Two climate patterns on habitable planets in eccentric orbits around M dwarfs

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Abstract

Previous studies of habitable planets in the synchronous rotation state show that the surface of such a planet should be mostly frozen except open water region near the sub-stellar point, an "eyeball" pattern. With non-zero eccentricities, habitable planets of M dwarfs can be captured in other spin-orbit resonance states. For these planets we found that open water occupies all longitudes at low to middle latitudes and ice only exists at high latitudes -- a striped ball pattern. The correlation between climate patterns and orbital eccentricities will be observable by future exoplanet characterization missions.

Introduction

The habitable zones of M dwarfs are typically at ~0.1 AU. At this small distance, planets are subject to strong tidal forces which will lock the planets in spin-orbit resonance states. In the case of near-zero eccentricity, such as the moon around the Earth, the planet's spin angular velocity (ω) is equal to its orbit angular velocity (n), the 1:1 resonance state or synchronous rotation. Pierrehumbert found that a planet in synchronous rotation should be mostly frozen except a substantial stable open water region near the sub-stellar point -- an "eyeball" planet.

But the increasing observations show that many exoplanets have significant eccentricities. Considering the eccentricities for close-in exoplanets, the spin-orbit resonances are not necessarily captured into 1:1 states. Define the spin-orbit resonance number $p = \frac{\omega}{n}$, and a solid planet can be locked into any spin-orbit resonances with p being equal to an integer or a half. For example, p= 1.5 and e=0.206 for Mercury. This eccentricity-caused different p values can have a great influence on the planet's climate, via the migration of sub-stellar point.

Spin-Orbit Resonance States

For constant-Q tides, the capture probability P for an exact spin-orbit resonance p value and an exact eccentricity is independent of the planet's interior structure.

It is interesting to note that the final resonance states depend on the initial states.

If the planet spins slowly at the beginning, it will speed up over time and should encounter p=1.0 resonance first. In this case only if the planet is not captured into synchronous resonance, will other resonances be possible.

For planets spin rapidly at the beginning, the planets with non-zero eccentricities will encounter non-synchronous resonance states first and thus the probabilities for the planet to be in these resonance states are enhanced. For e between 0.15 and 0.3, p=1.5 resonance is most probable; for e between 0.3 and 0.4, the most probable resonance is p=2. The most probable resonance states for planets with near-zero eccentricity is the p=1 synchronous rotation state.

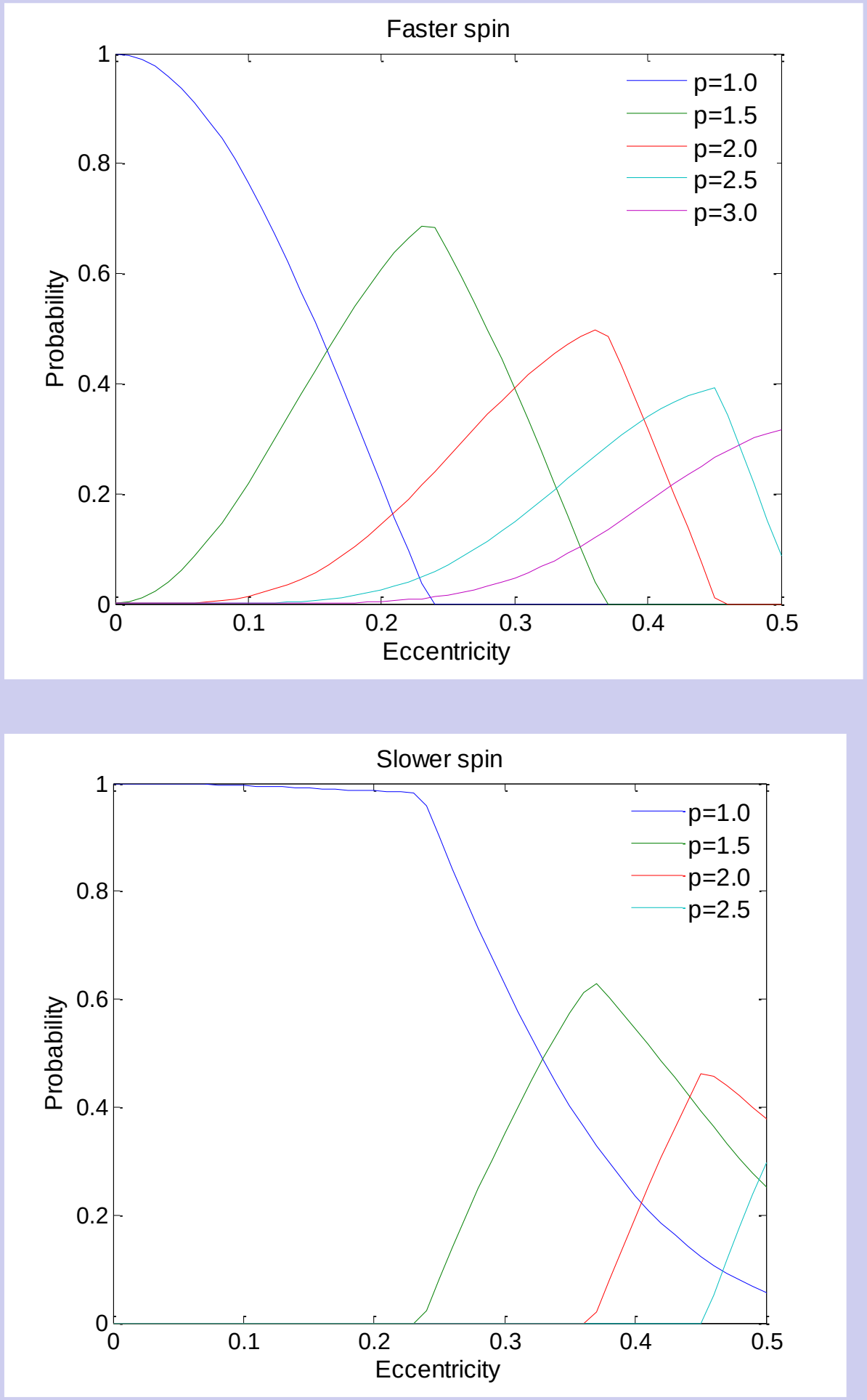

Figure 1. Probability of spin-orbit resonance states

Time Scale for resonance state

For Q=10 and a star with 0.33 solar mass, the eccentricity decay timescale for a planet with the same mean density and mass as those of the Earth at 0.1AU is 3.6Gyrs.

With the same configuration as above, this timescale for a planet to be captured into spin-orbit resonance states is as short as 7 thousand years, more than 5 orders of magnitude shorter than timescale of eccentricity damping.

Thus habitable planets in different spin-orbit resonance states should be observable.

Migration of sub-stellar point

Planets in different resonance states have different stellar radiation patterns.

Let the periastron correspond to 180° longitude.

When ω is larger than n, the sub-stellar point moves westwards, and vice versa. The spin angular velocity of a planet is normally a constant, but its instantaneous orbit angular velocity is faster near periastron and slower near apoastron. Thus the movement of sub-stellar point is not constant.

For p ≥ 2.5, the sub-stellar point always moves westwards. The Earth is a good example. But for p=1.0, 1.5, and 2.0, the sub-stellar point sometimes moves westwards and sometimes moves eastwards. In all cases except for p=1.0, the sub-stellar point can go over entire planet.

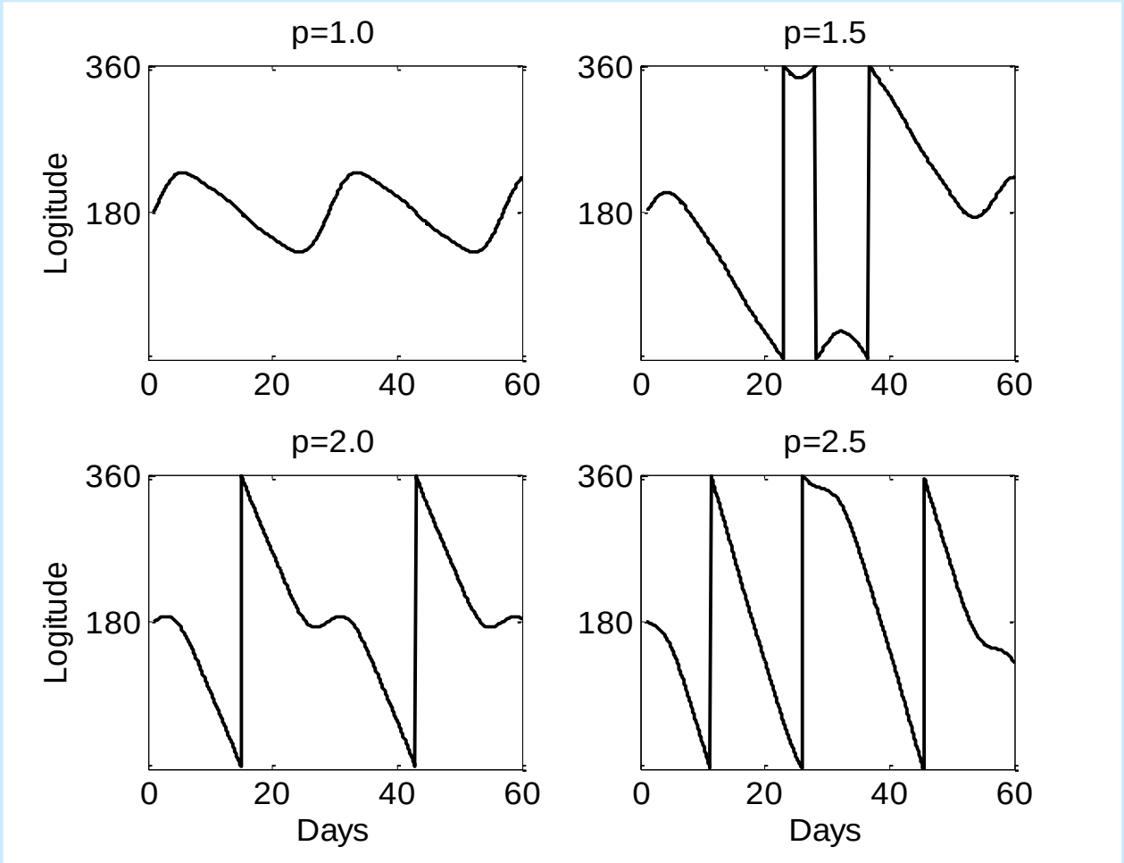

Figure 2. The longitude of sub-stellar point varies with time for various p. The eccentricity is 0.4.

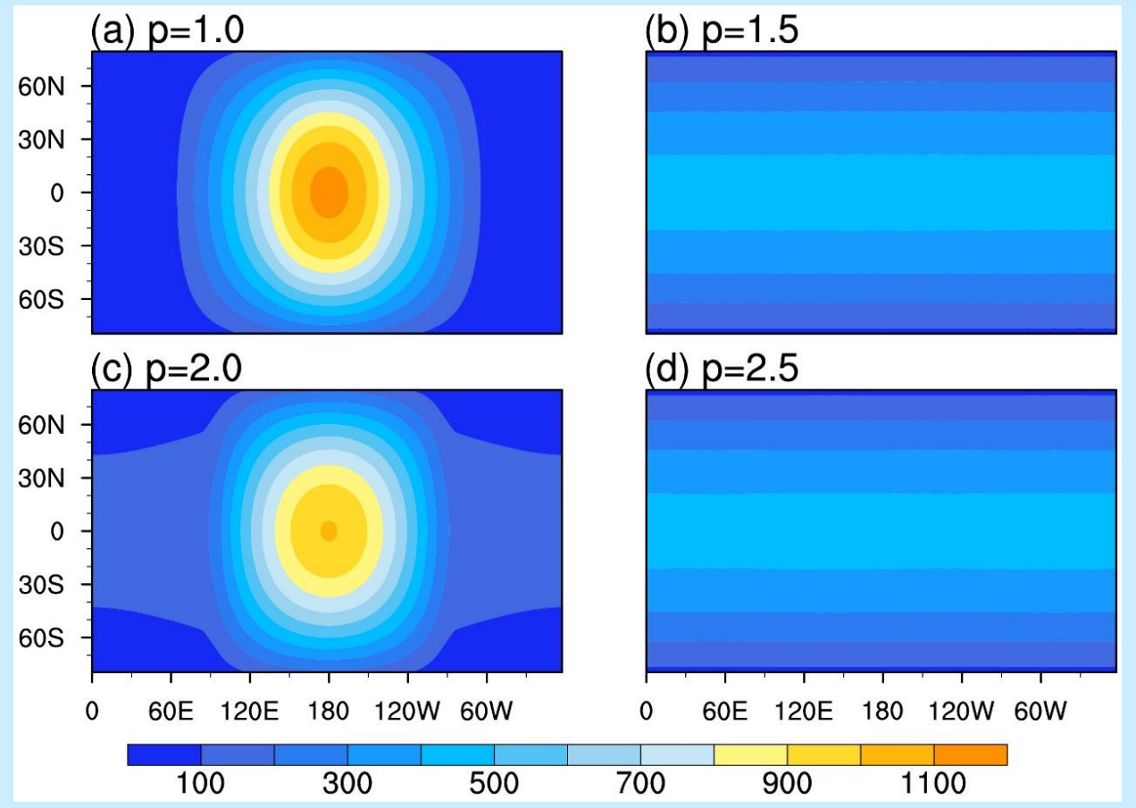

Figure 3. Average stellar insolation during one orbit for various p values

Model and Method

I: Model

CAM (the Community Atmosphere Model version 3)

Slab Ocean

CSIM

II: Planet Parameters

$M(M_{\oplus})$	$r(r_{\oplus})$	$G(m\ s^{-2})$	a(AU)	P(days)	Eccentricity	Obliquity
4.27	1.7	16.2	0.123	28	0.4	0

III: Atmosphere composition

1 bar background gas N_2, 355ppmv CO_2

IV: Stellar Spectrum and Stellar Constant

Plank function at 3700K and 90.5% of solar constant

Surface Temperature and Ice Fraction

Table 2 Globally Averaged Surface Temperature and Ice Fraction for various p values

p	1	1.5	2.0	2.5	3.0	3.5
Temperature (K)	257	281	264	284	293	290
Ice Fraction (%)	55	17	55	18	13	15

The climate patterns of habitable planets around M dwarfs can be divided into two categories: Eyeball (p=1.0 and 2.0) and Striped ball (all p values except p=1.0 and p=2.0).

For an eyeball planet, the warm region is on the near side of the planet and the far side is cold. Isothermals are nearly concentric circles. The open water region corresponds to the warm region and ice covers other parts of the planet. The p=1.0 state is synchronous rotation with the planet always facing the star with one side. Although the sub-stellar point covers all longitudes in the p=2.0 state, there is a fixed relationship between the substellar point longitude and the orbital distance of the planet. Thus the 0 degree longitude on the planet always corresponds to the apoastron and the stellar energy flux received by this longitude is inadequate to melt the ice in the e=0.4 case (Fig. 3).

On the other hand, the stellar fluxes in the p=1.5 and 2.5 cases are distributed more uniformly (Fig. 3) and thus the isothermals are zonally distributed with lower temperature regions at higher latitudes. Correspondingly the open water region can go around the planet in low and middle latitude region and ice only exists at the high latitude regions (Fig. 4).

These two climate patterns are quite different (Table 2). The difference in globally average surface temperature can be as high as 36K although the yearly average incident flux and the composition of the planet's atmosphere remains identical. An eyeball planet is covered with more ice and has higher albedo, while a striped-ball planet is warmer.

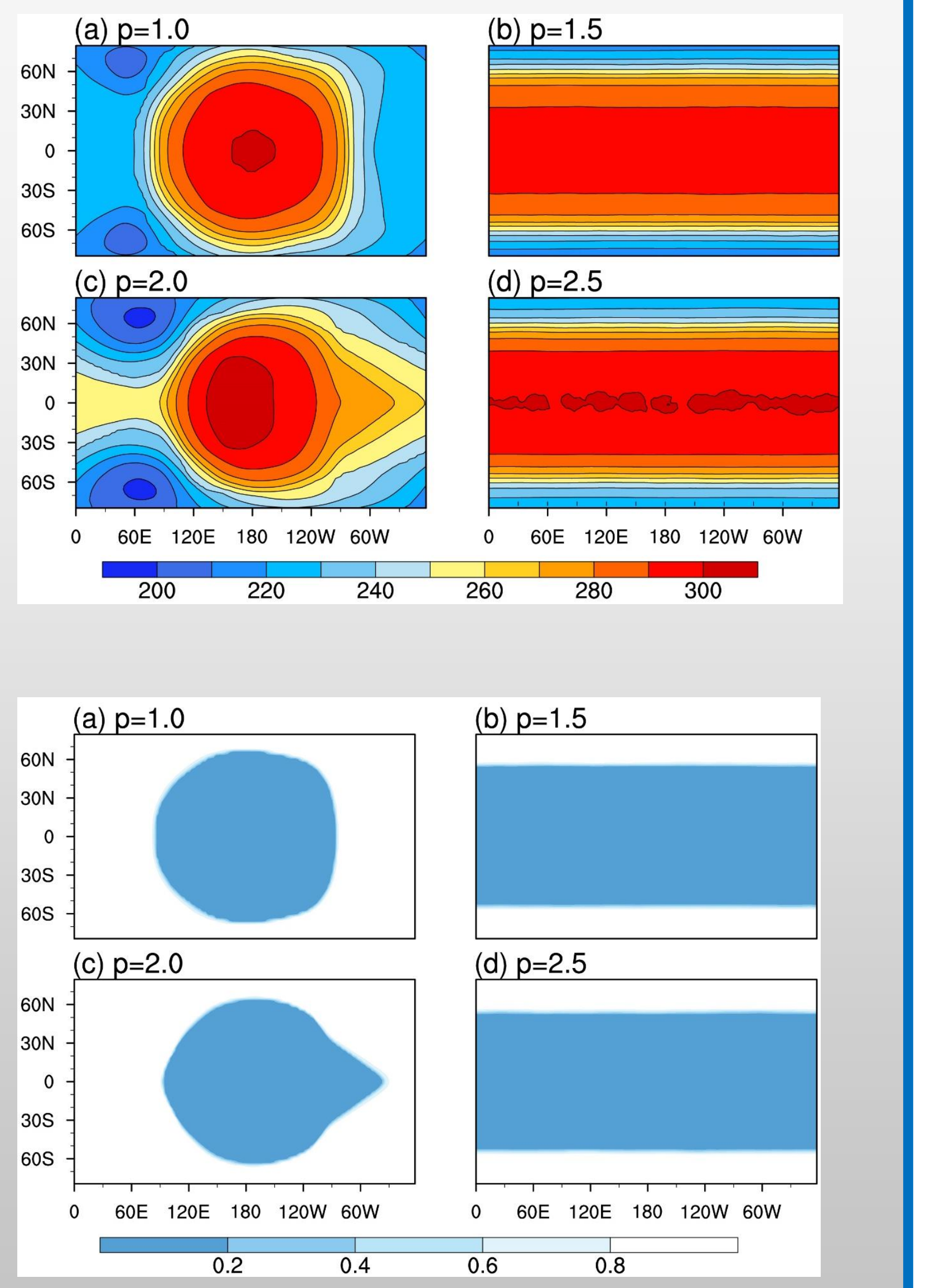

Figure 4.top: Annual average surface temperature for various p value; bottom: Annual averagedice fraction for various p value

Correlation between climate pattern and spin-orbit resonance

The strong correlation between a habitable planet's climate pattern and its spin-orbit resonance state is summarized in Table 3.

As the detection technique develops, future exoplanet characterization missions might have the potential to observe the relationship between climate patterns and spin-orbit resonances.

Table 3 Most possible climate pattern for a certain eccentricity

Faster Spin Initial State			Slower Spin Initial State		
Eccentricity Range	Most Possible P Value	Most Possible Climate Pattern	Eccentricity Range	Most Possible P Value	Most Possible Climate Pattern
$0 \le e \le 0.15$	P=1	Eyeball	$0 \le e \le 0.33$	P=1	Eyeball
$0.15 \le e \le 0.3$	P=1.5	Striped	$0.33 \le e \le 0.44$	P=1.5	Striped
$0.3 \le e \le 0.4$	P=2.0	Eyeball			
$0.4 \le e \le 0.47$	P=2.5	Striped			

Conclusions

Using a 3D GCM model, we found that two possible climate patterns exist for habitable planets around M dwarfs with eccentric orbits.

The climate pattern of a planet is closely related to its eccentricity and spin-orbit resonance state, which control the longitude migration of sub-stellar point and therefore determines where liquid water instead of solid ice may exist on the planet's surface.

For fast initial spin state, an eyeball planet (Pierrehumbert, 2011) is most likely for eccentricity from 0.1 to 0.15 and 0.3 to 0.4; but a striped ball planet, not discussed before, is possible for other eccentricities. It will be interesting for future exoplanet characterization missions to observe the climate patterns on planets with different spin-orbit resonance states.

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