Introduction

The \textit{Kepler} era has revealed a plethora of planetary systems whose orbital configurations are quite unlike those of our own solar system.\textsuperscript{3} The discovery of planets of similar mass and size to those of the Earth has ignited a strong interest in modeling the possibility of worlds in such systems’ habitable zones (HZs). As of 2016 November there are 31 planets\textsuperscript{4} with masses less than 2.5 $M_{\oplus}$ with eccentricities larger than 0.1, albeit with relatively large errors bars in each quantity for most objects. Of these, six are in multi-planet systems. Using a different criterion Bolmont et al. (2016) found four possible terrestrial-type planets with a non-negligible percentage of their orbit in the HZ for eccentricities greater than 0.1. More such systems will be discovered in the future and it is likely that there will exist cases where a Jupiter-like planet may be influencing the orbital parameters of an Earth-like terrestrial world more so than in the present-day Earth-Jupiter case. Understanding variations such as eccentricity and polar obliquity ($\theta_p$) will be important for the climate and habitability potential of a terrestrial planet in such a system. For example, the effect Jupiter has on the eccentricity and obliquity states of Mars are well known (Ward & Rudy 1991; Armstrong et al. 2004; Laskar et al. 2004), but Jupiter also has an effect on Earth (Spiegel et al. 2010, hereafter SP2010), which we see as part of the Milankovich cycles (Milankovitch 1941). At the same time, some studies show that Earth’s large moon offers it more obliquity stability against Jupiter’s influence (e.g., Laskar et al. 1993) and may be a requirement for climate stability and life (e.g., Waltam 2004), although Lissauer et al. (2011) claim it is not as important as previously thought. In fact Jupiter plays a role in the present-day orbital dynamics of Venus, Earth, and Mars, but it may also have played a role in their formation and sizes (e.g., Fritz et al. 2014; Batygin & Laughlin 2015). This will be no less true for similar or more “tightly packed” extrasolar planetary systems.

The effects of the orbital eccentricity and the obliquity of an Earth-like planet have been investigated in several studies. Williams & Pollard (2002, hereafter WP2002) used a 3D General Circulation Model (GCM) and a 1D Energy Balance Model (EBM) to show that, the “average stellar flux received over an entire orbit, not the length of the time spent within the HZ,” determine the long-term climate stability of systems with a broad range of eccentricities (0.1–0.7). All of their simulations used a semimajor axis of 1 au for the Earth-like planet. They found that one avoids reaching the moist-greenhouse and runaway-greenhouse limits as long as eccentricities are less than 0.42 and 0.70, respectively. A 3D GCM was also used by the same authors for investigating the effects that various $\theta_p$ angles may have on the climate of an Earth-like planet (Williams & Pollard 2003). They concluded that most Earth-like planets should be hospitable to life at high obliquity. None of their simulated planets were warm enough to develop a runaway-greenhouse or cold enough to freeze over completely. A recent study by Bolmont et al. (2016), though not directly comparable to this study because of their model choices, is nonetheless interesting. They investigated the effectiveness of the mean flux approximation as previously studied by WP2002. However, their setup was distinct: they ran 3D GCM simulations using 3 different stellar luminosities ($L_\star = L_\odot, 10^{-2}L_\odot, 10^{-4}L_\odot$), with a range of semimajor axes, fixed eccentricities and orbital periods while keeping $\theta_p = 0$. All systems were in a 1:1 spin–orbit resonance. They concluded “that the higher the eccentricity and the higher the luminosity of the star, the less reliable the mean flux approximation.”

Dressing et al. (2010, hereafter D2010) used an EBM to examine how different fixed values of eccentricity, $\theta_p$, azimuthal obliquity, ocean fraction, and rotation rate of a terrestrial-type world might affect climate. They also explored

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the transition to a snowball state by reducing the stellar luminosity. They found that the polar regions at higher eccentricities (where $\theta_p = 23.5^\circ$) were kept fixed) receive more mean insolation and the regional habitability fraction increased. The result is clear: if Earth had a larger orbital eccentricity it may have had even larger areas of habitability than it does today (see Section 3 for direct comparison to this work). They also showed that the outer edge of the HZ expands with values of eccentricity 0.4–0.7. The findings of D2010 confirm the GCM results of WP2002 in that increasing the eccentricity of a terrestrial world can increase the allowed semimajor axis for the outer edge of the HZ. D2010 also note that as one increases eccentricity regional and seasonal variability also increase in amplitude, leading to “a more gradual transition from habitable to non-habitable planets with increasing semimajor axis.”

A companion paper to that of D2010 is by (Spiegel et al. 2010, hereafter SP2010, who use the same EBM as D2010 but have no 3D GCM simulations. The focus in SP2010 is slightly different, as much of the paper examines what sorts of eccentricities are required to “break out” of a cold-start condition like that of a snowball state. At the same time, it is one of the few papers to consider the effects of variable eccentricity on long-term climatic habitability.

Other recent studies regarding habitable worlds include Linsenmeier et al. (2015), who used a GCM to explore the effects of seasonal variability for the climate of Earth-like planets as determined by $\theta_p$ and orbital eccentricity, and Armstrong et al. (2014), who used an EBM to study the impact of obliquity variations on planetary habitability in hypothetical systems. Ferreira et al. (2014) used a 3D GCM to investigate high obliquity states with a fully coupled ocean in the context of an aquaworld. They explored three obliquities (23.5°, 54°, and 90°) and found in all cases that their world still appears to be habitable.

In this work, we investigate how the climate of an Earth-like planet is affected when its orbit is perturbed by the presence of a nearby giant planet. For the first time, a GCM coupled with analytical equations that describe the orbital evolution of a terrestrial planet are used. An additional major difference between our work and previous studies is that we utilize a fully coupled ocean model and an Earth continental layout. This is in contrast to WP2002 who used a 50 m “thermodynamic slab” ocean model without horizontal ocean heat transport or Linsenmeier et al. (2015), who used an aquaplanet model and a 50 m slab ocean, but again with no horizontal ocean heat transport. We use a fully coupled ocean model because alongside atmospheric heat transport, ocean heat transport plays a vital role in the climate of Earth (Peixoto & Oort 1992). In particular, the work of Hu & Yang (2014) has shown that the effects of a fully coupled ocean versus a shallow slab ocean can be significant when looking at synchronously rotating worlds around M-dwarf stars. Godolt et al. (2015) demonstrated stark differences for planets orbiting F-type stars when changing ocean heat transport, while Rose (2015) nicely demonstrated the climatic effects of changing ocean heat transport equations for aqua-type and ridge-type worlds. The downside of a fully coupled ocean approach is that it can take hundreds of model years for a fully coupled ocean to come into equilibrium with the atmosphere. Yet, it will provide a more accurate picture of the climate of the world being modeled. In this study we focus on the effects of the terrestrial planet’s orbital eccentricity on the planet’s climate, which is an under-researched area in 3D GCM studies. At the same time, we keep $\theta_p = 23.5^\circ$, following for modern Earth. The latter is a necessary requirement for comparing with past and future work in the literature since obliquity plays such an important role in the possible climate states of terrestrial planets.

2. Methods

Our terrestrial planet climate simulations utilize the Goddard Institute for Space Studies 3D GCM known as Model E2 (Schmidt et al. 2014). The version used for this work is referred to as ROCKE-3D6 (Way et al. 2017). ROCKE-3D has extensions to Model E2 to allow for a larger range of temperatures, different atmospheric constituents, topographies, rotation rates, and variable eccentricity in time. An Earth-like topography is used for the atmospheric simulations herein, but with modest changes from present-day Earth to make the model more robust to possibly extreme conditions encountered by the perturbed orbits modeled. The model is run on a $4 \times 5^\circ$ latitude-longitude grid with 20 vertical atmospheric layers with the top set to 0.1 hPa. A 13-layer fully coupled ocean is utilized, but is a simplified “bathtub” type of ocean topography with depths along coasts of 591 m, and 1360 m elsewhere. The shallow ocean allows the model to attain thermodynamic equilibrium more quickly than it would if using an actual Earth ~5000 m depth ocean. Some shallow basins were also filled in such as Hudson Bay, the Mediterranean, the Baltic Sea, and the Black Sea. A number of straits were opened up, like that north of Baffin Bay and those north of Australia. The same solar insolation at 1 au used for Earth studies is used here. The atmospheric constituents and greenhouse gas amounts are the same as those for modern day Earth, with 984 mb of atmospheric pressure at the surface. The $\theta_p$ angle and rotation rate are also the same as that for modern Earth. ROCKE-3D does not take into account the resolved effects of non-diluted species, although it does take this into account for determining parcel buoyancy in the cumulus parameterization. Water vapor is the largest potential problem in this regard. However, not until the water vapor becomes greater than 10%–15% of the mass does it start to become problematic, as pointed out in Pierrehumbert & Ding (2016), and we do not reach this limit in any of the simulations presented herein (see Section 3).

In order to model the orbital evolution of the Earth-like planet, we make use of the work by Georgakarakos et al. (2016). This study, which builds on previous results (e.g., Georgakarakos 2003; Georgakarakos & Eggl 2015), focuses on the long-term orbital evolution of a terrestrial planet under the gravitational influence of a Jupiter-like world, with the latter relatively close to the former. The analytical equations for the orbital motion of the Earth-like planet derived in Georgakarakos et al. (2016) are used to provide eccentricity and pericenter values for the 3D GCM simulations herein. In the context of this work, all bodies are treated as point masses, they lie on the same plane of motion, and the system is not close to a mean motion resonance.

We simulated two different climate evolution scenarios as outlined in Table 1. Unlike the previous studies mentioned in the introduction, we were not able to run as many parameter

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7 The ocean depth numbers correspond to specific ocean layers in the model.
ensembles because of the length of time it takes the GCM to run one secular period of the Earth-like planet’s motion (see column 9 in Table 1). The GCM initial conditions are the same as modern Earth surface and ocean temperature values, unlike those of SP2010, who started many of their simulations in a snowball state and then examined how differing eccentricities might pull the world out of that state and into a possibly more temperate one. As mentioned above, we maintain a fixed Earth-like polar obliquity ($\theta_p = \theta_\oplus$) to make it more directly comparable to modern Earth. Certainly, a broader range of obliquities needs to be considered in the future, not to mention the possible coupling of variable obliquity with variable eccentricity with values driven by work similar to that in Georgakarakos et al. (2016).

| Case | Jupiter | Earth | Runtime |
|------|---------|-------|---------|
|      | Eccentricity | Semimajor Axis | Eccentricity | Obliquity | Orbital/Rotation Period | Semimajor Axis | Model Years | Wall Clock |
| 1    | 0.27 | 2.15 | variable | 23° | 365d/24 hr | 1.00 | 7000 | 108 days |
| 2    | 0.05 | 1.80 | variable | 23° | 365d/24 hr | 1.00 | 5000 | 62 days |

Figure 1. Case 1 from Table 1. The solid black lines are a 10-year running mean. Plot A is the mean surface air temperature for the Earth-like planet. Plot B is the planetary albedo as a percentage. Plot C is the amount of incident solar flux that the planet receives in Watts per meter squared. Plot D is the orbital eccentricity as a function of time. Plot E is the globally averaged specific humidity at 100 mb (the top layer of our GCM atmosphere) given in units of kilograms of H$_2$O per kilogram of air. Plot F is the surface air relative humidity (the lowest atmospheric layer in our GCM). Plot G is the precipitation in mm per day, and plot H is the ocean ice fraction, defined as the percentage of the ocean that is covered in ice.

Figure 2. Case 2 from Table 1. All ordinates are the same as for Case 1, except for plots C and E, which have been adjusted to allow for more visible detail.
3. Results and Discussion

There are a number of interesting similarities and differences between the results herein and those of WP2002 (the work that most closely corresponds to ours). We show, as demonstrated in WP2002, that relative humidity and precipitation increase with increasing temperature (Figures 1 and 2 plots F and G) when the planet is near periastron for a given orbit at the higher eccentricities shown in Figures 1(D) and 2(D).

These effects are more pronounced for Case 1 (shown in Figure 1) because of the higher eccentricities achieved. The planetary mean relative humidity for the first layer of the atmosphere for Case 1, as shown in Figure 1(F) when the planet is near periastron for a given orbit, is quite higher than that of present-day Earth (∼73%). The precipitation in Figure 1(G) goes to higher values than the average modern Earth value of ∼3 mm day⁻¹ (Legates & Willmott 1990). Values higher than those of modern Earth specific humidities in the top atmospheric layer (less than 2 × 10⁻⁶ kg H₂O/kg AIR) for Case 1 also manifest themselves in Figures 1(E) and 3(A), but they are two orders of magnitude below the Kasting (1988) moist-greenhouse limit (the “Kasting limit”) near each periastron crossing when the eccentricities are at their highest. It should be noted that at model year 3359, when the highest eccentricity and solar insolation were reached at periastron, the max gridpoint temperature was 53.9°C (see Figure 4(A)). This is within the range of validity of the ROCKE-3D GCM radiation scheme. WP2002 stated that their eccentricity limit for a moist-greenhouse state is 0.42, but in Case 1 (Figures 1(E) and 3(A)) it is clear that at our max eccentricity of 0.283, we are very far from approaching a moist-greenhouse state. In neither Case 1 nor 2 are these worlds anywhere near the moist-greenhouse limit, as evidenced in Figures 1(E) and 2(E). No individual grid cell in either case approaches the moist-greenhouse limit at periastron. For Case 1 the highest monthly averaged specific humidity achieved in a given grid cell at 100 mb at periastron for the highest eccentricity achieved is 6.7 × 10⁻⁵ kg H₂O/kg AIR (Figure 3(A)). While this is nearly 3 times the max globally averaged monthly value plotted in

![Case 1 Specific Humidity at 100mb at periastron (top) and apoastron (bottom). Note that the scale of the figures is different. The apoastron limits are 1/5 the limits of those for periastron.](image)

**Figure 3.** Case 1 Specific Humidity at 100mb at periastron (top) and apoastron (bottom). Note that the scale of the figures is different. The apoastron limits are 1/5 the limits of those for periastron.
Figure 1(E), it is still nearly 1.5 orders of magnitude lower than the moist-greenhouse limit. As mentioned in Section 2 ROCKE-3D does not take into account the resolved effects of non-diluted species. For Case 1 we quantified this effect for water vapor at the highest eccentricity achieved, 0.283. We looked at 30-minute intervals (our physics time-step) over the month around periastron. The highest surface specific humidity found was nearly 0.048 kg H₂O/kg AIR. This corresponds to less than 5% of the mass of the atmosphere, and therefore should not be a significant source of error.

The closest simulation in WP2002 to our Case 1 at maximum eccentricity is their run “GCM 2,” which has a fixed eccentricity of 0.3. Their mean surface temperature is 22.90°C, which is very close to our Case 1 22.5°C for our largest eccentricity near orbital periastron. This gives us confidence that our results are consistent with WP2002 in some ways.

As in WP2002 our albedo and ocean ice fraction in Case 1 (Figures 1(B) and (H)) show some interesting behavior (it is more difficult to discern in Case 2). At higher eccentricities the ocean ice fraction decreases at the same time that the spread in albedos is largest. Surely this is related to the world’s ability to keep the ocean ice fraction low at high eccentricities, even at apoastron. This is likely a side effect of the bulk heat capacity of our temperate world (Cowan et al. 2012). It is also due to our fully coupled ocean’s horizontal heat transport and the relatively short amount of time Case 1 spends at its farthest distance from the Sun.

D2010 also discuss the importance of model relaxation in their appendix. We have also tested this, which is necessary given that we have a fully coupled ocean rather than their shallow 50 m slab ocean. Using a 10-year running mean we found that the net radiative balance for our world was within +/−0.2 Watts m⁻² for the entirety of Simulations 1 and 2. This demonstrates that even for our most rapidly changing world (Simulation 1) it is not changing fast enough to throw the planet’s radiative balance off enough to affect our results.

4. Conclusion

With upcoming space missions such as the Transiting Exoplanet Survey Satellite (Ricker et al. 2014) and the James Webb Space Telescope (Gardner et al. 2006), and large ground-
based observatories such as the European Extremely Large Telescope (Gilmozzi & Spryromillio 2007), systems similar to those described herein are likely to be discovered. Prior to follow-up observations, which may be costly in terms of telescope observing time, it will be important to constrain any evolution in the orbital parameters of worlds like those of Case 1, whose regional habitability may be larger than other potential candidates. We have not discussed the evolution of the polar orbital inclination of the Earth-like planet in this work, but other 3D GCM studies (e.g., Williams & Pollard 2003; Linsenmeier et al. 2015) have shown that it plays an additional role in the habitability states of worlds like those that we have modeled in this work. Future studies in this series will include polar orbital inclination evolution to better understand its effects in combination with eccentricity. Rotation rate will also be examined since it is clear that it plays a very important role in understanding the extent of the HZ (Iro & Deming 2010; Yang et al. 2013).

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