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# Exotic water worlds: how life-friendly is a deep ocean?

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## Abstract

Water is necessary for the origin and survival of life like we know it. In the search for life-friendly worlds, ocean planets therefore seem to be obvious candidates and have attracted increasing attention in the past years. The ocean on such planets could be hundreds of kilometers deep depending on the water content and the evolution of the proto-atmosphere.

In our study we address the question if life can form and develop in these oceans, i.e. if they are habitable, from a geophysical point of view. We concentrate on the necessary condition of liquid water and sufficient nutrients supply for the origin of life. We employ an ocean model to infer the depth-dependent physical state and the different phases of water and ice.

## 1. Introduction

The search for suitable habitable planets has been dominated in the last decade by Earth-like exoplanets up to 10 Earth masses, the so-called super-Earths. Neptune-like planets or ocean planets attracted some attention in the last years as they contain a large amount of (liquid or frozen) $H_2O$.

These planets can have oceans with hundreds to thousands of kilometers depth. High-pressure ice may form, which restricts the possible habitability of such planets. Another constraint is the supply of sufficient nutrients, which [2] postulate is only possible in shallow oceans.

## 2. Model

The existence and thickness of a possible ice layer depends on the melting temperature of ice and the temperature profile in the ocean. The melting temperature of ice has to be exceeded to obtain liquid water. To determine the temperature in the ocean-ice-layer, we use different surface temperatures. We only consider ocean planets where the surface is not covered by an ice layer, and hence assume surface temperatures between 273.2K and 373K (i.e. 0°C and 100°C). We consider pure water and neglect other influences on the melting temperature (e.g. salinity).

For the sake of simplicity, we model a temperature that increases adiabatically with depth in the whole ocean layer, i.e. we assume strong convection in both solid and liquid parts and neglect possible thermal boundary layers. We vary the adiabatic increase of the temperature with depth over a wide range of values and investigate if general tendencies may be observed for an increase or decrease in habitability, where we considerer a planet to be most likely habitable (see Fig. 2), if its ocean is entirely liquid without temperatures in the lower ocean exceeding the maximal temperature extremophiles on Earth can cope with (~400K). Note, however, that non-Earth-like life may as well exist at larger temperatures.

The gravitational acceleration $g$ depends on the mass of a planet and the distance to the planet's center $r$ (Eq. 1). $g$ is integrated from the surface downwards. The pressure $p$ is also obtained by integration from surface downwards (Eq. 2), where standard equations of state (e.g. [3]) are used for the pressure-dependent density $\rho$ of water and silicates. Note that for the sake of simplicity we neglect the minor temperature influences on the density. We do however consider different depth-dependent densities for water and ice phases.

$$dg/dr = 4\pi G \rho - 2g/r \quad (1)$$

$$dp/dr = -g \rho \quad (2)$$

## 3. Formation of High-Pressure Ice

We assess the influence of variations in surface temperature, mass, as well as ocean layer depth on the ocean habitability, see Fig. 1.

We observe that the larger the planet's mass, the shallower is the depth where the ice-layer forms. Second, for larger surface temperatures, the size of the liquid water layer increases. Depending on the adiabatic increase of the temperature with depth, in few cases a second liquid layer can appear above the ocean-mantle boundary (OMB). Ocean planets with such a liquid-ice-liquid structure may be restricted habitable (H2 in next section).

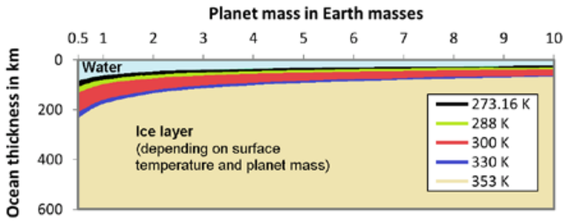


Figure 1: Coloured regions show the start of the ice layer depending on the surface temperature; the light blue area denotes liquid water.

## 4. New Habitability Class System

[1] introduced an habitability classification where ocean planets have been considered as Class V habitats next to Earth-like (Class I), Venus- and Mars-like (Class II), Europa-like (Class III) and Ganymede-like bodies (Class IV). We discuss possible sub-classes for Class V habitats in this study.

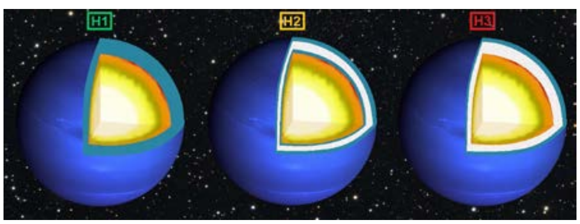


Figure 2: Possible interior structures of ocean worlds with liquid water at their surface. The ocean layer can be completely liquid (H1), frozen in the bottom part (H3), or have a liquid-ice-liquid structure (H2).

There are three conceivable scenarios for a planet with an ocean that is liquid at the surface (Fig. 2). The first would be an ocean that is completely liquid. The second scenario involves the formation of a high-pressure ice layer on the bottom of the ocean. The third alternative would be an ocean with a high-pressure ice layer which is molten at its bottom, creating a layered structure of liquid-ice-liquid .

## 5. Summary and Conclusions

Concerning candidates for the highest possible habitability in the ocean planets category, we observe the following trends for different ocean sizes, surface temperatures and planet masses concerning the likely habitability class:

- An increasing surface temperature allows for increasingly large, entirely liquid oceans (H1 ocean planets).
- A high surface temperature furthermore reduces the thickness of a possible ice shell, and therefore shifts H3 planets back to the H2 class.
- An increasing planet mass reduces the maximal ocean size for H1 planets and rather shifts a planet into the H2/H3 class.
- The larger the planet radius for a fixed mass (i.e. the smaller the average density of a planet), the larger is the liquid water layer, increasing the likelihood of it being in the H1 habitability class.

In addition, both plate tectonics and active volcanism contribute to the possible habitability of an ocean. The non-existence of one or both mechanisms would reduce the habitability, and should therefore be considered as habitability restriction for H1 and H2, see Fig. 3. The temperature at the bottom of the ocean should be considered as well.

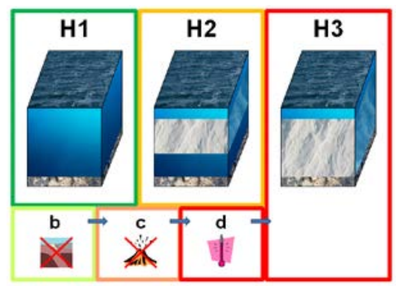


Figure 3: Our proposed new habitability classification for ocean planets.

## Acknowledgements

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