Behavior and Stability of Ground Ice on Ceres: Initial Clues from Dawn

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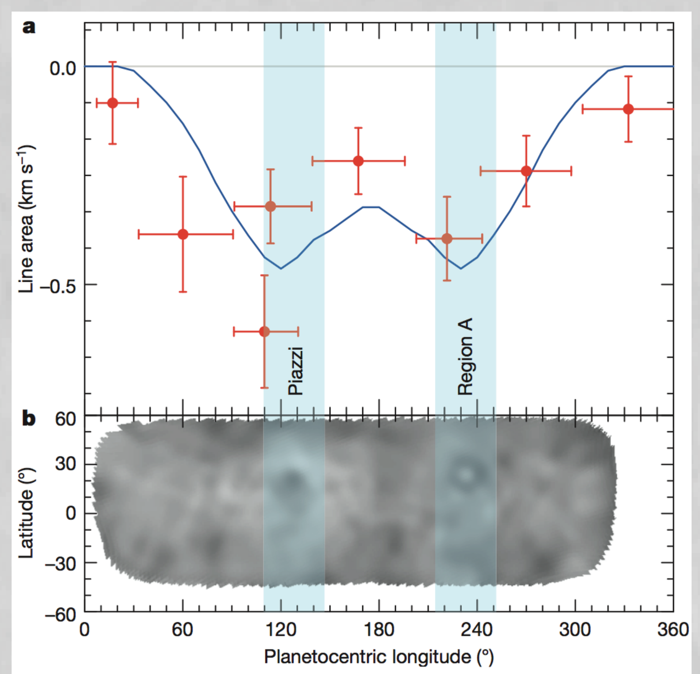
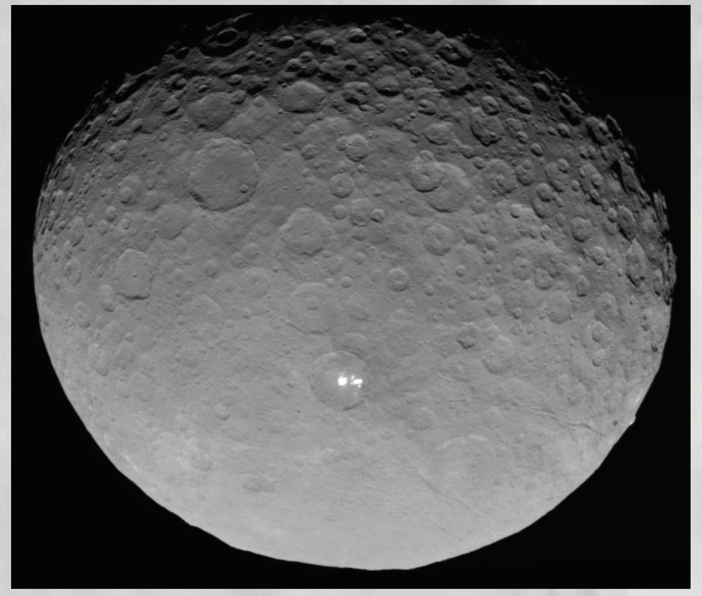
30-Second Summary

- Ceres is an ice-rich body surrounded by water vapor.
- Ground ice retreats up to decameters over geologic time, but this cannot explain the observed quantities of water vapor.
- If ice exists in the Occator-Crater bright spot then its sublimation would explain the observed quantities of water vapor.
- Dawn's neutron spectrometer should expect to detect ground ice at latitudes >65.

Observations

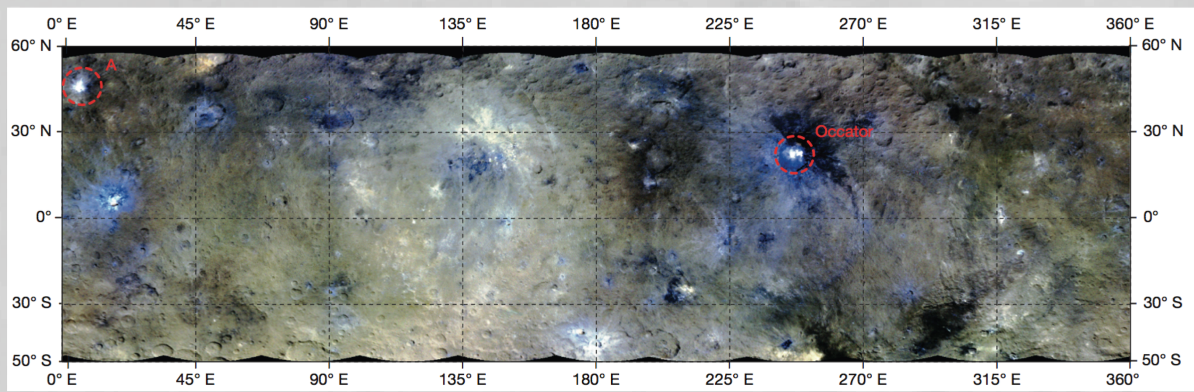


Kuppers et al. (2014) used Herschel sub-millimeter data to discover water vapor surrounding Ceres that appears to vary spatially. They estimate a vapor production rate of 6 kg/s



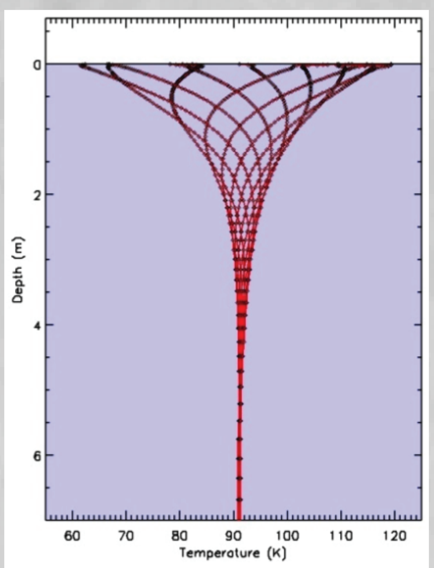
Dawn Framing Camera data show an absence of polar frosts and several high-albedo spots such as those in Occator crater.

Nathues et al. (2015) assign a composition of hydrated magnesium sulfate to Occator's bright spot & argue its diurnal brightness variations can be explained by a haze generated by sublimating ice.



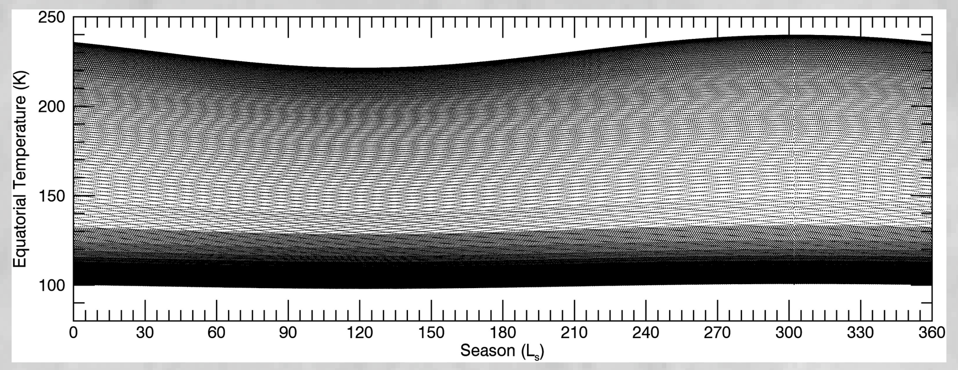
Thermal Model

- One-dimensional stack of layers that exchange energy via conduction. Solved with a semi-implicit numerical scheme.
- Top boundary balances thermal emission with insolation and conduction to the interior. Bottom boundary has a constant heat flow.
- Material thermophysical parameters can change with depth.
- Surface slopes and multiply-scattered radiation can also be included

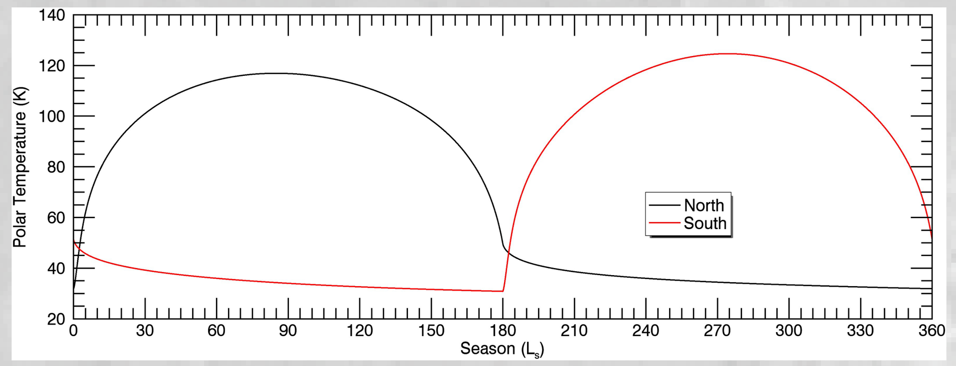


Runs shown here use a surface albedo of 0.09 and thermal inertia of 15 unless otherwise noted.

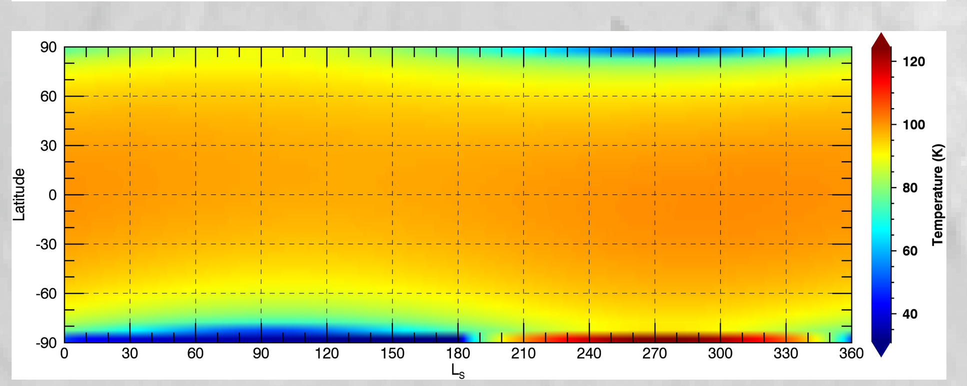
Typical Temperatures on Ceres



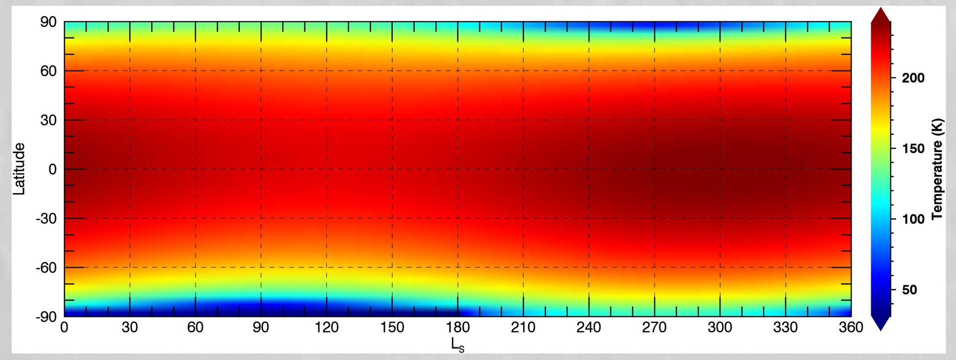
At the equator



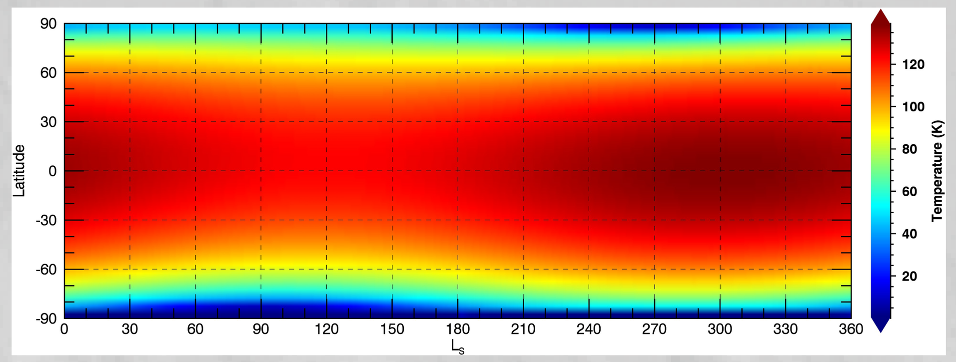
At the poles



Diurnal minima



Diurnal maxima



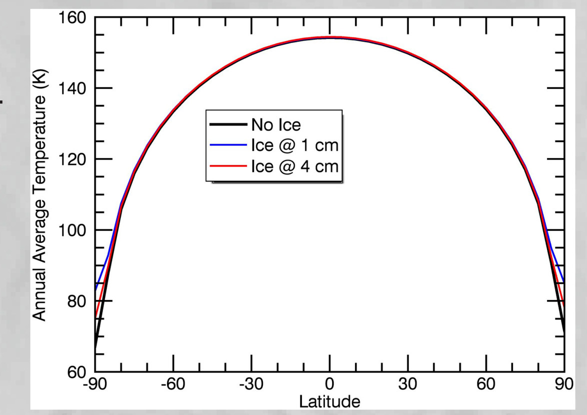
Diurnal range

Retreat of buried ice

Ice sublimates away in a vacuum environment at a temperature-dependant rate. Buried ice sublimates more slowly than surface ice but always retreats without a resupply mechanism.

Can slow retreat of buried ice explain near-Ceres water vapor?

Ice buried by more than a few centimeters is at the annual average surface temperature. This ice also doesn't affect annual average surface temperature



Mass flux exposed to vacuum: $J = \left[\sqrt{\frac{\mu}{2\pi kT}} P_{vap}\right]$

Mass flux through granular medium: $J = \left(\frac{4\pi}{8+\pi}\frac{\phi}{1-\phi}\frac{1}{\tau}\right)\left(\frac{r}{h}\right)\left[\sqrt{\frac{\mu}{2\pi kT}} P_{vap}\right]$

Where: Vapor pressure, $P_{vap} = P_o e^{-\frac{L}{R}\left(\frac{1}{T}-\frac{1}{T_o}\right)}$
R is the universal gas constant
k is Boltzmann's constant
L is the latent heat of sublimation of water
P_o and T_o are a reference pressure and temperature
μ is the molecular mass of water
r is the particle radius
ϕ is the porosity
τ is the tortuosity
ρ_{ice} is ice density

We calculate annual average surface temperatures and convert to mass flux of sublimated water through a granular medium using the approach of Schorghofer (2008) based on Evans et al. (1961)

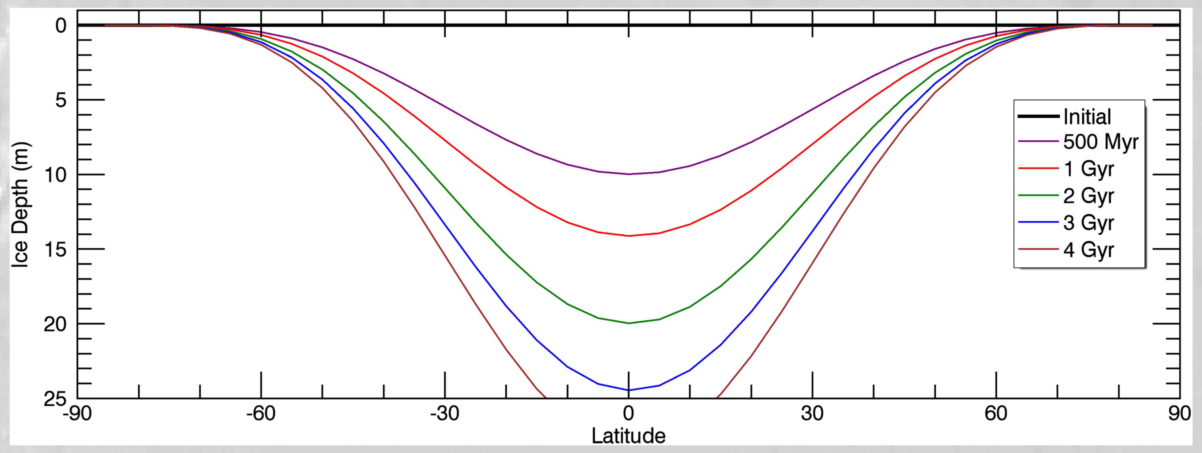
Ice table retreat rates are both time and latitude dependant.

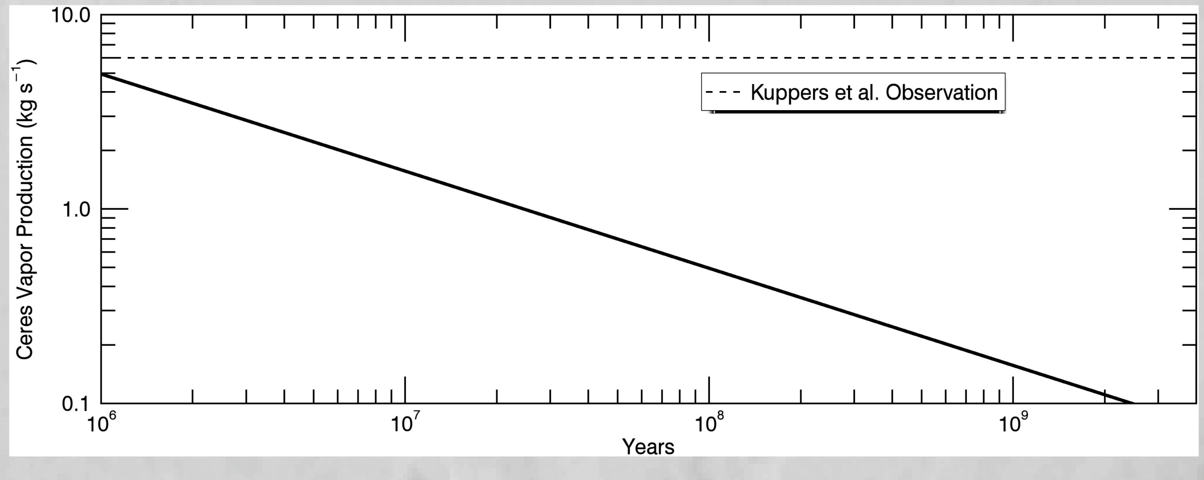
Retreat of an ice table: $\frac{dh}{dt} = \frac{J}{\phi \rho_{ice}}$

When $\phi = 0.5$ and $\tau = 2$: $\frac{dh}{dt} = 1.1\left(\frac{r}{\rho_{ice}}\right)\left[\sqrt{\frac{\mu}{2\pi kT}} P_{vap}\right]\frac{1}{h}$

Solving: $h = \sqrt{h_o^2 + 2.2\left(\frac{r}{\rho_{ice}}\right)\left[\sqrt{\frac{\mu}{2\pi kT}} P_{vap}\right] t}$

We start the model with a global ice-table at a depth of 1cm. Results are regolith-grain-size dependent, plots below have r=100 microns.

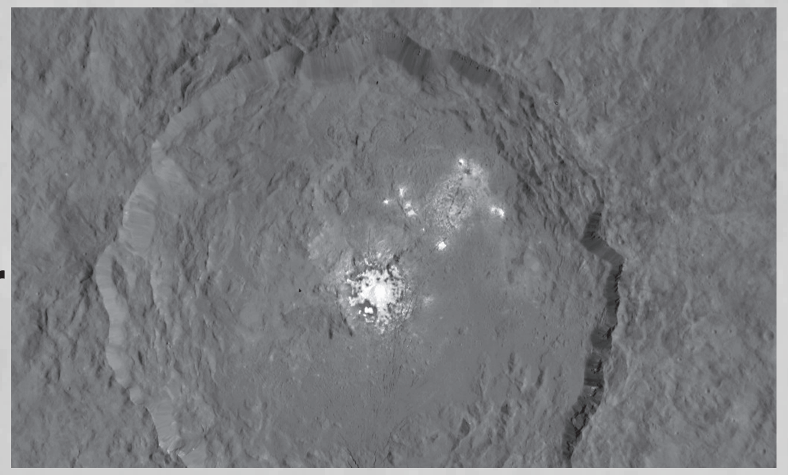


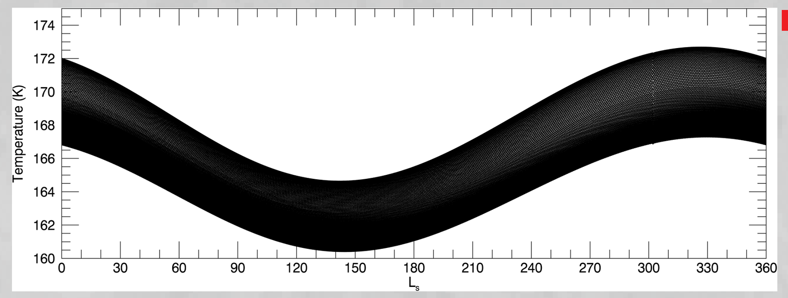


- Equatorial ice retreats to depths of10s of meters over the age of the solar system. Polar ice hardly changes. Grand may still detect ice (in the upper 0.5m) at latitudes of 65-90.
- Global vapor output declines with time, but is never as high as observed by Kuppers et al. (2014)

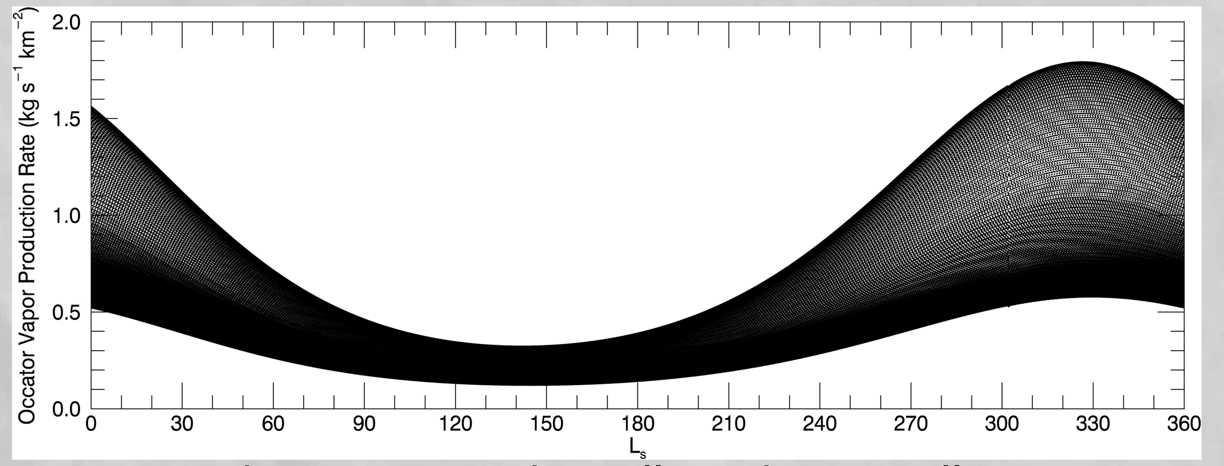
Sublimation at Occator Crater

Can sublimation of ice within Occator explain near-Ceres water vapor?





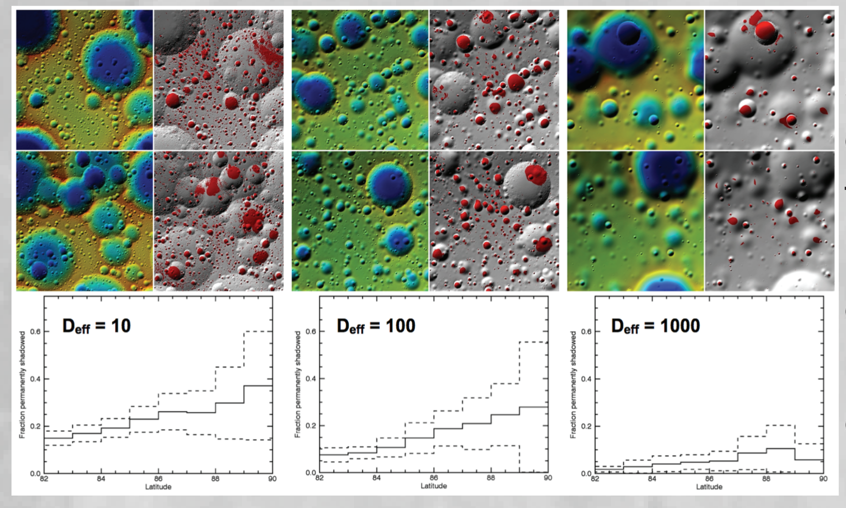
- Here, we use ice-like thermal inertia, a higher albedo and sublimation from an exposed surface.



- Vapor production varies diurnally and seasonally, consistent with Nathues et al. (2015).
- A few km^2 can easily supply the vapor observed by Kuppers et al. (2014).

Future work

- Monte Carlo simulations of ballistic transport of water molecules to link sources &sinks and investigate seasonal effects.
- Simulation of cratered landscapes based on crater addition and downhill mass wasting (controlled by landscape diffusivity D_{eff})
- These synthetic DTMs can investigate surface frosts and permanent shadow below instrument resolutions.



Example landscapes with three different diffusivities. Red areas are permanently shadowed when these landscapes are centered on the north pole of Ceres

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References: Kuppers et al. (2014), Nature, 505, 525-527. Nathues et al. (2105), Nature, 528, 237-240. Schorghofer (2008), Ap. J. 682, 697-705. Evans et al. (1961), J. Chem. Phys. 35, 2076.