THE EFFECT OF CO₂ ICE CLOUD CONDENSATION ON THE HABITABLE ZONE

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In the traditional habitable zone the radiative effects of clouds have been ignored

The outer edge of the habitable zone has been defined by the maximum greenhouse effect, a clear-sky case where greenhouse warming by additional CO₂ is balanced by additional Rayleigh scattering. The radiative effects of CO₂ clouds have been ignored because they were thought to always warm the surface (Forget & Pierrehumbert 1997).

However, recent work by Kitzmann et al (2013) and Kitzmann (2016) used multi-stream radiative transfer to show that the early 2-stream approximations exaggerated the warming effect. We now know that the previously neglected radiative effects of CO₂ clouds must be considered when taking into account the outer edge of the habitable zone.

Validation of Kitzmann et al (2013): CO₂ ice clouds may be warming or cooling depending on particle properties

We ran our radiative transfer model (SMART) for over 2500 combinations of optical depth and particle size and placed a CO₂ ice cloud in the atmospheric region of condensation. We then determined if the cloud produced a net warming or cooling effect compared to the clear-sky case, as shown in the figure to the right. CO₂ ice cloud effects in our multi-stream model atmosphere show clouds may be warming or cooling depending on the effective particle size and cloud optical depth, which matches the results of Kitzmann et al (2013).

Our Radiative Transfer Model: SMART

Spectral Mapping and Atmospheric Radiative Transfer

Line-by-line
Multi-stream
Multiple scattering
Vertically-resolved atmospheric layers
Computes spectra and layer-resolved heating rates

Our Climate Model

Using SMART as the core, we have developed a generalized 1D radiative-convective equilibrium (RCE) climate model for terrestrial exoplanets with secondary outgassed atmospheres. The model includes bulk thermodynamics and simple cloud microphysics, which allows us to self-consistently determine cloud properties and radiative effects for a range of condensates.

Model Attributes:

Convective adjustment (Manabe & Strickler, 1964)
simple or turbulent mixing length theory with eddy diffusion
exchange of sensible heat
phase changes
condensation & evaporation
adjustment of condensate vapor mixing ratios
exchange of latent heat
Cloud formation
tracking of condensate material flow and sedimentation (rainout)
full radiative/scattering treatment w/evolution of optical depth

Preliminary Conclusions

Using our new climate model with self-consistent CO₂ ice cloud condensation and multi-stream, multi-scattering radiative transfer, our results suggest that the true outer edge of the habitable zone is likely the CO₂ first condensation limit, as originally suggested from qualitative arguments by Kasting et al (1993), not the maximum greenhouse limit, which neglects the radiative properties of clouds.

We have a new generalized terrestrial climate model that we can apply to exoplanet studies, which has been validated for Earth, Mars, and Venus, which includes sophisticated radiative transfer with convection, condensation, and cloud treatment.

Future Work

We will soon investigate non-spherical particles since ices are likely not well-approximated by spheres, which most climate models use when they compute aerosol scattering. We will conclude this work with both CO₂ and H₂O cloud condensation together with their radiative effects treated self-consistently.

References

Arney et al (2016)
Kasting et al (1993)
Kitzmann (2016)
Meadows & Crisp (1996)
Manabe & Strickler (1964)
Robinson et al (2011)
Tepley et al (2005)

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