SIMULATING THE EVOLUTION OF TITAN'S SURFACE THROUGH FLUVIAL & DISSOLUTION EROSION: II. THE DETAILS. S.P.D. Birch[1], O.M. Umurhan[1,2], A.G. Hayes[1], M.J. Malaska[3]. [1]Cornell Center for Astrophysics and Planetary Science, Cornell University, Ithaca NY (sb2222@cornell.edu), [2]SETI Institute at NASA-ARC, MS 245-3, Moffett Field, CA, 94035, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

Introduction: The landscape model used in our work here is based off of the MARSSIM model as described in [1,2] with individual modules responsible for modeling the physical/chemical weathering of rocks into a transportable regolith, mass wasting by non-linear creep, fluvial channel erosion, and fluvial transport and deposition. While these modules have been successfully applied to problems on the Martian surface many times, and recently across the solar system, it is not sufficient to capture the full complexity of Titan's surface. Specifically, there is ample evidence for at least a polar groundwater water aquifer [3], while most interestingly, there may be both dissolve and non-dissolvable bedrock in close proximity on the surface. This necessitated the development of two additional modules to capture the effects of groundwater fluid and solute transport and dissolution erosion (FIG. 1).

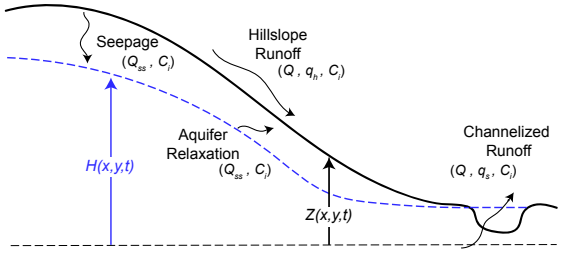

FIG. 1: Schematic of the processes now covered in MARSSIM. The program tracks the surface elevation (Z), the hydraulic head (H), fluid discharge (Q), hillslope (q_h) and channel (q_s) sediment discharges, and the concentration of dissolved products within the fluid (C_i). Dissolution occurs at any point so long as the dissolved concentration is not at saturation.

Unfortunately, we could not simply add modules to the existing MARSSIM model without complications. For instance, there is a vast gap in temporal and spatial scales over which these processes act, where the timescale of groundwater flow is many orders-of-magnitude larger than the time it takes to dissolve a given volume of bedrock. Further, for the Titan environment nearly all the parameters that go into these calculations are unknown or poorly constrained. To tackle this issue requires many simulations that sweep across broad parameter spaces. The previous framework of the MARSSIM model was not capable of performing such massive calculations over reasonable timescales, necessitating a re-write and optimization of the underlying source code.

In this presentation, we will describe these many additions to MARSSIM, including a new parallelization of how material is routed across the surface, and the new routines that MARSSIM now incorporates. A general overview of these additions is provided in [2].

Aims: Our first run of simulations focus on two important, though poorly constrained, processes responsible for the transport and deposition of materials on Titan: the influence of varying liquid levels on the evolution of the largest sedimentary basins (via mechanical erosion), and the relative role of dissolution erosion (and subsurface flow).

As part of this work, we have developed a coupled mechanical-dissolution based erosion model. The model can be adjusted as necessary and, given Titan's unknown surface composition(s), must be iteratively run to develop a suite of plausible solutions.

Precipitation Parameterization: For each time step of our simulations, we rain onto the surface a given fluid discharge. Previously, simulations would assume a bankfull discharge that is sufficient to mobilize sediment and erode the landscape. Because these discharges are relatively infrequent (once per 1-2 years) this allows for sufficiently long times steps over the course of a 1000+ year simulation. In practice then, the simulations rain a constant discharge across the whole simulation grid every time step.

However, dissolution erosion occurs even for small discharges with any "fresh" methane rain capable of wearing away exposed dissolvable substrates. Therefore, we need to account for these small discharges, in addition to the larger ones capable of mechanical erosion.

To estimate evaporation/precipitation rates, we adopt the Titan Atmospheric Model [4], which provides precipitation maps as a function of latitude on Titan along with the probability distribution functions (PDF) of discharge events for each given latitude range across a Titan year. For each time step, we randomly sample the PDF of the precipitation rate for our chosen latitude range, and rain that precipitation across the entire landscape, assuming that it rains for the entire Titan day. This captures the reality, that there are a range of "storm sizes" that occur on Titan, where it rains small amounts often, and every once in a while a larger storm occurs that more significantly alters the surface.

Flow Routing: For each time step, we first quickly determine every path that material can flow, ordered hierarchically for each catchment beginning at the highest point of relief – which we deem the master flow path (FIG. 2). For every path, material is then assumed to flow down the path of steepest descent until it encounters another path, where it is added. Very quickly, all the paths in a given catchment are mapped out. This method allows for efficient parallelization, which drastically improves the speed of our computations.

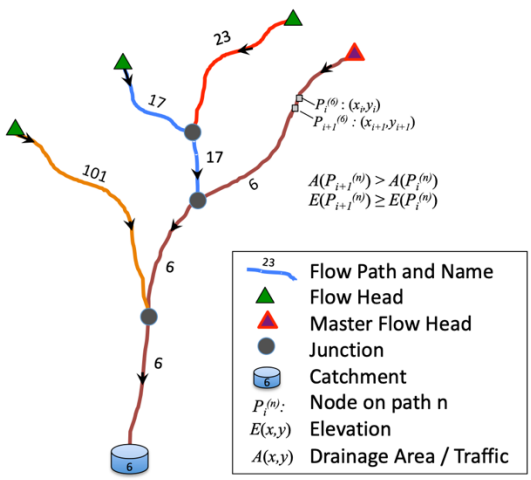

FIG. 2: Schematic of our flow path calculations for a given catchment. We first do the mapping, which gives every path and junction, with everything ordered by elevation. In parallel material is transported down to each successive junction, adding to the main path when it is encountered.

Hillslopes: Sediment is generated on hillslopes via weathering. As is now standard in landscape evolution modeling, the rate of weathering is assumed to decrease exponentially with the regolith thickness [5]. After being detached from the bedrock via weathering, sediment produced on the hillslopes is free to move down slope via gravity. The rate of erosion on hillslopes is described by the spatial divergence of the regolith mass flux, where the regolith mass flux is driven both by diffusive processes over low slopes, and non-linear mass wasting on higher slopes [6].

Channels: Channels are responsible for both eroding the landscape through abrasion of the bed, and the transport of bed load through the system to depositional basins. Generally, the nature of the channel bed determines the mechanics of channel erosion, though considerable study still exists as to the physical controls on the rates of erosion of rivers. Typically, landscape evolution models apply empirical bedrock incision scaling arguments that are only loosely related to the physics of bedrock wear, usually assuming that the erosion rate is proportional to some measure of flow intensity such as stream power. One such model that we have implemented in MARSSIM is the erosion by fluvial detachment, where it is assumed that the channel is always transporting sediment below some maximum level, or "capacity" [1].

Groundwater Flow: We assume a laterally homogenous aquifer in which the vertically averaged permeability has an exponential dependence on the depth of the methane table. Flow is then tracked to the aquifer, while flow, via lateral diffusion, of the aquifer itself is also accounted for. When the level of the aquifer is higher than the surface elevation, in the case of subsurface storm flow, the liquid volumes are directly added to the channel depth. Finally, the porosity and permeability of the subsurface can be modified via dissolution, where mass loss in the subsurface is accounted for by lowering of the surface elevation.

Dissolution: For dissolution erosion, we assume a well-mixed medium of soluble and insoluble materials, in varying fractions. Generally, slower moving, unsaturated liquid will "pick up" more bedrock for each unit of the simulation domain. The rate at which this occurs, via what amounts to an additional weathering mechanism, is proportional to the fluid concentration raised to some power, which varies for the chosen fluid/solid properties. This necessitates tracking the fluid concentration throughout the entire simulation. Assuming that flow is fast and fully turbulent, we are able to efficiently track this concentration.

Summary: Therefore, for both hillslopes and channels, the rate of these processes are derived such that they are a function of the regolith thickness, drainage area, and slope. For dissolution erosion, an additional variable is the fluid concentration. As these four quantities are mapped out in their entirety during our initial flow routing calculations, the many empirical erosion and transport equations (not described above) can be applied in series, as simple vector multiplications. This drastically increases the speed of our calculations.

Acknowledgments: This research was supported by the NASA Astrobiology Institute through its JPL-led project entitled Habitability of Hydrocarbon Worlds: Titan and Beyond.

References: [1] Howard, A.D., Geomorphology 91, 332-63, 2007. [2] Hayes, A.G., AREPS 44, 57-83, 2016. [3] Faulk, S.P., et al., Nature Astronomy, 2019. [4] Umurhan, O.M. et al., LPSC 51, Abstract #xxx, 2020. [5] Heimsath, A.M., et al., Nature 388, 358-361, 1997. [6] Roering, J.J., et al., Water Resources Research 35, 853-870, 1999.