Mechanisms of Melt Pond Control on Arctic Sea Ice

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

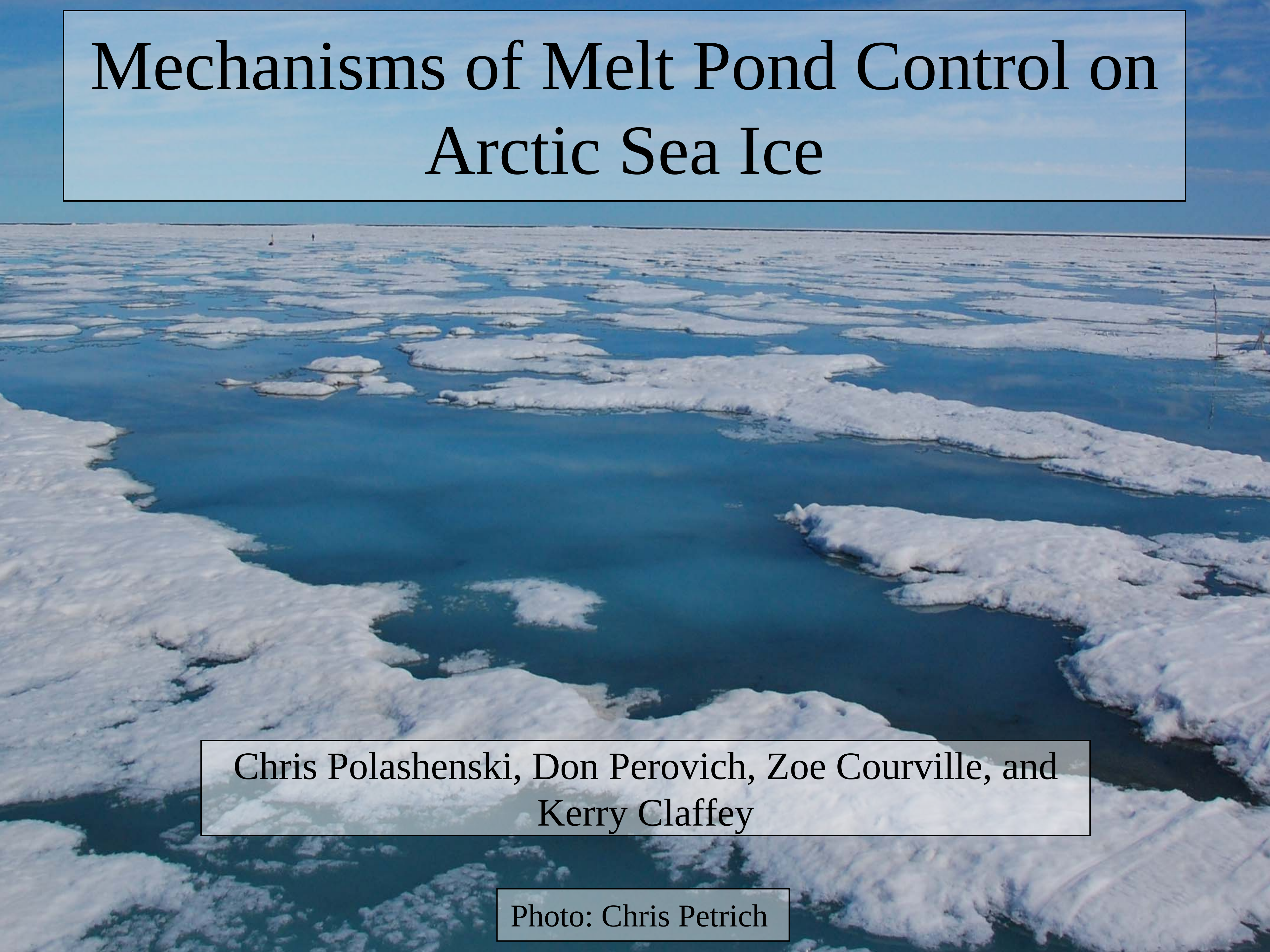
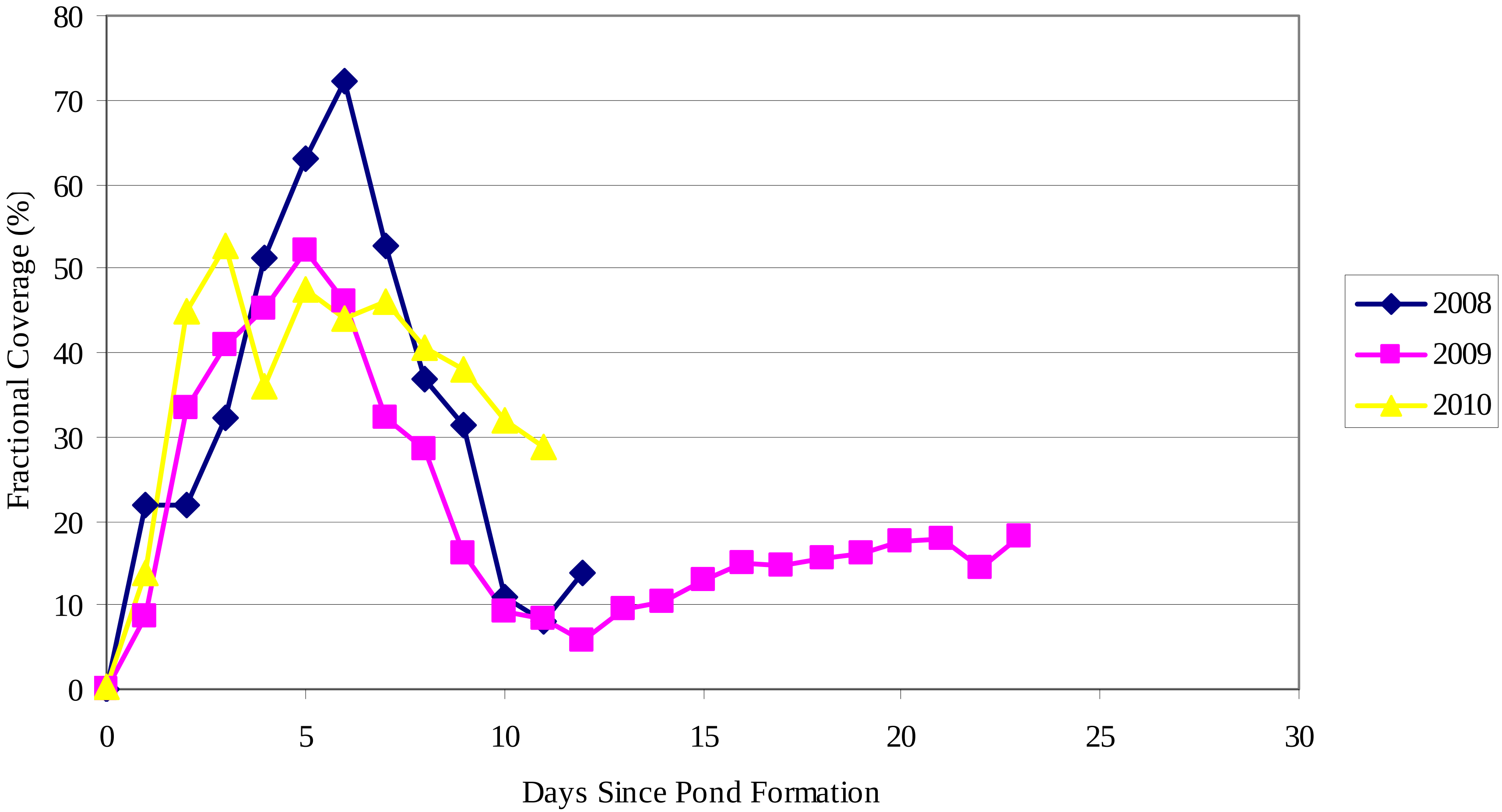


Photo: Chris Petrich

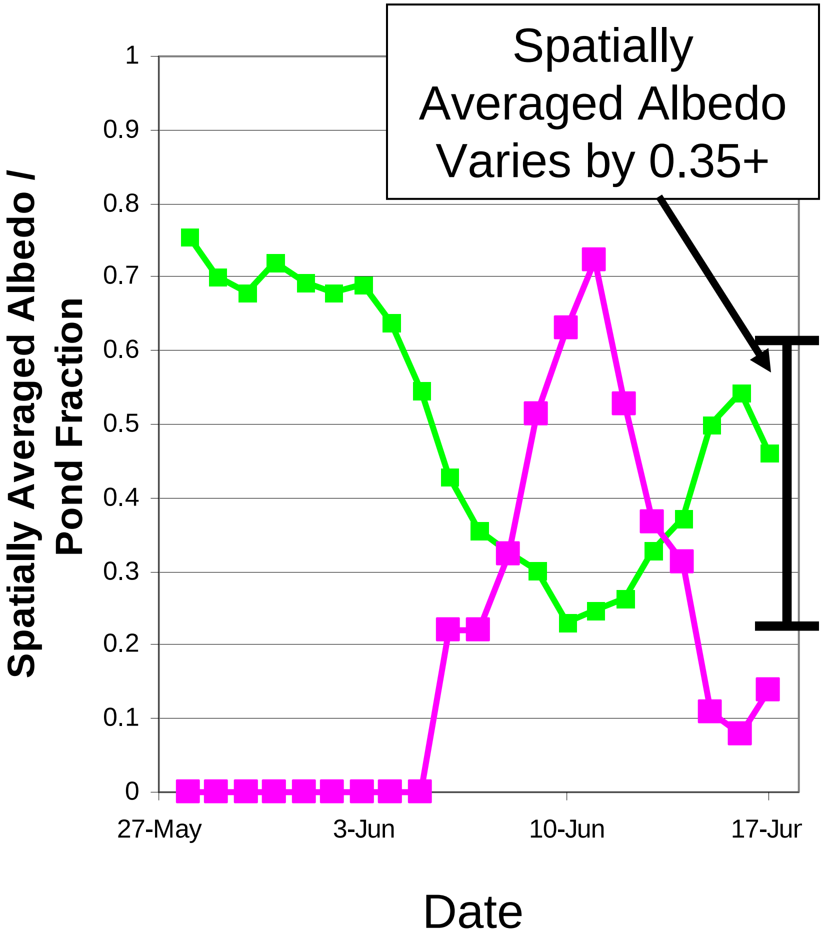

Albedo = ~0.15
Albedo = ~0.60
Photo: Chris Petrich

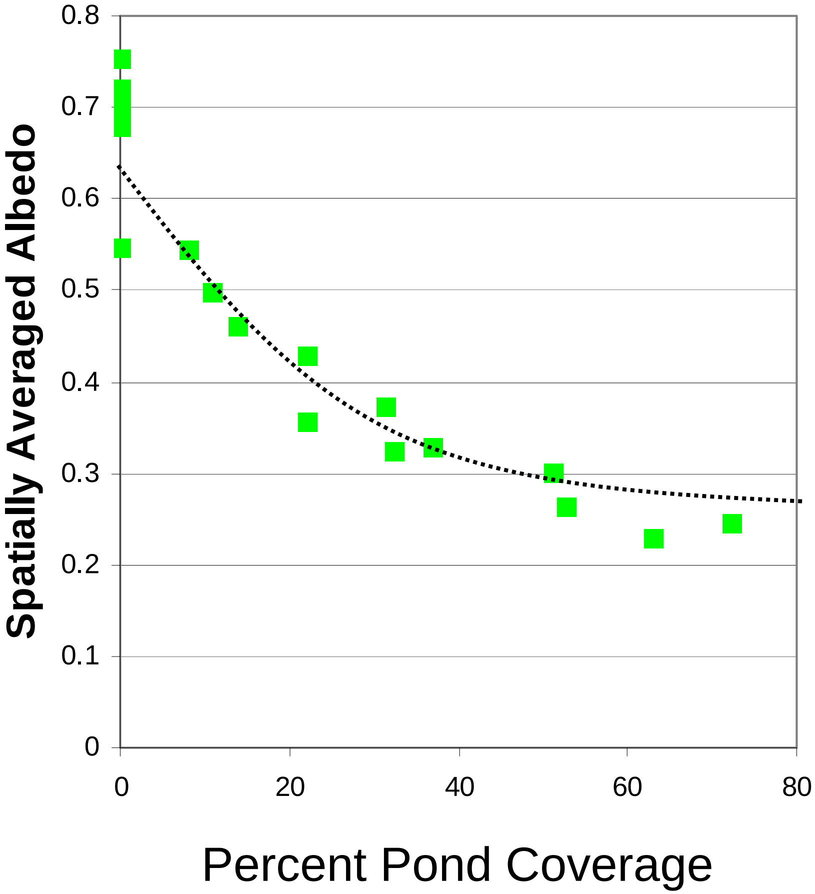
Seasonal Evolution of Melt Pond Spatial Coverage

Barrow AK 2008-2010



Pond coverage shows tremendous temporal variability



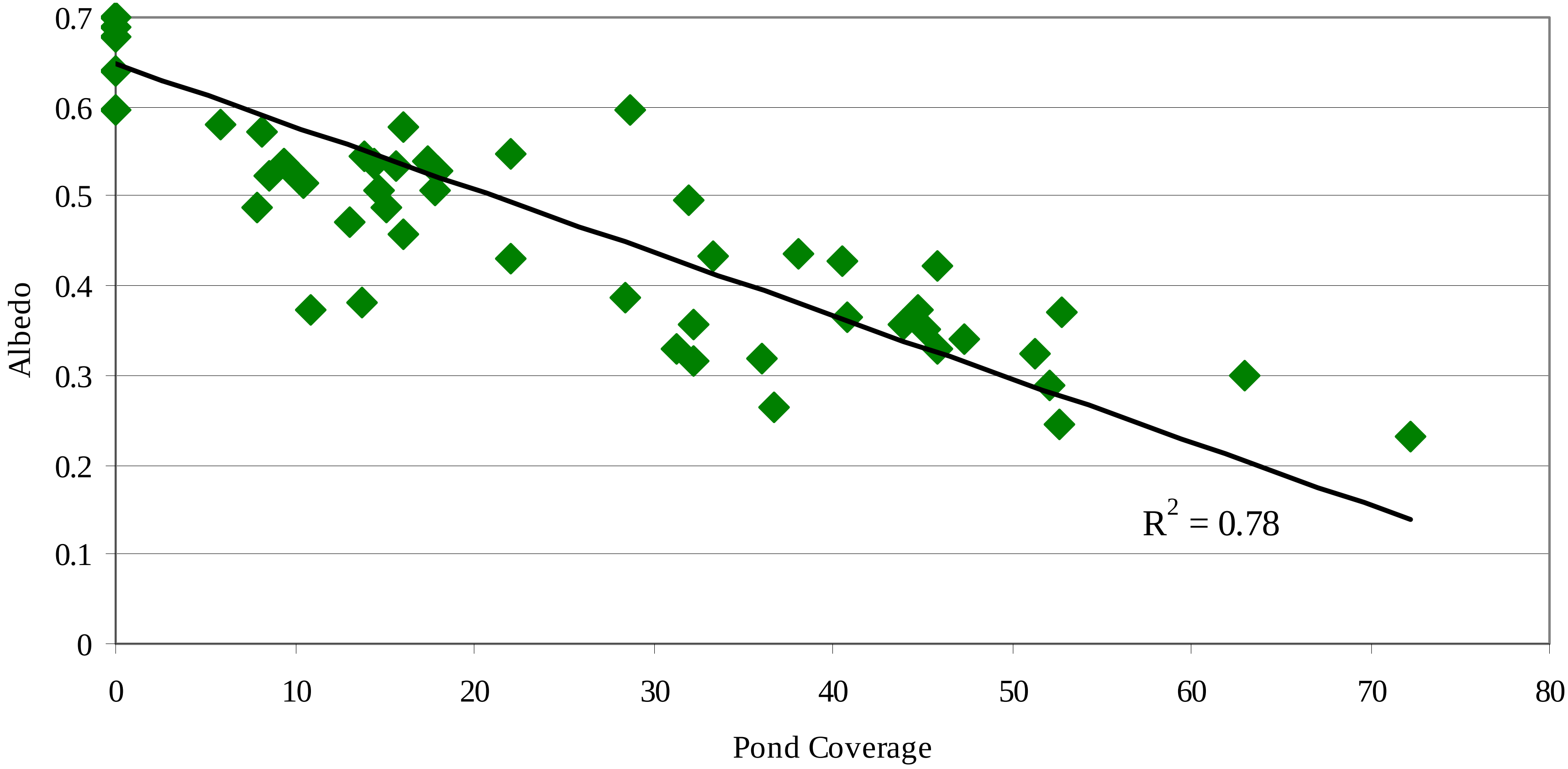


Pink = Pond Coverage

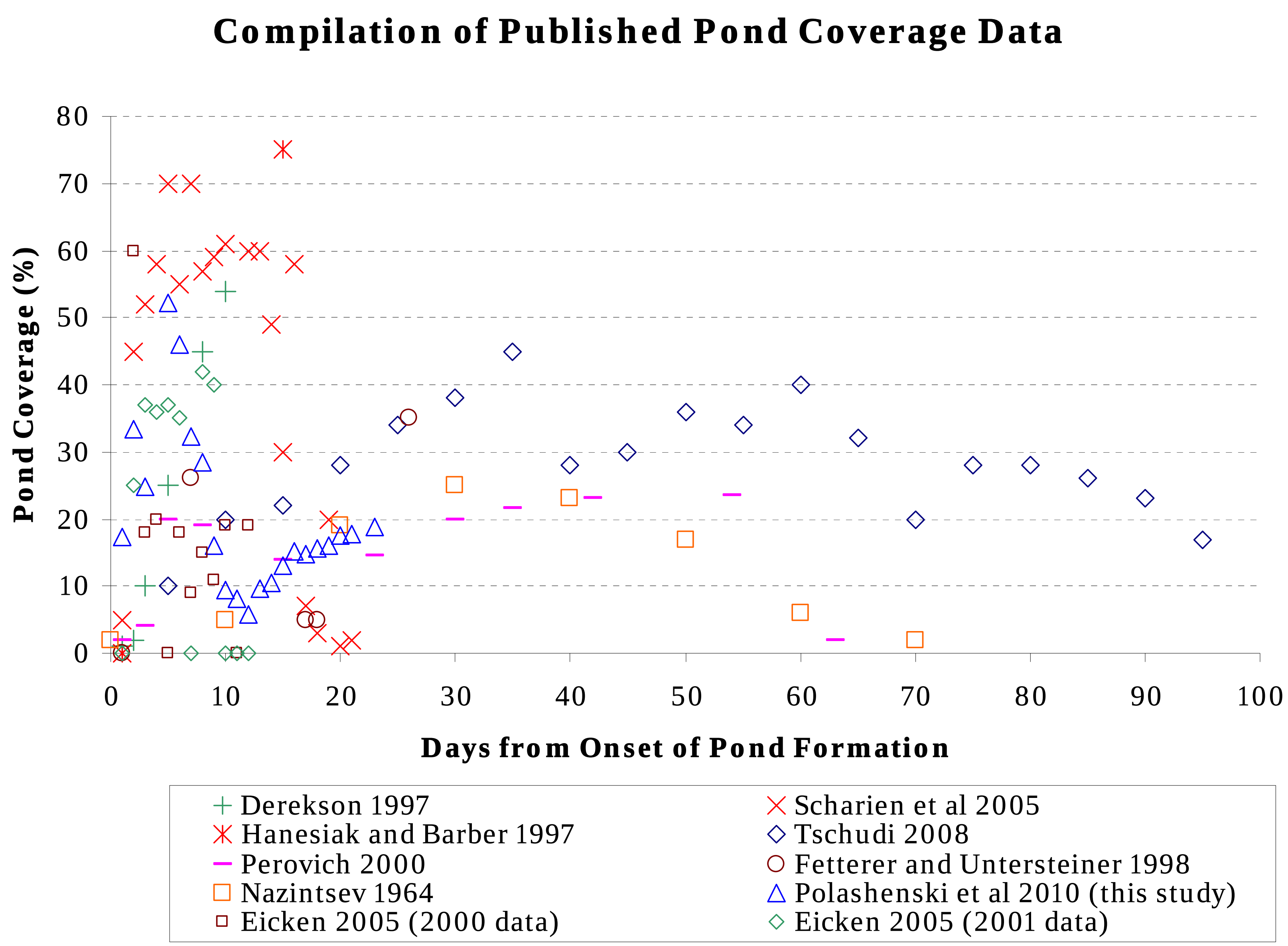
Green = Albedo

Pond Coverage vs Ice Albedo

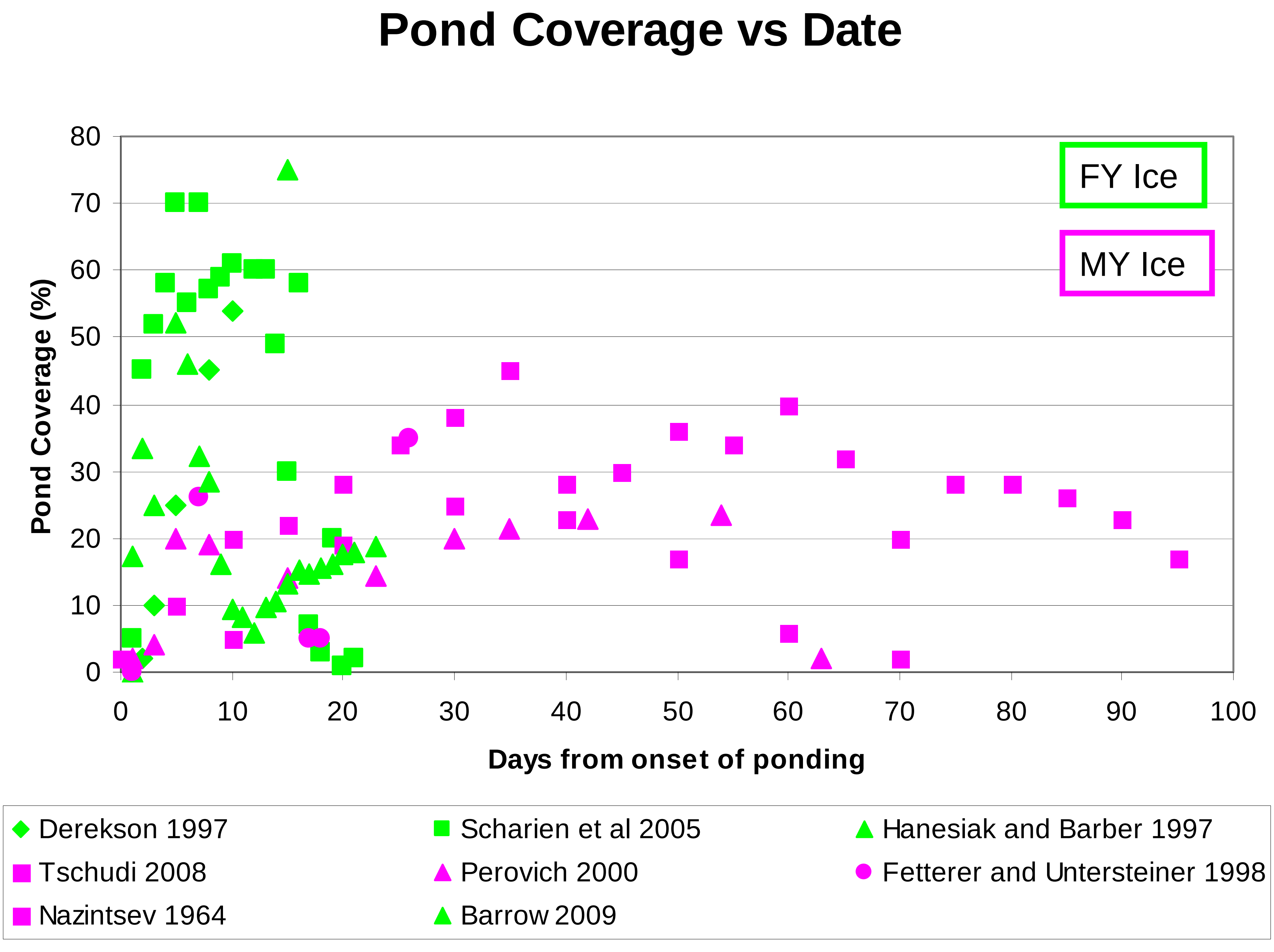
Barrow, AK 2008-2010



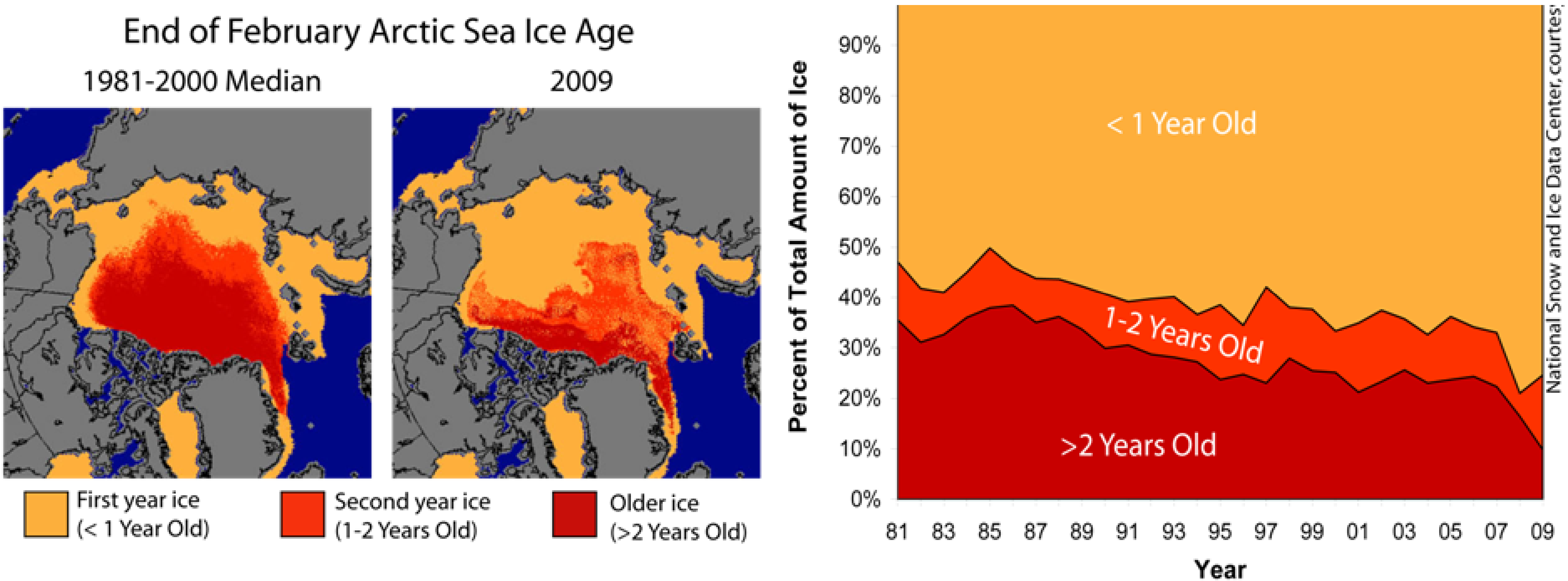
Pond coverage is the predominant driver of summer ice albedo



Pond coverage shows tremendous spatial and interannual variability


Pond Coverage vs Date
FY Ice
MY Ice
Pond Coverage (%)
Days from onset of ponding
0
10
20
30
40
50
60
70
80
90
100
Derekson 1997
Scharien et al 2005
Hanesiak and Barber 1997
Tschudi 2008
Perovich 2000
Fetterer and Untersteiner 1998
Nazintsev 1964
Barrow 2009

Changing Ice = Changing Pond Coverage



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

Photo: Chris Petrich

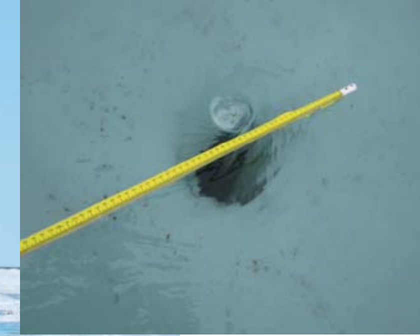
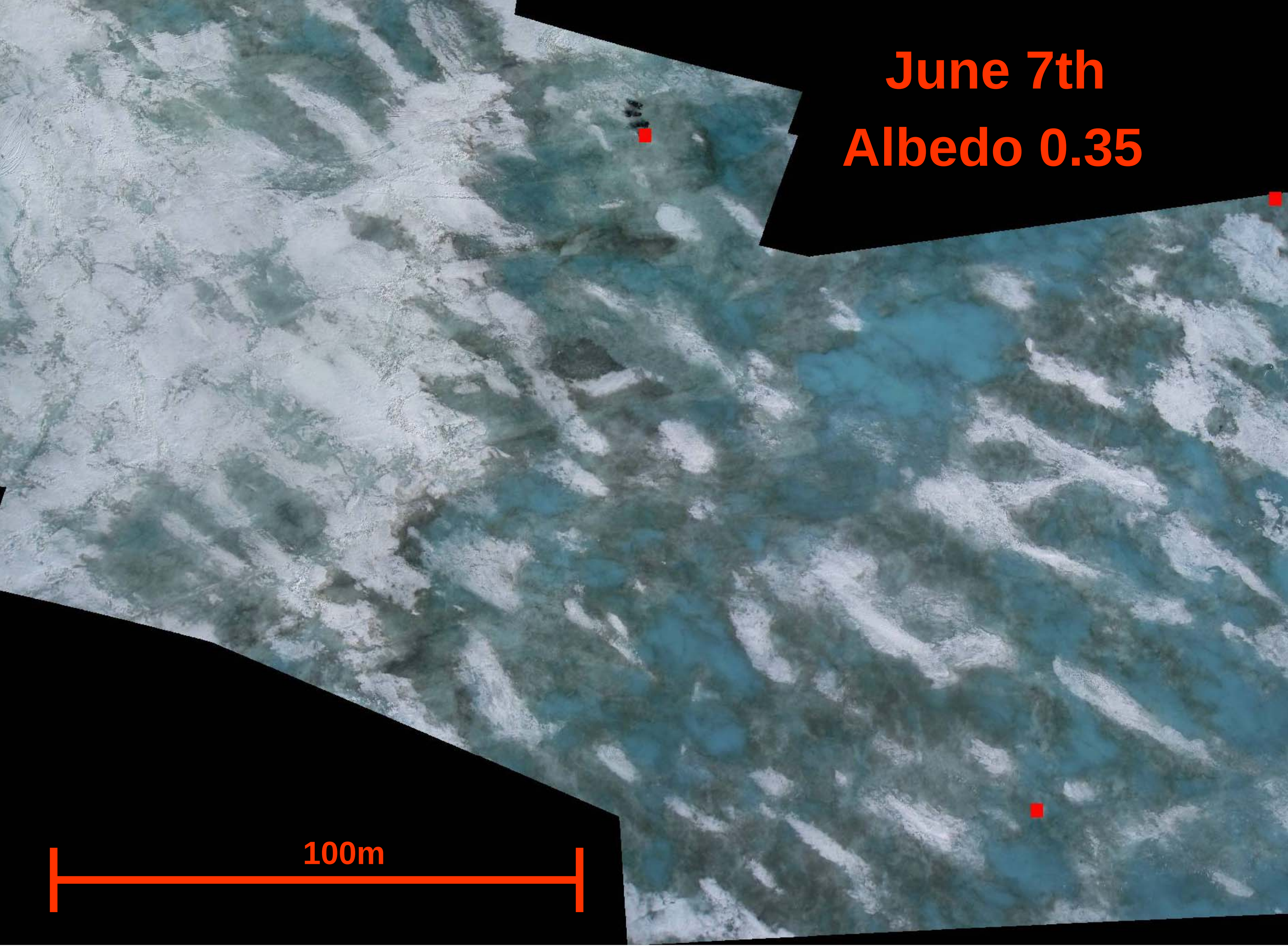


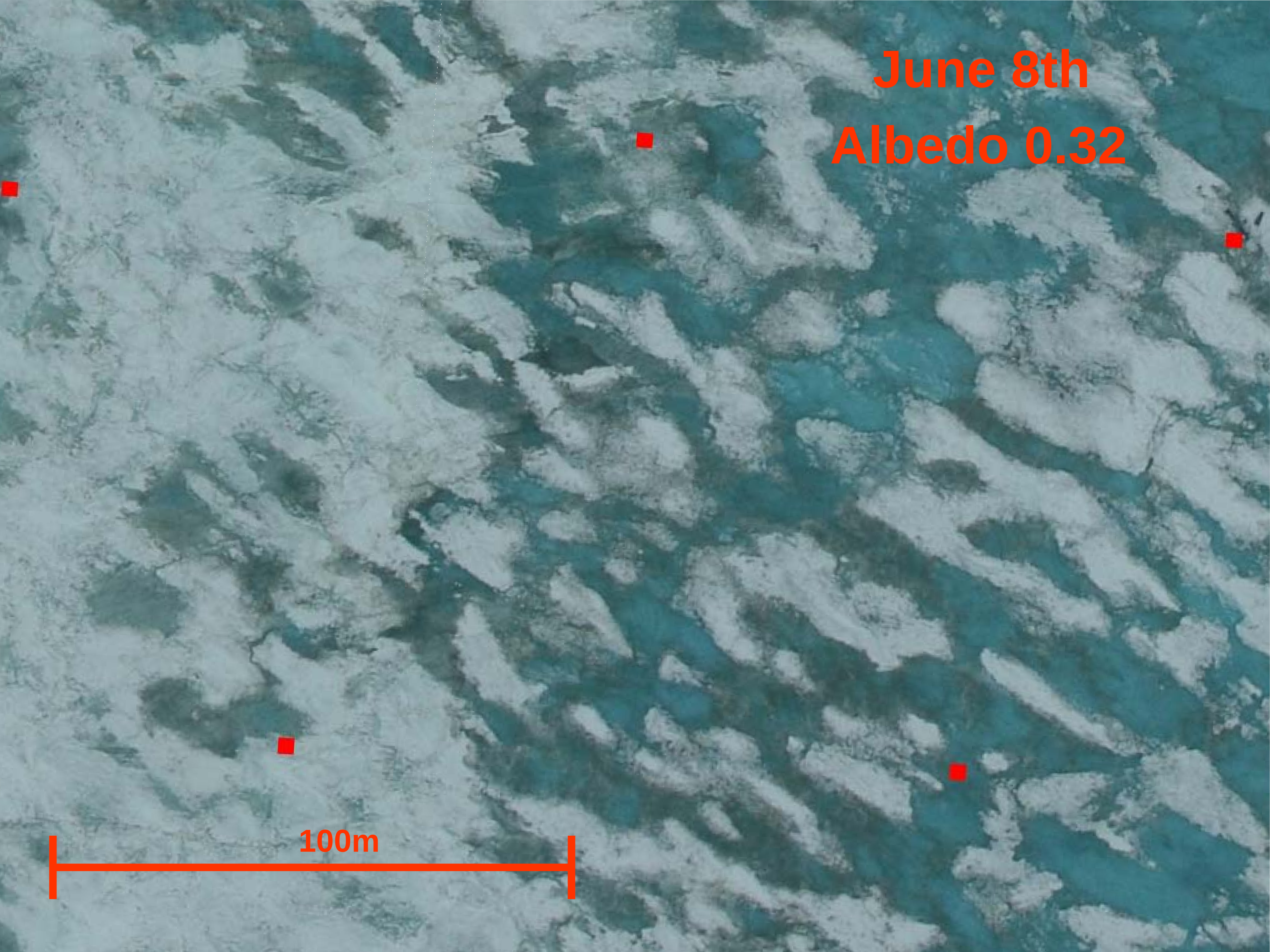
Photo: Chris Petrich

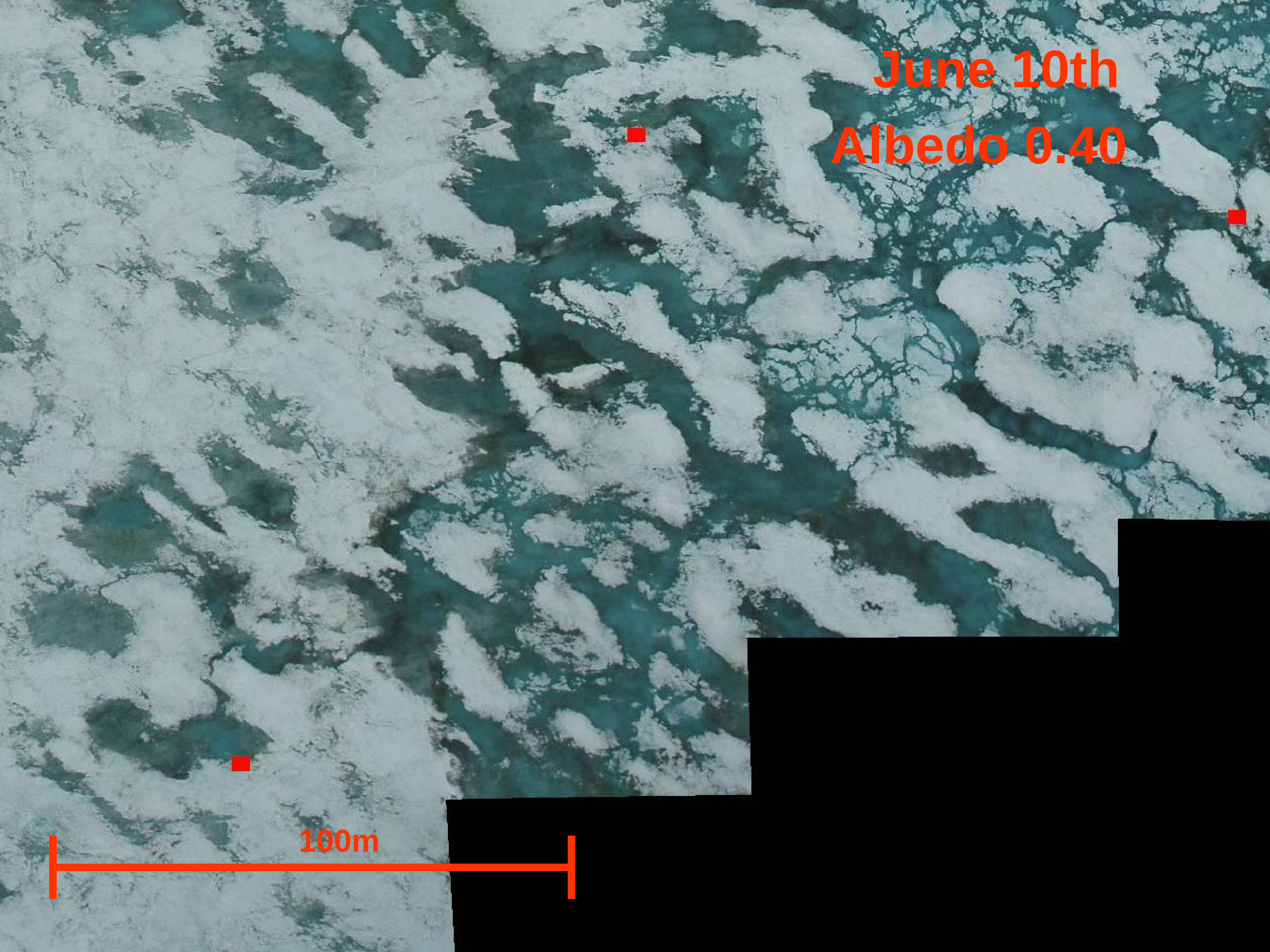
Photo: Chris Petrich

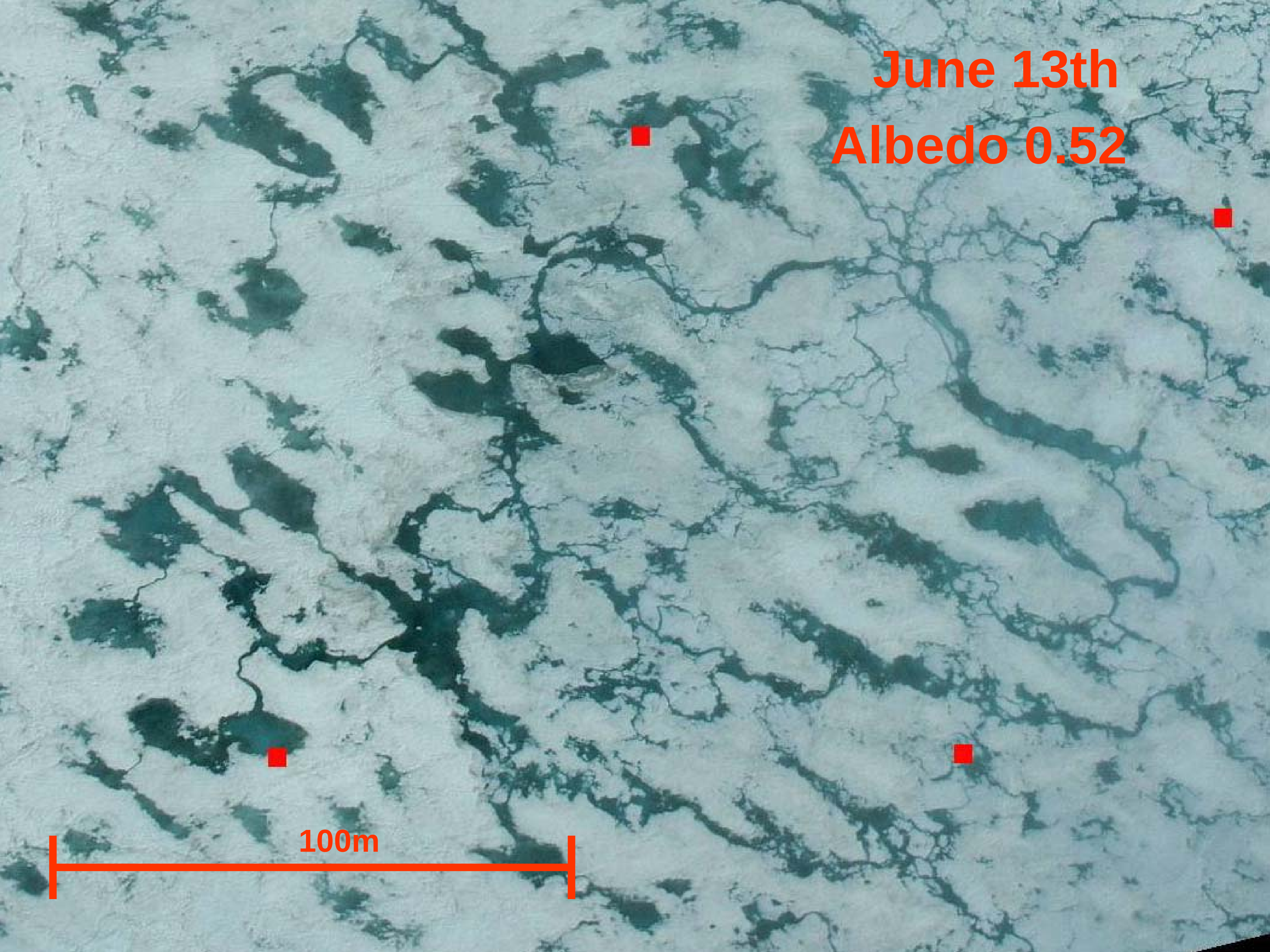

June 1st
Albedo ~0.79
100m


June 3rd
Albedo 0.59
100m

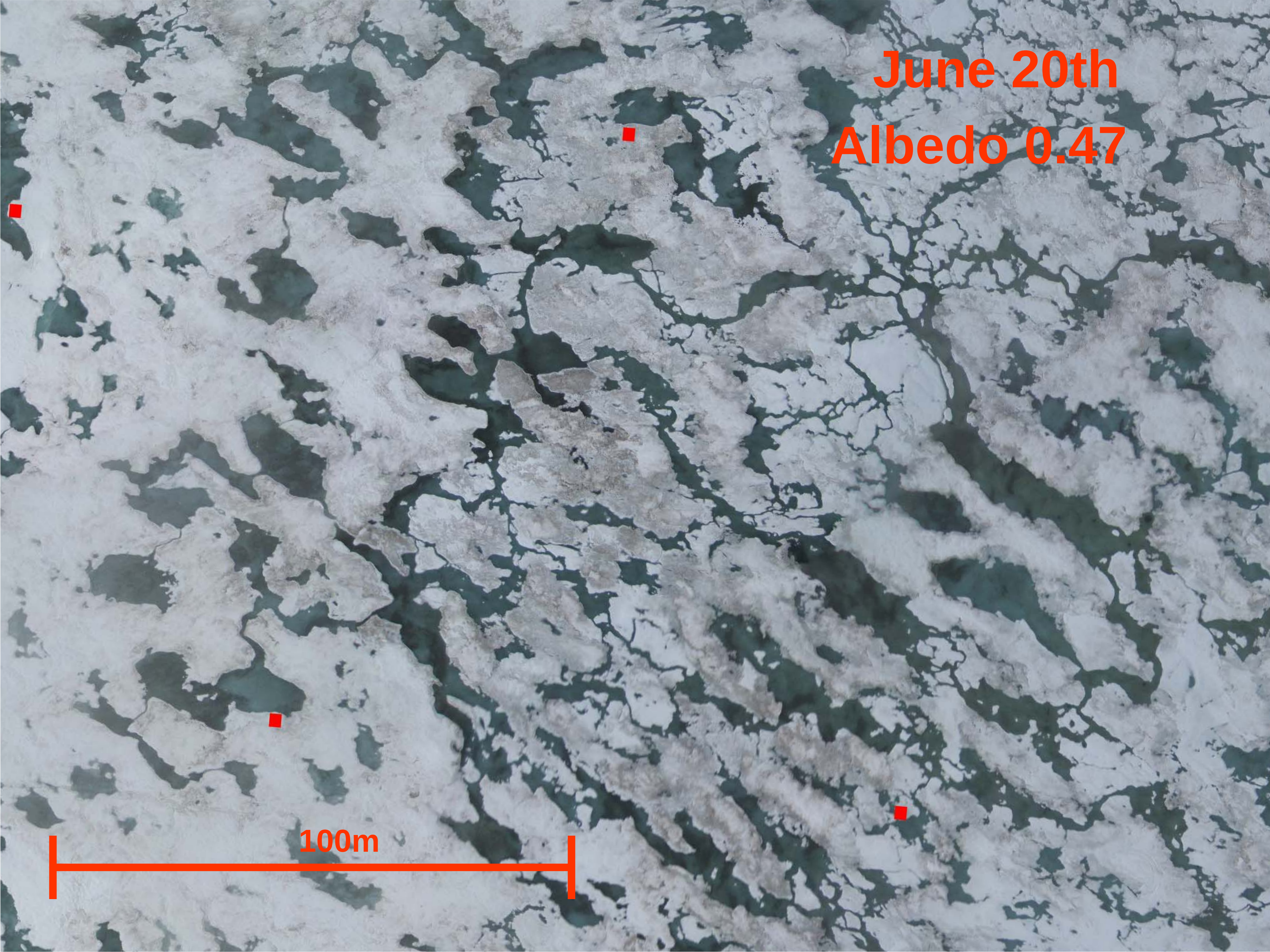

June 7th
Albedo 0.35
100m

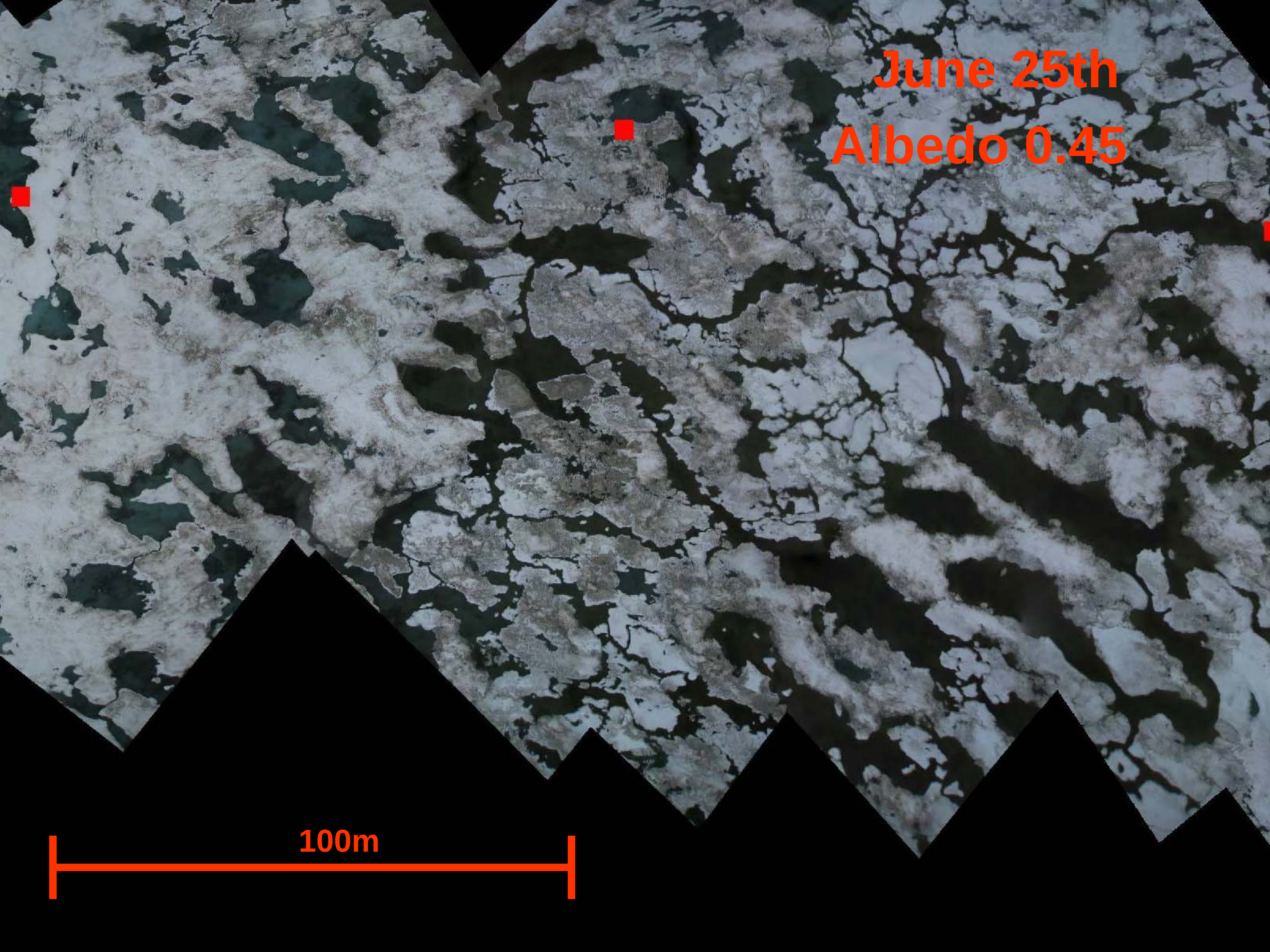

June 8th
Albedo 0.32
100m

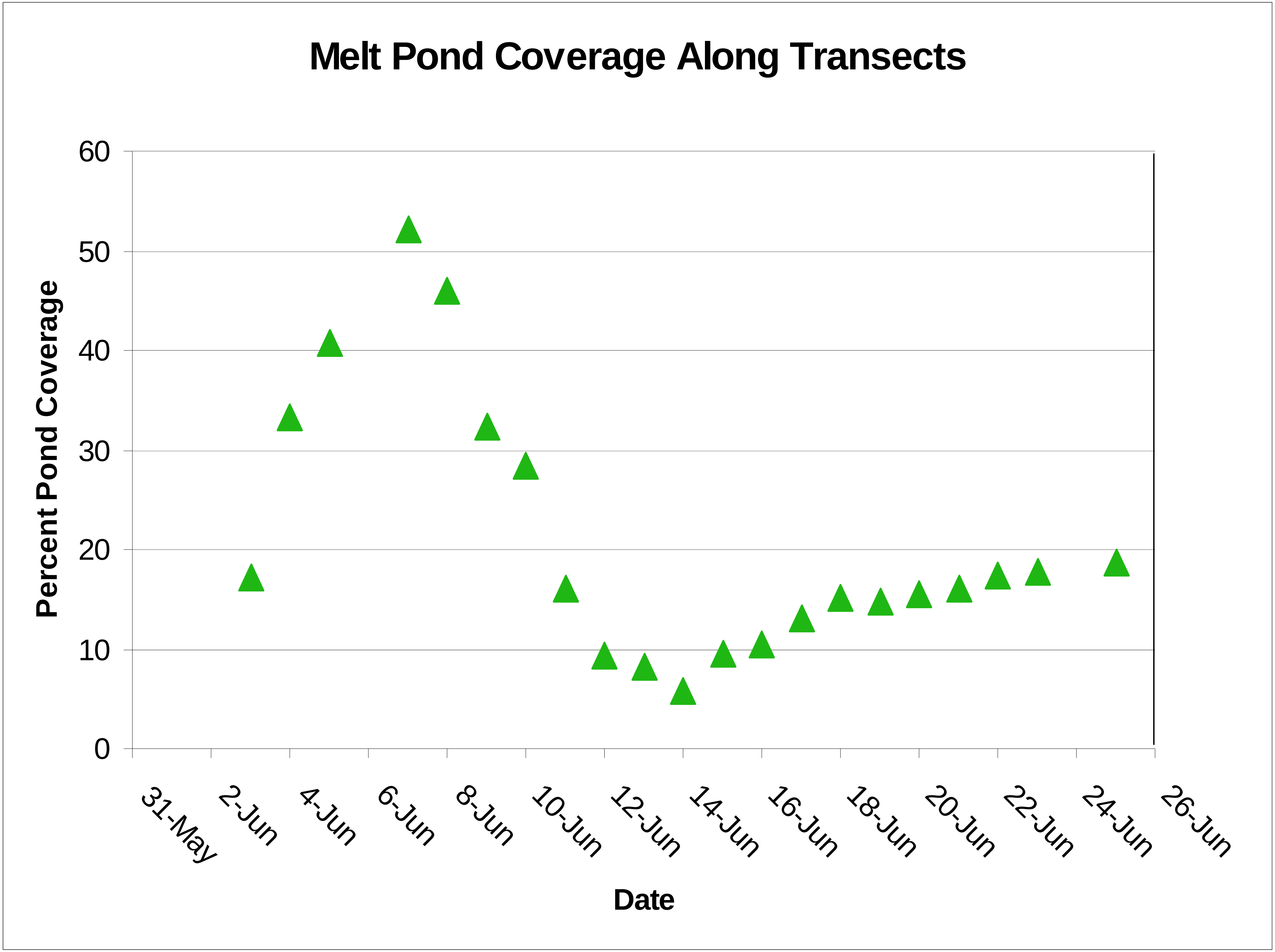

June 10th
Albedo 0.40
100m

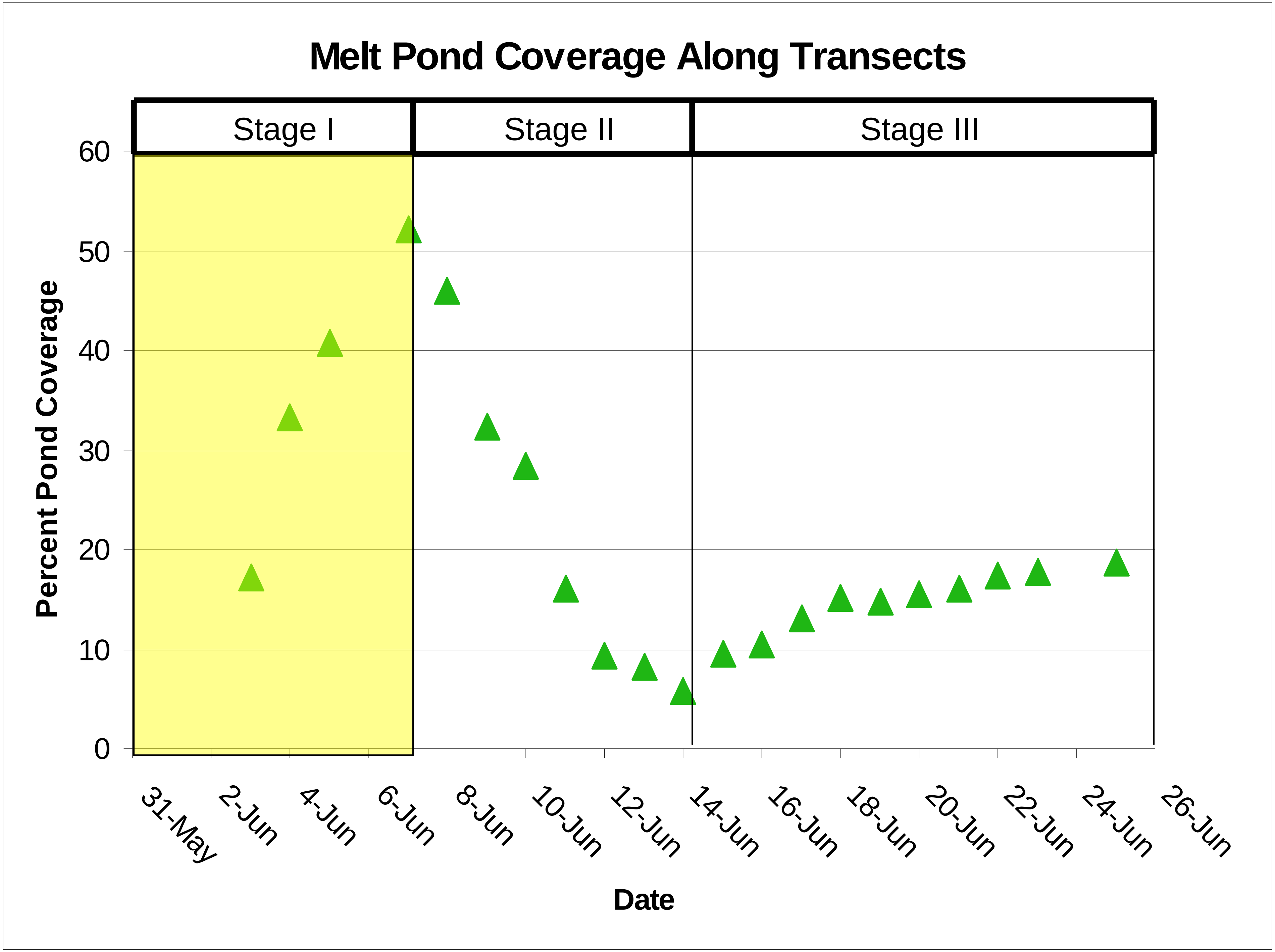

June 13th
Albedo 0.52
100m


June 15th
Albedo 0.58
100m

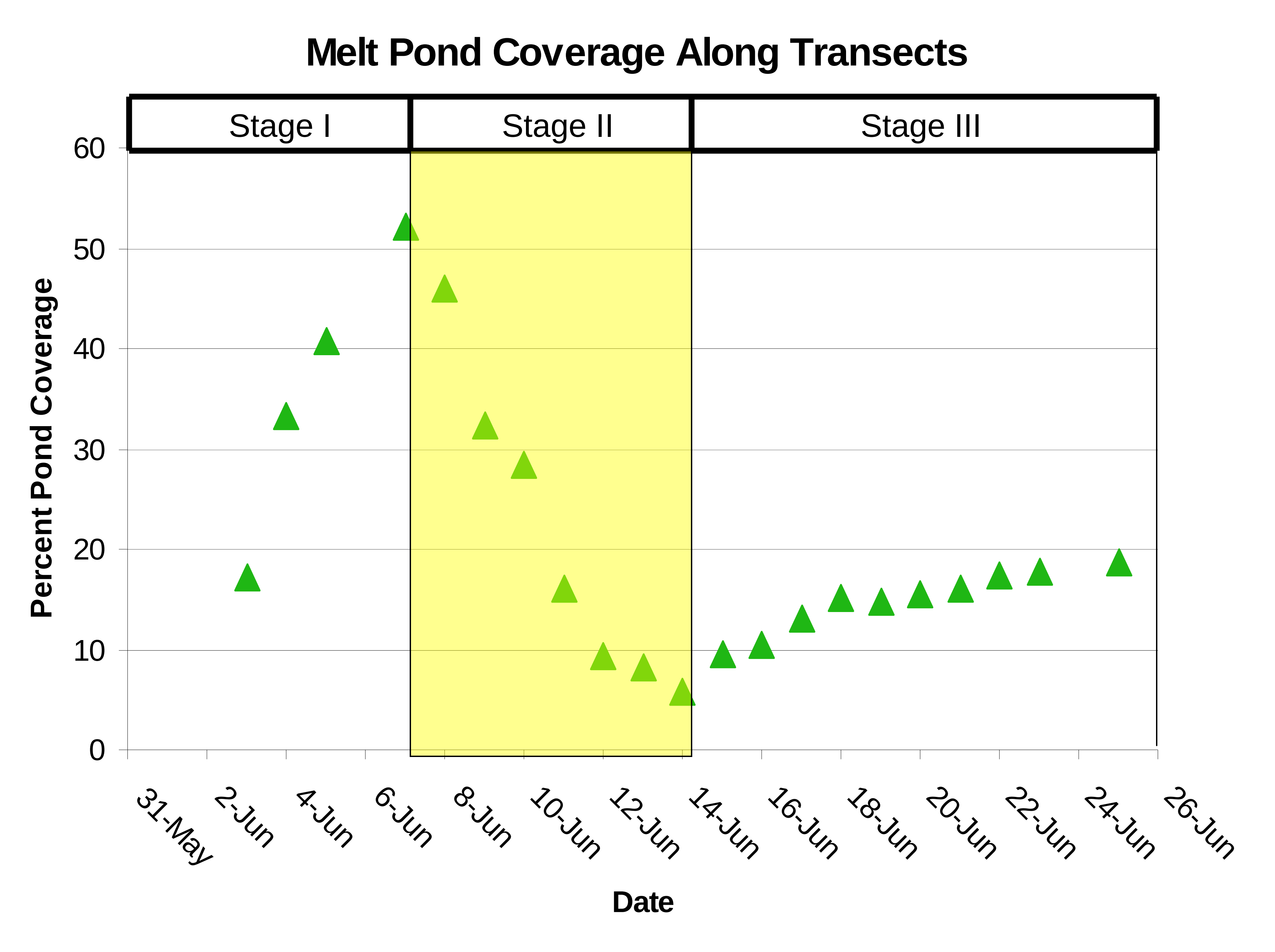

June 20th
Albedo 0.47
100m


June 25th
Albedo 0.45
100m

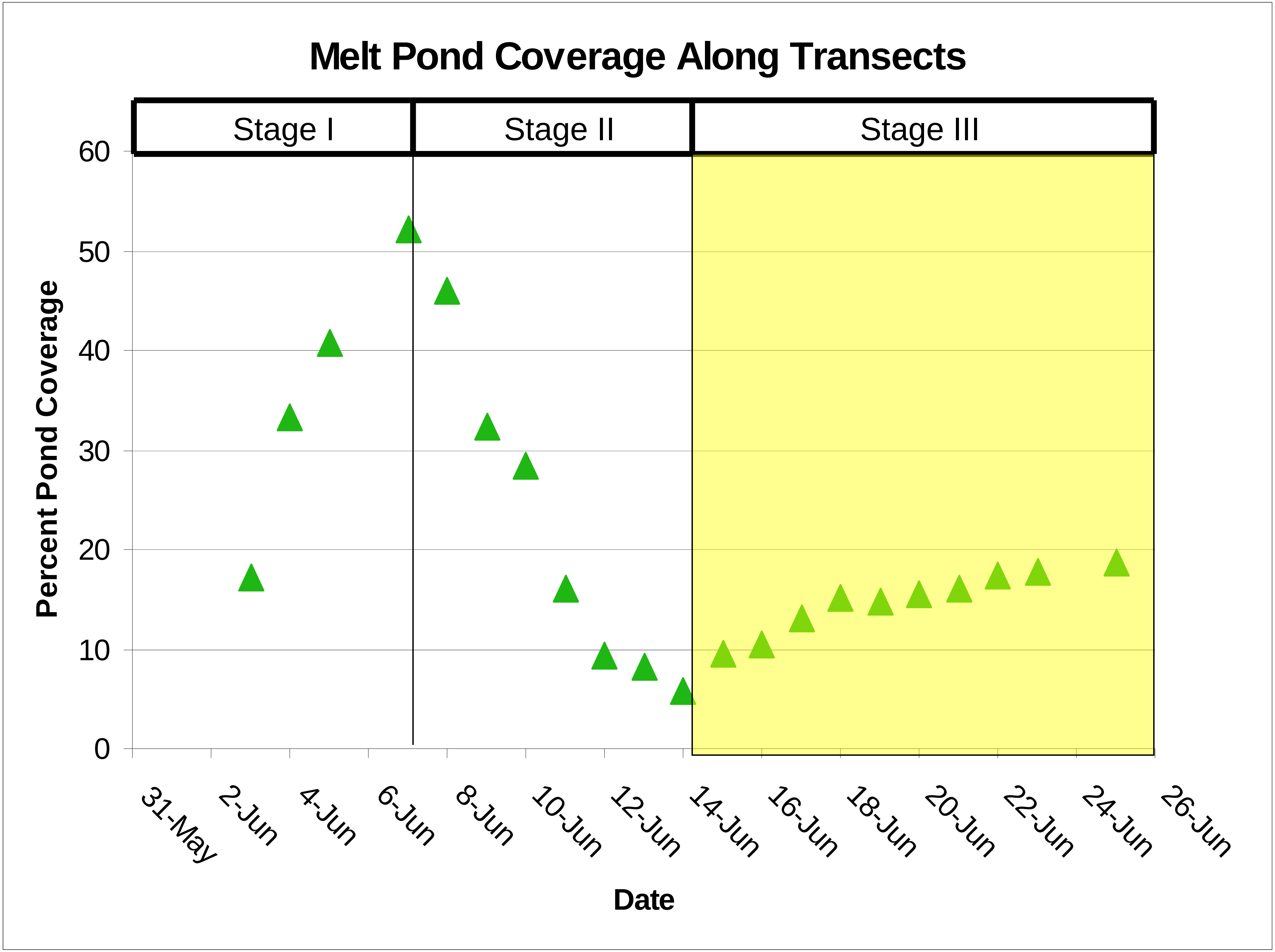

Melt Pond Coverage Along Transects
Percent Pond Coverage
60
50
40
30
20
10
0
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date



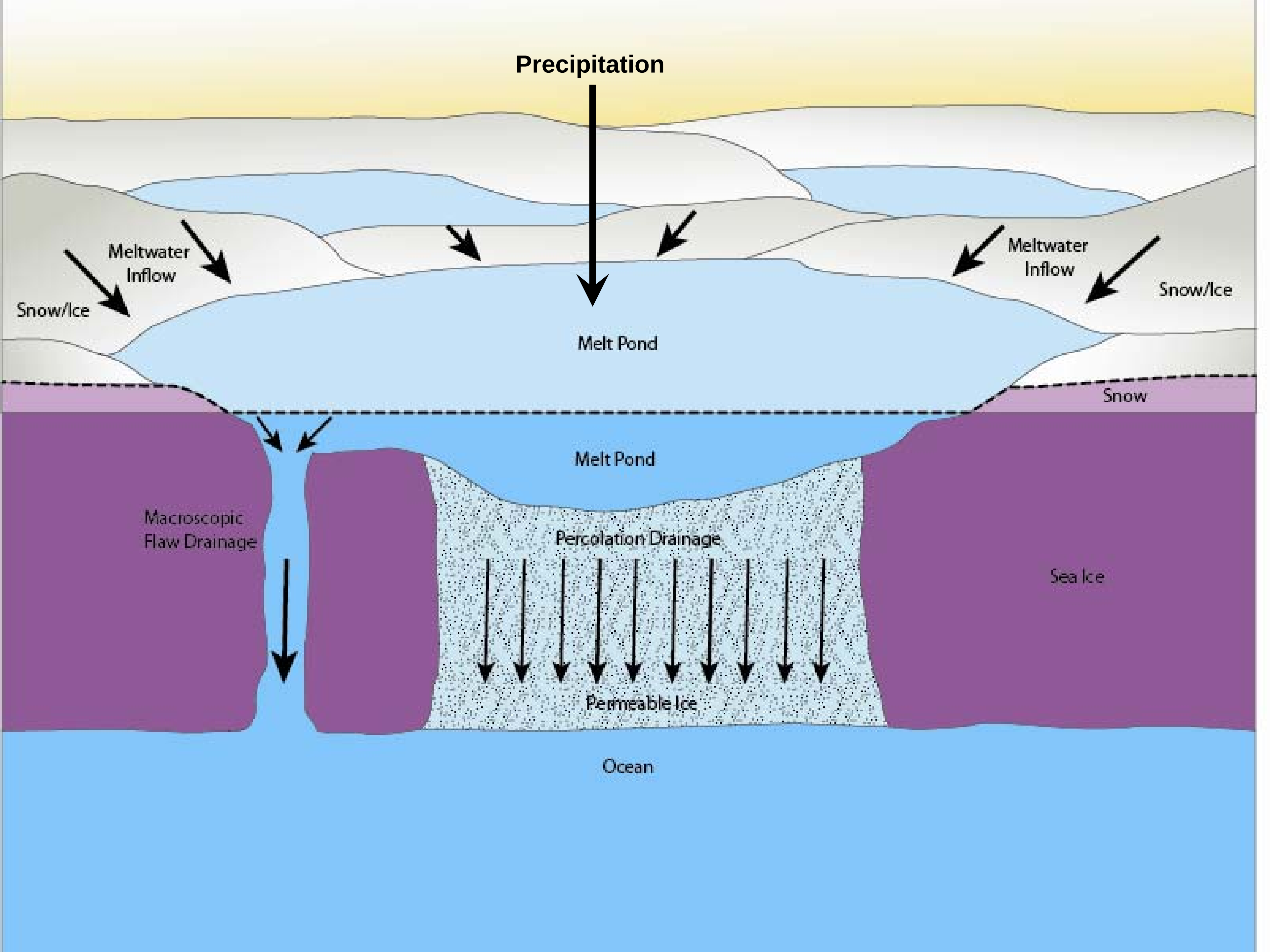
Melt Pond Coverage Along Transects
Stage I
Stage II
Stage III
Percent Pond Coverage
0
10
20
30
40
50
60
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date

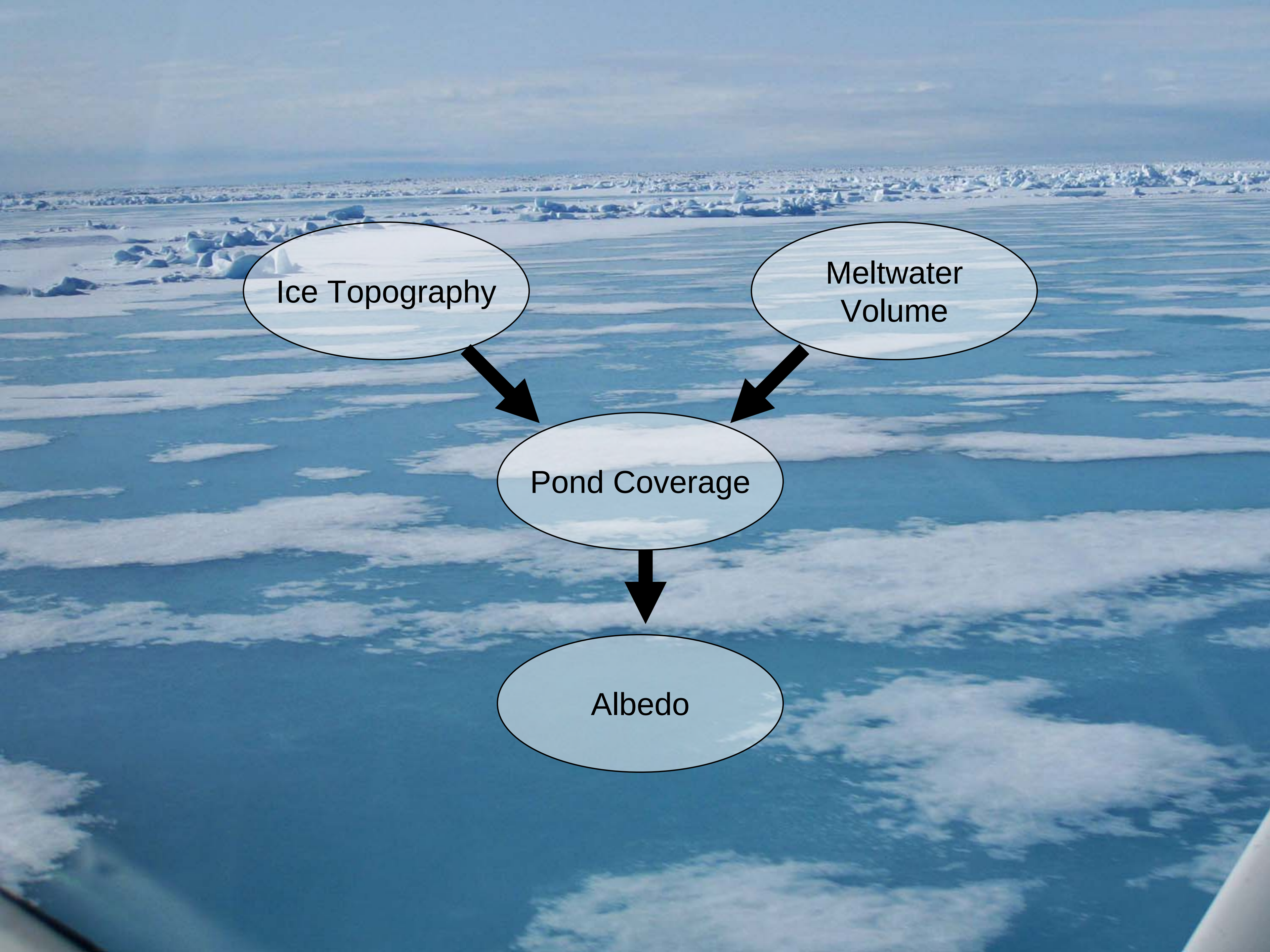


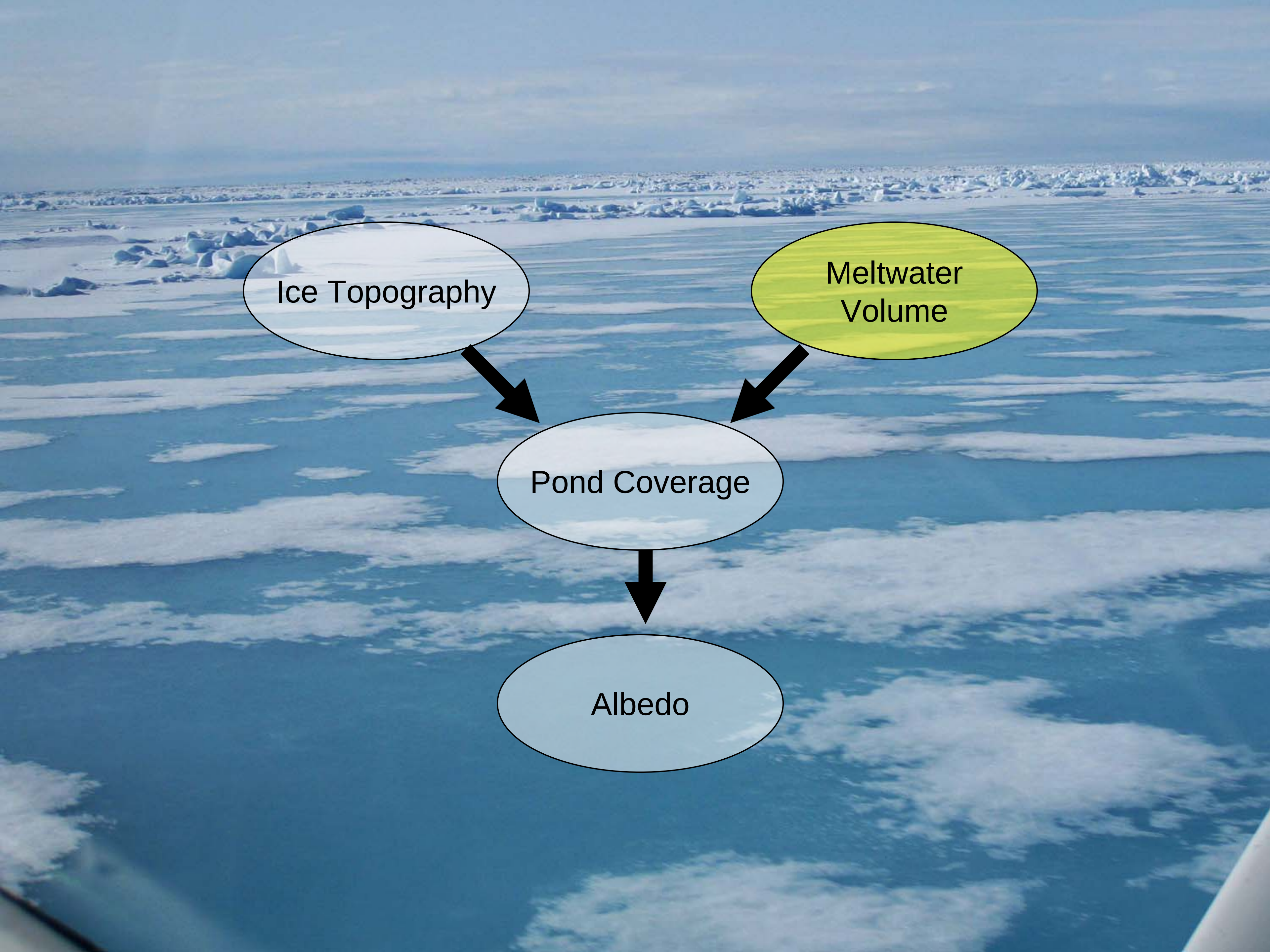
Melt Pond Coverage Along Transects
Stage I
Stage II
Stage III
Percent Pond Coverage
0
10
20
30
40
50
60
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date

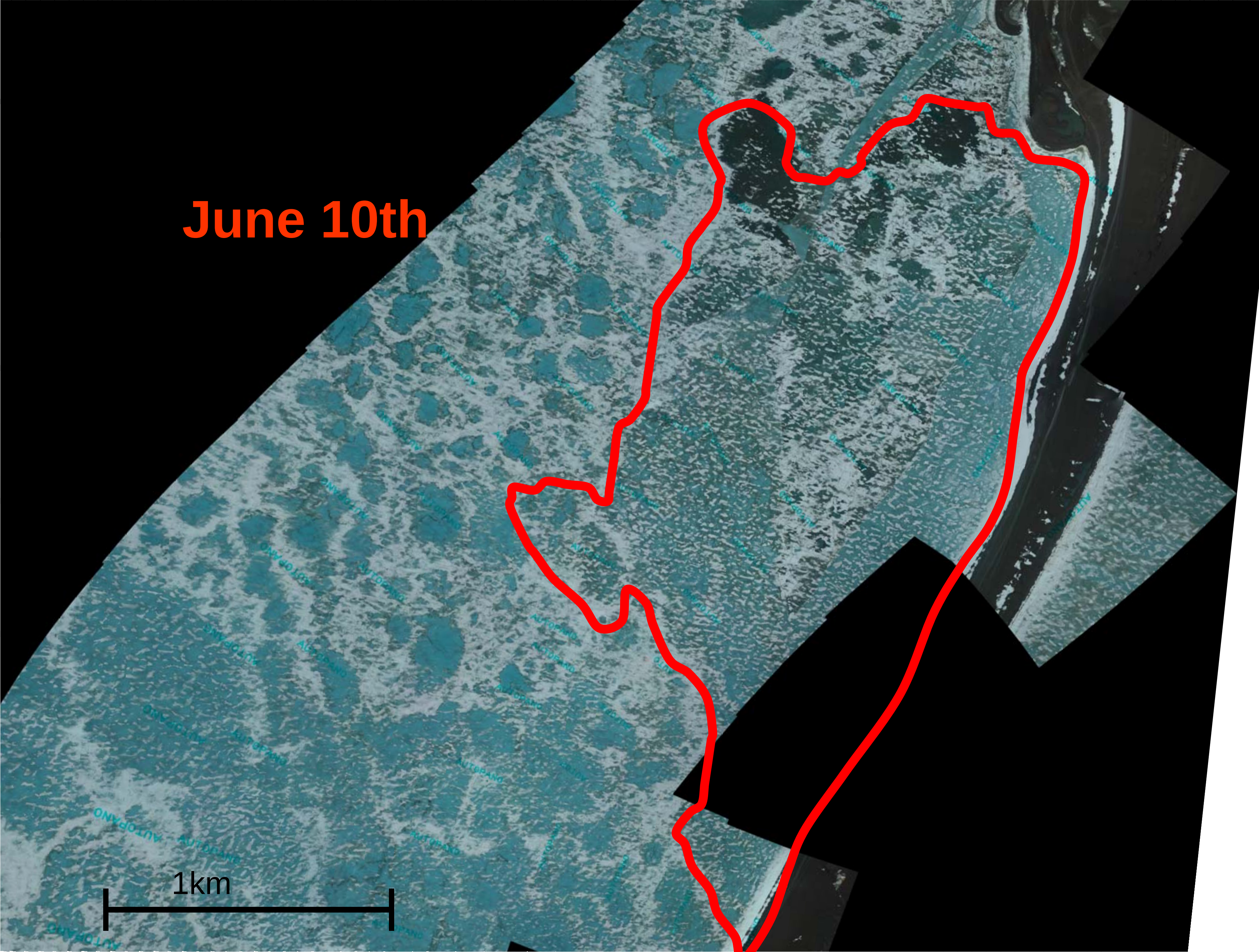


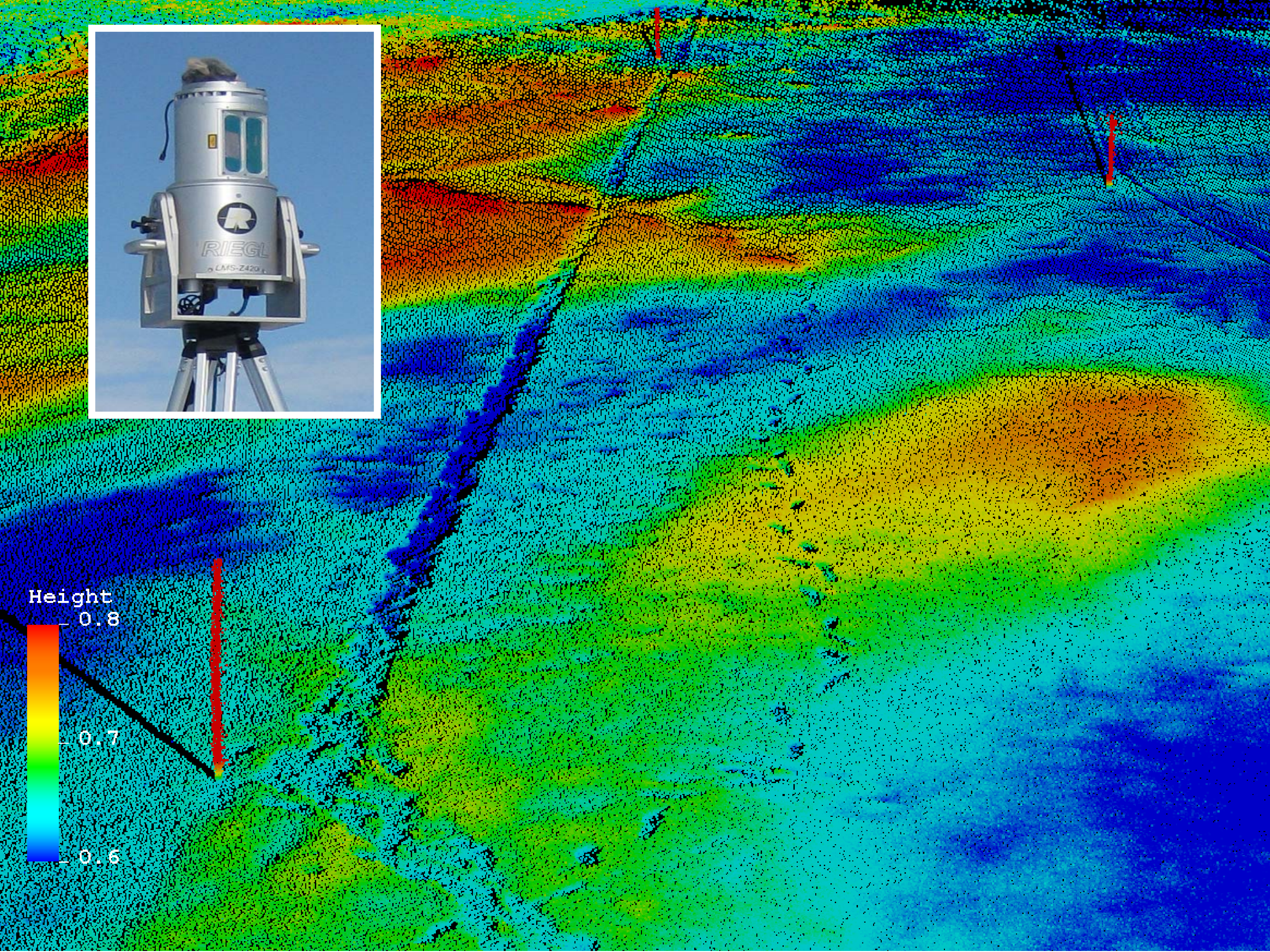
Melt Pond Coverage Along Transects
Stage I
Stage II
Stage III
Percent Pond Coverage
0
10
20
30
40
50
60
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date

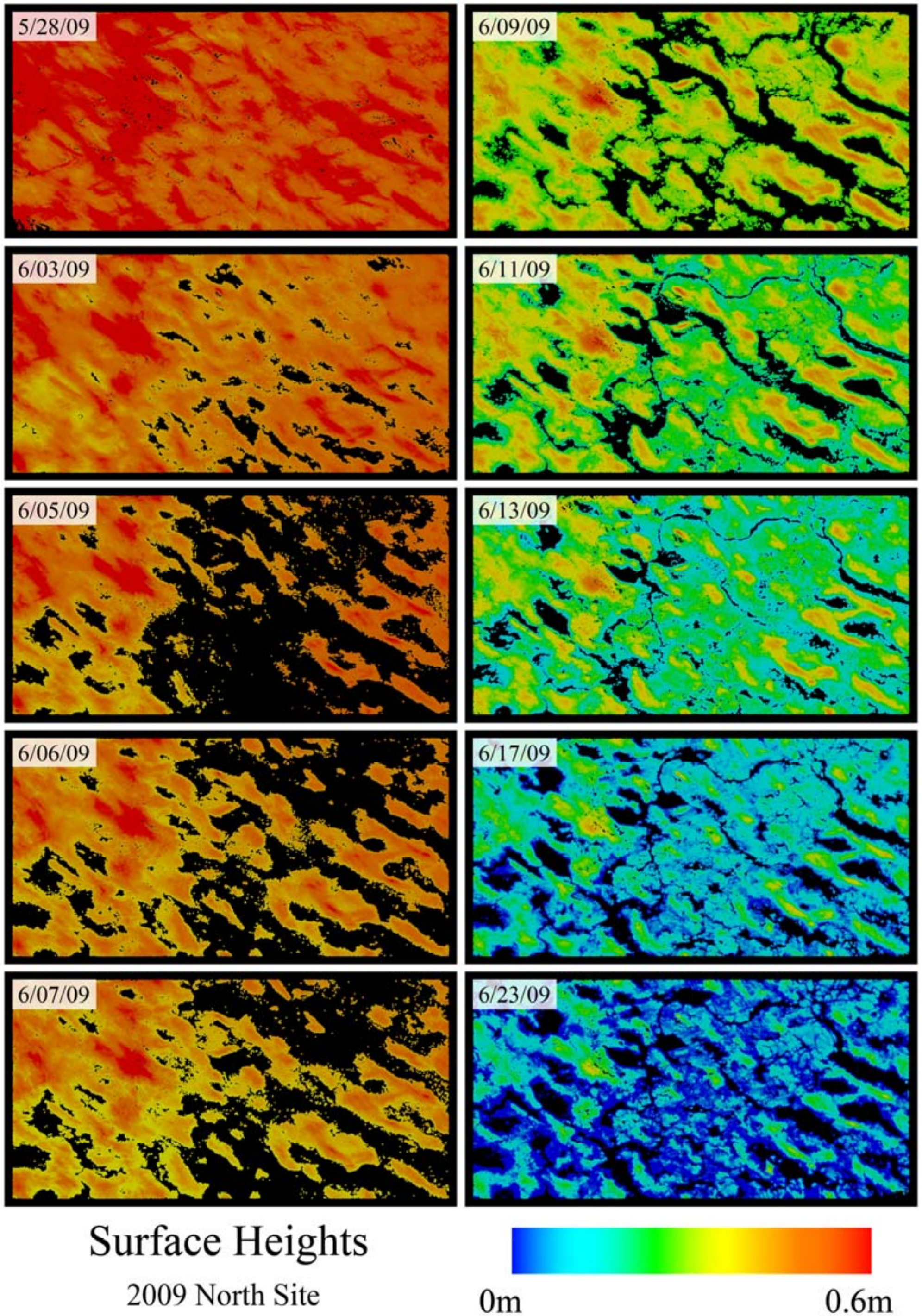

Precipitation
Meltwater
Inflow
Snow/Ice
Meltwater
Inflow
Snow/Ice
Melt Pond
Snow
Melt Pond
Macroscopic
Flaw Drainage
Percolation Drainage
Sea Ice
Permeable Ice
Ocean

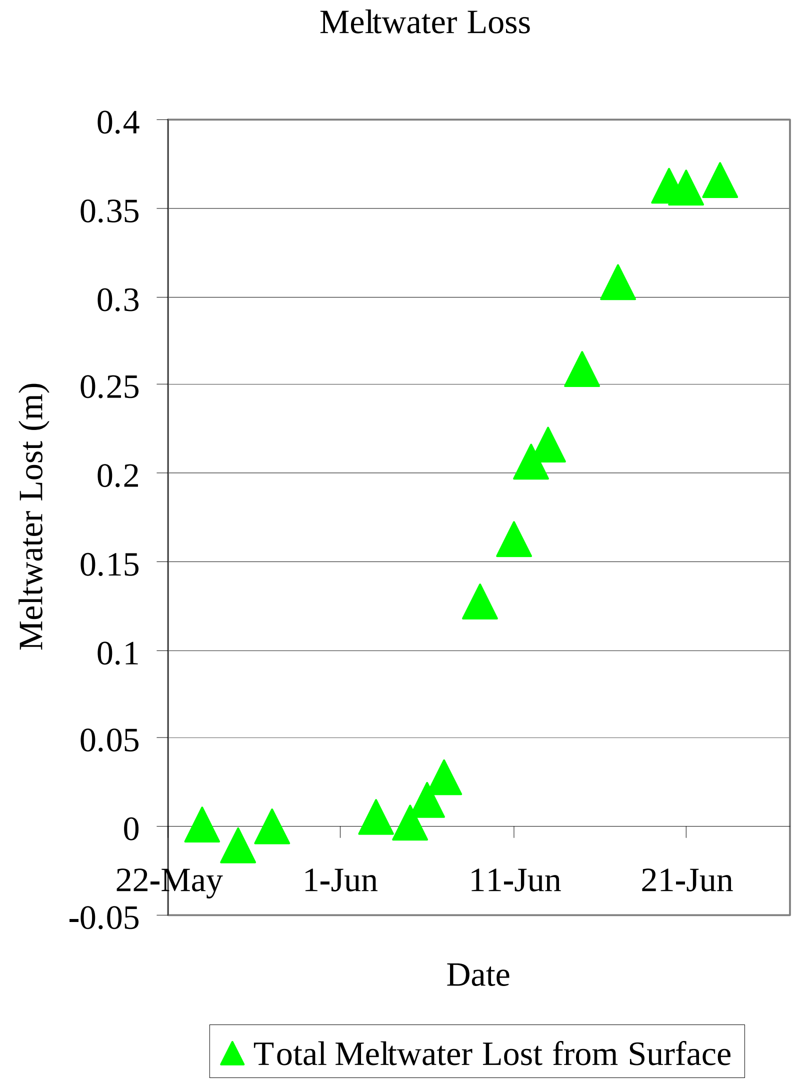

Ice Topography
Meltwater Volume
Pond Coverage
Albedo

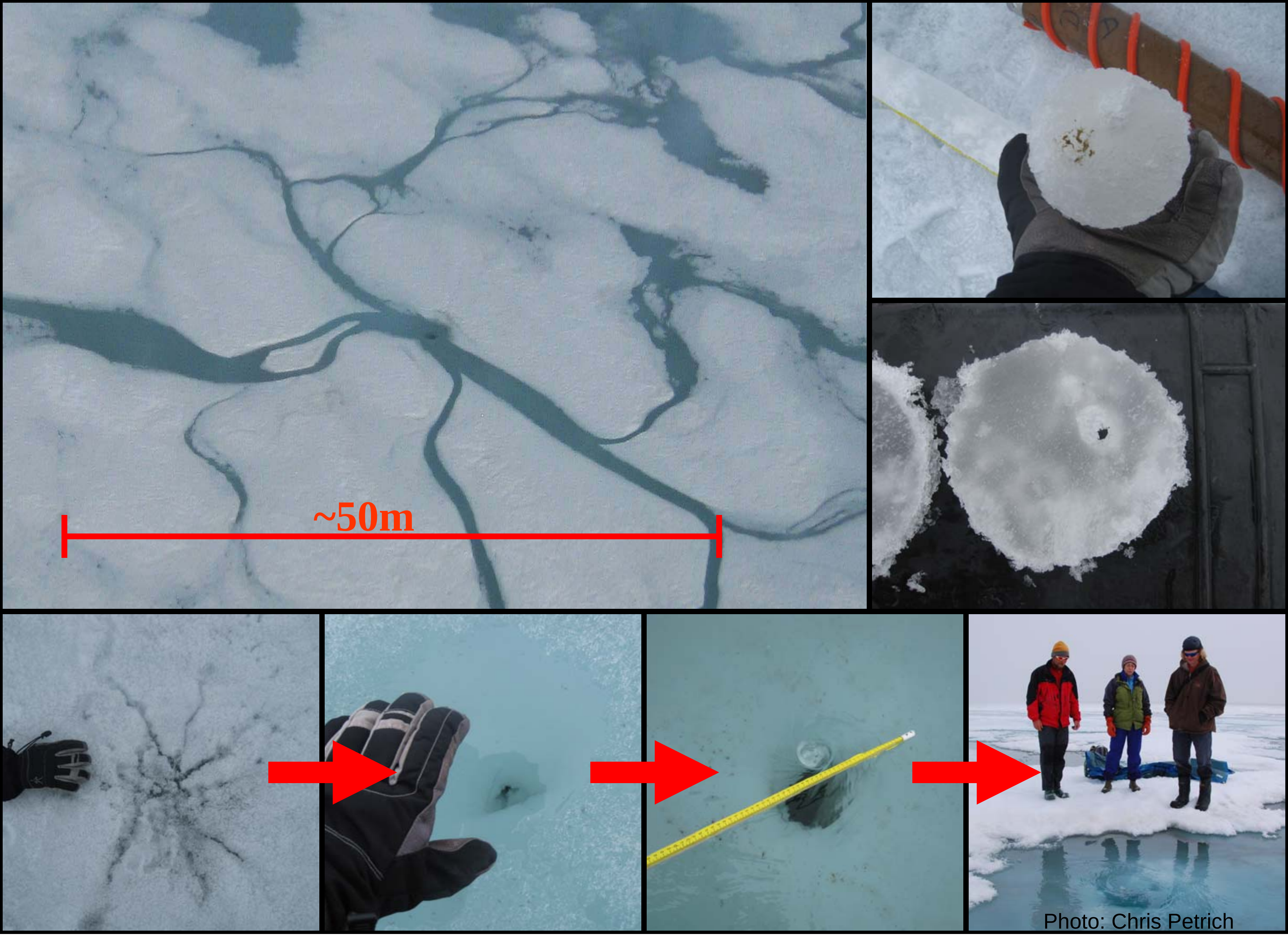

Ice Topography
Meltwater
Volume
Pond Coverage
Albedo

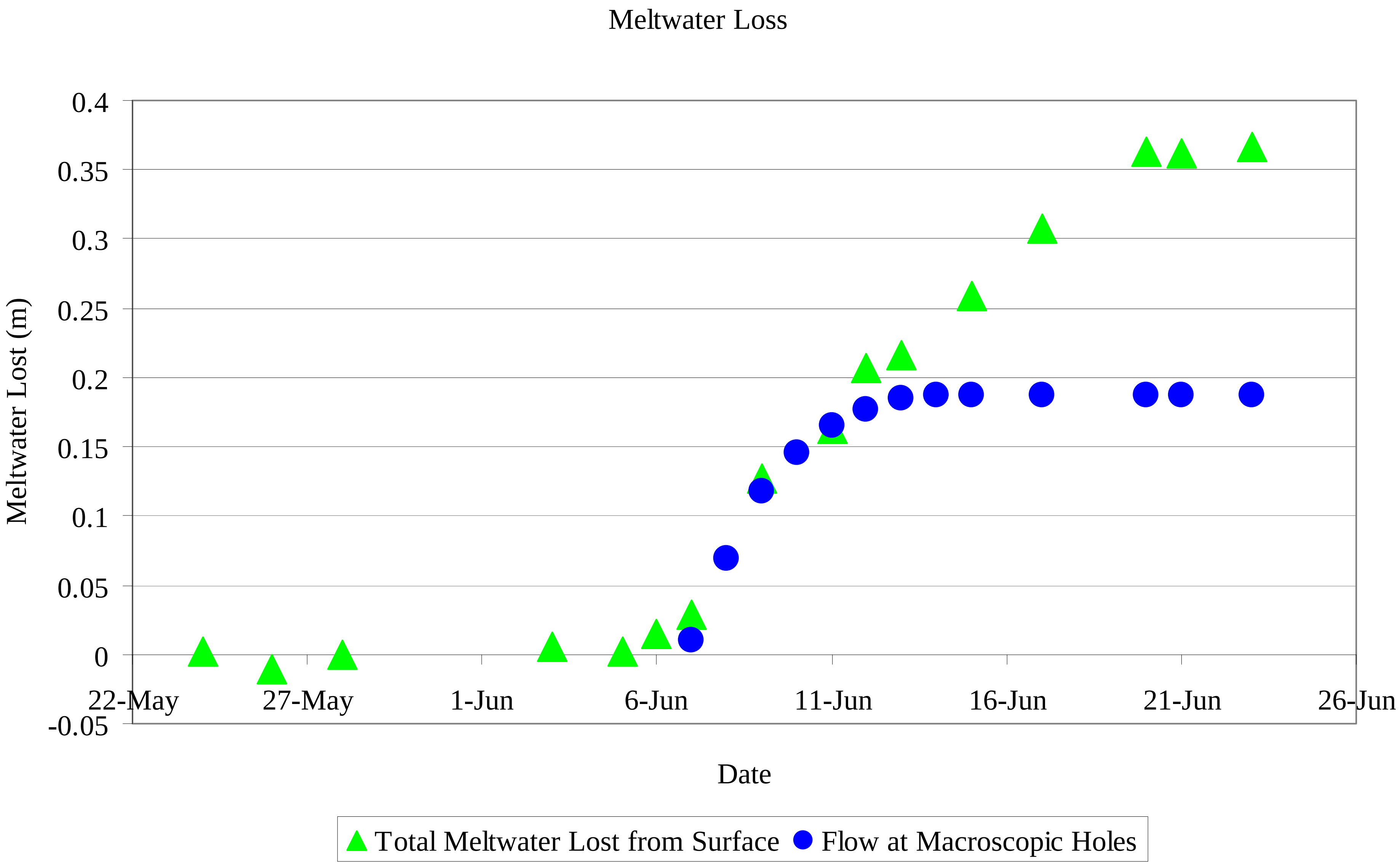

June 10th
1km

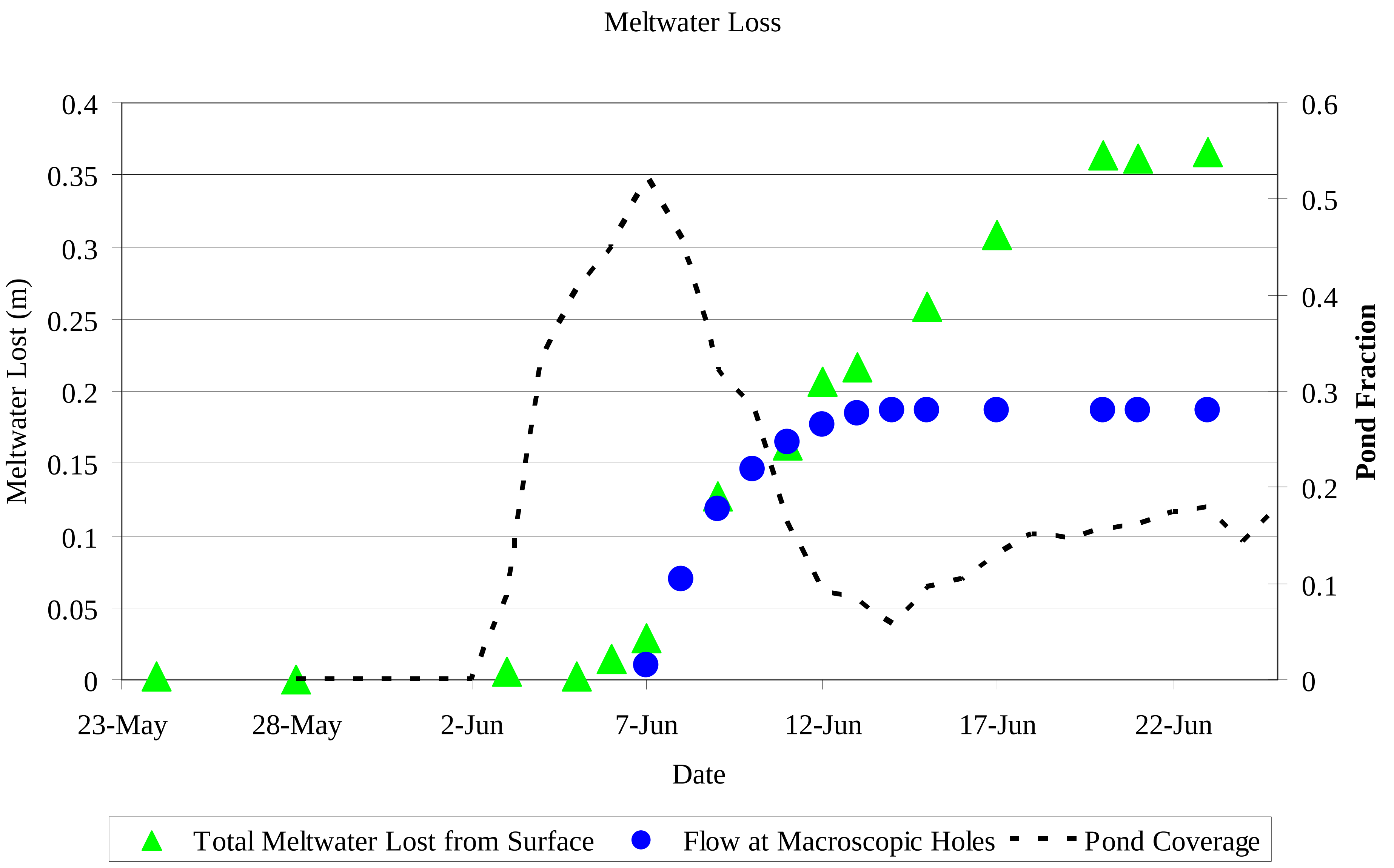

RIEGL
LMS-Z420i
Height
0.8
0.7
0.6

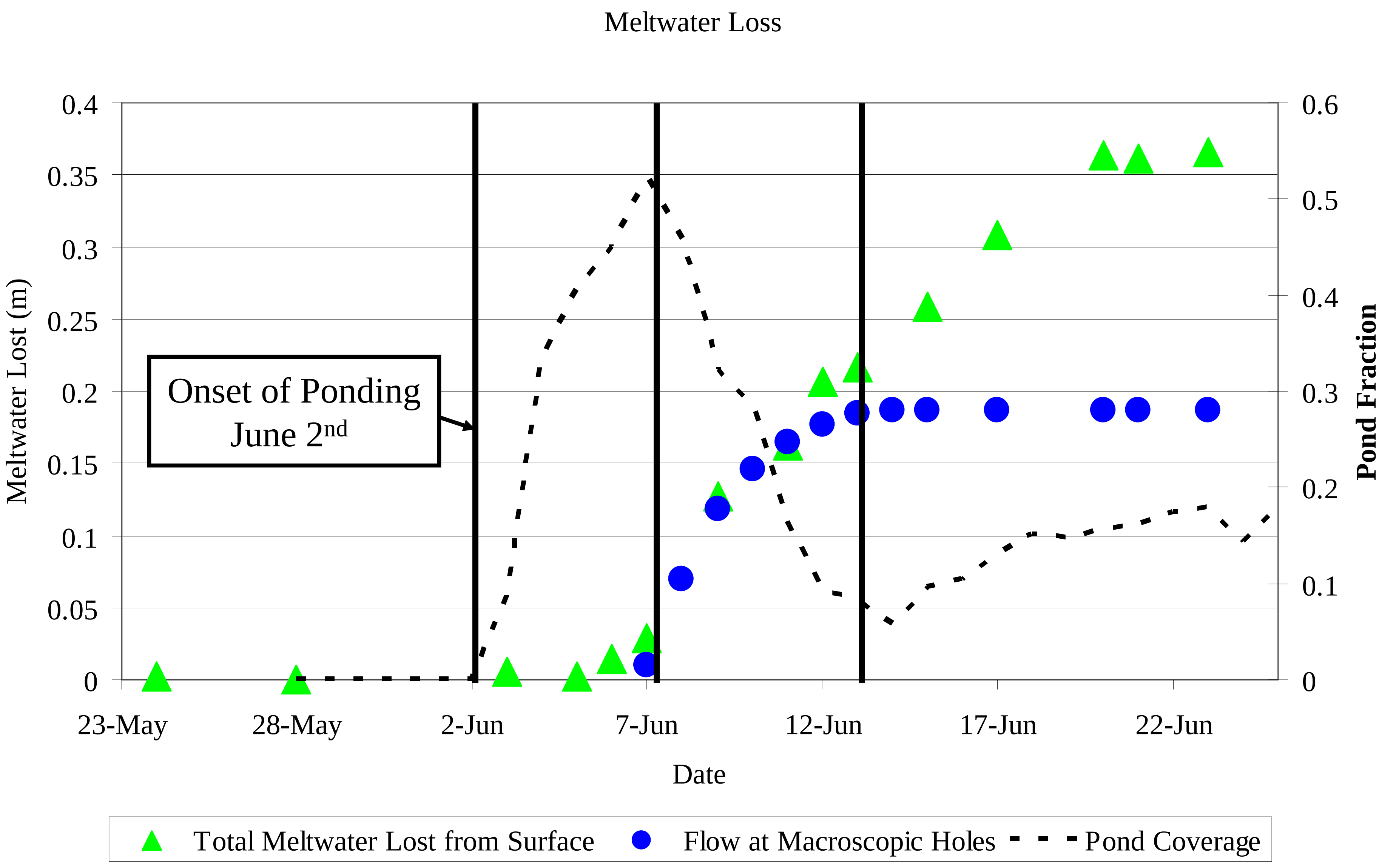

5/28/09
6/03/09
6/05/09
6/06/09
6/07/09
6/09/09
6/11/09
6/13/09
6/17/09
6/23/09
Surface Heights
2009 North Site
0m
0.6m

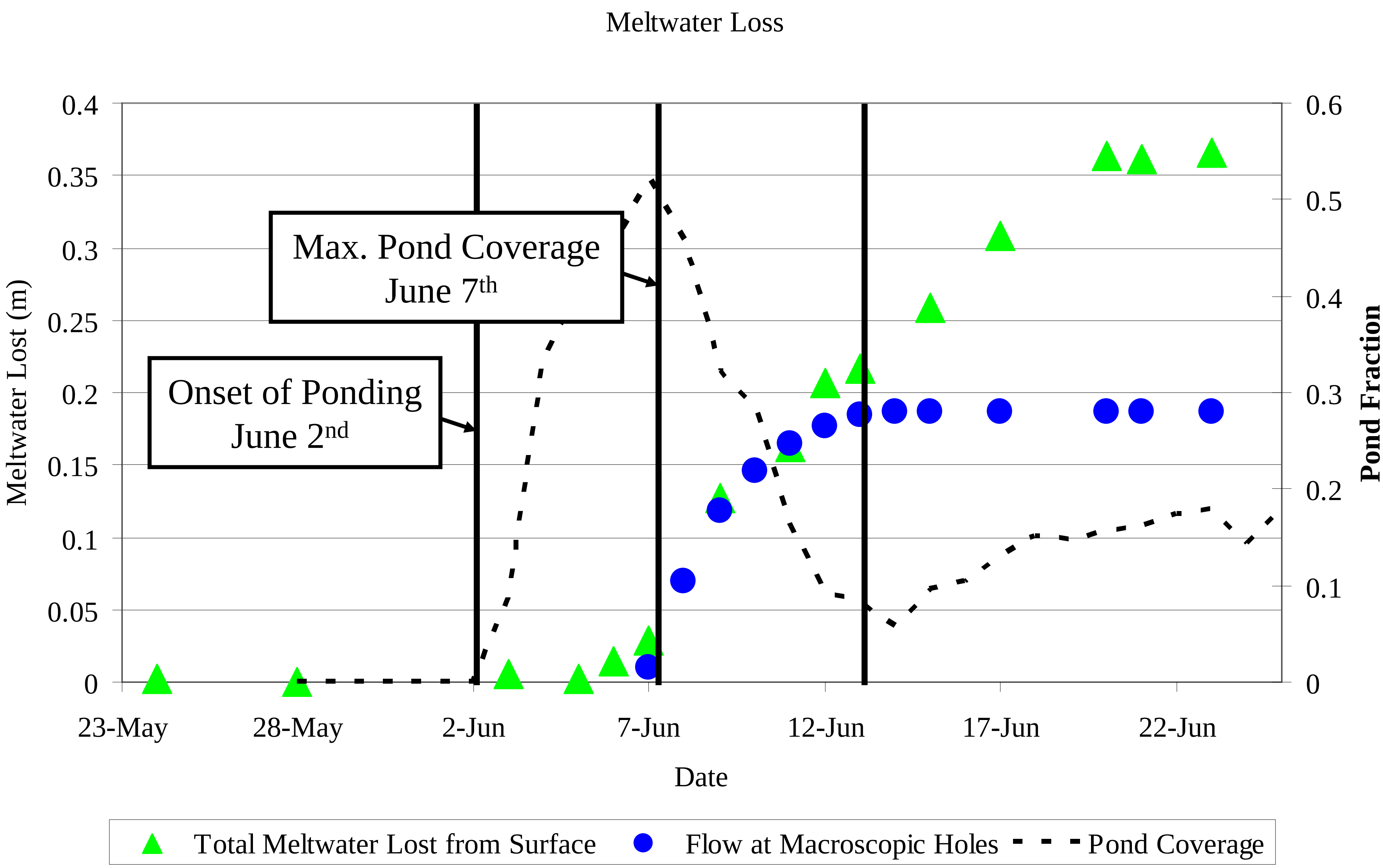

Meltwater Loss
Meltwater Lost (m)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
22-May
1-Jun
11-Jun
21-Jun
Date
Total Meltwater Lost from Surface

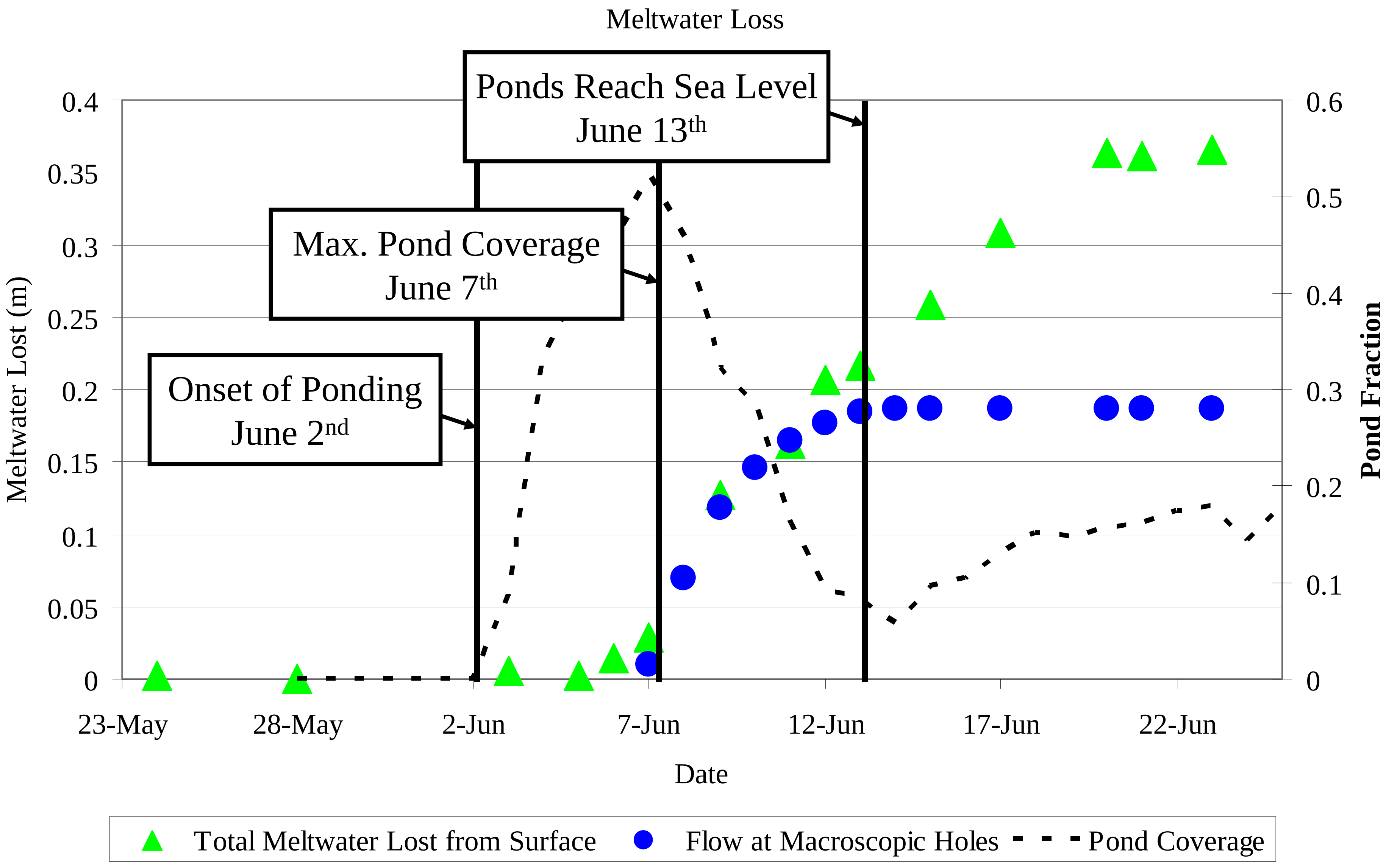

~50m
Photo: Chris Petrich

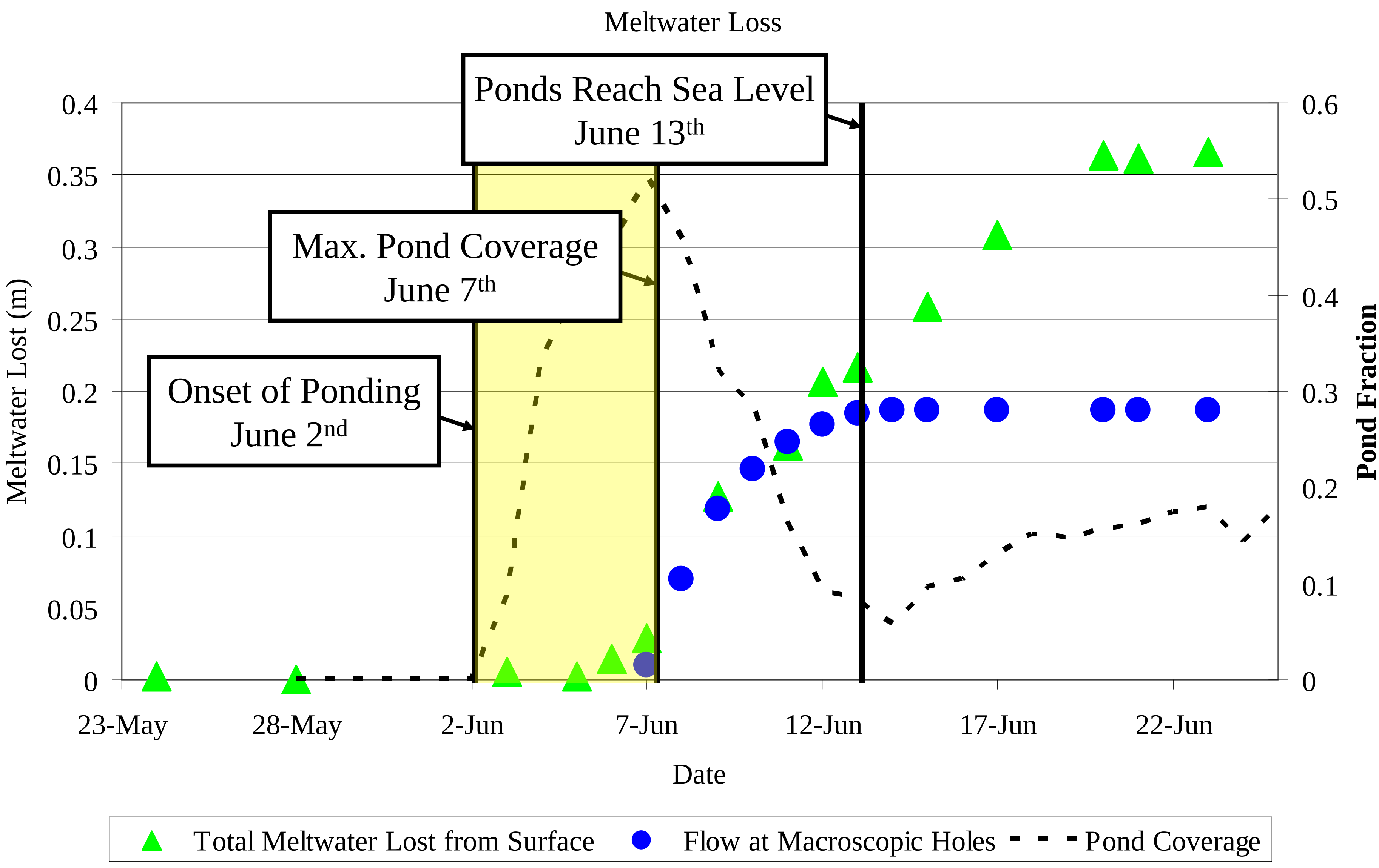

Meltwater Loss
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
Meltwater Lost (m)
22-May
27-May
1-Jun
6-Jun
11-Jun
16-Jun
21-Jun
26-Jun
Date
Total Meltwater Lost from Surface
Flow at Macroscopic Holes


Meltwater Loss
Meltwater Lost (m)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Pond Fraction
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

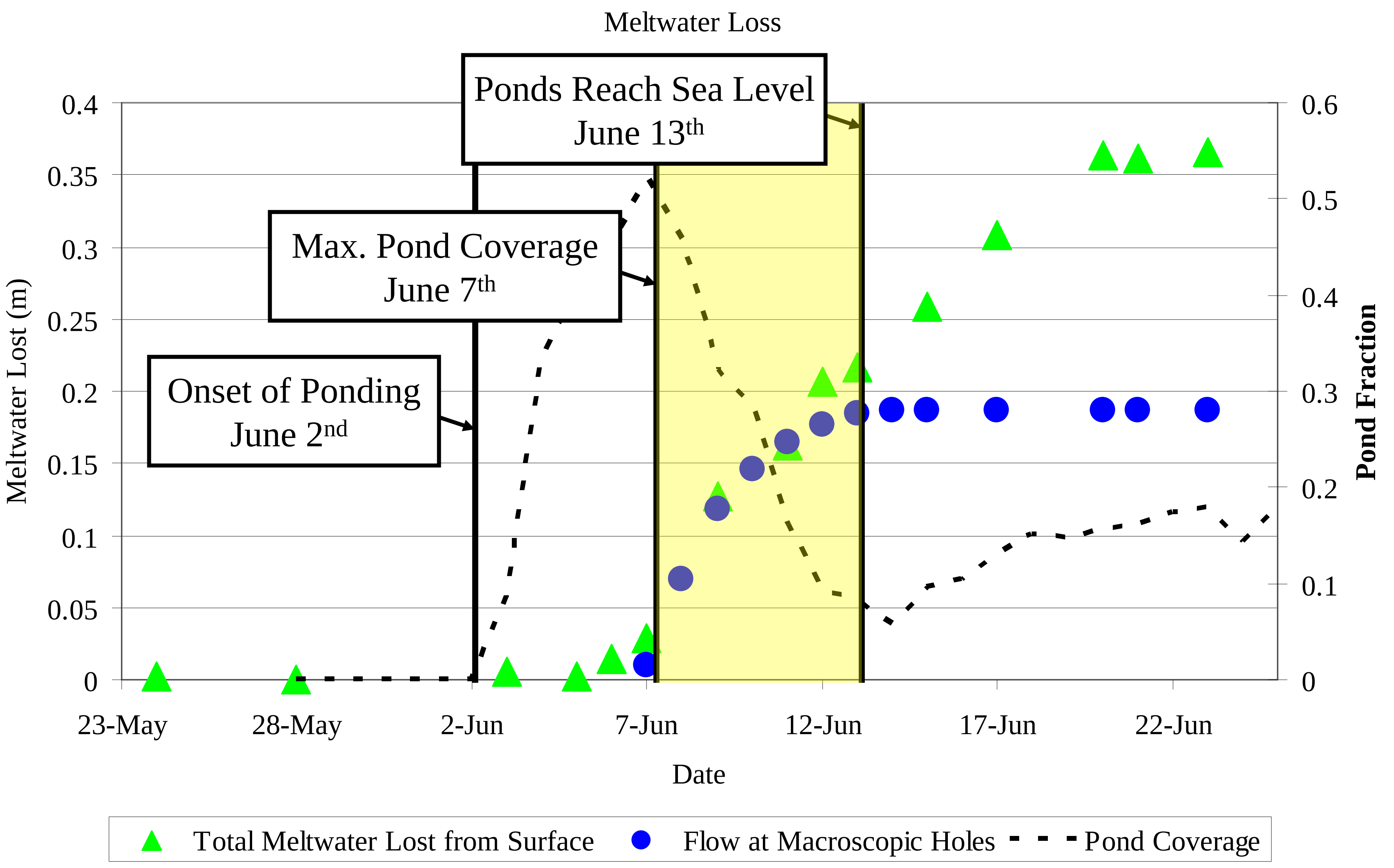

Meltwater Loss
Meltwater Lost (m)
Pond Fraction
Date
Onset of Ponding June 2nd
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.6
0.5
0.4
0.3
0.2
0.1
0
23-May
28-May
2-Jun
7-Jun
12-Jun
17-Jun
22-Jun
Total Meltwater Lost from Surface
Flow at Macroscopic Holes
Pond Coverage


Meltwater Loss
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

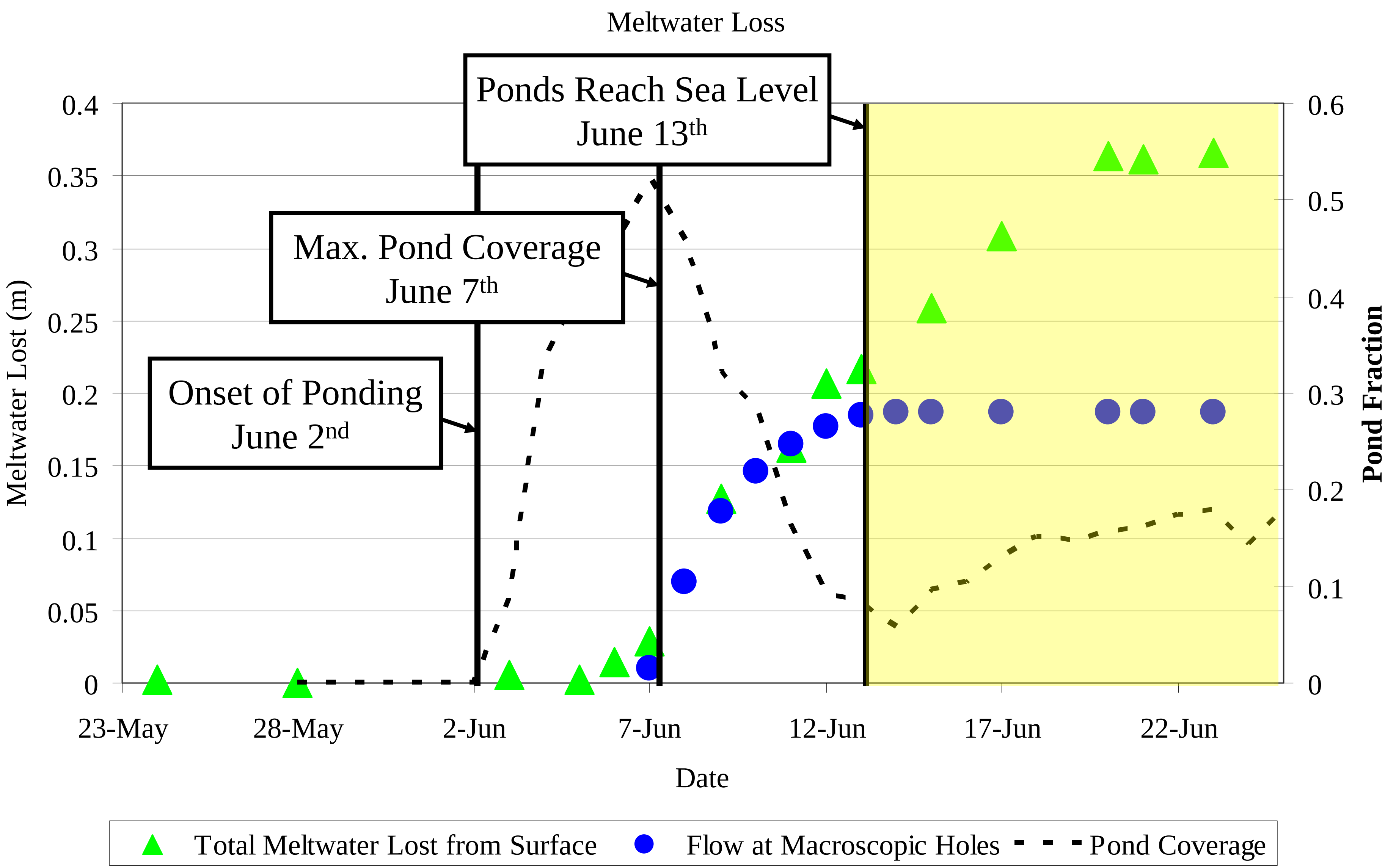

Meltwater Loss
Ponds Reach Sea Level
June 13th
Max. Pond Coverage
June 7th
Onset of Ponding
June 2nd
Meltwater Lost (m)
Pond Fraction
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.6
0.5
0.4
0.3
0.2
0.1
0
23-May
28-May
2-Jun
7-Jun
12-Jun
17-Jun
22-Jun
Date
Total Meltwater Lost from Surface
Flow at Macroscopic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



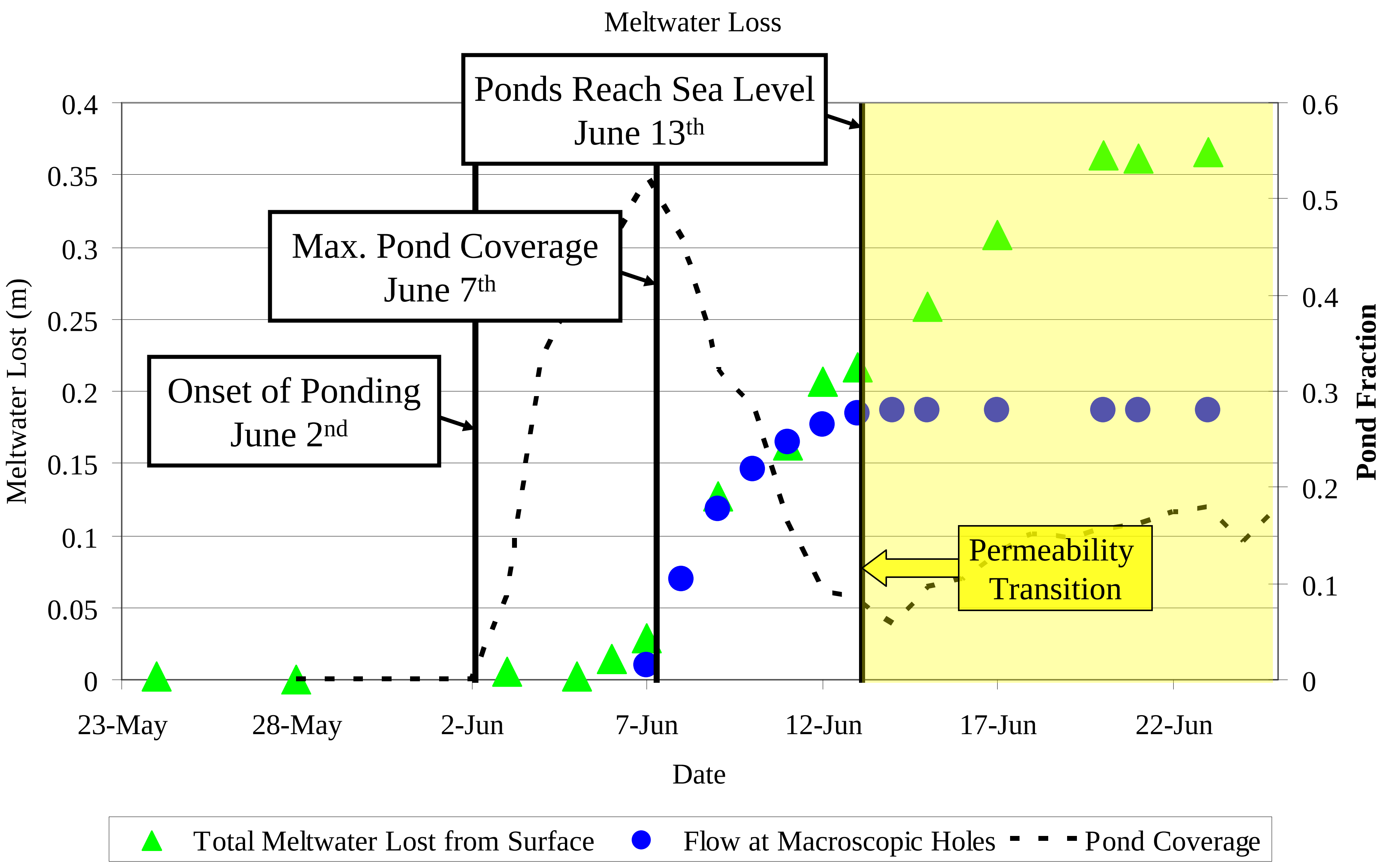
Meltwater Loss
Ponds Reach Sea Level
June 13th
Max. Pond Coverage
June 7th
Onset of Ponding
June 2nd
Meltwater Lost (m)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Pond Fraction
0.6
0.5
0.4
0.3
0.2
0.1
0
23-May
28-May
2-Jun
7-Jun
12-Jun
17-Jun
22-Jun
Date
Total Meltwater Lost from Surface
Flow at Macroscopic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



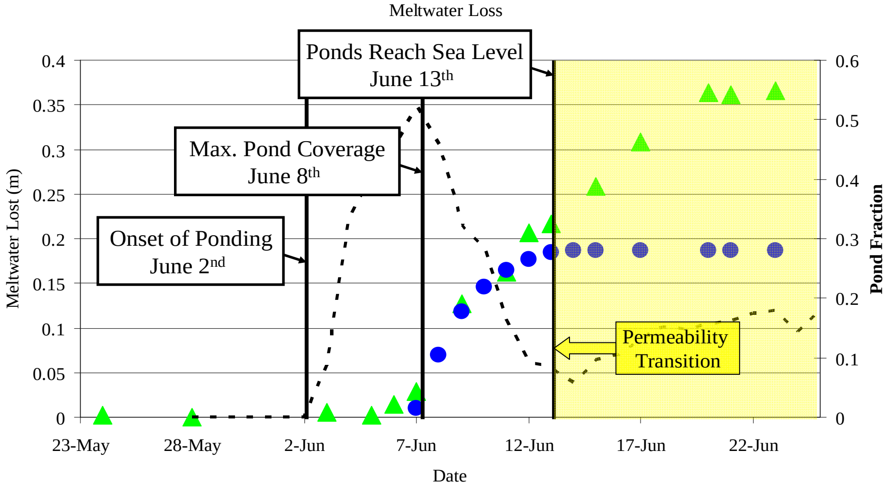
Meltwater Loss
Ponds Reach Sea Level
June 13th
Max. Pond Coverage
June 7th
Onset of Ponding
June 2nd
Meltwater Lost (m)
Pond Fraction
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.6
0.5
0.4
0.3
0.2
0.1
0
23-May
28-May
2-Jun
7-Jun
12-Jun
17-Jun
22-Jun
Date
Total Meltwater Lost from Surface
Flow at Macroscopic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



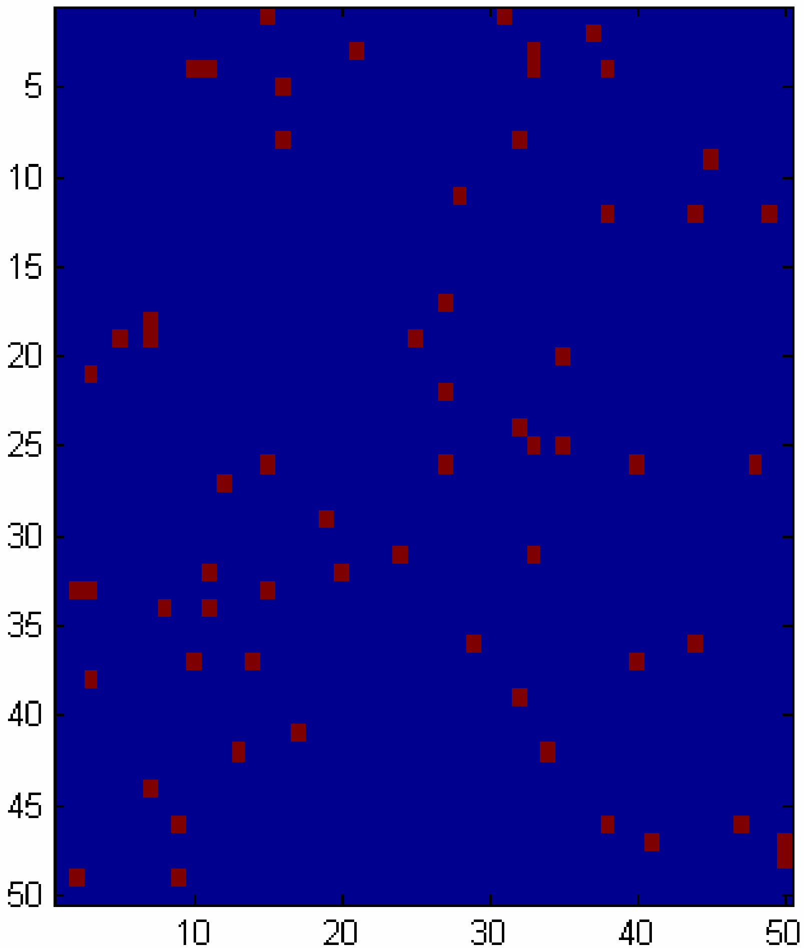
Changes in the meltwater balance drive pond coverage

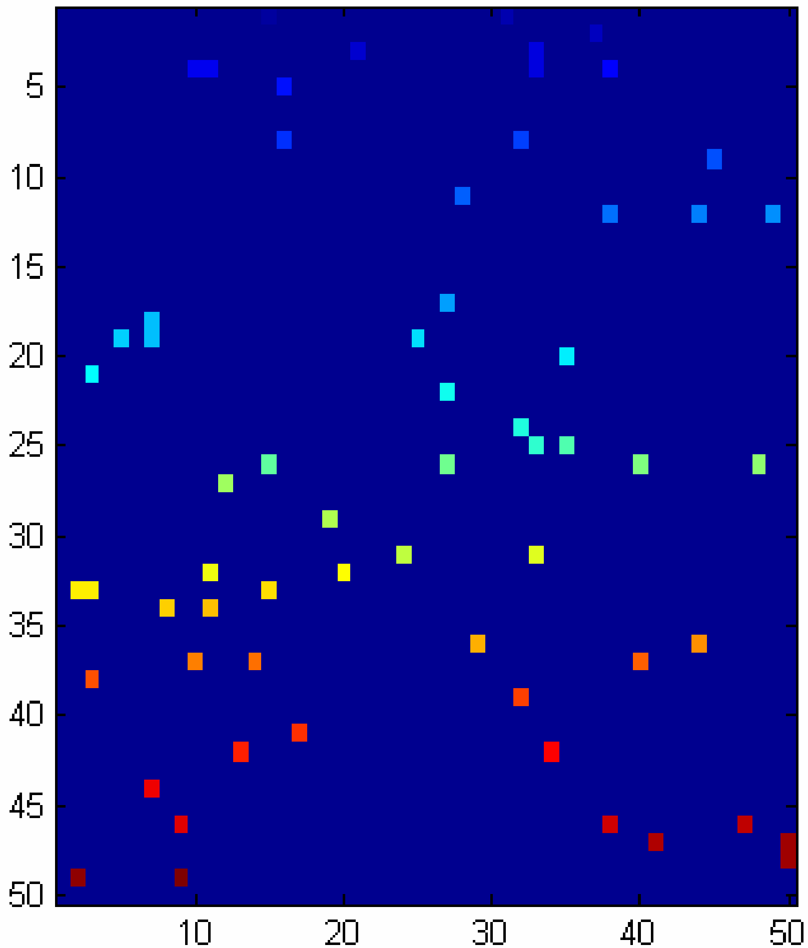
- Why do brine channels spontaneously open and enlarge?

- What causes the permeability transition?



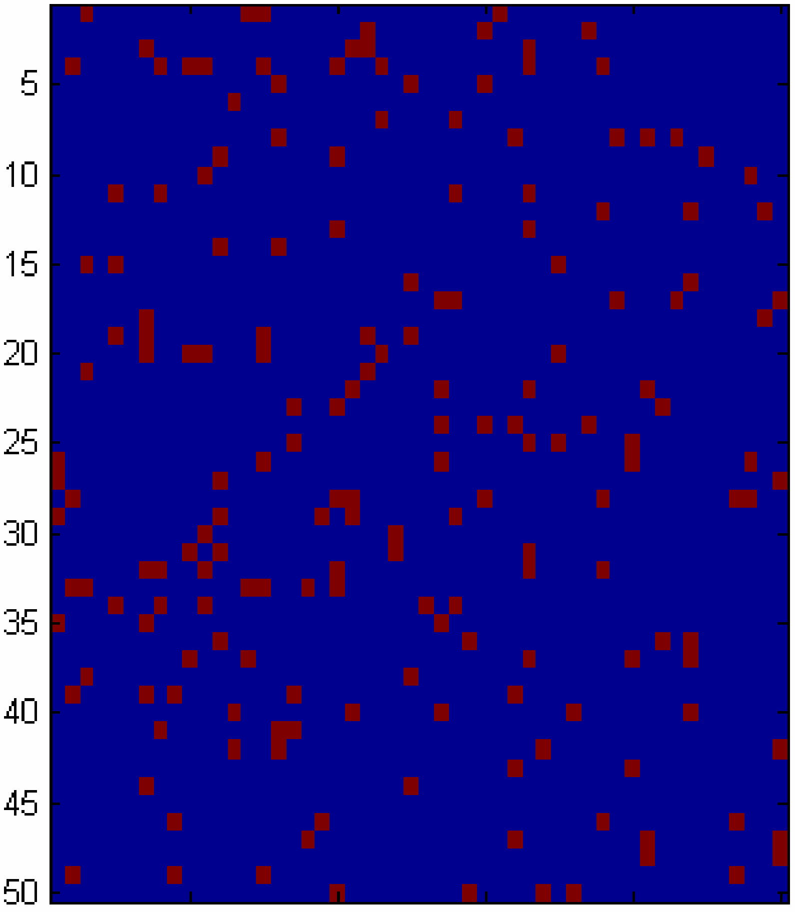
A Conceptual Model: 2D Lattice

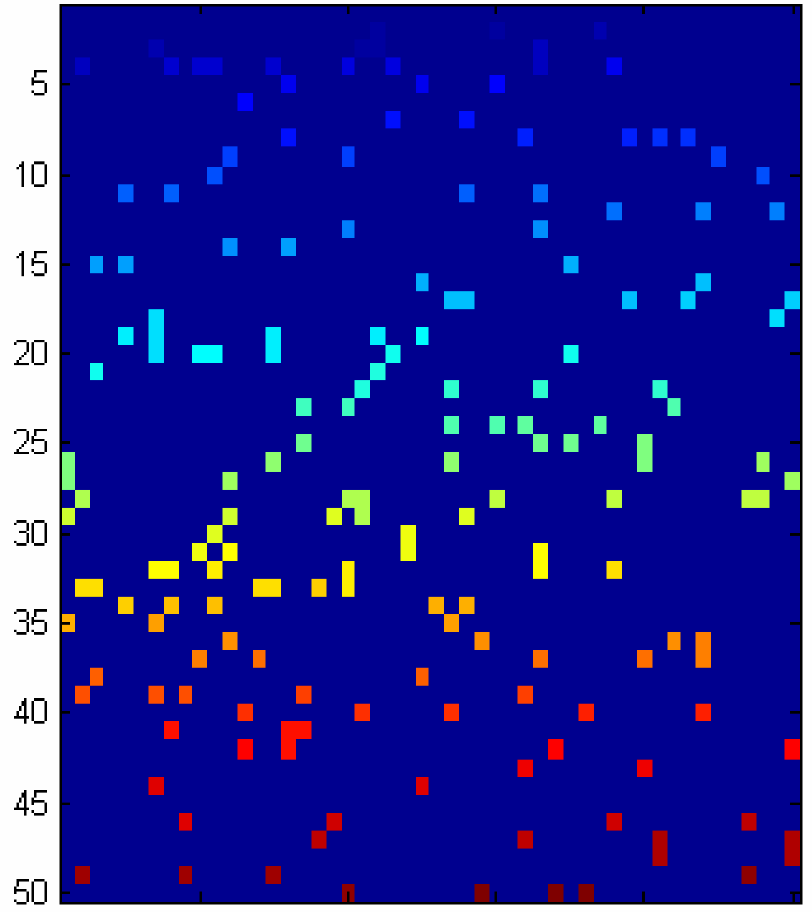




2.5% Liquid

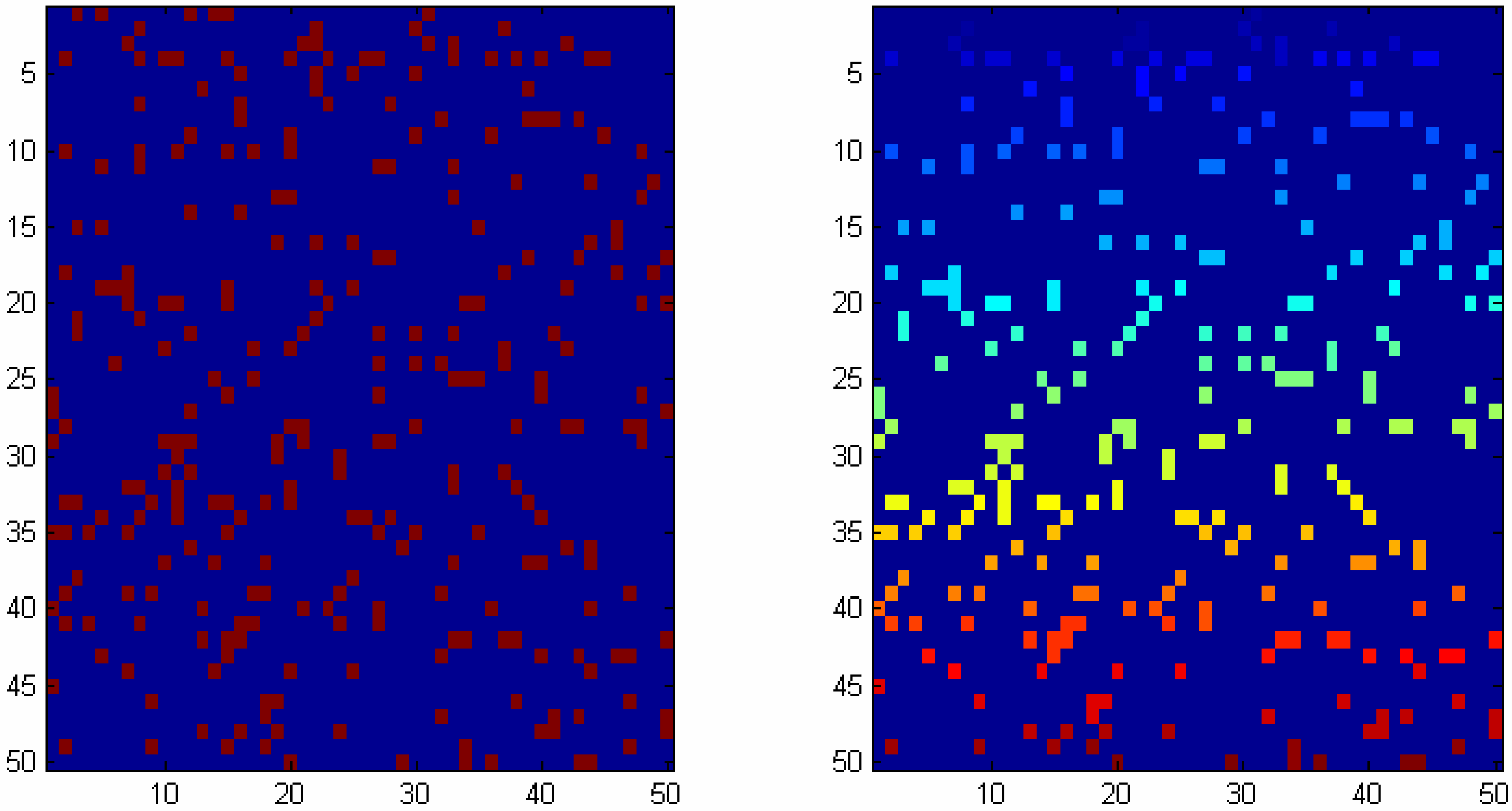
A Conceptual Model: 2D Lattice





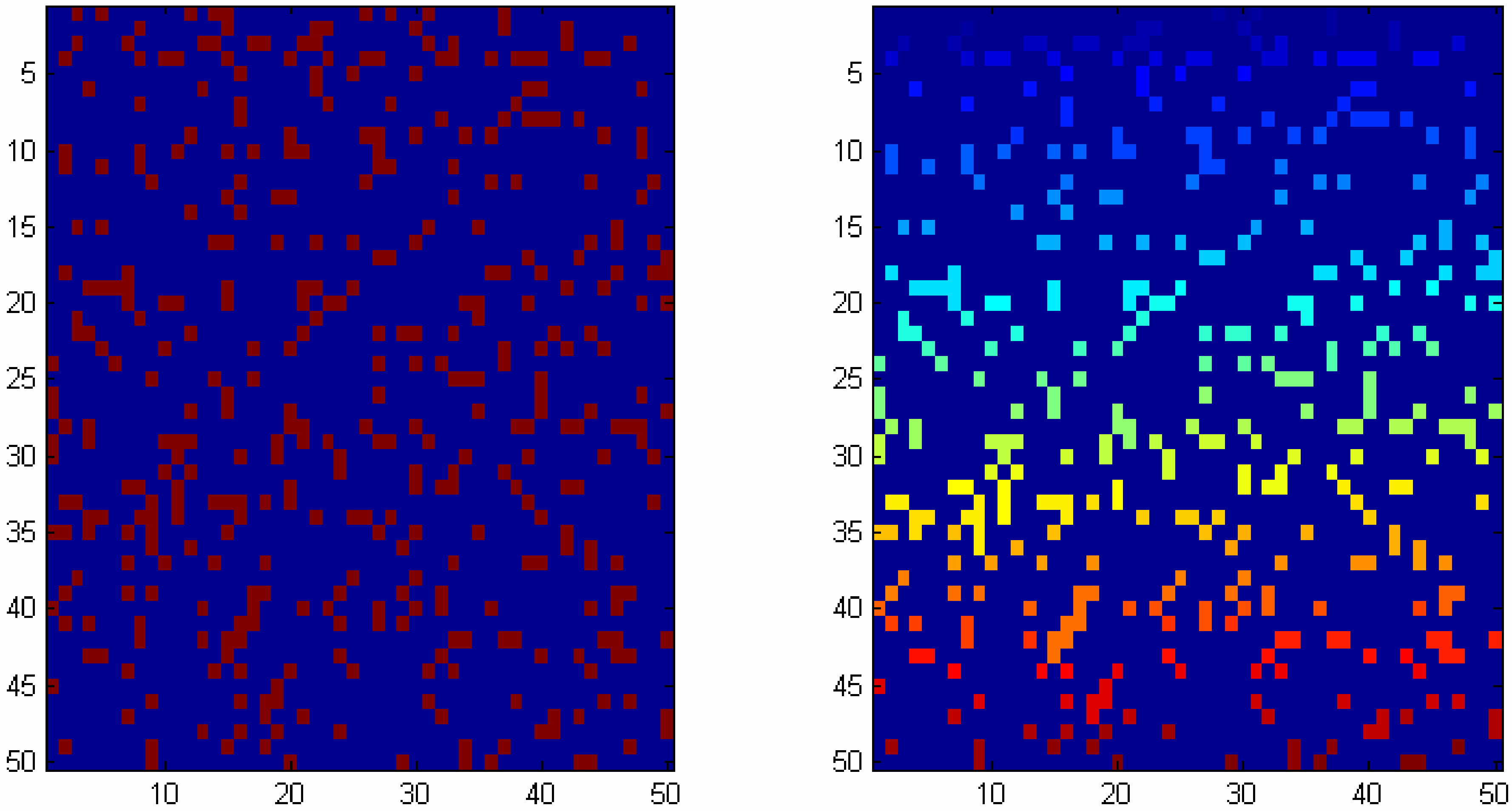
5% Liquid

A Conceptual Model: 2D Lattice

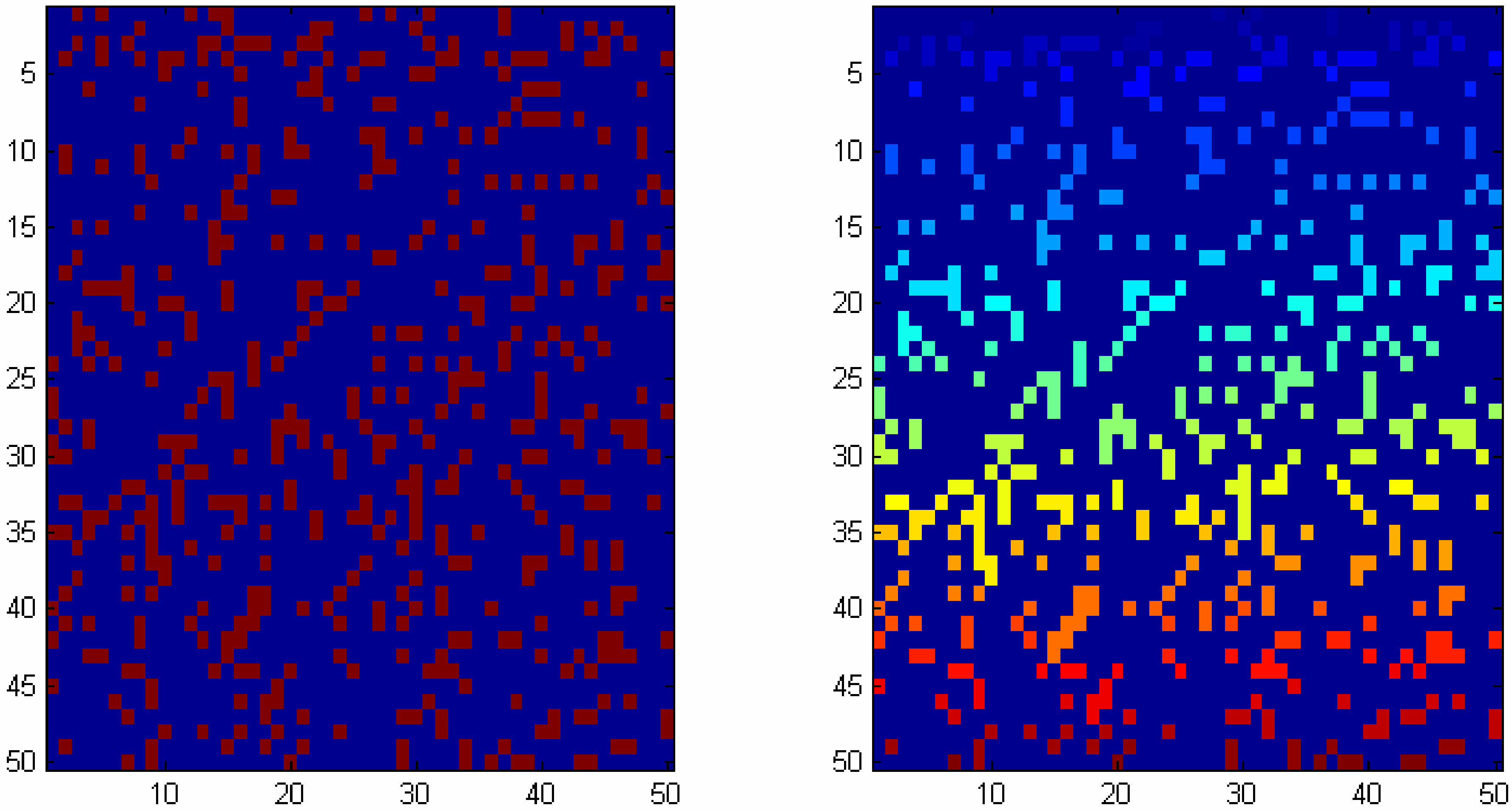


7.5% Liquid

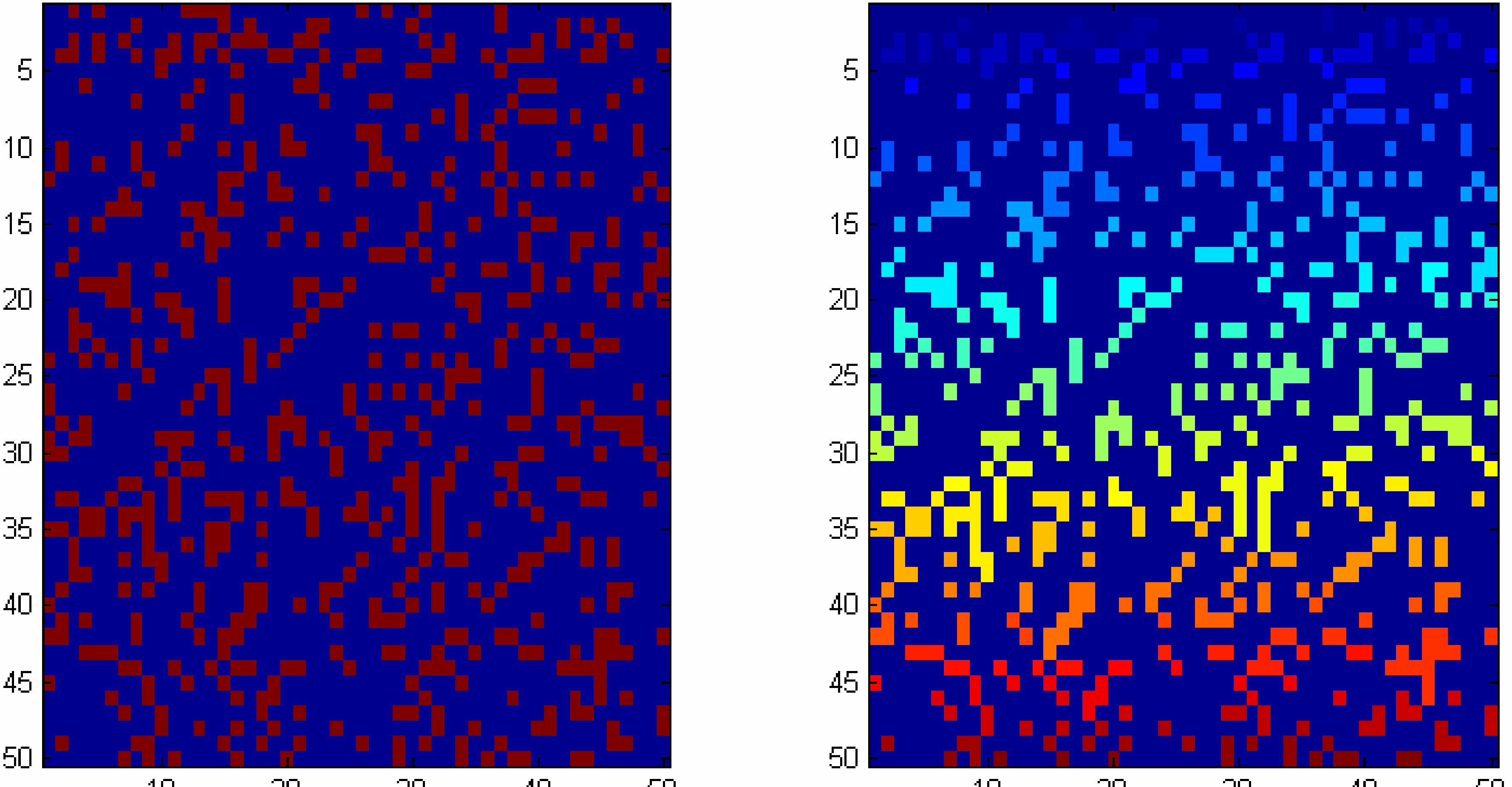
A Conceptual Model: 2D Lattice



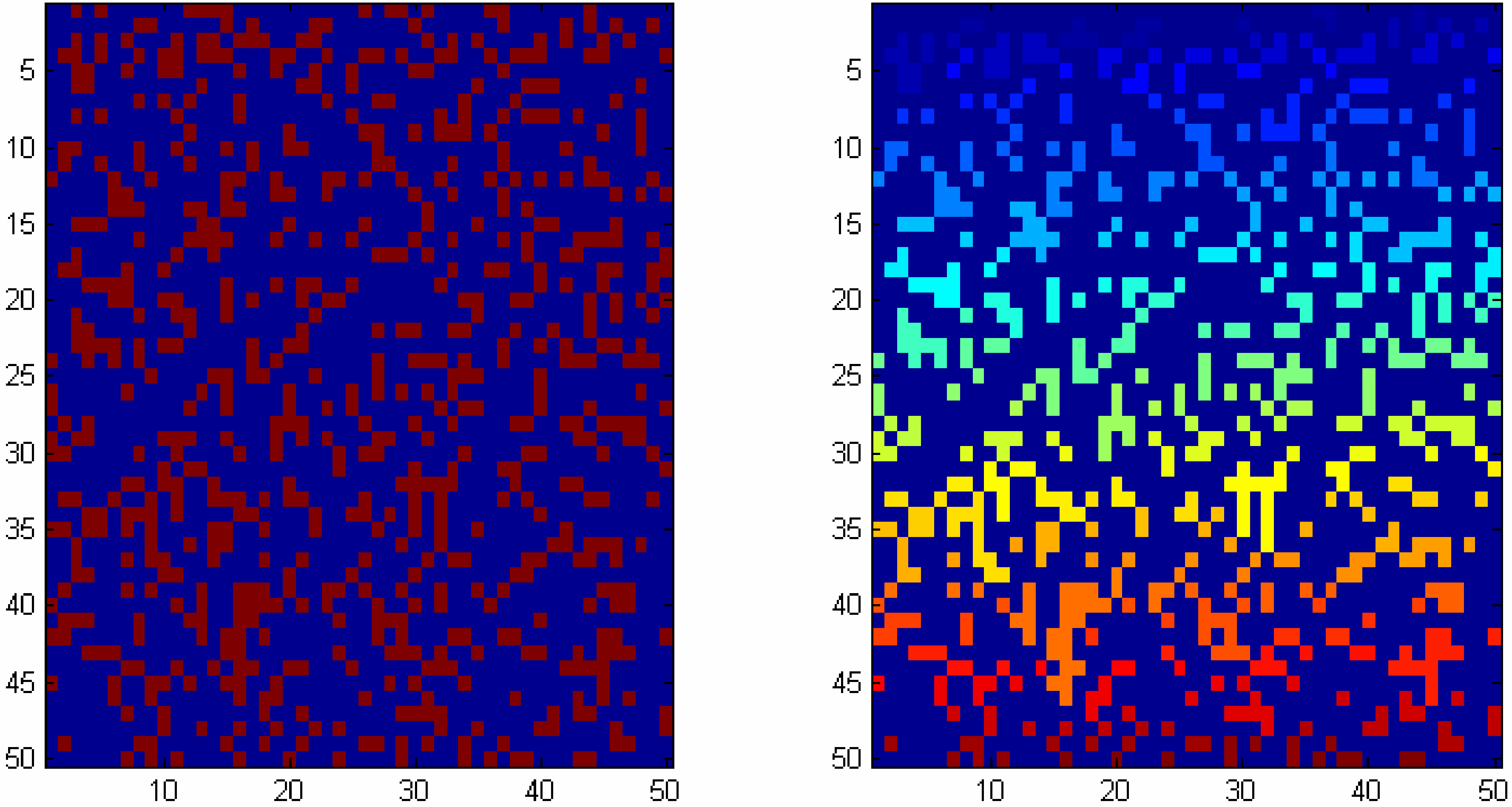
A Conceptual Model: 2D Lattice



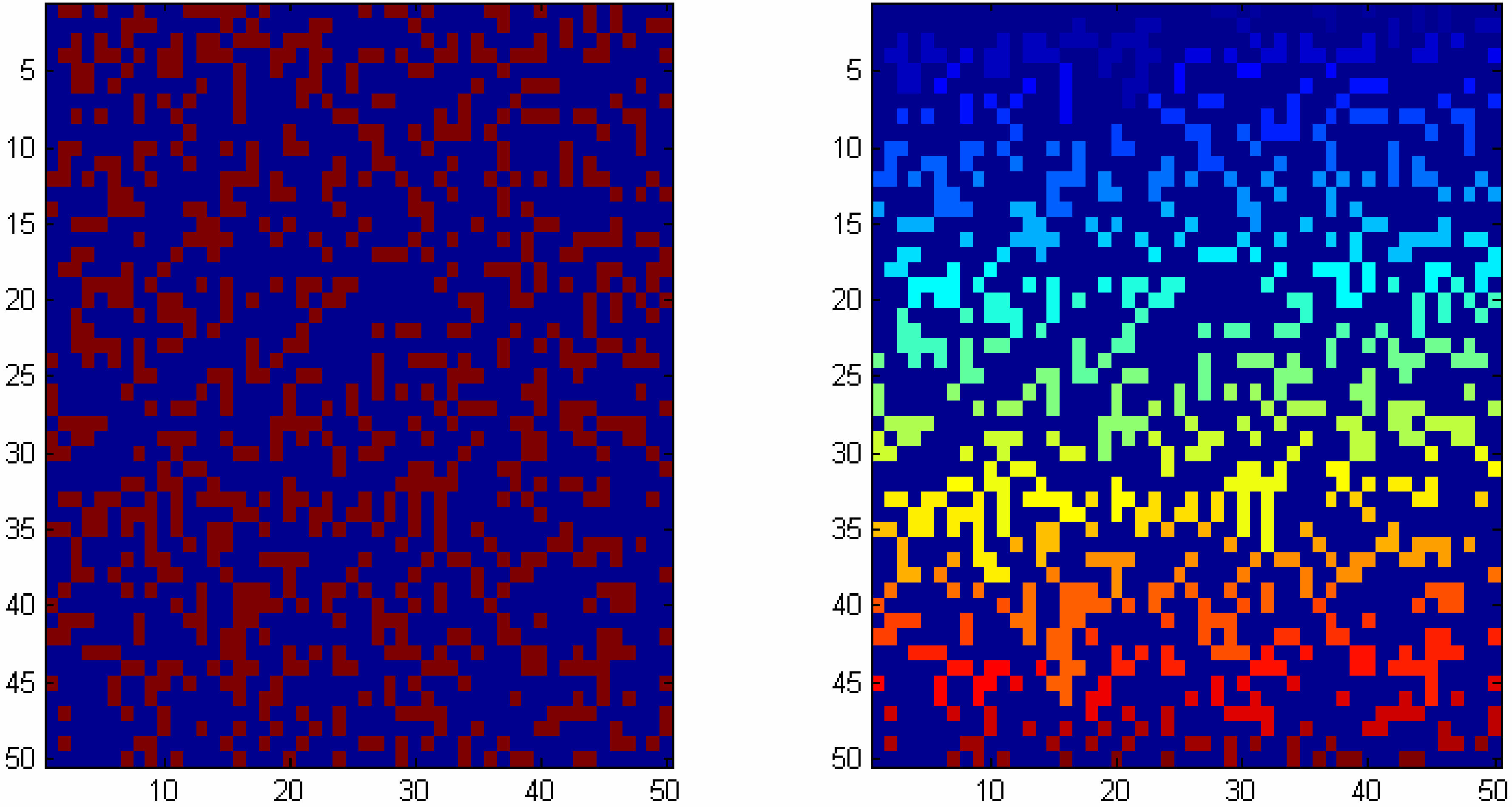
A Conceptual Model: 2D Lattice



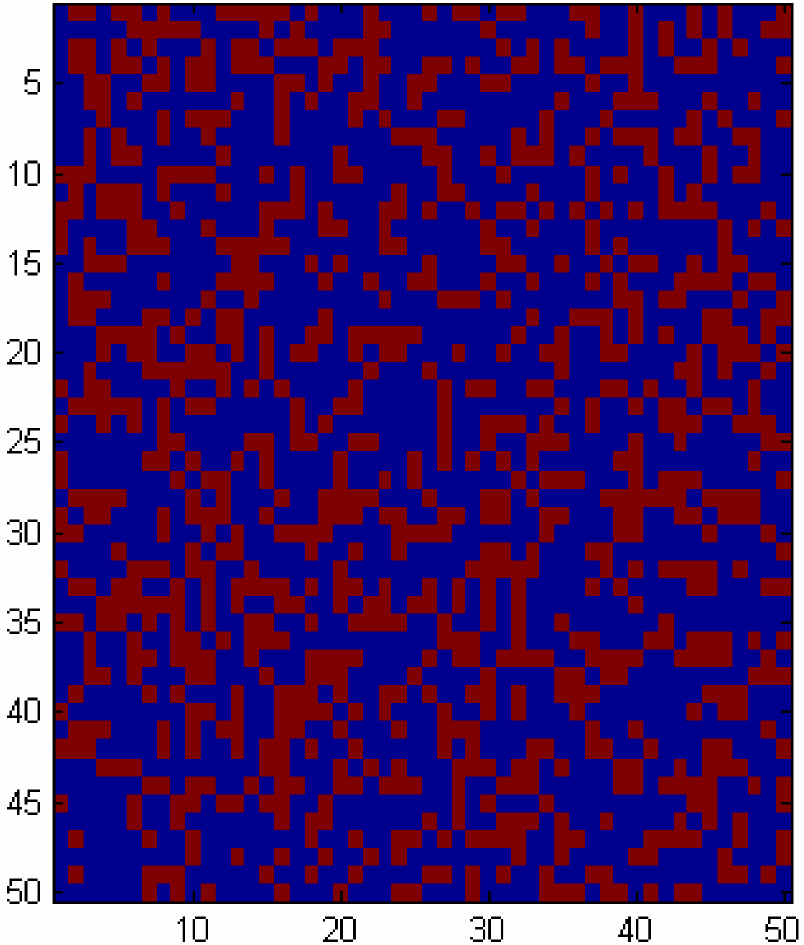
A Conceptual Model: 2D Lattice

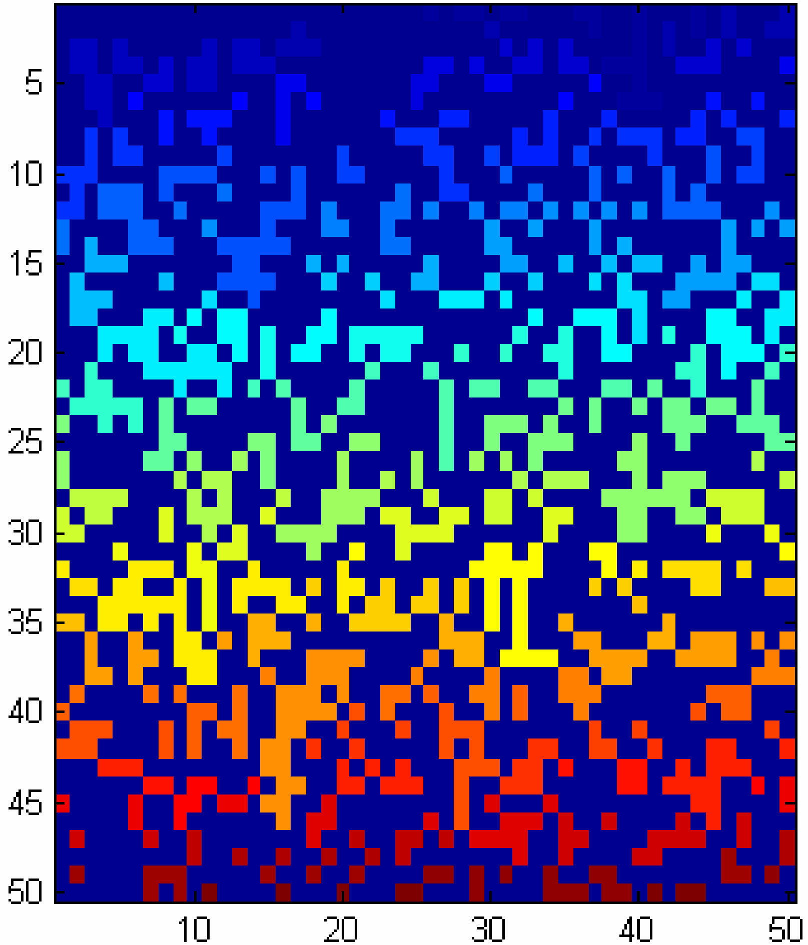


A Conceptual Model: 2D Lattice

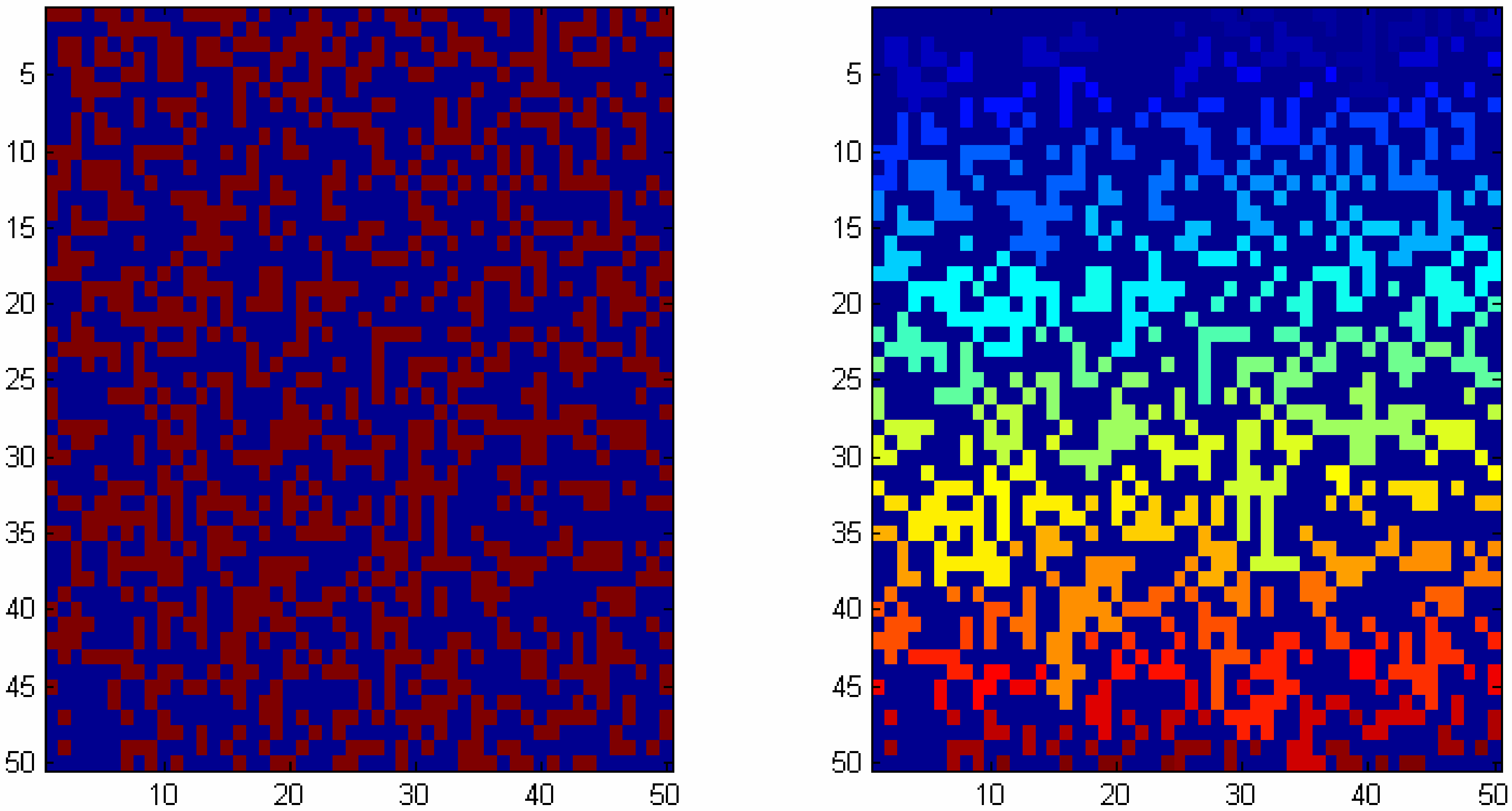


A Conceptual Model: 2D Lattice

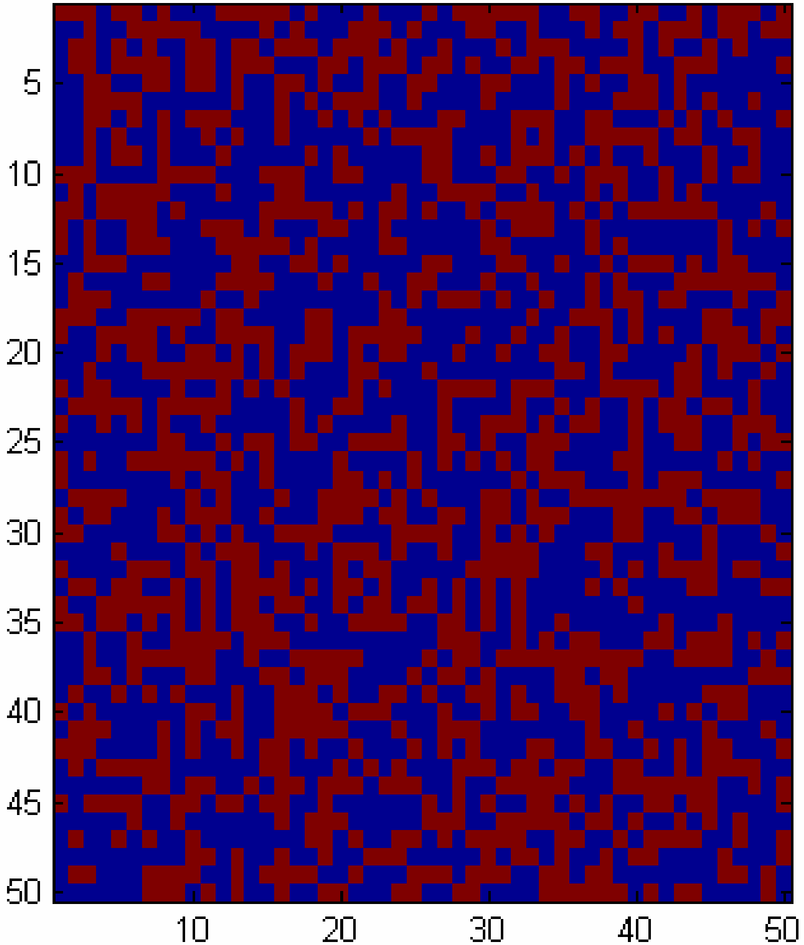


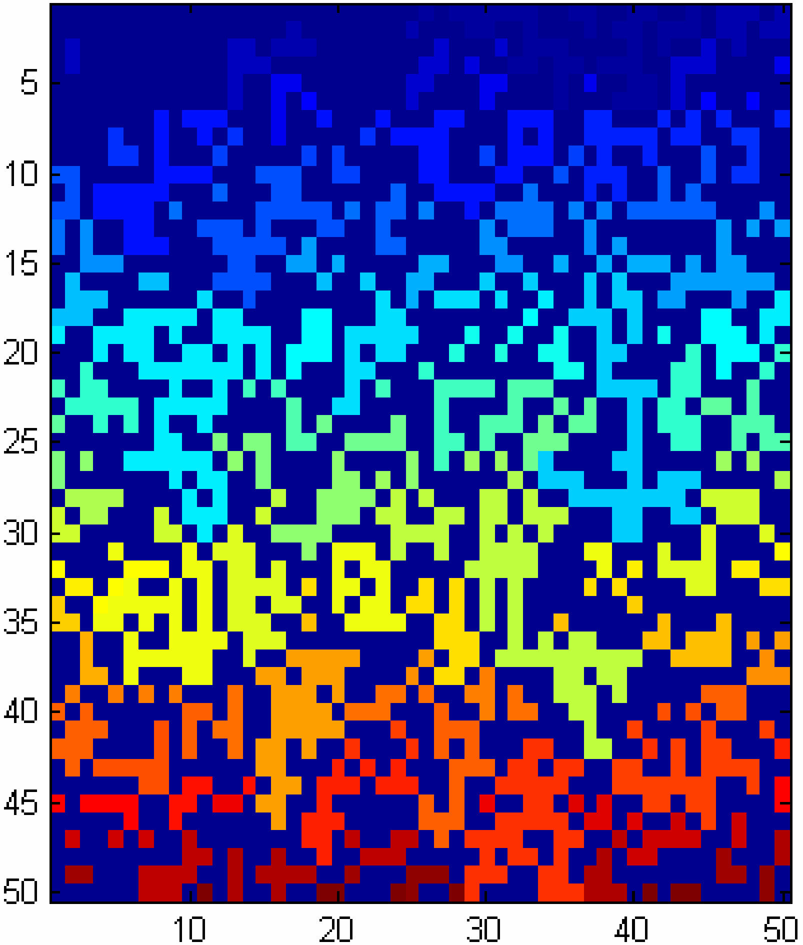


A Conceptual Model: 2D Lattice

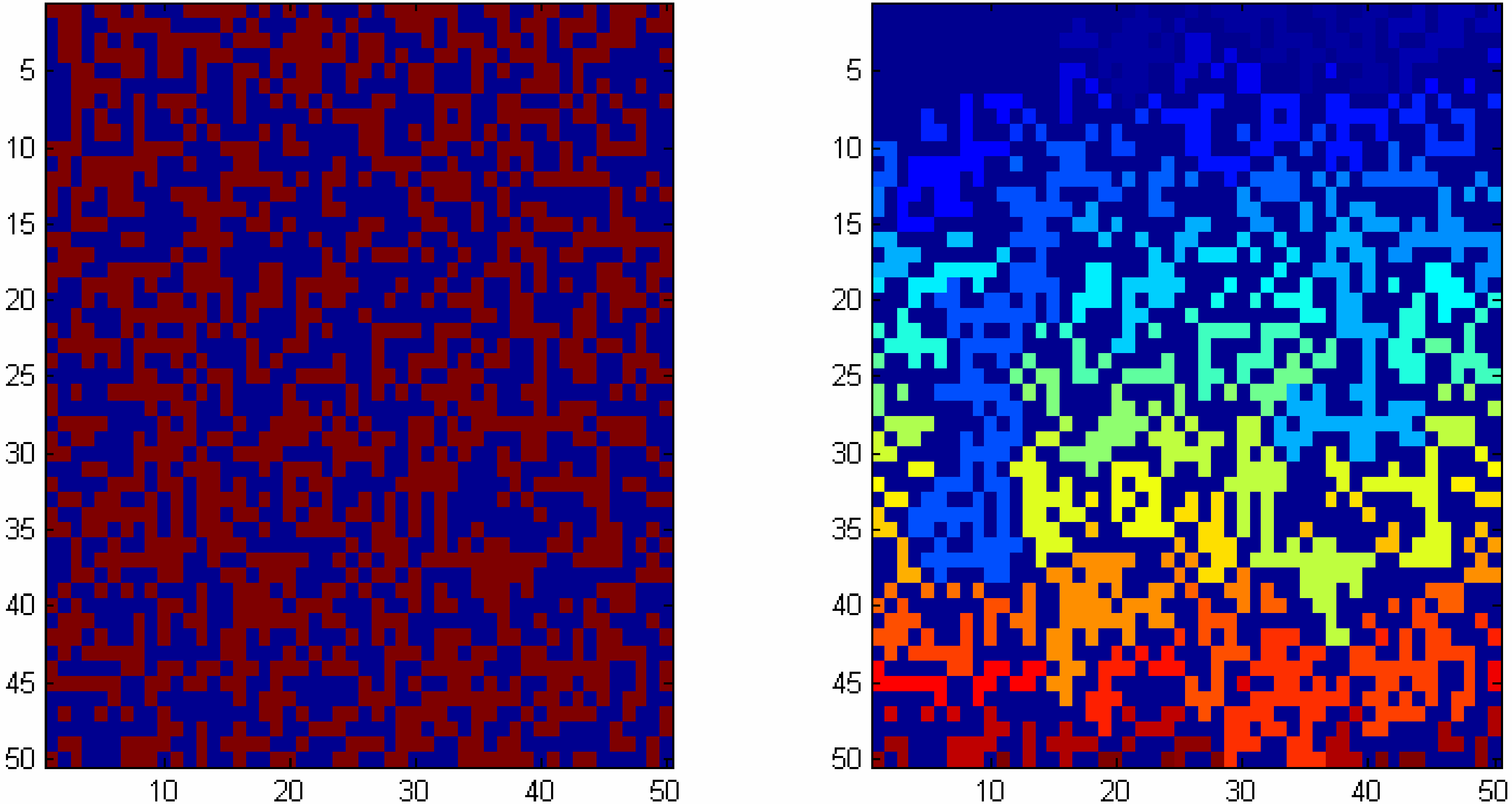


A Conceptual Model: 2D Lattice

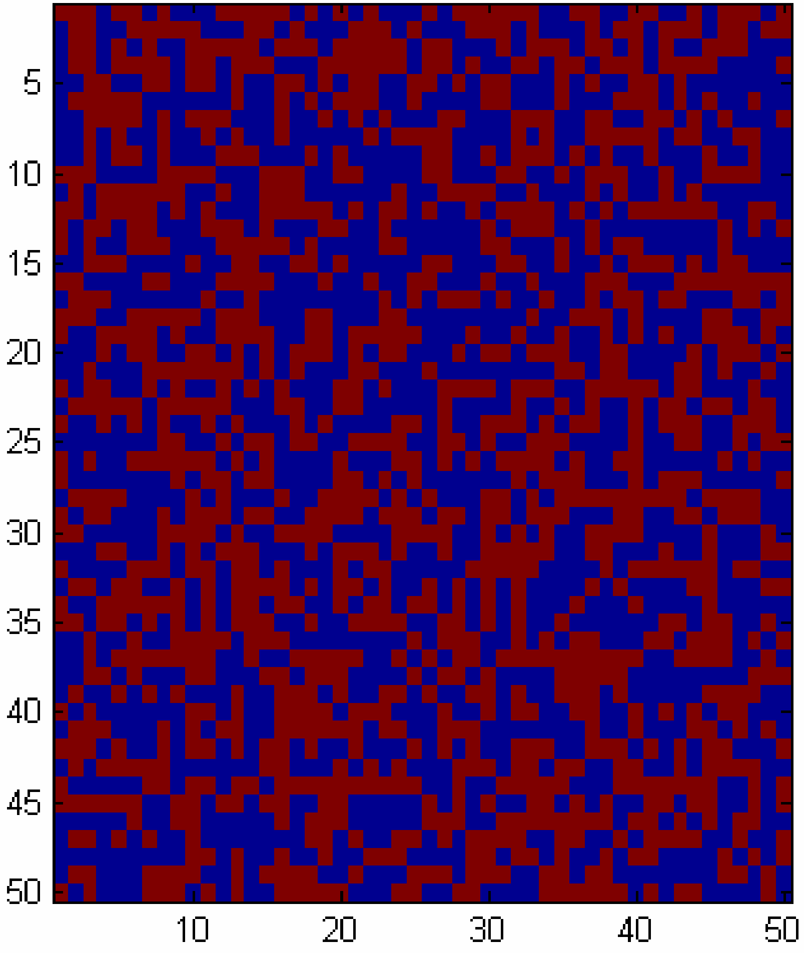


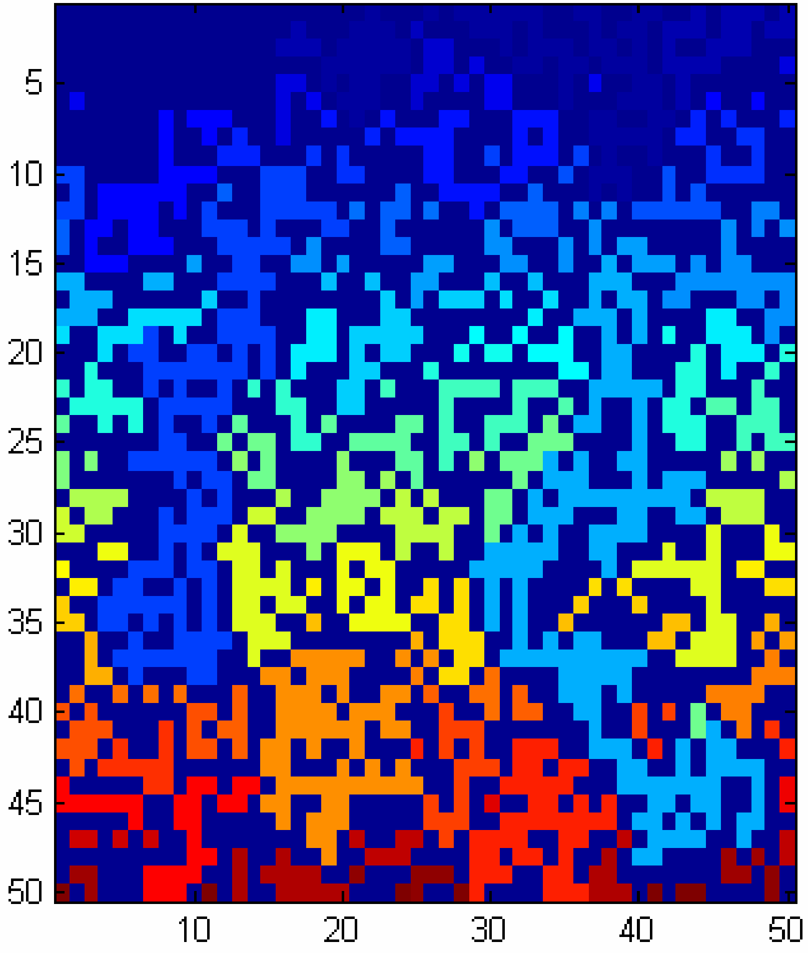


A Conceptual Model: 2D Lattice

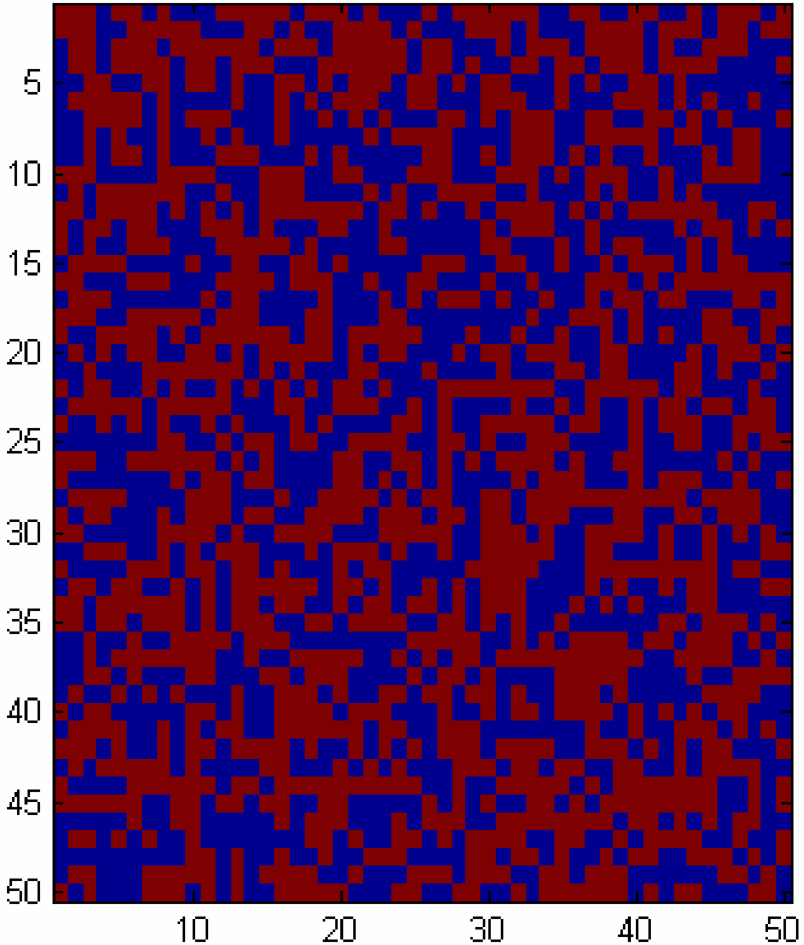


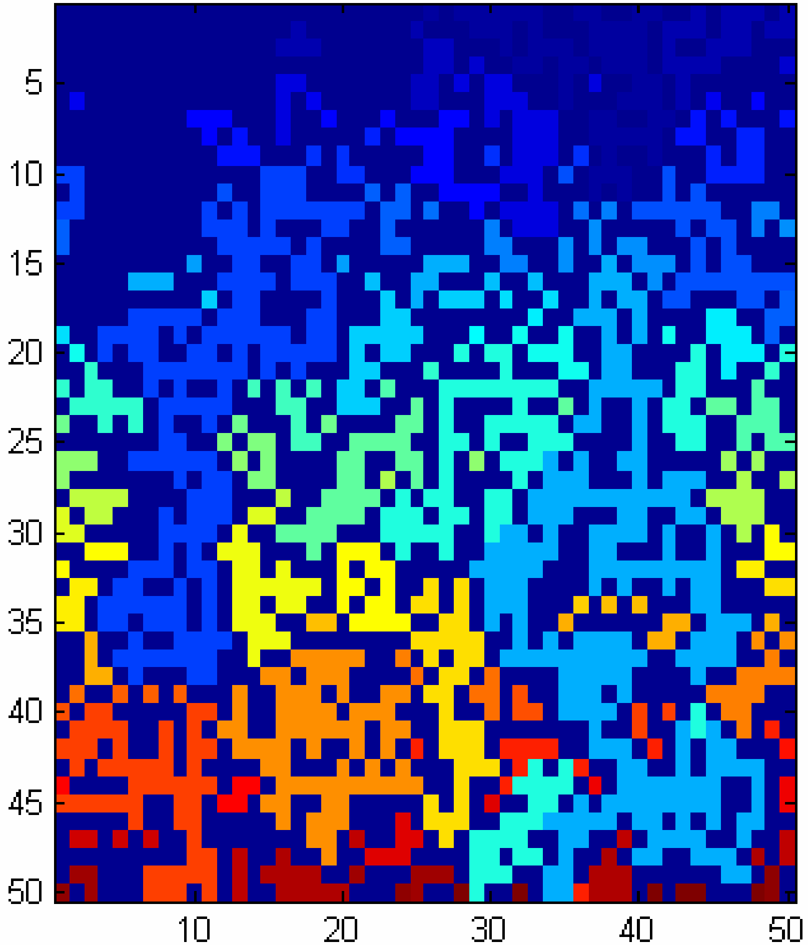
A Conceptual Model: 2D Lattice



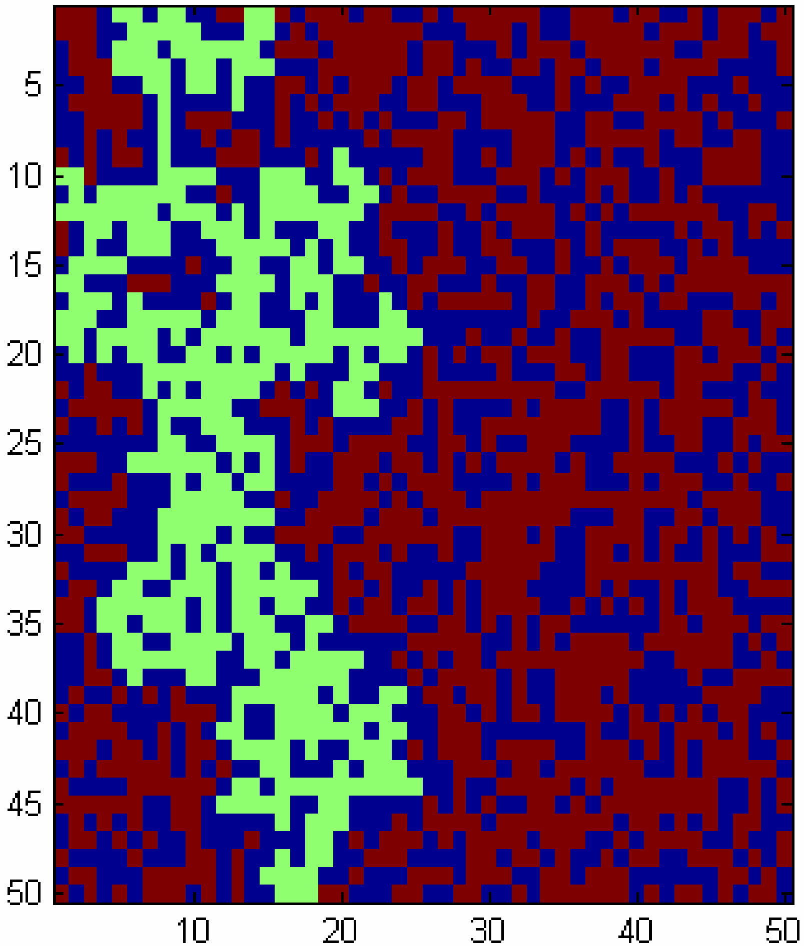


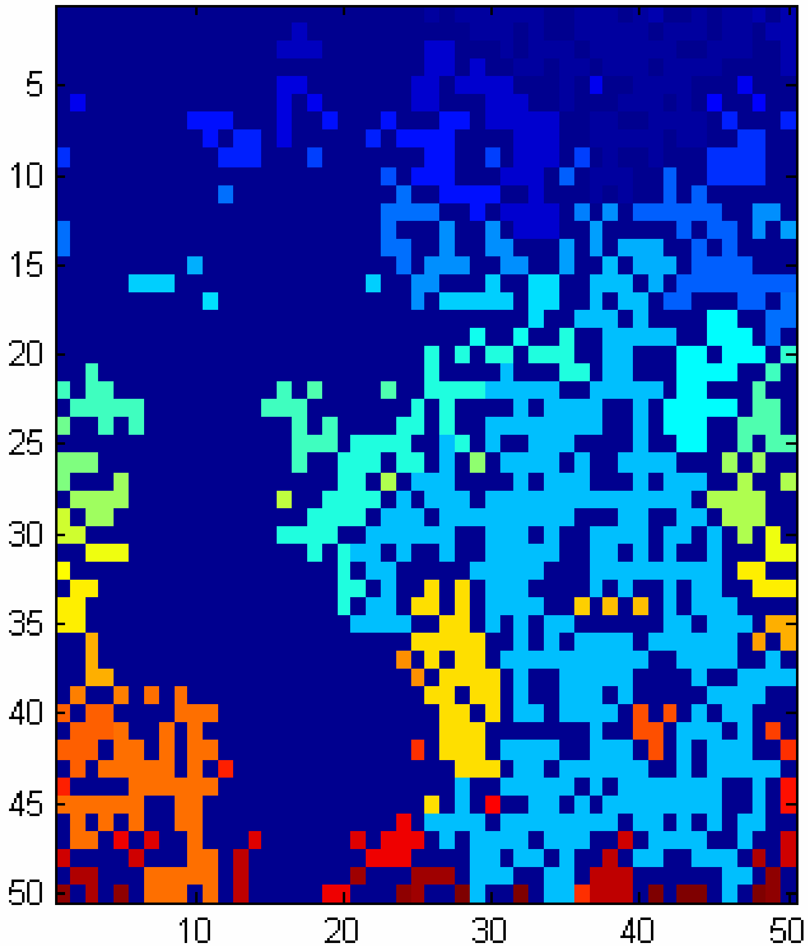
A Conceptual Model: 2D Lattice





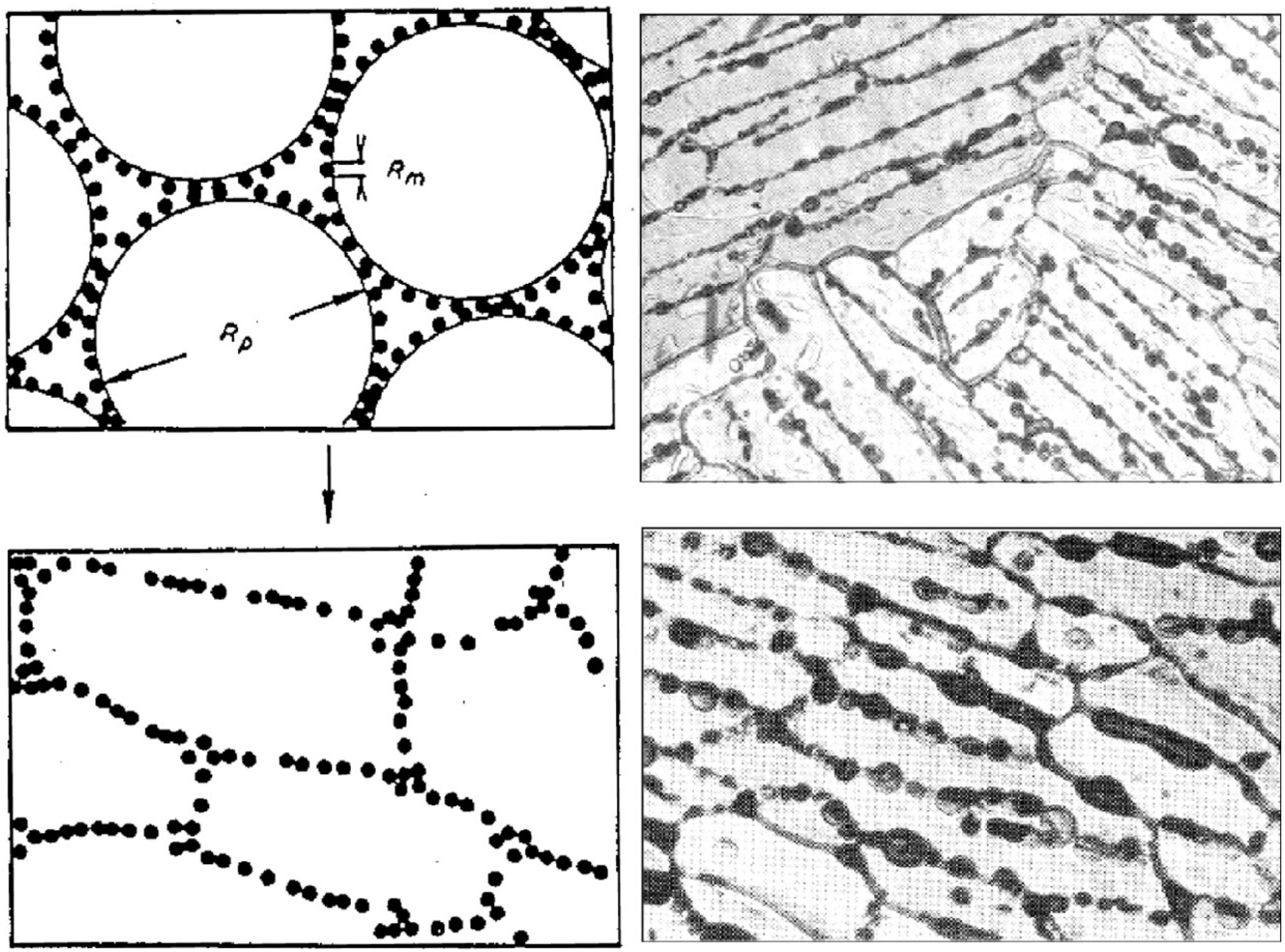
A Conceptual Model: 2D Lattice



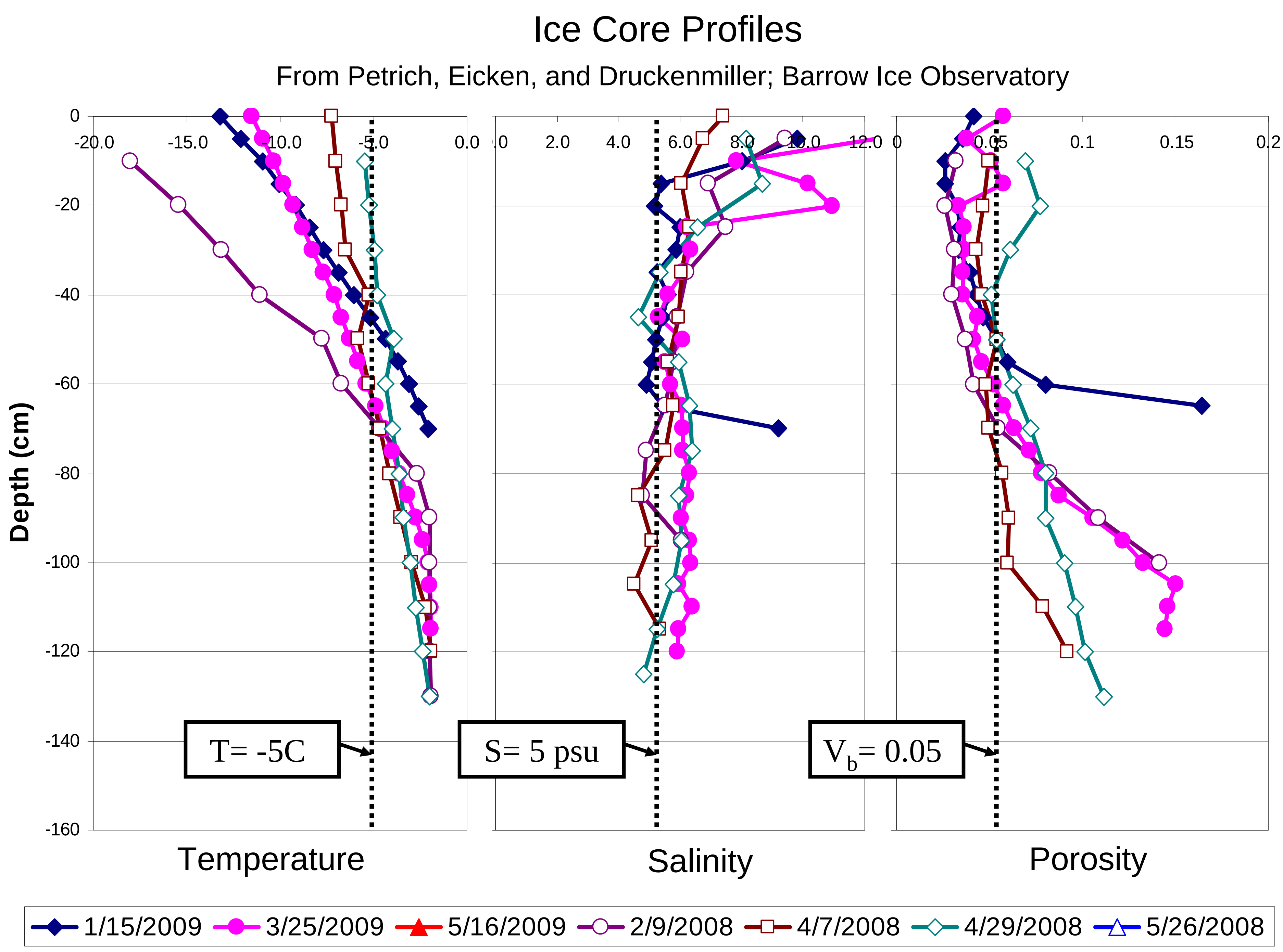


52% Liquid

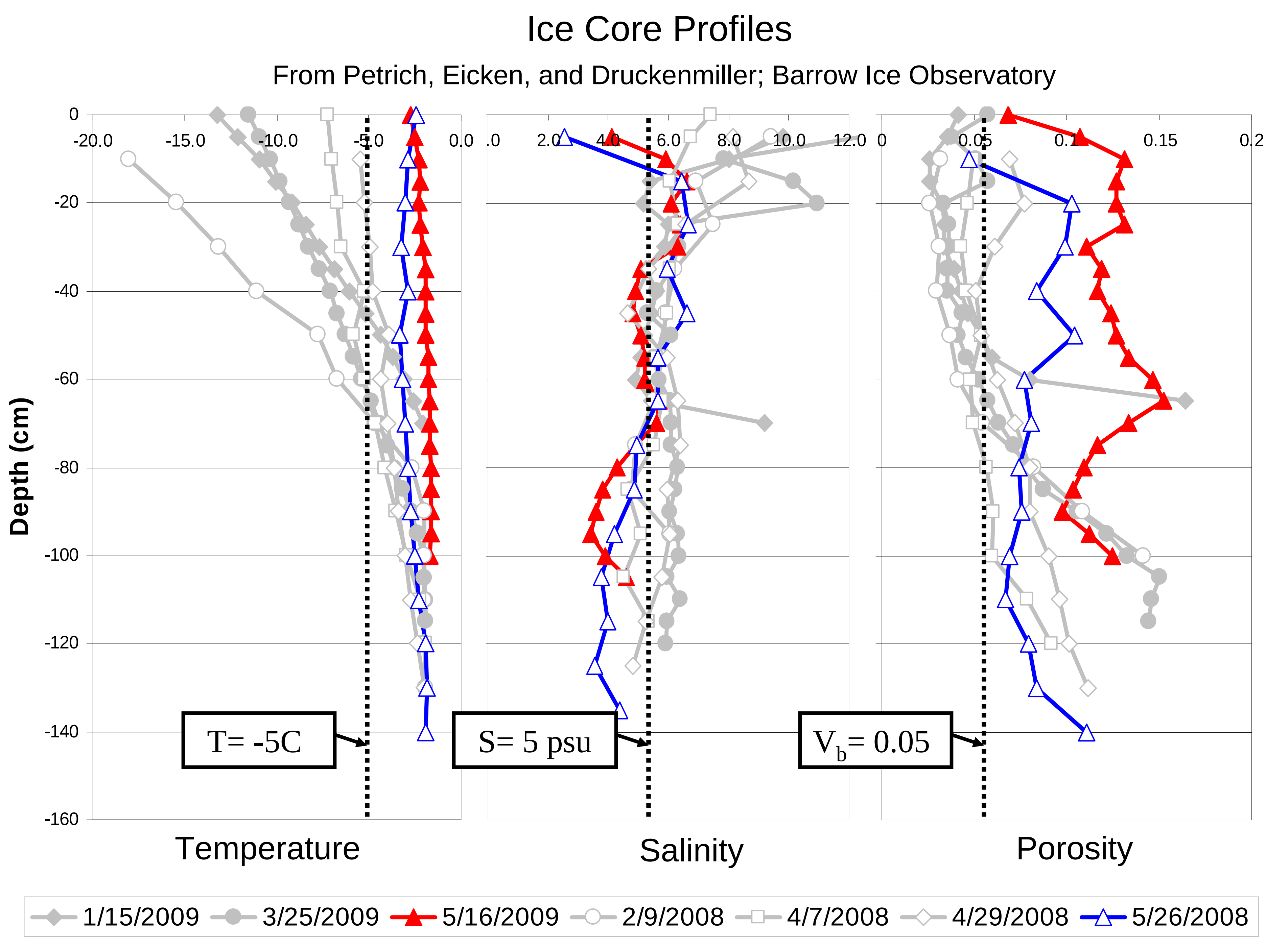
Compressed Powder Sea Ice

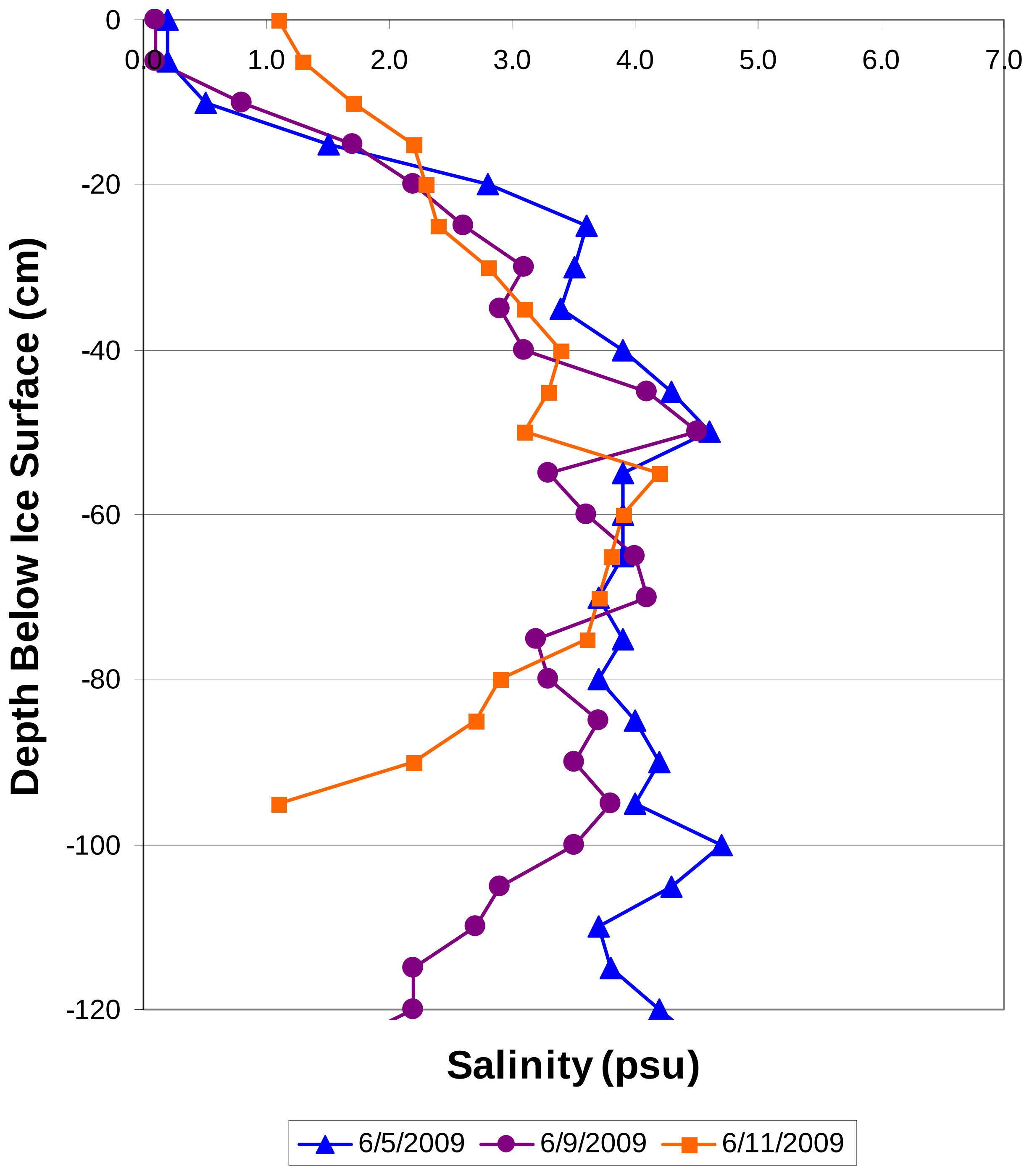


Golden, Ackley, and Lytle. "The Percolation Phase Transition in Ice." Science. Vol 232, 1998.



Ice Core Profiles
From Petrich, Eicken, and Druckenmiller; Barrow Ice Observatory
Depth (cm)
0
-20
-40
-60
-80
-100
-120
-140
-160
-20.0
-15.0
-10.0
-5.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
0
0.05
0.1
0.15
0.2
T= -5C
S= 5 psu
V$_b$= 0.05
Temperature
Salinity
Porosity
1/15/2009
3/25/2009
5/16/2009
2/9/2008
4/7/2008
4/29/2008
5/26/2008


Ice Core Profiles
From Petrich, Eicken, and Druckenmiller; Barrow Ice Observatory
Depth (cm)
0
-20
-40
-60
-80
-100
-120
-140
-160
-20.0
-15.0
-10.0
-5.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
0
0.05
0.1
0.15
0.2
T= -5C
S= 5 psu
V_b= 0.05
Temperature
Salinity
Porosity
1/15/2009
3/25/2009
5/16/2009
2/9/2008
4/7/2008
4/29/2008
5/26/2008



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

Photo: Chris Petrich

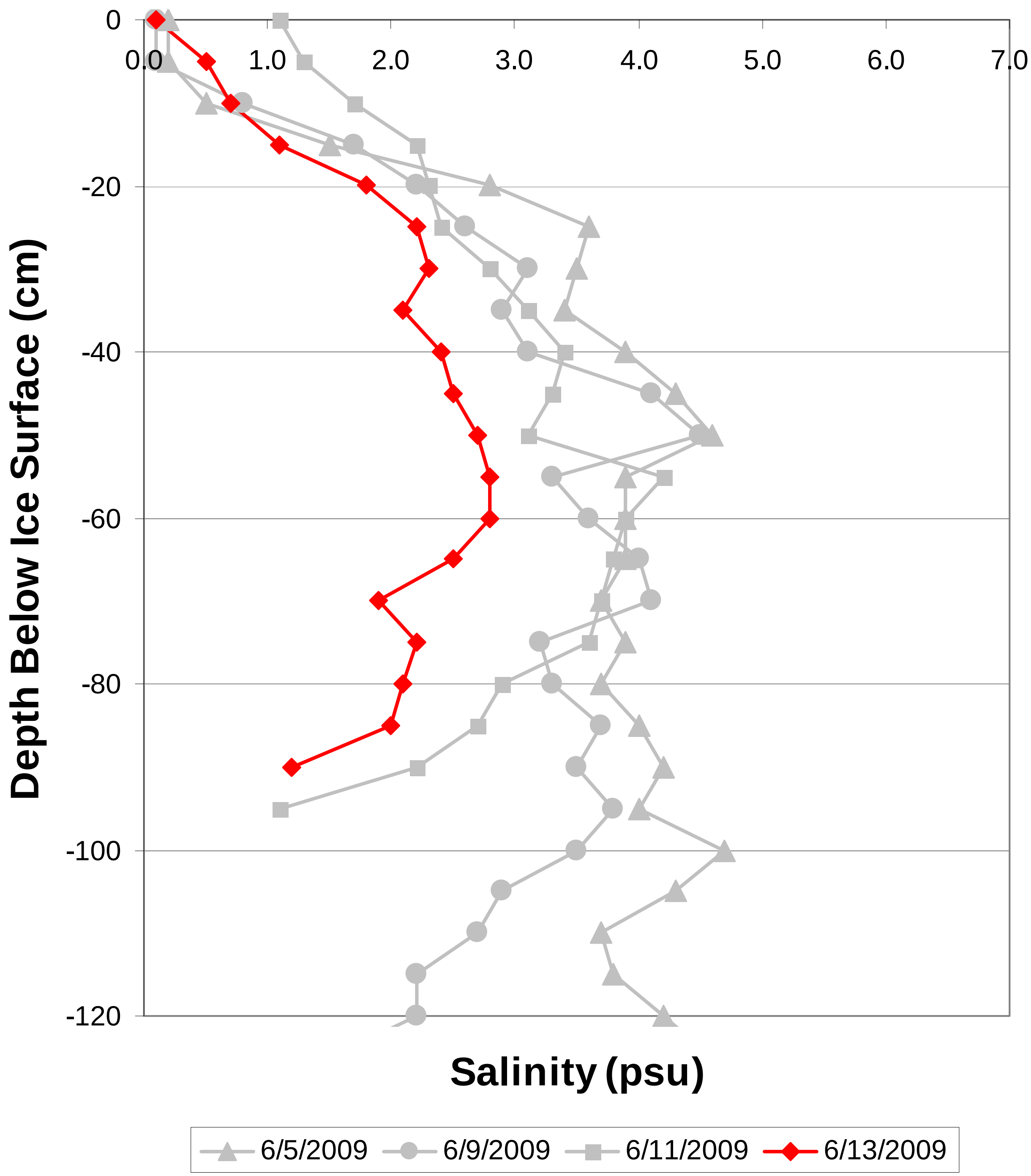

0
-20
-40
-60
-80
-100
-120
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Depth Below Ice Surface (cm)
Salinity (psu)
6/5/2009
6/9/2009
6/11/2009
6/13/2009


Photo: Chris Petrich

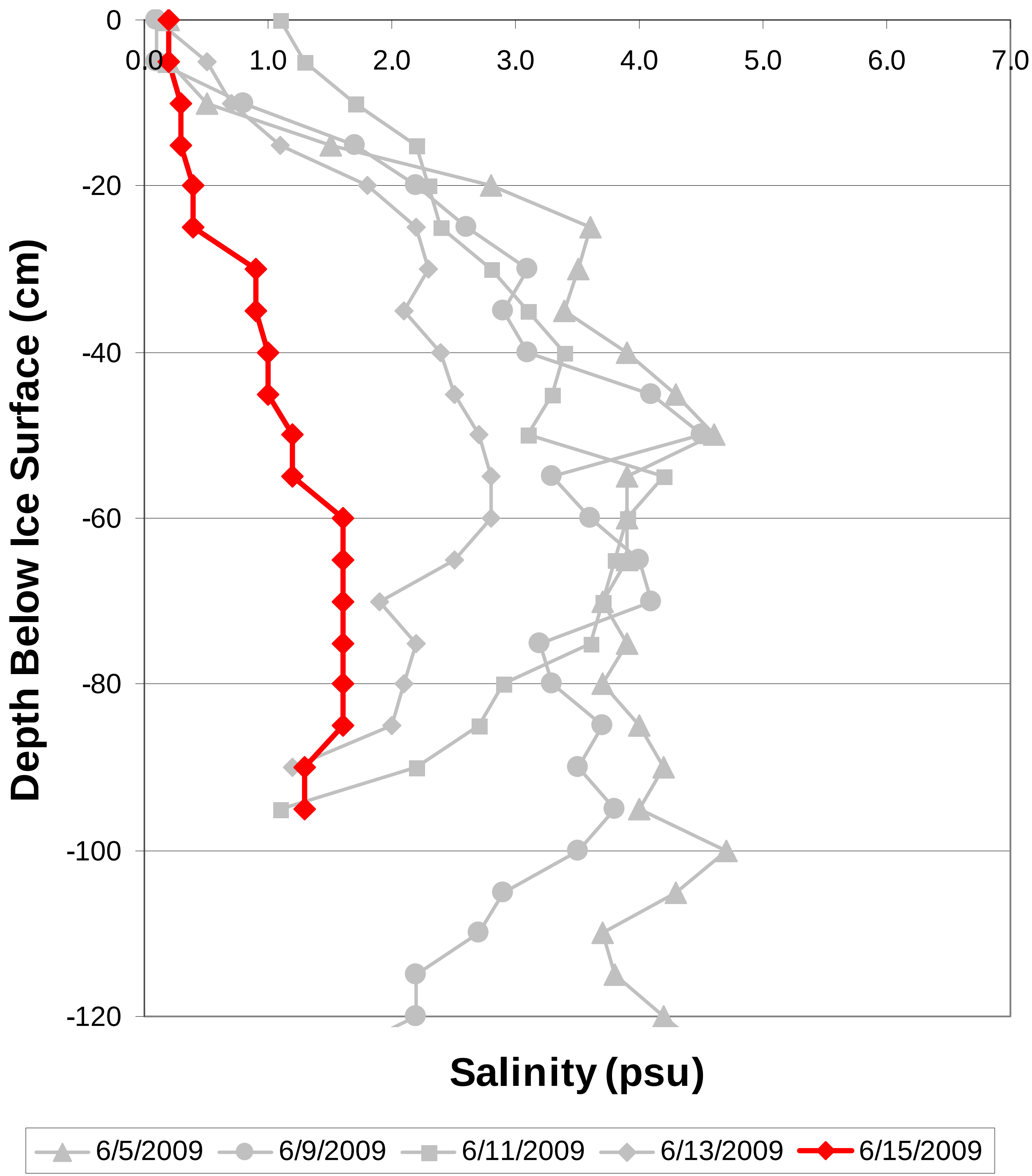
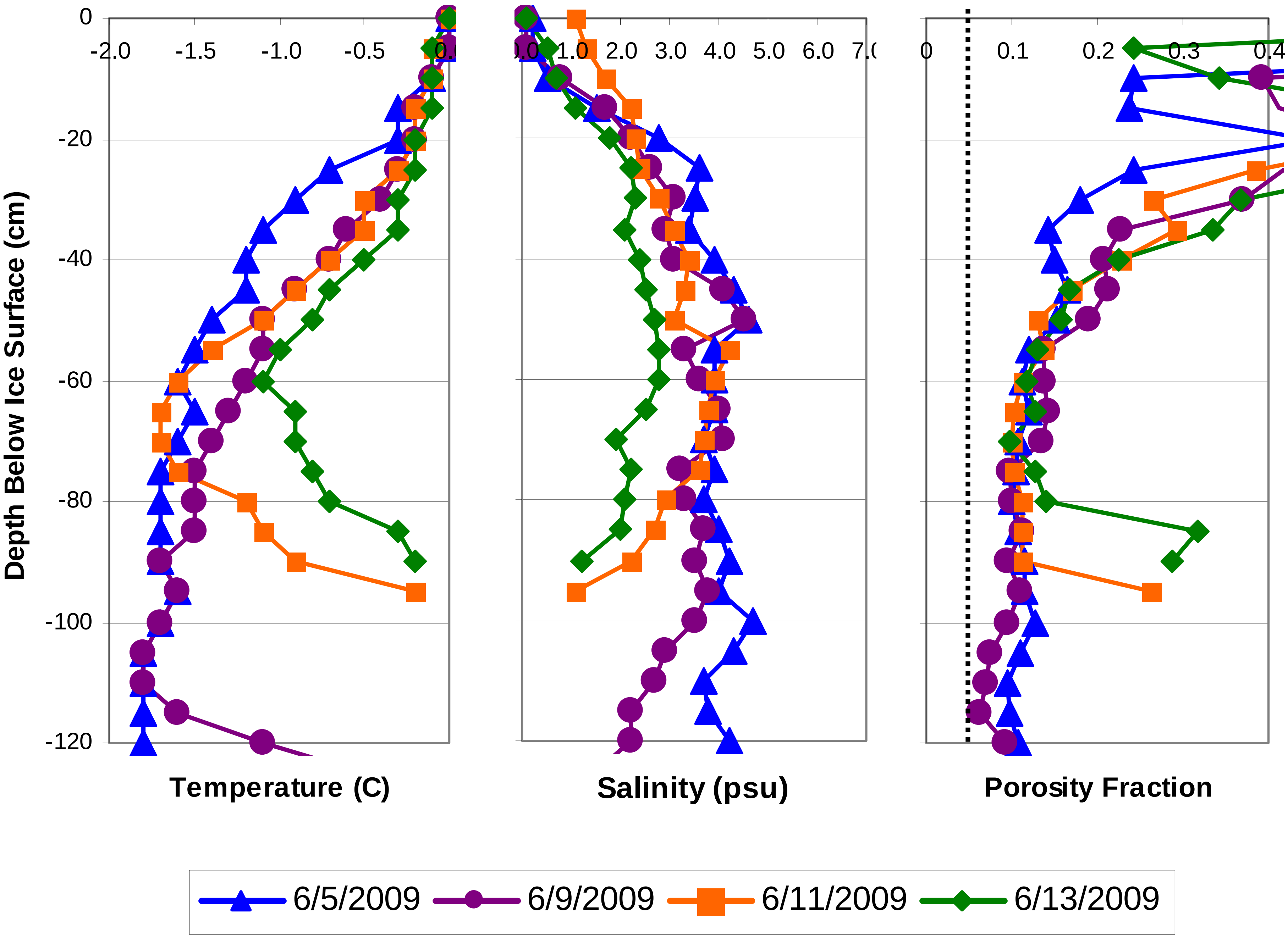
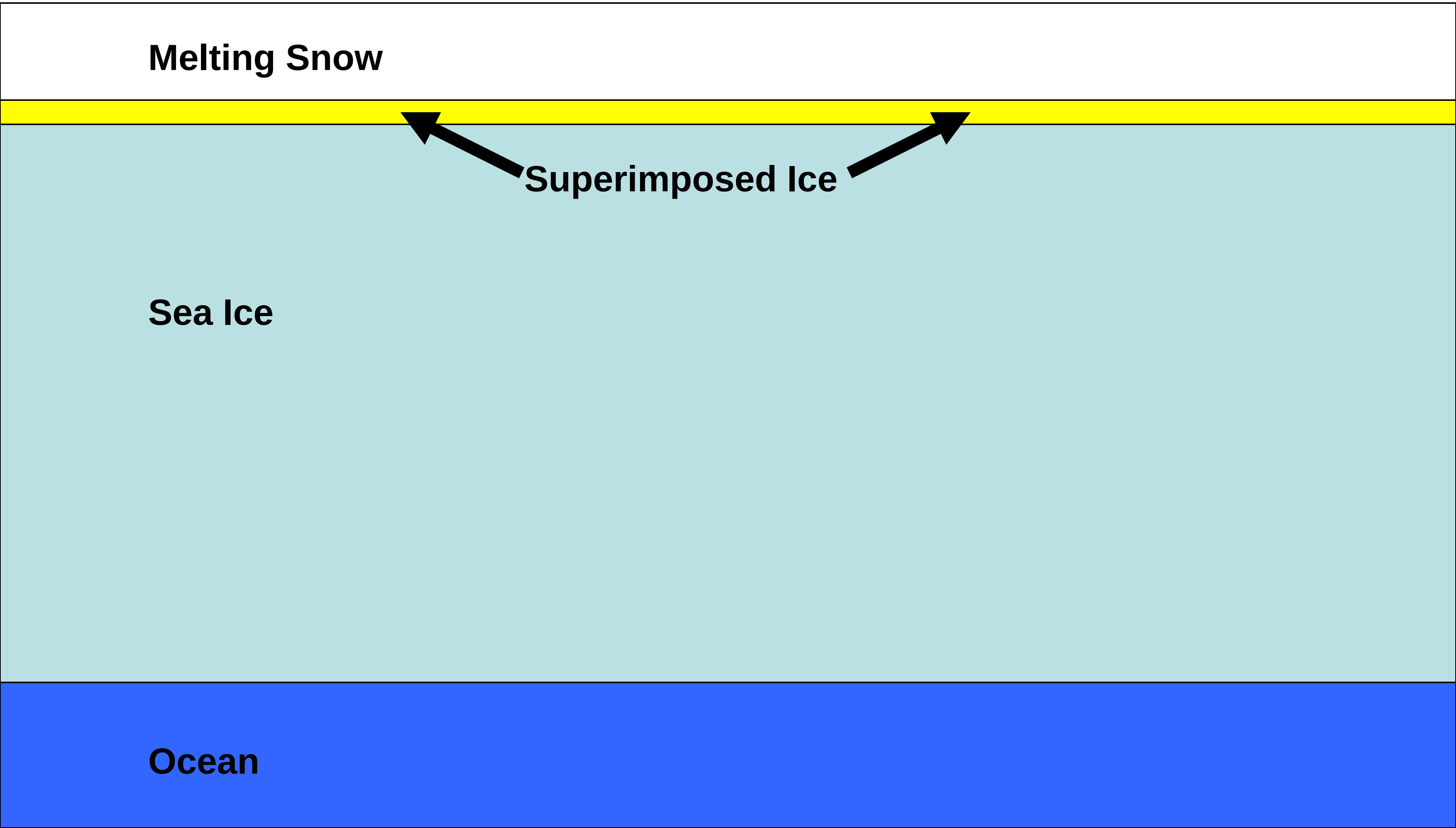
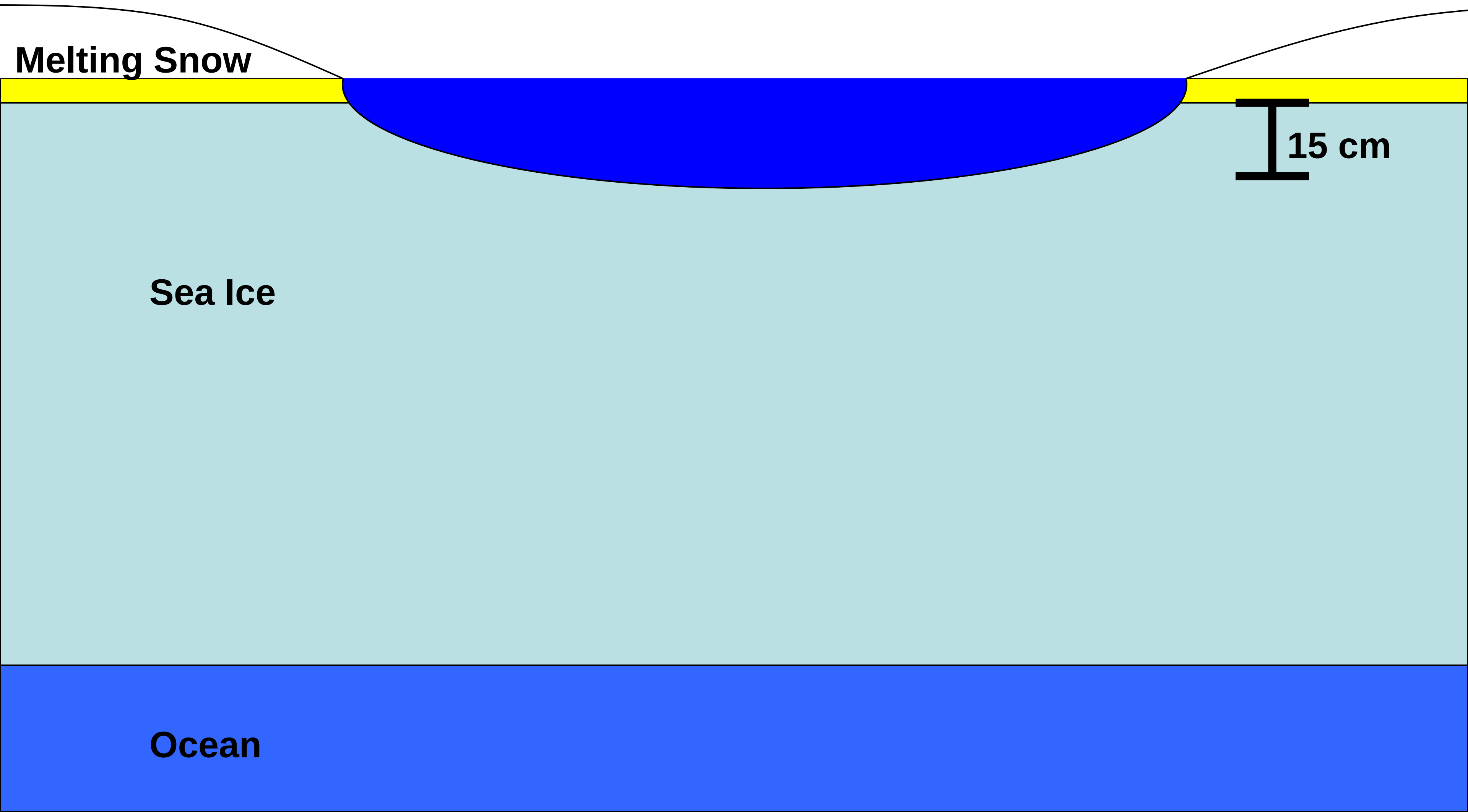

Depth Below Ice Surface (cm)
Salinity (psu)
0
-20
-40
-60
-80
-100
-120
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
6/5/2009
6/9/2009
6/11/2009
6/13/2009
6/15/2009


Photo: Chris Petrich

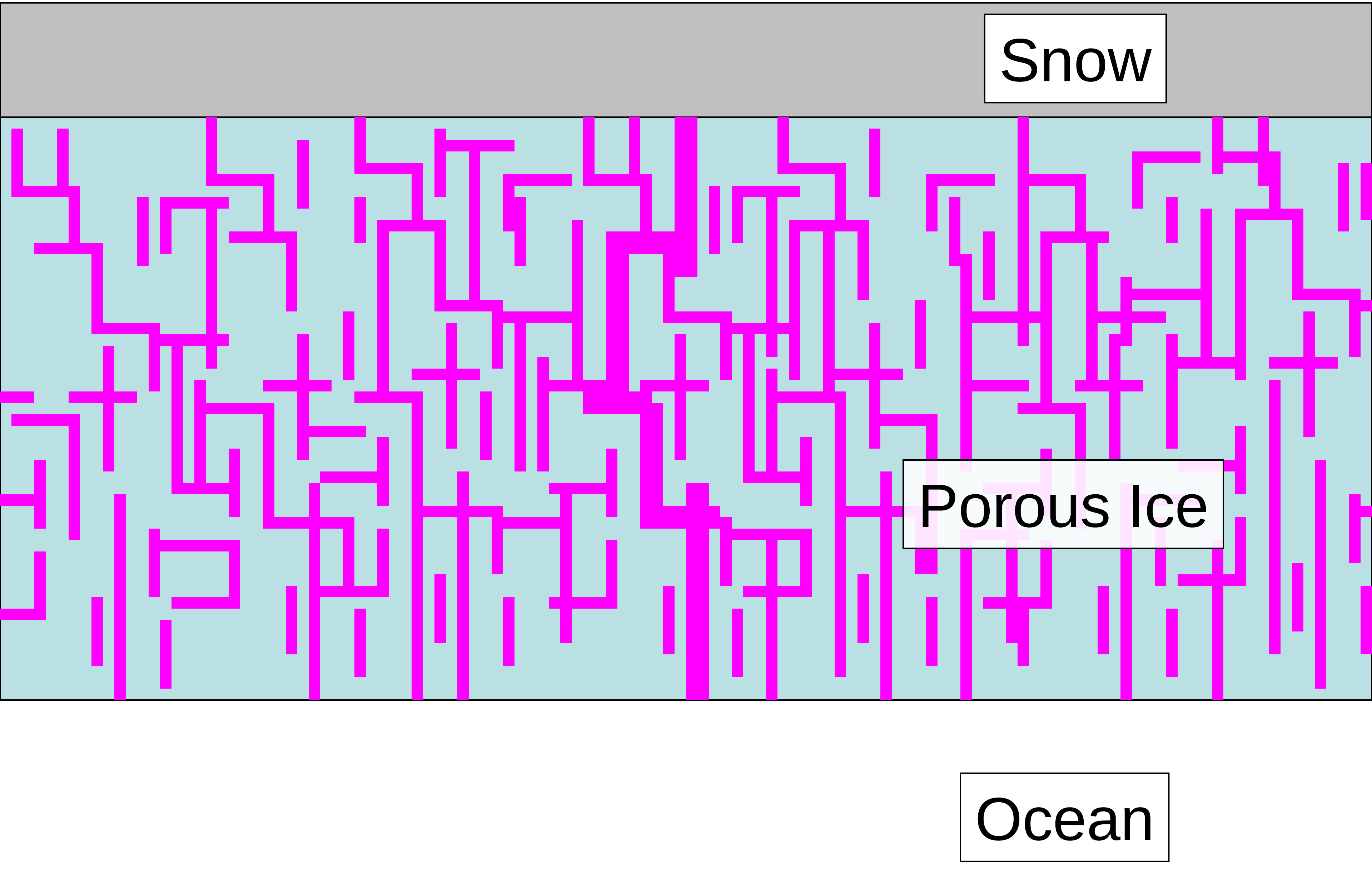


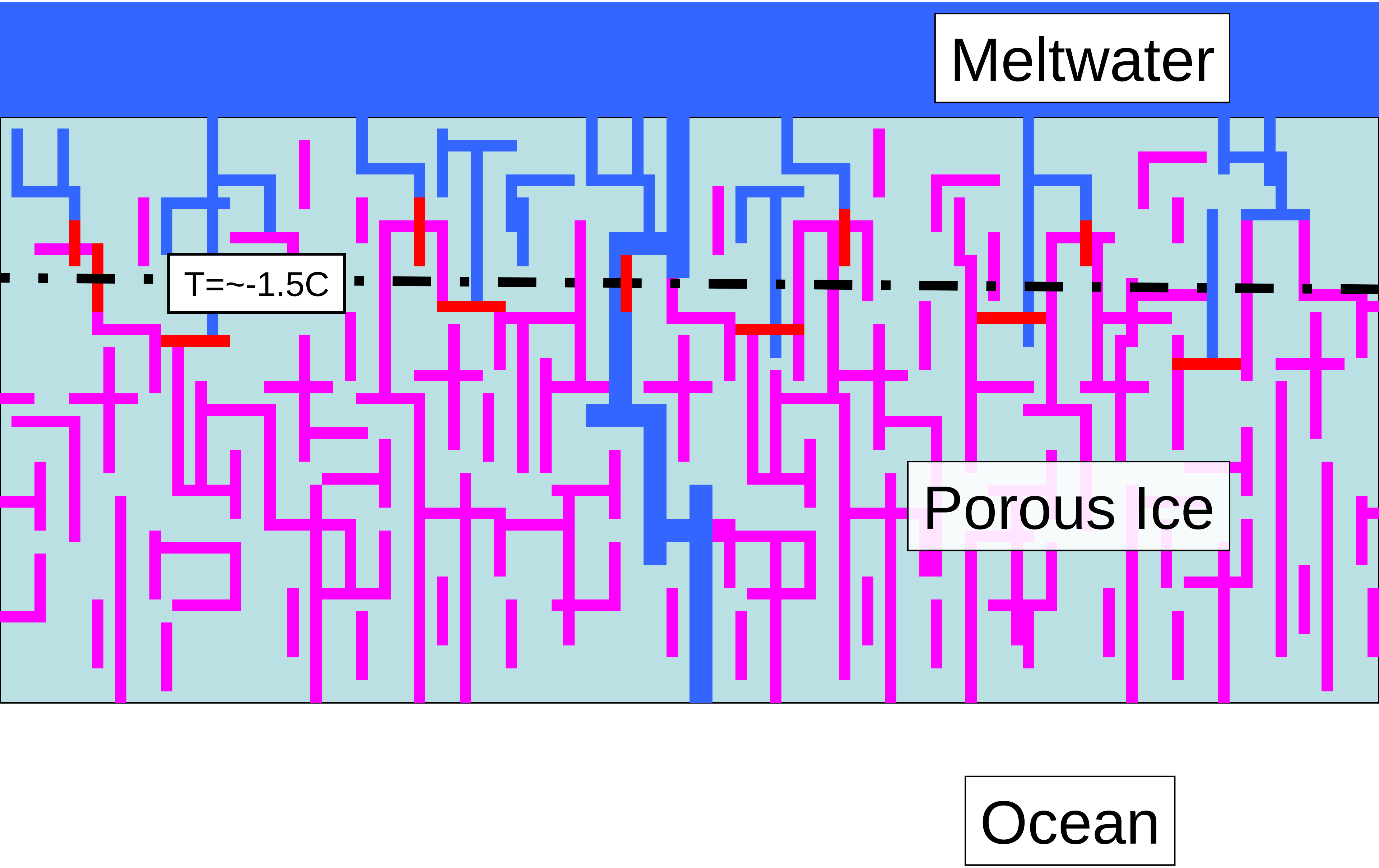
Depth Below Ice Surface (cm)
0
-20
-40
-60
-80
-100
-120
-2.0
-1.5
-1.0
-0.5
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
0
0.1
0.2
0.3
0.4
Temperature (C)
Salinity (psu)
Porosity Fraction
6/5/2009
6/9/2009
6/11/2009
6/13/2009

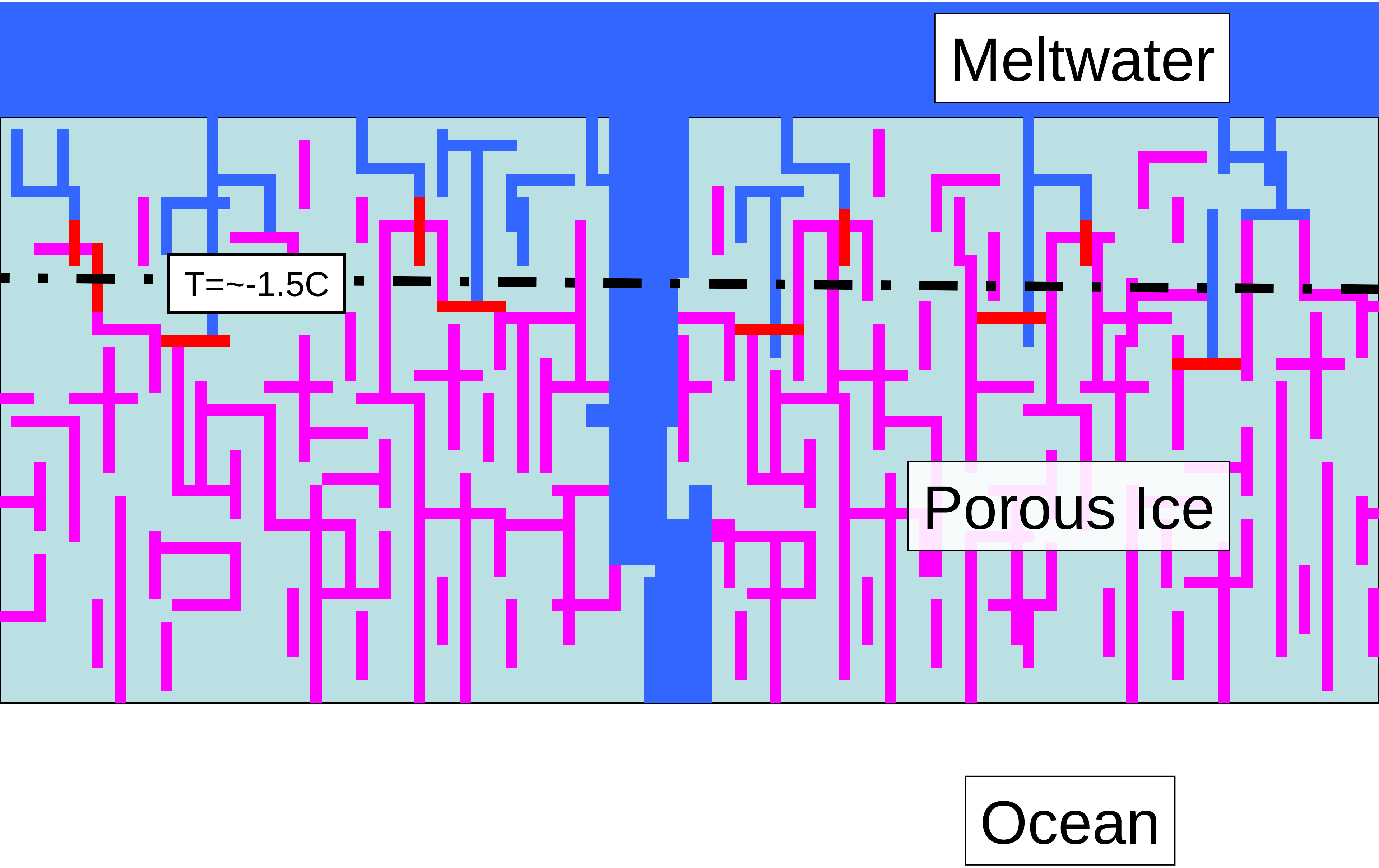

Melting Snow
Superimposed Ice
Sea Ice
Ocean

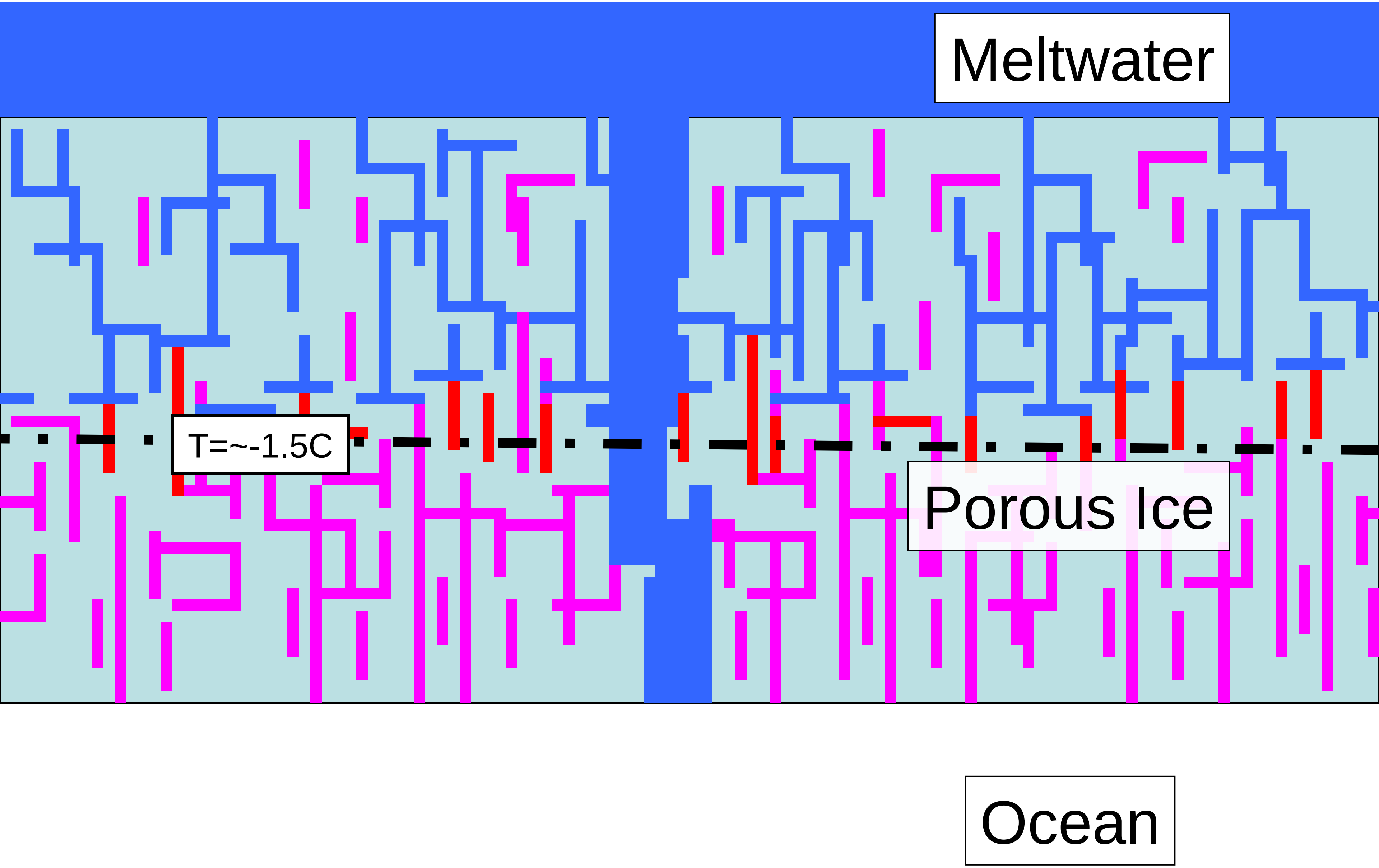


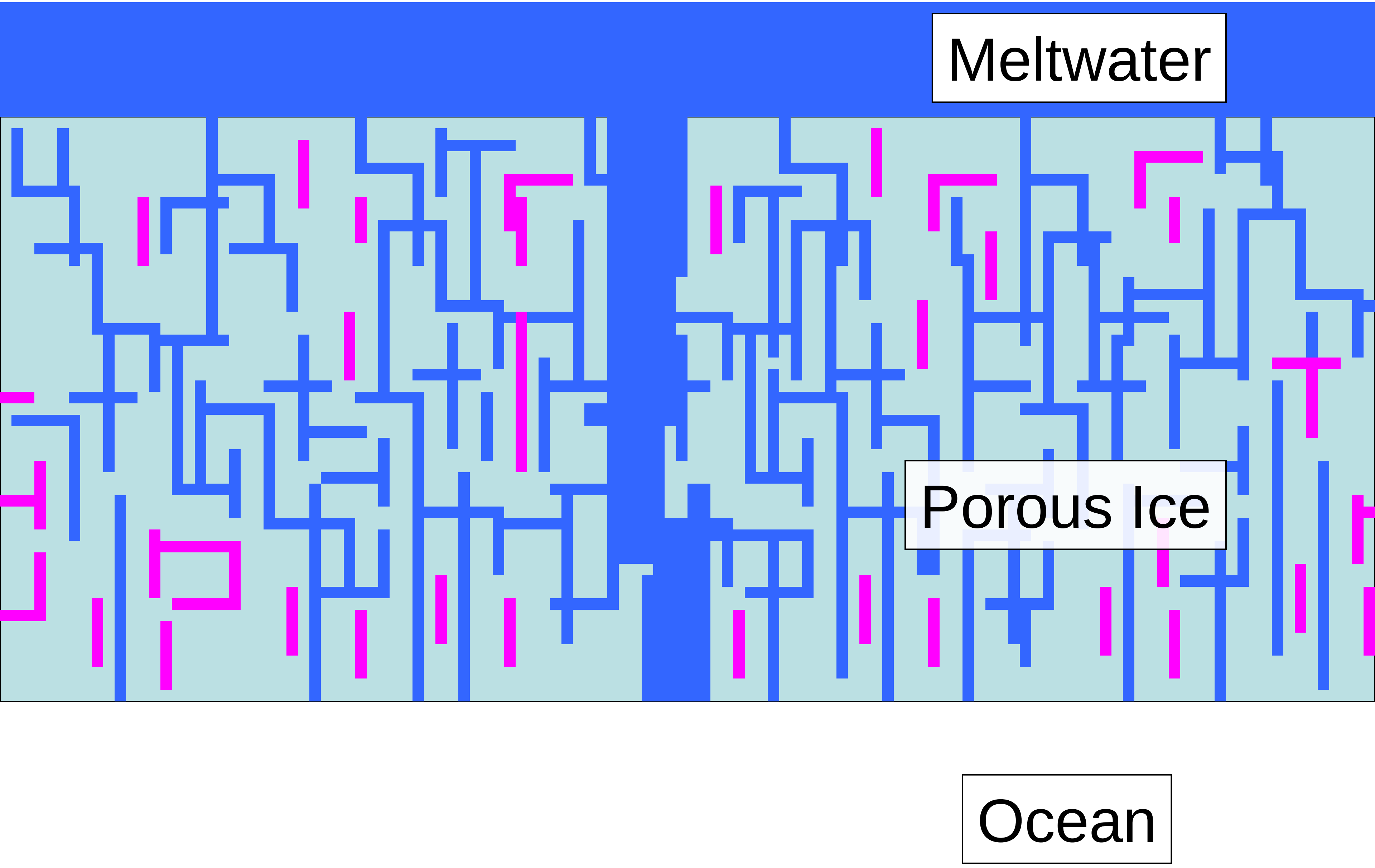
Melting Snow
15 cm
Sea Ice
Ocean


Snow
Porous Ice
Ocean

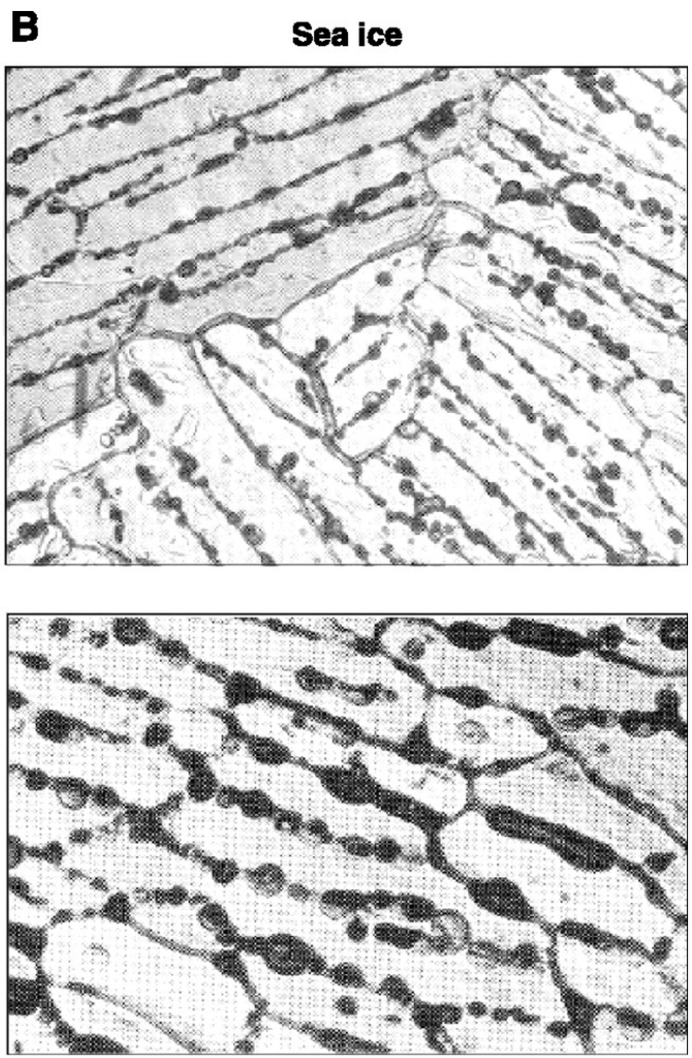

Meltwater
T=~-1.5C
Porous Ice
Ocean

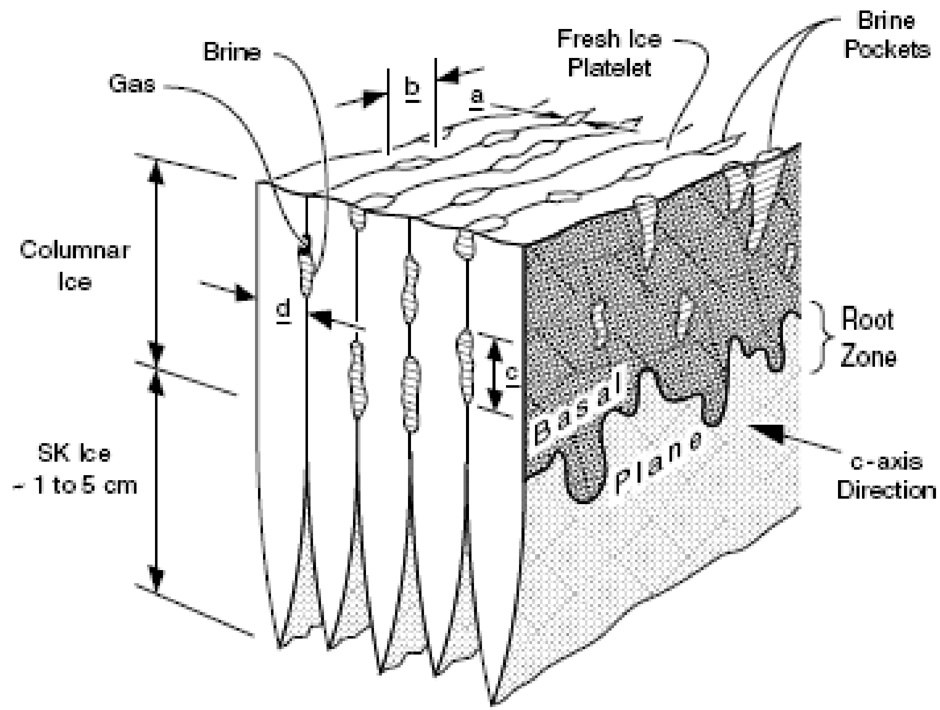

Meltwater
T=~-1.5C
Porous Ice
Ocean


Meltwater
T=~-1.5C
Porous Ice
Ocean


Meltwater
Porous Ice
Ocean

Inter – Lamellar Brine Inclusions





$\underline{a} \leq \underline{b} < \underline{c}$

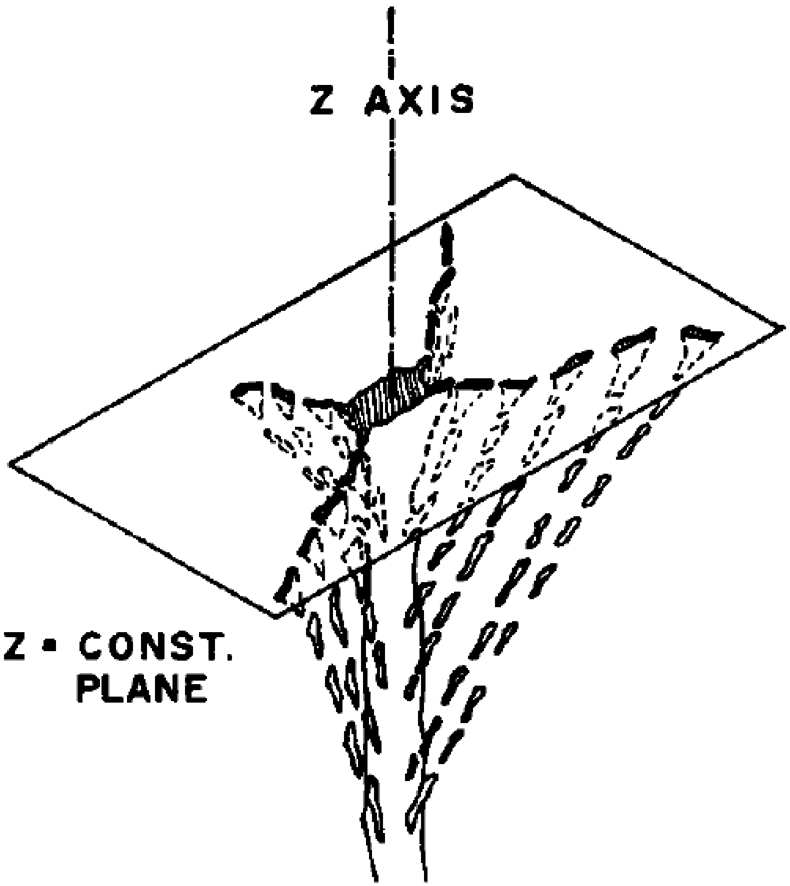
$\underline{a}$ ~ 0.1 to 0.3 mm; $\underline{b}$ ~ 1 to 5 × $\underline{a}$; $\underline{c}$ > 5 × $\underline{a}$

$\underline{d}$ ~ 0.25 to 1.25 mm (avg 0.7)

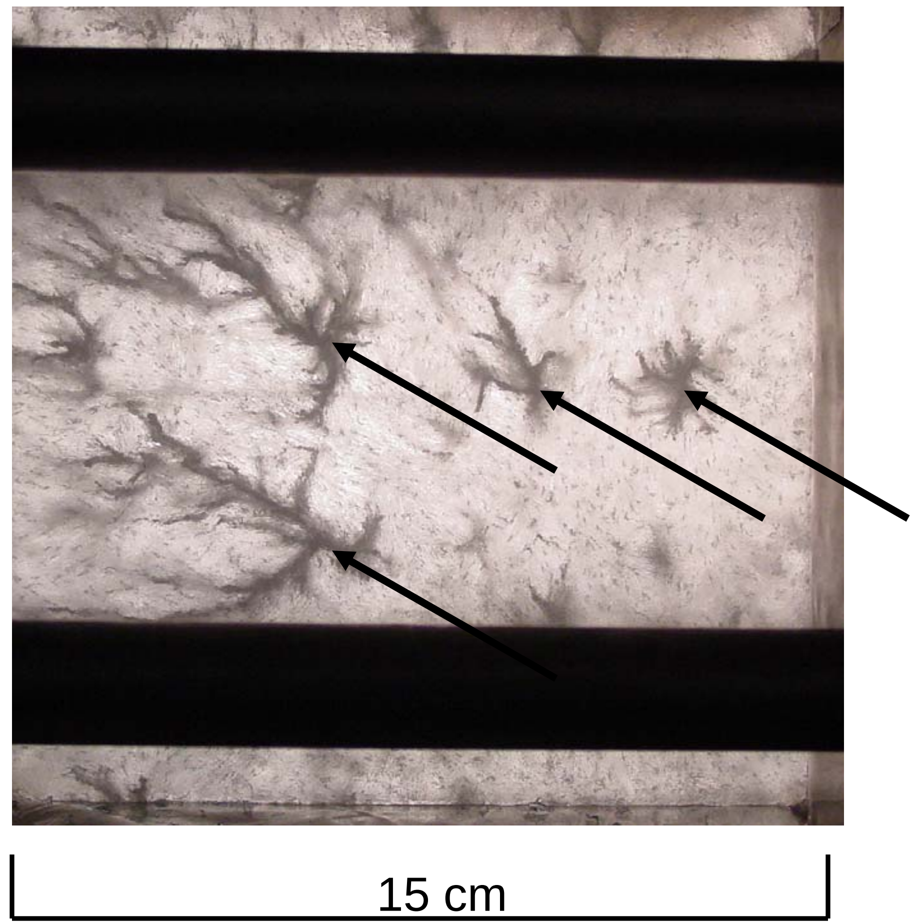
Frozen Interface

Seawater Interface

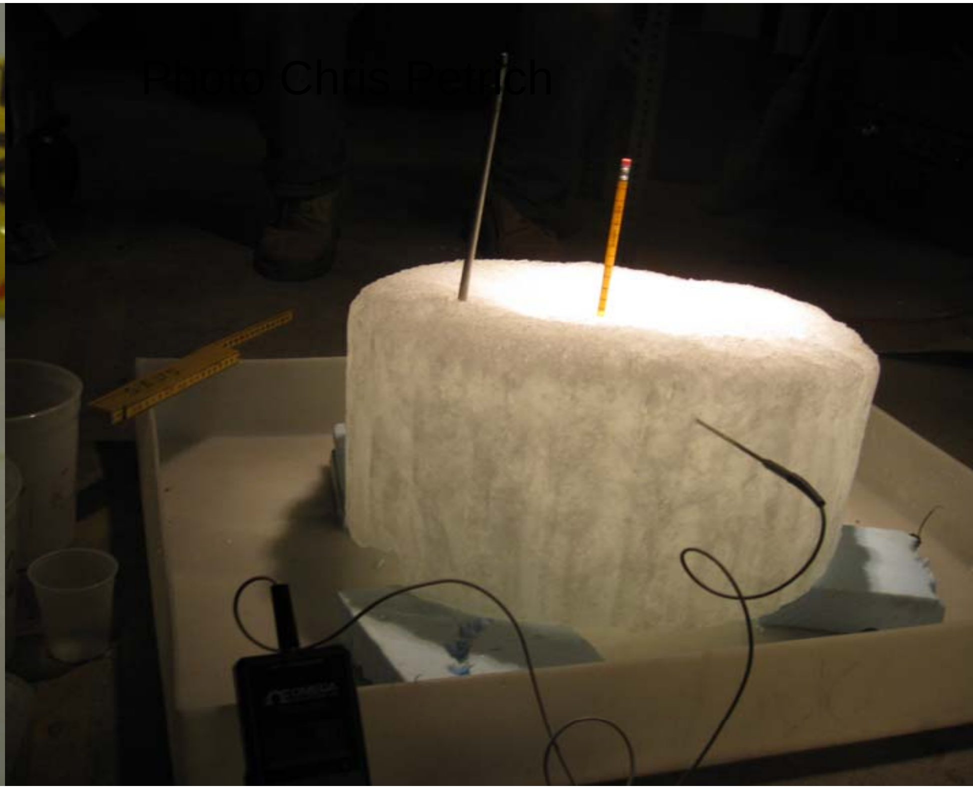
Organized Arborescent Brine Channels



Horizontal Section

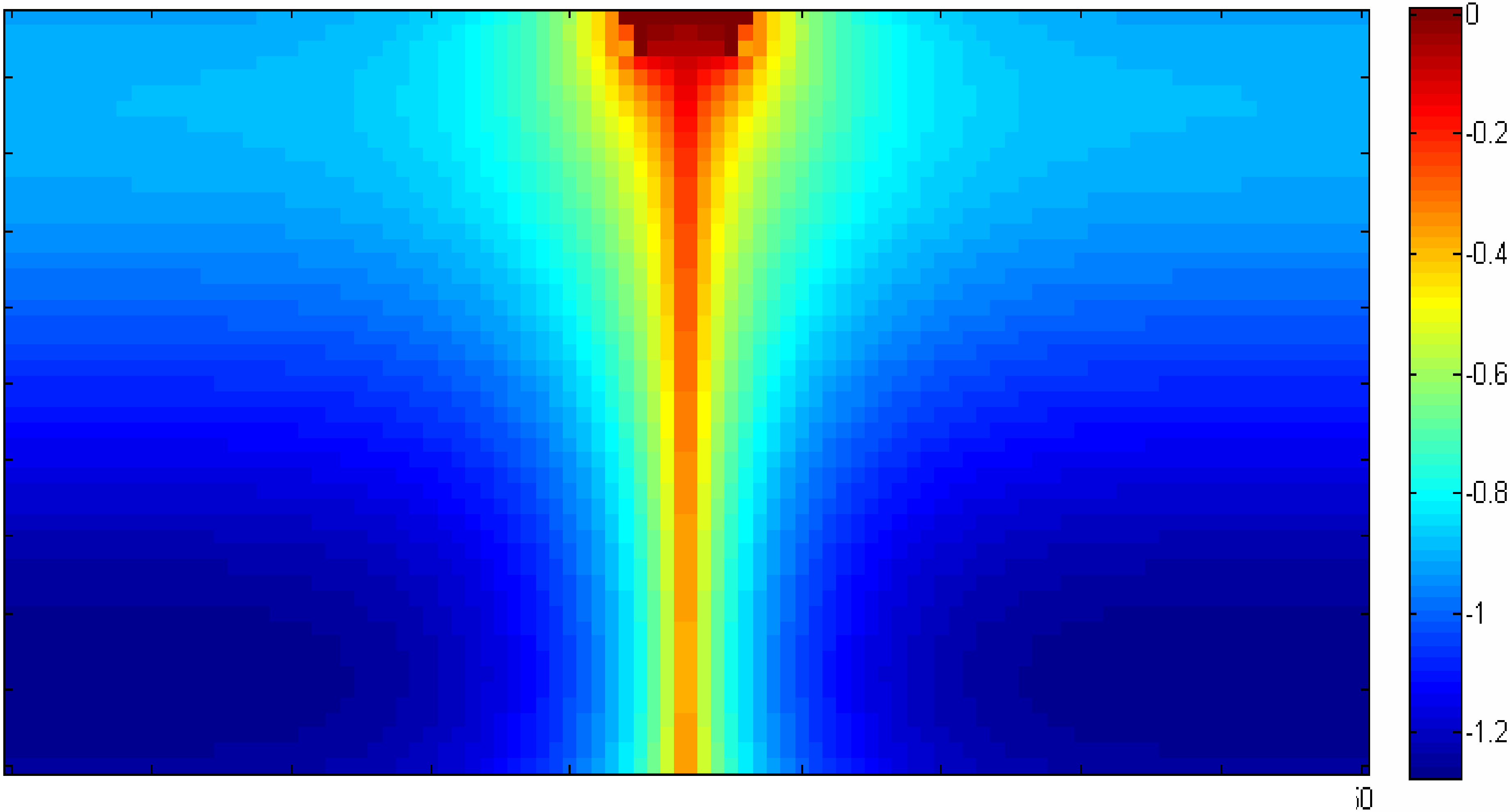


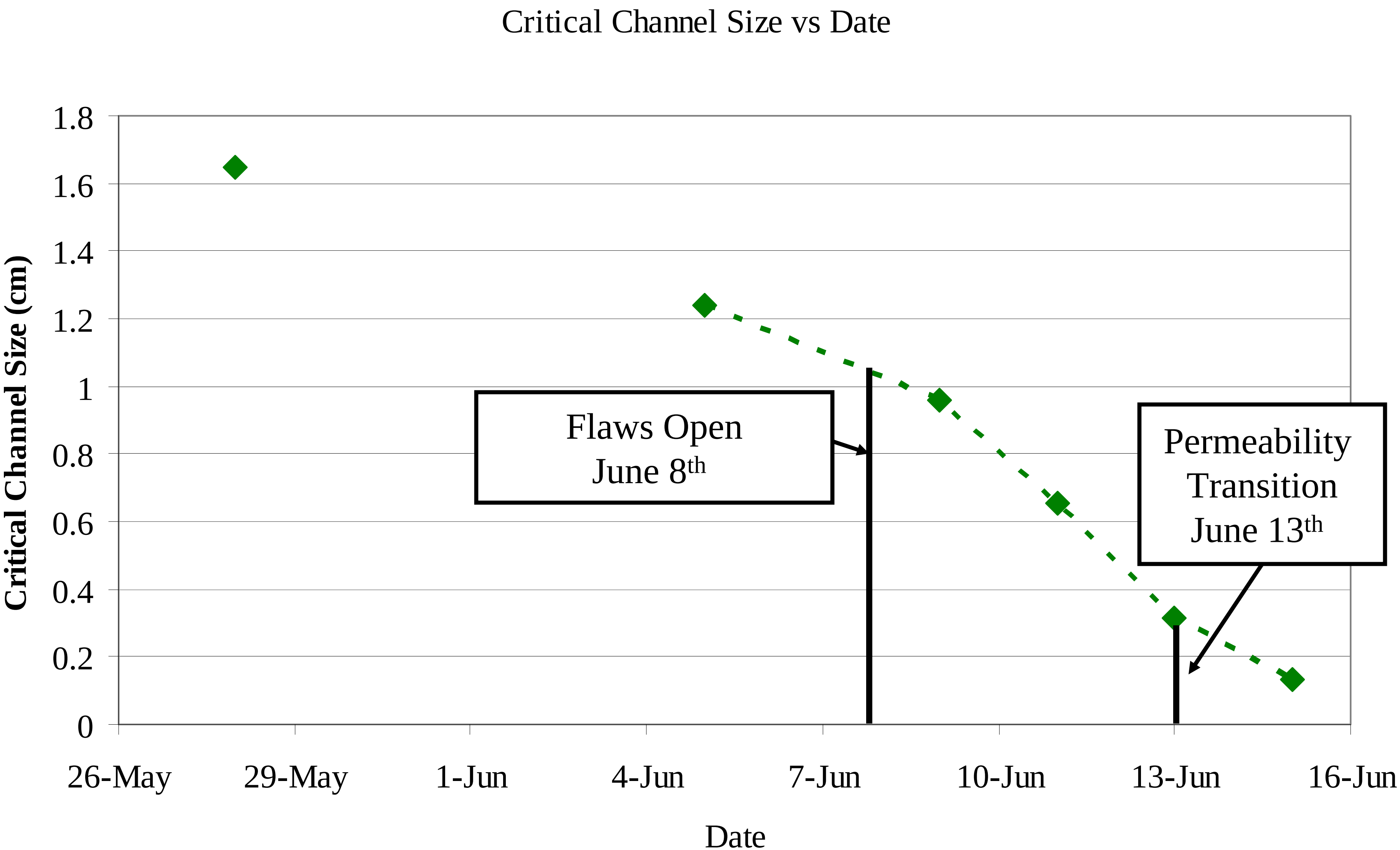
Large core holes are enlarged by flowing water

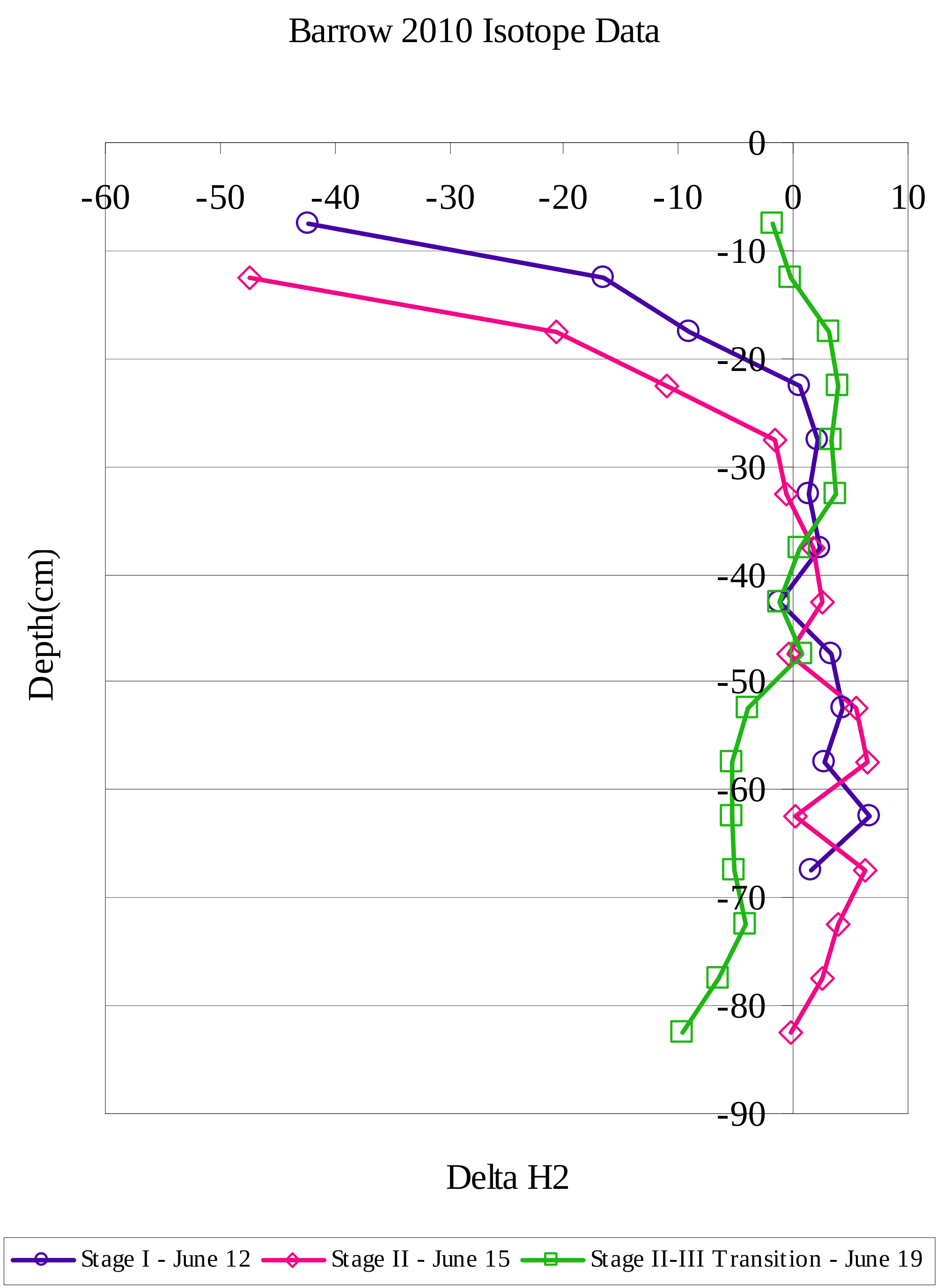


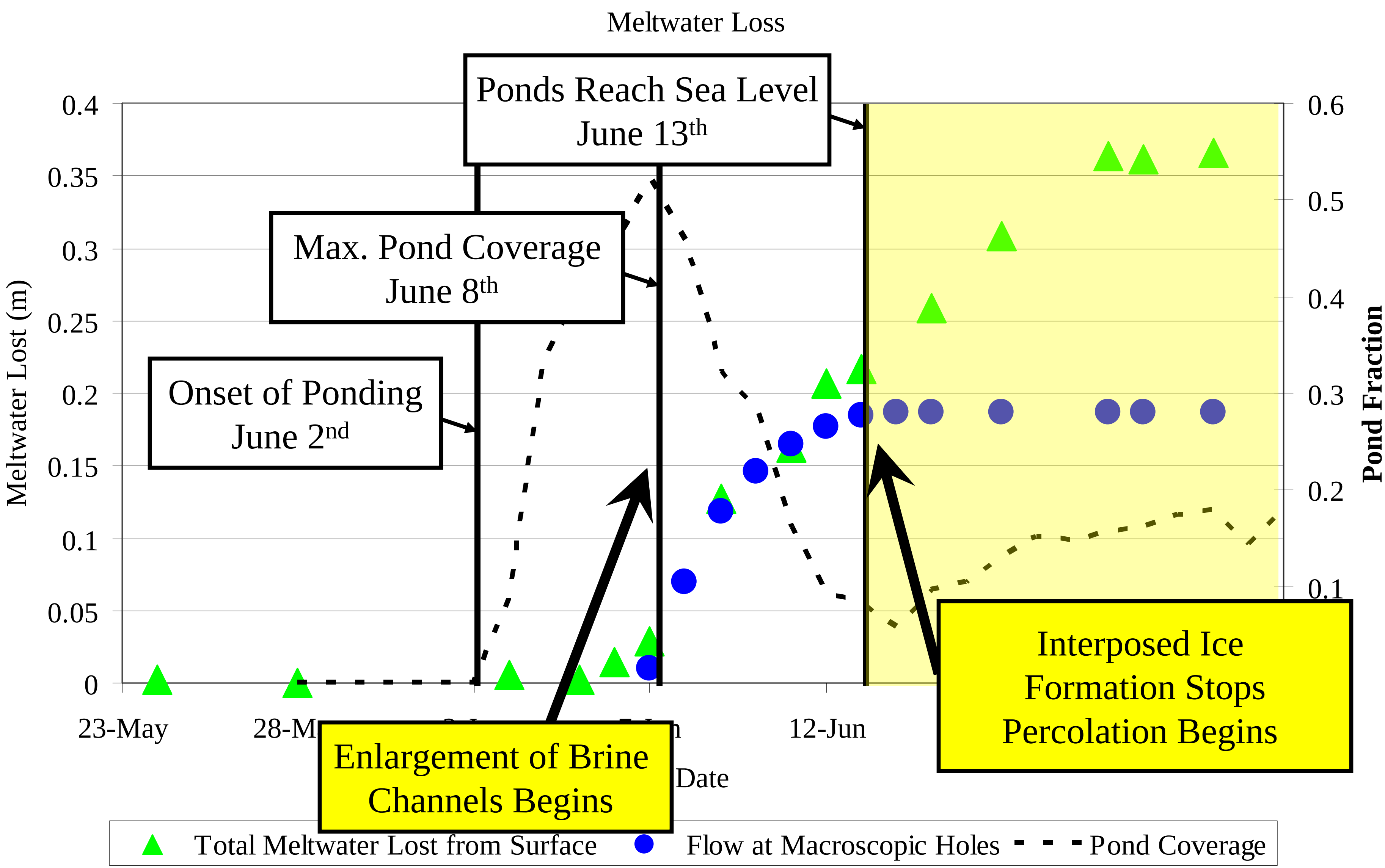
Photos: Becky Niemiec

Small holes are repaired by refreezing meltwater

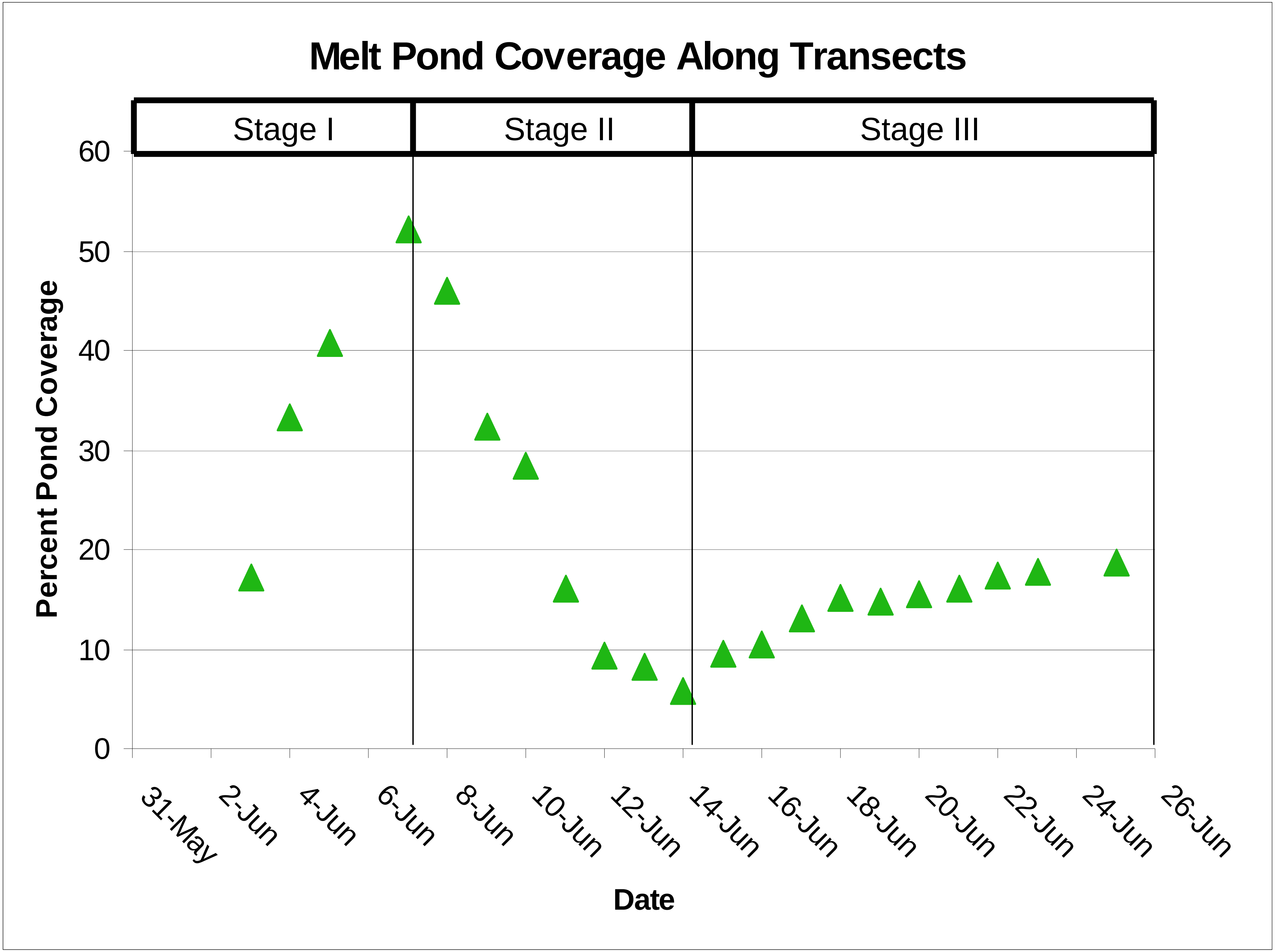

0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
i0

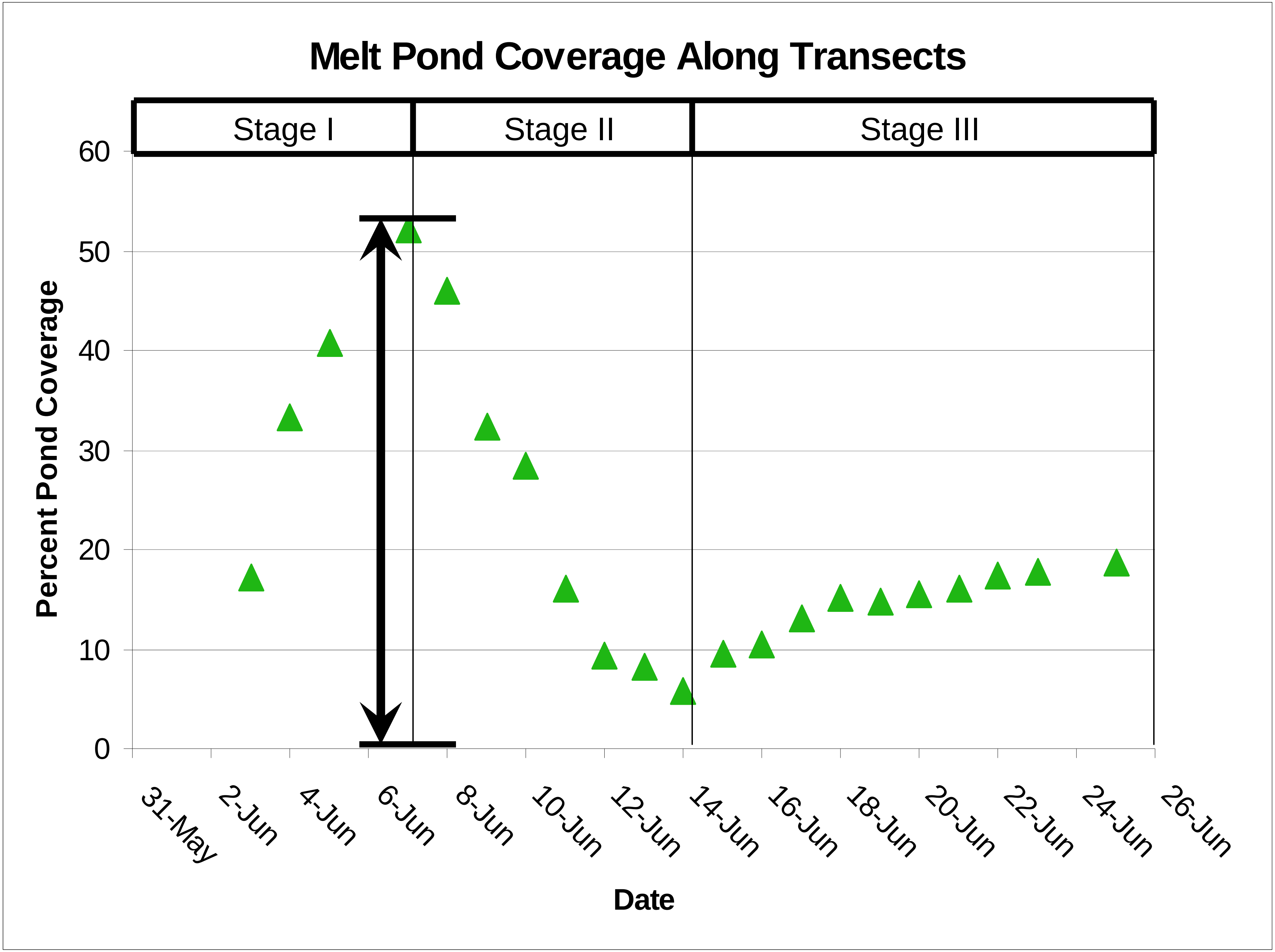

Critical Channel Size vs Date
Critical Channel Size (cm)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
26-May
29-May
1-Jun
4-Jun
7-Jun
10-Jun
13-Jun
16-Jun
Date
Flaws Open June 8th
Permeability Transition June 13th


Barrow 2010 Isotope Data
-60
-50
-40
-30
-20
-10
0
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
Depth(cm)
Delta H2
Stage I - June 12
Stage II - June 15
Stage II-III Transition - June 19

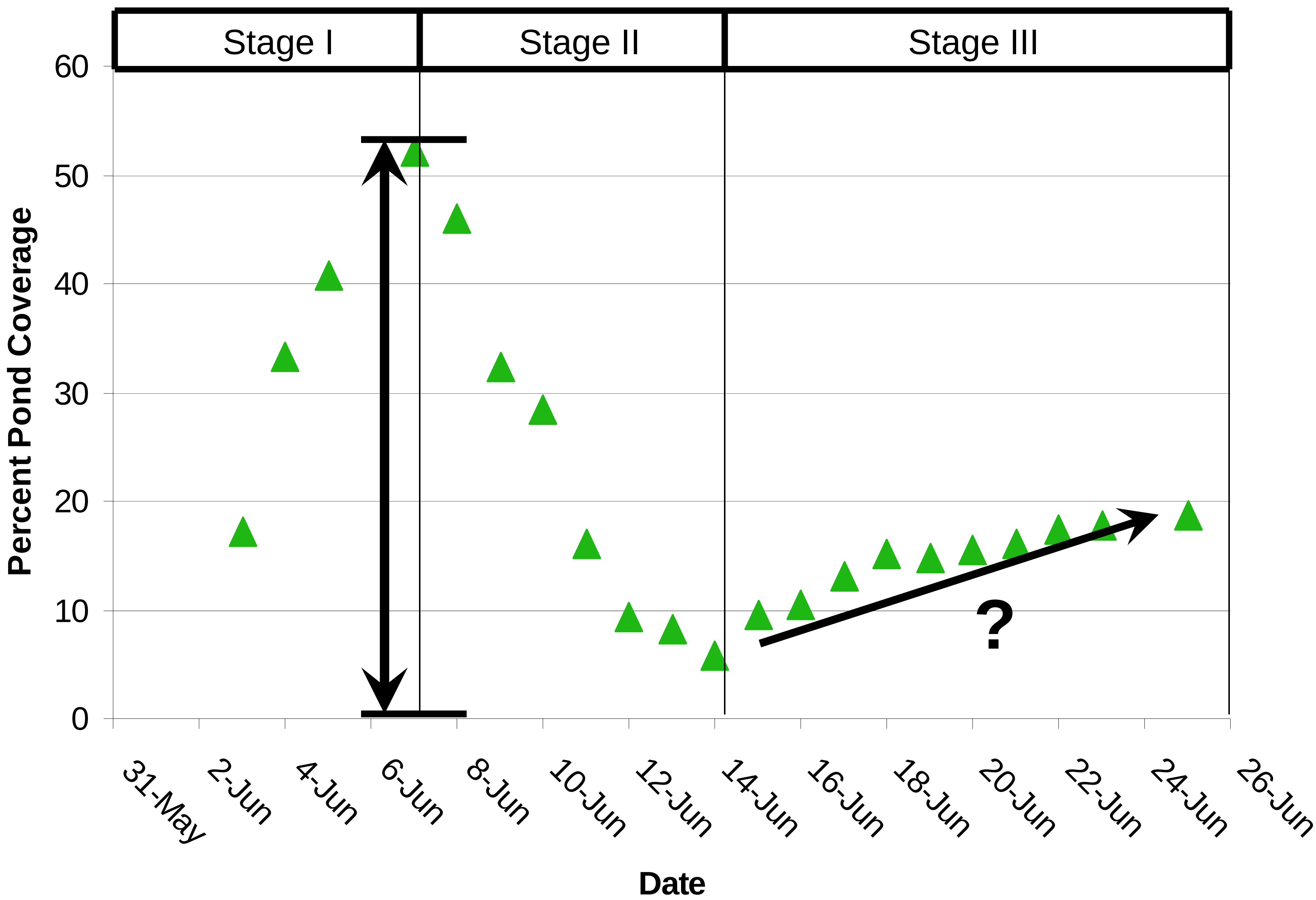


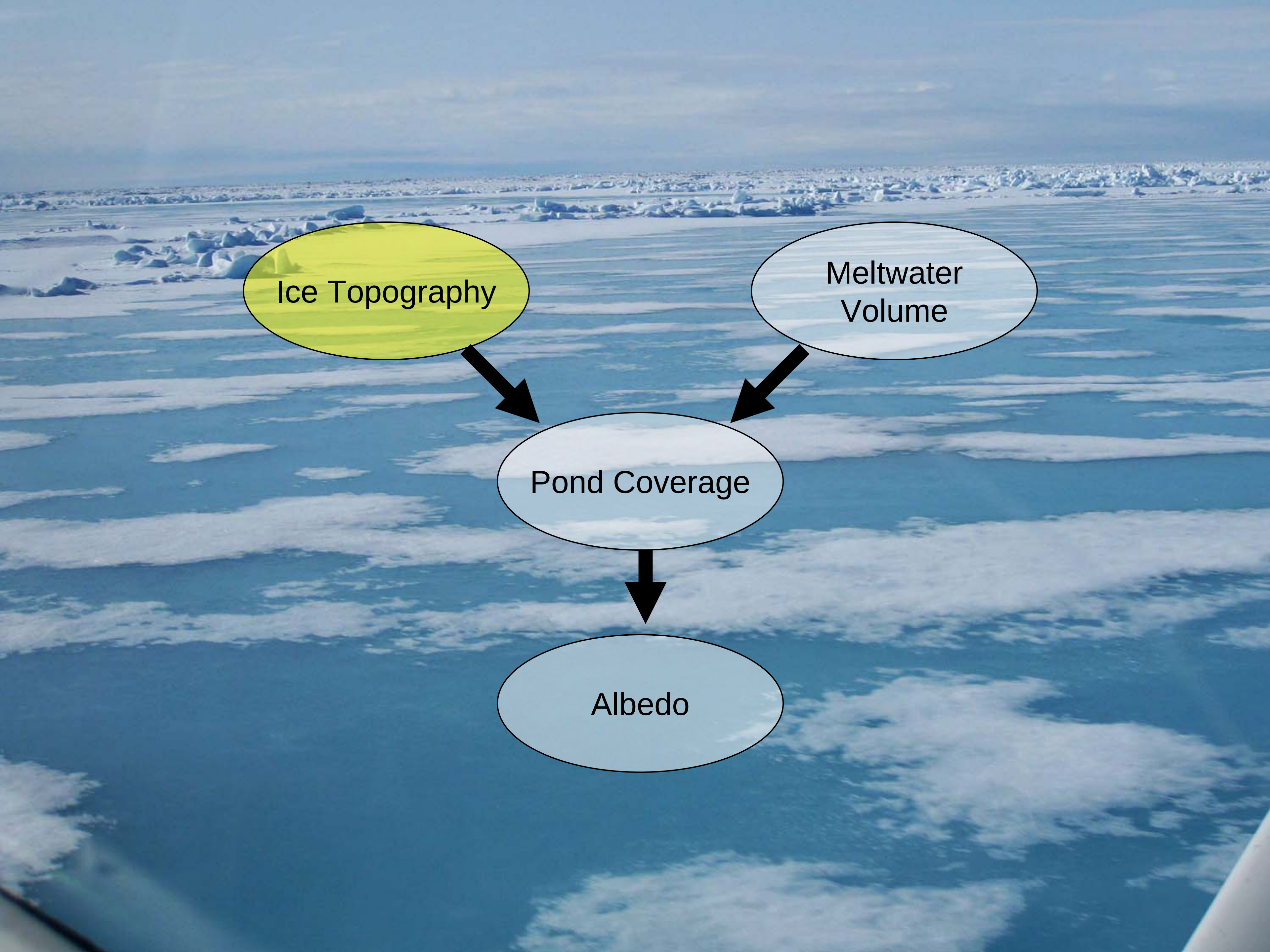
Ice Temperature Drives the formation of Outflow Pathways


Melt Pond Coverage Along Transects
Stage I
Stage II
Stage III
Percent Pond Coverage
0
10
20
30
40
50
60
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

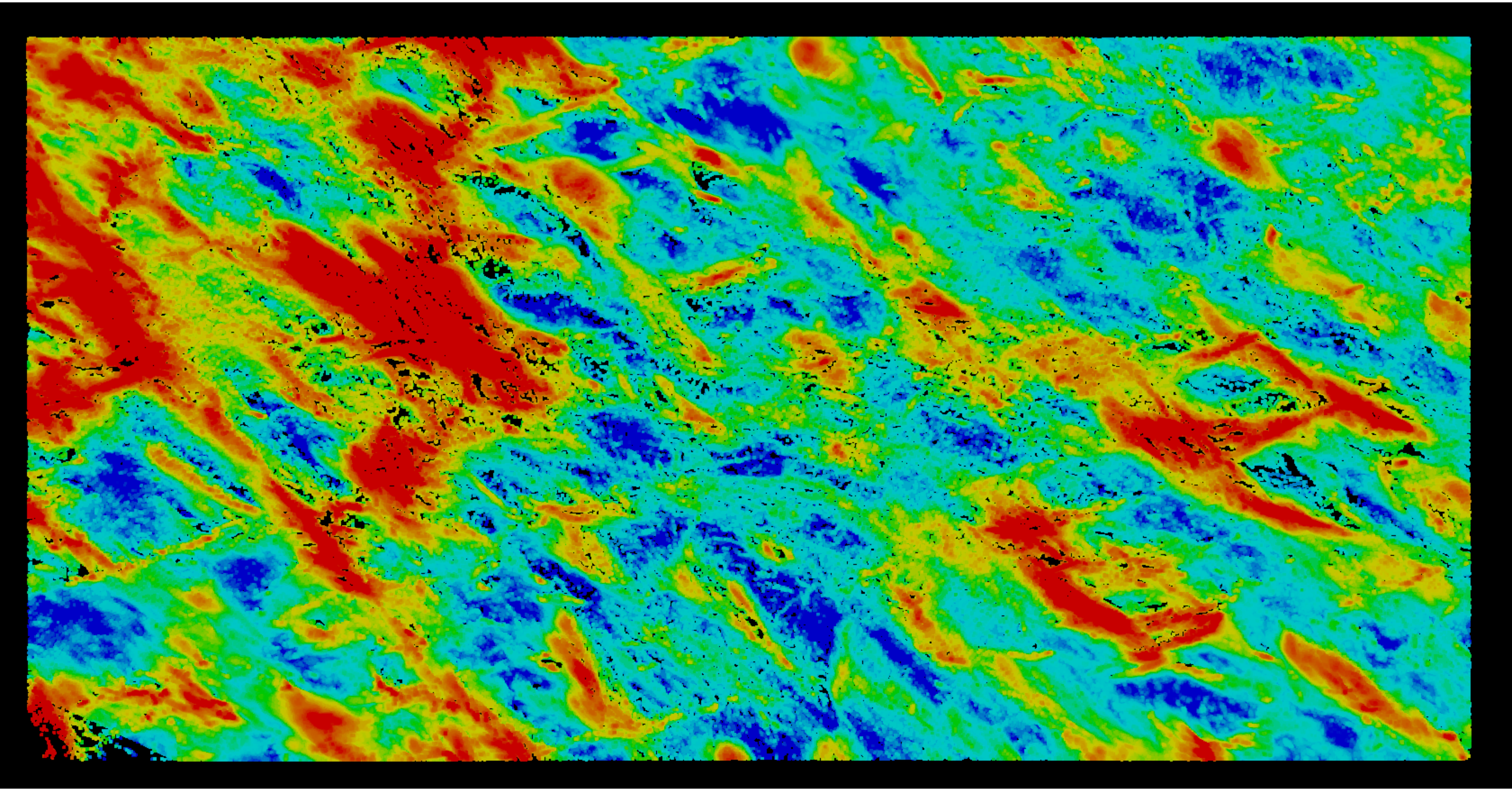

Melt Pond Coverage Along Transects
Stage I
Stage II
Stage III
Percent Pond Coverage
0
10
20
30
40
50
60
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date

Melt Pond Coverage Along Transects

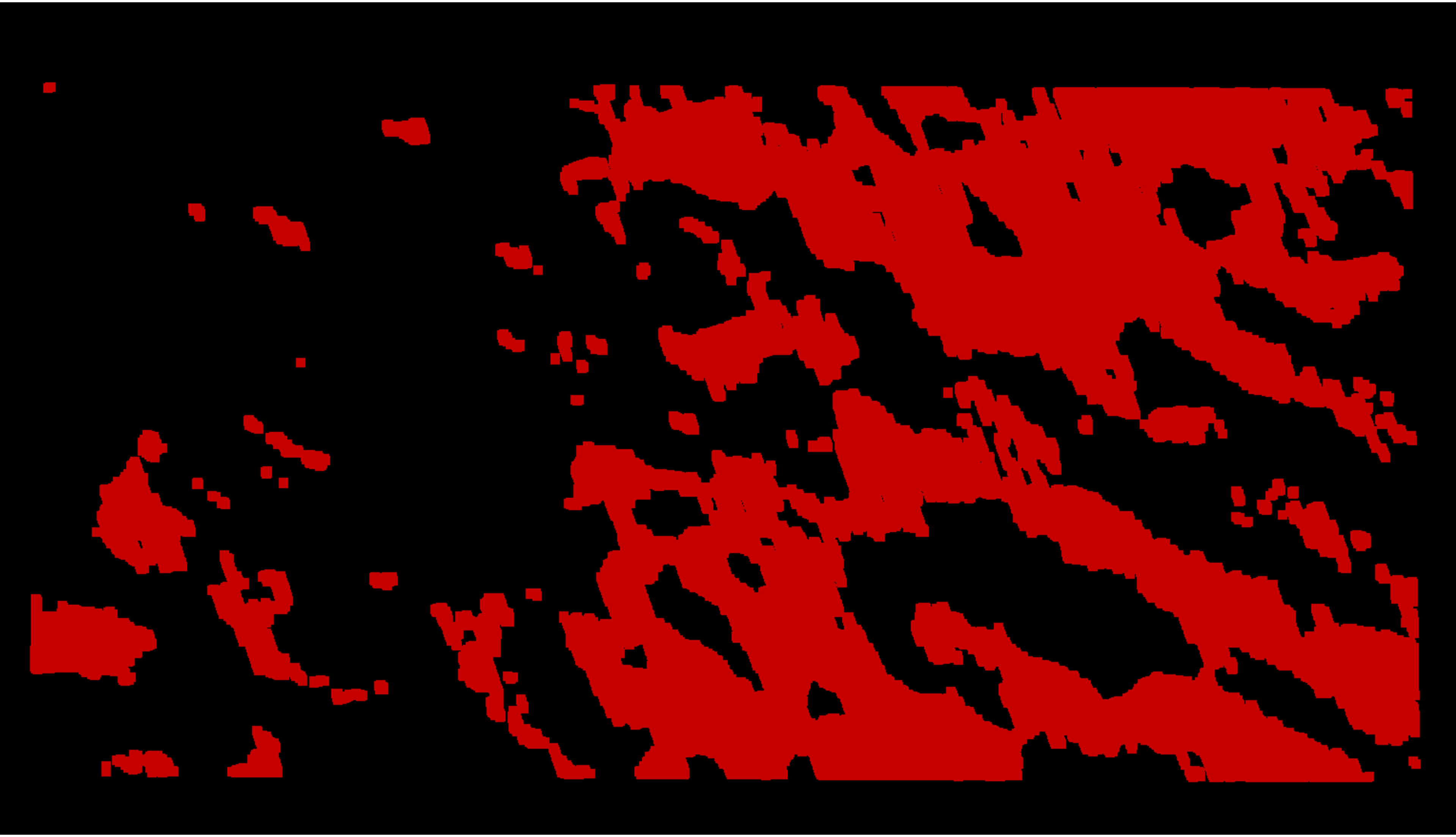



Ice Topography
Meltwater Volume
Pond Coverage
Albedo

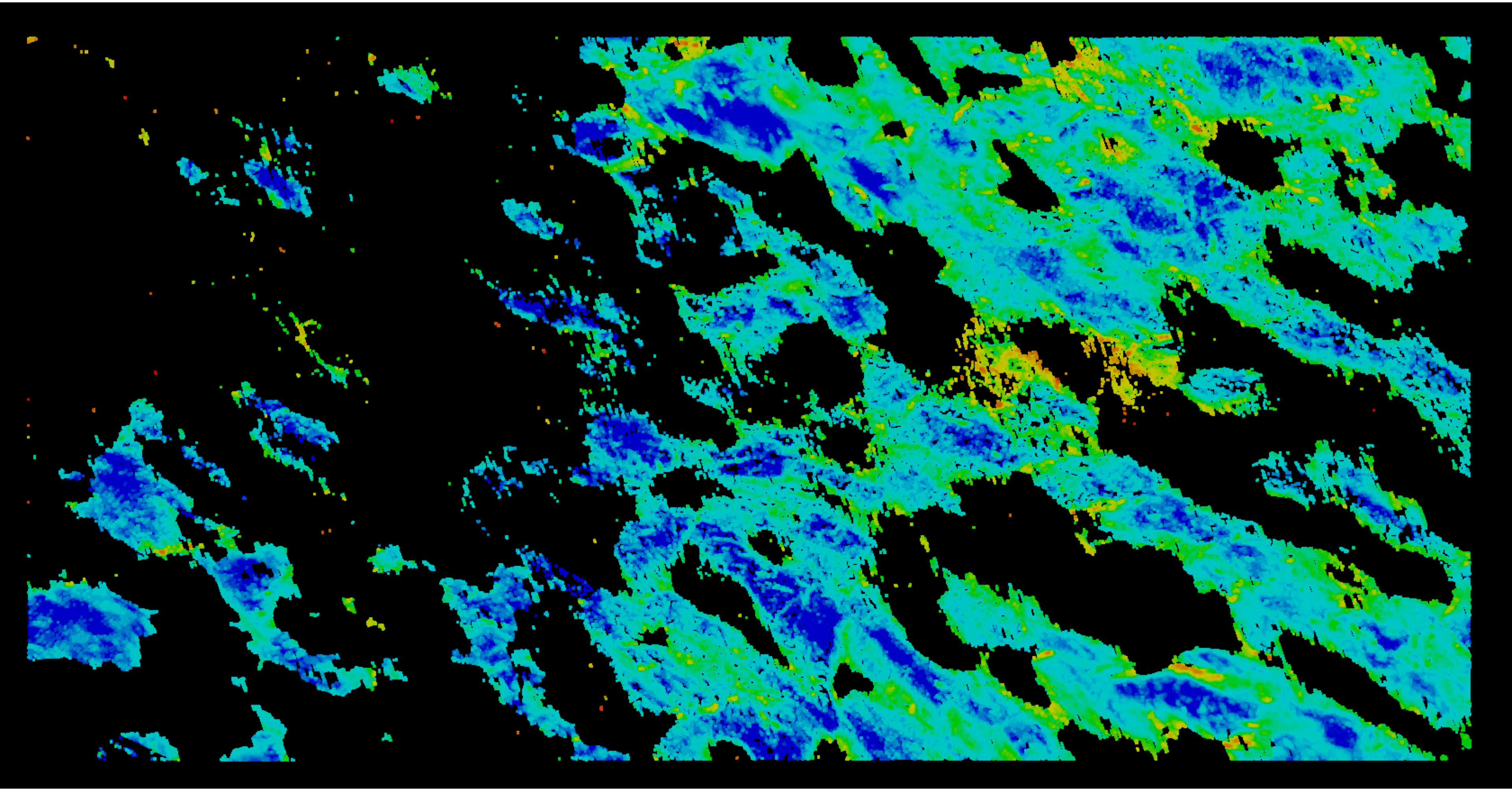
Pre-Melt Surface Topography

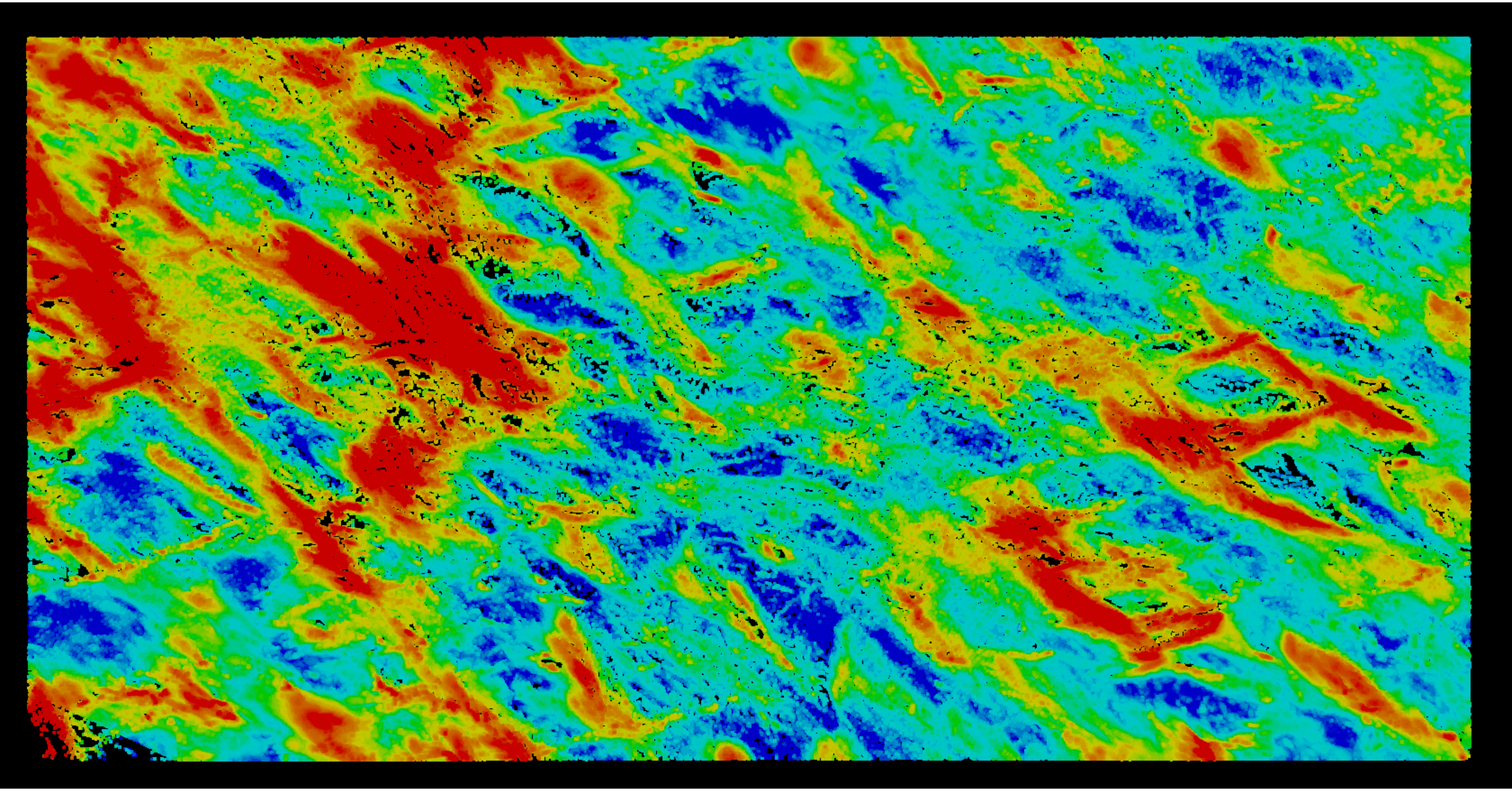


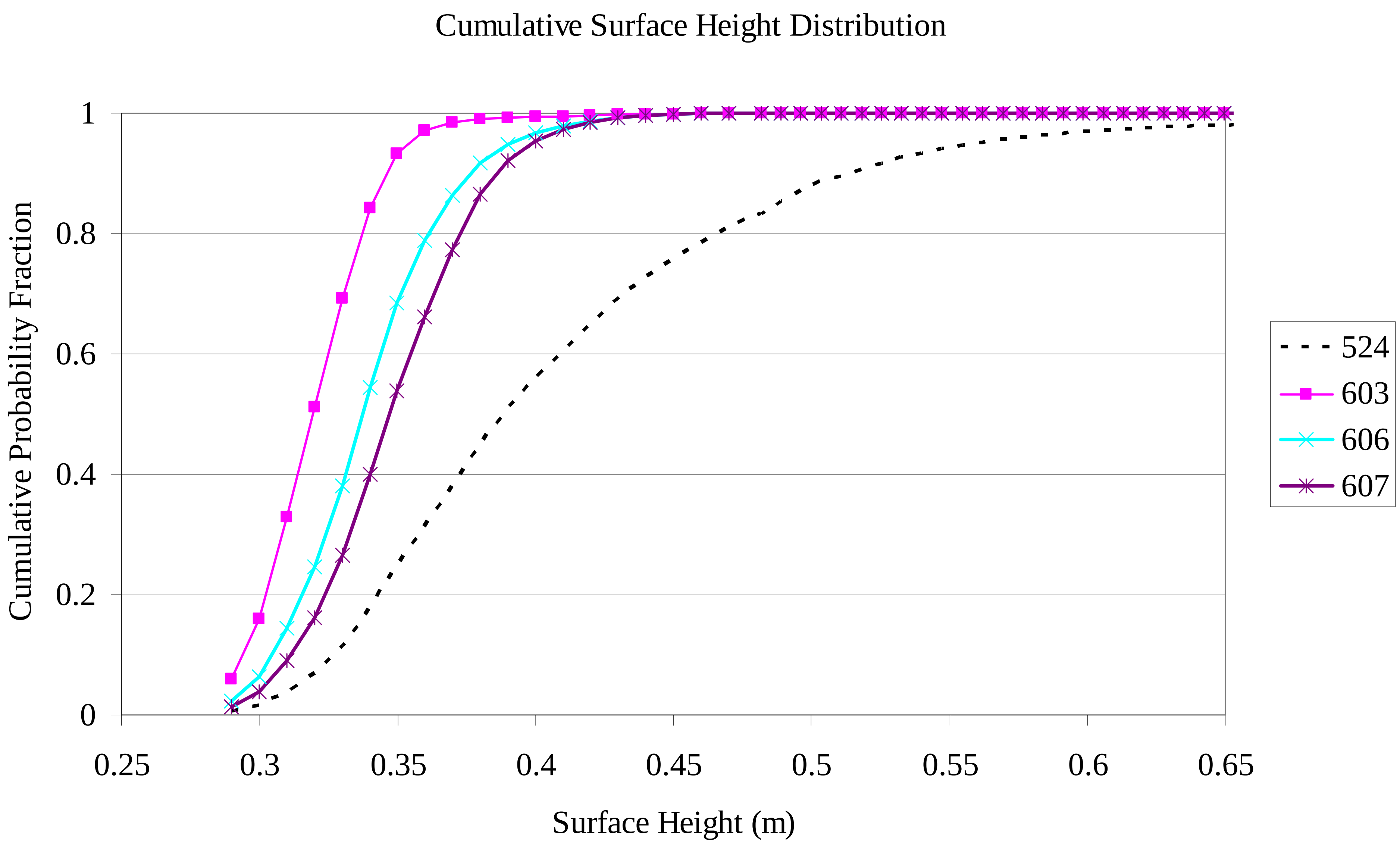
Areas Pond Covered on June 7th



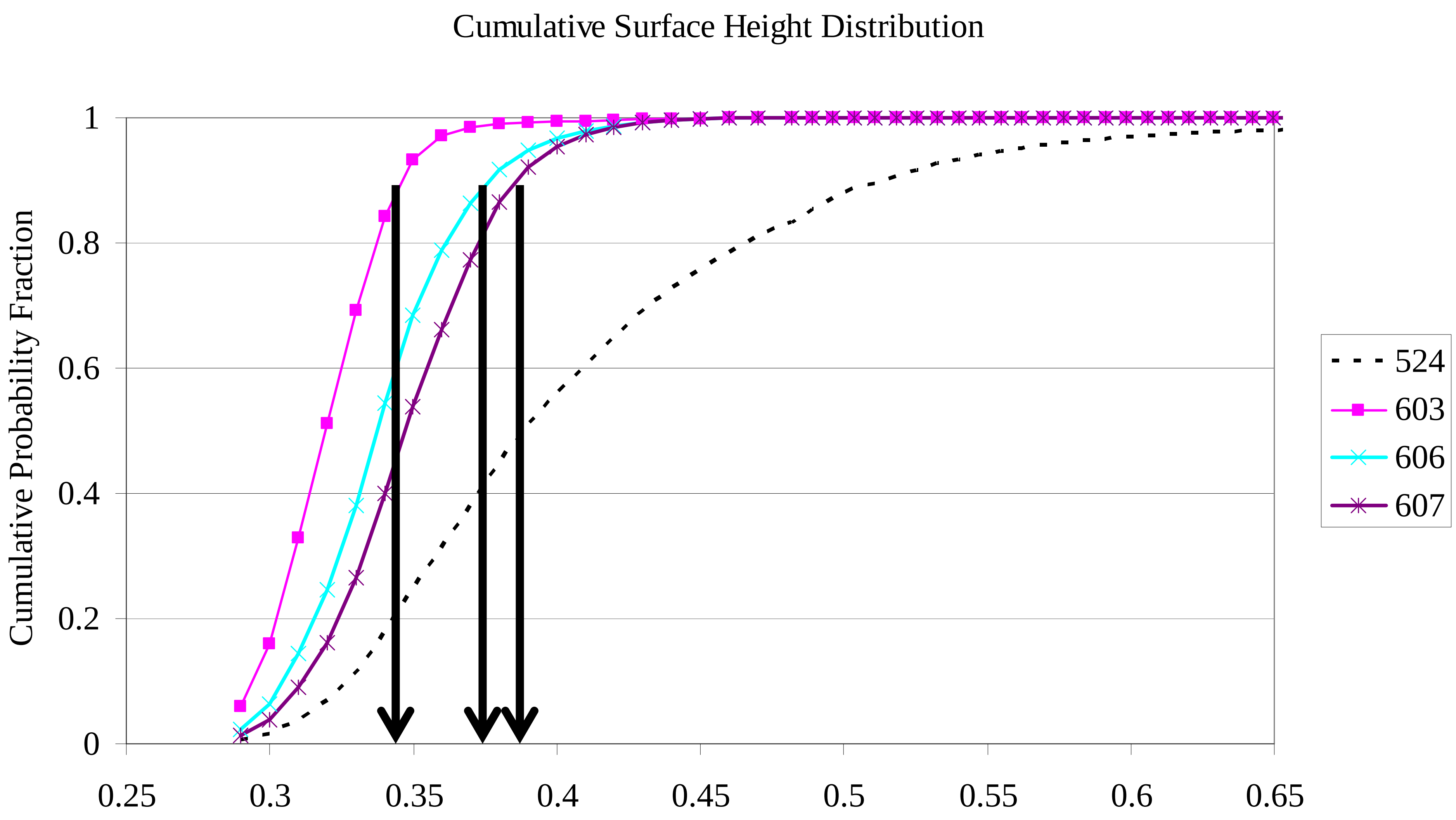
Topography Where Ponds Will Form



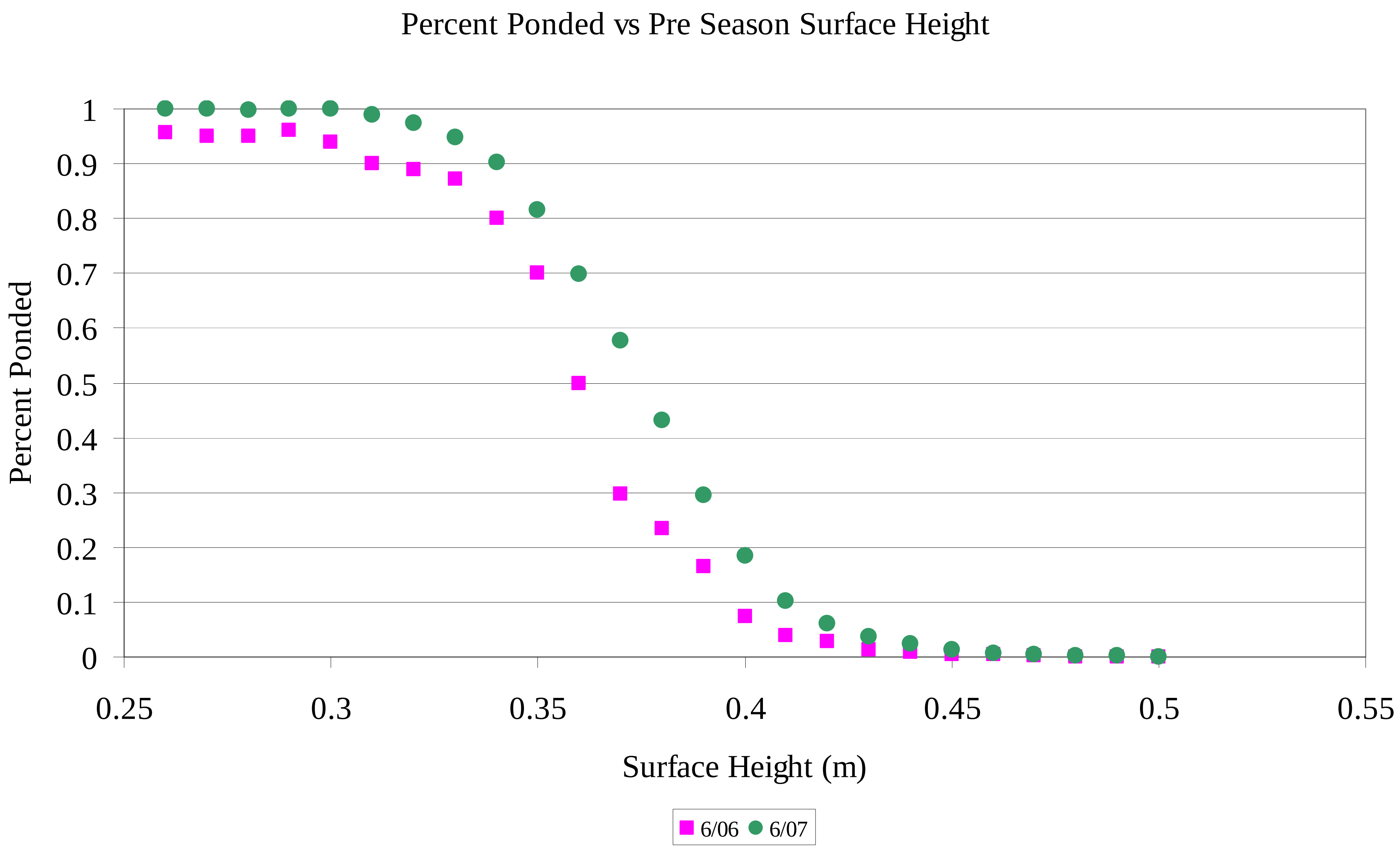




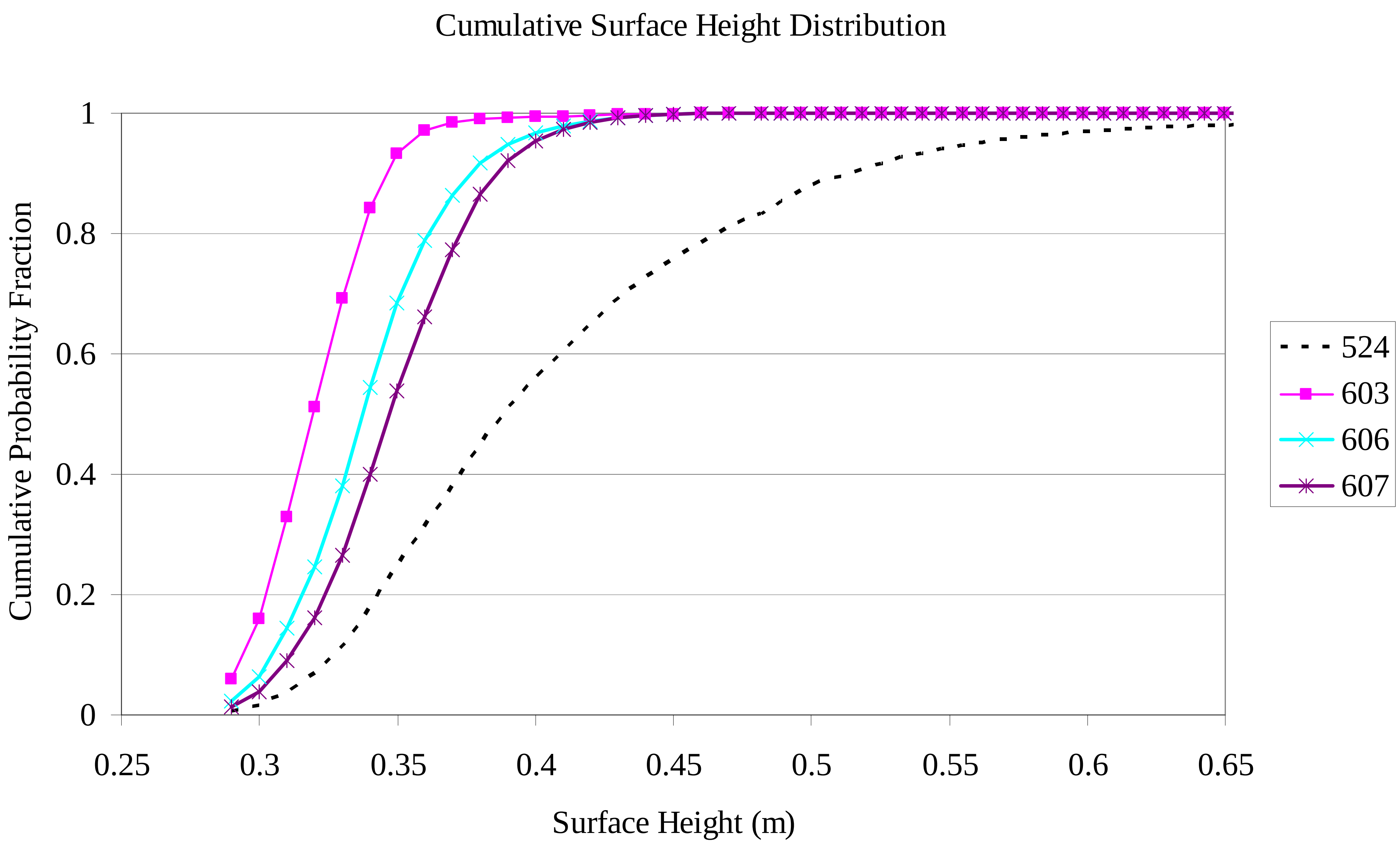
Cumulative Surface Height Distribution
Cumulative Probability Fraction
1
0.8
0.6
0.4
0.2
0
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
Surface Height (m)
524
603
606
607



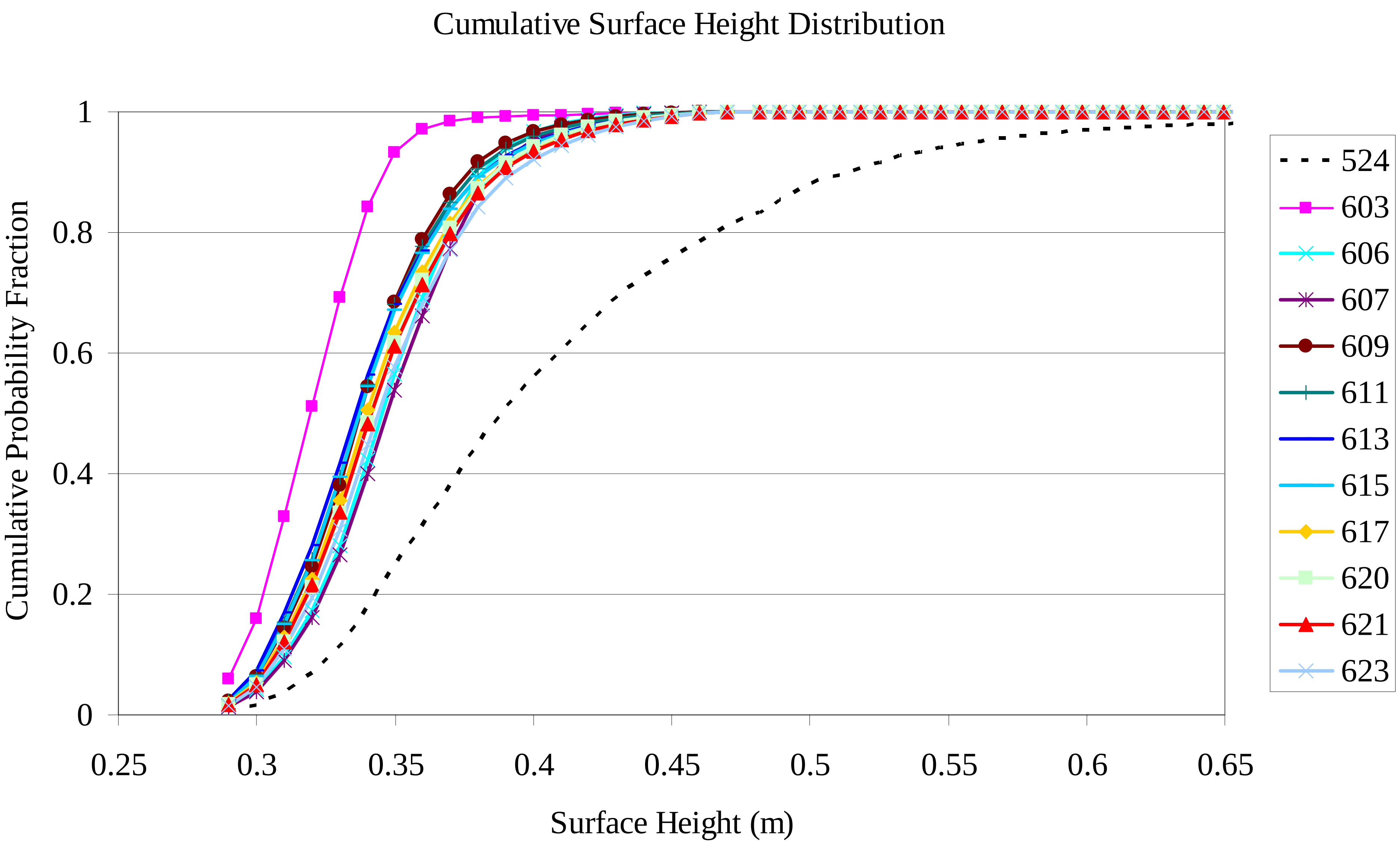
Stage I Pond Growth is Essentially Surface Flooding



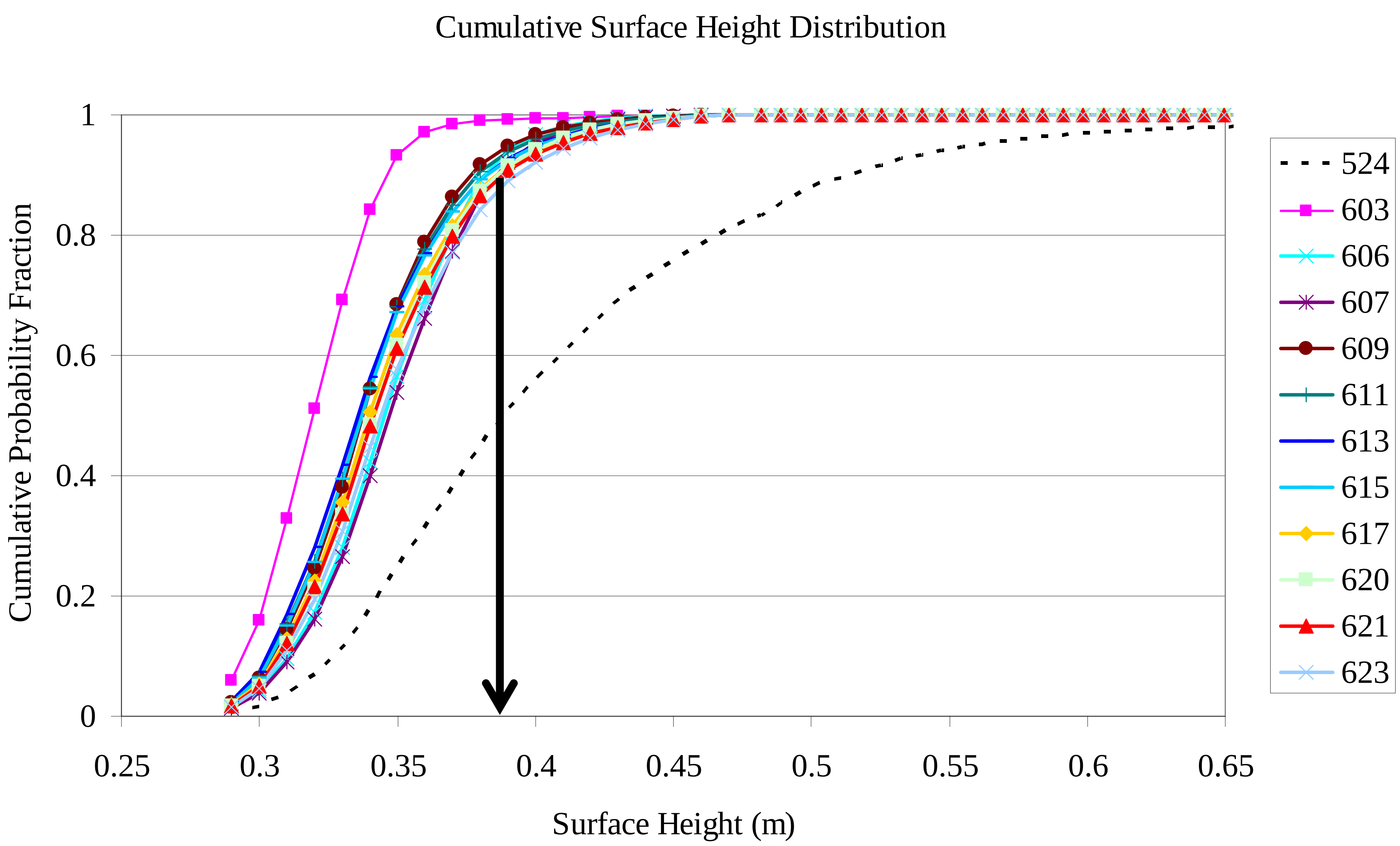
Percent Ponded vs Pre Season Surface Height
Percent Ponded
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.25
0.3
0.35
0.4
0.45
0.5
0.55
Surface Height (m)
6/06
6/07



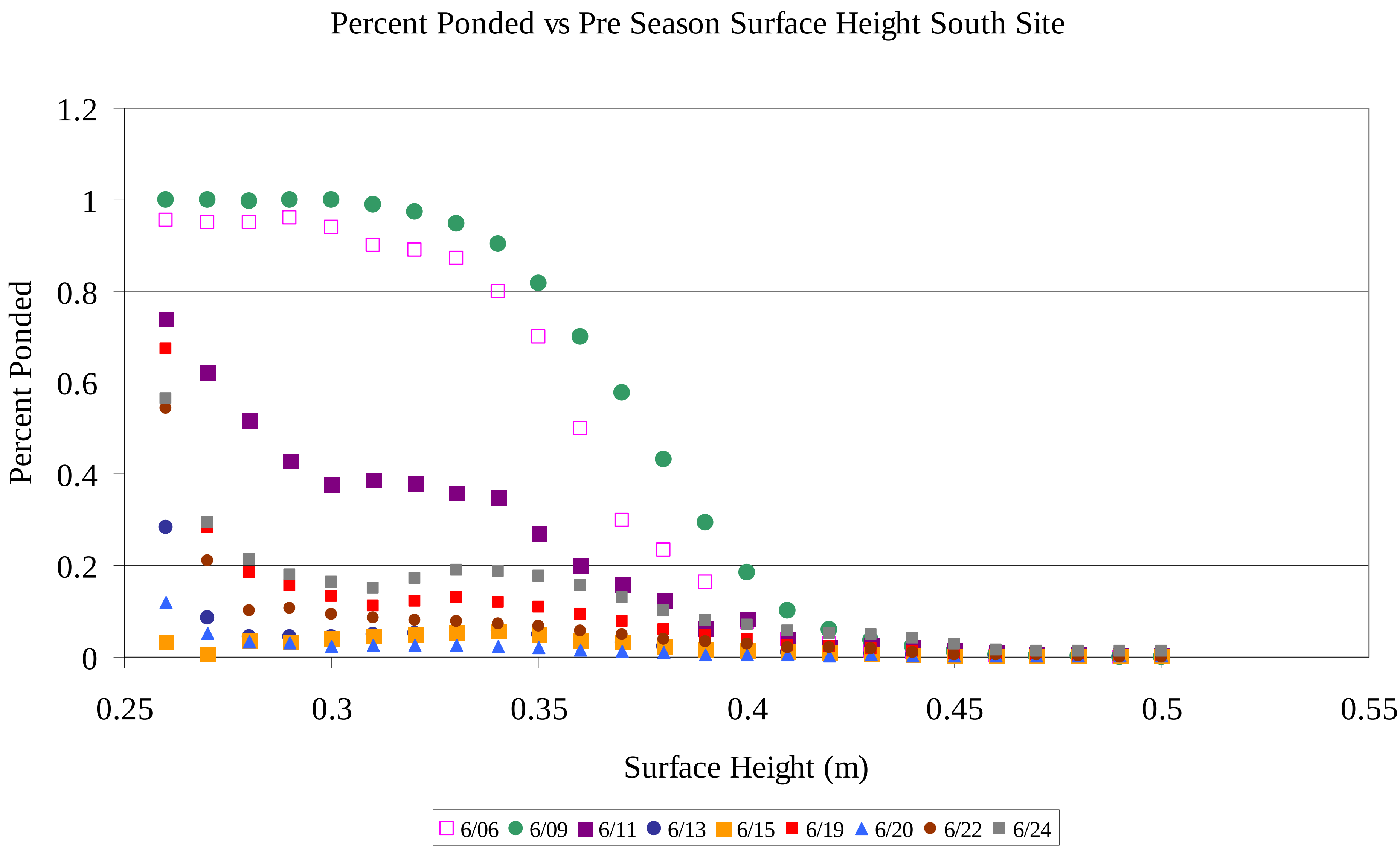
Cumulative Surface Height Distribution
Cumulative Probability Fraction
Surface Height (m)
1
0.8
0.6
0.4
0.2
0
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
524
603
606
607



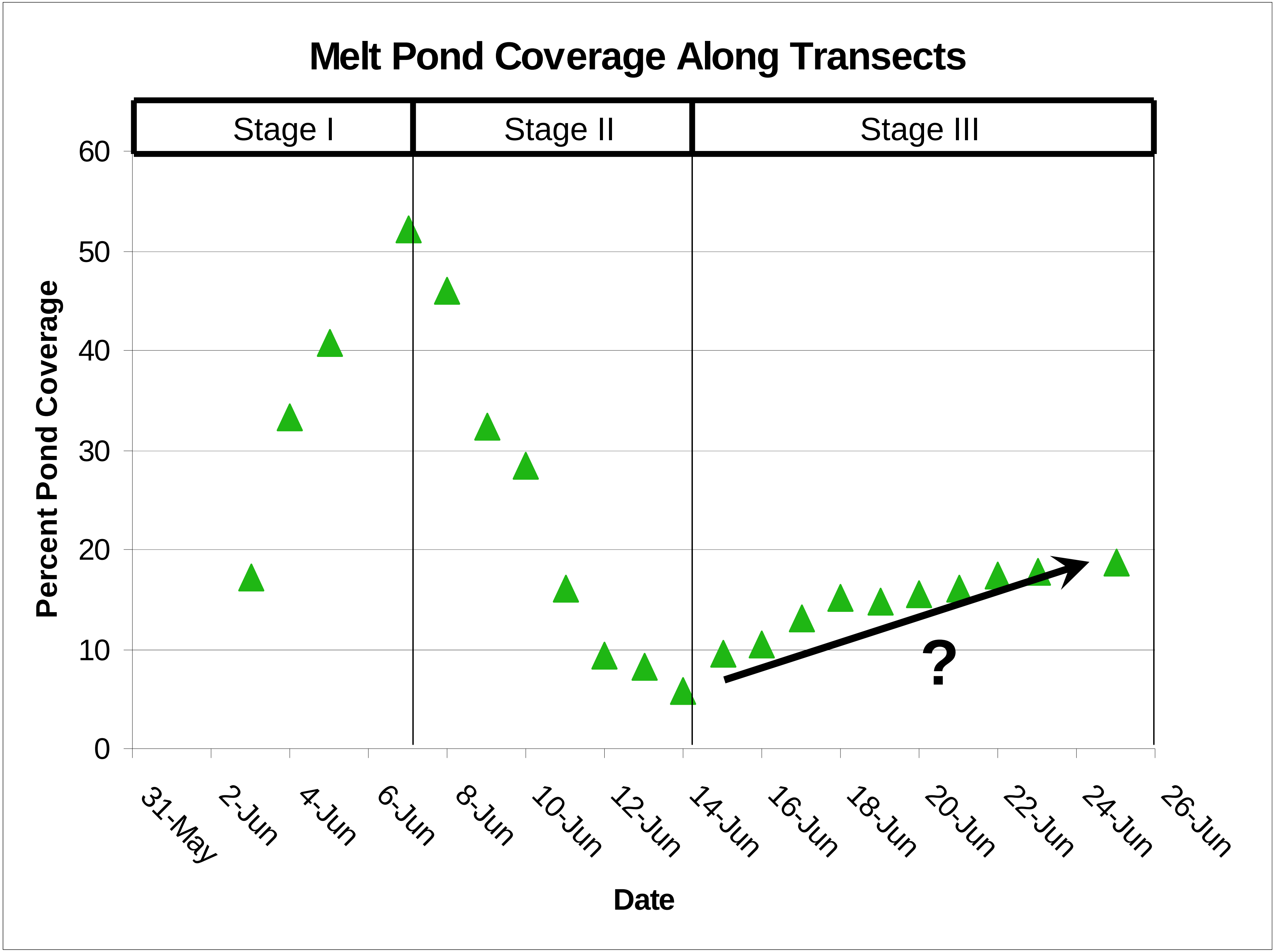
Stage II and III Ponds only form where ponds formed in stage one



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

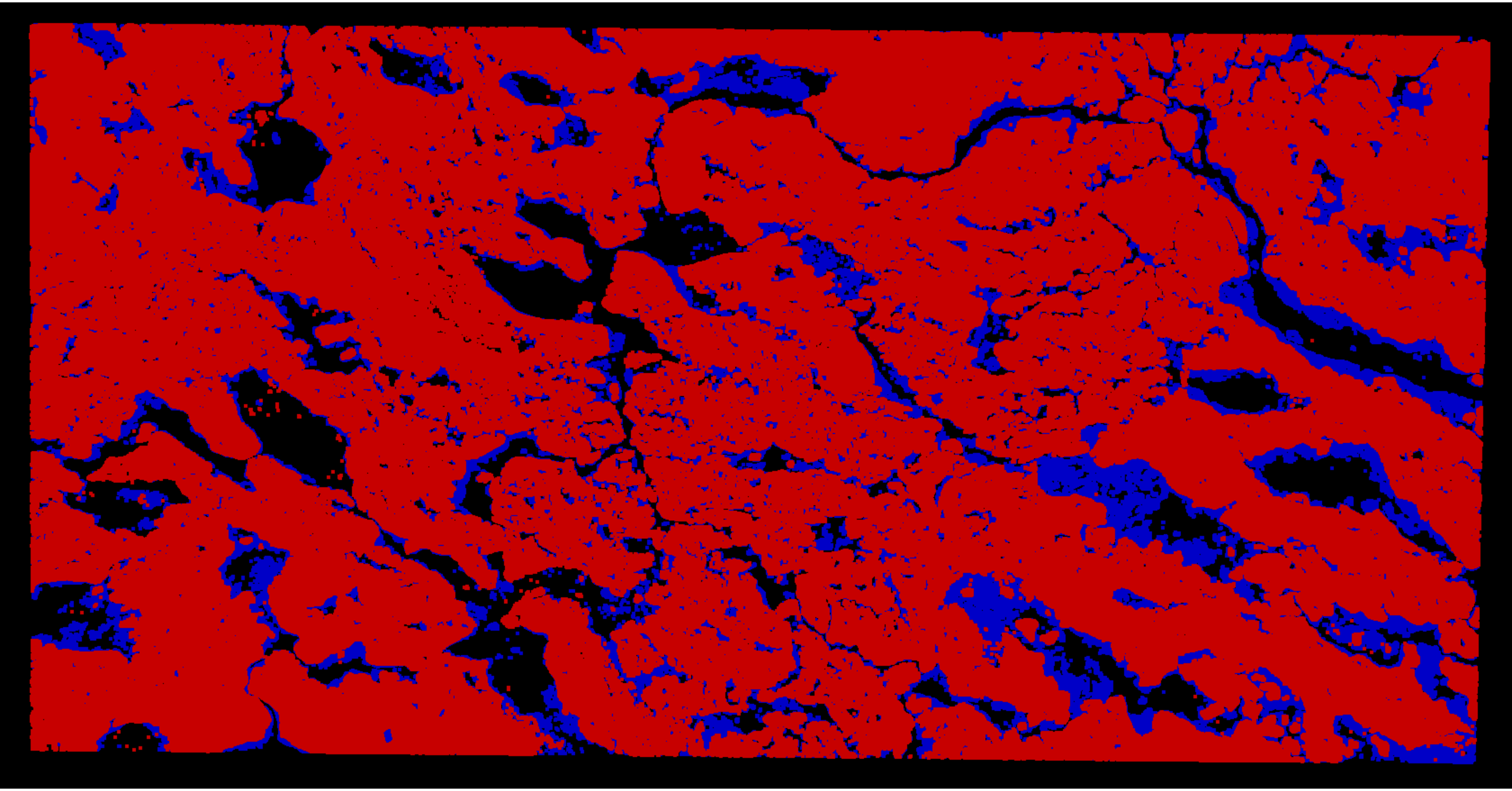


On level ice, snow dunes control surface height distribution and pond formation.



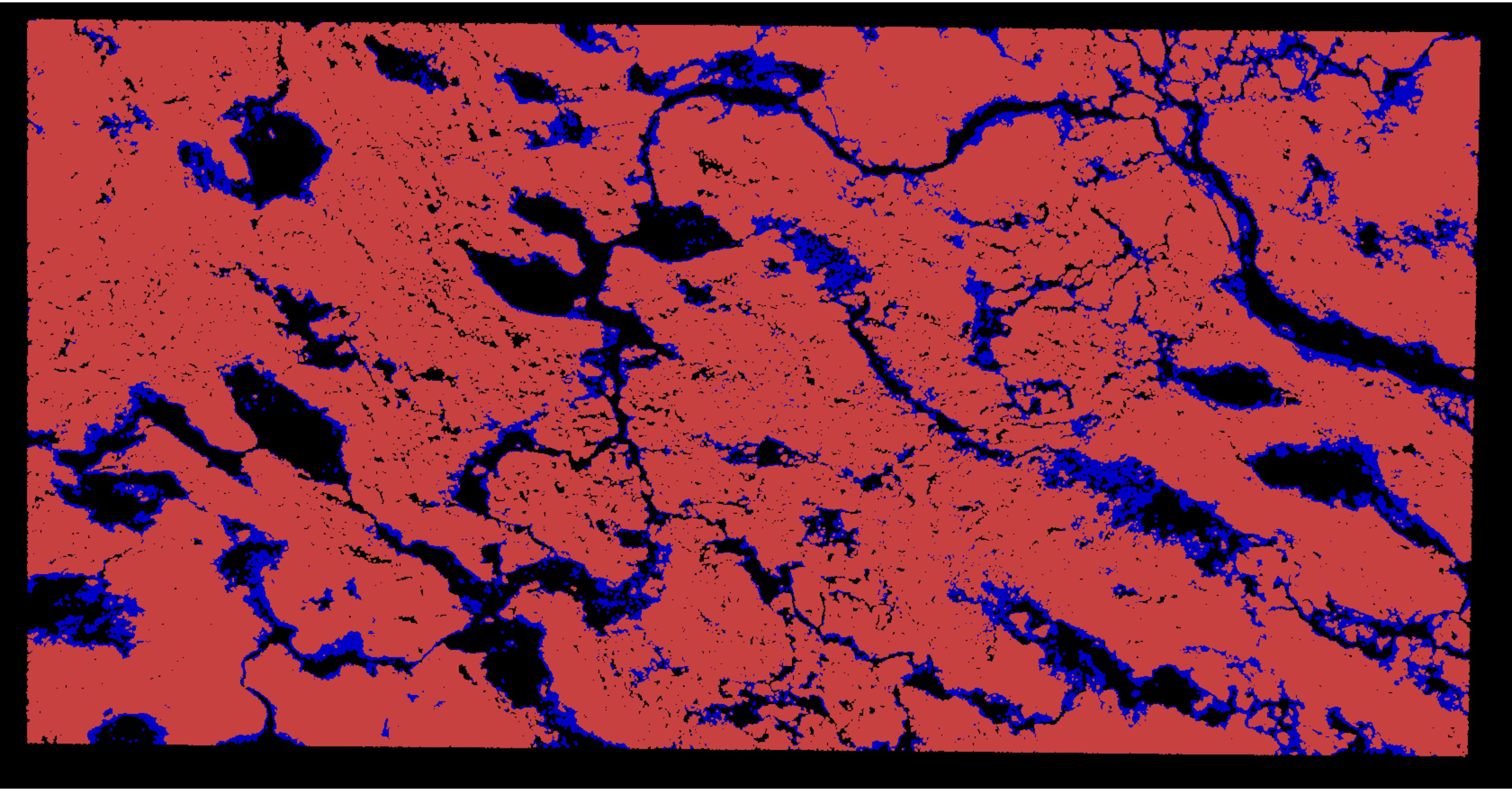
Melt Pond Coverage Along Transects
Stage I
Stage II
Stage III
Percent Pond Coverage
0
10
20
30
40
50
60
31-May
2-Jun
4-Jun
6-Jun
8-Jun
10-Jun
12-Jun
14-Jun
16-Jun
18-Jun
20-Jun
22-Jun
24-Jun
26-Jun
Date
?

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

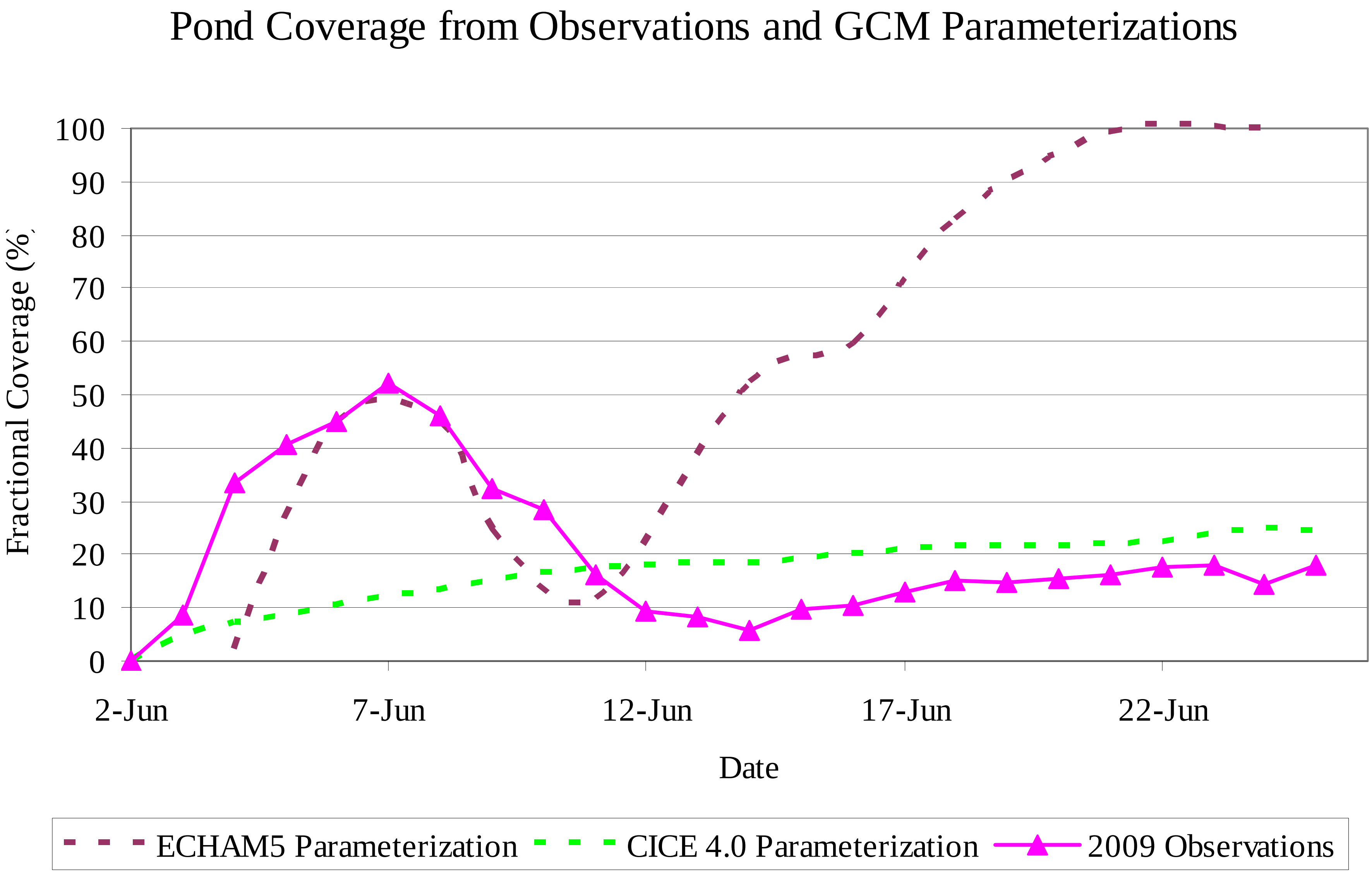
CICE 4.0 Documentation

Pond Parameterization

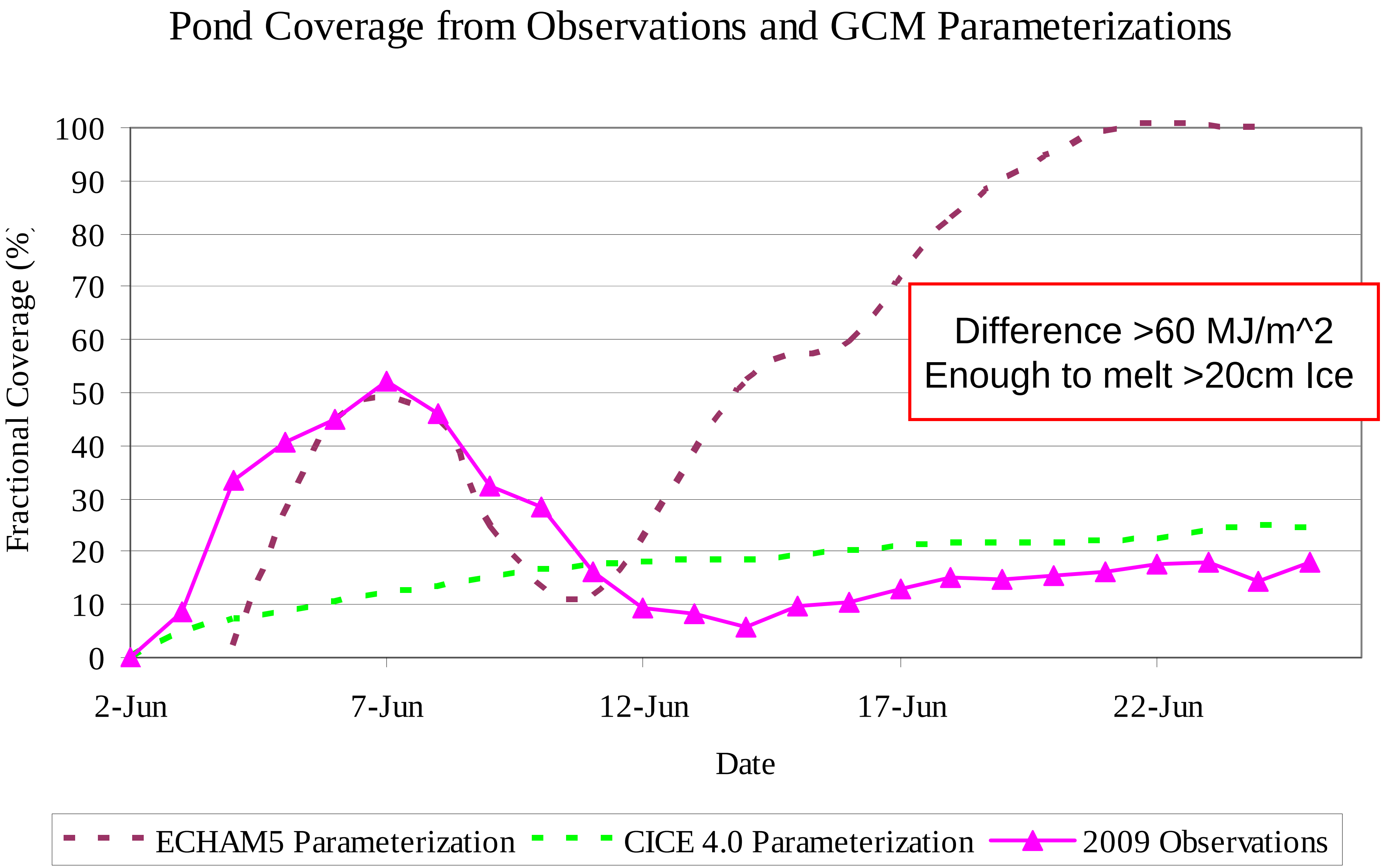
ECHAM 5

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

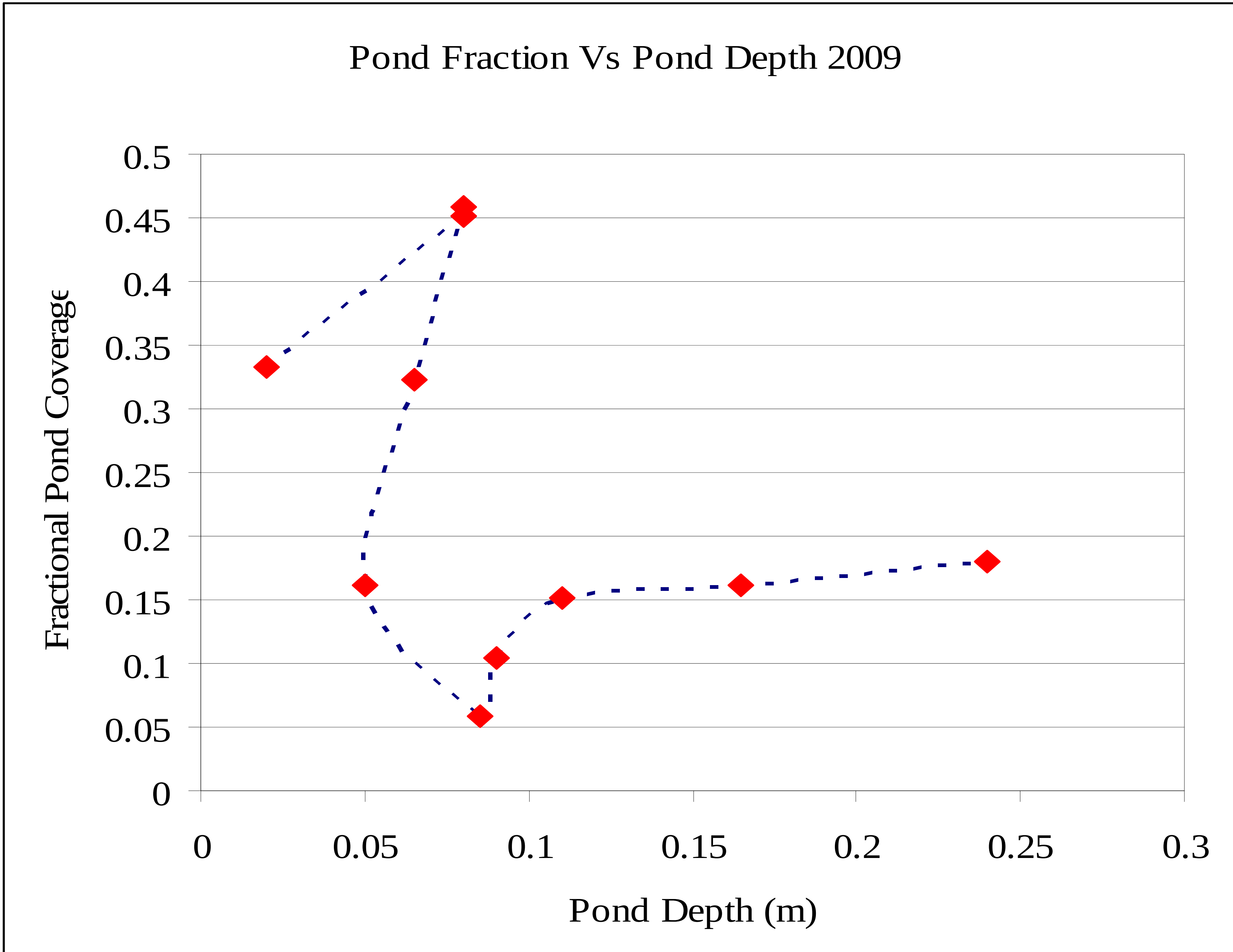
Pond fraction is related to pond depth by this function



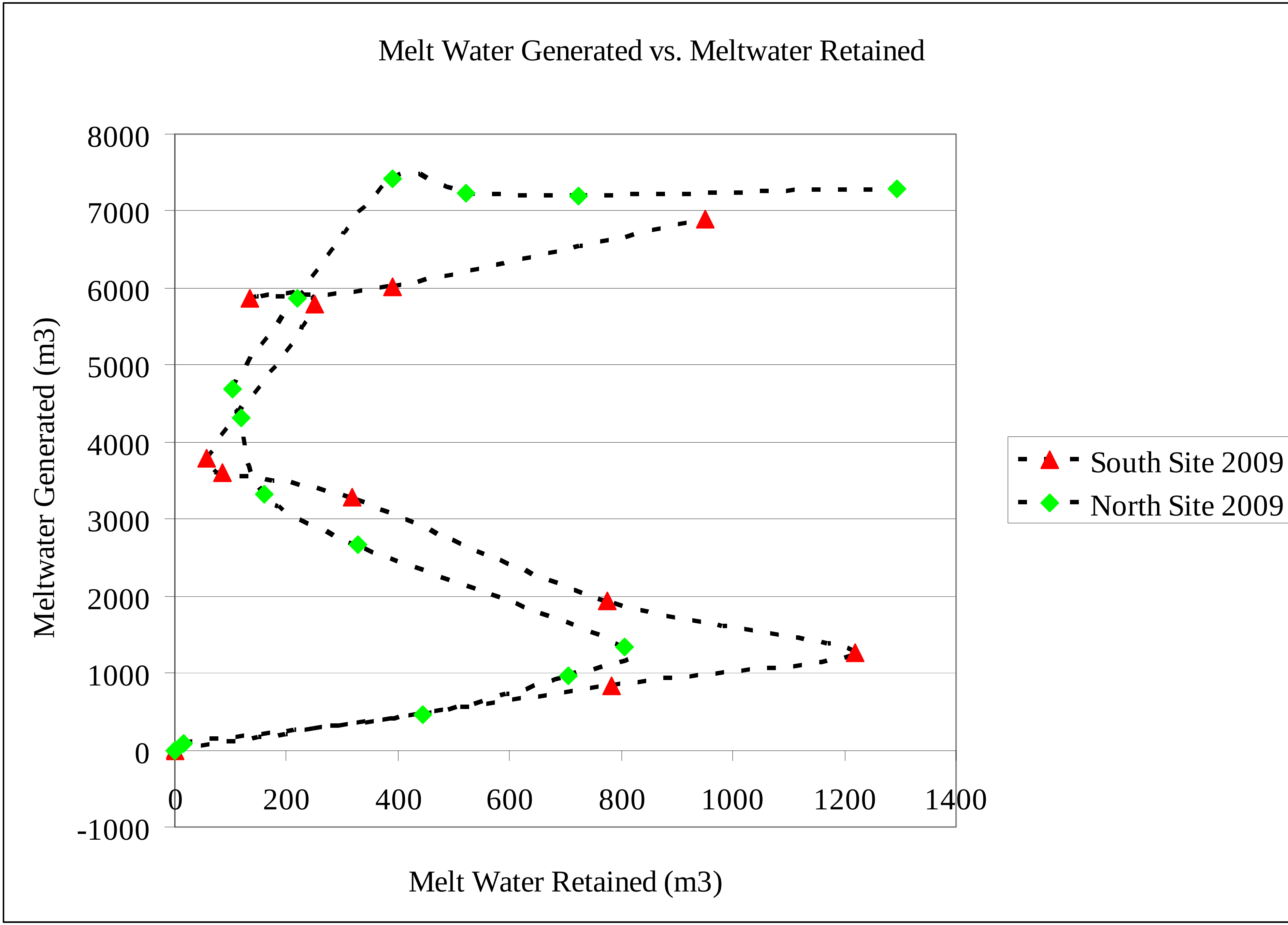
Pond Coverage from Observations and GCM Parameterizations
Fractional Coverage (%)
100
90
80
70
60
50
40
30
20
10
0
2-Jun
7-Jun
12-Jun
17-Jun
22-Jun
Date
ECHAM5 Parameterization
CICE 4.0 Parameterization
2009 Observations



Pond Coverage from Observations and GCM Parameterizations
Fractional Coverage (%)
100
90
80
70
60
50
40
30
20
10
0
2-Jun
7-Jun
12-Jun
17-Jun
22-Jun
Date
Difference >60 MJ/m^2
Enough to melt >20cm Ice
ECHAM5 Parameterization
CICE 4.0 Parameterization
2009 Observations



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
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
0
200
400
600
800
1000
1200
1400
Meltwater Generated (m3)
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