THE CLIMATE OF EARTH AND EARTH-LIKE (EXO)PLANETS IN COUPLED EVOLUTION MODELS: INSIGHTS FROM 3D GCM.

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Introduction: We investigate the past evolution of the climate of Earth and Earth-like planets as a coupled interior/atmosphere system. We compare climatic states obtained through parameterized modelling versus a physics-based 3D General Circulation Model (GCM). Finally, we identify characteristics in the 3D simulations that most affect the climate, and how that impacts the reliability of parameterized modeling.

Motivation: In long-term planetary evolution studies, surface conditions are often characterized using global average temperatures, and calculated using simple models (i.e., Eddington approximation, 1D radiative convective gray atmosphere). For instance, these models treat albedo and cloud cover in a parameterized way and are not always able to assess local variations (i.e., latitudinal). A more self-consistent approach uses a 3D GCM, which requires extensive computing resources and time. This makes GCMs unpractical for long-term evolution modelling. Instead, here, we do time slice experiments, with successive windows into the past states of the atmosphere/surface are modeled.

Methods: The past thermal history of Earth's interior is used as a representative case for a range of possible past states and evolution of the mantles of Earth-like exoplanets under the plate tectonics regime [1]. This feeds a parameterized model for mantle thermal and dynamic evolution. From the computation of melt generation and volcanism, the volatile delivery from the mantle into the atmosphere is estimated. The model is coupled with a simple parameterization of surface temperature depending on greenhouse gases concentration and a model of surface weathering depending on surface water and surface temperature. This setup produces a variety of atmospheric composition evolutionary pathways, which, in turn, govern planetary climate evolution [2].

Climate: We use the ROCKE3D GCM [3] during significant windows of the long-term evolution to understand the differences between the parameterized (coupled evolution) and more complete (GCM) approaches. We compare average surface temperatures and albedos obtained in both simulations. We then evaluate the ice coverage obtained in GCM simulations and compare it to the usual criteria for habitability (such as average temperatures above 273-258 K). Finally, we assess the reasons for discrepancies between the models.

Parameters: We study the influence of the total atmosphere pressure, and its composition (N_2, CO_2, O_2, CH_4), consistently with Earth observation, as well as solar insolation and length of day variation with time, depending on the different eras we consider. We further study the impact of continental distribution (i.e., present-day-like or supercontinent distributions) and topography. We use the mantle dynamics output in the coupled model, based on the thermal history, to assess the characteristics of the surface features from mantle convection velocity.

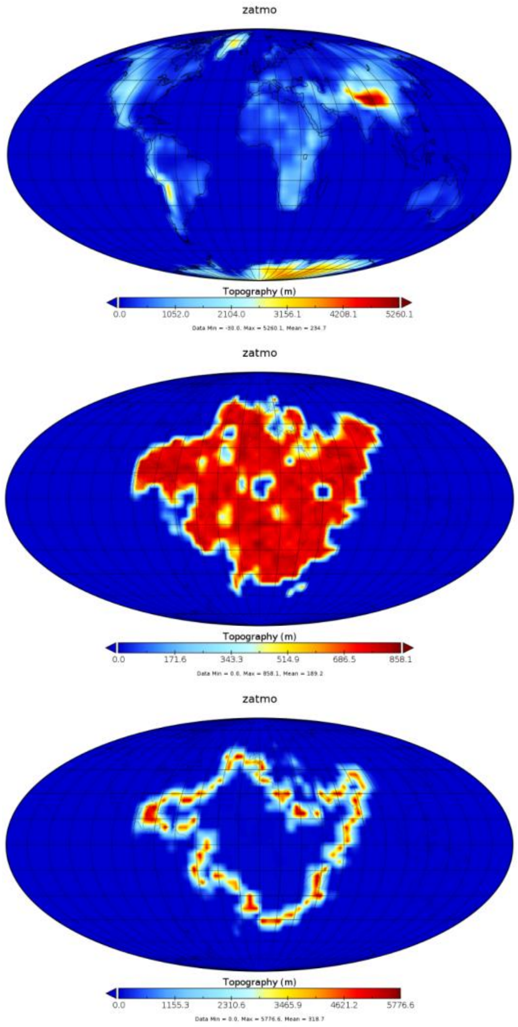

Figure 1: Continental setups (elevation) tested in the GCM simulations. Top: present-day continents, middle: supercontinent, bottom: supercontinent with high mountain at the rim and low (1-200m) plains [4].

Results: The trend of the variations of average temperature through time (and CO_2 abundances) is consistent in parameterized vs. GCM models. In general, lower past insolation results in lower surface temperatures, but is compensated by higher greenhouse gas abundances. Perturbation around the reference model results in stronger temperature variations in the GCM due to albedo feedback. Indeed, the albedo variations can be significant in 3D simulations and are not considered in the parameterized approach (fixed albedo at present-day Earth value). Albedo evolution is dominated by the effect of the ice layer at high latitudes, with a secondary contribution of clouds at low latitudes.

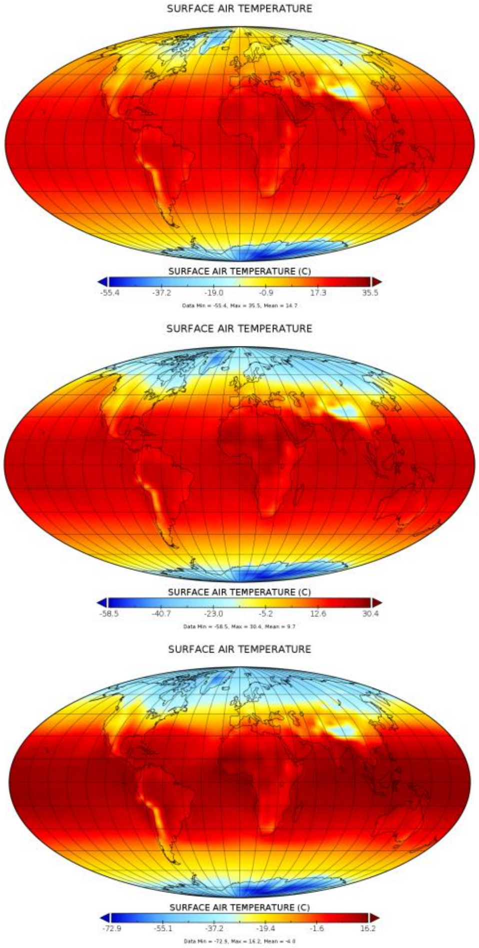

Figure 2: Surface temperatures from GCM simulations (present-day continent layout, blue crosses in figure 3), present-day (top), 1 Ga (middle) and 2.9 Ga (bottom).

Length of day has a marginal effect on the simulations. Simulations where the only difference is the continental setup result in only 1-2 K difference in average surface temperatures. Supercontinent setups result in markedly dryer land than present-day Earth, which has implication for their habitability. Even models with average temperatures below 273-268 K have significant ice-free ground in all continental setups, with less than 20% ice coverage: low to mid latitudes remain ice-free.

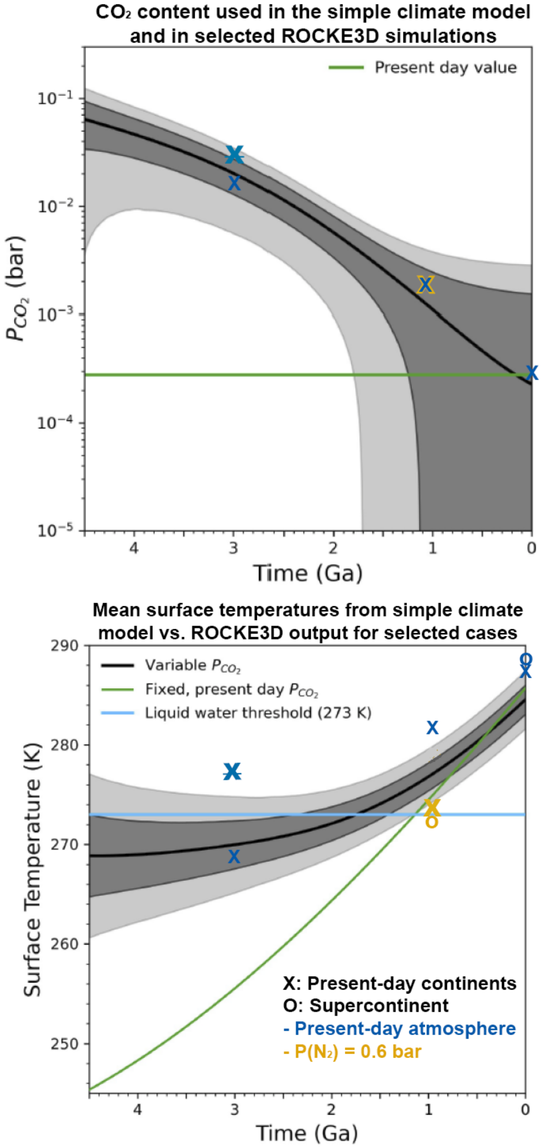

Figure 3: comparison between the evolution scenarios calculated from coupled parameterized models from [1] and corresponding GCM simulations. Blue crosses are the most direct comparison between the models (GCM vs parameterized).

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References:

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