Atmospheric Structures of Ocean Planets: A Study of Mechanisms to Determine Inner Edge of Habitable Zone

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Introduction
The inner edge of the “Habitable Zone” is determined by “Radiation Limit” mechanisms!

Previous study 1: Nakajima et al. [1992]
RL 1: the KI-limit
A condition for a stratospheric structure is obtained by a parameter α.

Previous study 2: Nakajima [2006]
The RLs depend on planetary mass!

RL 2: the radiation limit of the troposphere
The radiation limit becomes larger when the heating by the absorption occurs r < 0.1.

Method for Structure Calculation
These studies ignore the absorption of incoming central star radiation in the planetary atmosphere!

In this study
We assumed a plane parallel atmosphere as previous studies. As a first step, we assumed the atmospheric composition is pure water vapor and the mass is same as the Earth’s one.

Method 1: simplified absorption model
Absorption of Incoming Radiation
Incoming radiation heat balance equation

\[ F_{\text{in}} = \frac{k_{\text{tot}}}{\pi \alpha} \left( 1 - e^{-\tau} \right) \]

Planetary Emission and Absorption
Can be calculated using two-stripen approximation

Method 2: line-by-line calculation
Absorption of Incoming Radiation
Can be calculated using line-by-line approximation with HITRAN database

Absorption of Incoming Radiation
\[ F_{\text{in}} = \frac{k_{\text{tot}}}{\pi \alpha} \left( 1 - e^{-\tau} \right) \]

Purpose
These studies ignore the absorption of incoming central star radiation in the planetary atmosphere!

(1) We clarify the effect of the absorption on the two kind of radiation limits!

Method 1: the absorption reduces the KI-limit at lower layer.
Method 2: the absorption makes the radiation limit of the troposphere larger. This is because the absorption reduces the incoming radiation reaching photosphere.

(2) We suggest a new atmospheric structure of an ocean planet, and the condition for the structure to form is obtained!

Change of KI-limit
The result shown in Fig. 6 can roughly be separated into two regions:

- a < 0.3: The KI-limit becomes smaller,
- b > 0.3: The KI-limit becomes unchanged.

Values of the KI-limit calculated with method 2 are shown in Table 1.

<table>
<thead>
<tr>
<th>Method</th>
<th>KI-limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1</td>
<td>3500 [K]</td>
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<tr>
<td>Method 2</td>
<td>3500 [K]</td>
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</tbody>
</table>

Values of the KI-limit with method 1 correspond to the change of a and b.

Another Radiation Limit
When the incoming radiation is larger than the KI-limit, the atmosphere can not have moist-convective troposphere.

Fig. 10: radiative equilibrium atmospheric structure corresponds to radiating the layer which is larger than the KI-limit

Conclusion
We studied the effect of the absorption of incoming central star radiation, using (method 1) “Simplified absorption model” and (method 2) line-by-line calculation.

(1) The KI-limit becomes smaller when the heating by the absorption occurs r < 0.1.

(2) The possibility of a new atmospheric structure of an ocean planet, “dry atmosphere”, was obtained.

As a future work:
- We consider dry- and moist-convective in line-by-line structure calculation.
- We include the effect of “continuum absorption” of water vapor in the calculation.