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Habitability of Earth-like planets with high obliquity and eccentric orbits: results from a general circulation model

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We explore the implications of seasonal variability for the habitability of idealized Earth-like planets as determined by the two parameters polar obliquity and orbital eccentricity. Commonly, the outer boundary of the habitable zone (HZ) is set by a completely frozen planet, or snowball state. Using a general circulation model coupled to a thermodynamic sea-ice model, we show that seasonal variability can extend this outer limit of the habitable zone (HZ) from 1.03 AU (no seasonal variability) to a maximum of 1.69 AU in our experiments.

Moreover, our results show that also the multistability property of planets close to the outer edge of the HZ is influenced by seasonal variability. Cold states extend farest into the HZ for non-oblique planets. On highly oblique planets, cold states can also allow for habitable regions, which highlights the sufficient but not necessary condition of a warm climate state for habitability. Further, the range of distances that allow for two stable climate states decreases with eccentricity, possibly leading to monostability for planets with very large seasonal variations.

Sensitivity experiments exploring the role of azimuthal obliquity, surface heat capacity, and maximal sea-ice thickness show the robustness of our results. An uneven distribution of annual mean irradiation among the two hemispheres extends the HZ outwards, whereas a reduction of heat capacity has only a negligible effect on the extent of the HZ. On circular orbits, our results are in good agreement with previous studies that use a one-dimensional energy balance model. Yet large differences on eccentric orbits hint to limitations of these simpler models.

To our knowledge, this study provides for the first time a qualitative assessment of the effects of seasonal variability on the habitability of Earth-like planets that is based on a three-dimensional climate model. Differences found in the comparison with previous work underline the importance of using climate models that explicitly account for potentially very different atmospheric circulations and further climate processes such as ice formation and melting in parametric investigations of the HZ.