THE EFFECT OF CO_2 ICE CLOUD CONDENSATION ON THE HABITABLE ZONE

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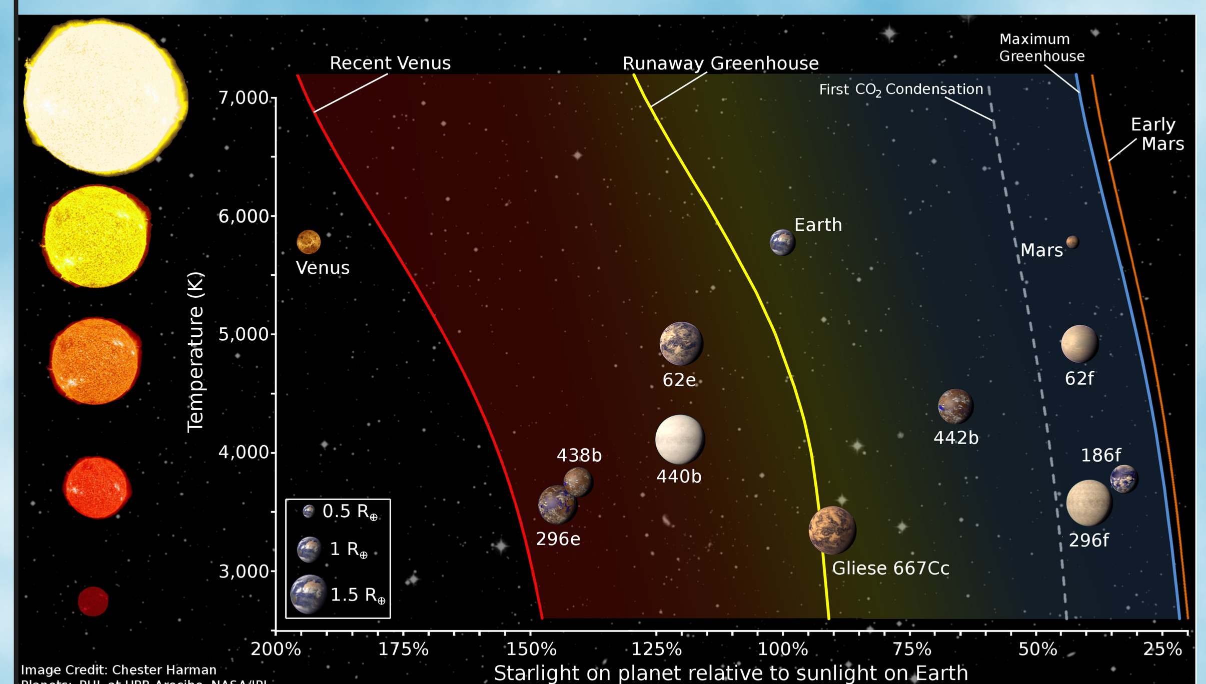
IN THE TRADITIONAL HABITABLE ZONE THE RADIATIVE EFFECTS OF CLOUDS HAVE BEEN IGNORED



The outer edge of the habitable zone has been defined by the maximum greenhouse effect, a clear-sky case where greenhouse warming by additional CO_2 is balanced by additional Rayleigh scattering. The radiative effects of CO_2 clouds hve been ignored because they were thought to always warm the surface (Forget & Pierrehumbert 1997).

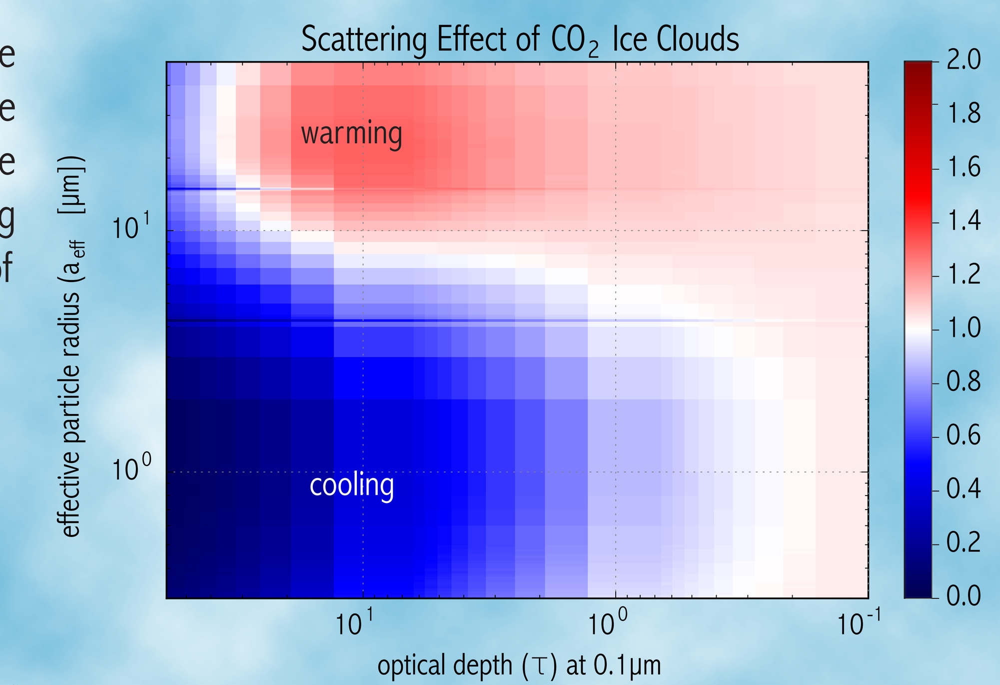
However, recent work by Kitzmann et al (2013) and Kitzmann (2016) used multi-stream radiative transfer to show that the early 2-stream approximations exaggerated the warming effect. We now know that the previously neglected radiative effects of CO_2 clouds must be considered when taking into account the outer edge of the habitable zone.

VALIDATION OF KITZMANN ET AL (2013): CO_2 ICE CLOUDS MAY BE WARMING OR COOLING DEPENDING ON PARTICLE PROPERTIES

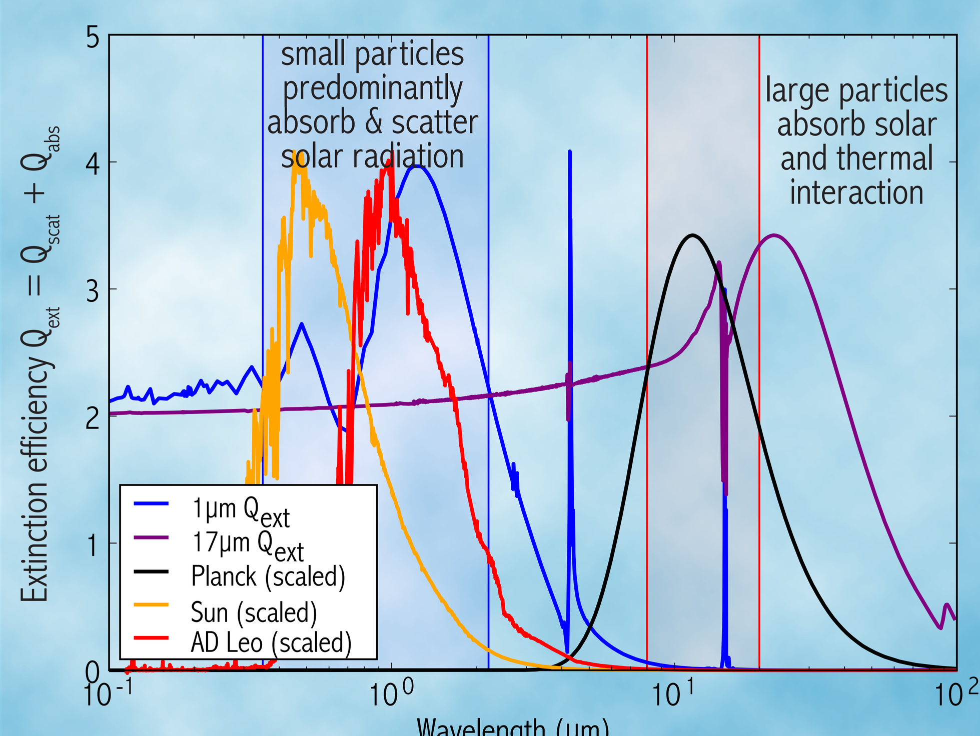
We ran our radiative transfer model (SMART) for over 2500 combinations of optical depth and particle size and placed a CO_2 ice cloud in the atmospheric region of condensation. We then determined if the cloud produced a net warming or cooling effect compared to the clear sky case, as shown in the figure to the right. CO_2 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 match the results of Kitzmann et al (2013).

OUR RADIATIVE TRANSFER MODEL: SMART

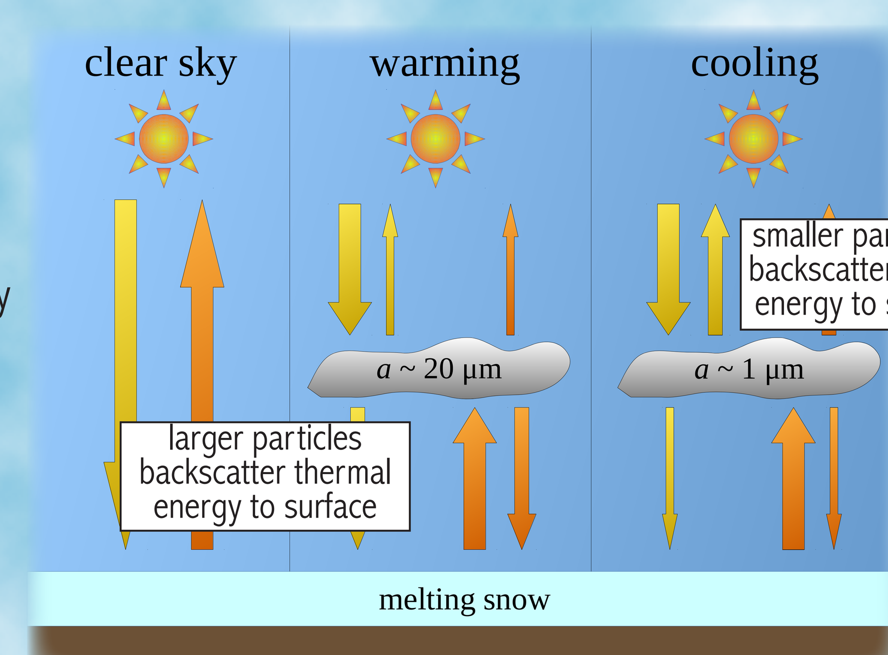
Spectral Mapping and Atmospheric Radiative Transfer	
(Meadows & Crisp, 1996)	Line-by-line
Terrestrial validations:	Multi-stream
Venus: Arney et al (2014)	Multiple scattering
Earth: Robinson et al (2011)	Vertically-resolved atmospheric layers
Mars: Tinetti et al (2005)	Computes spectra and layer-resolved heating rates



WARMING OR COOLING BY CLOUDS IS DETERMINED BY THE INTERPLAY BETWEEN WAVELENGTH AND PARTICLE SIZE



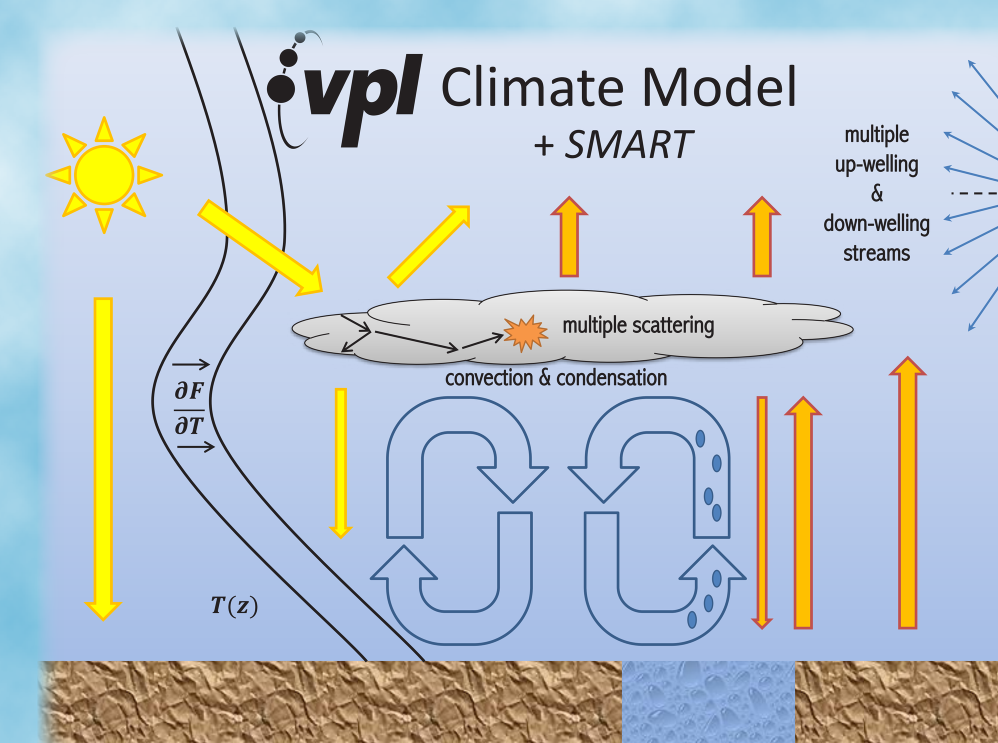
Left: Extinction efficiency of CO_2 ice particles of radii 1 μm (blue) and 17 μm (purple), scaled stellar spectra of the Sun (yellow) and AD Leo (red), and a 273 K blackbody (black). Larger particles (purple) interact with stellar (yellow/red) and thermal (black) wavelengths, while the smallest particles have reduced extinction at thermal wavelengths and so predominantly interact with stellar wavelengths. This implies that larger particles may have a mild warming effect as concluded by previous studies, while smaller particles can scatter most of the incoming stellar energy and cool the surface.



Right: Illustration of how clouds composed of different particle sizes can interact with incoming and outgoing stellar and thermal radiation. Depending on the fraction of radiation transmitted and the ratio of upward scattered solar and downward scattered thermal flux, these clouds could either cool or warm the surface.

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:

CONVECTION
simple convective adjustment (Manabe & Strickler, 1964)
simple or turbulent mixing length theory with eddy diffusion
exchange of sensible heat

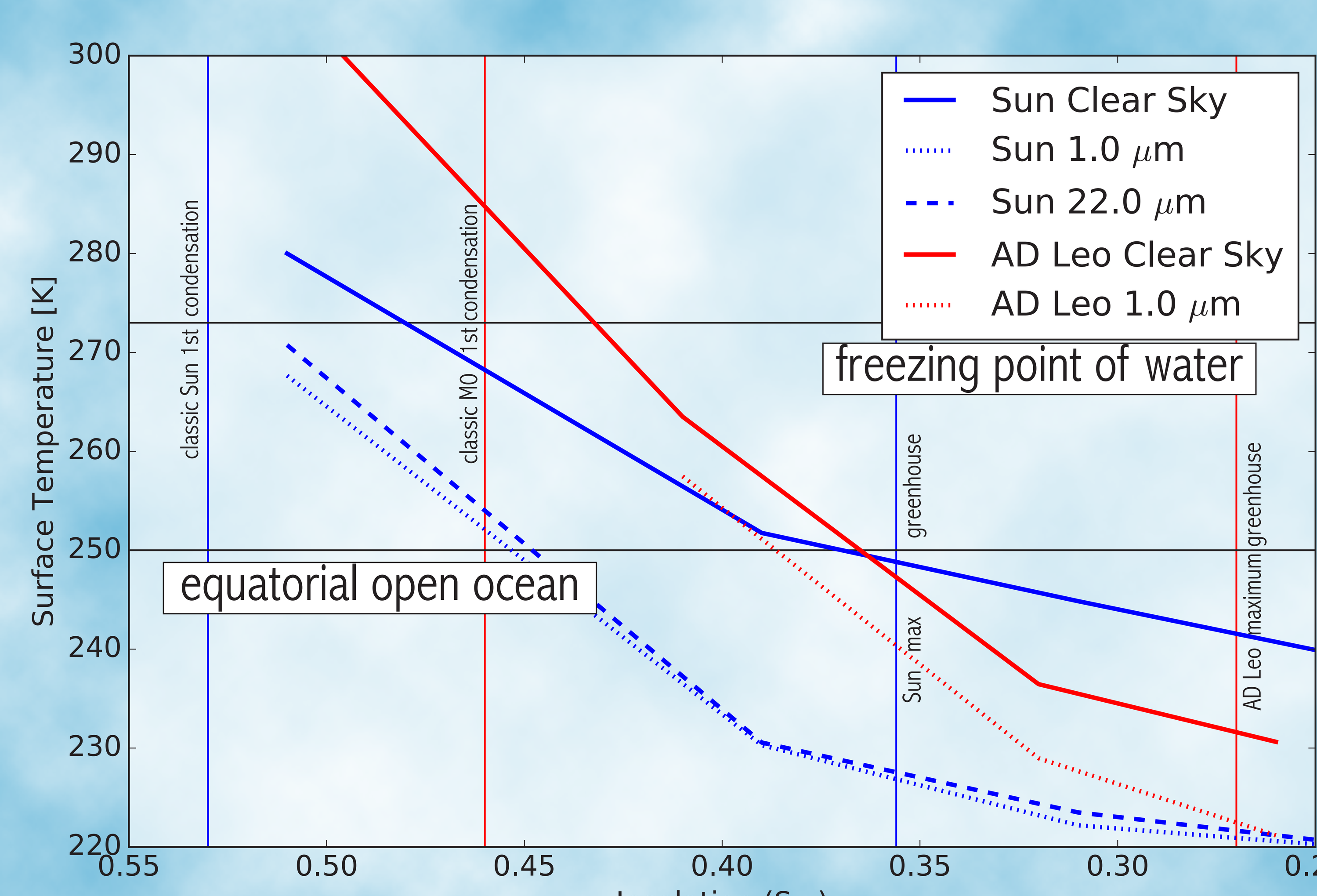
PHASE CHANGES
condensation & evaporation
adjustment of condensate vapor mixing ratios
exchange of latent heat

CLOUD FORMATION
tracking of condensate mass
sedimentation (rainout)
full radiative/scattering treatment w/evolution of optical depth

CO_2 CLOUDS LOWER SURFACE TEMPERATURE AND TRUNCATE THE OUTER EDGE OF THE HABITABLE ZONE

Right: Planetary surface temperature vs insolation relative to Earth for planetary atmospheres with 7 bar CO_2 and 1 bar N_2 orbiting the Sun and M dwarf AD Leo. Initially, we ran the clear sky case with radiative transfer and convective adjustment. Once the clear sky case indicated CO_2 condensation, subsequent runs used self-consistently determined cloud mass and optical depth, and used mixing length theory for convection. Each model was then iterated and evolved, allowing the radiative and convective processes to affect the atmospheric/surface temperature and cloud properties. Even though the larger CO_2 ice particles locally warm the atmosphere, there is insufficient warming to maintain a surface temperature above the freezing point of water.

These preliminary results using our multi-stream, multi-scattering 1D RCE climate model indicate that the first condensation limit of CO_2 represents the outer edge of the habitable zone, as originally argued qualitatively by Kasting et al (1993).



PRELIMINARY CONCLUSIONS

Using our new climate model with self consistent CO_2 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 CO_2 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 CO_2 and H_2O cloud condensation together with their radiative effects treated self-consistently.

REFERENCES

Arney et al (2014)
Charnay et al (2015)
Colaprete & Toon (2003)
Forget & Pierrehumbert (1997)
Forget et al (2013)
Kasting et al (1993)
Kitzmann et al (2013)
Kitzmann (2016)
Kopparapu et al (2013)
Manabe & Strickler (1964)
Meadows & Crisp (1996)
Robinson et al (2011)
Tinetti et al (2005)

ACKNOWLEDGEMENTS

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