Visualizing Frost Boils

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The Arctic Tundra is home to a uniquely patterned ground feature that, due to lack of conclusive study, has researchers fascinated. Instances of circles of bare soil interrupt the ubiquitous vegetation of Arctic Tundra at regular intervals, a series of barren, earthy dots on a green, carpeted plain. Each winter, large boils averaging 1.5 meters in diameter rise out of the ground in domed heaves before receding each spring. These patterned ground features, formally termed non-sorted circles, are more familiarly dubbed 'frost boils.'

A frost boil in the early stages of development shows signs of devegetation where the heave occurs, and the interboil radius where the vegetation is nourished by thawing ground. *Photo courtesy of Teresa Turner.*

The study of frost boils is of interest to the Alaska Geobotany Center (AGC), at the Institute of Arctic Biology (UAF). One key project of the AGC is the Biocomplexity of Patterned Ground Project. This project, funded by the National Science Foundation, is investigating the linkages between plant systems, biogeochemical cycles, and climate in the Arctic. In particular, the project is examining the role frost boils play in plant development and proliferation, and how a changing climate might impact these biological patterns. As these patterned ground formations have been little studied, they represent a still largely unknown aspect of the arctic system.

Dr. Debasmita Misra, Associate Professor of Mining and Geological Engineering at UAF, and Dr. Ronald Daanen, Post-Doctoral Fellow at UAF, worked with the Biocomplexity Project to develop a three-dimensional model of the generation of a frost boil. Having gained experience with supercomputing during his post-doctorate work at the University of Minnesota, Misra saw that a three-dimensional simulation of frost boil generation would be impossible without an allocation of massive computing capability. Misra and Daanen applied for, and were awarded, funding and resources from ARSC, and, with additional support from AGC, began to study and model these nebulous formations. This summer, with the contribution of two summer interns at ARSC, Cory Mohn, from Northland College, Wisconsin, and Theresa Turner, from the University of South Carolina, Aiken, Misra and Daanen were able to realize a three-dimensional visualization tool that simulates the growth cycle of non-sorted circles: WIT 3-D.

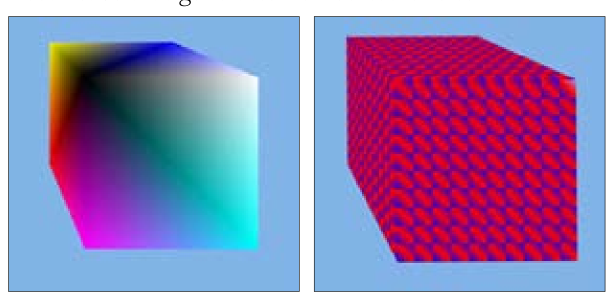
Story by Lorien Nettleton

The Model

The researchers involved in the Biocomplexity Project have identified hydrology and temperature as driving forces in the differential heave that leads to non-sorted circle formation. Inspired by these findings, Misra and Daanen have used temperature differentials that cause hydrological differences as the driver for their model.

Daanen contributed his numeric model, Water Ice and Temperature (WIT), originally designed for studying liquid water flow in snow, and re-wrote it specifically to describe the localized temperature and hydrology of the frost boils.

The code is a numerical solution for the strongly coupled heat and mass transfer problem with phase change in porous media. Daanen combined the code with an arctic vegetation succession model, called ArcVeg, developed by Howard Epstein at the University of Virginia, which provides an estimate of surface insulation by vegetation. He then wrote new code to simulate ice accumulation as a result of surface insulation and three-dimensional mass transfer in the active layer. The outcome of the modeling exercise is ice accumulation, which is used to represent frost heave that generates non-sorted circles.

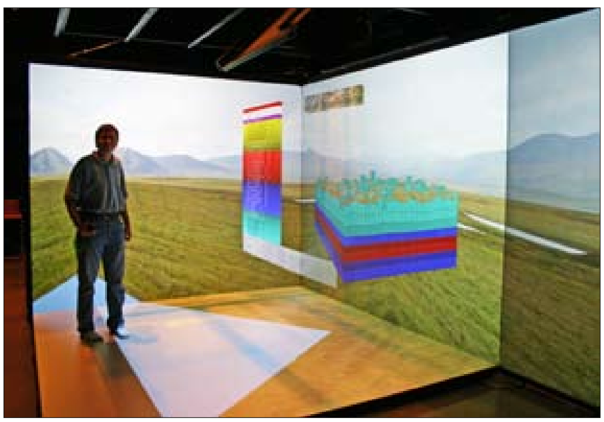


On the left is a cube with vertex shading applied to it. On the right is a grid made up of smaller cubes.

Theresa Turner optimized the WIT program for parallel processing on *Iceberg*, ARSC's 800-processor IBM supercomputer. By converting the data files from ASCII to Binary, Turner was able to significantly speed up the overall processing time. Turner also optimized the output data to merge with the load files of WIT3D's modeling program.

The numerical model was adapted into the visualization program WIT3D, written by Cory Mohn. Using C++, OpenGL and VR Juggler to visualize the temperature, hydrological and vegetative data, and to provide a tool to allow vertical flux to indicate heave, Mohn was able to construct a visualizing tool that enables the viewer to manipulate and examine multiple internal and external angles of the freezing and heaving scenarios, using the virtual immersion environment of the Discovery Lab. *(see Challenges, page 14)*

"I always saw the visualization as a key part of the study," Misra says. "Without the visualization we can't achieve what we want to. And we couldn't create the visualization until Cory Mohn came along and wrote the program single-handedly."



Cory Mohn demonstrates the frost boil model which visualizes the temperature, hydrological and vegetative data.

Theories on Formation

For a frost boil to form, it is theorized that a bare area of ground serves as the initiation for accelerated freezing of the active layer, or the regularly thawing and freezing top layer of soil bounded on the bottom by permafrost. As non-insulated areas freeze more rapidly than insulated areas, the bare soil will experience greater temperature variation when the mercury drops or rises.

Assuming a constant amount of water in the soil, a solid mass will develop at the site of the barren soil and freeze from the top down, becoming a completely rigid body.

Through a process called cryosuction, the water from the surrounding area gets pulled into the freezing body, creating vertical lift, or differential heave, which forms the boil. The heave exerts sheer stress on the surface of the soil and kills the roots of plant life within the area, enlarging the region of bare soil with each freeze cycle.

Barren soil is a prime identifier of frost boils, caused by differential heave exerts sheer stress on the vegetation layer, destroying roots and rendering plant live unstable. *Photo courtesy of Chory Mohn*

The size of the boils is limited by how far water can be pulled towards its freezing mass – the maximum distance water can travel through soil is about 1.5 meters, governed by the soil's hydraulic conductivity. This process regulates frost boils to an average size of one and a half to two meters, with similar distances of one and a half to two meters between each boil. Around the perimeter of each boil, a formation known as the interboil radius forms – a ring of thriving plant life nourished by water released during the thaw cycle that insulates the area around the ring during the freeze cycle. This behavior ensures the persistence of the feature.

Preliminary Findings

Initial runs of the modeled visualization using warmer climate temperatures show a decrease in non-sorted circle generation. Using the model to simulate the effects of warming on the horizontal liquid water movement in the active layer during freezing, Misra and Daanen found that during freezing, air temperatures an average of ten percent warmer limit the horizontal water movement by eight percent, while air temperatures that are twenty percent warmer reduce the water movement by fourteen percent. For example, air temperatures raised from -10 degrees Celsius to -9 degrees Celsius would reduce water movement from 1.04 cm to 0.95 cm over the freeze cycle, and air temperatures raised from -10 Celsius to -8 Celsius would reduce water movement from 1.04 cm to 0.9 cm. These findings have led to a hypothesis that warmer air temperatures will reduce the cryosuction that contributes to differential heave and will thereby reduce the sheer stress exerted on plant roots, and promote plant encroachment on the existing boils.

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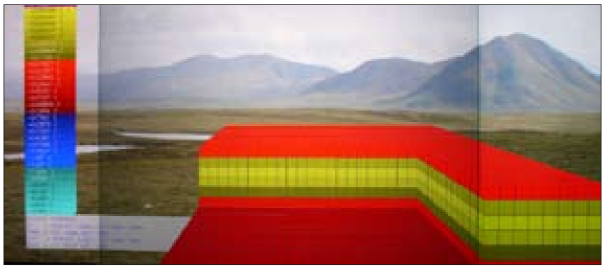
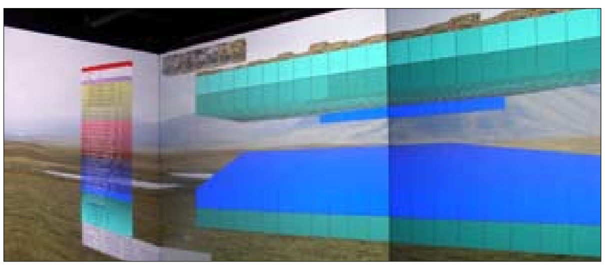
Frost Boils *continued from page 19*



The data grid of the frost boil model with the cutaway feature being used.

WIT3D was also used to simulate the effect of changing differential insulation at the surface. Given the hypothesis of promoted plant growth and migration towards the center of the circle, the simulation showed that plants would prevent freeze-up in the rapid fashion that forms the frost boils. The combination of warmer temperatures and more vegetative insulation of the non-sorted circles would lessen the horizontal water movement, and could lead to the degradation of the non-sorted circle formation.



The effects of transparency and the varying thickness of the vegetation layer in the frost boil model.

Potential Applications

Currently, the combined code for the project is used for small-scale modeling – areas of seven meters by seven meters – Daanen is hoping to increase the scale of the model and to increase the density of grid node points – mirroring potential intergalactic modeling and terra studies applications.

Additionally, with the aid of ample satellite information, the researchers could extrapolate the model through remote sensing to look at areas all over the Arctic, with potential to extend the studies to other frozen landscapes with similar potential for patterned ground features. Daanen even envisions that the model will one day provide insights into the landscapes of neighboring planets like Mars, which the Biocomplexity Project has shown to have polygonal patterned ground features similar to those of the polar region of Earth.

This work could have an impact on climate studies; as more is understood about non-sorted circles and how they form, the patterns of their subsidence may become yet another substantial indicator of global warming. ▣

Permafrost Modeling *continued from page 21*

representations such as snow cover and the greening and browning of spring and autumn.

The new incarnation also features a series of contour lines that allows the user to scale perspective of the active and deeper permafrost layers in order to emphasize or de-emphasize the cyclical changes. Now a user can scale the depth from ten to 90 meters, effectively condensing the deeper permafrost into the lower twenty percent of the display, making the upper five meter deep active layer the dominant feature of the virtual representation. This scaling feature can be performed on the fly, allowing the virtual driver to expand and reduce the representation of the most dynamic zone in relation to the other permafrost and topsoil features as the program runs.

Webb improved the way the data sets are preprocessed to run in one uniform format. Due to the number of researchers contributing datasets for visualization, many files were provided in differing formats – and rarely in the ASCII or binary formats which FrostByte reads. To resolve the time-intensive challenges of manually converting the datasets to a binary form, Webb created a conversion tool that automates the process, freeing the programmer to focus on other aspects of the program.

Other improvements include moving FrostByte between different kinds of computers, including SGI, IBM, Cray and Sun Microsystems platforms. Because the processing configuration varies from system to system, the program must be altered to optimally package and retrieve the information.

Perhaps the most exciting new feature of FrostByte is called directed visualization, which allows scientists to manipulate input data as the program is imaging it. This allows them to evaluate the variables visually and change them dynamically. Parameters such as fire, snow and heavy rains can be adjusted, with instant change in the imaging display, giving feedback about climate conditions. For example, the researchers could be viewing the representation, and decide to see what it would look like with air temperatures that are 10 degrees warmer. They could input the command and watch as the model adjusts its display to reflect that change.

For Webb, the most rewarding part of being the primary developer is dedicating the time to develop the program beyond its original edition.

“In some ways it’s completely different from the way it started out,” Webb says. “The pieces are more elegant and smooth, they run more efficiently together.”

For the last year Webb, was the sole developer of the program and refined a number of its features. Webb, now a graduate student of computer science at UAF, is leaving the development of FrostByte in the hands of a new round of students while he moves on to new challenges. ▣