Network models for ponding on sea ice

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- **Ponding is important for evolution of Arctic sea ice**
- **We develop a network model for pond formation**
- **We compare the output of the model to published observations**
- **Model can be used to study physical processes in pond evolution**

Please open with something capable of playing mp4

Image from NASA

Motivation

- Sea ice surface melts in summer
- Ponds grow in hollows → interact → join → drain

- Process creates individual ponds AND connected systems

- Ponds show clear perimeter-area scaling law
- Transition of scaling at Area~30 m^2
  - Ponds suddenly become densely interconnected → “Percolation transition”
- Suggested that ponds systems tend to this point
- Leads to ways to parameterise ponds in larger models

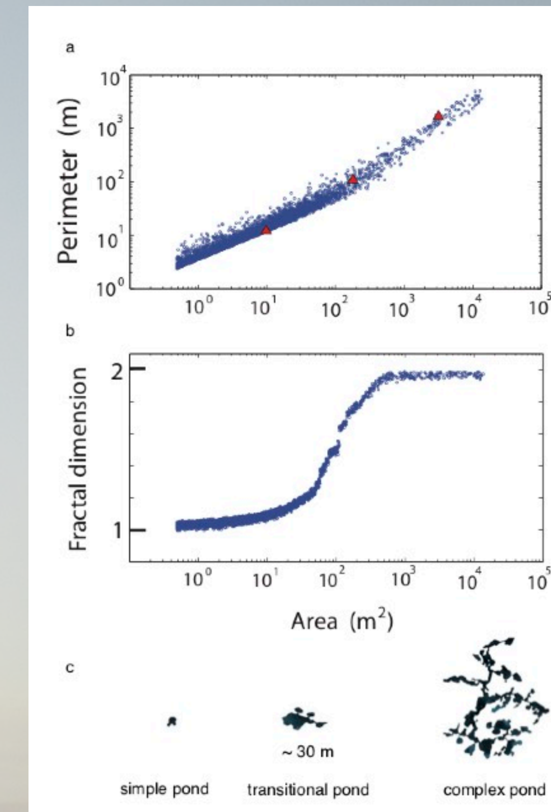


Image from Hohenegger 2012
doi:10.5194/tc-6-1157-2012

- Model as a network
  - Ponds as nodes
  - Channels/fluxes as edges
- Network can model development of percolation process

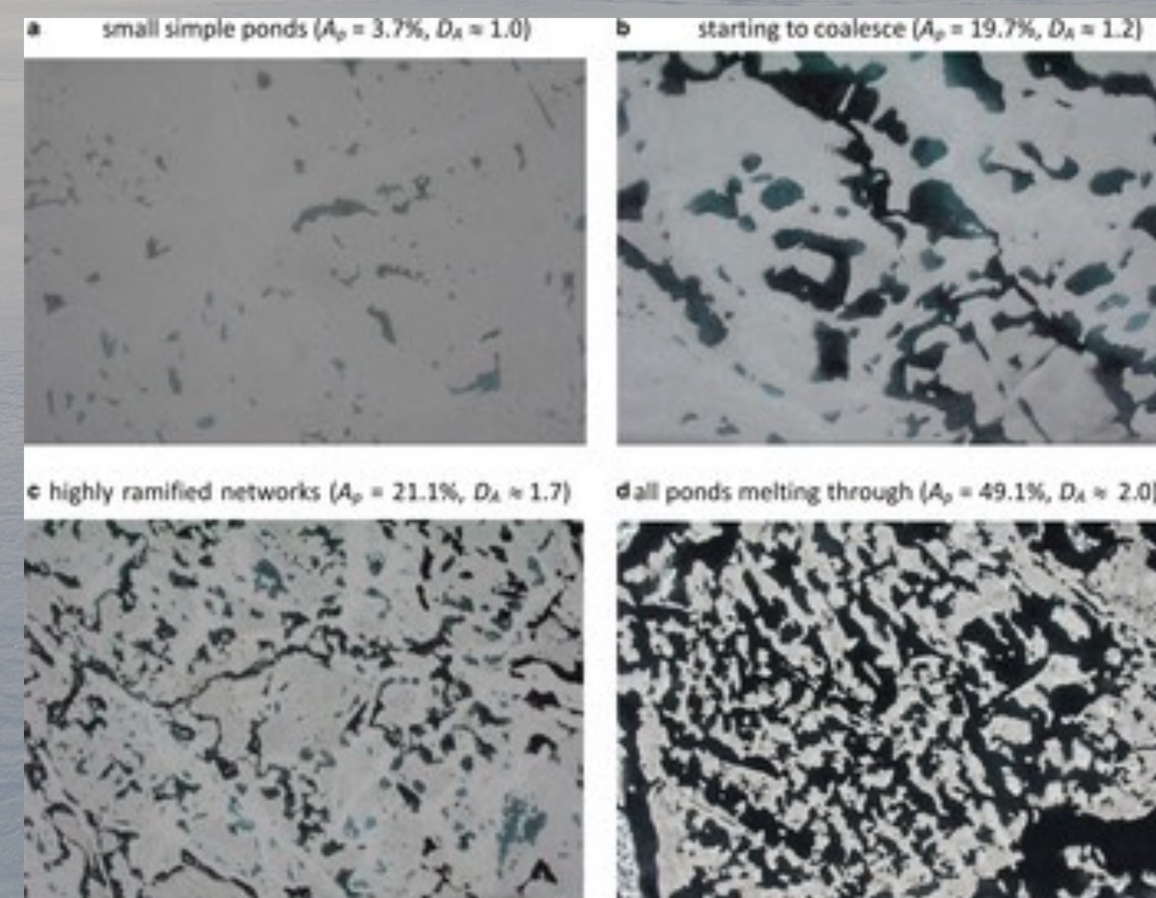


Image from Huang 2016 doi:10.1017/aog.2016.30

Approach

A. Model a single pond growing in a catchment

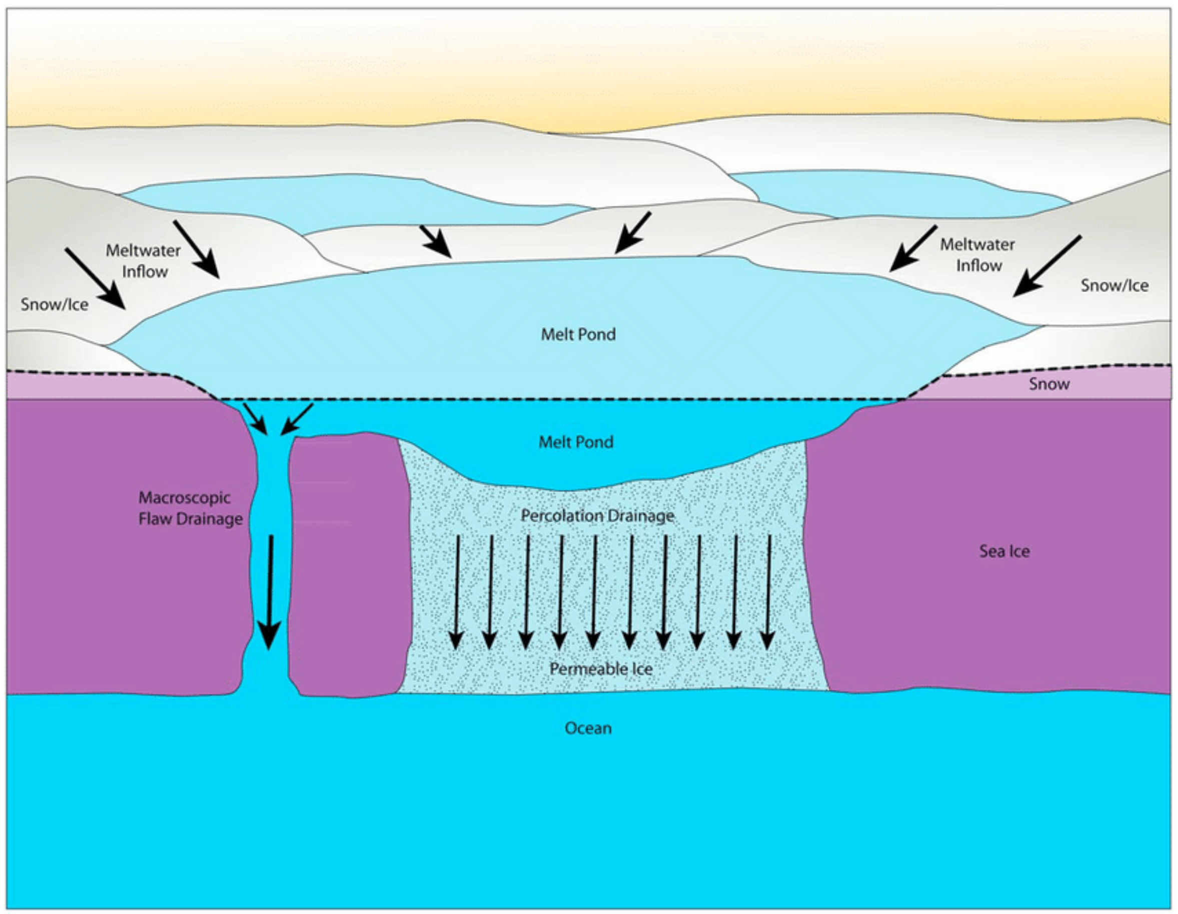


Image from Polashenski 2012 doi:10.1029/2011JC007231

- Incoming solar flux causes surface melt
- Water formed collects at lowest point in catchment
- Neighbouring catchments may eventually join
- Possibility of drainage

B. Modelling collective behaviour as pond network

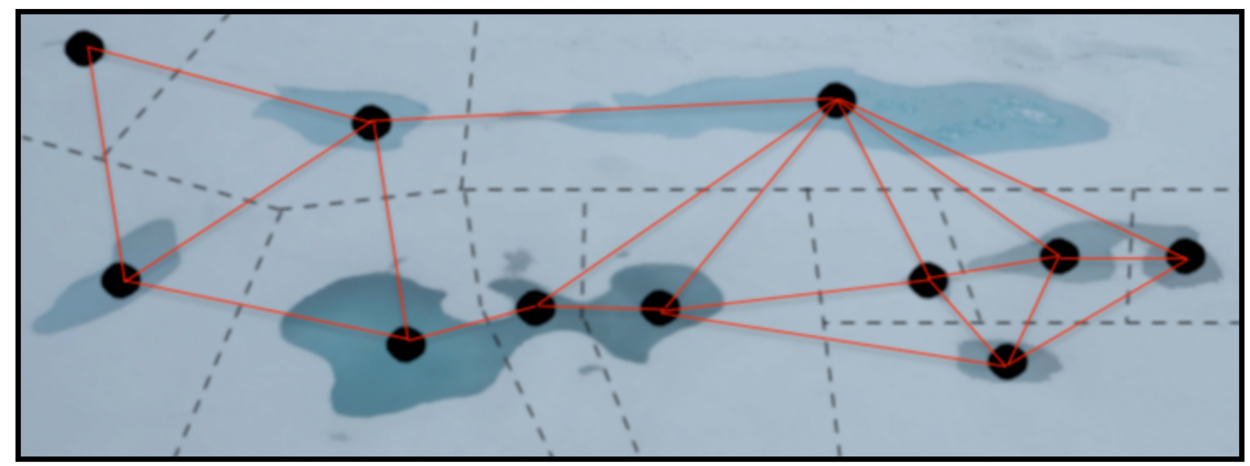


Image from 2018 Lu doi:10.5194/tc-12-1331-2018

- Identify individual catchments as nodes (boundaries are dashed)
- Build graph of neighbouring catchments (red)
- Calculate fluxes as water levels change
- Determine water levels, water covered areas
- Connected components of graph as compound ponds
- Examine behaviour and derive statistics

The model - node behaviour

Density parameter (taken to be 0.9)

$$\rho_{iw} = \frac{\rho_{ice}}{\rho_{water}}$$

Melt ratio

$$\nu = \frac{v_w}{v_b}$$

Melt rate on bare ice; Ice surface height; Melt rate in pond; Water level

$$\frac{\partial h}{\partial t}(\mathbf{x}, t) = \begin{cases} -v_b(t), & h(\mathbf{x}, t) \geq H(t) \\ -v_w(t), & h(\mathbf{x}, t) < H(t) \end{cases}$$

Ice surface height evolves according to melt rates, with enhanced melting in ponds

Volume of melt; Catchment area

$$\dot{V}_m = \rho_{iw} \iint_{a_0} -\frac{\partial h(\mathbf{x}, t)}{\partial t}\, \mathrm{dA}$$

Water production depends on the integral of These melt rates over whole catchment

Volume accumulated; Pond area

$$V_A(t) = \iint_a H(t) - h(\mathbf{x}, t)\, \mathrm{d}A$$

Water accumulates at lowest point in catchment up to a height of water level

Fluxes between pond i and j

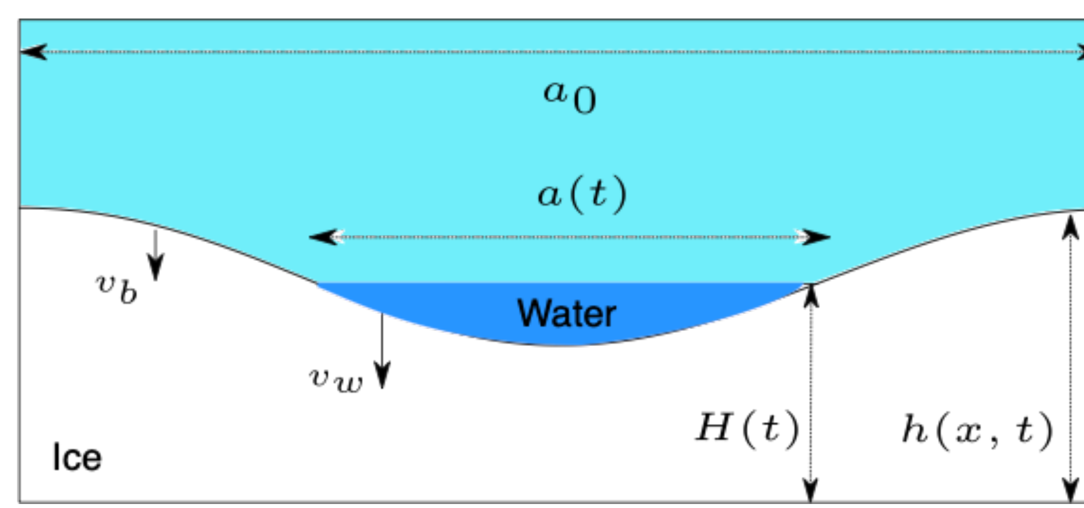
$$\dot{V}_{Ai} = \dot{V}_{mi} - \sum_j q_{i,j}$$

Water in each catchment changes due to melting and transfer of water between neighbours

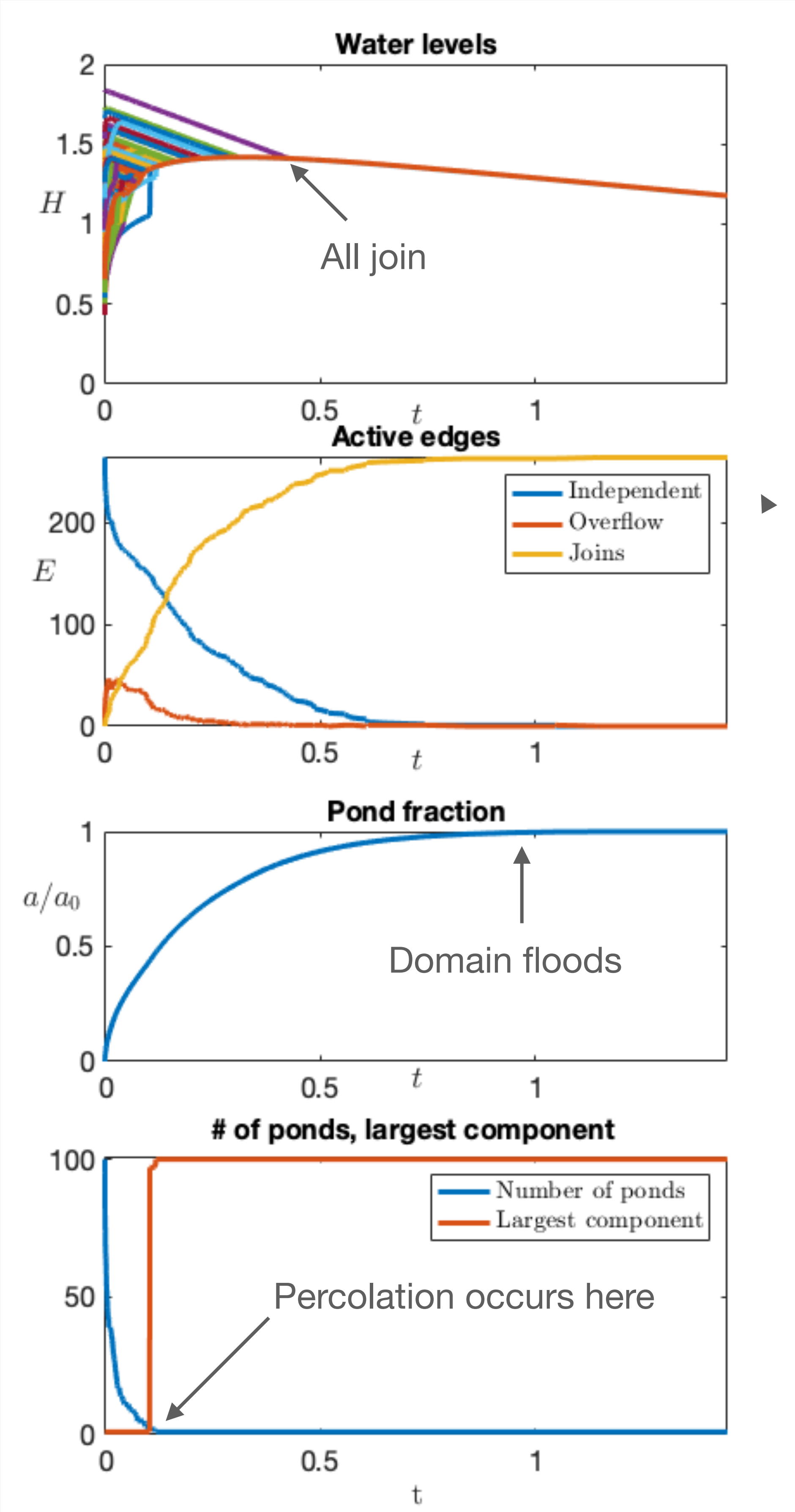
$$\dot{H}_i = \frac{\rho_{iw} v_b a_{0i}}{a_i} - [v_w - \rho(v_w - v_b)] - \frac{1}{a_i} \sum_j q_{i,j}$$

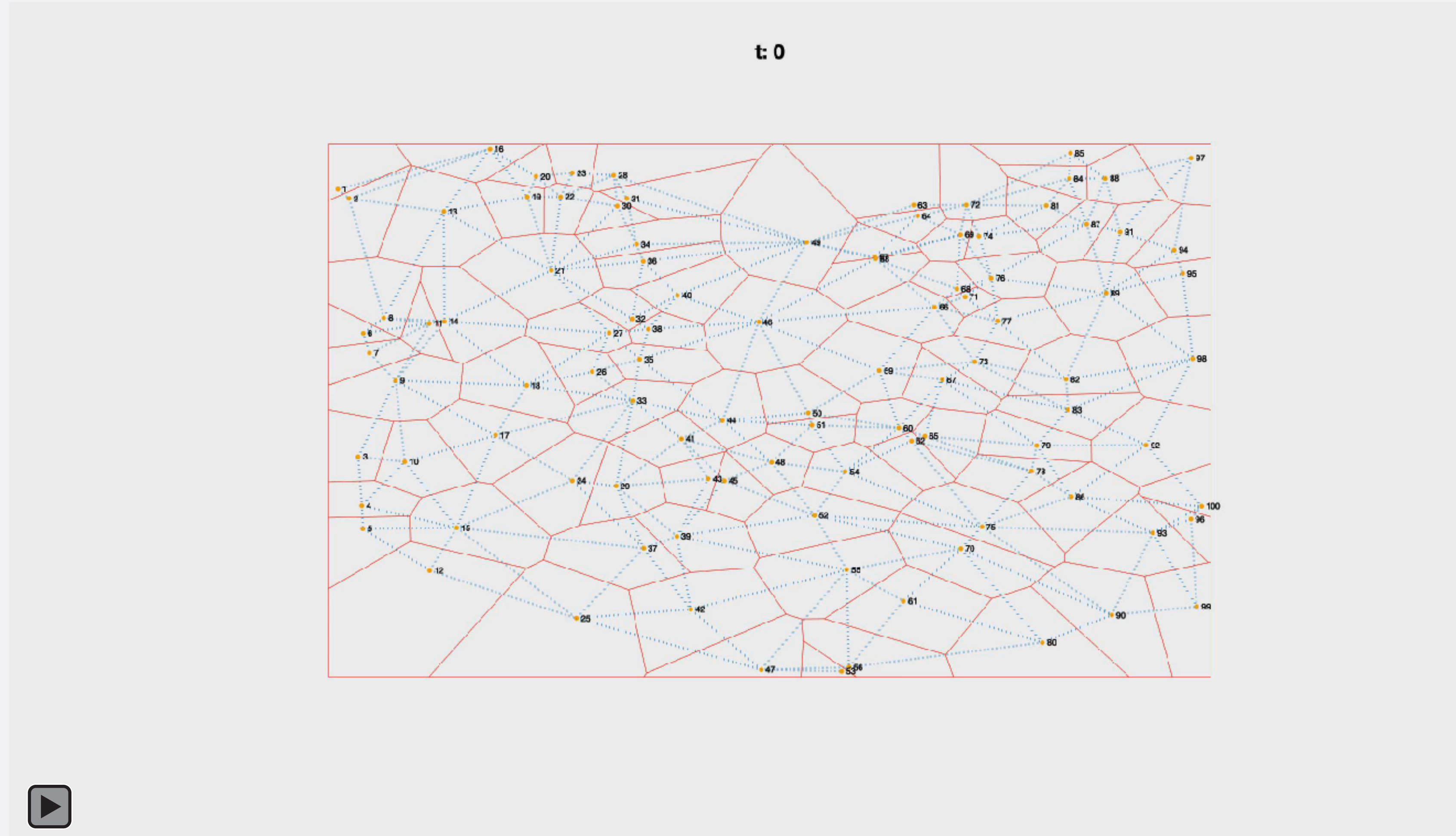
Node behaviour (water level) along with hypsometry

$$a_i = f_i(H_i, t)$$



Simulations without drainage





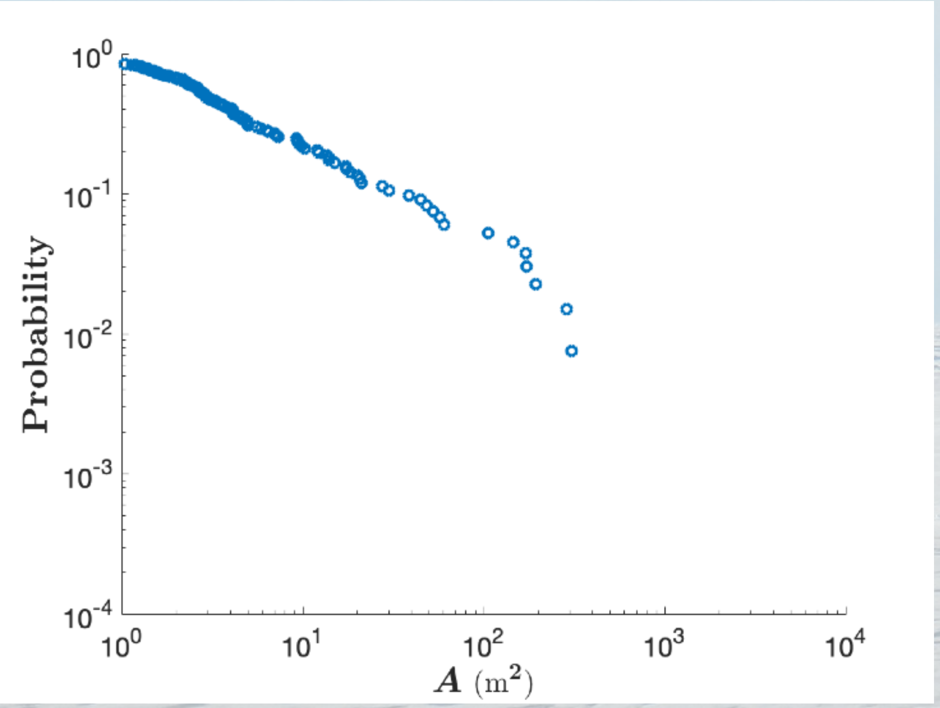
System eventually behaves as one pond

Evolution of area coverage from start of melt season to flooding of floe or when floe disappears*

Output from model run show clear percolation behaviour at t~0.1

* Time of model run here is exaggerated to show all possible behaviour without drainage

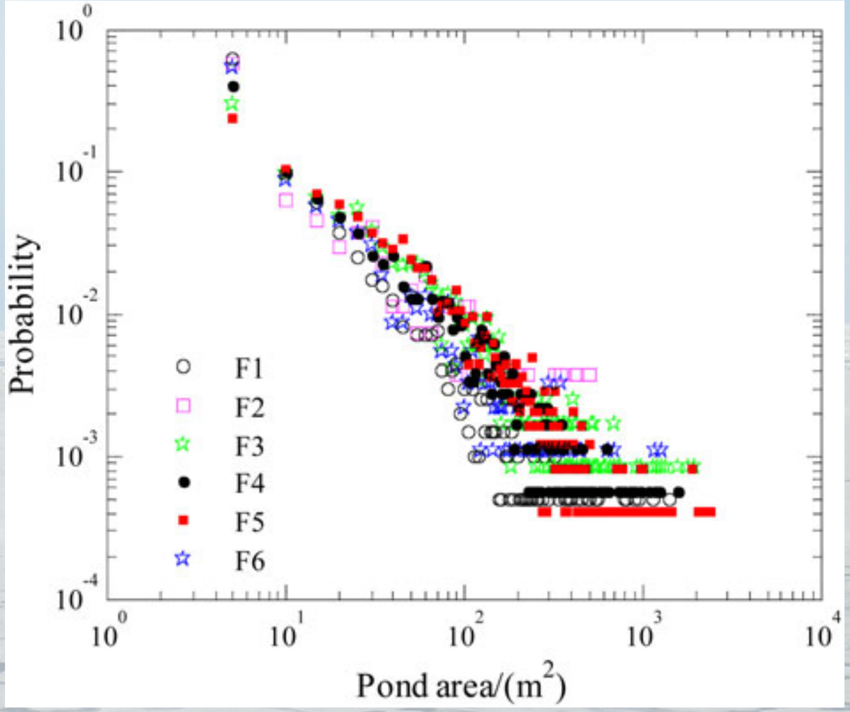
Model results vs. Observations



- Experiments on random topography of 150 catchments (melt ratio of 2.5)
- Ponds sampled at early time, and shortly after the percolation transition
- MARS regression used to find change in area-perimeter relations (below)

Frequencies of pond areas

- Model results (left) at two time points in a simulation (proxy for ponds at different latitudes)
- Results show similar pond size distribution as field observations (right)



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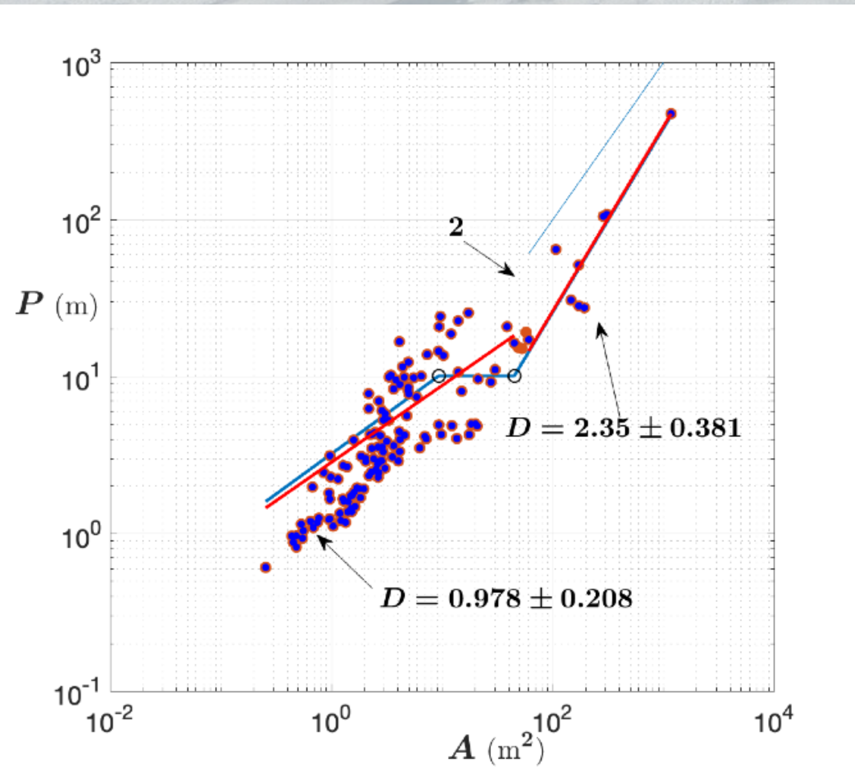


Changes in perimeter-area scaling

- Distinct change in perimeter-area relationship → ponds beginning to connect
- Change implies transition closely aligned with percolation transition of network

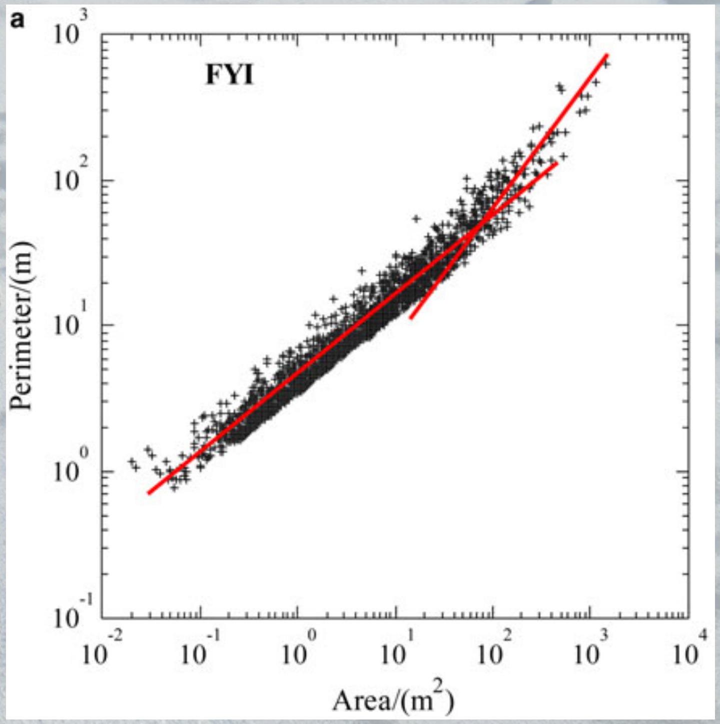
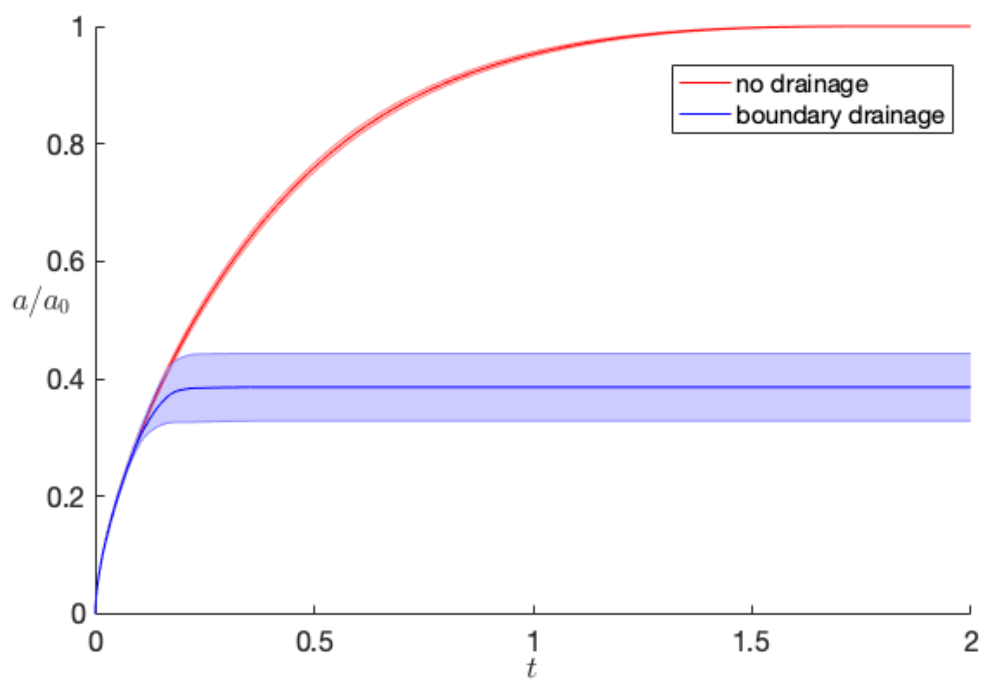


Image from Huang 2016 doi:10.1017/aog.2016.30

Incorporating drainage

- Allow drainage over the sides of the floe
- Add an extra ‘ocean’ node, sea level kept below lowest point on floe boundary
- Wire all catchments along the floe boundary to ocean node and allow them to overflow
- Drainage over the side of floe strongly controls maximum area fraction



- Averaged trajectories of pond fraction, 20 realisations of random topographies, each of 100 catchments
- Experiments with and without drainage done on each
- Solid line is mean, shaded region within one standard deviation
- Melt ratio is 2.5

Simplicity of network model allows easy analysis of other physical effects

Conclusions

- Network model represents physics and geometry, and allows study of percolation processes
- Pond statistics a result of the percolation process
  Percolation happens early, at low pond fraction (~0.35)
- Model recreates pond statistics qualitatively
- Maximum area fraction strongly dependent on drainage (especially on first year ice)