Geophysical Self-Organization as an Indicator of Global Climate Change

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Global Climate-Change Considerations

- Observable on 10 to 100-year time scale
- Not subject to direct anthropogenic disturbances
- Observable via remote sensing
Remote Sensing Shows Sharp Dividing Line in Arctic Tundra
Arctic Frost Boils
Frost Boils as an Indicator of Global Climate Change

Northward movement of line between acidic & nonacidic tundra indicative of global warming causing reduced frost-boil activity – vegetation changes provide early warning system if they can be related to frost-boil activity
Differential Frost Heave (DFH) Model for Frost-Boil Formation

Model assumes DFH causes ground surface corrugations – lateral extension of ground surface owing to more frost action prevents development of vegetation under crest regions – this causes centers of frost boils to appear barren relative to trough regions – moisture accumulation in troughs relative to crests accentuates differences in the micro-ecosystem created by the frost boils
Effect of Pore Size on Freezing Temperature Depression

Ice cannot penetrate into smaller pores until temperature is reduced sufficiently – i.e., freezing point depression.
Why Freezing Causes Upward Flow of Water

- Soils are wet by liquid water not ice
- Ice fingers in pores becomes thicker with decreasing temperature
- Pressure in thin film of liquid water between ice and soil decreases
- This ‘cryostatic suction’ draws water up from the underlying water table
Cryostatic Suction in a Pore

- **pore**
- **Ice finger**
- **Thin film of water at reduced pressure**
- **Unfrozen water**
- **Upward water flow**
Frost Heave

Occurs due to expansion of freezing water drawn upward by cryostatic suction – ice carries progressively more of soil load until net force compressing soil particles is zero – this permits ice-lens formation between soil grains – ice-lens formation continues until downward penetrating freezing front reduces soil permeability sufficiently to cut off subterranean water upflow – this process then repeats with successive ice lenses becoming thicker owing to the decrease in frost penetration.
Frost boils are manifestation of differential frost heave, i.e., frost heave that varies laterally – for this to occur, there has to be greater capacity to remove latent heat of fusion of ice under regions where frost heave is greater.
Paradox Presented by Differential Frost Heave!

Distance for heat conduction is greater under a heaved ground peak relative to ground trough.

Underlying permafrost table $\approx 0^\circ C$
Reason Why Frost Boils Form (geophysical self-organization)

Upward water flow owing to cryostatic suction

Heat transfer
Stability theory approach to differential frost heave (DFH) mathematically asks question “Is there any tendency for the one-dimensional frost-penetration process to evolve into multidimensional frost heave?” – it considers whether small departures from one-dimensional frost penetration are energetically favorable – it can determine conditions required for DFH to occur and how environmental parameters (temperature, ground cover, snow depth, wind speed, etc.) influence its occurrence.
Illustration of Stability Analysis

Linear Stability Theory

Nonlinear Stability Theory
Typical Linear Stability Theory Predictions for DFH

Plot of growth coefficient as a function of wave number (reciprocal wavelength) for Chena silt.
Frost Boils and the Ecosystem

Ecosystem variables that impact frost-boil activity include the following:

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Wind speed</th>
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<tbody>
<tr>
<td>Moisture content</td>
<td>Snow depth</td>
</tr>
<tr>
<td>Permafrost table</td>
<td>Vegetation cover</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Rate of freezing</td>
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Soil Type Effect on Frost-Boils

Silts promote frost boils more than sands and clays owing to an optimal ability to generate significant heave pressure while maintaining sufficient soil permeability.
Air Temperature Effect on Frost Boils

Colder climate conditions promote frost-boil growth.
Wind effect on frost boils

Wind speed enters the model through the heat-transfer coefficient (HTC), which increases monotonically with wind speed—interestingly, the propensity to form frost boils is not a monotonic function of the HTC!
Snow depth has effect similar to HTC – small to moderate snow depths (5-50 cm) promote frost boils, whereas large depths (> 50 cm) provide an insulating effect that retards frost boils.
Computer Simulation of Frost Boils

Patterns arising from DFH can take shape of stripes, squares, rectangles, equilateral triangles, and hexagons – the latter are preferred.

Wavelength predicted by stability theory.
Laboratory Studies of Frost Boils
Field Sites

Field Studies of Frost Boils
Active Frost Boils
Frost Boils Becoming Less Active
Inactive Frost Boils
Evidence of Relict Frost Boils