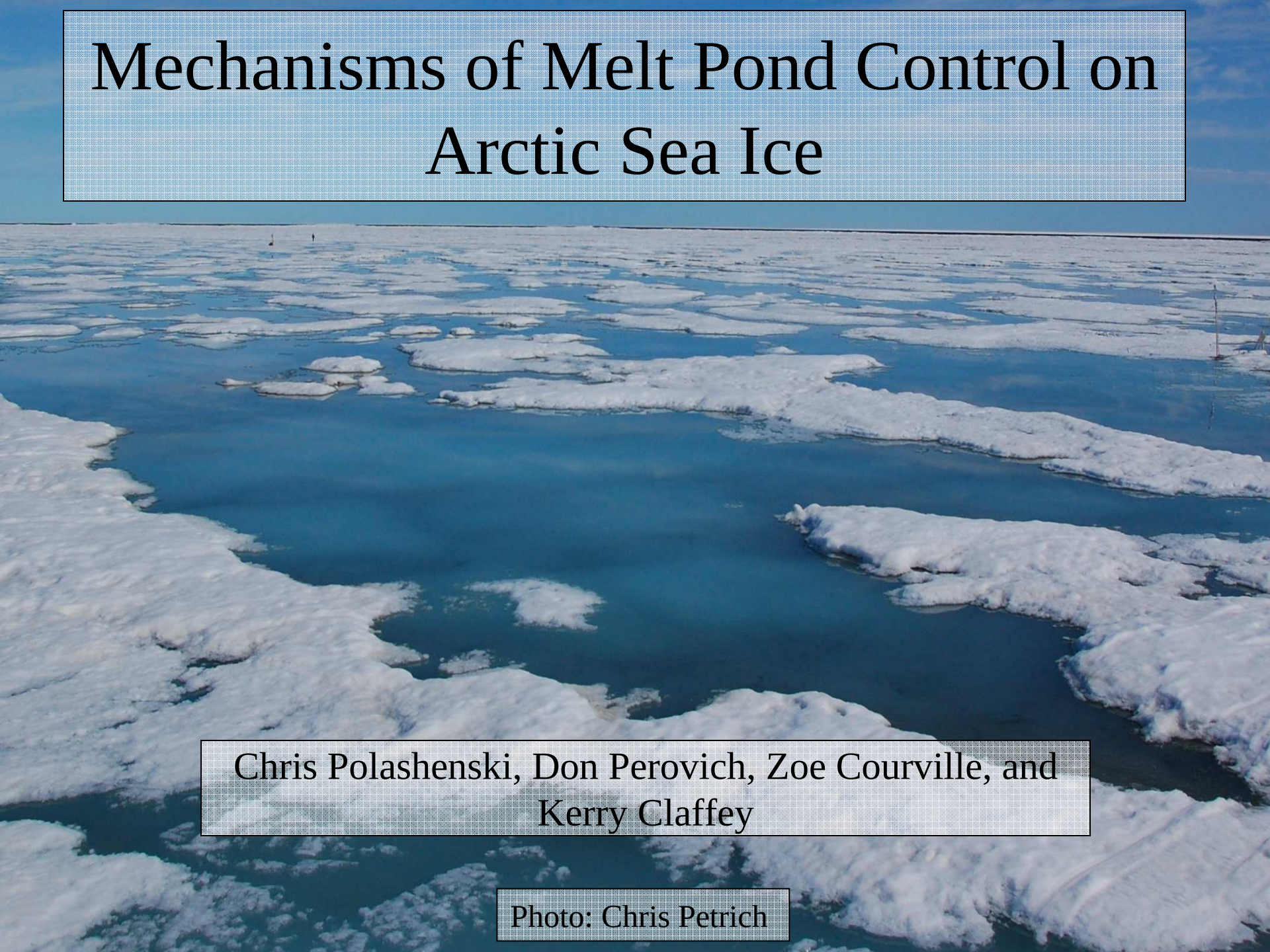
Mechanisms of Melt Pond Control on Arctic Sea Ice



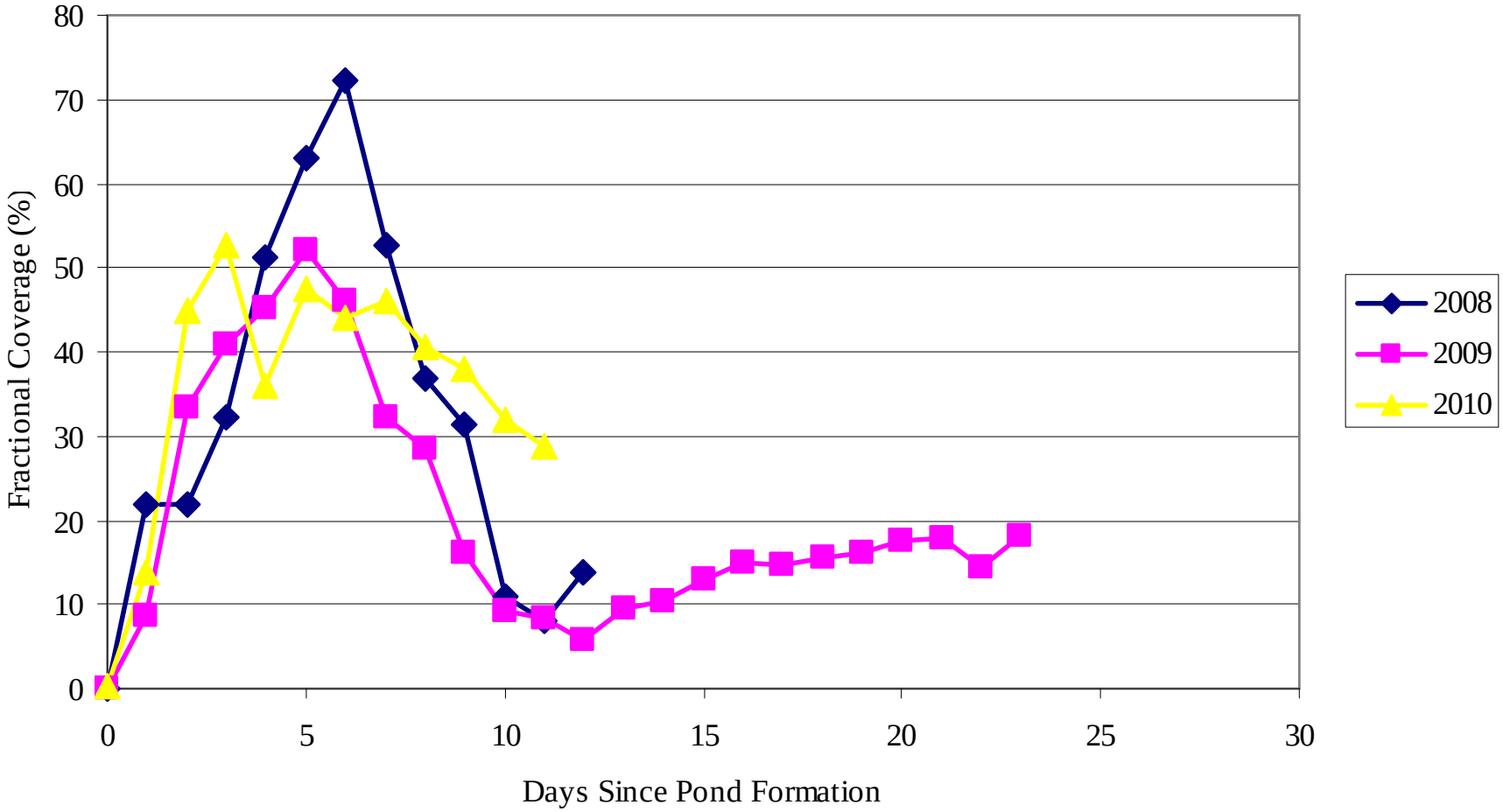
Chris Polashenski, Don Perovich, Zoe Courville, and Kerry Claffey

Photo: Chris Petrich

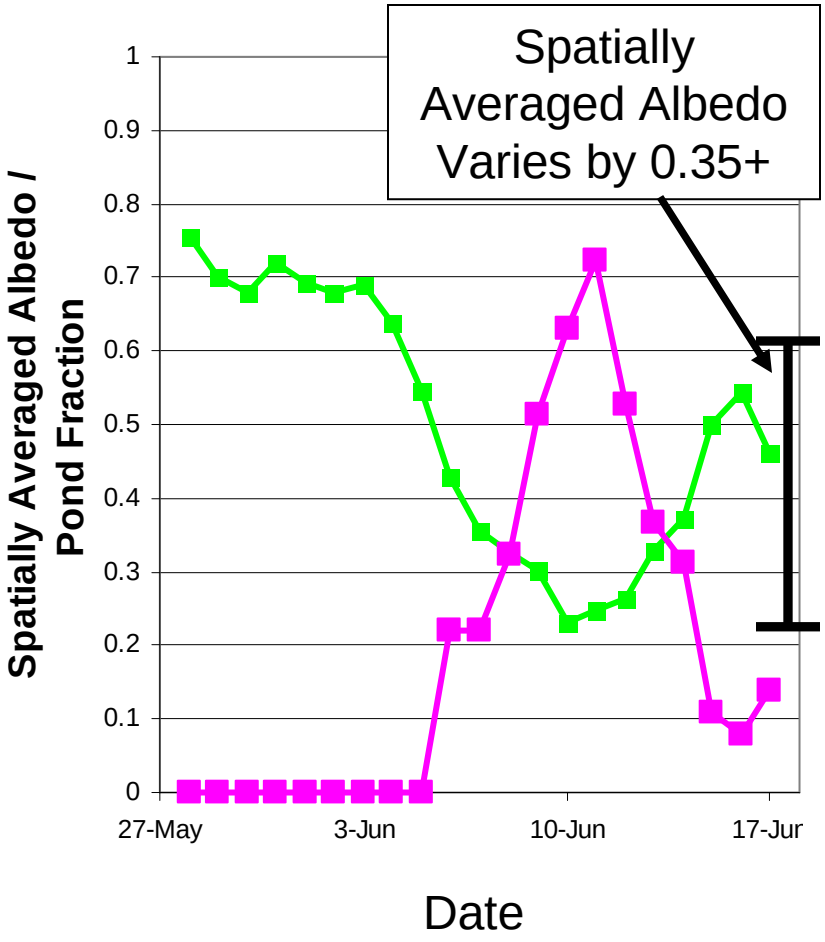

Albedo = ~0.15
Albedo = ~0.60
Photo: Chris Petrich

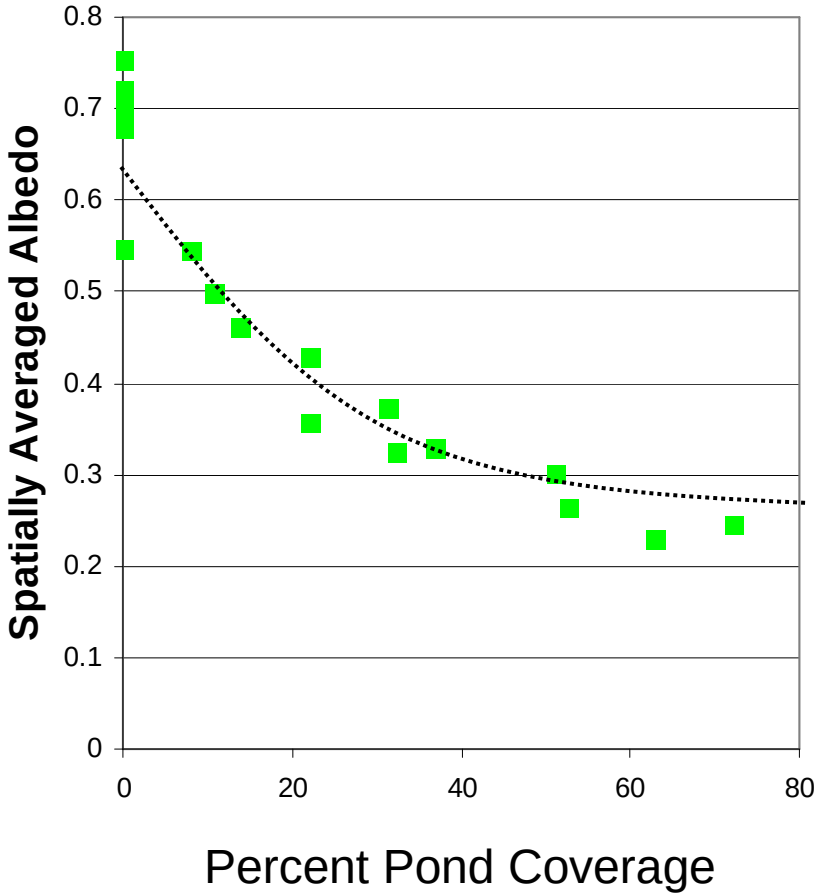
Seasonal Evolution of Melt Pond Spatial Coverage

Barrow AK 2008-2010



Pond coverage shows tremendous temporal variability



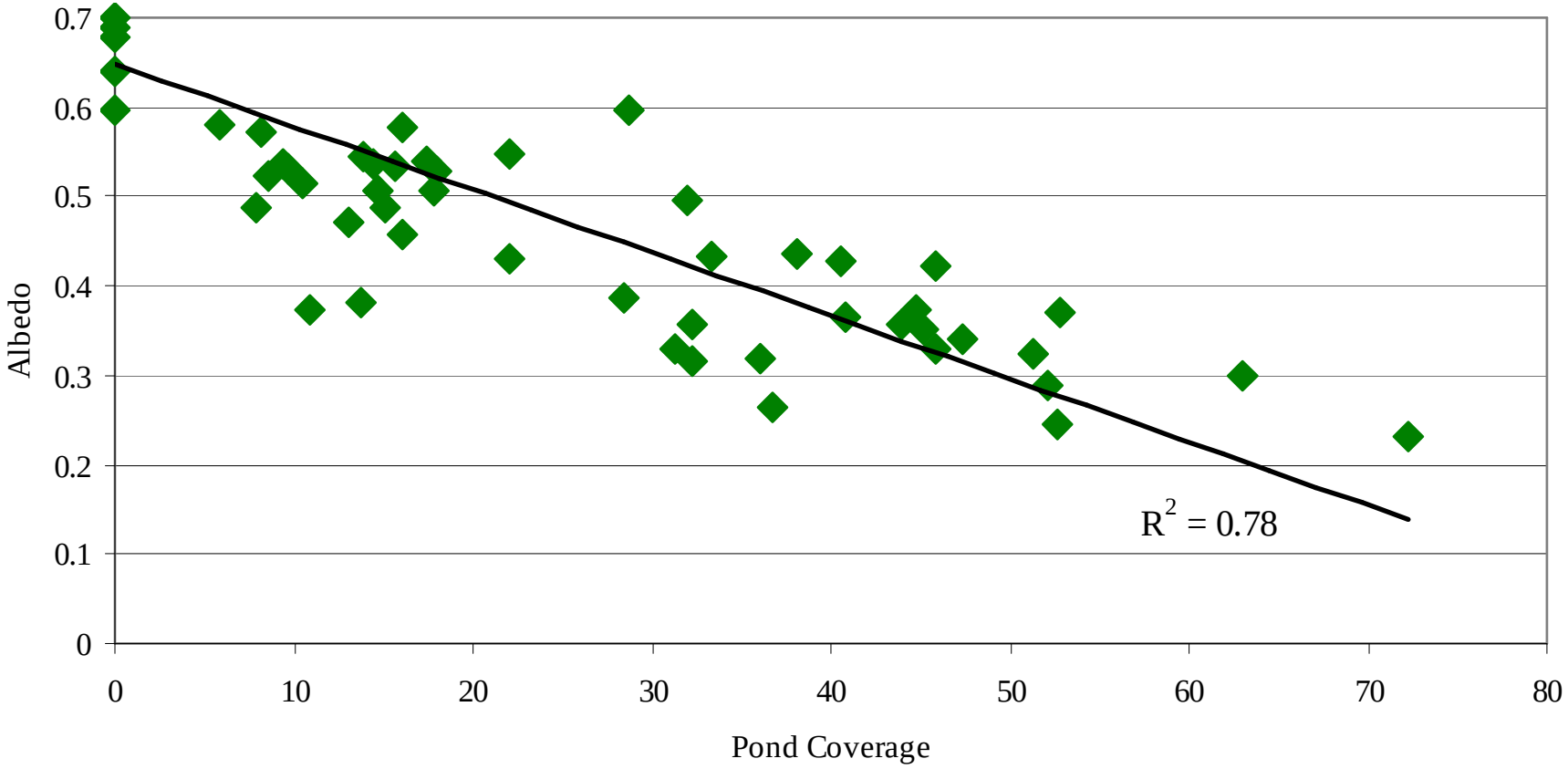


Pink = Pond Coverage

Green = Albedo

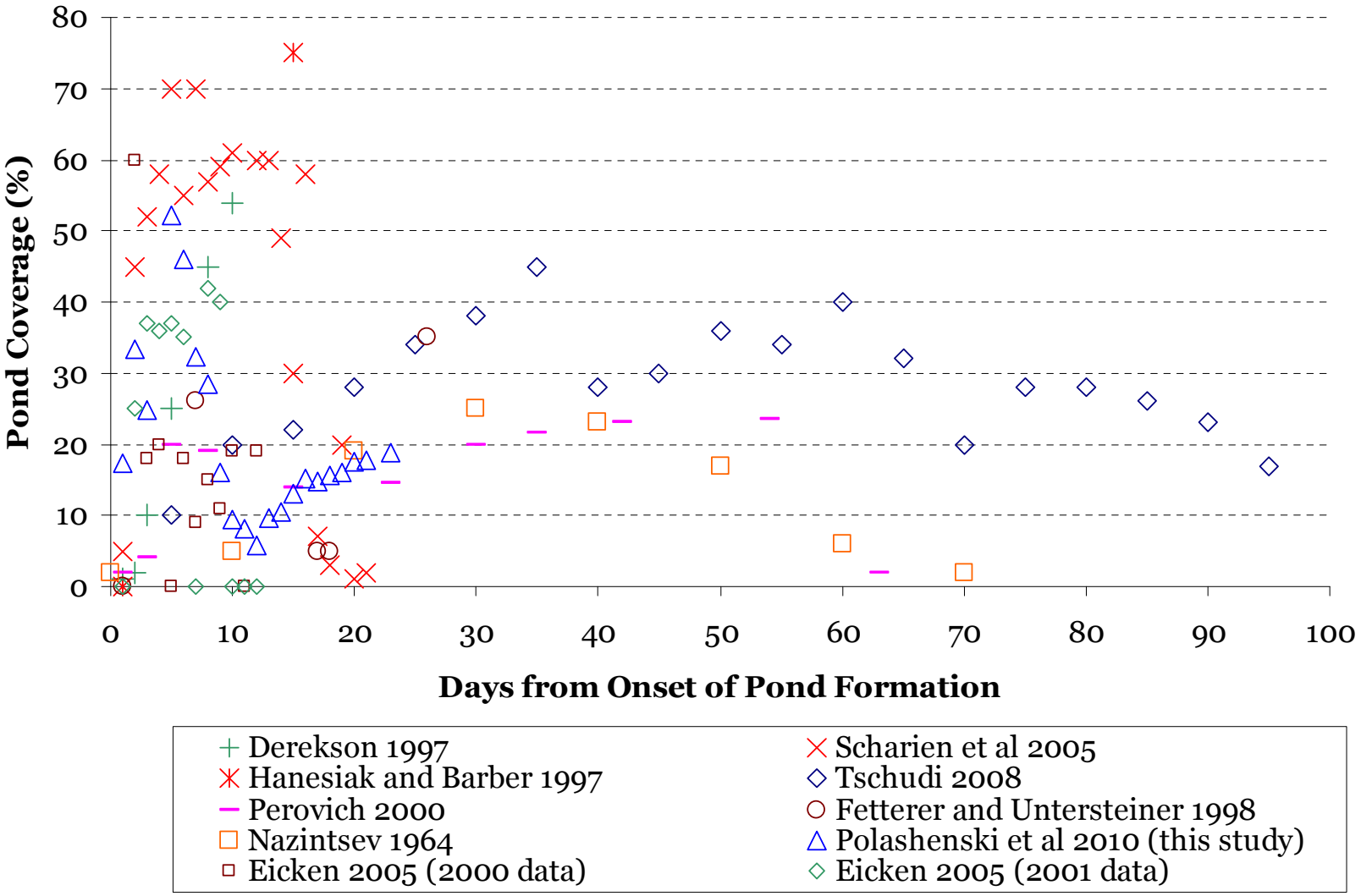
Pond Coverage vs Ice Albedo

Barrow, AK 2008-2010



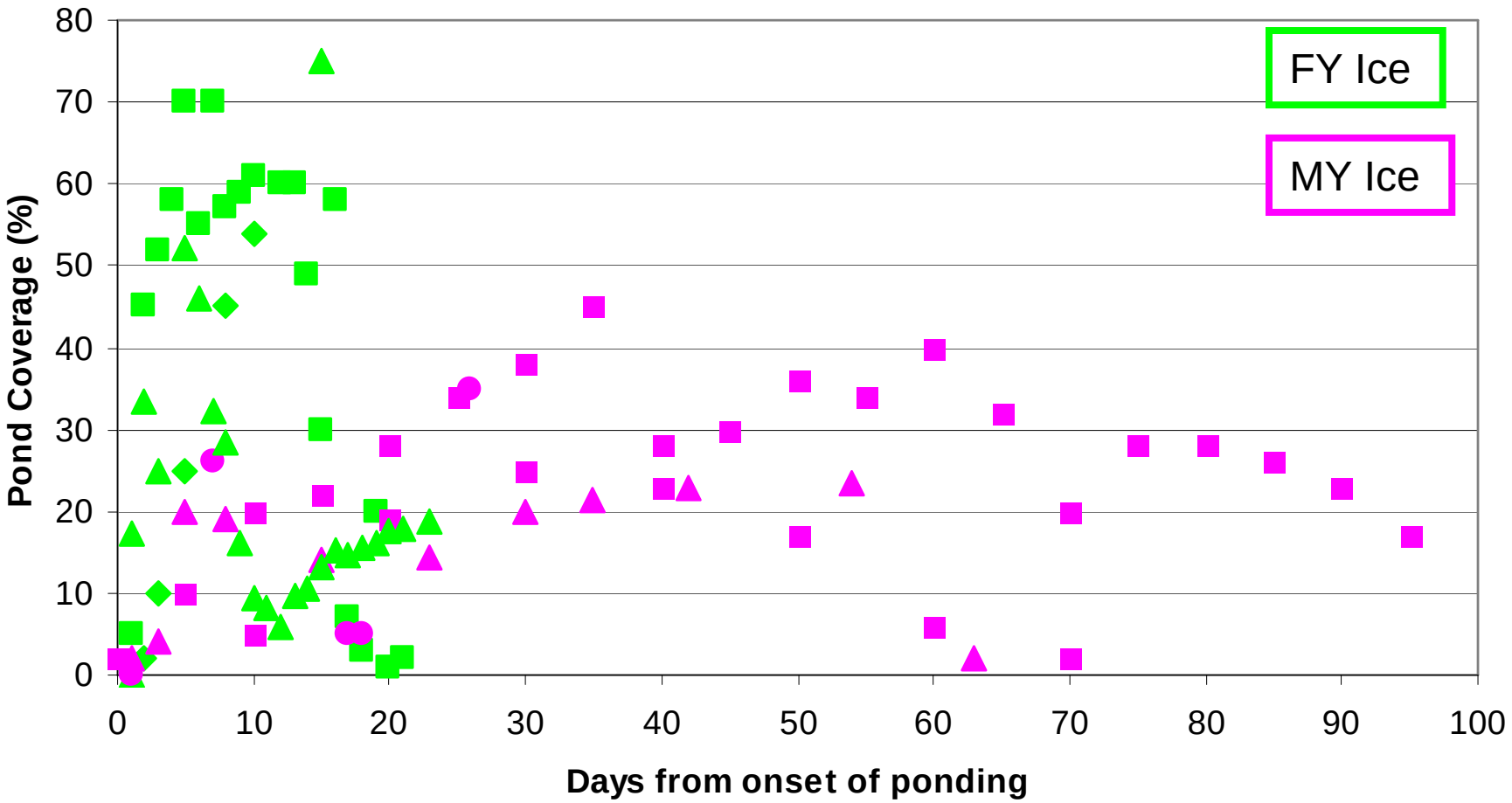
Pond coverage is the predominant driver of summer ice albedo

Compilation of Published Pond Coverage Data

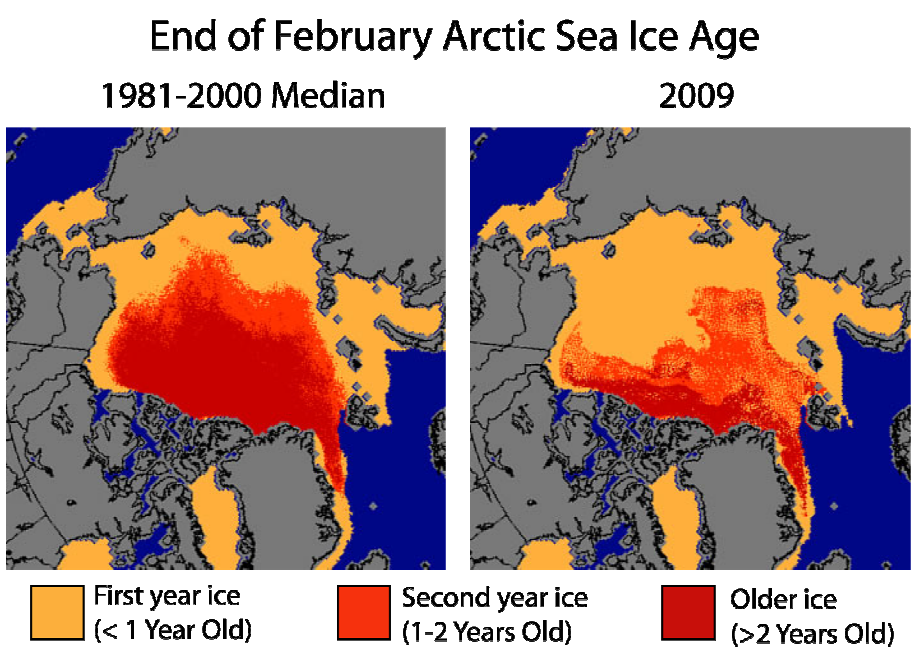


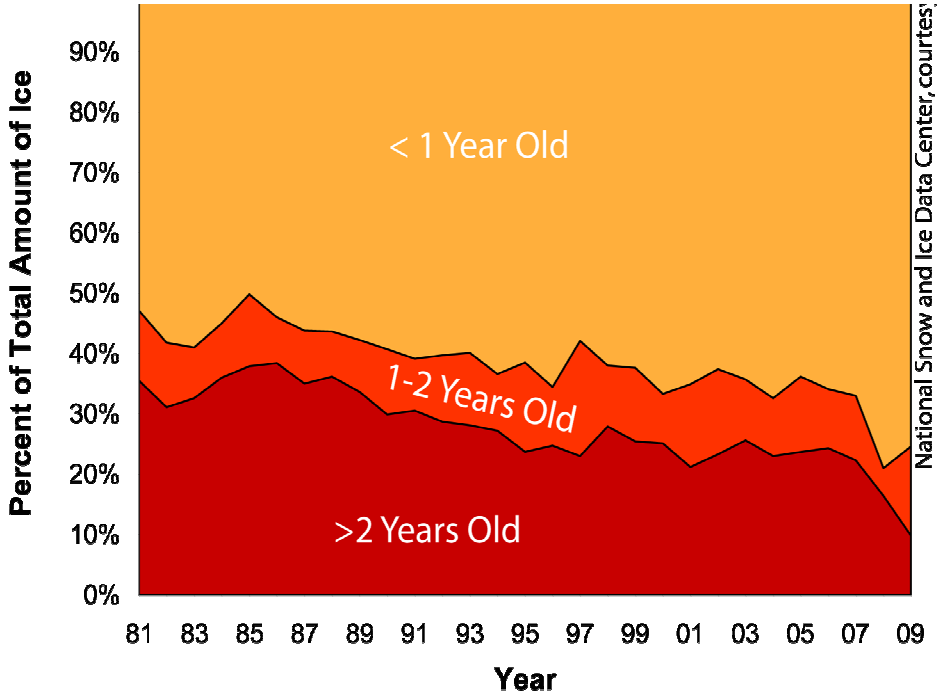
Pond coverage shows tremendous spatial and interannual variability

Pond Coverage vs Date



Changing Ice = Changing Pond Coverage



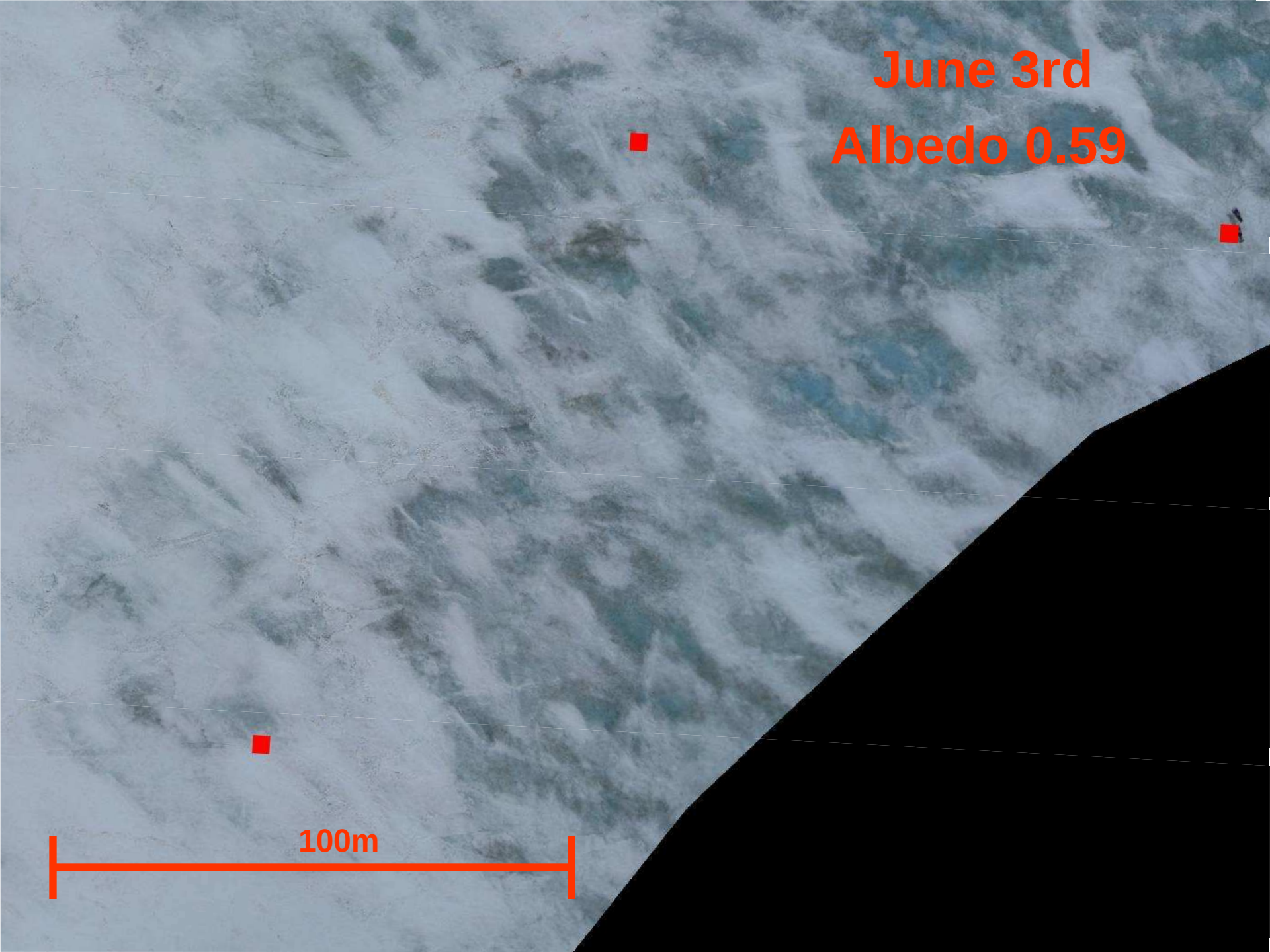


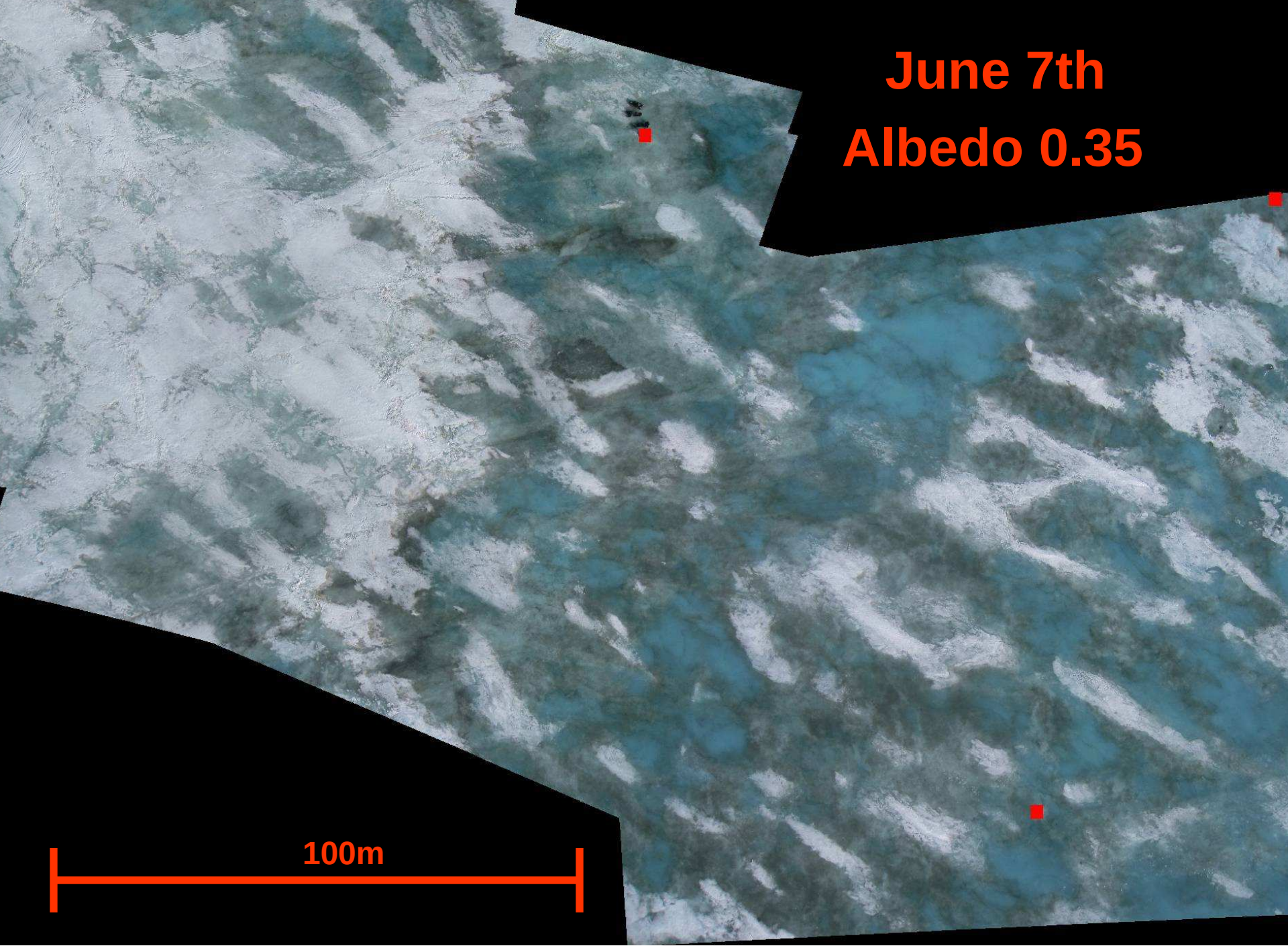
Explicit treatment of melt ponds will increase resilience of ice albedo predictions in a changing climate

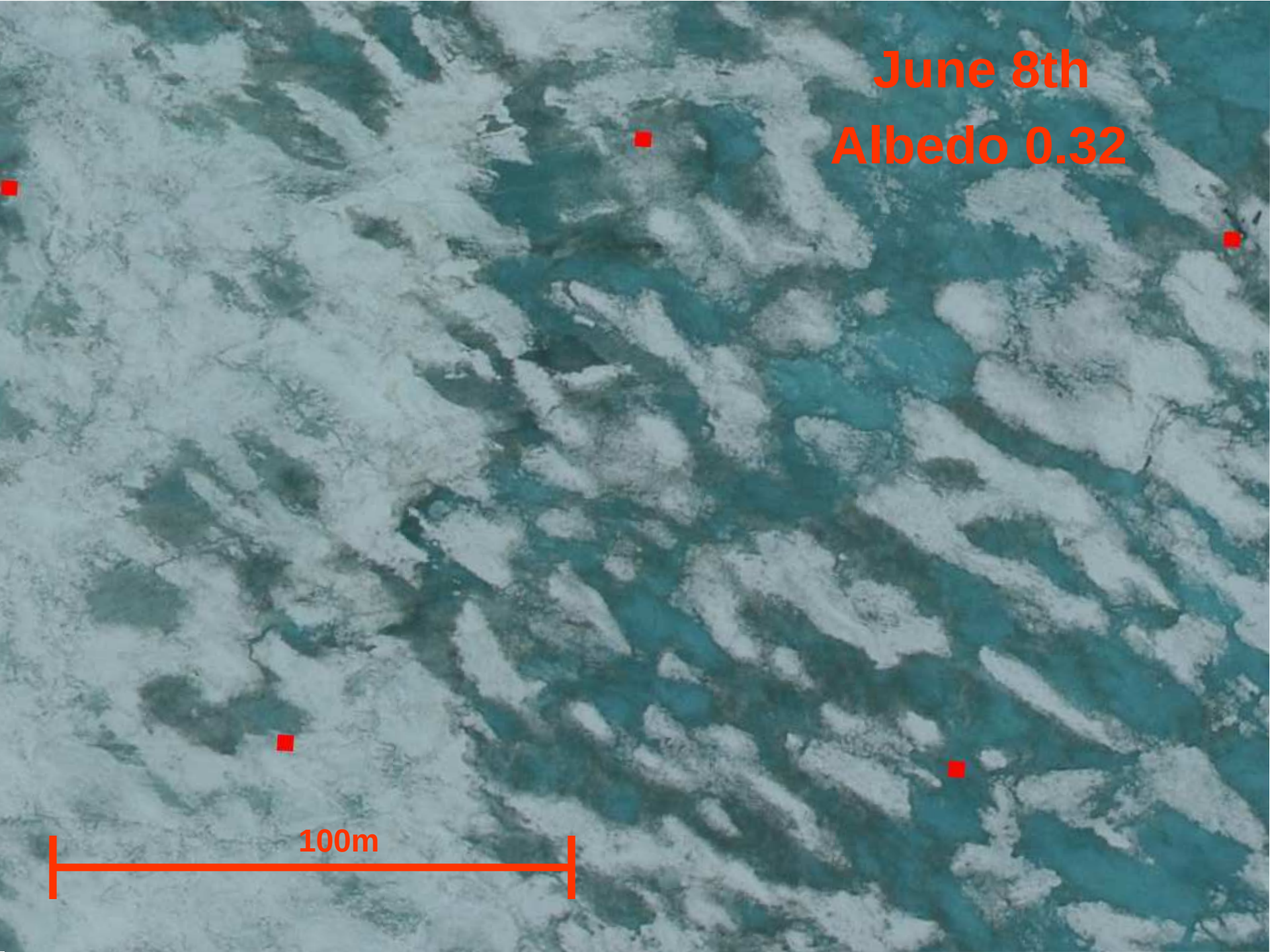

Russia
Arctic Ocean
Chukchi Bay
Bering Sea
Queen Elizabeth Islands
Greenland
Iceland
Reykjavik
Ellesmere Island
Baffin Bay
Banks Island
Fairbanks
Anchorage
Victoria Island
Baffin Island
Godthab
Kodiak Island
Gulf of Alaska
Labrador Sea
Hudson Bay
Queen Charlotte Islands
Vancouver
Edmonton
Calgary
Seattle
Portland
Canada
Montreal
Ottawa
Saint Paul
Minneapolis
Toronto
Buffalo
Milwaukee
Detroit
London
Chicago
Sacramento
San Francisco
Oakland
Pittsburgh
Denver
Omaha
Columbus
Kansas City
Indianapolis
Cincinnati
Wichita
Saint Louis
Los Angeles
San Diego
Albuquerque
Phoenix
Tulsa
Nashville
Memphis
Charlotte
Oklahoma City
Atlanta
Ensenada
Tucson
Birmingham
El Paso
Fort Worth
Dallas
Guadalupe
Austin
Houston
New Orleans
Pacific Ocean
Hermosillo
Chihuahua
San Antonio
Monterrey
Gulf of Mexico
Miami
Culiacan
Saltillo
Havana
Pinar Del Rio
North America
Aguascalientes
Guadalajara
Guanajuato
Merida
Cayman Islands
Morelia
Mexico City
Toluca De Lerdo
Puebla
Belmopan
Belize
Acapulco De Juarez
San Pedro Sula
Guatemala City
Tegucigalpa
San Salvador
El Salvador
Managua
San Jose
Costa Rica
David
★ National Capitals
• Cities 3,000,000+
• Cities 900,000-2,999,999
International Boundaries
Highways
Primary Roads
Major Rivers
Lakes
0 320 640 Miles
0 320 640 KM

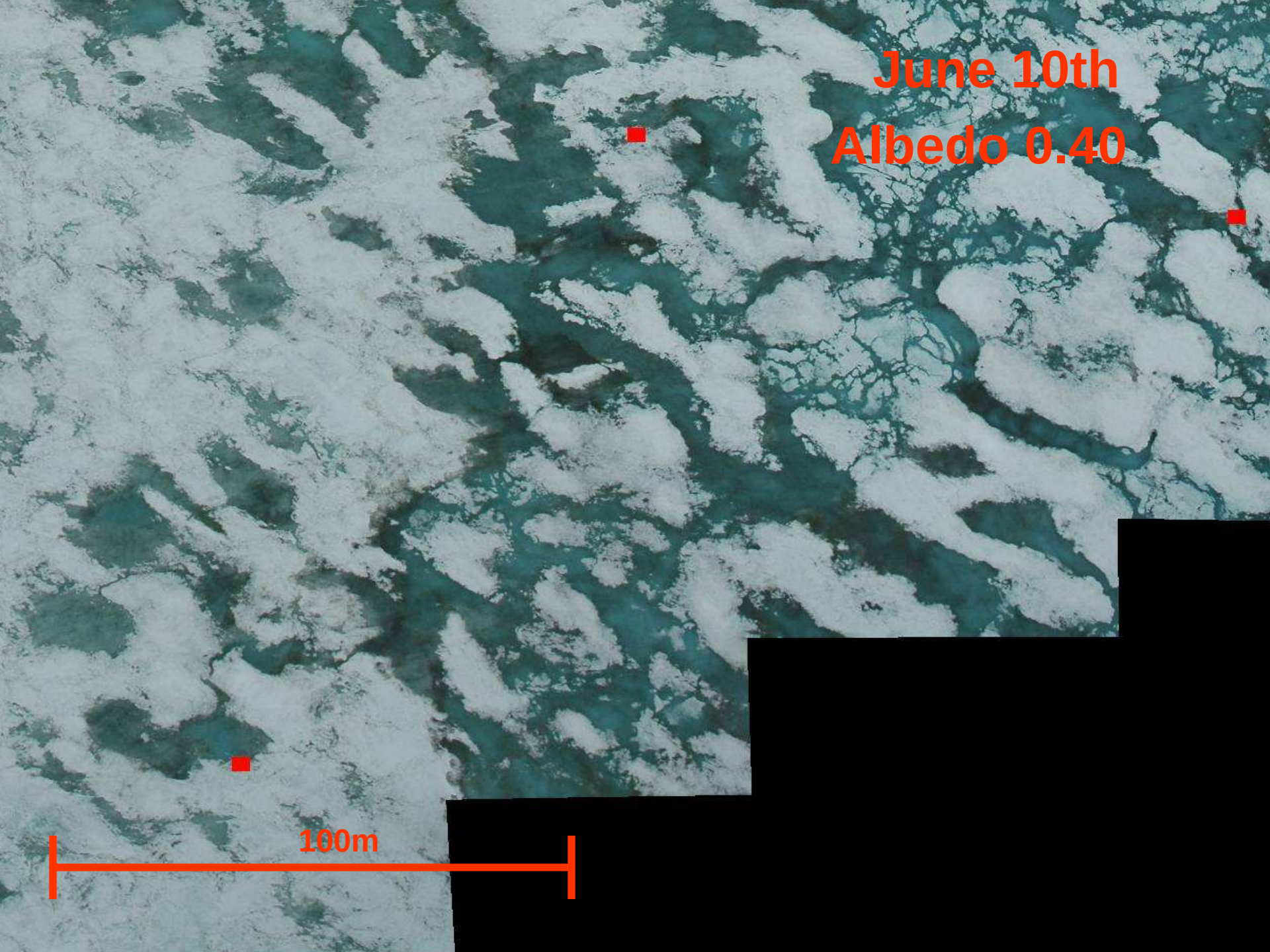
RIEGL
VMS-Z420i
RIEGL

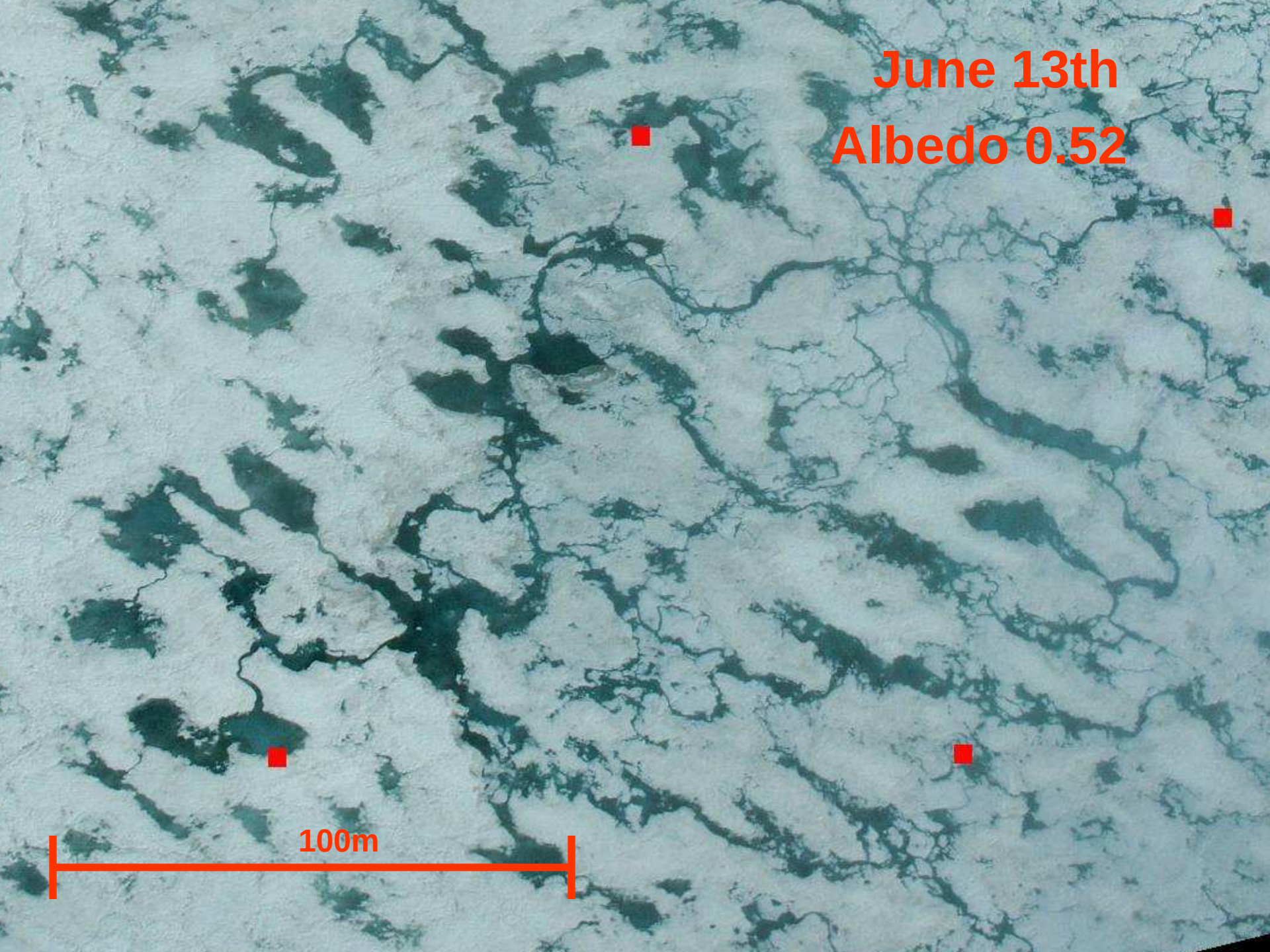

June 1st
Albedo ~0.79
100m


June 3rd
Albedo 0.59
100m

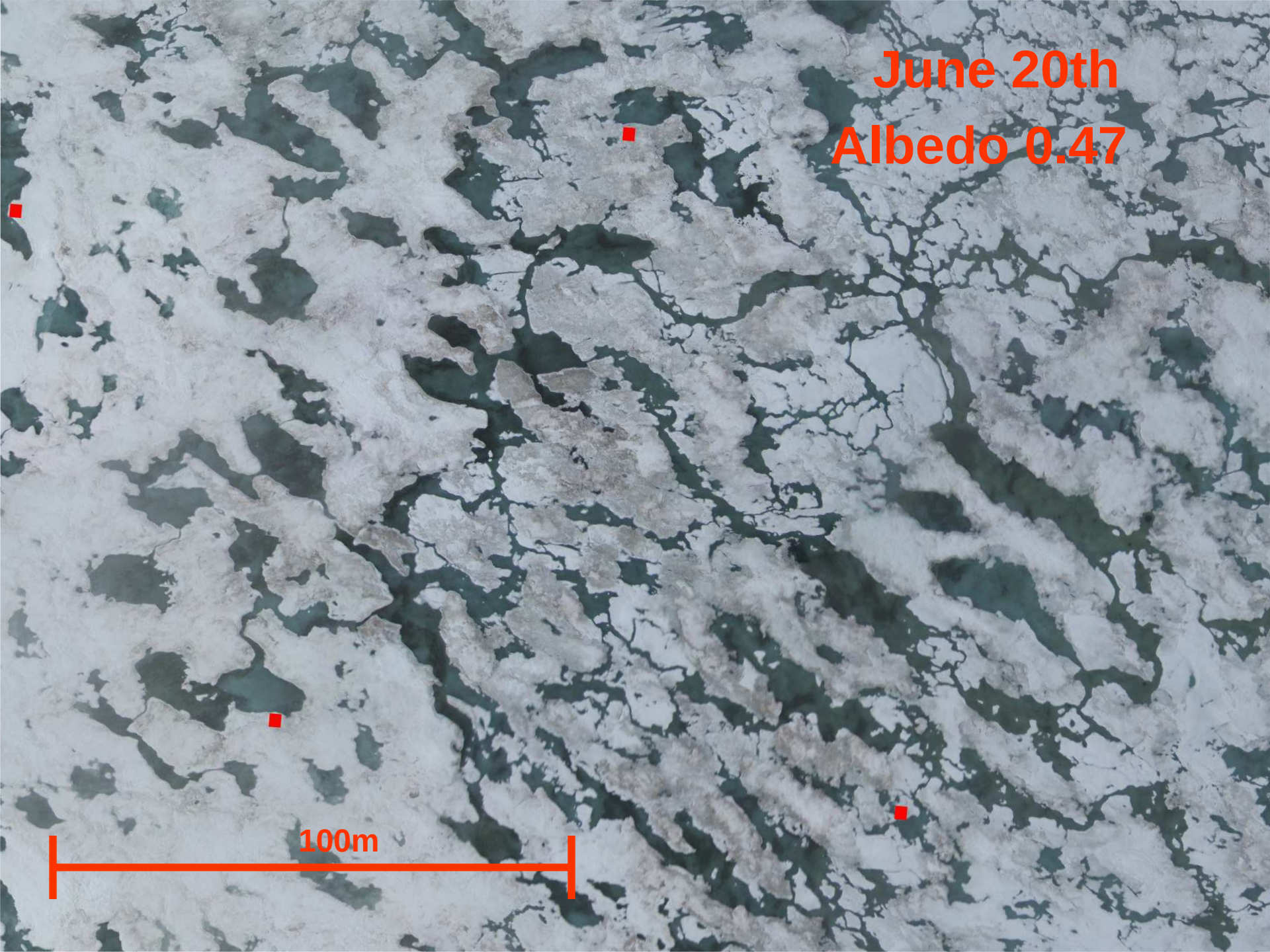

June 7th
Albedo 0.35
100m

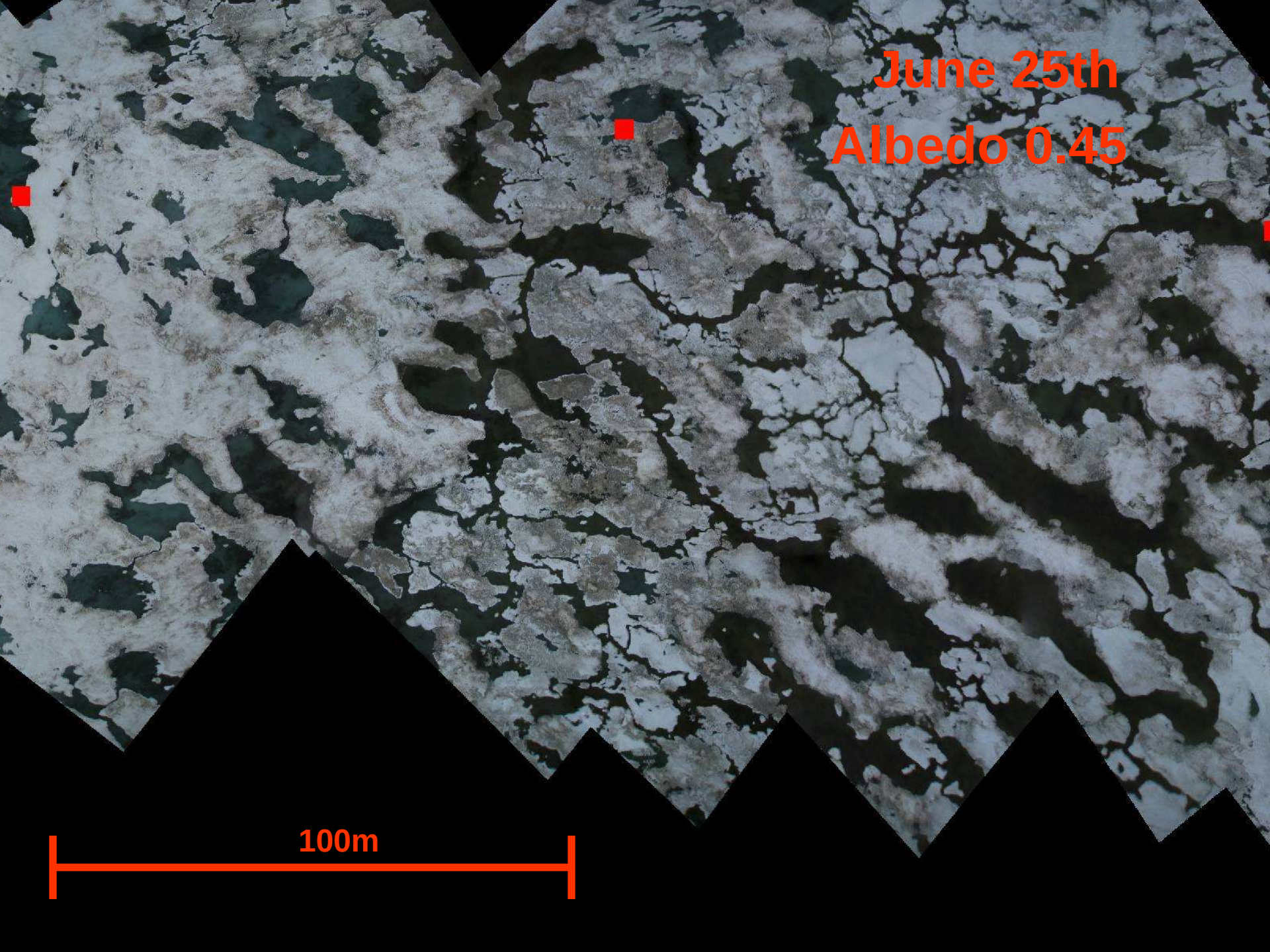

June 8th
Albedo 0.32
100m

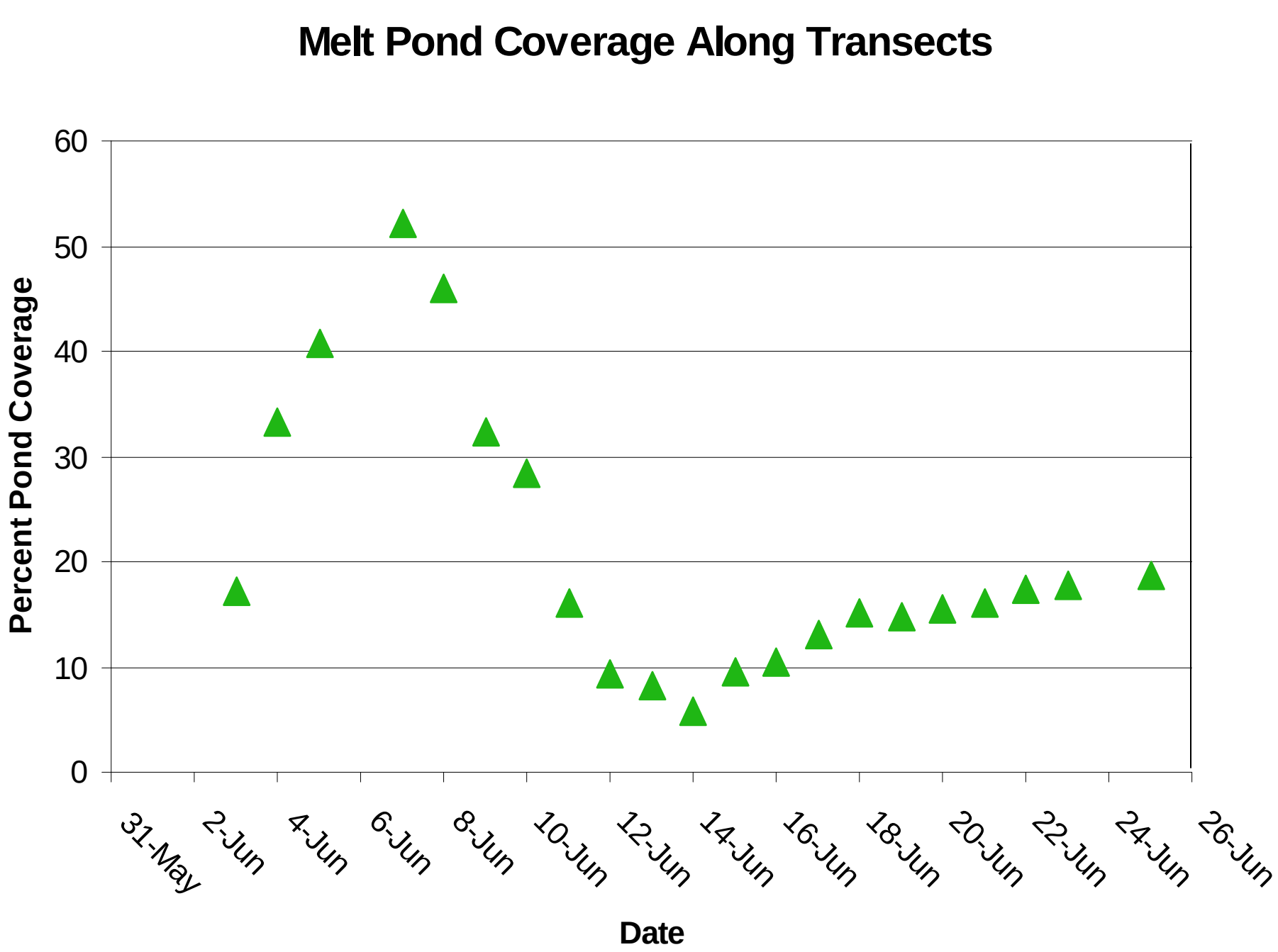

June 10th
Albedo 0.40
100m

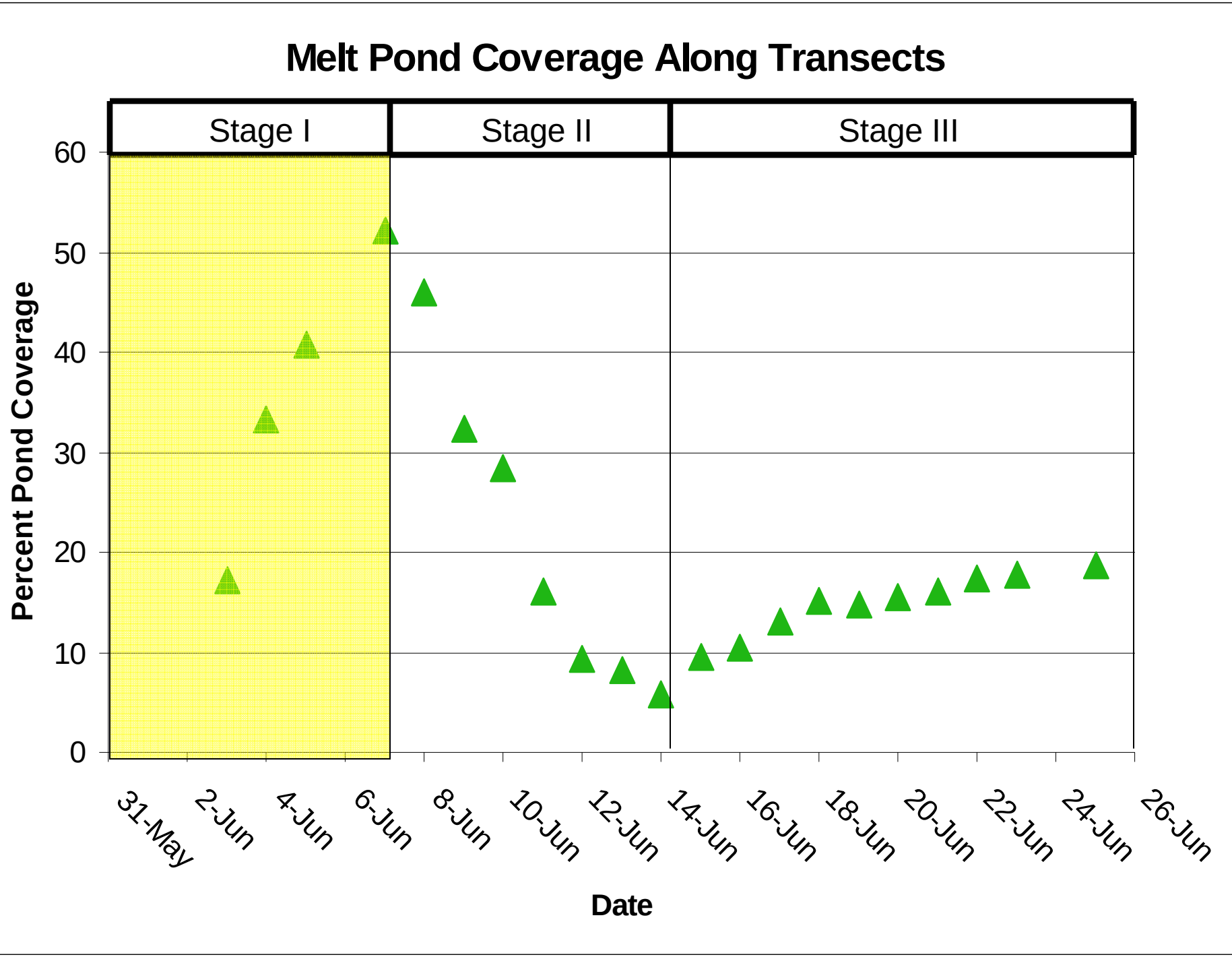

June 13th
Albedo 0.52
100m

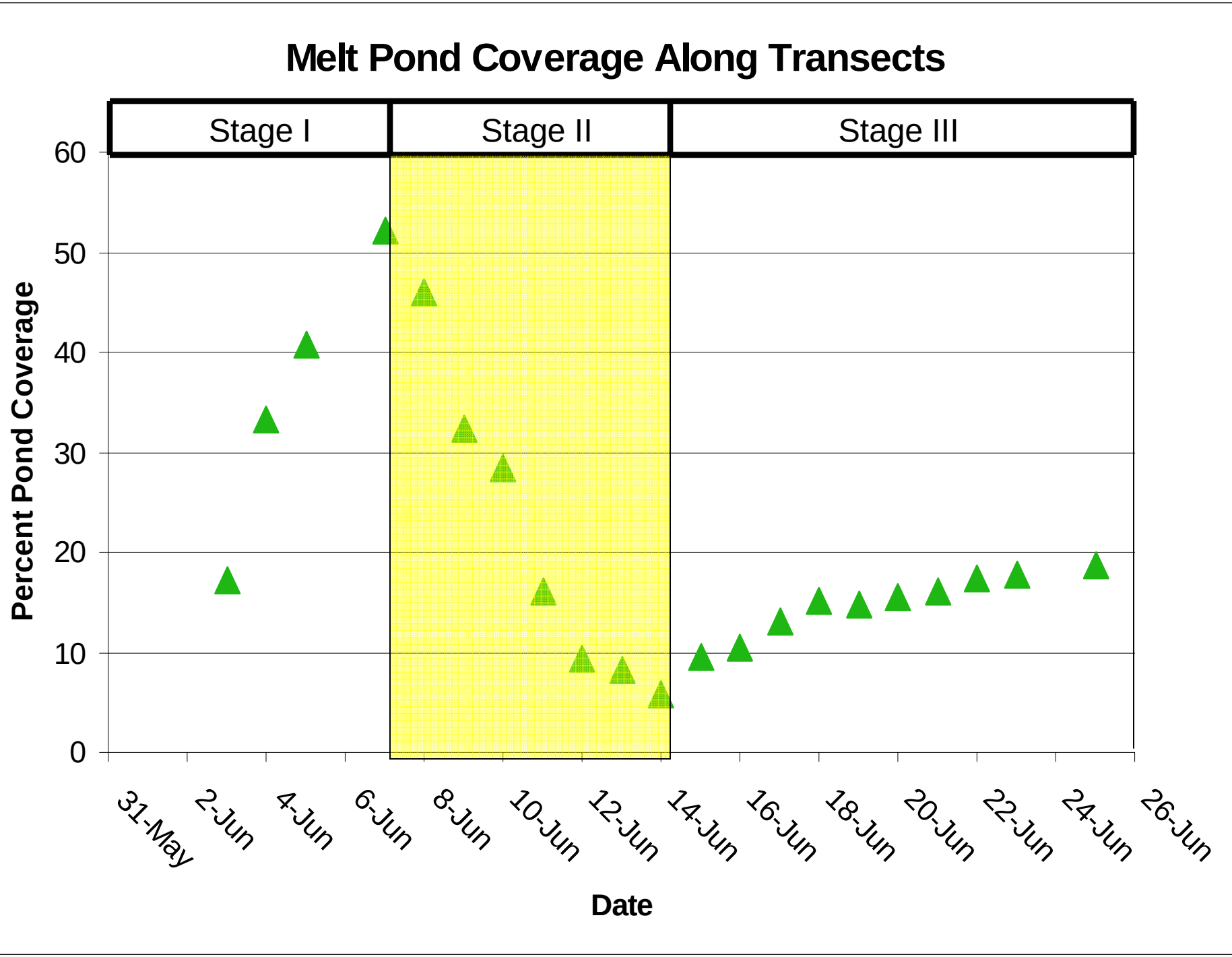

June 15th
Albedo 0.58
100m

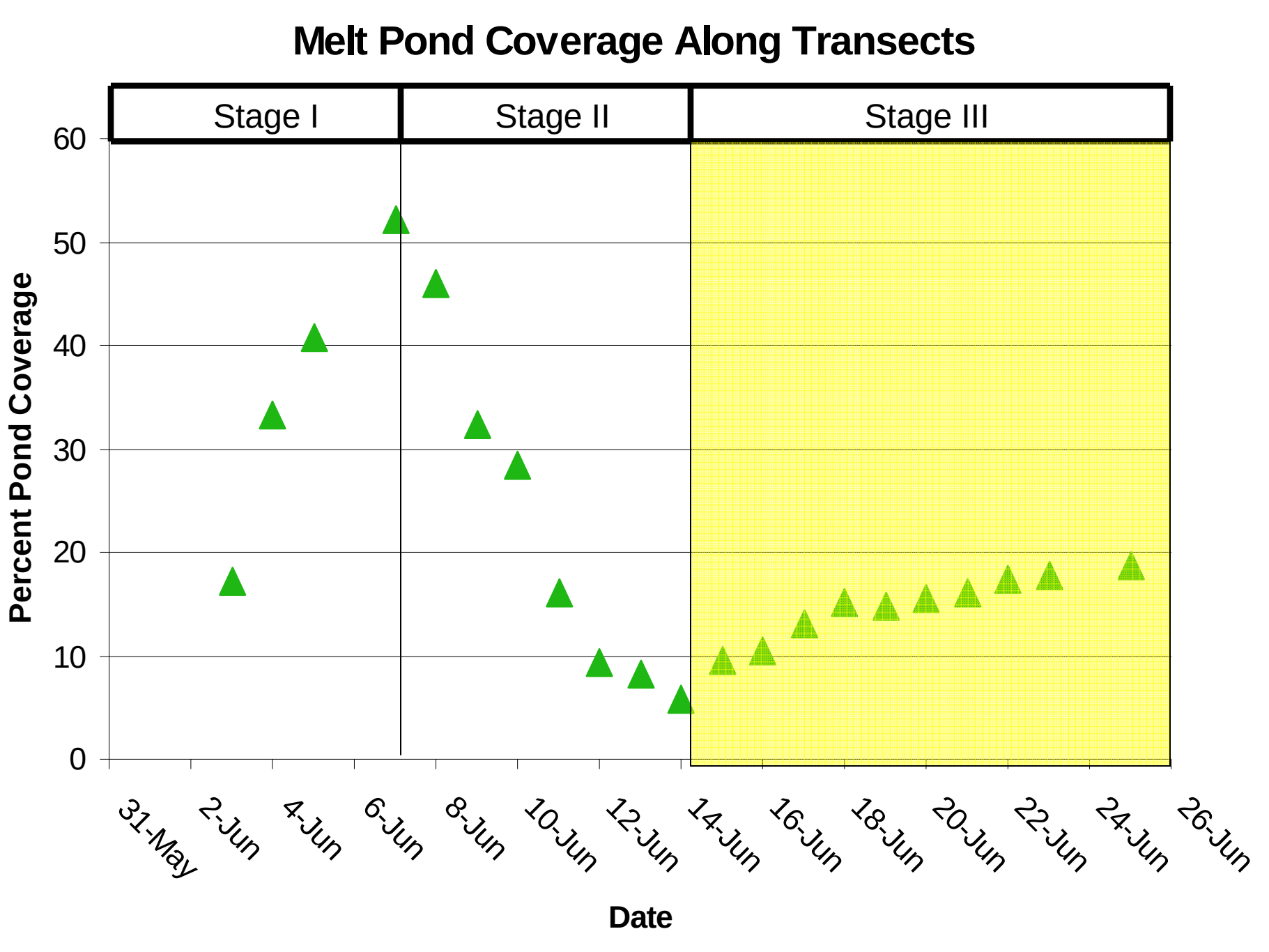

June 20th
Albedo 0.47
100m

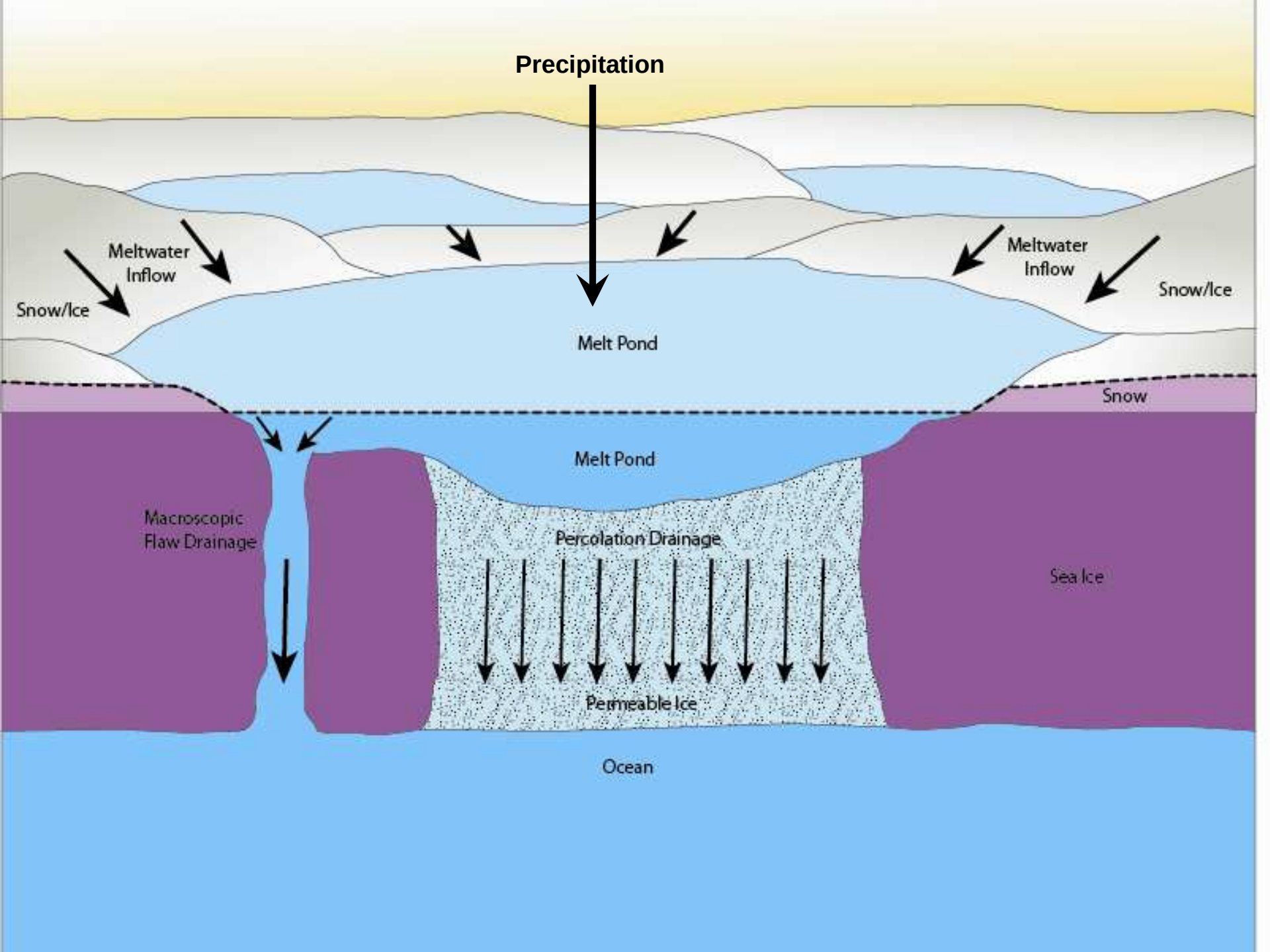

June 25th
Albedo 0.45
100m

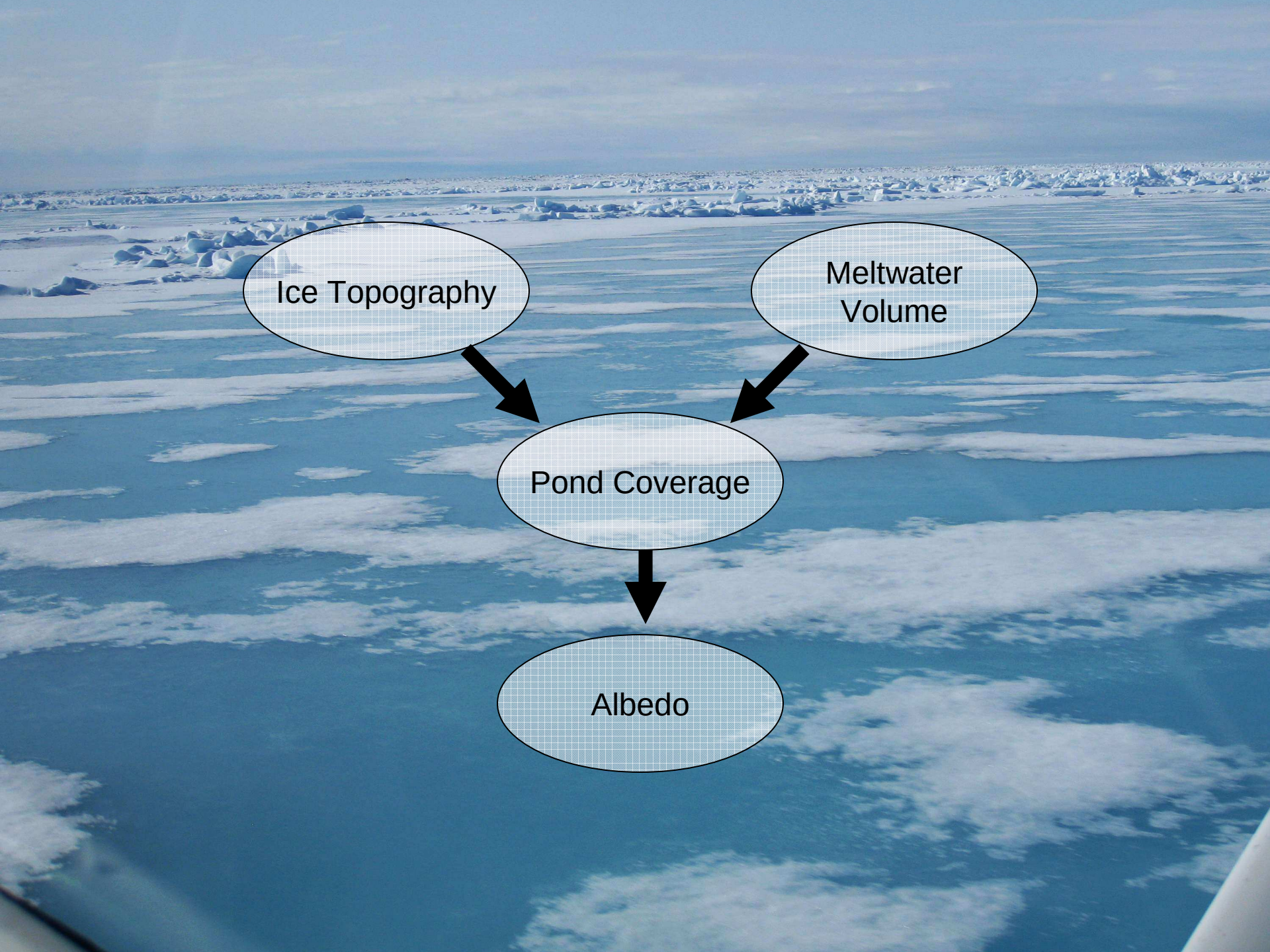

Melt Pond Coverage Along Transects
Percent Pond Coverage
60
50
40
30
20
10
0
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date

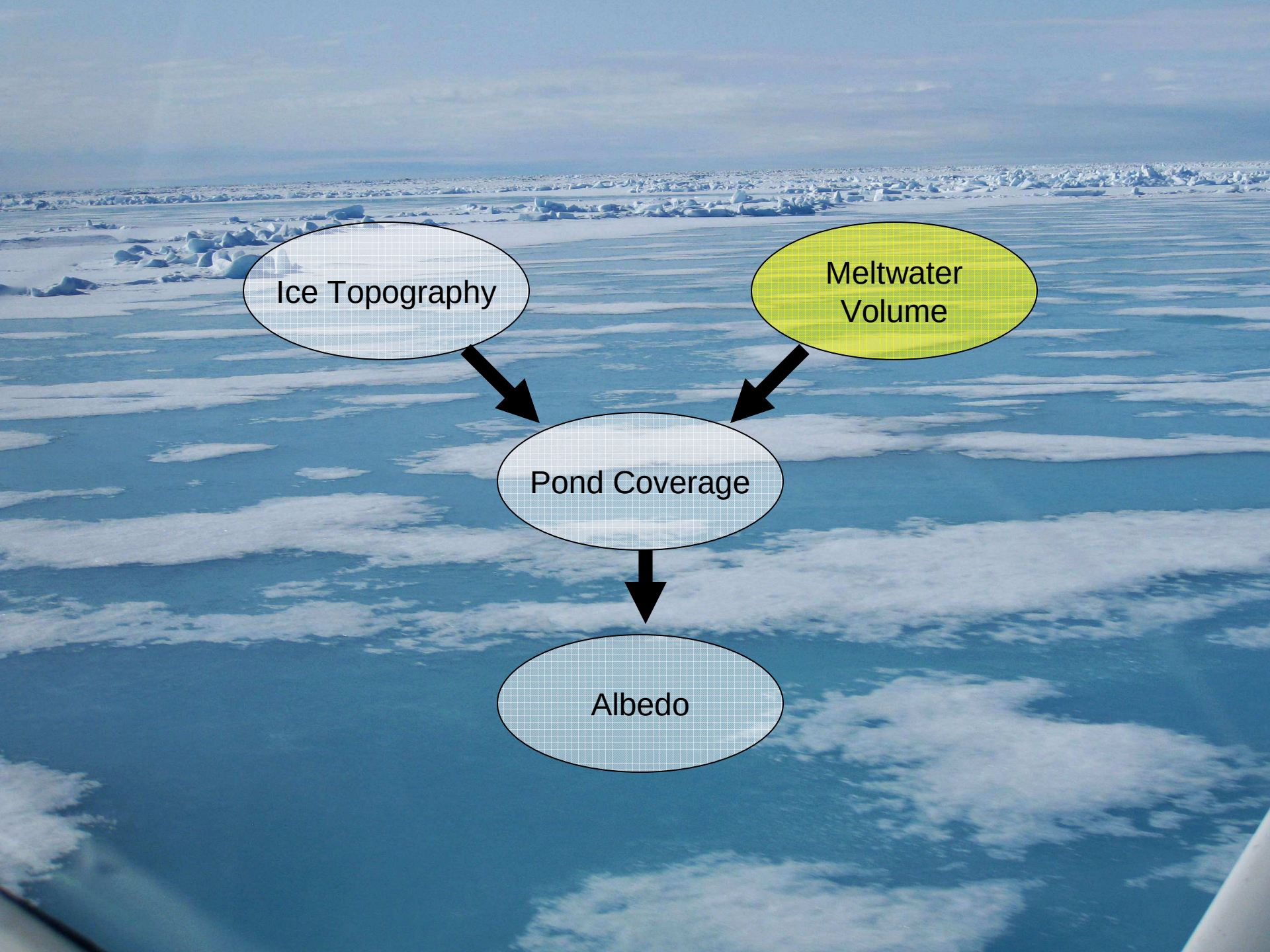

Melt Pond Coverage Along Transects
Stage I
Stage II
Stage III
Percent Pond Coverage
60
50
40
30
20
10
0
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date

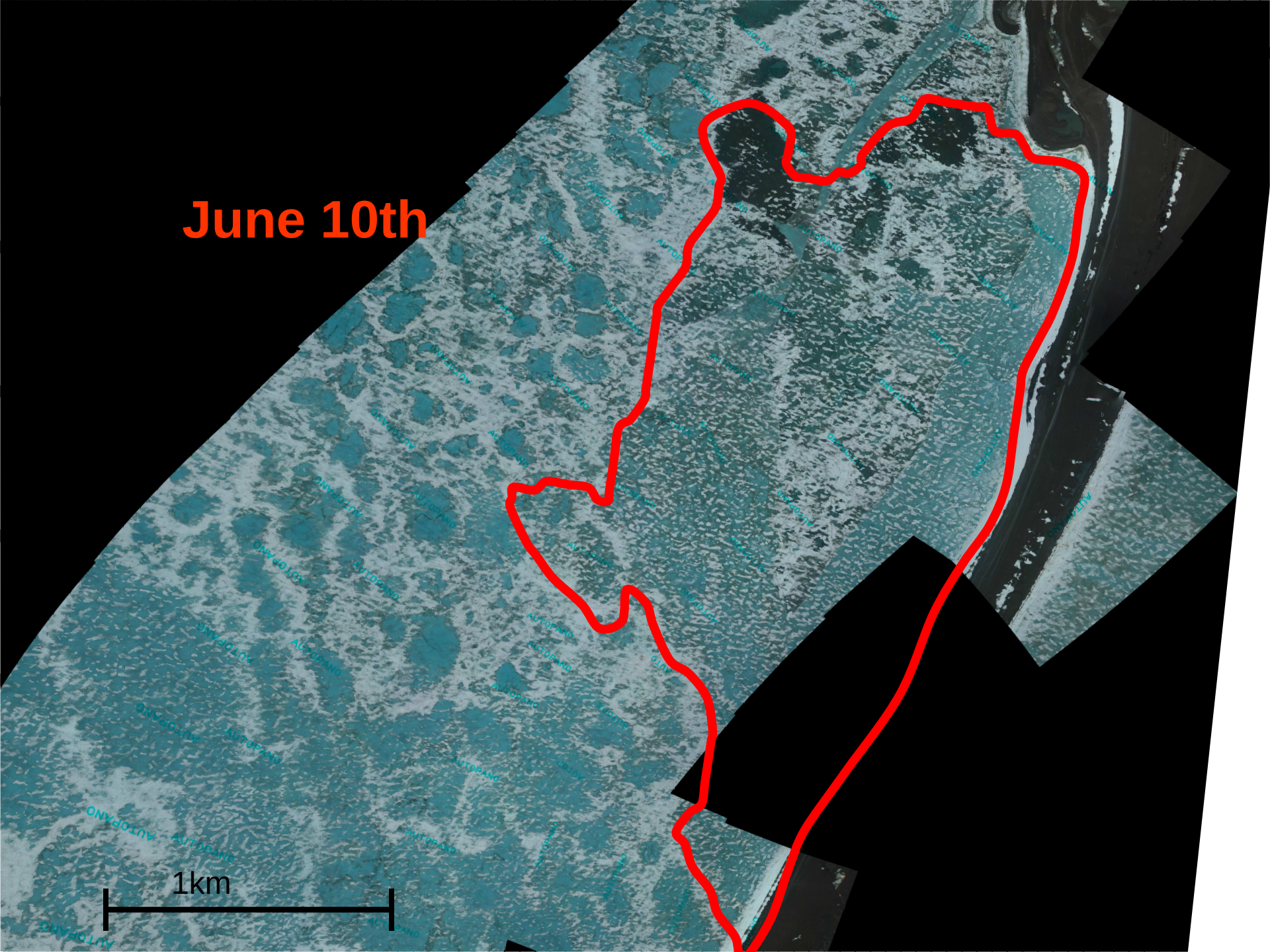

Melt Pond Coverage Along Transects
Stage I
Stage II
Stage III
Percent Pond Coverage
60
50
40
30
20
10
0
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date


Melt Pond Coverage Along Transects
Stage I
Stage II
Stage III
Percent Pond Coverage
60
50
40
30
20
10
0
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date

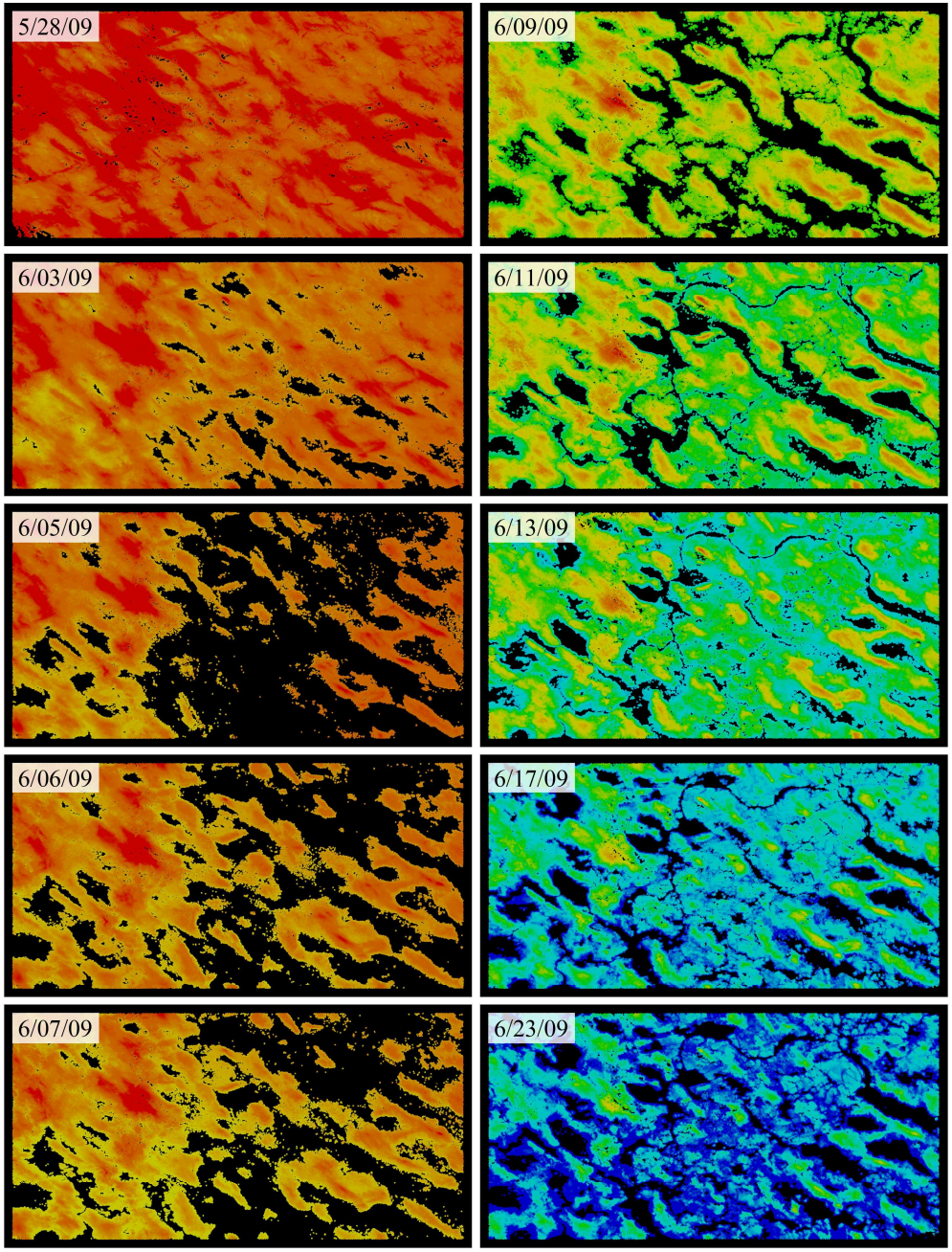

Precipitation
Meltwater Inflow
Snow/Ice
Meltwater Inflow
Snow/Ice
Melt Pond
Snow
Melt Pond
Macroscopic Flaw Drainage
Percolation Drainage
Sea Ice
Permeable Ice
Ocean


Ice Topography
Meltwater Volume
Pond Coverage
Albedo


Ice Topography
Meltwater Volume
Pond Coverage
Albedo

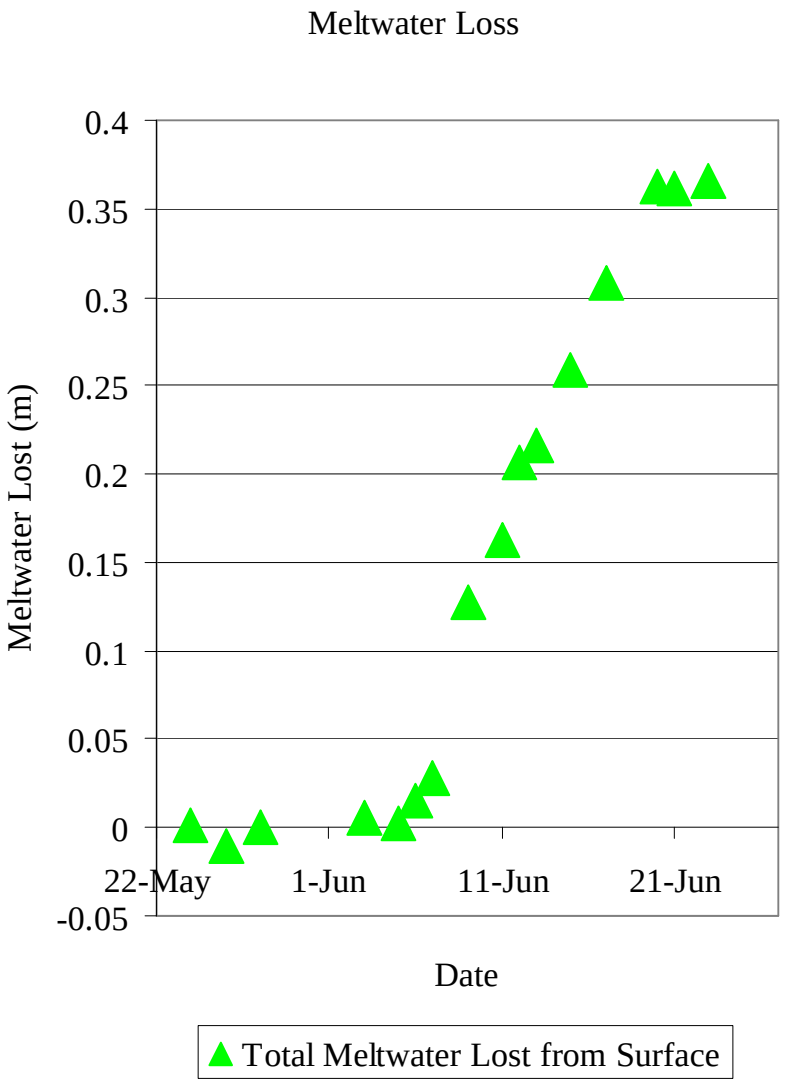

June 10th
1km

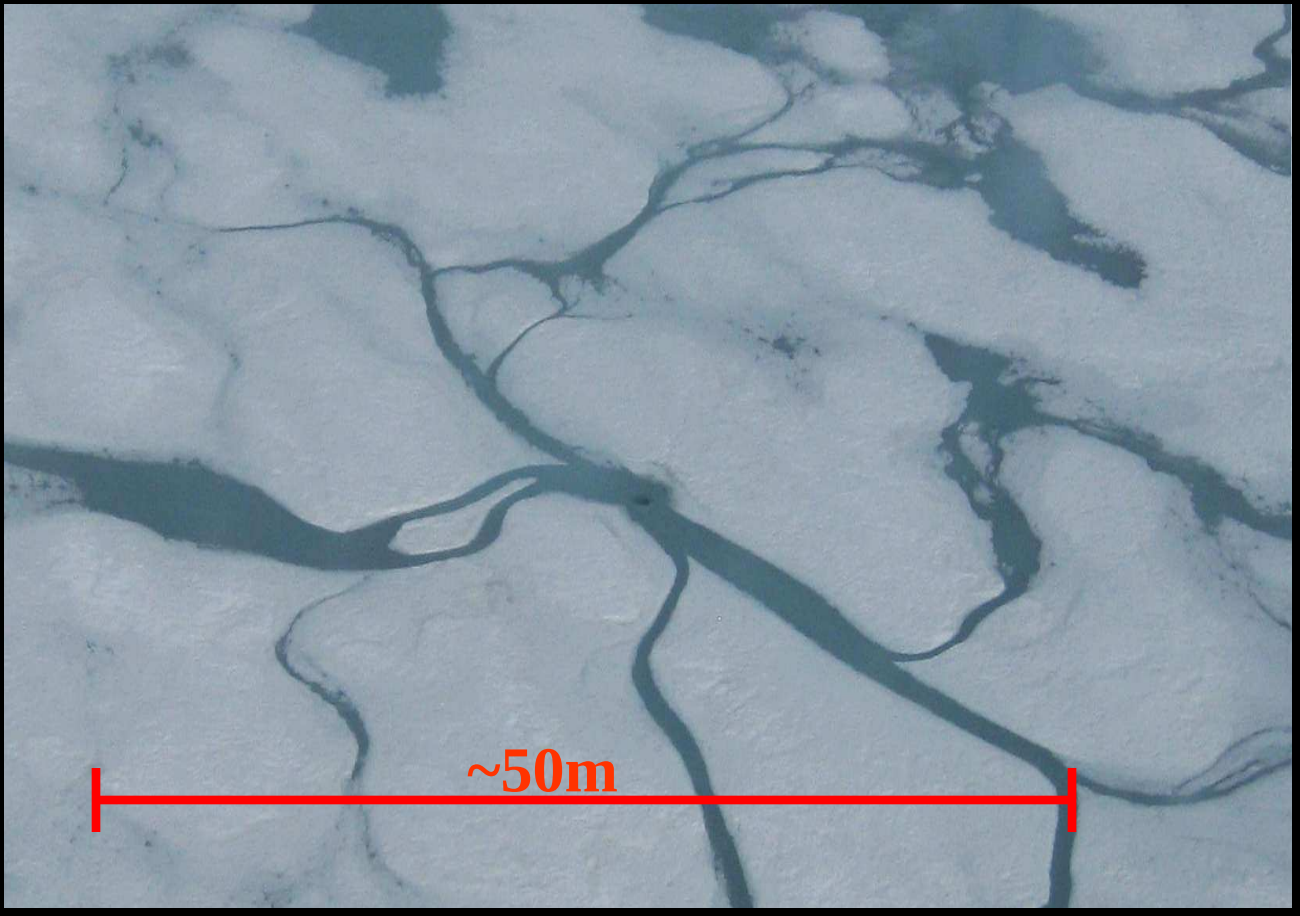
Height
0.8
0.7
0.6

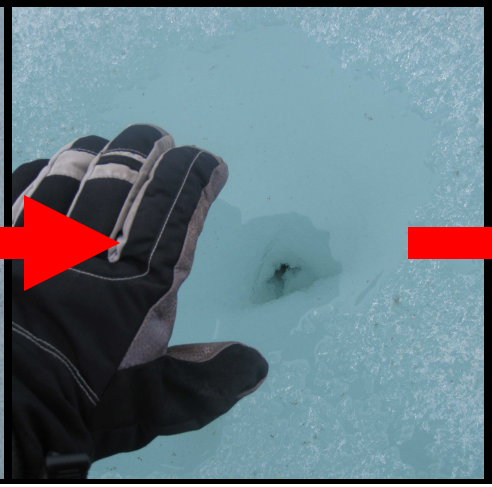


Surface Heights

2009 North Site







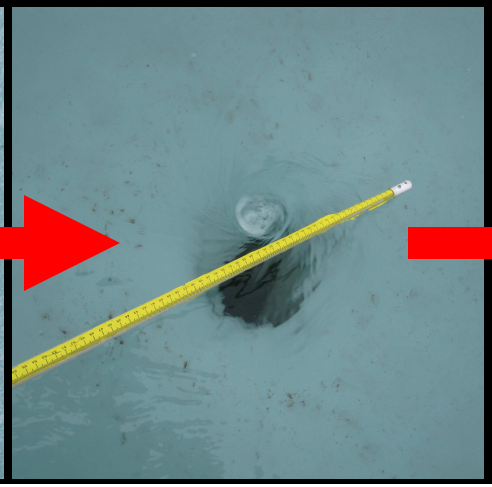
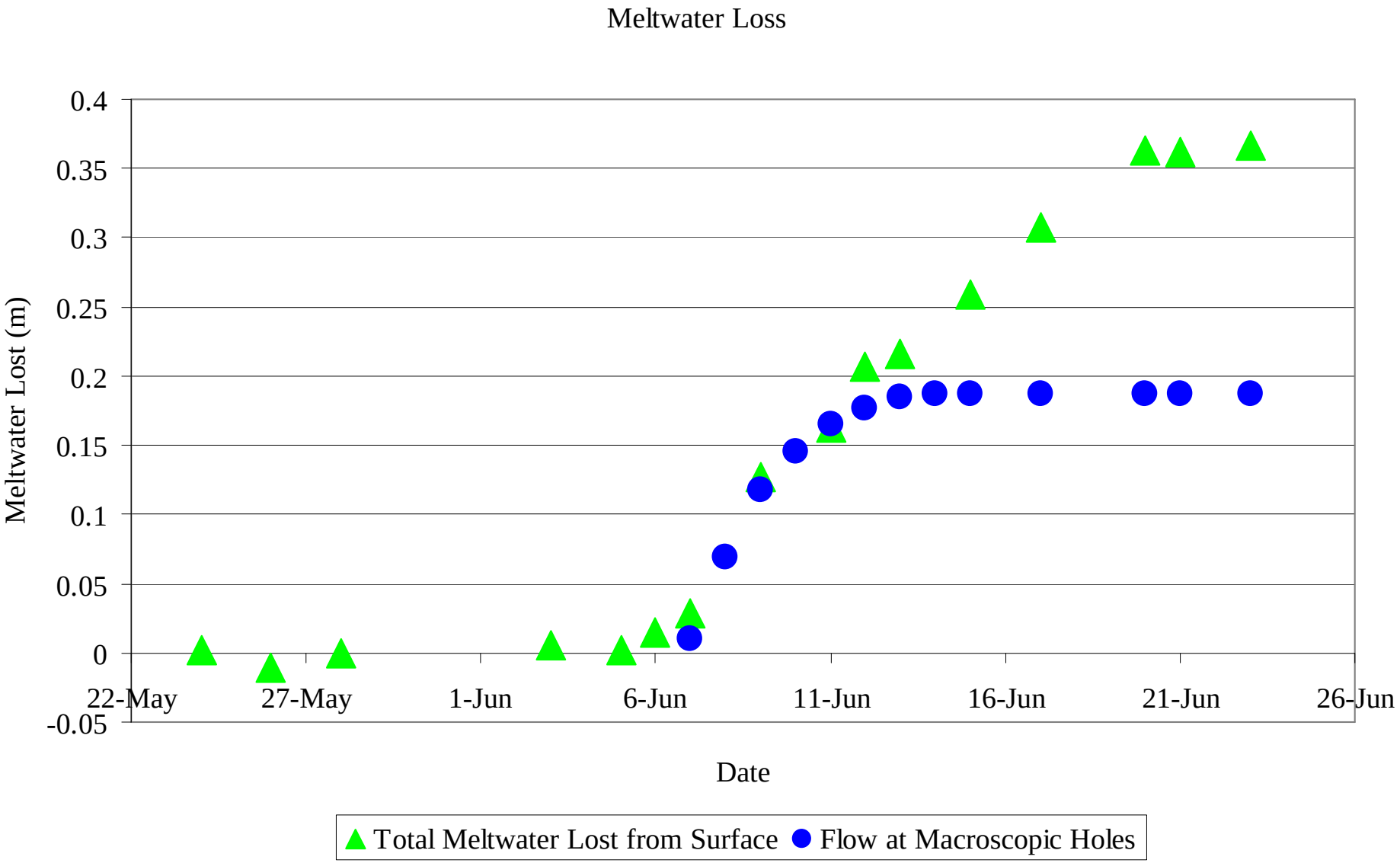
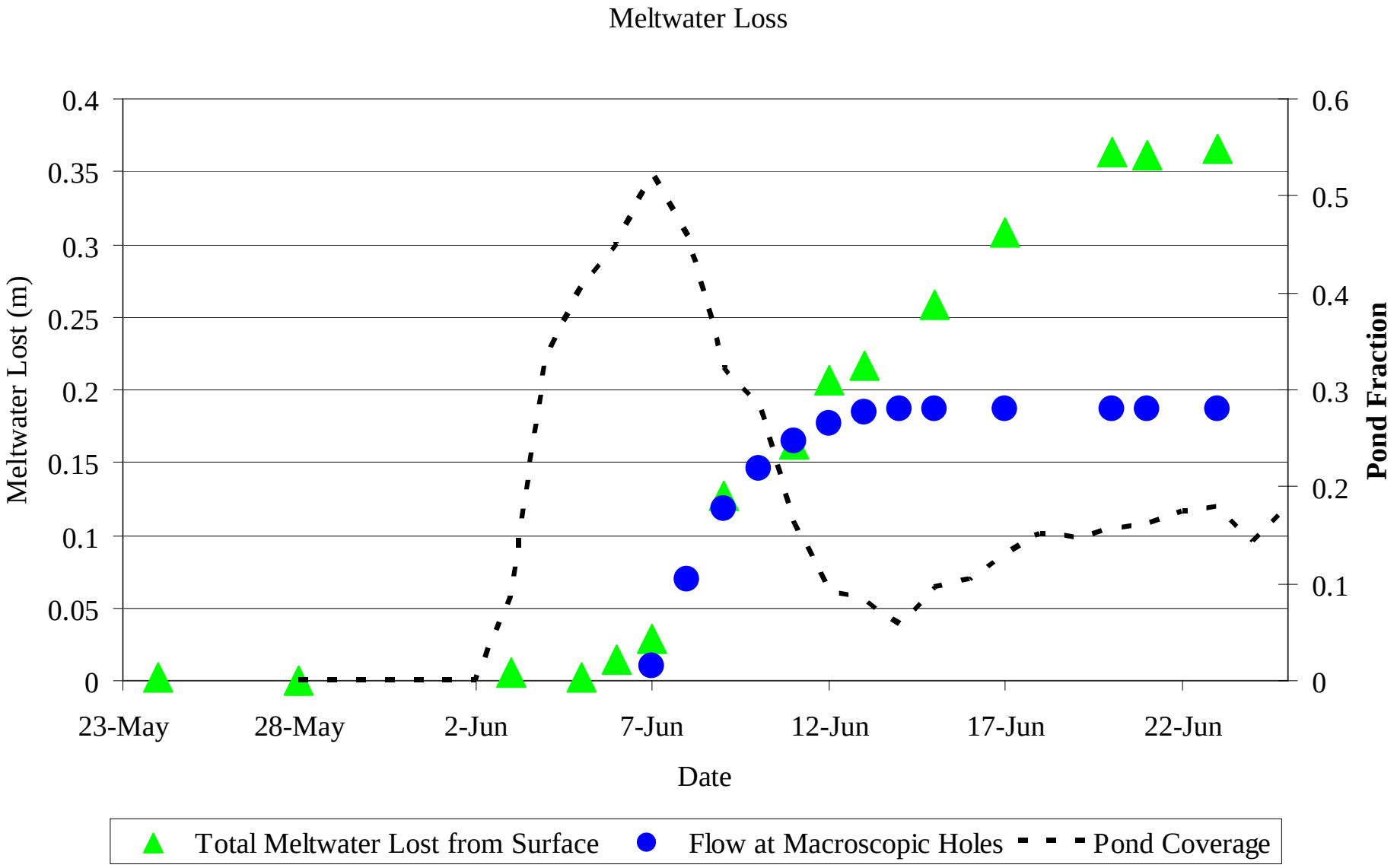
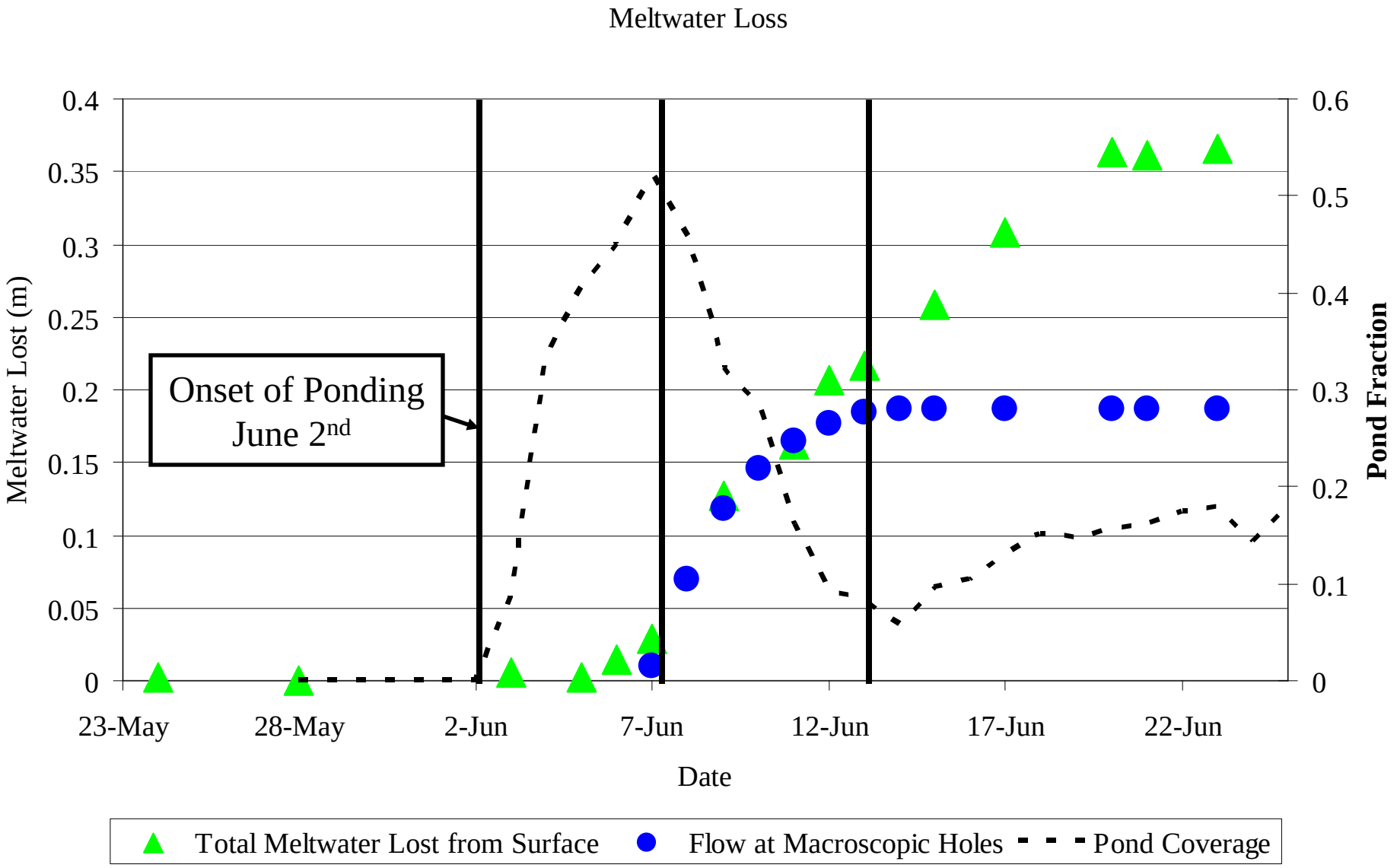
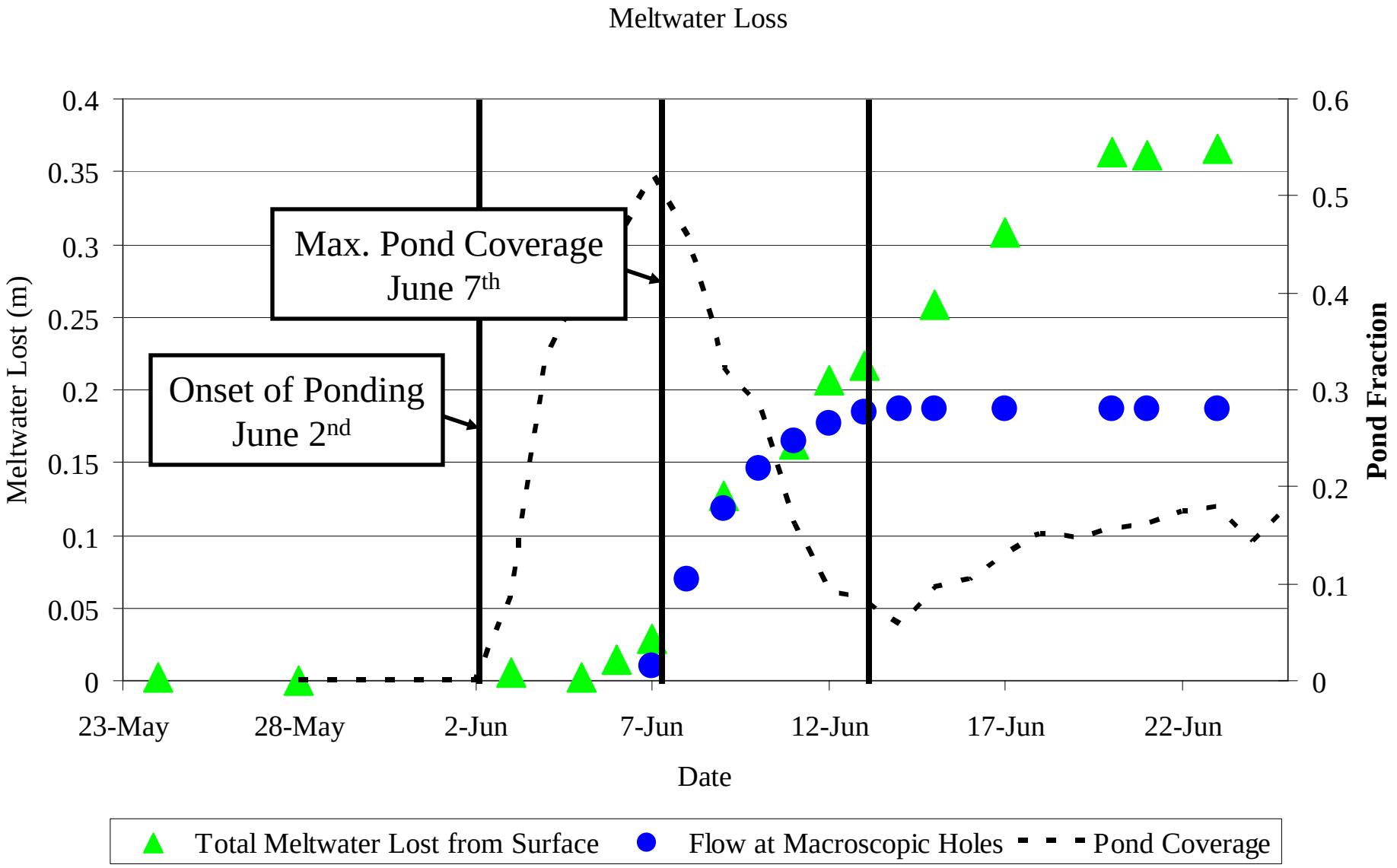


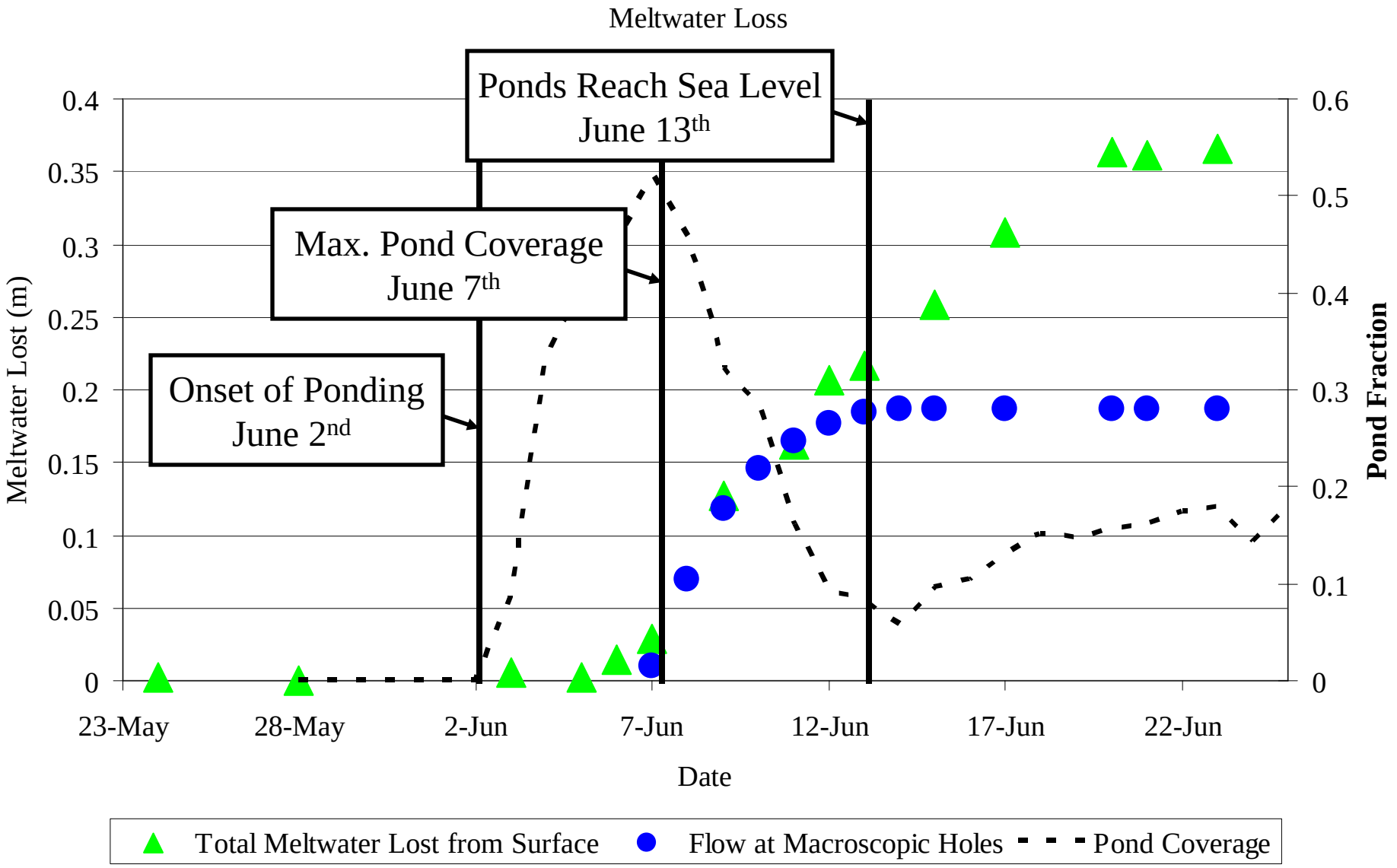
Photo: Chris Petrich

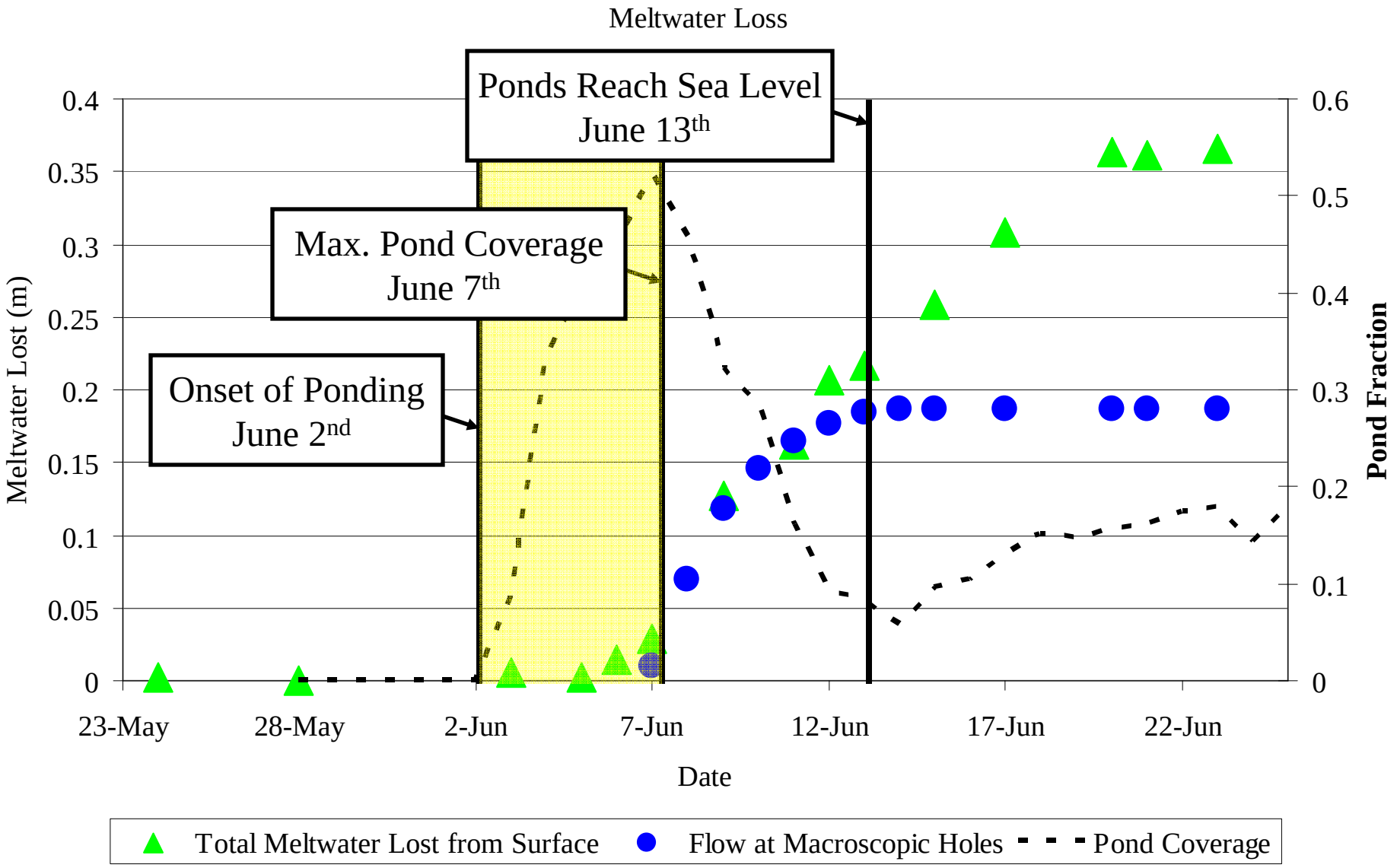

Meltwater Loss
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
Meltwater Lost (m)
22-May
27-May
1-Jun
6-Jun
11-Jun
16-Jun
21-Jun
26-Jun
Date
Total Meltwater Lost from Surface
Flow at Macroscopic Holes

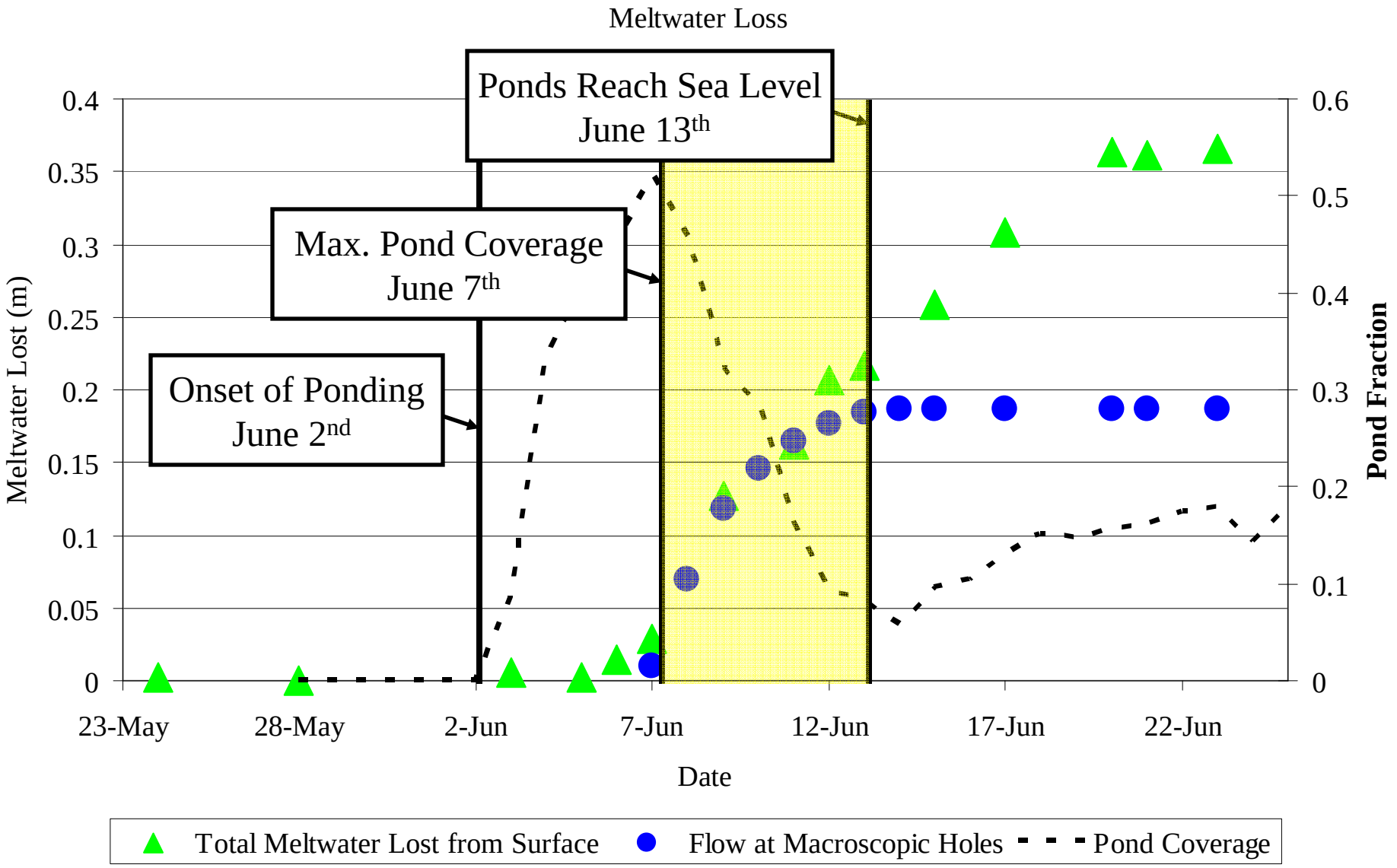

Meltwater Loss
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Meltwater Lost (m)
0.6
0.5
0.4
0.3
0.2
0.1
0
Pond Fraction
23-May
28-May
2-Jun
7-Jun
12-Jun
17-Jun
22-Jun
Date
Total Meltwater Lost from Surface
Flow at Macroscopic Holes
Pond Coverage

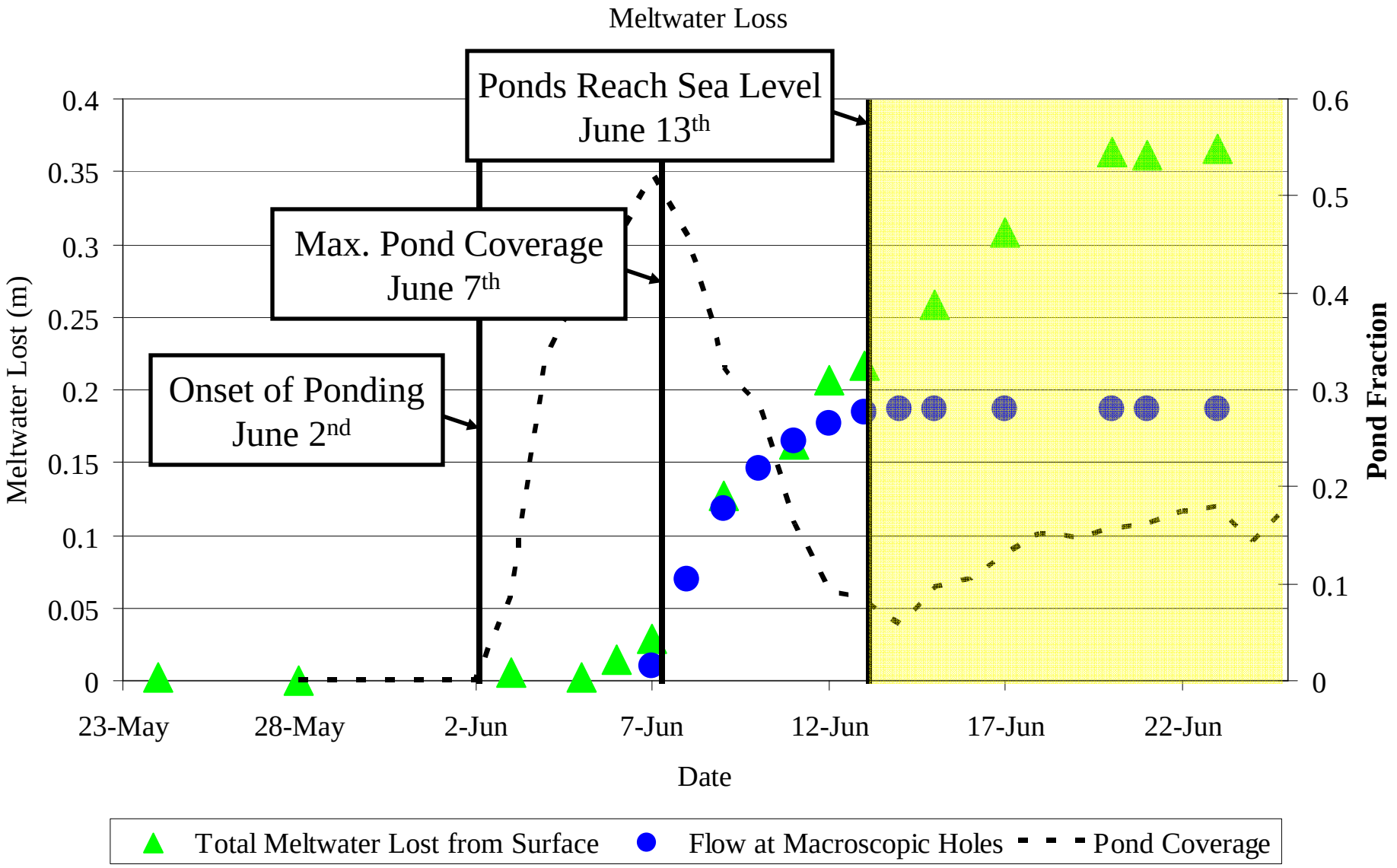

Meltwater Loss
Meltwater Lost (m)
Pond Fraction
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.6
0.5
0.4
0.3
0.2
0.1
0
Onset of Ponding
June 2nd
23-May
28-May
2-Jun
7-Jun
12-Jun
17-Jun
22-Jun
Date
Total Meltwater Lost from Surface
Flow at Macroscopic Holes
Pond Coverage

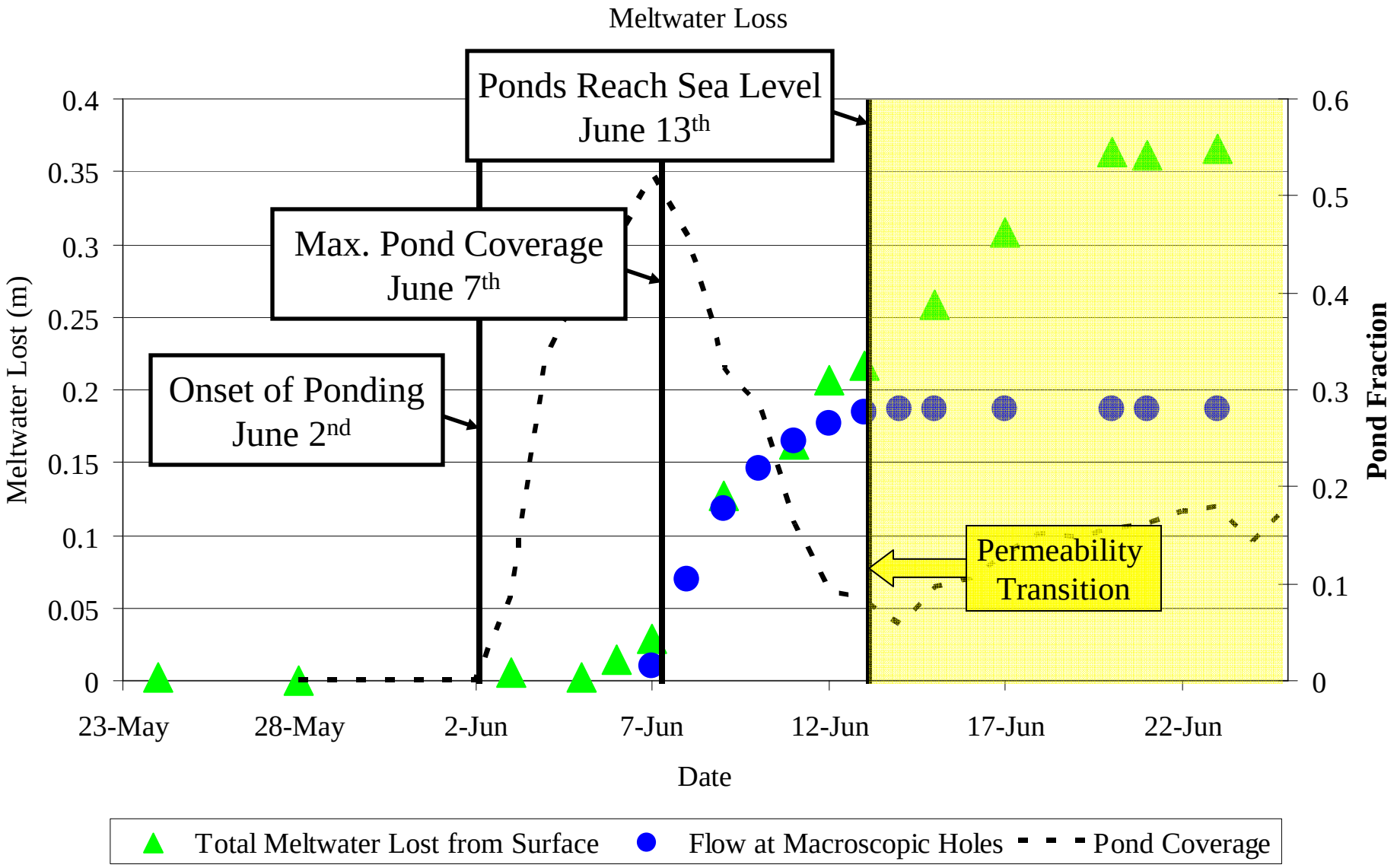

Meltwater Loss
Meltwater Lost (m)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.6
0.5
0.4
0.3
0.2
0.1
0
Pond Fraction
Max. Pond Coverage
June 7th
Onset of Ponding
June 2nd
23-May
28-May
2-Jun
7-Jun
12-Jun
17-Jun
22-Jun
Date
Total Meltwater Lost from Surface
Flow at Macroscopic Holes
Pond Coverage


Meltwater Loss
Ponds Reach Sea Level
June 13th
Max. Pond Coverage
June 7th
Onset of Ponding
June 2nd
Meltwater Lost (m)
Pond Fraction
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.6
0.5
0.4
0.3
0.2
0.1
0
23-May
28-May
2-Jun
7-Jun
12-Jun
17-Jun
22-Jun
Date
Total Meltwater Lost from Surface
Flow at Macroscopic Holes
Pond Coverage


Meltwater Loss
Ponds Reach Sea Level
June 13th
Max. Pond Coverage
June 7th
Onset of Ponding
June 2nd
Meltwater Lost (m)
Pond Fraction
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.6
0.5
0.4
0.3
0.2
0.1
0
23-May
28-May
2-Jun
7-Jun
12-Jun
17-Jun
22-Jun
Date
Total Meltwater Lost from Surface
Flow at Macroscopic Holes
Pond Coverage

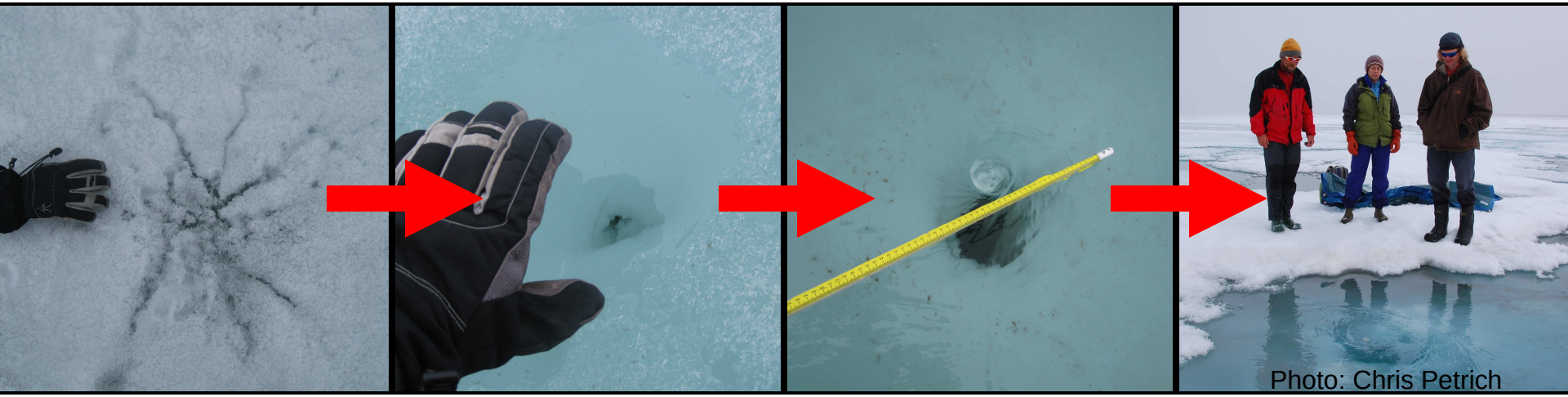

Meltwater Loss
Ponds Reach Sea Level
June 13th
Max. Pond Coverage
June 7th
Onset of Ponding
June 2nd
Meltwater Lost (m)
Pond Fraction
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.6
0.5
0.4
0.3
0.2
0.1
0
23-May
28-May
2-Jun
7-Jun
12-Jun
17-Jun
22-Jun
Date
Total Meltwater Lost from Surface
Flow at Macroscopic Holes
Pond Coverage


Meltwater Loss
Ponds Reach Sea Level
June 13th
Max. Pond Coverage
June 7th
Onset of Ponding
June 2nd
Meltwater Lost (m)
Pond Fraction
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.6
0.5
0.4
0.3
0.2
0.1
0
23-May
28-May
2-Jun
7-Jun
12-Jun
17-Jun
22-Jun
Date
Total Meltwater Lost from Surface
Flow at Macroscopic Holes
Pond Coverage

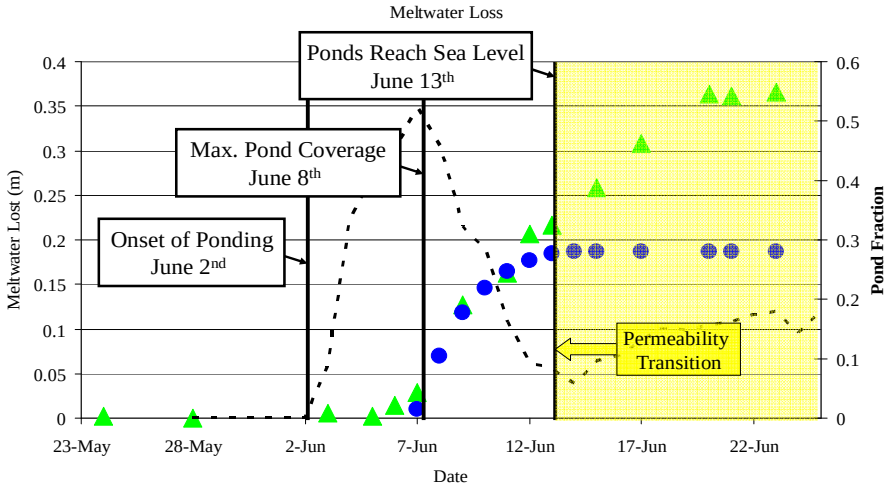


Changes in the meltwater balance drive pond coverage

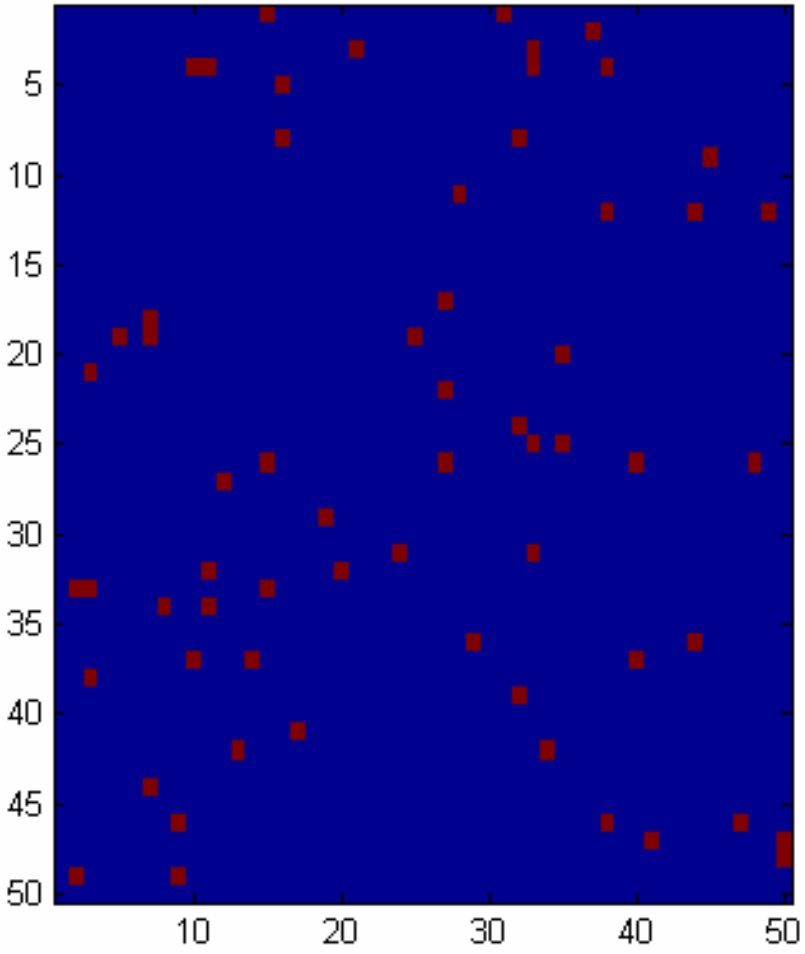
- Why do brine channels spontaneously open and enlarge?

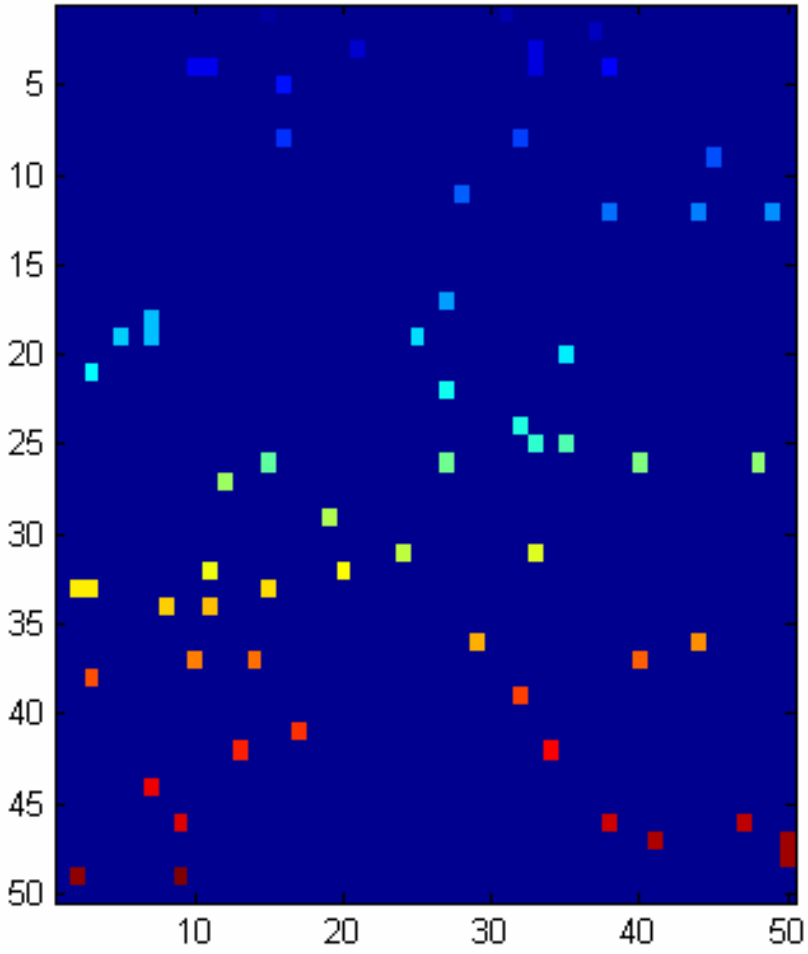


- What causes the permeability transition?



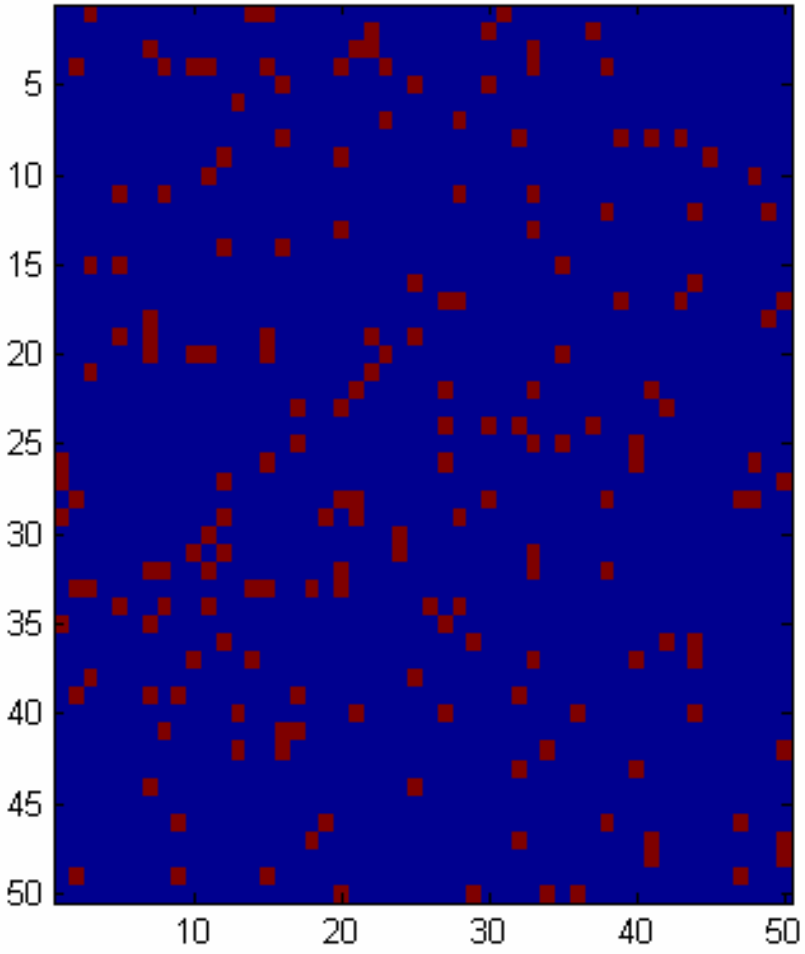
A Conceptual Model: 2D Lattice

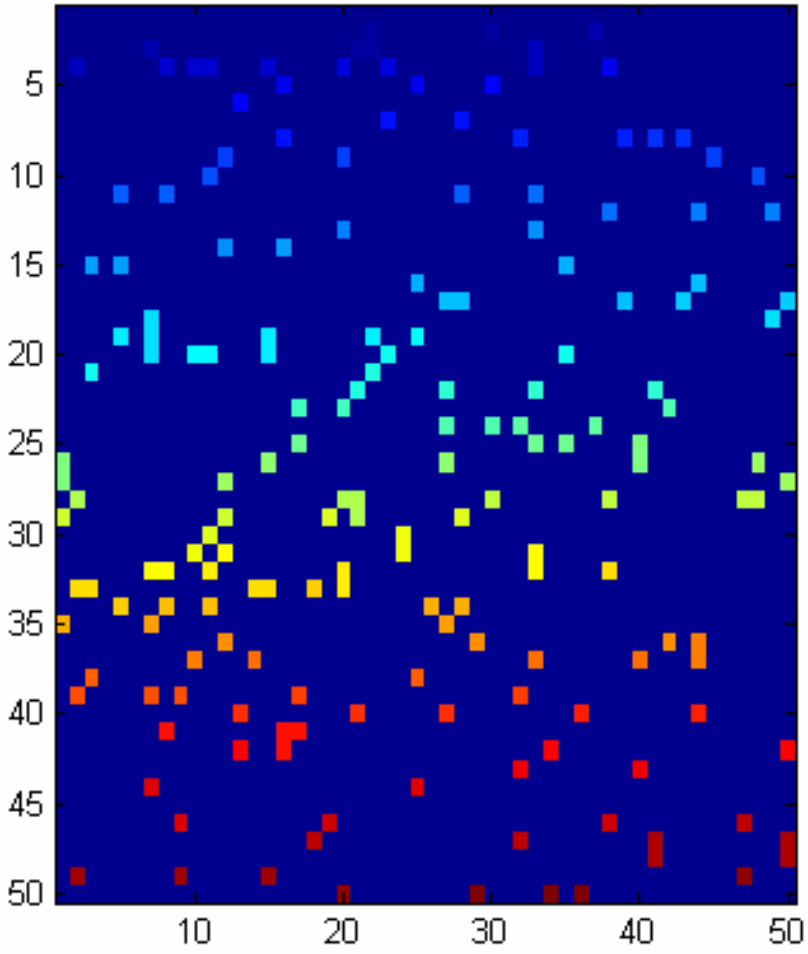




2.5% Liquid

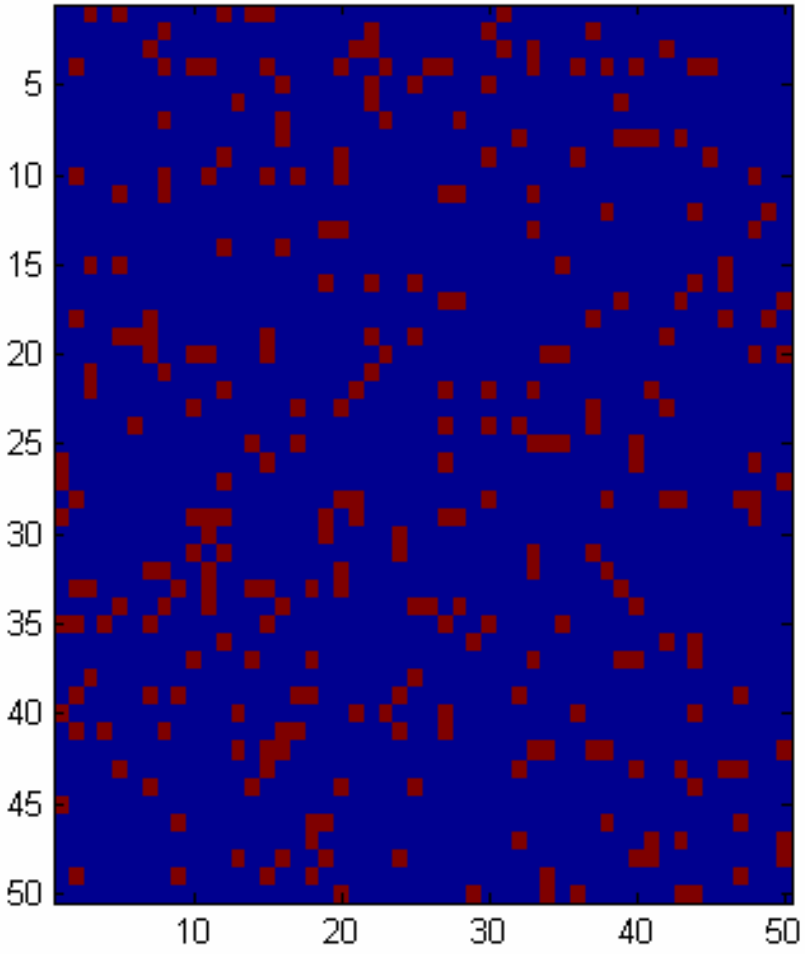
A Conceptual Model: 2D Lattice

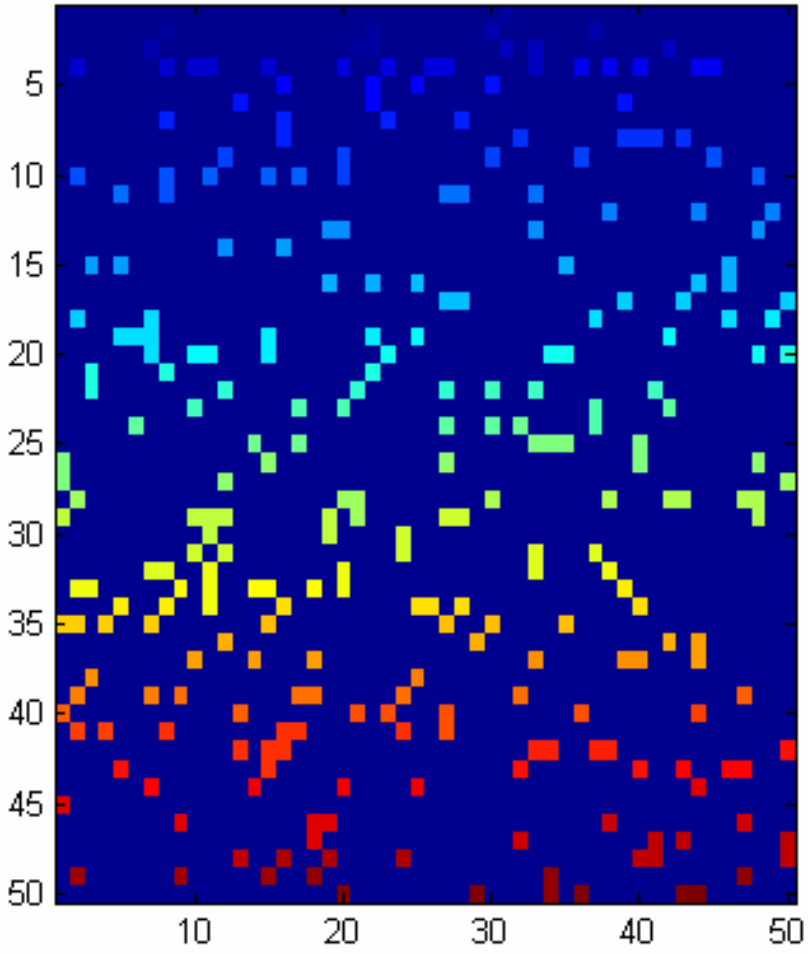




5% Liquid

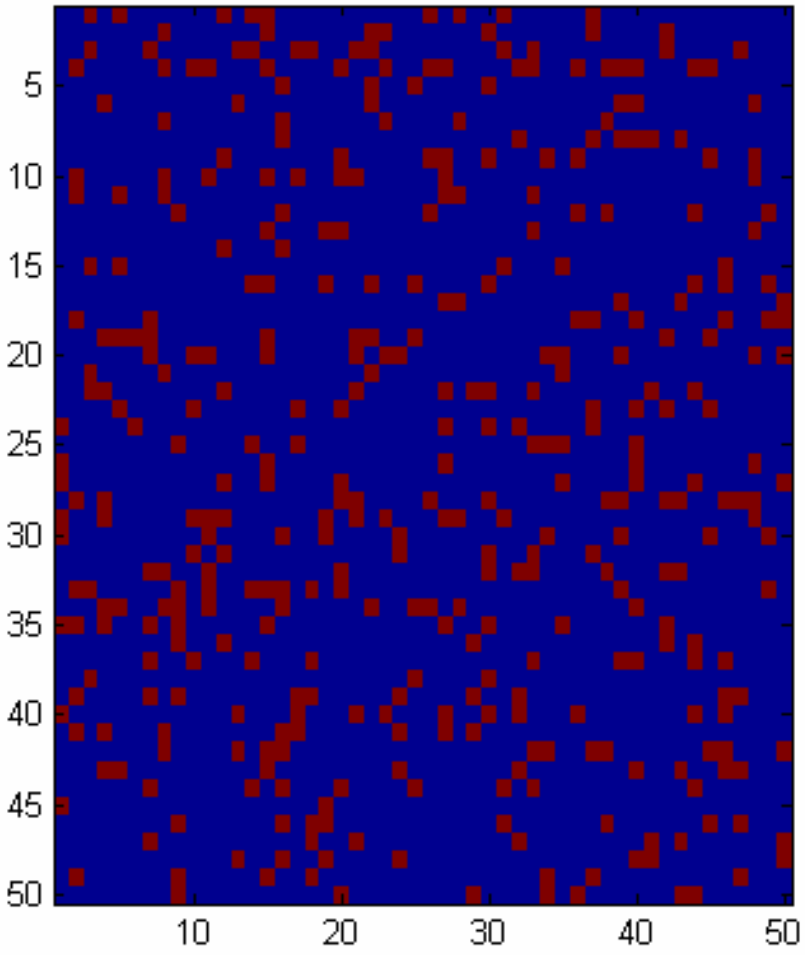
A Conceptual Model: 2D Lattice

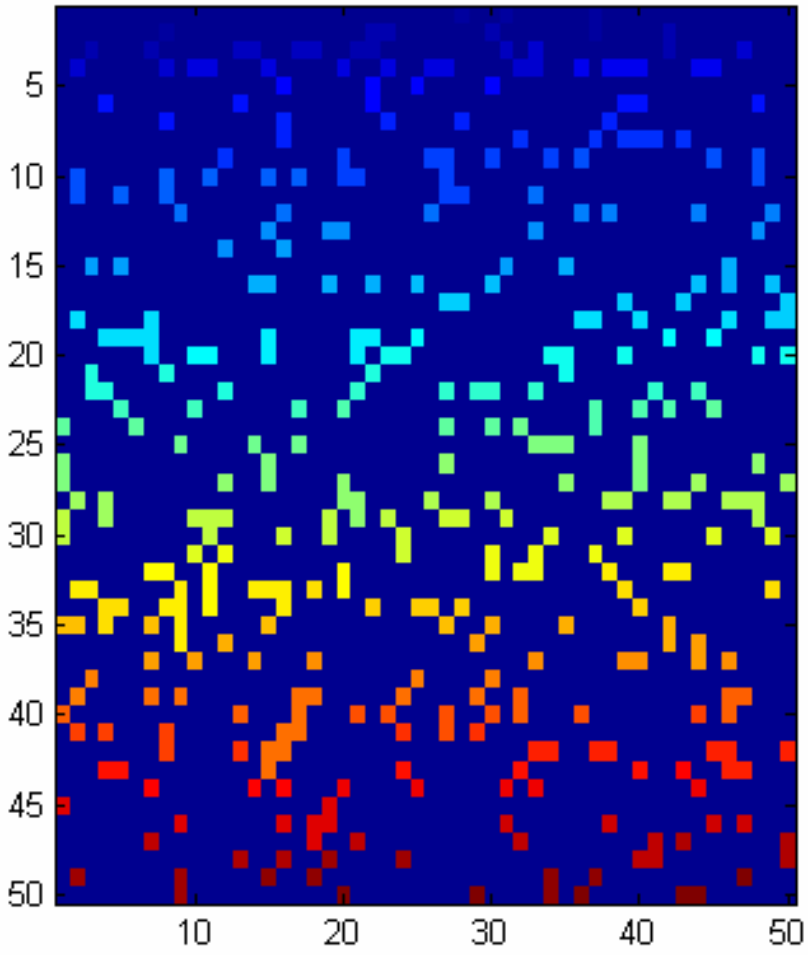




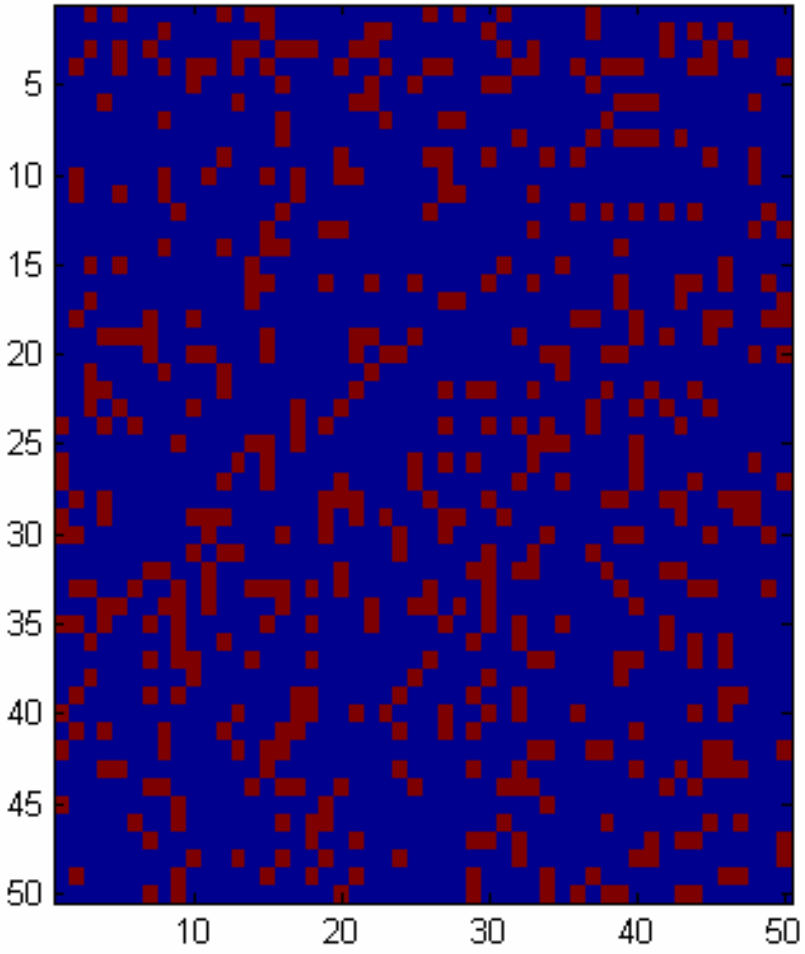
7.5% Liquid

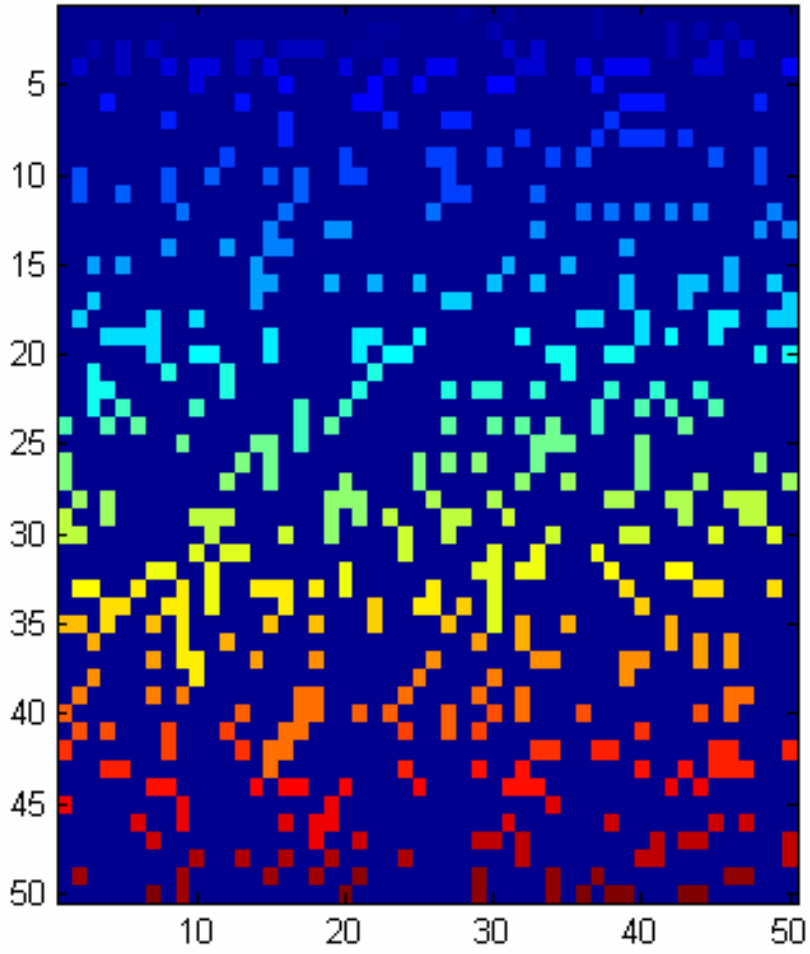
A Conceptual Model: 2D Lattice



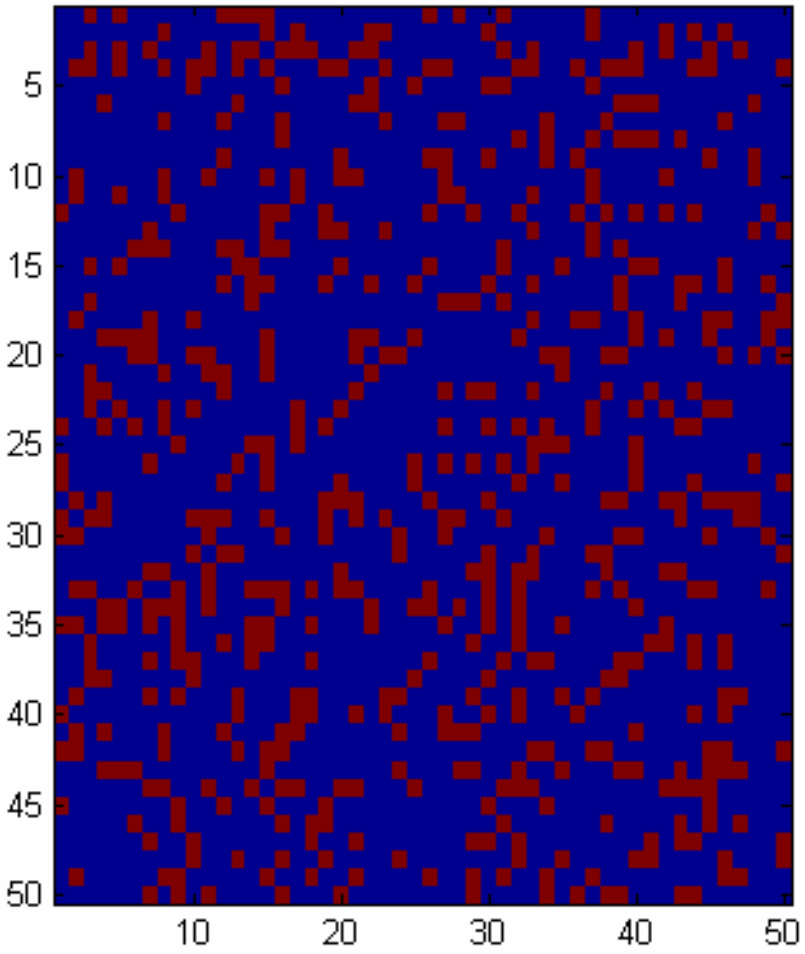


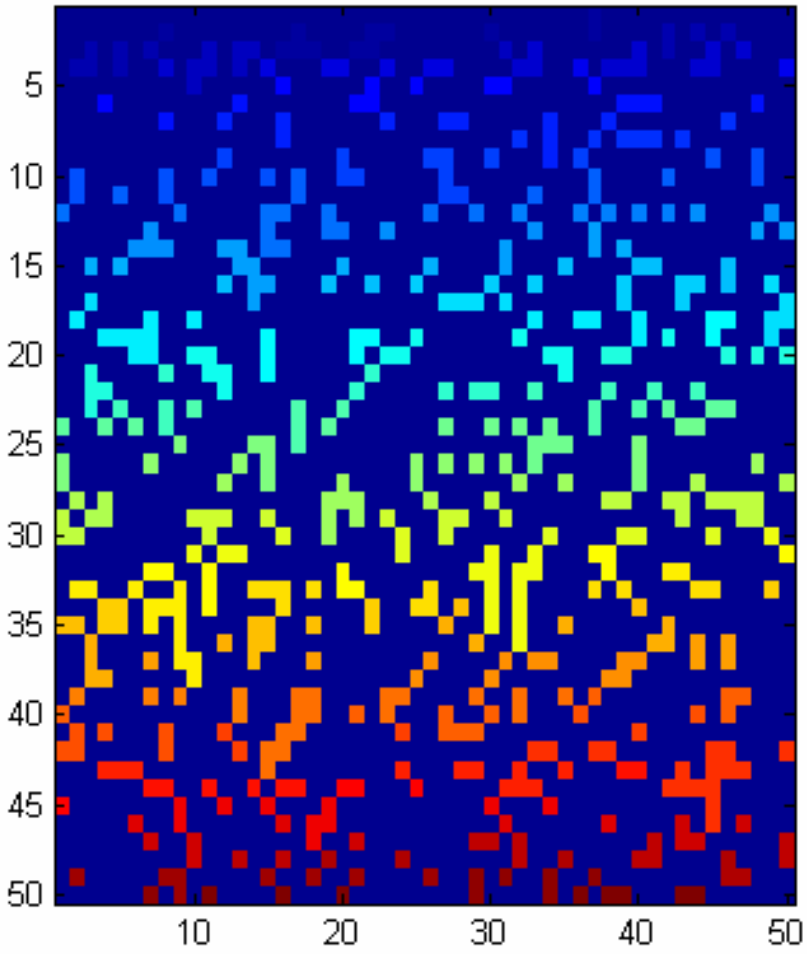
A Conceptual Model: 2D Lattice



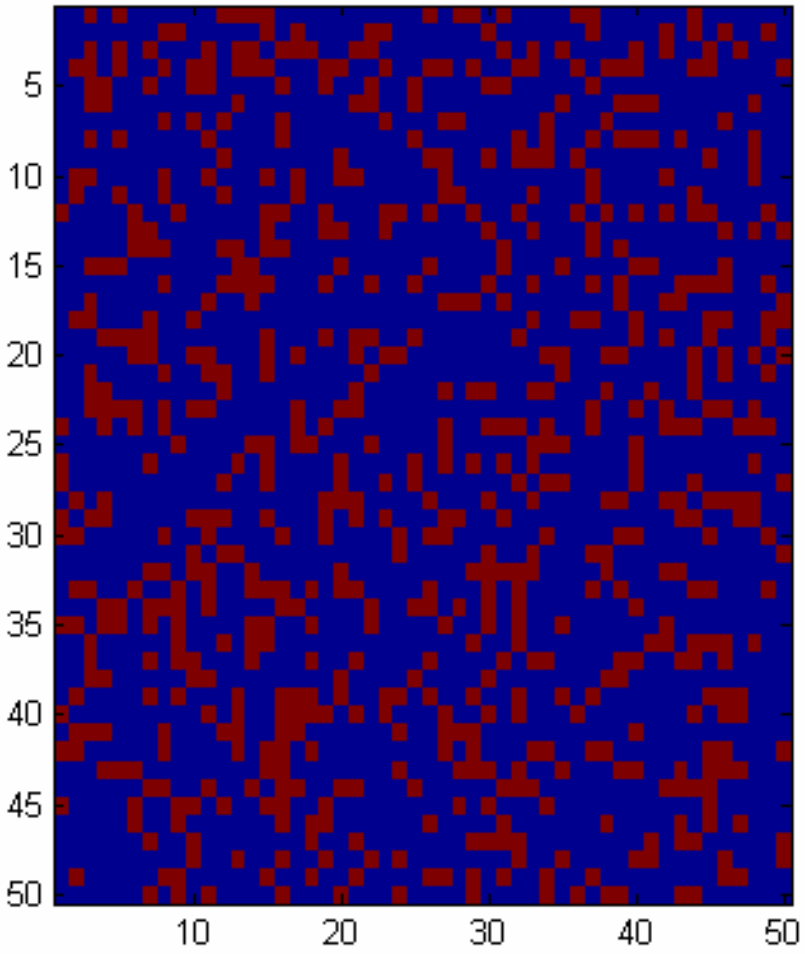


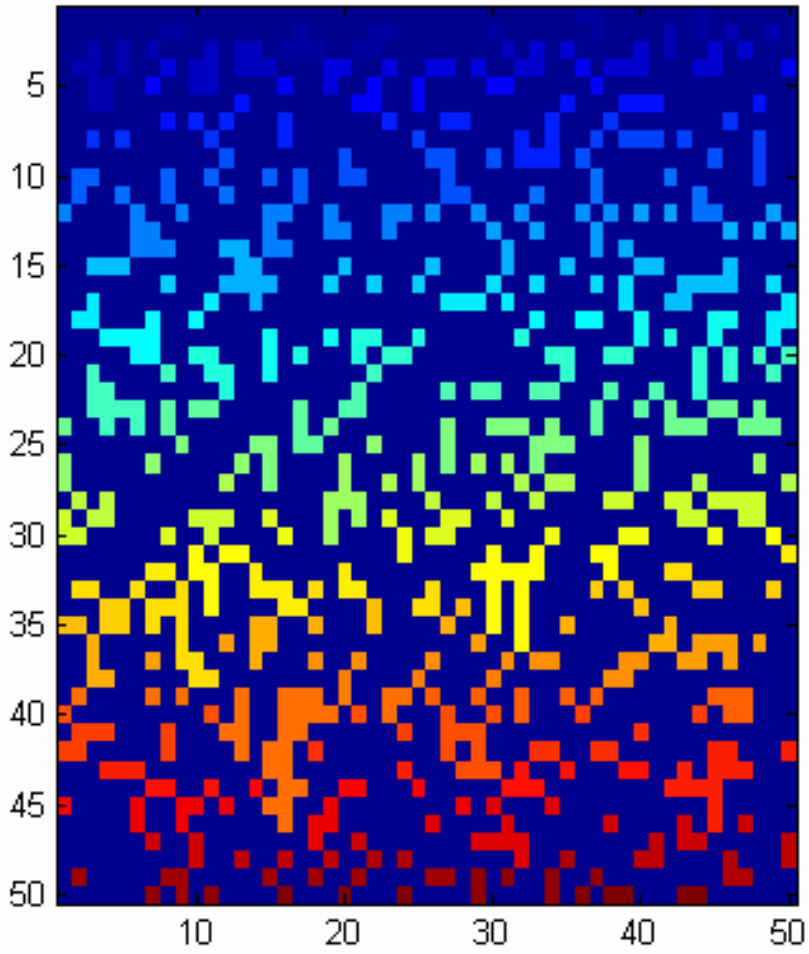
A Conceptual Model: 2D Lattice



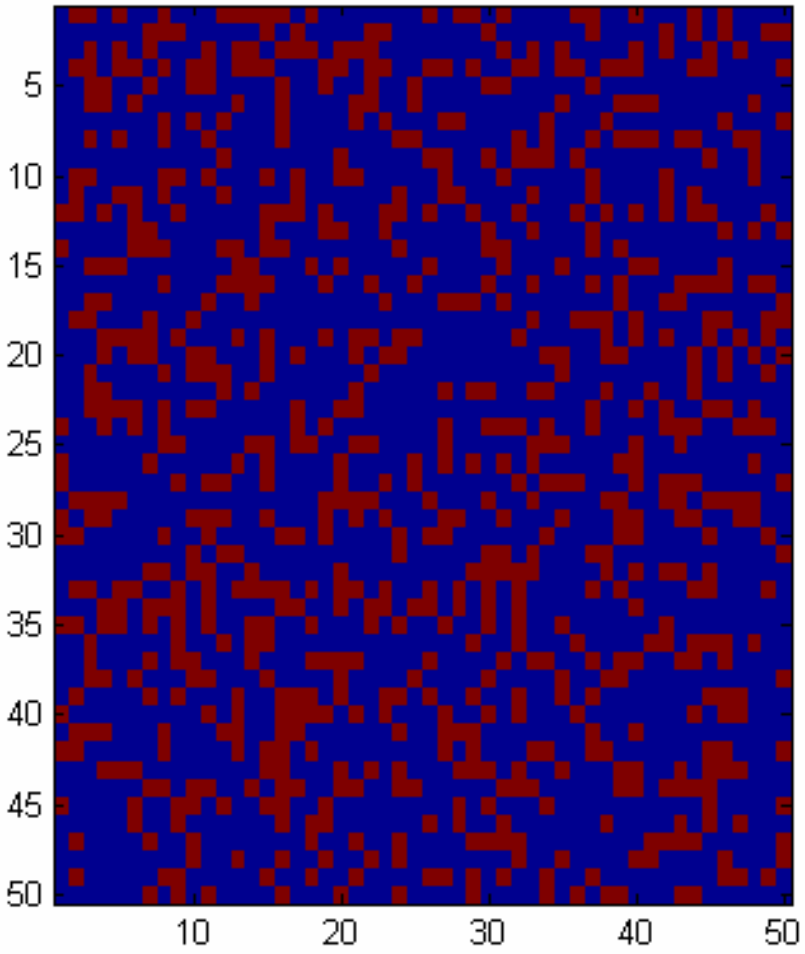


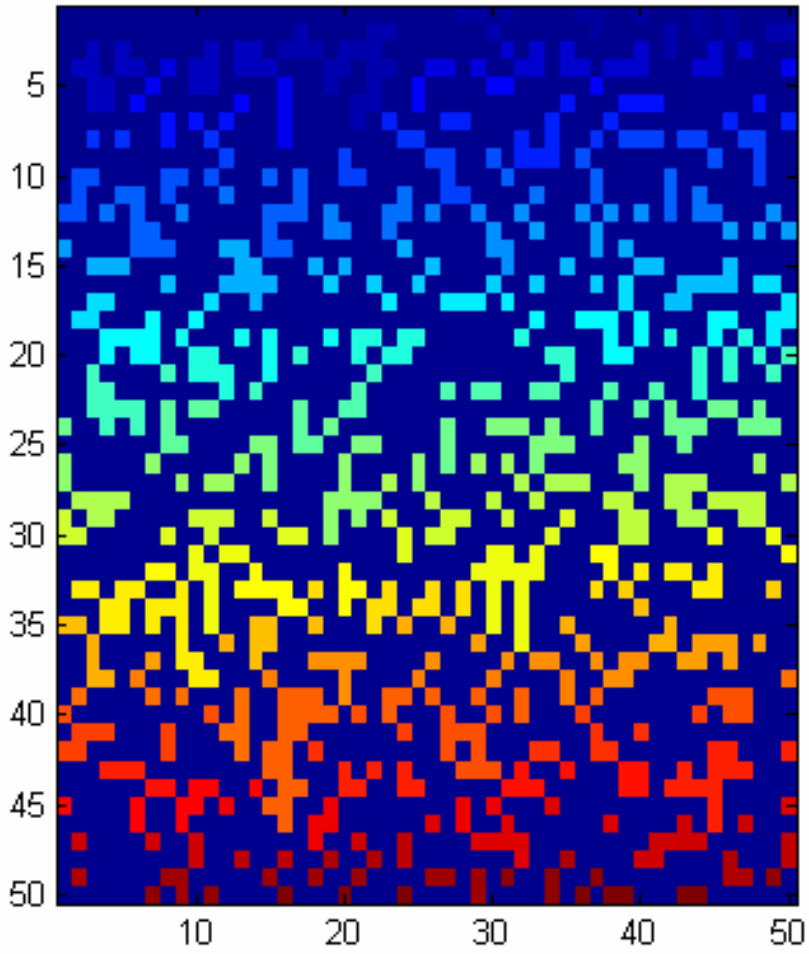
A Conceptual Model: 2D Lattice



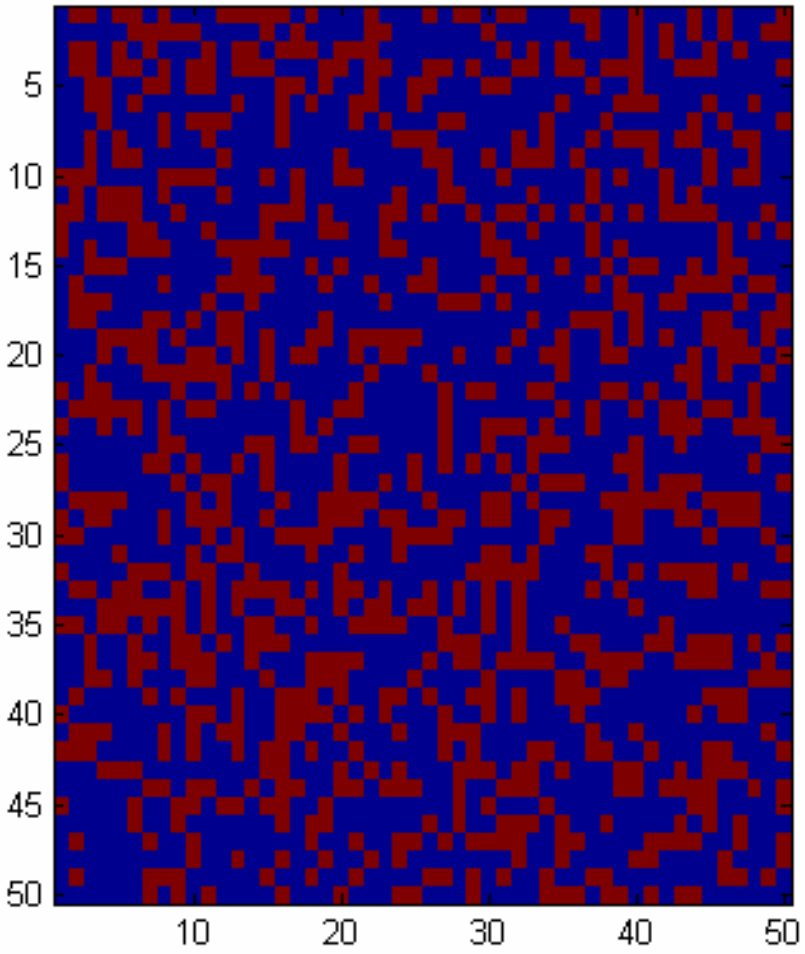


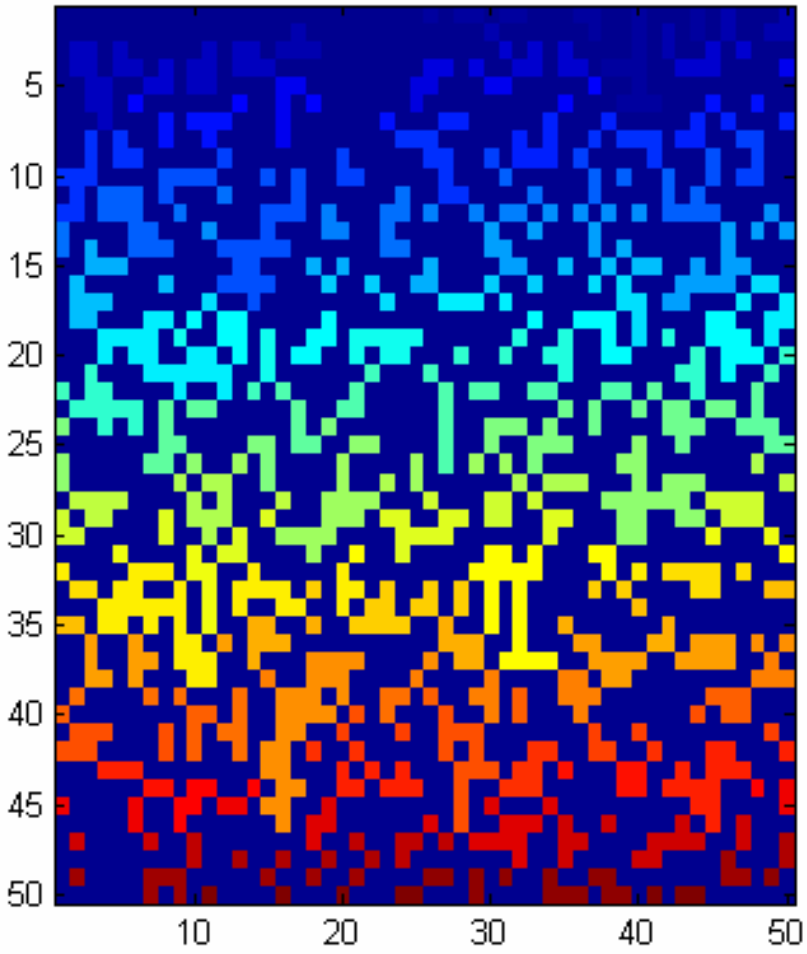
A Conceptual Model: 2D Lattice



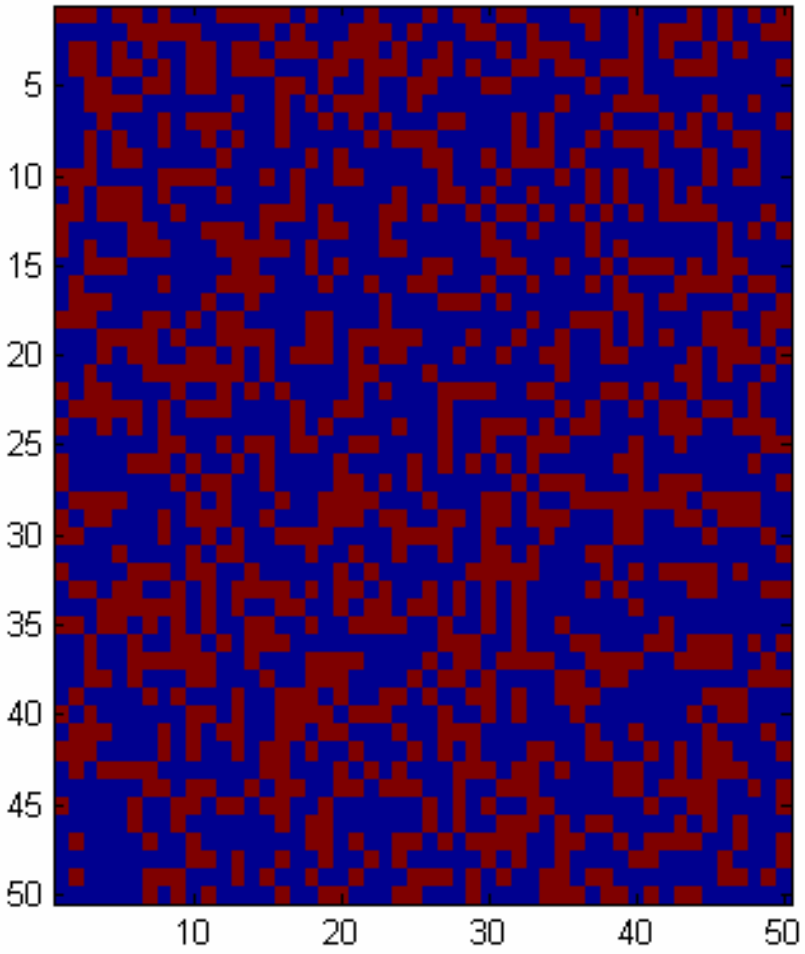


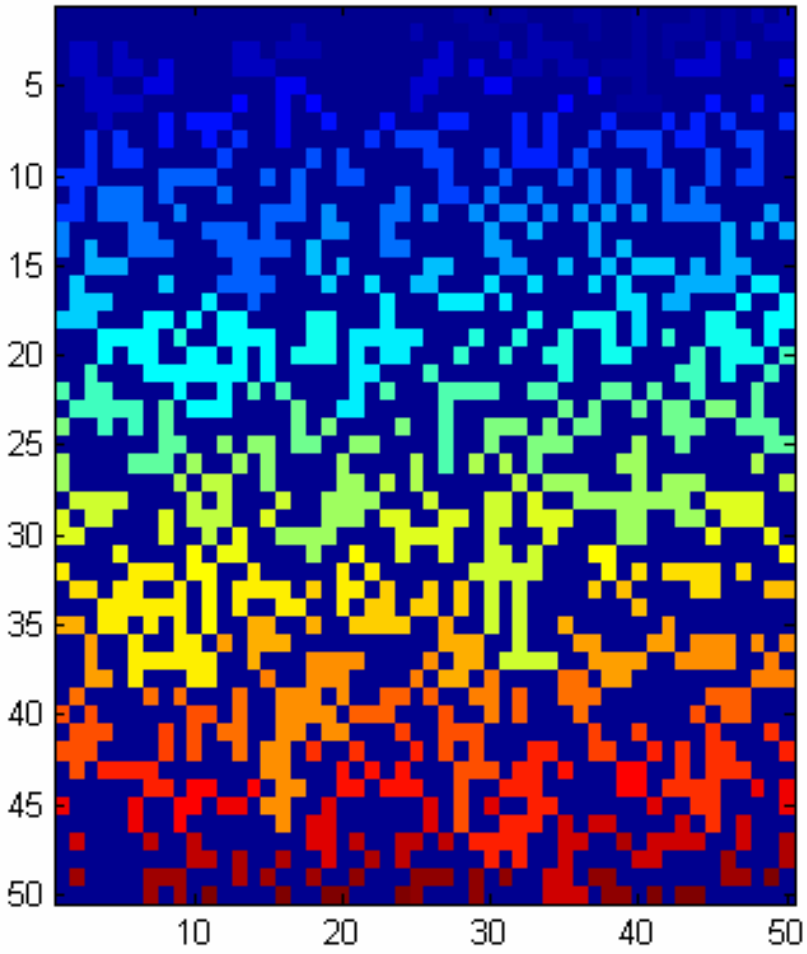
A Conceptual Model: 2D Lattice



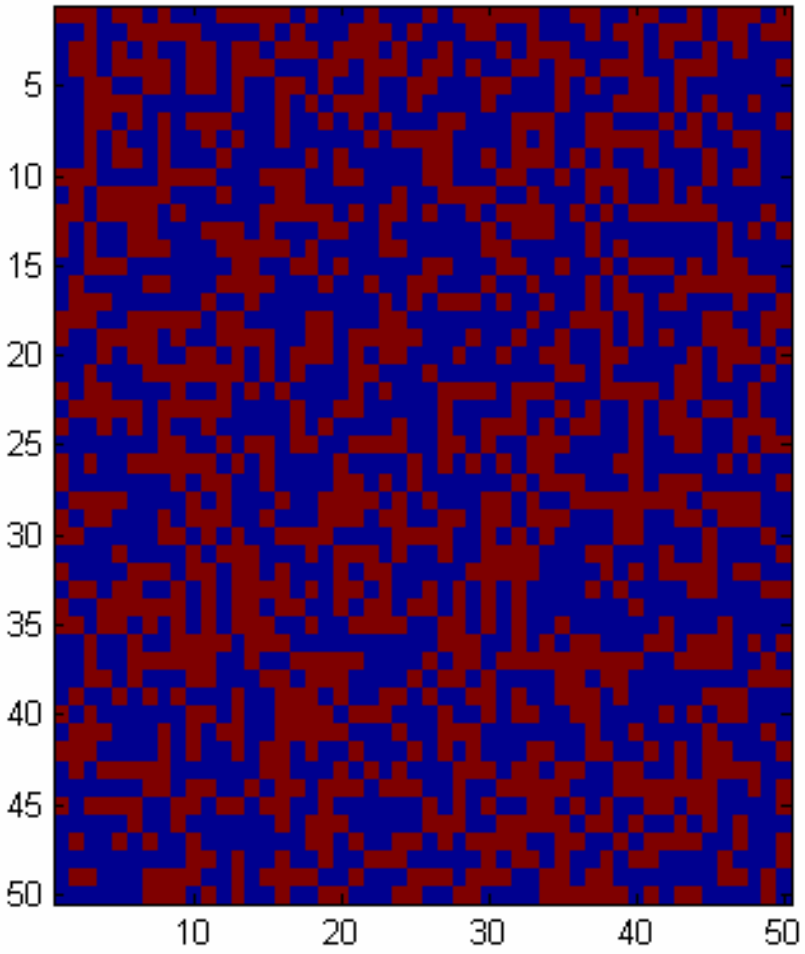


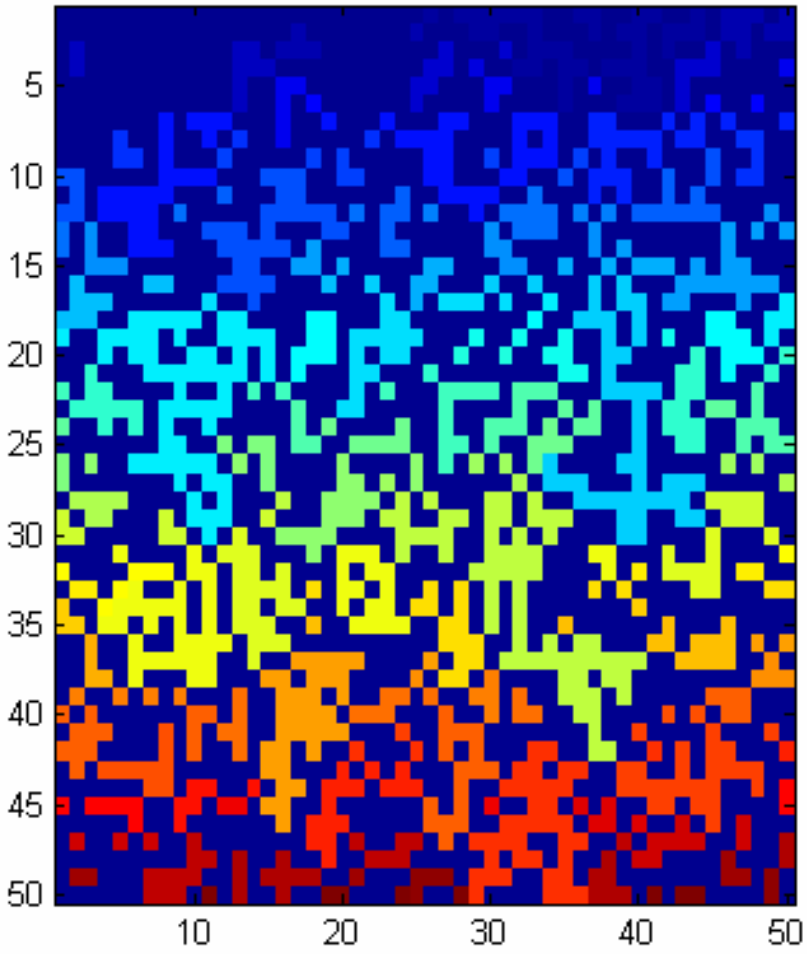
A Conceptual Model: 2D Lattice



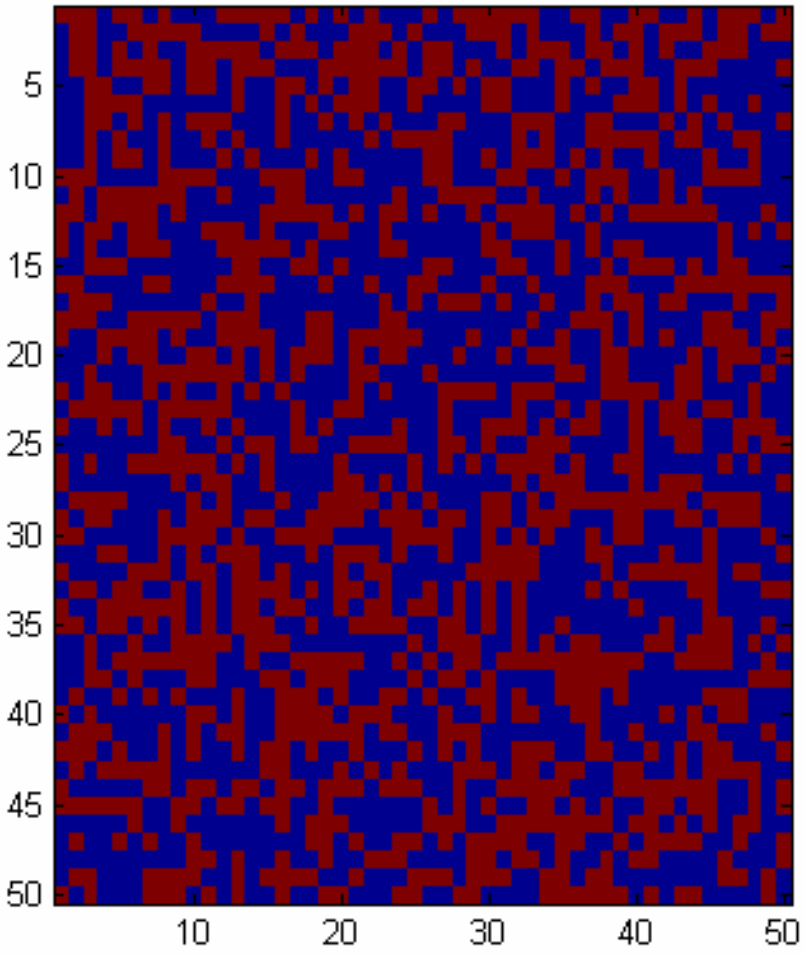


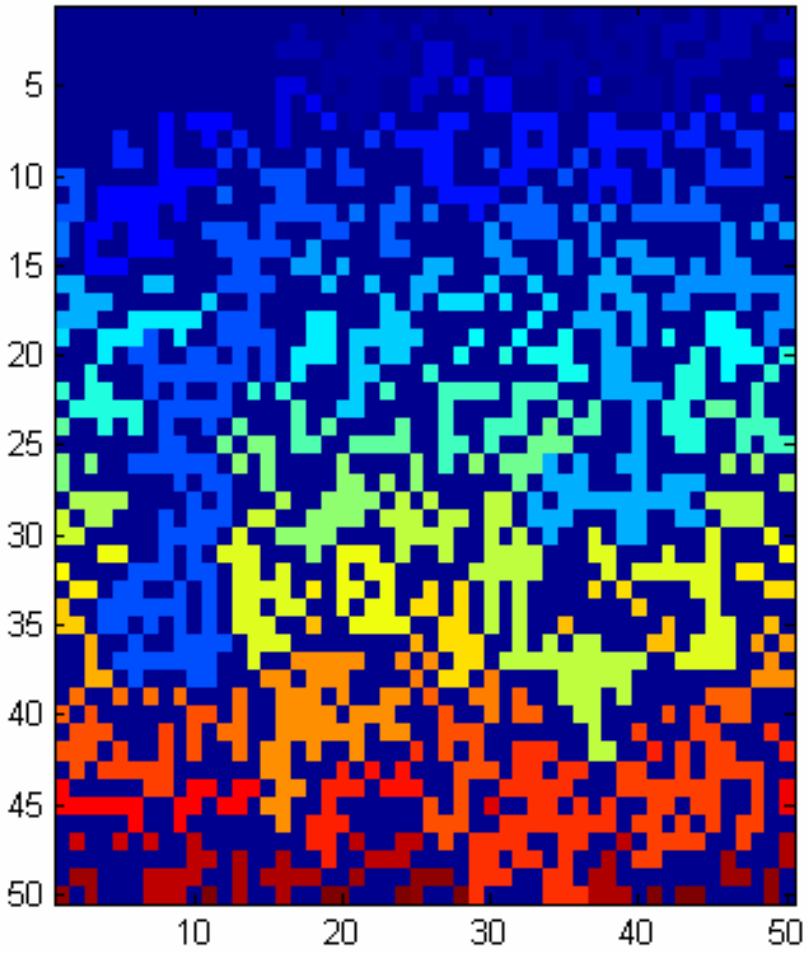
A Conceptual Model: 2D Lattice



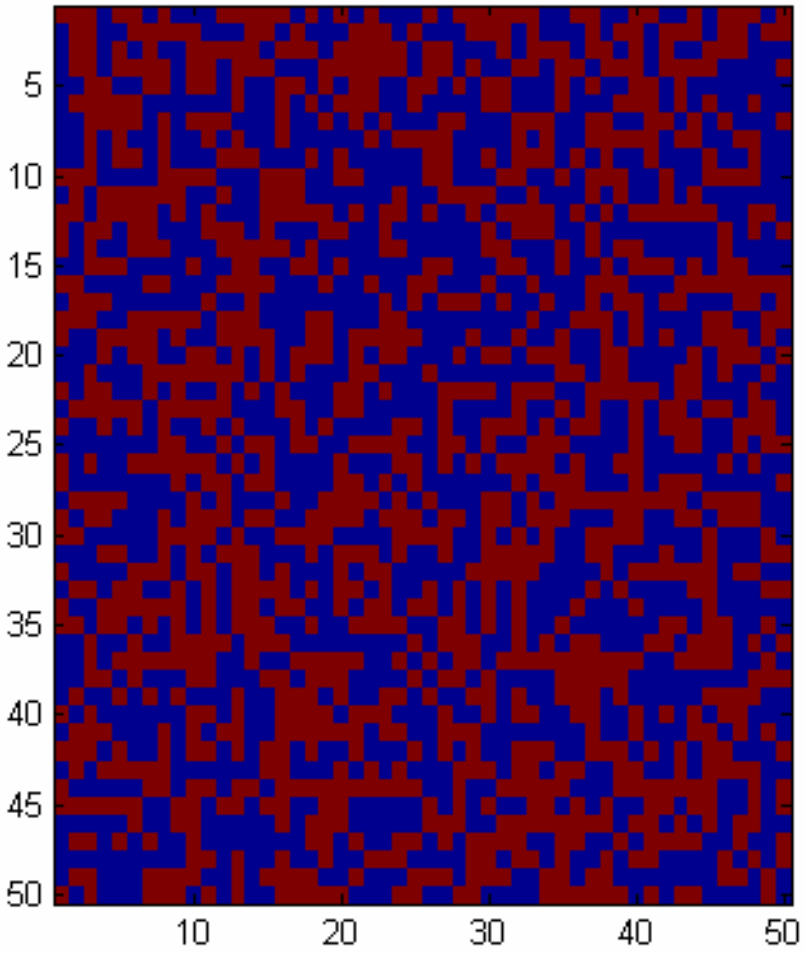


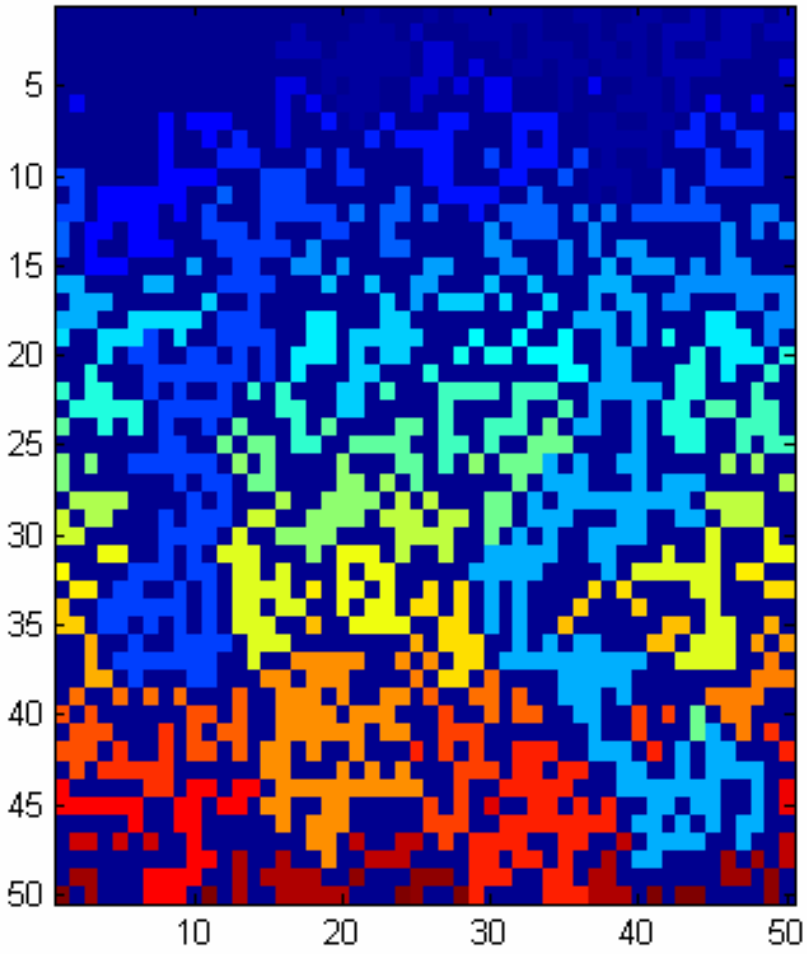
A Conceptual Model: 2D Lattice



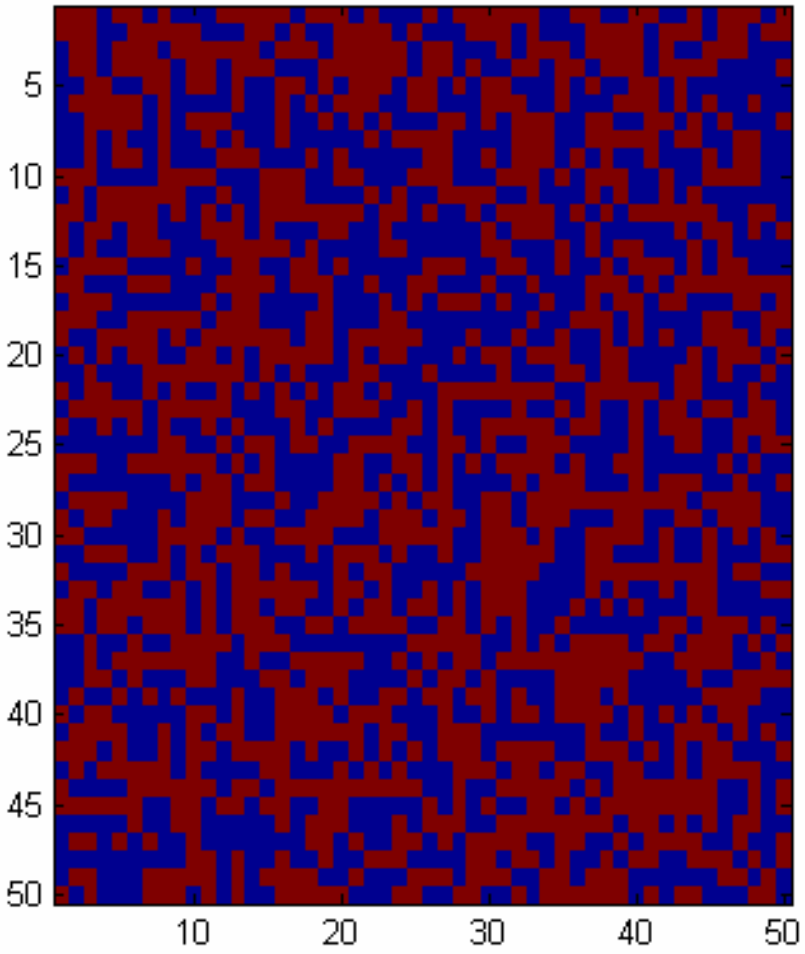


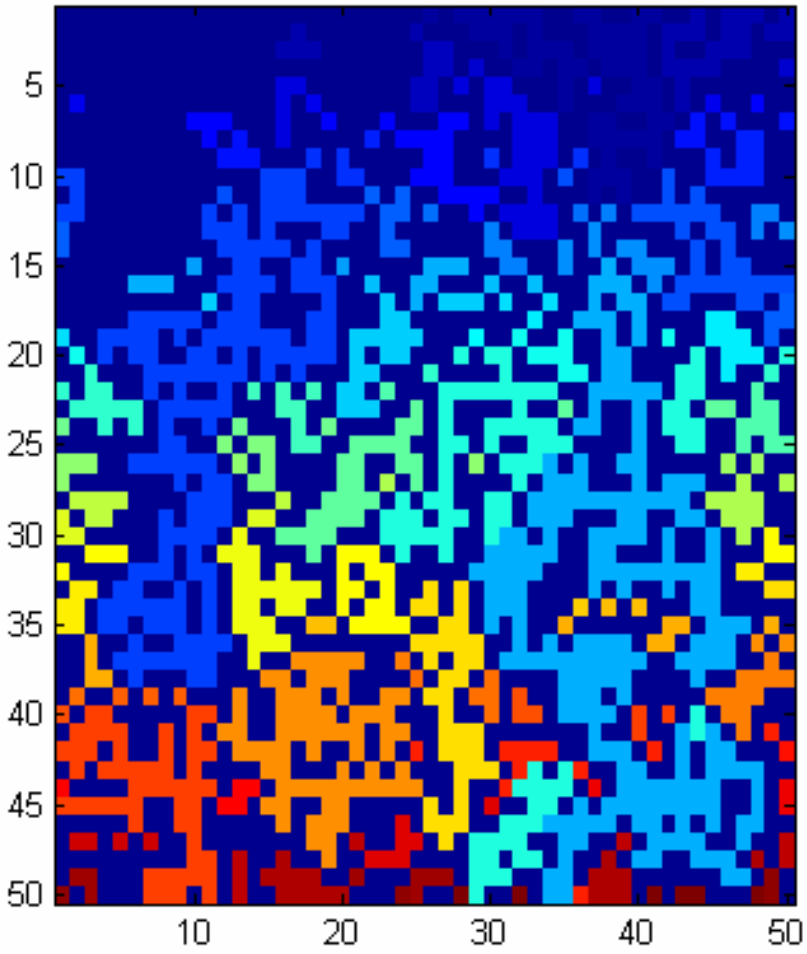
A Conceptual Model: 2D Lattice



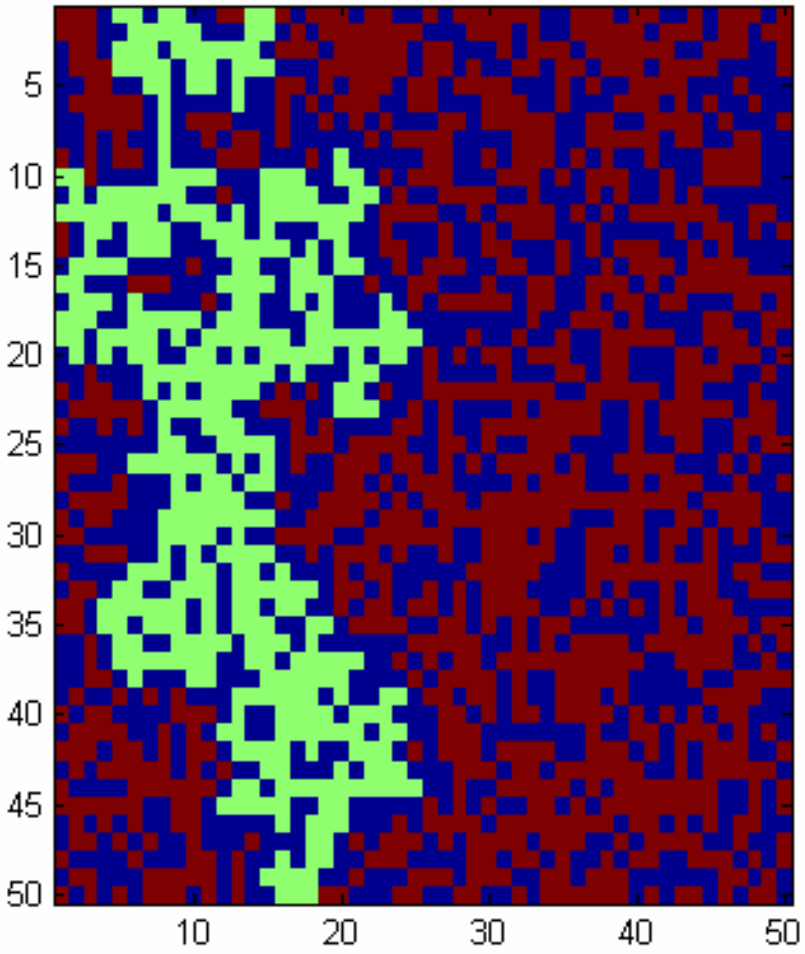


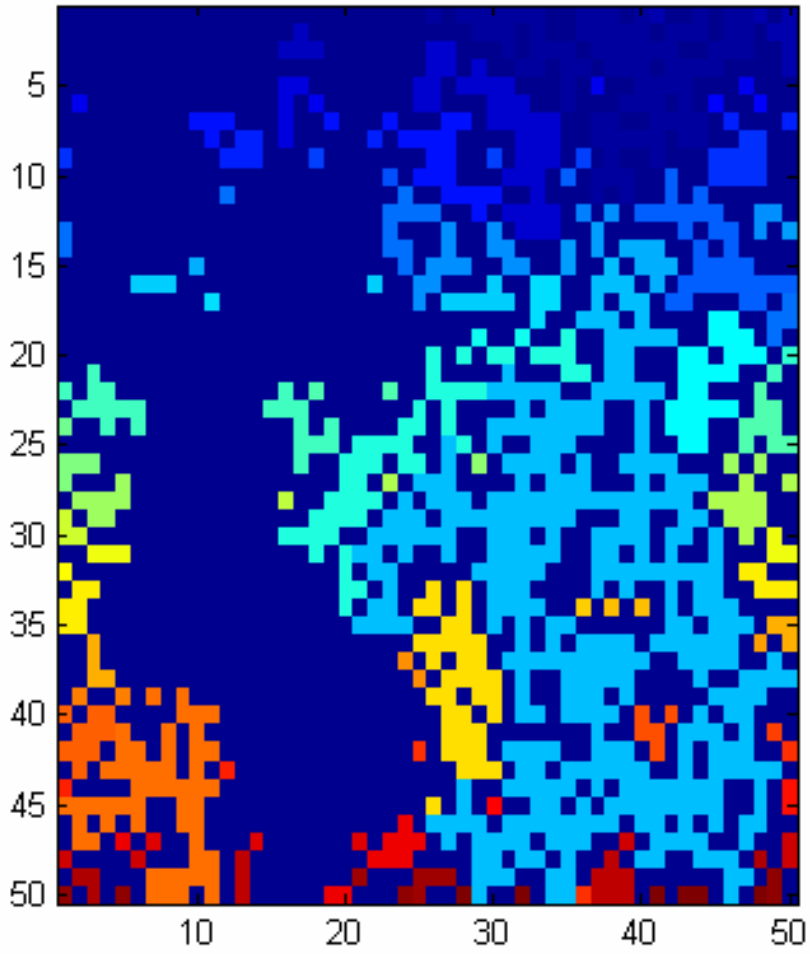
A Conceptual Model: 2D Lattice





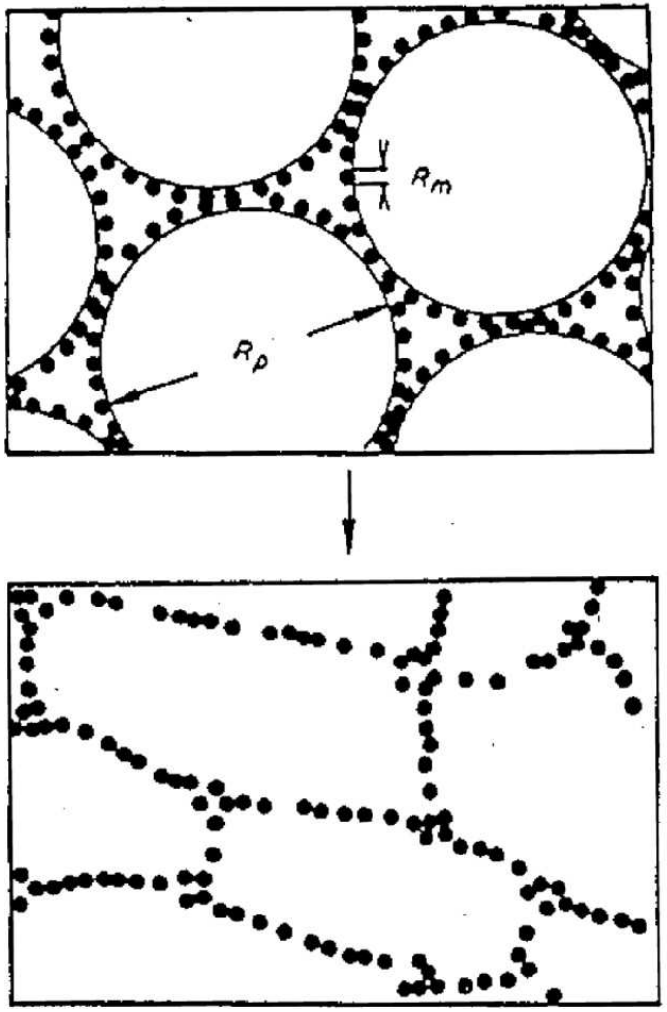
A Conceptual Model: 2D Lattice



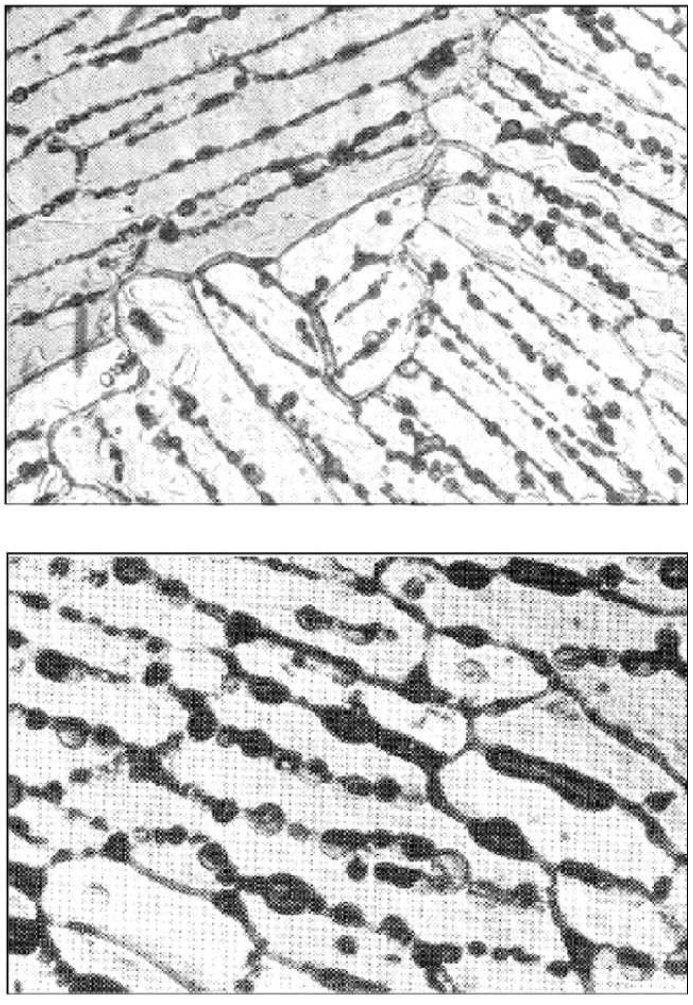


52% Liquid

Compressed Powder



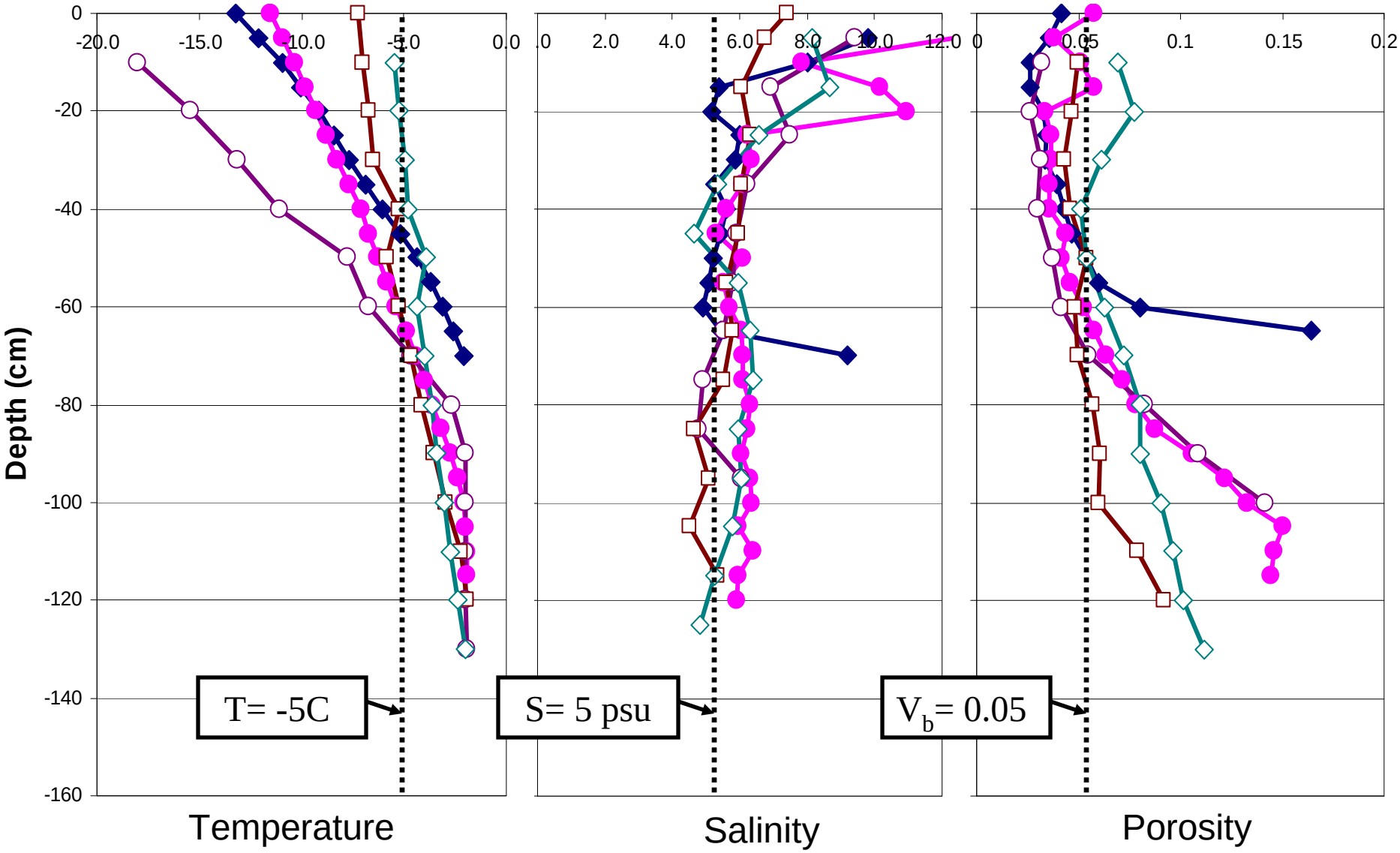
Sea Ice



Golden, Ackley, and Lytle. “The Percolation Phase Transition in Ice.” Science. Vol 232, 1998.

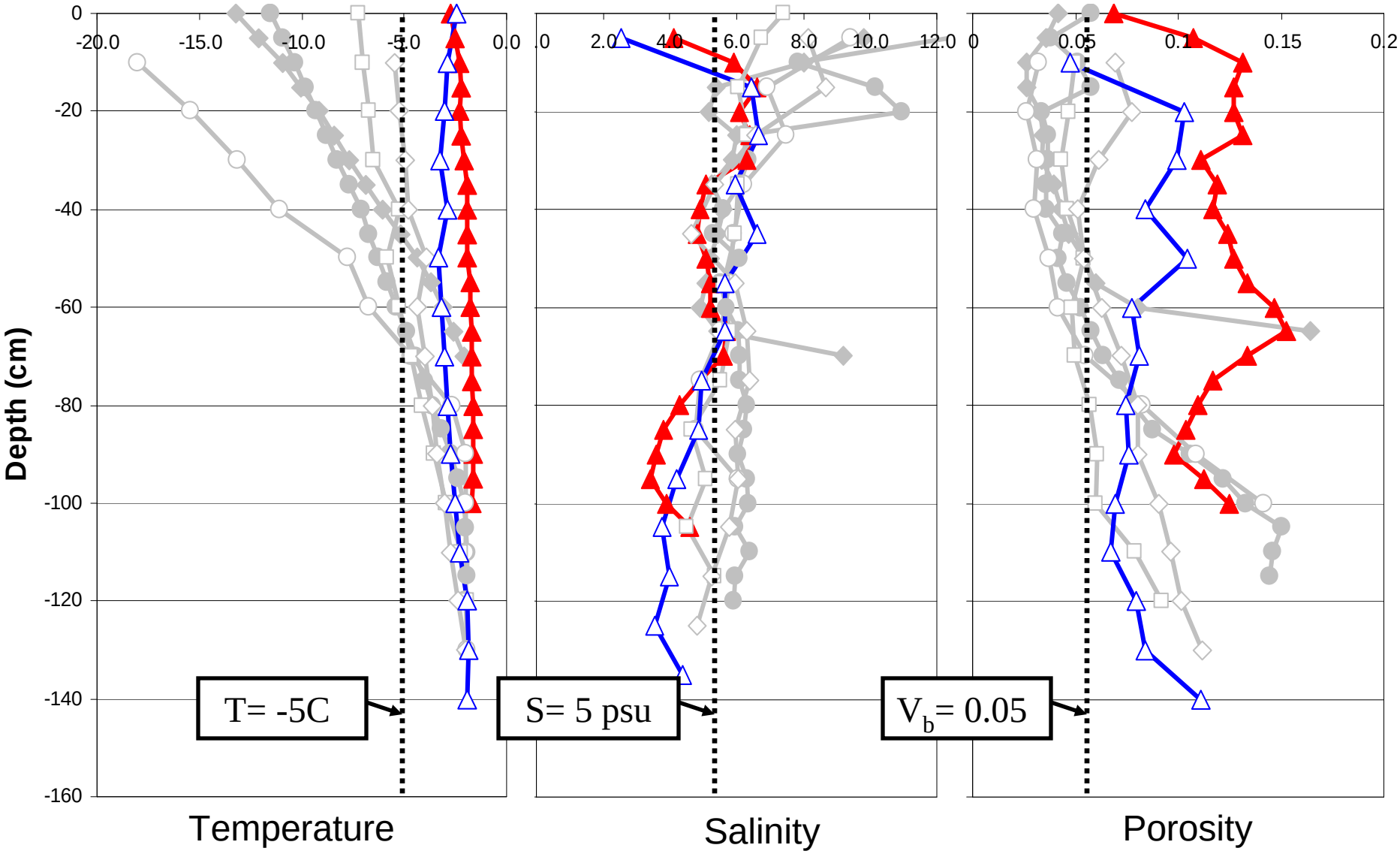
Ice Core Profiles

From Petrich, Eicken, and Druckenmiller; Barrow Ice Observatory



Ice Core Profiles

From Petrich, Eicken, and Druckenmiller; Barrow Ice Observatory



1/15/2009 3/25/2009 5/16/2009 2/9/2008 4/7/2008 4/29/2008 5/26/2008

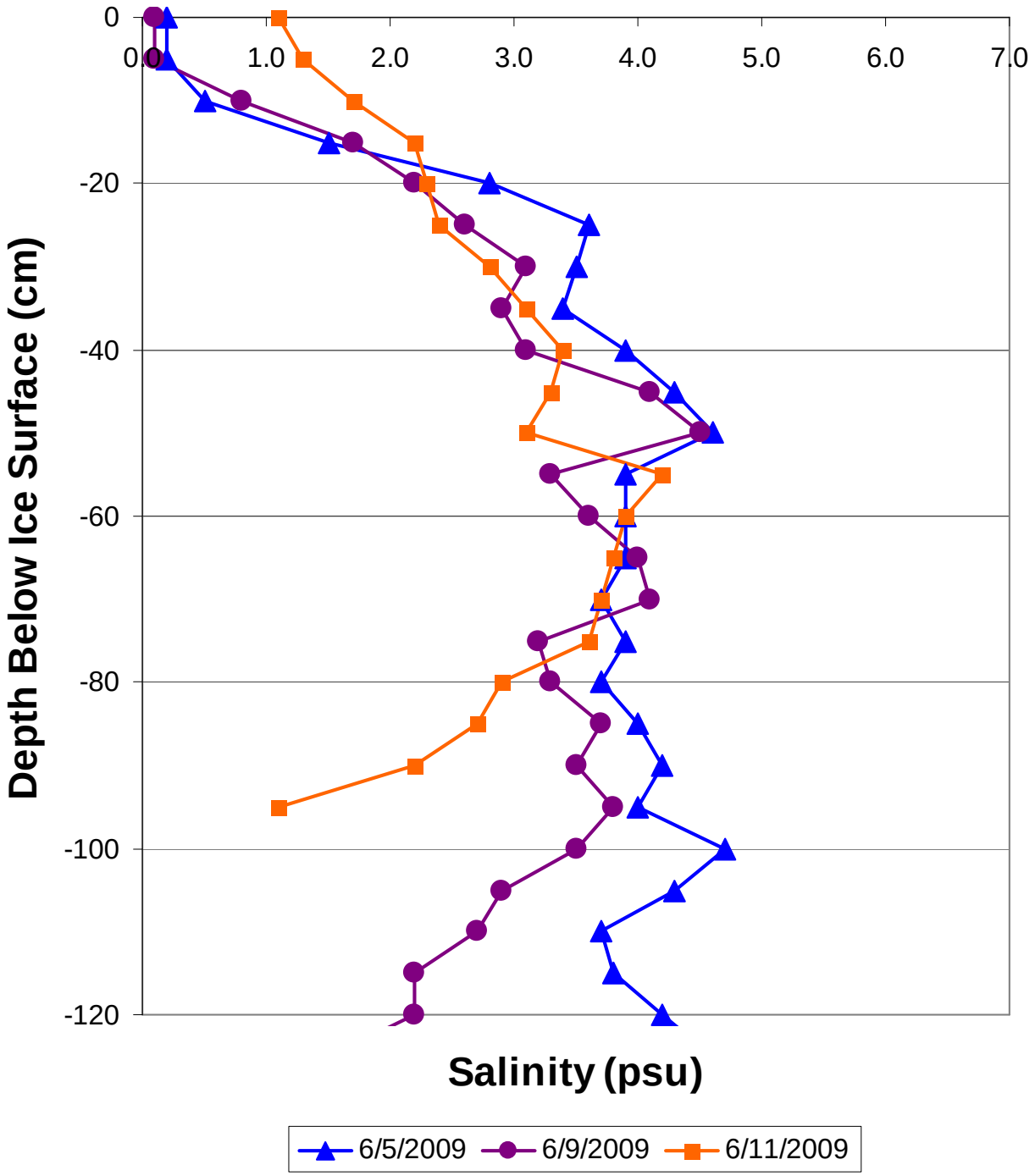

0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
-20
-40
-60
-80
-100
-120
Depth Below Ice Surface (cm)
Salinity (psu)
6/5/2009
6/9/2009
6/11/2009


Photo: Chris Petrich

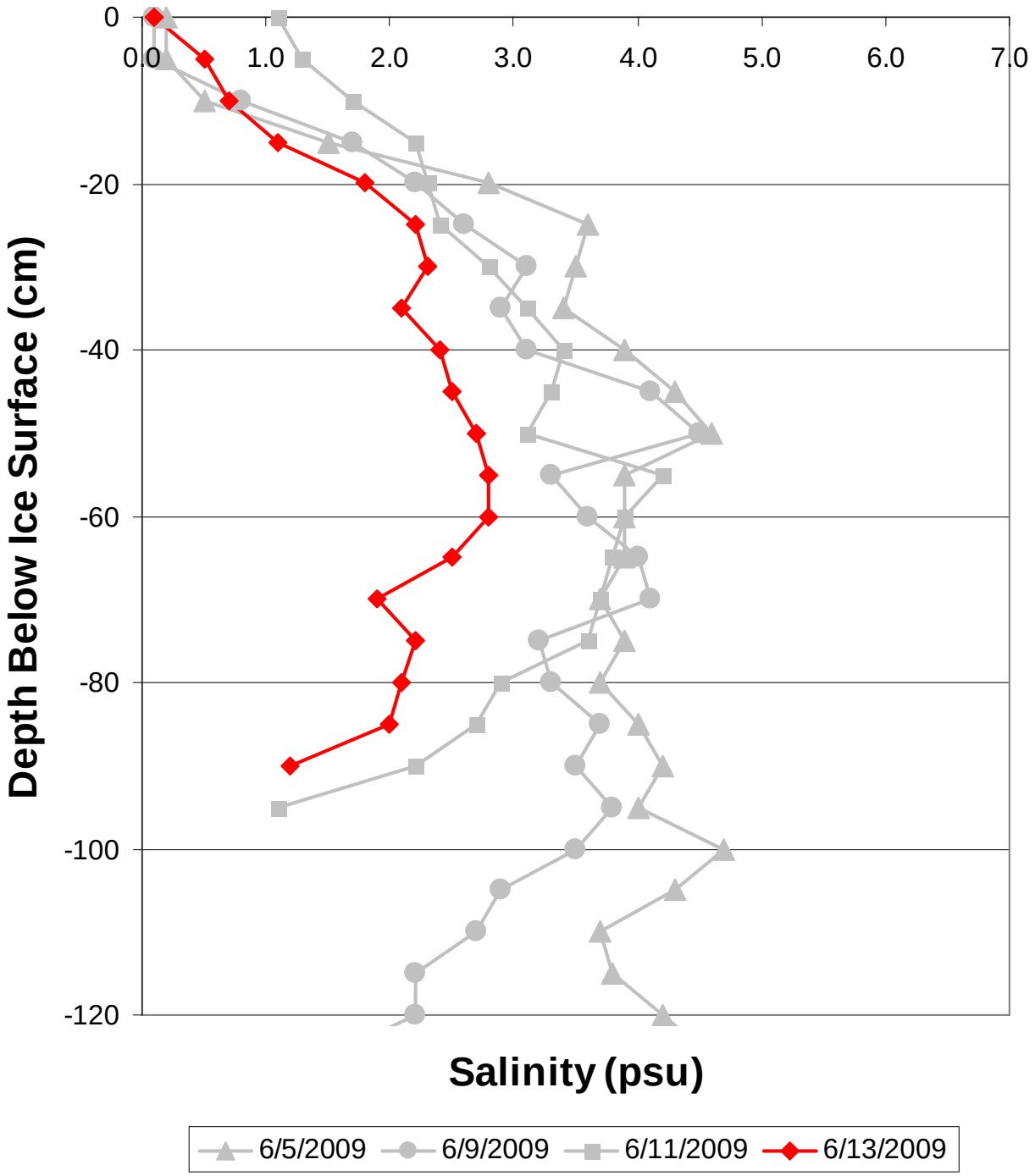

0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
-20
-40
-60
-80
-100
-120
Depth Below Ice Surface (cm)
Salinity (psu)
6/5/2009
6/9/2009
6/11/2009
6/13/2009


Photo: Chris Petrich

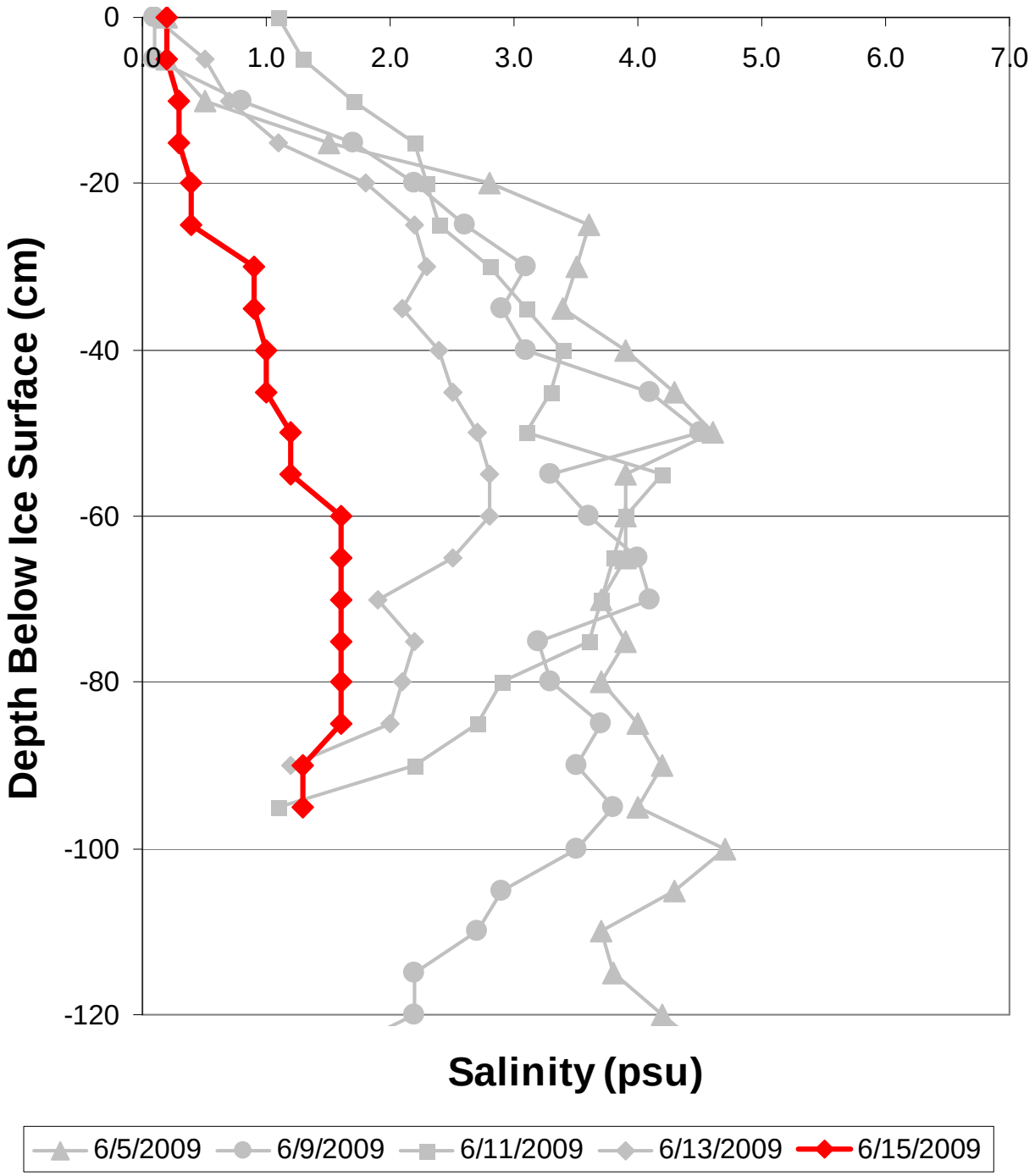
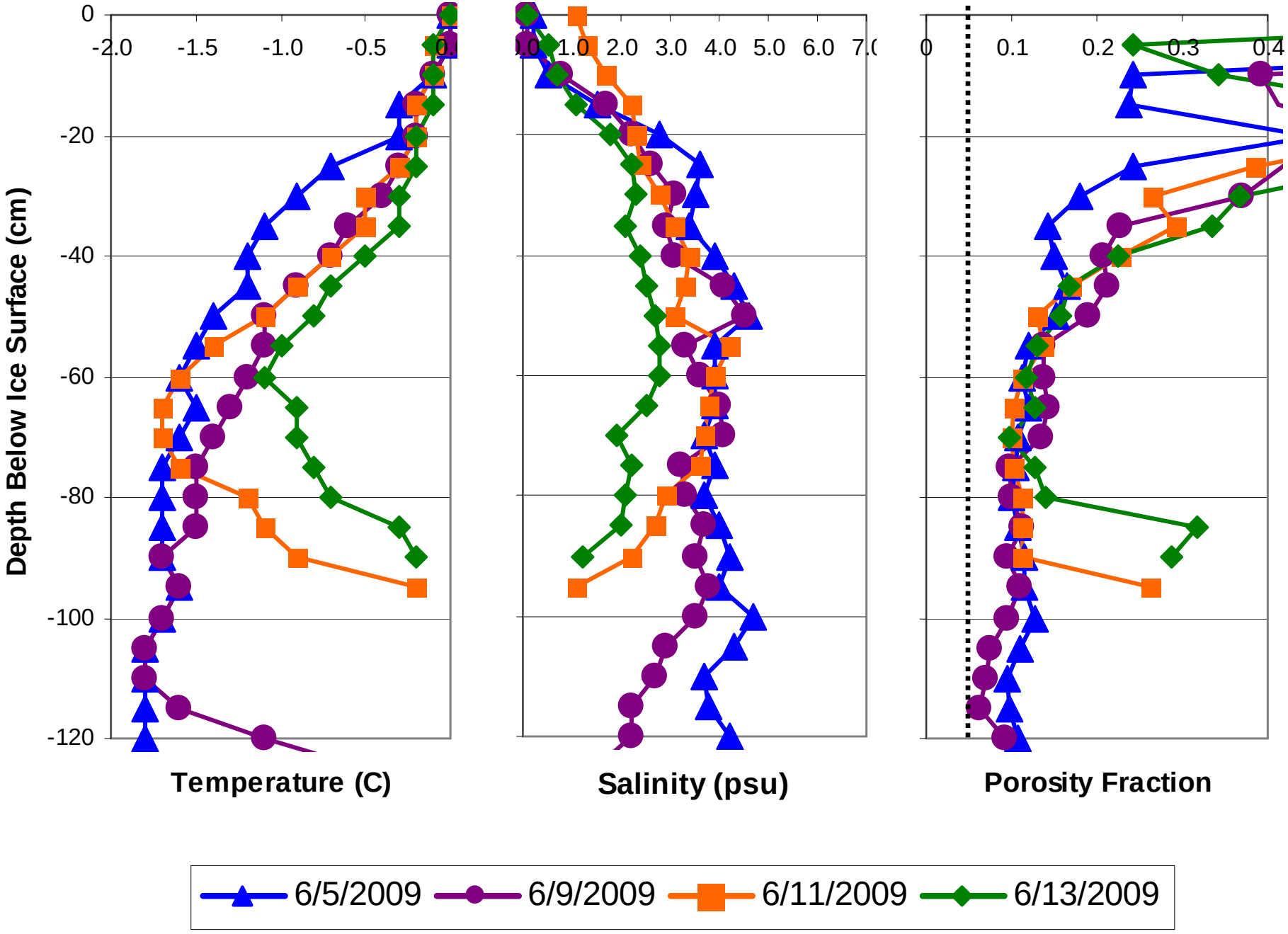
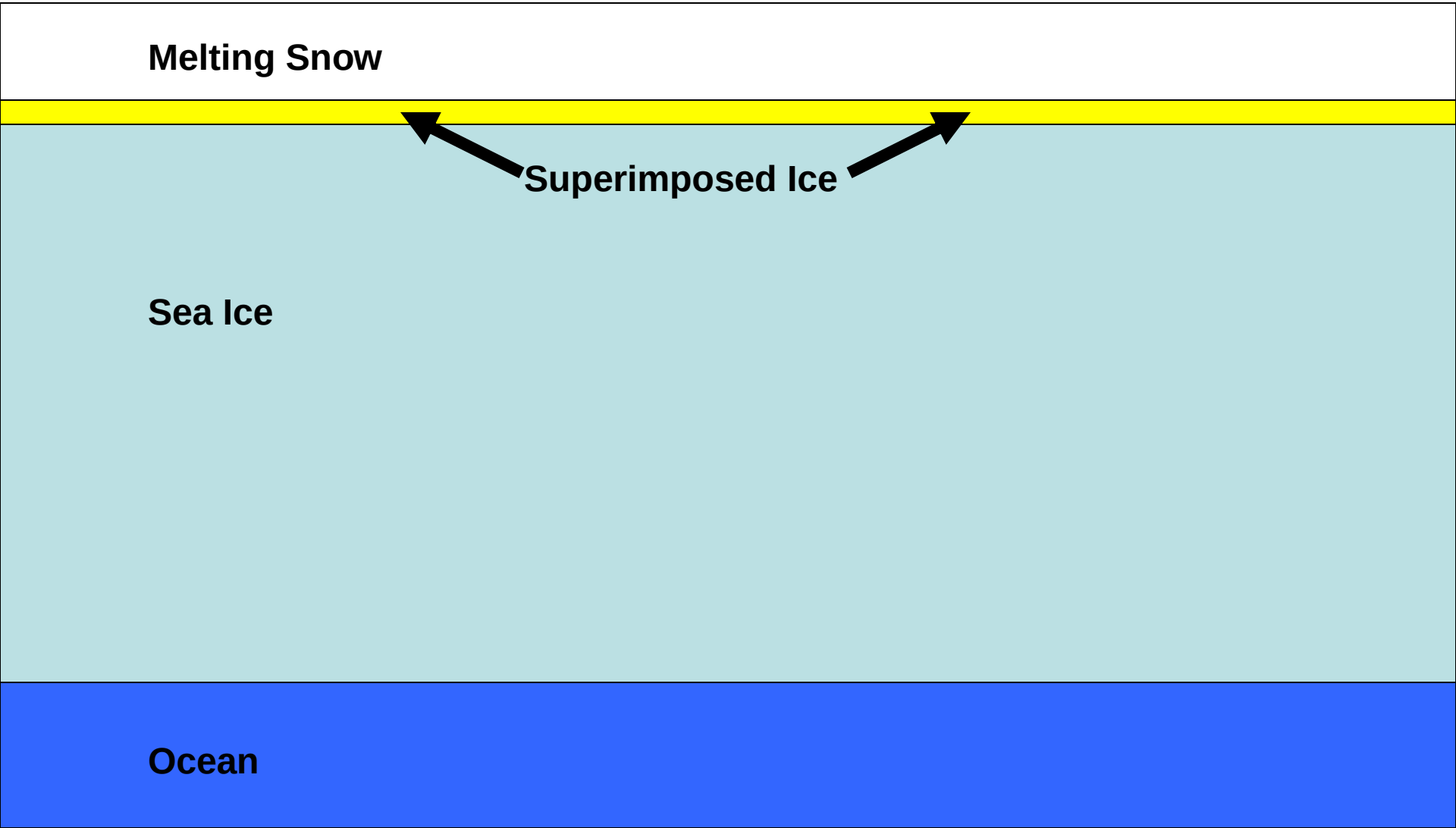
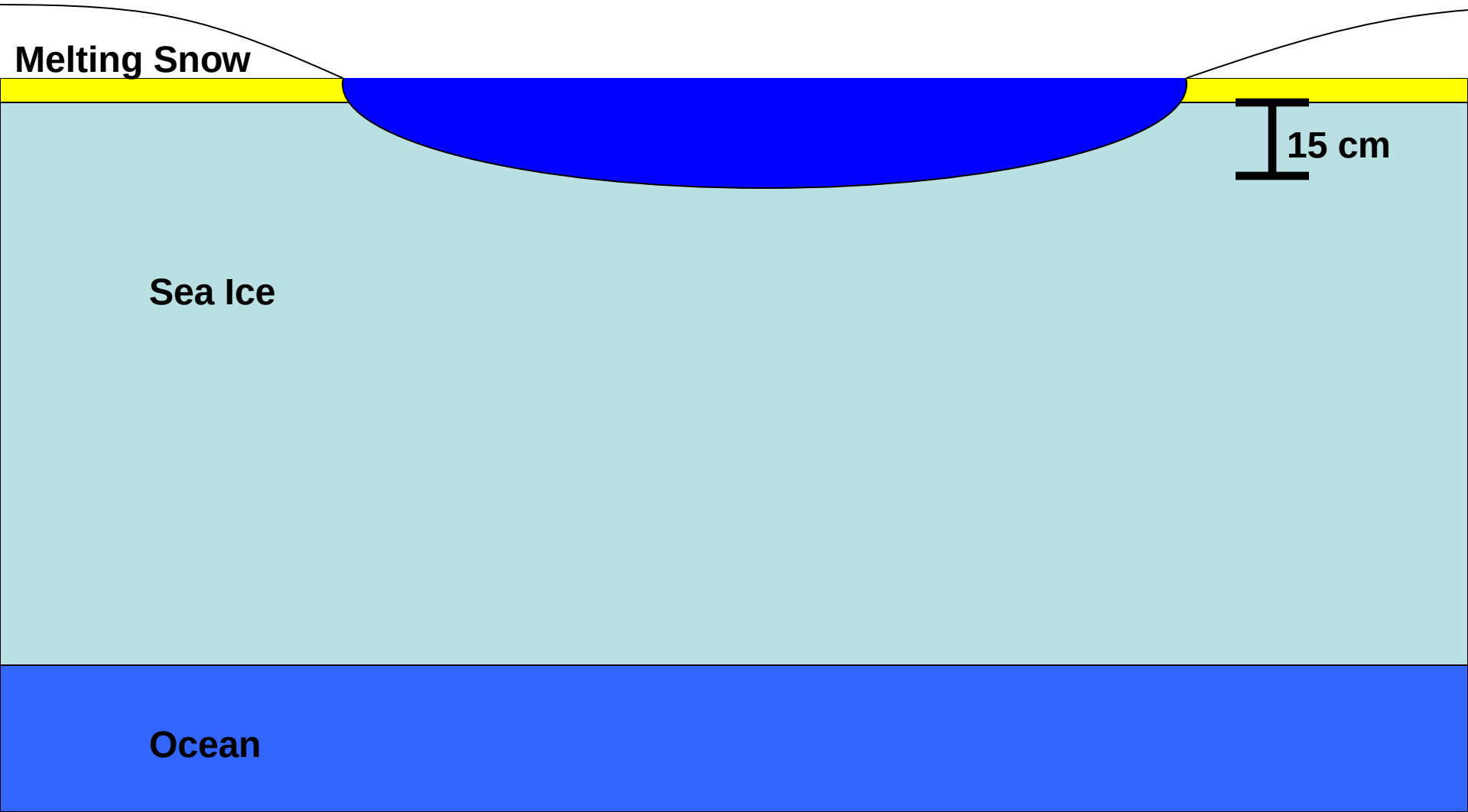
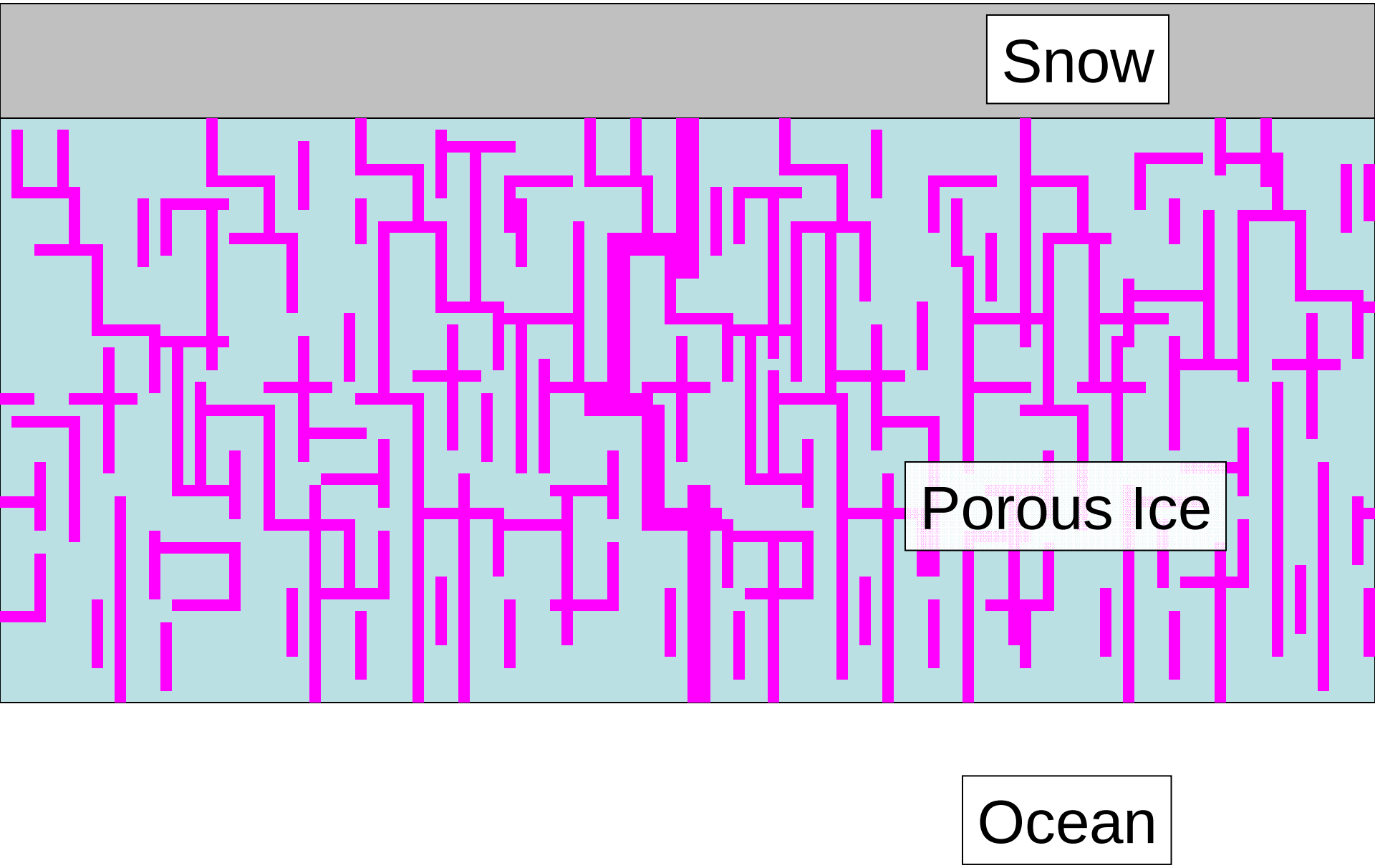

0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
-20
-40
-60
-80
-100
-120
Depth Below Ice Surface (cm)
Salinity (psu)
6/5/2009
6/9/2009
6/11/2009
6/13/2009
6/15/2009

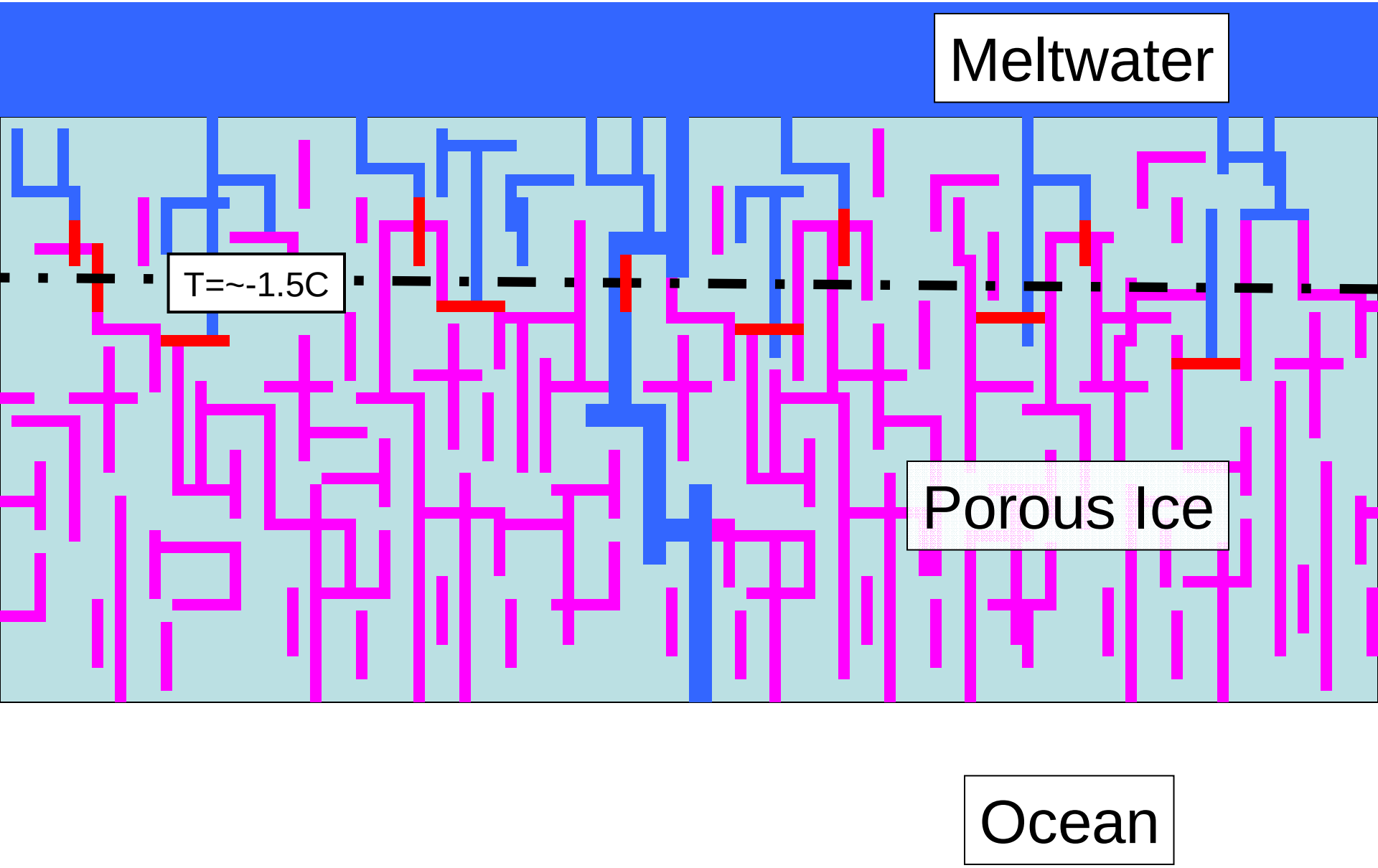

Photo: Chris Petrich

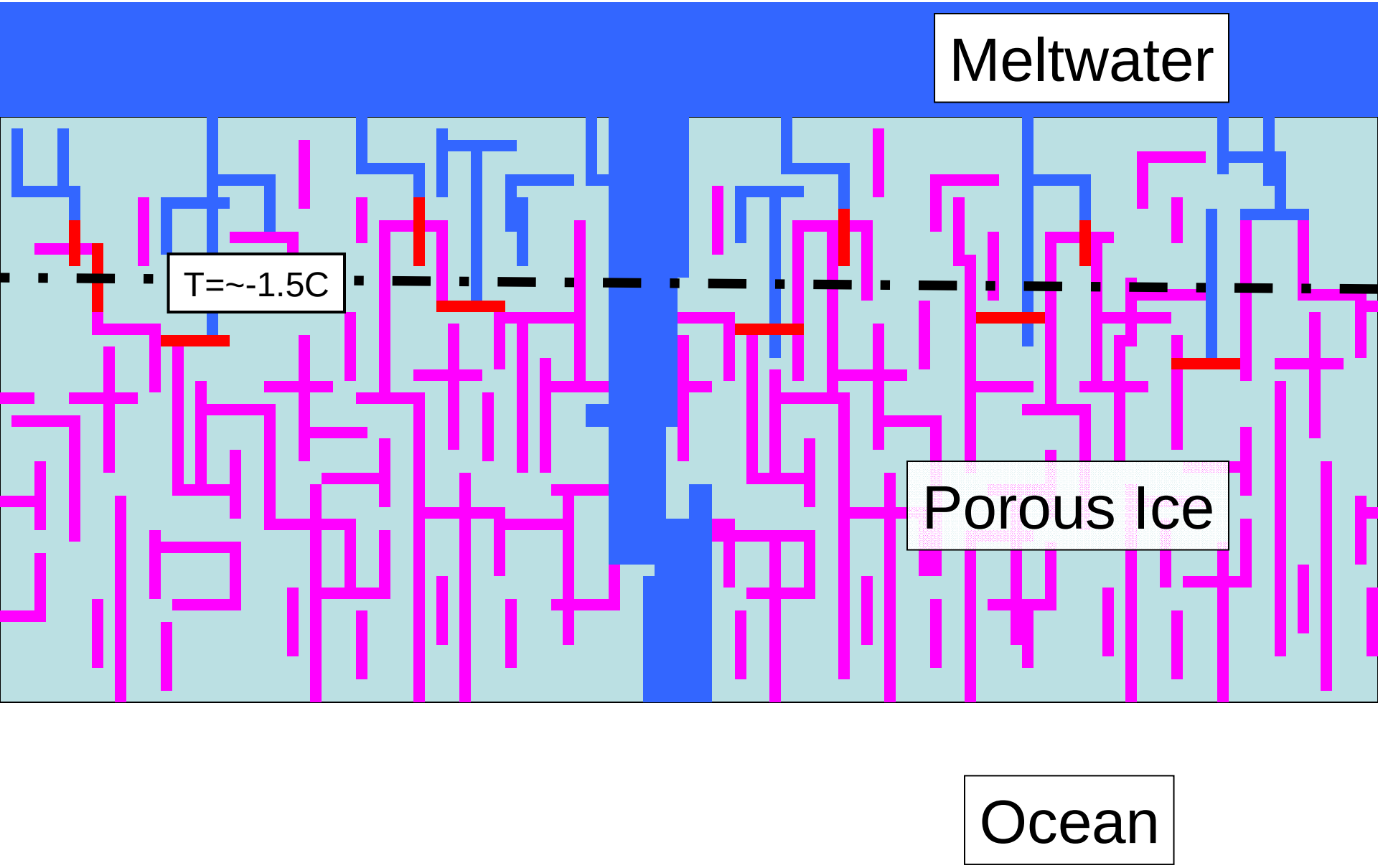

Depth Below Ice Surface (cm)
0
-20
-40
-60
-80
-100
-120
-2.0
-1.5
-1.0
-0.5
0.0
1.0
2.0
3.0
4.0
5.0
6.0
0
0.1
0.2
0.3
0.4
Temperature (C)
Salinity (psu)
Porosity Fraction
6/5/2009
6/9/2009
6/11/2009
6/13/2009

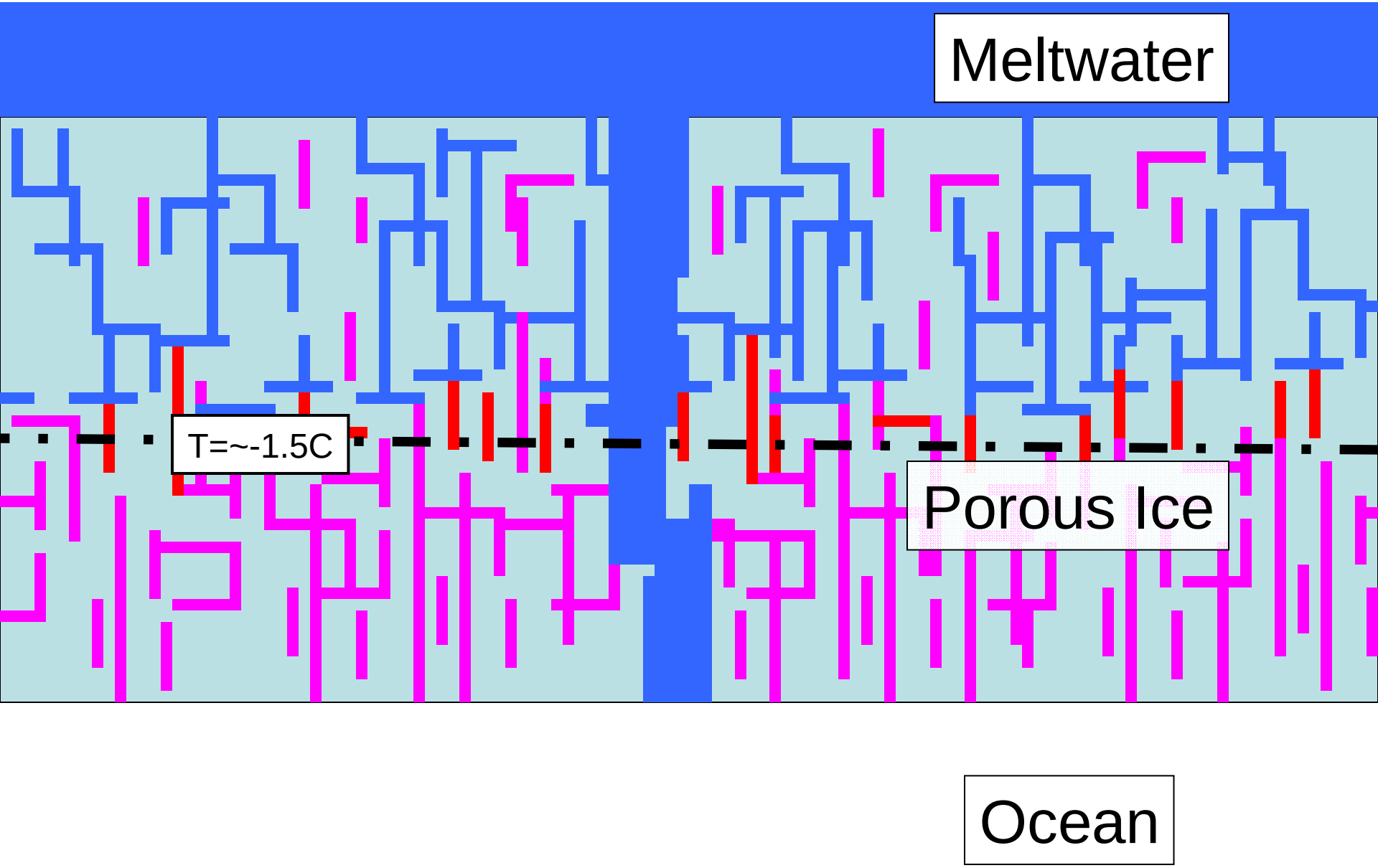

Melting Snow
Superimposed Ice
Sea Ice
Ocean

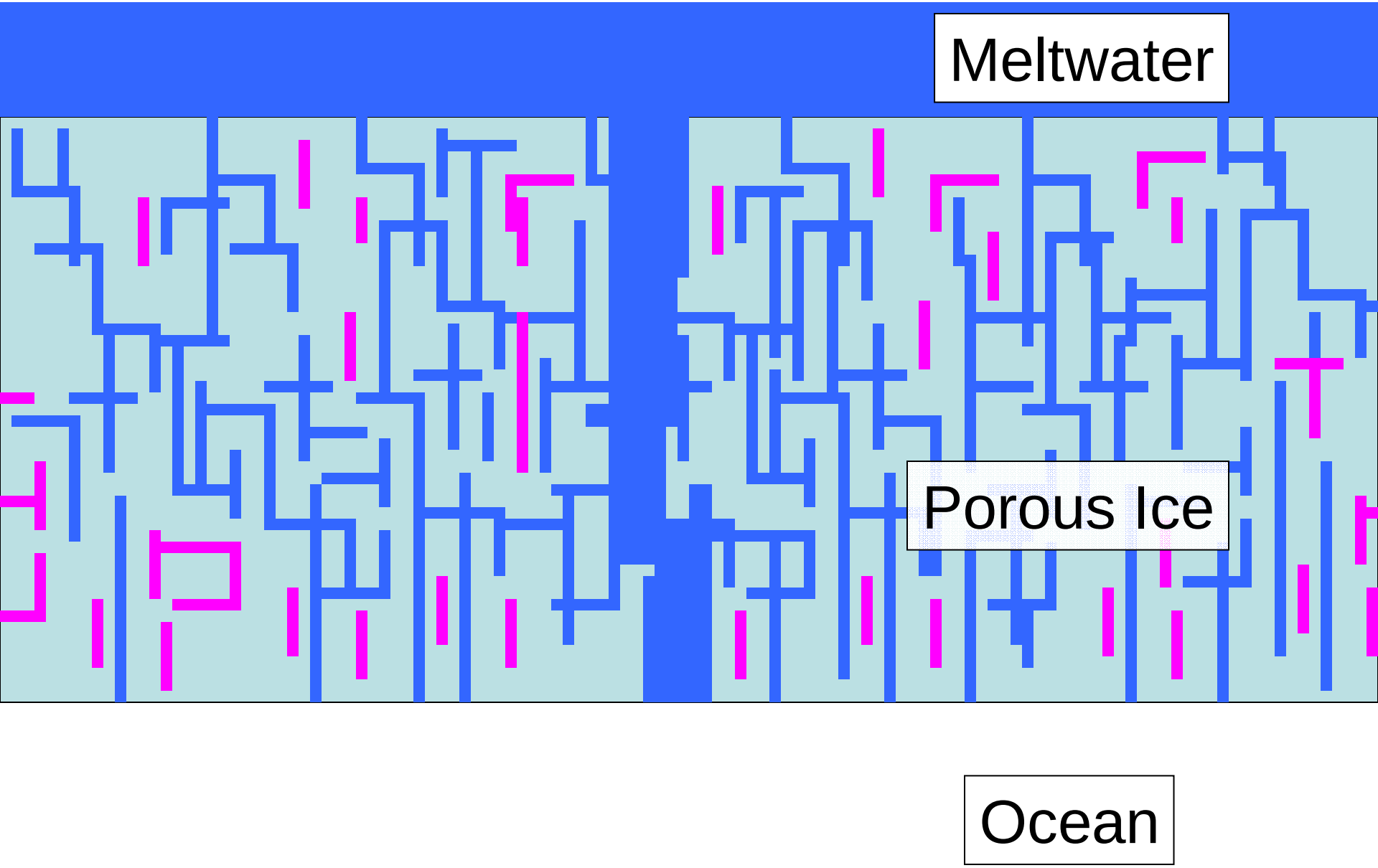

Melting Snow
15 cm
Sea Ice
Ocean


Snow
Porous Ice
Ocean

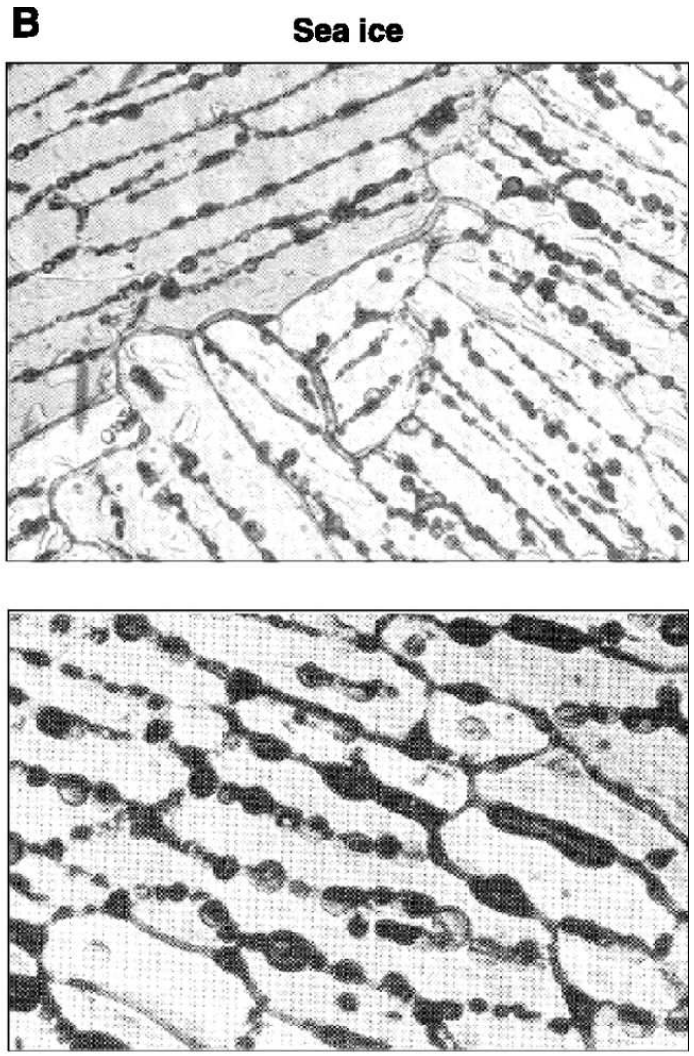

Meltwater
T=~-1.5C
Porous Ice
Ocean

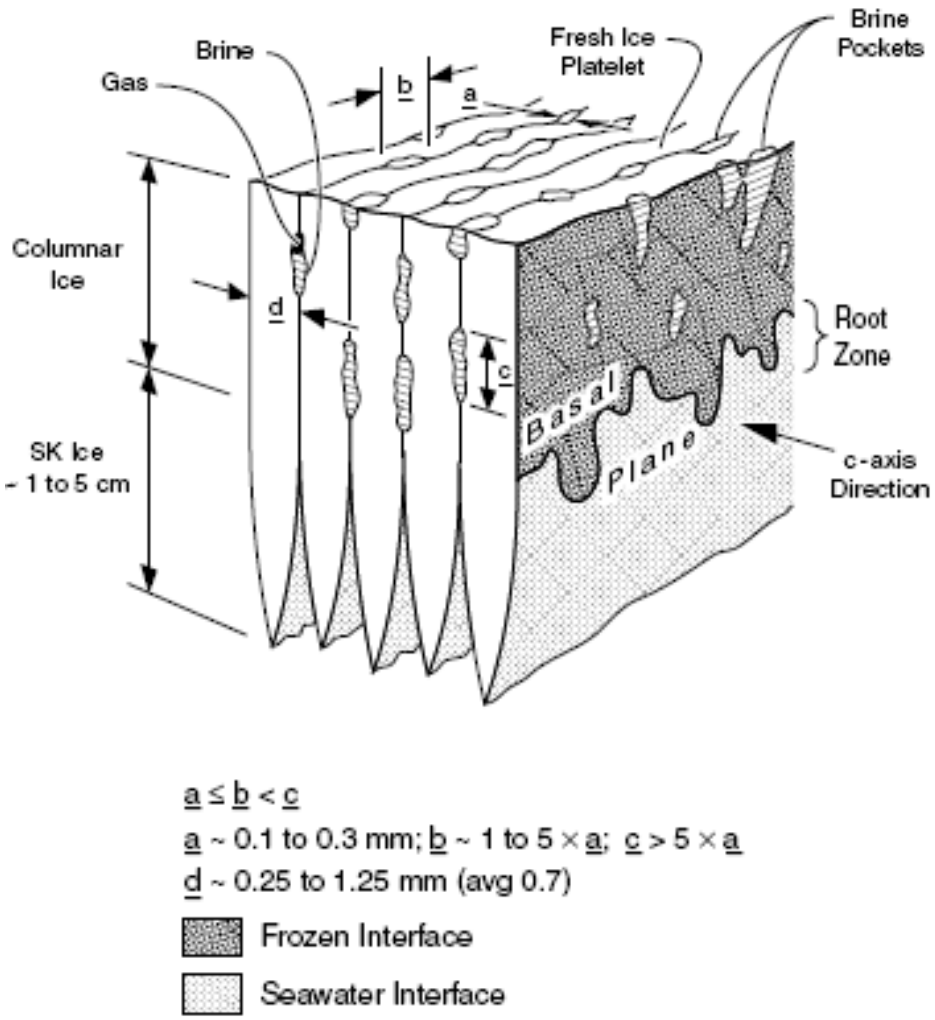

Meltwater
T=~-1.5C
Porous Ice
Ocean


Meltwater
T=~-1.5C
Porous Ice
Ocean


Meltwater
Porous Ice
Ocean

Inter – Lamellar Brine Inclusions





$a \le b < c$

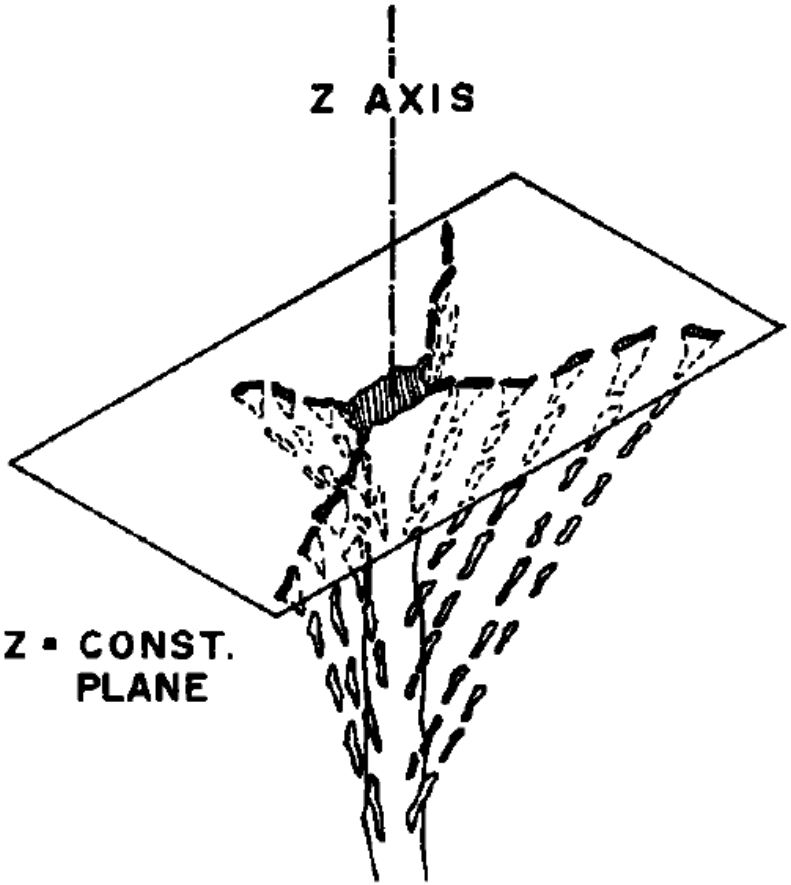
a ~ 0.1 to 0.3 mm; b ~ 1 to 5 × a; $c > 5 \times a$

d ~ 0.25 to 1.25 mm (avg 0.7)

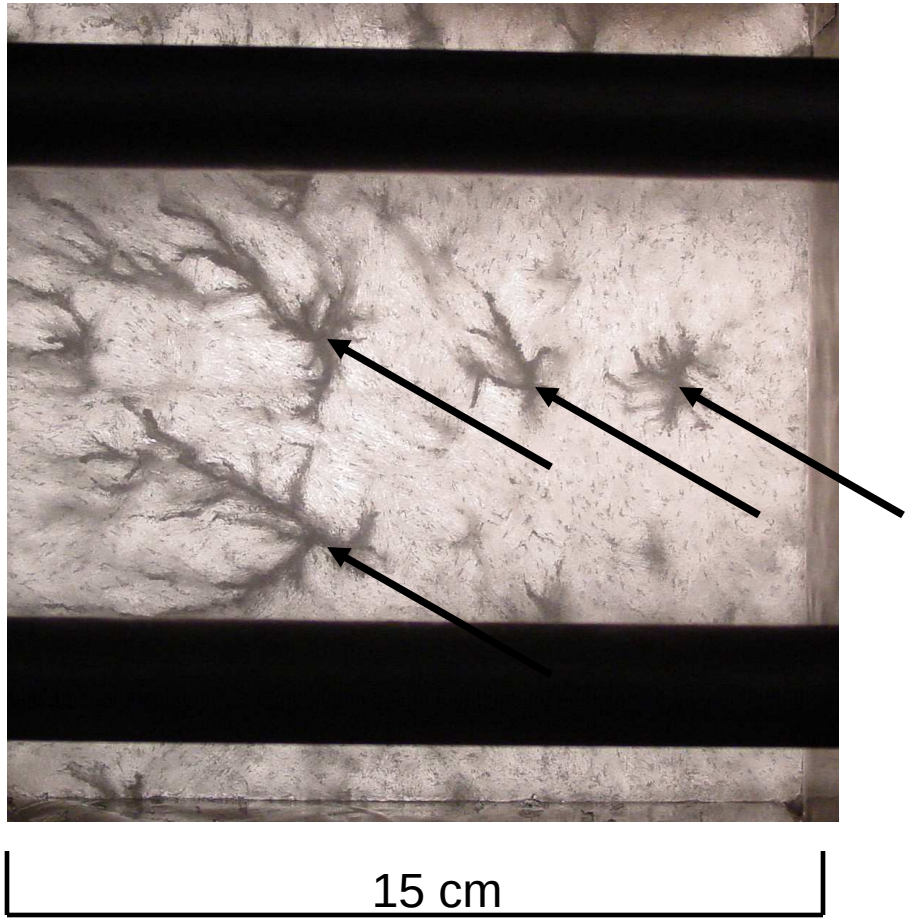
Frozen Interface

Seawater Interface

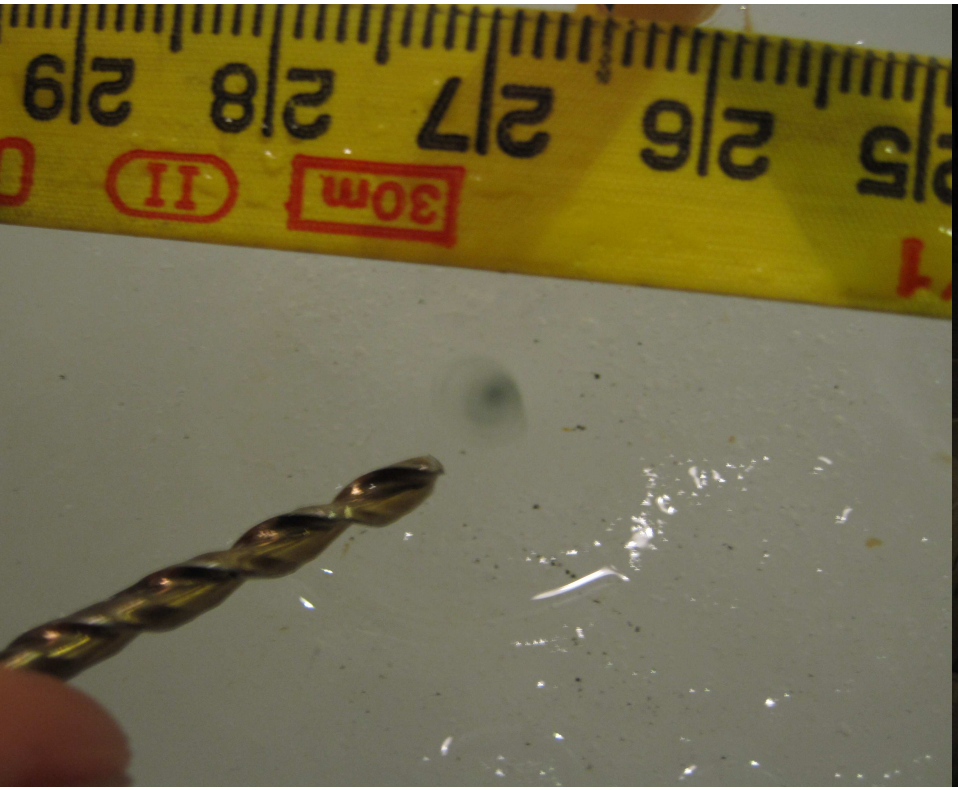
Organized Arborescent Brine Channels

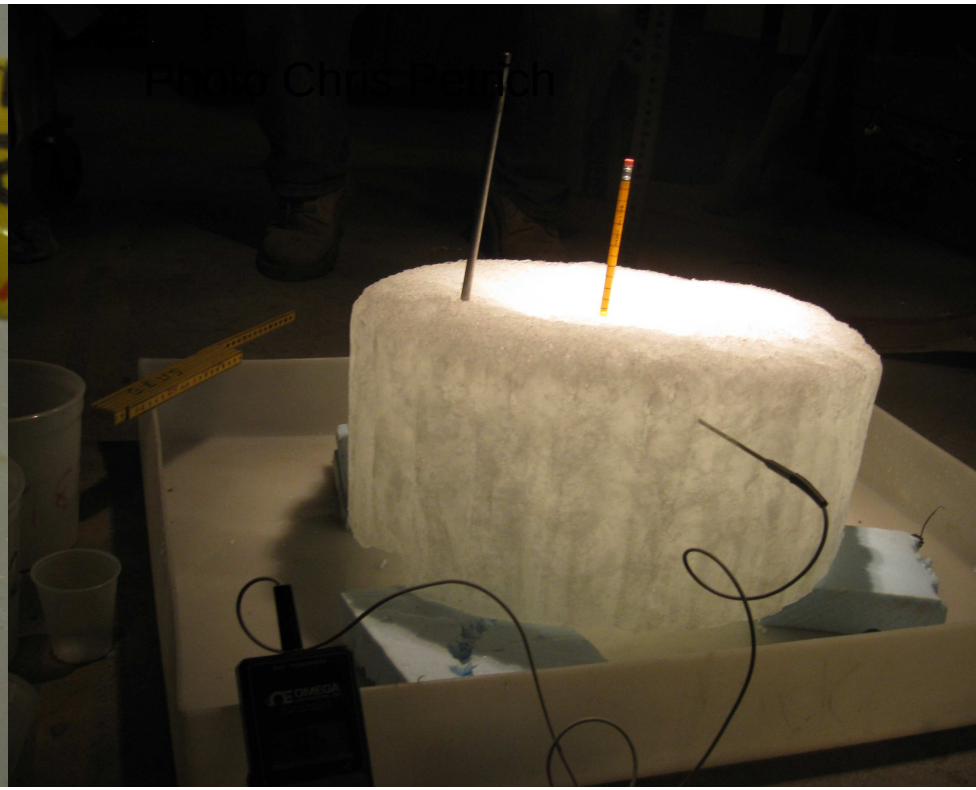


Horizontal Section



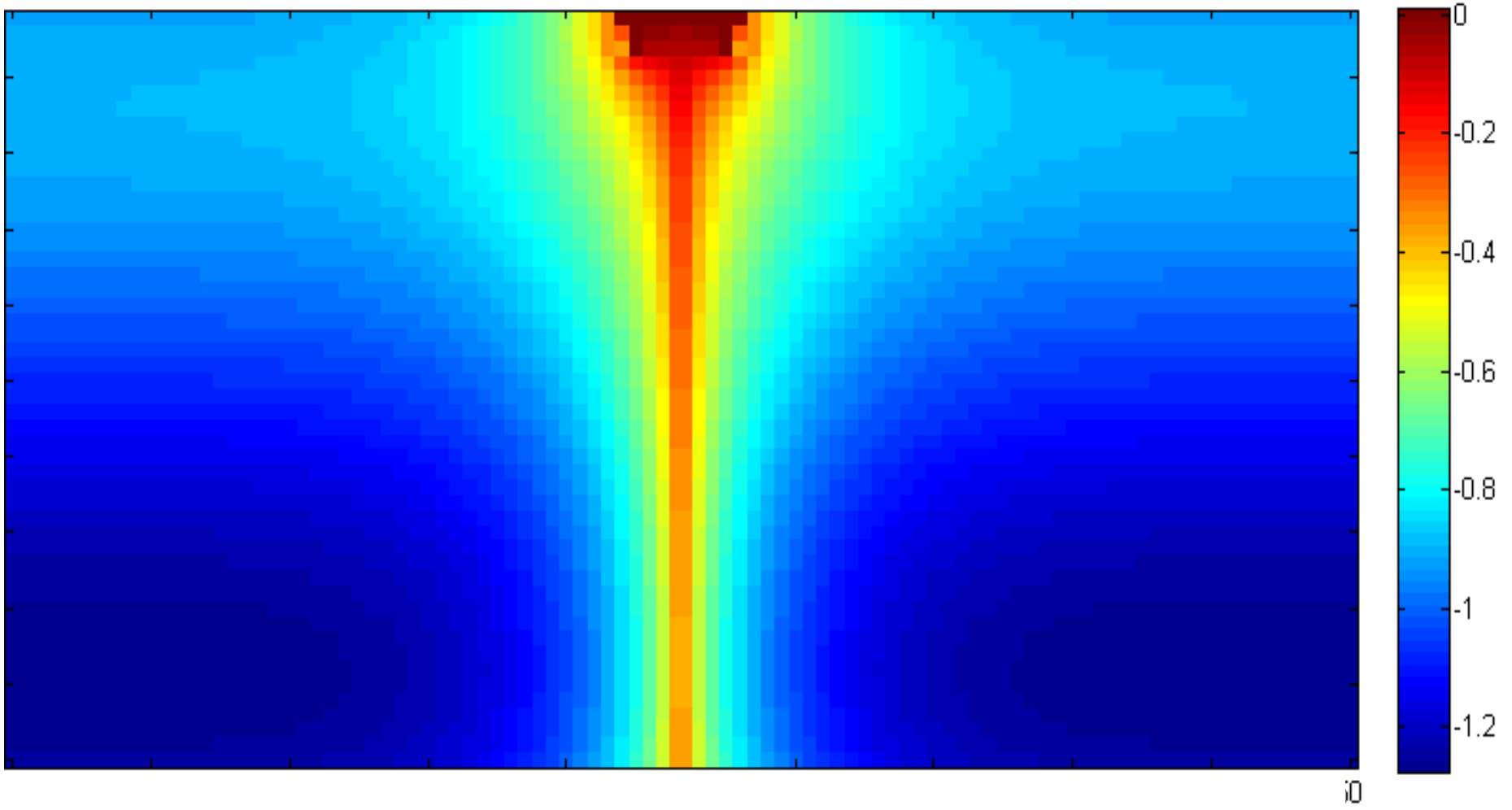
Large core holes are enlarged by flowing water

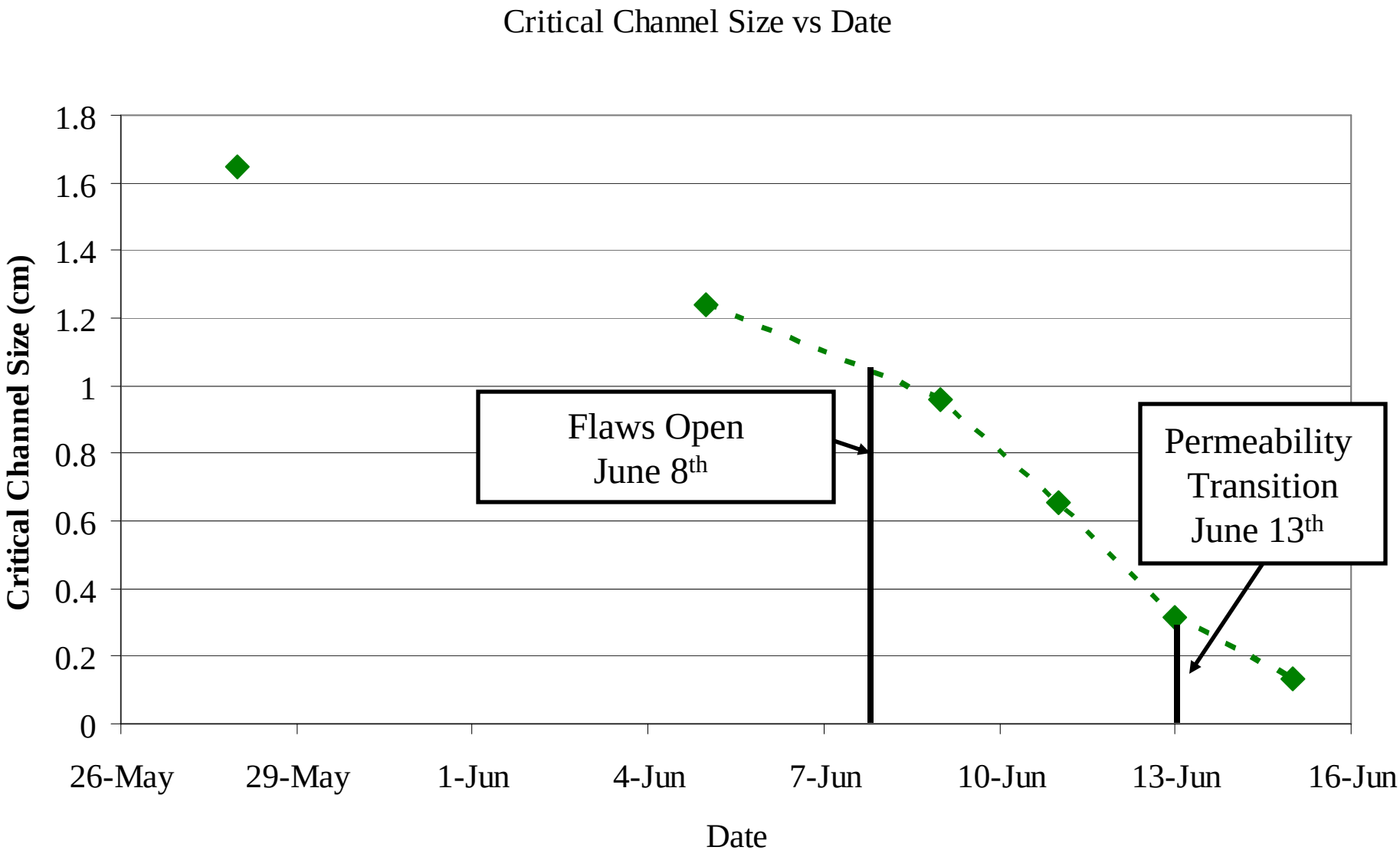




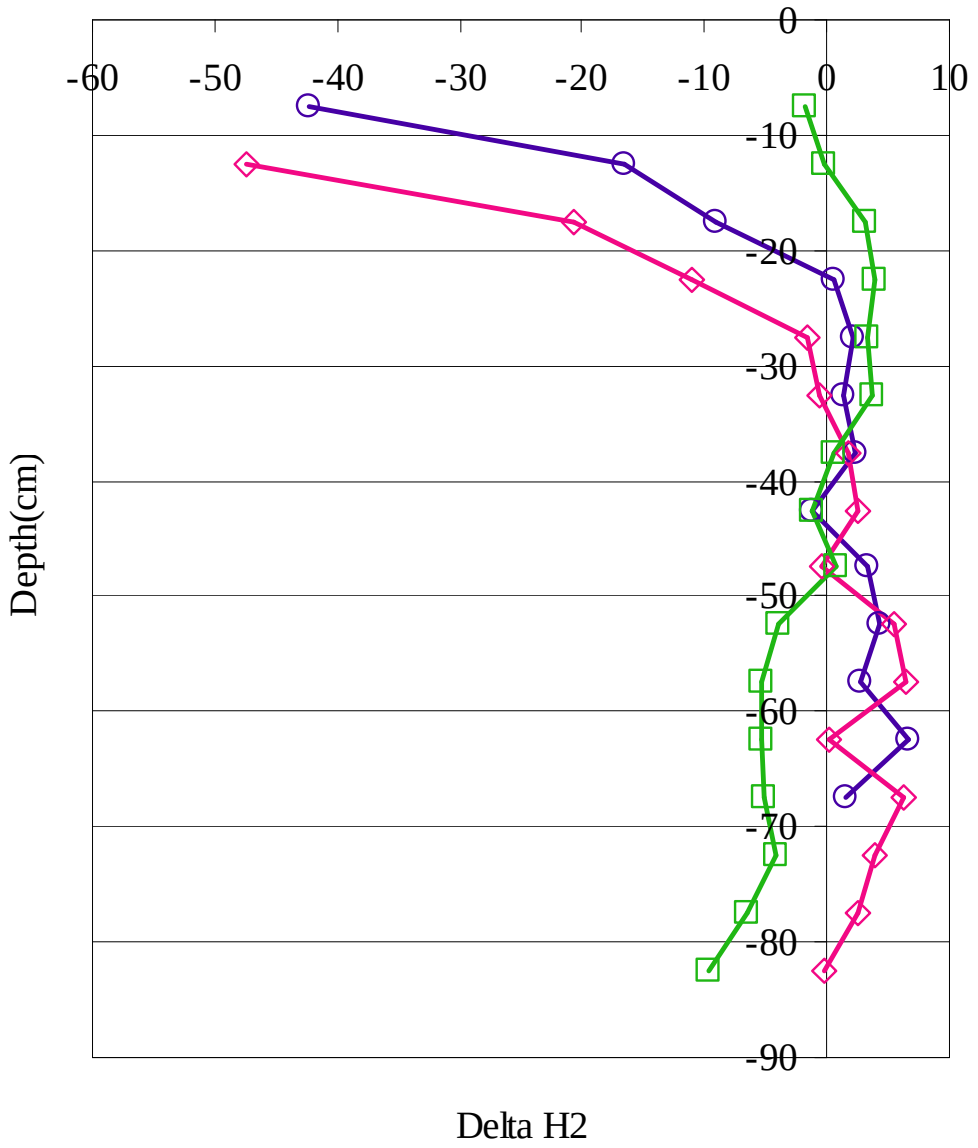
Photos: Becky Niemiec

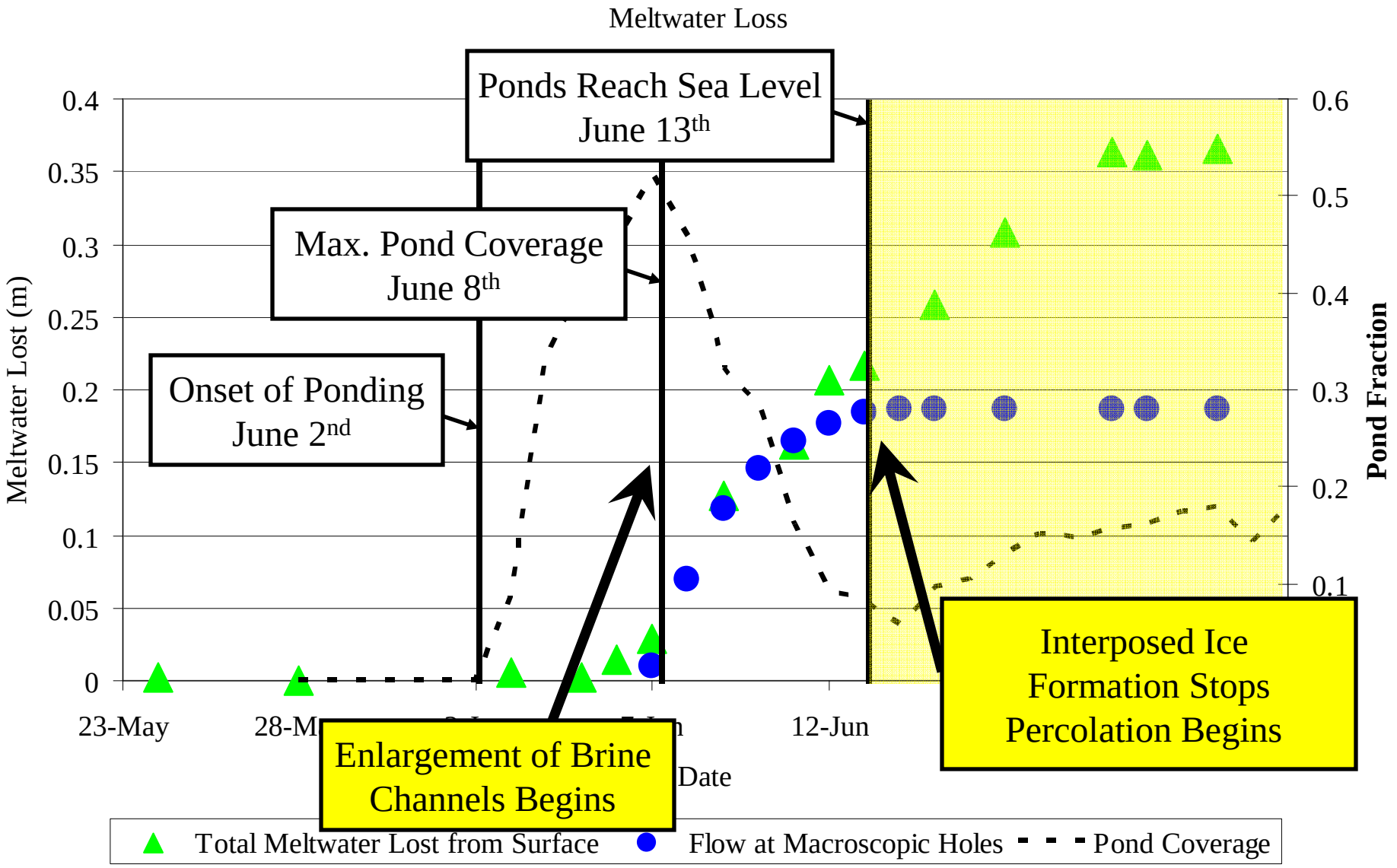
Small holes are repaired by refreezing meltwater


0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
i0

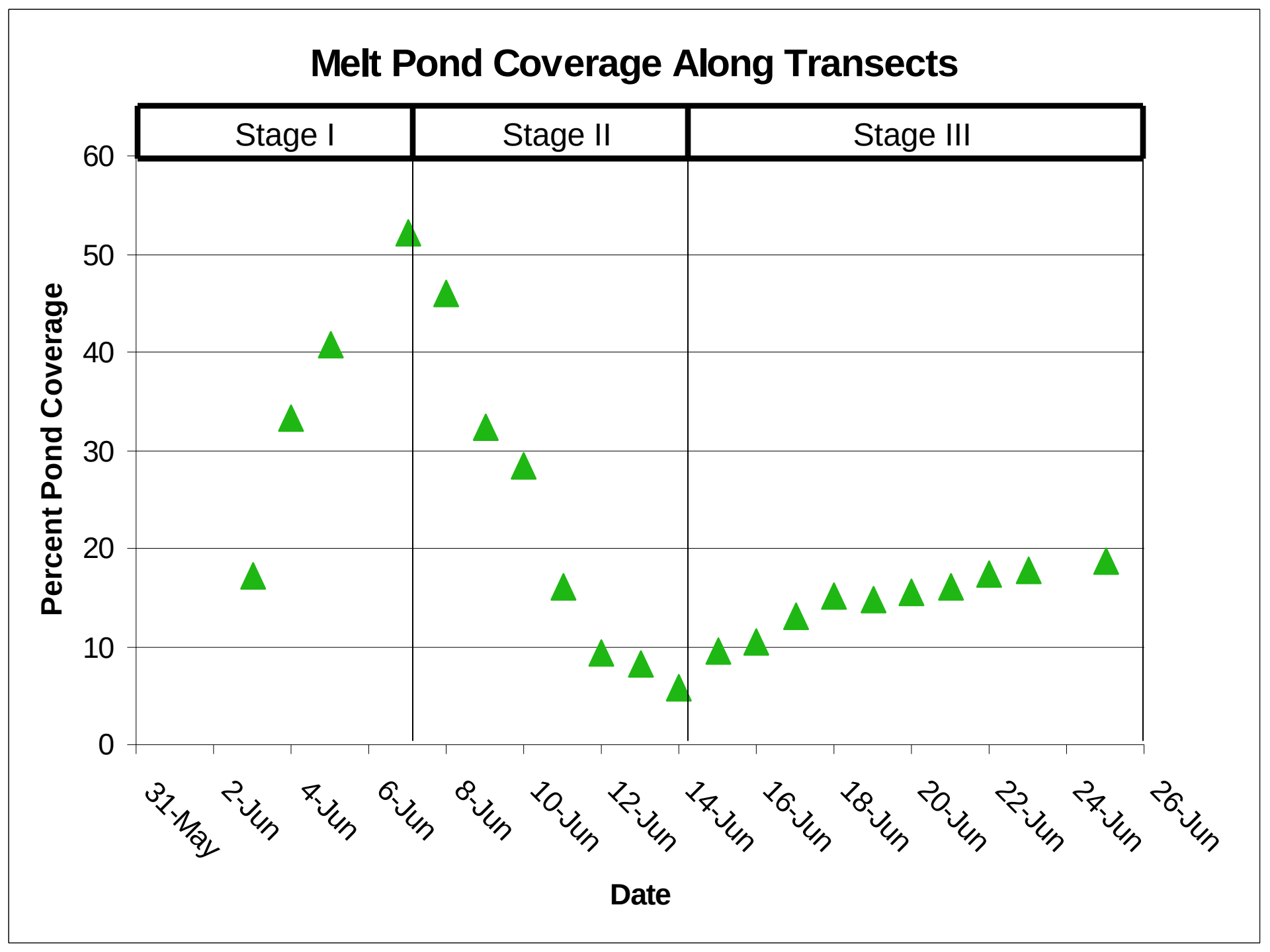

Critical Channel Size vs Date
Critical Channel Size (cm)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
26-May
29-May
1-Jun
4-Jun
7-Jun
10-Jun
13-Jun
16-Jun
Date
Flaws Open
June 8th
Permeability
Transition
June 13th

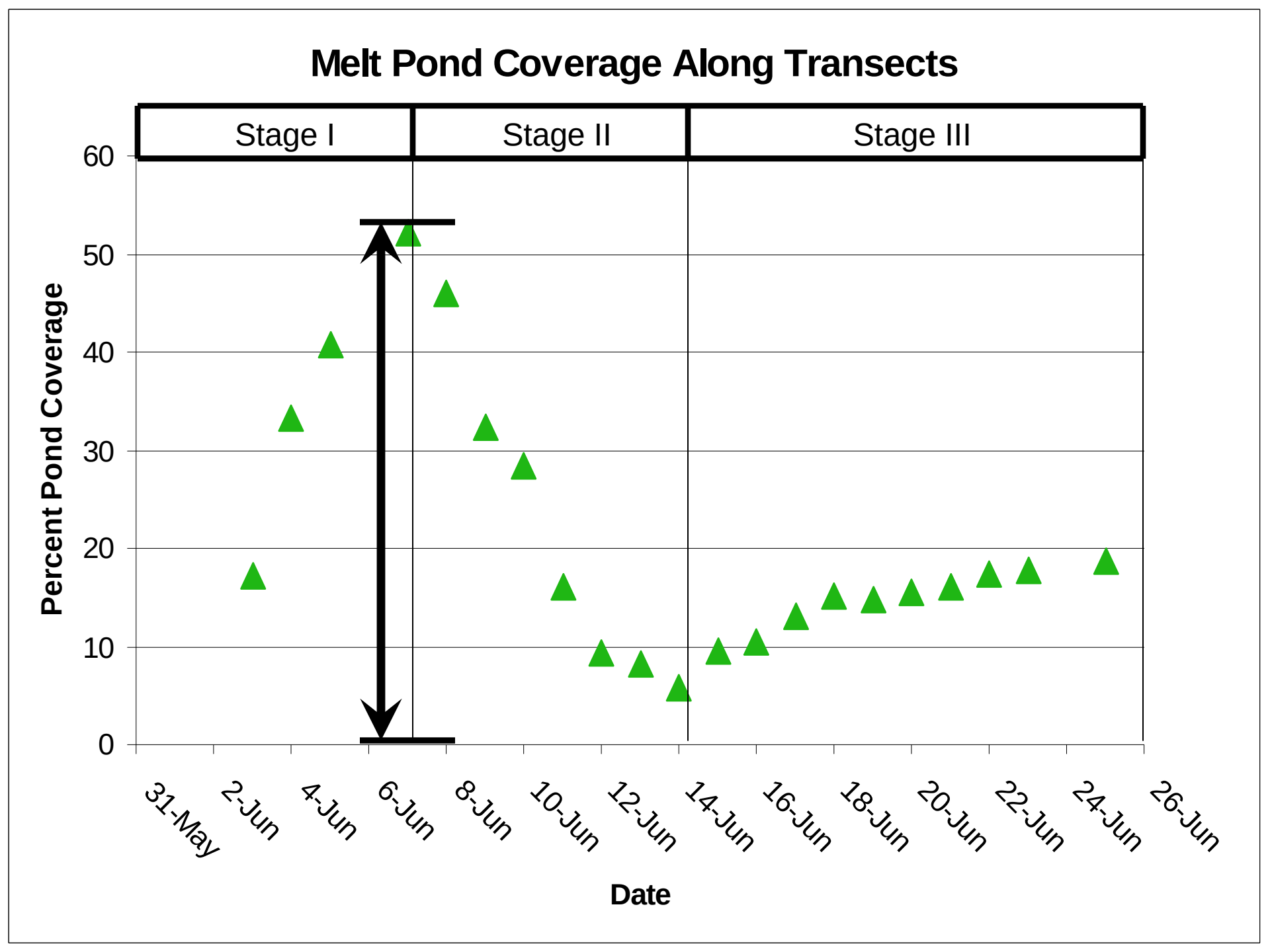
Barrow 2010 Isotope Data

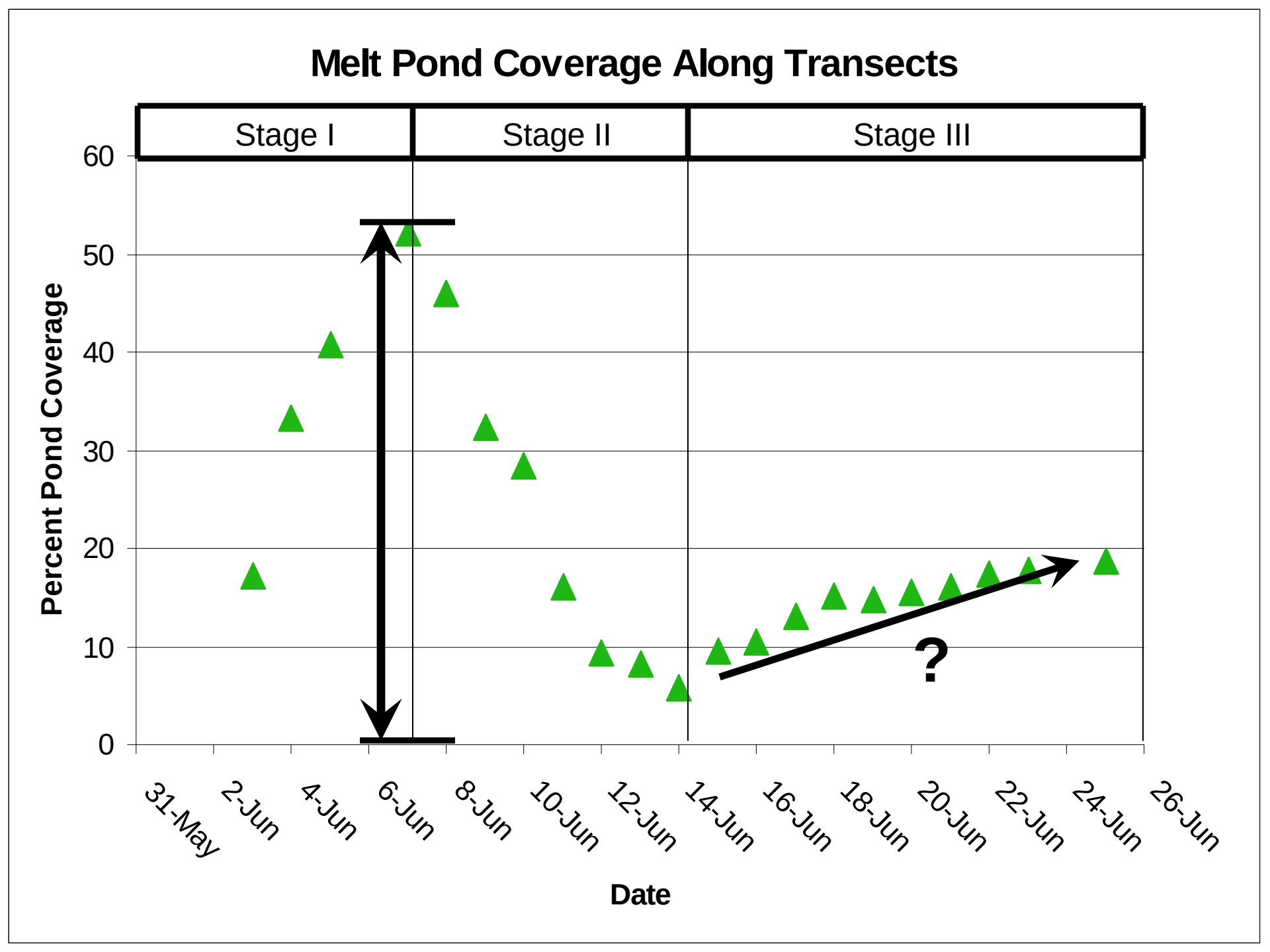


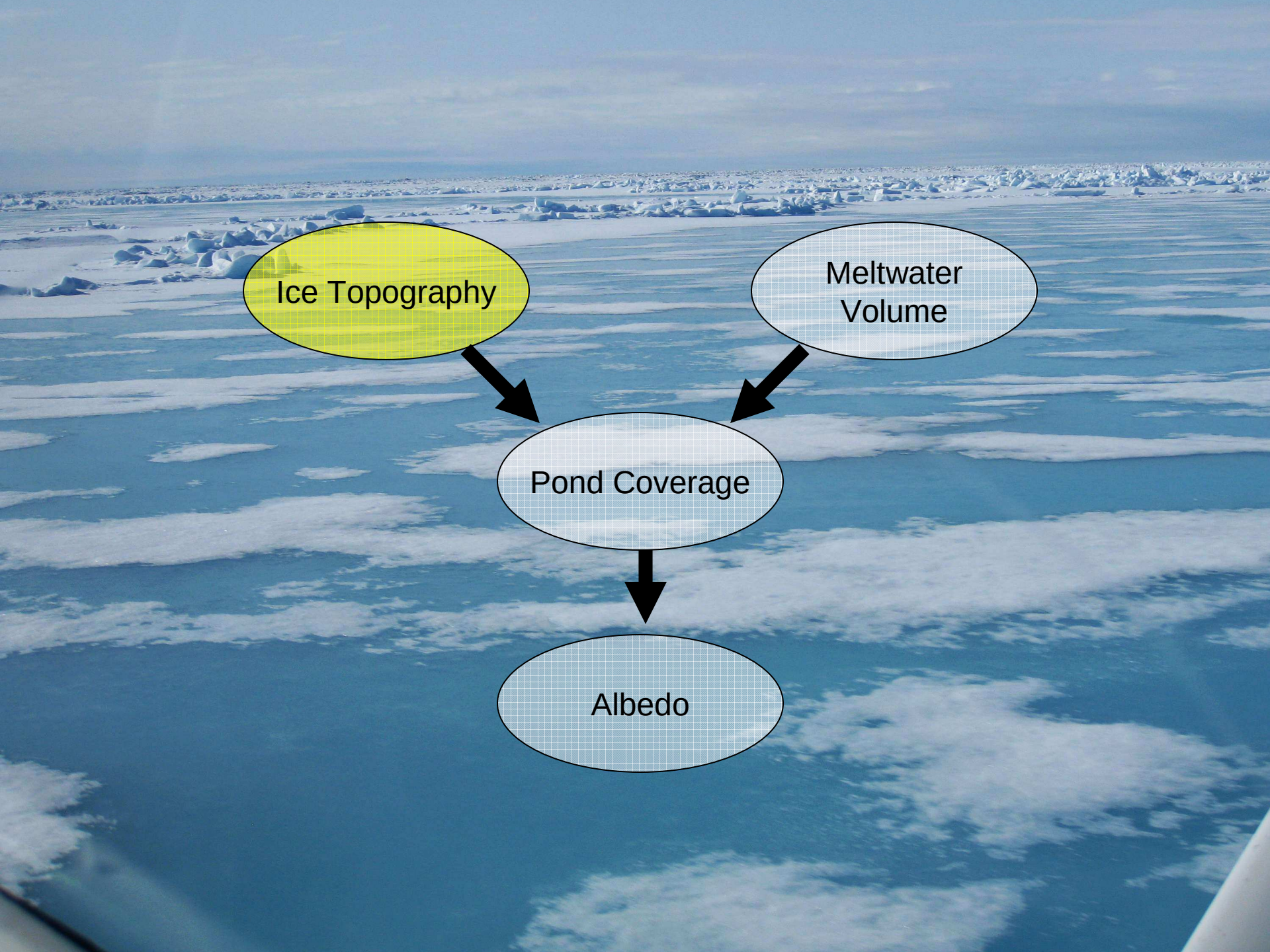


Ice Temperature Drives the formation of Outflow Pathways

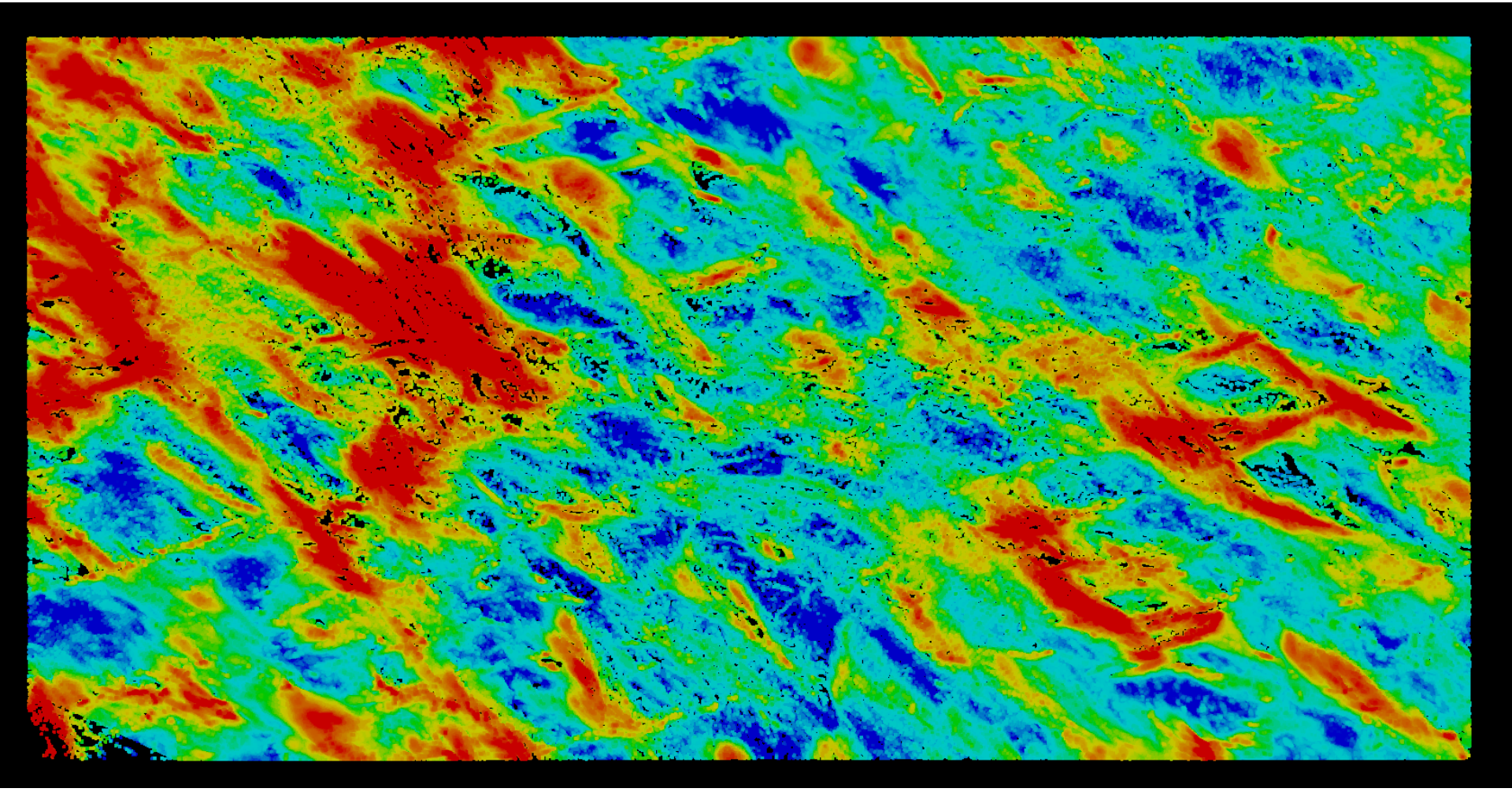

Melt Pond Coverage Along Transects
Stage I
Stage II
Stage III
Percent Pond Coverage
60
50
40
30
20
10
0
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date


Melt Pond Coverage Along Transects
Stage I
Stage II
Stage III
Percent Pond Coverage
60
50
40
30
20
10
0
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date

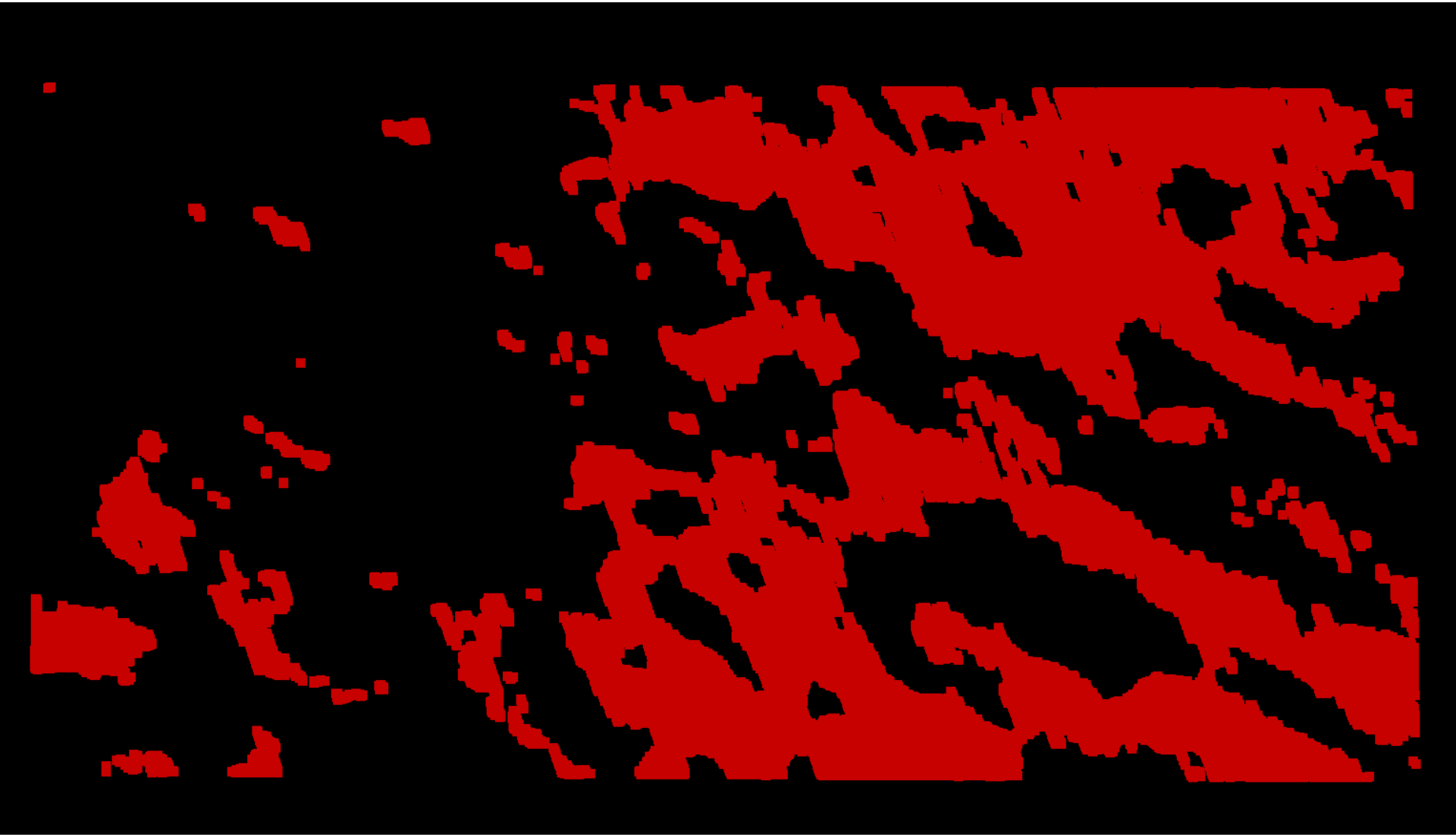

Melt Pond Coverage Along Transects
Stage I
Stage II
Stage III
Percent Pond Coverage
60
50
40
30
20
10
0
?
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date


Ice Topography
Meltwater Volume
Pond Coverage
Albedo

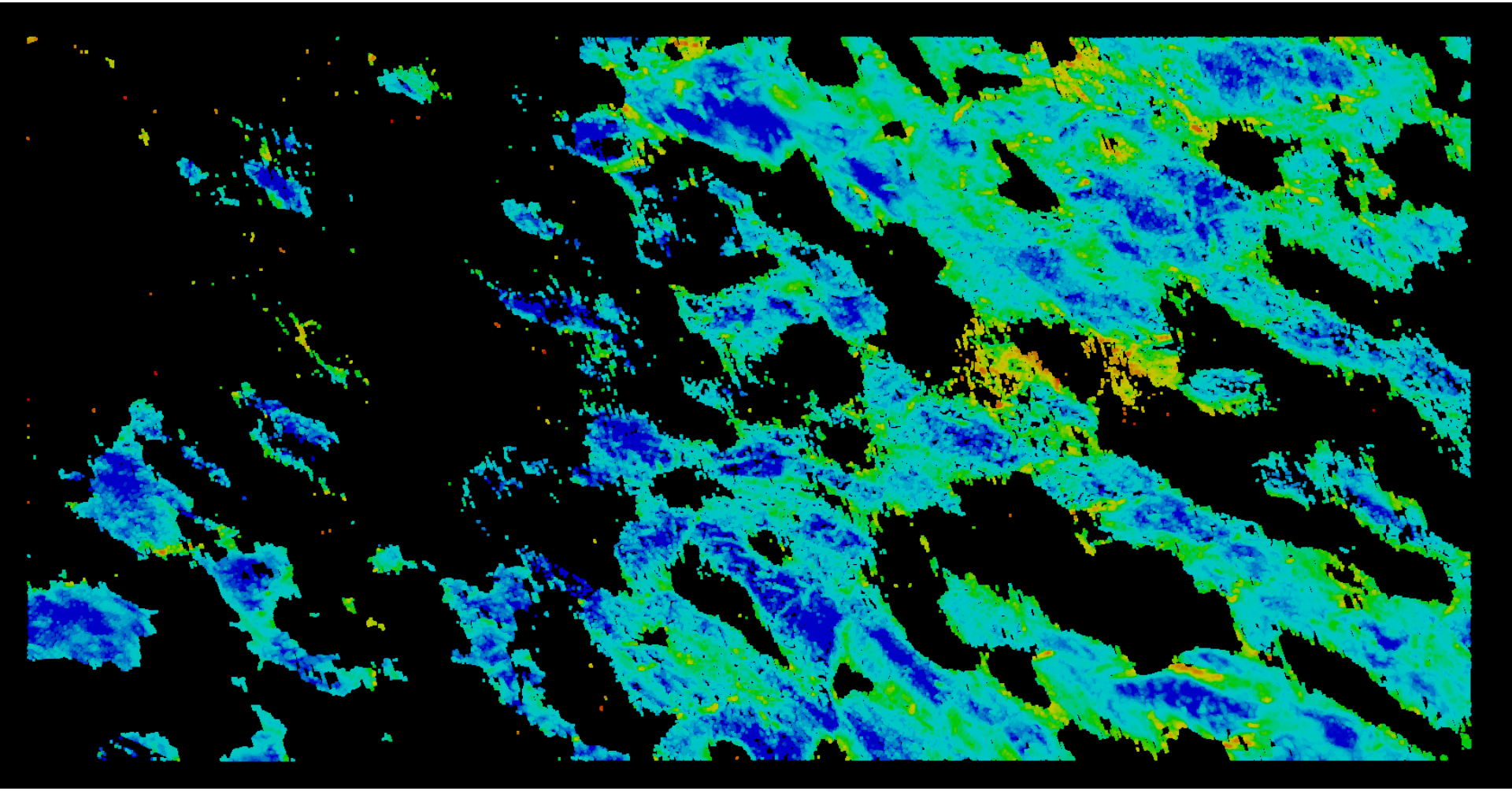
Pre-Melt Surface Topography

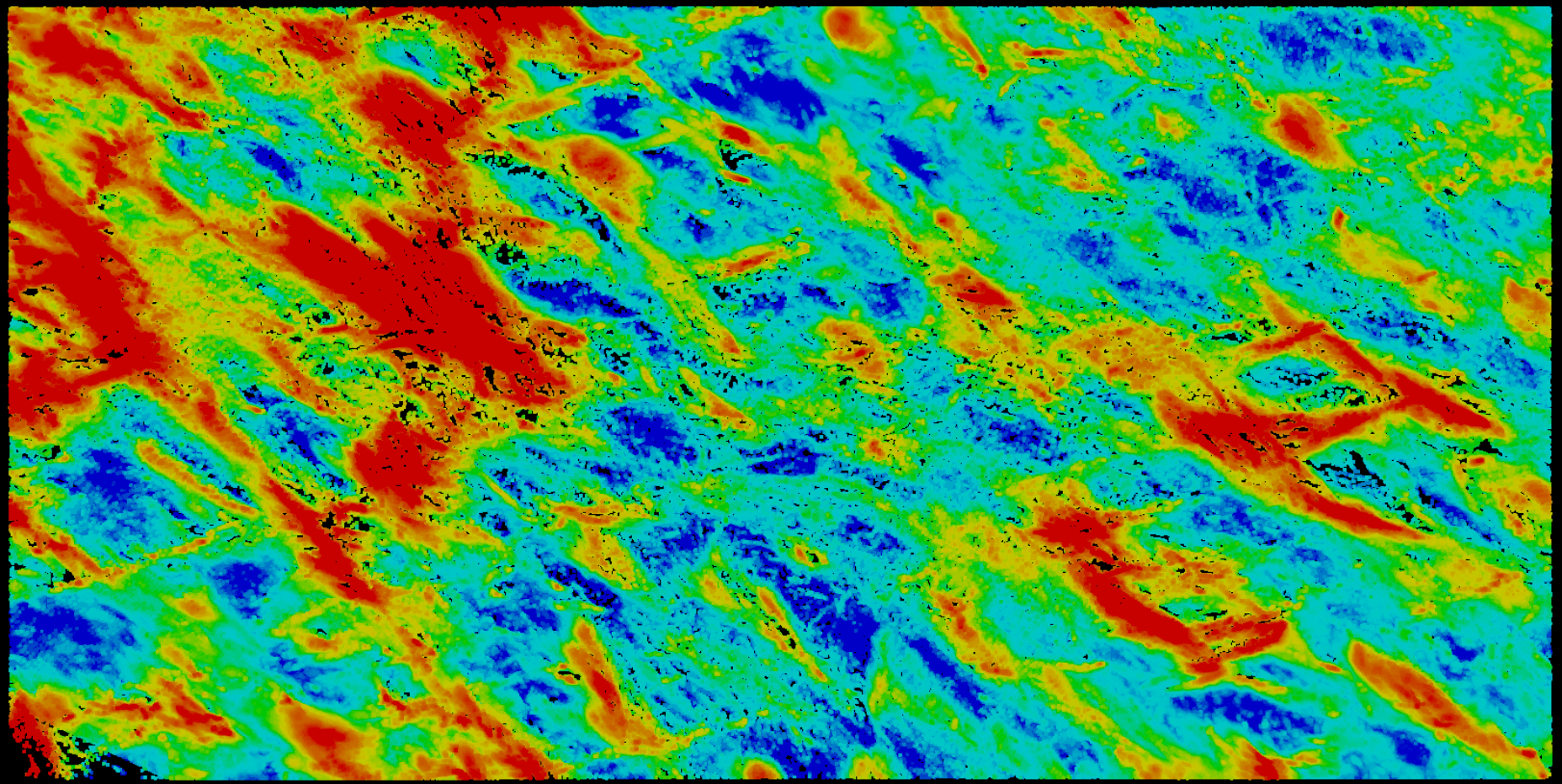


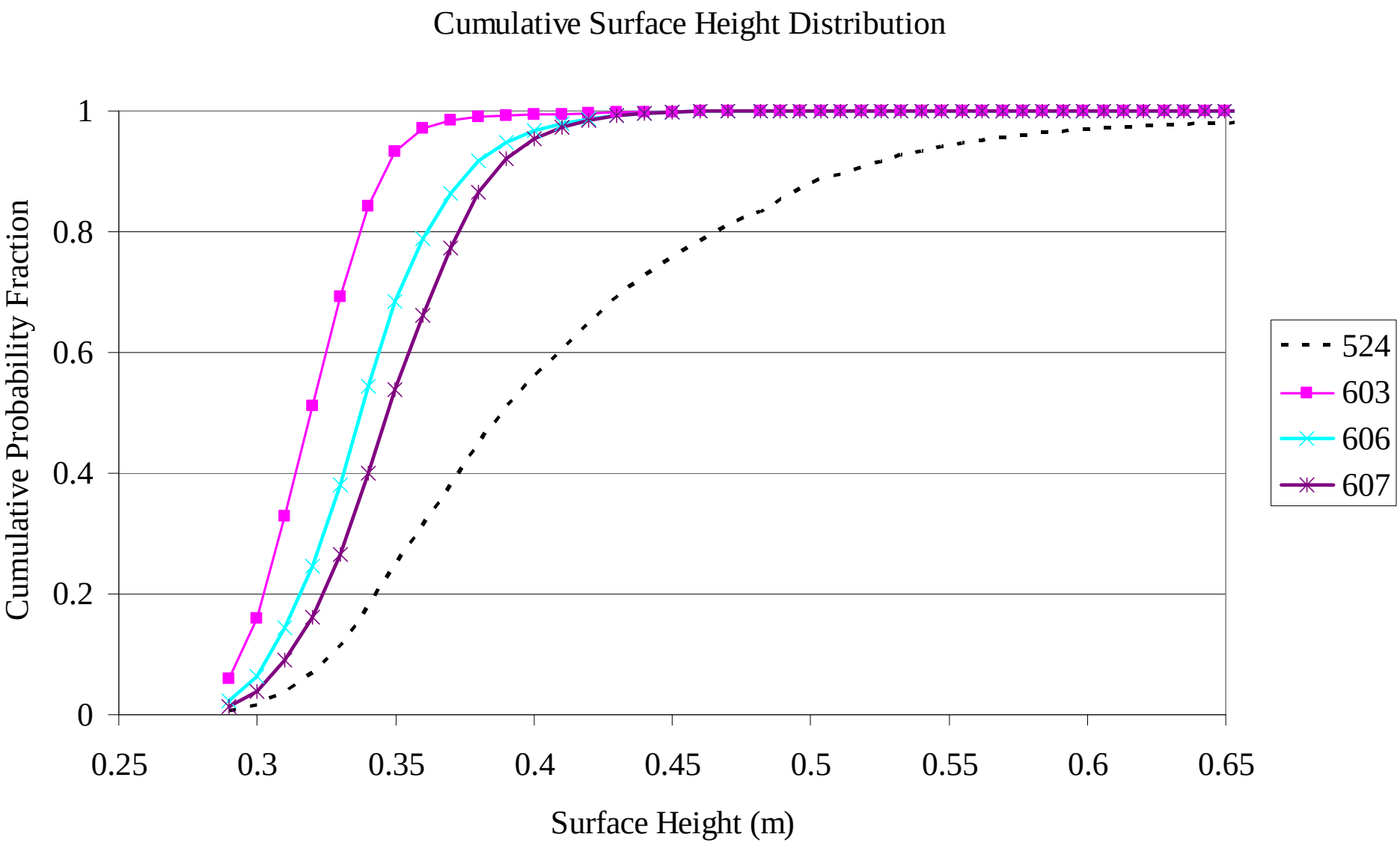
Areas Pond Covered on June 7th

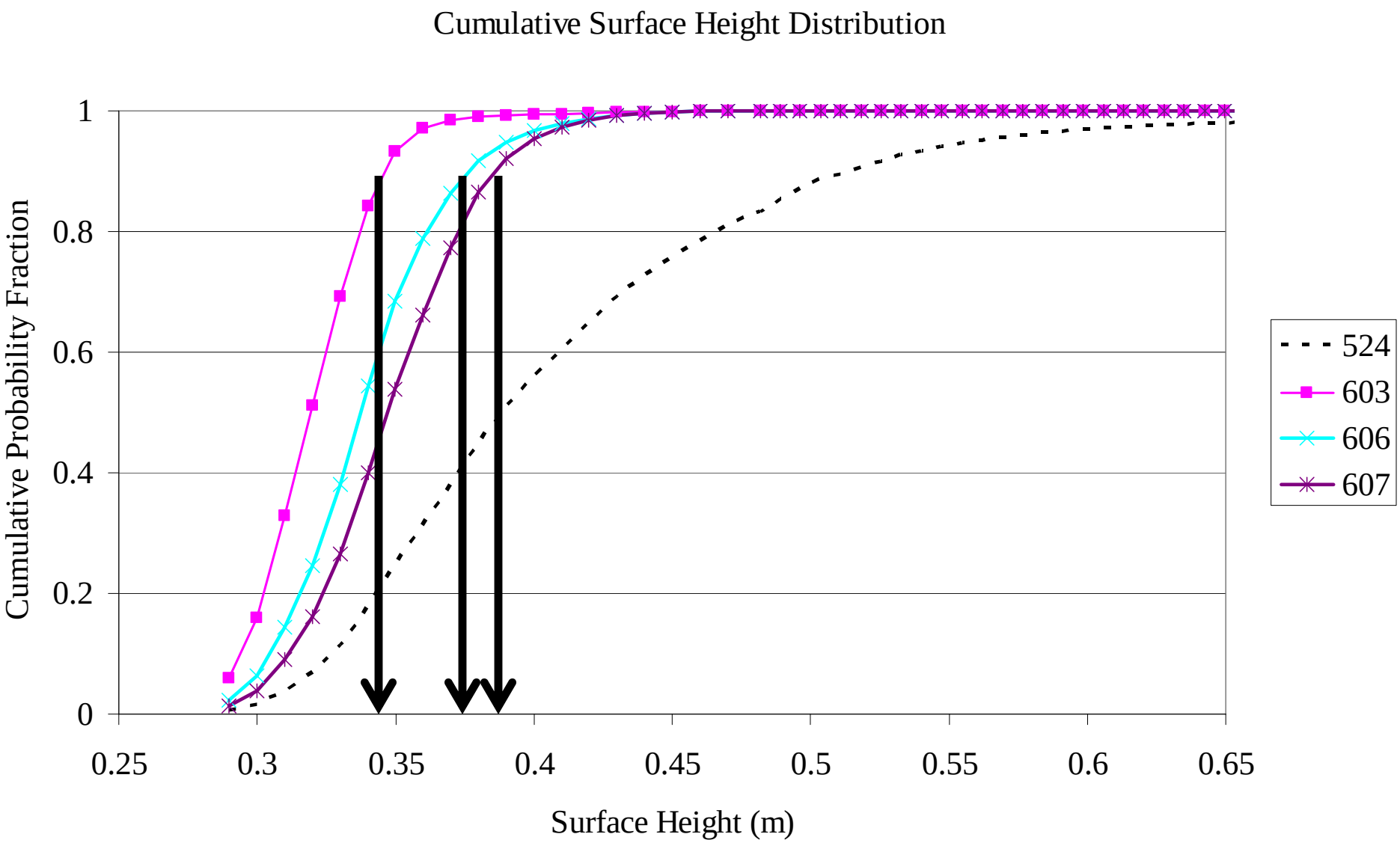


Topography Where Ponds Will Form

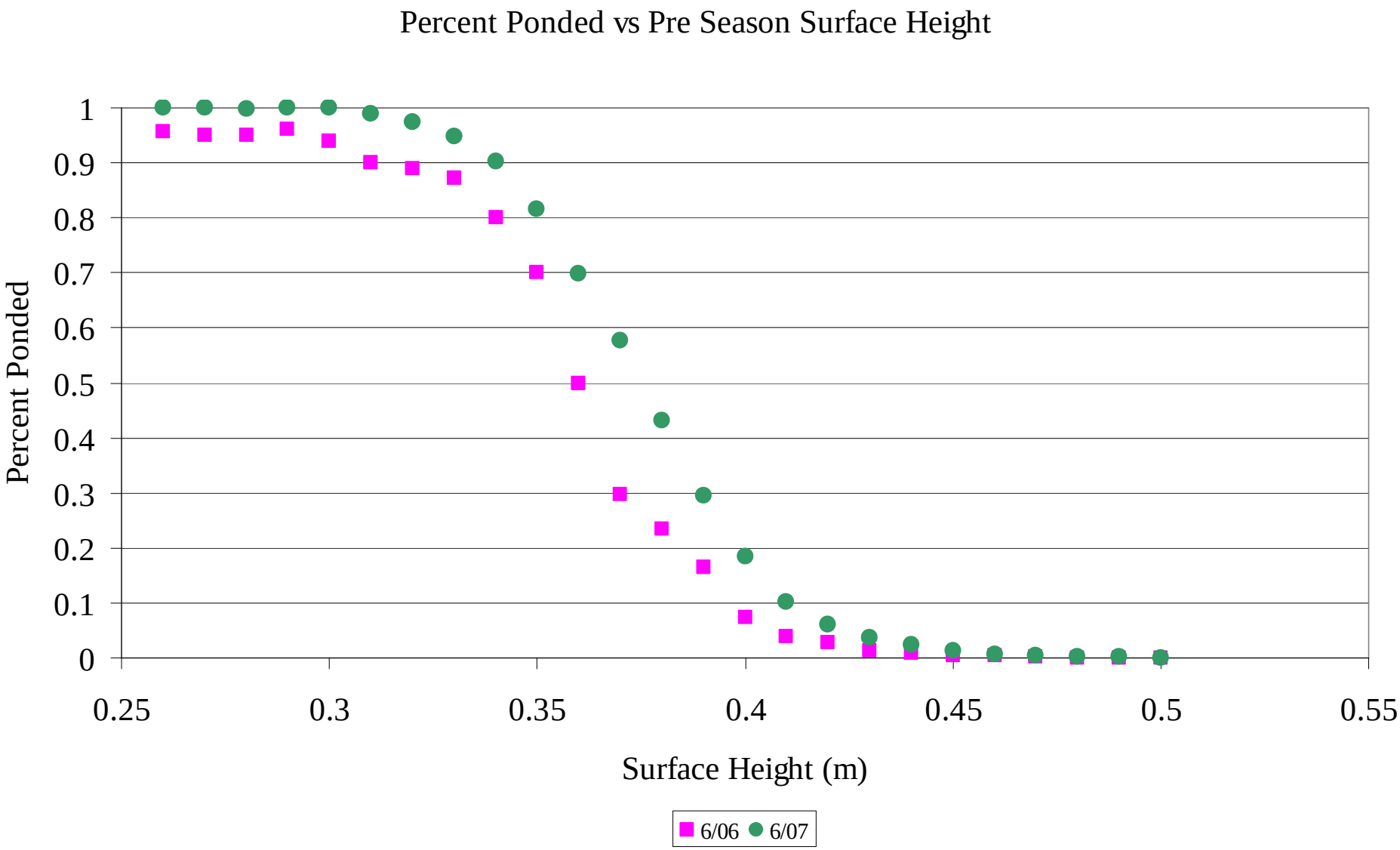


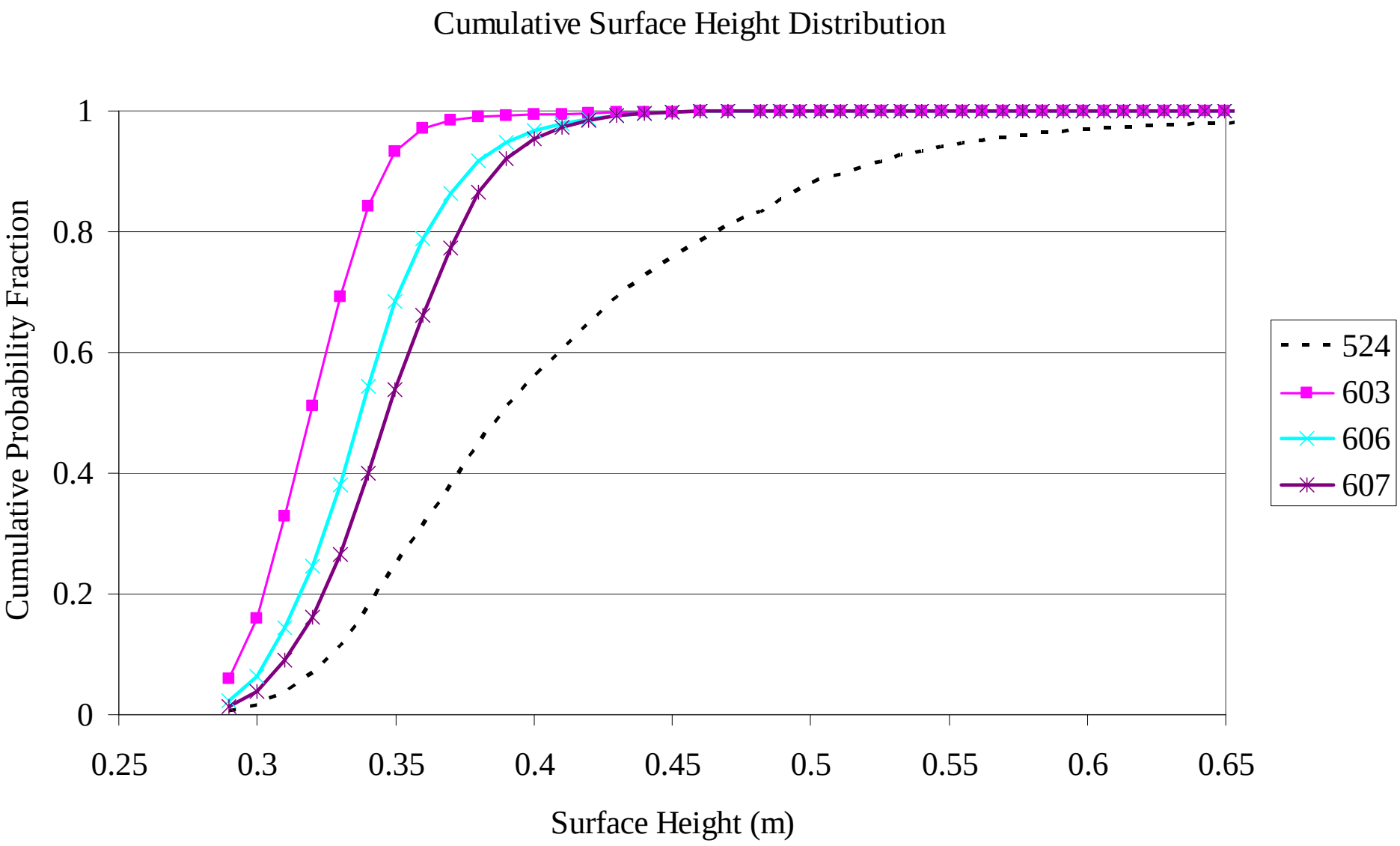


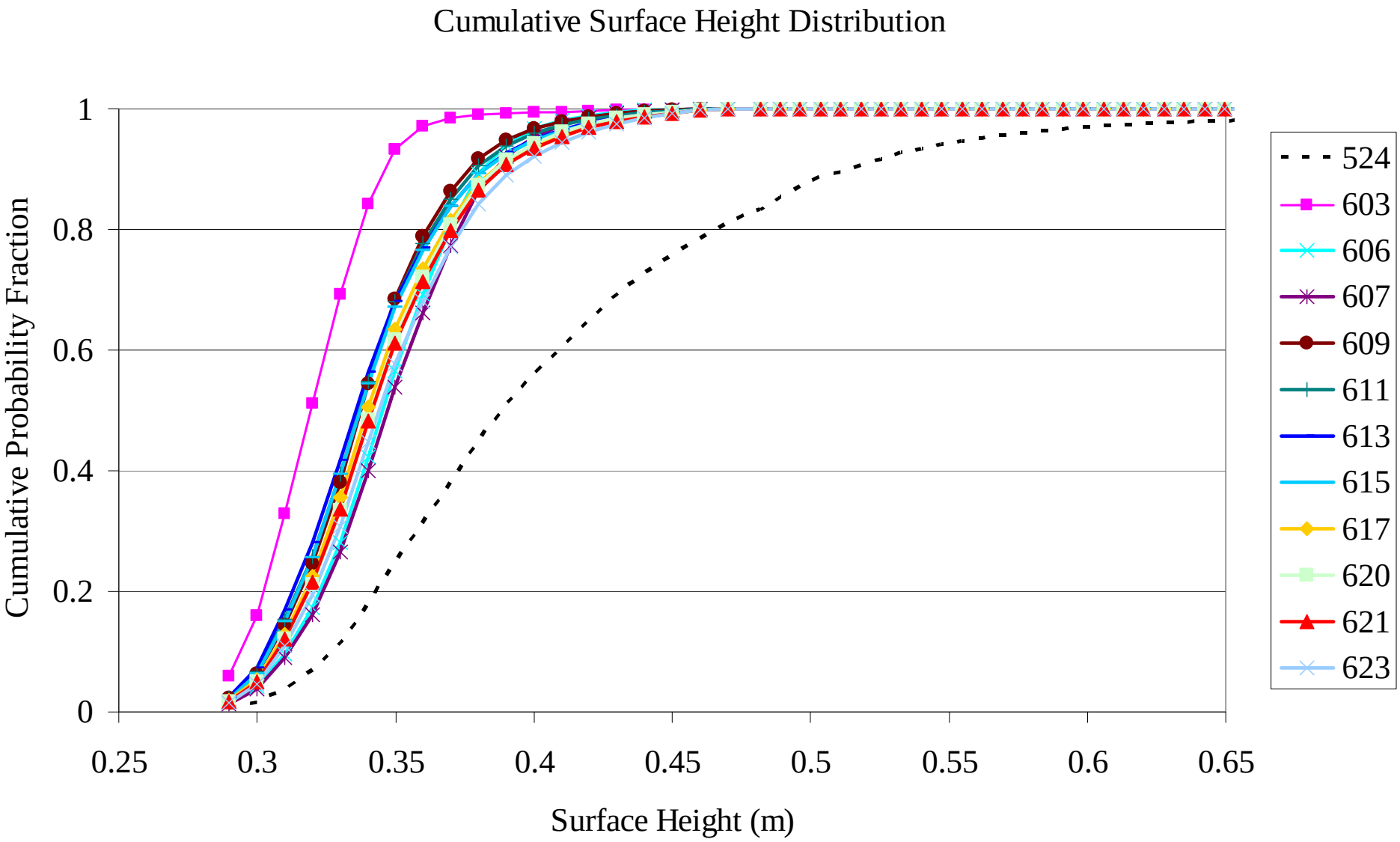

Cumulative Surface Height Distribution
Cumulative Probability Fraction
1
0.8
0.6
0.4
0.2
0
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
Surface Height (m)
524
603
606
607



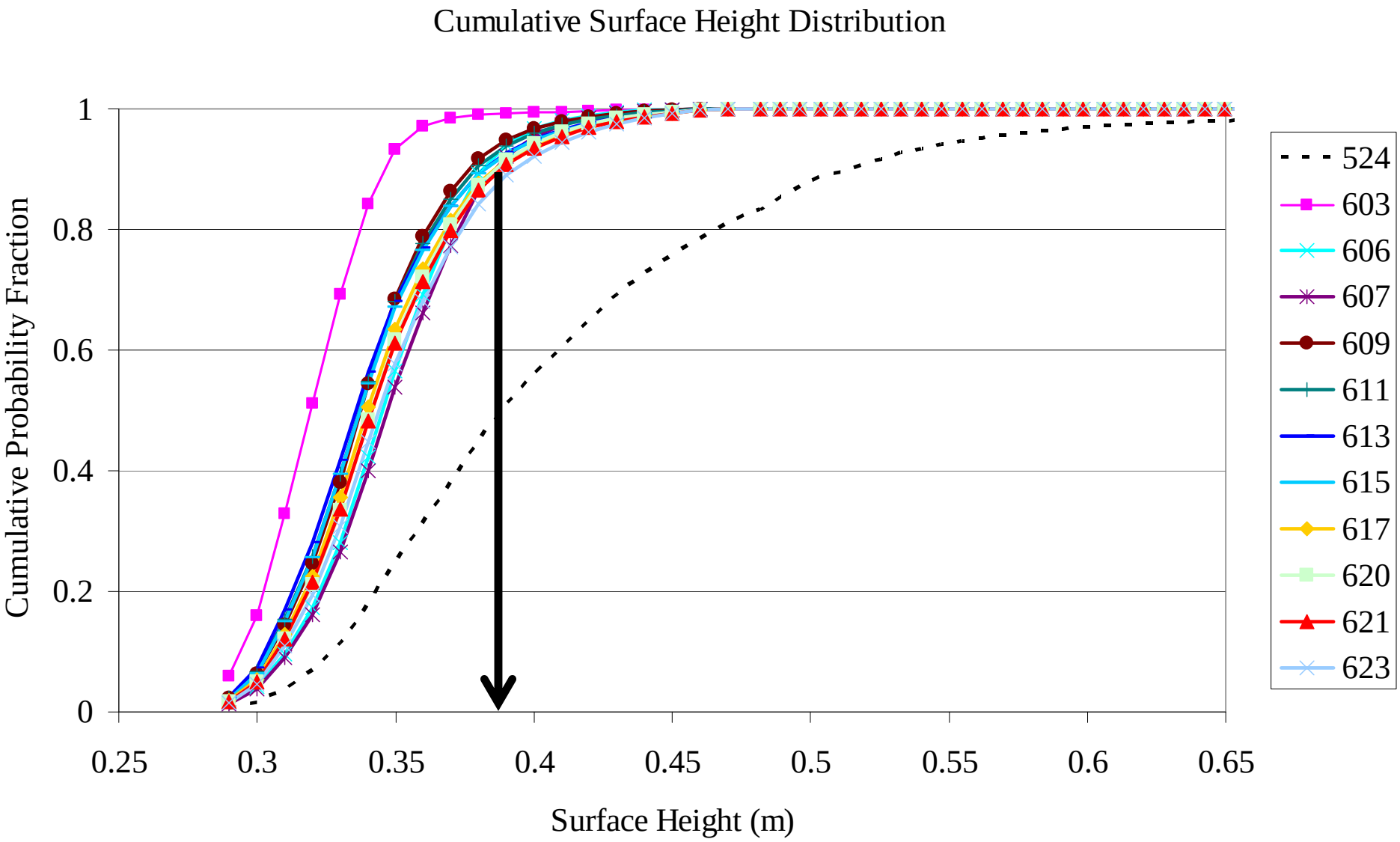
Stage I Pond Growth is Essentially Surface Flooding


Percent Ponded vs Pre Season Surface Height
Percent Ponded
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.25
0.3
0.35
0.4
0.45
0.5
0.55
Surface Height (m)
6/06
6/07

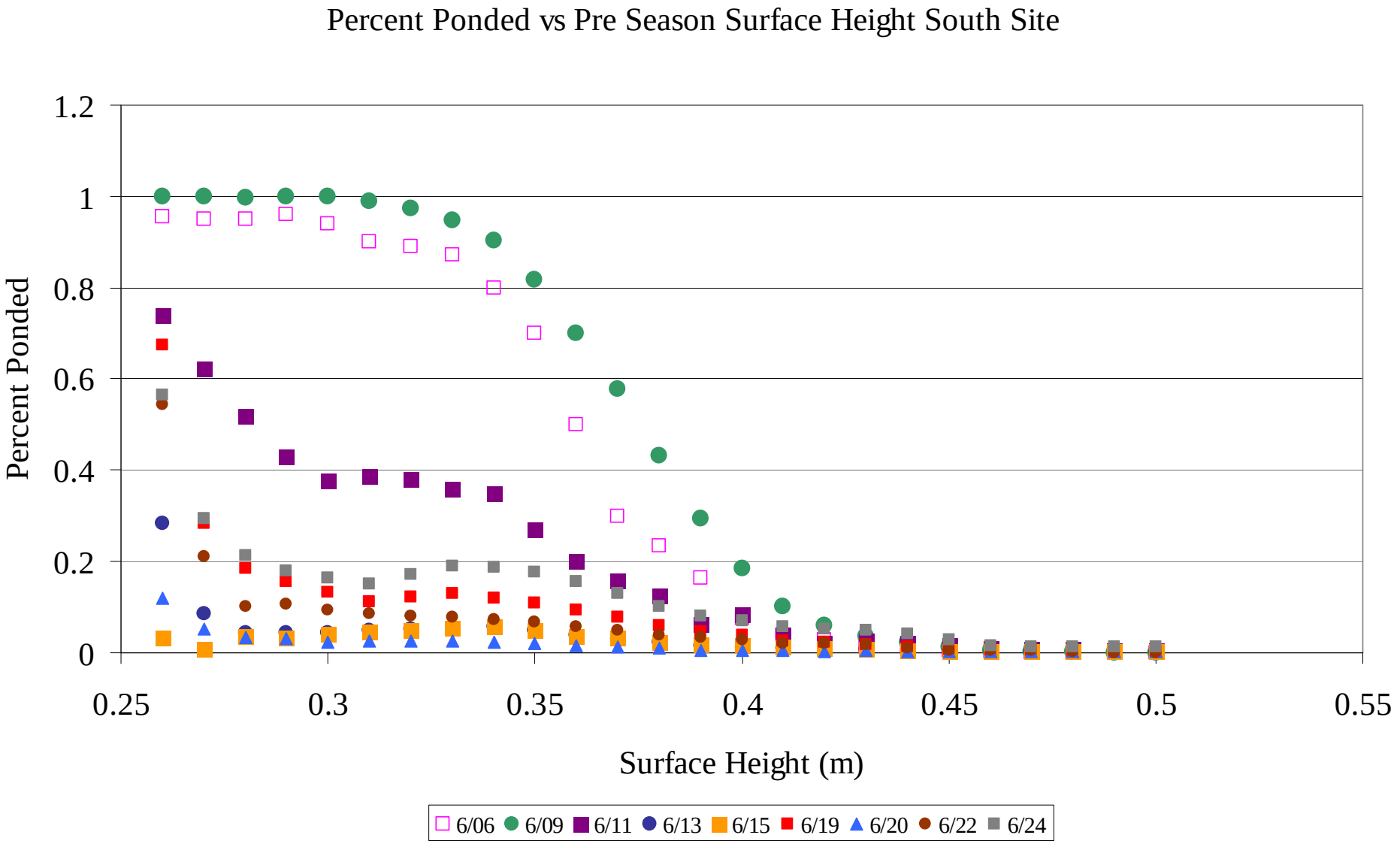

Cumulative Surface Height Distribution
Cumulative Probability Fraction
1
0.8
0.6
0.4
0.2
0
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
Surface Height (m)
524
603
606
607



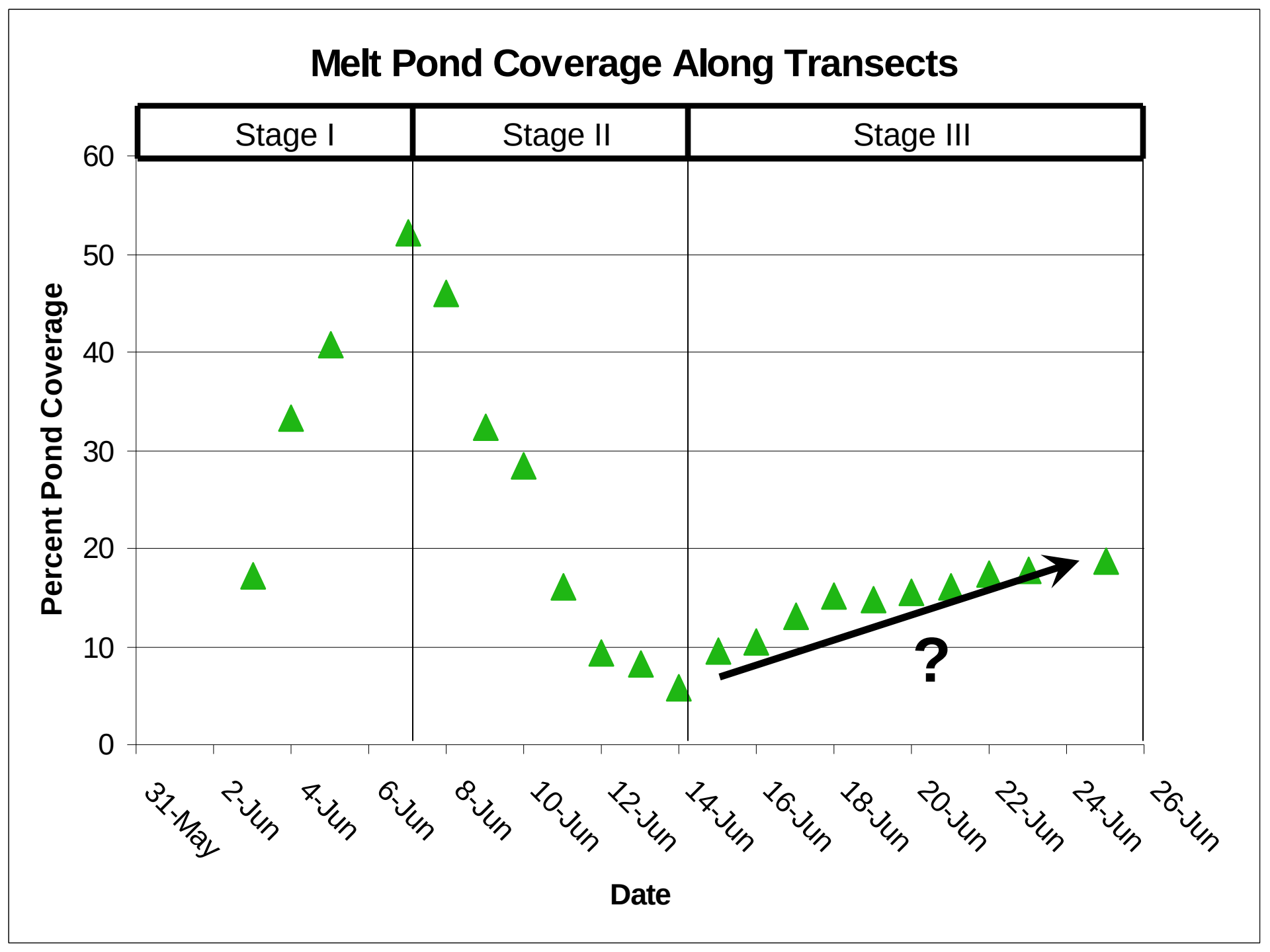
Stage II and III Ponds only form where ponds formed in stage one



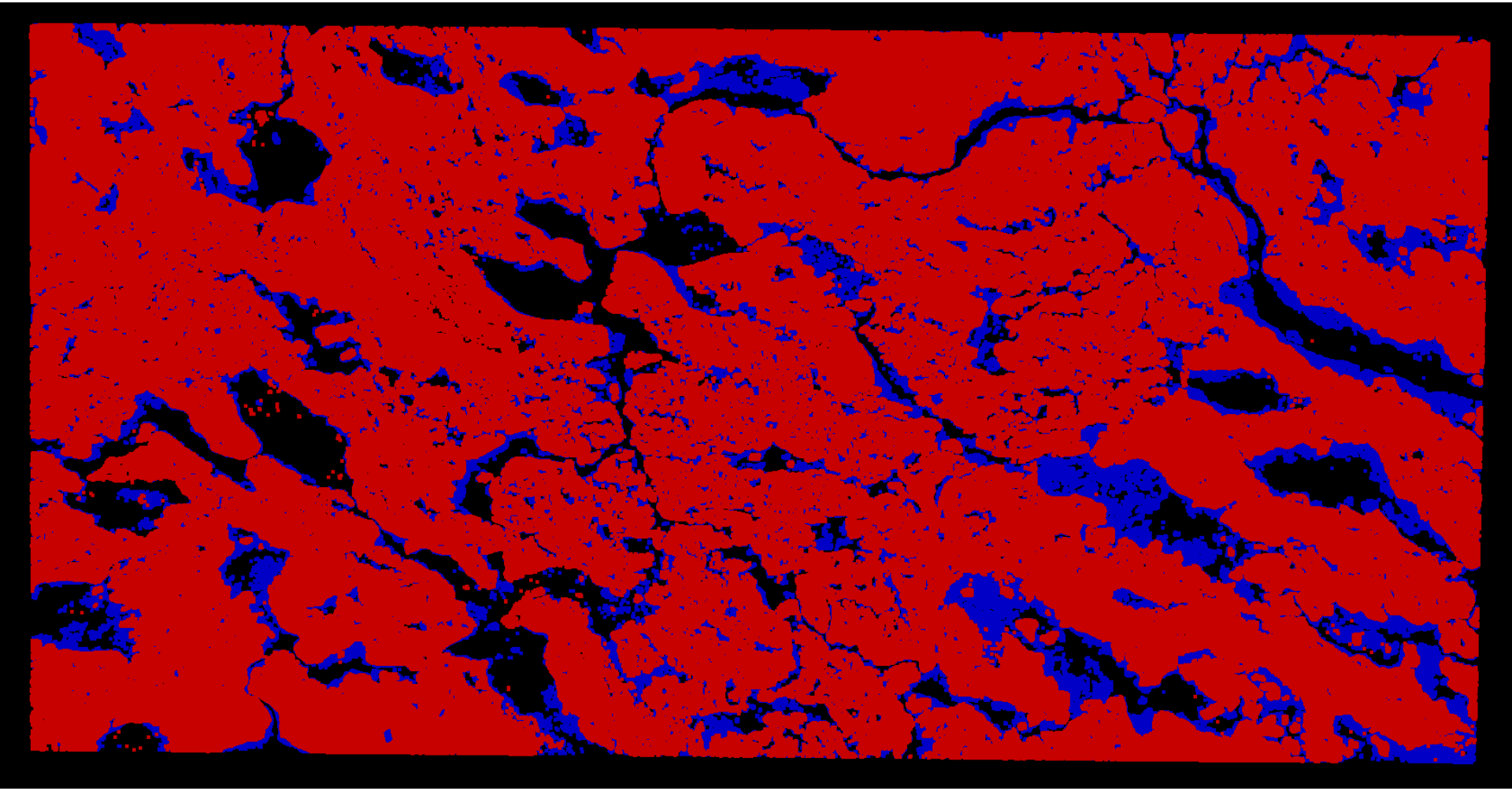
Stage II and III Ponds only form where ponds formed in stage one



On level ice, snow dunes control surface height distribution and pond formation.

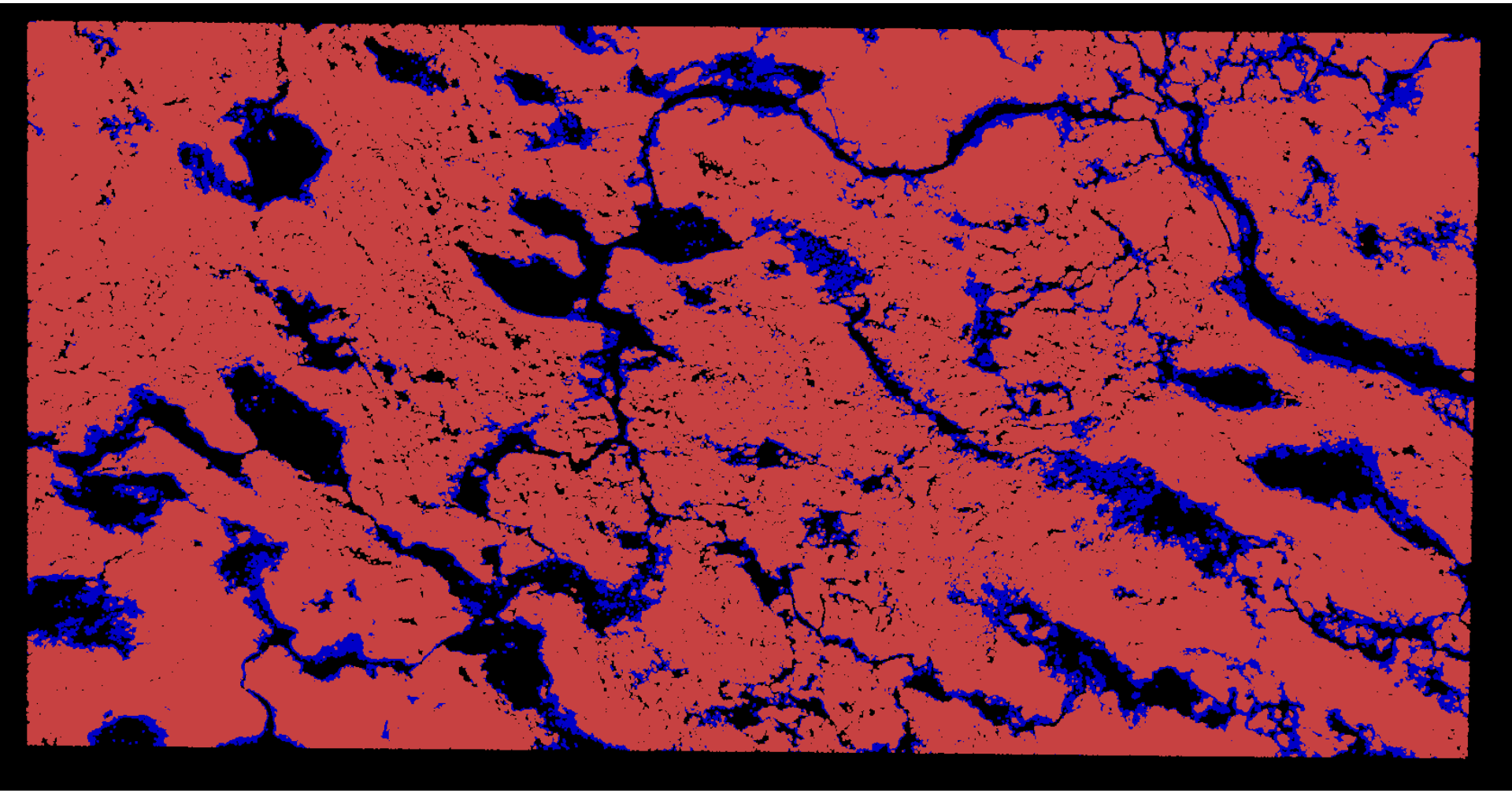

Melt Pond Coverage Along Transects
Stage I
Stage II
Stage III
Percent Pond Coverage
60
50
40
30
20
10
0
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date
?

What Causes Late Season Pond Growth?



Areas which become ponded during Stage III

What Causes Late Season Pond Growth?



Areas which are within 5 cm of freeboard at the start of stage III

Pond Parameterization
CCSM CICE 4.0

$$v_p^{'} = v_p(t) + 0.1(dh_i \frac{\rho_i}{\rho_w} + dh_s \frac{\rho_s}{\rho_w} + F_{rain} \frac{\Delta t}{\rho_w})$$

New pond volume = old pond volume + 10% of the new melt water

$$h_p = 0.8 f_p$$

Pond fraction is related to pond depth by a factor of 0.8

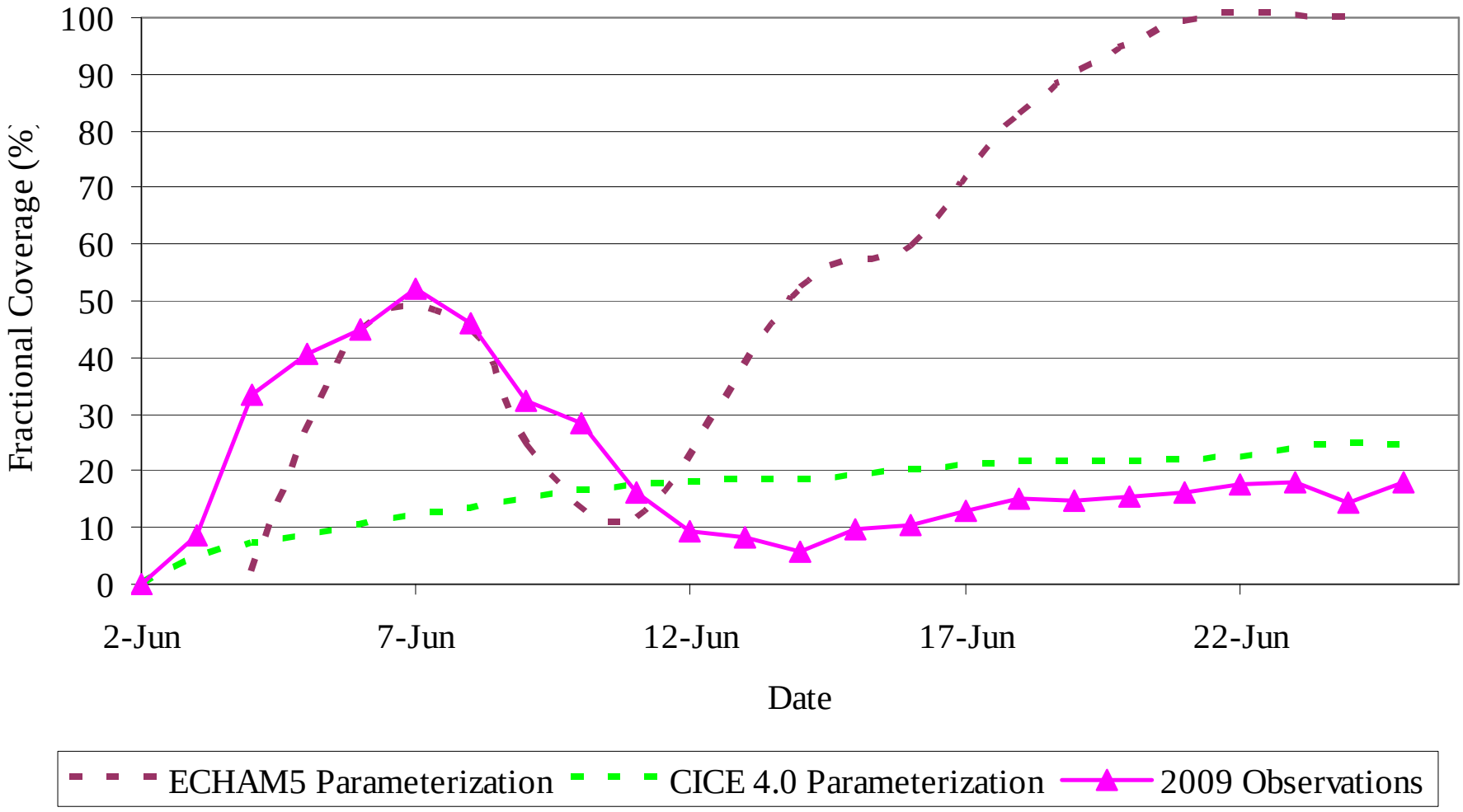
CICE 4.0 Documentation

Pond Parameterization
ECHAM 5

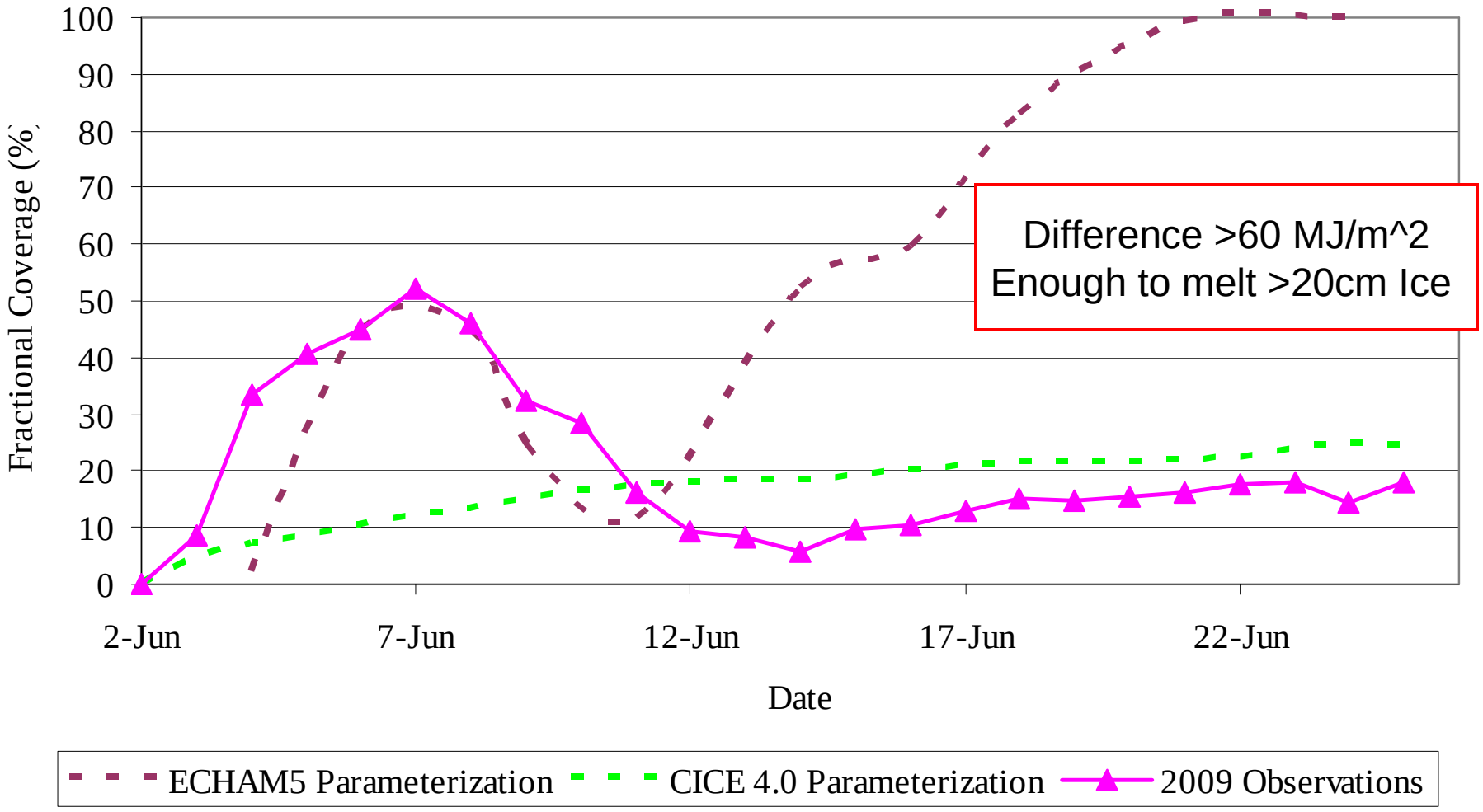
$$f_{mp} = 0.5 * \tanh(30 d_{mp} - 2.5) + 0.5$$

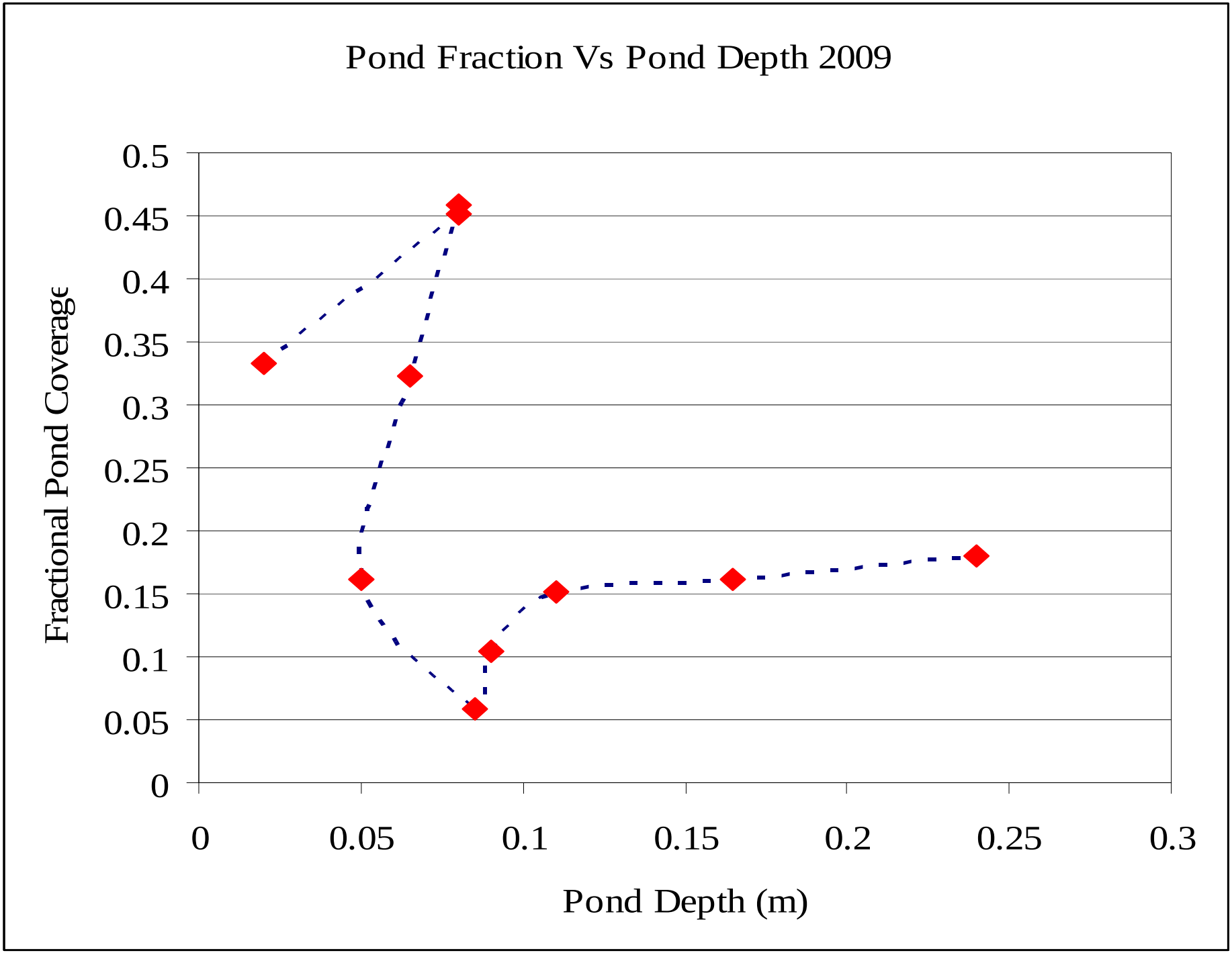
Pond fraction is related to pond depth by this function

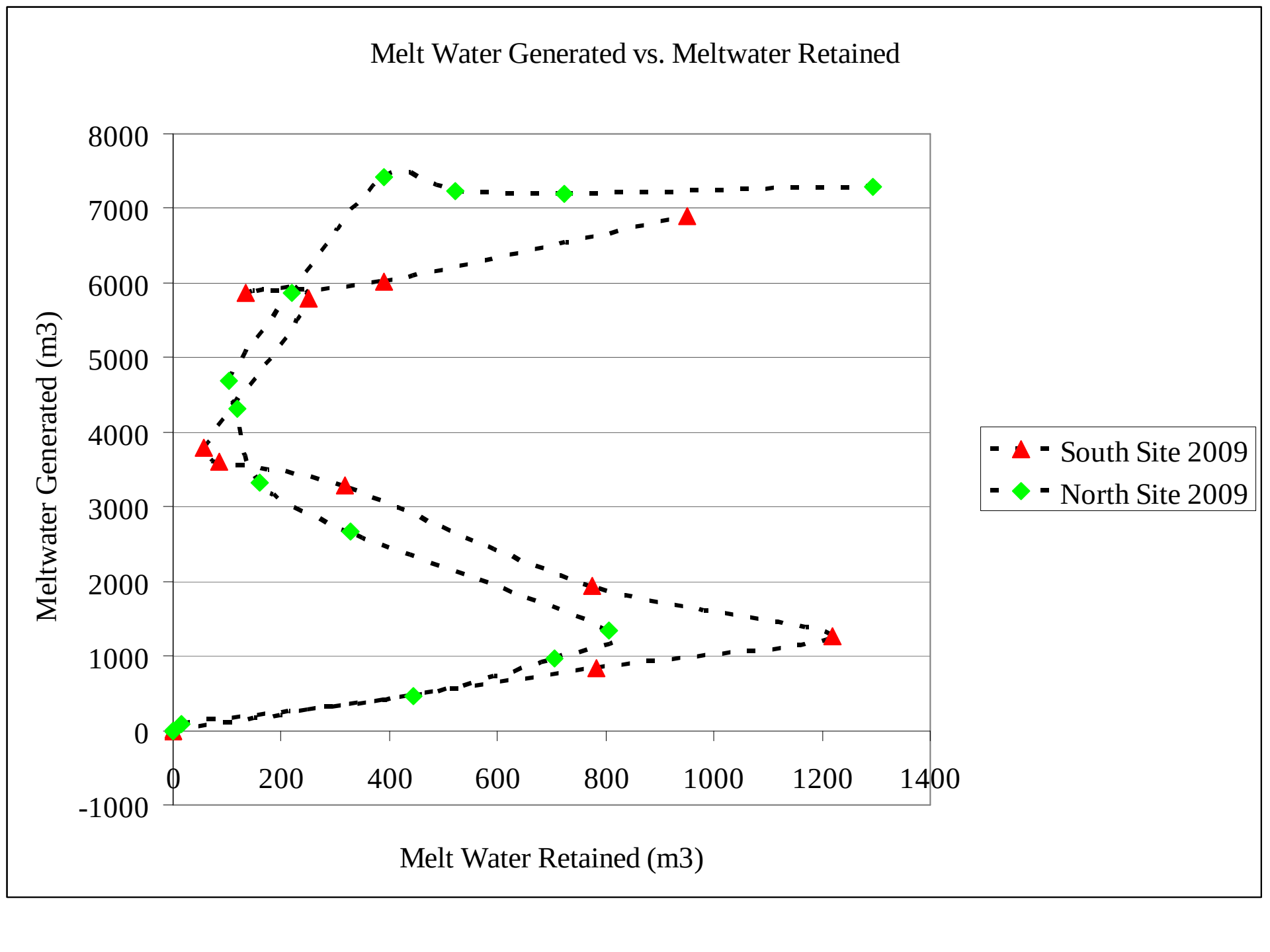
Pond Coverage from Observations and GCM Parameterizations



Pond Coverage from Observations and GCM Parameterizations




Pond Fraction Vs Pond Depth 2009
Fractional Pond Coverage
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.05
0.1
0.15
0.2
0.25
0.3
Pond Depth (m)


Melt Water Generated vs. Meltwater Retained
Meltwater Generated (m3)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
0
200
400
600
800
1000
1200
1400
Melt Water Retained (m3)
South Site 2009
North Site 2009

Conclusions:

- Melt ponds are quite important to sea ice
- Modern model validation does not ensure good future albedo predictions
- Melt ponds can be incorporated explicitly with modest computational investment.

Melt Ponds Controlled by

- Meltwater Balance
  - Two mechanisms of drainage
  - Direct functions of ice temperature/salinity
- Ice/Snow Surface Topography
  - Strong function surface height distribution
  - Controlled by ice type
  - Snow distribution important
  - Insufficient observations

Good, Yet Simple Melt Pond Parameterizations Are Possible (There's lots of physics that would be fun to incorporate though!)

Thank You

Collaborators

Don Perovich, Kerry Claffey, Zoe Courville, Dave Finnegan, Matthew Druckenmiller, Hajo Eicken, Chris Petrich, Matthew Sturm, Karen Frey, Luke Trusel, and Christie Wood

Barrow Arctic Science Consortium
USCGS Healy Crew

National Science Foundation Grant No. ARC-0454900
NASA ICESCAPE Program