学位論文

Evolution of atmosphere of terrestrial habitable planets against luminosity evolution of central stars

(中心星光度進化に対する地球型ハビタブル惑星の大気進化)

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Abstract

Evolution of atmosphere of terrestrial habitable planets against luminosity evolution of central stars

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Recently, many extrasolar planets have been detected and the habitability of extrasolar planets has been actively discussed. In general, it is assumed that an Earth-like planet with oceans is a habitable planet. Such a planet is implicitly assumed to be a planet whose surface is covered with oceans, like the Earth, which is called an aqua planet. According to studies on the evolution of an aqua planet (or the early Venus), the planetary atmosphere enters the moist greenhouse state, when the luminosity of the central star increases to a certain critical value. In the moist greenhouse state, the upper atmosphere is wet, leading to a rapid water loss. When the luminosity of the central star increases further, the planetary atmosphere becomes into the runaway greenhouse state. In the runaway greenhouse state, all the water on the planetary surface evaporates to form a steam atmosphere, and the planetary surface would be covered with a magma ocean owing to the greenhouse effect of the steam atmosphere.

On the other hand, when the amount of water on the planetary surface is so small that the precipitation and the evaporation are locally balanced, the evolution of the atmosphere with an increase in stellar luminosity could be different than in the case of aqua planets. Such a planet is called a land planet. Although a land planet also evolves to the runaway greenhouse state, the critical insolation for a land planet to enter the runaway greenhouse state is higher than that for an aqua planet because of the localization of water in high latitudes on a land planet. The distribution of surface water is strongly linked to the amount of water and hence important for the evolution of a habitable planet.

To understand a variety of habitable planets and their long-term evolution, I

have focused on the amount of water on the planetary surface and its evolution in this study. Because the amount of water on the surface of an aqua planet decreases by a rapid water loss to space in the moist greenhouse stage, an aqua planet might be able to evolve to a land planet. I investigate this possibility in Chapter 2. The relationship between the distribution of surface water and the threshold insolation for the runaway greenhouse for a land planet is also investigated in Chapter 3. Finally, based on the results, I discuss the evolution of a habitable planet in Chapter 4

I estimate changes in the amounts of water on the planetary surface and in the planetary atmosphere, considering the escape of water to space and the luminosity evolution of the central star, in order to discuss the evolution from the aqua planet to the land planet. A vertical, one-dimensional, non-gray radiative-convective equilibrium model is used to estimate the amount of water in the atmosphere, as well as the mixing ratio of water vapor in the upper atmosphere. Evolution of the luminosity and EUV flux of the central star is considered in estimating both the diffusion-limited escape flux and the energy-limited escape flux from the planetary atmosphere in the moist greenhouse state. Two parameters are considered for the transition condition from the aqua to land planet: the amount of water on the planetary surface on the land planet (1, 5 and 10% of the present Earth's ocean mass) and that in the planetary atmosphere just before the onset of the runaway greenhouse (0.1, 0.3, 0.5 and 1 bar). I have found that an aqua planet with a relatively small amount of water (for example, 10% of the present Earth's ocean mass at 0.8 AU) could evolve to a land planet. Such a planet can maintain liquid water on its surface for more 2 Gyr. It is therefore suggested that a rapid water loss could result in extending the lifetime of the planetary habitability, although it has been considered as the end of the habitable world.

Previous studies suggest that the threshold insolation for the runaway greenhouse state significantly depends on the distribution of water on the surface of a land planet. However, the quantitative relationship between former and latter is still not clear. The distribution of the surface water is determined by the surface topography, the surface water flow and the transport of water vapor in the atmosphere. The limit for the latitude of water transport on the surface is treated as a parameter (named the water flow limit) in this study, and the threshold insolation for the runaway greenhouse state is estimated for various distributions of the surface water using an Atmospheric General Circulation Model (AGCM 5.4g). As a result, I figure out that the climate of a water planet is divided into the two regimes, the aqua planet regime and the land planet regime, by the influence of the Hadley circulation. When the water flow limit is located at low latitudes of the Hadley circulation, equatorward transportation of water vapor occurs in the atmosphere and the surface of the planet is covered with oceans globally. In such a case, the threshold insolation for the runaway greenhouse state corresponds to that in the case of an aqua planet. On the other hand, when the water flow limit is located of latitudes higher than the region of the Hadley circulation, the threshold insolation increases with an increase in latitude of the water flow limit. In this land planet regime, my calculations show that the threshold insolation changes from 130 % to 180 % of the present solar flux at the Earth's orbit as the water flow limit changes from 30.5° to 80.3°. In addition, I investigate the relationship between the amount of water and the water flow limit assuming the surface topography. As a result, the critical amount of water on the surface, which divides the climate of the water planet into the aqua planet regime and the land planet regime, is estimated to be about 10^{16} m^3 assuming the topography of the Earth.

Finally, the evolution of a land planet is discussed. One of the unsolved questions is whether the atmosphere of a land planet evolves to the moist greenhouse state, like the atmosphere of an aqua planet does. If possible, a land planet loses more water in the moist greenhouse stage, which results in an increase of the threshold insolation of the runaway greenhouse. In other words, a land planet can extend its habitability by pushing the water flow limit toward high latitudes. In conclusion, the evolution of a planet with water on its surface is divided into three paths: evolution only in the aqua planet mode, that from the aqua planet mode to the land planet mode and that only in the land planet mode. The atmospheric features on the evolutionary paths will provide valuable information for the detection of habitable exoplanets. From observations of habitable planets in the extrasolar planetary systems, the results of this study will be verified in the future.

Contents

Chapter 1 Background

1.1 Water planets

In our solar system, there are four terrestrial planets and four giant planets. What is the difference between the Earth and the other planets? The answer is that only the Earth has life. Are there life-supporting planets in the universe? This question is the largest problem beyond the Earth and planetary science and astronomy and ranging over biology and religion study. Recently, the advancement of observation technologies has facilitated detection of a large number of extrasolar planets. Some of these planets are considered to be terrestrial or rocky planets based on the relationship between their mass and radius (e.g., Batalha et al. 2013). Are there life-supporting planets in extrasolar systems? This question has been discussed actively these days (e.g., Borucki et al. 2013).

Most primary producers on the Earth use the energy from the Sun as an energy source, and they also need liquid water in their life cycles. Water (H_2O) is an universal substance in space, which is known to have special physical properties (Green and Perry 2008). The melting and freezing points of water are higher than those of substances that have a similar molar weight to H_2O. Additionally, water is a good solvent. Thus, it is inevitable that the life on the Earth uses liquid water on their life cycles. If the life on the Earth-like planets also needs liquid water, investigating the conditions for the existence of liquid water on the planetary surface is an important issue. Therefore, in many previous studies of habitable planets, discussion is not limited to biologically habitable environments but is about the stability and evolution of liquid water on the planetary surface (e.g., Kasting et al. 1993).

The Earth is a planet that is composed mainly of rocks and iron. The radius and mass of the Earth are 6.371×10^{6} m and 5.972×10^{24} kg, respectively. The atmosphere of the Earth is composed mainly of N_2, O_2, Ar and CO_2 and its pressure is 1 bar. On the Earth, there are globally connected oceans, and plate tectonics is working. Many previous studies implicitly assumed such "Earth-like" planets (e.g., Kasting et al. 1993; Kopparapu et al. 2013). This assumption is not only on the planetary size or mass but also on the history of the planet. However, recent planetary formation theories indicate a large variety in the amount of water of terrestrial planets (e.g., Raymond et al. 2004; Tian and Ida 2015). It is therefore expected that extrasolar terrestrial planets have a variety of the amount of water. Thus, we need to consider the formation and evolution of the planets in the water planet state to understand the habitable planets in more detail.

Figure 1.1 summarizes the formation and evolution of habitable planets based on the knowledge gained from studies of the formation and evolution the Earth. There are two approaches in understanding of a habitable planet. One is to understand its formation and the other is to understand the stability and evolution of habitable climates. According to the standard formation theory of terrestrial planets, accretion of planetesimals ($\sim10^{15}$ kg) occurs to form Mars-sized protoplanets (e.g., Kokubo and Ida 1998; 2000). Then, after this phase of planetary formation, called the accretion stage, these protoplanets undergo giant impacts several times, and grow to the present terrestrial planetary size as seen today (e.g., Chambers and Wetherill 1998). In the accretion stage of planetesimals, the proto-atmosphere should be formed, which is composed of a mixture of disk gas and degassed gas from planetesimals. The surface of the proto-planet should be completely molten (Abe and Matsui 1988). This phase is called the magma ocean stage. In this stage, volatile components should dissolve into the magma ocean. When planetesimals grow to the Mars-sized protoplanets, the oligarchic growth ceases and the energy released in protoplanets by accretion of planetesimals decreases. As a result, water vapor in the atmosphere condenses and the first primordial ocean appears on the protoplanetary surface. In the next stage where giant collisions of protoplanets occur, the protoplanetary surface is molten again and exchange of volatile components between the water-rich atmosphere and magma ocean should occur (Elkins-Tanton 2008). As a result of an interaction between them, the amount of water on the planetary surface is determined (e.g., Abe and Matsui 1986). Subsequently, the escape of hydrogen and CO_2 fixation occur and the atmosphere composed mainly of N_2 is formed. In addition, a giant impact determines the planetary obliquity and rotation rate. This scenario would describe the formation of a habitable planet that corresponds to a water planet like the Earth.

Of special importance here are the final planetary mass and the processes of the entrainment of volatile components. When we focus on the amount of water on the planetary surface, it is important to know the partition of water between the planetary surface and interior in the magma ocean stage or by the plate tectonics. These questions should boil down to the final planetary mass and the processes of the entrainment of volatile compounds. In the case of the proto-Earth, the formation of an ocean should be considered inevitable (e.g., Matsui and Abe 1986). Therefore, it is necessary to view a habitable planet as a result of the formation of a planetary system. Note that this scenario for the formation of a habitable planet is relatively classical. Recently, the formation and migration of gas giant planets are thought to have a great important on the formation of terrestrial planets (e.g., Walsh et al. 2011).

On the other hand, I consider a habitable planet from the viewpoint of the evolution of habitable climates. From this approach, planetary habitability and its duration (known as the continuous habitability) are discussed based on the stability and evolution of liquid water on the planetary surface. Many studies for habitable planets have adopted this approach (e.g., Kasting et al. 1993; Kopparapu et al. 2013). Recent discussions for extrasolar habitable planets have also adopted this approach based on the habitable zone which has been defined as the region around the central star where liquid water is stable on the planetary surface (e.g., Kasting et al. 1993; Kopparapu et al. 2013). More details are described in section 1.3.

Both of the two approaches are not independent but closely related with each other. However, while we assimilate extrasolar systems, we know only the Earth as a habitable planet. As it stands now, we lack a full understanding of a variety of habitable planets because our understanding is just for a little bit of aspects of habitable planets, although we can focus on the Earth and discuss an Earth-like habitable planet. Thus, it is necessary to increase the degree of freedom toward the formation of a habitable planet, in other words, to trace the processes of the formation of a habitable planet and to extend an understanding of a variety of habitable planets. We will able to establish a general theory for a habitable planet from information of extrasolar planets at the same time.

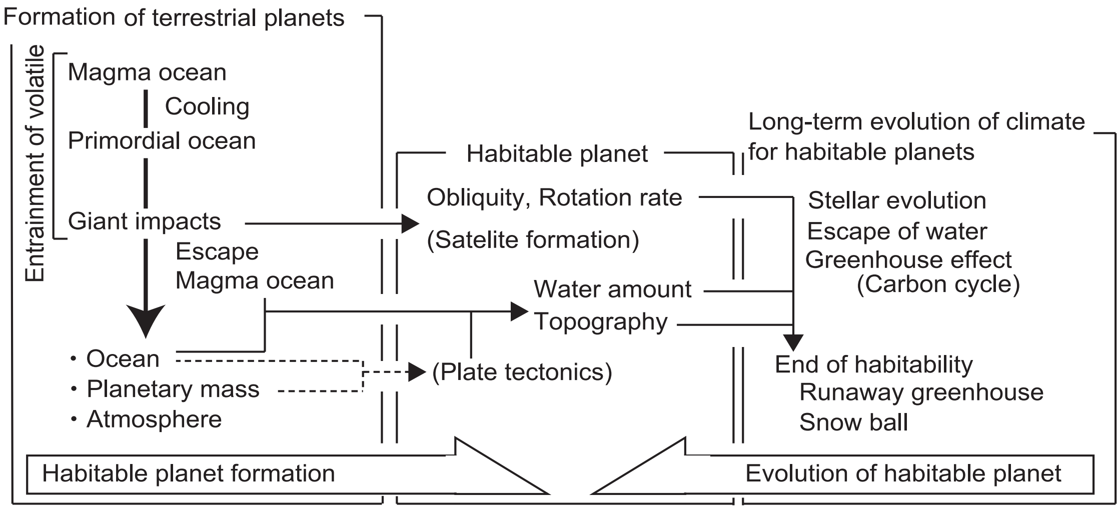

Figure 1.1. Formation and evolution of a habitable planet. There are two approaches for understanding “What is a habitable planet? ”.

1.2 Classification of water planets

Planets with surface water can be divided into three states: the steam planet state, the snowball planet state and the water planet state. When the planet with water receives a strong insolation from the central star, all of water on the surface evaporates and is transported to the atmosphere (e.g., Abe and Matsui 1988; Kasting 1988; Zahnle et al. 1988; Nakajima et al. 1992). In this study, such a state is termed the steam planet state. When the planet with water receives a weak insolation from the central star, the surface temperature of the planet could be below the freezing point of water, then all of water on the planetary surface freezes. Such a planet is covered globally with ice and that state is termed the snowball planet state (Tajika 2008). The state of planets with water other than the steam and snowball planet states are termed the water planet state in this study. The planet in the water planet state has an ocean on the planetary surface. It is typical to consider planets with oceans as habitable planets. On the other hand, the state of a planet with no water is classified into the “dry planet state”.

Among these, the water planet state should be further subdivided. In this study, I focus on the amount of water that is determined in the final stage of the formation of a habitable planet. Depending on the amount of water on the planetary surface changes, the water planet state is subdivided into three types that differ in the distribution of surface water: ocean planet type, partial ocean planet type and land planet type. The distribution of surface water is determined by the transportation of water on the surface and also in the atmosphere. Figure 1.2 summarizes the terms for planetary states and types, which are defined and used in this study.

An ocean planet type is characterized by the surface fully covered with a global ocean and no continent that appears because of a large amount of water (Leger et al. 2004). On the ocean planet, the transportation of water on the planetary surface is much more efficient than that in the planetary atmosphere. Thus, the distribution of surface water is controlled by the transportation of water flow on the planetary surface.

A planet of the partial ocean planet type has less amount of water than an ocean planet. A partial ocean planet also has globally linked oceans (but it is not fully covered with a global ocean) and has some continents (Abbot et al. 2012). Also, on such a partial ocean planet, the transportation of water on the planetary surface is more efficient than that in the planetary atmosphere. Thus, the distribution of surface water is controlled by the transportation of water on the planetary surface. The Earth is classified into the partial ocean planet type. Because many studies assumed an Earth-like planet, most studies for a habitable planet focused on the habitability for a partial ocean planet. In order for the carbon cycle to work on the planet, plate tectonics is required (e.g., Tajika and Matsui 1992; Tajika 2007). On the partial ocean planet type, chemical weathering of silicate minerals are dominant on the continental weathering relative to the seafloor weathering (e.g., Caldeira 1995). On the other hand, seafloor weathering should be dominant on an ocean planet.

The distribution of surface water is controlled by the transportation of water on the planetary surface both on the ocean planet and the partial ocean planet. Thus, these two types of planets can be categorized together as the aqua planet "mode" (Abe et al. 2011) (see Figure 1.2). A water planet that has a very small amount of surface water is called the land planet mode. A major feature of a land planet is the localization of surface water owing to a local balance between precipitation and evaporation. On a land planet, the distribution of surface water is controlled by the transportation of water in the planetary atmosphere (Abe et al. 2005; Abe et al. 2011).

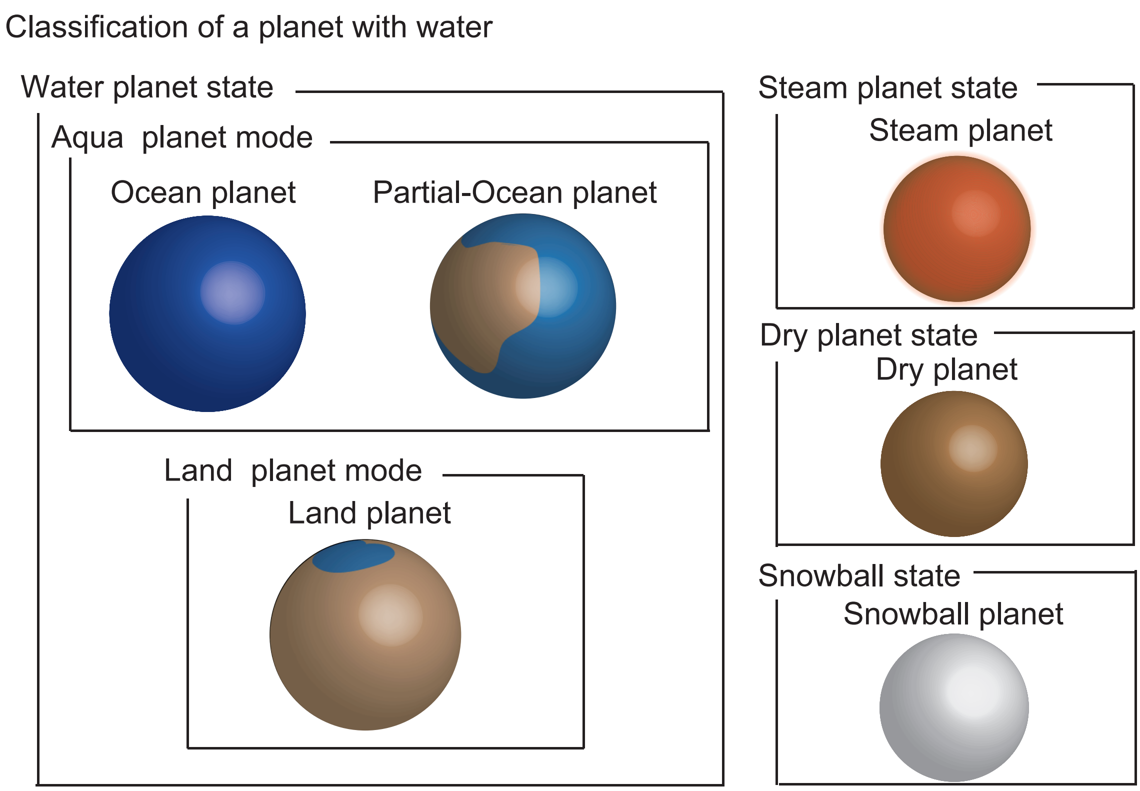

Figure 1.2. Classification of terrestrial planets. Terrestrial planets are divided into four states depending on the amount of water on surface water. Planets with ocean are further divided into two modes. The difference between the aqua planet mode and the land planet mode is that in the dominant process of the transportation of water.

1.3 Long-term evolution of water planets

1.3.1 Evolution of aqua planets

As mentioned above, it is usually assumed that the surface of the habitable planets, like the Earth, are covered with liquid water oceans. Therefore, studies of planetary habitability and its duration (i.e., continuous habitability) have focused on the stability of oceans (e.g., Kasting et al. 1993; Kopparapu et al. 2013).

If the insolation that an aqua planet receives from the central star is not too high, the upper atmosphere would have a very low mixing ratio of water vapor owing to the presence of a cold trap. A cold trap plays a role in limiting a water vapor transport to the upper atmosphere owing to the condensation of water vapor. On the Earth, the mixing ratio of water vapor at the tropopause takes the lowest value in the lower atmosphere. Under this condition, hydrogen escape to space from the upper atmosphere is rather slow, and is partly dependent on the presence of other gases containing hydrogen (e.g., methane) (Walker 1977). As the luminosity of the central star increases with time, the climate of an aqua planet becomes warmer and the mixing ratio of water vapor in the upper atmosphere increases with time. When the central star becomes bright enough, the cold trap disappears because the temperature at the tropopause increases and the saturated vapor pressure also increases, resulting in the mixing ratio of water vapor in the upper atmosphere to be high enough to cause a rapid water loss. In the case that the mixing ratio of water vapor in the upper atmosphere is larger than 10^{-3}, water comparable in total mass with the Earth's ocean mass can be escaped to space within 4.6 billion years. Such a condition is named the moist greenhouse condition. This planetary climate state is called the moist greenhouse state (Kasting 1988; Kasting et al. 1993). Somewhat later, the central star becomes bright enough to trigger the onset of the so-called runaway greenhouse: Because water vapor is a strong greenhouse gas, a positive feedback works until all the liquid water evaporates under the runaway greenhouse state (e.g., Abe and Matsui 1988; Kasting 1988; Zahnle et al. 1988; Nakajima et al. 1992). Such an atmosphere has a limit to outgoing planetary radiation, called the radiation limit of the steam atmosphere (e.g., Nakajima et al. 1992). When the radiation from the central star is higher than the radiation limit, energy balance cannot be achieved anymore, and all of the oceans should evaporate.

The habitable zone (HZ) has been defined as the circumstellar region around the central star where liquid water is retained on the planetary surface (e.g., Kasting et al. 1993; Kopparapu et al. 2013). The conditions for inner and outer edges of the HZs for aqua planets with various planetary masses around central stars of various spectral types have been investigated (e.g., Kopparapu et al. 2014).

Two different concepts have been proposed to describe the inner edge of the HZ. One is the instantaneous HZ; that is, it does not matter how long the aqua planet remains habitable. The other is the continuously habitable zone (CHZ), which means that a given planet has been in the HZ from the time it was formed until present. The onset of the runaway greenhouse effect determines the instantaneous HZ. When the long-term stability of liquid water on the planetary surface being considered, water loss from the planet is important consideration. If the escape of hydrogen occurs rapidly enough, compared with the evolution of the luminosity of the central star, the inner edge of the CHZ may be characterized by the onset of the moist greenhouse state (e.g., Kasting et al. 1993; Kopparapu et al. 2013).

On the other hand, the outer edge of the HZ is determined by the formation of CO_2 clouds in the planetary atmosphere (e.g., Kasting 1991; Kasting et al. 1993) or the maximum greenhouse effect of CO_2 (Kasting et al. 1993) The surface temperature on an aqua planet is below the freezing point of water owing to the increase of the amount of CO_2 and Rayleigh scattering (e.g., Kasting et al. 1993; Kopparapu et al. 2013).

1.3.2 Evolution of land planets

It was recently shown that the climate of land planets is different from that of aqua planets (Abe et al. 2005; Abe et al. 2011). Abe et al. (2011) investigated the HZ of a land planet using a general circulation model (GCM). As mentioned above, they found that, on the land planet, the local balance between the precipitation and the evaporation of water is controlled by the relationship between the transportation of water on the surface and in the atmosphere, in other words, the distribution of surface water. Liquid water tends to accumulate in cooler regions on the planet; that is, the high latitude regions become wet while the low latitude regions become dry. In the wet regions, there is an upper limit on the planetary radiation (e.g., Nakajima et al. 1992) due to water saturation. On the other hand, in the dry regions, there is no upper limit on the planetary radiation. Abe et al. (2011) showed that a land planet has a higher insolation threshold of the runaway greenhouse effect (~415 W/m^2) than an aqua planet, and has very low mixing ratio of water vapor in the upper atmosphere (~10^{-9}), which means the hydrogen escape is hard to occur.

However, all the liquid water on a land planet eventually evaporates if the incident stellar radiation is higher than a critical value, which is called the threshold of complete evaporation for a land planet. According to Abe et al. (2011), it is estimated to be 415 Wm^{-2}. The inner edge of the HZ for a land planet is determined by this threshold, which corresponds to 0.77 AU in our solar system at present. The onset of the runaway greenhouse effect for an aqua planet is estimated to be about 375 Wm^{-2} (Leconte et al. 2013b). Therefore, the inner edge of the HZ for a land planet is much closer to the central star than that for an aqua planet.

A land planet is more resistant to global glaciation than an aqua planet (Abe et al. 2011). While the climate of an aqua planet is warmer than that of a land planet when a planet receives the present solar radiation, the latter is warmer than the former when a planet receives weaker radiation from the central star than the present solar radiation. This is because a greenhouse effect of water vapor is weak owing to a drier atmosphere of a land planet. A land planet has lower planetary albedo and weaker ice albedo feedback. Thus, a land planet is less subject to global glaciation than an aqua planet. According to Abe et al. (2011), the onset of global glaciation on a land planet is estimated to be 188 Wm^{-2}, while that on an aqua planet is estimated to be 220 Wm^{-2}. Therefore, the width of the HZ of a land planet is larger than that of an aqua planet.

1.4 Objective of this study

The objective of this study is to investigate the evolution of the terrestrial water planet, based on difference and variation of the amount of water on the planetary surface. In particular, I investigate the condition for an aqua planet to evolve to be a land planet, and reveal the insolation threshold of complete evaporation of oceans for the land planets with various water amounts, in order to understand the variety and evolution of habitable planets. Theoretical predictions of habitable planets in extrasolar systems will be implied.

Chapter 2 Evolution of Aqua Planets

2.1 Evolution from aqua planets to land planets

The difference between an aqua planet and a land planet is the amount of water on the planetary surface. If an aqua planet evolves to a land planet by rapid water loss to space leaving a small amount of water on the planetary surface, the lifetime of habitability for such a planet can be extended because the land planet mode is more resistant to both the water loss and the runaway greenhouse effect than the aqua planet mode. In that case, a rapid water loss to space might lead to maintaining, rather than ending, the habitable world.

Abe et al. (2011) discussed the evolution from an aqua planet to a land planet. The transition condition they assumed is that the planetary surface becomes almost completely dry before the onset of the runaway greenhouse condition that makes the planet uninhabitable. They estimated how much water could escape from the aqua planet at the Earth's orbit using models that assumes both constant (0.3) and variable albedos. In the constant albedo case, the aqua planet with the present Earth's ocean mass does not lose all of the water before the onset of the runaway greenhouse condition. It is because the duration of the moist greenhouse state was too short. In such a case, the aqua planet lapses into the runaway greenhouse state and becomes uninhabitable. Conversely, in the variable albedo case, the increase of albedo due to Rayleigh scattering of the atmosphere prolongs the duration of the moist greenhouse state. In such a case, the aqua planet with water of the present Earth's ocean mass loses almost all of the surface water before the onset of the runaway greenhouse condition. Then, that aqua planet can evolve to a land planet.

However, under the transition condition they assumed, an aqua planet with a tiny amount water on the surface, but a large amount of water in the planetary atmosphere can also evolve to a land planet. Thus, more realistic conditions for the amount of water in the planetary atmosphere and on the planetary surface are needed to quantitatively investigate the evolution from the aqua planet mode to the land planet mode. (see section 2.2.5)

In the evolution from an aqua planet to a land planet, there is a competition between a rapid water loss to space and an increase in the luminosity of the central star that triggers the onset of the runaway greenhouse effect. If an aqua planet loses a large amount of water by rapid escape before the onset of the runaway greenhouse state, such an aqua planet evolves to the land planet mode. This is a qualitative condition to evolve from the aqua planet mode to the land planet mode.

Therefore, I have systematically investigated whether the evolution from the aqua planet mode to the land planet mode occurs under more realistic conditions with different initial amounts of water and different orbital distances of the planet from the central star. In addition, I also re-evaluate the inner edge of the habitable zone.

2.2 Evolution model from the aqua planet mode to the land planet mode

2.2.1 Change in the amount of water

The initial amount of water is treated here as a parameter, because how much water is provided to terrestrial planets at time of formation is not known so far. According to theoretical studies on planetary formation, the amount of water that a terrestrial planet initially has shows a wide range of variety (e.g., Raymond et al. 2004; Raymond et al. 2007). The amount of water on the planetary surface would change through interactions between planetary surface and interior such as subduction of hydrous minerals, outgassing of water at mid-ocean ridges and arcs, and so on. For the present Earth, the ingassing rate is estimated to be $5{\times}10^{22} - 1.1{\times}10^{23}\ \mathrm{mol\,Gyr^{-1}}$ (Rea & Ruff 1996; Javoy 1998) and the degassing rate is estimated to be $5.5{\times}10^{21} - 1.1{\times}10^{23}\ \mathrm{mol\,Gyr^{-1}}$ (Ito et al. 1983; Bounama et al. 2001; Hilton et al. 2002). These estimates have large uncertainties.

On the other hand, as the luminosity from the central star increases, a rapid water loss to space occurs. The flux exceeds $10^{23}\ \mathrm{mol\,Gyr^{-1}}$ (see section 2.3). In this study, I assume, for simplicity, that the change in the total amount of water on the planetary surface is attributed solely to the loss of water to space. I assume that the amount of water decreases via the escape of molecular hydrogen. The change in the amount of water is given by

$$\frac{dM_{\mathrm{H_2O}}}{dt} = -\phi_{\mathrm{esc}} \qquad (1)$$

where $M_{\mathrm{H_2O}}$ is the total mole number of water and ϕ_{esc} is the mole number of the molecular hydrogen escaping per unit time from the planetary entire surface, which I call the escape flux simply hereafter. The escape process of molecular hydrogen is described in section 2.2.3.

2.2.2 Climate model

The amount of water in the planetary atmosphere depends on the climate state of the water planet. This section describes how to estimate the amount of water vapor in the planetary atmosphere.

For the aqua planet mode, I estimate the amount of water in the planetary atmosphere is estimated by using a one-dimensional (1D), cloud-free, radiative-convective climate model. The discussion of the planetary habitability is divided into two approaches. One is to discuss the short-term habitability. In this approach, a steady-state climate is considered. On the other hand, the other is to discuss the long-term habitability. In this approach, the climatic change derived by the increase of the luminosity of the central star is considered. While the short-term habitability of terrestrial planets is often studied with three-dimensional (3D), general circulation models, the long-term evolution of climate is studied usually with 1D climate models and the HZ has been also estimated by using such 1D models. In this study, the change of the amount of water is important during the moist greenhouse state. Thus, I need to describe high temperature and pressure atmosphere. Abe and Matsui (1988) investigated the formation of proto-ocean on the early Earth. The model is applicable to high temperature and pressure conditions. Following Abe and Matsui (1988), I estimate the amount of water in the atmosphere. In Figure 2.1, I show examples of the vertical atmospheric structures. It is seen that the tropopause gets higher with an increase in the surface temperature. In this calculation, I assume the isothermal stratosphere (150 K). I also show the mixing ratio of water vapor in the upper atmosphere increases with increasing incident solar radiation, as shown in Figure 2.2.

For the land planet mode, the amount of water in the planetary atmosphere estimated by Abe et al. (2011) is used in this study. They used 3D GCM with a limited amount of water on the planetary surface. They showed the relationships of the net insolation to the precipitable water in the atmosphere and to the absolute humidity at the top of the atmosphere. The former and latter correspond to the amount of water in the atmosphere and the mixing ratio of water vapor in the upper atmosphere ($f(H_2O)$), respectively. From Abe et al. (2011), I use their results in this study. The absolute humidity in the top of the atmosphere significantly increases just beyond the threshold for complete evaporation, as shown in Figure 2.3. The threshold for complete evaporation corresponds with the threshold for the runaway greenhouse effect.

The amount of water on the surface can be, then, estimated by subtracting the amount of water in the atmosphere from the total amount of water on the planet. The mixing ratio of water vapor in the upper atmosphere is needed for the estimation of the diffusion-limited escape flux of hydrogen molecules to space.

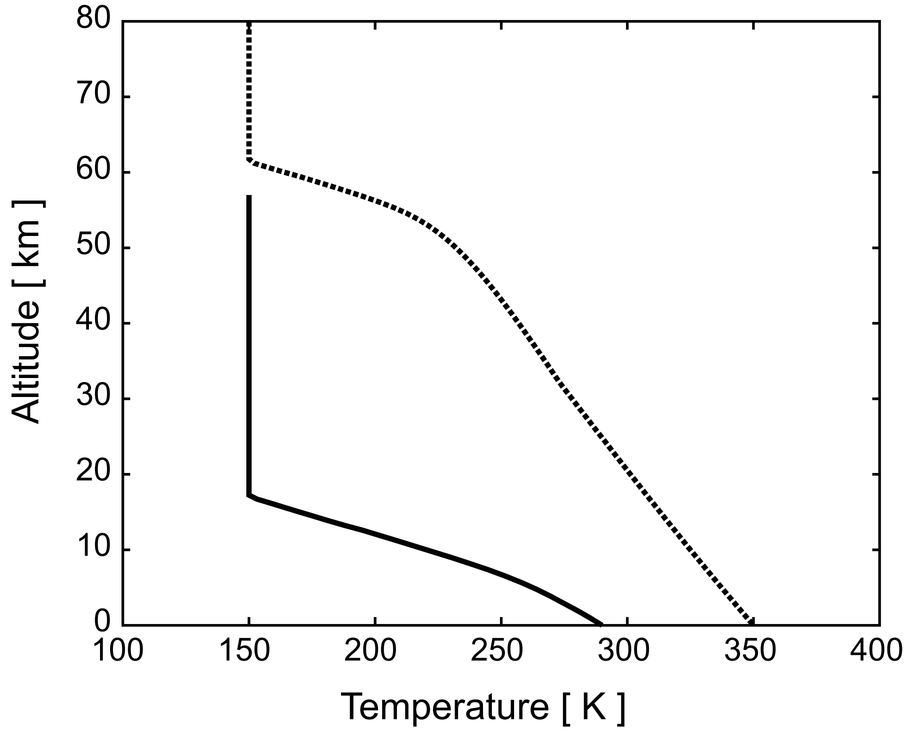

Figure 2.1. The vertical atmospheric structure in the aqua planet mode. While the tropopause locates at low altitude when the surface temperature is low (solid), it locates at high altitude when the surface temperature is high (dashed).

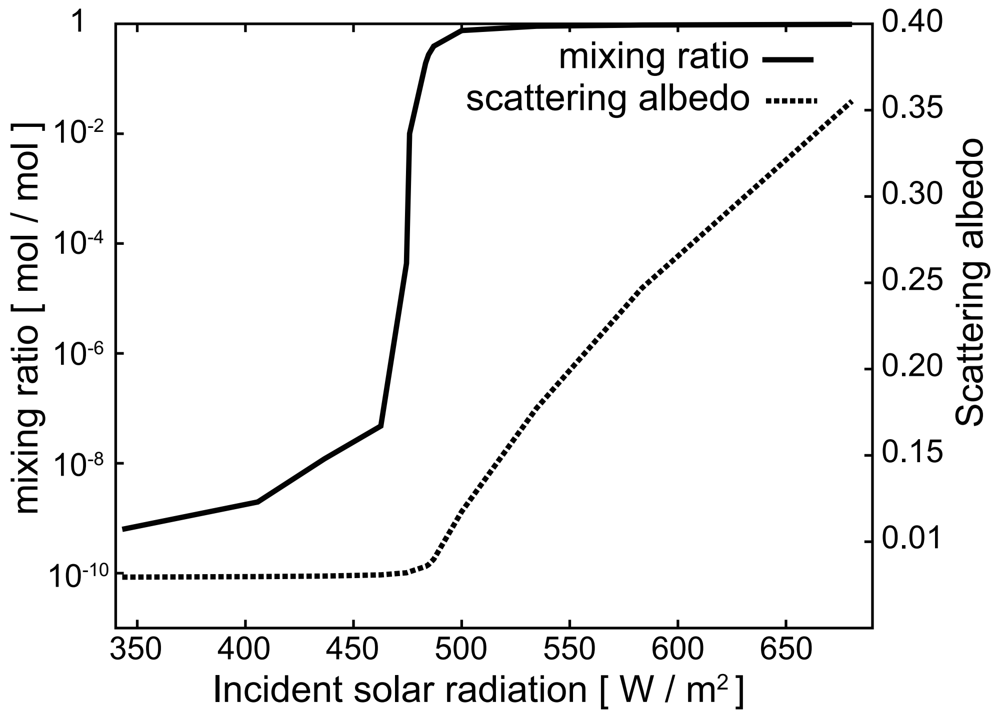

Figure 2.2. The mixing ratio of water vapor in the upper atmosphere for the aqua planet mode. The solid line describes the mixing ratio of water vapor in the upper atmosphere and the dashed line describes the scattering albedo. The mixing ratio of water vapor in the upper atmosphere rapidly increases at a critical value of incident solar radiation at which disappearing the cold trap disappears.

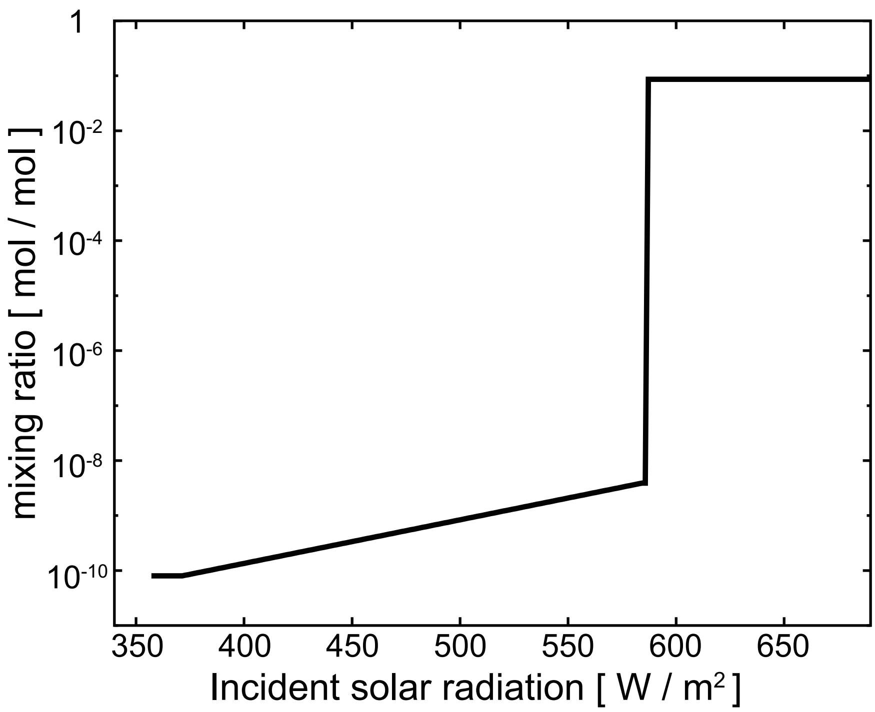

Figure 2.3. The mixing ratio of water vapor in the upper atmosphere for the land planet mode. When the land planet receives the threshold of insolation for the runaway greenhouse in the land planet mode, the mixing ratio of water vapor rapidly increases.

2.2.3 Water loss

Atmospheric escape is an important process in the atmospheric evolution. H_2O molecules in the planetary atmosphere are dissociated by UV radiation from the central star (via $H_2O + h\nu \rightarrow H + OH$) (e.g., Brinkmann 1969). Then, hydrogen molecules are transported to the upper atmosphere, where EUV radiation reaches. Hydrogen molecules are heated by the radiation, and, then, escape to space (e.g., Kasting et al. 1984).

Hydrodynamic escape of hydrogen molecules has the most potential to decrease the water reservoir of a planet. In this study, it is assumed as the water loss process from planetary atmosphere. There are two major bottleneck factors in the escape of the hydrogen molecules from the planetary atmosphere to space. The first is the heat source required to drive the escape of hydrogen molecules. The hydrogen molecules and atoms can absorb the EUV ($\lambda < 100$ nm) from the central star. It is the main source of energy for the escape of the hydrogen molecules. When the escape flux is controlled by the EUV flux from the central star, such an escape mode is called the energy-limited escape. The other major bottleneck factor is the diffusion of hydrogen-containing molecules through the background atmosphere to reach the altitude where the escape occurs. When the escape flux is controlled by the diffusion of molecules through the atmosphere, such an escape is called the diffusion-limited escape.

Other possible bottleneck factors, such as photon-limited photochemistry that converts H_2O to H_2, magnetospheric drag, radiative cooling by ions (e.g., H_3^+) and molecules embedded in the outflowing wind, are less well established and are neglected here.

If the planetary upper atmosphere is rich in hydrogen-rich atmosphere, the escape flux is limited by EUV flux from the central star. The energy-limited escape flux (ϕ_e) is given by Watson et al. (1981) as

$$\phi_e = \frac{\varepsilon\, S_{EUV}\, r_p}{4\, m_i\, G\, M_p} \qquad (2)$$

where εS_{EUV} represents the effective stellar EUV heating rate, G is the gravitational constant, $r_{\rm p}$ is the radius of the planet and M_p is the planetary mass. There is a large uncertainty of the effective stellar EUV heating. Then, when I confine all of the uncertainty about it to ε, it is over ranges between 1.5×10^{-2} and 3, because the heating efficiency is over a range between 0.15 and 0.3 (Watson et al. 1981) and, the EUV flux from the central star has the uncertainty of less than 2 order magnitudes and, thus, is also over a range between 10^{-1} and 10 times of the EUV flux, as described in section 2.2.4. In this study, the effective stellar EUV heating ($\varepsilon S_{\rm EUV}$) assumes to be 0.6 as a standard case. I will have a discussion about the uncertainty of the effective stellar EUV heating in section 2.4.3. The factors M_p and r_p are assumed to be Earth's mass and radius, respectively.

The escape flux in the diffusion-limited escape mode depends on the mixing ratio of hydrogen-containing species in the planetary upper atmosphere (Walker 1977, p. 164). The diffusion-limited escape flux (ϕ_d) of hydrogen molecules is given by

$$\phi_d = f_T(H_2)\frac{b\,(m_a - m_i)\,g}{k\,T_{str}} \qquad (3)$$

where $f_T(H_2)$ is the total mixing ratio of hydrogen molecules in all forms at homopause ($f_T(H_2) = f(H_2O) + f(H_2) + 2\,f(CH_4) + \cdots$), T_{str} is the temperature in the stratosphere ($T_{\rm str} = 150\ {\rm K}$), b is the binary diffusion coefficient between the background gas and H_2 ($b = 1.9\times10^{19}\,(T_{\rm str}/300\ {\rm K})^{0.75}\ {\rm cm^{-1}s^{-1}}$ for H_2 in the air), g is the acceleration due to gravity, k is the Boltzmanns constant, m_a and m_i are the average molecular masses of the background gas and hydrogen, respectively. As the luminosity of the central star increases, the planetary upper atmosphere becomes wet. In such a situation, the major carrier of hydrogen appears to be water vapor. Thus, I assume $f_{\rm T}({\rm H_2}) = f({\rm H_2O})$.

In this study, the smaller of the escape fluxes in both modes is adopted as the actual escape flux, namely, $\phi_{\rm esc} = \min\,(\phi_{\rm e}, \phi_{\rm d})$.

When hydrogen escapes, the oxygen left behind can build up in the planetary atmosphere. If the amount of water equivalent to the Earth's ocean mass escapes, approximately 240 bars of O_2 would be produced (Kasting, 1997). In this study, I assume that all of the oxygen is consumed by reducing materials in the crust and gases degassed via volcanoes. In section 2.4.5, this oxygen problem will be discussed.

2.2.4 Stellar evolution

The evolutions of the total luminosity and EUV flux from the central star are considered in this study. The central star is assumed as a solar-type (G-type) star with the solar mass. According to Gough (1981), the following expression of the evolution of the total luminosity of the Sun is adopted:

$$S(t) = \left[1 + \frac{2}{5}\left(1 - \frac{t}{t_\odot}\right)\right]^{-1} S_\odot \qquad (4)$$

where $S(t)$ is the incident stellar flux from a G-type star as a function of time, t is time in Gyr, $t_\odot$ is the age of the Sun ($t_\odot$ = 4.5 Gyr), and $S_\odot$ is the solar constant ($S_\odot$ = 1366 W m^{-2}).

Since the EUV flux for a young star is stronger than that for an old star, we employ the following expression of Lammer et al. (2009) for a G-type star:

$$L_{\mathrm{EUV}} = \begin{cases} 0.375\, L_0\, t^{-0.425}, & t \leq 0.6\ \mathrm{Gyr} \\ 0.19\, L_0\, t^{-1.69}, & t > 0.6\ \mathrm{Gyr} \end{cases} \qquad (5)$$

where L_{EUV} is the luminosity of EUV in W s^{-1}, and $L_0 = 10^{22.35}$ W. The relation between the luminosity and the incident flux is given by $S_{\mathrm{EUV}} = L_{\mathrm{EUV}} / 4\pi a^2$, where a is the distance from the central star to the planet in meters.

2.2.5 Condition for the transition from aqua to land planets

Abe et al. (2011) performed numerical experiments of decreasing net insolation from the runaway greenhouse state of the land planet to investigate the early evolution of the atmosphere during accretion (Figure 8 in Abe et al., 2011). They performed three cases of numerical experiments with changes of the amount of water; 20, 40 and 60 cm in the depth of the amount of water on the entire planetary surface. They showed that no water vapor in the atmosphere condense when the net solar flux is lower than the threshold of the runaway greenhouse state of the aqua planet mode. It means that ocean forms when the luminosity of the accretion decreases to about 150 W/m^2.

As a result, they showed that whether a large amount of water is on the surface or in the atmosphere exhibits a hysteresis between the radiation limit of the runaway greenhouse threshold for an aqua planet and that for a land planet. The net solar flux where the precipitation occurs depends on the amount of water vapor in the atmosphere when the net solar flux decreases. For the purpose of convenience, I refer to a state where a large amount of water locates in the planetary atmosphere as the heated state and to a state where a large amount of water locates on the planetary surface as the cooled state. In early evolution of growing planets, the planetary atmosphere is in the heated state due to incoming accretion energy. When the accretion energy flux decreases, the planetary atmosphere evolves from the heated state to the cooled state and water vapor in the planetary atmosphere condenses. It leads to the formation of ocean. In a case that the planetary atmosphere becomes the heated state by increase of the luminosity from the central star, no water vapor condenses because the luminosity from the central star keeps increasing. On the evolution from the aqua planet mode to the land planet mode by rapid water loss, aqua planets should not evolve to the land planet mode (cooled state) if the planetary atmosphere on the aqua planet mode becomes the heated state. Thus, it is necessary to focus on the amount of water in the planetary atmosphere just before the onset of the runaway greenhouse effect.

The dependence of the luminosity for the runaway greenhouse atmosphere to condense to form oceans on the amount of water vapor in the atmosphere is still unclear. To know the actual transition condition regarding the amount of water in the planetary atmosphere, it is needed to investigate the dependence of the amount of water on the net insolation where the precipitation occurs just before the onset of the runaway greenhouse state using 3D GCM. (Abe et al. 2011) investigated only three cases of the amount of water on the planetary atmosphere. Thus, it requires a lot of numerical experiments using GCM to clear the transition condition regarding the amount of water in the planetary atmosphere.

However, when imbalance between the incoming radiation and the outgoing radiation occurs, we can estimate the amount of water in the planetary atmosphere at the beginning of the runaway greenhouse effect. Using a 1-D cloud-free radiative-convective (non-gray) climate model, the amount of water in the planetary atmosphere at the onset of the runaway greenhouse is found to correspond to 3 m depth of water on the planetary surface (Abe and Matsui 1988). Also, when a 1-D cloud-free radiative-convective climate model (gray atmosphere) (Nakajima et al., 1992) is used, the amount of water in the planetary atmosphere is found to correspond to 0.6 m. Then, I treat the amount of water in the atmosphere that maintains the heated state as a parameter, which I denote by M_{cv} and refer to as the critical amount of water vapor for the runaway greenhouse effect. I consider the range of M_{cv} of 1-10 m. The lower value is middle value between non-gray and gray models and the atmosphere dose not become the moist greenhouse state if M_{cv} is less than 1 m. The upper value is as much the amount of water as the background atmosphere. In these cases, it is large enough to maintain the heated state of the planetary atmosphere. Thus, this parameter range could be reasonable.

Another important factor is the amount of water on the planetary surface on the land planet mode. If a planet with a relatively large amount of water on its surface, such a planet appears to be the aqua planet mode. Thus, how much water a land planet has in maximum becomes another problem. I consider the maximum amount of water that a land planet can have and still behave as a land planet. According to Abe et al. (2011), surface water on a land planet is typically located at latitude above 60°, which corresponds to 10% of the entire planetary surface. According to the percolation theory, for any given area, at least a half of that area is required to form a connected area (which is covered with water in this case). The maximum unconnected oceanic area is thus a half of the area in latitude above 60°, which corresponds to 5% of the planetary surface. In that case and if planetary topography can be ignored, the maximum amount of water on a land planet is 5% of the Earth's surface area, or ocean mass. If a planet has more water, water may extend equatorward out of latitude 60°. Therefore, I assume here that 5% of the present Earth's ocean mass on the planetary surface approximates the transition condition that are required for the maximum amount of water required for an aqua planet to evolve to a land planet. We refer to this condition as the maximum liquid water mass for a land planet mode, which we denote by M_{ml}. When the amounts of water on the planetary surface and in the atmosphere meet these conditions, then an aqua planet can evolve to a land planet. I will show results for $M_{ml} = 0.05\,M_{oc}$ as the standard case, but also treat M_{ml} as a parameter that varies from 0.01 to 0.1 M_{oc}, where M_{oc} is the amount of the present Earth's ocean (8.4×10^{22} moles).

2.2.6 Other setting

Planetary albedo, which plays an important role in the planetary climate, depends on the properties of the planetary surface and atmosphere. In this study, I fix the albedo of the planetary surface at 0.3, which is the typical value for deserts on the Earth. When the amount of water vapor in the planetary atmosphere increases owing to warming caused by an increase in the luminosity of the central star, the atmosphere becomes denser and radiation from the central star is scattered more efficiently. Thus, the albedo changes due to the scattering by the atmospheric gas on an aqua planet. For a land planet, the scattering albedo is negligible because the atmosphere of a land planet is sufficiently dry before the threshold of the complete evaporation is attained. Thus, the planetary albedo for a land planet is also assumed to be 0.3 in this study.

It is assumed that the planets considered in this study have zero obliquity and zero eccentricity, with the mass and radius equivalent to those of the Earth. The background atmosphere is assumed to be that composed of 1 bar N_2. It is possible that the carbon cycle works on Earth-like planets. The carbon cycle with liquid water provides a negative feedback on the climatic system that could maintain a warm and wet climate on long timescales (Walker et al. 1981). However, when a planet receives a very high luminosity from the central star, such a negative feedback never works anymore because the relative abundance of CO_2 is too low in its atmosphere to affect the surface temperature. This is because a rapid fixing of CO_2 as a carbonate rock could occur because of the high surface temperature. Therefore, the evolution of the atmosphere is driven only by changes in the amount of water in the planetary atmosphere.

2.2.7 Numerical calculation procedure

First, I estimate the evolution both of the luminosity and EUV flux from the central star (see section 2.2.4). Then, the 1D structure of the planetary atmosphere in the aqua planet mode is simulated with the luminosity of the central star given above (see section 2.2.2). I get both the total amount of water in the planetary atmosphere and the mixing ratio of water vapor in the upper atmosphere as a function of the incident solar flux. After these procedures, I calculate the escape fluxes of hydrogen molecules both in the diffusion-limited escape mode and the energy-limited escape mode at the same time, and estimate the change of the amount of water that the planet has.

In this study, I focus on two variables as the initial conditions, the initial amount of water and the distance between the planet and the central star, to investigate the evolution of the aqua planet. In the numerical simulations, I classify the reservoirs of water into two ones: the atmosphere and surface. In calculating the change of the amount of water, I subtract the escaped water from the whole on of the planet. Then, both the amounts of water on the surface and in the atmosphere are determined from the simulated structure of the atmosphere at given time.

To investigate the evolution from the aqua planet mode to the land planet mode, I set two boundary conditions: M_{cv} and M_{ml}. In the calculations, the aqua planet evolves to the land planet when both amounts of water in the atmosphere and on the surface meet the transition conditions.

2.3 Results

2.3.1 The evolution of aqua planets: Dependence on the initial amount of water

Figure 2.4 shows the numerical results of the changes of the amount of water on the planetary surface and in the atmosphere for a planet with oceans of the present Earth's ocean at the beginning (M_{ini} = 1.0 M_{oc}; M_{ini} is the initial amount of water), and orbiting at 0.80 AU from the central star (i.e., a = 0.80 AU).

During the young stage (< 3 Gyr) of the central star when its luminosity is low, a mixing ratio of water vapor in the upper atmosphere of the planet remains low value. In this stage, the escape of hydrogen to space is in the diffusion-limited escape mode and the escape flux is extremely low. The amount of water on the planetary surface hardly changes during this stage. As the luminosity of the central star increases with time, the atmosphere becomes wetter. After 3 Gyr passes, a mixing ratio of water vapor in the upper atmosphere increases rapidly. The increase in the mixing ratio of water vapor in the upper atmosphere causes a rapid water loss to space on the energy-limited escape mode. The amount of water on a planet decreases owing to the rapid water loss process. In this case, however, the transition condition from the aqua planet mode to the land planet mode is not satisfied: the amount of water on the surface exceeds the maximum water mass for the land planet mode (M_{ml} = 0.05 M_{oc}) when the average column mass of water vapor in the planetary atmosphere reaches the value just before the onset of the runaway greenhouse effect for an aqua planet (M_{cv} = 3 m). Therefore, the planet with a large amount of water remains in the aqua planet mode until the onset of the runaway greenhouse effect for an aqua planet. The planet evolves into the runaway greenhouse state for an aqua planet. All of the water on the planetary surface evaporates and is lost it to space. Eventually, such a planet evolves to the dry planet state.

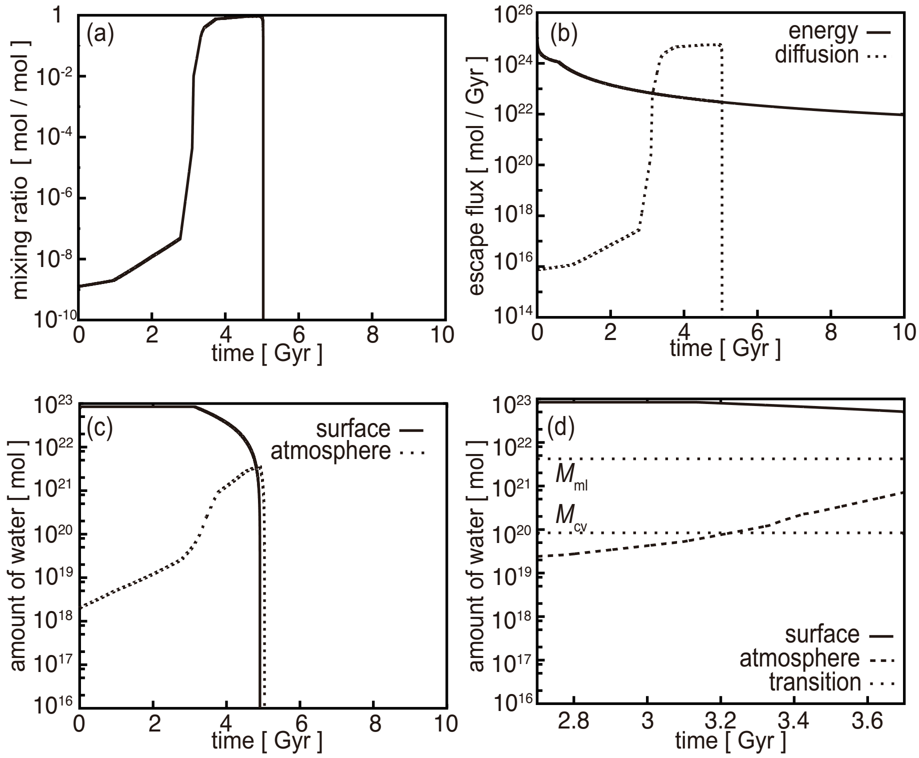

Figure 2.4. The change of the amount of water on surface and in atmosphere in a case of M_{ini} = 1.0 M_{oc} at 0.8 AU. Figure (a) shows the change of the mixing ratio of water vapor in the upper atmosphere. (b) is the escape flux of hydrogen molecular. (c) shows the amount of water on the planetary surface and in the planetary atmosphere. (d) is an extended figure around t = 3.2 Gyr.

Figure 2.5 shows the results of the changes of the amount of water on the surface and in the atmosphere in case of $M_{\rm ini}$ = 0.1 $M_{\rm oc}$ and a = 0.8 AU. The difference between this and previous cases (Figure 2.4 and 2.5) is the initial amount of water on the planets. The overall changes of the amount of water on the surface and in the atmosphere are very similar to those of the previous case (Figure 2.4) until 3.19 Gyr. However, this planet can evolve to the land planet mode because the amount of water in the planetary atmosphere is less than the value just before the onset of the runaway greenhouse effect ($M_{\rm cv}$ = 3 m) when the amount of water on the planetary surface decreases to the maximum water mass for the land planet mode ($M_{\rm ml}$ = 0.05 $M_{\rm oc}$), as shown in Figure 2.5(d). Once the planet evolves to the land planet mode, the atmosphere becomes dry (Figure 2.5a) and an escape of water shuts off (Figure 2.5b). In this case the planet maintains liquid water on its surface until the stellar flux reaches the threshold of the complete evaporation of water on the land planet mode (Figure 2.5c). The planet evolves from the land planet mode to the steam planet state, and then, to a dry planet state within about 0.17 Gyr, once the threshold condition is achieved.

For the evolution from the aqua planet mode to the land planet mode, what is most important is the relationship between the amount of water in the atmosphere and the mixing ratio of water vapor in the upper atmosphere. The amount of water in the atmosphere increases after the mixing ratio of water vapor in the upper atmosphere. An aqua planet with a larger amount of water than the escapable amount of water over the period from the increase of the mixing ratio of water vapor in the upper atmosphere to the increase of the amount of water in the planetary atmosphere can evolve to a land planet.

It is therefore clear that, whether or not an aqua planet evolves to a land planet depends on the initial amount of water on a planet. Qualitatively, an aqua planet with a relatively small initial amount of water can evolve from the aqua planet mode to the land planet mode.

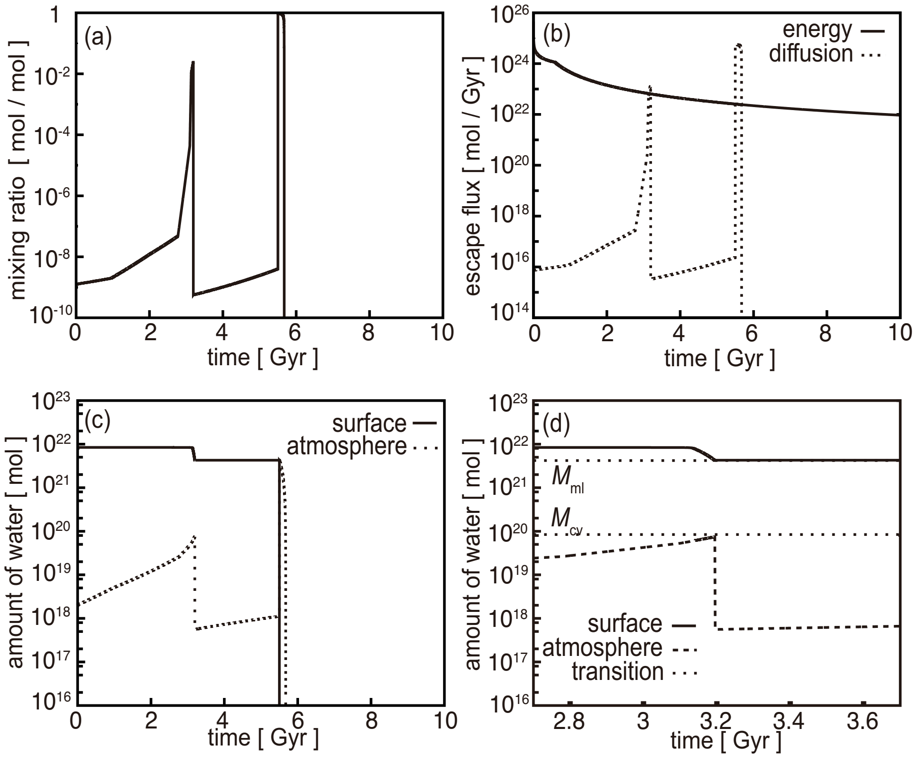

Figure 2.5. The change of the amount of water on surface and in atmosphere in a case of M_{ini} = 0.1 M_{oc} at 0.8 AU. Each figure shows results in the same manner. This planet evolves from the aqua planet mode to the land planet mode.

2.3.2 The evolution of aqua planets: Dependence on the distance from the central star

In this section, the typical results for the evolution of an aqua planet with different distance from the central star are shown. Figure 2.6 shows the changes of the amount of water on the surface and in the atmosphere of an aqua planet with M_{ini} = 0.1 M_{oc} and a = 1.0 AU. In this case, the planet does not evolve from the aqua planet mode to the land planet mode because the amount of water in its atmosphere exceeds the critical amount of water vapor for the runaway greenhouse effect of the aqua planet before the amount of water on the planetary surface decreases to the maximum liquid water mass for the land planet mode (Figure 2.6d). Eventually, such a planet far from the central star evolves into the steam planet state.

The onset of the moist greenhouse state and its duration are important for whether or not an aqua planet will evolve to a land planet. In the case of an aqua planet far from the central star, it receives low EUV flux when the planetary atmosphere becomes the moist greenhouse state. Thus, the onset of the rapid escape of water vapor occurs later than the case of an aqua planet near the central star.

It takes time for a distant planet to lose the surface water; in other words, the more distant planet loses less water from increase of the mixing ratio of water vapor in the upper atmosphere to increase of the amount of water in the planetary atmosphere. Moreover, distant planets do not have enough time to lose excess water before the onset of the runaway greenhouse effect because the increasing rate of the luminosity of the central star is increasing with time. As a result, it is more difficult for an aqua planet far from the central star to evolve from the aqua planet mode to the land planet mode. On the other hand, an aqua planet near the central star is easier to evolve from the aqua planet mode to the land planet mode.

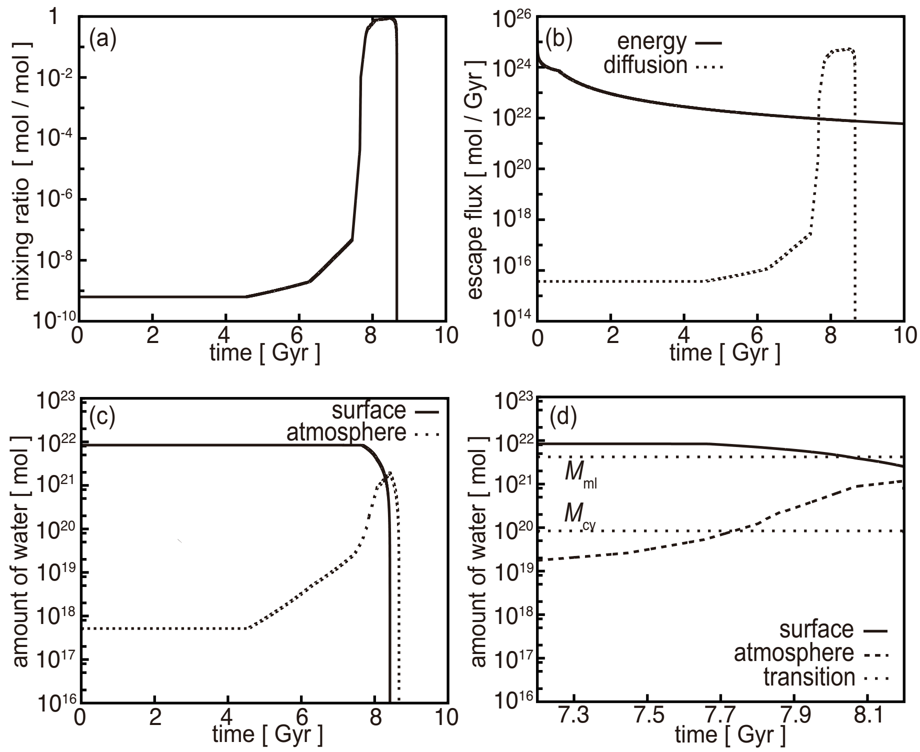

Figure 2.6. The change of the amount of water on surface and in atmosphere in a case of M_{ini} = 0.1 M_{oc} at 1.0 AU. Each figure is in the same manner.

2.3.3 The evolution of aqua planets: The upper limit of the initial amount of water

Figure 2.7 shows the upper limit of the initial amount of water for an aqua planet to evolve to the land planet mode as a function of the distance from the central star to a planet. In this figure, M_{cv} and M_{ml} are set to be 3 m and 5% M_{oc}, respectively. Aqua planets below the curve can evolve from the aqua planet mode to the land planet mode (Figure 2.7). The upper limit of the initial amount of water to evolve to the land planet mode is determined by the relationship between the escape flux and the period from increase of the mixing ratio of water vapor in the upper atmosphere to increase of the amount of water in the planetary atmosphere. Aqua planets close to the central star with a relative small amount of water (~0.1 M_{oc}) can evolve from the aqua planet mode to the land planet mode. On the other hand, aqua planets with a large amount of water or far from the central star lapses inevitably into the steam planet state without passing through the land planet mode.

Planets with water less than the maximum liquid water mass for land planets ($M_{ini} < M_{ml}$) remain in the land planet mode from the beginning until the onset of the complete evaporation of water for the land planet mode. In cases of the planets with small semi-major axis (a < 0.72 AU), all of the water on the planetary surface evaporates and such planets are in the steam planet state from the beginning (Hamano et al., 2013).

In discussion of Abe et al. (2011), an aqua planet with 1 M_{oc} evolves to a land planet because their transition condition permits a large amount of water in the planetary atmosphere just before the onset of the runaway greenhouse effect. Thus, even an aqua planet with a large amount of water can evolve to a land planet. From the results of this study, however, such a planet cannot evolve to a land planet because of the hysteresis of the climatic state just before the onset of the runaway greenhouse effect. It should be noted that the upper limit of the initial amount of water to evolve to the land planet mode is a reasonable value.

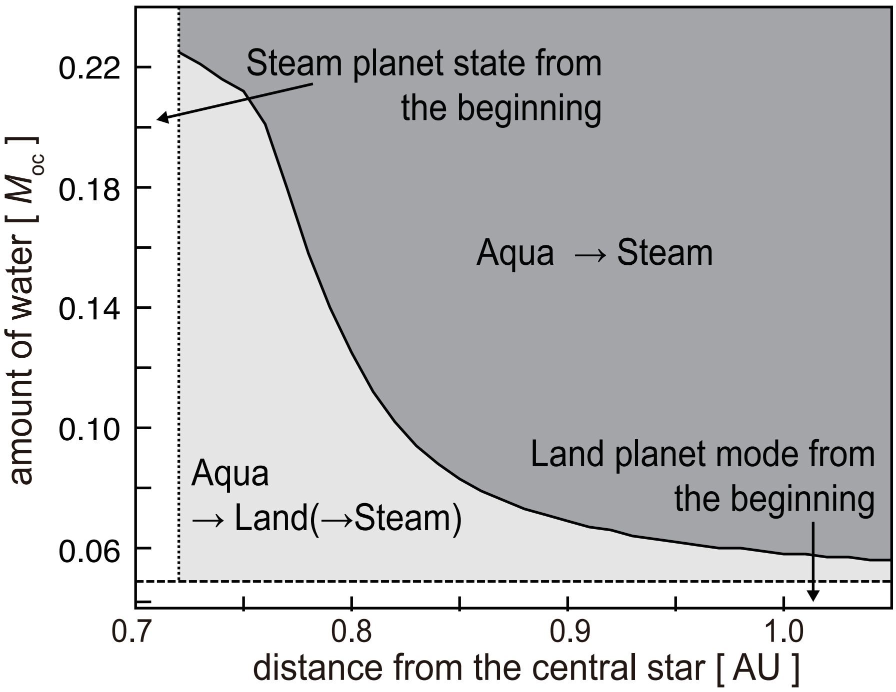

Figure 2.7. The upper limit of the initial amount of water to evolve from the aqua planet mode to the land planet mode in a case of M_{cv} = 3 m and M_{ml} = 0.05 M_{oc}.

2.3.4 Re-evaluation of the inner edge of the habitable zone

In this section, the inner edge of the habitable zone for a solar-type (G-type) star is discussed based on the results from this study. Figure 2.8 shows the evolution map of a planet with M_{ini} = 1.0 M_{oc} around a solar-type star. Results shown here are obtained under the same transition condition as results in mentioned above. For an aqua planet with initial water mass of 1.0 M_{oc}, a rapid escape of water occurs, but such a planet cannot evolve into the land planet mode because they cannot lose enough water before the onset of the runaway greenhouse effect for the aqua planet mode. Therefore, the boundary between the aqua planet mode and the steam planet state corresponds to the inner edge of the classical instantaneous habitable zone, proposed by Kasting et al. (1993).

As in Figure 2.8, Figure 2.9 shows the time evolution of aqua planets with M_{ini} = 0.1 M_{oc}. When such aqua planets locate between 0.72 and 0.82 AU, they evolve from the aqua planet mode to the land planet mode. Planets in the land planet mode remain liquid water on the planetary surface for an additional 2 Gyr before evolving into the steam planet state, and then, to the dry planet state as the luminosity of the central star increases with time.

In both Figure 2.8 and 2.9, aqua planets orbiting closer than about 0.7 AU from the central star should be in the steam planet state from the beginning. Such planets lose all of the water rapidly over a few tens of million years owing to an escape of hydrogen to space because the EUV flux from the central star is very high early in its history and at such a close distance to the planets (< 0.7 AU); such planets are called Type-II terrestrial planets (Hamano et al., 2013).

Figure 2.10 shows the inner edge of the continuously habitable zone (CHZ), which is defined as the region where a planet has liquid water on its surface for more than 4.6 Gyr. The CHZ is divided into two regions according to the initial amount of water. One type of the CHZ refers to the regions for the planets in the aqua planet mode. This type corresponds to the classical CHZ (e.g., Kasting et al., 1993) and is referred to here as a type-I CHZ.

On the other hand, the other type of the CHZ refers to the region for the planets in the land planet mode. In this region, planets maintain liquid water on the planetary surface for more than 4.6 Gyr. This region is referred to as a type-II CHZ.

From these results, the CHZ for an aqua planet is classified by the initial amount of water. An aqua planets with $M_{ini} > 0.22\ M_{oc}$ does not evolve from the aqua planet mode to the land planet mode. For such a planet, there is the type-I CHZ. Thus, in this region, the inner edge of the CHZ corresponds to the classical CHZ, proposed by Kasting et al. (1993).

On the other hand, an aqua planet with $M_{ini} < 0.22\ M_{oc}$ can evolve from the aqua planet mode to the land planet mode. However, this region is divided further into two regions. An aqua planet with $0.19\ M_{oc} < M_{ini} < 0.22\ M_{oc}$ can evolve from the aqua planet mode to the land planet mode but cannot maintain liquid water on its surface as long as 4.6 Gyr. This is because the insolation on such a planet exceeds the threshold of the complete evaporation for the land planet mode before the age becomes 4.6 Gyr.

The CHZ of an aqua planets with $M_{ini} \leqq 0.19\ M_{oc}$ corresponds to the type-II CHZ. Figure 2.10 shows that an aqua planet with $0.09\ M_{oc} < M_{ini} \leqq 0.19\ M_{oc}$ has both type-I and type-II continuous habitable zone. However, these are not contiguous. Thus, there is a region where planets cannot maintain liquid water on its surface for 4.6 Gyr according to the initial amount of water. Planets with an initial amount of water less than the maximum amount of water for the land planet mode ($M_{ml} = 0.05\ M_{oc}$) on their surface are in the land planet mode from the beginning.

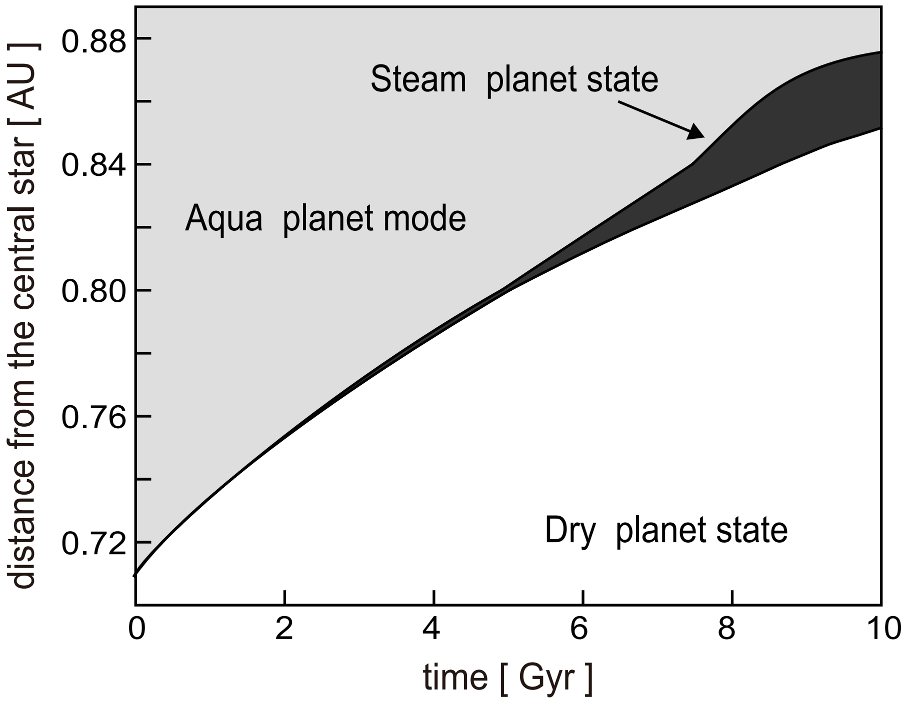

Figure 2.8. The evolution of planets on the aqua planet mode in a case of M_{ini} = 1.0 M_{oc} around a solar-type star.

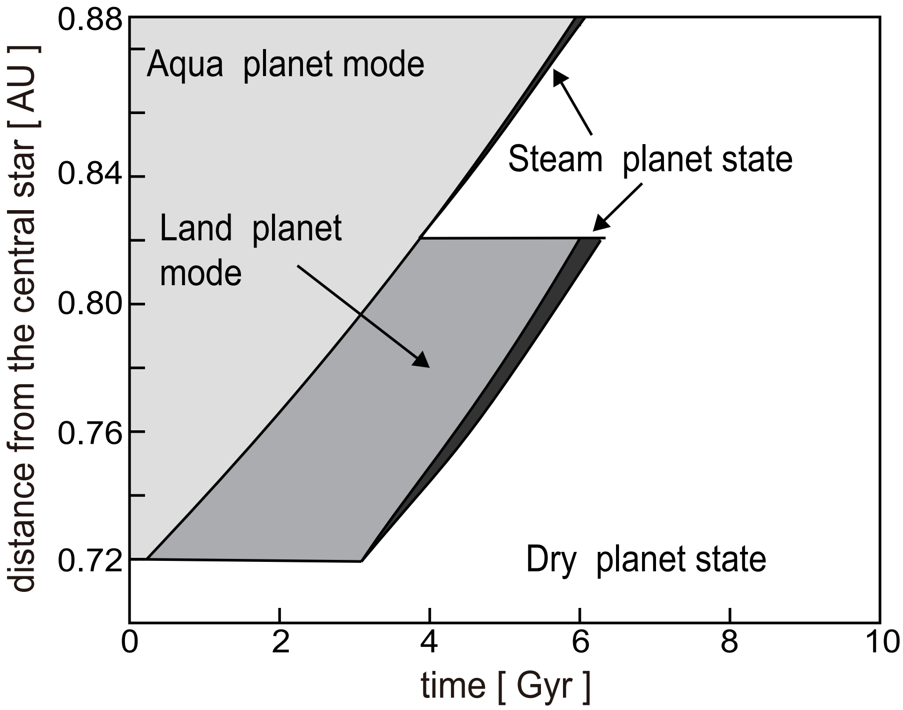

Figure 2.9. The evolution of planets on the aqua planet mode in a case of M_{ini} = 0.1 M_{oc} around a solar-type star.

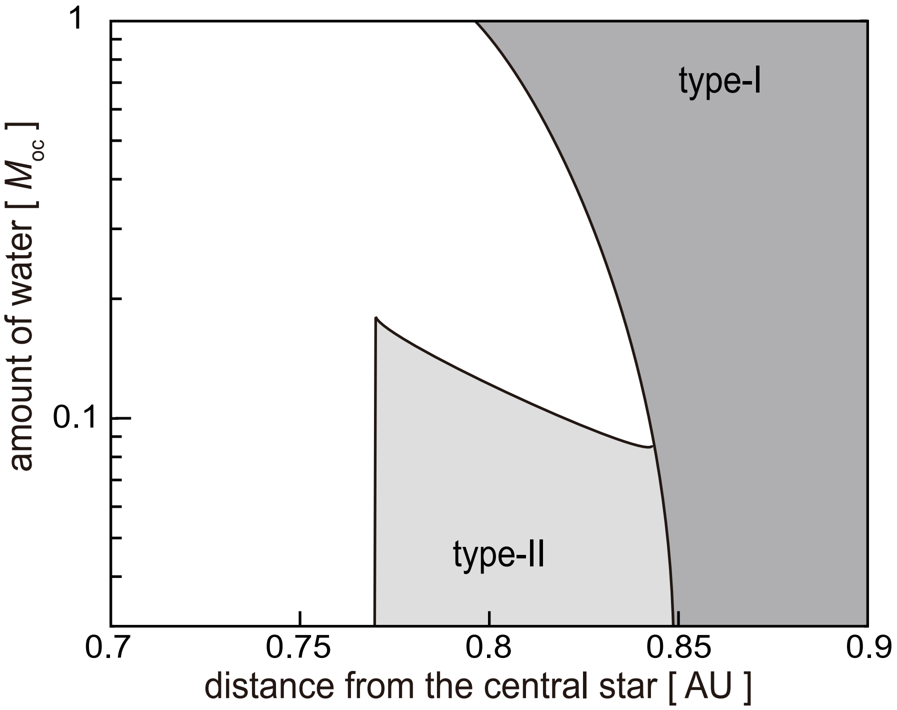

Figure 2.10. The continuously habitable zone (CHZ) considering the evolution from the aqua planet mode to the land planet mode.

2.4 Discussion

2.4.1 Dependence on the transition condition

In the previous section, the critical amount of water vapor just before the runaway greenhouse, M_{cv}, was taken as a global average of 3 m water depth equivalent, and the maximum liquid water mass for the land planet mode, M_{ml}, was taken to be 0.05 M_{oc}. In this section, the dependence of the evolution from the aqua planet mode to the land planet mode on the transition condition is discussed.

Figure 2.11 shows the dependence of the critical water vapor amount for the runaway greenhouse (M_{cv}) on the initial amount of water (M_{ini}) to evolve from the aqua planet mode to the land planet mode. In these results, the maximum liquid water mass for the land planet mode, M_{ml}, is fixed at 0.05 M_{oc}. If the M_{cv} exceeds 3 m depth in global average, then the upper limit of the initial amount of water to evolve from an aqua planet mode to the land planet mode should increase owing to increase the period from increase of the mixing ratio of water vapor in the upper atmosphere to increase of the amount of water in the planetary atmosphere. For a planet close to the central star, the upper limit of the initial amount of water to evolve to the land planet mode increases. In this case, the EUV flux from the central star remains large when a planet is at the onset of the moist greenhouse state. Thus, a larger amount of water should escape early in its evolution. However, if a planet is too close to the central star (i.e., a = 0.72 AU), the upper limit of the initial amount of water to evolve from the aqua planet mode to the land planet mode decreases suddenly, creating a peak (see Figure 2.11). The total amount of water that escapes is determined by the duration of the moist greenhouse stage (until the onset of the runaway greenhouse effect) and also by the escape flux of hydrogen during this stage. For a planet very close to the central star, the onset of the runway greenhouse effect is very early in its history and the duration of the period of rapid escape (i.e., the duration of the moist greenhouse stage) is very short.

Although the escape flux in the energy-limited escape mode is large, the rapid escape of water occurs in the diffusion-limited escape mode for these planets. Thus, the total amount of water that escapes makes a peak, which is shown by the upper limit of the initial amount of water (Figure 2.11).

An aqua planet cannot evolve into a land planet when M_{cv} is 1 m in global average. In the model used in this study, a mixing ratio of water vapor in the upper atmosphere reached 10^{-3} when the water in the column of the atmosphere is 1.9 m in global average. If M_{cv} is less than 1.9 m, then an aqua planet cannot have enough water to experience the moist greenhouse state, and evolves directly to the steam planet state. It is therefore concluded that whether or not the planetary atmosphere on the aqua planet mode has water vapor more than 1.9 m in global average is one of necessary conditions for the evolution from the aqua planet mode to the land planet mode.

In our standard case, the maximum liquid water mass for the land planet mode (M_{ml}) is assumed to be 0.05 M_{oc}. However, the maximum liquid water mass for the land planet mode, M_{ml}, may be dependent upon the planetary topography. Figure 2.12 shows the dependence of the upper limit of the initial amount of water on M_{ml} for a planet evolving from the aqua planet mode to the land planet mode. In these calculations, the value of M_{cv} is fixed at a standard value of 3 m in global average. Although a smaller value of M_{ml} results in a smaller upper limit of the initial amount of water, M_{ini}, it is possible for an aqua planet to evolve into a land planet even if M_{ml} = 0.01 M_{oc}. However, an aqua planet cannot evolve to a land planet when M_{cv} is less than 1 m in global average (see Figure 2.11). Therefore, as compared the critical water vapor amount for the runaway greenhouse, M_{cv}, to the maximum liquid water mass for the land planet mode, M_{ml}, the parameter M_{cv} has a greater influence on the evolution path from the aqua planet mode to the land planet mode than the parameter M_{ml}.

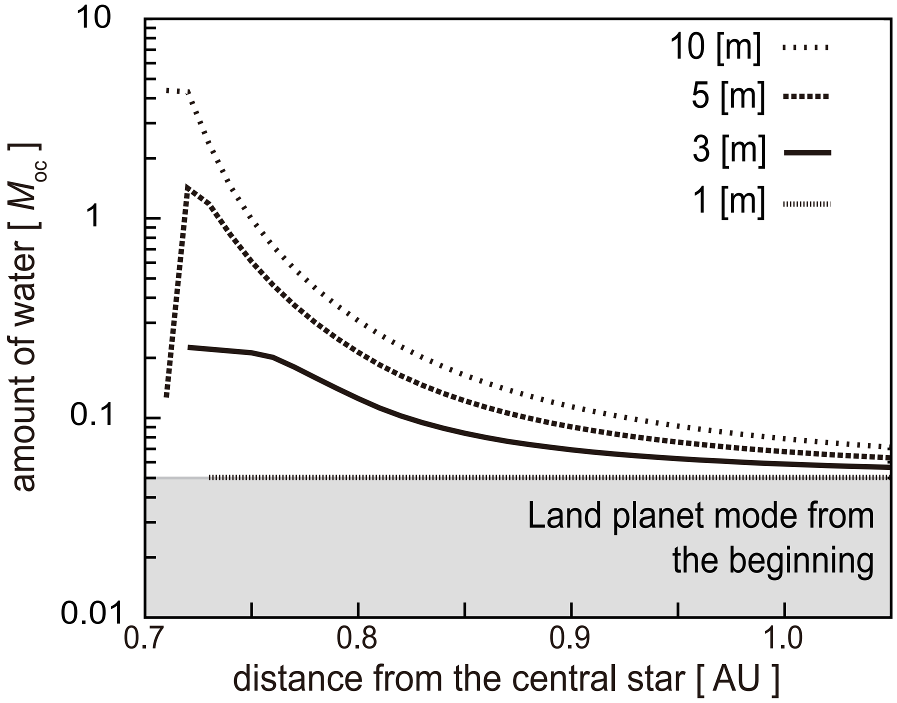

Figure 2.11. The effect of the M_{cv} on the initial amount of water to evolve from the aqua planet mode to the land planet mode.

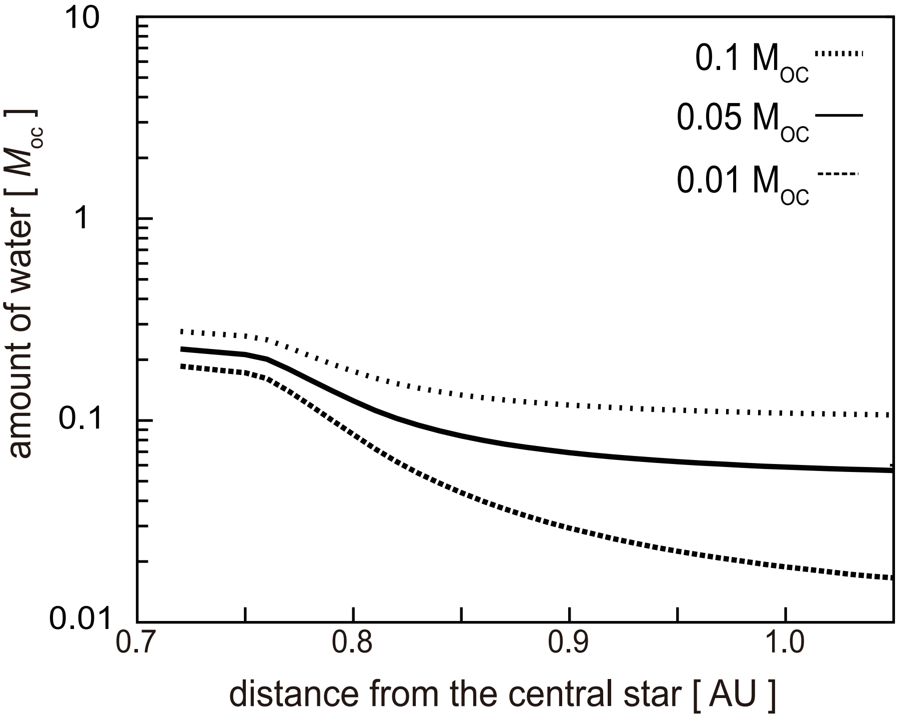

Figure 2.12. The effect of the M_{ml} on the initial amount of water to evolve from the aqua planet mode to the land planet mode.

2.4.2 Difference between atmospheric models

I investigated the evolution paths of water planets using a one dimensional, cloud-free, radiative-convective atmospheric model used in the 1980s (Abe and Matsui, 1988). Recently, the 1-D atmospheric models have been improved by using more accurate opacity estimates for water vapor (Goldblatt et al., 2013; Kopparapu et al., 2013, 2014). The inner edge of the continuously habitable zone (CHZ), which is defined by the onset of the moist greenhouse state, is estimated to be 0.99 AU by one of such models (Kopparapu et al., 2013). In a model in this study, the onset of the moist greenhouse effect is estimated to be 1.39 $S_{\odot}$. It is not clear whether or not a planet with a large amount of water in its atmosphere can go back from heated state to cool state. When M_{cv} is set to 3 m in global average, an aqua planet lapses into such a situation at 1.40 $S_{\odot}$. In Kopparapu et al. (2013), the onset of the moist and runaway greenhouse effects are 1.015 and 1.06 $S_{\odot}$, respectively. Thus, the timing of the onset of rapid water loss and the amount of water that escapes should be different between the atmospheric model of this study and that of Kopparapu et al. (2013). To investigate the evolution from the aqua planet mode to the land planet mode, a relationship between the incident solar flux and a mixing ratio of water vapor in the upper atmosphere is needed, but it was not shown in Kopparapu et al. (2013). The results of this study are therefore compared qualitatively to those of Kopparapu et al. (2013).

I estimated how much water escapes during the moist greenhouse stage using the results from Kopparapu et al. (2013). In order to estimate the escaped water amount by Kopparapu et al. (2013), I assume that a mixing ratio of water vapor in the upper atmosphere is 10^{-3}, so that the amount of water may escape during the moist greenhouse stage owing to the diffusion-limited escape. It is estimated to be approximately 3×10^{21} moles (ca. 0.04 M_{oc}), whereas the amount of escaped water in the same period owing to the energy-limited escape mode is estimated to be 10^{23} moles (ca. 1.19 M_{oc}). The actual amount of escaped water will be between these estimates (between 3×10^{21} moles and 1×10^{23} moles) (see Figure 2.13). In results in this study, an aqua planet that can evolve from the aqua planet mode to the land planet mode typically loses about 0.1 M_{oc} of their water (see the section 2.3.3), which is comparable to, or less than, the estimated amount of escaped water from results in Kopparapu et al. (2013). In Kopparapu et al. (2013), the planets orbiting semi-major axis less than 0.84 AU are in the steam planet state from the beginning. Thus, the orbital region where an aqua planet can evolve into the land planet mode moves outward (about 0.1 AU) when the climate model of Kopparapu et al. (2013) is applied. The inner edge of the type-II CHZ (see Figure 2.10), in which a aqua planets evolves to a land planet, should also move outward.

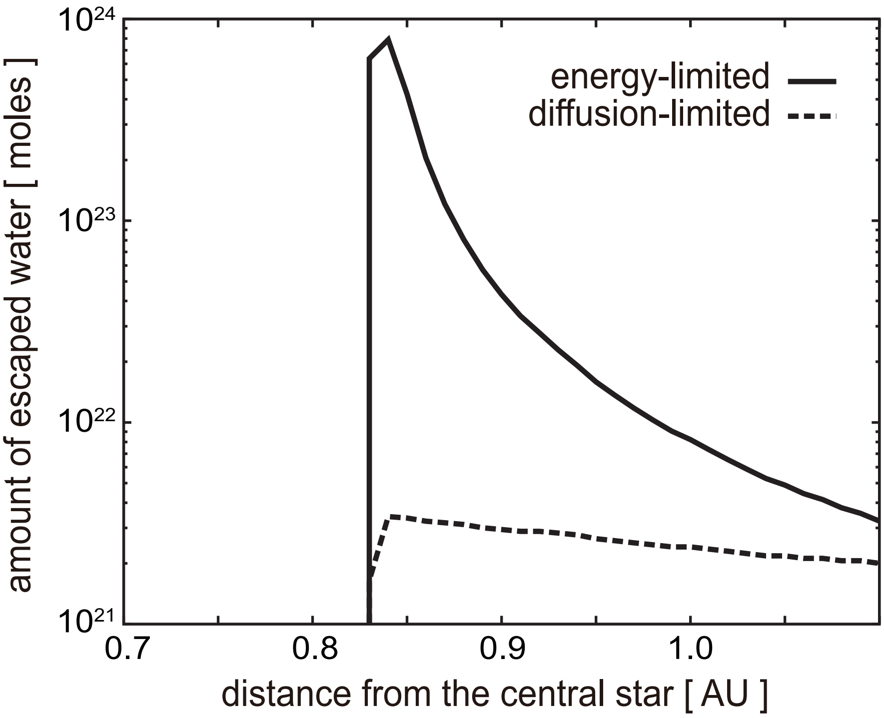

Figure 2.13. The amount of escaped water in the moist greenhouse state using results from Kopparapu et al. (2013).

2.4.3 Intensity of EUV flux

As mentioned in section 2.2.3, the uncertainty associated with the effective stellar EUV heating is large (e.g., Zahnle and Walker, 1982; Lammer et al., 2009). The actual escape of water is determined by the competition of escape fluxes between the diffusion-limited mode and the energy-limited mode. A mixing ratio of water vapor in the upper atmosphere is very low until a planet is in the moist greenhouse state. The escape flux of water on the diffusion-limited escape mode is therefore lower than that on the energy-limited escape mode over this period. When the upper atmosphere becomes wet just before the onset the moist greenhouse state, the escape flux of water on the diffusion-limited escape mode rapidly increases. At this situation, the diffusion-limited escape mode is larger than that on the energy-limited escape mode, in other words, the actual escape of water is on the energy-limited escape mode. A rapid water loss is on the energy-limited escape mode just before an aqua planet evolves to a land planet (see Figure 2.6).

If the effective stellar EUV heating is larger than that used in a model in this study, then the escape flux on the energy-limited escape mode should increases. It should cause the increase of the initial amount of water to evolve to the land planet mode. However, the actual escape flux is limited by the diffusion process of water vapor in the atmosphere until the onset of the moist greenhouse state. Thus, in a larger EUV flux case, the points from results in this study are almost same and the upper limit of the initial amount of water increases.

On the other hand, if the effective stellar EUV heating is smaller than that used in this study, the escape flux of water on the diffusion-limited intersect with that on the energy-limited escape mode before the upper atmosphere becomes wet enough to occur a rapid water loss. The actual escape flux of water is smaller than that in results in this study. Thus, this makes it harder for aqua planets to evolve to land planets.

2.4.4 Atmospheric CO_2

An important complication could be the evolution of the amount of CO_2 in the atmosphere. On the Earth, it is considered that the carbon cycle controls atmospheric CO_2 level and stabilizes the climate. Since the carbon cycle on the land planet mode has not been investigated so far, I need to consider possible effects of the carbon cycle on the climate evolution of the land planet mode.

The amount of CO_2 in the planetary atmosphere is governed by the balance between the degassing flux of CO_2 and its removal due to chemical weathering of silicate minerals followed by carbonate precipitation. I expect that the degassing flux of CO_2 would be smaller on a land planet than on an aqua planet because plate tectonics is likely to be less efficient on a water-poor planet. Efficiency of chemical weathering of silicate minerals may be also small on a land planet, because it is restricted only in the region where water flows. In that case, the CO_2 level in the atmosphere is uncertain, and the study of the carbon cycle on a land planet is required to understand the climate evolution of a land planet.

Therefore, it is not clear whether there would be more or less CO_2 on a land planet compared to an aqua planet. If the amount of CO_2 is balanced at a very high value, then a large amount of CO_2 has an insignificant effect on the onset of the runaway greenhouse effect. On the other hand, if the CO2 amount is balanced at a very low value, the climate is cooler than that estimated in this study. However, it is likely that such an effect is minor, because the insolation is high enough to keep from the global freezing without CO_2 greenhouse effect. It should also be noted that a land planet is relatively resistant to global freezing. Even if ice caps appear, their size is regulated by the carbon cycle, because CO_2 removal through chemical weathering would be restricted in the non-ice-covered area. Under such scenarios, the lifetime of a habitability environment would likely be similar to that estimated in this study.

2.4.5 Atmospheric O_2

The amount of oxygen is determined by a balance between generation and consumption. In the Earth, oxygen level maintains high level because lives emit oxygen to the atmosphere. If there is not life on the Earth, oxygen would not be major composition in the Earth's atmosphere. The Earth's atmosphere has the ozone layer that is formed in oxygen-rich atmosphere. Thus, oxygen in the atmosphere is considered as signs of life in survey of exoplanets.

As mentioned above, a rapid water loss would be accompanied by accumulation of oxygen in the planetary atmosphere. It causes a false positive for signs of life. However, it would be a valuable sign for a rapid water loss. The planetary atmosphere reflects its story until now. To clarify a variety of terrestrial habitable planets, it is necessary that dying or dead habitable planets give us significant information. Thus, detectable features of the planetary atmosphere and its evolution are considered of value.

The increase of the amount of oxygen in the planetary atmosphere should cause two conflicting effect on a rapid water loss: one is an increased effect on the escape flux of hydrogen due to the increase of temperature at tropopause and the other is an decreased effect on the escape flux of hydrogen due to the increase of the amount of atmosphere. In this study, I assume no ozone in atmosphere and temperature at tropopause is 150 K. For the Earth, temperature at tropopause is ~220 K. When a water planet experience the moist greenhouse state, the escape flux of hydrogen would be larger than that estimated in this study. However, the amount of atmosphere is increasing during the moist greenhouse state. If the amount of atmosphere increases, the escape flux on the diffusion-limited escape mode would be smaller. Additionally, in this study, I assume that background atmosphere is assumed to be 1 bar composed of N_2. In a case of a larger than the amount of the atmosphere assumed in this study, the escape flux in the diffusion-limited mode also decreases as is the case with the problem of the accumulation of oxygen. In such a case, it should be hard to evolve to the land planet mode and the upper limit of the initial amount of water to evolve to the land planet mode decreases.

The amounts of oxygen and water are strongly depended on the atmospheric evolution. Thus, it is necessary to quantitatively estimate the evolution of such atmospheric components to sidestep a false positive sign due to abiotic oxygen.

2.4.6 The geologic H_2O cycle

I have neglected the geologic water cycle by presuming that the fluxes of water into and out of the mantle are approximately in balance. The balance is likely to break down after an aqua planet becomes a land planet. This is because the mantle may still be wet and outgassing may still be considerable, but the subduction of hydrous minerals is restricted to locations near the poles. Thus, water outgassing would be a potential hazard to the future habitability of the land planet over long timescale. However, while the aqua planet is losing its hydrogen in the moist greenhouse state, it is possible that the imbalance goes in the other direction, as the generally warm, wet climate of the moist greenhouse would likely promote weathering reactions and possibly promote the subduction of hydrous minerals. Thus, I think it probable that the geologic water cycle would aid rather than subvert the transition of a suitable planet from the aqua planet mode to the land planet mode. On the other hand, water outgassing would also prolong the aqua planet mode over long timescale, and change the surface water distribution. If water outgassing prolongs the period on the aqua planet mode, an aqua planet is hard to evolve the land planet mode, compared with results in this study, owing to a large amount of water on the surface.

2.4.7 Other stars

Stars of different spectral types (or with different masses) evolve differently from the Sun. In particular, the luminosity evolution of stars of later spectral type (late G dwarfs, K dwarfs and M dwarfs) is slower than that of the Sun. These stars are fainter than the Sun and hence the habitable zone is closer to these stars than that to the Sun. A ratio of EUV radiation to luminosity is about the same for K stars as for G stars, and the ratio is higher for most M stars (Lammer et al., 2009). Hence, these stars are at least as effective at driving hydrogen escape as a Sun-like star, and so I would expect similar or faster rates of hydrogen escape for an aqua planet in the habitable zone around these other stars. The slower rate of luminosity evolution means that there is more time available for escape to take place before the moist greenhouse becomes a runaway greenhouse, and therefore I expect that late-type stars are more favorable for an aqua planet to evolve the land planet mode.

Chapter 3 The Threshold of Runaway Greenhouse Effect for Land Planets

3.1 Runaway greenhouse effect for the terrestrial water planets

As mentioned above, there are two definitions of the inner edge of the habitable zone: One is the moist greenhouse condition, which is referred to as the water loss limit, and the other is the runaway greenhouse condition. When we consider the long-term evolution, the onset of the moist greenhouse effect is important for the evolution of the terrestrial water planet. However, the strictest inner edge of the habitable zone is the onset of the runaway greenhouse effect. The runaway greenhouse threshold gives a temporal limit of habitability for a water planet, because the Sun increases its own luminosity with time (e.g., Gough 1981).

Most of the previous studies that investigated the condition for the runaway greenhouse state used vertically one-dimensional (1-D), radiative-convective equilibrium models. According to such studies, there is an upper limit of the infrared radiation from a planet with an abundant supply of water vapor from the surface (Abe and Matsui, 1988; Kasting, 1988). This upper limit is called the radiation limit (Nakajima et al., 1992). In these studies with 1-D models, the runaway greenhouse threshold is considered just as the same in value as the radiation limit of a water saturated atmosphere (e.g., Kasting et al. 1993; Abe 1993; Kopparapu et al. 2013; Goldblatt et al. 2013). According to recent studies with the newest spectral database, the radiation limit of a pure water vapor atmosphere is estimated to be 282 W/m^2 (102% of the insolation at the present Earth's orbit, which hereafter we call the relative solar flux) (Goldblatt et al. 2013) or 291 W/m^2 (106% in the relative solar flux) (Kopparapu et al. 2013).

Recently, the threshold of the runaway greenhouse effect has been studied by use of general circulation models (GCMs) with three-dimensional dynamics (Abe et al. 2011; Leconte et al. 2013b; Wolf and Toon 2014; Wolf and Toon 2015).

Leconte et al. (2013b) calculated the threshold of the runaway greenhouse for the Earth by using LMD (Laboratoire de Météorologie Dynamique) generic GCM. This model was developed specifically for the study of exoplanets and paleoclimates based on LMDZ earth GCM, which was used for the simulations of the climate of the present Earth (Wordsworth et al., 2011; Leconte et al., 2013a; Forget et al., 2013). With the setups for the surface boundary conditions of the present Earth, they showed that the planet could stabilize the climate with the insolation up to 110% in the relative solar flux because the unsaturated region is formed in the depression region of the Hadley circulation. On previous studies using 1-D vertical model, they assumed saturated atmospheres and such atmospheres cannot radiate the strong planetary radiation, compared with the cases of saturated atmosphere. This threshold of the runaway greenhouse obtained by 3-D climate model is higher than that obtained by 1-D vertical models (102% by Goldblatt et al. (2013), 106% by Kopparapu et al. (2013)). Their model also showed that the stratospheric temperature and humidity are low. This means that an aqua planet avoids the moist greenhouse state and a rapid water loss.

Wolf and Toon (2015) used the GCM, CAM (Community Atmosphere Model) ver.4, which was developed in National Center for Atmospheric Research, and also investigated the stability of climate for the present Earth against the brightening Sun. The purpose of their study is to clarify whether the moist greenhouse state occurs or not. They showed that the moist greenhouse state occurs from 119% of the relative solar flux and a rapid water loss should occur. The climate is stable until 121% of the relative solar flux. They concluded that water loss from the aqua planet covered with oceans of Earth's ocean mass in the moist greenhouse state prevents the onset of the runaway greenhouse state. They also discussed the difference between their results and results of Leconte et al. (2013b) and pointed out the difference in treating moist physics, especially the formation of cloud. However, it is still not clear and whether an aqua planet evolves to the moist greenhouse state or not remains a matter of debate.

Both of the two values of the runaway greenhouse threshold and the moist greenhouse threshold obtained above in 3-D GCMs are higher than those obtained by 1-D models. They suggest that the atmospheric circulation, especially, the higher planetary radiation from the drier region, causes this higher value of the threshold of the runaway greenhouse effect. The dry region in the atmosphere is formed by the descending flow of the Hadley circulation. This is qualitatively consistent with the results in Ishiwatari et al. (2002) who used a simplified GCM. These studies indicate that the runaway greenhouse threshold depends on the atmospheric circulation.

Abe et al. (2011) investigated the climate of an idealized planet with a GCM, CCSR/NIES AGCM 5.4g, developed by the Center for Climate System Research, University of Tokyo and the National Institute for Environmental Research (Numaguchi 1999). They estimated the threshold of the runaway greenhouse effect for a planet with an extremely small amount of water on its surface. The liquid water is localized around both poles and dry regions appear at low latitudes when the planet's obliquity is low (Abe et al. 2005). They showed that the planetary radiation in the low latitude region could be significantly higher than the radiation limit because the low latitude region is dry and the greenhouse effect of water vapor was weak. As a result, they found that the runaway greenhouse threshold of such a planet is 170% in the relative solar flux. It is much higher than that obtained by 1-D vertical model or even 3-D GCM calculated by Leconte et al. (2013b) and Wolf and Toon (2015). Abe et al. (2011) called this type of planets land planets. Abe et al. (2011) indicates that the runaway threshold depends on the surface water distribution as well as the atmospheric circulation.

The surface water distribution is determined by the balance between the water vapor transportation by atmospheric circulation and the liquid water transportation on the surface. The atmospheric circulation transports surface water poleward due to the latitudinal temperature gradient, if the planet has low obliquity and no surface water transportation (Abe et al. 2005; Abe et al. 2011). This stream is the typical characteristic of the land planet mode from a view of Lagrange average. Water vapor transported to cold regions condenses and precipitates to the surface of high latitudes. If the total amount of water in the planetary surface is very small, precipitated water would be trapped in regional depressions at high latitudes. Then, the distribution of surface water is determined so that the precipitation and evaporation are locally balanced.

On the other hand, if the amount of precipitated water is larger than the capacity of the depression, it runs off and flows down to lower latitudes. This is the surface water transportation. The lowest latitude where the surface water flow reaches is determined by the water amount and topography, which are both intrinsic features in each planet. The flatter the topography is, the lower latitude the surface water can reach. With the steeper topography, more amount of water is needed to reach the lower latitude. Hereafter, we call the lowest latitude where the surface water flow reaches the water flow limit.

As mentioned above, we classify the terrestrial planets with water on their surface into three types: ocean planet, partial-ocean planet and land planet. Planets with a large amount of water are classified into ocean planets or partial-ocean planets depending on the their topography. Planets with a tiny amount of water localized around both poles are classified into land planets (Abe et al., 2005; Abe et al., 2011). On land planets, the dominant process of water transportation would be the water vapor transportation in the atmosphere, because the surface water transportation is less efficient.

Although there is a large difference in the runaway greenhouse threshold between aqua planets and land planets, no study investigates the intermediate condition between aqua planets and the extreme land planets considered in Abe et al. (2011). In other words, there is no study that reveals the dependence of the runaway threshold for land planets on the distribution and transportation of surface water. In addition, the exact boundary condition between the aqua planet mode and the land planet mode is unclear. It is important to investigate both these problems for understanding of the evolution of land planets.

In this chapter, I clarify this dependence for Earth-like planets by performing numerical simulations with a GCM. However, because the influence of 2-D surface water distribution and transportation is too complicated to be clarified, I simplify these effects in the simulations by introducing a single parameter the water flow limit. At higher latitudes from the water flow limit, the surface is always wet, whereas the surface condition (wet or dry) is numerically determined at lower latitudes than this limit in the simulations.

3.2 Numerical method

I perform a series of numerical experiments to clarify the dependence of the runaway threshold of land planets on the latitudinal surface water distribution. In this study, I calculate water vapor transportation through the atmospheric circulation with vaporization and condensation of water by using GCM, while I do not calculate surface water transportation explicitly. Instead, I introduce a parameter called the water flow limit in the GCM calculations to describe the efficiency of the surface water transportation. In the GCM simulations, I assume that the surface in the higher latitude region than this water flow limit is always kept wet, while the surface condition at lower latitudes is numerically determined, which is controlled by the atmospheric equatorward transportation of water vapor. If this transportation is efficient, the lower latitude region than the water flow limit would be also wet. Here, I call the latitudinal boundary between the dry surface and wet surface the dry edge. The latitude of the numerically obtained dry edge should be lower than or equal to that of the water flow limit (see Figure 3.1). If the dry edge does not reach to the equator, surface water is localized on the cool region where the amount of precipitation is larger than that of evaporation, that is, such planets are land planets. On the other hand, if the atmospheric water vapor transportation is efficient enough to make the equator wet, the entire surface should be wet, that is, such planets are aqua planets. When the topography is given, the water flow limit is simply a function of the water amount (see section 3.5).

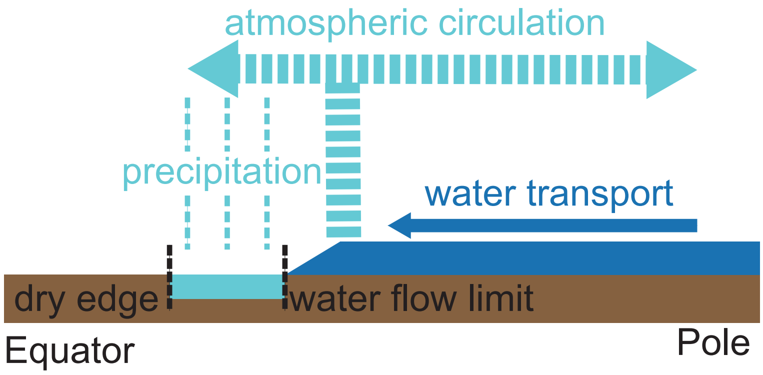

Figure 3.1. Schematic picture of the water transportation processes on the surface and in the atmosphere. The region at latitudes higher than the water flow limit is assumed to be always wet. On the other hand, the region at latitudes lower than the water flow limit is dry, if precipitation does not occur. If precipitation occurs there, the surface gets wet. The lowest latitude above which the surface is wet is defined as the dry edge.

3.2.1 GCM descriptions

I develop an idealized water planet model by removing the ozone, topography and vegetation from CCSR/NIES AGCM 5.4g, which have been developed for the Earth's climate modeling by the Center for Climate System Research, University of Tokyo and the National Institute for Environmental Research (Numaguchi, 1999). For the idealized planet, the setting in this study is the same as that in Abe et al. (2011). I assume that the planetary orbit is circular and the planetary obliquity is zero to avoid the effect of a seasonal change in the insolation.

I do not modify the model processes from those for the terrestrial use, except for the surface runoff, ocean horizontal heat flux, and ozone radiation effects. Atmospheric composition except ozone, surface pressure, planetary size (including the surface gravity), and orbital period are unchanged from the original current Earth's values.

The large-scale transportation in the model uses the spectrum transform method in the horizontal direction and grid discretization in the sigma coordinate. The grid size is 5.625° in both longitude and latitude. The number of vertical layers is 20. The primitive equations are adopted as equations of dynamical processes (Haltiner and Williams 1980). Radiative transfer is calculated using the two-stream k-distribution method (Nakajima and Tanaka 1986). In this method, the number of wavenumber channels is eight with additional 37 sub-channels. Two types of precipitation are treated, namely, large-scale condensation and cumulus convection. The large-scale condensation is treated by a prognostic cloud water scheme (Le Treut and Li 1991). The cumulus precipitation is treated by the Arakawa-Schubert scheme (Arakawa and Schubert 1974; Moorthi and Suarez 1992). If the temperature at the low atmospheric layers is above the freezing point, precipitation is treated as rain. On the other hand, it is below the freezing point, precipitation is treated as snow.

The surface and underground water transportations are not calculated. However, the surface water transportation is considered based on the information of the surface environment. The surface at latitudes higher than the water flow limit is kept wet. In order to reproduce the results of Abe et al. (2011), I follow the model settings and parameters used in Abe et al. (2011). I therefore use the bucket model for the soil (Manabe 1969). The bucket model was developed to introduce the information of the soil moisture in GCM. If the soil moisture is above the field capacity, surface water runoff occurs. The field capacity is the amount of water that the soil can hold. However, to avoid surface water runoff, the field capacity is set to be 5000 m in this study. This value is sufficiently deep because this value is larger than the amount of water of precipitation. The soil moisture is calculated in each grid. When it is above 10 cm, the surface is assumed to be wet. On the other hand, when it is below 10 cm, the evaporation efficiency is proportional to the soil moisture. The evaporation efficiency β that means ease of evaporation is expressed as

$$\beta = \min\{1, W_{\mathrm{g}}/W_{\mathrm{g,\,crit}}\}, \qquad (6)$$

where W_{g} is soil moisture and $W_{\mathrm{g,\,crit}}$ is the critical value of soil moisture beyond which surface water runoff occurs, i.e. 10 cm. When $\beta = 1$, the surface is wet. On the other hand, when $\beta = 0$, the surface is dry. The planetary albedo is determined from the relationship between cloud and ground properties. Cloud is calculated in GCM. In this study, ground properties are determined by whether the surface is covered with snow or not. When the amount of snow is above $100\ \mathrm{kg/m^2}$, the surface is assumed to be completely covered with snow. The surface albedo on such a surface increases from 0.5 to 0.75 with decreasing the surface temperature from 273.15 to 258.15 K. When the snow amount is below $100\ \mathrm{kg/m^3}$, the surface albedo over snow is assumed to be proportional to the square root of the thickness of snow. On the other hand, the ground surface is assumed as desert. The planetary albedo without snow is fixed at 0.3.

3.2.2 Procedures to obtain the runaway threshold

The method to determine the dry edge and the runaway threshold for a given water flow limit consists of three steps. At the first step, the ground surface at latitudes higher than the given water flow limit is kept wet as a boundary condition. I put 10 cm depth of water on the surface at latitudes lower than the water flow limit as an initial condition. Since 10 cm of water on the surface makes the evaporation efficiency unity, the surface is globally wet from the beginning. Then, assuming the present insolation of the Earth, I calculate water vapor transportation in the atmosphere until a steady state is attained. The timescale for attaining steady states is about 10 years. In the calculations, the initially wet surface becomes dry when the evaporation exceeds the precipitation. On the other hand, the surface is kept wet where the precipitation exceeds the evaporation.

As the second step, the GCM calculation is performed for 10 years with increased insolation. The results with the present insolation of Earth are treated as the initial condition for this step. Finally, two steps are repeated until I find a solution in which the climate never reaches a steady state. Practically, when the thermal equilibrium breaks, the GCM calculation is stopped. In this study, the runaway threshold is defined as the upper limit of the insolation below which the planet can keep the equilibrium with a certain amount of liquid water on the planetary surface. When the insolation is near the runaway threshold, the isolation is increased by 1% in the relative solar flux. Conducting these steps for various water flow limits, I derive the relationship between the runaway threshold and the water flow limit. In GCM calculations, the atmospheric dynamics and radiation profiles are calculated. For a land planet, the most important character is the localization of the surface water. Thus, the boundary between the aqua planet mode and the land planet mode can be discriminated based on the distribution of the evaporation efficiency (β).

3.3 The runaway greenhouse threshold for land planets

3.3.1 Effect of water flow limit on the runaway greenhouse threshold

Figure 3.2 shows the dry edge latitude and the runaway threshold as a function of the water flow limit. The runaway threshold is expressed in a percentage of the relative solar flux (i.e., the present solar flux is defined by 100%). It is found to vary continuously from 126% to 180% of the relative solar flux with the latitude of the water flow limit. Abe et al. (2011) estimated the runaway threshold of a land planet is 170% of the relative solar flux in the extreme case of a strongly localized surface water distribution.

The results can be divided into two regimes. When the water flow limit locates at latitudes higher than about 25°, the dry edge latitude is the same as that of the water flow limit. Namely, the low latitude region is kept dry. In this regime, the runaway threshold strongly depends on the latitude of the water flow limit. This result indicates that the runaway threshold is higher when the transportation of surface water is weaker. Hereafter, this regime is called the land planet regime.

On the other hand, when the water flow limit locates at latitudes lower than about 25°, the dry edge is at the equator, regardless of the water flow limit. Namely, the surface is globally kept wet. In this regime, the runaway threshold is almost constant of about 130% of the relative solar flux. Hereafter, this regime is called the aqua planet regime.

The distributions of the relative humidity and the evaporation efficiency, the mass stream functions and the radiative profiles for the water flow limit located at 69.2° and 19.3° are shown as a typical example of each regime just before the runaway threshold (Figures 3.3-3.8). When the water flow limit located at 69.2° and 19.3°, the insolation of the runaway threshold are 174.1% and 127%, respectively. In the land planet regime, the atmosphere over the latitudes lower than the water flow limit latitude (69.2°), which is the same as the latitude of the dry edge, gets dry (see Figure 3.3). Figure 3.4 shows the mass stream function. As seen in this figure, the direction of the atmospheric circulation in the lower atmosphere is poleward at high latitudes. As a consequence, the transportation of water vapor in the atmosphere is only poleward, so that the dry edge coincides with the water flow limit. Such a dry atmosphere in the low latitude region can emit large outgoing long-wave radiation (OLR) (see Figure 3.5). When the water flow limit and the dry edge are located at higher latitudes, in other words, the dry region on the planetary surface is broader, the land planet can radiative large OLR to space. As a result, the land planet can maintain liquid water on its surface for a longer time than that of the aqua planet.

The climate in aqua planet regime is cleanly different from that in the land planet regime. In this regime, the planetary atmosphere and surface get wet totally (see Figure 3.6). Water vapor evaporated at the water flow limit is transported not only poleward, but also equatorward (see Figure 3.7). Therefore, the atmosphere and surface are wet even in the latitude lower than the water flow limit. In this case, the dry edge is located at the equator; hence all the surface is wet. The distribution of precipitation and evaporation is very similar to those observed on the Earth at present. Such a wet atmosphere cannot radiate OLR larger than the radiation limit of the steam atmosphere (see Figure 3.5 and 3.8). As shown in Leconte et al. (2013a), there are unsaturated regions that formed by the decreasing flow of the Hadley circulation in the planetary atmosphere. It is known that such unsaturated regions can emit a larger OLR than the radiation limit of a H_2O saturated atmosphere, estimated by 1-D climate models. I find that the runaway threshold is almost constant (about 130% in the relative solar flux) in the aqua planet regime, as shown in Figure 3.2. The increase of the runaway threshold from near the boundary condition between the aqua planet and land planet regimes is caused by the effect of cloud albedo. Cloud albedo is high when the water flow limit is located in the ascending region of the Hadley circulation.

The Hadley circulation can be seen in Figures 3.4 and 3.7. The Hadley circulation flows poleward in the upper troposphere and, whereas flows equatorward near the surface. Because the lower portion of the Hadley circulation transports water vapor equatorward, a globally wet atmosphere is formed. The latitude covered by the Hadley circulation divides those regimes. Thus, the width of the Hadley circulation is important for the classification of water planets.

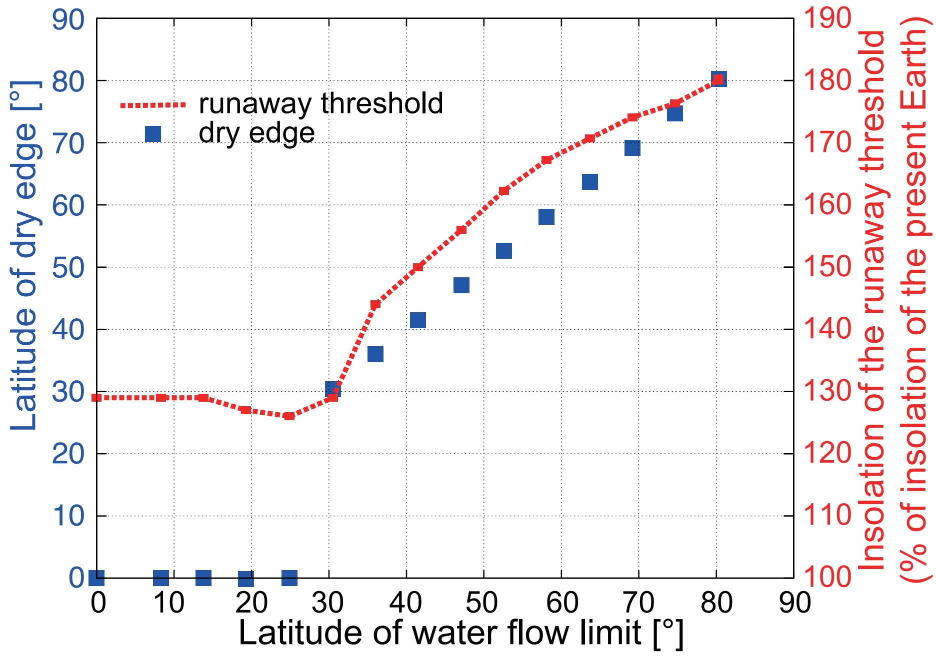

Figure 3.2. The dry edge latitude and the runaway threshold are shown as a function of water flow limit. The runaway threshold is expressed in the unit of the relative solar flux (dashed line). Square symbols represent the latitudes of the dry edge.

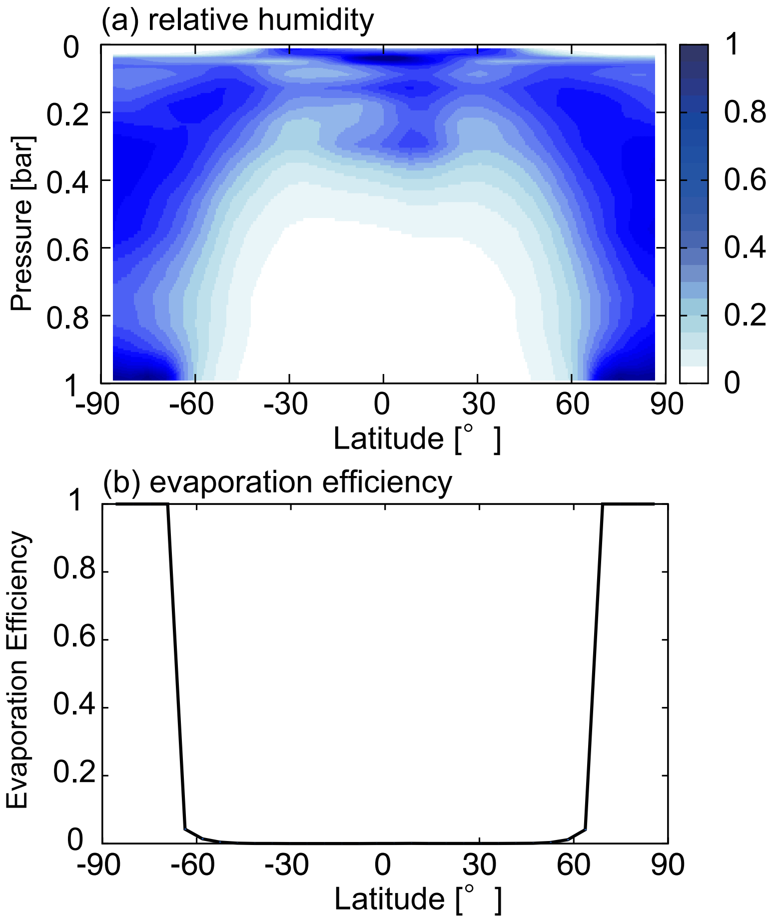

Figure 3.3. (a) The relative humidity and (b) the evaporation efficiency (β) in the case of the water flow limit = 69.2°. The region with latitudes lower than the water flow limit is found to be dry.

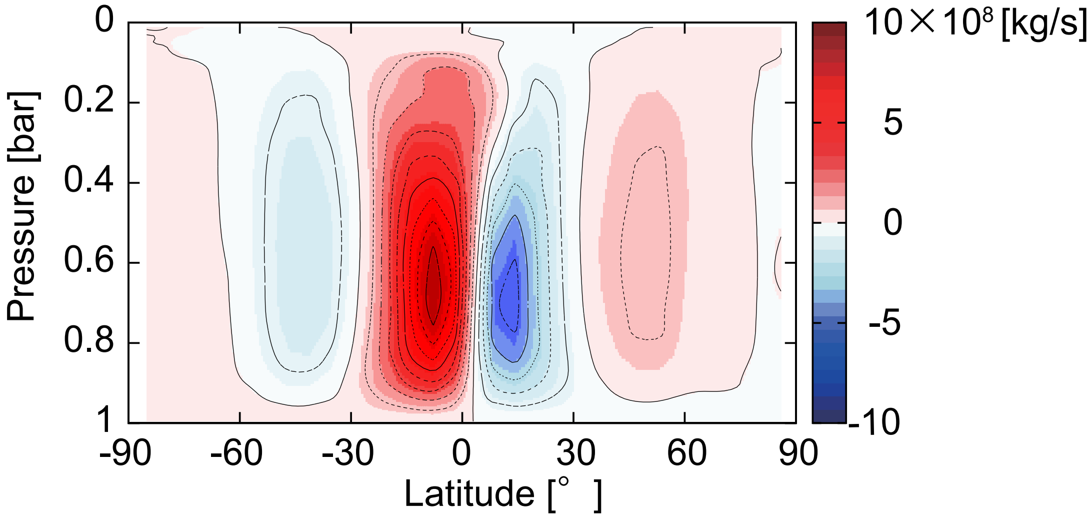

Figure 3.4. The mass stream function in the case of the water flow limit = 69.2°. Negative values represent the mass stream of right-hand circular and, on the other hand, positive values represent that of left-hand circular.

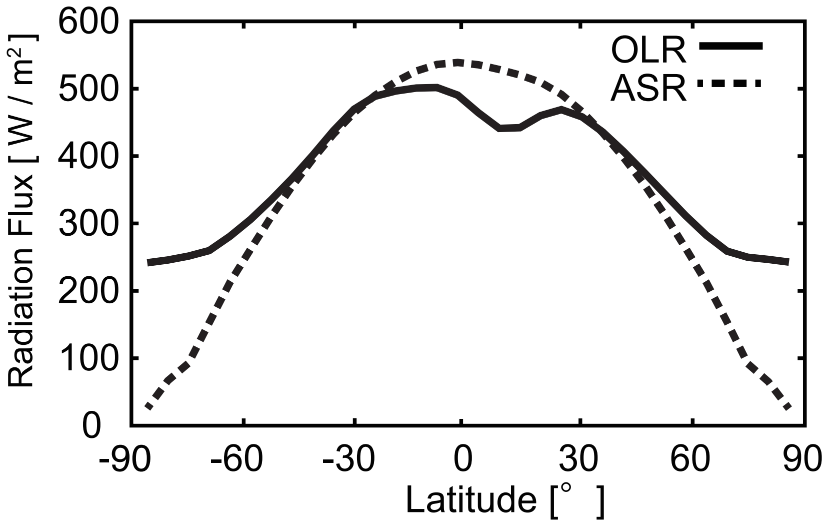

Figure 3.5. The absorbed shortwave radiation (ASR, dashed line) and the outgoing long-wave radiation (OLR, solid line) in the case of the water flow limit = 69.2°. Note that, in lower latitudes, a very large OLR is found to be emitted.

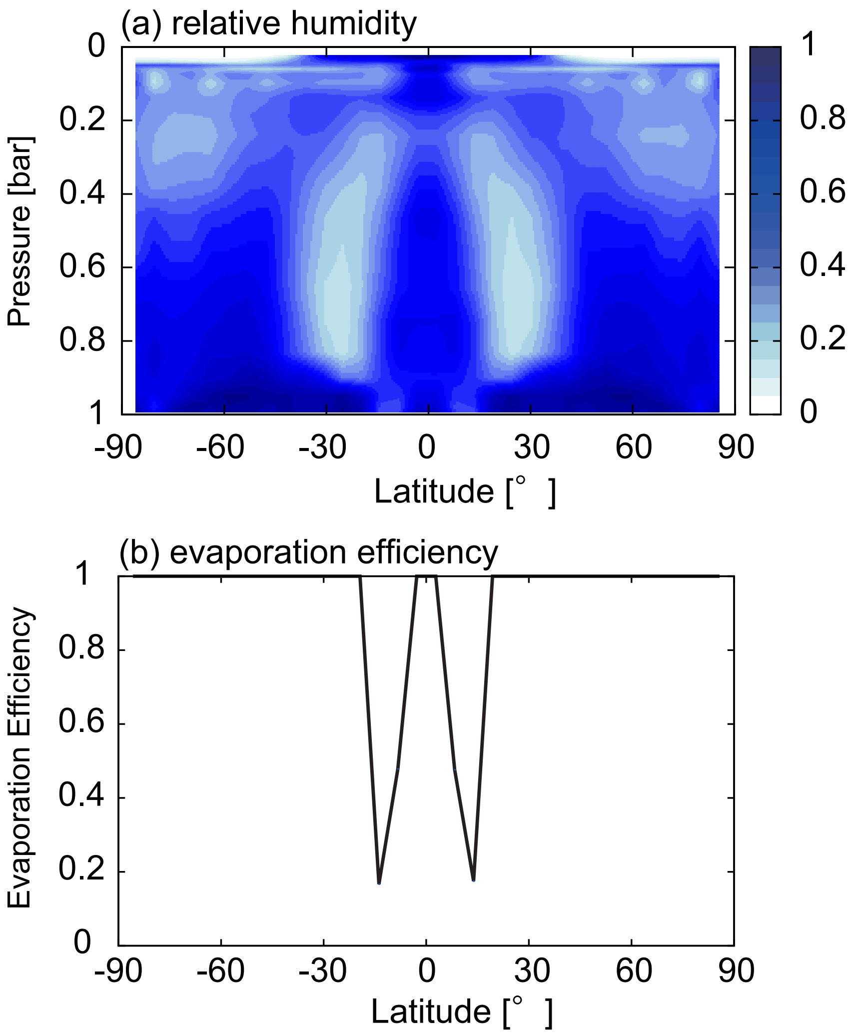

Figure 3.6. (a) The relative humidity and (b) the evaporation efficiency (β) in the case of the water flow limit = 19.3°.

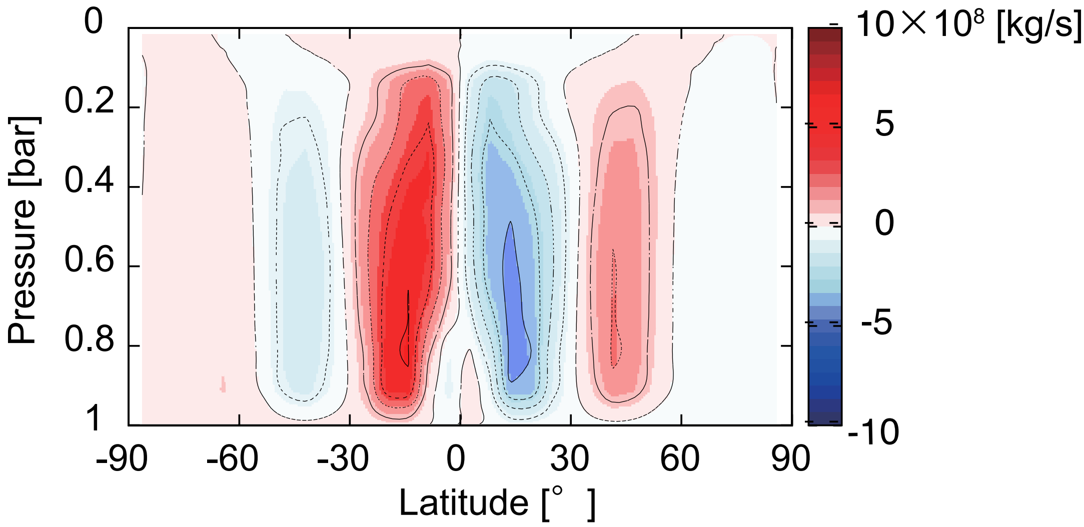

Figure 3.7. The mass stream function in the case of the water flow limit = 19.3°. Negative values represent the mass stream of right-hand circular and, on the other hand, positive values represent that of left-hand circular.

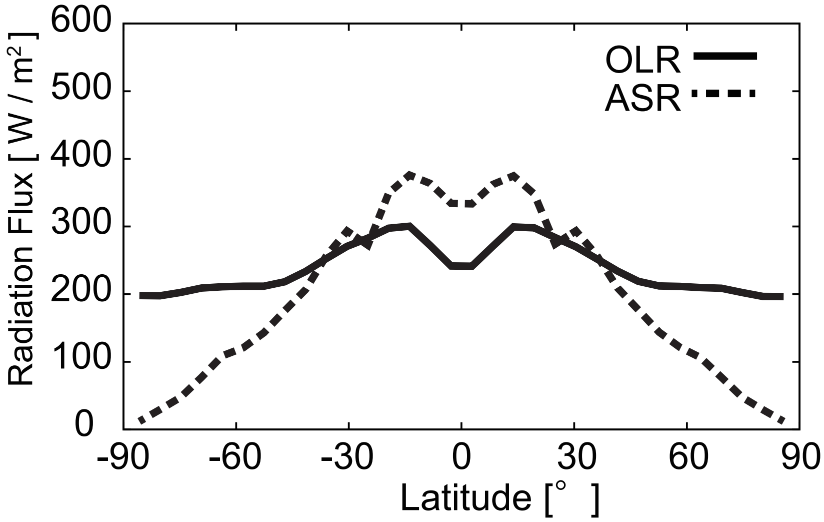

Figure 3.8. The absorbed shortwave radiation (ASR, dashed line) and the outgoing long-wave radiation (OLR, solid line) in the case of the water flow limit = 19.3°.

3.3.2 The condition between of the aqua and land planet regimes

As shown in Section 3.3.1, the relative latitudinal position between the water flow limit and the edge of the Hadley circulation determines the planetary climate regimes: the aqua planet regime and the land planet regime. If the water flow limit reaches the region of the Hadley circulations, the planet is in the aqua planet regime because the whole of the planetary surface gets wet. Thus, to classify the climate of the water planets, it is important to understand how the width of Hadley circulation is determined.

The atmospheric circulation is sensitive to various planetary parameters such as the planetary rotation rate, the planetary mass, the surface gravity, the insolation from the central star, the mass of the planetary atmosphere, obliquity and so on. Although all of such parameters have strong effects on the strength of the atmospheric circulation, the width of the Hadley circulation is only affected by the rotation rate (e.g., Held and Hou 1980; Satoh 1994; Kaspi and Showman 2015). That is because the Hadley circulation is controlled by the mid-latitude westerlies. The strength of mid-latitude westerlies is determined by the Coriolis force (e.g., Schneider 2006). When the planetary rotation rate is faster, the region of the westerlies is wider. Thus, in such a case, the width of the Hadley circulation is narrower and the climate of such a water planet tends take the climate of the land planet mode. On the other hand, when the planetary rotation is slow like Venus, the width of the Hadley circulation becomes wider and expands up to the polar region (e.g., Pinto and Mitchell 2014) and the climate of such a water planet tends to take the climate of the aqua planet mode.

The results of this study show that neither the surface water distribution (the location of the dry edge) nor the insolation from the central star has much influence on the width of the Hadley circulation (see Figures 3.4 and 3.7). Thus, the surface water distribution as well as the planetary rotation rate strongly affects the runaway threshold through the determination of the climate region.

In this study, I assume that the obliquity of the planet is zero. When a planet has finite obliquity, a seasonal climate change is produced. Although the global annual mean insolation from the central star is not affected by the planetary obliquity, the planetary climate is affected by the latter owing to a seasonal change. Abe et al. (2005) investigated the dependence of the climate state on the planetary obliquity for a land planet using GCM. They found that the planetary climate is divided into four climate regimes (warm-upright, warm-oblique, frozen-upright and frozen-oblique) as functions of the summer surface temperature and the planetary obliquity.

When the summer surface temperature is above the freezing point of water (273 K), the planetary climates are classified into warm-upright and warm-oblique regimes. The major differences between two regimes are in the annual mean precipitation and rainfall area. When the value of the obliquity is less than the value of the latitude for the width of the Hadley circulation, a land planet is in the upright regime. On the other hand, when the value of the obliquity is larger than the value of the latitude for the width of the Hadley circulation, the climate of a land planet is in the oblique regime. In the upright regime, the low latitude area becomes dry and the precipitation occurs at high latitudes owing to the water transportation in the planetary atmosphere. On the other hand, in the oblique regime, the precipitation occurs in the low latitude area on the summer hemisphere owing to the equatorward water transportation because the temperature at the mid latitude is higher than that at the low latitude in the summer hemisphere. Thus, a planet gets wet globally. The boundary between these two regimes is determined by the width of the Hadley circulation.

According to the results of Abe et al. (2005), the runaway threshold of a land planet is applicable to the upright regime. When the climate regime is in the oblique regime, the dry edge locates near the equator. Such a planet should behave an aqua planet.

As mentioned above, the boundary between the land planet regime and the aqua planet regime is determined by the width of the Hadley circulation. Also, the boundary between the upright regime and the oblique regime is determined by the width of the Hadley circulation. Both climate boundaries are controlled by the planetary rotation rate of planets. Therefore, although the planetary rotation rate has not measured yet, such information is important to classify the planetary climate through the atmospheric dynamics.

In this study, I assume circular orbits as the planetary orbit, in other words, the eccentricity of the planetary orbit is zero. The difference in the intensity of insolation between the pericenter and the apocenter appears in the case of finite the eccentricity. When a planet with a large eccentricity, it is possible that a planet receives a strong insolation above the critical flux at the pericenter and a planet gets cold below the freezing point of water at the apocenter. Of particular importance here are, however, the annual average insolation and the heat capacity of the planet. Although a land planet has a strong resistance to the strong insolation, the heat capacity of a land planet is lower than that of an aqua planet because oceans have large capacity. Thus, the change of surface temperature of an aqua planet with a large eccentricity is relatively smaller than that of a land planet. In such a situation, it is possible that an aqua planet has a wider HZ than a land planet.

3.3.3 Characteristics features of the onset of the runaway greenhouse state

In this section, I examine characteristic features of a land planet at the runaway threshold. Figure 3.9 shows the zonal mean outgoing long-wave radiation (OLR) in the northern hemisphere at the runaway threshold for the cases with various dry edge latitudes. In this figure, the filled circle on each curve indicates the infrared radiation at each dry edge. Because the insolation at the runaway threshold increases as the dry edge latitude increases, the globally integrated OLR is different on each curve. The OLR at low latitudes is higher, as the dry edge is at higher latitudes.

The OLR in some cases have a depression in the low latitude region because of the greenhouse effect of clouds (see Figure 3.9). The latitude of depression corresponds to the ascending region of the Hadley circulation. Under the large insolation, the Hadley circulation changes its position a little, northward or southward.

While the OLR from the dry low latitudes largely varies with the dry edge latitude, the radiation from the wet high latitudes does not vary so much. This is because efficient transportation of latent heat homogenizes the surface temperature in the wet high latitudes. Moreover, the OLR at the dry edge falls in the rather narrow range between about 250 and 300 W/m^2, in spite of large difference in the peak value at low latitudes (see Figure 3.9). For comparison, I have evaluated the 1-D radiation limit for the different relative humidity using the radiation code extracted from AGCM 5.4g (see Figure 3.10). The radiation limit of this model depends on the relative humidity (RH). Since the RH at the dry edge is about 20% to 60% in the GCM simulations as shown in Figure 3.3 (a). The OLR at the dry edge at the runaway threshold is approximately equal to the radiation limit estimated with 1-D models (from 300 W/m^2 for RH=0.6 to 380 W/m^2 for RH=0.2). Although it is not conclusive whether this value corresponds to the radiation limit itself, it is a common feature that emerges at the runaway threshold for land planets.

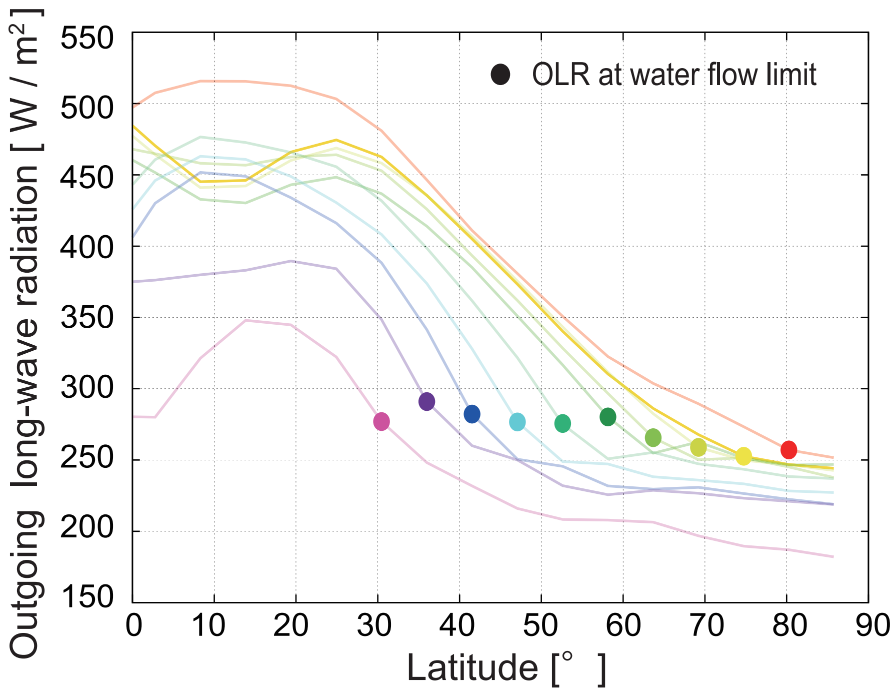

Figure 3.9. The zonal mean outgoing long-wave radiation (OLR) at the runaway threshold for various dry edge latitudes (corresponds to the latitude of the water flow limit). Each circle is the OLR at the water flow limit.

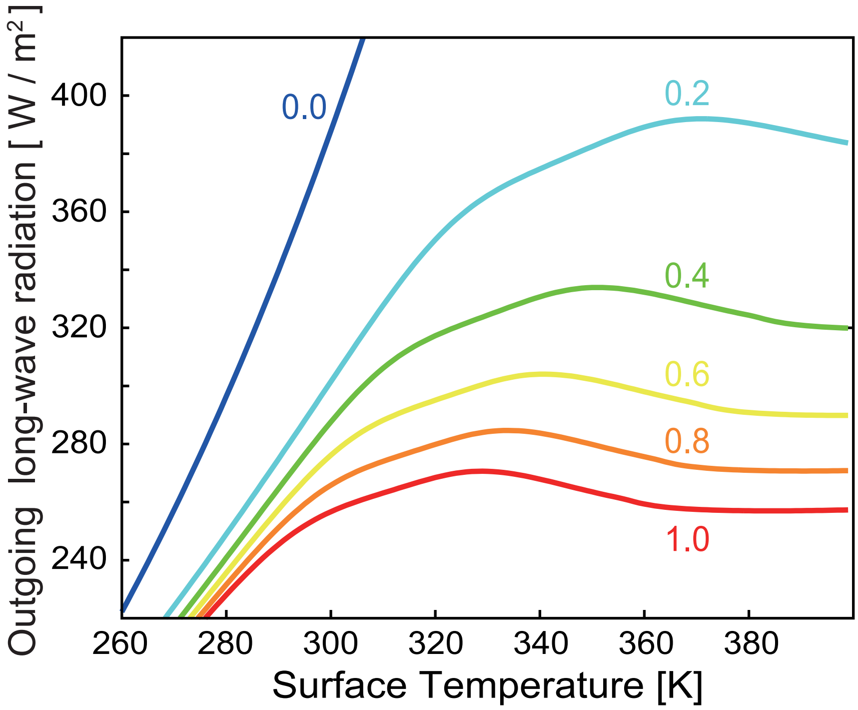

Figure 3.10. 1-D radiation limit with various values of the relative humidity, obtained by use of the radiation code in AGCM 5.4g.

3.4 Estimation of the water flow limit assuming the planetary topography

I have discussed the boundary between the aqua planet mode and the land planet mode in the preceding section, considering the water flow limit. However, it is unclear how much amount of water corresponds to the water flow limit at the boundary. The latter should be closely related to the former on the planetary surface. In order to understand their relationship, here I model the planetary topography and investigate the relationship between the water flow limit and the amount of water on the planetary surface.

3.4.1 The planetary topography

Two kinds of planetary topography are modeled here: ones like the present Earth topography and the present Venus topography. The planetary topography is described by spherical harmonics as (e.g., Rappaport et al. 1999; Wieczorek 2007; Hirt et al. 2012)

$$R(\theta,\phi) = \sum_{l=0}^{\infty}\sum_{m=0}^{l}(\ A_l^m \cos m\theta +\ B_l^m \sin m\theta\ )\ \overline{P_l^m}\ (\sin\phi), \quad (7)$$

where A_l^m and B_l^m are the corresponding expansion coefficients, l and m represent the order of the term, $\theta\ (0 \le \theta \le 2\pi)$ is the longitude, $\phi\ (-\pi/2 \le \phi \le \pi/2)$ is the latitude and $\overline{P_l^m}\ (\sin\phi)$ is normalized Legendre function, which is described as

$$\overline{P_l^m}\ (\sin\phi) =\ (-1)^{-m} \sqrt{(2-\delta_{0m})(2l+1)\frac{(l-m)!}{(l+m)!}}\ P_l^m(x), \quad (8)$$

where the Legendre function is described by

$$P_l^m(x) =\ (-1)^{-m}\ (1-x^2)^{m/2}\ \frac{d^m}{dx^m}\ P_l(x) \quad (9)$$

$$P_l(x) = \tfrac{1}{2^l l!}\tfrac{d^l}{dx^l}(x^2-1)^l. \qquad (10)$$

In order to represent the topography, the normalized Legendre functions is integrated over θ and ϕ. The sets of expansion coefficients for the present Earth and Venus are obtained from the public databases (https://geodesy.curtin.edu.au/research/harmonic.cfm). In this study, $m = l = 84$ is adopted. If l and m are smaller than this value, the roughness of the topography is larger than meshes in the GCM calculations used in this study.

3.4.2 The water flow limit considering the topography

The amount of water on the planetary surface is estimated for each water flow limit with assumed topography in the model. The water flow limit and the amount of water are determined from water capacity of topographic lows (depressions and basins) at higher latitudes.

First of all, the water flow limit is given. Then, if there are no depressions at latitudes higher than the given water flow limit, a new water flow limit is reconfigured. If, on the other hand, there are depressions in this region, the lowest and second lowest depths are searched. The amount of water increases until the lowest ocean level reaches a depression with the second lowest depth. When the lowest latitude of the ocean reaches the water flow limit, the relationship between the water flow limit and the amount of water is determined. In this calculation procedure, each hemispheres is treated separately. Thus, when the water flow limits are difference between both hemispheres, the lower latitude of the water flow limit is treated as the water flow limit.

3.5 The boundary of the amount of water between the aqua planet mode and the land planet mode

Assuming the topographies of the present Earth and Venus, the total amount of water determines the latitude of the water flow limit. In this section, I show the relationship among the water flow limit, the land fraction and the amount of water using the topography of the Earth and Venus.

Figures 3.11 and 3.12 show the water flow limit and the land fraction as a function of the amount of water for the topographies of the Earth and Venus, respectively. In these calculations, water was poured out from the both poles; hence the water flows out from high to low latitudes. The water is stored in depressions at higher latitudes than the water flow limit. Although the edge of the water flow depends on the longitudinal distribution of topography, I have assumed here that the lowest latitudinal edge of the water flow is the latitude of the water flow limit. The longitudinal water transportation is faster than the latitudinal water transportation and the longitudinal surface would get wet uniformly. Thus, I consider such an assumption is valid.

When the amount of water just equal to the one corresponding to the present Earth ocean volume (1.35×10^{18} m^3) (e.g., Menard, 1996) is given, the land fraction is resulted to be 0.26 (compared to the present Earth's land fraction 0.29). The slight difference in the land fraction has come, probably because some lands lower than the average sea level of the current Earth are covered by water in our calculation.

When the amount of water reaches roughly three times the ocean mass of the present Earth, all the planetary surface is covered by the ocean globally (see Figure 3.11). Such planets are ocean planets. Although the latitude of the water flow limit monotonically decreases with increasing amount of water, it changes rather drastically beyond a certain amount of water. With the topography of the Earth, a drastic change in the water flow limit occurs at the amount of water of 10^{16} m^3 (1 % of the present Earth ocean mass). When the amount of water is less than this value, the water flow limit is higher than the latitude 58°. Provided the width of the Hadley cell is comparable with that of the present Earth, such a planet should be in the land planet regime. When the amount of water is more than this value, the water flow limit reaches the Hadley circulation region, and the planet belongs to the aqua planet regime, which is the case with the current Earth. The drastic change of the water flow limit seems to occur at the amount of water that corresponds to the capacity of the topographic lows around the north pole (the Amerasian basin and the Eurasian basin) on the sea floor.

In spite of no ocean on Venus, the Venusian case shows a similar result to that for the Earth's case (see Figure 3.12). A drastic change in the water flow limit occurs around the amount of water of 10^{16} m^3. Intrinsic factors (such as tectonics and mantle evolution) and external factors (such as surface wethering) are responsible for the planetary topography. This issue is important for the planetary climate, but beyond the scope of this thesis.

In this study, I have assumed a symmetric water distribution between hemispheres. An asymmetric surface water distribution is more realistic, as seen in the cases of the present Earth and Venus. It is however suggested that the runaway threshold of such an asymmetric planet can be determined by the dry edge at the lower latitude.

I have also assumed a zonally uniform distribution of surface water for simplicity. Hence, for an aqua planet, the partial ocean planets and ocean planets cannot be distinguished in this study. On the other hand, even when the water flow limit reaches equator, the land fraction is about 0.9 (see Figure 3.11). This means that the area covered with water could be very small at the boundary between the aqua and land planets, suggesting the importance of the longitudinal heterogeneity of water distribution for the climate of land planets. Planets with large ocean cover, should differ little from those fully covered with oceans. On the other hand, in the case of planets with small ocean cover, it might be necessary to consider the longitudinal water distribution to estimate the runaway threshold for land planets with various amounts of water. The longitudinal heterogeneity of water distribution is a further problem. It should be, however, noted that the assumption of the zonally uniform distribution of surface water gives the wettest surface condition for a given water flow limit. Thus, the runaway threshold obtained from this study should be a lower estimate.

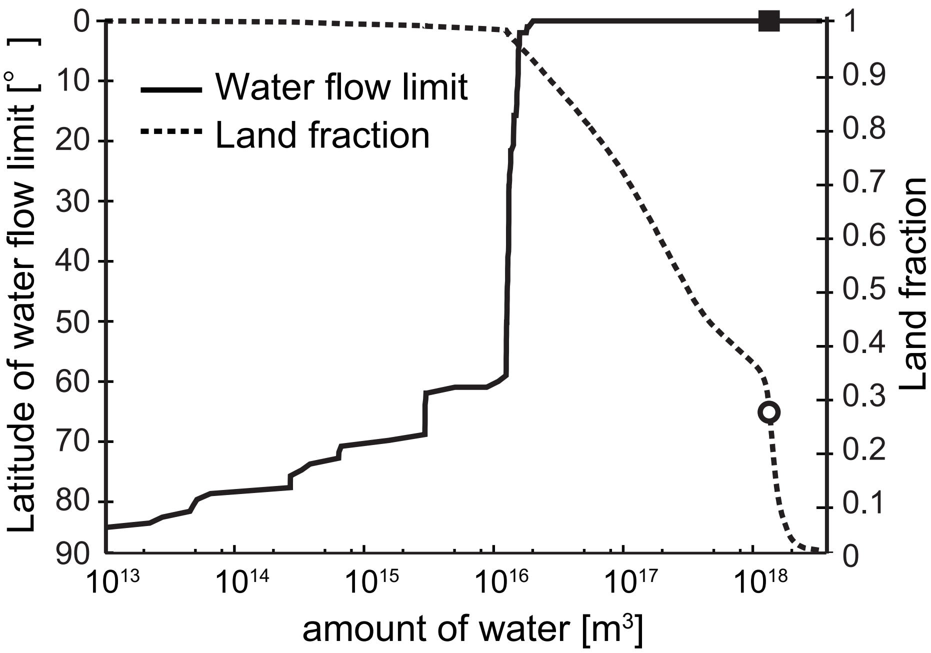

Figure 3.11. Latitude of the water flow limit (solid line) and the land fraction (dashed line) as a function of the amount of water calculated with the present Earth's topography. Circle and square symbols are the latitude of the water flow limit and the land fraction for the present Earth.

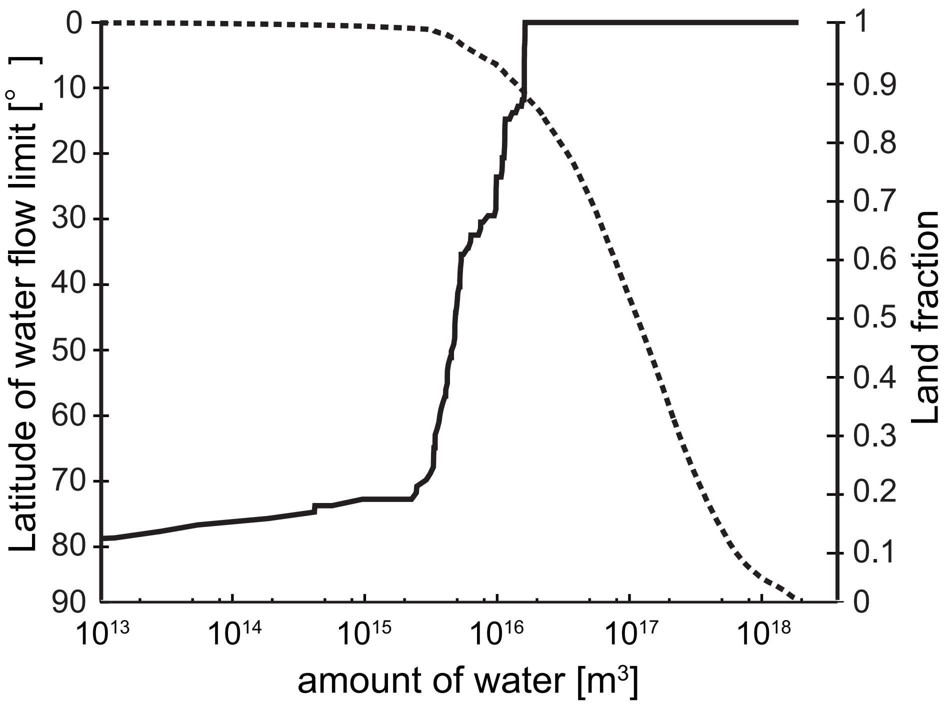

Figure 3.12. Latitude of the water flow limit (solid line) and the land fraction (dashed line) as a function of the amount of water calculated with the present Venus's topography.

Chapter 4 Evolution of Water Planets

I have discussed the evolution of aqua planets through water loss to space, and also the climate stability of land planets with various amounts of surface water. In this chapter, I will discuss the evolution of land planets against an increase in the incident stellar radiation and develope a big picture of the evolution of water planets.

4.1 Evolution of land planets

Based on 1-D climate models, the climate of aqua planets is considered to enter the moist greenhouse state before the onset of the runaway greenhouse effect. This conclusion was verified by 3-D GCM studies. Leconte et al. (2013b) showed that the mixing ratio of water vapor in the upper atmosphere of Earth-like planets remains low until just before the onset of the runaway greenhouse effect. By contrast, Wolf and Toon (2015) derived the opposite result: The climate of Earth-like planets lapse into the moist greenhouse state before the onset of the runaway greenhouse effect. They also showed that if the incident solar radiation increases further by about 2% in the relative solar flux from the incident solar radiation where the moist greenhouse effect occurs, the runaway greenhouse effect takes place.

Abe et al. (2011) considered the extreme case of a land planet with a strongly localized distribution of surface water. The runaway greenhouse threshold for land planets increases with increasing latitude of the water flow limit. It is still unclear whether the climate of land planets lapses into the moist greenhouse state or not. If the atmosphere of a land planet becomes the moist greenhouse state, the surface water of the planet should decrease.

Figure 3.11 in section 3.5 shows the water flow limit and the land fraction as a function of the amount of water, assuming the present Earth's topography. The water flow limit at the boundary between the aqua planet regime and the land planet regime is 25° (see Figure 3.2). With the topography of the Earth, the water flow limit changes rapidly around the water amount of 10^{16} m^3 where the water flow limit changes from 25° to 58° (see Figure 3.11). Although the time elapsed for an increase by 2% in the relative solar flux differs from location to location, it is of the order of ~100 Myr. On the other hand, when the escape of water is diffusion limited (the mixing ratio of water vapor being 10^{-3}), it takes as short as ~10 Myr to escape water of 10^{15} m^3. The mixing ratio of water vapor in the upper atmosphere increases during the period of the moist greenhouse state with increasing the incident stellar radiation. Thus, a land planet can evolve with changing the water flow limit polewards due to the change in the amount of water through water loss, if its atmosphere has lapsed into the moist greenhouse state.

4.2 A big picture of the evolution of water planet

An aqua planet with a relatively small amount of water can evolve from the aqua planet mode to the land planet mode, as discussed in Chapter 2. In the following, I will discuss and redraw the evolution path of a habitable planet focusing the amount of water on the planetary surface.

An aqua planet with the water amount, larger than 0.1 M_{oc} should trace the evolution path proposed in previous studies (e.g., Kasting et al., 1993). Such an aqua planet with a relatively large amount of water evolves into the moist greenhouse state, followed by entering the runaway greenhouse state. Although a rapid water loss to space occurs in the moist greenhouse stage, some of the water survives in this phase. The climate of such a planet eventually lapses into the runaway greenhouse state because of an increase of the incident stellar radiation. In this phase, the planet loses all of the remaining water to space. In the previous studies on the evolution of habitable planets, only this evolution path is considered. This picture for habitable planets and the HZ has been widely applied to discussion of extrasolar habitable planets.

An aqua planet with water amount of water, less than 0.1 M_{oc} could evolve from the aqua planet mode to the land planet mode through a rapid water loss during the moist greenhouse stage. When the amount of water on the planetary surface reaches ~10^{16} m^3 which corresponds to the boundary between the aqua and land planet modes, the planet evolves to a land planet. After that, this planet should evolve as a land planet. As discussed in section 4.1, a land planet loses water on the planetary surface and has the water flow limit move poleward during the moist greenhouse stage. The runaway threshold for a land planet becomes higher with an increase in the latitude of the water flow limit. Thus, a land planet can extend the lifetime of planetary habitability with an increase in the latitude of the water flow limit (see Figure 4.1).

Finally, a land planet from the beginning can maintain liquid water on the planetary surface until a land planet lapse into the runaway greenhouse state. As discussed above, a land planet can evolve with decreasing the amount of water when a land planet becomes the moist greenhouse state. Thus, a planet on the land planet mode from the beginning could maintain liquid water for a long term, and evolve with decreasing the amount of water.

Most studies on habitable planets so far assumed Earth-like planets. Potentially habitable planets in extrasolar planetary systems are discussed based also on the knowledge gained from studies of the Earth. However, I have showed that the habitability is strongly affected by the history of the planet, including the formation and climatic change of the planet. Habitable planets with a wide variety of water amounts should exist in extrasolar systems, because of various formation processes of the habitable planets. Focusing on the amount of water on the planetary surface, there are three evolution paths and two fates of habitable planets. Some habitable planets end up as aqua planets and the others as land planets. At present stage, we are unable to estimate the amount of water on the upper atmosphere using AGCM 5.4g because of technical issues. Thus, whether a land planet evolves to the moist greenhouse state or not remains a challenging problem to be addressed in future.

4.3 Implication for extrasolar habitable planets

In the last two decades, one of the most attractive progresses in science would be the detection of exoplanets in astronomy. The number of exoplanets is increasing day by day and some of them are considered to be terrestrial rocky planets. The improvement of observation technologies allows us to characterize their atmospheric compositions. Discussion for habitable planets in extrasolar planetary systems is based on the classical HZ for an aqua planet, like the Earth. Most recently, a super-Earth sized planet located within the HZ of Proxima Centauri, which is the closest star from the Sun, is detected by radial velocity monitoring (Anglada-Escudé et al. 2016) and the habitability of Proxima Centauri b is discussed with GCM simulations (Turbet et al. 2016). In the next decade, the number of detections of transiting exoplanets around Sun's neighbor stars will rapidly increase via observations by TESS (Transiting Exoplanet Survey Satellite proposed by NASA) and PLATO (PLAnetary Transits and Oscillations of stars proposed by ESA). The number of exoplanets detected by Kepler mission is large, but most of them locate far from the Sun. Thus, both TESS and PLATO in combination with the radial velocity method will tell us more detailed information of exoplanets, such as the information of the internal structure of super-Earths. After these missions, understanding of the atmospheric compositions of the super-Earths will deepen from spectroscopy of the planetary atmospheres by JWST (James Webb Space Telescope) mission. While it would be still difficult to obtain the information of the surface environments on extrasolar terrestrial planets from these missions, TMT (Thirty Meter Telescope) is planned to be constructed, and the extreme adaptive optics equipped in TMT may give us the information of habitable planets. Thus, it is time for preparing for the future observations of the extrasolar habitable planets.

As mentioned above, the threshold of the runaway greenhouse for land planets is larger than that for aqua planets; in other words, the HZ for land planets is wider than that for aqua planets. Therefore, land planets would be interesting targets to be observed. However, it is difficult to identify the amount of water of much less than 1% of the planetary mass from the relationship between the planetary mass and radius even with future observations. Although the spectroscopy of exoplanet atmospheres will tell us whether the planetary atmospheres have water vapor or not, it would be difficult to distinguish aqua planets from land planets.

Furthermore, even if an aqua planet locates in the HZ and has water in its atmosphere, the issue with clouds remains. In the case of the Earth, clouds distribute globally and mask the information of surface properties of the planet. By contrast, clouds on a land planet locate around the polar regions because of the localization of liquid water on the planetary surface. If the distributions of clouds and surface water around poles are detected by highly accurate direct imaging with TMT, we might be able to distinguish aqua planets from land planets. Land planets may be good objects to be observed because of its characteristic features of surface water distribution. We will be able to get closer to extrasolar terrestrial habitable planets by considering land planets as observable targets.

The atmospheric composition of a planet reflects the processes of planetary formation and the climatic evolution. If some spectral features of the planetary atmosphere that depend strongly on planetary history are detected by future observations, we might be able to understand not only what the detected planet is like but also what it was like. Thus, it is necessary to consider atmospheric features caused by events on planets. Although organisms, like oxygen-producing photoautotroph may be necessary to maintain a large amount of oxygen in the planetary atmosphere like the Earth, oxygen can also build up in the planetary atmosphere via a rapid water loss to space that changes the amount of water on the planet surface. If not all of the oxygen is consumed by reductants provided from crusts or volcanic activity, a large amount of oxygen would remain. That causes the false positive on the detection of life. Thus, the detection of oxygen is not always the detection of life.

Additionally, a dying planet would show a typical feature of its atmosphere. Here the “dying planet” means that the planet is approaching the end of its habitability. When a habitable planet receives the radiation from the central star larger than the threshold of the runaway greenhouse, such a planet loses all of water on its surface and its habitability ends because of the onset of the runaway greenhouse effect. Such a planet has a large amount of water in its atmosphere. The surface of the planet may be molten, depending on the amount of water in its atmosphere in the runaway greenhouse state. In this case, the surface of the planet would be covered with a thin magma ocean, and a large amount of carbon dioxide would be released to the atmosphere. The atmospheric features that may trace the planetary evolution will be obtained from future missions. Joint efforts between theoretical and observational studies are strongly required.

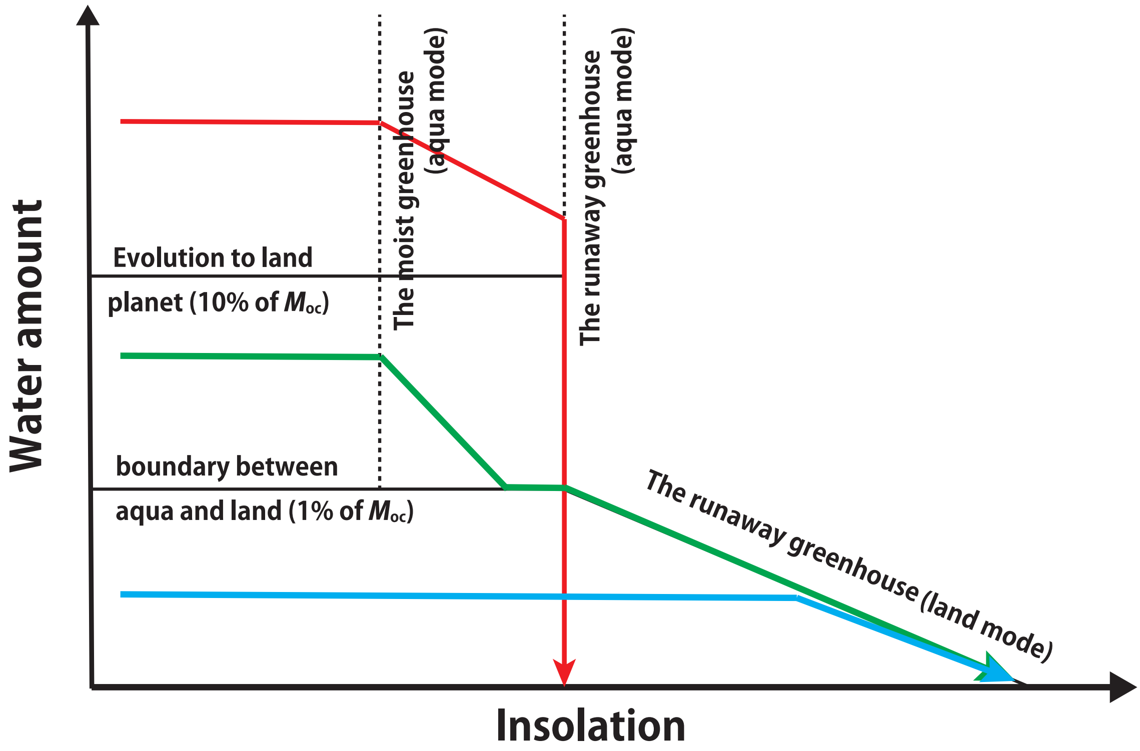

Figure 4.1. Schematic picture of evolution pathways for water planets. Aqua planets with a larger amount of water eventually lapse into the runaway greenhouse state (red line). On the other hand, aqua planets with less than 10% of M_{oc} evolve to land planets, as discussed chapter 2 (green line). If land planets become the moist greenhouse state, such planets evolve with decreasing water amount (blue line).

Chapter 5 Conclusions

In this thesis, I have focused on the amount of water on the planetary surface, which should be one of the key factors for controlling the climate of a habitable planet, and investigated the evolution of a habitable planet through a rapid water loss to space during the moist greenhouse stage to find a possible evolutionary pathway from an aqua planet to a land planet.

As a result, I have found that an aqua planet can evolve to a land planet, provided the initial amount of water on the planetary surface is relatively small (for example, 10% of the present Earth's ocean mass at 0.8 AU). I have assessed various requirements for such evolution. It has turned out that the transition from the aqua to land planet modes can occur if the amount of water on the surface is reduced rapidly by hydrogen escape via photodissociation of H_2O vapor in the upper atmosphere, while the amount of water vapor in the atmosphere remains sufficiently low to prevent the onset of the runaway greenhouse effect. As a result, the planet can maintain liquid water on its surface for a longer time. The two factors are key to the evolution: the critical vapor amount for the runaway greenhouse, M_{cv}, and the maximum liquid water mass for the land planet mode, M_{ml}. The star assumed in this study is basically the same as the Sun. Examining temporal changes in the amount of water on the planetary surface for different choices of the initial amount of water and orbital distance, this study has determined the condition for the evolution from the aqua to land planet modes, and applied these results to re-evaluate the inner edge of the habitable zone.

The evolutionary paths of aqua planets are determined mostly by the initial amount of water, M_{ini}. The climates of aqua planets with large initial amounts of water should evolve to the runaway greenhouse state without evolving to land planets. On the other hand, aqua planets with small initial amounts of water can evolve to land planets. Planets closer to the central star lose their water more quickly, because these evolutionary events take place when the star is younger and thus emits stronger EUV radiation that drives atmospheric hydrogen escape. This implies that aqua planets more easily evolve to land planets at locations closer to the central star.

If M_{cv} is equivalent to 3 m of precipitable water, then an aqua planet with M_{ini} = 0.1 M_{oc} at 0.8 AU can evolve to a land planet, as show in section 2.3. In addition, such a planet can retain liquid water on its surface for an additional 2 Gyr as a land planet. On the other hand, if M_{cv} is less than about 1 m, it is unlikely for any aqua planet to evolve to a land planet. This value of M_{cv} corresponds to the amount of water vapor in the atmosphere that causes the rapid loss of water equivalent to a substantial fraction of the Earth's ocean mass. By contrast, the dependence of the evolutionary pathway on M_{ml} (the upper bound on the amount of water that defines a land planet) is weak relative to that on M_{cv}, indicating that the value of M_{cv} is more important as a condition from the aqua to land planet mode.

It is important to stress that the evolution pathway newly found in this study suggests the presence of a new type of continuously habitable zone where aqua planets can evolve into land planets and maintain liquid water on their surface for an additional period of time. Rapid escape of water not always leads to terminating the habitability of the planets, but instead results in extending the habitable period by evolving to a new and different kind of habitable planets, namely land planets.

On land planets, the surface water distribution is important for habitability, which is controlled by the water transport both on the planetary surface and in the planetary atmosphere. Thus, I have introduced a parameter called the water flow limit in this study. This parameter represents the efficiency of the water transport on the planetary surface. Then I have investigated the effect of the surface water distribution on the threshold of the runaway greenhouse effect using the GCM, AGCM 5.4g.

From the 3-D simulations, I have confirmed that there are two regimes on the threshold of the runaway greenhouse effect with respect to the latitudinal surface water distribution, namely, the aqua planet regime and is the land planet regime. The difference between two regimes is due to that in the behavior of the atmospheric circulation. Water vapor is in general transported not only poleward but also equatorward. When the water flow limit is located inside the region of the Hadley circulation, the planetary surface is wet globally. In this case, even a planet with a small amount of water, behaves as an aqua planet. Thus, the threshold of the runaway greenhouse in this regime is almost the sane as that for aqua planets. On the other hand, when the water flow limit is located at high latitudes and outside the Hadley circulation region, the atmosphere at latitudes lower than the water flow limit is dry and the threshold of the runaway greenhouse increases with an increase in the latitude of the water flow limit.

The latitude of the water flow limit is a function of the amount of water. To relate the water flow limit with the amount of water, I have assumed the planetary topography and estimated the amount of water for various values of the water flow limit. I have found that the amount of water at the boundary latitude between the aqua planet regime and the land planet regime is approximately 1% of the present Earth's ocean volume, assuming the present Earth's topography.

In conclusion, there are three evolutionary pathways depending on the amount of water on the planetary surface: evolution only in the aqua planet mode, evolution from the aqua planet mode to the land planet mode and evolution only in the land planet mode. The atmospheric features of planets with each evolutionary pathway will provide valuable information to future detect of habitable exoplanets. These suggestions will make a significant impact on the further survey of terrestrial habitable planets.

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