ATMOSPHERIC COMPOSITIONAL VARIATIONS DUE TO CHANGES IN MANTLE REDOX STATE

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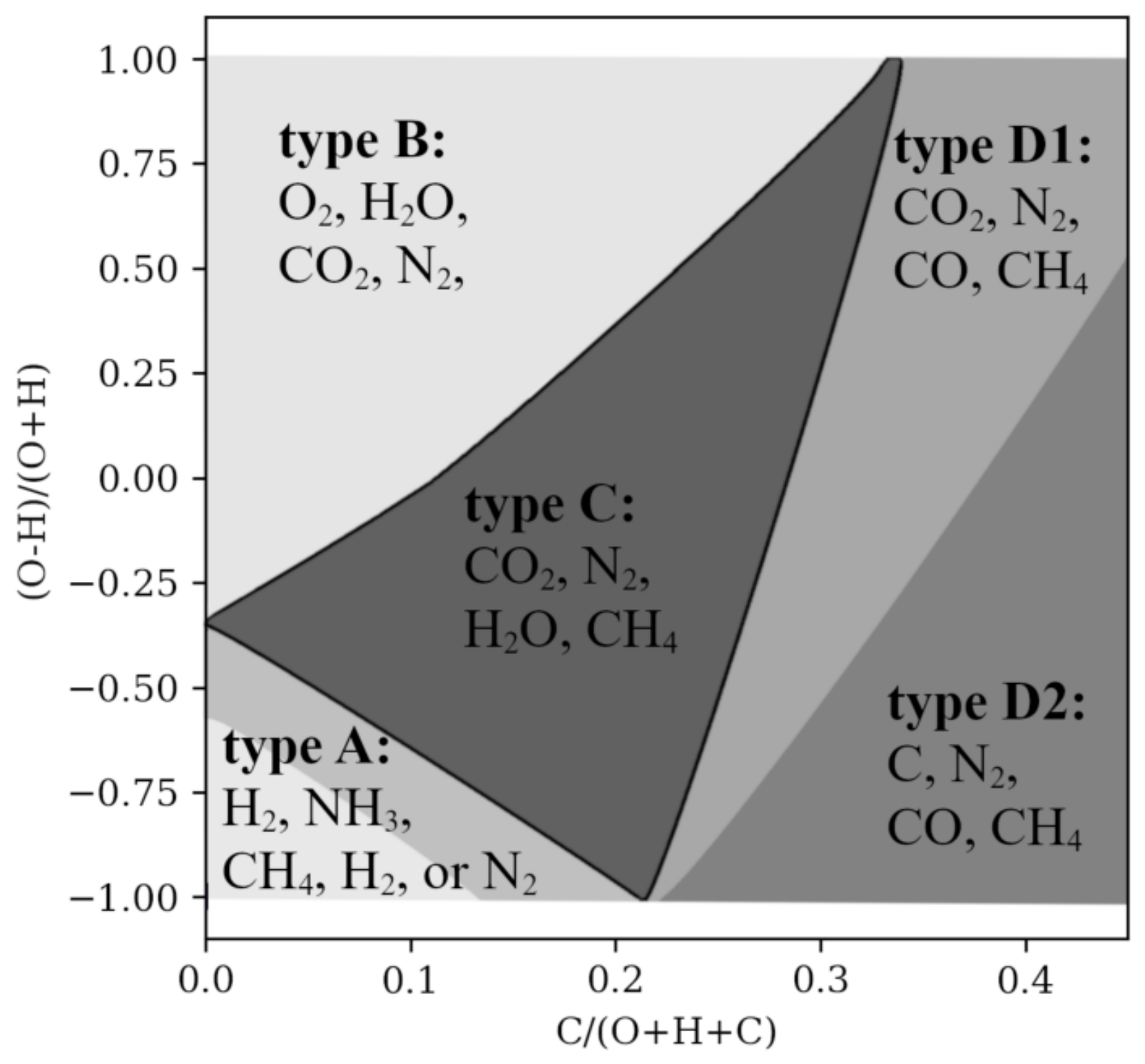
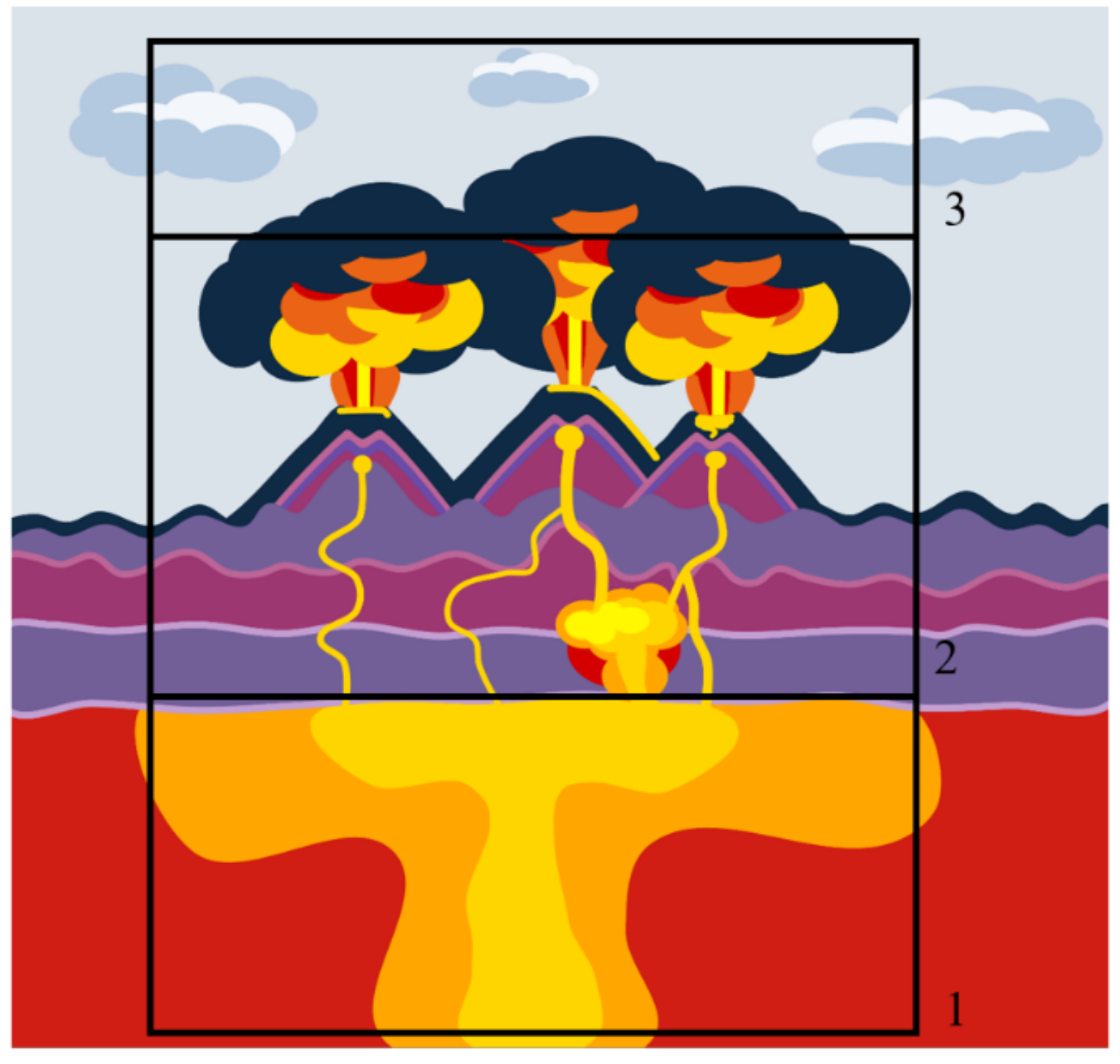
Introduction

The internal constitution of rocky exoplanets can be inferred only indirectly via their atmospheric composition. To address this issue with confidence requires the coupling of interior and atmospheric models to each other. In the past, various atmospheric redistribution models were developed to determine the composition of exoplanetary atmospheres by varying element abundance, temperature, and pressure. One example of such a model was published by Woitke et al., 2021, they used a simple stochiometric approach to calculate chemical equilibrium in the C-H-O-N system and proposed a classification of exoplanet atmospheres based on their 4 most abundant gases: type A atmospheres contain H_2O, CH_4, NH_3 and H_2 (A1) or N_2 (A2). Type B Atmospheres contain O_2, H_2O, CO_2 and N_2 and type C atmospheres contain H_2O, CO_2, CH_4 and N_2, these types are visualized in Fig. 1. However, this model as well as similar work neglects that present-day atmospheres were formed via volcanic degassing and, consequently, elemental abundances are limited by thermodynamic processes accompanying magma ascent and volatile release. Here we combine a volcanic outgassing model with the model used by (Woitke et al., 2021) to simulate the evolution of C-H-O-N atmospheres in thermal equilibrium below 650 K.



1.

Methods

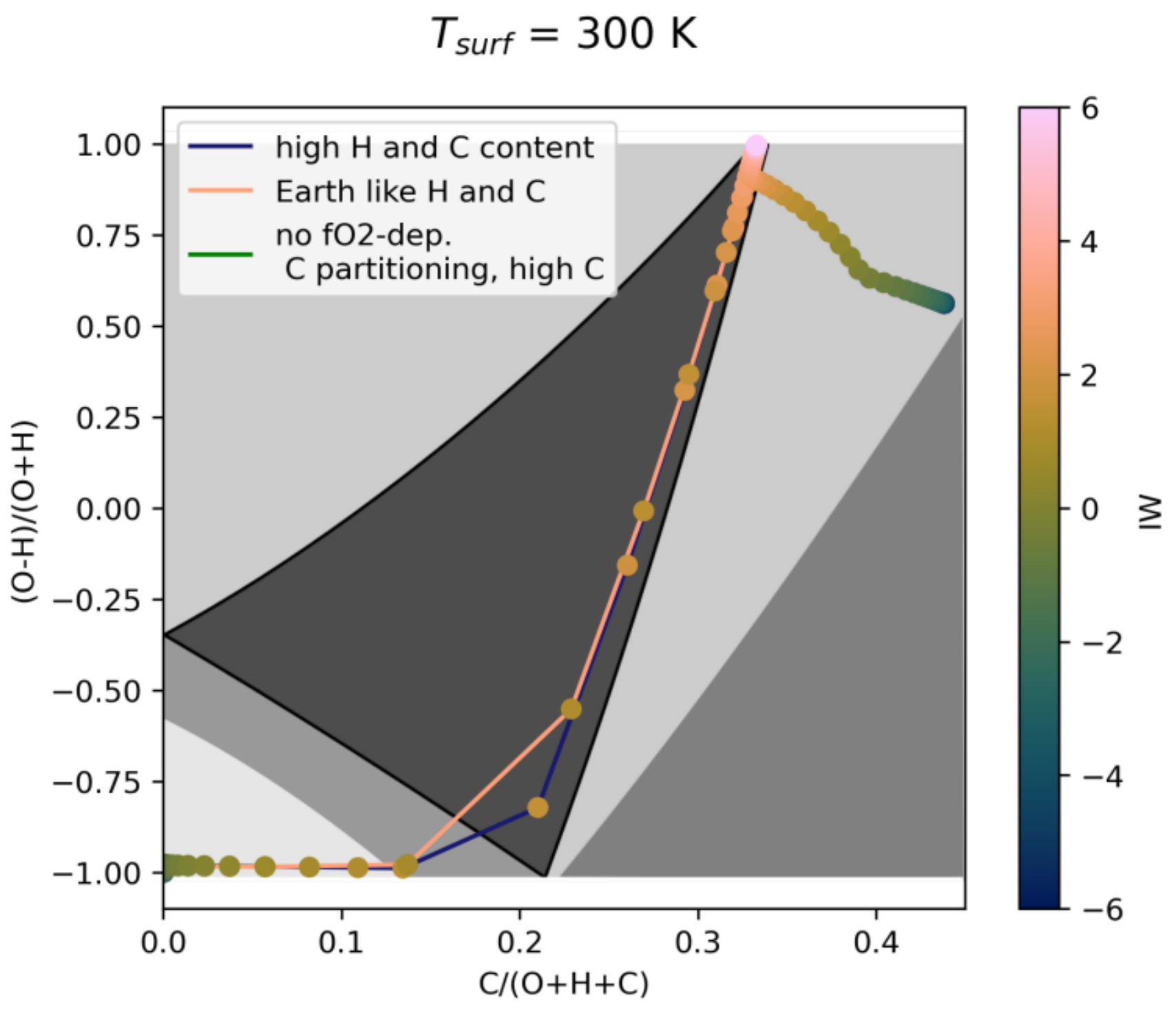


Parameter	Unit
mantle temperature	2000 K
melt temperature	1400 K
mantle pressure	10 GPa
planet radius	6371 km
gravitational acceleration	$9.81\,m\,s^{-2}$
initial atmospheric pressure	10^{-8} bar
mantle Hydrogen	450 ppm
mantle Carbon	50 ppm
mantle Nitrogen	10 ppm
melt fraction	0.1

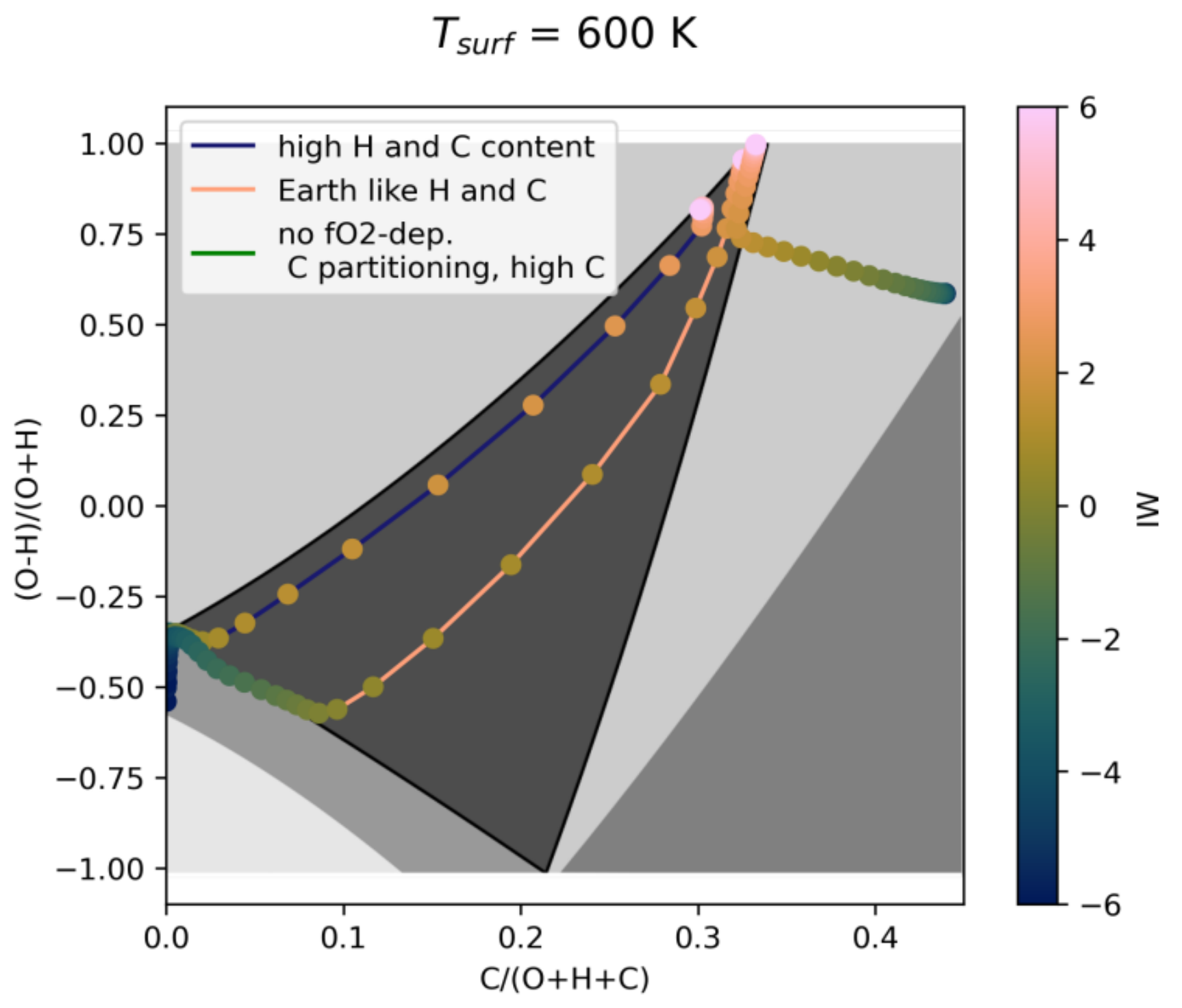
Tab. 1: Model parameters held constant for a generic planet of one Earth mass used in all computations

Figure 2 shows a simple sketch of the routine built to calculate secondary atmospheric composition on Earth-like planets. The 3 main steps of the routine are: 1. mantle melting 2. volcanic gas speciation and degassing (modified after (Ortenzi et al., 2020)) 3. atmospheric redistribution after (Woitke et al., 2021) and Fastchem (Stock et al., 2022). Furthermore, we consider atmospheric processes such as water condensation, hydrogen escape, and the effect an already existing atmosphere has on further degassing.

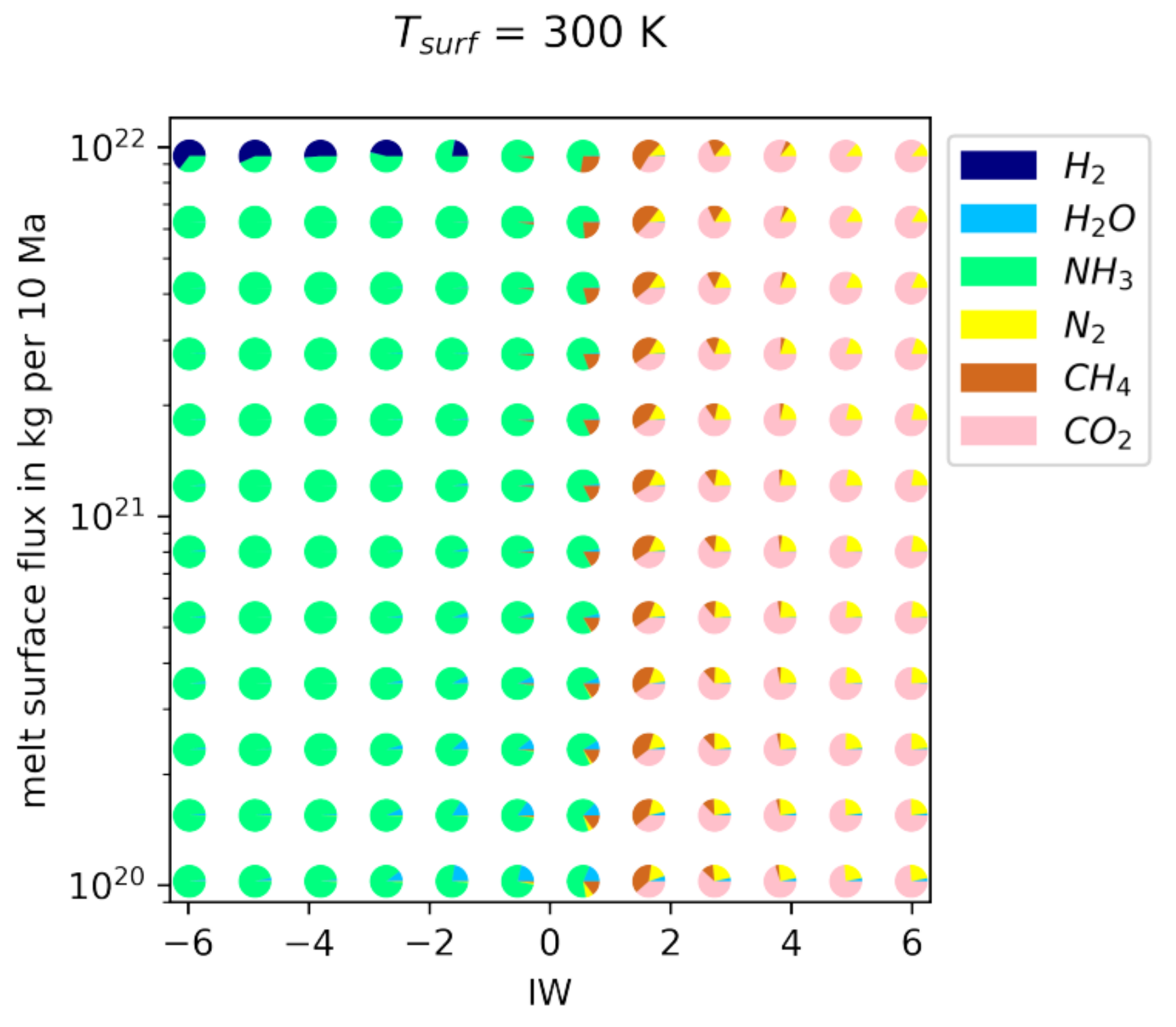
Results and Discussion



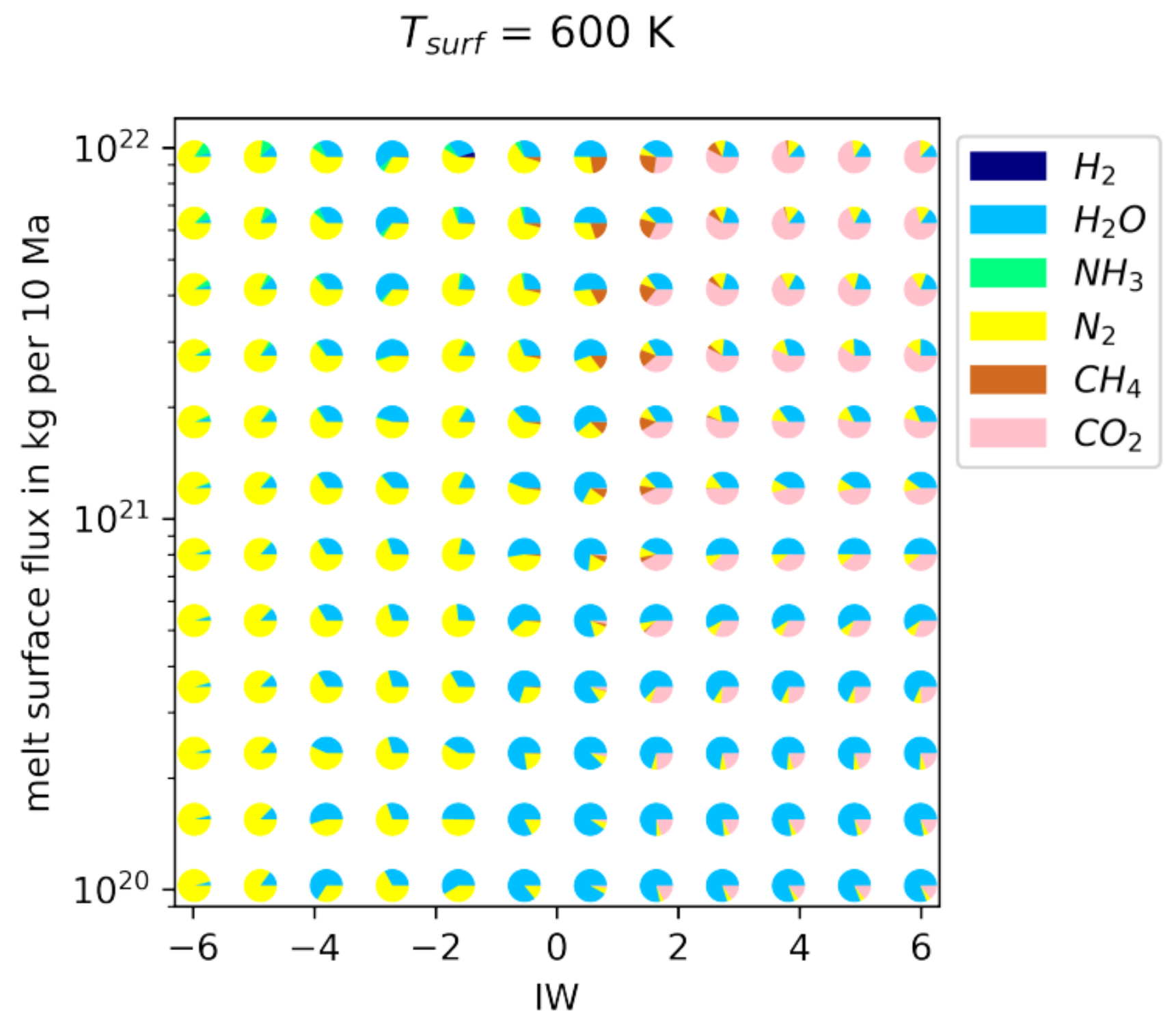
3a.



3b.

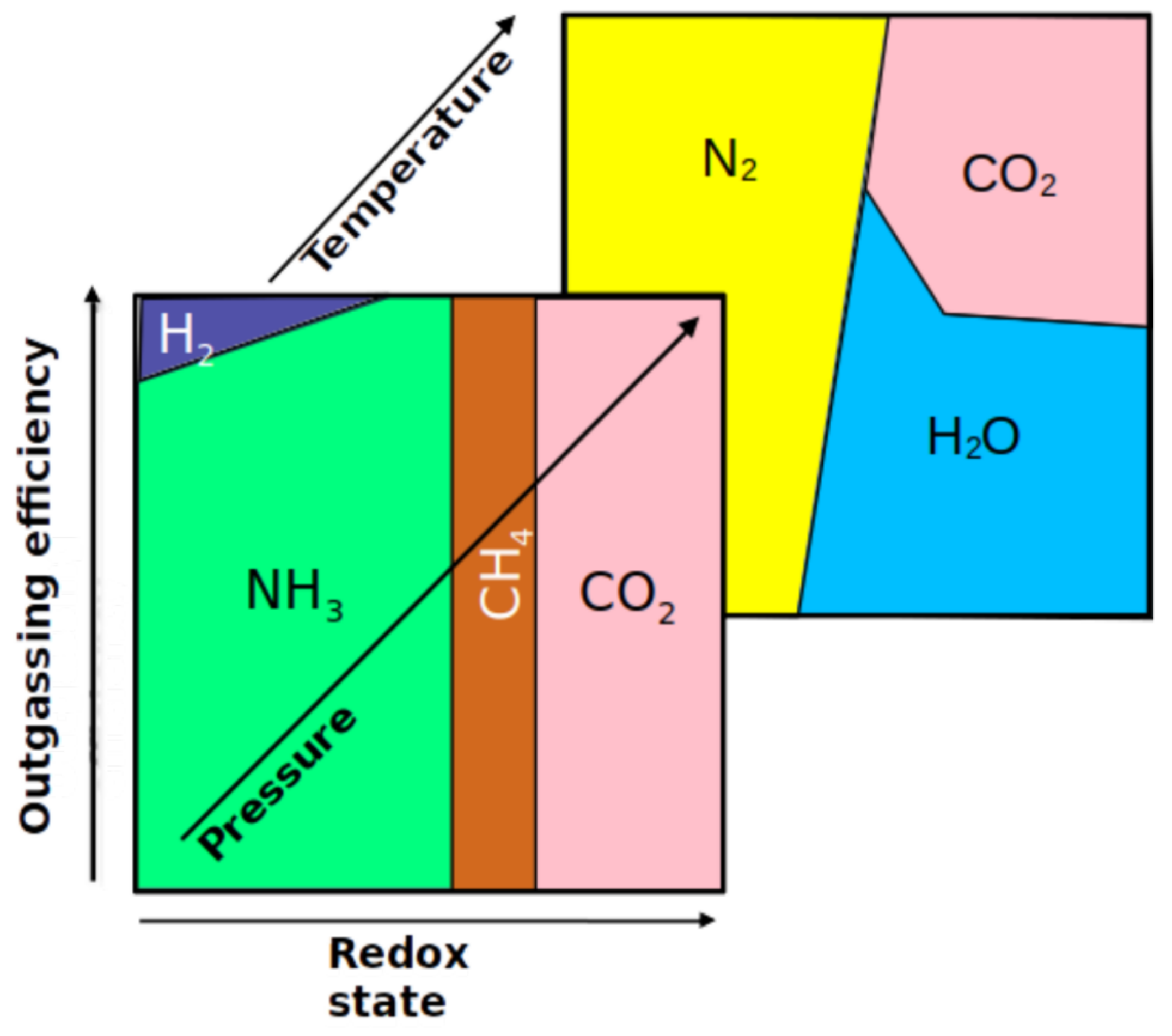


4a.



4b.

Figures 3a and 3b show the resulting atmospheric composition after 1 Ga at 300 K (3a) surface temperature and 600 K (3b) respectively for different initial oxygen fugacities and volatile contents within the Woitke Diagram. The color-coded dots show the mantle fugacity varying from IW -6 to IW +6. Figures 4a and 4b show the resulting atmospheric compositions as pie charts while varying not only oxygen fugacity but also the amount of extrusive melt produced by the planet We vary the melt production between 10^{13} kg/ and 10^{15} kg/ extending the lower and upper limits shown by (Guimond et al., 2021). Melts with low oxygen fugacities produce H_2-NH_3 dominated atmospheres with very low atmospheric pressures and only minor amounts of Carbon species. With increasing oxygen fugacities the atmospheric pressure increases and more carbon species (commonly CO_2 and CH_4) appear in the atmosphere as well as H_2O and N_2. Super oxidized magmas produce CO_2, N_2 and depending on surface temperature also H_2O dominated atmospheres with high atmospheric pressures. Varying the initial volatile abundance generally just leads to a shift along the lines but not to a significantly different atmospheric composition. The most common atmospheric type is type C atmospheres. Reduced mantles can lead to the formation of A atmospheres. O_2 dominated Type B atmospheres are never produced via degassing since O_2 does not degas by itself but always as CO_2, CO or H_2O. Type D atmospheres may form if oxygen-fugacity-dependent carbonate partitioning is ignored, oxygen fugacities are low, and/or carbon contents are high.



Summary and Conclusions

We have developed a model to investigate how volcanic degassing will affect the evolution of terrestrial planet atmospheres in the C-H-O-N system below 650 K.

- **The mantle redox state has a significant influence on the composition of planetary atmospheres**
- **The most common atmospheres to be expected on exoplanets are type C atmospheres**
- **Type A atmospheres are formed at low mantle oxygen fugacities**
- **Type B atmospheres are never formed in our calculations**
- **Type D atmospheres may form under certain conditions**
- **Surface temperature and melt production rates are additional key parameters for bulk atmospheric composition**

References

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