Supplementary information

Sensitivity to runaway albedo feedback

Pluto's and Triton's N_2 atmospheres are in global solid-gas equilibrium with their surface N_2 ice. For a high-enough surface pressure, the pressure at a reference altitude will be nearly the same across the globe, and the surface pressures and N_2 ice temperatures will follow vapor-pressure equilibrium. This global balance is maintained through N_2 sublimation and condensation processes, with sublimation winds transporting atmospheric mass and latent heat from areas of sublimation to areas of condensation. Local energy balance determines where N_2 sublimes or condenses. In general, sublimation tends to occur from areas of high insolation, while condensation tends to occur onto areas of low insolation, with the transition near the terminator. Locally, changes in N_2 ice albedo can impact the energy balance and modify the condensation-sublimation rates. A local decrease (resp. increase) in N_2 ice albedo can even invert the surface energy balance and trigger sublimation (resp. condensation) instead of condensation (resp. sublimation). Such an inversion of the surface energy balance is more likely to happen at places where condensation-sublimation rates are the lowest, i.e. near the terminator or more generally in the diurnal zone, where day/night cycles occur.

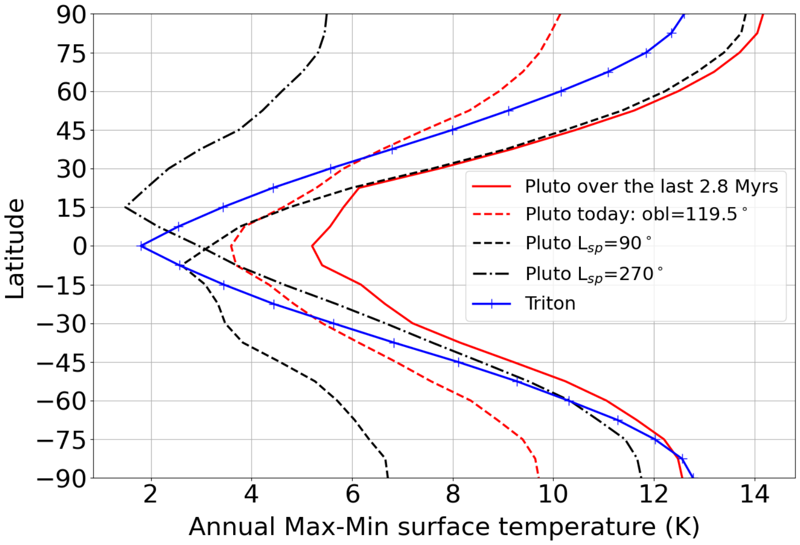
For instance, we can roughly estimate the diurnal mean sublimation rate of N_2 on Pluto by neglecting the internal heat flux and the sensible heat flux from the atmosphere and write the daytime surface energy balance as follows:

$$\epsilon\sigma T^4 = (1 - A)\,F - L\,dM/dt$$

where F is the diurnal mean incoming solar flux (W m^{-2}), A is the N_2 ice surface albedo (e.g., 0.8), T is the diurnal mean N_2 ice surface temperature (here assumed to be ~37 K for a surface pressure of ~1 Pa), ϵ is the N_2 ice emissivity (here assumed to be ~0.8), and σ is the Stefan-Boltzmann constant, L is the N_2 latent heat of sublimation (~2.5×10^5 J kg^{-1}), and dM/dt is the N_2 ice sublimation rate (kg s^{-1}). In these conditions, the term $\epsilon\sigma T^4$ is equal to 0.085 W m^{-2}. At the north pole, F varies from ~1 W m^{-2} (summer solstice) to 0 W m^{-2} (polar night) over an annual cycle, and therefore dM/dt varies from large positive to large negative values, i.e., the poles are dominated by intense sublimation (0.25 mm/Pluto day) followed by intense condensation (0.19 mm/Pluto day) over an annual cycle. A local change in N_2 ice surface albedo does not significantly change this trend. By contrast, in the diurnal zone (30°S-30°N), F remains in the range 0.2-0.4 W m^{-2} over an annual cycle, and both sublimation and condensation can be maintained throughout the year depending on whether the N_2 ice surface albedo is low (<0.58) or high (>0.78). Albedo positive feedbacks occurring at the seasonal timescale are therefore easier to occur in the diurnal zone than at the poles.

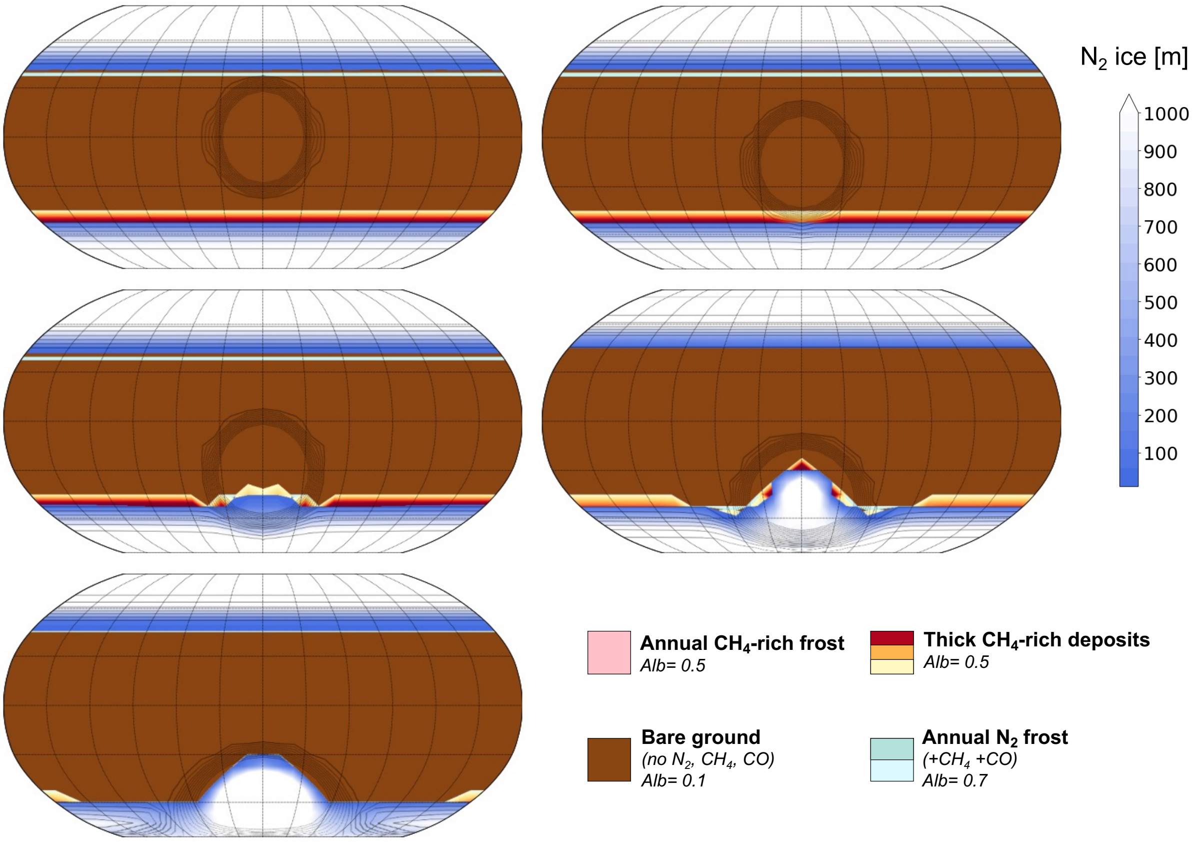
The sensitivity of a N_2 ice surface to albedo positive feedbacks can be qualitatively represented by its ability to maintain sublimation or condensation throughout an annual cycle, which is best obtained when the annual contrasts in diurnal mean surface temperature are small (or diurnal mean insolation, but using surface temperatures seem to be a better proxy, because it includes the effects of subsurface thermal inertia).

On Supplementary Figure 1, we compare the sensitivity of Pluto's and Triton's latitudes to runaway albedo feedback for the annual and astronomical timescales. This sensitivity is qualitatively estimated by the difference between the maximum and minimum diurnal mean surface temperatures reached over the considered timescale, with low values likely to create conditions for runaway albedo variations. We find that on both Pluto and Triton, the temperature difference is minimal in the equatorial regions over annual and astronomical timescales, because these regions correspond to the diurnal zone with a day/night cycle, and maximal at the poles, because these regions experience long polar winter and summer. On Pluto, the lowest values are obtained during the periods corresponding to a solar longitude of perihelion of 90° and 270°, i.e., when one hemisphere is much warmer or much colder than the opposite hemisphere on annual average. Note that the equatorial temperature difference is even smaller for Triton than on Pluto, thus suggesting that Triton's equatorial regions are even more sensitive to runaway albedo variations than Pluto's equatorial regions. This could explain the diversity of terrains and colors observed in Triton's equatorial regions, at the edge of the southern bright cap.



Supplementary Figure 1. Latitude versus the variation between the minimum and maximum diurnal mean surface temperature at that latitude over Pluto and Triton. For Pluto we consider the timescale of the last obliquity cycle (i.e. the minimum and maximum are calculated over the last 2.8 Myr, solid red line), the annual timescale at the current epoch (dashed red line), and the epochs with solar longitude of perihelion of 90° and 270° (black lines). For Triton, both annual and astronomical timescales give the same results (blue solid line). Minimal variations are obtained in the equatorial regions on both objects, suggesting that these regions are the most sensitive to albedo runaway forcings.

Alternative simulations of Triton



Supplementary Figure 2. Volatile ice distribution obtained after a 20-Myr simulation performed with the LMD volatile transport model for Triton with a 8-km deep (Sputnik-like) crater centered at the equator, 15°S, 30°S, 45°S, and 60°S. Black contours show the bedrock's topography.