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New inner boundaries of the habitable zones around M dwarfs

Jiayu Bin[a,b], Feng Tian[a,b,*], Lei Liu[a,b]

[a] Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University, Beijing 100084, China
[b] Joint Center for Global Change Studies, Beijing 100875, China

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ABSTRACT

Two general circulation models CAM4 and CAM5 are used to study the climate of ocean planets around M dwarfs with different effective temperatures. The atmospheres in CAM5 simulations are warmer and contain more water vapor than those in CAM4 under identical model settings, a result likely caused by improved treatments of radiation and possibly clouds in CAM5. The inner boundary of the habitable zones of M dwarfs based on CAM5 simulations, expressed as a second order polynomial function, are farther away from the stars than what are suggested by previous works and the corresponding atmospheres are in the moist greenhouse state.

1. Introduction

Kasting et al. (1984) pointed out that all Earth's oceans could be lost within 5 billion years (Gyrs) if water vapor volume mixing ratio (r_{H_2O}) reaches $\sim 10^{-3}$ in the stratosphere, in which case rapid water vapor photolysis could occur and the subsequent loss of hydrogen could be efficient. This is the so called moist greenhouse state. If the surface temperature (T_s) is $>\sim 360$ K, the IR opacity of water vapor would be so large (assuming adequate source of water to the atmosphere) that the outgoing IR radiation can no longer match the incoming short-wavelength radiation and the planet would continue to heat up until $T_s \sim 1600$ K, when the visible wavelength part of outgoing radiation becomes significant and a new radiative equilibrium is reached. This is the so called runaway greenhouse state (Kasting, 1988; Nakajima et al., 1992).

The inner edge of the habitable zone (IHZ) is defined as the orbital distance or stellar insolation at the planet (S) at which the moist or the runaway greenhouse state is reached. By definition planets in the runaway greenhouse state lose water more rapidly than planets in the moist greenhouse state do if adequate soft X-ray and XUV is available for hydrogen (and oxygen) to be lost from their upper atmospheres. Otherwise the planets would be able to keep their water vapor while maintaining moist or steam atmospheres. In addition, whether a planet can be completely dehydrated depends on the initial water inventory. The timescale for Earth-mass planets to lose oceans with mass equivalent to >1% of Earth mass could well exceed 100 Gyrs (Tian and Ida, 2015). Thus a planet closer to its star than the IHZ may or may not be completely depleted of water. Furthermore, even if they are able to keep water, steam atmospheres would not likely be habitable in a conventional sense. Nevertheless the concept of the IHZ is important now because rocky exoplanets are discovered near the IHZ of nearby M dwarfs (Charbonneau et al., 2009; Berta-Thompson et al., 2015; Anglada-Escude et al., 2016; Gillon et al., 2017; Dittmann et al., 2017).

Multiple efforts have been devoted to study the IHZ problem using 1D (Kasting et al., 1993; Kopparapu et al., 2013, 2014) and 3D general circulation models (GCM; Leconte et al., 2013; Yang et al., 2014, 2016; Wolf and Toon, 2014, 2015; Wang et al., 2016; Kopparapu et al., 2016, 2017, the later 2 are referred as K16 and K17 in the following;) on Earth-size ocean planets. One difficulty in the IHZ study is the model stability. Most previous works cannot reach the runaway greenhouse state because the corresponding atmosphere involves extremely large r_{H_2O}, and the numerical problems related to clouds, radiation, convection, or precipitation lead to a model crash. Thus the last converged solution, the last stable climate state the models could reach when continuously increasing the top-of-atmosphere (TOA) stellar radiation (S), is commonly used as a proxy for the runaway greenhouse state. Note that the last converged solutions could mark the threshold for exoplanet climate to shift to a different physical state, or could be a manifestation of issues in numerical treatment, in which case no specific physical meaning is associated with it. Conceptually a last converged solution associated with physics is preferred.

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[*] Corresponding author at: Department of Earth System Science, Tsinghua University, Beijing, 100084, China.
E-mail address: tianfengco@126.com (F. Tian).

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Table 1
The last converged solutions of CAM4/CAM5 simulations (1 ppmv CO_2), the corresponding r_{H_2O} and timescale of losing one Earth ocean (τ_{EO}) in CAM5 simulations.

Stellar properties			CAM4				CAM5				
T_{eff} (K)	M/M_s	L/L_s	S/S_0	P (d)	r_{H_2O} (10 hPa)	r_{H_2O} (100 hPa)	S/S_0	P (d)	r_{H_2O} (10 hPa)	r_{H_2O} (100 hPa)	τ_{EO} (Gyr)
2550	0.08	5.3×10^{-4}	1.05	4.3	1.0×10^{-6}	1.7×10^{-5}	0.9	4.8	2.1×10^{-3}	8.3×10^{-3}	1.5–6.0
3050	0.12	1.6×10^{-3}	1.15	7.4	1.3×10^{-5}	5.3×10^{-4}	1.0	8.2	1.1×10^{-4}	4.6×10^{-3}	2.8–118
3290	0.2	4.9×10^{-3}	1.35	12.0	5.3×10^{-5}	2.9×10^{-3}	1.15	13.6	9.0×10^{-4}	7.8×10^{-3}	1.6–14
3650	0.5	3.4×10^{-2}	1.8	26.4	1.1×10^{-2}	2.5×10^{-2}	1.275	34.2	2.0×10^{-3}	1.8×10^{-2}	0.72–6.1
3960	0.62	7.6×10^{-2}	1.95	40.7	1.4×10^{-2}	2.7×10^{-2}	1.35	53.7	3.9×10^{-3}	2.8×10^{-2}	0.46–3.3
4460	0.75	1.9×10^{-1}	2.25	65.1	2.9×10^{-2}	4.2×10^{-2}	1.495	88.4	6.9×10^{-3}	4.0×10^{-2}	0.32–1.8

The r_{H_2O} listed are the mean values in the regions where the TOA radiation is greater than 50% of the radiation value at the substellar point. This analysis is more useful when evaluating water loss because of the lack of water vapor photolysis on the night side of the tidally locked planets. The timescales of water-loss τ_{EO} are estimated based on r (10 hPa) and r (100 hPa) assuming the diffusion limited escape and 1 Earth ocean.

Leconte et al. (2013) found the last converged solution of the IHZ for our Sun at 1.1 times solar luminosity (S_0) using the Laboratoire de Météorologie Dynamique Generic (LMDG) climate model. Wolf and Toon (2014, 2015) studied the same problem using the Community Atmosphere Model Version 3 (CAM3) and the Community Earth System Model (CESM) with CAM4 as its atmosphere component. They found that the last converged solutions of the Sun should correspond to 1.155 (Wolf and Toon, 2014) and 1.21 S_0 (Wolf and Toon, 2015), respectively. These solutions are for planets with rotation period of 24 h.

Planets near the HZ around M dwarfs should be tidally locked and thus should rotate slower than the Earth does. CAM3 simulations for planets with long rotation periods (60 days for M and K stars, 128 days for G and F stars) showed that high cloud coverage in the substellar region dramatically increases planetary albedo and pushes the last converged solutions rather close to stars (Yang et al., 2014). K16 revisited the cloud effects for tidally locked exoplanets around M dwarfs by considering realistic rotation periods (a few to a few tens of days). For mid-to-late M-dwarfs (stellar temperature between 3300 and 3700 K) with high metallicity stars and for mid-K to early-M dwarfs, the CAM4 results in K16 agreed with the results in Yang et al. (2014). But for mid-to-late M dwarfs with low metallicity, K16 showed banded cloud structure and smaller S for the last converged solutions than those in Yang et al. (2014) – the IHZ around such stars should be further away than predicted in Yang et al. (2014). K17 updated the water vapor absorption coefficients in radiative transfer scheme in CAM4 following the method used in Wolf and Toon (2013) and found that the IHZ of M dwarfs should correspond to much smaller stellar radiation when compared to those in K16 and Yang et al. (2014).

Since previous works showed that clouds and radiation schemes in GCMs significantly affect the locations of IHZ (Yang et al., 2014, K16, K17) and CESM-CAM5 includes more detailed cloud macro- and micro-physics and updated radiation treatments (Neale et al., 2012), we use both CESM-CAM5 and CESM-CAM4 to revisit the IHZ problem around M dwarfs. We show that the IHZ of M dwarfs should be even further away from the central stars than previously predicted.

2. Methods

CESM 1.2 is used on Earth-size, synchronously rotating ocean planets with blackbody spectra ($T_{eff} = 2550$–4460 K) used as TOA incident radiation. The luminosities and masses of TRAPPIST-1 and Proxima Centauri are used for the stars with $T_{eff} = 2550$ and 3050 K respectively. For other stars, the mass–luminosity–temperature relationships of 5-Gyr-age M dwarfs in the NextGen dataset (Baraffe et al., 1998) are used. Following K16, planet rotation periods are based on the masses and luminosities of the stars and the planets' orbital distances (see Table 1).

The models use $1.9° \times 2.5°$ horizontal resolution and 26 vertical levels, assume 1 bar N_2 atmosphere, zero obliquity, zero eccentricity, and use slab oceans (depth set to 1 or 50 m) with zero ocean heat transport and thermodynamic sea ice. The upper boundary is set to 3 hPa. All CAM4 simulations use the CAMRT radiation scheme (Kiehl and Briegleb, 1991; Kiehl and Ramanathan, 1983; Briegleb, 1992), the RK scheme for condensation, precipitation, and evaporation processes (Rasch and Kristjánsson, 1998; Zhang et al., 2003), the Zhang–McFalane scheme for deep convection (Zhang and McFarlane, 1995; Richter and Rasch, 2008; Raymond and Blyth, 1986, 1992; Gregory et al., 1997), and the Hack scheme for shallow convection (Hack, 1994). All CAM5 simulations use the RRTMG radiation scheme (Iacono et al., 2008; Mlawer et al., 1997), the Park scheme for macrophysics (Park et al., 2014), the MG scheme for microphysics (Morrison and Gettelman, 2008; Gettelman et al., 2010), the Zhang–McFalane scheme for deep convection (Zhang and McFarlane, 1995; Richter and Rasch, 2008; Raymond and Blyth, 1986, 1992; Gregory et al., 1997), and the UW scheme (Park and Bretherton, 2009) or the Hack scheme (Hack, 1994) for shallow convection.

Section 3.1 compares CAM4 and CAM5, and explores the effect of atmospheric CO_2 and ocean depth on the last converged solutions of TRAPPIST-1. We conclude that while ocean depth has little effect on the last converged solutions, a higher CO_2 level does lead to a warmer climate. Thus atmospheric CO_2 of 1 ppmv is used for IHZ discussions in Section 3.2 in order to produce a conservative estimate on the IHZ.

3. Results and discussions

3.1. Comparisons between CAM4 and CAM5

The distributions of surface temperature in the last converged solution of CAM4 simulations for TRAPPIST-1 (1.05 S_0, 4.3-day rotation period) are shown in Fig. 1. Our results show that increasing atmospheric CO_2 concentration from 1 ppmv (Fig. 1a) to 355 ppmv (Fig. 1b) while keeping other model parameters identical can sufficiently warm up the planet and increase the coverage of open ocean (also see the trends shown by the blue and black curves in Fig. 1d). When increasing atmospheric CO_2 from 1 to 355 ppmv, the region with highest temperature still concentrates near the sub-stellar point and the warm region expands to cover more planet surface. As a result, the ice coverage shrinks and the open ocean extends to the night side. Although it seems that the climate pattern shifts from an eyeball pattern to a banded one, the pattern shown in Fig. 1b and 1c is different from a real banded climate pattern caused by the migration of substellar point (see Fig. 2 in Wang et al., 2014). Since a lower CO_2 concentration should provide less greenhouse effect, a cold climate, and an IHZ closer to the star, our discussions of IHZ in Section 3.2 uses a CO_2 concentration of 1 ppmv.

Although simulation with shallower ocean (1-m, red in Fig. 1d) presents larger temporal variability than that in deeper-ocean simulation (50-m, black in Fig. 1d), the steady states in these two sim-