MODELLING CO_2 GLACIERS ON MARS WITH THE 3D ICE SHEET AND SEA-LEVEL SYSTEM MODEL (ISSM). K. B. Fard[1] (kbfard@yorku.ca), I. B. Smith[1], E. Larour[2], N. J. Schlegel[2]. [1]York University, 4700 Keele St, Toronto, ON, Canada, [2]Jet Propulsion Laboratory, California, USA

Introduction: Recent work found evidence for massive carbon dioxide (CO_2) ice deposits (MCID) at the south pole of Mars [1, 2]; within these deposits are bounding layers of H_2O ice [2, 3]. Figure 1 shows that the thickness of the deposits reaches 1000 m [2]. The volume of CO_2 deposits is estimated to be about 16,500 km^3 [1, 4], more massive than the current Martian atmosphere, and in the context of the bounding layers, likely indicates multiple periods of atmospheric collapse in Mars' past [7].

CO_2 ice is less viscous than H_2O ice, especially when experiencing high stresses on slopes, meaning that it may flow more quickly than H_2O on Mars [5]. To test this scenario, geomorphic and modelling evidence demonstrated that the MCID flowed as glaciers to reach their present 3-D volumetric distribution [6], an important result because deposition models were unable to explain the thickness or the volumetric distribution of the CO_2 [6] and because it provides context to the history of climate on Mars in the most recent 600 kyrs.

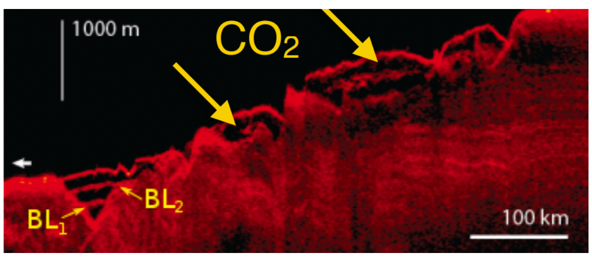

Figure 1: Radar observations showing the presence of massive CO2 ice deposits on the south polar layered deposits. The deposits frequently contain water ice bounding layers [1].

Motivation: Studying the workings of the solar system (including its mechanics) requires a detailed understanding of various bodies that exist in the solar system, their histories, and their evolution including their climatic changes. There is sufficient evidence that ice deposits on Solar System bodies (other than Earth) have varied chemical compositions (also known as, exotic ice deposits). For instance, ice deposits with alternating layers of CO_2, H_2O, and H_2O containing dust in MCID are observed [2]. Since different types of ice possess different physical properties and are governed by different rheological laws, the knowledge gained from terrestrial ice deposits, while conceptually useful, will be insufficient for estimating dynamics of stratified or exotic ice deposits on Mars and other planets.

[5] showed that CO_2 ice has a viscosity low enough to flow in south polar conditions of Mars, and [7] found that as the ice was deposited in periods of low obliquity, it flowed downhill into basins, where it rests today [6]. [6] did not account for the bounding layers that are observed [1, 3] and modeled [1, 7]; however, stratification with multiple materials must affect the strain rate of a flowing body of ice [6].

This motivates the continuation of the work done by [6] to enable the use of three-dimensional models of stratified ice deposits on the south pole of Mars and to enable a view into the history of the ice deposits and the history of the climatic cycles and changes that Mars has experienced in these timeframes. More complex simulations will support scientific ways to:

1) Understand Mars CO_2 glacial flow rates, even when stratified.

2) Examine the current hypotheses about the timing of the atmospheric collapse events (i.e., collapse into CO_2 ice deposits).

3) Further investigate exotic forms of ice, which are critical to understanding the surface evolution of solar system bodies.

Through modelling Mars CO_2 glacial flow rates, we can tease out details of the depositional history. Understanding Mars recent climate will help us extend our knowledge further back in time, teaching us more about historical martian climate scenarios.

Model Description: The Jet Propulsion Laboratory (JPL) at NASA has developed an open-source software application called *the Ice Sheet and Sea Level System Model* (ISSM) [8]. ISSM estimates the flow of ice sheets and their thermal characteristics. To determine the differential stresses and temperatures across an ice deposit in these models, ISSM sets up thermodynamical differential equations. Solving these differential equations will produce the equations of motions that describe the flow of the modelled ice deposits. ISSM uses Finite Element Method (FEM) to solve these thermodynamical differential equations. FEM comes at a cost of computational speed than other modelling methods; however, ISSM results in more accurate ice flow predictions [4, 9].

New Development: This team has already extended the ISSM code to function in the Martian environment (temperature, gravity, geothermal flux, etc.) and use CO_2 rheological flow laws [6] based on [5]. However, that work made the simplifying assumption that the deposits consist of pure CO_2 ice without bounding layers. This left open the question of how much the bounding layers inhibit flow.

We are upgrading the ISSM modelling capability and its FEM solver engine to model ice deposits that consist of various layers with alternating ice compound types. We have also upgraded the libraries of ISSM to be able to simulate planets or moons with different environmental properties than those on Earth.

We are in the validation stage now – comparing the results of the enhanced ISSM to the results of [6]. Once this step is complete, we will use the updated ISSM to develop more complete 3D models of Mars south polar ice deposits. Figure 2 is an example of how the model in 3D will look. Once validated, the changed code will be integrated into the main code and become open source for the wider community to use.

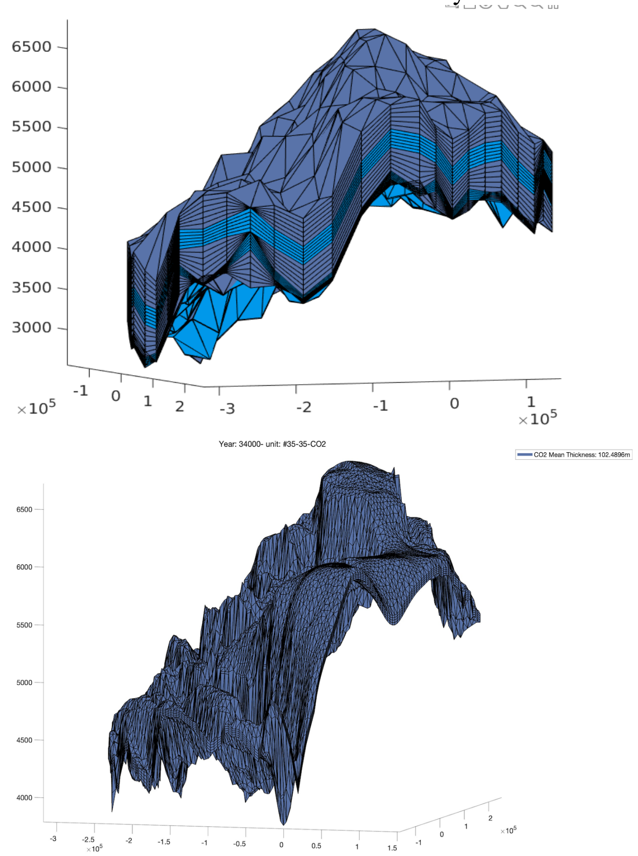

Figure 2: ISSM is being upgraded to support multi-layered, multi-ice 3D models of ice deposits. At present, the CO_2 ice cap in the south pole of Mars can be modelled with alternating layers of H_2O ice and CO_2 ice. We are validating stratified CO_2 ice against the previous massive ice that was modeled. **Above**, *how the models will look like in lower resolution.* **Below**, *model with a finer resolution.*

The following guiding principles will ensure extensibility of the modelling of ISSM: (1) generalizing the ISSM modelling capability for other planets and exotic ices (i.e., beyond CO_2 based ice caps on Mars and H_2O glaciers on Earth); this is to ensure the rheological laws for different ice compounds with various non-terrestrial environments are supported; (2) the capability to leverage multiple cores (i.e., CPUs) of computer clusters to solve models; and (3) expanding all tools and techniques offered by ISSM accordingly to leverage various functionality that exists in ISSM for multiple types of ice layers.

This work will have an additional benefit of supporting terrestrial modelling, for glaciers that have stratified material properties. Currently, stratified ice can be simulated using the glacier's bulk properties – a simplifying assumption. The ability to model layers ice with variation material flow properties will allow for the simulation of glaciers with distinct layering, such as rock glaciers, deformable layers of temperate ice, or deformable layers of firn.

Results: As the modelling work continues, substantial tests demonstrate that upgraded models, if used for a single ice, result in nearly identical result as to those demonstrated by [6]. This validation is specifically promising as multiple major changes to the modelling process were developed simultaneously, exposing this project to the risk of divergent results. Based on the similarity between modeled results from [6] and the new enhanced version of ISSM, we can demonstrate the upgrades are working and move towards simulating multiple ice types.

Discussion: Detailed 3D simulation of glaciers on other planets and moons (e.g., Mars, Umbiel, Triton, Pluto), while still being a new approach, offers more scientific perspective than 2D models; and with powerful computing powers that are readily available at lower costs now, such simulations will be used more.

In case of Mars, the simulations will offer a modelling tool capable of simulating the flow of glaciers that consist of different layers of ice. This includes the north polar layered deposits, composed of stratified ice and dusty layers. Also, such simulations can be used to further scientific insight into the climatic variations and the evolution of other ice-rich, non-terrestrial bodies such as Europa and Pluto. It can also be used to more accurately model glacial flows on Earth where glaciers consist of layers of dust and other compounds, in support of better understanding the terrestrial climatic changes.

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