MODELING OF SUBLIMATION-DRIVEN EROSION AND ICE PINNACLE FORMATION ON CALLISTO. O. L. White\textsuperscript{1}, O. M. Umurhan\textsuperscript{1}, A. D. Howard\textsuperscript{2}, and J. M. Moore\textsuperscript{1}. \textsuperscript{1}NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035-1000 (oliver.l.white@nasa.gov), \textsuperscript{2}University of Virginia, Department of Environmental Sciences, P.O. Box 400123, Charlottesville, VA 22904-4123.

Introduction: Most of the areas observed at high resolution on the Galilean satellite Callisto have a morphology that implies sublimation-driven landform modification and mass wasting is at work [1]. These areas comprise rolling dark plains with interspersed bright pinacles. Using the MARSSIM landform evolution model, evolution of this landscape has been simulated heuristically as a combination of bedrock volatile sublimation, mass wasting of the dark, non-coherent residue, and redeposition of ice at high-elevation cold traps sheltered from thermal re-radiation to form the pinacles [2]. The goal of our study is to advance the physical treatment of these processes within the framework of the existing MARSSIM model, and to quantitatively relate our model results to the actual surface of Callisto through visual and topographic characterization of surface features. Simulations performed using this refined version of the model will ultimately allow us to form a coherent narrative of the evolution of Callisto’s surface that illustrates the influence of factors such as ice composition and total radiation input on the relative rates of pinnacle formation and sublimation weathering.

A New Physics-Based Model for MARSSIM: The MARSSIM landform evolution model has been developed to quantitatively evaluate a wide range of processes modifying planetary surfaces, and includes a variety of statistical routines to characterize landform morphology [3]. Adapted for the purpose of modeling ice sublimation and deposition on Callisto, mass wasting modules from earlier terrestrial and Martian investigations were retained, but new routines to simulate exposure-influenced bedrock weathering and frost deposition were included [2]. We have incorporated a number of refinements into a new version of the model that more strictly adheres to the physical processes interpreted to be operating on Callisto, which we describe below.

The earlier form of MARSSIM modeled sublimation weathering of the “bedrock” (i.e. crustal material comprising fine-grained refractory material that is cemented by ice, and which is not subject to creep) via surface decrescence and depending on exposure to thermal re-radiation in eight directions from the surrounding landscape [2]. We have modified the exposure criteria such that the effect of direct solar illumination is considered in addition to thermal re-radiation. The illumination angle is set according to the latitude the scene exists at; it is assumed that midday illumination always prevails (Fig. 1).

We use these exposure criteria, in combination with the surface albedo, to determine a surface temperature at each point [4] that is used to calculate volatile escape rates of ice in exposed bedrock and in bedrock covered by a regolith layer. If bedrock is exposed, we calculate an escape rate based on the vapor pressure of the relevant ice and the surface temperature [5]. Our model also allows for sublimation weathering of pinnacle ice itself.

If the bedrock is covered with regolith, then we define a temperature profile through the regolith based on values for the thermal inertia of the regolith layer and the bedrock underneath [6] in order to determine the diurnal temperature variation at the regolith/bedrock interface where sublimation will occur. We input the mean interface temperature into Fick’s Law in order to calculate the rate of passage of sublimated volatiles through the regolith layer, and its escape rate at the surface [7].

Current results. Fig. 2 presents the results of our current simulations, assuming $\text{H}_2\text{O}$ ice composition for the volatile component of the bedrock. The figures illustrate the correlation of low surface temperatures to low exposure localities, which act as sites of pinnacle growth. Over a billion year timescale, we see development of pinnacle ice thicknesses reaching up to 90 m, a figure that is consistent with measurements of total pinnacle relief [8].
Sublimation of CO₂ ice is therefore the likely source of the majority of the regolith covering the low-lying parts of Callisto’s landscape – at Callisto’s equator, our simulations indicate build-up of several meters of regolith cover over a 4 Gyr timescale due to CO₂ sublimation. Indeed, an analytical calculation shows that CO₂ sublimation-driven surface regolith production on a flat surface at the equator will have a regolith depth as a function of time given by $L \sim 3\sqrt{t}$ meters with a corresponding surface outgassing rate of $2.7 \times 10^7 \sqrt{t}$ mols cm$^{-2}$ s$^{-1}$ ($t$ in units of billions of years). The corresponding present-day sublimation rate through such a regolith cover is comparable (within a factor of two) to that which is needed to replenish Callisto’s tenuous CO₂ atmosphere [11].

We find that sublimation of H₂O ice can occur at a sufficient rate to produce pinnacle ice thicknesses that are consistent with observations (Fig. 2); however, the vapor pressure of H₂O ice is low enough such that only a negligible amount of exposed bedrock is available for sublimation of H₂O. Instead, pinnacle formation would have been a more protracted process stemming from the sublimation of H₂O ice that remained in the regolith left behind after CO₂ sublimation, rather than H₂O ice in the bedrock itself. We aim to eventually develop a version of the model that can simultaneously simulate independent sublimation of multiple ice species in order to refine our understanding of the relative development of pinnacles and sublimation regolith.

**Conclusion:** The rapid growth of regolith cover caused by CO₂ sublimation implies that this cover was already well-developed by early on in Callisto’s history, leaving a negligible amount of exposed bedrock available for sublimation of H₂O. Instead, pinnacle formation would have been a more protracted process stemming from the sublimation of H₂O ice that remained in the regolith left behind after CO₂ sublimation, rather than H₂O ice in the bedrock itself. We aim to eventually develop a version of the model that can simultaneously simulate independent sublimation of multiple ice species in order to refine our understanding of the relative development of pinnacles and sublimation regolith.

**References:**